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by
C. A. Hart

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GEOMETRY

by

C. A. Hart

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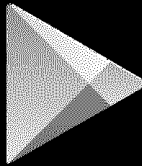
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PLANE AND SOLID GEOMETRY

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H.-F. PLANE AND SOLID GEOMETRY.

W. P. I

PREFACE

THIS book is the outgrowth of an experience of many years in the teaching of mathematics in secondary schools. The text has been used by many different teachers, in classes of all stages of development, and under varying conditions of secondary school teaching. The proofs have had the benefit of the criticisms of hundreds of experienced teachers of mathematics throughout the country. The book in its present form is therefore the combined product of experience, classroom test, and severe criticism.

The following are some of the leading features of the book :

The student is rapidly initiated into the subject. Definitions are given only as needed.

The selection and arrangement of theorems is such as to meet the general demand of teachers, as expressed through the Mathematical Associations of the country.

Most of the proofs have been given in full. In the Plane Geometry, proofs of some of the easier theorems and constructions are left as exercises for the student, or are given in an incomplete form. In the Solid Geometry, more proofs and parts of proofs are thus left to the student; but in every case in which the proof is not complete, the incompleteness is specifically stated.

The indirect method of proof is consistently applied. The usual method of proving such propositions, for example, as Arts. 189 and 415, is confusing to the student. The method used here is convincing and clear.

The exercises are carefully selected. In choosing exercises, each of the following groups has been given due importance :

(a) Concrete exercises, including numerical problems and problems of construction.

(b) So-called practical problems, such as indirect measurements of heights and distances by means of equal and similar triangles, drawing to scale as an application of similar figures, problems from physics, from design, etc,

(c) Traditional exercises of a more or less abstract nature.

The arrangement of the exercises is pedagogical. Comparatively easy exercises are placed immediately after the theorems of which they are applications, instead of being grouped together without regard to the principles involved in them. For the benefit of the brighter pupils, however, and for review classes, long lists of more or less difficult exercises are grouped at the end of each book.

The definitions of closed figures are unique. The student's natural conception of a plane closed figure, for example, is not the boundary line only, nor the plane only, but the *whole figure* composed of the boundary line and the plane bounded. All definitions of closed figures involve this idea, which is entirely consistent with the higher mathematics.

The numerical treatment of magnitudes is explicit, the fundamental principles being definitely assumed (Art. 336, proof in Appendix, Art. 595). This novel procedure furnishes a logical, as well as a teachable, method of dealing with incommensurables.

The area of a rectangle is introduced by actually measuring it, thereby obtaining its measure-number. This method permits the same order of theorems and corollaries as is used in the parallelogram and the triangle. The *correlation with arithmetic* in this connection is valuable. A similar method is employed for introducing the volume of a parallelepiped.

Proofs of the superposition theorems and the concurrent line theorems will be found exceptionally accurate and complete.

The many historical notes will add life and interest to the work.

The carefully arranged summaries throughout the book, the collection of formulas of Plane Geometry, and the collection of formulas of Solid Geometry, it is hoped, will be found helpful to teacher and student alike.

Argument and reasons are arranged in parallel form. This arrangement gives a definite model for proving exercises, renders the careless omission of the reasons in a demonstration impossible, leads to accurate thinking, and greatly lightens the labor of reading papers.

Every construction figure contains all necessary construction lines. This method keeps constantly before the student a model for his construction work, and distinguishes between a figure for a construction and a figure for a theorem.

The mechanical arrangement is such as to give the student every possible aid in comprehending the subject matter.

The following are some of the special features of the Solid Geometry :

The vital relation of the Solid Geometry to the Plane Geometry is emphasized at every point. (See Arts. 703, 786, 794, 813, 853, 924, 951, 955, 961, etc.)

The student is given every possible aid in forming his early space concepts. In the early work in Solid Geometry, the average student experiences difficulty in fully comprehending space relations, that is, in *seeing* geometric figures in space. The student is aided in overcoming this difficulty by the introduction of many easy and practical questions and exercises, as well as by being encouraged to *make* his figures. (See § 605.) As a further aid in this direction, reproductions of models made by students themselves are shown in a group (p. 302) and at various points throughout Book VI.

The student's knowledge of the things about him is constantly drawn upon. Especially is this true of the work on the sphere, where the student's knowledge of mathematical geography has been appealed to in making clear the terms and the relations of figures connected with the sphere.

The same logical rigor that characterizes the demonstrations in the Plane Geometry is used throughout the Solid.

The treatment of the polyhedral angle (p. 336), of the prism (p. 345), and of the pyramid (p. 350) is similar to that of the cylinder and of the cone. This is in accordance with the recommendations of the leading Mathematical Associations throughout the country.

The grateful acknowledgment of the authors is due to many friends for helpful suggestions; especially to Miss Grace A. Bruce, of the Wadleigh High School, New York; to Mr. Edward B. Parsons, of the Boys' High School, Brooklyn; and to Professor McMahan, of Cornell University.

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SYMBOLS AND ABBREVIATIONS

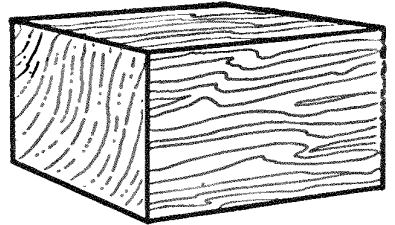
| | | |
|---|----------|----------------|
| $=$ equals, equal to, is equal to. | $rt.$ | right. |
| \neq does not equal. | $str.$ | straight. |
| $>$ greater than, is greater than. | $ext.$ | exterior. |
| $<$ less than, is less than. | $int.$ | interior. |
| \cong equivalent, equivalent to, is equivalent to. | $alt.$ | alternate. |
| \sim similar, similar to, is similar to. | $def.$ | definition. |
| \propto is measured by. | $ax.$ | axiom. |
| \perp perpendicular, perpendicular to, is perpendicular to. | $post.$ | postulate. |
| $\perp s$ perpendiculars. | $hyp.$ | hypothesis. |
| \parallel parallel, parallel to, is parallel to. | $prop.$ | proposition. |
| $\parallel s$ parallels. | $prob.$ | problem. |
| \dots and so on (sign of continuation). | $th.$ | theorem. |
| \because since. | $cor.$ | corollary. |
| \therefore therefore. | $cons.$ | construction. |
| \frown arc; \widehat{AB} , arc AB . | $ex.$ | exercise. |
| \square , \square parallelogram, parallelograms. | $fig.$ | figure. |
| \odot , \odot circle, circles. | $iden.$ | identity. |
| \sphericalangle , \sphericalangle angle, angles. | $comp.$ | complementary. |
| \triangle , \triangle triangle, triangles. | $sup.$ | supplementary. |
| | $adj.$ | adjacent. |
| | $homol.$ | homologous. |
| <p>Q.E.D. Quod erat demonstrandum, <i>which was to be proved.</i></p> <p>Q.E.F. Quod erat faciendum, <i>which was to be done.</i></p> <p>The signs $+$, $-$, \times, \div have the same meanings as in algebra.</p> | | |

PLANE GEOMETRY

INTRODUCTION

1. The Subject Matter of Geometry. In geometry, although we shall continue the use of arithmetic and algebra, our main work will be a study of what will later be defined (§ 13) as geometric figures. The student is already familiar with the physical objects about him, such as a ball or a block of wood. By a careful study of the following exercise, he may be led to see the relation of such physical solids to the geometric figures with which he must become familiar.

Exercise. Look at a block of wood (or a chalk box). Has it weight? color? taste? shape? size? These are called *properties* of the solid. What do we call such a solid? *A physical solid.* Can you think of the properties of this solid apart from the block of wood? Imagine the block removed. Can you imagine the space which it occupied? What name would you give to this space? *A geometric solid.*



What properties has it that the block possessed? *Shape and size.* What is it that separates this geometric solid from surrounding space? How thick is this surface? How many surfaces has the block? Where do they intersect? How many intersections are there? How wide are the intersections? how long? What is their name? *They are lines.* Do these lines intersect? where? How wide are these intersections? how thick? how long? Can you say *where* this one is and so distinguish from *where* that one is? What is its name? *It is a point.*

If you move the block through space, what will it generate as it moves? What will the surfaces of the block generate? all of them? Can you move a surface so that it will not generate a solid? *Yes, by moving it along itself.* What will the edges of the block generate? Can you move an edge so that it will not generate a surface? What will the corners generate? Can you move a point so that it will not generate a line?

FOUR FUNDAMENTAL GEOMETRIC CONCEPTS

2. The space in which we live, although boundless and unlimited in extent, may be thought of as divided into parts. A physical solid occupies a limited portion of space. The portion of space occupied by a physical solid is called a **geometric solid**.

3. A geometric solid has length, breadth, and thickness. It may also be divided into parts. The boundary of a solid is called a **surface**.

4. A surface is no part of a solid. It has length and breadth, but no thickness. It may also be divided into parts. The boundary of a surface is called a **line**.

5. A line is no part of a surface. It has length only. It may also be divided into parts. The boundary or extremity of a line is called a **point**.

A point is no part of a line. It has neither length, nor breadth, nor thickness. It cannot be divided into parts. It is position only.

THE FOUR CONCEPTS IN REVERSE ORDER

6. As we have considered geometric solid independently of surface, line, and point, so we may consider point independently, and from it build up to the solid.

A small dot made with a sharp pencil on a sheet of paper represents approximately a **geometric point**.

7. If a point is allowed to move in space, the path in which it moves will be a **line**.

A piece of fine wire, or a line drawn on paper with a sharp pencil, represents approximately a geometric line. This, however fine it may be, has *some* thickness and is not therefore an *ideal*, or geometric, line.

8. If a line is allowed to move in space, its path in general will be a **surface**.

9. If a surface is allowed to move in space, its path in general will be a **geometric solid**.

10. A solid has threefold extent and so is said to have three dimensions; a surface has twofold extent and is said to have two dimensions; a line has onefold extent or one dimension; a point has no extent and has therefore no dimensions.

11. The following may be used as working definitions of these four fundamental concepts:

A **geometric solid** is a limited portion of space.

A **surface** is that which bounds a solid or separates it from an adjoining solid or from the surrounding space.

A **line** is that which has length only.

A **point** is position only.

DEFINITIONS AND ASSUMPTIONS

12. The primary object of elementary geometry is to determine, by a definite process of reasoning that will be introduced and developed later, the properties of geometric figures. In all logical arguments of this kind, just as in a debate, certain fundamental principles are agreed upon at the outset, and upon these as a foundation the argument is built. In elementary geometry these fundamental principles are called *definitions* and *assumptions*.

The assumptions here mentioned are divided into two classes, *axioms* and *postulates*. These, as well as the definitions, will be given throughout the book as occasion for them arises.

13. Def. A **geometric figure** is a point, line, surface, or solid, or a combination of any or all of these.

14. Def. **Geometry** is the science which treats of the properties of geometric figures.

15. Def. A **postulate** may be defined as the assumption of the possibility of performing a certain geometric operation.

Before giving the next definition, it will be necessary to introduce a postulate.

16. Transference postulate. *Any geometric figure may be moved from one position to another without change of size or shape.*

17. Def. Two geometric figures are said to **coincide** if, when either is placed upon the other, each point of one lies upon some point of the other.

18. Def. Two geometric figures are **equal** if they can be made to coincide.

19. Def. The process of placing one figure upon another so that the two shall coincide is called **superposition**.

This is an *imaginary* operation, no actual movement taking place.

LINES

20. A line is usually designated by two capital letters, as line AB . It may be designated also by a small letter placed somewhere on the line, as line a .



21. Straight Lines. In § 7 we learned that a piece of fine wire or a line drawn on a sheet of paper represented approximately a geometric line. So also a geometric *straight line* may be represented approximately by a string stretched taut between two points, or by the line made by placing a *ruler* (also called a *straightedge*) on a flat surface and drawing a sharp pencil along its edge.



FIG. 1.

22. Questions. How does a gardener test the straightness of the edge of a flower bed? How does he get his plants set out in straight rows? How could you test the straightness of a wire? Can you think of a wire not straight, but of such shape that you could cut out a piece of it and slip it along the wire so that it would always fit? If you reversed this piece, so that its ends changed places, would it still fit along the entire length of the wire? If you turned it over, would it fit? Would the piece cut out fit under these various conditions if the wire were straight?

23. Def. A straight line is a line such that, if any portion of it is placed with its ends in the line, the entire portion so placed will lie in the line, however it may be applied.

Thus, if AB is a straight line, and if any portion of AB , as CD , is placed on any other part of AB , with its ends in AB , every point of CD will lie in AB .



FIG. 2.

A straight line is called also a **right line**. The word line, unqualified, is understood to mean straight line.

24. Straight line postulate. *A straight line may be drawn from any one point to any other.*

25. Draw a straight line AB . Can you draw a second straight line from A to B ? If so, where will every point of the second line lie (§ 23)? It then follows that:

Only one straight line can be drawn between two points; i.e. a straight line is determined by two points.

26. Draw two straight lines AB and CD intersecting in point P . Show that AB and CD cannot have a second point in common (§ 23). It then follows that:

Two intersecting straight lines can have only one point in common; i.e. two intersecting straight lines determine a point.

27. Def. A limited portion of a straight line is called a **line segment**, or simply a **line**, or a **segment**. Thus, in Fig. 2, AC , CD , and DB are line segments.

28. Def. Two line segments which lie in the same straight line are said to be **collinear segments**.

29. Def. A **curved line** (or **curve**) is a line no portion of which is straight, as GH .

30. Def. A **broken line** is a line made up of different successive straight lines, as KL .

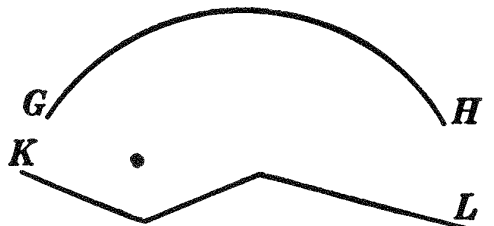


FIG. 3.

31. Use of Instruments. Only two instruments are permitted in the constructions of plane geometry: the *ruler* or *straight-edge* for drawing a straight line, already spoken of in § 21; and the *compasses*, for constructing circles or arcs of circles, and for transferring line segments from one position to another.

Thus to add two lines, as AB and CD , draw, with a ruler, a straight line OX . Place one leg of the compasses at A and the other at B . Next place one leg at O and cut off segment OM equal to AB . In a similar manner lay off MN equal to CD . Then $AB + CD = OM + MN = ON$.

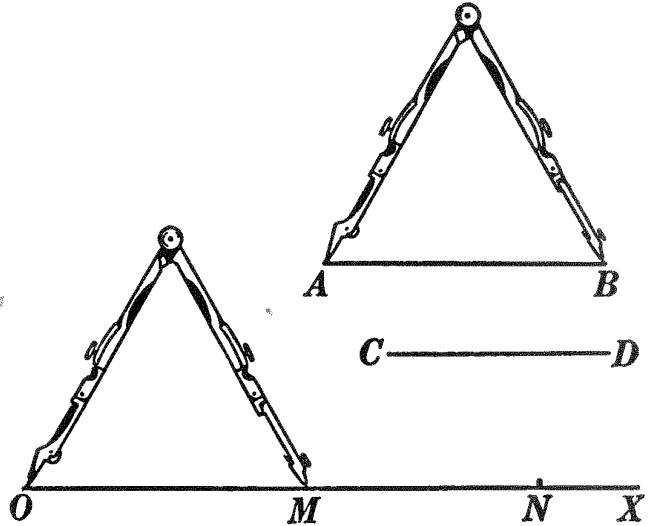


FIG. 4.

Show how to subtract AB from ON . What is the remainder?

Ex. 1. Can a straight line move so that its path will not be a surface? If so, how?

Ex. 2. Can a curved line move in space so that its path will not be a surface? If so, how?

Ex. 3. Can a broken line move in space so that its path will not be a surface?

Ex. 4. Draw three lines as AB , CD , and EF . Construct the sum of AB and CD ; of AB and EF ; of AB , CD , and EF .

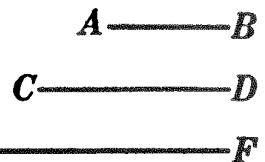


FIG. 5.

Ex. 5. Construct: (a) the difference between AB and CD ; (b) the difference between CD and EF ; (c) the difference between AB and EF . Add the results obtained for (a) and (b) and see whether the sum is the result obtained for (c).

Ex. 6. Draw a line twice as long as AB (the sum of AB and AB); three times as long as AB .

SURFACES

32. Plane Surface. It is well known that the carpenter's straightedge is applied to surfaces to test whether they are flat and even. If, no matter where the straightedge is placed on the surface, it always fits, the surface is called a plane. Now if we should use a powerful magnifier, we should doubtless discover that in certain places the straightedge did not exactly fit the surface on which it was placed. A sheet of fine plate glass more nearly approaches the ideal.

33. Questions. Test the surface of the blackboard with a ruler to see whether it is a plane. How many times must you apply the ruler? Can you think of a surface such that the ruler would fit in some positions (a great many) but not in all? Can you think of a surface not plane but such that a piece of it could be cut out and slipped along the rest so that it would fit? Would it fit if turned over (inside out)?

34. Def. A plane surface (or plane) is a surface of unlimited extent such that whatever two of its points are taken, a straight line joining them will lie wholly in the surface.

35. Def. A curved surface is a surface no portion of which is plane.

36. Def. A plane figure is a geometric figure all of whose points lie in one plane. **Plane Geometry** treats of plane figures.

37. Def. A rectilinear figure is a plane figure all the lines of which are straight lines.

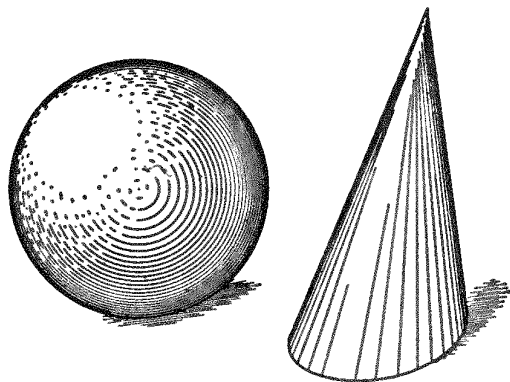


FIG. 6.

Ex. 7. How can a plane move in space so that its path will not be a solid?

Ex. 8. Can a curved surface move in space so that its path will not be a solid? If so, how?

ANGLES

38. Def. An angle is the figure formed by two straight lines which diverge from a point.

The point is the **vertex** of the angle and the lines are its **sides**.

39. An angle may be **designated** by a number placed within it, as angle 1 and angle 2 in Fig. 7, and angle 3 in Fig. 8. Or

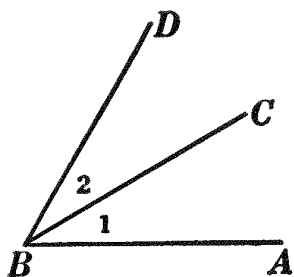


FIG. 7.

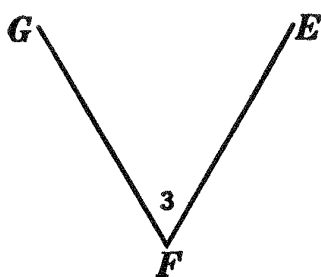


FIG. 8.

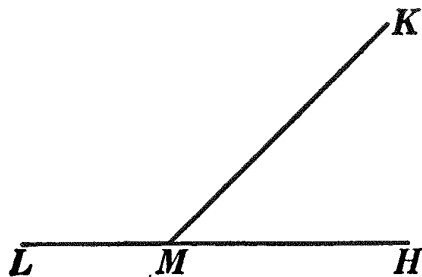


FIG. 9.

three letters may be used, one on each side and one at the vertex, the last being read between the other two; thus in Fig. 7, angle 1 may be read angle ABC , and angle 2, angle CBD . An angle is often designated also by the single letter at its vertex, when no other angle has the same vertex, as angle F in Fig. 8.

40. Revolution postulate. *A straight line may revolve in a plane, about a point as a pivot, and when it does revolve continuously from one position to another, it passes once and only once through every intermediate position.*

41. A clear notion of the *magnitude* of an angle may be obtained by imagining that its two sides were at first collinear, and that one of them has *revolved* about a point common to the two. Thus in Fig. 8. we may imagine FG first to have been in the position FE and then to have revolved about F as a pivot to the position FG .

42. Def. Two angles are **adjacent** if they have a common vertex and a common side which lies between them; thus in Fig. 7, angle 1 and angle 2 are adjacent; also in Fig. 9, angle HMK and angle KML are adjacent.

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46. Def. If two lines meet, but are not perpendicular to each other, they are said to be **oblique** to each other.

47. Def. An **acute angle** is an angle that is less than a right angle; as angle 1, Fig. 13.

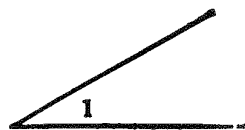


FIG. 13.

48. Def. An **obtuse angle** is an angle that is greater than a right angle and less than two right angles; as angle 2, Fig. 14.

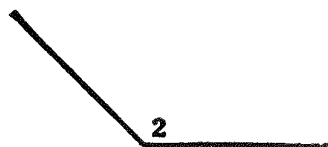


FIG. 14.

49. Def. A **reflex angle** is an angle that is greater than two right angles and less than four right angles; as angle 2, Fig. 15.

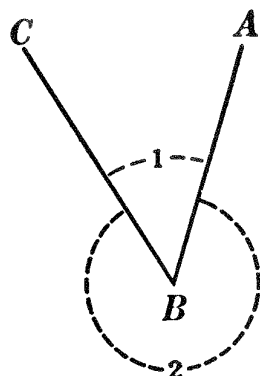


FIG. 15.

50. Note. Two lines diverging from the same point, as BA and BC , Fig. 15, always form two positive angles, as the acute angle 1 and the reflex angle 2. Angle 1 may be thought of as formed by the revolution of a line counter-clockwise from the position BA to the position BC , and should be read angle ABC . Angle 2 may be thought of as formed by the revolution of a line counter-clockwise from the position BC to the position BA , and should be read angle CBA .

51. Def. Acute, obtuse, and reflex angles are sometimes called **oblique angles**.

Ex. 9. (a) In Fig. 16, if angle 1 equals angle 2, what kind of angles are they?

(b) Make a statement with regard to the lines AB and CD .

(c) If angle 3 does not equal angle 4, what kind of angles are they?

(d) Make a statement with regard to the lines AB and CE .

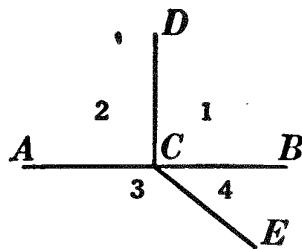


FIG. 16.

Ex. 10. A plumb line is suspended from the top of the blackboard. What kind of angles does it make with a horizontal line drawn on the blackboard? with a line on the blackboard neither horizontal nor vertical?

Ex. 11. Suppose the minute hand of a clock is at twelve. Where may the hour hand be so that the two hands make with each other: (a) an acute angle? (b) a right angle? (c) an obtuse angle?

Ex. 12. Draw: (a) a pair of adjacent angles; (b) a pair of non-adjacent angles.

Ex. 13. Draw two adjacent angles such that: (a) each is an acute angle; (b) each is a right angle; (c) each is an obtuse angle; (d) one is acute and the other right; (e) one is acute and the other obtuse.

Ex. 14. In Fig. 17, angle 1 + angle 2 = ? angle 3 + angle 4 = ? angle BAD + angle DAF = ? angle DAF - angle 3 = ? angle 2 + angle DAF - angle 4 = ? angle 4 + angle BAE - angle 1 = ?

Ex. 15. Name six pairs of adjacent angles in Fig. 17.

Ex. 16. Draw two non-adjacent angles that have: (a) a common vertex; (b) a common side; (c) a common vertex and a common side.

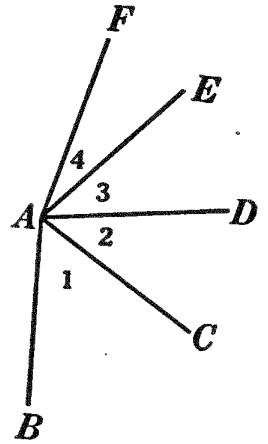


FIG. 17.

52. Def. A line is said to be bisected if it is divided into two equal parts.

53. Def. The bisector of an angle is the line which divides the angle into two equal angles.*

Ex. 17. Draw a line AB , neither horizontal nor vertical. (a) Draw freehand a line perpendicular to AB and not bisecting it: (b) a line bisecting AB and not perpendicular to it.

ASSUMPTIONS

54. 1. Things equal to the same thing, or to equal things, are equal to each other.

2. If equals are added to equals, the sums are equal.

3. If equals are subtracted from equals, the remainders are equal.

4. If equals are added to unequals, the sums are unequal in the same order.

5. If equals are subtracted from unequals, the remainders are unequal in the same order.

* The proof that every angle has but one bisector will be found in the Appendix, § 599.

6. *If unequals are subtracted from equals, the remainders are unequal in the reverse order.*

7. (a) *If equals are multiplied by equals, the products are equal;* (b) *if unequals are multiplied by equals, the products are unequal in the same order.*

8. (a) *If equals are divided by equals, the quotients are equal;* (b) *if unequals are divided by equals, the quotients are unequal in the same order.*

9. *If unequals are added to unequals, the less to the less and the greater to the greater, the sums are unequal in the same order.*

10. *If three magnitudes of the same kind are so related that the first is greater than the second and the second greater than the third, then the first is greater than the third.*

11. *The whole is equal to the sum of all its parts.*

12. *The whole is greater than any of its parts.*

13. *Like powers of equal numbers are equal, and like roots of equal numbers are equal.*

14. **Transference postulate.** *Any geometric figure may be moved from one position to another without change of size or shape. (See § 16.)*

15. **Straight line postulate I.** *A straight line may be drawn from any one point to any other. (See § 24.)*

16. **Straight line postulate II.** *A line segment may be prolonged indefinitely at either end.*

17. **Revolution postulate.** *A straight line may revolve in a plane, about a point as a pivot, and when it does revolve continuously from one position to another, it passes once and only once through every intermediate position. (See § 40.)*

55. Assumptions 1–13 are usually called axioms. That is, an **axiom** may be defined as a statement whose truth is assumed.*

Ex. 18. Illustrate the first five assumptions above by using arithmetical numbers only.

Ex. 19. Illustrate the next five by using general numbers (letters) only

* See Appendix, § 600.

DEMONSTRATIONS

56. It has been stated (§ 12) that the fundamental principles agreed upon at the outset as forming the basis of the logical arguments in geometry are called definitions, axioms, and postulates. Every new proposition advanced, whether it is a statement of a truth or a statement of something to be performed, must by a process of reasoning be shown to depend upon these fundamental principles. This process of reasoning is called a **proof** or **demonstration**. After the truth of a statement has thus been established, it in turn may be used to establish new truths.

The propositions here mentioned are divided into two classes, *theorems* and *problems*.

57. Def. A **theorem** is a statement whose truth is required to be proved or demonstrated. For example, “*If two angles of a triangle are equal, the sides opposite are equal*” is a theorem.

There are two parts to every theorem: the **hypothesis**, or the conditional part; and the **conclusion**, or the part to be proved. In the theorem just quoted, “*If two angles of a triangle are equal*” is the hypothesis; and “*the sides opposite are equal*” is the conclusion.

Ex. 20. Write out carefully the hypothesis and the conclusion of each of the following :

- (a) If you do your duty at all times, you will be rewarded.
- (b) If you try to memorize your proofs, you will never learn geometry.
- (c) You must suffer if you disobey a law of nature.
- (d) Things equal to the same thing are equal to each other.
- (e) All right angles are equal.

58. Def. A **corollary** is a statement of a truth easily deduced from another truth. Its correctness, like that of a theorem, must be proved.

59. Def. A **problem**, in general, is a question to be solved. As applied to geometry, problems are of two kinds, namely, **problems of construction** and **problems of computation**.

60. From the revolution postulate (§ 40) and from the definition of a perpendicular (§ 45) we may deduce the following corollaries:

61. Cor. I. *At every point in a straight line there exists a perpendicular to the line.*

Given line AB and point C in AB .

To prove that there exists a \perp to AB at C , as CD .

Let CE (Fig. 18) meet AB at C , so that $\angle 1 < \angle 2$. Then if CE is revolved about C as a pivot toward position CA , $\angle 1$ will continuously increase and $\angle 2$ will continuously decrease (§ 40). \therefore there must be one position of CE , as CD , in which the two \sphericalangle s formed with AB are equal. In this position $CD \perp AB$ (§ 45).

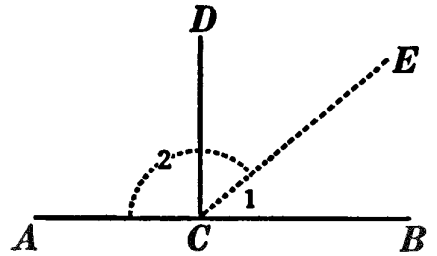


FIG. 18.

62. Cor. II. *At every point in a straight line there exists only one perpendicular to the line.*

Given $CD \perp AB$ at C , i.e. $\angle BCD = \angle DCA$.

To prove CD the only \perp to AB at C .

Let CE (Fig. 19) be any line from C other than CD . Let CE fall between CD and CA *. Then $\angle BCE > \angle BCD$; i.e. $> \angle DCA$. And $\angle ECA < \angle DCA$ (§ 54, 12). $\therefore \sphericalangle BCE$ and ECA are not equal and CE is not \perp to AB (§ 45).

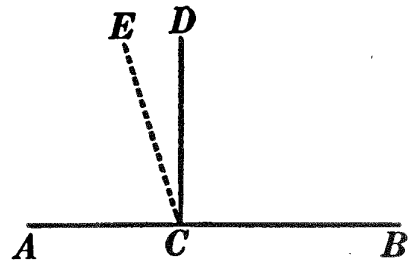


FIG. 19.

63. §§ 61 and 62 may be combined in one statement as follows:

At every point in a straight line there exists one and only one perpendicular to the line.

* A similar proof may be given if we suppose CE to fall between CB and CD .

64. Cor. III. *All right angles are equal.*



FIG. 20.

Given $\angle AOB$ and $\angle CPD$, any two rt. \sphericalangle .

To prove $\angle AOB = \angle CPD$.

Place $\angle CPD$ upon $\angle AOB$ so that point P shall fall upon point O , and so that PC shall be collinear with OA . Then PD and OB , both being \perp to OA at O , must be collinear (§ 62). \therefore the two \sphericalangle coincide and are equal (§ 18).

65. Cor. IV. *If one straight line meets another straight line, the sum of the two adjacent angles is two right angles.*

Given str. line CD meeting str. line AB at C , forming $\sphericalangle BCD$ and DCA .

To prove $\angle BCD + \angle DCA = 2 \text{ rt. } \sphericalangle$.

Let CE be \perp to AB at C (§ 63).

Then $\angle BCD + \angle DCE = 1 \text{ rt. } \sphericalangle$;

$$\therefore \angle BCD = 1 \text{ rt. } \sphericalangle - \angle DCE.$$

Again $\angle DCA = 1 \text{ rt. } \sphericalangle + \angle DCE$.

$$\therefore \angle BCD + \angle DCA = 2 \text{ rt. } \sphericalangle.$$

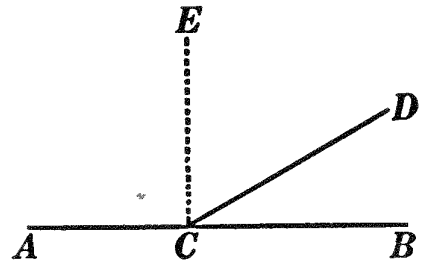


FIG. 21.

66. Cor. V. *The sum of all the angles about a point on one side of a straight line passing through that point equals two right angles.*

Given $\sphericalangle 1, 2, 3, 4, 5$, and 6 , all the \sphericalangle about point O on one side of str. line CA .

To prove $\angle 1 + \angle 2 + \angle 3 + \angle 4 + \angle 5 + \angle 6 = 2 \text{ rt. } \sphericalangle$.

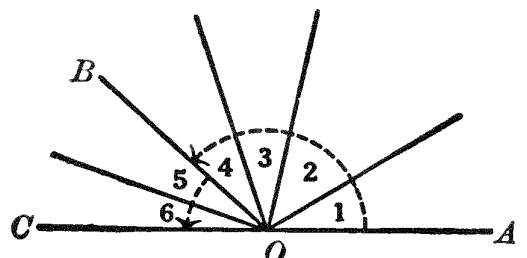


FIG. 22.

The sum of the six \sphericalangle (Fig. 22) is equal to $\angle AOB + \angle BOC$.

67. Cor. VI. *The sum of all the angles about a point equals four right angles.*

Prolong one of the lines through the vertex and apply Cor. V.

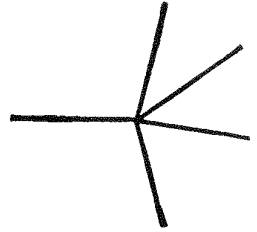


FIG. 23.

68. Def. Two angles whose sum is one right angle are called **complementary** angles, as angles 1 and 2, Fig. 25. Either of two such angles is said to be the **complement** of the other.

69. Def. Two angles whose sum is two right angles are called **supplementary** angles, as angles 1 and 2, Fig. 26. Either of two such angles is said to be the **supplement** of the other.

An angle that is equal to the sum of two right angles is sometimes called a **straight angle**, as angle ABC , Fig. 26.

70. Def. Two angles are said to be **vertical** if the sides of each are the prolongations of the sides of the other; thus, in Fig. 24, angles 1 and 2 are vertical angles, and angles 3 and 4 are likewise vertical angles.

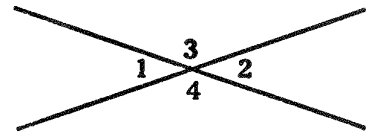


FIG. 24.

71. Def. An angle of one degree is one ninetyeth of a right angle. A right angle, therefore, contains 90 angle degrees.

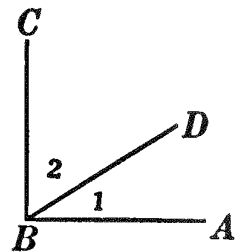


FIG. 25.

Ex. 21. In Fig. 25, angle ABC is a right angle. If angle $1 = 40^\circ$, how many degrees are there in angle 2? How many degrees, then, are there in the complement of an angle of 40° ?

Ex. 22. How many degrees are there in the complement of 20° ? of 35° ? of a° ? of $\frac{1}{3}$ right angles? of k right angles?

Ex. 23. In Fig. 26, angle $1 +$ angle 2, or angle ABC , equals 2 right angles. If angle $1 = 40^\circ$, how many degrees are there in angle 2? How many degrees, then, are there in the supplement of an angle of 40° ?

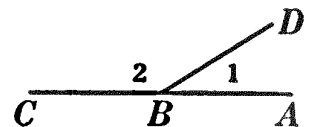


FIG. 26.

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Ex. 36. (a) Can two angles be supplementary and not adjacent? Illustrate.

(b) Can two angles be adjacent and not supplementary? Illustrate.

(c) Can two angles be both supplementary and adjacent? Illustrate.

(d) Can two angles be neither supplementary nor adjacent? Illustrate.

(e) Can two angles be both complementary and adjacent? Illustrate.

(f) Can two angles be both complementary and supplementary? Illustrate.

73. From the definitions of complementary and supplementary angles may be deduced three additional corollaries as follows:

74. Cor. I. *Complements of the same angle or of equal angles are equal.*

75. Cor. II. *Supplements of the same angle or of equal angles are equal.*

76. Cor. III. *If two adjacent angles are supplementary, their exterior sides are collinear.*

Given $\angle ABC + \angle CBD = 2 \text{ rt. } \sphericalangle$.

To prove BD the prolongation of AB .

If BD is not the prolongation of AB , then some other line from B , as BE , must be its prolongation.

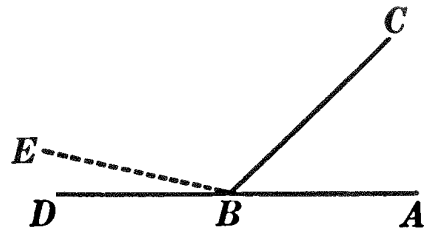


FIG. 29.

Then $\angle ABC + \angle CBD = 2 \text{ rt. } \sphericalangle$ (By hyp.).

Also $\angle ABC + \angle CBE = 2 \text{ rt. } \sphericalangle$ (§ 65).

$\therefore \angle CBD = \angle CBE$ (§ 75).

This is impossible (§ 54, 12); *i.e.* the supposition that BE is the prolongation of AB leads, by correct reasoning, to the impossible conclusion that $\angle CBD = \angle CBE$. Hence this supposition itself is false.

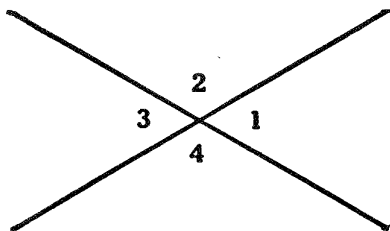
$\therefore BD$ is the prolongation of AB .

BOOK I

RECTILINEAR FIGURES

PROPOSITION I. THEOREM

77. *If two straight lines intersect, the vertical angles are equal.*



Given two intersecting str. lines, forming the vertical \sphericalangle s, 1 and 3, also 2 and 4.

To prove $\sphericalangle 1 = \sphericalangle 3$ and $\sphericalangle 2 = \sphericalangle 4$.

ARGUMENT

1. $\sphericalangle 1 + \sphericalangle 2 = 2$ rt. \sphericalangle s.
2. $\sphericalangle 3 + \sphericalangle 2 = 2$ rt. \sphericalangle s.
3. $\therefore \sphericalangle 1 + \sphericalangle 2 = \sphericalangle 3 + \sphericalangle 2$.
4. $\therefore \sphericalangle 1 = \sphericalangle 3$.
5. Likewise $\sphericalangle 2 = \sphericalangle 4$.

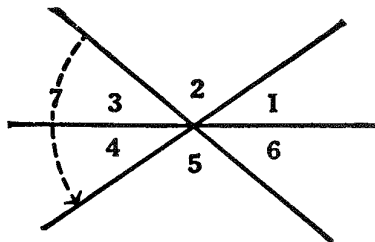
Q.E.D.

REASONS

1. If one str. line meets another str. line, the sum of the two adj. \sphericalangle s is 2 rt. \sphericalangle s. § 65.
2. Same reason as 1.
3. Things equal to the same thing are equal to each other. § 54, 1.
4. If equals are subtracted from equals, the remainders are equal. § 54, 3.
5. By steps similar to 1, 2, 3, and 4.

78. **Cor.** *If two straight lines intersect so that any two adjacent angles thus formed are equal, all the angles are equal, and each angle is a right angle.*

Ex. 37. If three straight lines intersect at a common point, the sum of any three angles, no two of which are adjacent, as 1, 3, and 5, in the accompanying diagram, is equal to two right angles.



Ex. 38. In the same diagram, show that :

(a) Angle 1 + angle 3 = angle 7.

(b) Angle 7 - angle 4 = angle 6.

(c) Angle 7 + angle 4 - angle 3 = twice angle 1.

(d) Angle 2 + angle 4 + angle 6 = 2 right angles.

Ex. 39. The line which bisects one of two vertical angles bisects the other also.

Ex. 40. The bisectors of two adjacent complementary angles form an angle of 45° .

Ex. 41. Show the relation of the bisectors of two adjacent supplementary angles to each other.

Ex. 42. The bisectors of two pairs of vertical angles are perpendicular to each other.

79. The student will observe from Prop. I that the complete solution of a theorem consists of four distinct steps :

(1) *The statement of the theorem*, including a general statement of the hypothesis and conclusion.

(2) *The drawing of a figure* (as general as possible), to satisfy the conditions set forth in the hypothesis.

(3) *The application*, i.e. the restatement of the hypothesis and conclusion as applied to the particular figure just drawn, under the headings of "Given" and "To prove."

(4) *The proof*, or demonstration, the argument by which the truth or falsity of a statement is established, with the reason for each step in the argument.

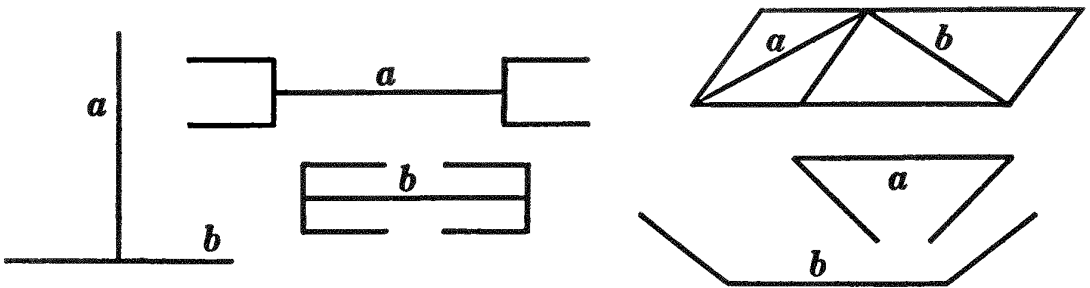
80. The student should be careful to quote the reason for every step in the argument which he makes in proving a theorem. The only reasons admissible are of two kinds :

1. Something assumed, i.e. definitions, axioms, postulates, and the hypothesis.

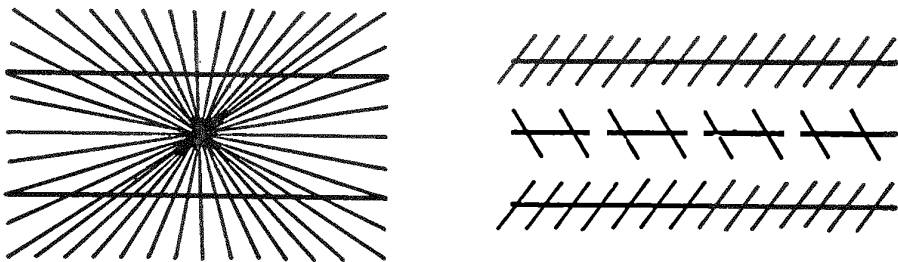
2. Something previously proved, i.e. theorems, corollaries, and problems.

81. The necessity for proof. Some theorems seem evident by merely looking at the figure, and the student will doubtless think a proof unnecessary. The eye, however, cannot always detect error, and *reasoning* enables us to be sure of our conclusions. The danger of trusting the eye is illustrated in the following exercises.*

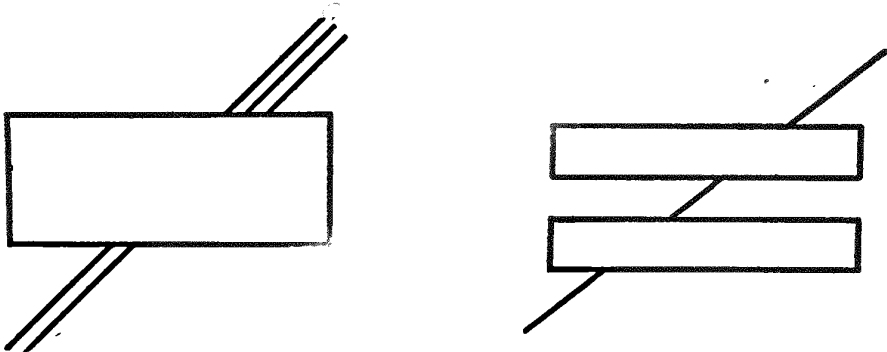
Ex. 43. In the diagrams given below, tell which line of each pair is the longer, *a* or *b*, and verify your answer by careful measurement.



Ex. 44. In the figures below, are the lines everywhere the same distance apart? Verify your answer by using a ruler or a slip of paper.



Ex. 45. In the figures below, tell which lines are prolongations of other lines. Verify your answers.



* These diagrams are taken by permission from the Report of the Committee on Geometry, Proceedings of the Eighth Meeting of the Central Association of Science and Mathematics Teachers.

POLYGONS. TRIANGLES

82. Def. A line on a plane is said to be **closed** if it separates a finite portion of the plane from the remaining portion.

83. Def. A **plane closed figure** is a plane figure composed of a closed line and the finite portion of the plane bounded by it.

84. Def. A **polygon** is a plane closed figure whose boundary is composed of straight lines only.

The points of intersection of the lines are the **vertices** of the polygon, and the segments of the boundary lines included between adjacent vertices are the **sides** of the polygon.

85. Def. The sum of the sides of a polygon is its **perimeter**.

86. Def. Any angle formed by two consecutive sides and found on the right in passing clockwise around the perimeter of a polygon is called an **interior angle** of the polygon, or, for brevity, an **angle of the polygon**. In Fig. 1, $\angle ABC$, $\angle BCD$, $\angle CDE$, $\angle DEA$, and $\angle EAB$ are interior angles of the polygon.

87. Def. If any side of a polygon is prolonged through a vertex, the angle formed by the prolongation and the adjacent side is called an **exterior angle** of the polygon.

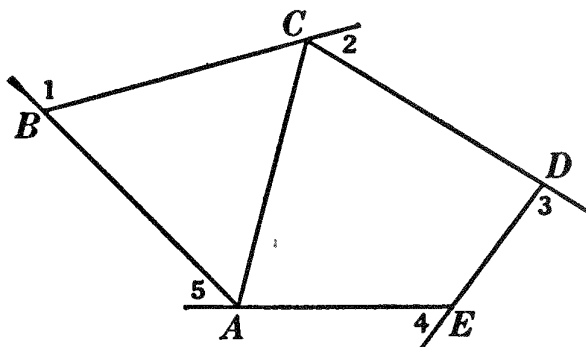


FIG. 1.

In Fig. 1, $\angle 1$, $\angle 2$, $\angle 3$, $\angle 4$, and $\angle 5$ are exterior angles.

88. Def. A line joining any two non-adjacent vertices of a polygon is called a **diagonal**; as AC , Fig. 1.

89. Def. A polygon which has all of its sides equal is an **equilateral polygon**.

90. Def. A polygon which has all of its angles equal is an **equiangular polygon**.

91. Def. A polygon which is both equilateral and equiangular is a **regular polygon**.

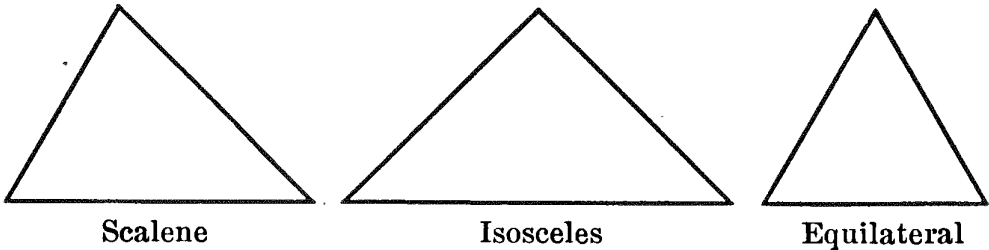
92. Def. A polygon of three sides is called a **triangle**; one of four sides, a **quadrilateral**; one of five sides, a **pentagon**; one of six sides, a **hexagon**; and so on.

TRIANGLES CLASSIFIED WITH RESPECT TO SIDES

93. Def. A triangle having no two sides equal is a **scalene triangle**.

94. Def. A triangle having two sides equal is an **isosceles triangle**. The equal sides are spoken of as **the sides** * of the triangle. The angle between the equal sides is the **vertex angle**, and the side opposite the vertex angle is called the **base**.

95. Def. A triangle having its three sides equal is an **equilateral triangle**.



TRIANGLES CLASSIFIED WITH RESPECT TO ANGLES

96. Def. A **right triangle** is a triangle which has a right angle. The side opposite the right angle is called the **hypotenuse**. The other two sides are spoken of as **the sides** † of the triangle.

97. Def. An **obtuse triangle** is a triangle which has an obtuse angle.

98. Def. An **acute triangle** is a triangle in which *all* the angles are acute.

* The equal sides are sometimes called the *arms* of the isosceles triangle. This term will be used occasionally in the exercises.

† Sometimes the sides of a right triangle including the right angle are called the *arms* of the triangle. This term will be found in the exercises.

Ex. 46. Draw a scalene triangle freehand: (a) with all its angles acute and with its shortest side horizontal; (b) with one right angle.

Ex. 47. Draw an isosceles triangle: (a) with one of its arms horizontal and one of its angles a right angle; (b) with one angle obtuse.

99. Def. The side upon which a polygon is supposed to stand is usually called its **base**; however, since a polygon may be supposed to stand upon any one of its sides, any side may be considered as its base.

The angle opposite the base of a triangle is the **vertex angle**, and the vertex of the angle is called the **vertex** of the triangle.

100. Def. The **altitude** of a triangle is the perpendicular to its base from the opposite vertex. In general any side of a triangle may be considered as its base. Thus in triangle EFG , if FG is taken as base, EH is the altitude; if GE is taken as base, FK will be the altitude; if EF is taken as base, the third altitude can be drawn. Thus every triangle has *three* altitudes.

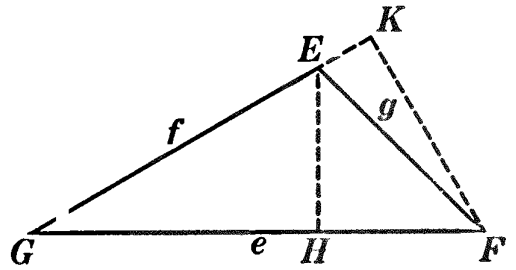


FIG. 1.

It will be proved later that one perpendicular, and only one, can be drawn from a point to a line.

101. The sides of a triangle are often designated by the small letters corresponding to the capitals at the opposite vertices; as, sides e , f , and g , Fig. 1.

Ex. 48. Draw an acute triangle; draw its three altitudes freehand. Do they seem to meet in a point? Where is this point located?

Ex. 49. Draw an obtuse triangle; draw its three altitudes freehand. Do they meet in a point? Where is this point located?

Ex. 50. Where do the three altitudes of a right triangle meet?

102. Def. The **medians** of a triangle are the lines from the vertices of the triangle to the mid-points of the opposite sides.

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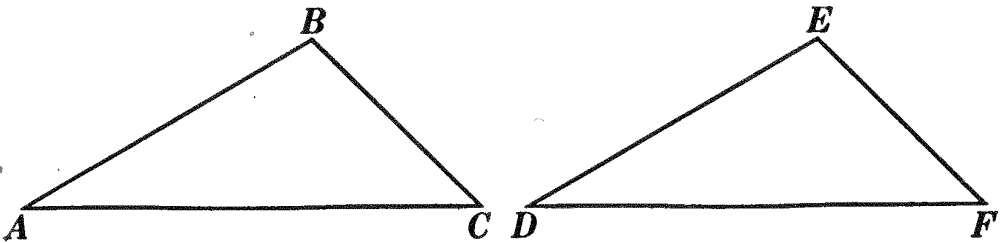
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PROPOSITION II. THEOREM

105. *Two triangles are equal if a side and the two adjacent angles of one are equal respectively to a side and the two adjacent angles of the other.*



Given $\triangle ABC$ and DEF , $AC = DF$, $\angle A = \angle D$, and $\angle C = \angle F$.
To prove $\triangle ABC = \triangle DEF$.

ARGUMENT

1. Place $\triangle ABC$ upon $\triangle DEF$ so that AC shall fall upon its equal DF , A upon D , C upon F .
2. Then AB will become collinear with DE , and B will fall somewhere on DE , or on its prolongation.
3. Also CB will become collinear with FE , and B will fall somewhere on FE , or on its prolongation.
4. \therefore point B must fall on point E .
5. $\therefore \triangle ABC = \triangle DEF$.

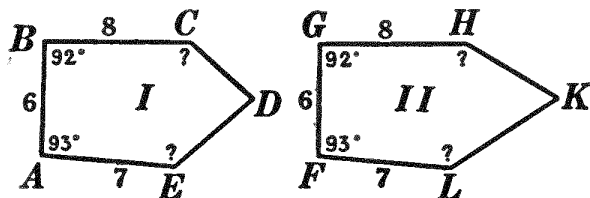
REASONS

1. Any geometric figure may be moved from one position to another without change of size or shape. § 54, 14.
2. $\angle A = \angle D$, by hyp.
3. $\angle C = \angle F$, by hyp.
4. Two intersecting str. lines determine a point. § 26.
5. Two geometric figures are equal if they can be made to coincide. § 18.

Q.E.D.

Ex. 53. In the figure for Prop. II, assume $AB = DE$, angle $A =$ angle D , and angle $B =$ angle E ; repeat the proof by superposition, marking the lines with colored crayon as soon as their positions are determined.

Ex. 54. Place polygon I upon polygon II so that some part of I shall fall upon its equal in II. Discuss the resulting positions of the remaining parts of the figure.



Ex. 55. If two quadrilaterals have three sides and the included angles of one equal respectively to three sides and the included angles of the other, and arranged in the same order, are the quadrilaterals equal? Prove.

106. Note. The method of superposition should be used for proving fundamental propositions only. In proving other propositions it is necessary to show merely that certain conditions are present and to quote theorems, previously proved, which state conclusions regarding such conditions.

Ex. 56. If at any point in the bisector of an angle a perpendicular to the bisector is drawn meeting the sides of the angle, the two triangles thus formed will be equal.

Ex. 57. If equal segments, measured from the point of intersection of two lines, are laid off on one of the lines, and if perpendiculars to this line are drawn at the ends of these segments, two equal triangles will be formed.

Ex. 58. If at the ends of a straight line perpendiculars to it are drawn, these perpendiculars will cut off equal segments upon any line which bisects the given line and is not perpendicular to it.

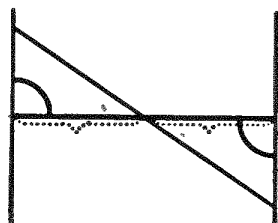


FIG. 1.



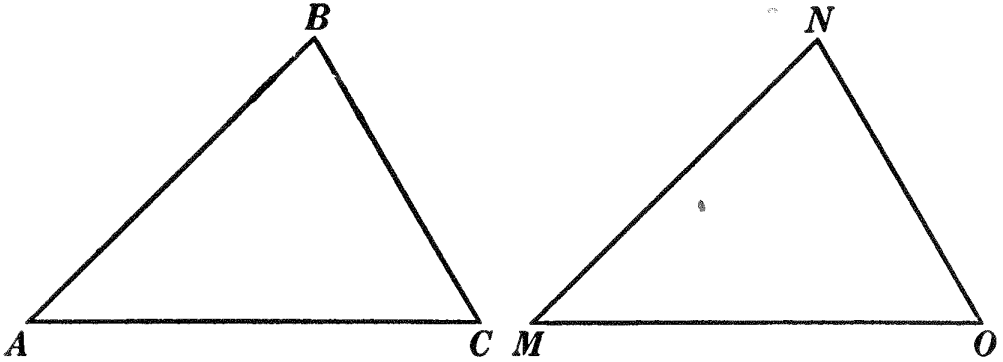
FIG. 2.

Ex. 59. If two angles of a triangle are equal, the bisectors of these angles are equal (Fig. 1).

Ex. 60. If two triangles are equal, the bisector of any angle of one is equal to the bisector of the corresponding angle of the other (Fig. 2).

PROPOSITION III. THEOREM

107. *Two triangles are equal if two sides and the included angle of one are equal respectively to two sides and the included angle of the other.*



Given $\triangle ABC$ and MNO , $AB = MN$, $AC = MO$, and $\angle A = \angle M$.

To prove $\triangle ABC = \triangle MNO$.

| ARGUMENT | REASONS |
|---|--|
| 1. Place $\triangle ABC$ upon $\triangle MNO$ so that AC shall fall upon its equal MO , A upon M , C upon O . | 1. Any geometric figure may be moved from one position to another without change of size or shape. § 54, 14. |
| 2. Then AB will become collinear with MN . | 2. $\angle A = \angle M$, by hyp. |
| 3. Point B will fall on point N . | 3. $AB = MN$, by hyp. |
| 4. $\therefore BC$ will coincide with NO . | 4. Only one str. line can be drawn between two points. § 25. |
| 5. $\triangle ABC = \triangle MNO$. | 5. Two geometric figures are equal if they can be made to coincide. § 18. |
| Q.E.D. | |

108. Cor. *Two right triangles are equal if the two sides including the right angle of one are equal respectively to the two sides including the right angle of the other.*

Ex. 61. Prove Prop. III by placing AB upon MN .

109. Def. In equal figures, the points, lines, and angles in one which, when superposed, coincide respectively with points, lines, and angles in the other, are called **homologous parts**. Hence:

110. *Homologous parts of equal figures are equal.*

Ex. 62. If two straight lines bisect each other, the lines joining their extremities are equal in pairs.

HINT. To prove two lines or two angles equal, try to find two triangles, each containing one of the lines or one of the angles. If the triangles can be proved equal, and the two lines or two angles are *homologous* parts of the triangles, then the lines or angles are equal. The parts given equal may be more easily remembered by marking them with the same symbol, or with colored crayon.

Ex. 63. In case the lines in Ex. 62 are perpendicular to each other, what additional statement can you make? Prove its correctness.

Ex. 64. If equal segments measured from the vertex are laid off on the sides of an angle, and if their extremities are joined to any point in the bisector of the angle, two equal triangles will be formed.

Ex. 65. If two medians of a triangle are perpendicular to the sides to which they are drawn, the triangle is equilateral.

Ex. 66. If equal segments measured from the vertex are laid off on the arms of an isosceles triangle, the lines joining the ends of these segments to the opposite ends of the base will be equal (Fig. 1).

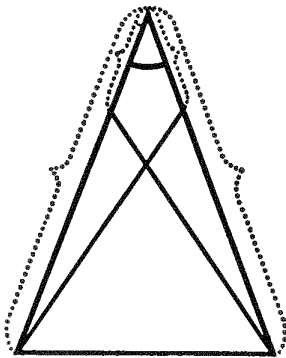


FIG. 1.

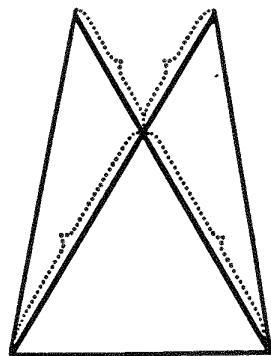
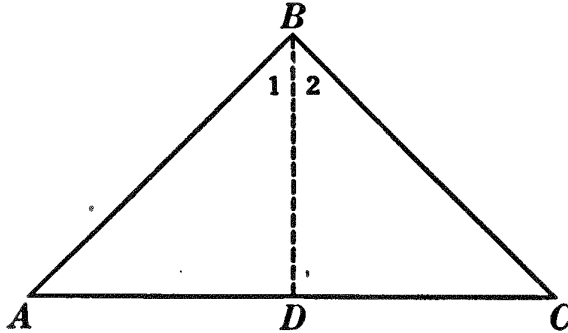


FIG. 2.

Ex. 67. Extend Ex. 66 to the case in which the equal segments are laid off on the arms prolonged through the vertex (Fig. 2).

PROPOSITION IV. THEOREM

111. *The base angles of an isosceles triangle are equal.*



Given isosceles $\triangle ABC$, with AB and BC its equal sides.

To prove $\angle A = \angle C$.

| ARGUMENT | REASONS |
|--|---|
| 1. Let BD bisect $\angle ABC$. | 1. Every \angle has but one bisector. § 53. |
| 2. In $\triangle ABD$ and DBC , $AB = BC$. | 2. By hyp. |
| 3. $BD = BD$. | 3. By iden. |
| 4. $\angle 1 = \angle 2$. | 4. By cons. |
| 5. $\therefore \triangle ABD = \triangle DBC$. | 5. Two \triangle are equal if two sides and the included \angle of one are equal respectively to two sides and the included \angle of the other. § 107. |
| 6. $\therefore \angle A = \angle C$. | 6. Homol. parts of equal figures are equal. § 110. |

Q.E.D.

112. Cor. I. *The bisector of the angle at the vertex of an isosceles triangle is perpendicular to the base and bisects it.*

113. Cor. II. *An equilateral triangle is also equiangular.*

Ex. 68. The bisectors of the base angles of an isosceles triangle are equal.

114. Historical Note. Exercise 69 is known as the *pons asinorum*, or bridge of asses, since it has proved difficult to many beginners in geometry. This proposition and the proof here suggested are due to Euclid, a great mathematician who wrote the first systematic text-book on geometry. In this work, known as Euclid's *Elements*, the exercise here given is the fifth proposition in Book I.

Of the life of Euclid there is but little known except that he was gentle and modest and "was a Greek who lived and taught in Alexandria about 300 B.C." To him is attributed the saying, "There is no royal road to geometry." His appreciation

of the culture value of geometry is shown in a story related by Stobaeus (which is probably authentic). "A lad who had just begun geometry asked, 'What do I gain by learning all this stuff?' Euclid called his slave and said, 'Give this boy some coppers, since he must make a profit out of what he learns.'"

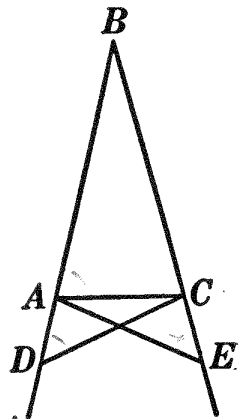


EUCLID

Ex. 69. By using the accompanying diagram prove that the base angles of an isosceles triangle are equal.

HINT. Prove $\triangle ABE = \triangle DBC$. Then prove $\triangle ACE = \triangle DAC$.

Ex. 70. (a) If equal segments measured from the vertex are laid off on the arms of an isosceles triangle, the lines drawn from the ends of the segments to the foot of the bisector of the vertex angle will be equal.



(b) Extend (a) to the case in which the equal segments are laid off on the arms prolonged through the vertex.

Ex. 71. (a) If equal segments measured from the ends of the base are laid off on the arms of an isosceles triangle, the lines drawn from the ends of the segments to the foot of the bisector of the vertex angle will be equal.

(b) Extend (a) to the case in which the equal segments are laid off on the arms prolonged through the ends of the base.

Ex. 72. (a) If equal segments measured from the ends of the base are laid off on the base of an isosceles triangle, the lines joining the vertex of the triangle to the ends of the segments will be equal.

(b) Extend (a) to the case in which the equal segments are laid off on the base prolonged (Fig. 1).

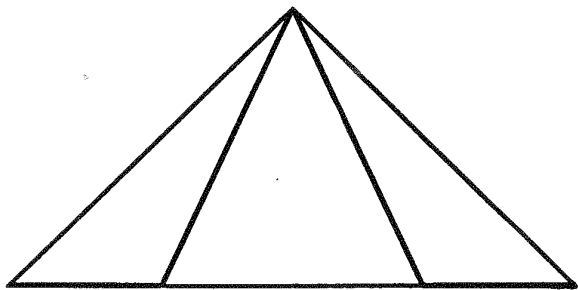


FIG. 1.

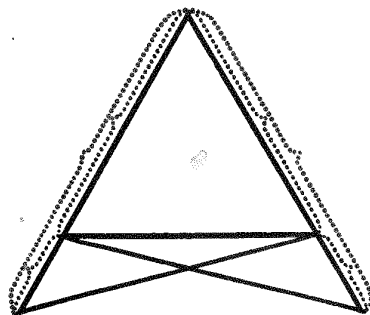
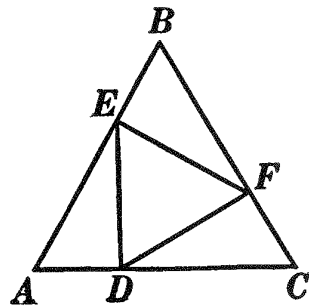


FIG. 2.

Ex. 73. (a) If equal segments measured from the ends of the base are laid off on the arms of an isosceles triangle, the lines drawn from the ends of the segments to the opposite ends of the base will be equal.

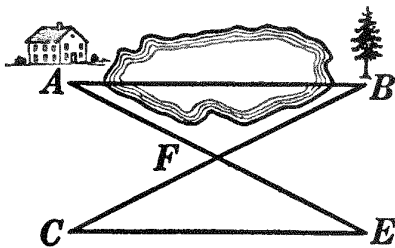
(b) Extend (a) to the case in which the equal segments are laid off on the arms prolonged through the ends of the base (Fig. 2).

Ex. 74. Triangle ABC is equilateral, and $AE = BF = CD$. Prove triangle EFD equilateral.



115. Measurement of Distances by Means

of Triangles. The theorems which prove triangles equal are applied practically in measuring distances on the surface of the earth. Thus, if it is desired to find the distance between two places, A and B , which are separated by a pond or other obstruction, place a stake at some point accessible to both A and B , as F . Measure the distances FA and FB ; then, keeping in line with F and B , measure CF equal to FB , and, in line with F and A , measure FE equal to FA . Lastly measure CE , and the distance from A to B is thus obtained, since AB is equal to CE . Can this method be used when A and B are on opposite sides of a hill and each is invisible from the other?



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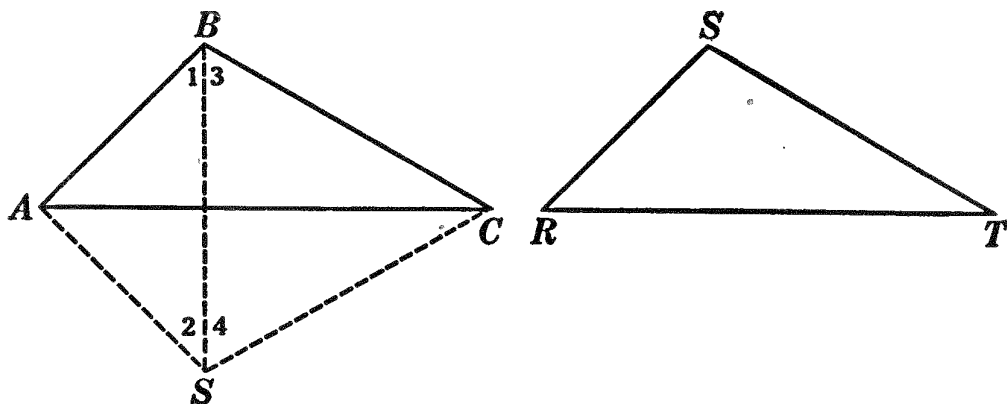
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PROPOSITION V. THEOREM

116. *Two triangles are equal if the three sides of one are equal respectively to the three sides of the other.*



Given $\triangle ABC$ and RST , $AB = RS$, $BC = ST$, and $CA = TR$.

To prove $\triangle ABC = \triangle RST$.

ARGUMENT

1. Place $\triangle RST$ so that the longest side RT shall fall upon its equal AC , R upon A , T upon C , and so that S shall fall opposite B .
2. Draw BS .
3. $\triangle ABS$ is isosceles.
4. $\therefore \angle 1 = \angle 2$.
5. $\triangle BCS$ is isosceles.
6. $\therefore \angle 3 = \angle 4$.
7. $\angle 1 + \angle 3 = \angle 2 + \angle 4$.

REASONS

1. Any geometric figure may be moved from one position to another without change of size or shape. § 54, 14.
2. A str. line may be drawn from any one point to any other. § 54, 15.
3. $AB = RS$, by hyp.
4. The base \sphericalangle s of an isosceles \triangle are equal. § 111.
5. $BC = ST$, by hyp.
6. Same reason as 4.
7. If equals are added to equals, the sums are equal. § 54, 2.

| ARGUMENT | REASONS |
|--|---|
| 8. $\therefore \angle ABC = \angle CSA.$ | 8. The whole = the sum of all its parts. § 54, 11. |
| 9. $\therefore \triangle ABC = \triangle CSA;$ <i>i.e.</i> $\triangle ABC = \triangle RST.$ | 9. Two \triangle are equal if two sides and the included \angle of one are equal respectively to two sides and the included \angle of the other. § 107. |
| Q.E.D. | |

Ex. 81. (a) Prove Prop. V, using two obtuse triangles and applying the shortest side of one to the shortest side of the other.

(b) Prove Prop. V, using two right triangles and applying the shortest side of one to the shortest side of the other.

117. Question. Why is not Prop. V proved by superposition?

SUMMARY OF CONDITIONS FOR EQUALITY OF TRIANGLES

| | | |
|---|---|---|
| <p>118. Two triangles are equal if</p> | { | <p>a side and the two adjacent angles</p> |
| <p>of one are equal respectively to</p> | { | <p>two sides and the included angle</p> |
| <p>of the other.</p> | { | <p>three sides</p> |
| | { | <p>a side and the two adjacent angles</p> |
| | { | <p>two sides and the included angle</p> |
| | { | <p>three sides</p> |

Ex. 82. The median to the base of an isosceles triangle bisects the angle at the vertex and is perpendicular to the base.

Ex. 83. In a certain quadrilateral two adjacent sides are equal; the other two sides are also equal. Find a pair of triangles which you can prove equal.

Ex. 84. If the opposite sides of a quadrilateral are equal, the opposite angles also are equal.

Ex. 85. If two isosceles triangles have the same base, the line joining their vertices bisects each vertex angle and is perpendicular to the common base. (Two cases.)

Ex. 86. In what triangles are the three medians equal?

Ex. 87. In what triangles are two medians equal?

Ex. 88. If three rods of different lengths are put together to form a triangle, can a different triangle be formed by arranging the rods in a different order? Will the angles opposite the same rods always be the same?

Ex. 89. If two sides of one triangle are equal respectively to two sides of another, and the median drawn to one of these sides in the first is equal to the median drawn to the corresponding side in the second, the triangles are equal.

119. Def. A **circle** is a plane closed figure whose boundary is a curve such that all straight lines to it from a fixed point within are equal.

The curve which forms the boundary of a circle is called the **circumference**. The fixed point within is called the **center**, and a line joining the center to any point on the circumference is a **radius**.

120. It follows from the definition of a circle that:

All radii of the same circle are equal.

121. Def. Any portion of a circumference is called an **arc**.

122. Assumption 18. Circle postulate. *A circle may be constructed having any point as center, and having a radius equal to any finite line.*

123. The *solution* of a *problem of construction* consists of three distinct steps:

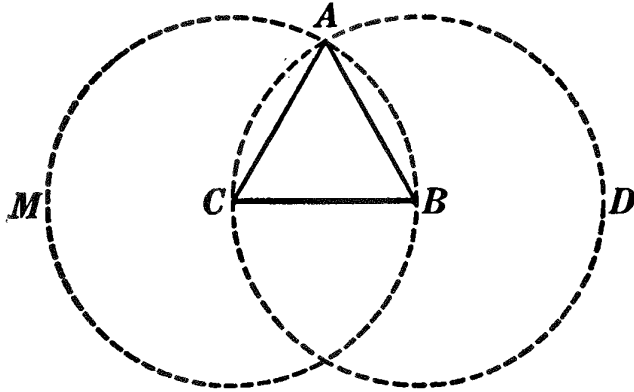
(1) *The construction*, i.e. the process of drawing the required figure with ruler and compasses.

(2) *The proof*, a demonstration that the figure constructed fulfills the given conditions.

(3) *The discussion*, i.e. a statement of the conditions under which there may be no solution, one solution, or more than one.

PROPOSITION VI. PROBLEM

124. *To construct an equilateral triangle, with a given line as side.*



Given line BC .

To construct an equilateral triangle on BC .

I. Construction

1. With B as center and BC as radius, construct circle CAD .
2. With C as center and BC as radius, construct circle BMA .
3. Connect point A , at which the circumferences intersect, with B and C .
4. $\triangle ABC$ is the required triangle.

II. Proof

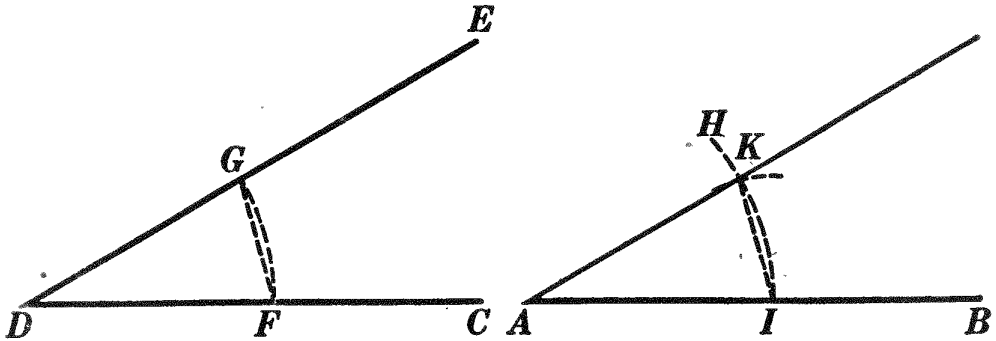
| ARGUMENT | REASONS |
|---|---|
| 1. $AB = BC$ and $CA = BC$. | 1. All radii of the same circle are equal. § 120. |
| 2. $\therefore AB = BC = CA$. | 2. Things equal to the same thing are equal to each other. § 54, 1. |
| 3. $\therefore \triangle ABC$ is equilateral. | 3. A \triangle having its three sides equal is equilateral. § 95. |
| Q.E.D. | |

III. Discussion

This construction is always possible, and there is only one solution. (See § 116.)

PROPOSITION VII. PROBLEM

125. *With a given vertex and a given side, to construct an angle equal to a given angle.*



Given vertex A , side AB , and $\angle CDE$.

To construct an \angle equal to $\angle CDE$ and having A as vertex and AB as side.

I. Construction

1. With D as center, and with any convenient radius, describe an arc intersecting the sides of $\angle D$ at F and G , respectively.
2. With A as center, and with the same radius, describe the indefinite arc IH , cutting AB at I .
3. With I as center, and with a radius equal to str. line FG , describe an arc intersecting the arc IH at K .
4. Draw AK .
5. $\angle BAK = \angle CDE$, and is the \angle required.

II. Proof

| ARGUMENT | REASONS |
|---|--|
| 1. Draw FG and IK . | 1. A str. line may be drawn from any one point to any other. § 54, 15. |
| 2. In $\triangle FDG$ and IAK , $DF = AI$. | 2. By cons. |
| 3. $DG = AK$. | 3. By cons. |
| 4. $FG = IK$. | 4. By cons. |

| ARGUMENT | REASONS |
|--|---|
| 5. $\therefore \triangle FDG = \triangle IAK.$ | 5. Two \triangle are equal if the three sides of one are equal respectively to the three sides of the other. § 116. |
| 6. $\therefore \angle BAK = \angle CDE.$ | 6. Homol. parts of equal figures are equal. § 110. |

Q.E.D.

III. Discussion

This construction is always possible, and there is only one solution.

Ex. 90. Construct a triangle, given two sides and the included angle.

Ex. 91. Construct an isosceles triangle, given the vertex angle and an arm.

Ex. 92. Construct a triangle, given a side and the two adjacent angles.

Ex. 93. Construct an isosceles triangle, given an arm and one of the equal angles.

Ex. 94. How many parts determine a triangle? Do three angles determine it? Explain.

Ex. 95. Construct an isosceles triangle, given the base and an arm.

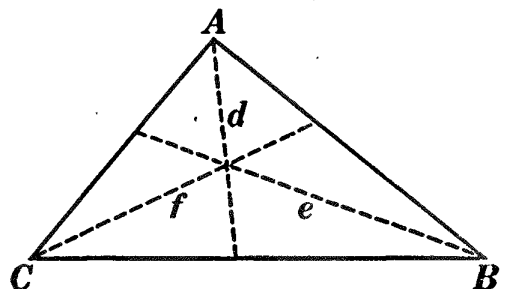
Ex. 96. Construct a scalene triangle, given the three sides.

126. Def. The bisector of an angle of a triangle is the line from the vertex of the angle bisecting the angle and limited by the opposite side of the triangle.

Ex. 97. In what triangles are the three bisectors equal?

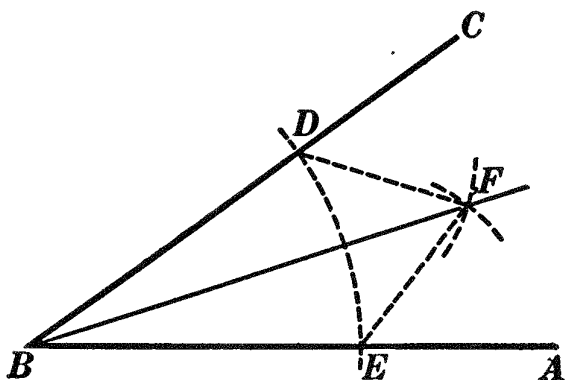
Ex. 98. In what triangles are two bisectors, and only two, equal?

Ex. 99. In what triangles are the medians, the bisectors, and the altitudes identical?



PROPOSITION VIII. PROBLEM

127. *To construct the bisector of a given angle.*



Given $\angle ABC$.

To construct the bisector of $\angle ABC$.

I. Construction

1. With B as center, and with any convenient radius, describe an arc intersecting BA at E and BC at D .
2. With D and E as centers, and with equal radii, describe arcs intersecting at F .
3. Draw BF .
4. BF is the bisector of $\angle ABC$.

II. Proof

| ARGUMENT | REASONS |
|--|---|
| 1. In $\triangle EBF$ and FBD , $BE = BD$. | 1. By cons. |
| 2. $EF = DF$. | 2. By cons. |
| 3. $BF = BF$. | 3. By iden. |
| 4. $\therefore \triangle EBF = \triangle FBD$. | 4. Two \triangle are equal if the three sides of one are equal respectively to the three sides of the other. § 116. |
| 5. $\therefore \angle EBF = \angle FBD$. | 5. Homol. parts of equal figures are equal. § 110. |

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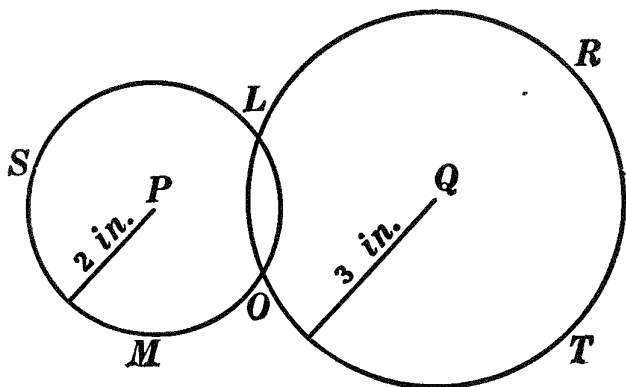
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LOCI

129. In many geometric problems it is necessary to *locate* all points which satisfy certain prescribed conditions, or to determine the path traced by a point which moves according to certain fixed laws. Thus, the points in a plane two inches from a given point are in the circumference of a circle whose center is the given point and whose radius is two inches.

Again, let it be required to find all points in a plane two inches from one fixed point and three inches from another. All points two inches from the fixed point P are in the circumference of the circle LMS , having P for center and having a radius equal to two inches. All points three inches from the fixed point Q are in the circumference of the circle LRT , having Q for center and having a radius equal to three inches.



If the two circles are wholly outside of each other, there will be *no* points satisfying the two prescribed conditions; if the two circumferences touch, but do not intersect, there will be *one* point; if the two circumferences intersect, there will be *two* points. It will be proved later (§ 324) that there cannot be more than two points which satisfy both of the given conditions.

130. Def. A figure is the *locus* of all points which satisfy one or more given conditions, if all points in the figure satisfy the given conditions and if these conditions are satisfied by no other points.

A *locus*, then, is an *assemblage of points* which obey one or more definite laws.

It is often convenient to locate these points by thinking of them as *the path* traced by a moving point the motion of which is controlled by certain fixed laws.

131. In plane geometry a *locus* may be composed of one or more points or of one or more lines, or of any combination of points and lines.

132. Questions.*—What is the locus of all points in space two inches from a given point? What is the locus of all points in space two inches from a given plane? What is the locus of all points in space such that perpendiculars from them to a given plane shall be equal to a given line? What is the locus of all points on the surface of the earth midway between the north and south poles? $23\frac{1}{2}^\circ$ from the equator? $23\frac{1}{2}^\circ$ from the north pole? 90° from the equator? What is the locus of a gas jet four feet from the ceiling of this room? four feet from the ceiling and five feet from a side wall? four feet from the ceiling, five feet from a side wall, and six feet from an end wall?

Ex. 109. Given an *unlimited line* AB and a point P . Find all points in AB which are also: (a) three inches from P ; (b) at a given distance, a , from P .

Ex. 110. Given a circle with center O and radius six inches. State, without proof, the locus: (a) of all points four inches from O ; (b) of all points five inches from the circumference of the circle, measured on the radius or radius prolonged.

Ex. 111. Given the base and one adjacent angle of a triangle, what is the locus of the vertex of the angle opposite the base? (State without proof.)

Ex. 112. Given the base and one other side of a triangle, what is the locus of the vertex of the angle opposite the base? (State without proof.)

Ex. 113. Given the base and the other two sides of a triangle, what is the locus of the vertex of the angle opposite the base?

Ex. 114. Given the base of a triangle and the median to the base, what is the locus of the end of the median which is remote from the base?

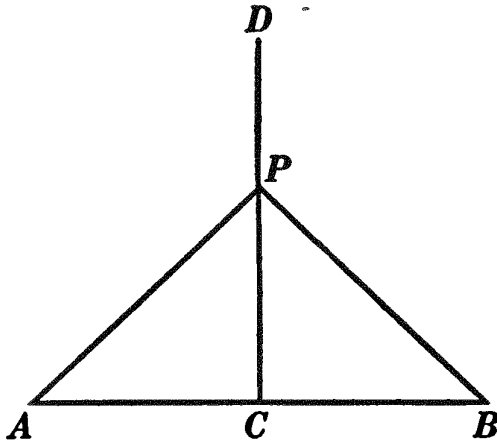
Ex. 115. Given the base of a triangle, one other side, and the median to the base, what is the locus of the vertex of the angle opposite the base?

133. Question. In which of the exercises above was a triangle *determined*?

* In order to develop the imagination of the student the authors deem it advisable in this article to introduce questions involving loci in space. It should be noted that no proofs of answers to these questions are demanded.

PROPOSITION IX. THEOREM

134. *Every point in the perpendicular bisector of a line is equidistant from the ends of that line.*



Given line AB , its \perp bisector CD , and P any point in CD .

To prove $PA = PB$.

| ARGUMENT | REASONS |
|--|---|
| 1. In $\triangle APC$ and CPB , $AC = CB$. | 1. By hyp. |
| 2. $PC = PC$. | 2. By iden. |
| 3. $\angle PCA = \angle BCP$. | 3. All rt. \sphericalangle s are equal. § 64. |
| 4. $\therefore \triangle APC = \triangle CPB$. | 4. Two \triangle s are equal if two sides and the included \angle of one are equal respectively to two sides and the included \angle of the other. § 107. |
| 5. $\therefore PA = PB$. | 5. Homol. parts of equal figures are equal. § 110. |

Q. E. D.

Ex. 116. Four villages are so located that B is 25 miles east of A , C 20 miles north of A , and D 20 miles south of A . Prove that B is as far from C as it is from D .

Ex. 117. In a given circumference, find the points equidistant from two given points. A and B .

135. Def. One theorem is the **converse** of another when the conclusion of the first is the hypothesis of the second, and the hypothesis of the first is the conclusion of the second.

The converse of a truth is not always true; thus, "*All men are bipeds*" is true, but the converse, "*All bipeds are men,*" is false. "*All right angles are equal*" is true, but "*All equal angles are right angles*" is false.

136. Def. One theorem is the **opposite** of another when the hypothesis of the first is the contradiction of the hypothesis of the second, and the conclusion of the first is the contradiction of the conclusion of the second.

The opposite of a truth is not always true; thus, "*If a man lives in the city of New York, he lives in New York State,*" is true, but the opposite, "*If a man does not live in the city of New York, he does not live in New York State,*" is false.

137. Note. If the converse of a proposition is true, the opposite also is true; so, too, if the opposite of a proposition is true, the converse also is true.

This may be evident to the student after a consideration of the following type forms:

| (1) DIRECT | (2) CONVERSE | (3) OPPOSITE |
|-------------------|-------------------|-----------------------|
| If A is B , | If C is D , | If A is not B , |
| Then C is D . | Then A is B . | Then C is not D . |

If (2) is true, then (3) must be true. Again, if (3) is true, then (2) must be true.

138. A necessary and sufficient *test* of the *completeness* of a definition is that its converse shall also be true. Hence a definition may be quoted as the reason for a converse or for an opposite as well as for a direct statement in an argument.

Ex. 118. State the converse of the definition for equal figures; straight line; plane surface.

Ex. 119. State the converse of: If one straight line meets another straight line, the sum of the two adjacent angles is two right angles.

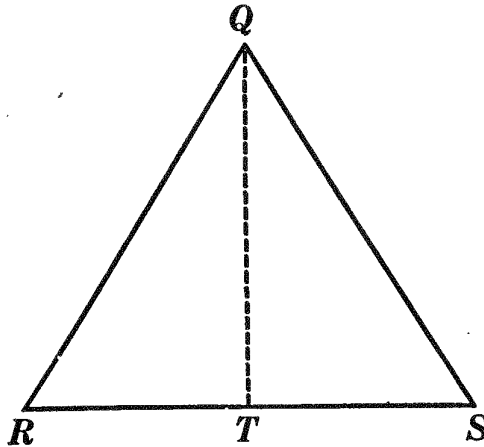
Ex. 120. State the converse and opposite of Prop. IX.

Ex. 121. State the converse of Prop. I. Is it true?

PROPOSITION X. THEOREM

(Converse of Prop. IX)

139. *Every point equidistant from the ends of a line lies in the perpendicular bisector of that line.*



Given line RS , and point Q such that $QR = QS$.

To prove that Q lies in the \perp bisector of RS .

| ARGUMENT | REASONS |
|--|---|
| 1. Let QT bisect $\angle RQS$. | 1. Every \angle has but one bisector. § 53. |
| 2. $QR = QS$. | 2. By hyp. |
| 3. $\therefore \triangle RQS$ is isosceles. | 3. A \triangle having two sides equal is an isosceles \triangle . § 94. |
| 4. $\therefore QT$ is the \perp bisector of RS . | 4. The bisector of the \angle at the vertex of an isosceles \triangle is \perp to the base and bisects it. § 112. |
| 5. $\therefore Q$ lies in the \perp bisector of RS . | 5. By proof. |

Q. E. D.

140. Cor. I. *Every point not in the perpendicular bisector of a line is not equidistant from the ends of the line.*

HINT. Use § 137, or contradict the conclusion and tell why the contradiction is false.

141. Cor. II. *The locus of all points equidistant from the ends of a given line is the perpendicular bisector of that line.*

(For model proofs of locus theorems, see pp. 297 and 298.)

142. Cor. III. *Two points each equidistant from the ends of a line determine the perpendicular bisector of the line.*

HINT. Use § 139 and § 25.

143. In order to prove that a locus problem is *solved* it is *necessary and sufficient* to show two things:

(1) That every point *in* the proposed locus satisfies the prescribed conditions.

(2) That every point *outside* of the proposed locus does not satisfy the prescribed conditions.

Instead of proving (2), it may frequently be more convenient to prove:

(2') That every point which satisfies the prescribed conditions lies in the proposed locus.

144. Note. In exercises in which the student is asked to "Find a locus," it must be understood that he has not *found* a locus until he has given a *proof* with regard to it as outlined above. The proof must be based upon a *direct proposition* and its *opposite*; or, upon a *direct proposition* and its *converse*.

Ex. 122. Find the locus of all points equidistant from two given points A and B .

Ex. 123. In a given *unlimited line* AB , find a point equidistant from two given points C and D not on this line.

Ex. 124. Given a circle with center O , also a point P . Find all points which lie in the circumference of circle O , and which are also (a) two inches from P ; (b) a distance of d from P .

Ex. 125. Find all points at a distance of d from a given point P , and at the same time at a distance of m from a given point Q .

Ex. 126. Given a circle O with radius r . Find the locus of the mid-points of the radii of the circle.

Ex. 127. Given two circles having the same center. State, without proof, the locus of a point equidistant from their circumferences.

Ex. 128. The perpendicular bisector of the base of an isosceles triangle passes through the vertex,

PROPOSITION XI. PROBLEM

145. *To construct the perpendicular bisector of a given straight line.*

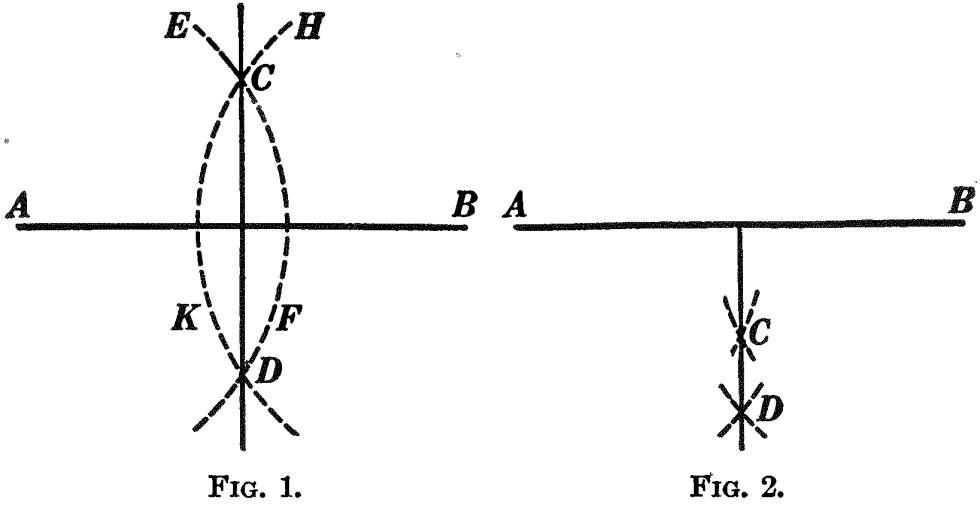


FIG. 1.

FIG. 2.

Given line AB (Fig. 1).

To construct the perpendicular bisector of AB .

I. Construction

1. With A as center, and with a convenient radius greater than half AB , describe the arc EF .
2. With B as center, and with the same radius, describe the arc HK .
3. Let C and D be the points of intersection of these two arcs.
4. Connect points C and D .
5. CD is the \perp bisector of AB .

II. The proof and discussion are left as an exercise for the student.

HINT. Apply § 142.

146. Note. The construction given in Fig. 2 may be used when the position of the given line makes it more convenient.

147. Question. Is it necessary that CA shall equal CB ? that CA shall equal DA (Fig. 1)? Give the equations that *must* hold,

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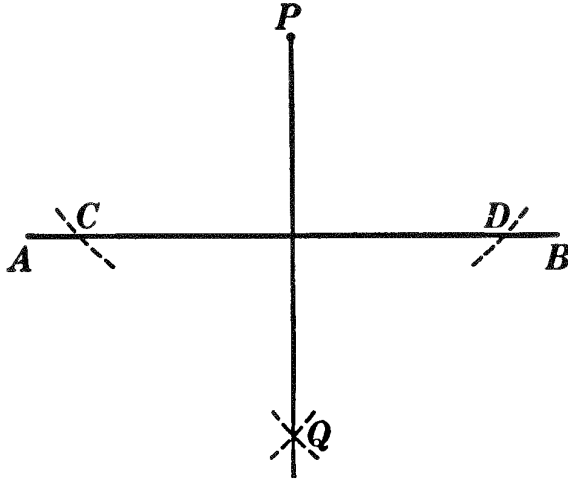
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PROPOSITION XIII. PROBLEM

149. *From a point outside a line to construct a perpendicular to the line.*



Given line AB and point P outside of AB .

To construct a \perp from P to AB .

I. Construction

1. With P as center, and with a radius of sufficient length, describe an arc cutting AB at points C and D .
2. With C and D as centers, and with any convenient radius, describe arcs intersecting at Q .
3. Draw PQ .
4. PQ is a \perp from P to AB .

II. The proof is left as an exercise for the student. The discussion will be given in § 154.

150. Question. Must P and Q be on opposite sides of AB ? Is it necessary that $PC = QC$? _____

Ex. 138. Construct the three altitudes of an acute triangle. Do they seem to meet? where?

Ex. 139. Construct the three altitudes of a right triangle. Where do they seem to meet?

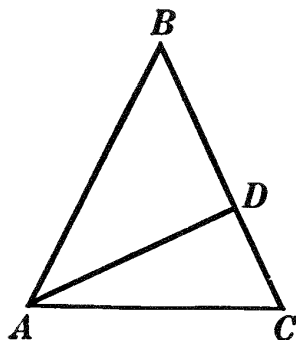
Ex. 140. Construct the three altitudes of an obtuse triangle. Where do they seem to meet?

Ex. 141. Construct a triangle ABC , given two sides and the median drawn to one of them. Abbreviate thus: given a , b , and m_a .

151. Analysis of a problem of construction. In the more difficult problems of construction a course of reasoning is sometimes necessary to enable the student to discover the process of drawing the required figure. This course of reasoning is called the **analysis** of the problem. It is illustrated in § 152 and is more fully treated in the exercises following § 274.

152. Note. • In such problems as Ex. 141, it is well first to imagine the problem solved and to sketch a figure to represent the desired construction. Then mark (with colored crayon, if convenient) the parts supposed to be given. By studying carefully the relation of the given parts to the whole figure, try to find some part of the figure that you can construct. This will generally be a *triangle*. After this part is constructed it is usually an easy matter to complete the required figure.

Thus: Problem. Let it be required to construct an isosceles triangle, given an arm and the altitude upon it. By studying the figure with the given parts marked (heavy or with colored crayon), it will be seen that the solution of the problem depends in this case upon the construction of a right triangle, given the hypotenuse and one arm.



The right triangle ABD may now be constructed, and it will be readily seen that to complete the construction it is only necessary to prolong BD to C , making $BC = AB$, and to connect A and C .

Ex. 142. Construct a triangle ABC , given two sides and an altitude to one of the given sides. Abbreviate thus: given a , b , and h_b .

Ex. 143. Construct a triangle ABC , given a side, an adjacent angle, and the altitude to the side opposite the given angle. Abbreviate thus: given a , B , and h_b .

Ex. 144. Construct an isosceles triangle, given an arm and the median to it.

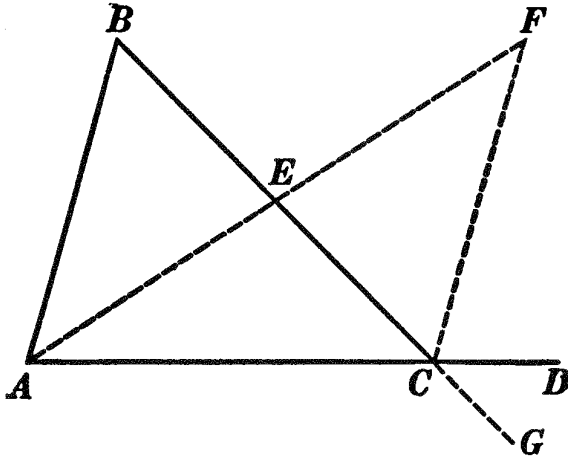
Ex. 145. Construct an isosceles triangle, given an arm and the angle which the median to it makes with it.

Ex. 146. Construct a triangle, given two sides and the angle which a median to one side makes: (a) with that side; (b) with the other side.

Ex. 147. Construct a triangle, given a side, an adjacent angle, and its bisector.

PROPOSITION XIV. THEOREM

153. *If one side of a triangle is prolonged, the exterior angle formed is greater than either of the remote interior angles.*



Given $\triangle ABC$ with AC prolonged to D , making exterior $\angle DCB$.

To prove $\angle DCB > \angle ABC$ or $\angle CAB$.

ARGUMENT

REASONS

1. Let E be the mid-point of BC ; draw AE , and prolong it to F , making $EF = AE$. Draw CF .

1. A str. line may be drawn from any one point to any other. § 54, 15.

2. In $\triangle ABE$ and EFC ,
 $BE = EC$.

2. By cons. E is the mid-point of BC .

3. $AE = EF$.

3. By cons.

4. $\angle BEA = \angle CEF$.

4. If two str. lines intersect, the vertical \sphericalangle s are equal. § 77.

5. $\therefore \triangle ABE = \triangle EFC$.

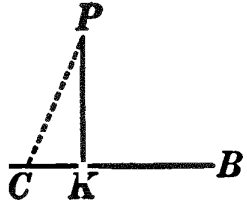
5. Two \triangle s are equal if two sides and the included \angle of one are equal respectively to two sides and the included \angle of the other. § 107.

6. $\therefore \angle B = \angle FCE$.

6. Homol. parts of equal figures are equal. § 110.

| ARGUMENT | REASONS |
|---|---|
| 7. $\angle DCB > \angle FCE.$ | 7. The whole $>$ any of its parts. § 54, 12. |
| 8. $\therefore \angle DCB > \angle B.$ | 8. Substituting $\angle B$ for its equal $\angle FCE.$ |
| 9. Likewise, if BC is prolonged to G , $\angle ACG > \angle CAB.$ | 9. By bisecting line AC , and by steps similar to 1-8. |
| 10. But $\angle DCB = \angle ACG.$ | 10. Same reason as 4. |
| 11. $\therefore \angle DCB > \angle CAB.$ | 11. Substituting $\angle DCB$ for its equal $\angle ACG.$ |
| 12. $\therefore \angle DCB > \angle ABC$ or $\angle CAB.$ Q.E.D. | 12. By proof. |

154. Cor. *From a point outside a line there exists only one perpendicular to the line.*

HINT. If there exists a second \perp to AB from A  as PC , then $\angle PCA$ and $\angle PKA$ are both rt. \sphericalangle and are therefore equal. But this is impossible by § 153.

155. §§ 149 and 154 may be combined in one statement as follows:

From a point outside a line there exists one and only one perpendicular to the line.

Ex. 148. A triangle cannot contain two right angles.

Ex. 149. In the figure of Prop. XIV, is angle DCB necessarily greater than angle BCA ? than angle B ?

Ex. 150. In Fig. 1, prove that :

- (1) Angle 1 is greater than angle CAE or angle AEC ;
- (2) Angle 5 is greater than angle CBA or angle BAE ;
- (3) Angle EDA is greater than angle 3;
- (4) Angle 4 is greater than angle DAE .

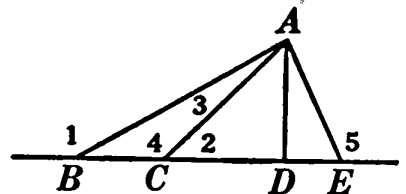


FIG. 1.

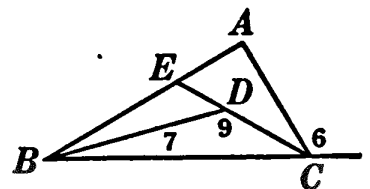
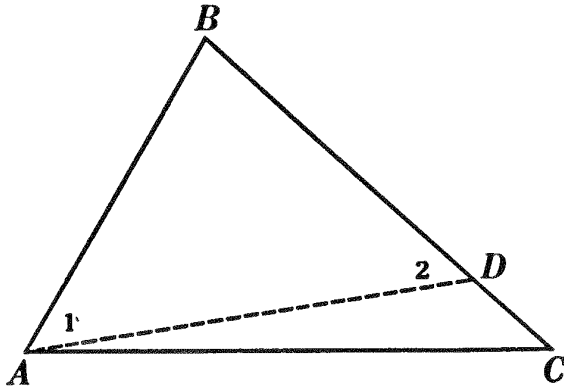


FIG. 2.

Ex. 151. In Fig. 2, show that angle 6 is greater than angle 7; also that angle 9 is greater than angle A .

PROPOSITION XV. THEOREM

156. *If two sides of a triangle are unequal, the angle opposite the greater side is greater than the angle opposite the less side.*



Given $\triangle ABC$ with $BC > BA$.

To prove $\angle CAB > \angle C$.

ARGUMENT

1. On BC lay off $BD = AB$.
2. Draw AD .
3. Then $\angle 1 = \angle 2$.
4. Now $\angle 2 > \angle C$.
5. $\therefore \angle 1 > \angle C$.
6. But $\angle CAB > \angle 1$.
7. $\therefore \angle CAB > \angle C$.

REASONS

1. Circle post. §§ 122, 157.
2. Str. line post. I. § 54, 15.
3. The base \sphericalangle s of an isosceles \triangle are equal. § 111.
4. If one side of a \triangle is prolonged, the ext. \sphericalangle formed $>$ either of the remote int. \sphericalangle s. § 153.
5. Substituting $\angle 1$ for its equal $\angle 2$.
6. The whole $>$ any of its parts. § 54, 12.
7. If three magnitudes of the same kind are so related that the first $>$ the second and the second $>$ the third, then the first $>$ the third. § 54, 10.

Q.E.D.

157. Note. Hereafter the student will not be required to state postulates and definitions in full unless requested to do so by the teacher.

158. Note. When two magnitudes are given unequal, the laying off of the less upon the greater will often serve as the initial step in developing a proof.

Ex. 152. Given the isosceles triangle RST , with ST the base and RT prolonged any length, as to K . Prove angle KSR greater than angle K .

Ex. 153. If two adjacent sides of a quadrilateral are greater respectively than the other two sides, the angle included between the two shorter sides is greater than the angle between the two greater sides.

Ex. 154. If from a point within a triangle lines are drawn to the ends of one of its sides, the angle between these lines is greater than the angle between the other two sides of the triangle. (See Ex. 151.)

159. The **indirect method**, or proof by exclusion, consists in contradicting the conclusion of a proposition, then showing the contradiction to be false. The conclusion of the proposition is thus established. This process requires an examination of *every possible contradiction* of the conclusion. For example, to prove indirectly that A equals B it would be necessary to consider the only three suppositions that are admissible in this case, viz.:

- (1) $A > B$,
- (2) $A < B$,
- (3) $A = B$.

By proving (1) and (2) false, the truth of (3) is established, *i.e.* $A = B$. This method of reasoning is called *reductio ad absurdum*. It enables us to establish a conclusion by showing that every contradiction of it leads to an absurdity. Props. XVI and XVII will be proved by the indirect method.

160. Question. Would it be possible to base a proof upon a contradiction of the hypothesis?

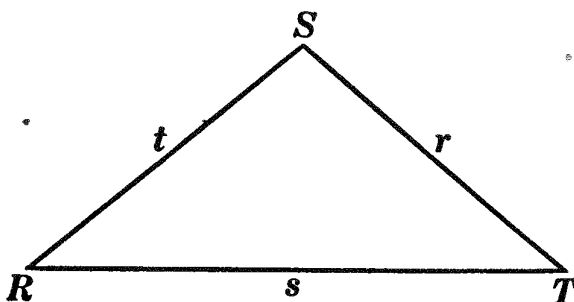
161. (a) In the use of the indirect method the student should give, as argument 1, all the suppositions of which the case he is considering admits, including the conclusion. As reason 1 the number of such possible suppositions should be cited.

(b) As a reason for the last step in the argument he should state which of these suppositions have been proved false.

PROPOSITION XVI. THEOREM

(Converse of Prop. IV)

162. *If two angles of a triangle are equal, the sides opposite are equal.*



Given $\triangle RST$ with $\angle R = \angle T$.

To prove $r = t$.

| ARGUMENT | REASONS |
|--|---|
| 1. $r > t$, $r < t$, or $r = t$. | 1. In this case only three suppositions are admissible. |
| 2. First suppose $r > t$; then $\angle R > \angle T$. | 2. If two sides of a \triangle are unequal, the \angle opposite the greater side $>$ the \angle opposite the less side. § 156. |
| 3. This is impossible. | 3. By hyp., $\angle R = \angle T$. |
| 4. Next suppose $r < t$; then $\angle R < \angle T$. | 4. Same reason as 2. |
| 5. This is impossible. | 5. Same reason as 3. |
| 6. $\therefore r = t$. | 6. The two suppositions, $r > t$ and $r < t$, have been proved false. |

Q.E.D.

163. Cor. *An equiangular triangle is also equilateral.*

Ex. 155. The bisectors of the base angles of an isosceles triangle form an isosceles triangle.

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Ex. 156. The sum of the altitudes of any triangle is less than the perimeter of the triangle.

Ex. 157. Given the quadrilateral $ABCD$ with B and D right angles and BC greater than CD . Prove AD greater than AB .

Ex. 158. Given triangle ABC , with $AC > BC$. Let bisectors of angles A and B meet at O . Prove $AO > BO$.

Ex. 159. A line drawn from the vertex of an isosceles triangle to any point in the base is less than one of the equal sides of the triangle.

Ex. 160. If ABC and ABD are two triangles on the same base and on the same side of it such that $AC = BD$ and $AD = BC$, and if AC and BD intersect at O , prove triangle AOB isosceles.

Ex. 161. Prove Prop. XVI by using the figure and method of Ex. 69.

Ex. 162. Upon a given base is constructed a triangle one of the base angles of which is double the other. The bisector of the larger base angle meets the opposite side at the point P . Find the locus of P .

Ex. 163. If the four sides of a quadrilateral are equal, its diagonals bisect each other.

Ex. 164. The diagonals of an equilateral quadrilateral are perpendicular to each other, and they bisect the angles of the quadrilateral.

Ex. 165. If two adjacent sides of a quadrilateral are equal and the other two sides are equal, one diagonal is the perpendicular bisector of the other. Tell which one is the bisector and prove the correctness of your answer.

Ex. 166. If, from a point in a perpendicular to a line, oblique lines are drawn cutting off equal segments from the foot of the perpendicular, the oblique lines are equal.

Ex. 167. State and prove the converse of Ex. 166.

Ex. 168. If, from a point in a perpendicular to a line, oblique lines are drawn cutting off unequal segments from the foot of the perpendicular, the oblique lines are unequal. Prove by laying off the less segment upon the greater. Then use Ex. 166, § 153, and § 164.

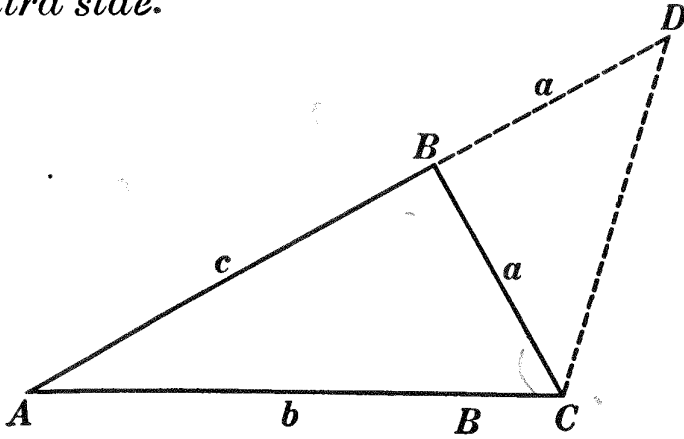
Ex. 169. If, from any point in a perpendicular to a line, two unequal oblique lines are drawn to the line, the oblique lines will cut off unequal segments from the foot of the perpendicular. Prove by the indirect method.

Ex. 170. By means of Prop. XIV, prove that the sum of any two angles of a triangle is less than two right angles.

Ex. 171. Construct a triangle ABC , given two sides, a and b , and the altitude to the third side, c . (See § 152.)

PROPOSITION XVIII. THEOREM

167. *The sum of any two sides of a triangle is greater than the third side.*



Given $\triangle ABC$.

To prove $a + c > b$.

| ARGUMENT | REASONS |
|--|---|
| 1. Prolong c through B until prolongation $BD = a$. | 1. Str. line post. II. § 54, 16. |
| 2. Draw CD . | 2. Str. line post. I. § 54, 15. |
| 3. In isosceles $\triangle BDC$, $\angle D = \angle DCB$. | 3. The base \sphericalangle of an isosceles \triangle are equal. § 111. |
| 4. But $\angle DCA > \angle DCB$. | 4. The whole $>$ any of its parts. § 54, 12. |
| 5. $\therefore \angle DCA > \angle D$. | 5. Substituting $\angle D$ for its equal, $\angle DCB$. |
| 6. \therefore in $\triangle ADC$, $AD > b$. | 6. If two \sphericalangle of a \triangle are unequal, the side opposite the greater \sphericalangle is $>$ the side opposite the less angle. § 164. |
| 7. $\therefore a + c > b$. Q.E.D. | 7. Substituting $a + c$ for AD . |

168. Cor. I. *Any side of a triangle is less than the sum and greater than the difference of the other two.*

169. Cor. II. *Any straight line is less than the sum of the parts of a broken line having the same extremities.*

170. Note to Teacher. Teachers who prefer to assume that “a straight line is the shortest line between two points” may omit Prop. XVIII entirely. Then Prop. XVII may be proved by a method similar to that used in Prop. XV. (See Ex. 172.)

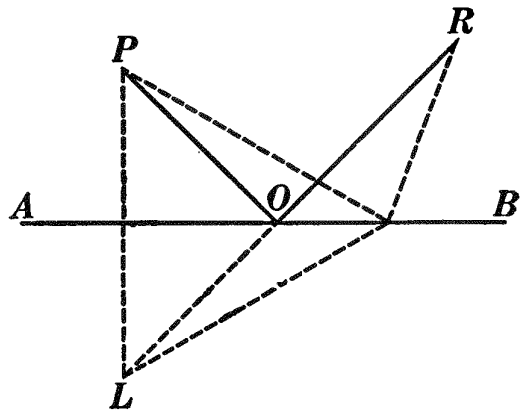
Ex. 172. Prove Prop. XVII by using the hint contained in § 158.

Ex. 173. If two sides of a triangle are 14 and 9, between what limiting values must the third side be ?

Ex. 174. If the opposite ends of any two non-intersecting line segments are joined, the sum of the joining lines is greater than the sum of the other two lines.

Ex. 175. Given two points, P and R , and a line AB not passing through either. To find a point O , on AB , such that $PO + OR$ shall be as small as possible.

This exercise illustrates the law by which light is reflected from a mirror. The light from the object, P , is reflected and appears to come from L , as far behind the mirror as P is in front of it.



Ex. 176. If from any point within a triangle lines are drawn to the extremities of any side of the triangle, the sum of these lines is less than the sum of the other two sides of the triangle.

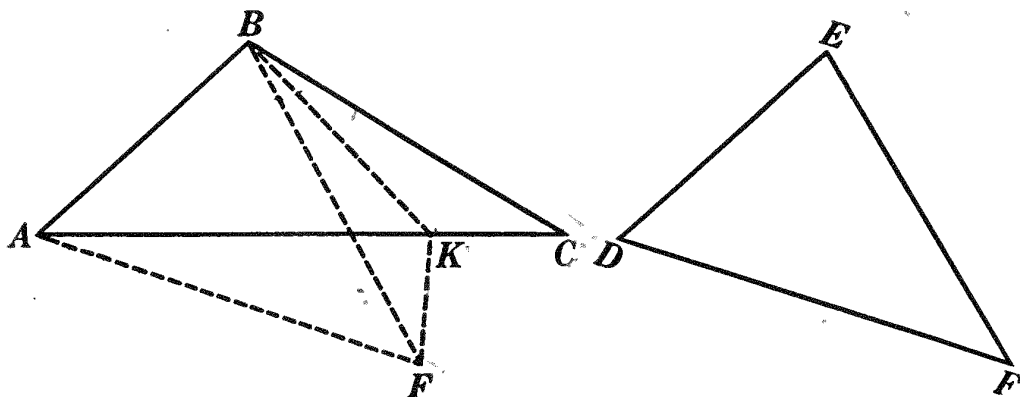
HINT. Let ABC be the given triangle, D the point within. Prolong AD until it intersects BC at E . Apply Prop. XVIII.

171. Note to Teacher. Up to this point all proofs given have been complete, including argument and reasons. In written work it is frequently convenient, however, to have students give the argument only. These two forms will be distinguished by calling the former a **complete demonstration** and the latter, which is illustrated in Prop. XIX, **argument only**.

It is often a sufficient test of a student's understanding of a theorem to have him state merely the main points involved in a proof. This may be given in enumerated steps, as in Prop. XXXV, or in the form of a paragraph, as in Prop. XLIV. This form will be called **outline of proof**.

PROPOSITION XIX. THEOREM

172. *If two triangles have two sides of one equal respectively to two sides of the other, but the included angle of the first greater than the included angle of the second, then the third side of the first is greater than the third side of the second.*



Given two $\triangle ABC$ and DEF with $AB = DE$, $BC = EF$, but $\angle ABC > \angle E$.

To prove $AC > DF$.

ARGUMENT ONLY

1. Place $\triangle DEF$ on $\triangle ABC$ so that DE shall fall upon its equal AB , D upon A , E upon B .
2. EF will then fall between AB and BC . Denote $\triangle DEF$ in its new position by ABF .
3. Draw BK bisecting $\angle FBC$ and meeting AC at K .
4. Draw KF .
5. In $\triangle FBK$ and KBC , $BC = BF$.
6. $BK = BK$.
7. $\angle FBK = \angle KBC$.
8. $\therefore \triangle FBK = \triangle KBC$.
9. $\therefore KF = KC$.
10. $AK + KF > AF$.
11. $\therefore AK + KC > AF$.
12. That is, $AC > AF$.
13. $\therefore AC > DF$.

Q.E.D.

Ex. 177. (a) Draw a figure and discuss the case for Prop. XIX when F falls on AC ; when F falls within triangle ABC . (b) Discuss Prop. XIX, taking AC (the base) = DF , $AB = DE$, and angle CAB greater than angle D .

Ex. 178. Prove Prop. XIX by using Fig. 1.

HINT. In $\triangle ACE$, $\angle CEA > \angle BEA$.

$\therefore \angle CEA > \angle EAB > \angle EAC$.

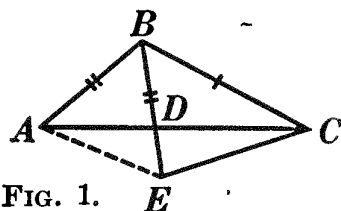
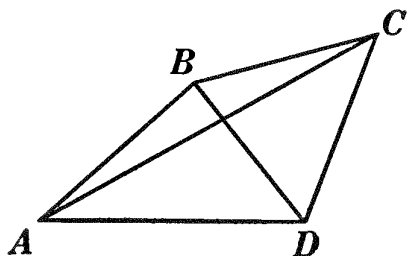


FIG. 1.

Ex. 179. Given triangle ABC with AB greater than BC , and let point P be taken on AB and point Q on CB , so that $AP = CQ$. Prove AQ greater than CP .

Ex. 180. Would the conclusion of Ex. 179 be true if P were taken on AB prolonged and Q on CB prolonged? Prove.

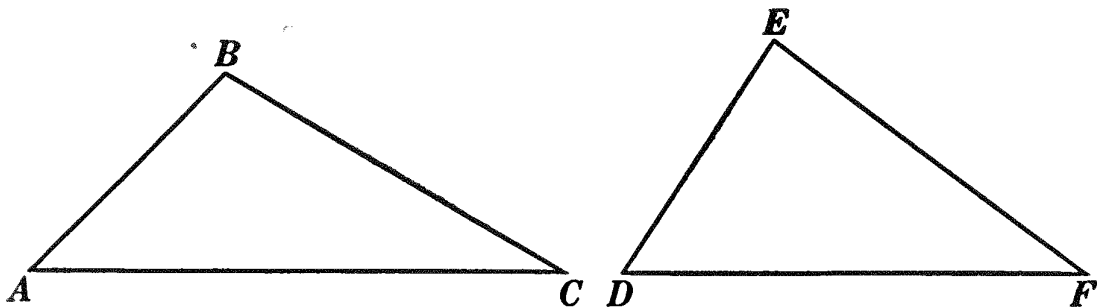
Ex. 181. In quadrilateral $ABCD$ if $AB = CD$, and angle CDA is greater than angle DAB , prove AC greater than BD .



PROPOSITION XX. THEOREM

(Converse of Prop. XIX)

173. *If two triangles have two sides of one equal respectively to two sides of the other, but the third side of the first greater than the third side of the second, then the angle opposite the third side of the first is greater than the angle opposite the third side of the second.*



Given $\triangle ABC$ and DEF with $AB = DE$, $BC = EF$, but $AC > DF$.

To prove $\angle B > \angle E$.

| ARGUMENT | REASONS |
|---|--|
| 1. $\angle B < \angle E$, $\angle B = \angle E$, or $\angle B > \angle E$. | 1. In this case only three suppositions are admissible. |
| 2. First suppose $\angle B < \angle E$; then $AC < DF$. | 2. If two \triangle have two sides of one equal respectively to two sides of the other, but the included \angle of the first $>$ the included \angle of the second, then the third side of the first $>$ the third side of the second. §172. |
| 3. This is impossible. | 3. By hyp., $AC > DF$. |
| 4. Next suppose $\angle B = \angle E$; then $\triangle ABC = \triangle DEF$. | 4. Two \triangle are equal if two sides and the included \angle of one are equal respectively to two sides and the included \angle of the other. §107. |
| 5. $\therefore AC = DF$. | 5. Homol. parts of equal figures are equal. §110. |
| 6. This is impossible. | 6. Same reason as 3. |
| 7. $\therefore \angle B > \angle E$. | 7. The two suppositions, $\angle B < \angle E$ and $\angle B = \angle E$, have been proved false. |
| Q.E.D. | |

Ex. 182. If two opposite sides of a quadrilateral are equal, but its diagonals are unequal, then one angle opposite the greater diagonal is greater than one angle opposite the less diagonal.

Ex. 183. If two sides of a triangle are unequal, the median drawn to the third side makes unequal angles with the third side.

Ex. 184. If from the vertex S of an isosceles triangle RST a line is drawn to point P in the base RT so that RP is greater than PT , then angle RSP is greater than angle PST .

Ex. 185. If one angle of a triangle is equal to the sum of the other two, the triangle can be divided into two isosceles triangles.

SUMMARY OF THEOREMS FOR PROVING ANGLES UNEQUAL

174. (a) *When the angles are in the same triangle:*

If two sides of a triangle are unequal, the angle opposite the greater side is greater than the angle opposite the less side.

(b) *When the angles are in different triangles:*

If two triangles have two sides of one equal respectively to two sides of the other, but the third side of the first greater than the third side of the second, then the angle opposite the third side of the first is greater than the angle opposite the third side of the second.

(c) An exterior angle of a triangle is greater than either remote interior angle.

SUMMARY OF THEOREMS FOR PROVING LINES UNEQUAL

175. (a) *When the lines are in the same triangle:*

The sum of any two sides of a triangle is greater than the third side.

Any side of a triangle is less than the sum and greater than the difference of the other two.

If two angles of a triangle are unequal, the side opposite the greater angle is greater than the side opposite the less angle.

(b) *When the lines are in different triangles:*

If two triangles have two sides of one equal respectively to two sides of the other, but the included angle of the first greater than the included angle of the second, then the third side of the first is greater than the third side of the second.

(c) Every point not in the perpendicular bisector of a line is not equidistant from the ends of the line.

The perpendicular is the shortest straight line from a point to a line.

Any straight line is less than the sum of the parts of a broken line having the same extremities.

In some texts Exs. 168 and 169 are given as theorems.

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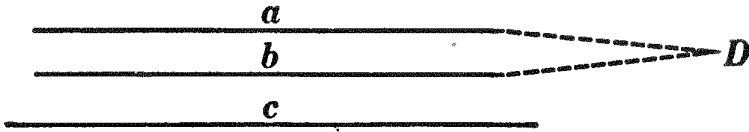
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PROPOSITION XXI. THEOREM

180. *If two straight lines are parallel to a third straight line, they are parallel to each other.*



Given lines a and b , each $\parallel c$.

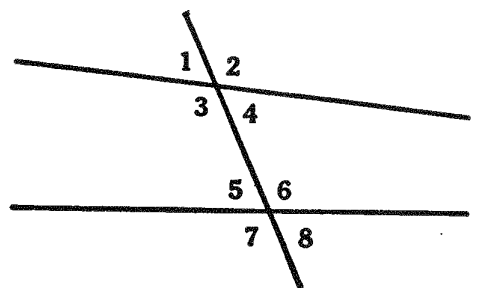
To prove $a \parallel b$.

| ARGUMENT | REASONS |
|---|--|
| 1. a and b are either \parallel or not \parallel . | 1. In this case only two suppositions are admissible. |
| 2. Suppose that a is not $\parallel b$; then they will meet at some point as D . | 2. By def. of \parallel lines. § 177. |
| 3. This is impossible. | 3. Parallel line post. § 178. |
| 4. $\therefore a \parallel b$. | 4. The supposition that a and b are not \parallel has been proved false. |
| Q.E.D. | |

181. **Def.** A transversal is a line that intersects two or more other lines.

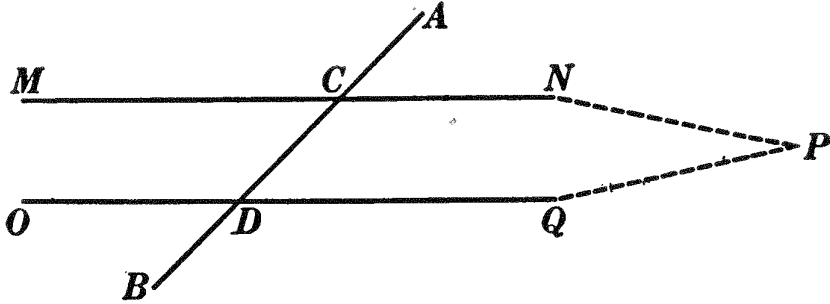
182. **Defs.** If two straight lines are cut by a transversal, of the eight angles formed,

- 3, 4, 5, 6 are interior angles ;
- 1, 2, 7, 8 are exterior angles ;
- 4 and 5, 3 and 6, are alternate interior angles ;
- 1 and 8, 2 and 7, are alternate exterior angles ;
- 1 and 5, 3 and 7, 2 and 6, 4 and 8, are corresponding angles (called also exterior interior angles)



PROPOSITION XXII. THEOREM

183. *If two straight lines are cut by a transversal making a pair of alternate interior angles equal, the lines are parallel.*



Given two str. lines MN and OQ cut by the transversal AB in points C and D , making $\angle MCD = \angle QDC$.

To prove $MN \parallel OQ$.

| ARGUMENT | REASONS |
|---|---|
| 1. MN and OQ are either \parallel or not \parallel . | 1. In this case only two suppositions are admissible. |
| 2. Suppose that MN is not $\parallel OQ$; then they will meet at some point as P , forming, with line DC , $\triangle PDC$. | 2. By def. of \parallel lines. § 177. |
| 3. Then $\angle MCD > \angle QDC$. | 3. If one side of a \triangle is prolonged, the ext. \angle formed $>$ either of the remote int. \angle s. § 153. |
| 4. This is impossible. | 4. $\angle MCD = \angle QDC$, by hyp. |
| 5. $\therefore MN \parallel OQ$. | 5. The supposition that MN and OQ are not \parallel has been proved false. |
| Q.E.D. | |

184. Cor. I. *If two straight lines are cut by a transversal making a pair of corresponding angles equal, the lines are parallel.*

HINT. Prove a pair of alt. int. \angle s equal, and apply the theorem.

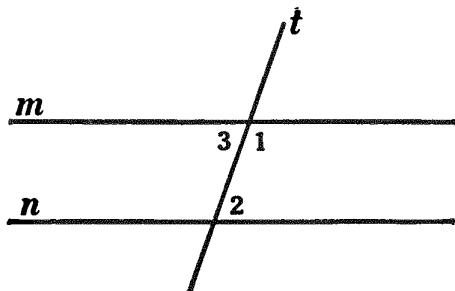
185. Cor. II. *If two straight lines are cut by a transversal making a pair of alternate exterior angles equal, the lines are parallel. (HINT. Prove a pair of alt. int. \sphericalangle equal.)*

186. Cor. III. *If two straight lines are cut by a transversal making the sum of the two interior angles on the same side of the transversal equal to two right angles, the lines are parallel.*

Given lines m and n cut by the transversal t making

$$\angle 1 + \angle 2 = 2 \text{ rt. } \sphericalangle.$$

To prove $m \parallel n$.



ARGUMENT

1. $\angle 1 + \angle 2 = 2 \text{ rt. } \sphericalangle.$
2. $\angle 1 + \angle 3 = 2 \text{ rt. } \sphericalangle.$
3. $\therefore \angle 1 + \angle 2 = \angle 1 + \angle 3.$
4. $\therefore \angle 2 = \angle 3.$
5. $\therefore m \parallel n.$

Q.E.D.

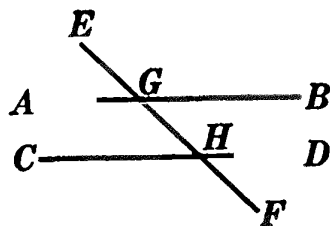
REASONS

1. By hyp.
2. If one str. line meets another str. line, the sum of the two adj. \sphericalangle is 2 rt. \sphericalangle . § 65.
3. Things equal to the same thing are equal to each other. § 54, 1.
4. If equals are subtracted from equals, the remainders are equal. § 54, 3.
5. If two str. lines are cut by a transversal making a pair of alt. int. \sphericalangle equal, the lines are \parallel . § 183.

187. Cor. IV. *If two straight lines are perpendicular to a third straight line, they are parallel to each other.*

Ex. 190. If two straight lines are cut by a transversal making the sum of the two exterior angles on the same side of the transversal equal to two right angles, the lines are parallel.

Ex. 191. In the annexed diagram, if angle $BGE = \text{angle } CHF$, are AB and CD parallel? Prove.



Ex. 192. In the same diagram, if angle $HGB = \text{angle } GHC$, prove that the bisectors of these angles are parallel.

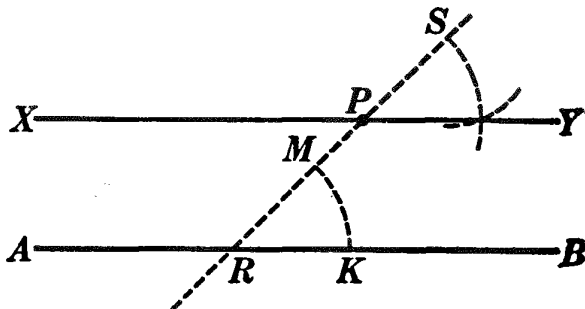
Ex. 193. If two straight lines bisect each other, the lines joining their extremities are parallel in pairs.

Ex. 194. In the diagram for Ex. 191, if angle BGE and angle FHD are supplementary, prove AB parallel to CD .

Ex. 195. If two adjacent angles of any quadrilateral are supplementary, two sides of the quadrilateral will be parallel.

PROPOSITION XXIII. PROBLEM

188. Through a given point to construct a line parallel to a given line.



Given line AB and point P .

To construct, through point P , a line $\parallel AB$.

I. Construction

1. Draw a line through P cutting AB at some point, as R .
2. With P as vertex and PS as side, construct $\angle YPS = \angle BRP$. § 125.
3. XY will be $\parallel AB$.

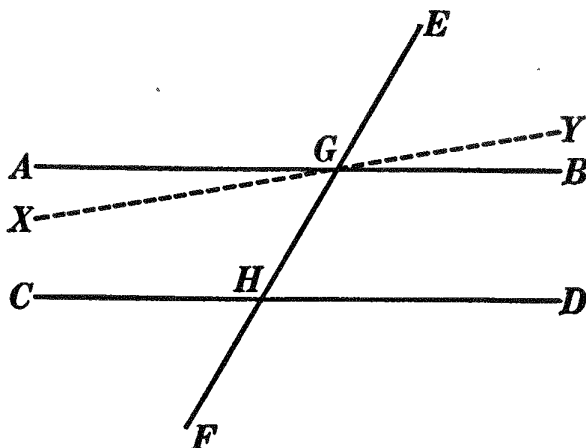
II. The proof and discussion are left as an exercise for the student.

Ex. 196. Through a given point construct a parallel to a given line by using: (a) § 183; (b) § 185; (c) § 187.

PROPOSITION XXIV. THEOREM

(Converse of Prop. XXII)

189. *If two parallel lines are cut by a transversal, the alternate interior angles are equal.*



Given \parallel lines AB and CD cut by the transversal EF at points G and H .

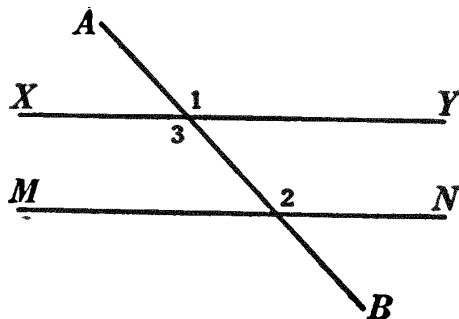
To prove $\angle AGH = \angle DHG$.

| ARGUMENT | REASONS |
|---|---|
| 1. Either $\angle AGH = \angle DHG$, or $\angle AGH \neq \angle DHG$. | 1. In this case only two sup- positions are admissible. |
| 2. Suppose $\angle AGH \neq \angle DHG$, but that line XY , through G , makes $\angle XGH = \angle DHG$. | 2. With a given vertex and a given side, an \angle may be constructed equal to a given \angle . § 125. |
| 3. Then $XY \parallel CD$. | 3. If two str. lines are cut by a transversal making a pair of alt. int. \sphericalangle s equal, the lines are \parallel . § 183. |
| 4. But $AB \parallel CD$. | 4. By hyp. |
| 5. It is impossible that AB and XY both are $\parallel CD$. | 5. Parallel line post. § 178. |
| 6. $\therefore \angle AGH = \angle DHG$. | 6. The supposition that $\angle AGH \neq \angle DHG$ has been proved false. |

Q.E.D.

190. Cor. I. (Converse of Cor. I of Prop. XXII). *If two parallel lines are cut by a transversal, the corresponding angles are equal.*

Given two \parallel lines XY and MN cut by the transversal AB , forming corresponding \sphericalangle s 1 and 2.



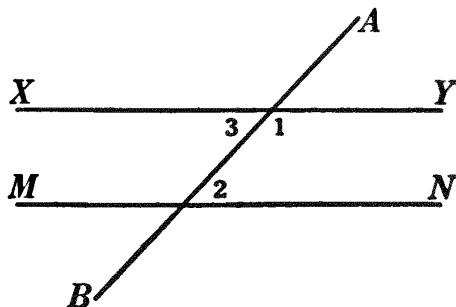
To prove $\sphericalangle 1 = \sphericalangle 2$.

HINT. $\sphericalangle 3 = \sphericalangle 2$ by § 189.

191. Cor. II. (Converse of Cor. II of Prop. XXII). *If two parallel lines are cut by a transversal, the alternate exterior angles are equal.*

192. Cor. III. (Converse of Cor. III of Prop. XXII). *If two parallel lines are cut by a transversal, the sum of the two interior angles on the same side of the transversal is two right angles.*

Given two \parallel lines XY and MN cut by the transversal AB , forming int. \sphericalangle s 1 and 2.



To prove $\sphericalangle 1 + \sphericalangle 2 = 2 \text{ rt. } \sphericalangle$ s.

ARGUMENT ONLY

1. $\sphericalangle 1 + \sphericalangle 3 = 2 \text{ rt. } \sphericalangle$ s.

2. $\sphericalangle 3 = \sphericalangle 2$.

3. $\therefore \sphericalangle 1 + \sphericalangle 2 = 2 \text{ rt. } \sphericalangle$ s.

Q.E.D.

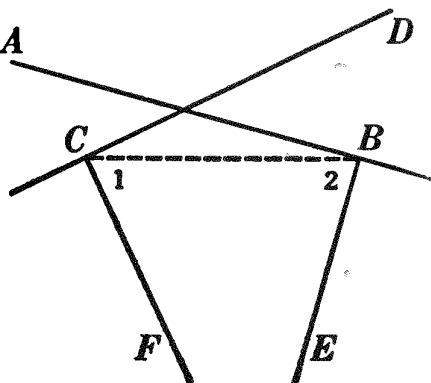
193. Cor. IV. *A straight line perpendicular to one of two parallels is perpendicular to the other also.*

194. Cor. V. (Opposite of Cor. III of Prop. XXII). *If two straight lines are cut by a transversal making the sum of the two interior angles on the same side of the transversal not equal to two right angles, the lines are not parallel.* (HINT. Apply § 137, or use the indirect method.)

195. Cor. VI. *Two lines perpendicular respectively to two intersecting lines also intersect.*

Given two intersecting lines AB and CD , and $BE \perp AB$, $CF \perp CD$.

To prove that BE and CF also intersect.



ARGUMENT ONLY

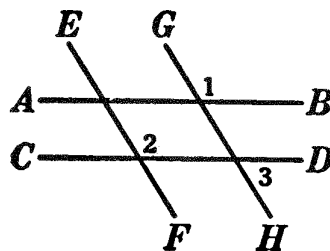
1. Draw CB .
2. $\angle FCD$ is a rt. \angle .
3. $\therefore \angle 1 < \text{a rt. } \angle$.
4. Likewise $\angle 2 < \text{a rt. } \angle$.
5. $\therefore \angle 1 + \angle 2 < 2 \text{ rt. } \angle$.
6. $\therefore BE$ and CF also intersect. Q.E.D.

196. Def. Two or more lines are said to be **concurrent** if they intersect at a common point.

Ex. 197. If two parallels are cut by a transversal so that one of the angles formed is 45° , how many degrees are there in each of the other seven angles?

Ex. 198. If a quadrilateral has two of its sides parallel, two pairs of its angles will be supplementary.

Ex. 199. In the annexed diagram AB is parallel to CD , and EF is parallel to GH . Prove



- (a) angle 1 - angle 2;
- (b) angle 1 + angle 3 = 2 right angles.

Ex. 200. If a line is drawn through any point in the bisector of an angle, parallel to one of the sides of the angle, an isosceles triangle will be formed.

Ex. 201. Draw a line parallel to the base of a triangle, cutting the sides so that the sum of the segments adjacent to the base shall equal the parallel line.

Ex. 202. If two parallel lines are cut by a transversal, the bisectors of a pair of corresponding angles are parallel.

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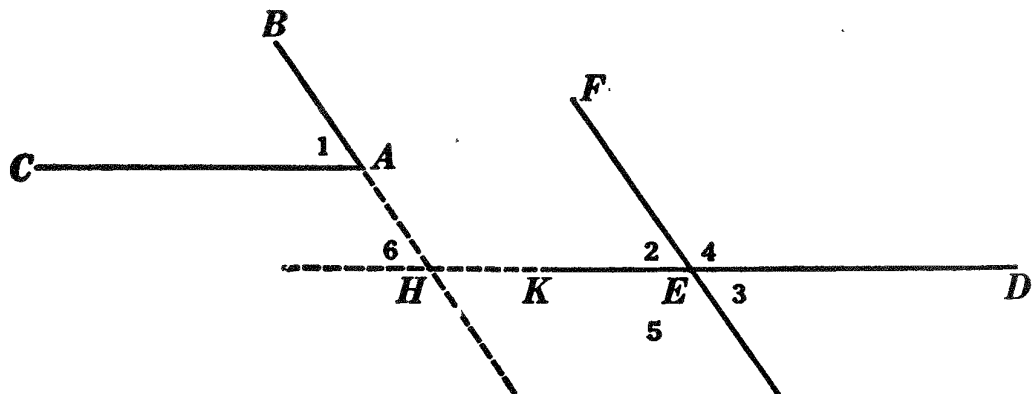
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PROPOSITION XXV. THEOREM

198. *Two angles whose sides are parallel, each to each, are either equal or supplementary.*



Given $\angle 1$ and the \sphericalangle s at E , with $AB \parallel EF$ and $AC \parallel DE$.

To prove $\angle 1 = \angle 2 = \angle 3$, and $\angle 1 + \angle 4 = 2 \text{ rt. } \sphericalangle$, $\angle 1 + \angle 5 = 2 \text{ rt. } \sphericalangle$.

ARGUMENT

1. Prolong BA and DE until they intersect at some point as H .
2. $\angle 1 = \angle 6$.
3. $\angle 2 = \angle 6$.
4. $\therefore \angle 1 = \angle 2$.
5. $\angle 3 = \angle 2$.
6. $\therefore \angle 1 = \angle 3$.
7. $\angle 2 + \angle 4 = 2 \text{ rt. } \sphericalangle$.
8. $\therefore \angle 1 + \angle 4 = 2 \text{ rt. } \sphericalangle$.

REASONS

1. Str. line post. II. § 54, 16.
2. Corresponding \sphericalangle s of \parallel lines are equal. § 190.
3. Same reason as 2.
4. Things equal to the same thing are equal to each other. § 54, 1.
5. If two str. lines intersect, the vertical \sphericalangle s are equal. § 77.
6. Same reason as 4.
7. If one str. line meets another str. line, the sum of the two adj. \sphericalangle s is 2 rt. \sphericalangle . § 65.
8. Substituting $\angle 1$ for its equal $\angle 2$.

| ARGUMENT | REASONS |
|--|--|
| 9. $\angle 5 = \angle 4$. | 9. Same reason as 5. |
| 10. $\therefore \angle 1 + \angle 5 = 2 \text{ rt. } \angle$. | 10. Substituting $\angle 5$ for its equal $\angle 4$. |
| Q.E.D. | |

199. Note. Every angle viewed from its vertex has a right and a left side; thus, in the annexed diagram, the right side of $\angle A$ is r and the left side, l ; the right side of $\angle B$ is r and the left, l .

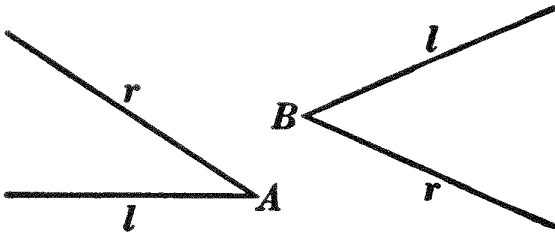


FIG. 1.

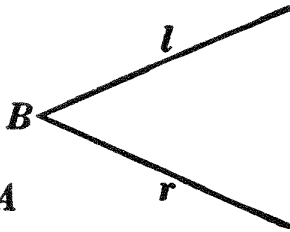


FIG. 2.

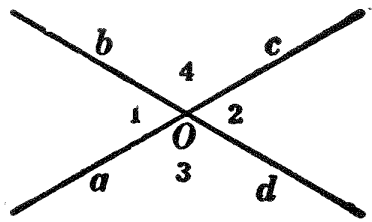


FIG. 3.

In the diagram of Prop. XXV, $\angle 1$ and $\angle 2$, whose sides are \parallel right to right (AB to EF) and left to left (AC to EK) are equal; while $\angle 1$ and $\angle 4$, whose sides are \parallel right to left (AB to EF) and left to right (AC to ED) are supplementary. Hence:

200. (a) *If two angles have their sides parallel right to right and left to left, they are equal.*

(b) *If two angles have their sides parallel right to left and left to right, they are supplementary.*

Ex. 213. In Fig. 3, above, show which is the right side of each of the four angles about O .

Ex. 214. If a quadrilateral has its opposite sides parallel, its opposite angles are equal.

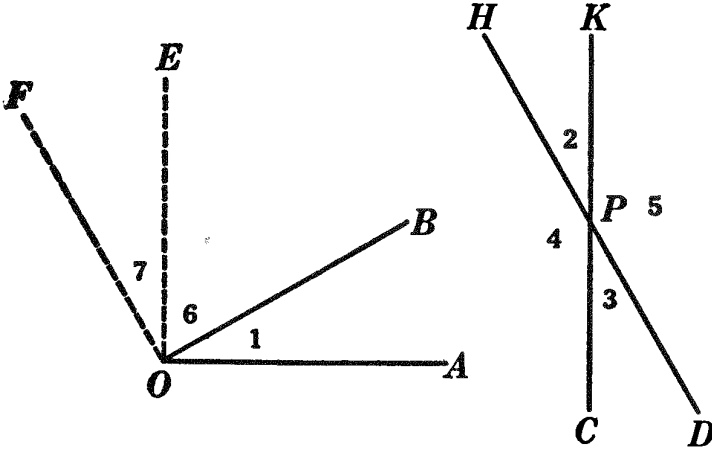
Ex. 215. Given two equal angles having a side of one parallel to a side of the other, are the other sides necessarily parallel? Prove.

Ex. 216. If two sides of a triangle are parallel respectively to two homologous sides of an equal triangle, the third side of the first is parallel to the third side of the second.

Ex. 217. Construct a triangle, given an angle and its bisector and the altitude drawn from the vertex of the given angle.

PROPOSITION XXVI. THEOREM

201. *Two angles whose sides are perpendicular, each to each, are either equal or supplementary.*



Given $\angle 1$ and the \sphericalangle s at P , with $OA \perp KC$ and $OB \perp HD$.

To prove $\angle 1 = \angle 2 = \angle 3$, $\angle 1 + \angle 4 = 2 \text{ rt. } \sphericalangle$, $\angle 1 + \angle 5 = 2 \text{ rt. } \sphericalangle$.

HINT. Draw $OE \parallel CK$ and $OF \parallel DH$. Prove $OE \perp OA$ and $OF \perp OB$. Prove $\angle 7 = \angle 1$, and prove $\angle 7 = \angle 2$.

202. Note. It will be seen that $\angle 1$ and $\angle 2$, whose sides are \perp right to right (OA to PK) and left to left (OB to PH), are equal; while $\angle 1$ and $\angle 4$, whose sides are \perp right to left (OA to PC) and left to right (OB to PH), are supplementary. Hence:

203. (a) *If two angles have their sides perpendicular right to right and left to left, they are equal.*

(b) *If two angles have their sides perpendicular right to left and left to right, they are supplementary.*

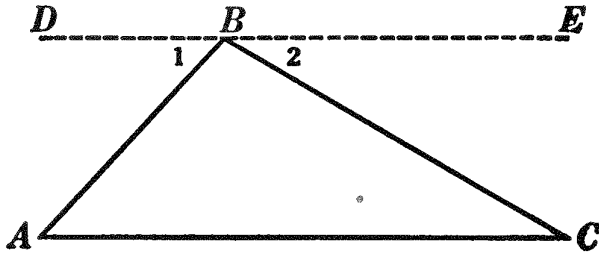
Ex. 218. If from a point outside of an angle perpendiculars are drawn to the sides of the angle, an angle is formed which is equal to the given angle.

Ex. 219. In a right triangle if a perpendicular is drawn from the vertex of the right angle to the hypotenuse, the right angle is divided into two angles which are equal respectively to the acute angles of the triangle.

Ex. 220. If from the end of the bisector of the vertex angle of an isosceles triangle a perpendicular is dropped upon one of the arms, the perpendicular forms with the base an angle equal to half the vertex angle.

PROPOSITION XXVII. THEOREM

204. *The sum of the angles of any triangle is two right angles.*



Given $\triangle ABC$.

To prove $\angle A + \angle ABC + \angle C = 2 \text{ rt. } \sphericalangle$.

| ARGUMENT | REASONS |
|---|---|
| 1. Through B draw $DE \parallel AC$. | 1. Parallel line post. § 179. |
| 2. $\angle 1 + \angle ABC + \angle 2 = 2 \text{ rt. } \sphericalangle$. | 2. The sum of all the \sphericalangle about a point on one side of a str. line passing through that point = 2 rt. \sphericalangle . § 66. |
| 3. $\angle 1 = \angle A$. | 3. Alt. int. \sphericalangle of \parallel lines are equal. § 189. |
| 4. $\angle 2 = \angle C$. | 4. Same reason as 3. |
| 5. $\therefore \angle A + \angle ABC + \angle C = 2 \text{ rt. } \sphericalangle$. | 5. Substituting for $\sphericalangle 1$ and 2 their equals, $\sphericalangle A$ and C , respectively. |
| Q.E.D. | |

205. Cor. I. *In a right triangle the two acute angles are complementary.*

206. Cor. II. *In a triangle there can be but one right angle or one obtuse angle.*

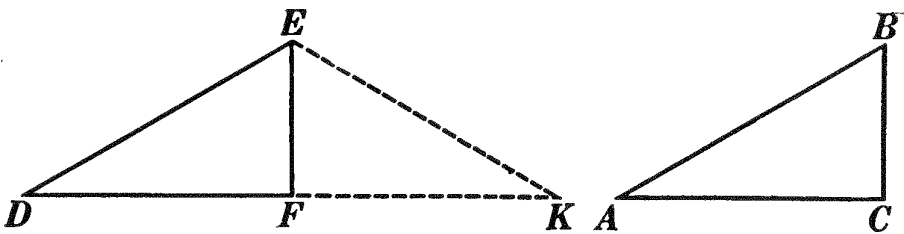
207. Cor. III. *If two angles of one triangle are equal respectively to two angles of another, then the third angle of the first is equal to the third angle of the second.*

208. Cor. IV. *If two right triangles have an acute angle of one equal to an acute angle of the other, the other acute angles are equal.*

209. Cor. V. *Two right triangles are equal if the hypotenuse and an acute angle of one are equal respectively to the hypotenuse and an acute angle of the other.*

210. Cor. VI. *Two right triangles are equal if a side and an acute angle of one are equal respectively to a side and the homologous acute angle of the other.*

211. Cor. VII. *Two right triangles are equal if the hypotenuse and a side of one are equal respectively to the hypotenuse and a side of the other.*



Given rt. $\triangle ABC$ and DEF , with $AB = DE$ and $BC = EF$.

To prove $\triangle ABC = \triangle DEF$.

HINT. Prove DFK a str. line; then $\triangle DEK$ is isosceles.

212. Cor. VIII. *The altitude upon the base of an isosceles triangle bisects the base and also the vertex angle.*

213. Cor. IX. *Each angle of an equilateral triangle is one third of two right angles, or 60° .*

214. Question. Why is the word *homologous* used in Cor. VI but not in Cor. V?

Ex. 221. If any angle of an isosceles triangle is 60° , what is the value of each of the two remaining angles?

Ex. 222. If the vertex angle of an isosceles triangle is 20° , find the angle included by the bisectors of the base angles.

Ex. 223. Find each angle of a triangle if the second angle equals twice the first and the third equals three times the second.

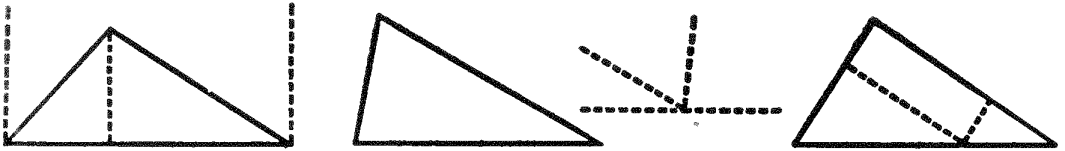
Ex. 224. If one angle of a triangle is m° and another angle l° , write an expression for the third angle.

Ex. 225. If the vertex angle of an isosceles triangle is a° , write an expression for each base angle.

Ex. 226. Construct an angle of 60° ; 120° ; 30° ; 15° .

Ex. 227. Construct a right triangle having one of its acute angles 60° . How large is the other acute angle?

Ex. 228. Construct an angle of 150° .



Ex. 229. Prove Prop. XXVII by using each of the diagrams given above.

Ex. 230. Given two angles of a triangle, construct the third angle.

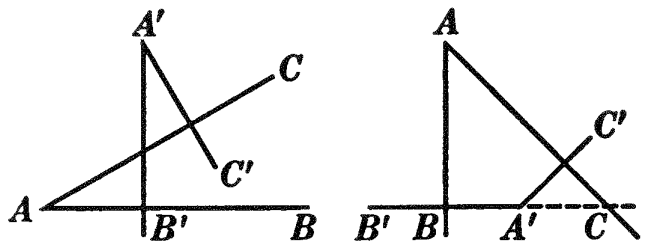
Ex. 231. Find the sum of the angles of a quadrilateral.

Ex. 232. The angle between the bisectors of two adjacent angles of a quadrilateral is equal to half the sum of the two remaining angles.

Ex. 233. The angle between the bisectors of the base angles of an isosceles triangle is equal to the exterior angle formed by prolonging the base.

Ex. 234. If two straight lines are cut by a transversal and the bisectors of two interior angles on the same side of the transversal are perpendicular to each other, the lines are parallel.

Ex. 235. If in an isosceles triangle each of the base angles is one fourth the angle at the vertex, a line drawn perpendicular to the base at one of its ends and meeting the opposite side prolonged will form with the adjacent side and the exterior portion of the opposite side an equilateral triangle.



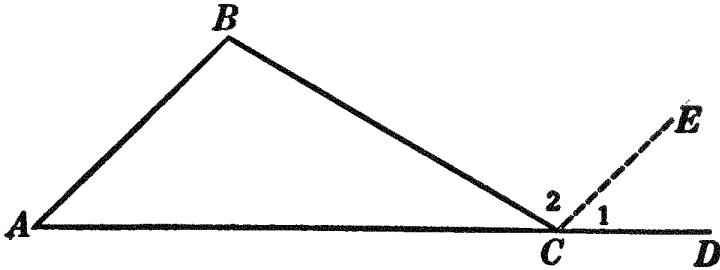
Ex. 236. Two angles whose sides are perpendicular each to each are either equal or supplementary. (Prove by using the annexed diagram.)

Ex. 237. If at the ends of the hypotenuse of a right triangle perpendiculars to the hypotenuse are drawn meeting the other two sides of the triangle prolonged, then the figure contains five triangles which are mutually equiangular.

Ex. 238. If one angle of a triangle is 50° and another angle is 70° , find the other interior angle of the triangle; also the exterior angles of the triangle. What relation is there between an exterior angle and the two remote interior angles of the triangle?

PROPOSITION XXVIII. THEOREM

215. *An exterior angle of a triangle is equal to the sum of the two remote interior angles.*



Given $\triangle ABC$ with $\angle DCB$ an exterior \angle .

To prove $\angle DCB = \angle A + \angle B$.

The proof is left as an exercise for the student.

HINT. Draw $CE \parallel AB$.

Ex. 239. The bisector of an exterior angle at the vertex of an isosceles triangle is parallel to the base.

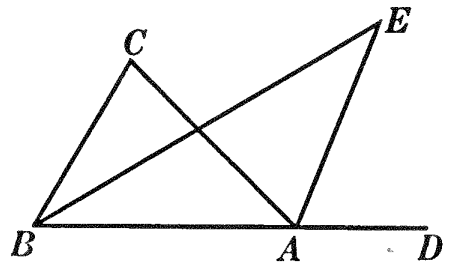
Ex. 240. If the sum of two exterior angles of a triangle is equal to three right angles, the triangle is a right triangle.

Ex. 241. The sum of the three exterior angles of a triangle is four right angles.

Ex. 242. What is the sum of the exterior angles of a quadrilateral?

Ex. 243. If the two exterior angles at the base of any triangle are bisected, the angle between these bisectors is equal to half the sum of the interior base angles of the triangle.

Ex. 244. If BE bisects angle B of triangle ABC , and AE bisects the exterior angle DAC , angle E is equal to one half angle C .



Ex. 245. D is any point in the base BC of isosceles triangle ABC . The side AC is prolonged through C to E so that $CE = CD$, and DE is drawn meeting AB at F . Prove angle EFA equal to three times angle AEF .

Ex. 246. The mid-point of the hypotenuse of a right triangle is equidistant from the three vertices. Prove by laying off on the right angle either acute angle.

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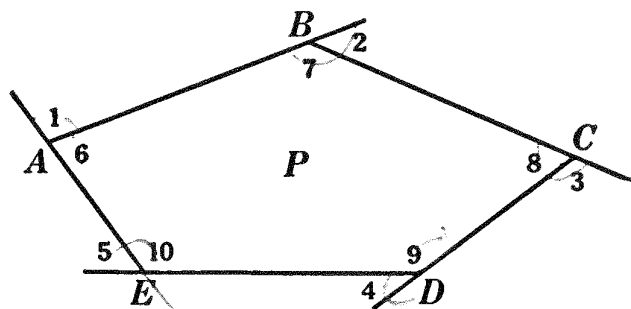
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PROPOSITION XXX. THEOREM

218. *If the sides of any polygon are prolonged in succession one way, no two adjacent sides being prolonged through the same vertex, the sum of the exterior angles thus formed is four right angles.*



Given polygon P with $\angle 1, \angle 2, \angle 3, \angle 4, \dots$ its successive exterior angles.

To prove $\angle 1 + \angle 2 + \angle 3 + \angle 4 + \dots = 4 \text{ rt. } \sphericalangle$.

| ARGUMENT | REASONS |
|---|--|
| 1. $\angle 1 + \angle 6 = 2 \text{ rt. } \sphericalangle$, $\angle 2 + \angle 7 = 2 \text{ rt. } \sphericalangle$, and so on; <i>i.e.</i> the sum of the int. \sphericalangle and the ext. \sphericalangle at one vertex $= 2 \text{ rt. } \sphericalangle$. | 1. If one str. line meets another str. line, the sum of the two adj. \sphericalangle is $2 \text{ rt. } \sphericalangle$. § 65. |
| 2. \therefore the sum of the int. and ext. \sphericalangle at the n vertices $= 2n \text{ rt. } \sphericalangle$. | 2. If equals are multiplied by equals, the products are equal. § 54, 7 a. |
| 3. Denote the sum of all the interior \sphericalangle by I and the sum of all the ext. \sphericalangle by E ; then $E + I = 2n \text{ rt. } \sphericalangle$. | 3. Arg. 2. |
| 4. But $I = 2n \text{ rt. } \sphericalangle - 4 \text{ rt. } \sphericalangle$. | 4. The sum of all the \sphericalangle of any polygon $= 2n \text{ rt. } \sphericalangle - 4 \text{ rt. } \sphericalangle$. § 216. |
| 5. $\therefore E = 4 \text{ rt. } \sphericalangle$; <i>i.e.</i> $\angle 1 + \angle 2 + \angle 3 + \angle 4 + \dots = 4 \text{ rt. } \sphericalangle$. Q.E.D. | 5. If equals are subtracted from equals, the remainders are equal. § 54, 3. |

219. Note. The formula $2n \text{ rt. } \sphericalangle - 4 \text{ rt. } \sphericalangle$ (§ 216) is sometimes more useful in the form $(n - 2) 2 \text{ rt. } \sphericalangle$.

Ex. 247. Find the sum of the angles of a polygon of 7 sides ; of 8 sides ; of 10 sides.

Ex. 248. Prove Prop. XXIX by drawing as many diagonals as possible from one vertex.

Ex. 249. How many diagonals can be drawn from one vertex in a polygon of 8 sides ? of 50 sides ? of n sides ? Show that the greatest number of diagonals possible in a polygon of n sides (using all vertices) is $\frac{n(n - 3)}{2}$.

Ex. 250. How many degrees are there in each angle of an equiangular quadrilateral ? in each angle of an equiangular pentagon ?

Ex. 251. How many sides has a polygon the sum of whose angles is 14 right angles ? 20 right angles ? 540° ?

Ex. 252. How many sides has a polygon the sum of whose interior angles is double the sum of its exterior angles ?

Ex. 253. Is it possible for an exterior angle of an equiangular polygon to be 70° ? 72° ? 140° ? 144° ?

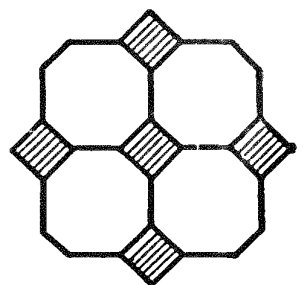
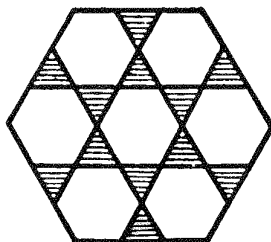
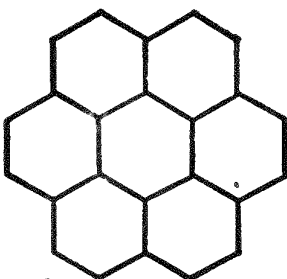
Ex. 254. How many sides has a polygon each of whose exterior angles equals 12° ?

Ex. 255. How many sides has a polygon each of whose exterior angles is one eleventh of its adjacent interior angle ?

Ex. 256. How many sides has a polygon the sum of whose interior angles is six times the sum of its exterior angles ?

Ex. 257. How many sides has an equiangular polygon if the sum of three of its exterior angles is 180° ?

Ex. 258. Tell what equiangular polygons can be put together to make a pavement. How many equiangular triangles must be placed with a common vertex to fill the angular magnitude around a point ?



QUADRILATERALS. PARALLELOGRAMS

QUADRILATERALS CLASSIFIED WITH RESPECT TO PARALLELISM

220. Def. A **parallelogram** is a quadrilateral whose opposite sides are parallel.

221. Def. A **trapezoid** is a quadrilateral having two of its opposite sides parallel and the other two not parallel.

222. Def. A **trapezium** is a quadrilateral having no two of its sides parallel.

PARALLELOGRAMS CLASSIFIED WITH RESPECT TO ANGLES

223. Def. A **rectangle** is a parallelogram having one right angle.

It is shown later that all the angles of a rectangle are right angles.

224. Def. A **rhomboid** is a parallelogram having an oblique angle.

It is shown later that all the angles of a rhomboid are oblique.

225. Def. A rectangle having two adjacent sides equal is a **square**.

It is shown later that all the sides of a square are equal.

226. Def. A rhomboid having two adjacent sides equal is a **rhombus**.

It is shown later that all the sides of a rhombus are equal.

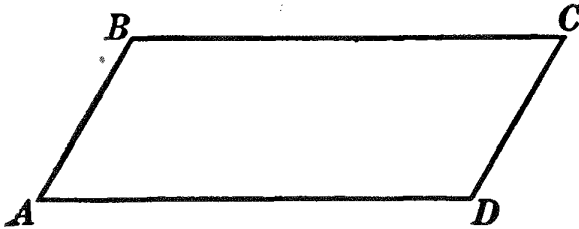
227. Def. A trapezoid having its two non-parallel sides equal is an **isosceles trapezoid**.

228. Def. Any side of a parallelogram may be regarded as its **base**, and the line drawn perpendicular to the base from any point in the opposite side is then the **altitude**.

229. Def. The **bases** of a trapezoid are its parallel sides, and its **altitude** is a line drawn from any point in one base perpendicular to the other.

PROPOSITION XXXI. THEOREM

230. *Any two opposite angles of a parallelogram are equal, and any two consecutive angles are supplementary.*



Given $\square ABCD$.

To prove: (a) $\angle A = \angle C$, and $\angle B = \angle D$;
 (b) any two consecutive \sphericalangle s, as A and B , sup.

| ARGUMENT | REASONS |
|--|--|
| 1. $\angle A = \angle C$ and $\angle B = \angle D$. | 1. If two \sphericalangle s have their sides \parallel right to right and left to left, they are equal. § 200, a. |
| 2. $\sphericalangle A$ and B are sup. | 2. If two \parallel lines are cut by a transversal, the sum of the two int. \sphericalangle s on the same side of the transversal is two rt. \sphericalangle s. § 192. |
| Q.E.D. | |

231. Cor. *All the angles of a rectangle are right angles, and all the angles of a rhomboid are oblique angles.*

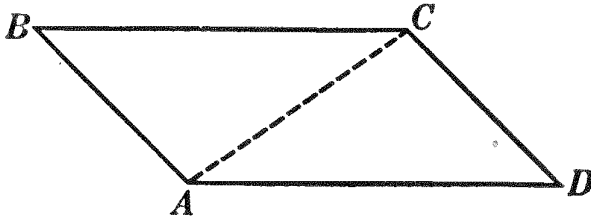
Ex. 259. If the opposite angles of a quadrilateral are equal, the figure is a parallelogram.

Ex. 260. If an angle of one parallelogram is equal to an angle of another, the remaining angles are equal each to each.

Ex. 261. The bisectors of the angles of a parallelogram (not a rhombus or a square) inclose a rectangle.

PROPOSITION XXXII. THEOREM

232. *The opposite sides of a parallelogram are equal.*



Given $\square ABCD$.

To prove $AB = CD$ and $BC = AD$.

The proof is left as an exercise for the student.

233. Cor. I. *All the sides of a square are equal, and all the sides of a rhombus are equal.*

234. Cor. II. *Parallel lines intercepted between the same parallel lines are equal.*

235. Cor. III. *The perpendiculars drawn to one of two parallel lines from any two points in the other are equal.*

236. Cor. IV. *A diagonal of a parallelogram divides it into two equal triangles.*

Ex. 262. The perpendiculars drawn to a diagonal of a parallelogram from the opposite vertices are equal.

Ex. 263. The diagonals of a rhombus are perpendicular to each other and so are the diagonals of a square.

Ex. 264. The diagonals of a rectangle are equal.

Ex. 265. The diagonals of a rhomboid are unequal.

Ex. 266. If the diagonals of a parallelogram are equal, the figure is a rectangle.

Ex. 267. If the diagonals of a parallelogram are not equal, the figure is a rhomboid.

Ex. 268. Draw a line parallel to the base of a triangle so that the portion intercepted between the sides may be equal to a given line.

Ex. 269. Explain the statement: Parallel lines are everywhere equidistant. Has this been proved?

Ex. 270. Find the locus of a point that is equidistant from two given parallel lines.

Ex. 271. Find the locus of a point: (a) one inch above a given horizontal line; (b) two inches below the given line.

Ex. 272. Find the locus of a point: (a) one inch to the right of a given vertical line; (b) one inch to the left of the given line.

Ex. 273. Given a horizontal line OX and a line OY perpendicular to OX . Find the locus of a point three inches above OX and two inches to the right of OY .

237. Historical Note. René Descartes (1596–1650) was the first to observe the importance of the fact that the position of a point in a plane is determined if its distances, say x and y , from two fixed lines in the plane, perpendicular to each other, are known. He showed that geometric figures can be represented by algebraic equations, and developed the subject of analytic geometry, which is known by his name as *Cartesian geometry*.



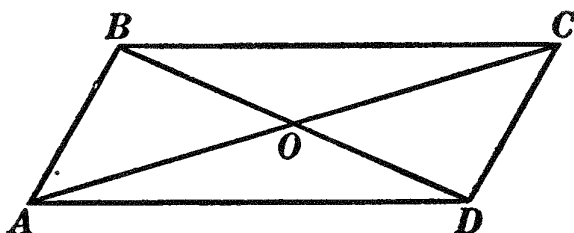
DESCARTES

Descartes was born near Tours in France, and was sent at eight years of age to the famous Jesuit school at La Flèche. He was of good family, and since, at that time, most men of position entered either the church or the army, he chose the latter, and joined the army of the Prince of Orange.

One day, while walking in a street in a Holland town, he saw a placard which challenged every one who read it to solve a certain geometric problem. Descartes solved it with little difficulty and is said to have realized then that he had no taste for military life. He soon resigned his commission and spent five years in travel and study. After this he lived a short time in Paris, but soon retired to Holland, where he lived for twenty years, devoting his time to mathematics, philosophy, astronomy, and physics. His work in philosophy was of such importance as to give him the name of the Father of Modern Philosophy.

PROPOSITION XXXIII. THEOREM

238. *The diagonals of a parallelogram bisect each other.*



Given $\square ABCD$ with its diagonals AC and BD intersecting at O .
To prove $AO = OC$ and $BO = OD$.

HINT. Prove $\triangle OBC = \triangle ODA$. $\therefore AO = OC$ and $BO = OD$.

Ex. 274. If through the vertices of a triangle lines are drawn parallel to the opposite sides of the triangle, the lines which join the vertices of the triangle thus formed to the opposite vertices of the given triangle are bisected by the sides of the given triangle.

Ex. 275. A line terminated by the sides of a parallelogram and passing through the point of intersection of its diagonals is bisected at that point.

Ex. 276. How many parallelograms can be constructed having a given base and altitude? What is the locus of the point of intersection of the diagonals of all these parallelograms?

Ex. 277. If the diagonals of a parallelogram are perpendicular to each other, the figure is a rhombus or a square.

Ex. 278. If the diagonals of a parallelogram bisect the angles of the parallelogram, the figure is a rhombus or a square.

Ex. 279. Find on one side of a triangle the point from which straight lines drawn parallel to the other two sides, and terminated by those sides, are equal. (See § 232.)

Ex. 280. Find the locus of a point at a given distance from a given finite line AB .

Ex. 281. Find the locus of a point at a given distance from a given line and also equidistant from the ends of another given line.

Ex. 282. Construct a parallelogram, given a side, a diagonal, and the altitude upon the given side.

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Ex. 284. Construct a rectangle, given the base and the altitude.

Ex. 285. Construct a square, given a side.

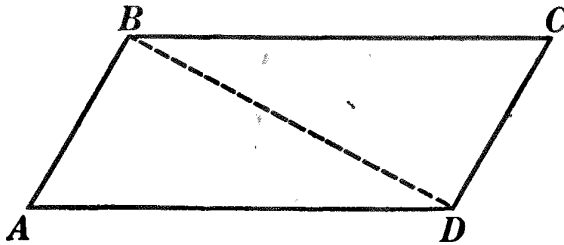
Ex. 286. Through a given point construct a parallel to a given line by means of Prop. XXXIV.

Ex. 287. Construct a median of a triangle by means of a parallelogram, (1) using §§ 239 and 238 ; (2) using §§ 220 and 238.

Ex. 288. An angle of a triangle is right, acute, or obtuse according as the median drawn from its vertex is equal to, greater than, or less than half the side it bisects.

PROPOSITION XXXV. THEOREM

240. *If two opposite sides of a quadrilateral are equal and parallel, the figure is a parallelogram.*



Given quadrilateral $ABCD$, with BC both equal and \parallel to AD .

To prove $ABCD$ a \square .

OUTLINE OF PROOF

1. Draw diagonal BD .
2. Prove $\triangle BCD = \triangle ABD$.
3. Then $\angle CDB = \angle ABD$ and $AB \parallel CD$.
4. $\therefore ABCD$ is a \square .

Ex. 289. If the mid-points of two opposite sides of a parallelogram are joined to a pair of opposite vertices, a parallelogram will be formed.

Ex. 290. Construct a parallelogram, having given a base, an adjacent angle, and the altitude, making your construction depend upon § 240.

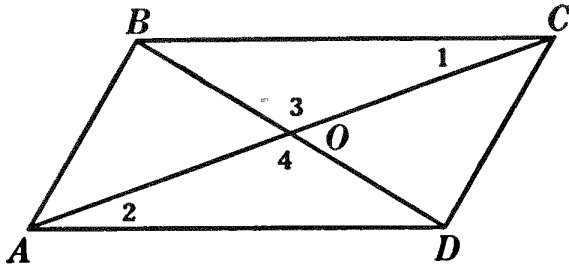
Ex. 291. If the perpendiculars to a line from any two points in another line are equal, then the lines are parallel.

Ex. 292. If two parallelograms have two vertices and a diagonal in common, the lines joining the other four vertices form a parallelogram.

PROPOSITION XXXVI. THEOREM

(Converse of Prop. XXXIII)

241. *If the diagonals of a quadrilateral bisect each other, the figure is a parallelogram.*



Given quadrilateral $ABCD$ with its diagonals AC and BD intersecting at O so that $AO = CO$ and $BO = DO$.

To prove $ABCD$ a \square .

ARGUMENT ONLY

1. In $\triangle OBC$ and ODA ,
 $BO = DO$.
2. $CO = AO$.
3. $\angle 3 = \angle 4$.
4. $\therefore \triangle OBC = \triangle ODA$.
5. $\therefore BC = AD$.
6. Also $\angle 1 = \angle 2$.
7. $\therefore BC \parallel AD$.
8. $\therefore ABCD$ is a \square .

Q.E.D.

Ex. 293. In parallelogram $ABCD$, let diagonal AC be prolonged through A and C to X and Y , respectively, making $AX = CY$. Prove $XB YD$ a parallelogram.

Ex. 294. If each half of each diagonal of a parallelogram is bisected, the lines joining the points of bisection form a parallelogram.

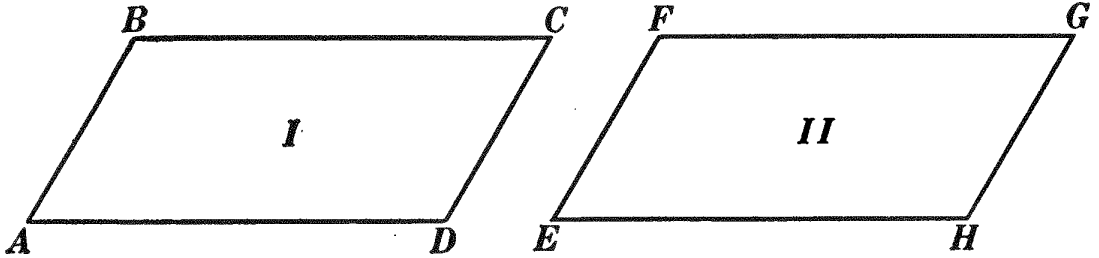
Ex. 295. Lines drawn from the vertices of two angles of a triangle and terminating in the opposite sides cannot bisect each other.

Ex. 296. State four independent hypotheses which would lead to the conclusion, "the quadrilateral is a parallelogram."

Ex. 297. Construct a parallelogram, given its diagonals and an angle between them.

PROPOSITION XXXVII. THEOREM

242. *Two parallelograms are equal if two sides and the included angle of one are equal respectively to two sides and the included angle of the other.*



Given \square I and II with $AB = EF$, $AD = EH$, and $\angle A = \angle E$.

To prove \square I = \square II.

| ARGUMENT | REASONS |
|--|---|
| 1. Place \square I upon \square II so that AB shall fall upon its equal EF , A upon E , B upon F . | 1. Transference post. § 54, 14. |
| 2. Then AD will become collinear with EH . | 2. $\angle A = \angle E$, by hyp. |
| 3. Point D will fall on H . | 3. $AD = EH$, by hyp. |
| 4. Now $DC \parallel AB$, and $HG \parallel EF$. | 4. By def. of a \square . § 220. |
| 5. $\therefore DC$ and HG are both $\parallel AB$. | 5. AB and EF coincide, Arg. 1. |
| 6. $\therefore DC$ will become collinear with HG , and C will fall somewhere on HG or its prolongation. | 6. Parallel line post. § 179. |
| 7. Likewise BC will become collinear with FG , and C will fall somewhere on FG or its prolongation. | 7. By steps similar to 4, 5, and 6. |
| 8. \therefore point C must fall on point G . | 8. Two intersecting str. lines can have only one point in common. § 26. |
| 9. $\therefore \square$ I = \square II. Q.E.D. | 9. By def. of equal figures. § 18. |

QUADRILATERALS CLASSIFIED

243. Quadrilaterals
- 1. Opposite sides \parallel : Parallelogram.
 - (a) Right-angled: Rectangle.
Two adj. sides equal:
Square.
 - (b) Oblique-angled: Rhomboid.
Two adj. sides equal:
Rhombus.
 - 2. Two sides \parallel , other two non- \parallel : Trapezoid.
 - (a) Two non- \parallel sides equal:
Isosceles trapezoid.
 - 3. No two sides \parallel : Trapezium.

Ex. 298. If it is required to prove a given quadrilateral a rectangle, show by reference to § 243 that the logical steps are to prove first that it is a parallelogram; then that it has one right angle.

Ex. 299. If a given quadrilateral is to be proved a square, show that the only additional step after those in Ex. 298 is to prove two adjacent sides equal.

Ex. 300. If a given quadrilateral is to be proved a rhombus, what are the three steps corresponding to those given in Ex. 298 and Ex. 299?

Ex. 301. Since rectangles and rhomboids are parallelograms, they possess all the general properties of parallelograms. What property differentiates rectangles from rhomboids (1) by definition? (2) by proof? (See Ex. 266 and Ex. 267.)

Ex. 302. (a) What two properties that have been *proved* distinguish squares from other rectangles? (See Ex. 277 and Ex. 278.)

(b) What two properties that have been proved distinguish rhombuses from other rhomboids? (See Ex. 277 and Ex. 278.)

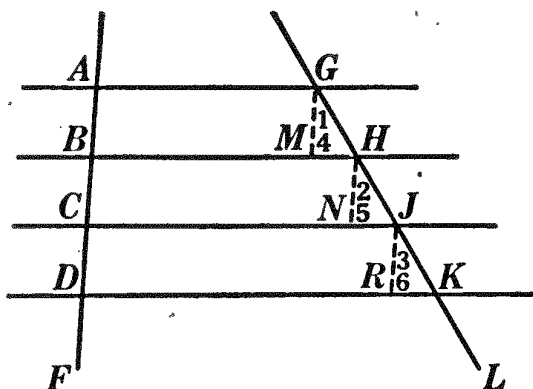
(c) Show that the two properties which distinguish squares and rhombuses from the other members of their class are due to the common property possessed by squares and rhombuses by definition.

Ex. 303. The mid-point of the hypotenuse of a right triangle is equidistant from the three vertices.

Ex. 304. If a line AB of given length is moved so that its ends always touch the sides of a given right angle, what is the locus of the mid-point of AB ?

PROPOSITION XXXVIII. THEOREM

244. *If three or more parallel lines intercept equal segments on one transversal, they intercept equal segments on any other transversal.*



Given \parallel lines AG, BH, CJ, DK , etc., which intercept the equal segments AB, BC, CD , etc., on transversal AF , and which intercept segments GH, HJ, JK , etc., on transversal GL .

To prove $GH = HJ = JK$, etc.

| ARGUMENT | REASONS |
|--|---|
| 1. Draw GM, HN, JR , etc. $\parallel AF$. | 1. Parallel line post. § 179. |
| 2. Now $AGMB, BHNC, CJRD$, etc., are \square . | 2. By def. of a \square . § 220. |
| 3. $\therefore GM = AB, HN = BC, JR = CD$, etc. | 3. The opposite sides of a \square are equal. § 232. |
| 4. And $AB = BC = CD$, etc. | 4. By hyp. |
| 5. $\therefore GM = HN = JR$, etc. | 5. Ax. 1. § 54, 1. |
| 6. Again GM, HN, JR , etc., are \parallel to each other. | 6. If two str. lines are \parallel to a third str. line, they are \parallel to each other. § 180. |
| 7. $\therefore \angle 1 = \angle 2 = \angle 3$, etc. | 7. Corresponding \sphericalangle s of \parallel lines are equal. § 190. |
| 8. And $\angle 4 = \angle 5 = \angle 6$, etc. | 8. If two \sphericalangle s have their sides \parallel right to right and left to left, they are equal. § 200, a. |

9. $\therefore \triangle GHM = \triangle HJN = \triangle JKR$, etc.

10. $\therefore GH = HJ = JK$, etc.

Q.E.D.

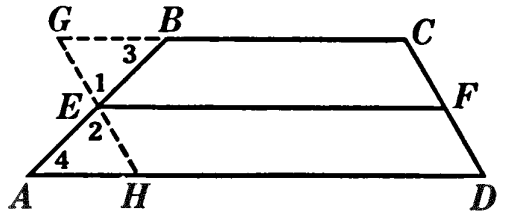
9. Two \triangle are equal if a side and the two adj. \sphericalangle of one are equal respectively to a side and the two adj. \sphericalangle of the other. § 105.

10. Homol. parts of equal figures are equal. § 110.

245. Question. Are the segments that the parallels intercept on one transversal equal to the segments that they intercept on another transversal? Illustrate.

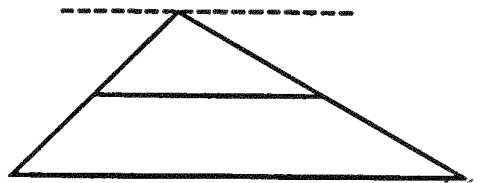
246. Cor. I. *The line bisecting one of the non-parallel sides of a trapezoid and parallel to the bases bisects the other of the non-parallel sides also.*

247. Cor. II. *The line joining the mid-points of the non-parallel sides of a trapezoid is (a) parallel to the bases; and (b) equal to one half their sum.*

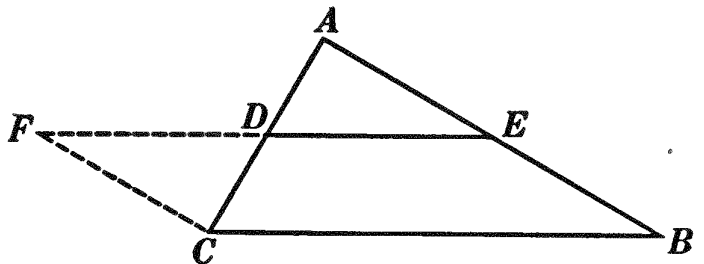


HINT. (a) Prove $EF \parallel BC$ and AD by the indirect method. (b) Draw $GH \parallel CD$. Prove $AH = GB$; then prove $EF = GC = \frac{1}{2}(GC + HD) = \frac{1}{2}(BC + AD)$.

248. Cor. III. *The line bisecting one side of a triangle and parallel to another side bisects the third side.*



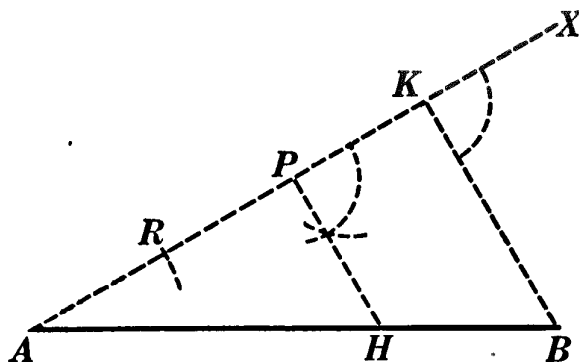
249. Cor. IV. *The line joining the mid-points of two sides of a triangle is parallel to the third side and equal to one half the third side.*



HINT. Draw $CF \parallel BA$. Prove $CF = AE = EB$.

PROPOSITION XXXIX. PROBLEM

250. *To divide a given straight line into any number of equal parts.*



Given straight line AB .

To divide AB into n equal parts.

I. Construction

1. Draw the unlimited line AX .
2. Take any convenient segment, as AR , and, beginning at A , lay it off n times on AX .
3. Connect the n th point of division, as K , with B .
4. Through the preceding point of division, as P , draw a line $PH \parallel KB$. § 188.
5. Then HB is one n th of AB .
6. $\therefore HB$, if laid off successively on AB , will divide AB into n equal parts.

II. The proof and discussion are left as an exercise for the student.

Ex. 305. Divide a straight line into 7 equal parts.

Ex. 306. Construct an equilateral triangle, having given the perimeter.

Ex. 307. Construct a square, having given the perimeter.

251. Def. The line joining the mid-points of the non-parallel sides of a trapezoid is called the **median** of the trapezoid.

Ex. 308. Show, by generalizing, that Cor. III, Prop. XXXVIII, may be obtained from Cor. I and Cor. IV from Cor. II.

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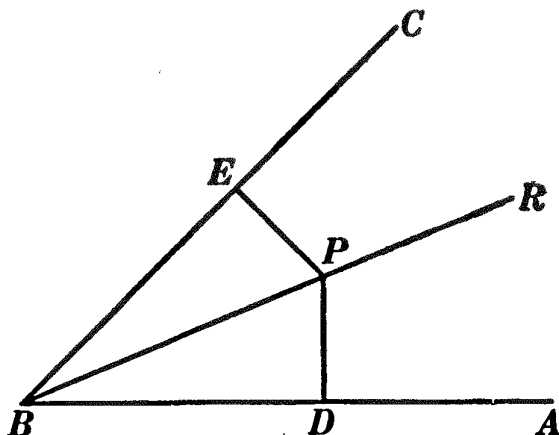
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PROPOSITION XL. THEOREM

252. *The two perpendiculars to the sides of an angle from any point in its bisector are equal.*



Given $\angle ABC$; P any point in BR , the bisector of $\angle ABC$; PD and PE , the \perp s from P to BA and BC respectively.

To prove $PD = PE$.

ARGUMENT ONLY

1. In rt. $\triangle DBP$ and PBE , $PB = PB$.
2. $\angle DBP = \angle PBE$.
3. $\therefore \triangle DBP = \triangle PBE$.
4. $\therefore PD = PE$.

Q.E.D.

253. Prop. XL may be stated as follows:

Every point in the bisector of an angle is equidistant from the sides of the angle.

Ex. 322. Find a point in one side of a triangle which is equidistant from the other two sides of the triangle.

Ex. 323. Find a point equidistant from two given intersecting lines and also at a given distance from a fixed third line.

Ex. 324. Find a point equidistant from two given intersecting lines and also equidistant from two given parallel lines.

Ex. 325. Find a point equidistant from the four sides of a rhombus.

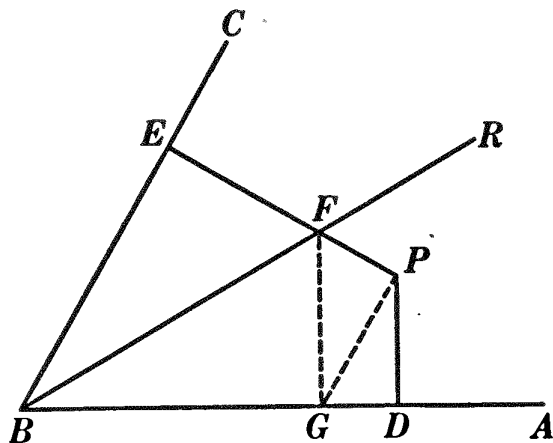
Ex. 326. The two altitudes of a rhombus are equal. Prove.

Ex. 327. Construct the locus of the center of a circle of given radius, which rolls so that it always touches the sides of a given angle. Do not prove.

PROPOSITION XLI. THEOREM

(Opposite of Prop. XL)

254. *The two perpendiculars to the sides of an angle from any point not in its bisector are unequal.*



Given $\angle ABC$; P any point not in BR , the bisector of $\angle ABC$;
 PD and PE , \perp s from P to BA and BC respectively.

To prove $PD \neq PE$.

OUTLINE OF PROOF

Draw $FG \perp BA$; draw PG . Then $FE = FG$.

Now $PF + FG > PG$. $\therefore PE > PG$. But $PG > PD$.

$\therefore PE > PD$.

255. Prop. XLI may be stated as follows:

Every point not in the bisector of an angle is not equidistant from the sides of the angle.

256. Cor. I. (Converse of Prop. XL). *Every point equidistant from the sides of an angle lies in the bisector of the angle.*

HINT. Prove directly, using the figure for § 252, or apply § 137.

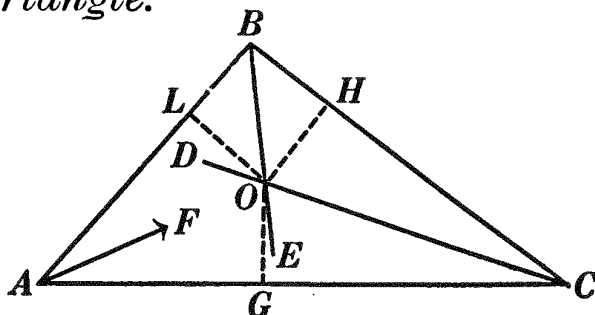
257. Cor. II. *The bisector of an angle is the locus of all points equidistant from the sides of the angle.*

Ex. 328. What is the locus of all points that are equidistant from a pair of intersecting lines?

.CONCURRENT LINE THEOREMS

PROPOSITION XLII. THEOREM

258. *The bisectors of the angles of a triangle are concurrent in a point which is equidistant from the three sides of the triangle.*



Given $\triangle ABC$ with AF , BE , CD the bisectors of $\sphericalangle A$, B , and C respectively.

To prove: (a) AF , BE , CD concurrent in some point as O ;
 (b) the point O equidistant from AB , BC , and CA .

ARGUMENT

1. BE and CD will intersect at some point as O .
2. Draw OL , OH , and OG , \perp from O to AB , BC , and CA respectively.
3. $\therefore O$ is in BE , $OL = OH$.
4. $\therefore O$ is in CD , $OG = OH$.
5. $\therefore OL = OG$:

REASONS

1. If two str. lines are cut by a transversal making the sum of the two int. \sphericalangle s on the same side of the transversal not equal to 2 rt. \sphericalangle s, the lines are not \parallel . § 194.
2. From a point outside a line there exists one and only one \perp to the line. § 155.
3. The two \perp s to the sides of an \sphericalangle from any point in its bisector are equal. § 252.
4. Same reason as 3.
5. Things equal to the same thing are equal to each other. § 54, 1.

| ARGUMENT | REASONS |
|--|--|
| 6. $\therefore AF$, the bisector of $\angle CAB$, passes through O . | 6. Every point equidistant from the sides of an \angle lies in the bisector of the \angle . § 256. |
| 7. $\therefore AF$, BE , and CD are concurrent in O . | 7. By def. of concurrent lines. § 196. |
| 8. Also O is equidistant from AB , BC , and CA . Q.E.D. | 8. By proof, $OL = OH = OG$. |

259. Cor. *The point of intersection of the bisectors of the three angles of a triangle is the locus of all points equidistant from the three sides of the triangle.*

Ex. 329. Is it always possible to find a point equidistant from three given straight lines? from four given straight lines?

Ex. 330. Find a point such that the perpendiculars from it to three sides of a quadrilateral shall be equal. (Give geometric construction.)

Ex. 331. Prove that if the sides AB and AC of a triangle ABC are prolonged to E and F , respectively, the bisectors of the three angles BAC , EBC , and BCF all pass through a point which is equally distant from the three lines AE , AF , and BC . Is any other point in the bisector of the angle BAC equally distant from these three lines? Give reason for your answer.

Ex. 332. Through a given point P draw a straight line such that perpendiculars to it from two fixed points Q and R shall cut off on it equal segments from P . (HINT. See § 246.)

Ex. 333. Construct the locus of the center of a circle of given radius, which rolls so that it always touches the sides of a given triangle. Do not prove.

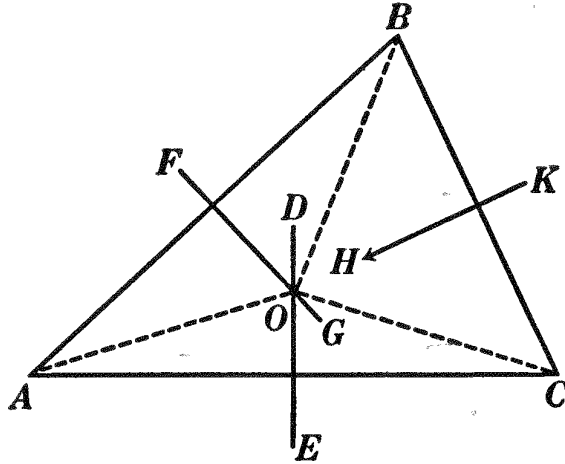
Ex. 334. Find the locus of a point in one side of a parallelogram and equidistant from two other sides. In what parallelograms is this locus a vertex of the parallelogram?

Ex. 335. Find the locus of a point in one side of a parallelogram and equidistant from two of the vertices of the parallelogram. In what class of parallelograms is this locus a vertex of the parallelogram?

Ex. 336. Construct the locus of the center of a circle of given radius which rolls so that it constantly touches a given circumference. Do not prove.

PROPOSITION XLIII. THEOREM

260. *The perpendicular bisectors of the sides of a triangle are concurrent in a point which is equidistant from the three vertices of the triangle.*



Given $\triangle ABC$ with FG , HK , ED , the \perp bisectors of AB , BC , CA .

To prove: (a) FG , HK , ED concurrent in some point as O ;

(b) the point O equidistant from A , B , and C .

| ARGUMENT | REASONS |
|--|--|
| 1. FG and ED will intersect at some point as O . | 1. Two lines \perp respectively to two intersecting lines also intersect. § 195. |
| 2. Draw OA , OB , and OC . | 2. Str. line post. I. § 54, 15. |
| 3. $\because O$ is in FG , the \perp bisector of AB , $OB = OA$; and $\because O$ is in DE , the \perp bisector of CA , $OC = OA$. | 3. Every point in the \perp bisector of a line is equidistant from the ends of that line. § 134. |
| 4. $\therefore OB = OC$. | 4. Ax. 1. § 54, 1. |
| 5. $\therefore HK$, the \perp bisector of BC , passes through O . | 5. Every point equidistant from the ends of a line lies in the \perp bisector of that line. § 139. |
| 6. $\therefore FG$, HK , and ED are concurrent in O . | 6. By def. of concurrent lines § 196. |
| 7. Also O is equidistant from A , B , and C . Q.E.D. | 7. By proof, $OA = OB = OC$. |

261. Cor. *The point of intersection of the perpendicular bisectors of the three sides of a triangle is the locus of all points equidistant from the three vertices of the triangle.*

Ex. 337. Is it always possible to find a point equidistant from three given points? from four given points?

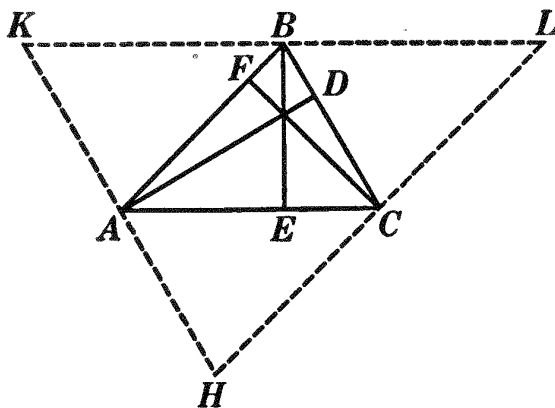
Ex. 338. Construct the perpendicular bisectors of two sides of an acute triangle, and then construct a circle whose circumference shall pass through the vertices of the triangle.

Ex. 339. Construct a circle whose circumference shall pass through the vertices of a right triangle.

Ex. 340. Construct a circle whose circumference shall pass through the vertices of an obtuse triangle.

PROPOSITION XLIV. THEOREM

262. *The altitudes of a triangle are concurrent.*



Given $\triangle ABC$ with its altitudes AD , BE , and CF .

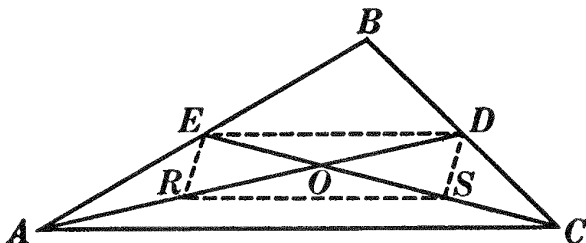
To prove AD , BE , and CF concurrent.

OUTLINE OF PROOF

Through the vertices A , B , and C , of triangle ABC , draw lines $\parallel BC$, AC , and AB , respectively. Then prove, by means of \square , that AD , BE , and CF are the \perp bisectors, respectively, of the sides of the auxiliary $\triangle HKL$. Then, by Prop. XLIII, AD , BE , and CF are concurrent. Q.E.D.

PROPOSITION XLV. THEOREM

263. *Any two medians of a triangle intersect each other in a trisection point of each.*



Given $\triangle ABC$ with AD and CE any two of its medians.

To prove that AD and CE intersect in a point O such that $OD = \frac{1}{3} AD$ and $OE = \frac{1}{3} CE$.

OUTLINE OF PROOF

1. AD and CE will intersect at some point as O . § 194.
2. Let R and S be the mid-points of AO and CO respectively.
3. Quadrilateral $REDS$ is a \square .
4. $\therefore AR = RO = OD$ and $CS = SO = OE$.
5. That is, $OD = \frac{1}{3} AD$ and $OE = \frac{1}{3} CE$. Q.E.D.

264. Cor. *The three medians of a triangle are concurrent.*

265. Def. The point of intersection of the medians of a triangle is called the **median center** of the triangle. It is also called the **centroid** of the triangle. This point is the center of mass or center of gravity of the triangle.

Ex. 341. Draw a triangle whose altitudes will intersect on one of its sides, and repeat the proof for Prop. XLIV.

Ex. 342. Draw a triangle whose altitudes will intersect outside of the triangle, and repeat the proof for Prop. XLIV.

Ex. 343. Prove Prop. XLV by prolonging OD its own length and drawing lines to B and C from the end of the prolongation.

Ex. 344. Construct a triangle, given two of its medians and the angle between them.

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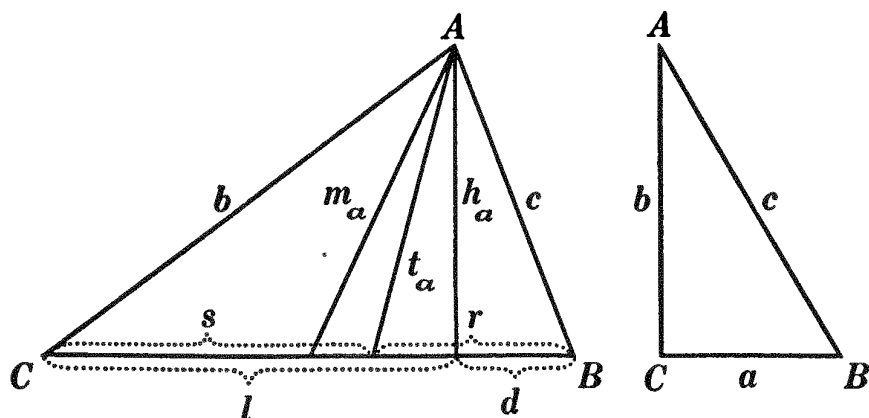
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CONSTRUCTION OF TRIANGLES

269. A triangle is *determined*, in general, when *three* parts are given, provided that at least *one* of the given parts is a *line*.

The three sides and the three angles of a triangle are called its *parts*; but there are also many *indirect* parts; as the three medians, the three altitudes, the three bisectors, and the parts into which both the sides and the angles are divided by these lines.



270. The notation given in the annexed figures may be used for brevity :

$A, B, C,$ the angles of the triangle; in a right triangle, angle C is the right angle.

$a, b, c,$ the sides of the triangle; in a right triangle, c is the hypotenuse.

$m_a, m_b, m_c,$ the medians to $a, b,$ and c respectively.

$h_a, h_b, h_c,$ the altitudes to $a, b,$ and c respectively.

$t_a, t_b, t_c,$ the bisectors of $A, B,$ and C respectively.

$l_a, d_a,$ the segments of a made by the altitude to a .

$s_a, r_a,$ the segments of a made by the bisector of angle A .

271. The student should review the chief cases of construction of triangles already given: viz. a, B, c ; A, b, C ; a, b, c ; right triangles: a, b ; b, c ; b, B ; b, A ; c, A ; review also § 152.

Ex. 347. State in words the first eight cases given in § 271.

PROPOSITION XLVII. PROBLEM

272. To construct a triangle having two of its sides equal respectively to two given lines, and the angle opposite one of these lines equal to a given angle.

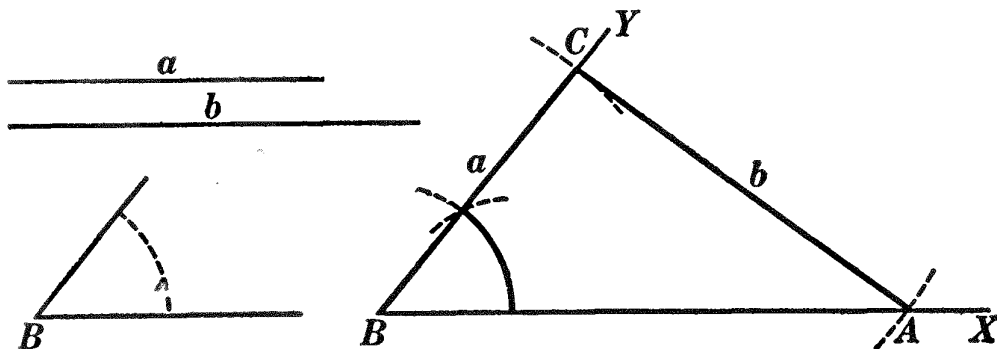


FIG. 1.

Given lines a and b , and $\angle B$.

To construct $\triangle ABC$.

I. Construction

1. Draw any line, as BX .
2. At any point in BX , as B , construct $\angle XBY =$ to the given $\angle B$. § 125.
3. On BY lay off $BC = a$.
4. With C as center and with b as radius, describe an arc cutting BX at A .
5. $\triangle ABC$ is the required \triangle .

II. The proof is left as an exercise for the student.

III. Discussion

- (1) b may be greater than a ;
- (2) b may equal a ;
- (3) b may be less than a .

(1) If $b > a$, there will be one solution, *i.e.* one \triangle and only one can be constructed which shall contain the given parts. This case is shown in Fig. 1.

(2) If $b = a$, the \triangle will be isosceles. The construction will be the same as for case (1).

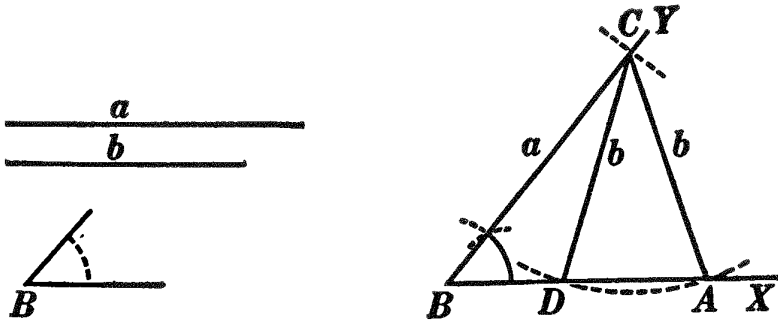


FIG. 2.

(3) If $b < a$. Make the construction as for case (1). If $b >$ the \perp from C to BX , there will be *two solutions*, since $\triangle ABC$ and DBC , Fig. 2, both contain the required parts. If b equals the \perp from C to BX there will be *one solution*. The \triangle will be a *rt. \triangle* . If $b <$ the \perp from C to BX , there will be *no solution*.

In the cases thus far considered, the given \angle was acute. The discussion of the cases in which the given \angle is a *rt. \angle* and in which it is an *obtuse \angle* is left to the student.

273. Question. Why is (1) the only case possible when the given angle is either right or obtuse?

274. The following exercises are given to illustrate *analysis* of problems and to show the use of auxiliary triangles in constructions.

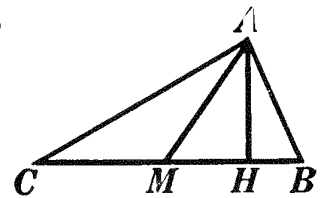


FIG. 1.

Ex. 348. Construct a triangle, given a, h_a, m_a .

ANALYSIS. Imagine the problem solved as in Fig. 1, and mark the given parts with heavy lines. The triangle AHM is determined and may be made the basis of the construction.

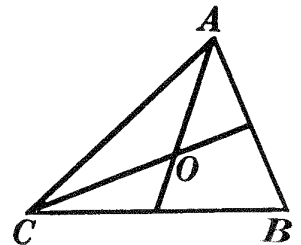


FIG. 2.

Ex. 349. Construct a triangle, given b, m_a, m_c .

ANALYSIS. From Fig. 2 it will be seen that triangle AOC may be constructed. Its three sides are known, since $AO = \frac{2}{3} m_a$ and $CO = \frac{2}{3} m_c$.

Ex. 350. Construct a triangle, given a, h_a, h_c .

ANALYSIS. In Fig. 3, right triangle CHB is determined. The locus of vertex A is a line parallel to CB , so that the distance between it and CB is equal to h_a .

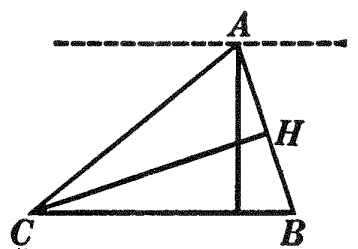


FIG. 3.

Ex. 351. Construct a triangle, given b, c, m_a .

ANALYSIS. Triangle ABK , Fig. 4, is determined by three sides, b, c , and $2m_a$. Since $ABKC$ is a parallelogram, AK bisects CB .

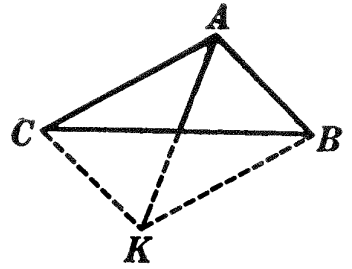


FIG. 4.

Ex. 352. Construct a triangle, given a, m_a , and the angle between m_a and a .

ANALYSIS. Triangle AMC is determined, as shown in Fig. 5.

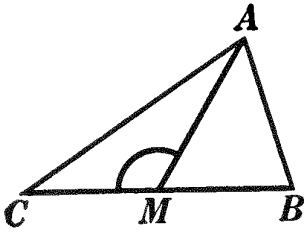


FIG. 5.

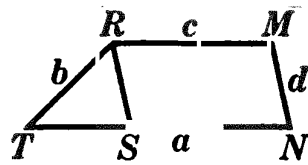


FIG. 6.

Ex. 353. Construct a trapezoid, given its four sides.

ANALYSIS. Triangle RST , Fig. 6, is determined.

Ex. 354. Construct a parallelogram, given the perimeter, one base angle, and the altitude.

CONSTRUCTION. The two parallels, CH and AE , Fig. 7, may be drawn so that the distance between them equals the altitude; at any point B construct angle EBC equal to the given base angle; draw CA , bisecting angle FCB ; measure AE equal to half the given perimeter; complete parallelogram $CHEB$.

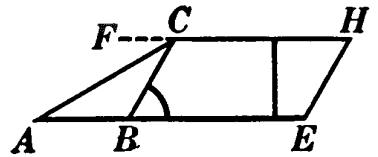


FIG. 7.

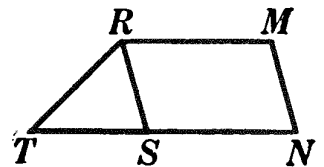


FIG. 8.

Ex. 355. Construct a trapezoid, given the two non-parallel sides and the difference between the bases. (See Fig. 8.)

Construct a triangle, given :

Ex. 356. A, h_a, t_a .

Ex. 360. B, h_a, b .

Ex. 357. h_a, l_a, d_a .

Ex. 361. s_a, t_a, h_a .

Ex. 358. h_a, m_a, l_a .

Ex. 362. a, m_b, C .

Ex. 359. a, t_b, C .

Ex. 363. a, t_b, B .

Construct an isosceles trapezoid, given :

Ex. 364. The two bases and the altitude.

Ex. 365. One base, the altitude, and a diagonal.

Ex. 366. A base, a diagonal, and the angle between them.

DIRECTIONS FOR THE SOLUTION OF EXERCISES

275. I. Make the figures clear, neat, accurate, and *general* in character.

II. Fix firmly in mind hypothesis and conclusion with reference to the given figure.

III. Recall fundamental propositions related to the proposition in question.

IV. If you can find no theorem which helps you, *contradict the conclusion* in every possible way (*reductio ad absurdum*) and try to show the absurdity of the contradiction.

V. Make frequent use of the *method of analysis*, which consists in assuming the proposition proved, seeing what results follow until a known truth is reached, and then retracing the steps taken.

VI. If it is required to find a point which fulfills two conditions, it is often convenient to find the point by the *Intersection of Loci*. By finding the locus of a point which satisfies each condition separately, it is possible to find the points in which the two loci intersect; *i.e.* the points which satisfy both conditions at the same time.

VII. See § 152 and exercises following § 274 for method of attacking problems of construction.

The method just described under V is a shifting of an uncertain issue to a certain one. It is sometimes called the *Method of Successive Substitutions*. It may be illustrated thus:

- | | |
|--------------------------------|----------------------------|
| 1. A is true if B is true. | 3. But C is true. |
| 2. B is true if C is true. | 4. $\therefore A$ is true. |

This is also called the *Analytic Method* of proof. The proofs of the theorems are put in what is called the *Synthetic* form. But these were first thought through analytically, then rearranged in the form in which we find them.

MISCELLANEOUS EXERCISES

Ex. 367. The perpendiculars drawn from the extremities of one side of a triangle to the median upon that side are equal.

Ex. 368. Construct an angle of 75° ; of $97\frac{1}{2}^\circ$.

Ex. 369. Upon a given line find a point such that perpendiculars from it to the sides of an angle shall be equal.

Ex. 370. Construct a triangle, given its perimeter and two of its angles.

Ex. 371. Construct a parallelogram, given the base, one base angle, and the bisector of the base angle.

Ex. 372. Given two lines that would meet if sufficiently prolonged. Construct the bisector of their angle, without prolonging the lines.

Ex. 373. Construct a triangle, having given one angle, one adjacent side, and the difference of the other two sides. Case 1: The side opposite the given angle less than the other unknown side. Case 2: The side opposite the given angle greater than the other unknown side.

Ex. 374. The difference between two adjacent angles of a parallelogram is 90° ; find all the angles.

Ex. 375. A straight railway passes 2 miles from a certain town. A place is described as 4 miles from the town and 1 mile from the railway. Represent the town by a point and find by construction how many places answer the description.

Ex. 376. Describe a circle through two given points which lie outside a given line, the center of the circle to be in that line. Show when no solution is possible.

Ex. 377. Construct a right triangle, given the hypotenuse and the difference of the other two sides.

Ex. 378. If two sides of a triangle are unequal, the median through their intersection makes the greater angle with the lesser side.

Ex. 379. Two trapezoids are equal if their sides taken in order are equal, each to each.

Ex. 380. Construct a right triangle, having given its perimeter and an acute angle.

Ex. 381. Draw a line such that its segment intercepted between two given indefinite lines shall be equal and parallel to a given finite line.

Ex. 382. One angle of a parallelogram is given in position and the point of intersection of the diagonals is given; construct the parallelogram.

Ex. 383. Construct a triangle, given two sides and the median to the third side.

Ex. 384. If from any point within a triangle lines are drawn to the three vertices of the triangle, the sum of these lines is less than the sum of the sides of the triangle, and greater than half their sum.

Ex. 385. Repeat the proof of Prop. XIX for two cases at once, using Figs. 1 and 2.

Ex. 386. If the angle at the vertex of an isosceles triangle is four times each base angle, the perpendicular to the base at one end of the base forms with one side of the triangle, and the prolongation of the other side through the vertex, an equilateral triangle.

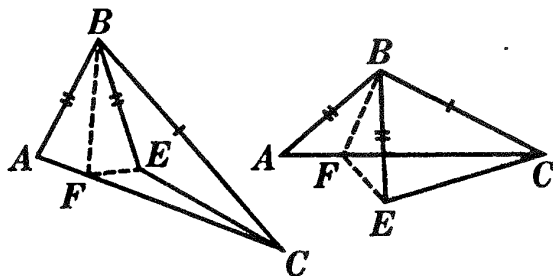


FIG. 1.

FIG. 2.

Ex. 387. The bisector of the angle C of a triangle ABC meets AB in D , and DE is drawn parallel to AC meeting BC in E and the bisector of the exterior angle at C in F . Prove $DE = EF$.

Ex. 388. Define a locus. Find the locus of the mid-points of all the lines drawn from a given point to a given line not passing through the point.

Ex. 389. Construct an isosceles trapezoid, given the bases and one angle.

Ex. 390. Construct a square, given the sum of a diagonal and one side.

Ex. 391. The difference of the distances from any point in the base prolonged of an isosceles triangle to the equal sides of the triangle is constant.

Ex. 392. Find a point X equidistant from two intersecting lines and at a given distance from a given point.

Ex. 393. When two lines are met by a transversal, the difference of two corresponding angles is equal to the angle between the two lines.

Construct a triangle, given :

Ex. 394. A, h_a, l_a .

Ex. 398. a, m_a, B .

Ex. 395. A, t_a, s_a .

Ex. 399. m_c, h_c, B .

Ex. 396. a, h_a, l_a .

Ex. 400. $b, c,$ [redacted]

Ex. 397. $a, b + c, A$

Ex. 401. $A, B, b + c$.

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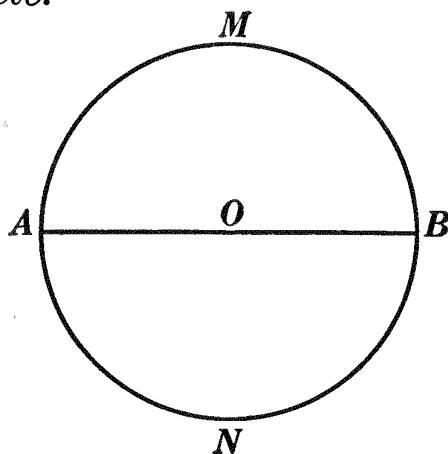
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PROPOSITION I. THEOREM

284. *Every diameter of a circle bisects the circumference and the circle.*



Given circle AMB with center O , and AB , any diameter.

To prove: (a) that AB bisects circumference AMB ;
 (b) that AB bisects circle AMB .

| ARGUMENT | REASONS |
|---|--------------|
| 1. Turn figure AMB on AB as an axis until it falls upon the plane of ANB . | 1. § 54, 14. |
| 2. Arc AMB will coincide with arc ANB . | 2. § 279, a. |
| 3. \therefore arc $AMB =$ arc ANB ; <i>i.e.</i> AB bisects circumference AMB . | 3. § 18. |
| 4. Also figure AMB will coincide with figure ANB . | 4. § 279, a. |
| 5. \therefore figure $AMB =$ figure ANB ; <i>i.e.</i> AB bisects circle AMB . <div style="text-align: right;">Q.E.D.</div> | 5. § 18. |

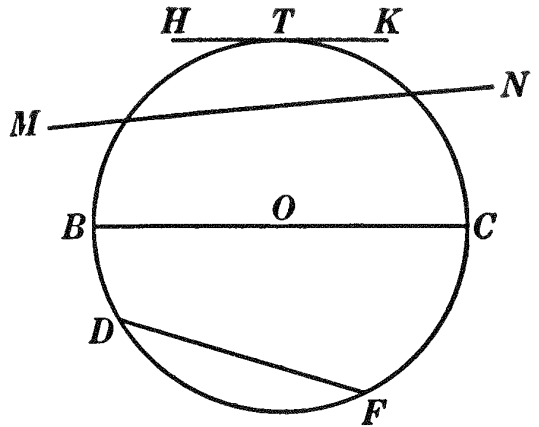
Ex. 402. A semicircle is described upon each of the diagonals of a rectangle as diameters. Prove the semicircles equal.

Ex. 403. Two diameters perpendicular to each other divide a circumference into four equal arcs. Prove by superposition.

Ex. 404. Construct a circle which shall pass through two given points.

Ex. 405. Construct a circle having a given radius r , and passing through two given points A and B

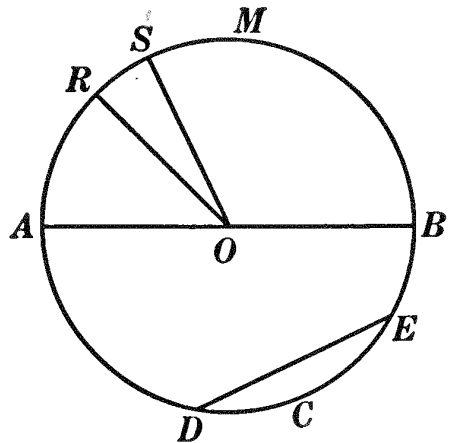
285. Def. A secant of a circle is a straight line which cuts the circumference in two points, but is not terminated by the circumference, as MN .



286. Def. A straight line is tangent to, or touches, a circle if, however far prolonged, it meets the circumference in but one point. This point is called the **point of tangency**. HK is tangent to circle O at point T , and T is the point of tangency.

287. Def. A sector of a circle is a plane closed figure whose boundary is composed of two radii and their intercepted arc, as sector SOR .

288. Def. A segment of a circle is a plane closed figure whose boundary is composed of an arc and the chord joining its extremities, as segment DCE .



289. Def. A segment which is one half of a circle is called a **semi-circle**, as segment AMB .

290. Def. An arc which is half of a circumference is called a **semicircumference**, as arc AMB .

291. Def. An arc greater than a semicircumference is called a **major arc**, as arc DME ; an arc less than a semicircumference is called a **minor arc**, as arc DCE .

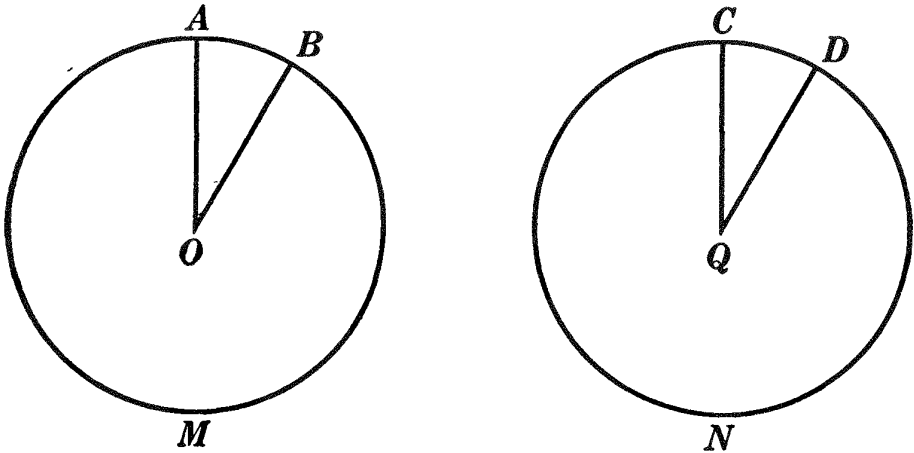
292. Def. A **central angle**, or **angle at the center**, is an angle whose vertex is at the center of a circle and whose sides are radii.

Ex. 406. The line joining the centers of two circles is 6, the radii are 8 and 10, respectively. What are the relative positions of the two circles?

Ex. 407. A circle can have only one center.

PROPOSITION II. THEOREM

293. *In equal circles, or in the same circle, if two central angles are equal, they intercept equal arcs on the circumference; conversely, if two arcs are equal, the central angles that intercept them are equal.*



I. **Given** equal circles ABM and CDN , and equal central $\sphericalangle O$ and Q , intercepting arcs AB and CD , respectively.

To prove $\widehat{AB} = \widehat{CD}$.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Place circle ABM upon circle CDN so that center O shall fall upon center Q , and OA shall be collinear with QC . | 1. § 54, 14. |
| 2. A will fall upon C . | 2. § 279, <i>b</i> . |
| 3. OB will become collinear with QD . | 3. By hyp. |
| 4. $\therefore B$ will fall upon D . | 4. § 279, <i>b</i> . |
| 5. $\therefore \widehat{AB}$ will coincide with CD . | 5. § 279, <i>b</i> . |
| 6. $\therefore \widehat{AB} = \widehat{CD}$. | 6. § 18. |

Q.E.D.

II. **Conversely:**

Given equal circles ABM and CDN , and equal arcs AB and CD , intercepted by $\sphericalangle O$ and Q , respectively.

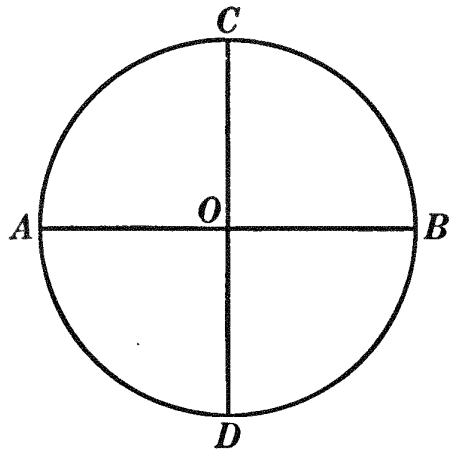
To prove $\sphericalangle O = \sphericalangle Q$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Place circle ABM upon circle CDN so that center O shall fall upon center Q . | 1. § 54, 14. |
| 2. Rotate circle ABM upon O as a pivot until AB falls upon its equal CD , A upon C , B upon D . | 2. § 54, 14. |
| 3. OA will coincide with QC and OB with QD . | 3. § 17. |
| 4. $\therefore \angle O = \angle Q$. Q.E.D. | 4. § 18. |

294. Cor. *In equal circles, or in the same circle, if two central angles are unequal, the greater angle intercepts the greater arc; conversely, if two arcs are unequal, the central angle that intercepts the greater arc is the greater.* (Hint. Lay off the smaller central angle upon the greater.)

295. Def. A fourth part of a circumference is called a quadrant.

From Prop. II it is evident that a right angle at the center intercepts a quadrant on the circumference. Thus, two \perp diameters AB and CD divide the circumference into four quadrants, AC , CB , BD , and DA .



296. Def. A degree of arc, or an arc degree, is the arc intercepted by a central angle of one degree.

297. A right angle contains ninety angle degrees (§ 71); therefore, since equal central angles intercept equal arcs on the circumference, a quadrant contains ninety arc degrees.

Again, four right angles contain 360 angle degrees, and four right angles at the center of a circle intercept a complete circumference; therefore, a circumference contains 360 arc degrees. Hence, a semicircumference contains 180 arc degrees.

Ex. 408. Divide a given circumference into eight equal arcs; sixteen equal arcs.

Ex. 409. Divide a given circumference into six equal arcs; three equal arcs; twelve equal arcs.

Ex. 410. A diameter and a secant perpendicular to it divide a circumference into two pairs of equal arcs.

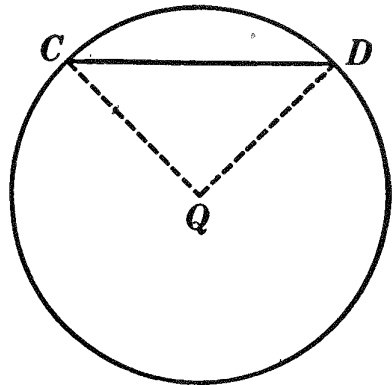
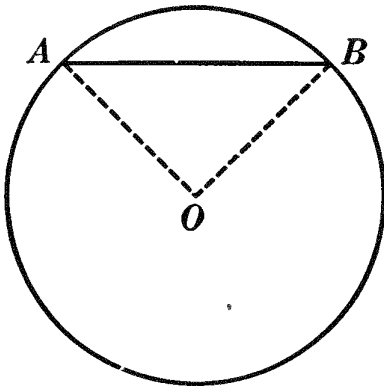
Ex. 411. Construct a circle which shall pass through two given points A and B and shall have its center in a given line c .

Ex. 412. If a diameter and another chord are drawn from a point in a circumference, the arc intercepted by the angle between them will be bisected by a diameter drawn parallel to the chord.

Ex. 413. If a diameter and another chord are drawn from a point in a circumference, the diameter which bisects their intercepted arc will be parallel to the chord.

PROPOSITION III. THEOREM

298. *In equal circles, or in the same circle, if two chords are equal, they subtend equal arcs; conversely, if two arcs are equal, the chords that subtend them are equal.*



I. **Given** equal circles O and Q , with equal chords AB and CD
To prove $\widehat{AB} = \widehat{CD}$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw radii OA , OB , QC , QD . | 1. § 54, 15. |
| 2. In $\triangle OAB$ and QCD , $AB = CD$. | 2. By hyp. |
| 3. $OA = QC$ and $OB = QD$. | 3. § 279, b. |
| 4. $\therefore \triangle OAB = \triangle QCD$. | 4. § 116. |
| 5. $\therefore \angle O = \angle Q$. | 5. § 110. |
| 6. $\therefore \widehat{AB} = \widehat{CD}$. | 6. § 293, I. |

Q.E.D.

II. Conversely :

Given equal circles O and Q , and equal arcs AB and CD .

To prove chord $AB =$ chord CD .

| ARGUMENT | REASONS |
|--|----------------------|
| 1. Draw radii OA, OB, QC, QD . | 1. § 54, 15. |
| 2. $\widehat{AB} = \widehat{CD}$. | 2. By hyp. |
| 3. $\therefore \angle BOA = \angle DQC$. | 3. § 293, II. |
| 4. $OA = QC$ and $OB = QD$. | 4. § 279, <i>b</i> . |
| 5. $\therefore \triangle OAB = \triangle QCD$. | 5. § 107. |
| 6. \therefore chord $AB =$ chord CD . Q.E.D. | 6. § 110. |

Ex. 414. If a circumference is divided into any number of equal arcs, the chords joining the points of division will be equal.

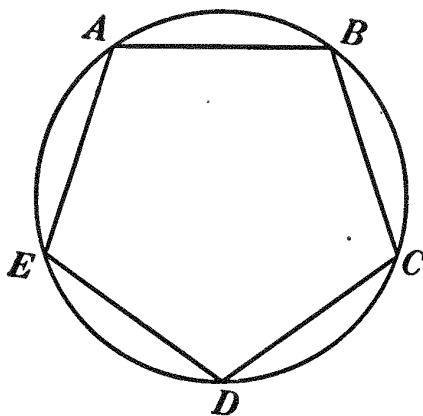
Ex. 415. A parallelogram inscribed in a circle is a rectangle.

Ex. 416. If two of the opposite sides of an inscribed quadrilateral are equal, its diagonals are equal.

Ex. 417. State and prove the converse of Ex. 416.

299. Def. A polygon is inscribed in a circle if all its vertices are on the circumference. Thus, polygon $ABCDE$ is an inscribed polygon.

300. Def. If a polygon is inscribed in a circle, the circle is said to be circumscribed about the polygon.



Ex. 418. Inscribe an equilateral hexagon in a circle; an equilateral triangle.

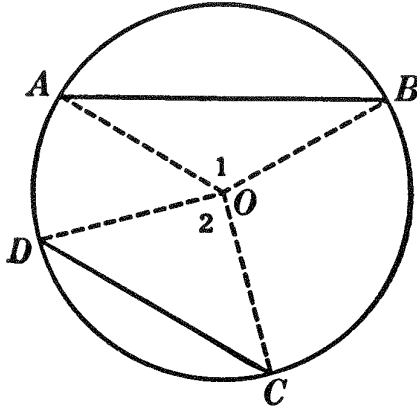
Ex. 419. The diagonals of an inscribed equilateral pentagon are equal.

Ex. 420. If the extremities of any two intersecting diameters are joined, an inscribed rectangle will be formed. Under what conditions will the rectangle be a square?

Ex. 421. State the theorems which may be used in proving arcs equal. State the theorems which may be used in proving chords equal.

PROPOSITION IV. THEOREM

301. *In equal circles, or in the same circle, if two chords are unequal, the greater chord subtends the greater minor arc; conversely, if two minor arcs are unequal, the chord that subtends the greater arc is the greater.*



I. **Given** circle O , with chord $AB >$ chord CD .

To prove $\widehat{AB} > \widehat{CD}$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw radii OA, OB, OC, OD . | 1. § 54, 15. |
| 2. In $\triangle OAB$ and OCD , $OA = OC, OB = OD$. | 2. § 279, a. |
| 3. Chord $AB >$ chord CD . | 3. By hyp. |
| 4. $\therefore \angle 1 > \angle 2$. | 4. § 173. |
| 5. $\therefore \widehat{AB} > \widehat{CD}$. Q.E.D. | 5. § 294. |

II. **Conversely:**

Given circle O , with $\widehat{AB} > \widehat{CD}$.

To prove chord $AB >$ chord CD .

| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw radii OA, OB, OC, OD . | 1. § 54, 15. |
| 2. In $\triangle OAB$ and OCD , $OA = OC, OB = OD$. | 2. § 279, a. |
| 3. $\widehat{AB} > \widehat{CD}$ | 3. By hyp. |
| 4. $\therefore \angle 1 > \angle 2$. | 4. § 294. |
| 5. \therefore chord $AB >$ chord CD . Q.E.D. | 5. § 172. |

Ex. 422. Prove the converse of Prop. IV by the indirect method.

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Ex. 424. Through a given point within a circle construct a chord which shall be bisected at the point.

Ex. 425. Given a line fulfilling any two of the five following conditions, prove that it fulfills the remaining three:

1. A diameter.
2. A perpendicular to a chord.
3. A bisector of a chord.
4. A bisector of the major arc of a chord.
5. A bisector of the minor arc of a chord.

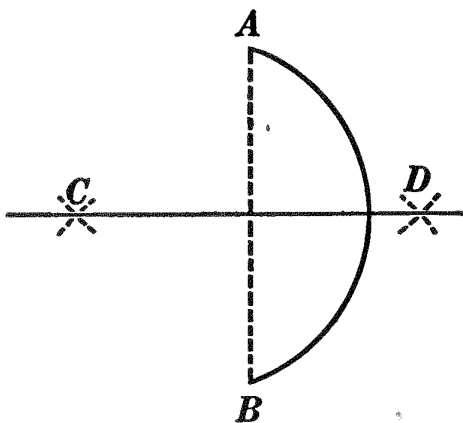
Ex. 426. Any two chords of a circle are given in position and magnitude; find the center of the circle.

Ex. 427. The line passing through the middle points of two parallel chords passes through the center of the circle.

Ex. 428. Given an arc of a circle, find the center of the circle.

PROPOSITION VI. PROBLEM

306. *To bisect a given arc.*



Given AB , an arc of any circle.

To bisect \widehat{AB} .

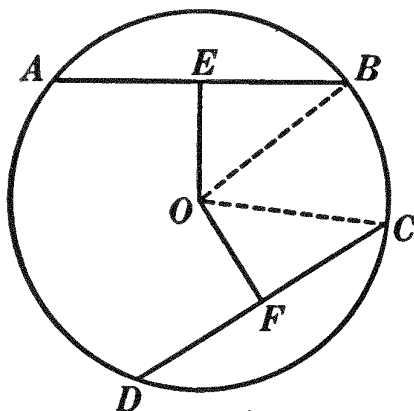
The construction, proof, and discussion are left as an exercise for the student.

Ex. 429. Construct an arc of 45° ; of 30° . Construct an arc of 30° , using a radius twice as long as the one previously used. Are these two 30° arcs equal?

Ex. 430. Distinguish between finding the "mid-point of an arc" and the "center of an arc."

PROPOSITION VII. THEOREM

307. *In equal circles, or in the same circle, if two chords are equal, they are equally distant from the center; conversely, if two chords are equally distant from the center, they are equal.*



I. **Given** circle O with chord $AB =$ chord CD , and let OE and OF be the distances of AB and CD from center O , respectively.

To prove $OE = OF$.

| ARGUMENT | REASONS |
|---|---------------|
| 1. Draw radii OB and OC . | 1. § 54, 15. |
| 2. E and F are the mid-points of AB and CD , respectively. | 2. § 302. |
| 3. \therefore in rt. $\triangle OEB$ and OCF , $EB = CF$. | 3. § 54, 8 a. |
| 4. $OB = OC$. | 4. § 279, a. |
| 5. $\therefore \triangle OEB = \triangle OCF$. | 5. § 211. |
| 6. $\therefore OE = OF$. Q.E.D. | 6. § 110. |

II. **Conversely:**

Given circle O with OE , the distance of chord AB from center O , equal to OF , the distance of chord CD from center O .

To prove chord $AB =$ chord CD .

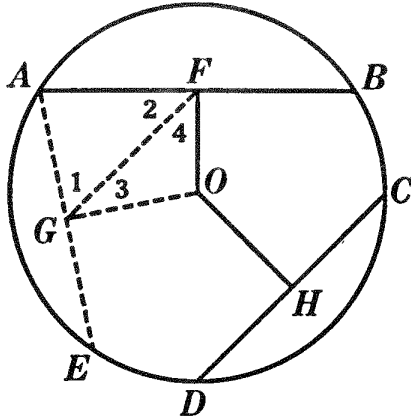
HINT. Prove $\triangle OEB = \triangle OCF$.

Ex. 431. If perpendiculars from the center of a circle to the sides of an inscribed polygon are equal, the polygon is equilateral.

Ex. 432. If through any point in a diameter two chords are drawn making equal angles with the diameter, the two chords are equal.

PROPOSITION VIII. THEOREM

308. *In equal circles, or in the same circle, if two chords are unequal, the greater chord is at the less distance from the center.*



Given circle O with chord $AB >$ chord CD , and let OF and OH be the distances of AB and CD from center O , respectively.

To prove $OF < OH$.

| ARGUMENT | REASONS |
|--|---------------|
| 1. From A draw a chord AE , equal to DC . | 1. § 54, 15. |
| 2. From O draw $OG \perp AE$. | 2. § 155. |
| 3. Draw FG . | 3. § 54, 15. |
| 4. $AB > CD$. | 4. § By hyp. |
| 5. $\therefore AB > AE$. | 5. § 309. |
| 6. F and G are the mid-points of AB and AE , respectively. | 6. § 302. |
| 7. $\therefore AF > AG$. | 7. § 54, 8 b. |
| 8. $\therefore \angle 1 > \angle 2$. | 8. § 156. |
| 9. $\angle AFO = \angle OGA$. | 9. § 64. |
| 10. $\therefore \angle 3 < \angle 4$. | 10. § 54, 6. |
| 11. $\therefore OF < OG$. | 11. § 164. |
| 12. $OG = OH$. | 12. § 307, I. |
| 13. $\therefore OF < OH$. | 13. § 309. |

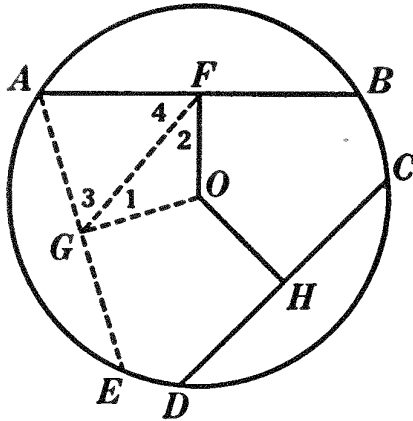
Q.E.D.

309. Note. The student should give the full statement of the substitution made; thus, reason 5 above should be: "Substituting AE for its equal CD ."

PROPOSITION IX. THEOREM

(Converse of Prop. VIII)

310. *In equal circles, or in the same circle, if two chords are unequally distant from the center, the chord at the less distance is the greater.*



Given circle O with OF , the distance of chord AB from center O , less than OH , the distance of chord CD from center O .

To prove chord $AB >$ chord CD .

The proof is left as an exercise for the student.

HINT. Begin with $\triangle OGF$.

311. Cor. I. *A diameter is greater than any other chord.*

312. Cor. II. *The locus of the mid-points of all chords of a circle equal to a given chord is the circumference having the same center as the given circle, and having for radius the perpendicular from the center to the given chord.*

Ex. 433. Prove Prop. IX by the indirect method.

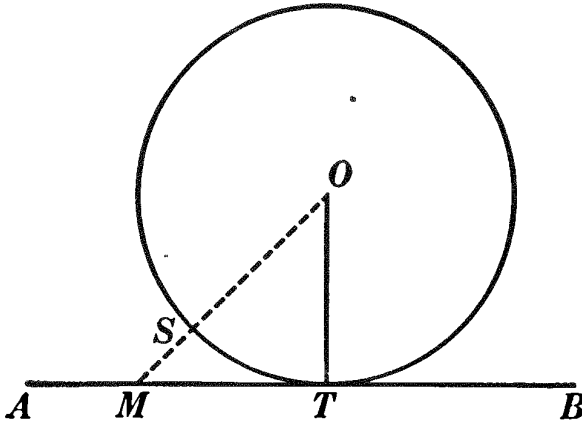
Ex. 434. Through a given point within a circle construct the minimum chord.

Ex. 435. If two chords are drawn from one extremity of a diameter, making unequal angles with it, the chords are unequal.

Ex. 436. The perpendicular from the center of a circle to a side of an inscribed equilateral triangle is less than the perpendicular from the center of the circle to a side of an inscribed square. (See § 308.)

PROPOSITION X. THEOREM

313. *A tangent to a circle is perpendicular to the radius drawn to the point of tangency.*



Given line AB , tangent to circle O at T , and OT , a radius drawn to the point of tangency.

To prove $AB \perp OT$.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Let M be any point on AB other than T ; then M is outside the circumference. | 1. § 286. |
| 2. Draw OM , intersecting the circumference at S . | 2. § 54, 15. |
| 3. $OS < OM$. | 3. § 54, 12. |
| 4. $OS = OT$. | 4. § 279, <i>a</i> . |
| 5. $\therefore OT < OM$. | 5. § 309. |
| 6. $\therefore OT$ is the shortest line that can be drawn from O to AB . | 6. Arg. 5. |
| 7. $\therefore OT \perp AB$; <i>i.e.</i> $AB \perp OT$. Q.E.D. | 7. § 165. |

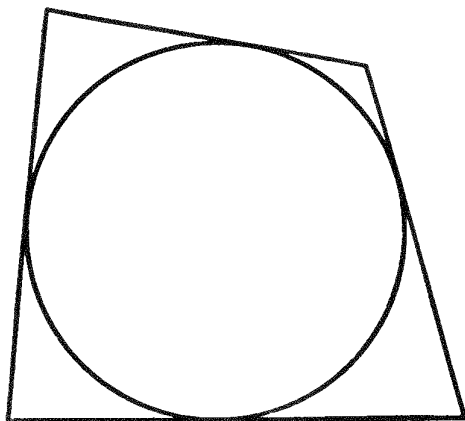
314. Cor. I. (Converse of Prop. X). *A straight line perpendicular to a radius at its outer extremity is tangent to the circle.*

HINT. Prove by the indirect method. In the figure for Prop. X, suppose that AB is not tangent to circle O at point T ; then draw CD through T , tangent to circle O . Apply § 63.

315. Cor. II. *A perpendicular to a tangent at the point of tangency passes through the center of the circle.*

316. Cor. III. *A line drawn from the center of a circle perpendicular to a tangent passes through the point of tangency.*

317. Def. A polygon is circumscribed about a circle if each side of the polygon is tangent to the circle. In the same figure the circle is said to be inscribed in the polygon.



Ex. 437. The perpendiculars to the sides of a circumscribed polygon at their points of tangency pass through a common point.

Ex. 438. The line drawn from any vertex of a circumscribed polygon to the center of the circle bisects the angle at that vertex and also the angle between radii drawn to the adjacent points of tangency.

Ex. 439. If two tangents are drawn from a point to a circle, the bisector of the angle between them passes through the center of the circle.

Ex. 440. The bisectors of the angles of a circumscribed quadrilateral pass through a common point.

Ex. 441. Tangents to a circle at the extremities of a diameter are parallel.

PROPOSITION XI. PROBLEM

318. *To construct a tangent to a circle at any given point in the circumference.*

The construction, proof, and discussion are left as an exercise for the student. (See § 314.)

Ex. 442. Construct a quadrilateral which shall be circumscribed about a circle. What kinds of quadrilaterals are circumscribable?

Ex. 443. Construct a parallelogram which shall be inscribed in a circle. What kinds of parallelograms are inscribable?

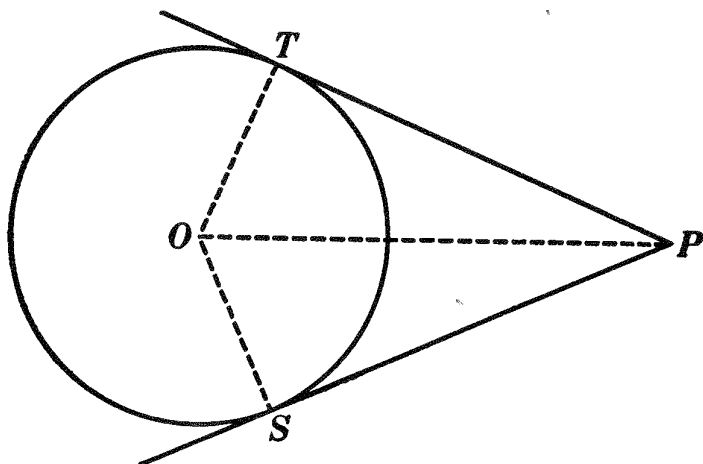
Ex. 444. Construct a line which shall be tangent to a given circle and parallel to a given line.

Ex. 445. Construct a line which shall be tangent to a given circle and perpendicular to a given line.

319. Def. The length of a tangent is the length of the segment included between the point of tangency and the point from which the tangent is drawn; as TP in the following figure.

PROPOSITION XII. THEOREM

320. *If two tangents are drawn from any given point to a circle, these tangents are equal.*



Given PT and PS , two tangents from point P to circle O .

To prove $PT = PS$.

The proof is left as an exercise for the student.

Ex. 446. The sum of two opposite sides of a circumscribed quadrilateral is equal to the sum of the other two sides.

Ex. 447. The median of a circumscribed trapezoid is one fourth the perimeter of the trapezoid.

Ex. 448. A parallelogram circumscribed about a circle is either a rhombus or a square.

Ex. 449. The hypotenuse of a right triangle circumscribed about a circle is equal to the sum of the other two sides minus a diameter of the circle.

Ex. 450. If a circle is inscribed in any triangle, and if three triangles are cut from the given triangle by drawing tangents to the circle, then the sum of the perimeters of the three triangles will equal the perimeter of the given triangle.

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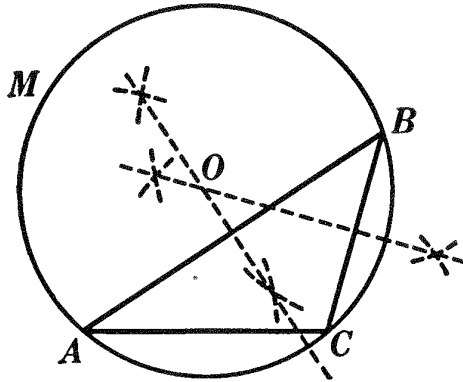
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PROPOSITION XIV. PROBLEM

323. *To circumscribe a circle about a given triangle.*



Given $\triangle ABC$.

To circumscribe a circle about $\triangle ABC$.

The construction, proof, and discussion are left as an exercise for the student.

324. Cor. *Three points not in the same straight line determine a circle.*

Ex. 455. Discuss the position of the center of a circle circumscribed about an acute triangle ; a right triangle ; an obtuse triangle.

Ex. 456. Circumscribe a circle about an isosceles trapezoid.

Ex. 457. Given the base of an isosceles triangle and the radius of the circumscribed circle, to construct the triangle.

Ex. 458. The inscribed and circumscribed circles of an equilateral triangle are concentric.

Ex. 459. If upon the sides of any triangle equilateral triangles are drawn, and circles circumscribed about the three triangles, these circles will intersect at a common point.

Ex. 460. The two segments of a secant which are between two concentric circumferences are equal.

Ex. 461. The perpendicular bisectors of the sides of an inscribed quadrilateral pass through a common point.

Ex. 462. The bisector of an arc of a circle is determined by the center of the circle and another point equidistant from the extremities of the chord of the arc.

Ex. 463. If two chords of a circle are equal, the lines which connect their mid-points with the center of the circle are equal.

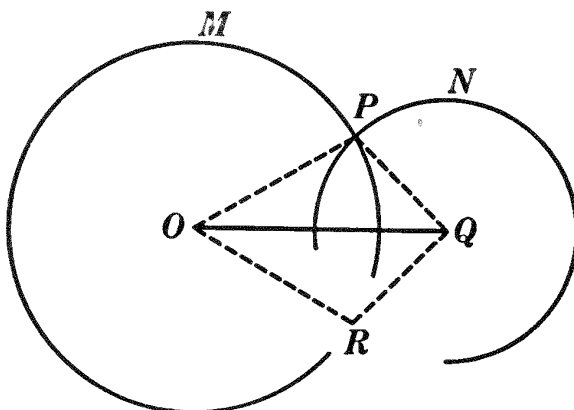
TWO CIRCLES

325. Def. The line determined by the centers of two circles is called their **line of centers** or **center-line**.

326. Def. **Concentric circles** are circles which have the same center.

PROPOSITION XV. THEOREM

327. *If two circumferences meet at a point which is not on their line of centers, they also meet in one other point.*



Given circumferences M and N meeting at P , a point not on their line of centers OQ .

To prove that the circumferences meet at one other point, as R .

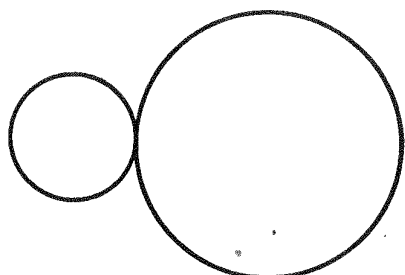
| ARGUMENT | REASONS |
|---|-------------------|
| 1. Draw OP and QP . | 1. § 54, 15. |
| 2. Rotate $\triangle OPQ$ about OQ as an axis until it falls in the position QRO . | 2. § 54, 14. |
| 3. $OR = OP =$ a radius of circle M . | 3. By cons. |
| 4. $\therefore R$ is on circumference M . | 4. § 279, a. |
| 5. Also $QR = QP =$ a radius of circle N . | 5. By cons. |
| 6. $\therefore R$ is on circumference N . | 6. § 279, a. |
| 7. $\therefore R$ is on both circumference M and circumference N ; <i>i.e.</i> circumferences M and N meet at R . | 7. Args. 4 and 6. |
| Q.E.D. | |

328. Cor. I. *If two circumferences intersect, their line of centers bisects their common chord at right angles.*

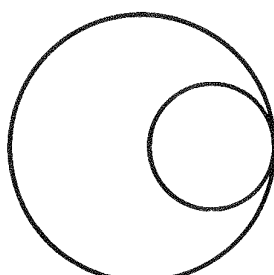
329. Cor. II. *If two circumferences meet at one point only, that point is on their line of centers.*

HINT. If they meet at a point which is not on their line of centers, they also meet in another point (§ 327). This contradicts the hypothesis.

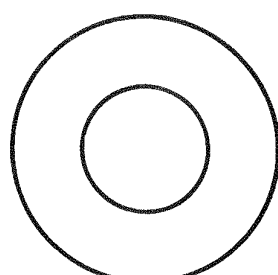
330. Def. Two circles are said to **touch** or be **tangent to each other** if they have one and only one point in common. They are tangent **internally** or **externally** according as one circle lies within or outside of the other.



Tangent externally.



Tangent internally.



Concentric.

331. From § 330, Cor. II may be stated as follows:

If two circles are tangent to each other, their common point lies on their line of centers.

332. Cor. III. *If two circles are tangent to each other, they have a common tangent line at their point of contact.*

HINT. Apply § 314.

333. Def. A line touching two circles is called an **external common tangent** if both circles lie on the same side of it; the line is called an **internal common tangent** if the two circles lie on opposite sides of it.

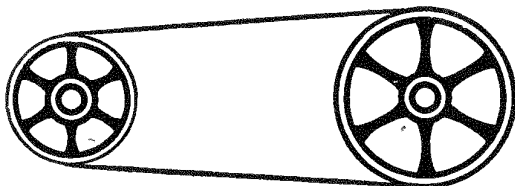


FIG. 1.

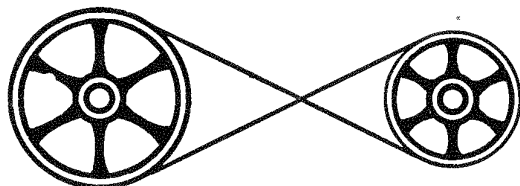


FIG. 2.

Thus a belt connecting two wheels as in Fig. 1 is an illustration of external common tangents, while a belt arranged as in Fig. 2 illustrates internal common tangents.

334. Questions. In case two circles are tangent internally how many common tangents can be drawn? in case their circumferences intersect? in case they are tangent externally? in case they are wholly outside of each other? in case one is wholly within the other?

Ex. 464. If two circles intersect, their line of centers bisects the angles between the radii drawn to the points of intersection.

Ex. 465. If the radii of two intersecting circles are 5 inches and 8 inches, what may be the length of the line joining their centers?

Ex. 466. If two circles are tangent externally, tangents drawn to them from any point in their common internal tangent are equal.

Ex. 467. Two circles are tangent to each other. Construct their common tangent at their point of contact.

Ex. 468. Construct a circle passing through a given point and tangent to a given circle at another given point.

Ex. 469. Find the locus of the centers of all circles tangent to a given circle at a given point.

MEASUREMENT

335. Def. To measure a quantity is to find how many times it contains another quantity of the same kind. The result of the measurement is a number and is called the **numerical measure**, or **measure-number**, of the quantity which is measured. The measure employed is called the **unit of measure**.

Thus, the length or breadth of a room is measured by finding how many feet there are in it; *i.e.* how many times it contains a foot as a measure.

336. It can be shown that to *every* geometric. magnitude there corresponds a definite number called its measure-number. The proof that *to every straight line segment there belongs a measure-number* is found in the Appendix, § 595. The method of proof there used shows that operations with measure-numbers follow the ordinary laws of algebra.

337. Def. Two quantities are **commensurable** if there exists a measure that is contained an integral number of times in each. Such a measure is called a **common measure** of the two quantities.

Thus, a yard and a foot are commensurable, each containing an inch a whole number of times; so, too, $12\frac{1}{2}$ inches and $18\frac{3}{4}$ inches are commensurable, each containing a fourth of an inch a whole number of times.

338. Questions. If two quantities have a common measure, *how many* common measures have they? Name some common measures of $12\frac{1}{2}$ inches and $18\frac{3}{4}$ inches. What is their greatest common measure? What is their least common measure?

339. Def. Two quantities are **incommensurable** if there exists no measure that is contained an integral number of times in each.

It will be shown later that a diagonal and a side of the same square cannot be measured by the same unit, without a remainder; and that the diagonal is equal to $\sqrt{2}$ times the numerical measure of the side. Now $\sqrt{2}$ can be expressed only approximately as a simple fraction or as a decimal. It lies between 1.4 and 1.5, for $(1.4)^2 = 1.96$, and $(1.5)^2 = 2.25$. Again, it lies between 1.41 and 1.42,* between 1.414 and 1.415, between 1.4142 and 1.4143, and so on. By repeated trials values may be found approximating more and more closely to $\sqrt{2}$, but no decimal number can be obtained that, taken twice as a factor, will give exactly 2.

340. When we speak of the *ratio* of one quantity to another, we have in mind their *relative* sizes. By this is meant not the *difference* between the two, but *how many times* one contains the other or some aliquot part of it. In algebra the *ratio of two numbers* has been defined as the indicated quotient of the first divided by the second. Since to each geometric magnitude there corresponds a number called its measure-number (§ 336), therefore:

341. Def. The **ratio of two geometric magnitudes** may be defined as the quotient of their measure-numbers, when the same measure is applied to each.

* The student should multiply to get the successive approximations.

Thus, if the length of a room is 36 feet and the width 27 feet, the ratio of the length to the width is said to be the ratio of 36 to 27; *i.e.* $\frac{36}{27}$, which is equal to $\frac{4}{3}$. The ratio of the width to the length is $\frac{27}{36}$, which is equal to $\frac{3}{4}$. The term ratio is never applied to two magnitudes that are unlike.

342. Def. If the two magnitudes compared are commensurable, the ratio is called a **commensurable ratio** and can always be expressed as a simple fraction.

343. Def. If the two magnitudes compared are incommensurable, the ratio is called an **incommensurable ratio** and can be expressed only approximately as a simple fraction. Closer and closer approximations to an incommensurable ratio may be obtained by repeatedly using smaller and smaller units as measures of the two magnitudes to be compared and by finding the quotient of the numbers thus obtained.

Two magnitudes, *e.g.* two line segments, taken at random are usually incommensurable, commensurability being comparatively rare.

344. Historical Note. The discovery of incommensurable magnitudes is ascribed to Pythagoras, whose followers for a long time kept the discovery a secret. It is believed that Pythagoras was the first to prove that the side and diagonal of a square are incommensurable. A more complete account of the work of Pythagoras will be found in § 510.

Ex. 470. What is the greatest common measure of 48 inches and 18 inches? Will it divide 48 inches — 18 inches? 48 inches — 2×18 inches?

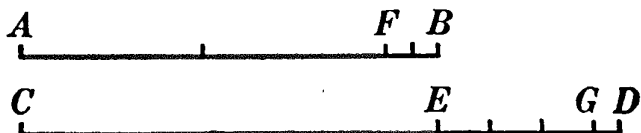
Ex. 471. Draw any two line segments which have a common measure. Find the sum of these lines and, by laying off the common measure, show that it is a measure of the sum of the lines.

Ex. 472. Given two lines, 5 inches and 4 inches long, respectively. Show by a diagram that any common measure of 5 inches and 4 inches is also a measure of 15 inches plus or minus 8 inches.

Ex. 473. Find the greatest common divisor of 728 and 844 by division and point out the similarity of the process to that used in Prop. XVI

PROPOSITION XVI. PROBLEM

345. *To determine whether two given lines are commensurable or not; and if they are commensurable, to find their common measure and their ratio.*



Given lines AB and CD .

To determine: (a) whether AB and CD are commensurable and if so,
 (b) what is their common measure; and
 (c) what is the ratio of AB to CD .

I. Construction

1. Measure off AB on CD as many times as possible. Suppose it is contained once, with a remainder ED .

2. Measure off ED on AB as many times as possible. Suppose it is contained twice, with a remainder FB .

3. Measure off FB on ED as many times as possible. Suppose it is contained three times, with a remainder GD .

4. Measure off GD on FB as many times as possible, and so on.

5. It is evident that this process will terminate only when a remainder is obtained which is a measure of the remainder immediately preceding.

6. If this process terminates, then the two given lines are commensurable, and the last remainder is their greatest common measure.

7. For example, if GD is a measure of FB , then AB and CD are commensurable, GD is their greatest common measure, and the ratio of AB to CD can be found.

II. Proof

| ARGUMENT | REASONS |
|--------------------------|--------------|
| 1. Suppose $FB = 2 GD$. | 1. See I, 7. |
| 2. $ED = EG + GD$. | 2. § 54, 11. |

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Ex. 475. Consider an isosceles triangle with constant base angles, but variable base. Tell what other constants and what other variables there would be in this case.

Ex. 476. If through any point in the base of an isosceles triangle lines are drawn parallel to the equal sides of the triangle, a parallelogram will be formed whose perimeter will be *constant*; *i.e.* the perimeter will be independent of the position of the point.

347. Def. A magnitude is **constant** if it does not change throughout a discussion.

348. Def. A magnitude is **variable** if it takes a series of different successive values during a discussion.

349. Def. If a variable approaches a constant in such a way that the difference between the variable and the constant may be made to become and remain smaller than any fixed number previously assigned, however small, the constant is called the **limit** of the variable.

350. The variable is said to **approach** its limit as it becomes more and more nearly equal to it. Thus, suppose a point to move from A toward B , by successive steps, under the restriction that at each step it must go over one half the segment between it and B . At the first step it reaches C , whereupon there remains the segment CB to be traveled over; at the next step it reaches D , and there remains an equal segment to be covered. Whatever the number of steps taken, there must always *remain* a segment equal to the segment last covered. But the segment between A and the moving point may be made to differ from AB by *as little as we please, i.e.* by less than *any previously assigned value*. For assign some value, say, half an inch. Then the point, continuing to move under its governing law, may approach B until there remains a segment less than half an inch. Whatever be the value assigned, the variable segment from A to the moving point may be made to differ from the constant segment AB by less than the assigned value.



Again, the numbers in the series 4, 2, 1, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, etc., in which each term is one half of the preceding term, approach 0 as a limit as the number of terms in the series is increased. For if we assign any value, as $\frac{1}{100000}$, it is evident that a term of the series may be found which is less than $\frac{1}{100000}$; it is also evident that no term of the series can become 0.

351. In elementary geometry the variables that approach limits are usually such that they cannot attain their limits. There are, however, variables that do attain their limits. The limiting values of algebraic expressions are frequently of this kind; thus, the expression $\frac{1}{x^2 + 1}$ approaches 1 as x approaches 0, and has the limit 1 when x becomes zero.

352. Def. Two variables are said to be related when one depends upon the other so that, if the value of one variable is known, the value of the other can be obtained.

For example, the diagonal and the area of a square are related variables, for there is a value for the area for any value which may be given to the diagonal, and *vice versa*.

353. Questions. On the floor is a bushel of sand. If we keep adding to this pile forever, how large will it become? Does it depend upon the law governing our additions? If we add one quart each hour, how large will it become? If we add one quart the first hour, a half quart the second hour, a fourth quart the third hour, etc., each hour adding one half as much as the preceding hour, how large will the pile become?

354. Historical Note. Achilles and the Tortoise. One of the early Greek schools of mathematics, founded during the fifth century B.C., at Elea, Italy, and known as the Eleatic School, was famous for its investigations of problems involving infinite series. Zeno, one of the most prominent members, proposed this question: He "argued that if Achilles ran ten times as fast as a tortoise, yet if the tortoise had (say) 1000 yards start, it could never be overtaken: for, when Achilles had gone the 1000 yards, the tortoise would still be 100 yards in front of him; by the time he had covered these 100 yards, it would still be 10 yards in front of him; and so on forever: thus Achilles would get nearer and nearer to the tortoise but never overtake it." Was Zeno right? If not, can you find the fallacy in his argument?

PROPOSITION XVII. THEOREM

355. *If two variables are always equal, and if each approaches a limit, then their limits are equal.*

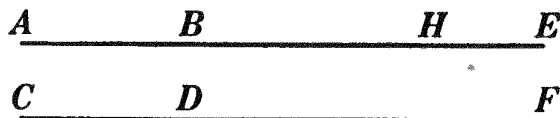
Given two variables, V and V' , which are always equal and which approach as limits L and L' , respectively.

To prove $L = L'$.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Either $L = L'$, or $L \neq L'$. | 1. § 161, <i>a</i> . |
| 2. Suppose that one limit is greater than the other, say $L > L'$; then V , in approaching L , may assume a value between L' and L , <i>i.e.</i> V may assume a value $> L'$. | 2. § 349. |
| 3. But V' cannot assume a value $> L'$. | 3. § 349. |
| 4. $\therefore V$ may become $> V'$. | 4. Args. 2 and 3. |
| 5. But this is impossible, since V and V' are always equal. | 5. By hyp. |
| 6. $\therefore L = L'$. Q.E.D. | 6. § 161, <i>b</i> . |

356. Question. In the above proof are V and V' increasing or decreasing variables? The student may adapt the argument above to the case in which V and V' are decreasing variables.

Ex. 477. Apply Prop. XVII to the accompanying figure, where variable V is represented by the line AB , variable V' by the line CD , limit L by line AE , and limit L' by line CF .

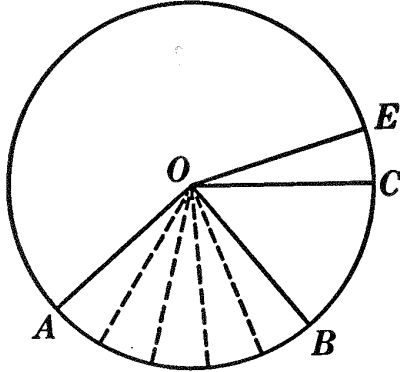


357. Note. It will be seen that, in the application of Prop. XVII, there are three distinct things to be considered :

- (1) Two variables that are *always equal*;
- (2) The *limits* of these two variables;
- (3) The *equality* of these limits themselves.

PROPOSITION XVIII. THEOREM

358. *An angle at the center of a circle is measured by its intercepted arc.*



Given central $\angle AOB$ and \widehat{AB} intercepted by it; let $\angle COE$ be any unit \angle (e.g. a degree), and let CE , intercepted by the unit \angle , be the unit arc.

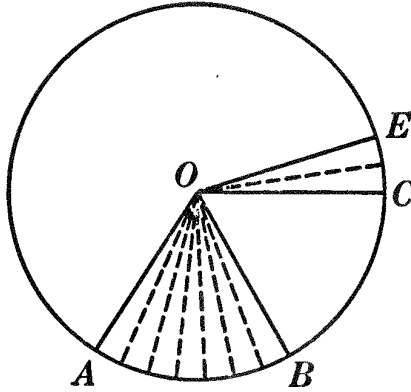
To prove the measure-number of $\angle AOB$, referred to $\angle COE$, equal to the measure-number of \widehat{AB} , referred to \widehat{CE} .

I. If $\angle AOB$ and $\angle COE$ are commensurable.

(a) Suppose that $\angle COE$ is contained in $\angle AOB$ an integral number of times.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Apply $\angle COE$ to $\angle AOB$ as a measure. Suppose that $\angle COE$ is contained in $\angle AOB$ r times. | 1. § 335. |
| 2. Then r is the measure-number of $\angle AOB$ referred to $\angle COE$ as a unit. | 2. § 335. |
| 3. Now the r equal central \sphericalangle s which compose $\angle AOB$ intercept r equal arcs on the circumference, each equal to CE . | 3. § 293, I. |
| 4. $\therefore r$ is the measure-number of AB referred to \widehat{CE} as a unit. | 4. § 335. |
| 5. \therefore the measure-number of $\angle AOB$, referred to $\angle COE$ as a unit, equals the measure-number of AB , referred to \widehat{CE} as a unit. | 5. § 54, 1. |

Q.E.D.

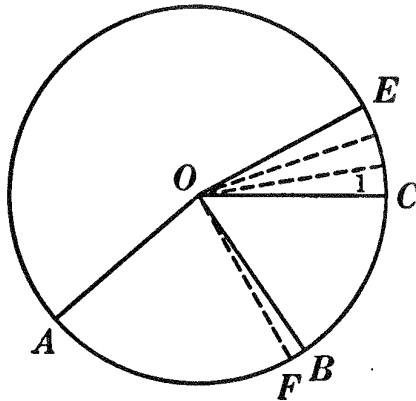


I. If $\angle AOB$ and $\angle COE$ are commensurable.

(b) Suppose that $\angle COE$ is not contained in $\angle AOB$ an integral number of times. The proof is left as an exercise for the student.

HINT. . Some aliquot part of $\angle COE$ must be a measure of $\angle AOB$. (Why?) Try $\frac{1}{2} \angle COE$, $\frac{1}{3} \angle COE$, etc.

II. If $\angle AOB$ and $\angle COE$ are incommensurable.



ARGUMENT

REASONS

1. Let $\angle 1$ be a measure of $\angle COE$. Apply $\angle 1$ to $\angle AOB$ as many times as possible. There will then be a remainder, $\angle FOB$, less than $\angle 1$.
2. $\angle AOF$ and $\angle COE$ are commensurable.
3. \therefore the measure-number of $\angle AOF$, referred to $\angle COE$ as a unit, equals the measure-number of AF , referred to \widehat{CE} as a unit.

1. § 339.
2. § 337.
3. § 358, I.

| ARGUMENT | REASONS |
|--|-------------------|
| 4. Now take a smaller measure of $\angle COE$. No matter how small a measure of $\angle COE$ is taken, when it is applied as a measure to $\angle AOB$, the remainder, $\angle FOB$, will be smaller than the \angle taken as a measure. | 4. § 335. |
| 5. Also \widehat{FB} will be smaller than the arc intercepted by the \angle taken as a measure. | 5. § 294. |
| 6. \therefore the difference between $\angle AOF$ and $\angle AOB$ may be made to become and remain less than any previously assigned \angle , however small; and likewise the difference between AF and \widehat{AB} , less than the arc intercepted by the assigned \angle . | 6. Args. 4 and 5. |
| 7. $\therefore \angle AOF$ approaches $\angle AOB$ as a limit, and AF approaches \widehat{AB} as a limit. | 7. § 349. |
| 8. Hence the measure-number of $\angle AOF$ approaches the measure-number of $\angle AOB$ as a limit, and the measure-number of \widehat{AF} approaches the measure-number of AB as a limit. | 8. § 359. |
| 9. But the measure-number of $\angle AOF$ is always equal to the measure-number of \widehat{AF} . | 9. Arg. 3. |
| 10. \therefore the measure-number of $\angle AOB$, referred to $\angle COE$ as a unit, equals the measure-number of AB , referred to \widehat{CE} as a unit. | 10. § 355. |

Q.E.D.

359. *If a magnitude is variable and approaches a limit, then, as the magnitude varies, the successive measure-numbers of the variable approach as their limit the measure-number of the limit of the magnitude.*

(This theorem will be found in the Appendix, § 597.)

360. Cor. *In equal circles, or in the same circle, two angles at the center have the same ratio as their intercepted arcs.*

HINT. The *measure-numbers* of the angles are equal respectively to the measure-numbers of their intercepted arcs. Therefore the ratio of the angles is equal to the ratio of the arcs.

Ex. 478. Construct a secant which shall cut off two thirds of a given circumference.

Ex. 479. Is the ratio of two chords in the same circle equal to the ratio of the arcs which they subtend? Illustrate your answer, using a semicircumference and a quadrant.

361. The symbol \propto will be used for *is measured by*. \propto is the symbol of variation, and the macron ($\bar{\quad}$) means long or length'. Hence $\underline{\propto}$ suggests *varies as the length of*.

362. From § 336 it follows directly that:

(a) *In equal circles, or in the same circle, equal angles are measured* by equal arcs; conversely, equal arcs measure equal angles.*

(b) *The measure of the $\left\{ \begin{array}{l} \text{sum} \\ \text{difference} \end{array} \right\}$ of two angles is equal to the $\left\{ \begin{array}{l} \text{sum} \\ \text{difference} \end{array} \right\}$ of the measures of the angles.*

(c) *The measure of any multiple of an angle is equal to that same multiple of the measure of the angle.*

363. Def. An angle is said to be **inscribed in a circle** if its vertex lies on the circumference and its sides are chords.

364. Def. An angle is said to be **inscribed in a segment of a circle** if its vertex lies on the arc of the segment and its sides pass through the extremities of that arc.

* It is, of course, inaccurate to speak of measuring one magnitude by another magnitude of a different kind; but, in this case, it has become a convention so general that the student needs to become familiar with it. More accurately, in Prop. XVIII, the *measure-number* of an angle at the center, referred to any unit angle, is the same as the *measure-number* of its intercepted arc when the unit arc is the arc intercepted by the unit angle:

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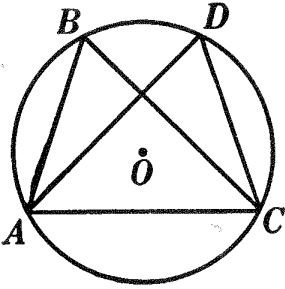


FIG. 1.

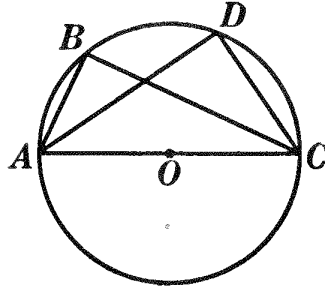


FIG. 2.

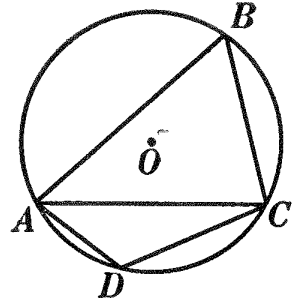


FIG. 3.

366. Cor. I. *All angles inscribed in the same segment are equal.* (See Fig. 1.)

367. Cor. II. *Any angle inscribed in a semicircle is a right angle.* (See Fig. 2.)

368. Cor. III. *The locus of the vertex of a right triangle having a given hypotenuse as base is the circumference having the same hypotenuse as diameter.*

369. Cor. IV. *Any angle inscribed in a segment less than a semicircle is an obtuse angle.* (See Fig. 3.)

370. Cor. V. *Any angle inscribed in a segment greater than a semicircle is an acute angle.* (See Fig. 3.)

Ex. 480. If an inscribed angle contains 24 angle degrees, how many arc degrees are there in the intercepted arc? how many in the rest of the circumference?

Ex. 481. If an inscribed angle intercepts an arc of 70° , how many degrees are there in the angle?

Ex. 482. How many degrees are there in an angle inscribed in a segment whose arc is 140° ?

Ex. 483. Construct any segment of a circle so that an angle inscribed in it shall be an angle of: (a) 60° ; (b) 45° ; (c) 30° .

Ex. 484. Repeat Ex. 483, using a given line as chord of the segment. How many solutions are there to each case of Ex. 483? how many to each case of Ex. 484?

Ex. 485. The opposite angles of an inscribed quadrilateral are supplementary.

Ex. 486. If the diameter of a circle is one of the equal sides of an isosceles triangle, the circumference will bisect the base of the triangle.

Ex. 487. By means of a circle construct a right triangle, given the hypotenuse and an arm.

Ex. 488. By means of a circle construct a right triangle, given the hypotenuse and an adjacent angle.

Ex. 489. Construct a right triangle, having given the hypotenuse and the altitude upon the hypotenuse.

371. Historical Note. Thales (640–546 B.C.), the founder of the earliest Greek school of mathematics, is said to have discovered that all triangles having a diameter of a circle as base, with their vertices on the circumference, have their vertex angles right angles. Thales was one of the Seven Wise Men. He had much business shrewdness and sagacity, and was renowned for his practical and political ability. He went to Egypt in his youth, and while there studied geometry and astronomy. The story is told that one day while viewing the stars, he fell into



THALES

a ditch; whereupon an old woman said, “How canst thou know what is doing in the heavens, when thou seest not what is at thy feet?”

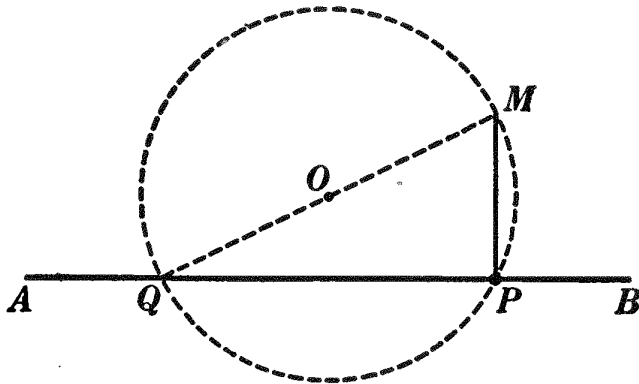
According to Plutarch, Thales computed the height of the Pyramids of Egypt from measurements of their shadows. Plutarch gives a dialogue in which Thales is addressed thus, “Placing your stick at the end of the shadow of the pyramid, you made by the same rays two triangles, and so proved that the height of the pyramid was to the length of the stick as the shadow of the pyramid to the shadow of the stick.” This computation was regarded by the Egyptians as quite remarkable, since they were not familiar with applications of abstract science.

The geometry of the Greeks was in general ideal and speculative, the Greek mind being more attracted by beauty and by abstract relations than by the practical affairs of everyday life.

PROPOSITION XX. PROBLEM

372. *To construct a perpendicular to a given straight line at a given point in the line.*

(Second method. For another method, see § 148.)



Given line AB and P , a point in AB .

To construct a \perp to AB at P .

I. Construction

1. With O , any convenient point outside of AB , as center, and with OP as radius, construct a circumference cutting AB at P and Q .

2. Draw diameter QM .

3. Draw PM .

4. PM is \perp AB at P .

II. The proof and discussion are left as an exercise for the student.

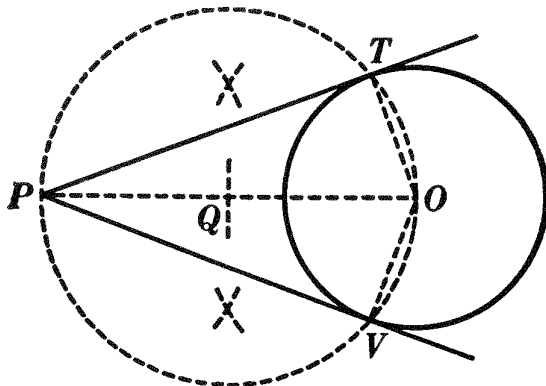
The method of § 372 is useful when the point P is at or near the end of the line AB .

Ex. 490. Construct a perpendicular to line AB at its extremity B , without prolonging AB .

Ex. 491. Through one of the points of intersection of two circumferences a diameter of each circle is drawn. Prove that the line joining the ends of the diameters passes through the other point of intersection.

PROPOSITION XXI. PROBLEM

373. *To construct a tangent to a circle from a point outside.*



Given circle O and point P outside the circle.

To construct a tangent from P to circle O .

I. Construction

1. Draw PO .
2. With Q , the mid-point of PO , as center, and with QO as radius, construct a circumference intersecting the circumference of circle O in points T and V .

3. Draw PT and PV .

4. PT and PV are tangents from P to circle O .

II. The proof and discussion are left as an exercise for the student.

HINT. Draw OT and OV and apply § 367.

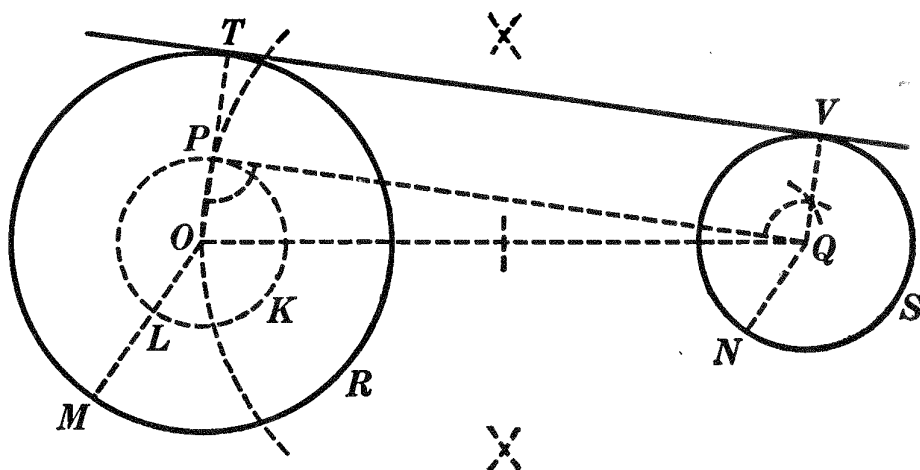
Ex. 492. Circumscribe an isosceles triangle about a given circle, the base of the isosceles triangle being equal to a given line. What restriction is there on the length of the base?

Ex. 493. Circumscribe a right triangle about a given circle, one arm of the triangle being equal to a given line. What is the least length possible for the given line, as compared with the diameter of the circle?

Ex. 494. If a circumference M passes through the center of a circle B , the tangents to B at the points of intersection of the circles intersect on circumference M .

Ex. 495. Circumscribe an isosceles triangle about a circle, the altitude upon the base of the triangle being given.

Ex. 496. Construct a common external tangent to two given circles



Given circles MTR and NVS .

To construct a common external tangent to circles MTR and NVS .

I. Construction

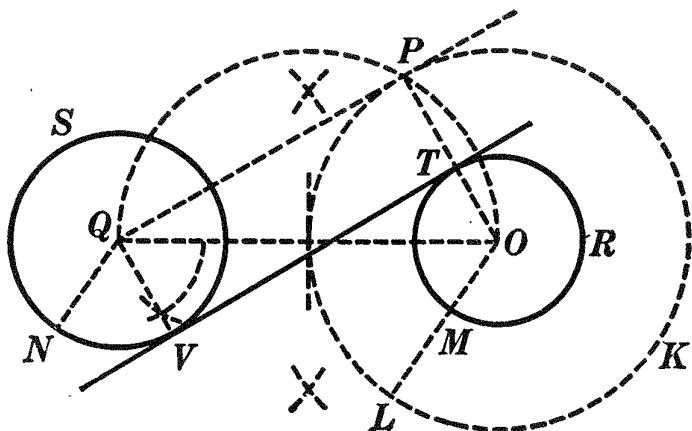
1. Draw the line of centers OQ .
2. Suppose radius $OM >$ radius QN . Then, with O as center and with $OL = OM - QN$ as radius, construct circle LPK .
3. Construct tangent QP from point Q to circle LPK . § 373.
4. Draw OP and prolong it to meet circumference MTR at T .
5. Draw $QV \parallel OT$. § 188.
6. Draw TV .
7. TV is tangent to circles MTR and NVS .

II. The proof and discussion are left as an exercise for the student.

Ex. 497. Construct a second common external tangent to circles MTR and NVS by same method. How is the method modified if the two circles are equal?

Ex. 498. Construct a common internal tangent to two circles.

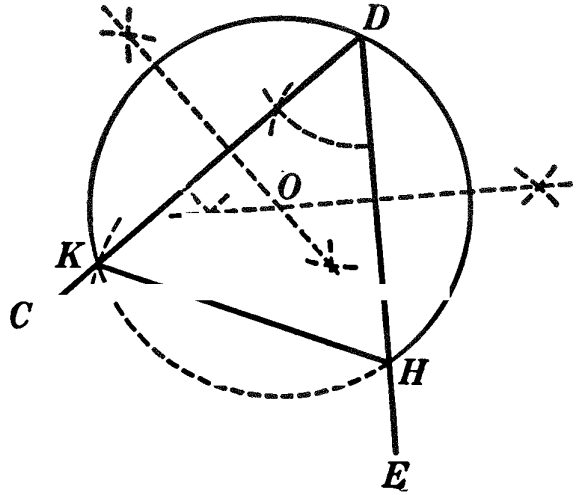
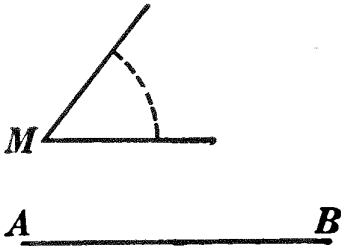
HINT. Follow steps of Ex. 496 except step 2. Make $OL = OM + QN$.



Ex. 499. By moving Q toward O in the preceding figure, show when there are four common tangents; when only three; when only two; when only one; when none.

PROPOSITION XXII. PROBLEM

374. *With a given line as chord, to construct a segment of a circle capable of containing a given angle.*



Given line AB and $\angle M$.

To construct, with AB as chord, a segment of a circle capable of containing $\angle M$.

I. Construction

1. Construct an \angle , as $\angle CDE$, equal to the given $\angle M$. § 125.
 2. With H , any convenient point on DE , as center and with AB as radius, describe an arc cutting DC at some point, as K .
 3. Draw HK .
 4. Circumscribe a circle about $\triangle KDH$. § 323.
 5. Segment KDH is the segment capable of containing $\angle M$.
- II. The proof and discussion are left to the student.

375. Questions. Without moving AB , can you construct a \triangle with AB as base and a vertex $\angle = \angle M$? What is the sum of the base \sphericalangle ?

376. Cor. *The locus of the vertices of all triangles having a given base and a given angle at their vertices is the arc which forms, with the given base, a segment capable of containing the given angle.*

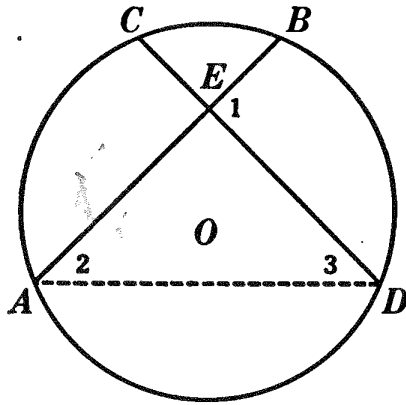
Ex. 500. On a given line construct a segment that shall contain an angle of 105° ; of 135° .

Ex. 501. Find the locus of the vertices of all triangles having a common base 2 inches long and having their vertex angles equal to 60° .

Ex. 502. Construct a triangle, having given b , h_b , and B .

PROPOSITION XXIII. THEOREM

377. *An angle formed by two chords which intersect within a circle is measured by one half the sum of the arc intercepted between its sides and the arc intercepted between the sides of its vertical angle.*



Given two chords AB and CD , intersecting at E .

To prove that $\angle 1 \propto \frac{1}{2} (\widehat{BD} + \widehat{AC})$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw AD . | 1. § 54, 15. |
| 2. $\angle 1 = \angle 2 + \angle 3$. | 2. § 215. |
| 3. $\angle 2 \propto \frac{1}{2} \widehat{BD}$. | 3. § 365. |
| 4. $\angle 3 \propto \frac{1}{2} \widehat{AC}$. | 4. § 365. |
| 5. $\therefore \angle 2 + \angle 3 \propto \frac{1}{2} (\widehat{BD} + \widehat{AC})$. | 5. § 362, b. |
| 6. $\therefore \angle 1 \propto \frac{1}{2} (\widehat{BD} + \widehat{AC})$. | 6. § 309. |

Q.E.D.

Ex. 503. One angle formed by two intersecting chords intercepts an arc of 40° . Its vertical angle intercepts an arc of 60° . How large is the angle?

Ex. 504. If an angle of two intersecting chords is 40° and its intercepted arc is 30° , how large is the opposite arc?

Ex. 505. If two chords intersect at right angles within a circumference, the sum of two opposite intercepted arcs is equal to a semicircumference.

Ex. 506. If M is the center of a circle inscribed in triangle ABC and if AM is prolonged to meet the circumference of the circumscribed circle at D , prove that $BD = DM = DC$.

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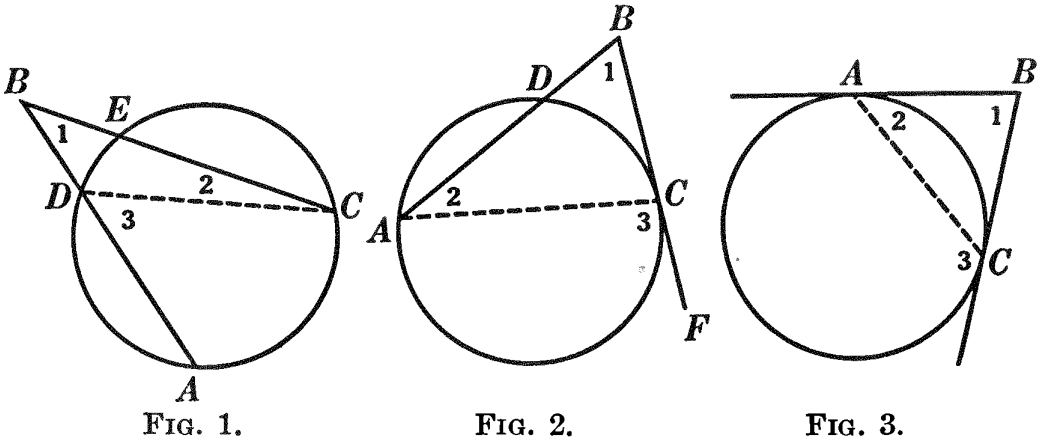
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PROPOSITION XXV. THEOREM

379. *An angle formed by two secants intersecting outside of a circumference, an angle formed by a secant and a tangent, and an angle formed by two tangents are each measured by one half the difference of the intercepted arcs.*



I. An angle formed by two secants (Fig. 1).

Given two secants BA and BC , forming $\angle 1$.

To prove that $\angle 1 \propto \frac{1}{2} (\widehat{AC} - \widehat{DE})$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Draw CD . | 1. § 54, 15. |
| 2. $\angle 1 + \angle 2 = \angle 3$. | 2. § 215. |
| 3. $\therefore \angle 1 = \angle 3 - \angle 2$. | 3. § 54, 3. |
| 4. $\angle 3 \propto \frac{1}{2} \widehat{AC}$, and $\angle 2 \propto \frac{1}{2} \widehat{DE}$. | 4. § 365. |
| 5. $\therefore \angle 3 - \angle 2 \propto \frac{1}{2} (\widehat{AC} - \widehat{DE})$. | 5. § 362, b. |
| 6. $\therefore \angle 1 \propto \frac{1}{2} (\widehat{AC} - \widehat{DE})$. | 6. § 309. |

Q.E.D.

II. An angle formed by a secant and a tangent (Fig. 2).

III. An angle formed by two tangents (Fig. 3).

The proofs of II and III are left to the student.

380. Note. In the preceding theorems the vertex of the angle may be: (1) within the circle; (2) on the circumference; (3) outside the circle.

Ex. 511. Tell how to measure an angle having its vertex in each of the three possible positions with regard to the circumference.

PROPOSITION XXVI. THEOREM

381. *Parallel lines intercept equal arcs on a circumference.*

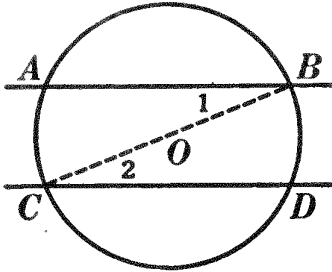


FIG. 1.

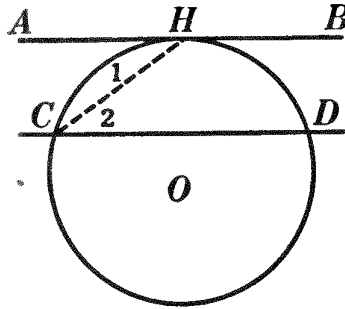


FIG. 2.

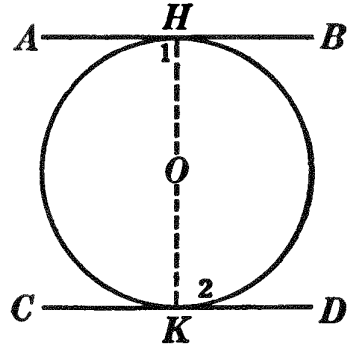


FIG. 3.

I. If the two \parallel lines are secants or chords (Fig. 1).

Given \parallel chords AB and CD , intercepting arcs AC and BD .

To prove $\widehat{AC} = \widehat{BD}$.

ARGUMENT

1. Draw CB .
2. $\angle 1 = \angle 2$.
3. $\angle 1 \propto \frac{1}{2} \widehat{AC}$, and $\angle 2 \propto \frac{1}{2} \widehat{BD}$.
4. $\therefore \frac{1}{2} AC = \frac{1}{2} BD$.
5. $\therefore AC = \widehat{BD}$.

REASONS

1. § 54, 15.
2. § 189.
3. § 365.
4. § 362, a.
5. § 54, 7 a.

Q.E.D.

II. If one of the \parallel lines is a secant and the other a tangent (Fig. 2).

III. If the two \parallel lines are tangents (Fig. 3).

The proofs of II and III are left as exercises for the student.

Ex. 512. In Fig. 1, Prop. XXV, if angle 1 equals 42° and arc DE equals 40° , how many degrees are there in angle 3? in arc AC ?

Ex. 513. In Fig. 2, if arc DC equals 60° and angle 3 equals 100° , find the number of degrees in angle 1.

Ex. 514. In Fig. 3, if angle 1 equals 65° , find angle 2 and angle 3.

Ex. 515. An angle formed by two tangents is measured by 180° minus the intercepted arc.

Ex. 516. If two tangents to a circle meet at an angle of 40° , how many degrees of arc do they intercept?

Ex. 517. Is the converse of Prop. XXVI true? Prove your answer.

Ex. 518. If two sides of an inscribed quadrilateral are parallel, the other two sides are equal.

Ex. 519. Is the converse of Ex. 518 true? Prove your answer.

Ex. 520. If, through the point where the bisector of an inscribed angle cuts the circumference, a chord is drawn parallel to one side of the angle, this chord will equal the other side of the angle.

Ex. 521. If through the points of intersection of two circumferences parallels are drawn terminating in the circumferences, these parallels will be equal.

Ex. 522. Prove that a trapezoid inscribed in a circle is isosceles.

Ex. 523. If two pairs of sides of an inscribed hexagon are parallel, the other two sides are equal.

Ex. 524. If the sides AB and BC of an inscribed quadrilateral $ABCD$ subtend arcs of 60° and 130° , respectively, and if angle AED , formed by the diagonals AC and BD intersecting at E , is 75° , how many degrees are there in arcs AD and DC ? how many degrees in each angle of the quadrilateral?

MISCELLANEOUS EXERCISES

Ex. 525. Equal chords of a circle whose center is C intersect at E . Prove that CE bisects the angle formed by the chords.

Ex. 526. A common tangent to two unequal circles intersects their line of centers at a point P ; from P a second tangent is drawn to one of the circles. Prove that it is also tangent to the other.

Ex. 527. Through one of the points of intersection of two circumferences draw a chord of one that shall be bisected by the other circumference.

Ex. 528. The angle ABC is any inscribed angle in a given segment of a circle; AC is prolonged to P , making CP equal to CB . Find the locus of P .

Ex. 529. Given two points P and Q , and a straight line through Q . Find the locus of the foot of the perpendicular from P to the given line, as the latter revolves around Q .

Ex. 530. If two circles touch each other and a line is drawn through the point of contact and terminated by the circumferences, the tangents at its ends are parallel.

Ex. 531. If two circles touch each other and two lines are drawn through the point of contact terminated by the circumferences, the chords joining the ends of these lines are parallel.

Ex. 532. If one arm of a right triangle is the diameter of a circle, the tangent at the point where the circumference cuts the hypotenuse bisects the other arm.

Ex. 533. Two fixed circles touch each other externally and a circle of variable radius touches both externally. Show that the difference of the distances from the center of the variable circle to the centers of the fixed circles is constant.

Ex. 534. If two circles are tangent externally, their common internal tangent bisects their common external tangent.

Ex. 535. If two circles are tangent externally and if their common external tangent is drawn, lines drawn from the point of contact of the circles to the points of contact of the external tangent are perpendicular to each other.

Ex. 536. The two common external tangents to two circles meet their line of centers at a common point. Also the two common internal tangents meet the line of centers at a common point.

Ex. 537. Two circles whose radii are 17 and 10 inches, respectively, are tangent externally. How long is the line joining their centers? how long if the same circles are tangent internally?

Ex. 538. If a right angle at the center of a circle is trisected, is the intercepted arc also trisected? Is the chord which subtends the arc trisected?

Ex. 539. Draw a line intersecting two given circumferences in such a way that the chords intercepted by the two circumferences shall equal two given lines. What restriction is there on the lengths of the given lines?

Ex. 540. Construct a triangle, given its base, the vertex angle, and the median to the base. Under what conditions will there be no solution?

Ex. 541. In the same circle, or in equal circles, two inscribed triangles are equal, if two sides of one are equal respectively to two sides of the other.

Ex. 542. If through the points of intersection of two circumferences two lines are drawn terminating in the circumferences, the chords which join their extremities are parallel.

Ex. 543. The tangents drawn through the vertices of an inscribed rectangle, which is not a square, form a rhombus.

Ex. 544. The line joining the center of the square described upon the hypotenuse of a right triangle, to the vertex of the right angle, bisects the right angle.

Ex. 545. If two common external tangents or two common internal tangents are drawn to two circles, the segments of these tangents intercepted between the points of contact are equal.

Ex. 546. Through two given points draw two parallel lines at a given distance apart.

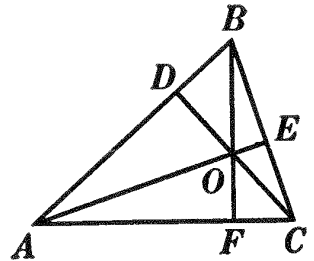
Ex. 547. In a given circle inscribe a chord of given length which prolonged shall be tangent to another given circle.

Ex. 548. Find the locus of the middle point of a chord drawn from a given point in a given circumference.

Ex. 549. The locus of the intersections of the altitudes of triangles having a given base and a given angle at the vertex is the arc which forms with the base a segment capable of containing an angle equal to the supplement of the given angle at the vertex.

HINT. Let ABC be one of the Δ and O the intersection of the altitudes. In quadrilateral $FOEC$, $\angle ECF$ is the supplement of $\angle FOE$. $\therefore \angle ECF$ is the supplement of $\angle BOA$.

Ex. 550. In a circle, prove that any chord which bisects a radius at right angles subtends an angle of 120° at the center.



Ex. 551. Construct an equilateral triangle, having given the radius of the inscribed circle.

Ex. 552. The two circles described upon two sides of a triangle as diameters intersect upon the third side.

Ex. 553. All triangles circumscribed about the same circle and mutually equiangular are equal.

Ex. 554. If two circumferences meet on their line of centers, the circles are tangent to each other.

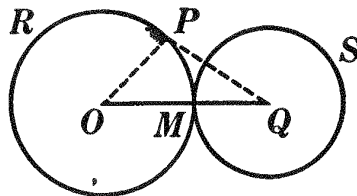


FIG. 1.

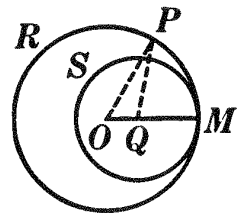


FIG. 2.

OUTLINE OF PROOF

I. M between O and Q , Fig. 1.

$$OP + PQ > OQ.$$

$$OP = OM.$$

$$\therefore PQ > MQ.$$

$\therefore P$ is not on circumference S .

II. M not between O and Q , Fig. 2.

$$OQ + QP > OP.$$

$$\therefore OQ + QP > OM.$$

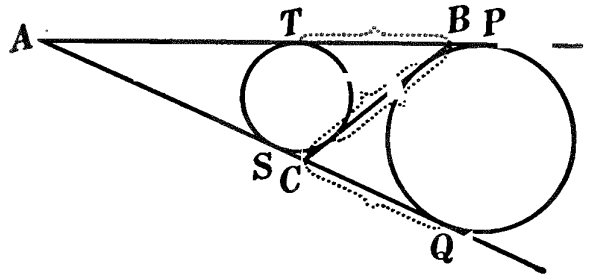
$$\therefore QP > QM.$$

$\therefore P$ is not on circumference S .

Ex. 555. If two circumferences intersect, neither point of intersection is on their line of centers.

Ex. 556. In any right triangle ABC , right-angled at C , the radius of the inscribed circle equals $\frac{1}{2}(a + b - c)$ and the radius of the escribed circle tangent to c equals $\frac{1}{2}(a + b + c)$.

Ex. 557. In the accompanying figure a, b, c , are the sides of triangle ABC . Prove :



1. $a = TP$;
2. $AP = \frac{1}{2}(a + b + c)$;
3. $TB = \frac{1}{2}(a + c - b)$.

Ex. 558. Trisect a quadrant ; a semicircumference ; a circumference.

Ex. 559. Describe circles about the vertices of a given triangle as centers, so that each shall touch the other two.

Ex. 560. Construct within a given circle three equal circles, so that each shall touch the other two and also the given circle.

Construct a triangle, having given :

- Ex. 561.** h_a, h_c, C .
- Ex. 562.** A, B , and R , the radius of the circumscribed circle.
- Ex. 563.** a, B, R .
- Ex. 564.** C and the segments of c made by t_c .
- Ex. 565.** C and the segments of c made by h_c .
- Ex. 566.** r , the radius of the inscribed circle, and the segments of c made by t_c .

Construct a right triangle ABC , right-angled at C , having given :

- Ex. 567.** c, h_c .
- Ex. 568.** c and one segment of c made by h_c .
- Ex. 569.** The segments of c made by h_c .
- Ex. 570.** The segments of c made by t_c .
- Ex. 571.** c and a line l , in which the vertex of C must lie.
- Ex. 572.** c and the perpendicular from vertex C to a line l .
- Ex. 573.** c and the distance from C to a point P .

Construct a square, having given :

- Ex. 574.** The perimeter.
- Ex. 575.** A diagonal.
- Ex. 576.** The sum of a diagonal and a side.

Construct a rectangle, having given :

Ex. 577. Two non-parallel sides.

Ex. 578. A side and a diagonal.

Ex. 579. The perimeter and a diagonal.

Ex. 580. A diagonal and an angle formed by the diagonals.

Ex. 581. A side and an angle formed by the diagonals.

Ex. 582. The perimeter and an angle formed by the diagonals.

Construct a rhombus, having given :

Ex. 583. A side and a diagonal.

Ex. 584. The perimeter and a diagonal.

Ex. 585. One angle and a diagonal.

Ex. 586. The two diagonals.

Ex. 587. A side and the sum of the diagonals.

Ex. 588. A side and the difference of the diagonals.

Construct a parallelogram, having given :

Ex. 589. Two non-parallel sides and an angle.

Ex. 590. Two non-parallel sides and a diagonal.

Ex. 591. One side and the two diagonals.

Ex. 592. The diagonals and an angle formed by them.

Construct an isosceles trapezoid, having given :

Ex. 593. The bases and a diagonal.

Ex. 594. The longer base, the altitude, and one of the equal sides.

Ex. 595. The shorter base, the altitude, and one of the equal sides.

Ex. 596. Two sides and their included angle.

Construct a trapezoid, having given :

Ex. 597. The bases and the angles adjacent to one base.

Ex. 598. The bases, the altitude, and an angle.

Ex. 599. One base, the two diagonals, and their included angle.

Ex. 600. The bases, a diagonal, and the angle between the diagonals.

Construct a circle which shall :

Ex. 601. Touch a given circle at P and pass through a given point Q

Ex. 602. Touch a given line l at P .

Ex. 603. Touch three given lines two of which are parallel.

Ex. 604. Touch a given line l at P and also touch another line m .

Ex. 605. Have its center in line l , cut l at P , and touch a circle K .

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PROPOSITION I. THEOREM

388. *If four numbers are in proportion, the product of the extremes is equal to the product of the means.*

Given $a : b = c : d$.

To prove $ad = bc$.

| | ARGUMENT | | REASONS |
|----|-------------------------------|--------|--------------|
| 1. | $\frac{a}{b} = \frac{c}{d}$. | Q.E.D. | 1. By hyp.* |
| 2. | $bd = bd$. | | 2. By iden. |
| 3. | $\therefore ad = bc$. | | 3. § 54, 7a. |

389. Note. The student should observe that the process used here is merely the algebraic "clearing of fractions," and that as fractional equations in algebra are usually simplified by this process, so, also, proportions may be simplified by placing the product of the means equal to the product of the extremes.

390. Cor. I. *The mean proportional between two numbers is equal to the square root of their product.*

391. Cor. II. *If two proportions have any three terms of one equal respectively to the three corresponding terms of the other, then the remaining term of the first is equal to the remaining term of the second.*

Ex. 606. Given the equation $m : r = d : c$; solve (1) for d , (2) for r , (3) for m , (4) for c .

Ex. 607. Find the fourth proportional to 4, 6, and 10; to 4, 10, and 6; to 10, 6, and 4.

Ex. 608. Find the mean proportional between 9 and 144; between 144 and 9.

Ex. 609. Find the third proportional to $\frac{4}{3}$ and $\frac{2}{3}$; to $\frac{2}{3}$ and $\frac{4}{3}$.

392. Questions. What rearrangement of numbers can be made in Ex. 607 without affecting the required term? in Ex. 608? in Ex. 609?

Ex. 610. Find the third proportional to $a^2 - b^2$ and $a - b$.

Ex. 611. Find the fourth proportional to $a^2 - b^2$, $a - b$, and $a + b$.

* See § 382 for the three ways of writing a proportion.

Ex. 612. If in any proportion the antecedents are equal, then the consequents are equal and conversely.

Ex. 613. If $a : b = c : d$, prove that $ma : kb = mc : kd$.

Ex. 614. If $l : k = b : m$, prove that $lr : kr = bc : mc$.

Ex. 615. If $x : y = b : c$, prove that $dx : y = bd : c$.

Ex. 616. If $x : y = b : c$, is $dx : y = b : cd$ a true proportion?

PROPOSITION II. THEOREM

(Converse of Prop. I)

393 *If the product of two numbers is equal to the product of two other numbers, either pair may be made the means and the other pair the extremes of a proportion.*

Given $ad = bc$.

To prove $a : b = c : d$.

| | ARGUMENT | | REASONS |
|----|--|--|--------------|
| 1. | $ad = bc$. | | 1. By hyp. |
| 2. | $bd = bd$. | | 2. By iden. |
| 3. | $\therefore \frac{a}{b} = \frac{c}{d}$; i.e. $a : b = c : d$. Q.E.D. | | 3. § 54, 8a. |

The proof that a and d may be made the means and b and c the extremes is left as an exercise for the student.

394. Note. The pupil should observe that the divisor in Arg. 2 above must be chosen so as to give the desired quotient in the first member of the equation: thus, if $hl = kf$, and we wish to prove that $\frac{h}{f} = \frac{k}{l}$, we must divide by fl ; then $\frac{hl}{fl} = \frac{kf}{fl}$, i.e. $\frac{h}{f} = \frac{k}{l}$.

Ex. 617. Given $pt = cr$. Prove $p : r = c : t$; also, $c : p = t : r$.

Ex. 618. From the equation $rs = lm$, derive the following eight proportions:

$$r : l = m : s, \quad s : l = m : r, \quad l : r = s : m, \quad m : r = s : l$$

$$r : m = l : s, \quad s : m = l : r, \quad l : s = r : m, \quad m : s = r : l.$$

Ex. 619. Form a proportion from $7 \times 4 = 3 \times a$; from $ft = gb$. How can the proportions obtained be verified?

Ex. 620. Form a proportion from $(a + c)(a - b) = de$.

Ex. 621. Form a proportion from $m^2 - 2mn + n^2 = ab$.

Ex. 622. Form a proportion from $c^2 + 2cd + d^2 = a + b$.

Ex. 623. Form a proportion from $(a + b)(a - b) = 4x$, making x (1) an extreme; (2) a mean.

Ex. 624. If $7x + 3y : 12 = 2x + y : 3$, find the ratio $x : y$.

PROPOSITION III. THEOREM

395. *If four numbers are in proportion, they are in proportion by inversion; that is, the second term is to the first as the fourth is to the third.*

Given $a : b = c : d$.

To prove $b : a = d : c$.

| | ARGUMENT | | REASONS |
|----|------------------------------|--------|------------|
| 1. | $a : b = c : d$. | Q.E.D. | 1. By hyp. |
| 2. | $\therefore ad = bc$. | | 2. § 388. |
| 3. | $\therefore b : a = d : c$. | | 3. § 393. |

PROPOSITION IV. THEOREM

396. *If four numbers are in proportion, they are in proportion by alternation; that is, the first term is to the third as the second is to the fourth.*

Given $a : b = c : d$.

To prove $a : c = b : d$.

| | ARGUMENT | | REASONS |
|----|------------------------------|--------|------------|
| 1. | $a : b = c : d$. | Q.E.D. | 1. By hyp. |
| 2. | $\therefore ad = bc$. | | 2. § 388. |
| 3. | $\therefore a : c = b : d$. | | 3. § 393. |

Ex. 625. If $x : \frac{1}{3} = y : \frac{7}{3}$, what is the value of the ratio $x : y$?

Ex. 626. Transform $a : x = 4 : 3$ so that x shall occupy in turn every place in the proportion.

397. Many transformations may be easily brought about by the following method :

(1) Reduce the conclusion to an equation in its simplest form (§ 388), then from this derive the hypothesis.

(2) Begin with the hypothesis and reverse the steps of (1).

This method is illustrated in the analysis of Prop. V.

PROPOSITION V. THEOREM

398. *If four numbers are in proportion, they are in proportion by composition; that is, the sum of the first two terms is to the first (or second) term as the sum of the last two terms is to the third (or fourth) term.*

Given $a : b = c : d$.

To prove: (a) $a + b : a = c + d : c$;

(b) $a + b : b = c + d : d$.

I. Analysis

(1) The conclusions required above, when reduced to equations in their simplest forms, are as follows :

- | (a) | (b) |
|---------------------------------|---------------------------------|
| 1. $ac + ad = ac + bc$. | 1. $bc + bd = ad + bd$. |
| 2. Whence $ad = bc$. | 2. Whence $bc = ad$. |
| 3. $\therefore a : b = c : d$. | 3. $\therefore a : b = c : d$. |

(2) Now begin with the hypothesis and reverse the steps.

II. Proof

| (a) | ARGUMENT | | REASONS |
|-----|--|--------|-------------|
| 1. | $a : b = c : d$. | | 1. By hyp. |
| 2. | $\therefore ad = bc$. | | 2. § 388. |
| 3. | $ac = ac$. | | 3. By iden. |
| 4. | $\therefore ac + ad = ac + bc$; i.e. $a(c + d) = c(a + b)$. | | 4. § 54, 2. |
| 5. | $\therefore a + b : a = c + d : c$. | Q.E.D. | 5. § 393. |

(b) The proof of (b) is left as an exercise for the student.

Ex. 627. If $\frac{x}{y} = \frac{6}{5}$, find $\frac{x+y}{x}$; $\frac{x+y}{y}$.

PROPOSITION VI. THEOREM

399. *If four numbers are in proportion, they are in proportion by division; that is, the difference of the first two terms is to the first (or second) term as the difference of the last two terms is to the third (or fourth) term.*

Given $a : b = c : d$.

To prove: (a) $a - b : a = c - d : c$;

(b) $a - b : b = c - d : d$.

I. The analysis is left as an exercise for the student.

II. Proof

| (a) | ARGUMENT | REASONS |
|-----|--|-------------|
| 1. | $a : b = c : d$. | 1. By hyp. |
| 2. | $\therefore ad = bc$. | 2. § 388. |
| 3. | $ac = ac$. | 3. By iden. |
| 4. | $\therefore ac - ad = ac - bc$, i.e. $a(c - d) = c(a - b)$. | 4. § 54, 3. |
| 5. | $\therefore a - b : a = c - d : c$. | 5. § 393. |

Q.E.D.

(b) The proof of (b) is left as an exercise for the student.

Ex. 628. If $\frac{x}{y} = \frac{8}{3}$, find $\frac{x-y}{x}$; $\frac{x-y}{y}$.

PROPOSITION VII. THEOREM

400. *If four numbers are in proportion, they are in proportion by composition and division; that is, the sum of the first two terms is to their difference as the sum of the last two terms is to their difference.*

Given $a : b = c : d$.

To prove $a + b : a - b = c + d : c - d$.

| | ARGUMENT | REASONS |
|--------|---|---------------|
| 1. | $a : b = c : d.$ | 1. By hyp. |
| 2. | $\therefore \frac{a + b}{a} = \frac{c + d}{c}.$ | 2. § 398. |
| 3. And | $\frac{a - b}{a} = \frac{c - d}{c}.$ | 3. § 399. |
| 4. | $\therefore \frac{a + b}{a - b} = \frac{c + d}{c - d};$ | 4. § 54, 8 a. |
| | i.e. $a + b : a - b = c + d : c - d.$ Q.E.D. | |

PROPOSITION VIII. THEOREM

401. *In a series of equal ratios the sum of any number of antecedents is to the sum of the corresponding consequents as any antecedent is to its consequent.*

Given $a : b = c : d = e : f = g : h.$

To prove $a + c + e + g : b + d + f + h = a : b.$

I. Analysis

Simplifying the conclusion above, we have:

$$ab + bc + be + bg = ab + ad + af + ah.$$

The terms required for the first member of this equation, and their equivalents for the second member, may be obtained from the hypothesis.

II. Proof

| | ARGUMENT | REASONS |
|----|--|-------------|
| 1. | $ab = ab.$ | 1. By iden. |
| 2. | $bc = ad.$ | 2. § 388. |
| 3. | $be = af.$ | 3. § 388. |
| 4. | $bg = ah.$ | 4. § 388. |
| 5. | $\therefore ab + bc + be + bg = ab + ad + af + ah;$ i.e. $b(a + c + e + g) = a(b + d + f + h).$ | 5. § 54, 2. |
| 6. | $\therefore a + c + e + g : b + d + f + h = a : b.$ | 6. § 393. |
| | Q.E.D. | |

Ex. 629. With the hypothesis of Prop. VIII, prove

$$a + c + e : b + d + f = g : h.$$

Ex. 630. If $\frac{m}{r} = \frac{s}{t} = \frac{k}{g} = \frac{p}{q}$, prove $\frac{m - s + k - p}{r - t + g - q} = \frac{p}{q}$.

Ex. 631. If $\frac{x + 2y}{2y} - \frac{7}{4}$, find $\frac{x}{y}$. **HINT.** Use Prop. VI.

Ex. 632. If $a : b = c : d$, show that $b - a : b + a = d - c : d + c$.

Ex. 633. Given the proportion $a : b = 11 : 6$. Write the proportions that result from taking the terms (1) by inversion; (2) by alternation; (3) by composition; (4) by division; (5) by composition and division.

PROPOSITION IX. THEOREM

402. *The products of the corresponding terms of any number of proportions form a proportion.*

Given $a : b = c : d, e : f = g : h, i : j = k : l$.

To prove $aei : bfj = cgk : dhl$.

| | ARGUMENT | REASONS |
|----|--|---------------|
| 1. | $\frac{a}{b} = \frac{c}{d};$ $\frac{e}{f} = \frac{g}{h};$ $\frac{i}{j} = \frac{k}{l}.$ | 1. By hyp. |
| 2. | $\therefore \frac{aei}{bfj} = \frac{cgk}{dhl};$ <p style="margin-left: 20px;">i.e. $aei : bfj = cgk : dhl$.</p> | 2. § 54, 7 a. |
| | Q.E.D. | |

403. Cor. *If four numbers are in proportion, equimultiples of the first two and equimultiples of the last two are also in proportion.*

HINT. Given $a : b = x : y$.

To prove $am : bm = nx : ny$.

Ex. 634. If $r : s = m : t$, is $fr : qs = gm : ft$? Prove your answer.

Ex. 635. If $a : b = 3 : 4$ and $x : y = 8 : 9$, find the value of $ax : by$.

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Ex. 642. In the continued proportion $a : b = b : c = c : d = d : e$, prove that :

$$\frac{a}{c} = \frac{a^2}{b^2}; \quad \frac{a}{d} = \frac{a^3}{b^3}; \quad \text{and} \quad \frac{a}{e} = \frac{a^4}{b^4}.$$

Ex. 643. If $x^3 : y^3 = 8 : 27$, find $\frac{x}{y}$.

Ex. 644. If $\sqrt{m} : 1 = \sqrt{n} : 16$, find $\frac{m}{n}$.

406. Def. The segments of a line are the parts into which it is divided. The line AB is divided internally at C if this point is between the extremities of the line. The segments into which it is divided are AC and CB .



AB is divided externally at D if this point is on the prolongation of the line. The segments are AD and DB .

It should be noted that in either case *the point of division is one end of each segment.*

407. Def. Two straight lines are divided proportionally if the ratio of one line to either of its segments is equal to the ratio of the other line to its corresponding segment.

408. In Prop. XI, II, the following theorems (Appendix, §§ 586 and 591) will be assumed :

- (a) *The quotient of a variable by a constant is a variable.*
- (b) *The limit of the quotient of a variable by a constant is the limit of the variable divided by the constant.*

Thus, if x is a variable and k a constant :

(1) $\frac{x}{k}$ is a variable.

(2) If the limit of x is y , then the limit of $\frac{x}{k}$ is $\frac{y}{k}$.

Ex. 645. In the figure of § 409, name the segments into which AB is divided by D ; the segments into which AD is divided by B .

PROPOSITION XI. THEOREM

409. *A straight line parallel to one side of a triangle divides the other two sides proportionally.*

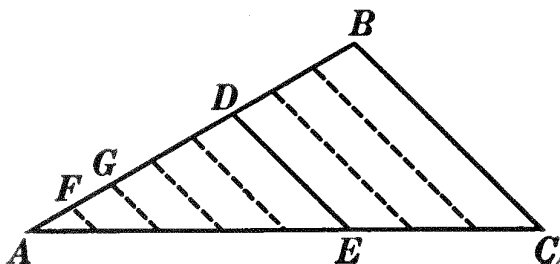


FIG. 1.

Given $\triangle ABC$ with line $DE \parallel BC$.

To prove $\frac{AB}{AD} = \frac{AC}{AE}$.

I. If AB and AD are commensurable (Fig. 1).

| ARGUMENT | REASONS |
|--|-------------|
| 1. Let AF be a common measure of AB and AD , and suppose that AF is contained in AB r times and in AD s times. | 1. § 335. |
| 2. Then $\frac{AB}{AD} = \frac{r}{s}$. | 2. § 341. |
| 3. Through the several points of division on AB , as F, G , etc., draw lines $\parallel BC$. | 3. § 179. |
| 4. These lines are $\parallel DE$ and to each other. | 4. § 180. |
| 5. $\therefore AC$ is divided into r equal parts and AE into s equal parts. | 5. § 244. |
| 6. $\therefore \frac{AC}{AE} = \frac{r}{s}$. | 6. § 341. |
| 7. $\therefore \frac{AB}{AD} = \frac{AC}{AE}$. | 7. § 54, 1. |

Q.E.D.

II. If AB and AD are incommensurable (Fig. 2).

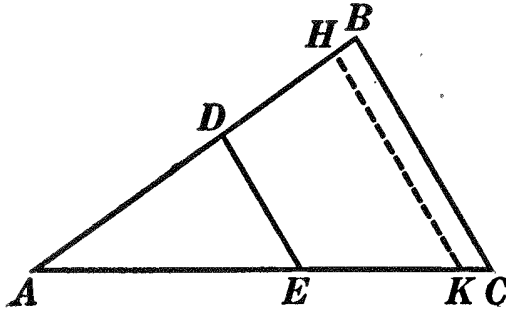


FIG. 2.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Let m be a measure of AD . Apply m as a measure to AB as many times as possible. There will then be a remainder, HB , less than m . | 1. § 339. |
| 2. AH and AD are commensurable. | 2. § 337. |
| 3. Draw $HK \parallel BC$. | 3. § 179. |
| 4. $\therefore \frac{AH}{AD} = \frac{AK}{AE}$. | 4. § 409, I. |
| 5. Now take a smaller measure of AD . No matter how small a measure of AD is taken, when it is applied as a measure to AB , the remainder, HB , will be smaller than the measure taken. | 5. § 335. |
| 6. \therefore the difference between AH and AB may be made to become and remain less than any previously assigned line, however small. | 6. Arg. 5. |
| 7. $\therefore AH$ approaches AB as a limit. | 7. § 349. |
| 8. $\therefore \frac{AH}{AD}$ approaches $\frac{AB}{AD}$ as a limit. | 8. § 408, <i>b</i> . |
| 9. Likewise the difference between AK and AC may be made to become and remain less than any previously assigned line, however small. | 9. Arg. 6. |

| ARGUMENT | REASONS |
|---|-----------------------|
| 10. $\therefore AK$ approaches AC as a limit. | 10. § 349. |
| 11. $\therefore \frac{AK}{AE}$ approaches $\frac{AC}{AE}$ as a limit. | 11. § 408, <i>b</i> . |
| 12. But $\frac{AH}{AD}$ is always equal to $\frac{AK}{AE}$. | 12. Arg. 4. |
| 13. $\therefore \frac{AB}{AD} = \frac{AC}{AE}$. | 13. § 355. |

Q.E.D.

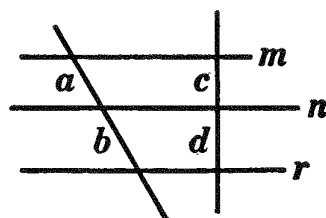
410. Cor. *A straight line parallel to one side of a triangle divides the other two sides into segments which are proportional.* Thus, in the figures for Prop. XI, $AD:DB = AE:EC$.

HINT. Prove by using division.

Ex. 646. Using Fig. 2 of Prop. XI, prove

$$(1) AB : AC = AD : AE; (2) AB : AC = DB : EC.$$

Ex. 647. In the diagram at the right, m , n , and r are parallel to each other. Prove that $a : b = c : d$; also that $a : c = b : d$.



Ex. 648. If two sides of a triangle are 12 inches and 18 inches, and if a line is drawn parallel to the third side and cuts off 3 inches from the vertex on the 12-inch side, into what segments will it cut the 18-inch side?

Ex. 649. If two lines are cut by any number of parallels, the two lines are divided into segments which are proportional: (*a*) if the two lines are parallel; (*b*) if the two lines are oblique.

Ex. 650. If through the point of intersection of the medians of a triangle a line is drawn parallel to any side of the triangle, this line divides the other two sides in the ratio of 2 to 1.

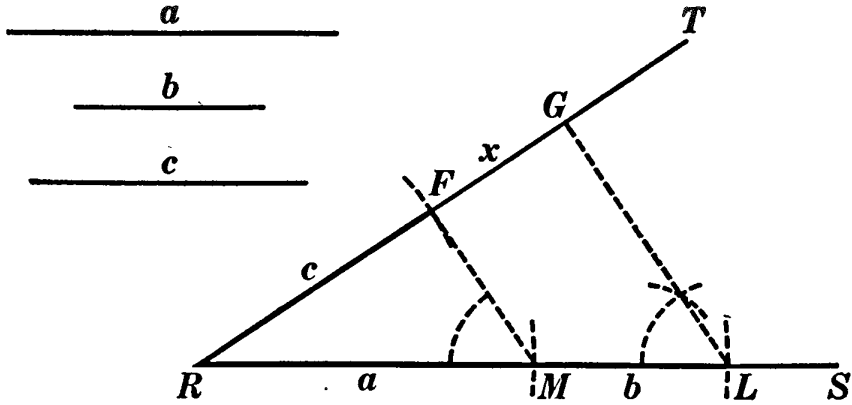
Ex. 651. A line can be divided at but one point into segments which have a given ratio (measured from one end).

Ex. 652. A line parallel to the bases of a trapezoid divides the other two sides and also the two diagonals proportionally.

Ex. 653. Apply the proof of Prop. XI to the case in which the parallel to the base cuts the sides prolonged: (*a*) through the ends of the base; (*b*) through the vertex.

PROPOSITION XII. PROBLEM

411. *To construct the fourth proportional to three given lines.*



Given lines a , b , and c .

To construct the fourth proportional to a , b , and c .

I. Construction

1. From any point, as R , draw two indefinite lines RS and RT .
2. On RS lay off $RM = a$ and $ML = b$.
3. On RT lay off $RF = c$.
4. Draw MF .
5. Through L construct $LG \parallel MF$. § 188.
6. FG is the fourth proportional to a , b , and c .

II. The proof and discussion are left as an exercise for the student.

412. Question. Could the segments a , b , and c be laid off in any other order?

413. Cor. I. *To construct the third proportional to two given lines.*

414. Cor. II. *To divide a given line into segments proportional to two or more given lines.*

Ex. 654. Divide a given line into segments in the ratio of 3 to 5.

Ex. 655. Divide a given line into segments proportional to 2, 3, and 4.

Ex. 656. Construct two lines, given their sum and their ratio.

Ex. 657. Construct two lines, given their difference and their ratio.

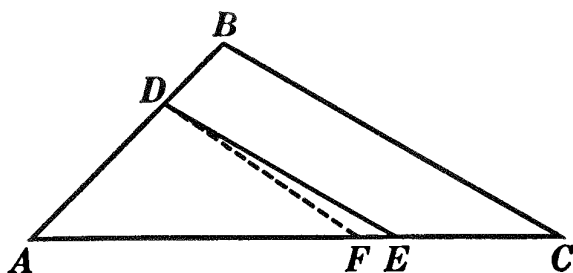
Ex. 658. If a , b , and c are three given lines, construct x so that:

$$(a) x : a = b : c; \quad (b) x = \frac{ac}{b}.$$

PROPOSITION XIII. THEOREM

(Converse of Prop. XI)

415. *If a straight line divides two sides of a triangle proportionally, it is parallel to the third side.*



Given $\triangle ABC$, and DE so drawn that $\frac{AB}{AD} = \frac{AC}{AE}$.

To prove $DE \parallel BC$.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. DE and BC are either \parallel or not \parallel . | 1. § 161, <i>a</i> . |
| 2. Suppose that DE is not $\parallel BC$, but that some other line through D , as DF , is $\parallel BC$. | 2. § 179. |
| 3. Then $\frac{AB}{AD} = \frac{AC}{AF}$. | 3. § 409. |
| 4. But $\frac{AB}{AD} = \frac{AC}{AE}$. | 4. By hyp. |
| 5. $\therefore AF = AE$. | 5. § 391. |
| 6. This is impossible. | 6. § 54, 12. |
| 7. $\therefore DE \parallel BC$. Q.E.D. | 7. § 161, <i>b</i> . |

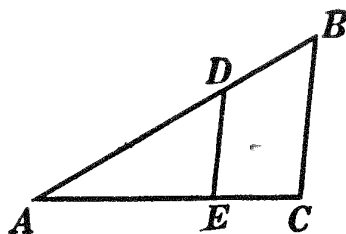
416. Cor. *If a straight line divides two sides of a triangle into segments which are proportional, it is parallel to the third side. Thus, if $AD : DB = AE : EC$, DE is $\parallel BC$.*

Ex. 659. In the diagram at the right, if $AB = 15$, $AC = 12$, $AD = 10$, and $AE = 8$, prove DE parallel to BC .

Ex. 660. If $AB = 50$, $DB = 15$, $AE = 28$, and $EC = 12$, is DE parallel to BC ? Prove.

Ex. 661. If $DE \parallel BC$, $AB = 25$, $DB = 5$, and $AC = 20$, find AE .

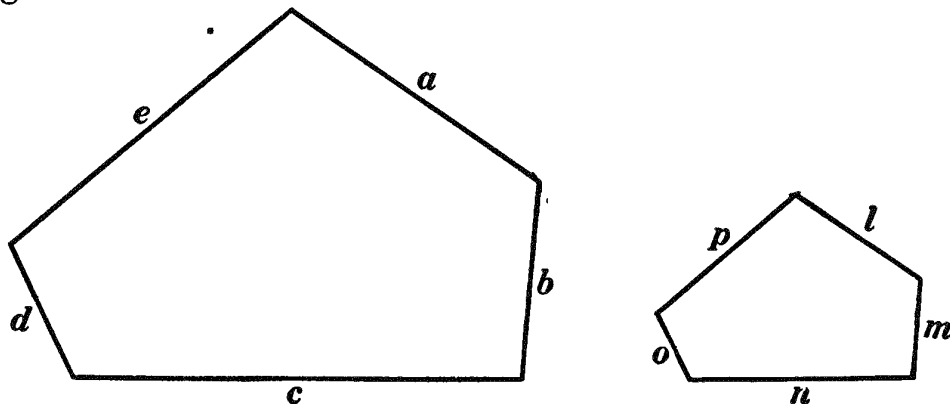
Ex. 662. If $DE \parallel BC$, $AB = 30$, $AD = 25$, and $EC = 4$, find AC .



SIMILAR POLYGONS

417. Def. If the angles of one polygon, taken in order, are equal respectively to those of another, taken in order, the polygons are said to be **mutually equiangular**. The pairs of equal angles in the two polygons, taken in order, are called **homologous angles** of the two polygons.

418. Def. If the sides of one polygon, taken in order as antecedents, form a series of equal ratios with the sides of another polygon, taken in order as consequents, the polygons are said to have their **sides proportional**. Thus, in the accompanying figure, if $a : l = b : m = c : n = d : o = e : p$, the two polygons have their sides proportional. The lines forming any ratio are called **homologous lines** of the two polygons, and the ratio of two such lines is called the **ratio of similitude** of the polygons.



419. Def. Two polygons are **similar** if they are mutually equiangular and if their sides are proportional.

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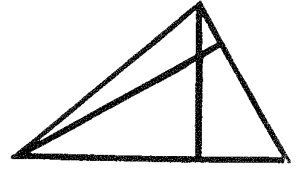
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422. Cor. II. *Two right triangles are similar if an acute angle of one is equal to an acute angle of the other.*

423. Cor. III. *If a line is drawn parallel to any side of a triangle, this line, with the other two sides, forms a triangle which is similar to the given triangle.*

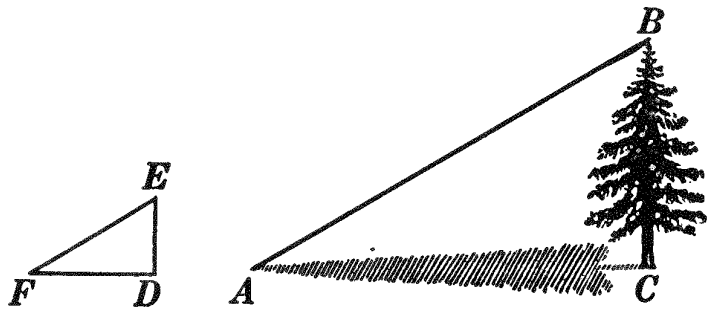
Ex. 663. Upon a given line as base construct a triangle similar to a given triangle.

Ex. 664. Draw a triangle ABC . Estimate the lengths of its sides. Draw a second triangle DEF similar to ABC and having DE equal to two thirds of AB . Compute DF and EF .



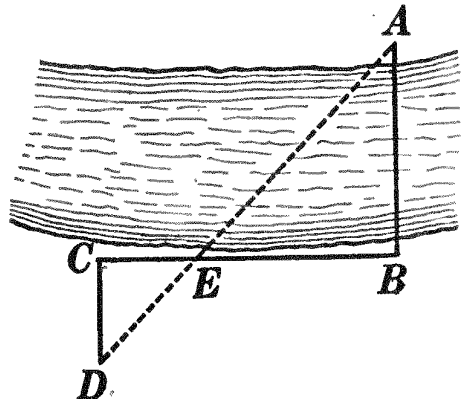
Ex. 665. Any two altitudes of a triangle are to each other inversely as the sides to which they are drawn.

Ex. 666. At a certain hour of the day a tree, BC , casts a shadow, CA . At the same time a vertical pole, ED , casts a shadow, DF . What measurements are necessary to determine the height of the tree?



Ex. 667. If CA is found to be 64 feet; DF , 16 feet; ED , 10 feet; what is the height of the tree?

Ex. 668. To find the distance across a river from A to B , a point C was located so that BC was perpendicular to AB at B . CD was then measured off 100 feet in length and perpendicular to BC at C . The line of sight from D to A intersected BC at E . By measurement CE was found to be 90 feet and EB 210 feet. What was the distance across the river?



Ex. 669. Two isosceles triangles are similar if the vertex angle of one equals the vertex angle of the other, or if a base angle of one equals a base angle of the other.

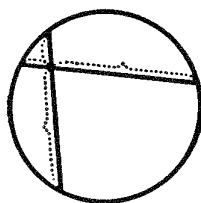
424. It follows from the definition of similar polygons, § 419, and from Prop. XIV that:

- (1) *Homologous angles of similar triangles are equal.*
- (2) *Homologous sides of similar triangles are proportional.*
- (3) *Homologous sides of similar triangles are the sides opposite equal angles.*

425. Note. In case, therefore, it is desired to prove four lines proportional, try to find a pair of triangles each having two of the given lines as sides. If, then, these triangles can be proved similar, their homologous sides will be proportional. By *marking with colored crayon* the lines required in the proportion, the triangles can readily be found. If it is desired to prove the product of two lines equal to the product of two other lines, prove the four lines proportional by the method just suggested, then put the product of the extremes equal to the product of the means.*

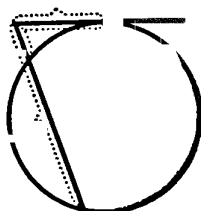
426. Def. The length of a secant from an external point to a circle is the length of the segment included between the point and the second point of intersection of the secant and the circumference.

Ex. 670. If two chords intersect within a circle, establish a proportionality among the segments of the chords. Place the product of the extremes equal to the product of the means, and state your result as a theorem.



Ex. 671. If two secants are drawn from any given point to a circle, what are the segments of the secants? Does the theorem of Ex. 670 still hold with regard to them?

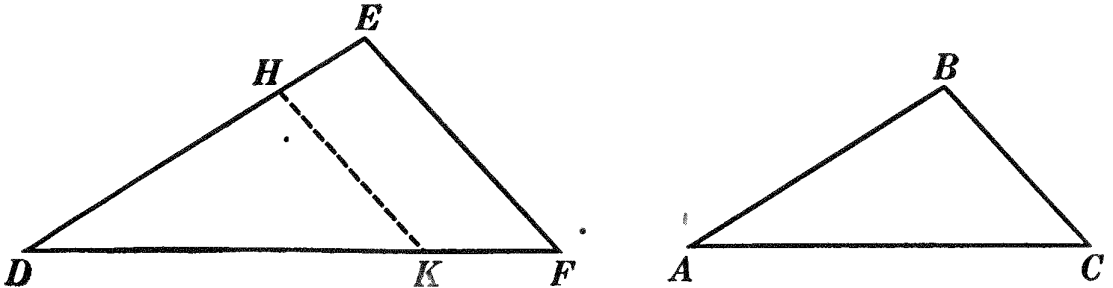
Ex. 672. Rotate one of the secants of Ex. 671 about the point of intersection of the two until the rotating secant becomes a tangent. What are the segments of the secant which has become a tangent? Does the theorem of Ex. 670 still hold? Prove.



* By the product of two lines is meant the product of their measure-numbers. This will be discussed again in Book IV.

PROPOSITION XV. THEOREM

427. Two triangles which have their sides proportional are similar.



Given $\triangle DEF$ and ABC such that $\frac{DE}{AB} = \frac{EF}{BC} = \frac{DF}{AC}$.

To prove $\triangle DEF \sim \triangle ABC$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. On DE lay off $DH = AB$, and on DF lay off $DK = AC$. | 1. § 54, 14. |
| 2. Draw HK . | 2. § 54, 15. |
| 3. $\frac{DE}{AB} = \frac{DF}{AC}$. | 3. By hyp. |
| 4. $\therefore \frac{DE}{DH} = \frac{DF}{DK}$. | 4. § 309. |
| 5. $\therefore HK \parallel EF$. | 5. § 415. |
| 6. $\therefore \triangle DEF \sim \triangle DHK$. | 6. § 423. |
| It remains to prove $\triangle DHK = \triangle ABC$. | |
| 7. $\frac{DE}{DH} = \frac{EF}{HK}$. | 7. § 424, 2. |
| 8. But $\frac{DE}{AB} = \frac{EF}{BC}$; i.e. $\frac{DE}{DH} = \frac{EF}{BC}$. | 8. By hyp. |
| 9. $\therefore HK = BC$. | 9. § 391. |
| 10. Now $DH = AB$ and $DK = AC$. | 10. Arg. 1. |
| 11. $\therefore \triangle DHK = \triangle ABC$. | 11. § 116. |
| 12. But $\triangle DEF \sim \triangle DHK$. | 12. Arg. 6. |
| 13. $\therefore \triangle DEF \sim \triangle ABC$. | 13. § 309. |

Q.E.D.

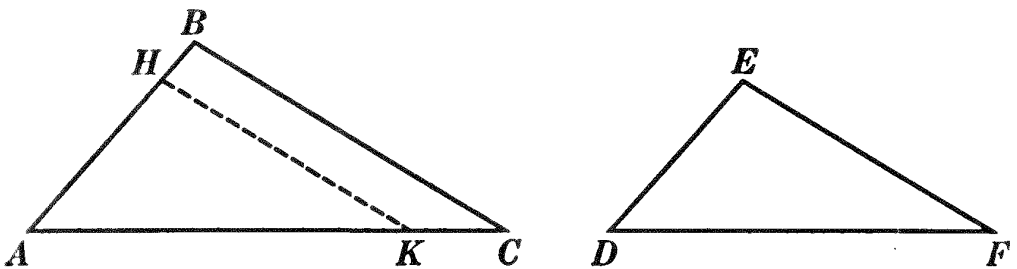
Ex. 673. If the sides of two triangles are 9, 12, 15, and 6, 8, 10, respectively, are the triangles similar? Explain.

Ex. 674. Construct a triangle that shall have a given perimeter and shall be similar to a given triangle.

Ex. 675. Construct a trapezoid, given the two bases and the two diagonals. **HINT.** How do the diagonals of a trapezoid divide each other?

PROPOSITION XVI. THEOREM

428. *If two triangles have an angle of one equal to an angle of the other, and the including sides proportional, the triangles are similar.*



Given $\triangle ABC$ and DEF with $\angle A = \angle D$ and $\frac{AB}{DE} = \frac{AC}{DF}$.

To prove $\triangle ABC \sim \triangle DEF$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Place $\triangle DEF$ on $\triangle ABC$ so that $\angle D$ shall coincide with $\angle A$, DE falling on AB , and DF on AC . Represent $\triangle DEF$ in its new position by $\triangle AHK$. | 1. § 54, 14. |
| 2. $\frac{AB}{DE} = \frac{AC}{DF}$. | 2. By hyp. |
| 3. $\therefore \frac{AB}{AH} = \frac{AC}{AK}$. | 3. § 309. |
| 4. $\therefore HK \parallel BC$. | 4. § 415. |
| 5. $\therefore \triangle ABC \sim \triangle AHK$. | 5. § 423. |
| 6. But $\triangle AHK$ is $\triangle DEF$ transferred to a different position. | 6. Arg. 1. |
| 7. $\therefore \triangle ABC \sim \triangle DEF$. Q.E.D. | 7. § 309. |

Ex. 676. Two triangles are similar if two sides and the median drawn to one of these sides in one triangle are proportional to two sides and the corresponding median in the other triangle.

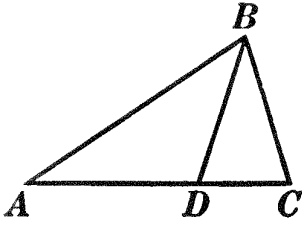


FIG. 1.

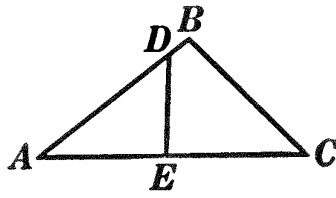


FIG. 2.

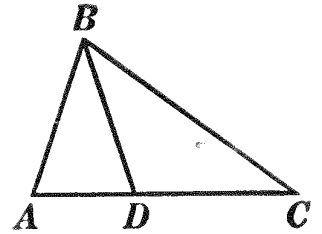


FIG. 3.

Ex. 677. In triangles ABC and DBC , Fig. 1, $AB = AC$ and $BD = BC$. Prove triangle ABC similar to triangle DBC .

Ex. 678. In Fig. 2, $AB : AC = AE : AD$. Prove triangle ABC similar to triangle ADE .

Ex. 679. If in triangle ABC , Fig. 3, $CA = BC$, and if D is a point such that $CA : AB = AB : AD$, prove $AB = BD$.

Ex. 680. Construct a triangle similar to a given triangle and having the sum of two sides equal to a given line.

PROPOSITION XVII. THEOREM

429. *Two triangles that have their sides parallel each to each, or perpendicular each to each, are similar.*

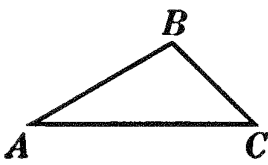


FIG. 1.

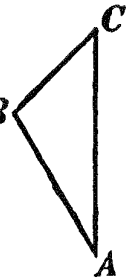
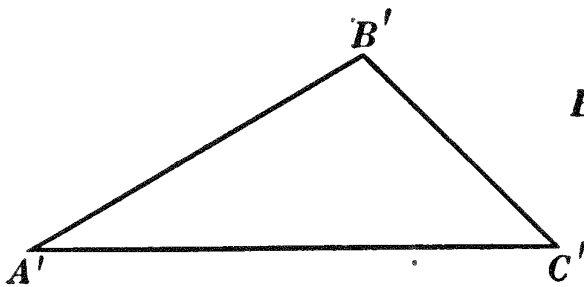


FIG. 2.

Given $\triangle ABC$ and $A'B'C'$, with $AB, BC,$ and $CA \parallel$ (Fig. 1) or \perp (Fig. 2) respectively to $A'B', B'C',$ and $C'A'$.

To prove $\triangle ABC \sim \triangle A'B'C'$.

ARGUMENT

1. $AB, BC,$ and CA are \parallel or \perp respectively to $A'B', B'C',$ and $C'A'$.
2. $\therefore \angle A, B,$ and C are equal respectively or are sup. respectively to $\angle A', B',$ and C' .

REASONS

1. By hyp.
2. §§ 198, 201.

| ARGUMENT | REASONS |
|--|----------------------|
| 3. Three suppositions may be made, therefore, as follows : | 3. § 161, <i>a</i> . |
| (1) $\angle A + \angle A' = 2 \text{ rt. } \sphericalangle, \angle B + \angle B' = 2 \text{ rt. } \sphericalangle, \angle C + \angle C' = 2 \text{ rt. } \sphericalangle.$ | |
| (2) $\angle A = \angle A', \angle B + \angle B' = 2 \text{ rt. } \sphericalangle, \angle C + \angle C' = 2 \text{ rt. } \sphericalangle.$ | |
| (3) $\angle A = \angle A', \angle B = \angle B';$ hence, also, $\angle C = \angle C'.$ | |
| 4. According to (1) and (2) the sum of the \sphericalangle s of the two \triangle s is more than four rt. \sphericalangle s. | 4. § 54, 2. |
| 5. But this is impossible. | 5. § 204. |
| 6. \therefore (3) is the only supposition admissible; <i>i.e.</i> the two \triangle s are mutually equiangular. | 6. 161, <i>b</i> . |
| 7. $\therefore \triangle ABC \sim \triangle A'B'C'.$ Q.E.D. | 7. § 420. |

430. Question. Can one pair of angles in Prop. XVII be supplementary and the other two pairs equal?

SUMMARY OF CONDITIONS FOR SIMILARITY OF TRIANGLES

431. I. Two triangles are similar if they are mutually equiangular.

(*a*) Two triangles are similar if two angles of one are equal respectively to two angles of the other.

(*b*) Two right triangles are similar if an acute angle of one is equal to an acute angle of the other.

(*c*) If a line is drawn parallel to any side of a triangle, this line, with the other two sides, forms a triangle which is similar to the given triangle.

II. Two triangles are similar if their sides are proportional.

III. Two triangles are similar if they have an angle of one equal to an angle of the other, and the including sides proportional.

IV. Two triangles are similar if their sides are parallel each to each, or perpendicular each to each.

Ex. 681. Inscribe a triangle in a circle and circumscribe about the circle a triangle similar to the inscribed triangle.

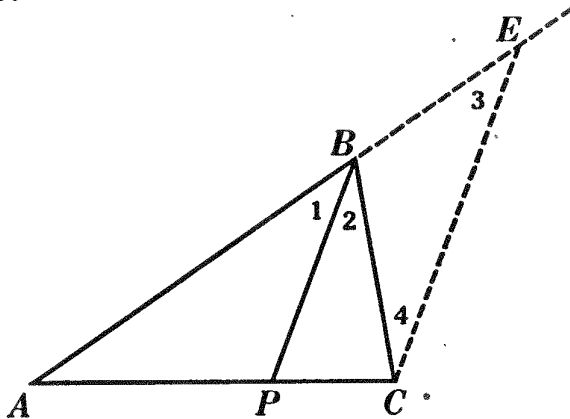
Ex. 682. Circumscribe a triangle about a circle and inscribe in the circle a similar triangle.

Ex. 683. The lines joining the mid-points of the sides of a triangle form a second triangle similar to the given triangle.

Ex. 684. ABC is a triangle inscribed in a circle. A line is drawn from A to P , any point of BC , and a chord is drawn from B to a point Q in arc BC so that angle ABQ equals angle APC . Prove $AB \times AC = AQ \times AP$.

PROPOSITION XVIII. THEOREM

432. *The bisector of an angle of a triangle divides the opposite side into segments which are proportional to the other two sides.*



Given $\triangle ABC$ with BP the bisector of $\angle ABC$.

To prove $AP : PC = AB : BC$.

| ARGUMENT | REASONS |
|---|-------------|
| 1. Through C draw $CE \parallel PB$, meeting AB prolonged at E . | 1. § 179. |
| 2. In $\triangle AEC$, $AP : PC = AB : BE$. | 2. § 410. |
| 3. Now $\angle 3 = \angle 1$. | 3. § 190. |
| 4. And $\angle 4 = \angle 2$. | 4. § 189. |
| 5. But $\angle 1 = \angle 2$. | 5. By hyp. |
| 6. $\therefore \angle 3 = \angle 4$. | 6. § 54, 1. |
| 7. $\therefore BC = BE$. | 7. § 162. |
| 8. $\therefore AP : PC = AB : BC$. Q.E.D. | 8. § 309. |

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434. Def. A line is divided harmonically if it is divided internally and externally into segments whose ratios are numerically equal; thus, if line AC is divided internally at P and externally at Q so that the ratio of AP to PC is numerically equal to the ratio of AQ to QC , AC is said to be divided harmonically.

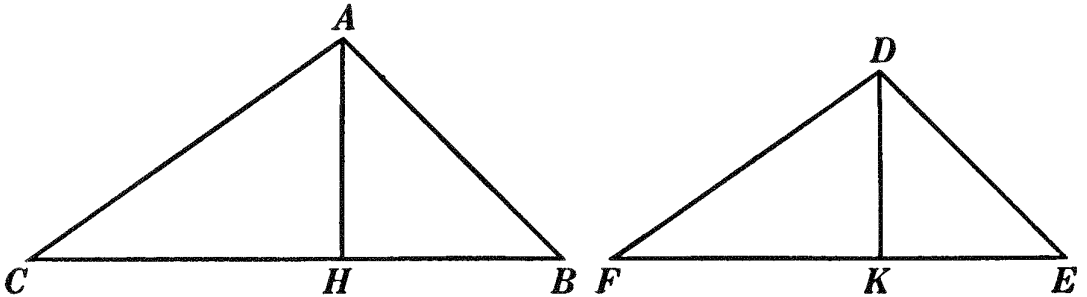


Ex. 689. The bisectors of the interior and exterior angles at any vertex of a triangle divide the opposite side harmonically.

Ex. 690. Divide a given straight line harmonically in the ratio of 3 to 5; in the ratio of a to b , where a and b are given straight lines.

PROPOSITION XX. THEOREM

435. In two similar triangles any two homologous altitudes have the same ratio as any two homologous sides.



Given two similar $\triangle ABC$ and DEF , with two corresponding altitudes AH and DK .

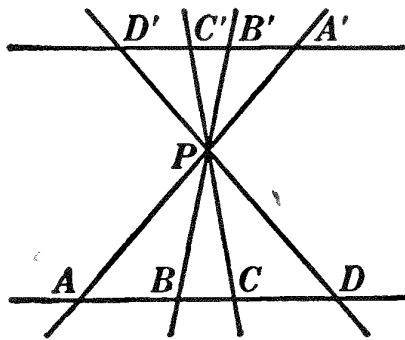
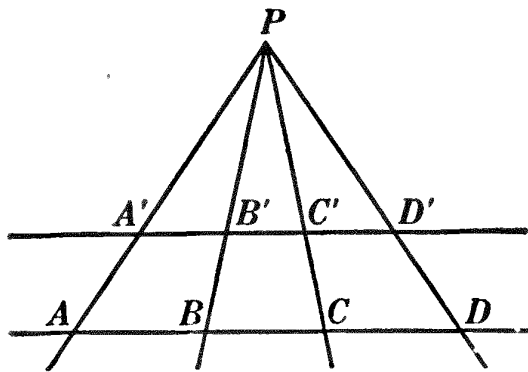
To prove $\frac{AH}{DK} = \frac{AB}{DE} = \frac{BC}{EF} = \frac{CA}{FD}$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. In rt. $\triangle ABH$ and DEK , $\angle B = \angle E$. | 1. § 424, 1. |
| 2. $\therefore \triangle ABH \sim \triangle DEK$. | 2. § 422. |
| 3. $\therefore \frac{AH, \text{opposite } \angle B}{DK, \text{opposite } \angle E} = \frac{AB, \text{opposite } \angle BHA}{DE, \text{opposite } \angle EKD}$. | 3. § 424, 2. |
| 4. But $\frac{AB}{DE} = \frac{BC}{EF} = \frac{CA}{FD}$. | 4. § 424, 2. |
| 5. $\therefore \frac{AH}{DK} = \frac{AB}{DE} = \frac{BC}{EF} = \frac{CA}{FD}$. | 5. § 54, 1. |

Q.E.D.

PROPOSITION XXI. THEOREM

436. If three or more straight lines drawn through a common point intersect two parallels, the corresponding segments of the parallels are proportional.



Given lines PA, PB, PC, PD drawn through a common point P and intersecting the \parallel lines AD and $A'D'$ at points A, B, C, D and A', B', C', D' , respectively.

To prove $\frac{AB}{A'B'} = \frac{BC}{B'C'} = \frac{CD}{C'D'}$.

ARGUMENT

REASONS

- | | |
|---|--|
| <p>1. $AD \parallel A'D'$.</p> <p>2. $\therefore \triangle APB \sim \triangle A'PB'$.</p> <p>3. $\therefore \frac{AB}{A'B'} = \frac{PB}{PB'}$.</p> <p>4. Likewise $\triangle BPC \sim \triangle B'PC'$.</p> <p>5. And $\frac{BC}{B'C'} = \frac{PB}{PB'}$.</p> <p>6. $\therefore \frac{AB}{A'B'} = \frac{BC}{B'C'}$.</p> <p>7. Likewise it can be proved that $\frac{BC}{B'C'} = \frac{CD}{C'D'}$.</p> <p>8. $\therefore \frac{AB}{A'B'} = \frac{BC}{B'C'} = \frac{CD}{C'D'}$.</p> | <p>1. By hyp.</p> <p>2. § 423.</p> <p>3. § 424, 2.</p> <p>4. Args. 1-2.</p> <p>5. § 424, 2.</p> <p>6. § 54, 1.</p> <p>7. By steps similar to 1-6.</p> <p>8. § 54, 1.</p> |
|---|--|

Q.E.D.

Ex. 691. If three or more non-parallel straight lines intercept proportional segments on two parallels, they pass through a common point.

Ex. 692. A man is riding in an automobile at the uniform rate of 30 miles an hour on one side of a road, while on a footpath on the other side a man is walking in the opposite direction. If the distance between the footpath and the auto track is 44 feet, and a tree 4 feet from the footpath continually hides the chauffeur from the pedestrian, does the pedestrian walk at a uniform rate? If so, at what rate does he walk?

Ex. 693. Two sides of a triangle are 8 and 11, and the altitude upon the third side is 6. A similar triangle has the side homologous to 8 equal to 12. Compute as many parts of the second triangle as you can.

Ex. 694. In two similar triangles, any two homologous bisectors are in the same ratio as any two homologous sides.

Ex. 695. In two similar triangles, any two homologous medians are in the same ratio as any two homologous sides.

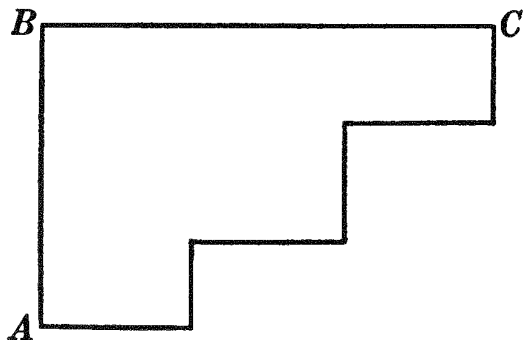
437. Drawing to Scale. Measure the top of your desk. Make a drawing on paper in which each line is $\frac{1}{12}$ as long as the corresponding line of your desk. Check your work by measuring the diagonal of your drawing, and the corresponding line of your desk. This is called **drawing to scale**. Map drawing is a common illustration of this principle. The *scale* of the drawing may be represented: (1) by saying, "Scale, $\frac{1}{12}$ " or "Scale, 1 inch to 12 inches"; (2) by actually drawing the scale as indicated.



Ex. 696. Using the scale above, draw lines on paper to represent 24 inches; 3 feet 3 inches.

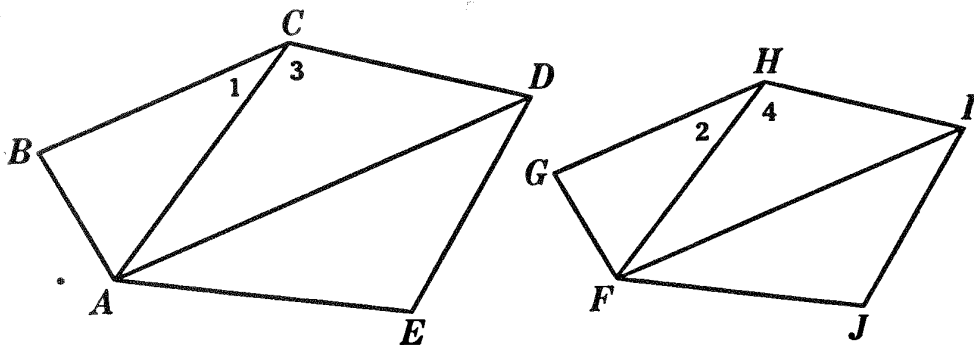
Ex. 697. On the black-board draw, to the scale above, a circle whose diameter is 28 feet.

Ex. 698. The figure represents a farm drawn to the scale indicated. Find the cost of putting a fence around the farm, if the fencing costs \$2.50 per rod.



PROPOSITION XXII. THEOREM

438. *If two polygons are composed of the same number of triangles, similar each to each and similarly placed, the polygons are similar.*



Given polygons $ABCDE$ and $FGHIJ$ with $\triangle ABC \sim \triangle FGH$, $\triangle ACD \sim \triangle FHI$, $\triangle ADE \sim \triangle FIJ$.

To prove polygon $ABCDE \sim$ polygon $FGHIJ$.

ARGUMENT

REASONS

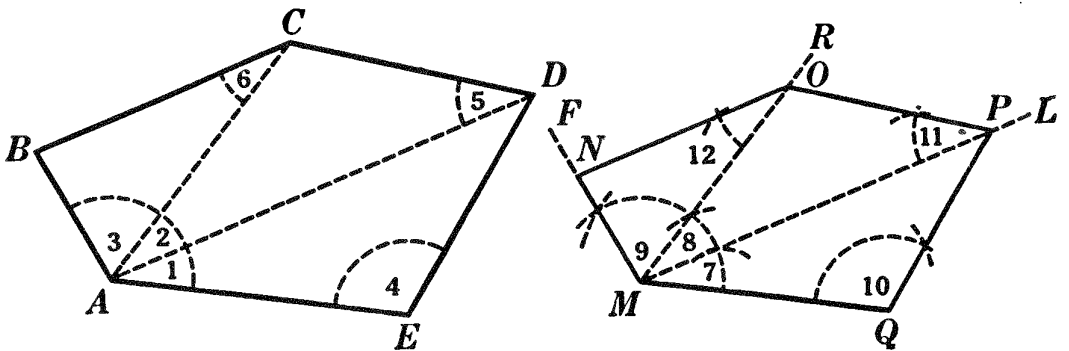
- | | |
|--|--|
| <p>1. In $\triangle ABC$ and FGH, $\angle B = \angle G$.</p> <p>2. Also $\angle 1 = \angle 2$.</p> <p>3. In $\triangle ACD$ and FHI, $\angle 3 = \angle 4$.</p> <p>4. $\therefore \angle 1 + \angle 3 = \angle 2 + \angle 4$.</p> <p>5. $\therefore \angle BCD = \angle GHI$.</p> <p>6. Likewise $\angle CDE = \angle HIJ$, $\angle E = \angle J$, and $\angle EAB = \angle JFG$.</p> <p>7. \therefore polygons $ABCDE$ and $FGHIJ$ are mutually equiangular.</p> <p>8. In $\triangle ABC$ and FGH, $\frac{AB}{FG} = \frac{BC}{GH} = \frac{CA}{HF}$.</p> <p>9. In $\triangle ACD$ and FHI, $\frac{CA}{HF} = \frac{CD}{HI} = \frac{DA}{IF}$.</p> <p>10. And in $\triangle ADE$ and FIJ, $\frac{DA}{IF} = \frac{DE}{IJ} = \frac{EA}{JF}$.</p> <p>11. $\therefore \frac{AB}{FG} = \frac{BC}{GH} = \frac{CD}{HI} = \frac{DE}{IJ} = \frac{EA}{JF}$.</p> <p>12. \therefore polygon $ABCDE \sim$ polygon $FGHIJ$.</p> | <p>1. § 424, 1.</p> <p>2. § 424, 1.</p> <p>3. § 424, 1.</p> <p>4. § 54, 2.</p> <p>5. § 309.</p> <p>6. By steps similar to 1-5.</p> <p>7. By proof.</p> <p>8. § 424, 2.</p> <p>9. § 424, 2.</p> <p>10. § 424, 2.</p> <p>11. § 54, 1.</p> <p>12. § 419</p> |
|--|--|

Q.E.D.

439. Cor. *Any two similar polygons may be divided into the same number of triangles similar each to each and similarly placed.*

PROPOSITION XXIII. PROBLEM

440. *Upon a line homologous to a side of a given polygon, to construct a polygon similar to the given polygon.*



Given polygon AD and line MQ homol. to side AE .

To construct, on MQ , a polygon \sim polygon AD .

I. Construction

1. Draw all possible diagonals from A , as AC and AD .
2. At M , beginning with MQ as a side, construct $\sphericalangle 7, 8,$ and 9 equal respectively to $\sphericalangle 1, 2,$ and 3 . § 125.
3. At Q , with MQ as a side, construct $\sphericalangle 10$ equal to $\sphericalangle 4$, and prolong side QP until it meets ML at P . § 125.
4. At P , with PM as a side, construct $\sphericalangle 11$ equal to $\sphericalangle 5$, and prolong side PO until it meets MR at O . § 125.
5. At O , with OM as a side, construct $\sphericalangle 12$ equal to $\sphericalangle 6$, and prolong side ON until it meets MF at N . § 125.
6. MP is the polygon required.

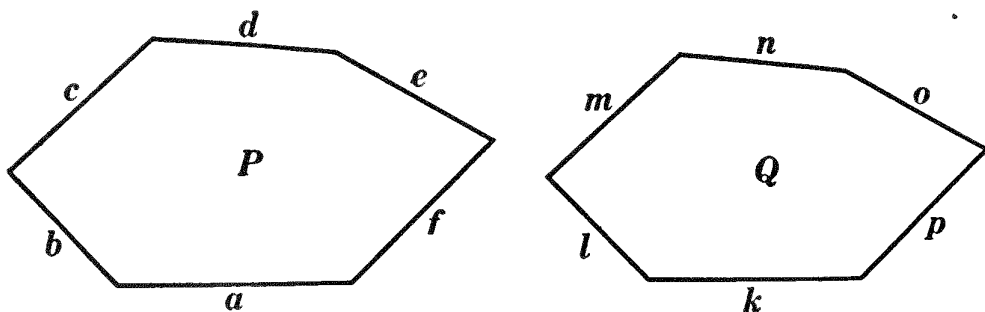
II. Proof

| ARGUMENT | REASONS |
|---|------------------|
| 1. $\triangle ADE \sim \triangle MPQ, \triangle ACD \sim \triangle MOP,$ and $\triangle ABC \sim \triangle MNO.$ | 1. § 421. |
| 2. \therefore polygon $MP \sim$ polygon $AD.$ | q.e.d. 2. § 438. |

III. The discussion is left as an exercise for the student.

PROPOSITION XXIV. THEOREM

441. *The perimeters of two similar polygons are to each other as any two homologous sides.*



Given \sim polygons P and Q , with sides $a, b, c, d, e,$ and f homol. respectively to sides $k, l, m, n, o,$ and p .

To prove $\frac{\text{perimeter of } P}{\text{perimeter of } Q} = \frac{a}{k}$.

| ARGUMENT | REASONS |
|--|-----------|
| 1. $\frac{a}{k} = \frac{b}{l} = \frac{c}{m} = \frac{d}{n} = \frac{e}{o} = \frac{f}{p}$ | 1. § 419. |
| 2. $\therefore \frac{a + b + c + d + e + f}{k + l + m + n + o + p} = \frac{a}{k}$ | 2. § 401. |
| 3. That is, $\frac{\text{perimeter of } P}{\text{perimeter of } Q} = \frac{a}{k}$ | 3. § 309. |

Q.E.D.

Ex. 699. The perimeters of two similar polygons are 152 and 138; a side of the first is 8. Find the homologous side of the second.

Ex. 700. The perimeters of two similar polygons are to each other as any two homologous diagonals.

Ex. 701. The perimeters of two similar triangles are to each other as any two homologous medians.

Ex. 702. If perpendiculars are drawn to the hypotenuse of a right triangle at its extremities, and if the other two sides of the triangle are prolonged to meet these perpendiculars, the figure thus formed contains five triangles each of which is similar to any one of the others.

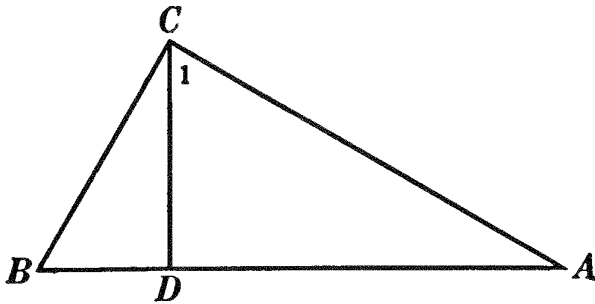
PROPOSITION XXV. THEOREM

442. *In a right triangle, if the altitude upon the hypotenuse is drawn:*

I. *The triangles thus formed are similar to the given triangle and to each other.*

II. *The altitude is a mean proportional between the segments of the hypotenuse.*

III. *Either side is a mean proportional between the whole hypotenuse and the segment of the hypotenuse adjacent to that side.*



Given rt. $\triangle ABC$ and the altitude CD upon the hypotenuse.

To prove:

I. $\triangle BCD \sim \triangle ABC$, $\triangle ADC \sim \triangle ABC$, and $\triangle BCD \sim \triangle ADC$.

II. $BD : CD = CD : DA$.

III. $AB : BC = BC : DB$ and $AB : AC = AC : AD$.

| I. | ARGUMENT | REASONS |
|----|--|--------------|
| 1. | In rt. $\triangle BCD$ and ABC , $\angle B = \angle B$. | 1. By iden. |
| 2. | $\therefore \triangle BCD \sim \triangle ABC$. | 2. § 422. |
| 3. | In rt. $\triangle ADC$ and ABC , $\angle A = \angle A$. | 3. By iden. |
| 4. | $\therefore \triangle ADC \sim \triangle ABC$. | 4. § 422. |
| 5. | $\therefore \angle 1 = \angle B$. | 5. § 424, 1. |
| 6. | $\therefore \triangle BCD \sim \triangle ADC$. | 6. § 422. |

Q.E.D.

II. The proof of II is left as an exercise for the student.

HINT. Mark (with colored chalk, if convenient) the lines required in the proportion. Decide which triangles will furnish these lines, and use the fact that homologous sides of similar triangles are proportional.

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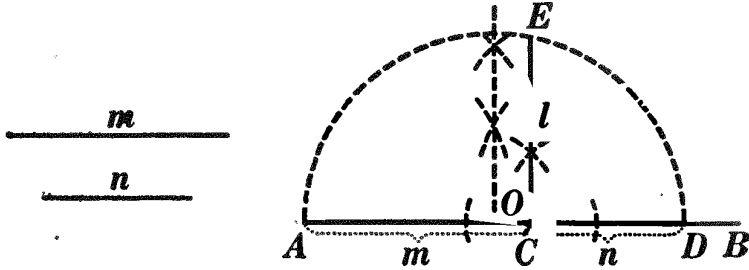
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PROPOSITION XXVI. PROBLEM

445. To construct a mean proportional between two given lines.



Given two lines, m and n .

To construct a line l so that $m : l = l : n$.

I. Construction

1. On any indefinite str. line, as AB , lay off $AC = m$ and $CD = n$.
2. With O , the mid-point of AD , as center and with a radius equal to OD , describe a semicircle.
3. At C construct $CE \perp AD$, meeting the semicircle at E . § 148.
4. CE is the required line l .

II. The proof and discussion are left as an exercise for the student.

Ex. 706. By means of § 444, II, construct a mean proportional between two given lines by a method different from that given in Prop. XXVI.

Ex. 707. Use the method of Prop. XXVI to construct a line equal to $\sqrt{3} ab$, a and b being given lines.

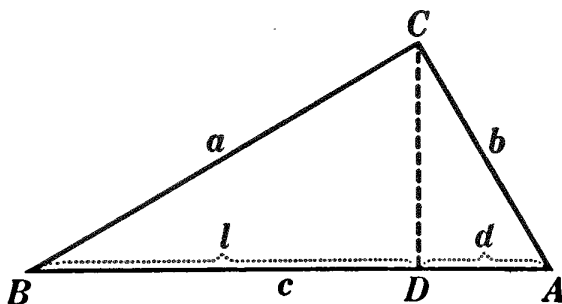
ANALYSIS. Let $x =$ the required line.
 Then $x = \sqrt{3} ab$.
 $\therefore x^2 = 3 ab$.
 $\therefore 3 a : x = x : b$.

Ex. 708. Construct a line equal to $a\sqrt{3}$, where a is a given line.

Ex. 709. Using a line one inch long as a unit, construct a line equal to $\sqrt{3}$; $\sqrt{5}$; $\sqrt{6}$. Choosing your own unit, construct a line equal to $3\sqrt{2}$, $2\sqrt{3}$, $5\sqrt{5}$.

PROPOSITION XXVII. THEOREM

445. *In any right triangle the square of the hypotenuse is equal to the sum of the squares of the other two sides.*



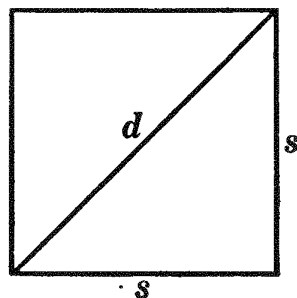
Given rt. $\triangle ABC$, with its rt. \angle at C .

To prove $a^2 + b^2 = c^2$.

| ARGUMENT | REASONS |
|---|---------------|
| 1. From C draw $CD \perp AB$ forming segments l and d . | 1. § 155. |
| 2. $a^2 = c \cdot l$. | 2. § 443, II. |
| 3. $b^2 = c \cdot d$. | 3. § 443, II. |
| 4. $\therefore a^2 + b^2 = c(l + d)$. | 4. § 54, 2. |
| 5. $\therefore a^2 + b^2 = c \cdot c = c^2$. Q.E.D. | 5. § 309. |

447. Cor. I. *The square of either side of a right triangle is equal to the square of the hypotenuse minus the square of the other side.*

448. Cor. II. *The diagonal of a square is equal to its side multiplied by the square root of two.*



OUTLINE OF PROOF

1. $d^2 = s^2 + s^2 = 2s^2$.

2. $\therefore d = s\sqrt{2}$.

Q.E.D.

449. Historical Note. The property of the right triangle stated in Prop. XXVII was known at a very early date, the ancient Egyptians, 2000 B.C., having made a right triangle by stretching around three pegs a cord measured off into 3, 4, and 5 units. See Note, Book IV, § 510.

Ex. 710. By means of § 448, construct a line equal to $\sqrt{2}$ inches.

Ex. 711. If a side of a square is 6 inches, find its diagonal.

Ex. 712. The hypotenuse of a right triangle is 15 and one arm is 9. Find the other arm and the segments of the hypotenuse made by the perpendicular from the vertex of the right angle.

Ex. 713. Find the altitude of an equilateral triangle whose side is 6 inches.

Ex. 714. Find a side of an equilateral triangle whose altitude is 8 inches.

Ex. 715. Divide a line into segments which shall be in the ratio of 1 to $\sqrt{2}$.

Ex. 716. The radius of a circle is 10 inches. Find the length of a chord 6 inches from the center ; 4 inches from the center.

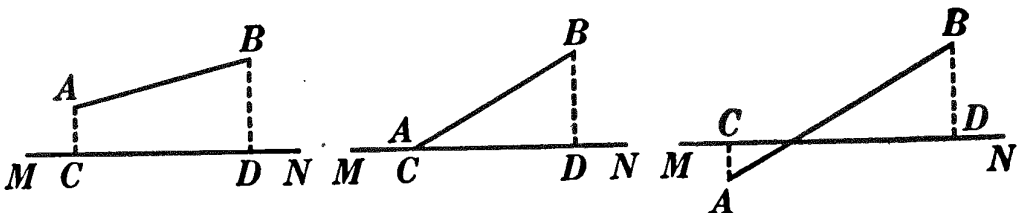
Ex. 717. The radius of a circle is 20 inches. How far from the center is a chord whose length is 32 inches ? whose length is 28 inches ?

Ex. 718. In a circle a chord 24 inches long is 5 inches from the center. How far from the center is a chord whose length is 12 inches ?

450. Def. The projection of a point upon a line is the foot of the perpendicular from the point to the line.

451. Def. The projection of a line segment upon a line is the segment of the second line included between the projections of the extremities of the first line upon the second.

Thus, C is the projection of A upon MN , D is the projection of B upon MN , and CD is the projection of AB upon MN .



Ex. 719. In the figures above, under what condition will the projection of AB on MN be a maximum ? a minimum ? Will the projection CD ever be equal to AB ? greater than AB ? Will the projection ever be a point ?

Ex. 720. In a right isosceles triangle the hypotenuse of which is 10 inches, find the length of the projection of either arm upon the hypotenuse.

Ex. 721. Find the projection of one side of an equilateral triangle upon another if each side is 6 inches.

Ex. 722. Draw the projections of the shortest side of a triangle upon each of the other sides: (1) in an acute triangle; (2) in a right triangle; (3) in an obtuse triangle. Draw the projections of the longest side in each case.

Ex. 723. Two sides of a triangle are 8 and 12 inches and their included angle is 60° . Find the projection of the shorter upon the longer.

Ex. 724. In Ex. 723, find the projection of the shorter side upon the longer if the included angle is 30° ; 45° .

Ex. 725. Parallel lines that have equal projections on the same line are equal.

PROPOSITION XXVIII. PROBLEM

452. *In any triangle to find the value of the square of the side opposite an acute angle in terms of the other two sides and of the projection of either of these sides upon the other.*

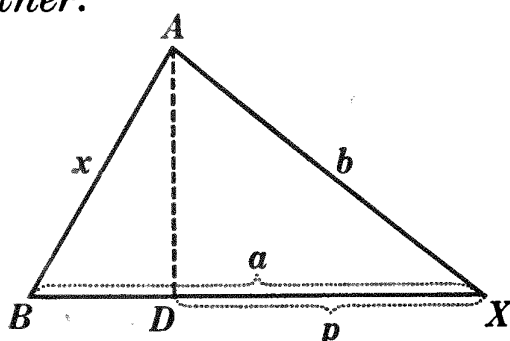


FIG. 1.

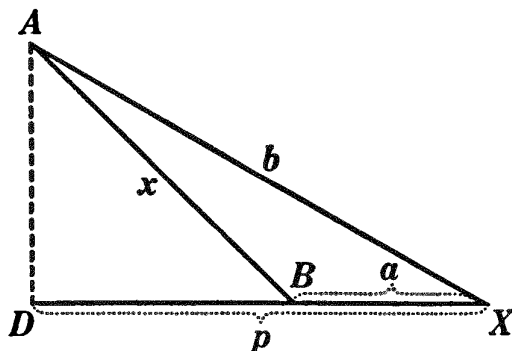


FIG. 2.

Given $\triangle BAX$, with $\angle X$ acute; and p , the projection of b upon a .

To find the value of x^2 in terms of a , b , and p .

ARGUMENT

1. In rt. $\triangle BAD$, $x^2 = \overline{AD}^2 + \overline{DB}^2$.
2. But $\overline{AD}^2 = b^2 - p^2$.
3. And $DB = a - p$ (Fig. 1) or $p - a$ (Fig. 2).
4. $\therefore DB^2 = a^2 - 2ap + p^2$.
5. $\therefore x^2 = b^2 - p^2 + a^2 - 2ap + p^2$;
i.e. $x^2 = a^2 + b^2 - 2ap$. Q.E.F.

REASONS

1. § 446.
2. § 447.
3. § 54, 11.
4. § 54, 13.
5. § 309.

453. Question. Why is it not necessary to include here the figure and discussion for a right triangle?

454. Prop. XXVIII may be stated in the form of a theorem as follows:

In any triangle, the square of the side opposite an acute-angle is equal to the sum of the squares of the other two sides diminished by twice the product of one of these sides and the projection of the other side upon it.

Ex. 726. If the sides of a triangle are 7, 8, and 10, is the angle opposite 10 obtuse, right, or acute? Why?

Ex. 727. Apply the statement of Prop. XXVIII to the square of an arm of a right triangle.

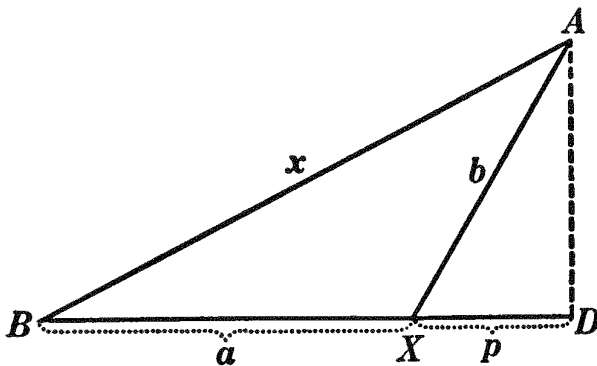
Ex. 728. Find x (in the figure for Prop. XXVIII) in terms of a and b and the projection of a upon b .

Ex. 729. If the sides of a triangle are 13, 14, and 15, find the projection of the first side upon the second.

Ex. 730. If two sides of a triangle are 4 and 12 and the projection of the first side upon the second is 2, find the third side of the triangle.

PROPOSITION XXIX. THEOREM

455. *In any obtuse triangle, the square of the side opposite the obtuse angle is equal to the sum of the squares of the other two sides increased by twice the product of one of these sides and the projection of the other side upon it.*



Given $\triangle BAX$ with $\angle X$ obtuse, and p , the projection of b upon a .

To prove $x^2 = a^2 + b^2 + 2ap$

| ARGUMENT | REASONS |
|--|--------------|
| 1. In rt. $\triangle BAD$, $x^2 = \overline{AD}^2 + \overline{DB}^2$. | 1. § 446. |
| 2. But $\overline{AD}^2 = b^2 - p^2$. | 2. § 447. |
| 3. And $DB = a + p$. | 3. § 54, 11. |
| 4. $\therefore DB^2 = a^2 + 2ap + p^2$. | 4. § 54, 13. |
| 5. $\therefore x^2 = b^2 - p^2 + a^2 + 2ap + p^2$; | 5. § 309. |
| i.e. $x^2 = a^2 + b^2 + 2ap$. Q.E.D. | |

456. From Props. XXVIII and XXIX, we may derive the following formulas for computing the projection of one side of a triangle upon another; thus if a , b , and c represent the sides of a triangle:

$$\text{From Prop. XXVIII, } p = \frac{a^2 + b^2 - c^2}{2a}. \tag{1}$$

$$\text{From Prop. XXIX, } -p = \frac{a^2 + b^2 - c^2}{2a}. \tag{2}$$

It is seen that the second members of these two equations are identical and that the first members differ only in sign. Hence, formula (1) may always be used for computing the length of a projection. It need only be remembered that if p is positive in any calculation, it indicates that the angle opposite c is acute; while if p is negative, the angle opposite c is obtuse. It can likewise be shown (see Prop. XXVII) that if $p = 0$, the angle opposite c is a right angle.

Ex. 731. Write the formula for the projection of a upon b .

Ex. 732. In triangle ABC , $a = 15$, $b = 20$, $c = 25$; find the projection of b upon c . Is angle A acute, right, or obtuse?

Ex. 733. In the triangle of Ex. 732, find the projection of a upon b . Is angle C acute, right, or obtuse?

Ex. 734. The sides of a triangle are 8, 14, and 20. Is the angle opposite the side 20 acute, right, or obtuse?

Ex. 735. If two sides of a triangle are 10 and 12, and their included angle is 120° , what is the value of the third side?

Ex. 736. If two sides of a triangle are 12 and 16, and their included angle is 45° , find the third side.

Ex. 737. If in triangle ABC , angle $C = 120^\circ$, prove that

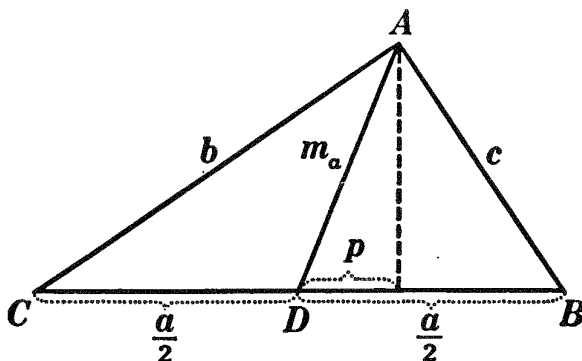
$$\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2 + AC \cdot BC.$$

Ex. 738. If a line is drawn from the vertex C of an isosceles triangle ABC , meeting base AB prolonged at D , prove that

$$\overline{CD}^2 - \overline{CB}^2 = AD \cdot BD.$$

PROPOSITION XXX. THEOREM

457. *In any triangle, the sum of the squares of any two sides is equal to twice the square of half the third side increased by twice the square of the median upon that side.*



Given $\triangle ABC$ with m_a , the median to side a .

To prove $b^2 + c^2 = 2\left(\frac{a}{2}\right)^2 + 2m_a^2$.

| ARGUMENT | REASONS |
|--|-------------|
| 1. Suppose $b > c$; then $\angle ADC$ is obtuse and $\angle BDA$ is acute. | 1. § 173. |
| 2. Let p be the projection of m_a upon a . | 2. § 451. |
| 3. Then from $\triangle ADC$, | 3. § 455. |
| $b^2 = \left(\frac{a}{2}\right)^2 + m_a^2 + 2\left(\frac{a}{2}\right)p.$ | |
| 4. And from $\triangle ABD$, | 4. § 454. |
| $c^2 = \left(\frac{a}{2}\right)^2 + m_a^2 - 2\left(\frac{a}{2}\right)p.$ | |
| 5. $\therefore b^2 + c^2 = 2\left(\frac{a}{2}\right)^2 + 2m_a^2$. Q.E.D. | 5. § 54, 2. |

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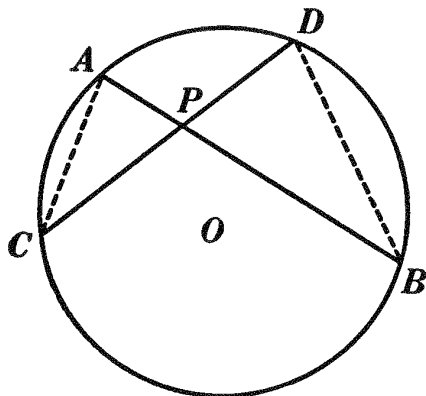
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PROPOSITION XXXI. THEOREM

460. *If through a point within a circle two chords are drawn, the product of the two segments of one of these chords is equal to the product of the two segments of the other.*



Given P , a point within circle O , and AB and CD , any two chords drawn through P .

To prove $PA \cdot PB = PC \cdot PD$.

The proof is left as an exercise for the student.

HINT. Prove $\triangle APC \sim \triangle PDB$.

Ex. 751. In the figure for Prop. XXXI, if $PA = 5$, $PB = 12$, and $PD = 6$, find PC .

Ex. 752. In the same figure, if $PC = 10$, $PD = 8$, and $AB = 21$, find PA and PB .

Ex. 753. In the same figure, if $PC = 6$, $DC = 22$, and $AB = 20$, find AP and PB .

Ex. 754. In the same figure, if $PA = m$, $PC = n$, and $PD = r$, find PB .

Ex. 755. If two chords intersecting within a circle are of lengths 8 and 10, and the second bisects the first, what are the segments of the second?

Ex. 756. By means of Prop. XXXI construct a mean proportional between two given lines.

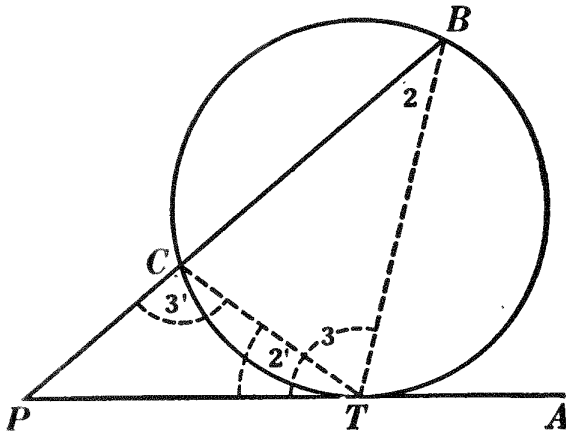
Ex. 757. If two chords intersect within a circle and the segments of one chord are a and b inches, while the second chord measures d inches, construct the segments of the second chord.

HINT. Find the locus of the mid-points of chords equal to d .

Ex. 758. If two lines AB and CD intersect at E so that $AE \cdot EB = CE \cdot ED$, then a circumference can be passed through the four points A, B, C, D .

PROPOSITION XXXII. THEOREM

461. If a tangent and a secant are drawn from any given point to a circle, the tangent is a mean proportional between the whole secant and its external segment.



Given tangent PT and secant PB drawn from the point P to the circle O .

To prove $\frac{PB}{PT} = \frac{PT}{PC}$.

ARGUMENT

1. Draw CT and BT .
2. In $\triangle PBT$ and CTP , $\angle P = \angle P$.
3. $\angle 2 = \angle 2'$.
4. $\therefore \triangle PBT \sim \triangle CTP$.
5. $\therefore \frac{PB, \text{ opposite } \angle 3 \text{ in } \triangle PBT}{PT, \text{ opposite } \angle 3' \text{ in } \triangle CTP} = \frac{PT, \text{ opposite } \angle 2 \text{ in } \triangle PBT}{PC, \text{ opposite } \angle 2' \text{ in } \triangle CTP}$.

REASONS

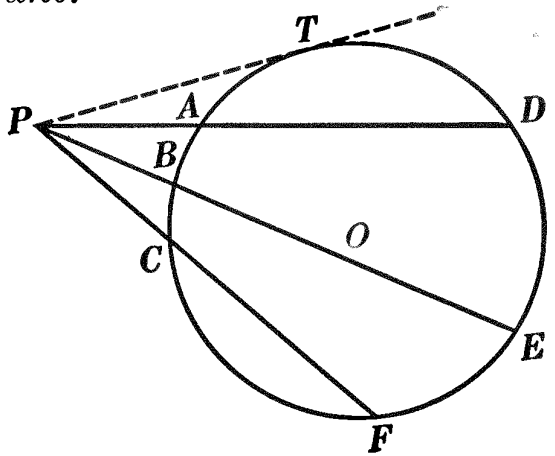
1. § 54, 15.
2. By iden.
3. § 362, a.
4. § 421.
5. § 424, 2.

Q.E.D.

462. Cor. I. If a tangent and a secant are drawn from any given point to a circle, the square of the tangent is equal to the product of the whole secant and its external segment.

463. Cor. II *If two or more secants are drawn from any given point to a circle, the product of any secant and its external segment is constant.*

Given secants PD , PE , PF , drawn from point P to circle O , and let their external segments be denoted by PA , PB , PC , respectively.



To prove

$$PD \cdot PA = PE \cdot PB = PF \cdot PC.$$

ARGUMENT

1. From P draw a tangent to circle O , as PT .
2. $\overline{PT}^2 = PD \cdot PA$; $\overline{PT}^2 = PE \cdot PB$; $\overline{PT}^2 = PF \cdot PC$.
3. $\therefore PD \cdot PA = PE \cdot PB = PF \cdot PC$. Q.E.D.

REASONS

1. § 286.
2. § 462.
3. § 54, 1.

Ex. 759. If a tangent and a secant drawn from the same point to a circle measure 6 and 18 inches, respectively, how long is the external segment of the secant?


Ex. 760. Two secants are drawn to a circle from an outside point. If their external segments are 12 and 9, and the internal segment of the first secant is 8, what is the length of the second secant?

Ex. 761. The tangents to two intersecting circles from any point in their common chord (prolonged) are equal.

Ex. 762. If two circumferences intersect, their common chord (prolonged) bisects their common tangents.

464. Def. A line is said to be divided in **extreme and mean ratio** if it is divided into two parts such that one part is a mean proportional between the whole line and the other part.

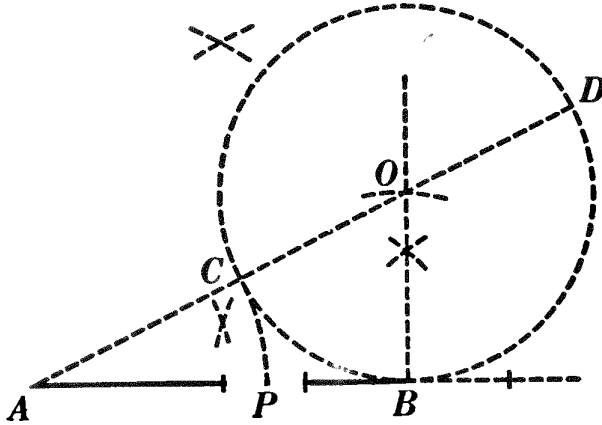
Thus, AB is divided in extreme

and mean ratio at P if $AB : AP =$ 

$AP : PB$. This division is known as the **golden section**.

PROPOSITION XXXIII. PROBLEM

465. To divide a line internally in extreme and mean ratio.



Given line AB .

To find, in AB , a point P such that $AB : AP = AP : PB$.

I. Construction

1. From B draw $BO \perp AB$ and $BO = \frac{1}{2} AB$. § 148.
2. With O as center and with BO as radius describe a circumference.
3. From A draw a secant through O , cutting the circumference at C and D .
4. With A as center and with AC as radius draw \widehat{CP} , cutting AB at P .
5. $AB : AP = AP : PB$.

II. Proof

| ARGUMENT | REASONS |
|---|-----------|
| 1. AB is tangent to circle O . | 1. § 314. |
| 2. $\therefore AD : AB = AB : AC$. | 2. § 461. |
| 3. $\therefore AD - AB : AB = AB - AC : AC$. | 3. § 399. |
| 4. $\therefore AD - CD : AB = AB - AP : AP$. | 4. § 309. |
| 5. $\therefore AP : AB = PB : AP$. | 5. § 309. |
| 6. $\therefore AB : AP = AP : PB$. | 6. § 395. |

Q.E.D.

III. The discussion is left as an exercise for the student.

Ex. 763. Divide a line AB externally in extreme and mean ratio.

HINT. In the figure for Prop. XXXIII prolong BA to P' , making $P'A = AD$. Then prove $AB : P'A = P'A : P'B$.

Ex. 764. If the line l is divided internally in extreme and mean ratio, and if s is the greater segment, find the value of s in terms of l .

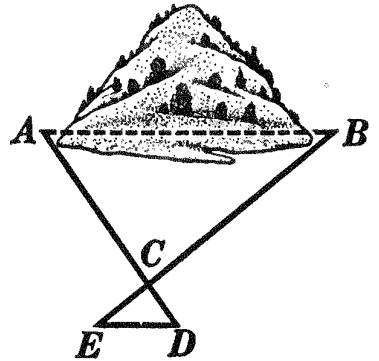
HINT. $l : s = s : l - s$.

Ex. 765. A line 10 inches long is divided internally in extreme and mean ratio. Find the lengths of the two segments.

Ex. 766. A line 8 inches long is divided externally in extreme and mean ratio. Find the length of the longer segment.

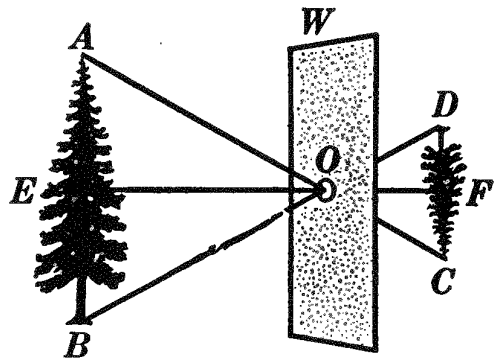
MISCELLANEOUS EXERCISES

Ex. 767. Explain how the accompanying figure can be used to find the distance from A to B on opposite sides of a hill. $CE = \frac{1}{4}BC$, $CD = \frac{1}{4}AC$. ED is found by measurement to be 125 feet. What is the distance AB ?



Ex. 768. A little boy wished to obtain the height of a tree in his yard. He set up a vertical pole 6 feet high and watched until the shadow of the pole measured exactly 6 feet. He then measured quickly the length of the tree's shadow and called this the height of the tree. Was his answer correct? Draw figures and explain. Use this method for measuring the height of your school building and flag pole.

Ex. 769. If light from a tree, as AB , is allowed to pass through a small aperture O , in a window shutter W , and strike a white screen or wall, an inverted image of the tree, as CD , is formed on the screen. If the distance $OE = 30$ feet, $OF = 8$ feet, and the length of the tree $AB = 35$ feet, find the length of the image CD . Under



what condition will the length of the image equal the length of the tree?

This exercise illustrates the principle of the photographer's camera.

Ex. 770. By means of Prop. XXXII construct a mean proportional between two given lines.

Ex. 771. In a certain circle a chord $5\sqrt{5}$ inches from the center is 20 inches in length. Find the length of a chord 9 inches from the center.

Ex. 772. Compute the length of : (1) the common external tangent, (2) the common internal tangent, to two circles whose radii are 8 and 6, respectively, and the distance between whose centers is 20.

Ex. 773. If the hypotenuse of an isosceles right triangle is 16 inches, what is the length of each arm ?

Ex. 774. If from a point a tangent and a secant are drawn and the segments of the secant are 4 and 12, how long is the tangent ?

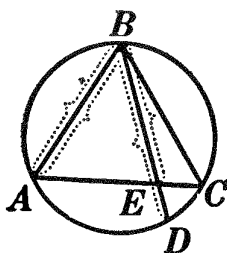
Ex. 775. Given the equation $\frac{m+n}{x+c} = \frac{2m}{c}$; solve for x .

Ex. 776. Find a mean proportional between $a^2 + 2ab + b^2$ and $a^2 - 2ab + b^2$.

Ex. 777. The mean proportional between two unequal lines is less than half their sum.

Ex. 778. The diagonals of a trapezoid divide each other into segments which are proportional.

Ex. 779. ABC is an isosceles triangle inscribed in a circle. Chord BD is drawn from the vertex B , cutting the base in any point, as E . Prove $BD : AB - AB : BE$.



Ex. 780. In a triangle ABC the side AB is 305 feet. If a line parallel to BC divides AC in the ratio of 2 to 3, what are the lengths of the segments into which it divides AB ?

Ex. 781. Construct, in one figure, four lines whose lengths shall be that of a given unit multiplied by $\sqrt{2}$, $\sqrt{3}$, 2, $\sqrt{5}$, respectively.

Ex. 782. Two sides of a triangle are 12 and 18 inches, and the perpendicular upon the first from the opposite vertex is 9 inches. What is the length of the altitude upon the second side ?

Ex. 783. If $a : b = c : d$, show that

$$\left(a + \frac{l}{m} a\right) : \left(b + \frac{l}{m} b\right) = \left(c + \frac{p}{q} c\right) : \left(d + \frac{p}{q} d\right).$$

Also translate this fact into a verbal statement.

Ex. 784. If a constant is added to or subtracted from each term of a proportion, will the resulting numbers be in proportion? Give proof.

Ex. 785. If $r : s = t : q$, is $3r + \frac{r}{2} : s = 7t : 2q$? Prove your answer.

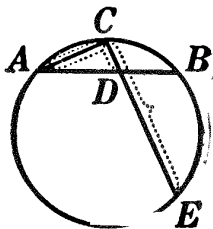
Ex. 786. One segment of a chord drawn through a point 7 units from the center of a circle is 4 units long. If the diameter of the circle is 15 units, what is the length of the other segment ?

Ex. 787. The non-parallel sides of a trapezoid and the line joining the mid-points of the parallel sides, if prolonged, are concurrent.

Ex. 788. Construct a circle which shall pass through two given points and be tangent to a given straight line.

Ex. 789. The sides of a triangle are 10, 12, 15. Compute the lengths of the two segments into which the least side is divided by the bisector of the opposite angle.

Ex. 790. AB is a chord of a circle, and CE is any chord drawn through the middle point C of arc AB , cutting chord AB at D . Prove $CE : CA = CA : CD$.



Ex. 791. Construct a right triangle, given its perimeter and an acute angle.

Ex. 792. The base of an isosceles triangle is a , and the perpendicular let fall from an extremity of the base to the opposite side is b . Find the lengths of the equal sides.

Ex. 793. AD and BE are two altitudes of triangle CAB . Prove that $AD : BE = CA : BC$.

Ex. 794. If two circles touch each other, their common external tangent is a mean proportional between their diameters.

Ex. 795. If two circles are tangent internally, all chords of the greater circle drawn from the point of contact are divided proportionally by the circumference of the smaller circle.

Ex. 796. If three circles intersect each other, their common chords pass through a common point.

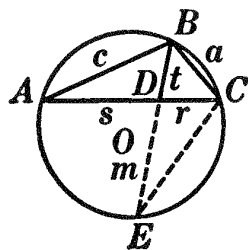
Ex. 797. The square of the bisector of an angle of a triangle is equal to the product of the sides of this angle diminished by the product of the segments of the third side made by the bisector.

Given $\triangle ABC$ with t , the bisector of $\angle B$, dividing side b into the two segments s and r .

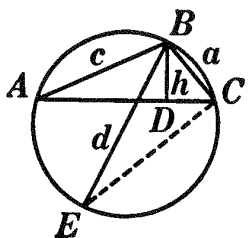
To prove $t^2 = ac - rs$.

OUTLINE OF PROOF

1. Prove that $a : t = t + m : c$.
2. Then $ac = t^2 + tm = t^2 + rs$.
3. $\therefore t^2 = ac - rs$.



Ex. 798. In any triangle the product of two sides is equal to the product of the altitude upon the third side and the diameter of the circumscribed circle.



HINT. Prove $\triangle ABD \sim \triangle EBC$. Then prove $ac = hd$.

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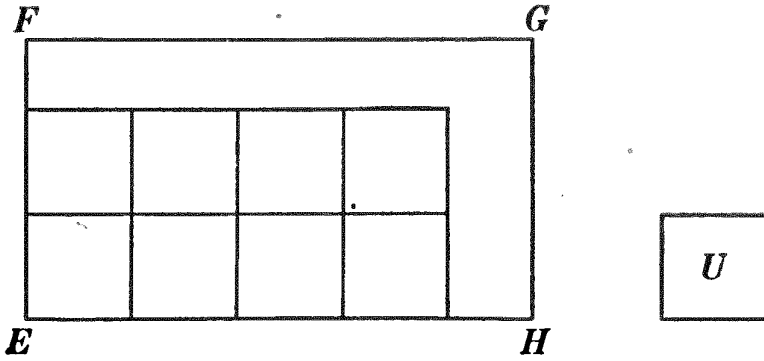


FIG. 2. Rectangle $EG = 8 U+$.

times without a remainder (see Fig. 2), then by taking a square which is an aliquot part of U , as one fourth of U , and applying

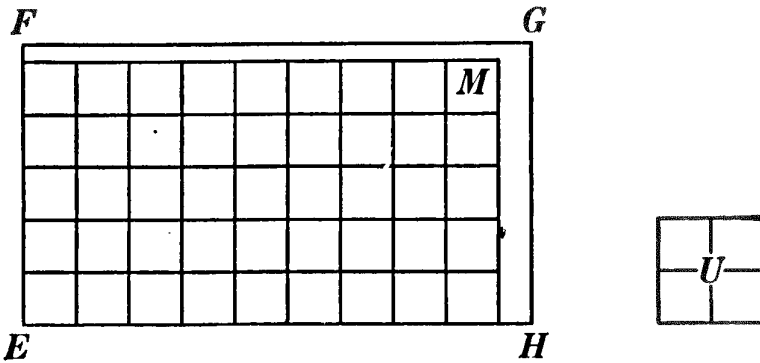


FIG. 3. Rectangle $EG = \frac{4}{5} U+ = 11\frac{1}{5} U+$.

it as a measure to the rectangle (see Fig. 3) a number will be obtained which, divided by four,* will give another (and

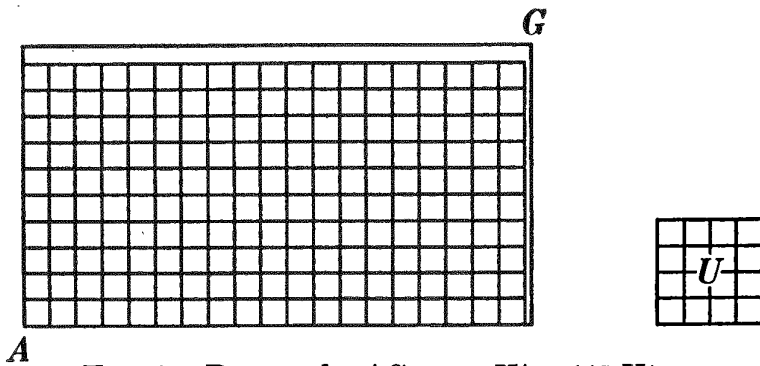


FIG. 4. Rectangle $AG = \frac{1}{8} U+ = 11\frac{1}{8} U+$.

usually closer) approximate area of the given rectangle. By proceeding in this way (see Fig. 4), closer and closer approximations of the true area may be obtained.

* It takes four of the small squares to make the *unit* itself.

469. If the sides of the given rectangle and of the unit square are *commensurable*, a square may be found which is an aliquot part of U , and which is contained in the rectangle also an integral number of times.

470. If the sides of the given rectangle and of the unit square are *incommensurable*, then closer and closer approximations to the area may be obtained, but no square which is an aliquot part of U will be also an aliquot part of the rectangle (by definition of incommensurable magnitudes). There is, however, a definite *limit* which is approached more and more closely by the approximations obtained by using smaller and smaller subdivisions of the unit square, as these subdivisions approach zero as a limit.*

471. Def. The *measure-number*, or *area*, of a rectangle which is incommensurable with the chosen unit square is the *limit* which successive approximate measure-numbers of the rectangle *approach* as the subdivisions of the unit square approach zero as a limit.

For brevity the expression, *the area of a figure*, is used to mean the measure-number of the surface of the figure with respect to a chosen unit.

472. Def. The *ratio* of any two surfaces is the ratio of their measure-numbers (based on the same unit).

473. Def. *Equivalent figures* are figures which have the same area.

The student should note that:

Equal figures have the same *shape* and *size*; such figures can be made to coincide.

Similar figures have the same *shape*.

Equivalent figures have the same *size*.

Ex. 799. Draw two equivalent figures that are not equal.

* For none of these approximations can exceed a certain fixed number, for example $(h+1)(b+1)$, where the measure applied is contained in the altitude h times with a remainder less than the measure, and in the base b times with a remainder less than the

Ex. 800. Draw two equal figures on the blackboard or cut them out of paper, and show that equal figures may be added to them in such a way that the resulting figures are not equal. Are they the same *size*?

Ex. 801. Draw figures to show that axioms 2, 7, and 8, when applied to equal figures, do not give results which satisfy the test for equal figures.

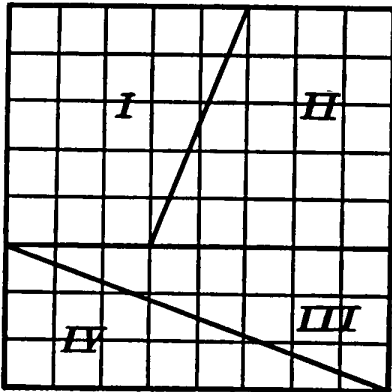


FIG. 1.

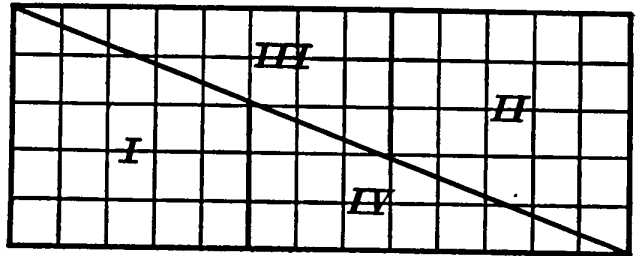


FIG. 2.

Ex. 802. Fig. 1 above represents a card containing 64 small squares, cut into four pieces, I, II, III, and IV. Fig. 2 represents these four pieces placed together in different positions forming, as it would seem, a rectangle containing 65 of these small squares. By your knowledge of similar triangles, try to explain the fallacy in the construction.

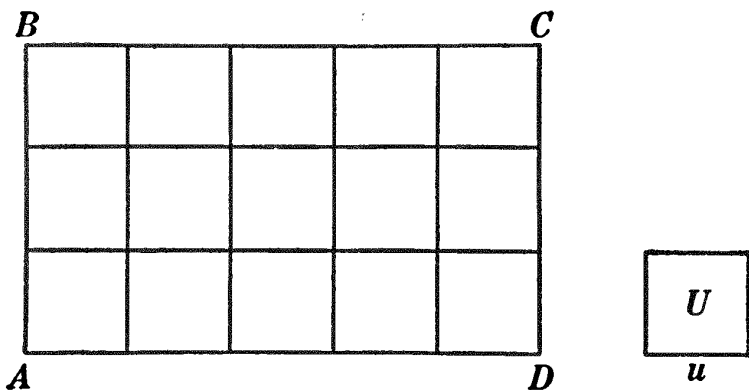
474. Historical Note. Geometry is supposed to have had its origin in land surveying, and the earliest traditions state that it had its beginning in Egypt and Babylon. The records of Babylon were made on clay tablets, and give methods for finding the approximate areas of several rectilinear figures, and also of the circle. The Egyptian records were made on papyrus. Herodotus states that the fact that the inundations of the Nile caused changes in the amount of taxable land, rendered it necessary to devise accurate land measurements.

This work was done by the Egyptian priests, and the earliest manuscript extant is that of Ahmes, who lived about 1700 B.C. This manuscript, known as the Rhind papyrus, is preserved in the British Museum. It is called "Directions for knowing all dark things," and is thought to be a copy of an older manuscript, dating about 3400 B.C. In addition to problems in arithmetic it contains a discussion of areas. Problems on pyramids follow, which show some knowledge of the properties of similar figures and of trigonometry, and which give dimensions, agreeing closely with those of the great pyramids of Egypt.

The geometry of the Egyptians was concrete and practical, unlike that of the Greeks, which was logical and deductive, even from its beginning.

PROPOSITION I. THEOREM

475. *The area of a rectangle is equal to the product of its base and its altitude.* (See § 476.)



Given rectangle $ABCD$, with base AD and altitude AB , and let U be the chosen unit of surface, whose side is u .

To prove the area of $ABCD = AD \cdot AB$.

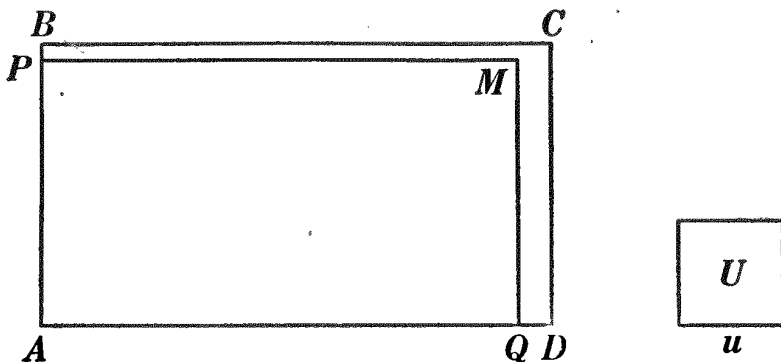
I. If AD and AB are each commensurable with u .

(a) Suppose that u is contained in AD and AB each an integral number of times.

| ARGUMENT | REASONS |
|---|------------|
| 1. Lay off u upon AD and AB , respectively. Suppose that u is contained in AD r times, and in AB s times. | 1. § 335. |
| 2. At the points of division on AD and on AB erect \perp s to AD and AB , respectively. | 2. § 63. |
| 3. Then rectangle $ABCD$ is divided into unit squares. | 3. § 466. |
| 4. There are r of these unit squares in a row on AD , and s rows of these squares in rectangle $ABCD$. | 4. Arg. 1. |
| 5. \therefore the area of $ABCD = r \cdot s$. | 5. § 467. |
| 6. But r and s are the measure-numbers of AD and AB , respectively, referred to the linear unit u . | 6. Arg. 1. |
| 7. \therefore the area of $ABCD = AD \cdot AB$. Q.E.D. | 7. § 309. |

(b) If u is not a measure of AD and AB , respectively, but if some aliquot part of u is such a measure.

The proof is left to the student.



II. If AD and AB are each incommensurable with u .

| ARGUMENT | REASONS |
|--|--------------|
| 1. Let m be a measure of u . Apply m as a measure to AD and AB as many times as possible. There will be a remainder, as QD , on AD , and a remainder, as PB , on AB , each less than m . | 1. § 339. |
| 2. Through Q draw $QM \perp AD$, and through P draw $PM \perp AB$. | 2. § 63. |
| 3. Now AQ and AP are each commensurable with the measure m , and hence commensurable with u . | 3. § 337. |
| 4. \therefore the area of rectangle $APMQ = AQ \cdot AP$. | 4. § 475, I. |
| 5. Now take a smaller measure of u . No matter how small a measure of u is taken, when it is applied as a measure to AD and AB , the remainders, QD and PB , will be smaller than the measure taken. | 5. § 335. |
| 6. \therefore the difference between AQ and AD may be made to become and remain less than any previously assigned segment, however small. | 6. Arg. 5. |

| ARGUMENT | REASONS |
|---|-------------|
| 7. Likewise the difference between AF and AB may be made to become and remain less than any previously assigned segment, however small. | 7. Arg. 5. |
| 8. $\therefore AQ$ approaches AD as a limit, and AP approaches AB as a limit. | 8. § 349. |
| 9. $\therefore AQ \cdot AP$ approaches $AD \cdot AB$ as a limit. | 9. § 477. |
| 10. Again, the difference between $APMQ$ and $ABCD$ may be made to become and remain less than any previously assigned area, however small. | 10. Arg. 5. |
| 11. $\therefore APMQ$ approaches $ABCD$ as a limit. | 11. § 349. |
| 12. But the area of $APMQ$ is always equal to $AQ \cdot AP$. | 12. Arg. 4. |
| 13. \therefore the area of $ABCD = AD \cdot AB$. | 13. § 355. |

Q.E.D.

III. If AD is commensurable with u but AB incommensurable with u . The proof is left as an exercise for the student.

476. Note. By the product of two lines is meant the product of the *measure-numbers* of the lines. The proof that *to every straight line segment there belongs a measure-number* is given in § 595.

477. *If each of any finite number of variables approaches a finite limit, not zero, then the limit of their product is equal to the product of their limits.* (See § 593.)

478. Cor. I. *The area of a square is equal to the square of its side.*

479. Cor. II. *Any two rectangles are to each other as the products of their bases and their altitudes.*

OUTLINE OF PROOF. Denote the two rectangles by R and R' , their bases by b and b' , and their altitudes by h and h' , respectively. Then $R = b \cdot h$ and $R' = b' \cdot h'$. $\therefore \frac{R}{R'} = \frac{b \cdot h}{b' \cdot h'}$.

480. Cor. III. (a) *Two rectangles having equal bases are to each other as their altitudes, and (b) two rectangles having equal altitudes are to each other as their bases.*

OUTLINE OF PROOF

$$(a) \frac{R}{R'} = \frac{b \cdot h}{b' \cdot h'} = \frac{h}{h'}. \quad (b) \frac{R}{R'} = \frac{b \cdot h}{b' \cdot h} = \frac{b}{b'}$$

Ex. 803. Draw a rectangle whose base is 7 units and whose altitude is 4 units and show how many unit squares it contains.

Ex. 804. Find the area of a rectangle whose base is 12 inches and whose altitude is 5 inches.

Ex. 805. Find the area of a rectangle whose diagonal is 10 inches, and one of whose sides is 6 inches.

Ex. 806. If the area of a rectangle is 60 square feet, and the base, 5 inches, what is the altitude?

Ex. 807. If the base and altitude of a rectangle are $2\frac{1}{4}$ inches and $1\frac{1}{4}$ inches, respectively, find the area of the rectangle.

Ex. 808. Find the area of a square whose diagonal is $8\sqrt{2}$ inches.

Ex. 809. Find the successive approximations to the area of a rectangle if its sides are $\sqrt{10}$ and $\sqrt{5}$, respectively, using 3 times 2 for the first approximation, taking the square roots to tenths for the next, to hundredths for the next, etc.

Ex. 810. Compare two rectangles if a diagonal and a side of one are d and s , respectively, while a diagonal and side of the other are d' and s' .

Ex. 811. Construct a rectangle whose area shall be three times that of a given rectangle.

Ex. 812. Construct a rectangle which shall be to a given rectangle in the ratio of two given lines, m and n .

Ex. 813. Compare two rectangles whose altitudes are equal, but whose bases are 15 inches and 3 inches, respectively.

Ex. 814. From a given rectangle cut off a rectangle whose area is two thirds that of the given one.

Ex. 815. If the base and altitude of a certain rectangle are 12 inches and 8 inches, respectively, and the base and altitude of a second rectangle are 6 inches and 4 inches, respectively, compare their areas.

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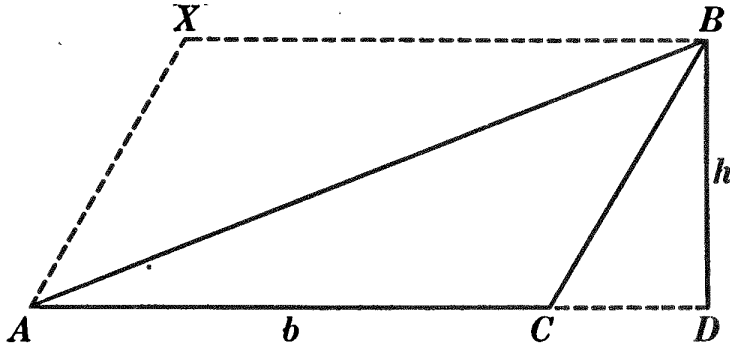
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PROPOSITION III. THEOREM

485. *The area of a triangle equals one half the product of its base and its altitude.*



Given $\triangle ABC$, with base b and altitude h .

To prove area of $\triangle ABC = \frac{1}{2} b \cdot h$.

| ARGUMENT | REASONS |
|---|---------------|
| 1. Through A draw a line $\parallel CB$, and through B draw a line $\parallel CA$. Let these lines intersect at X . | 1. § 179. |
| 2. Then $AXBC$ is a \square . | 2. § 220. |
| 3. $\therefore \triangle ABC = \frac{1}{2} \square AXBC$. | 3. § 236. |
| 4. But area of $AXBC = b \cdot h$. | 4. § 481. |
| 5. \therefore area of $\triangle ABC = \frac{1}{2} b \cdot h$. Q.E.D. | 5. § 54, 8 a. |

486. Cor. I. *Triangles having equal bases and equal altitudes are equivalent.*

487. Cor. II. *Any two triangles are to each other as the products of their bases and their altitudes.*

OUTLINE OF PROOF

Denote the two \triangle by T and T' , their bases by b and b' , and their altitudes by h and h' , respectively. Then $T = \frac{1}{2} b \cdot h$ and $T' = \frac{1}{2} b' \cdot h'$. $\therefore \frac{T}{T'} = \frac{\frac{1}{2} b \cdot h}{\frac{1}{2} b' \cdot h'} = \frac{b \cdot h}{b' \cdot h'}$.

488. Cor. III. (a) *Two triangles having equal bases are to each other as their altitudes, and (b) two triangles having equal altitudes are to each other as their bases.*

OUTLINE OF PROOF

$$(a) \frac{T}{T'} = \frac{b \cdot h}{b' \cdot h'} = \frac{h}{h'}, \quad (b) \frac{T}{T'} = \frac{b \cdot h}{b' \cdot h} = \frac{b}{b'}$$

489. Cor. IV. *A triangle is equivalent to one half of a parallelogram having the same base and altitude.*

Ex. 816. Draw four equivalent parallelograms on the same base.

Ex. 817. Find the area of a parallelogram having two sides 8 inches and 12 inches, respectively, and the included angle 60° . Find the area if the included angle is 45° .

Ex. 818. Find the ratio of two rhombuses whose perimeters are 24 inches and 16 inches, respectively, and whose smaller base angles are 30° .

Ex. 819. Find the area of an equilateral triangle having a side equal to 6 inches.

Ex. 820. Find the area of an equilateral triangle whose altitude is 8 inches.

Ex. 821. Construct three or more equivalent triangles on the same base.

Ex. 822. Find the locus of the vertices of all triangles equivalent to a given triangle and standing on the same base.

Ex. 823. Construct a triangle equivalent to a given triangle and having one of its sides equal to a given line.

Ex. 824. Construct a triangle equivalent to a given triangle and having one of its angles equal to a given angle.

Ex. 825. Construct a triangle equivalent to a given triangle and having two of its sides equal, respectively, to two given lines.

Ex. 826. Divide a triangle into three equivalent triangles by drawing lines through one of its vertices.

Ex. 827. Construct a triangle equivalent to $\frac{2}{3}$ of a given triangle; $\frac{3}{4}$ of a given triangle.

Ex. 828. Construct a triangle equivalent to a given square.

Ex. 829. The area of a rhombus is equal to one half the product of its diagonals.

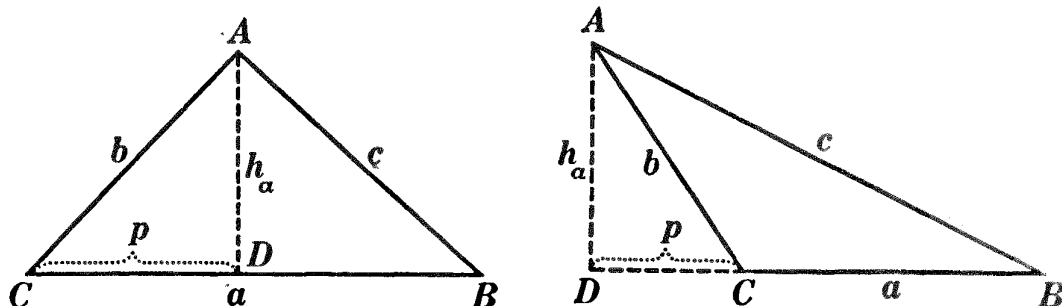
Ex. 830. If from any point in a diagonal of a parallelogram lines are drawn to the opposite vertices, two pairs of equivalent triangles are formed.

Ex. 831. Two lines joining the mid-point of the diagonal of a quadrilateral to the opposite vertices divide the figure into two equivalent parts.

Ex. 832. Find the area of a triangle if two of its sides are 6 inches and 9 inches, respectively, and the included angle is 60° .

PROPOSITION IV. PROBLEM

490. To derive a formula for the area of a triangle in terms of its sides.



Given $\triangle ABC$, with sides a , b , and c .

To derive a formula for the area of $\triangle ABC$ in terms of a , b , and c .

ARGUMENT

1. Let h_a denote the altitude upon a , p the projection of b upon a , and T the area of $\triangle ABC$.

$$\text{Then } T = \frac{1}{2} a h_a = \frac{a}{2} h_a.$$

2. $h_a^2 = b^2 - p^2 = (b + p)(b - p)$.

3. But $p = \frac{a^2 + b^2 - c^2}{2a}$ (Fig. 1), or $-\frac{a^2 + b^2 - c^2}{2a}$

(Fig. 2).

$$\begin{aligned} 4. \therefore h_a^2 &= \left(b + \frac{a^2 + b^2 - c^2}{2a} \right) \left(b - \frac{a^2 + b^2 - c^2}{2a} \right) \\ &= \frac{2ab + a^2 + b^2 - c^2}{2a} \cdot \frac{2ab - a^2 - b^2 + c^2}{2a} \\ &= \frac{(a + b + c)(a + b - c)(c + a - b)(c - a + b)}{4a^2}. \end{aligned}$$

$$5. \dots h_a = \sqrt{\frac{(a + b + c)(a + b - c)(c + a - b)(c - a + b)}{4a^2}}.$$

6. Now let $a + b + c = 2s$.

$$\text{Then } a + b - c = 2s - 2c = 2(s - c);$$

$$a - b + c = 2s - 2b = 2(s - b);$$

$$b + c - a = 2s - 2a = 2(s - a).$$

REASONS

1. § 485.

2. § 447.

3. § 456.

4. § 309.

5. § 54, 13.

6. § 54, 3.

| ARGUMENT | REASONS |
|---|-----------|
| 7. Then $h_a = \sqrt{\frac{2s \cdot 2(s-a) \cdot 2(s-b) \cdot 2(s-c)}{4a^2}}$ $= \frac{2}{a} \sqrt{s(s-a)(s-b)(s-c)}.$ | 7. § 309. |
| 8. $\therefore T = \frac{a}{2} \cdot \frac{2}{a} \sqrt{s(s-a)(s-b)(s-c)}$ $= \sqrt{s(s-a)(s-b)(s-c)}.$ | 8. § 309. |
| Q.E.F. | |

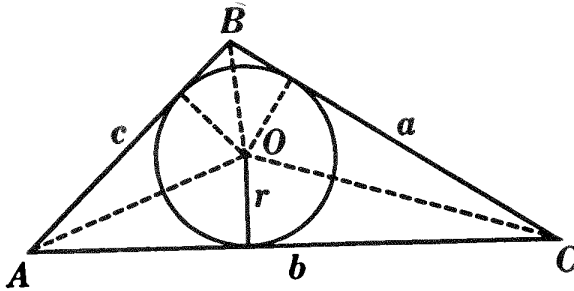
Ex. 833. Find the area of a triangle whose sides are 7, 10, and 13.

Ex. 834. If the sides of a triangle are a , b , and c , write the formula for the altitude upon b ; upon c . (See Prop. IV, Arg. 7.)

Ex. 835. In triangle ABC , $a = 8$, $b = 12$, $c = 16$; find the area of triangle ABC ; the altitude upon b ; the altitude upon c .

PROPOSITION V. THEOREM

491. *The area of a triangle is equal to one half the product of its perimeter and the radius of the inscribed circle.*



Given $\triangle ABC$, with area T , sides a , b , and c , and radius of inscribed circle r .

To prove $T = \frac{1}{2} (a + b + c) r.$

OUTLINE OF PROOF

1. Area of $\triangle OBC = \frac{1}{2} a \cdot r$; area of $\triangle OCA = \frac{1}{2} b \cdot r$; area of $\triangle OAB = \frac{1}{2} c \cdot r.$ 2. $\therefore T = \frac{1}{2} (a + b + c) r.$ Q.E.D.

492. Cor. *The area of any polygon circumscribed about a circle is equal to one half its perimeter multiplied by the radius of the inscribed circle.*

Ex. 836. If the area of a triangle is $15\sqrt{3}$ square inches and its sides are 3, 5, and 7 inches, find the radius of the inscribed circle.

Ex. 837. Derive a formula for the radius of a circle inscribed in a triangle in terms of the sides of the triangle.

OUTLINE OF SOLUTION

$$1. \quad T = \frac{1}{2}(a + b + c)r = \frac{1}{2}(2s)r = sr.$$

$$2. \quad \therefore r = \frac{T}{s} = \frac{\sqrt{s(s-a)(s-b)(s-c)}}{s}.$$

Q. E. F.

Ex. 838. Derive a formula for the radius of a circle circumscribed about a triangle, in terms of the sides of the triangle.

OUTLINE OF SOLUTION (See figure for Ex. 798.)

$$1. \quad dh = ac; \text{ i.e. } d \text{ or } 2R = \frac{ac}{h}.$$

$$2. \quad \therefore R = \frac{ac}{2h} = \frac{abc}{4\sqrt{s(s-a)(s-b)(s-c)}}.$$

Q. E. F.

Ex. 839. If the sides of a triangle are 9, 10, and 11, find the radius of the inscribed circle; the radius of the circumscribed circle.

Ex. 840. The sides of a triangle are $3a$, $4a$, and $5a$. Find the radius of the inscribed circle; the radius of the circumscribed circle. What kind of a triangle is it? Verify your answer by comparing the radius of the circumscribed circle with the longest side.

Ex. 841. Derive formulas for the bisectors of the angles of a triangle in terms of the sides of the triangle.

OUTLINE OF SOLUTION (See figure for Ex. 797.)

$$1. \quad t_b^2 = ac - rs. \quad 2. \quad \text{But } a : c = r : s. \quad 3. \quad \therefore a + c : a = b : r.$$

$$4. \quad \therefore r = \frac{ab}{a+c}. \quad 5. \quad \text{Likewise } s = \frac{bc}{a+c}. \quad 6. \quad \therefore t_b^2 = ac - \frac{ab^2c}{(a+c)^2}$$

$$\frac{ac(a+b+c)(a-b+c)}{(a+c)^2} = \frac{4acs(s-b)}{(a+c)^2}. \quad 7. \quad \therefore t_b = \frac{2}{a+c} \sqrt{acs(s-b)}.$$

$$8. \quad \text{Likewise } t_a = \frac{2}{b+c} \sqrt{bcs(s-a)}, \text{ and } t_c = \frac{2}{a+b} \sqrt{abs(s-c)}. \quad \text{Q. E. F.}$$

Find r , R , T , h_a , m_a , and t_a , having given:

Ex. 842. $a = 11$, $b = 9$, $c = 16$. What kind of an angle is C ?

Ex. 843. $a = 13$, $b = 15$, $c = 20$. What kind of an angle is C ?

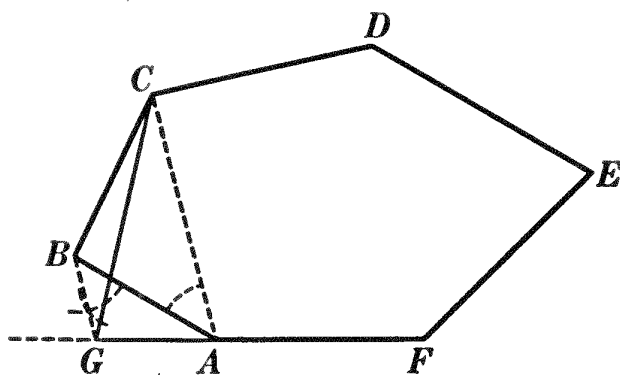
Ex. 844. $a = 24$, $b = 10$, $c = 26$. What kind of an angle is C ?

TRANSFORMATION OF FIGURES

493. Def. To transform a figure means to find another figure which is equivalent to it.

PROPOSITION VI. PROBLEM

494. To construct a triangle equivalent to a given polygon.



Given polygon $ABCDEF$.

To construct a $\triangle \simeq$ polygon $ABCDEF$.

(a) Construct a polygon $\simeq ABCDEF$, but having one side less.

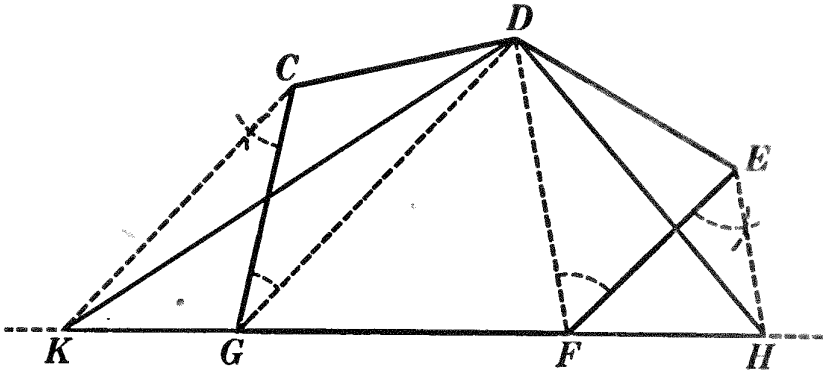
I. Construction

1. Join any two alternate vertices, as C and A .
2. Construct $BG \parallel CA$, meeting FA prolonged at G . § 188.
3. Draw CG .
4. Polygon $GCDEF \simeq$ polygon $ABCDEF$ and has one side less.

II. Proof

| ARGUMENT | REASONS |
|---|-------------|
| 1. $\triangle AGC$ and ABC have the same base CA , and the same altitude, the \perp between the \parallel s CA and BG . | 1. § 235. |
| 2. $\therefore \triangle AGC \simeq \triangle ABC$. | 2. § 486. |
| 3. But polygon $ACDEF$ — polygon $ACDEF$. | 3. By iden. |
| 4. \therefore polygon $GCDEF \simeq$ polygon $ABCDEF$. | 4. § 54, 2. |

Q.E.D.



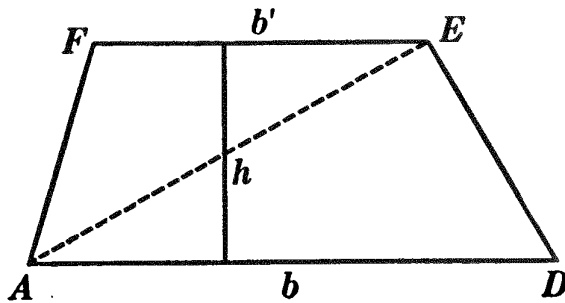
(b) In like manner, reduce the number of sides of the new polygon $GCDEF$ until $\triangle DHK$ is obtained.

The construction, proof, and discussion are left as an exercise for the student.

- Ex. 845. Transform a scalene triangle into an isosceles triangle.
- Ex. 846. Transform a trapezoid into a right triangle.
- Ex. 847. Transform a parallelogram into a trapezoid.
- Ex. 848. Transform a pentagon into an isosceles triangle.
- Ex. 849. Construct a triangle equivalent to $\frac{3}{5}$ of a given trapezium.
- Ex. 850. Transform $\frac{4}{7}$ of a given pentagon into a triangle.
- Ex. 851. Construct a rhomboid and a rhombus which are equivalent, and which have a common diagonal.

PROPOSITION VII. THEOREM

495. *The area of a trapezoid equals the product of its altitude and one half the sum of its bases.*



Given trapezoid $AFED$, with altitude h and bases b and b' .
 To prove area of $AFED = \frac{1}{2} (b + b')h$.

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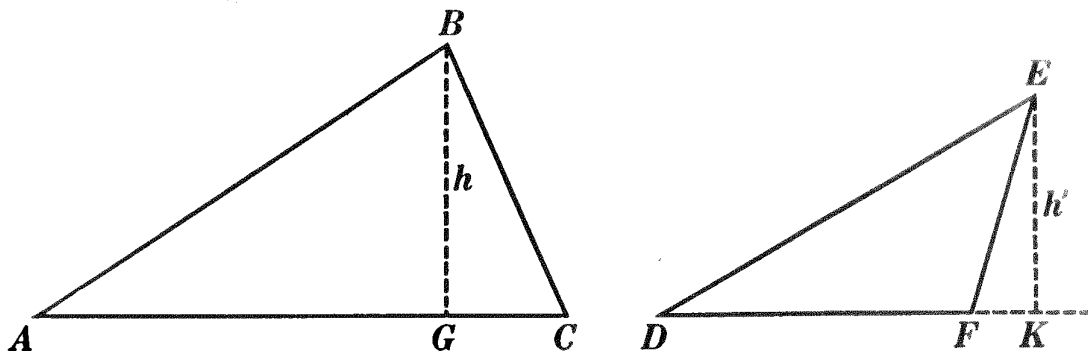
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PROPOSITION VIII. THEOREM

498. *Two triangles which have an angle of one equal to an angle of the other are to each other as the products of the sides including the equal angles.*



Given $\triangle ABC$ and DEF , with $\angle A = \angle D$.

To prove $\frac{\triangle ABC}{\triangle DEF} = \frac{AC \cdot AB}{DF \cdot DE}$.

ARGUMENT

1. Let h be the altitude of $\triangle ABC$ upon side AC , and h' the altitude of $\triangle DEF$ upon side DF . Then,

$$\frac{\triangle ABC}{\triangle DEF} = \frac{AC \cdot h}{DF \cdot h'} = \frac{AC}{DF} \cdot \frac{h}{h'}$$

2. In rt. $\triangle ABG$ and DEK , $\angle A = \angle D$.

3. $\therefore \triangle ABG \sim \triangle DEK$.

$$4. \therefore \frac{h}{h'} = \frac{AB}{DE}$$

$$5. \therefore \frac{\triangle ABC}{\triangle DEF} = \frac{AC}{DF} \cdot \frac{AB}{DE} = \frac{AC \cdot AB}{DF \cdot DE} \quad \text{Q.E.D.}$$

REASONS

1. § 487.

2. By hyp.

3. § 422.

4. § 424, 2.

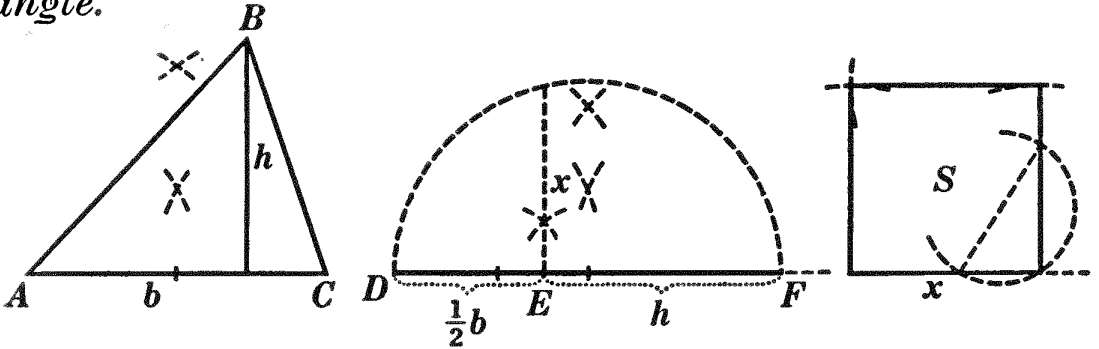
5. § 309.

Ex. 859. Draw two triangles upon the blackboard, so that an angle of one shall equal an angle of the other. Give a rough estimate in inches of the sides including the equal angles in the two triangles, and compute the numerical ratio of the triangles.

Ex. 860. If two triangles have an angle of one supplementary to an angle of the other, the triangles are to each other as the products of the sides including the supplementary angles.

PROPOSITION IX. PROBLEM

499. To construct a square equivalent to a given triangle.



Given $\triangle ABC$, with base b and altitude h .

To construct a square $\approx \triangle ABC$.

I. Analysis

1. Let $x =$ the side of the required square; then $x^2 =$ area of required square.
2. $\frac{1}{2} b \cdot h =$ area of the given $\triangle ABC$.
3. $\therefore x^2 = \frac{1}{2} b \cdot h$.
4. $\therefore \frac{1}{2} b : x = x : h$.
5. \therefore the side of the required square will be a mean proportional between $\frac{1}{2} b$ and h .

II. Construction

1. Construct a mean proportional between $\frac{1}{2} b$ and h . Call it x . § 445.
2. On x , as base, construct a square, S .
3. S is the required square.

III. Proof

| ARGUMENT | REASONS |
|--|-------------|
| 1. $\frac{1}{2} b : x = x : h$. | 1. By cons. |
| 2. $\therefore x^2 = \frac{1}{2} bh$. | 2. § 388. |
| 3. But $x^2 =$ area of S . | 3. § 478. |
| 4. And $\frac{1}{2} b \cdot h =$ area of $\triangle ABC$. | 4. § 485. |
| 5. $\therefore S \approx \triangle ABC$. | 5. § 54, 1. |

Q.E.D.

IV. The discussion is left as an exercise for the student.

500. Question. Could x be constructed as a mean proportional between b and $\frac{1}{2}h$?

501. Problem. *To construct a square equivalent to a given parallelogram.* _____

Ex. 861. Construct a square equivalent to a given rectangle.

Ex. 862. Construct a square equivalent to a given trapezoid.

Ex. 863. Upon a given base construct a triangle equivalent to a given parallelogram.

Ex. 864. Construct a rectangle having a given base and equivalent to a given square.

502. Props. VI, VIII, and IX form the basis of a large class of important constructions.

(a) Prop. VI enables us to construct a triangle equivalent to any polygon. It is then an easy matter to construct a trapezoid, an isosceles trapezoid, a parallelogram, a rectangle, or a rhombus equivalent to the triangle and hence equivalent to the given polygon.

(b) Prop. VIII gives us a method for constructing an equilateral triangle equivalent to any given triangle. (See Ex. 865.) Hence Prop. VIII, with Prop. VI, enables us to construct an equilateral triangle equivalent to any given polygon.

(c) Likewise Prop. IX, with Prop. VI, enables us to construct a square equivalent to any given polygon or to any fractional part or to any multiple of any given polygon.

Ex. 865. (a) Transform triangle ABC into triangle DBC , retaining base BC and making angle $DBC = 60^\circ$.

(b) Transform triangle DBC into triangle EBF , retaining angle $DBC = 60^\circ$ and making sides EB and BF equal. (Each will be a mean proportional between DB and BC .)

(c) What kind of a triangle is EBF ?

Ex. 866. Transform a parallelogram into an equilateral triangle.

Ex. 867. Construct an equilateral triangle equivalent to $\frac{2}{3}$ of a given trapezium.

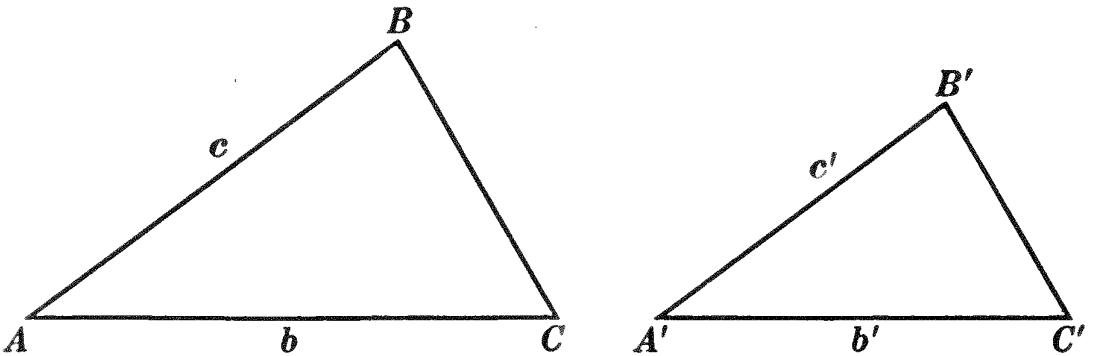
Ex. 868. Construct each of the following figures equivalent to $\frac{3}{8}$ of a given irregular pentagon : (1) a triangle ; (2) an isosceles triangle ; (3) a right triangle ; (4) an equilateral triangle ; (5) a trapezium ; (6) a trapezoid ; (7) an isosceles trapezoid ; (8) a parallelogram ; (9) a rhombus ; (10) a rectangle ; (11) a square.

Ex. 869. Transform a trapezoid into a right triangle having the hypotenuse equal to a given line. What restrictions are there upon the given line ?

Ex. 870. Construct a triangle equivalent to a given trapezoid, and having a given line as base and a given angle adjacent to the base.

PROPOSITION X. THEOREM

503. *Two similar triangles are to each other as the squares of any two homologous sides.*



Given two similar $\triangle ABC$ and $A'B'C'$, with b and b' two homol. sides.

To prove $\frac{\triangle ABC}{\triangle A'B'C'} = \frac{b^2}{b'^2}$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. $\triangle ABC \sim \triangle A'B'C'$. | 1. By hyp. |
| 2. $\therefore \angle A = \angle A'$. | 2. § 424, 1. |
| 3. Then $\frac{\triangle ABC}{\triangle A'B'C'} = \frac{b \cdot c}{b' \cdot c'} = \frac{b}{b'} \cdot \frac{c}{c'}$. | 3. § 498. |
| 4. But $\frac{c}{c'} = \frac{b}{b'}$. | 4. § 424, 2. |
| 5. $\therefore \frac{\triangle ABC}{\triangle A'B'C'} = \frac{b}{b'} \cdot \frac{b}{b'} = \frac{b^2}{b'^2}$. | 5. § 309. |

Q.E.D.

504. Cor. *Two similar triangles are to each other as the squares of any two homologous altitudes.* (See § 435.)

Ex. 871. Two similar triangles are to each other as the squares of two homologous medians.

Ex. 872. Construct a triangle similar to a given triangle and having an area four times as great.

Ex. 873. Construct a triangle similar to a given triangle and having an area twice as great.

Ex. 874. Divide a given triangle into two equivalent parts by a line parallel to the base.

Ex. 875. Prove Prop. X by using § 487.

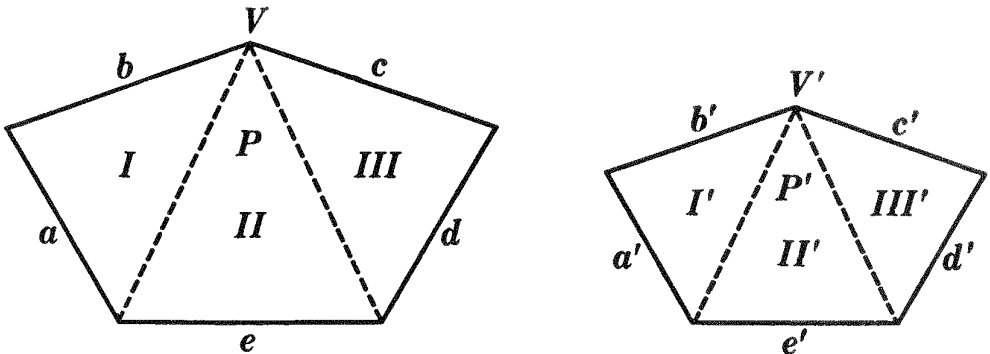
Ex. 876. Draw a line parallel to the base of a triangle and cutting off a triangle that shall be equivalent to one third of the given triangle.

Ex. 877. In two similar triangles a pair of homologous sides are 10 feet and 6 feet, respectively. Find the homologous side of a similar triangle equivalent to their difference.

Ex. 878. Construct an equilateral triangle whose area shall be three fourths that of a given square.

PROPOSITION XI. THEOREM

505. *Two similar polygons are to each other as the squares of any two homologous sides.*



Given two similar polygons P and P' in which a and a' , b and b' , etc., are pairs of homol. sides.

To prove $\frac{P}{P'} = \frac{a^2}{a'^2}$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw all possible diagonals from any two homol. vertices, as V and V' . | 1. § 54, 15. |
| 2. Then the polygons will be divided into the same number of $\Delta \sim$ each to each and similarly placed, as ΔI and $\Delta I'$, ΔII and $\Delta II'$, etc. | 2. § 439. |
| 3. Then $\frac{\Delta I}{\Delta I'} = \frac{a^2}{a'^2}$. | 3. § 503. |
| 4. $\frac{\Delta II}{\Delta II'} = \frac{e^2}{e'^2}$. | 4. § 503. |
| 5. $\frac{\Delta III}{\Delta III'} = \frac{d^2}{d'^2}$. | 5. § 503. |
| 6. But $\frac{a}{a'} = \frac{e}{e'} = \frac{d}{d'}$. | 6. § 419. |
| 7. $\therefore \frac{a^2}{a'^2} = \frac{e^2}{e'^2} = \frac{d^2}{d'^2}$. | 7. § 54, 13. |
| 8. $\therefore \frac{\Delta I}{\Delta I'} = \frac{\Delta II}{\Delta II'} = \frac{\Delta III}{\Delta III'}$. | 8. § 54, 1. |
| 9. $\therefore \frac{\Delta I + \Delta II + \Delta III}{\Delta I' + \Delta II' + \Delta III'} = \frac{\Delta I}{\Delta I'} = \frac{a^2}{a'^2}$. | 9. § 401. |
| 10. $\therefore \frac{P}{P'} = \frac{a^2}{a'^2}$. Q.E.D. | 10. § 309. |

506. Cor. *Two similar polygons are to each other as the squares of any two homologous diagonals.*

Ex. 879. If one square is double another, what is the ratio of their sides?

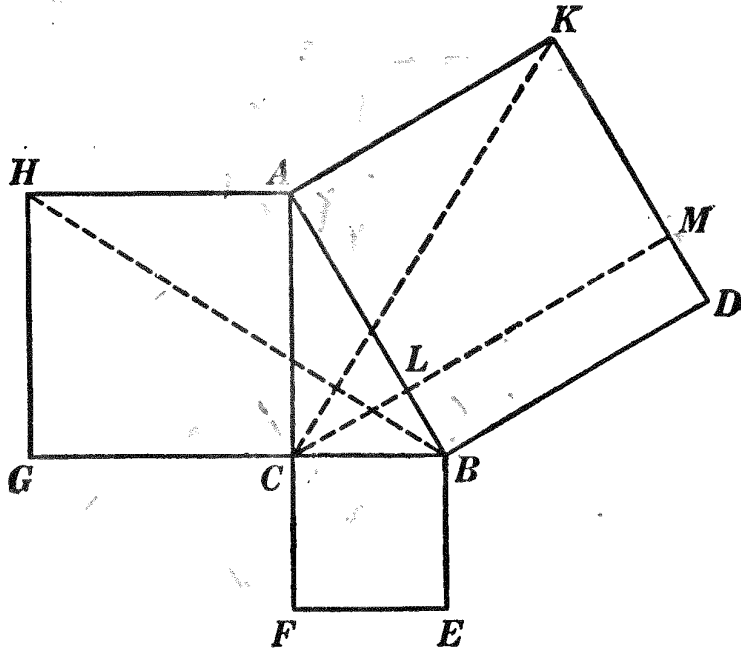
Ex. 880. Divide a given hexagon into two equivalent parts so that one part shall be a hexagon similar to the given hexagon.

Ex. 881. The areas of two similar rhombuses are to each other as the squares of their homologous diagonals.

Ex. 882. One side of a polygon is 8 and its area is 120. The homologous side of a similar polygon is 12; find its area.

PROPOSITION XII. THEOREM

507. *The square described on the hypotenuse of a right triangle is equivalent to the sum of the squares described on the other two sides.*



Given rt. $\triangle ABC$, right-angled at C , and the squares described on its three sides.

To prove square $AD \cong$ square $BF +$ square CH .

ARGUMENT

REASONS

- | | |
|---|--------------|
| 1. From C draw $CM \perp AB$, cutting AB at L and KD at M . | 1. § 155. |
| 2. Draw CK and BH . | 2. § 54, 15. |
| 3. $\angle ACG$, BCA , and FCB are all rt. \angle s. | 3. By hyp. |
| 4. $\therefore ACF$ and GCB are str. lines. | 4. § 76. |
| 5. In $\triangle CAK$ and HAB , $CA = HA$, $AK = AB$. | 5 § 233. |
| 6. $\angle CAB = \angle CAB$. | 6. By iden. |
| 7. $\angle BAK = \angle HAC$. | 7. § 64. |
| 8. $\therefore \angle CAK = \angle HAB$. | 8. § 54, 2. |
| 9. $\therefore \triangle CAK = \triangle HAB$. | 9. § 107. |
| 10. $\triangle CAK$ and rectangle AM have the same base AK and the same altitude, the \perp between the \parallel s AK and CM . | 10. § 235. |

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510. Historical Note. Prop. XII is usually known as the Pythagorean Proposition, because it was discovered by Pythagoras. The proof given here is that of Euclid (about 300 B.C.).

Pythagoras (569–500 B.C.), one of the most famous mathematicians of antiquity, was born at Samos. He spent his early years of manhood studying under Thales and traveled in Asia Minor and Egypt and probably also in Babylon and India. He returned to Samos where he established a school that was not a great success. Later he went to Crotona in Southern Italy and there gained many adherents. He formed, with his closest followers, a secret society, the members of which possessed all things in common. They



PYTHAGORAS

used as their badge the five-pointed star or pentagram which they knew how to construct and which they considered symbolical of health. They ate simple food and practiced severe discipline, having obedience, temperance, and purity as their ideals. The brotherhood regarded their leader with reverent esteem and attributed to him their most important discoveries, many of which were kept secret.

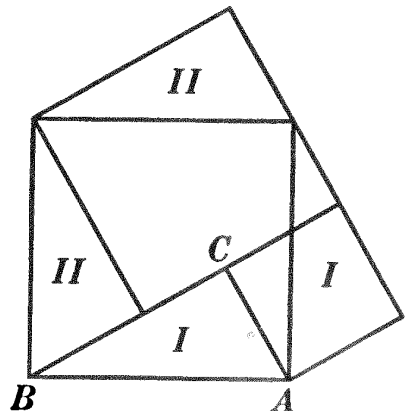
Pythagoras knew something of incommensurable numbers and proved that the diagonal and the side of a square are incommensurable.

The first man who propounded a theory of incommensurables is said to have suffered shipwreck on account of the sacrilege, since such numbers were thought to be symbolical of the Deity.

Pythagoras, having incurred the hatred of his political opponents, was murdered by them, but his school was reestablished after his death and it flourished for over a hundred years.

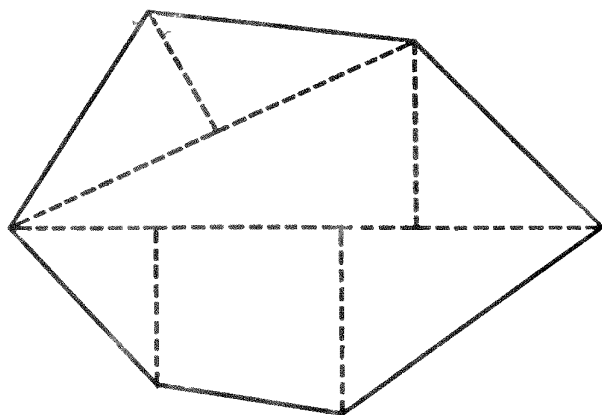
Ex. 884. Use the adjoining figure to prove the Pythagorean theorem.

Ex. 885. Construct a triangle equivalent to the sum of two given triangles.



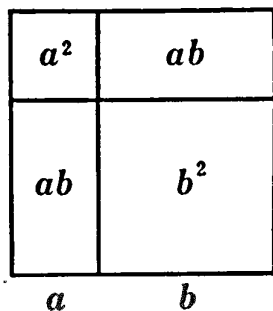
Ex. 886. The figure represents a farm drawn to the scale indicated. Make accurate measurements and calculate approximately the number of acres in the farm.

Ex. 887. A farm $XYZW$, in the form of a trapezium, has the following dimensions: $XY = 60$ rods, $YZ = 70$ rods, $ZW = 90$ rods, $WX = 100$ rods, and $XZ = 66$ rods. Draw a plot of the farm to the scale 1 inch = 40 rods, and calculate the area of the farm in acres.



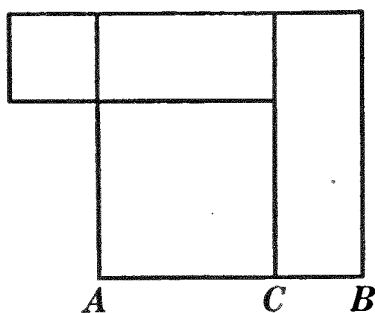
511. Def. By the rectangle of two lines is meant the rectangle having these two lines as adjacent sides.

Ex. 888. The square described on the sum of two lines is equivalent to the sum of the squares described on the lines plus twice their rectangle.



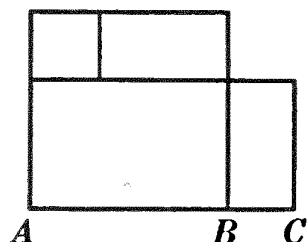
Ex. 889. The square described on the difference of two lines is equivalent to the sum of the squares described on the lines diminished by twice their rectangle.

HINT. Let AB and CB be the given lines.



Ex. 890. The rectangle whose sides are the sum and difference respectively of two lines is equivalent to the difference of the squares described on the lines.

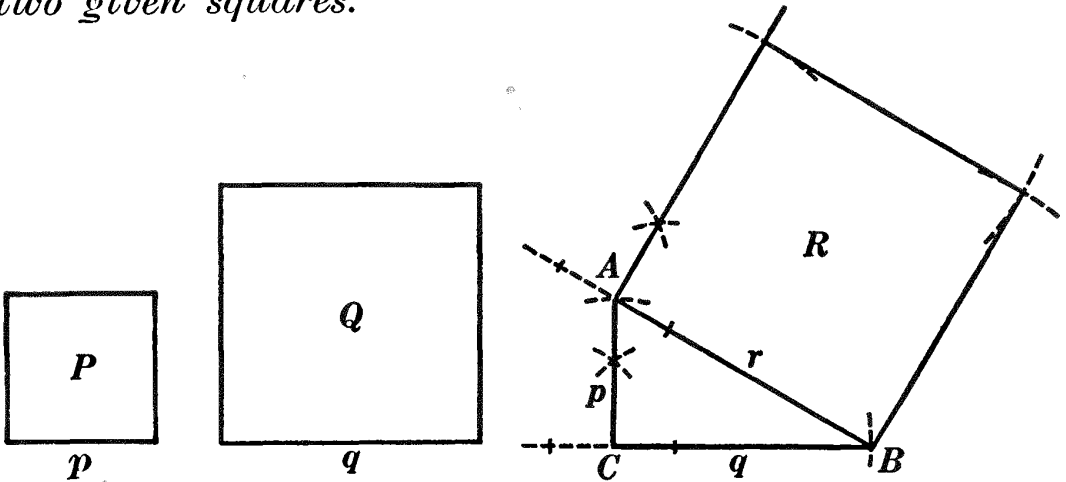
HINT. Let AB and BC be the given lines.



Ex. 891. Write the three algebraic formulas corresponding to the last three exercises.

PROPOSITION XIII. PROBLEM

512. *To construct a square equivalent to the sum of two given squares.*



Given squares P and Q .

To construct a square \simeq the sum of P and Q .

I. Construction

1. Construct the rt. $\triangle ABC$, having for its sides p and q , the sides of the given squares.

2. On r , the hypotenuse of the \triangle , construct the square R .

3. R is the required square.

II. The proof and discussion are left to the student.

Ex. 892. Construct a square equivalent to the sum of three or more given squares.

Ex. 893. Construct a square equivalent to the difference of two squares.

Ex. 894. Construct a square equivalent to the sum of a given square and a given triangle.

Ex. 895. Construct a polygon similar to two given similar polygons and equivalent to their sum. (See § 509.)

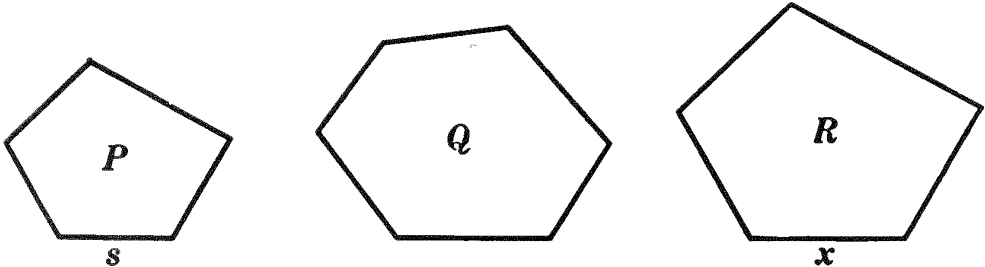
Ex. 896. Construct a polygon similar to two given similar polygons and equivalent to their difference.

Ex. 897. Construct an equilateral triangle equivalent to the sum of two given equilateral triangles.

Ex. 898. Construct an equilateral triangle equivalent to the difference of two given equilateral triangles.

PROPOSITION XIV. PROBLEM

513. *To construct a polygon similar to one of two given polygons and equivalent to the other.*



Given polygons P and Q , with s a side of P .

To construct a polygon $\sim P$ and $\approx Q$.

I. Analysis

1. Imagine the problem solved and let R be the required polygon with side x homol. to s , a side of P .

2. Then $P : R = s^2 : x^2$; i.e. $P : Q = s^2 : x^2$, since $Q \approx R$. (1)

3. Now to avoid comparing polygons which are not similar, we may reduce P and Q to \approx squares. Let the sides of these squares be m and n , respectively; then $m^2 \approx P$ and $n^2 \approx Q$.

4. $\therefore m^2 : n^2 = s^2 : x^2$, from (1).

5. $\therefore m : n = s : x$.

6. That is, x is the fourth proportional to m , n , and s .

II. The construction, proof, and discussion are left as an exercise for the student.

514. Historical Note. This problem was first solved by Pythagoras about 550 B.C.

Ex. 899. Construct a triangle similar to a given triangle and equivalent to a given parallelogram.

Ex. 900. Construct a square equivalent to a given pentagon.

Ex. 901. Construct a triangle, given its angles and its area (equal to that of a given parallelogram). **HINT.** See Prop. XIV.

Ex. 902. Divide a triangle into two equivalent parts by a line drawn perpendicular to the base. **HINT.** Draw a median to the base, then apply Prop. XIV.

Ex. 903. Fig. 1 represents maps of Utah and Colorado drawn to the scale indicated. By carefully measuring the maps: (1) Calculate the perimeter of each state. (2) Calculate the area of each state. (3) Check your results for (2) by comparing with the areas given for these states in your geography.

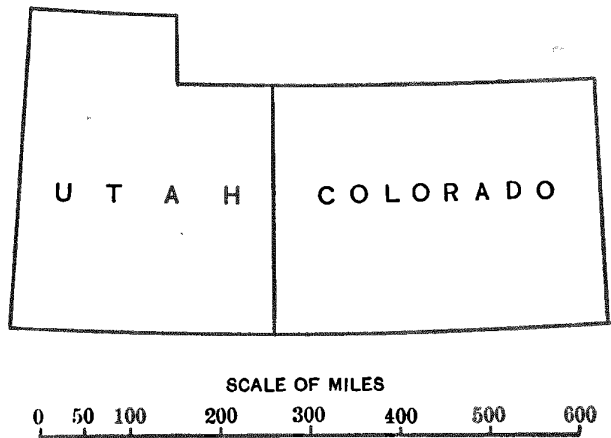


FIG. 1.

Ex. 904. Fig. 2 represents a map of Pennsylvania. A straight line from the southwest corner to the northeast corner is 300 miles long.

- (1) Determine the scale to which the map is drawn.
- (2) Calculate the distance from Pittsburg to Harrisburg; from Harrisburg to Philadelphia; from Philadelphia to Scranton; from Scranton to Harrisburg.
- (3) Calculate approximately the area of the state in square miles.

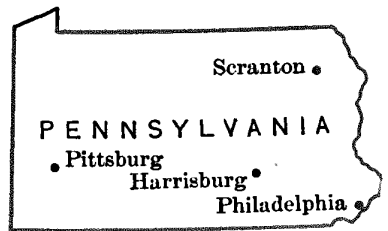


FIG. 2.

Ex. 905. Let C represent a candle; A a screen 1 foot square and 1 yard from C ; B a screen 2 feet square and 2 yards from C ; D a screen 3 feet square and 3 yards from C . If screen A were removed, the quantity of light it received would fall on B . What would happen if B were removed? On which screen, then, would the light be the least intense? From the figure, determine the *law of intensity of light*.

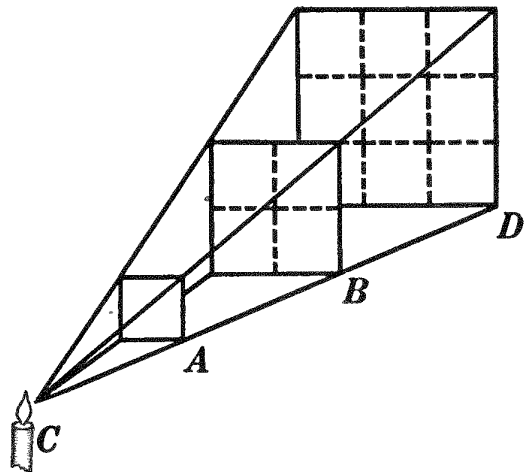


FIG. 3.

Ex. 906. Divide a triangle into two equivalent parts by a line drawn from a given point in one of its sides.

HINT. Let M be the given point in AC of triangle ABC ; then $\frac{1}{2} AB \cdot AC = AM \cdot AX$, where MX is the required line.

Ex. 907. A represents a station. Cars approach the station on track BA and leave the station on track AC . Construct an arc of a circle DE , with given radius r , connecting the two intersecting car lines, and so that each car line is tangent to the arc.

This same principle is involved in designing a building between two streets forming at their point of intersection a small acute angle, as the Flatiron Building in New York City.

Ex. 908. Find the area of a rhombus if its diagonals are in the ratio of 5 to 7 and their sum is 16.

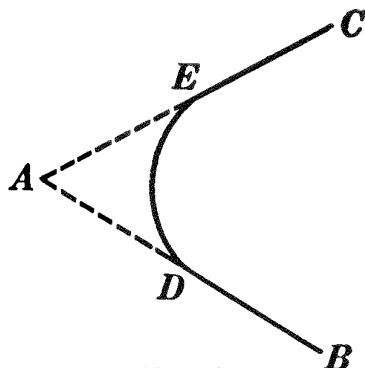


FIG. 4.

MISCELLANEOUS EXERCISES

Ex. 909. Show that if a and b are two sides of a triangle, the area is $\frac{1}{2} ab$ when the included angle is 30° or 150° ; $\frac{1}{2} ab\sqrt{2}$ when the included angle is 45° or 135° ; $\frac{1}{2} ab\sqrt{3}$ when the included angle is 60° or 120° .

Ex. 910. The sum of the perpendiculars from any point within a convex polygon upon the sides is constant.

HINT. Join the point with the vertices of the polygon, and consider the sum of the areas of the triangles.

Ex. 911. The sum of the squares on the segments of two perpendicular chords in a circle is equivalent to the square on the diameter.

Ex. 912. The hypotenuse of a right triangle is 20, and the projection of one arm upon the hypotenuse is 4. What is its area?

Ex. 913. A quadrilateral is equivalent to a triangle if its diagonals and the angle included between them are respectively equal to two sides and the included angle of the triangle.

Ex. 914. Transform a given triangle into another triangle containing two given angles.

Ex. 915. Prove geometrically the algebraic formula $(a + b)(c + d) = ac + bc + ad + bd$.

Ex. 916. If in any triangle an angle is equal to two thirds of a straight angle (§ 69), then the square on the side opposite is equivalent to the sum of the squares on the other two sides and the rectangle contained by them.

Ex. 917. The two medians RK and SH of the triangle RST intersect at P . Prove that the triangle RPS is equivalent to the quadrilateral $HPKT$.

Ex. 918. Find the area of a triangle if two of its sides are 6 inches and 7 inches and the included angle is 30° .

Ex. 919. By two different methods find the area of an equilateral triangle whose side is 10 inches.

Ex. 920. The area of an equilateral triangle is $36\sqrt{3}$; find a side and an altitude.

Ex. 921. By using the formula of Prop. IV, Arg. 8, derive the formula for the area of an equilateral triangle whose side is a .

Ex. 922. What does the formula for T in Prop. IV become if angle C is a right angle?

Ex. 923. Given an equilateral triangle ABC , inscribed in a circle whose center is O . At the vertex C erect a perpendicular to BC cutting the circumference at D . Draw the radii OD and OC . Prove that the triangle ODC is equilateral.

Ex. 924. Assuming that the areas of two triangles which have an angle of the one equal to an angle of the other are to each other as the products of the sides including the equal angles, prove that the bisector of an angle of a triangle divides the opposite side into segments proportional to the adjacent sides.

Ex. 925. A rhombus and a square have equal perimeters, and the altitude of the rhombus is three fourths its side; compare the areas of the two figures.

Ex. 926. The length of a chord is 10 feet, and the greatest perpendicular from the subtending arc to the chord is 2 feet $7\frac{1}{2}$ inches. Find the radius of the circle.

Ex. 927. In any right triangle a line from the vertex of the right angle perpendicular to the hypotenuse divides the given triangle into two triangles similar to each other and similar to the given triangle.

Ex. 928. The bases of a trapezoid are 16 feet and 10 feet, respectively, and each of the non-parallel sides is 5 feet. Find the area of the trapezoid. Also find the area of a similar trapezoid, if each of its non-parallel sides is 3 feet.

Ex. 929. A triangle having a base of 8 inches is cut by a line parallel to the base and 6 inches from it. If the base of the smaller triangle thus formed is 5 inches, find the area of the larger triangle.

Ex. 930. If the ratio of similitude of two similar triangles is 7 to 1, how often is the less contained in the greater? **HINT.** See §§ 418, 503.

Ex. 931. Construct a square equivalent to one third of a given square.

Ex. 932. If the side of one equilateral triangle is equal to the altitude of another, what is the ratio of their areas?

Ex. 933. Divide a right triangle into two isosceles triangles.

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Ex. 942. The feet of the perpendiculars dropped upon the sides of a triangle from any point in the circumference of the circumscribed circle are collinear.

OUTLINE OF PROOF. The circle having AP as diameter will pass through M and Q .

$\therefore \angle 1 = \angle 1'$ and $\angle 2 = \angle 2'$. Similarly

$$\angle 3 = \angle 3';$$

and

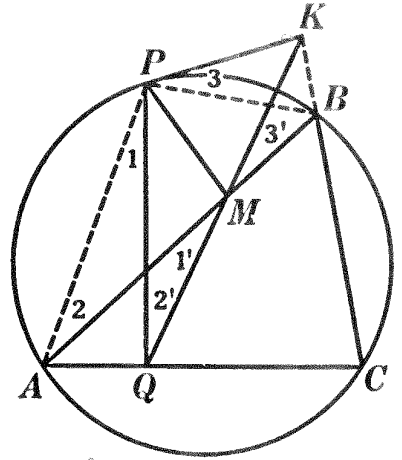
$$\angle PKM = \angle PBM.$$

$$\therefore \angle APB = \angle QPK.$$

$$\therefore \angle APQ = \angle BPK.$$

$$\therefore \angle AMQ = \angle BMK.$$

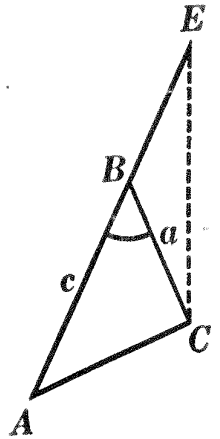
$\therefore QM$ and MK form one str. line.



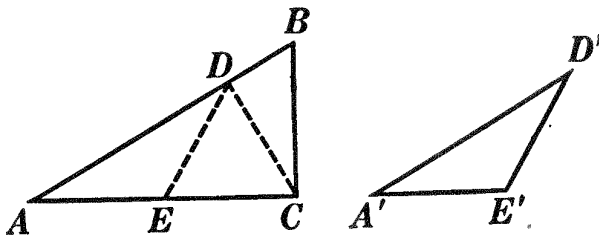
Ex. 943. Given the base, the angle at the vertex, and the sum of the other two sides of a triangle; construct the triangle.

ANALYSIS. Imagine the problem solved and draw $\triangle ABC$. Prolong AB , making $BE = BC$, since the line $c + a$ is given. Since $\angle E = \frac{1}{2} \angle ABC$, $\triangle AEC$ can be constructed.

Ex. 944. The hypotenuse of a right triangle is given in magnitude and position; find the locus of the center of the inscribed circle.



Ex. 945. Prove Prop. VIII, Book IV, by using the following figure, in which $A'D'E'$ is placed in the position ADE .

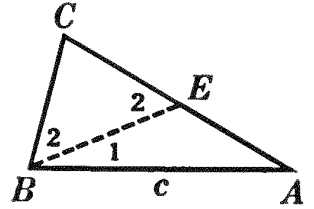


Ex. 946. Prove Prop. VIII, Book IV, using two triangles such that one will not fall wholly within the other.

Ex. 947. If two triangles have an angle of one supplementary to an angle of the other, the triangles are to each other as the products of the sides including the supplementary angles. (Prove by method similar to that of Ex. 945.)

Ex. 948. Given base, difference of sides, and difference of base angles; construct the triangle.

ANALYSIS. In the accompanying figure suppose c and EA , $(b - a)$, to be given. A consideration of the figure will show that $\angle 2 = \angle 1 + \angle A$. Add $\angle 1$ to both members of the equation; then $\angle 1 + \angle 2 = 2\angle 1 + \angle A$. But $\angle 1 + \angle 2 = \angle B$. $\therefore \angle B = 2\angle 1 + \angle A$. $\therefore \angle 1 = \frac{1}{2}(\angle B - \angle A)$.

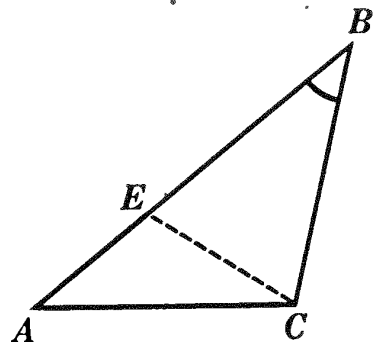


The $\triangle BEA$ may now be constructed. The rest of the construction is left for the student.

Ex. 949. Given base, vertex angle, and difference of sides, construct the triangle.

ANALYSIS. $AE = AB - BC$. $\angle AEC = 90^\circ + \frac{1}{2}\angle B$. $\therefore \triangle AEC$ can be constructed.

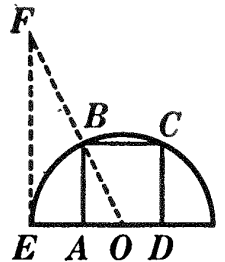
Ex. 950. If upon the sides of any triangle equilateral triangles are constructed, the lines joining the centers of the equilateral triangles form an equilateral triangle.



HINT. Circumscribe circles about the three equilateral \triangle . Join O , the common point of intersection of the three circles, to A , B , and C , the vertices of the given \triangle . Prove each \angle at O the supplement of the \angle opposite in an equilateral \triangle , and also the supplement of the \angle opposite in the \triangle to be proved equilateral.

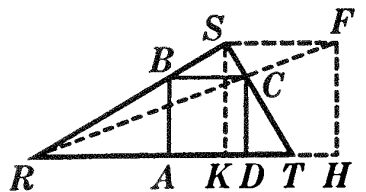
Ex. 951. To inscribe a square in a semicircle.

ANALYSIS. Imagine the problem solved and $ABCD$ the required square. Prove $OA = \frac{AB}{2}$. Draw $EF \perp EO$ meeting OB prolonged at F . $FE : EO = BA : AO$. $\therefore EF = 2 OE$.



Ex. 952. To inscribe a square in a given triangle.

OUTLINE OF SOLUTION. Imagine the problem solved and $ABCD$ the required square. Draw $SF \parallel RT$ and construct square $KSFH$. Draw RF , thus determining point C . The cons. will be evident from the figure. To prove $ABCD$ a square, prove $BC = CD$. $BC : SF = CD : FH$. But $SF = FH$. $\therefore BC = CD$.



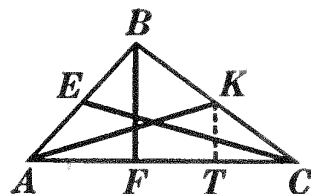
Ex. 953. In a given square construct a square, having a given side, so that its vertices shall lie in the sides of the given square.

HINT. Construct a rt. Δ , given the hypotenuse and sum of arms.

Ex. 954. Construct a triangle, given m_a, m_c, h_b .

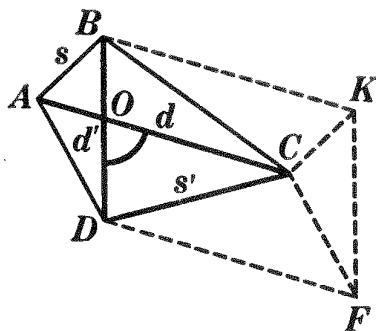
ANALYSIS. Imagine the problem solved and that ABC is the required Δ . If BF were moved \parallel to itself till it contained K , the rt. ΔAKT would be formed and KT would equal $\frac{1}{2} BF$.

Then ΔAKT can be made the basis of the required construction.

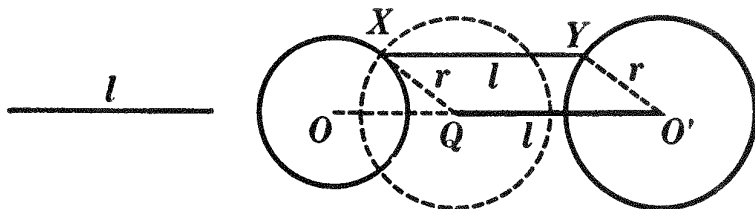


Ex. 955. Construct a quadrilateral, given two of its opposite sides, its two diagonals, and the angle between them.

OUTLINE OF CONSTRUCTION. Imagine the problem solved and that $ABCD$ is the required quadrilateral, s, s', d, d' , and $\angle DOC$ being given. By \parallel motion of d and d' the parallelogram $BKFD$ may be obtained. The required construction may be begun by drawing $\square BKFD$, since two sides and the included \angle are known. With K as center and s as radius, describe an arc; with D as center and s' as radius, describe an arc intersecting the first, as at C . Construct $\square ABKC$, or $\square DACF$, to locate A .



Ex. 956. Between two circles draw a line which shall be parallel to the line of centers and equal to a given line l .



Ex. 957. Find $x = \frac{abc}{d^2}$, where a, b, c , and d represent given lines.

HINT. Here $x = \frac{ab}{d} \cdot \frac{c}{d}$. Let $\frac{ab}{d} = y$ and construct y . Then construct x .

Ex. 958. Transform any given triangle into an equilateral triangle by a method different from that used in Ex. 865.

ANALYSIS. Call the base of the given triangle b and its altitude h .

Let $x =$ the side of the required equilateral triangle.

Then $\frac{x^2}{4} \sqrt{3} = \frac{1}{2} b \cdot h. \therefore \frac{2}{3} b : x = x : h \sqrt{3}.$

BOOK V

REGULAR POLYGONS. MEASUREMENT OF THE CIRCLE

515. Def. A regular polygon is one which is both equilateral and equiangular.

Ex. 959. Draw an equilateral triangle. Is it a regular polygon?

Ex. 960. Draw a quadrilateral that is equilateral but not equiangular; equiangular but not equilateral; neither equilateral nor equiangular; both equilateral and equiangular. Which of these quadrilaterals is a regular polygon?

Ex. 961. Find the number of degrees in an angle of a regular dodecagon.

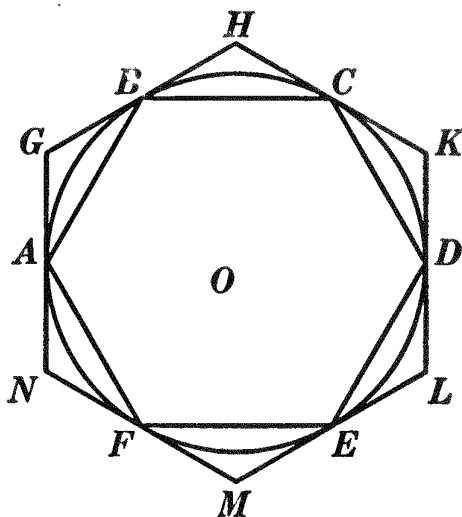
516. Historical Note. The following theorem presupposes the possibility of dividing the circumference into a number of equal arcs. The actual division cannot be obtained by the methods of elementary geometry, except in certain special cases which will be discussed later.

As early as Euclid's time it was known that the angular magnitude about a point (and hence a circumference) could be divided into 2^n , $2^n \cdot 3$, $2^n \cdot 5$, $2^n \cdot 15$ equal angles. In 1796 it was discovered by Gauss, then nineteen years of age, that a regular polygon of 17 sides can be constructed by means of ruler and compasses, and that in general it is possible to construct all polygons having $(2^n + 1)$ sides, n being an integer and $(2^n + 1)$ a prime number. The first four numbers satisfying this condition are 3, 5, 17, 257. Gauss proved also that polygons having a number of sides equal to the product of two or more different numbers of this series can be constructed.

Gauss proved, moreover, that *only a limited class* of regular polygons are constructible by elementary geometry. For a note on the life of Gauss, see § 520.

PROPOSITION I. THEOREM

517. *If the circumference of a circle is divided into any number of equal arcs: (a) the chords joining the points of division form a regular polygon inscribed in the circle; (b) tangents drawn at the points of division form a regular polygon circumscribed about the circle.*



Given circumference ACE divided into equal arcs AB, BC, CD , etc., and let chords AB, BC, CD , etc., join the several points of division, and let the tangents GH, HK, KL , etc., touch the circumference at the several points of division.

To prove $ABCD \dots$ and $GHKL \dots$ regular polygons.

| ARGUMENT | REASONS |
|---|---------------|
| 1. $\widehat{AB} = \widehat{BC} = \widehat{CD} = \dots$ | 1. By hyp. |
| 2. $\therefore \text{arc } CEA = \text{arc } DFB = \text{arc } EAC = \dots$ | 2. § 54, 7 a. |
| 3. $\therefore \angle ABC = \angle BCD = \angle CDE = \dots$ | 3. § 362, a. |
| 4. Also $AB = BC = CD = \dots$ | 4. § 298. |
| 5. $\therefore ABCD \dots$ is a regular polygon. | 5. § 515. |
| 6. Again, $\angle BAG = \angle GBA = \angle CBH = \angle HCB = \dots$ | 6. § 362, a. |
| 7. And $AB = BC = CD = \dots$ | 7. Arg. 4. |
| 8. $\therefore \triangle AGB = \triangle BHC = \triangle CKD = \dots$ | 8. § 105. |
| 9. $\therefore \angle G = \angle H = \angle K = \dots$ | 9. § 110. |
| 10. And $AG = GB = BH = \dots$ | 10. § 110. |

ARGUMENT

REASONS

11. $\therefore GH = HK = KL = \dots$

11. § 54, 7 a.

12. $\therefore GHKL \dots$ is a regular polygon. Q.E.D.

12. § 515.

518. Questions. If, in the figure of § 517, the circumference is divided into six equal parts, how many arcs, each equal to arc AB , will arc CEA contain? arc DFB ? How many will each contain if the circumference is divided into n equal parts? In step 10, why does $AG = GB$?

519. Cor. *If the vertices of a regular inscribed polygon are joined to the mid-points of the arcs subtended by the sides of the polygon, the joining lines will form a regular inscribed polygon of double the number of sides.*

Ex. 962. An equilateral polygon inscribed in a circle is regular.

Ex. 963. An equiangular polygon circumscribed about a circle is regular.

520. Historical Note. Karl Friedrich Gauss (1777–1855) was born at Brunswick, Germany. Although he was the son of a bricklayer, he was enabled to receive a liberal education, owing to the recognition of his unusual talents by a nobleman. He was sent to the Caroline College but, at the age of fifteen, it was admitted both by professors and pupils that Gauss already knew all that they could teach him. He became a student in the University of Göttingen and while there did some important work on the theory of numbers.



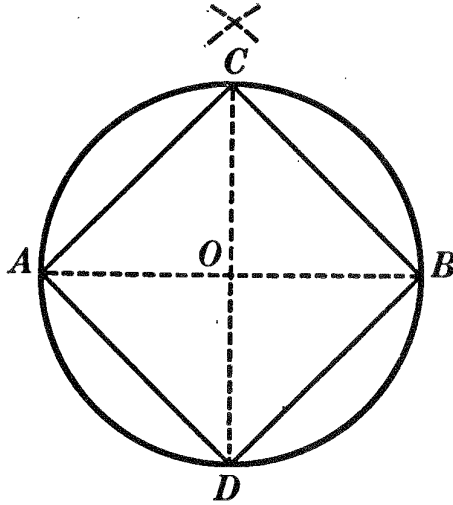
GAUSS

On his return to Brunswick, he lived humbly as a private tutor, until 1807, when he was appointed professor of astronomy and director of the observatory at Göttingen. While there he did important work in physics as well as in astronomy. He also invented the telegraph independently of S. F. B. Morse.

His lectures were unusually clear, and he is said to have given in them the analytic steps by which he developed his proofs; while in his writings there is no hint of the processes by which he discovered his results.

PROPOSITION II. PROBLEM

521. *To inscribe a square in a given circle.*



Given circle O .

To inscribe a square in circle O .

I. The construction is left as an exercise for the student.

II. Proof

| ARGUMENT | REASONS |
|--|--------------|
| 1. $AB \perp CD$. | 1. By cons. |
| 2. $\therefore \angle AOC = 90^\circ$. | 2. § 71. |
| 3. $\therefore \widehat{AC} = 90^\circ$, <i>i.e.</i> one fourth of the circumference. | 3. § 358. |
| 4. \therefore the circumference is divided into four equal parts. | 4. Arg. 3. |
| 5. \therefore polygon $ACBD$, formed by joining the points of division, is a square. Q.E.D. | 5. § 517, a. |

III. The discussion is left as an exercise for the student.

522. **Cor.** *The side of a square inscribed in a circle is equal to the radius multiplied by $\sqrt{2}$; the side of a square circumscribed about a circle is equal to twice the radius.*

Ex. 964. Inscribe a regular octagon in a circle.

Ex. 965. Inscribe in a circle a regular polygon of sixteen sides.

Ex. 966 Circumscribe a square about a circle.

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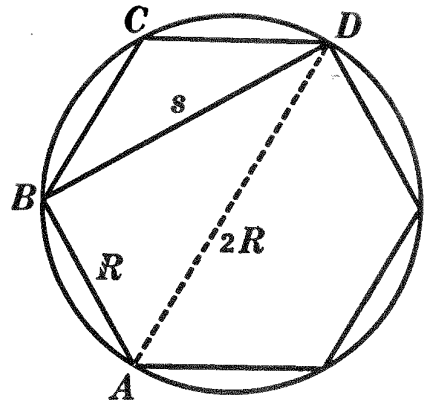
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524. Cor. I. *A regular inscribed triangle is formed by joining the alternate vertices of a regular inscribed hexagon.*

525. Cor. II. *A side of a regular inscribed triangle is equal to the radius of the circle multiplied by $\sqrt{3}$.*

HINT. $\triangle ABD$ is a right triangle whose hypotenuse is $2R$ and one side R .



Ex. 971. Inscribe a regular dodecagon in a circle.

Ex. 972. Divide a given circle into two segments such that any angle inscribed in one segment is five times an angle inscribed in the other.

Ex. 973. Circumscribe an equilateral triangle about a circle.

Ex. 974. Circumscribe a regular hexagon about a circle.

Ex. 975. On a given line as one side, construct a regular hexagon.

Ex. 976. On a given line as one side, construct a regular dodecagon.

Ex. 977. If a is the side of a regular dodecagon inscribed in a circle whose radius is R , then $a = R\sqrt{2 - \sqrt{3}}$.

PROPOSITION IV. PROBLEM

526. *To inscribe a regular decagon in a circle.*

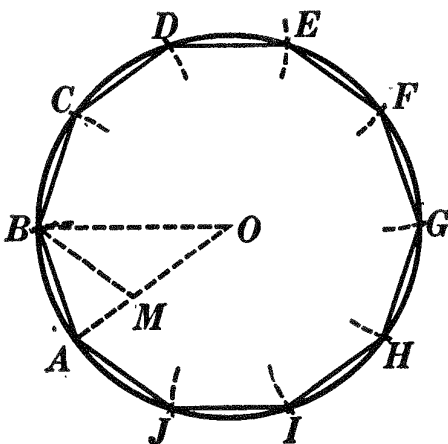


FIG. 1.

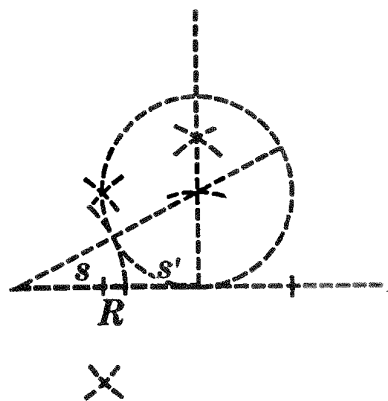


FIG. 2.

Given circle O .

To inscribe in circle O a regular decagon.

I. Construction

1. Divide a radius R , of circle O , in extreme and mean ratio. § 465. (See Fig. 2.)
2. In circle O draw a chord AB , equal to s , the greater segment of R .
3. AB is a side of the required decagon.

II. Proof

| ARGUMENT | REASONS |
|---|------------------------|
| 1. Draw radius OA . | 1 § 54, 15. |
| 2. On OA lay off $OM = s$. | 2. § 54, 14. |
| 3. Draw OB and BM . | 3. § 54, 15. |
| 4. Then $OA : OM = OM : MA$. | 4. By cons. |
| 5. $\therefore OA : AB = AB : MA$. | 5. § 309. |
| 6. Also in $\triangle OAB$ and MAB , $\angle A - \angle A$. | 6. By iden. |
| 7. $\therefore \triangle OAB \sim \triangle MAB$. | 7. § 428. |
| 8. $\because \triangle OAB$ is isosceles, $\triangle MAB$ is isosceles, and $BM = AB$. | 8. § 94. |
| 9. But $AB = s = OM$. | 9. By cons. |
| 10. $\therefore BM = OM$. | 10. § 54, 1. |
| 11. $\therefore \triangle BOM$ is isosceles and $\angle MBO = \angle O$. | 11. § 111. |
| 12. But $\angle ABM = \angle O$. | 12. § 424, 1. |
| 13. $\therefore \angle MBO + \angle ABM$, or $\angle ABO$, $= 2 \angle O$. | 13. § 54, 2. |
| 14. $\therefore \angle MAB = 2 \angle O$. | 14. § 111. |
| 15. In $\triangle ABO$, $\angle ABO + \angle MAB + \angle O = 180^\circ$. | 15. § 204. |
| 16. $\therefore 2 \angle O + 2 \angle O + \angle O$, or $5 \angle O$, $= 180^\circ$. | 16. § 309. |
| 17. $\therefore \angle O = 36^\circ$. | 17. § 54, 8 <i>a</i> . |
| 18. $\therefore \widehat{AB} = 36^\circ$, <i>i.e.</i> one tenth of the circumference. | 18. § 358. |
| 19. \therefore the circumference may be divided into ten equal parts. | 19. Arg. 18. |
| 20. \therefore polygon $ABCD \dots$, formed by joining the points of division, is a regular inscribed decagon. | 20. § 517, <i>a</i> . |

Q.E.D.

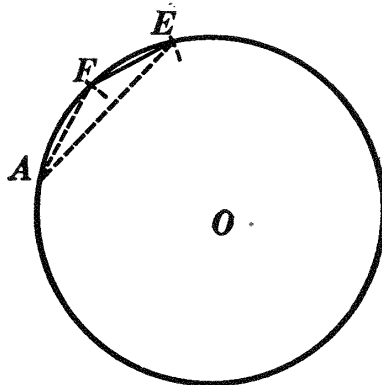
III. The discussion is left as an exercise for the student.

527. Cor. I. *A regular pentagon is formed by joining the alternate vertices of a regular inscribed decagon.*

- Ex. 978.** Construct a regular inscribed polygon of 20 sides.
Ex. 979. The diagonals of a regular inscribed pentagon are equal.
Ex. 980. Construct an angle of 36° ; of 72° .
Ex. 981. Divide a right angle into five equal parts.
Ex. 982. The eight diagonals of a regular decagon drawn from any vertex divide the angle at that vertex into eight equal angles.
Ex. 983. Circumscribe a regular pentagon about a circle.
Ex. 984. Circumscribe a regular decagon about a circle.
Ex. 985. On a given line as one side, construct a regular pentagon.
Ex. 986. On a given line as one side, construct a regular decagon.
Ex. 987. The side of a regular inscribed decagon is equal to $\frac{1}{2}R(\sqrt{5}-1)$, where R is the radius of the circle.
HINT. By cons., $R : s = s : R - s$. Solve this proportion for s .

PROPOSITION V. PROBLEM

528. *To inscribe a regular pentedecagon in a circle.*



Given circle O .

To inscribe in circle O a regular pentedecagon.

I. Construction

1. From A , any point in the circumference, lay off chord AE equal to a side of a regular inscribed hexagon. § 523.

2. Also lay off chord AF equal to a side of a regular inscribed decagon. § 526.
3. Draw chord FE .
4. FE is a side of the required pentadecagon.

II. Proof

| ARGUMENT | REASONS |
|--|--------------|
| 1. Arc $AE = \frac{1}{6}$ of the circumference. | 1. By cons. |
| 2. Arc $AF = \frac{1}{10}$ of the circumference. | 2. By cons. |
| 3. \therefore arc $FE = \frac{1}{6} - \frac{1}{10}$, i.e. $\frac{1}{15}$, of the circumference. | 3. § 54, 3. |
| 4. \therefore the circumference may be divided into fifteen equal parts. | 4. Arg. 3. |
| 5. \therefore the polygon formed by joining the points of division will be a regular inscribed pentadecagon. Q.E.D. | 5. § 517, a. |

III. The discussion is left as an exercise for the student.

529. Note. It has now been shown that a circumference can be divided into the number of equal parts indicated below :

$$\left. \begin{array}{l}
 2, 4, 8, 16, \dots \quad 2^n \\
 3, 6, 12, 24, \dots \quad 3 \times 2^n \\
 5, 10, 20, 40, \dots \quad 5 \times 2^n \\
 15, 30, 60, 120, \dots \quad 15 \times 2^n
 \end{array} \right\} [n \text{ being any positive integer}].$$

Ex. 988. Construct an angle of 24° .

Ex. 989. Circumscribe a regular pentadecagon about a given circle.

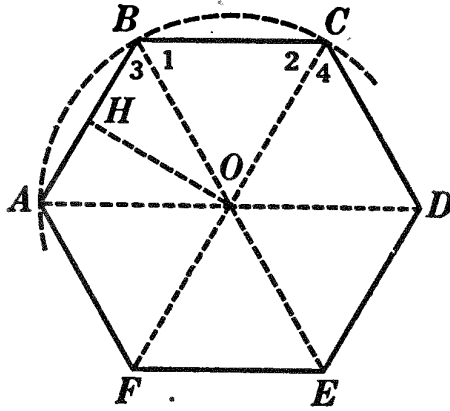
Ex. 990. On a given line as one side, construct a regular pentadecagon.

Ex. 991. Assuming that it is possible to inscribe in a circle a regular polygon of 17 sides, show how it is possible to inscribe a regular polygon of 51 sides.

Ex. 992. If a regular polygon is inscribed in a circle, the tangents drawn at the mid-points of the arcs subtended by the sides of the inscribed polygon form a circumscribed regular polygon whose sides are parallel to the sides of the inscribed polygon, and whose vertices lie on the prolongations of the radii drawn to the vertices of the inscribed polygon.

PROPOSITION VI. THEOREM

530. *A circle may be circumscribed about any regular polygon; and a circle may also be inscribed in it.*



Given regular polygon $ABCDEF \dots$

To prove: (a) that a circle may be circumscribed about it;
 (b) that a circle may be inscribed in it.

| (a) | ARGUMENT | REASONS |
|-----|---|------------------------------|
| 1. | Pass a circumference through points A , B , and C . | 1. § 324. |
| 2. | Connect O , the center of the circle, with all the vertices of the polygon. | 2. § 54, 15. |
| 3. | Then $OB = OC$. | 3. § 279, α . |
| 4. | $\therefore \angle 1 = \angle 2$. | 4. § 111. |
| 5. | But $\angle ABC = \angle BCD$. | 5. § 515. |
| 6. | $\therefore \angle 3 = \angle 4$. | 6. § 54, 3. |
| 7. | Also $AB = CD$. | 7. § 515. |
| 8. | $\therefore \triangle ABO = \triangle OCD$. | 8. § 107. |
| 9. | $\therefore OA = OD$ and circumference ABC passes through D . | 9. § 110. |
| 10. | In like manner it may be proved that circumference ABC passes through each of the vertices of the regular polygon; the circle will then be circumscribed about the polygon. | 10. By steps similar to 1-9. |

Q.E.D.

| (b) | ARGUMENT | REASONS |
|-----|--|-----------|
| 1. | Again AB, BC, CD , etc., the sides of the given polygon, are chords of the circumscribed circle. | 1. § 281. |
| 2. | Hence \perp s from the center of the circle to these chords are equal. | 2. § 307. |
| 3. | \therefore with O as center, and with a radius equal to one of these \perp s, as OH , a circle may be described to which all the sides of the polygon will be tangent. | 3. § 314. |
| 4. | \therefore this circle will be inscribed in the polygon. | 4. § 317. |
| | Q.E.D. | |

531. Def. The **center** of a regular polygon is the common center of the circumscribed and inscribed circles; as O , Prop. VI.

532. Def. The **radius** of a regular polygon is the radius of the circumscribed circle, as OA .

533. Def. The **apothem** of a regular polygon is the radius of the inscribed circle, as OH .

534. Def. In a regular polygon the **angle at the center** is the angle between radii of the polygon drawn to the extremities of any side, as $\angle AOF$.

535. Cor. I. *The angle at the center is equal to four right angles divided by the number of sides of the polygon.*

536. Cor. II. *An angle of a regular polygon is the supplement of the angle at the center.*

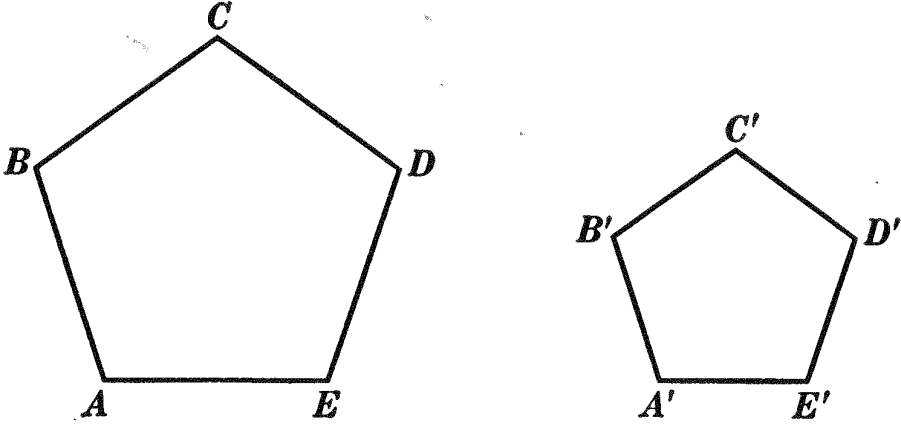
Ex. 993. Find the number of degrees in the angle at the center of a regular octagon. Find the number of degrees in an angle of the octagon.

Ex. 994. If the circle circumscribed about a triangle and the circle inscribed in it are concentric, the triangle is equilateral.

Ex. 995. How many sides has a regular polygon whose angle at the center is 30° ?

PROPOSITION VII. THEOREM

537. *Regular polygons of the same number of sides are similar.*



Given two regular polygons, $ABCDE$ and $A'B'C'D'E'$, of the same number of sides.

To prove polygon $ABCDE \sim$ polygon $A'B'C'D'E'$.

| ARGUMENT | REASONS |
|--|---------------|
| 1. Let n represent the number of sides of each polygon; then each angle of each polygon equals $\frac{(n - 2)2 \text{ rt. } \angle s}{n}$ | 1. § 217. |
| 2. \therefore the polygons are mutually equiangular. | 2. Arg. 1. |
| 3. $AB = BC = CD = \dots$ | 3. § 515. |
| 4. $A'B' = B'C' = C'D' = \dots$ | 4. § 515. |
| 5. $\therefore \frac{AB}{A'B'} = \frac{BC}{B'C'} = \frac{CD}{C'D'} = \dots$ | 5. § 54, 8 a. |
| 6. \therefore polygon $ABCDE \sim$ polygon $A'B'C'D'E'$. | 6. § 419. |
| Q.E.D. | |

Ex. 996. Two homologous sides of two regular pentagons are 3 inches and 5 inches, respectively; what is the ratio of their perimeters? of their areas?

Ex. 997. The perimeters of two regular hexagons are 30 inches and 72 inches, respectively; what is the ratio of their areas?

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MEASUREMENT OF THE CIRCUMFERENCE AND OF THE CIRCLE

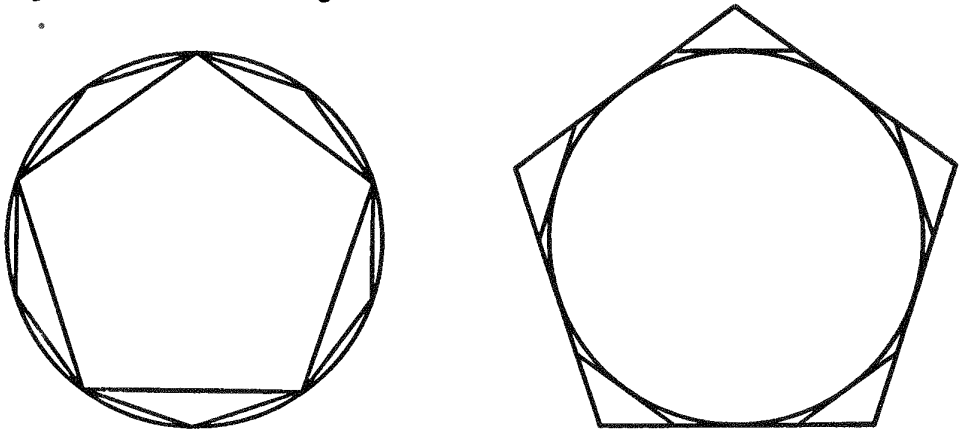
540. The measure of a straight line, *i.e.* its length, is obtained by laying off upon it a straight line taken as a standard or unit (§ 335).

Since a straight line cannot be made to coincide with a curve, it is obvious that some other system of measurement must be adopted for the circumference. The following theorems will develop the principles upon which such measurement is based.

PROPOSITION IX. THEOREM

541. I. *The perimeter and area of a regular polygon inscribed in a circle are less, respectively, than the perimeter and area of the regular inscribed polygon of twice as many sides.*

II. *The perimeter and area of a regular polygon circumscribed about a circle are greater, respectively, than the perimeter and area of the regular circumscribed polygon of twice as many sides.*



The proof is left as an exercise for the student.

HINT. The sum of two sides of a triangle is greater than the third side.

Ex. 1000. A square and a regular octagon are inscribed in a circle whose radius is 10 inches ; find :

- (a) The difference between their perimeters.
- (b) The difference between their areas.

542. Historical Note. Archimedes (285?-212 B.C.) found the circumference and area of the circle by a method similar to that given in this text. He was born in Syracuse, Sicily, but studied in Egypt at the University of Alexandria.

Although, like Plato, he regarded practical applications of mathematics as of minor importance, yet, on his return to Sicily he is said to have won the admiration of King Hiero by applying his extraordinary mechanical genius to the construction of war-engines with which great havoc was wrought on the Roman army. By means of large lenses and mirrors he is said to have focused the sun's rays and set the Roman ships on fire. Although this story may be untrue, nevertheless such a feat would be by no means impossible.



ARCHIMEDES

Archimedes invented the Archimedes screw, which was used in Egypt to drain the fields after the inundations of the Nile. A ship which was so large that Hiero could not get it launched was moved by a system of cogwheels devised by Archimedes, who remarked in this connection that had he but a fixed fulcrum, he could move the world itself.

The work most prized by Archimedes himself, however, and that which gives him rank among the greatest mathematicians of all time, is his investigation of the mechanics of solids and fluids, his measurement of the circumference and area of the circle, and his work in solid geometry.

Archimedes was killed when Syracuse was captured by the Romans. The story is told that he was drawing diagrams in the sand, as was the custom in those days, when the Roman soldiers came upon him. He begged them not to destroy his circles, but they, not knowing who he was, and thinking that he presumed to command them, killed him with their spears. The Romans, directed by Marcellus, who admired his genius and had given orders that he should be spared, erected a monument to his memory, on which were engraved a sphere inscribed in a cylinder.

The story of the re-discovery of this tomb in 75 B.C. is delightfully told by Cicero, who found it covered with rubbish, when visiting Syracuse.

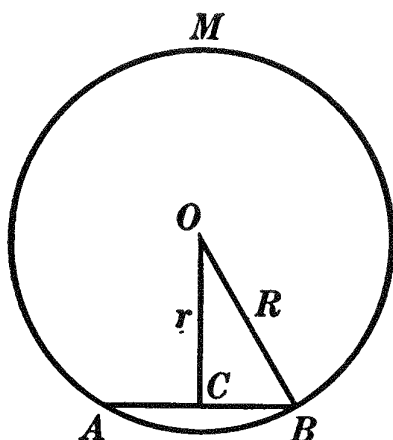
Archimedes is regarded as the greatest mathematician the world has known, with the sole exception of Newton.

PROPOSITION X. THEOREM

543. *By repeatedly doubling the number of sides of a regular polygon inscribed in a circle, and making the polygons always regular:*

I. *The apothem can be made to differ from the radius by less than any assigned value.*

II. *The square of the apothem can be made to differ from the square of the radius by less than any assigned value.*



Given AB the side, OC the apothem, and OB the radius of a regular polygon inscribed in circle AMB .

To prove that by repeatedly doubling the number of sides of the polygon:

I. $OB - OC$ can be made less than any assigned value.

II. $OB^2 - OC^2$ can be made less than any assigned value.

I.

ARGUMENT

REASONS

1. By repeatedly doubling the number of sides of the inscribed polygon and making the polygons always regular, \widehat{AB} , subtended by one side AB of the polygon, can be made less than any previously assigned arc, however small.

1. § 519.

2. \therefore chord AB can be made less than any previously assigned line segment, however small.

2. § 301.

| ARGUMENT | REASONS |
|---|--------------|
| 3. $\therefore CB$, which is $\frac{1}{2} AB$, can be made less than any previously assigned value, however small. | 3. § 544. |
| 4. But $OB - OC < CB$. | 4. § 168. |
| 5. $\therefore OB - OC$, being always less than CB , can be made less than any previously assigned value, however small. | 5. § 59, 10. |
| Q.E.D. | |

II.

| | |
|---|---------------|
| 1. Again, $\overline{OB}^2 - \overline{OC}^2 = \overline{CB}^2$. | 1. § 447. |
| 2. But CB can be made less than any previously assigned value, however small. | 2. I, Arg. 3. |
| 3. $\therefore CB$ can be made less than any previously assigned value, however small. | 3. § 545. |
| 4. $\therefore \overline{OB} - OC$, being always equal to CB , can be made less than any previously assigned value, however small. | 4. § 309. |
| Q.E.D. | |

544. *If a variable can be made less than any assigned value, the quotient of the variable by any constant, except zero, can be made less than any assigned value.*

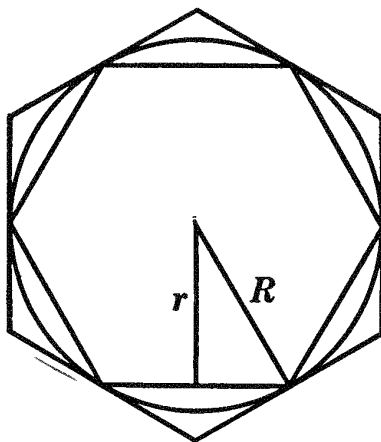
545. *If a variable can be made less than any assigned value, the square of that variable can be made less than any assigned value. (For proofs of these theorems see Appendix, §§ 586 and 589.)*

Ex. 1001. Construct the following designs: (1) on the blackboard, making each line 12 times as long as in the figure; (2) on paper, making each line 4 times as long:

PROPOSITION XI. THEOREM

546. *By repeatedly doubling the number of sides of regular circumscribed and inscribed polygons of the same number of sides, and making the polygons always regular:*

- I. *Their perimeters approach a common limit.*
- II. *Their areas approach a common limit.*



Given P and p the perimeters, R and r the apothems, and K and k the areas respectively of regular circumscribed and inscribed polygons of the same number of sides.

To prove that by repeatedly doubling the number of sides of the polygons, and making the polygons always regular:

- I. P and p approach a common limit.
- II. K and k approach a common limit.

| I. | ARGUMENT | REASONS |
|----|--|---------------|
| 1. | Since the two regular polygons have the same number of sides, $\frac{P}{p} = \frac{R}{r}$. | 1. § 538. |
| 2. | $\therefore \frac{P-p}{P} = \frac{R-r}{R}$. | 2. § 399. |
| 3. | $\therefore P-p = P \frac{R-r}{R}$. | 3. § 54, 7 a. |
| 4. | But by repeatedly doubling the number of sides of the polygons, and making them always regular, $R-r$ can be | 4. § 543, I. |

| ARGUMENT | REASONS |
|---|-----------|
| made less than any previously assigned value, however small. | |
| 5. $\therefore \frac{R-r}{R}$ can be made less than any previously assigned value, however small. | 5. § 544. |
| 6. $\therefore P \frac{R-r}{R}$ can be made less than any previously assigned value, however small, P being a decreasing variable. | 6. § 547. |
| 7. $\therefore P - p$, being always equal to $P \frac{R-r}{R}$, can be made less than any previously assigned value, however small. | 7. § 309. |
| 8. $\therefore P$ and p approach a common limit. | 8. § 548. |
| Q.E.D. | |

II. The proof of II is left as an exercise for the student.

HINT. Since the two regular polygons have the same number of sides, $\frac{K}{k} = \frac{R^2}{r^2}$ (§ 539). The rest of the proof is similar to steps 2–8, § 546, I.

547. *If a variable can be made less than any assigned value, the product of that variable and a decreasing value may be made less than any assigned value.*

548. *If two related variables are such that one is always greater than the other, and if the greater continually decreases while the less continually increases, so that the difference between the two may be made as small as we please, then the two variables have a common limit which lies between them.*

(For proofs of these theorems see Appendix, §§ 587 and 594.)

549. Note. The above proof is limited to *regular* polygons, but it can be shown that the limit of the perimeter of any inscribed (or circumscribed) polygon is the same by whatever method the number of its sides is successively increased, provided that each side approaches zero as a limit.

550. Def. The length of a circumference is the common limit which the successive perimeters of inscribed and circumscribed regular polygons (of 3, 4, 5, etc., sides) approach as the number of sides is successively increased and each side approaches zero as a limit.

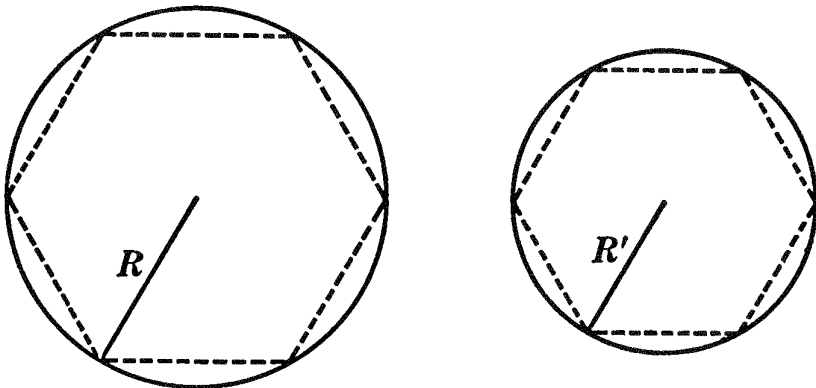
The term "circumference" is frequently used for "the length of a circumference." (See Prop. XII.)

551. The length of an arc of a circumference is such a part of the length of the circumference as the central angle which intercepts the arc is of 360° . (See § 360.)

552. The approximate length of a circumference is found in elementary geometry by computing the perimeters of a series of regular inscribed and circumscribed polygons which are obtained by repeatedly doubling the number of their sides. The perimeters of these inscribed and circumscribed polygons, since they approach a common limit, may be made to agree to as many decimal places as we please, according to the number of times we double the number of sides of the polygons.

PROPOSITION XII. THEOREM

553. *The ratio of the circumference of a circle to its diameter is the same for all circles.*



Given any two circles with circumferences C and C' , and with radii R and R' , respectively.

To prove $\frac{C}{2R} = \frac{C'}{2R'}$.

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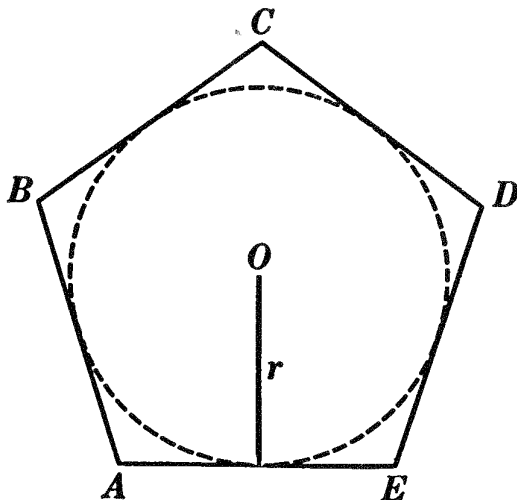
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PROPOSITION XIII. THEOREM

557. *The area of a regular polygon is equal to one half the product of its perimeter and its apothem.*



Given regular polygon $ABCD\dots$, P its perimeter, and r its apothem.

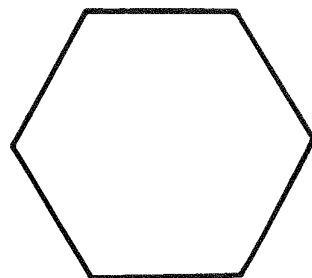
To prove area of $ABCD\dots = \frac{1}{2} P r$.

| ARGUMENT | REASONS |
|--|-----------|
| 1. In polygon $ABCD\dots$, inscribe a circle. | 1. § 530. |
| 2. Then r , the apothem of regular polygon $ABCD\dots$, is the radius of circle O . | 2. § 533. |
| 3. \therefore area of $ABCD\dots = \frac{1}{2} P r$. Q.E.D. | 3. § 492. |

Ex. 1005. Find the area of a regular hexagon whose side is 6 inches.

Ex. 1006. The area of an inscribed regular hexagon is a mean proportional between the areas of the inscribed and circumscribed equilateral triangles.

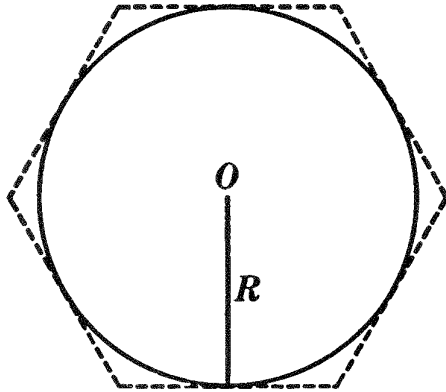
Ex. 1007. The figure represents a flower bed drawn to the scale of 1 inch to 20 feet. Find the number of square feet in the flower bed.



558. Def. The area of a circle is the common limit which the successive areas of inscribed and circumscribed regular polygons approach as the number of sides is successively increased and each side approaches zero as a limit.

PROPOSITION XIV. THEOREM

559. *The area of a circle is equal to one half the product of its circumference and its radius.*



Given circle O , with radius R , circumference C , and area K .

To prove $K = \frac{1}{2} CR$.

| ARGUMENT | REASONS |
|--|----------------------|
| 1. Circumscribe about circle O a regular polygon. Call its perimeter P and its area S . | 1. § 517, <i>b</i> . |
| 2. Then $S = \frac{1}{2} PR$. | 2. § 557. |
| 3. As the number of sides of the regular circumscribed polygon is repeatedly doubled, P approaches C as a limit. | 3. § 550. |
| 4. $\therefore \frac{1}{2} PR$ approaches $\frac{1}{2} CR$ as a limit. | 4. § 561. |
| 5. Also S approaches K as a limit. | 5. § 558. |
| 6. But S is always equal to $\frac{1}{2} PR$. | 6. Arg. 2. |
| 7. $\therefore K = \frac{1}{2} CR$. Q.E.D. | 7. § 355. |

560. *The product of a variable and a constant is a variable.*

561. *The limit of the product of a variable and a constant, not zero, is the limit of the variable multiplied by the constant.*

(Proofs of these theorems will be found in the Appendix, §§ 585 and 590.)

562. **Cor. I.** *The area of a circle is equal to πR^2 .*

HINT. $K = \frac{1}{2} C R = \frac{1}{2} \cdot 2\pi R \cdot R = \pi R^2$.

563. Cor. II. *The areas of two circles are to each other as the squares of their radii, or as the squares of their diameters.*

564. Cor. III. *The area of a sector whose angle is a° is $\frac{a}{360} \pi R^2$. (See § 551.)*

Ex. 1008. Find the area of a circle whose radius is 3 inches.

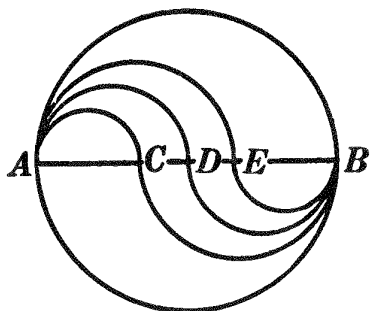
Ex. 1009. Find the area of a sector the angle of which is (a) 45° , (b) 120° , (c) 17° , and the radius, 5 inches. Find the area of the segment corresponding to (b). **HINT.** Segment = sector – triangle.

Ex. 1010. If the area of one circle is four times that of another, and the radius of the first is 6 inches, what is the radius of the second?

Ex. 1011. Find the area of the ring included between the circumferences of two concentric circles whose radii are 6 inches and 8 inches.

Ex. 1012. Find the radius of a circle whose area is equal to the sum of the areas of two circles with radii 3 and 4, respectively.

Ex. 1013. In the figure the diameter $AB = 2R$, $AC = \frac{1}{4}AB$, $AD = \frac{1}{2}AB$, and E is any point on AB . (1) Find arc $AC +$ arc CB ; arc $AD +$ arc DB ; arc $AE +$ arc EB . (2) Compare each result with semicircumference AB .



565. Def. In different circles **similar arcs**, **similar sectors**, and **similar segments** are arcs, sectors, and segments that correspond to equal central angles.

Ex. 1014. Similar arcs are to each other as their radii.

Ex. 1015. Similar sectors are to each other as the squares of their radii.

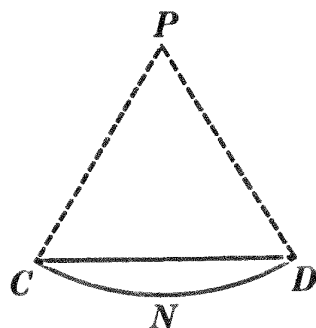
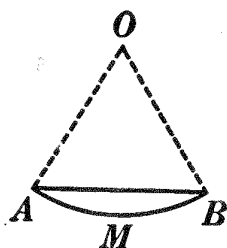
Ex. 1016. Similar segments are to each other as the squares of their radii.

HINT. Prove

$$\frac{\text{sector } AOB}{\text{sector } CPD} = \frac{\Delta AOB}{\Delta CPD}.$$

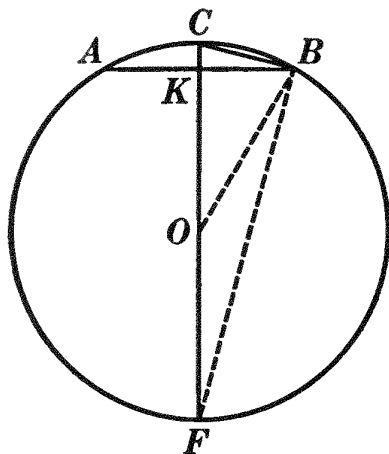
Then

apply §§ 396 and 399.



PROPOSITION XV. PROBLEM

566. Given a circle of unit diameter and the side of a regular inscribed polygon of n sides, to find the side of a regular inscribed polygon of $2n$ sides.



Given circle ABF of unit diameter, AB the side of a regular inscribed polygon of n sides, and CB the side of a regular inscribed polygon of $2n$ sides; denote AB by s and CB by x .

To find x in terms of s .

ARGUMENT

1. Draw diameter CF ; draw BO and BF .

2. $\angle CBF$ is a rt. \angle .

3. Also CF is the \perp bisector of AB .

4. $\therefore \overline{CB}^2 = CF \cdot CK$.

5. Now $CF = 1$, $BO = \frac{1}{2}$, $CO = \frac{1}{2}$.

6. $\therefore \overline{CB}^2 = x^2 = 1 \cdot CK = CK = CO - KO$
 $= \frac{1}{2} - KO$.

7. $\therefore x^2 = \frac{1}{2} - \sqrt{BO^2 - KB^2}$
 $= \frac{1}{2} - \sqrt{\left(\frac{1}{2}\right)^2 - \left(\frac{s}{2}\right)^2} = \frac{\sqrt{1 - s^2}}{2}$

8. $\therefore x = \sqrt{\frac{1 - \sqrt{1 - s^2}}{2}}$.

REASONS

1. § 54, 15.

2. § 367.

3. § 142.

4. § 443, II.

5. By cons.

6. § 309.

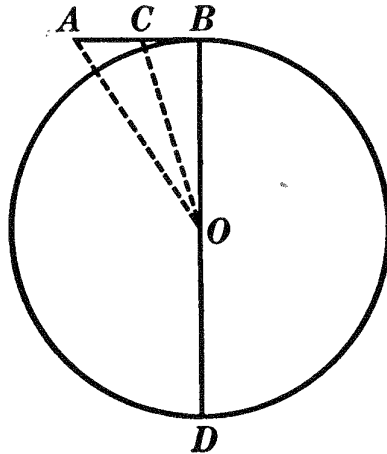
7. § 447.

8. § 54, 13.

Q.E.F.

PROPOSITION XVI. PROBLEM

567. Given a circle of unit diameter and the side of a regular circumscribed polygon of n sides, to find the side of a regular circumscribed polygon of $2n$ sides.



Given circle O of unit diameter, AB half the side of a regular circumscribed polygon of n sides, and CB half the side of a regular circumscribed polygon of $2n$ sides; denote AB by $\frac{s}{2}$ and CB by $\frac{x}{2}$.

To find x in terms of s .

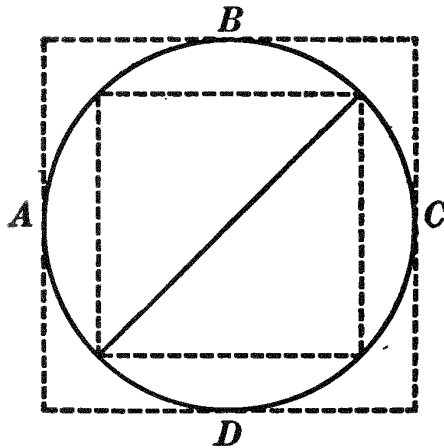
| ARGUMENT | REASONS |
|---|--------------|
| 1. Draw CO and AO . | 1. § 54, 15. |
| 2. $\angle BOC = \frac{1}{2} \angle BOA$. | 2. § 517, b. |
| 3. \therefore in $\triangle OAB$, $AC : CB = AO : BO$. | 3. § 432. |
| 4. But $AC = AB - CB$. | 4. § 54, 11. |
| 5. And $AO = \sqrt{AB^2 + BO^2}$. | 5. § 446. |
| 6. $\therefore AB - CB : CB = \sqrt{AB^2 + BO^2} : BO$. | 6. § 309. |
| 7. Substituting $\frac{s}{2}$ for AB , $\frac{x}{2}$ for CB , and $\frac{1}{2}$ for BO , $\frac{s}{2} - \frac{x}{2} : \frac{x}{2} = \sqrt{\left(\frac{s}{2}\right)^2 + \left(\frac{1}{2}\right)^2} : \frac{1}{2}$. | 7. § 309. |
| 8. $\therefore s - x : x = \sqrt{s^2 + 1} : 1$. | 8. § 403. |

| | ARGUMENT | REASONS |
|-----|--|-----------------------|
| 9. | $\therefore s - x = x \sqrt{s^2 + 1}.$ | 9. § 388. |
| 10. | $\therefore x = \frac{s}{1 + \sqrt{s^2 + 1}}.$ | 10. Solving for x . |
| | Q. E. F. | |

Ex. 1017. Given a circle of unit diameter and an inscribed and a circumscribed square; compute the side of the regular inscribed and the regular circumscribed octagon

PROPOSITION XVII. PROBLEM

568. *To compute the approximate value of the circumference of a circle in terms of its diameter; i.e. to compute the value of π .*



Given circle $ABCD$, with unit diameter.

To compute approximately the circumference of circle $ABCD$ in terms of its diameter; *i.e.* to compute the value of π .

| | ARGUMENT | REASONS |
|----|---|-----------|
| 1. | The ratio of the circumference of a circle to its diameter is the same for all circles. | 1. § 553. |
| 2. | Since the diameter of the given circle is unity, the side of an inscribed square will be $\frac{1}{2} \sqrt{2}$. | 2. § 522. |

ARGUMENT

REASONS

3. By using the formula $x = \sqrt{\frac{1 - \sqrt{1 - a^2}}{2}}$, 3 § 566.

the sides of regular inscribed polygons of 8, 16, 32, etc., sides may be computed; and by multiplying the length of one side by the number of sides, the length of the perimeter of each polygon may be obtained. The results are given in the table below.

4. Likewise if the diameter of the given circle is unity, the side of a circumscribed square will be 1. 4. § 522.

5. By using the formula $x = \frac{s}{1 + \sqrt{s^2 + 1}}$, 5. § 567.

the sides of regular circumscribed polygons of 8, 16, 32, etc., sides may be computed; and by multiplying the length of one side by the number of sides, the length of the perimeter of each polygon may be obtained. The results are given in the following table.

| NUMBER OF SIDES | PERIMETER OF INSCRIBED POLYGON | PERIMETER OF CIRCUMSCRIBED POLYGON |
|-----------------|--------------------------------|------------------------------------|
| 4 | 2.828427 | 4.000000 |
| 8 | 3.061467 | 3.313708 |
| 16 | 3.121445 | 3.182597 |
| 32 | 3.136548 | 3.151724 |
| 64 | 3.140331 | 3.144118 |
| 128 | 3.141277 | 3.142223 |
| 256 | 3.141513 | 3.141750 |
| 512 | 3.141572 | 3.141632 |
| 1024 | 3.141587 | 3.141602 |
| 2048 | 3.141591 | 3.141595 |
| 4096 | 3.141592 | 3.141593 |

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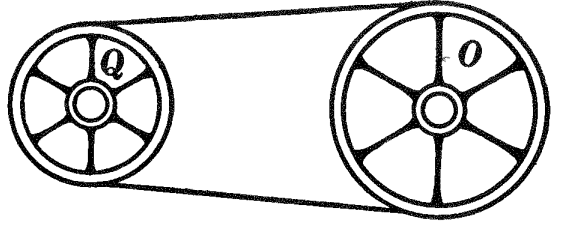
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Ex. 1022. The figure represents a belt from drive wheel O to wheel Q . The diameter of wheel O is 2 feet and of wheel Q 16 inches. If the drive wheel makes 75 revolutions per minute, how many revolutions per minute will the smaller wheel make?



Ex. 1023. The radius of a circle is 6 inches. What is the area of a segment whose arc is 60° ?

Ex. 1024. The radius of a circle is 8 inches. What is the area of the segment subtended by the side of an inscribed equilateral triangle?

Ex. 1025. The diagonals of a rhombus are 16 and 30; find the area of the circle inscribed in the rhombus.

MISCELLANEOUS EXERCISES

Ex. 1026. An equiangular polygon inscribed in a circle is regular if the number of sides is odd.

Ex. 1027. An equilateral polygon circumscribed about a circle is regular if the number of sides is odd.

Ex. 1028. Find the apothem and area in terms of the radius in an equilateral triangle; in a square; in a regular hexagon.

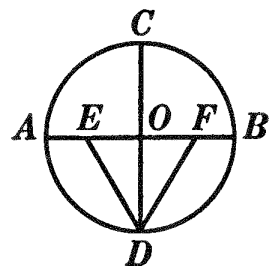
Ex. 1029. The lines joining the mid-points of the apothems of a regular pentagon form a regular pentagon. Find the ratio of its area to the area of the original pentagon.

Ex. 1030. Within a circular grass plot of radius 6 feet, a flower bed in the form of an equilateral triangle is inscribed. How many square feet of turf remain?

Ex. 1031. The area of a regular hexagon inscribed in a circle is $24\sqrt{3}$. What is the area of the circle?

Ex. 1032. From a circle of radius 6 is cut a sector whose central angle is 105° . Find the area and perimeter of the sector. ($\pi = \frac{22}{7}$.)

Ex. 1033. Prove that the following method of inscribing a regular pentagon and a regular decagon in a circle is correct. Draw diameter CD perpendicular to diameter AB ; bisect OA and join its mid-point to D ; take $EF = ED$ and draw FD . FD will be the side of the required pentagon, and OF the side of the required decagon.



Ex. 1034. Divide a given circle into two segments such that any angle inscribed in one segment is twice an angle inscribed in the other ; so that an angle inscribed in one segment is three times an angle inscribed in the other ; seven times.

Ex. 1035. Show how to cut off the corners of an equilateral triangle so as to leave a regular hexagon ; of a square to leave a regular octagon.

Ex. 1036. The diagonals of a regular pentagon form a regular pentagon.

Ex. 1037. The diagonals joining alternate vertices of a regular hexagon form a regular hexagon one third as large as the original one.

Ex. 1038. The area of a regular inscribed octagon is equal to the product of the side of an inscribed square and the diameter.

Ex. 1039. If a is the side of a regular pentagon inscribed in a circle whose radius is R , then $a = \frac{R}{2} \sqrt{10 - 2\sqrt{5}}$.

Ex. 1040. The area of a regular inscribed dodecagon is equal to three times the square of the radius.

Ex. 1041. Construct an angle of 9° .

Ex. 1042. Construct a regular pentagon, given one of the diagonals.

Ex. 1043. Through a given point construct a line which shall divide a given circumference into two parts in the ratio of 3 to 7 ; in the ratio of 3 to 5. Can the given point lie within the circle ?

Ex. 1044. Transform a given regular octagon into a square.

Ex. 1045. Construct a circumference equal to the sum of two given circumferences.

Ex. 1046. Divide a given circle by concentric circumferences into four equivalent parts.

Ex. 1047. In a given sector whose angle is a right angle inscribe a square.

Ex. 1048. In a given sector inscribe a circle.

Ex. 1049. If two chords of a circle are perpendicular to each other, the sum of the four circles having the four segments as diameters is equivalent to the given circle.

Ex. 1050. The area of a ring between two concentric circumferences whose radii are R and R' respectively is $\pi(R^2 - R'^2)$.

Ex. 1051. The area of the surface between two concentric circles is equal to twice the area of the smaller circle. Find the ratio between their radii.

MISCELLANEOUS EXERCISES ON PLANE GEOMETRY

Ex. 1052. If equilateral triangles are constructed on the sides of any given triangle, the lines joining the vertices of the given triangle to the outer vertices of the opposite equilateral triangles are equal.

Ex. 1053. If, on the arms of a right triangle as diameters, semicircles are drawn so as to lie outside of the triangle, and if, on the hypotenuse as a diameter, a semicircle is drawn passing through the vertex of the right angle, the sum of the areas of the two crescents included between the semicircles is equal to the area of the given triangle.

Ex. 1054. The area of the regular inscribed triangle is half that of the regular inscribed hexagon.

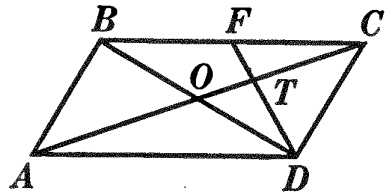
Ex. 1055. From a given point draw a secant to a circle such that its internal and external segments shall be equal.

Ex. 1056. Show that the diagonals of any quadrilateral inscribed in a circle divide the quadrilateral into four triangles which are similar, two and two.

Ex. 1057. Through a point P , outside of a circle, construct a secant PAB so that $\overline{AB}^2 = PA \times PB$.

Ex. 1058. The radius of a circle is 6 feet. What are the radii of the circles concentric with it whose circumferences divide its area into three equivalent parts?

Ex. 1059. Given parallelogram $ABCD$, F the mid-point of BC ; prove $OT = \frac{1}{2} TC$.



Ex. 1060. Given PT a tangent to a circle at point T , and two other tangents parallel to each other cutting PT at A and B respectively; prove that the radius of the circle is a mean proportional between AT and TB .

Ex. 1061. Show that a mean proportional between two unequal lines is less than half their sum.

Ex. 1062. Given two similar triangles, construct a triangle equivalent to their sum.

Ex. 1063. The square of the side of an inscribed equilateral triangle is equal to the sum of the squares of the sides of the inscribed square and of the inscribed regular hexagon.

Ex. 1064. Prove that the area of a circular ring is equal to the area of a circle whose diameter equals a chord of the outer circumference which is tangent to the inner,

Ex. 1065. If two chords drawn from a common point P on the circumference of a circle are cut by a line parallel to the tangent through P , the chords and the segments of the chords between the two parallel lines are inversely proportional.

Ex. 1066. Construct a segment of a circle similar to two given similar segments and equivalent to their sum.

Ex. 1067. The distance between two parallels is a , and the distance between two points A and B in one parallel is $2b$. Find the radius of the circle which passes through A and B , and is tangent to the other parallel.

Ex. 1068. Tangents are drawn through a point 6 inches from the circumference of a circle whose radius is 9 inches. Find the length of the tangents and also the length of the chord joining the points of contact.

Ex. 1069. If the perimeter of each of the figures, equilateral triangle, square, and circle, is 396 feet, what is the area of each figure?

Ex. 1070. The lengths of two sides of a triangle are 13 and 15 inches, and the altitude on the third side is 12 inches. Find the third side, and also the area of the triangle. (Give one solution only.)

Ex. 1071. If the diameter of a circle is 3 inches, what is the length of an arc of 80° ?

Ex. 1072. AD and BC are the parallel sides of a trapezoid $ABCD$, whose diagonals intersect at E . If F is the mid-point of BC , prove that FE prolonged bisects AD .

Ex. 1073. Given a square $ABCD$. Let E be the mid-point of CD , and draw BE . A line is drawn parallel to BE and cutting the square. Let P be the mid-point of the segment of this line within the square. Find the locus of P when the line moves, always remaining parallel to BE . Describe the locus exactly, and prove the correctness of your answer.

Ex. 1074. Let $ABCD$ be any parallelogram, and from any point P in the diagonal AC draw the straight line PM cutting AB in M , BC in N , CD in L , and AD in K . Prove that $PM \cdot PN = PK \cdot PL$.

Ex. 1075. Find the area of a segment of a circle whose height is 4 inches and chord $8\sqrt{3}$ inches.

Ex. 1076. A square, whose side is 5 inches long, has its corners cut off in such a way as to make it into a regular octagon. Find the area and the perimeter of the octagon.

Ex. 1077. Into what numbers of arcs less than 15 can the circumference of a circle be divided with ruler and compasses only?

Ex. 1078. Through a point A on the circumference of a circle chords are drawn. On each one of these chords a point is taken one third of the distance from A to the other end of the chord. Find the locus of these points, and prove that your answer is correct.

Ex. 1079. In what class of triangles do the altitudes meet within the triangle? on the boundary? outside the triangle? Prove.

Ex. 1080. Given a triangle ABC and a fixed point D on side AC ; draw the line through D which divides the triangle into two parts of equal area.

Ex. 1081. The sides of a triangle are 5, 12, 13. Find the radius of the circle whose area is equal to that of the triangle.

Ex. 1082. In a triangle ABC the angle C is a right angle, and the lengths of AC and BC are 5 and 12 respectively; the hypotenuse BA is prolonged through A to a point D so that the length of AD is 4; CA is prolonged through A to E so that the triangles AED and ABC have equal areas. What is the length of AE ?

Ex. 1083. Given three points A , B , and C , not in the same straight line; through A draw a straight line such that the distances of B and C from the line shall be equal.

Ex. 1084. Given two straight lines that cut each other; draw four circles of given radius that shall be tangent to both of these lines.

Ex. 1085. Construct two straight lines whose lengths are in the ratio of the areas of two given polygons.

Ex. 1086. The radius of a regular inscribed polygon is a mean proportional between its apothem and the radius of the similar circumscribed polygon.

Ex. 1087. Draw a circumference which shall pass through two given points and bisect a given circumference.

Ex. 1088. A parallelogram is constructed having its sides equal and parallel to the diagonals of a given parallelogram. Show that its diagonals are parallel to the sides of the given parallelogram.

HINT. Look for similar triangles.

Ex. 1089. If two chords are divided in the same ratio at their point of intersection, the chords are equal.

Ex. 1090. The sides AB and AC of a triangle ABC are bisected in D and E respectively. Prove that the area of the triangle DBC is twice that of the triangle DEB .

Ex. 1091. Two circles touch externally. How many common tangents have they? Give a construction for the common tangents.

Ex. 1092. Prove that the tangents at the extremities of a chord of a circle are equally inclined to the chord.

Ex. 1093. Two unequal circles touch externally at P ; line AB touches the circles at A and B respectively. Prove angle APB a right angle.

Ex. 1094. Find a point within a triangle such that the lines joining this point to the vertices shall divide the triangle into three equivalent parts.

Ex. 1095. A triangle ABC is inscribed in a circle. The angle B is equal to 50° and the angle C is equal to 60° . What angle does a tangent at A make with BC prolonged to meet it?

Ex. 1096. The bases of a trapezoid are 8 and 12, and the altitude is 6. Find the altitudes of the two triangles formed by prolonging the non-parallel sides until they intersect.

Ex. 1097. The circumferences of two circles intersect in the points A and B . Through A a diameter of each circle is drawn, viz. AC and AD . Prove that the straight line joining C and D passes through B .

Ex. 1098. How many lines can be drawn through a given point in a plane so as to form in each case an isosceles triangle with two given lines in the plane?

Ex. 1099. The lengths of two chords drawn from the same point in the circumference of a circle to the extremities of a diameter are 5 feet and 12 feet respectively. Find the area of the circle.

Ex. 1100. Through a point 21 inches from the center of a circle whose radius is 15 inches a secant is drawn. Find the product of the whole secant and its external segment.

Ex. 1101. The diagonals of a rhombus are 24 feet and 40 feet respectively. Compute its area.

Ex. 1102. On the sides AB, BC, CA of an equilateral triangle ABC measure off segments AD, BE, CF , respectively, each equal to one third the length of a side; draw triangle DEF ; prove that the sides of triangle DEF are perpendicular respectively to the sides of triangle ABC .

Ex. 1103. Construct x if (a) $\frac{2}{x} = \frac{x}{3}$; (b) $x = a\sqrt{5}$.

Ex. 1104. Find the area included between a circumference of radius 7 and an inscribed square.

Ex. 1105. What is the locus of the center of a circle of given radius whose circumference cuts at right angles a given circumference?

Ex. 1106. Two chords of a certain circle bisect each other. One of them is 10 inches long; how far is it from the center of the circle?

Ex. 1107. Show how to find on a given straight line of indefinite length a point O which shall be equidistant from two given points A and B in the plane. If A and B lie on a straight line which cuts the given line at an angle of 45° at a point 7 inches distant from A and 17 inches from B , show that OA will be 13 inches.

Ex. 1108. A variable chord passes, when prolonged, through a fixed point outside of a given circle. What is the locus of the mid-point of the chord?

Ex. 1109. A certain parallelogram inscribed in a circle has two sides 20 feet in length and two sides 15 feet in length. What are the lengths of the diagonals?

Ex. 1110. Upon a given base is constructed a triangle one of the base angles of which is double the other. The bisector of the larger base angle meets the opposite side at the point P . Find the locus of P .

Ex. 1111. What is the locus of the point of contact of tangents drawn from a fixed point to the different members of a system of concentric circles?

Ex. 1112. Find the locus of all points, the perpendicular distances of which from two intersecting lines are to each other as 3 to 2.

Ex. 1113. The sides of a triangle are a , b , c . Find the lengths of the three medians.

Ex. 1114. Given two triangles; construct a square equivalent to their sum.

Ex. 1115. In a circle whose radius is 10 feet, two parallel chords are drawn, each equal to the radius. Find the area of the portion between these chords.

Ex. 1116. A has a circular garden and B one that is square. The distance around each is the same, namely, 120 rods. Which has the more land, A or B? How much more has he?

Ex. 1117. Prove that the sum of the angles of a pentagram (a five-pointed star) is equal to two right angles.

Ex. 1118. AB and $A'B'$ are any two chords of the outer of two concentric circles; these chords intersect the circumference of the inner circle in points P , Q and P' , Q' respectively: prove that $AP \cdot PB = A'P' \cdot P'B'$.

Ex. 1119. A running track consists of two parallel straight portions joined together at the ends by semicircles. The extreme length of the plot inclosed by the track is 176 yards. If the inside line of the track is a quarter of a mile in length, find the cost of seeding this plot at $\frac{1}{4}$ cent a square yard. ($\pi = \frac{22}{7}$.)

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FORMULAS OF PLANE GEOMETRY

570. In addition to the notation given in § 270, the following will be used :

| | |
|--|--|
| a = side of polygon in general. | p = projection of b upon a . |
| b = base of a plane figure. | R = radius of circle, or radius of regular polygon. |
| b, b' = bases of a trapezoid. | r = apothem of regular polygon, or radius of inscribed circle. |
| C = circumference of a circle. | s = the longer of two segments of a line ; or |
| D = diameter of a circle. | $s = \frac{1}{2}(a + b + c)$. |
| E = sum of exterior angles of a polygon. | X = angle in general. |
| h = altitude of a plane figure. | x_a = side of a triangle opposite an acute angle. |
| I = sum of interior angles of a polygon. | x_o = side of a triangle opposite an obtuse angle. |
| K = area of a figure in general. | |
| l = line in general. | |
| P = perimeter of polygon in general. | |

| FIGURE | FORMULA | REFERENCE |
|-------------------------------------|---|--------------|
| Any triangle. | $A + B + C = 180^\circ$. | § 204. |
| Polygon. | $I = (n - 2)180^\circ$. | §§ 216, 219. |
| | $E = 4 \text{ rt. } \angle$. | § 218. |
| Central angle. | $X \propto$ intercepted arc. | § 358. |
| Inscribed angle. | $X \propto \frac{1}{2}$ intercepted arc. | § 365. |
| Angle formed by two chords. | $X \propto \frac{1}{2}$ sum of arcs. | § 377. |
| Angle formed by tangent and chord. | $X \propto \frac{1}{2}$ intercepted arc. | § 378. |
| Angle formed by two secants. | $X \propto \frac{1}{2}$ difference of arcs. | § 379. |
| Angle formed by secant and tangent. | $X \propto \frac{1}{2}$ difference of arcs. | § 379. |
| Angle formed by two tangents. | $X \propto \frac{1}{2}$ difference of arcs. | § 379. |
| Similar polygons. | $\frac{P}{P'} = \frac{a}{a'}$. | § 441. |
| Right triangle. | $c^2 = a^2 + b^2$. | § 446. |
| Any triangle. | $x_a^2 = a^2 + b^2 - 2ap$. | § 452. |
| Obtuse triangle. | $x_o^2 = a^2 + b^2 + 2ap$. | § 455. |

| FIGURE | FORMULA | REFERENCE |
|---|---|--------------------|
| Any triangle. | $b^2 + c^2 = 2\left(\frac{a}{2}\right)^2 + 2m_a^2.$ | § 457. |
| Line divided in extreme and mean ratio. | $l : s = s : l - s.$ | § 465 and Ex. 763. |
| Rectangle. | $K = b \cdot h.$ | § 475. |
| Square. | $K = a^2.$ | § 478. |
| Parallelogram. | $K = b \cdot h.$ | § 481. |
| Triangle. | $K = \frac{1}{2} b \cdot h.$ | § 485. |
| | $h_a = \frac{2}{a} \sqrt{s(s-a)(s-b)(s-c)}.$ | § 490. |
| | $K = \sqrt{s(s-a)(s-b)(s-c)}.$ | § 490. |
| | $K = \frac{1}{2}(a+b+c)r.$ | § 491. |
| Polygon. | $K = \frac{1}{2} P \cdot r.$ | § 492. |
| Circle inscribed in triangle. | $r = \frac{\sqrt{s(s-a)(s-b)(s-c)}}{s}.$ | Ex. 837. |
| Circle circumscribed about triangle. | $R = \frac{abc}{4\sqrt{s(s-a)(s-b)(s-c)}}.$ | Ex. 838. |
| Bisector of angle of triangle. | $t_a = \frac{2}{b+c} \sqrt{bcs(s-a)}.$ | Ex. 841. |
| Trapezoid. | $K = \frac{1}{2}(b+b')h.$ | § 495. |
| Regular polygons of same number of sides. | $\frac{P}{P'} = \frac{R}{R'} = \frac{r}{r'}.$ | § 538. |
| | $\frac{K}{K'} = \frac{R^2}{R'^2} = \frac{r^2}{r'^2}.$ | § 539. |
| Circles. | $\frac{C}{2R} = \frac{C'}{2R'}.$ | § 553. |
| | $C = 2\pi R.$ | § 555. |
| | $\frac{C}{C'} = \frac{R}{R'}.$ | § 556. |
| Regular polygon. | $K = \frac{1}{2} P \cdot r.$ | § 557. |
| Circle. | $K = \frac{1}{2} C \cdot R.$ | § 559. |
| | $K = \pi R^2.$ | § 562. |
| Circles. | $\frac{K}{K'} = \frac{R^2}{R'^2} = \frac{D^2}{D'^2}.$ | § 563. |
| Sector. | $K = \frac{\text{central } \angle}{360^\circ} \pi R^2.$ | § 564. |
| Segment. | $K = \text{sector} \mp \text{triangle}.$ | Ex. 1009. |

APPENDIX TO PLANE GEOMETRY

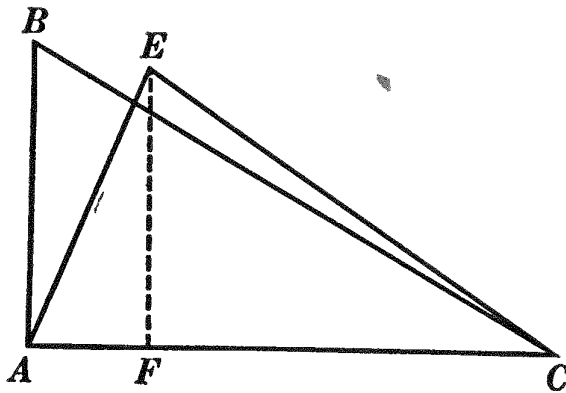
MAXIMA AND MINIMA

571. Def. Of all geometric magnitudes that satisfy given conditions, the greatest is called the **maximum**, and the least is called the **minimum**.*

572. Def. **Isoperimetric figures** are figures which have the same perimeter.

PROPOSITION I. THEOREM

573. *Of all triangles having two given sides, that in which these sides include a right angle is the maximum.*



Given $\triangle ABC$ and $\triangle AEC$, with AB and AC equal to AE and AC respectively. Let $\angle CAB$ be a rt. \angle and $\angle CAE$ an oblique \angle .

To prove $\triangle ABC > \triangle AEC$.

Draw the altitude EF .

$\triangle ABC$ and $\triangle AEC$ have the same base, AC .

Altitude $AB >$ altitude EF .

$\therefore \triangle ABC > \triangle AEC$.

Q.E.D.

574. Cor. I. *Conversely, if two sides are given, and if the triangle is a maximum, then the given sides include a right angle.*

HINT. Prove by *reductio ad absurdum*.

* In later mathematics a somewhat broader use will be made of these terms.

575. Cor. II. *Of all parallelograms having given sides, the one that is rectangular is a maximum, and conversely.*

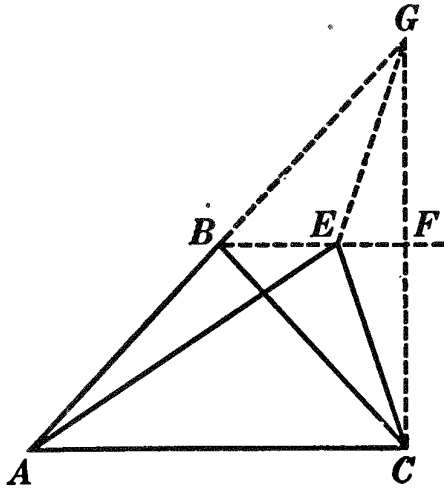
Ex. 1135. Construct the maximum parallelogram having two lines of given lengths as diagonals.

Ex. 1136. What is the minimum line from a given point to a given line?

Ex. 1137. Of all triangles having the same base and altitude, that which is isosceles has the minimum perimeter.

PROPOSITION II. THEOREM

576. *Of all equivalent triangles having the same base, that which is isosceles has the least perimeter.*



Given equivalent $\triangle ABC$ and AEC with the same base AC , and let $AB = BC$ and $AE \neq EC$.

To prove $AB + BC + CA < AE + EC + CA$.

Draw $CF \perp AC$ and let CF meet the prolongation of AB at G . Draw EG and BE and prolong BE to meet GC at F .

$BF \parallel AC$.

$\angle CBF = \angle FBG$.

BF bisects CG and is $\perp CG$.

$\therefore BC = BG$ and $EC = EG$.

$$AB + BG < AE + EG.$$

$$\therefore AB + BC < AE + EC.$$

$$\therefore AB + BC + CA < AE + EC + CA.$$

Q.E.D.

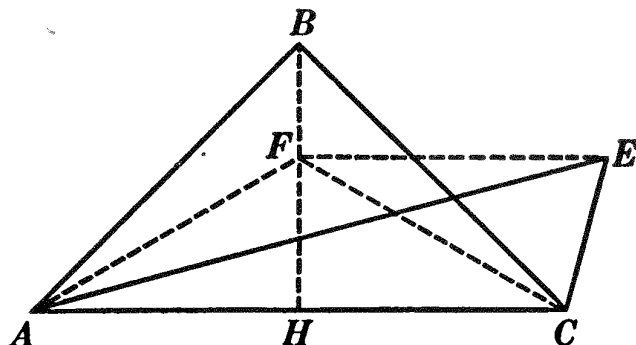
Ex. 1138. Of all equivalent triangles having the same base, that which has the least perimeter is isosceles. (Prove by *reductio ad absurdum*.)

Ex. 1139. Of all equivalent triangles, the one that has the minimum perimeter is equilateral.

Ex. 1140. State and prove the converse of Ex. 1139.

PROPOSITION III. THEOREM

577. *Of all isoperimetric triangles on the same base, the isosceles triangle is the maximum.*



Given isosceles $\triangle ABC$ and any other \triangle as AEC having the same base and the same perimeter as $\triangle ABC$.

To prove $\triangle ABC > \triangle AEC$.

Draw $BH \perp AC$, EF from $E \parallel AC$, and draw AF and FC .

$\triangle AFC$ is isosceles.

\therefore perimeter of $\triangle AFC <$ perimeter of $\triangle AEC$.

\therefore perimeter of $\triangle AFC <$ perimeter of $\triangle ABC$.

$\therefore AF < AB$.

$\therefore FH < BH$.

$\therefore \triangle AFC < \triangle ABC$.

$\therefore \triangle AEC < \triangle ABC$; i.e. $\triangle ABC > \triangle AEC$.

Q.E.D.

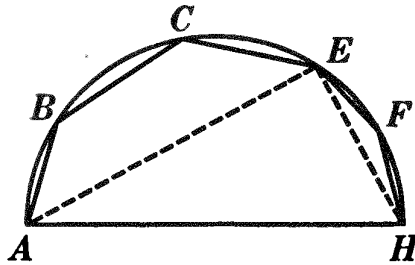
Ex. 1141. Of all triangles having a given perimeter and a given base, the one that has the maximum area is isosceles.

Ex. 1142. What is the maximum chord of a circle? What is the maximum and what the minimum line that can be drawn from a given exterior point to a given circumference?

Ex. 1143. Of all triangles having a given perimeter, the one that has the maximum area is equilateral.

PROPOSITION IV. THEOREM

578. *Of all polygons having all their sides but one equal, respectively, to given lines taken in order, the maximum can be inscribed in a semicircle having the undetermined side as diameter.*



Given polygon $ABCEFH$, the maximum of all polygons subject to the condition that AB, BC, CE, EF, FH , are equal respectively to given lines taken in order.

To prove that the semicircumference described with AH as diameter passes through B, C, E , and F .

Suppose that the semicircumference with AH as diameter does not pass through some vertex, as E . Draw AE and EH .

Then $\angle AEH$ is not a rt. \angle .

Then if the figures $ABCE$ and EFH are revolved about E until AEH becomes a rt. \angle , $\triangle AEH$ will be increased in area.

\therefore polygon $ABCEFH$ can be increased in area without changing any of the given sides.

But this contradicts the hypothesis that polygon $ABCEFH$ is a maximum.

\therefore the supposition that vertex E is not on the semicircumference is false.

\therefore the semicircumference passes through E .

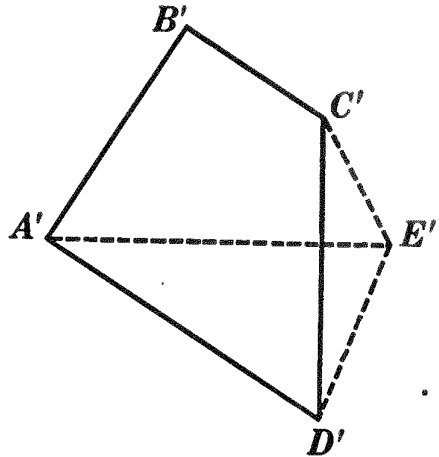
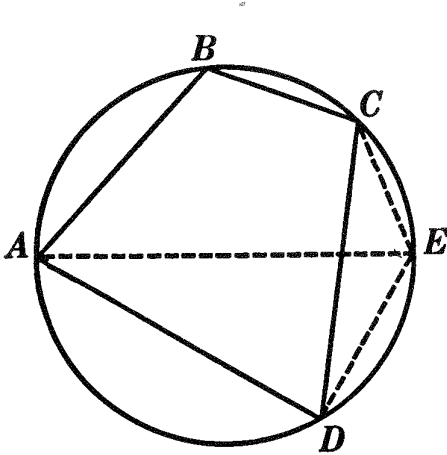
In the same way it may be proved that every vertex of the polygon lies on the semicircumference. Q.E.D.

Ex. 1144. Given the base and the vertex angle of a triangle, construct the triangle so that its area shall be a maximum.

Ex. 1145. Find the point in a given straight line such that the tangents drawn from it to a given circle contain a maximum angle.

PROPOSITION V. THEOREM

579. *Of all polygons that have their sides equal, respectively, to given lines taken in order, the polygon that can be circumscribed by a circle is a maximum.*



Given polygon $ABCD$ which is circumscribed by a \odot , and polygon $A'B'C'D'$ which cannot be circumscribed by a \odot , with $AB = A'B'$, $BC = B'C'$, $CD = C'D'$, and $DA = D'A'$.

To prove $ABCD > A'B'C'D'$.

From any vertex as A draw diameter AE ; draw EC and ED . On $C'D'$, which equals CD , construct $\triangle D'C'E'$ equal to $\triangle DCE$; draw $A'E'$.

The circle whose diameter is $A'E'$ does not pass through all the points B' , C' , D' . (Hyp.)

\therefore either $ABCE$ or EDA or both must be greater, and neither can be less, than the corresponding part of polygon $A'B'C'E'D'$ (§ 578).

$$\therefore ABCED > A'B'C'E'D'. \quad \text{But } \triangle DCE = \triangle D'C'E'.$$

$$\therefore ABCD > A'B'C'D'.$$

Q.E.D.

Ex. 1146. In a given semicircle inscribe a trapezoid whose area is a maximum.

Ex. 1147. Of all equilateral polygons having a given side and a given number of sides, the one that is regular is a maximum.

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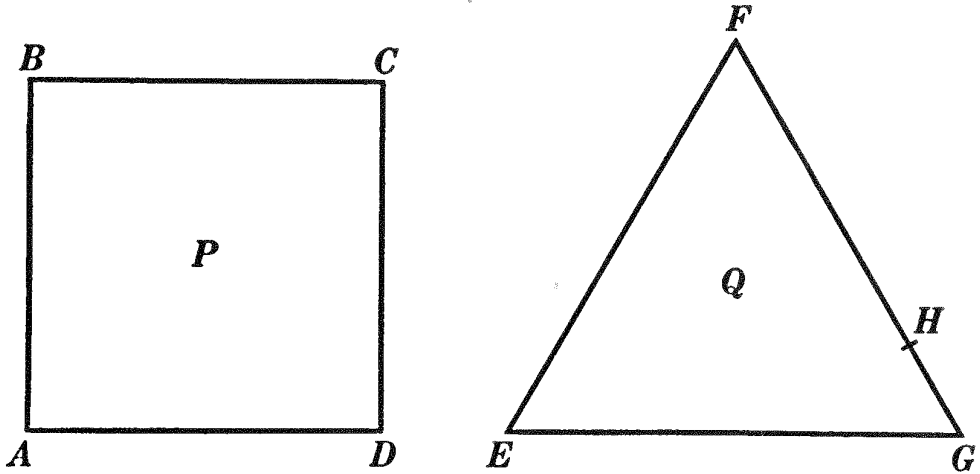
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PROPOSITION VII. THEOREM

582. *Of two isoperimetric regular polygons, that which has the greater number of sides has the greater area.*



Given the isoperimetric polygons P and Q , and let P have one more side than Q .

To prove $P > Q$.

In one side of Q take any point as H .

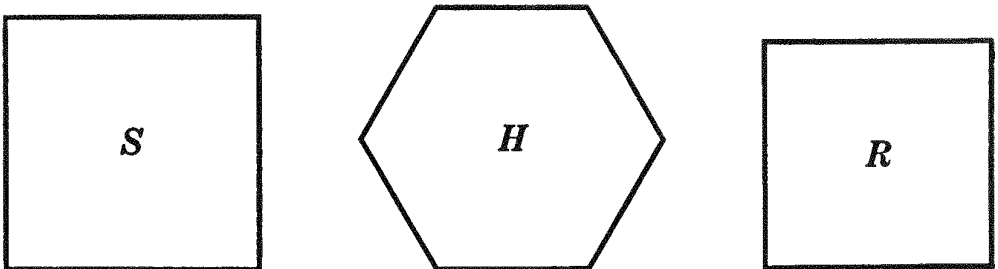
$EFHG$ may be considered as an irregular polygon having the same number of sides as P .

$\therefore P > EFHG$; i.e. $P > Q$.

Q.E.D.

PROPOSITION VIII. THEOREM

583. *Of two equivalent regular polygons, that which has the greater number of sides has the smaller perimeter.*



Given square $S \cong$ regular hexagon H .

To prove perimeter of $S >$ perimeter of H .

Construct square R isoperimetric with H .

Area of $H >$ area of R ; *i.e.* area of $S >$ area of R .

\therefore perimeter of $S >$ perimeter of R .

\therefore perimeter of $S >$ perimeter of H .

Q.E.D.

584. Cor. *Of all polygons having a given number of sides and a given area, that which has a minimum perimeter is regular.*

Ex. 1149. Among the triangles inscribed in a given circle, the one that has a maximum perimeter is equilateral.

Ex. 1150. Of all polygons having a given number of sides and inscribed in a given circle, the one that has a maximum perimeter is regular.

VARIABLES AND LIMITS. THEOREMS

PROPOSITION I. THEOREM

585. *If a variable can be made less than any assigned value, the product of the variable and any constant can be made less than any assigned value.*

Given a variable V , which can be made less than any previously assigned value, however small, and let K be any constant.

To prove that $V \cdot K$ may be made as small as we please, *i.e.* less than any assigned value.

Assign any value, as a , no matter how small.

Now a value for V may be found as small as we please.

Take $V < \frac{a}{K}$. Then $V \cdot K < a$; *i.e.* $V \cdot K$ may be made less than any assigned value. Q.E.D.

586. Cor. I. *If a variable can be made less than any assigned value, the quotient of the variable by any constant, except zero, can be made less than any assigned value.*

HINT. $\frac{V}{K} = \frac{1}{K} \cdot V$, which is the product of the variable and a constant.

587. Cor. II. *If a variable can be made less than any assigned value, the product of that variable and a de-*

creasing value may be made less than any assigned value.

HINT. Apply the preceding theorem, using as K a value greater than any value of the decreasing multiplier.

588. Cor. III. *The product of a variable and a variable may be a constant or a variable.*

589. Cor. IV. *If a variable can be made less than any assigned value, the square of that variable can be made less than any assigned value. (Apply Cor. II.)*

Ex. 1151. Which of the corollaries under Prop. I is illustrated by the theorem: "The product of the segments of a chord drawn through a fixed point within a circle is constant" ?

PROPOSITION II. THEOREM

590. *The limit of the product of a variable and a constant, not zero, is the limit of the variable multiplied by the constant.*

Given any variable V which approaches the finite limit L , and let K be any constant not zero.

To prove the limit of $K \cdot V = K \cdot L$.

Let $R = L - V$; then $V = L - R$.

$\therefore K \cdot V = K \cdot L - K \cdot R$.

But the limit of $K \cdot R = 0$.

\therefore the limit of $K \cdot V =$ the limit of $(K \cdot L - K \cdot R) = K \cdot L$.

Q.E.D.

591. Cor. *The limit of the quotient of a variable by a constant is the limit of the variable divided by the constant.*

HINT. $\frac{V}{K} = \frac{1}{K} \cdot V$, which is the product of the variable and a constant.

PROPOSITION III. THEOREM

592. *If two variables approach finite limits, not zero, then the limit of their product is equal to the product of their limits.*

Given variables V and V' which approach the finite limits L and L' , respectively.

To prove the limit of $V \cdot V' = L \cdot L'$.

Let $R = L - V$ and $R' = L' - V'$.

Then $V = L - R$ and $V' = L' - R'$.

$\therefore V \cdot V' = L \cdot L' - (L' \cdot R + L \cdot R' - R \cdot R')$.

But the limit of $(L' \cdot R + L \cdot R' - R \cdot R') = 0$.

\therefore the limit of $V \cdot V' =$ the limit of $[L \cdot L' - (L' \cdot R + L \cdot R' - R \cdot R')] = L \cdot L'$.

\therefore the limit of $V \cdot V' = L \cdot L'$.

Q.E.D.

593. Cor. *If each of any finite number of variables approaches a finite limit, not zero, then the limit of their product is equal to the product of their limits.*

PROPOSITION IV. THEOREM

594. *If two related variables are such that one is always greater than the other, and if the greater continually decreases while the less continually increases, so that the difference between the two may be made as small as we please, then the two variables have a common limit which lies between them.*



Given the two related variables AP and AP' , AP' greater than AP , and let AP and AP' be such that as AP increases AP' shall decrease, so that the difference between AP and AP' shall approach zero as a limit.

To prove that AP and AP' have a common limit, as AL , which lies between AP and AP' .

Denote successive values of AP by AQ , AR , etc., and denote the corresponding values of AP' by AQ' , AR' , etc.

Since every value which AP assumes is less than any value which AP' assumes (Hyp.) $\therefore AP < AR'$.

\therefore But AP is continually increasing.



Hence AP has some limit. (By def. of a limit, § 349.)

Since any value which AP' assumes is greater than every value which AP assumes (Hyp.) $\therefore AP' > AR$.

But AP' is continually decreasing.

Hence AP' has some limit. (By def. of a limit, § 349.)

Suppose the limit of $AP \neq$ the limit of AP' .

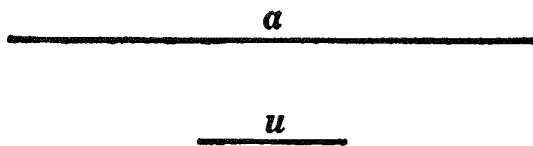
Then let the limit of AP be AK , while that of AP' is AK' . Then AK and AK' have some finite values, as m and m' , and their difference is a finite value, as d .

But the difference between some value of AP and the corresponding value of AP' cannot be less than the difference of the two limits AK and AK' .

This contradicts the hypothesis that the difference between AP and AP' shall approach zero as a limit.

\therefore the limit of $AP =$ the limit of AP' and lies between AP and AP' , as AL . Q.E.D.

595. THEOREM. *With every straight line segment there is associated a number which may be called its measure-number.*



For line segments commensurable with the unit this theorem was considered in §§ 335 and 336; we shall now consider the case where the segment is incommensurable with the chosen unit.

Given the straight line segment a and the unit segment u ; to express a in terms of u .

Apply u (as a measure) to a as many times as possible, suppose t times, then

$$t \cdot u < a < (t + 1) u.$$

Now apply some fractional part of u , say $\frac{u}{n}$, to a , and sup-

pose it is contained t_1 times, then

$$\frac{t_1}{p} \cdot u < a < \frac{t_1 + 1}{p} \cdot u.$$

Then apply smaller and smaller fractional parts of u to a , say $\frac{1}{p^2}$, $\frac{1}{p^3}$, $\frac{1}{p^4}$, \dots , and suppose them to be contained t_2, t_3, t_4, \dots times respectively, then

$$\frac{t_2}{p^2} \cdot u < a < \frac{t_2 + 1}{p^2} \cdot u, \quad \frac{t_3}{p^3} \cdot u < a < \frac{t_3 + 1}{p^3} \cdot u, \quad \dots$$

Now the infinite series of increasing numbers $t, \frac{t_1}{p}, \frac{t_2}{p^2}, \dots$, none of which exceeds the finite number $t + 1$, defines a number n (the limit of this series) which we shall call the measure-number of a with respect to u . Moreover, this number n is unique, *i.e.* independent of p (the number of parts into which the unit was divided), for if m is any number such that $m < n$, then $m \cdot u < a$, and if $m > n$, then $m \cdot u > a$; we are therefore justified in associating the number n with a , and in saying that $n \cdot u = a$.

596. Note. Manifestly, the above procedure may be applied to any geometric magnitude whatever, *i.e.* every geometric magnitude has a unique measure-number.

597. Cor. *If a magnitude is variable and approaches a limit, then, as the magnitude varies, the successive measure-numbers of the variable approach as their limit the measure-number of the limit of the magnitude.*

598. Discussion of the problem :

To determine whether two given lines are commensurable or not; and if they are commensurable, to find their common measure and their ratio (§ 345).

Moreover, GD is the greatest common measure of AB and CD . For every measure of AB is a measure of its multiple CE . Hence, every common measure of AB and CD is a common measure of CE and CD and therefore a measure of their differ-

ence ED , and therefore of AF , which is a multiple of ED . Hence, every common measure of AB and CD is a common measure of AB and AF and therefore a measure of their difference FB . Again, every common measure of ED and FB is a common measure of ED and EG (a multiple of FB) and hence of their difference GD . Hence, no common measure of AB and CD can exceed GD . Therefore, GD is the *greatest* common measure of AB and CD .

Now, if AB and CD are *commensurable*, the process must terminate; for any common measure of AB and CD is a measure of each remainder, and every segment applied as a measure is less than the preceding remainder. Now, if the process did not terminate, a remainder could be reached which would be less than any assigned value, however small, and therefore less than the greatest common measure, which is absurd.

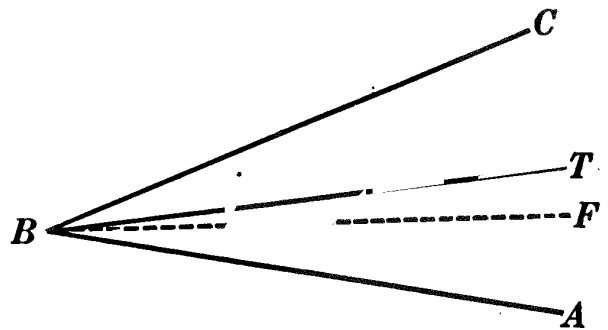
If AB and CD are *incommensurable*, the process will not terminate; for, if it did, the last remainder obtained would be a common measure of AB and CD , as shown above.

599. THEOREM. *An angle can be bisected by only one line.*

Given $\angle ABC$, bisected by BT .

To prove that no other bisector of $\angle ABC$ exists.

Suppose that another bisector of $\angle ABC$ exists, e.g. BF .



Then $\angle ABF = \angle ABT$. This is impossible.

\therefore no other bisector of $\angle ABC$ exists.

Q.E.D.

600. Note on Axioms. The thirteen axioms (§ 54) refer to *numbers* and may be used when referring to the *measure-numbers* of geometric magnitudes. Axioms 2–9 are not applicable always to *equal figures*. (See Exs. 800 and 801.) Axioms 7 and 8 hold for positive numbers only, but do not hold for negative numbers, for zero, nor for infinity; axioms 11 and 12 hold only when the number of parts is finite.

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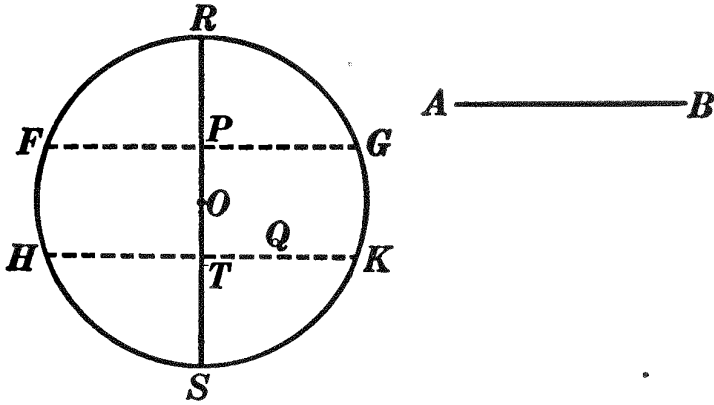
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(b) *The locus of the mid-points of all chords of a circle parallel to a given line is the diameter perpendicular to the line.*



Given circle O , line AB , and diameter $RS \perp AB$.

To prove RS the locus of the mid-points of all chords of circle O that are $\parallel AB$.

| ARGUMENT | REASONS |
|--|------------|
| 1. Let P be any point in diameter RS . Through P draw $FG \parallel AB$. | 1. § 179. |
| 2. Now $RS \perp AB$. | 2. By hyp. |
| 3. $\therefore RS \perp FG$. | 3. § 193. |
| 4. $\therefore P$ is the mid-point of FG , a chord $\parallel AB$. | 4. § 302. |
| 5. Let Q be any point not in diameter RS . Through Q draw $HK \parallel AB$, intersecting RS in T . | 5. § 179. |
| 6. Then $RS \perp HK$. | 6. § 193. |
| 7. $\therefore T$ is the mid-point of HK , <i>i.e.</i> Q is not the mid-point of HK , a chord $\parallel AB$. | 7. § 302. |
| 8. $\therefore RS$ is the locus of the mid-points of all chords of circle O that are $\parallel AB$. | 8. § 130 |

Q.E.D.

SOLID GEOMETRY

BOOK VI

LINES, PLANES, AND ANGLES IN SPACE

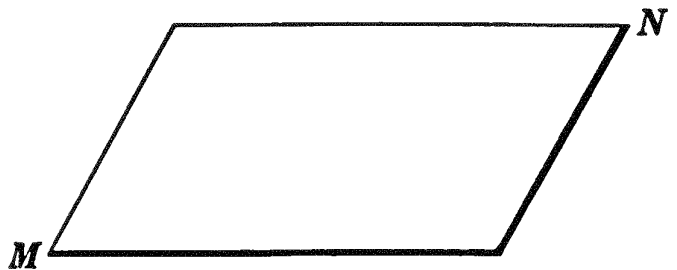
602. Def. Solid geometry or the geometry of space treats of figures whose parts are not all in the same plane. (For definition of *plane* or *plane surface*, see § 34.)

603. From the definition of a plane it follows that:

(a) *If two points of a straight line lie in a plane, the whole line lies in that plane.*

(b) *A straight line can intersect a plane in not more than one point.*

604. Since a plane is unlimited in its two dimensions (length and breadth) only a portion of it can be shown in a figure. This is usually represented by a quadrilateral drawn as a parallelogram. Thus MN represents a plane. Sometimes, however, conditions make it necessary to represent a plane by a figure other than a parallelogram, as in § 617.



Ex. 1152. Draw a rectangle freehand which is supposed to lie: (a) in a vertical plane; (b) in a horizontal plane. May the four angles of the rectangle of (a) be drawn equal? those of the rectangle of (b)?

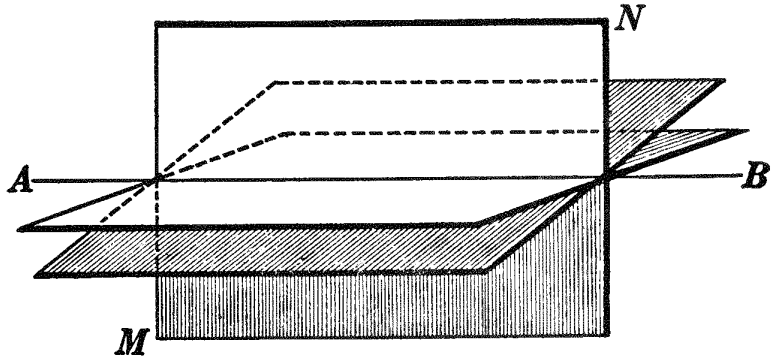
605. Note. In the figures in solid geometry dashed lines will be used to represent all auxiliary lines and lines that are not supposed to be visible but which, for purposes of proof, are represented in the figure. All other lines will be continuous. In the earlier work in solid geometry the student may experience difficulty in *imagining* the figures. If so, he may find it a great help, for a time at least, to *make* the figures. By using pasteboard to represent planes, thin sticks of wood or stiff wires to represent lines perpendicular to a plane, and strings to represent oblique lines, any figure may be actually made with a comparatively small expenditure of time and with practically no expense. For reproductions of models actually made by high school students, see group on p. 302 ; also §§ 622, 633, 678, 756, 762, 770, 797.

606. Assumption 20. Revolution postulate. *A plane may revolve about a line in it as an axis, and as it does so revolve, it can contain any particular point in space in one and only one position.*

607. From the revolution postulate it follows that:

Through a given straight line any number of planes may be passed.

For, as plane MN revolves about AB as an axis (§ 606) it may occupy an unlimited number of positions each of which will represent a different plane through AB .



608. Def. A plane is said to be **determined** by given conditions if that plane and no other plane fulfills those conditions.

609. From §§ 607 and 608 it is seen that:

A straight line does not determine a plane.

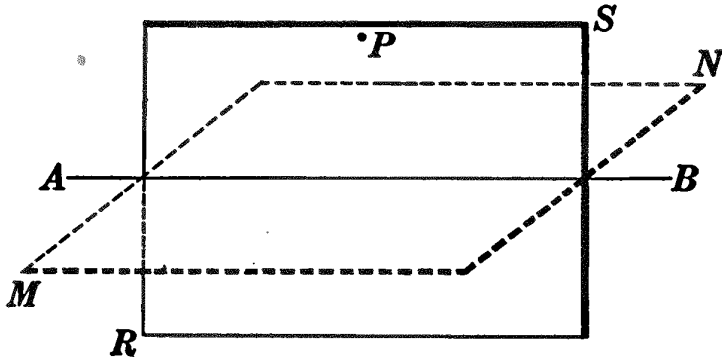
Ex. 1153. How many planes may be passed through any two points in space? why?

Ex. 1154. At a point P in a given straight line AB in space, construct a line perpendicular to AB . How many such lines can be drawn?

LINES AND PLANES

PROPOSITION I. THEOREM

610. *A plane is determined by a straight line and a point not in the line.*



Given line AB and P , a point not in AB .

To prove that AB and P determine a plane.

| ARGUMENT | REASONS |
|--|------------|
| 1. Through AB pass any plane, as MN . | 1. § 607. |
| 2. Revolve plane MN about AB as an axis until it contains point P . Call the plane in this position RS . | 2. § 606. |
| 3. Then plane RS contains line AB and point P . | 3. Arg. 2. |
| 4. Furthermore, in no other position can plane MN , in its rotation about AB , contain point P . | 4. § 606. |
| 5. $\therefore RS$ is the only plane that can contain AB and P . | 5. Arg. 4. |
| 6. $\therefore AB$ and P determine a plane. Q.E.D. | 6. § 608. |

611. Cor. I. *A plane is determined by three points not in the same straight line.*

HINT. Let A , B , and C be the three given points. Join A and B by a straight line, and apply § 610.

612. Cor. II. *A plane is determined by two intersecting straight lines.*

613. Cor. III. *A plane is determined by two parallel straight lines.*

Ex. 1155. Given line AB in space, and P a point not in AB . Construct, through P , a line perpendicular to AB .

Ex. 1156. Hold two pencils so that a plane can be passed through them. In how many ways can this be done, assuming that the pencils are lines? why?

Ex. 1157. Can two pencils be held so that no plane can be passed through them? If so, how?

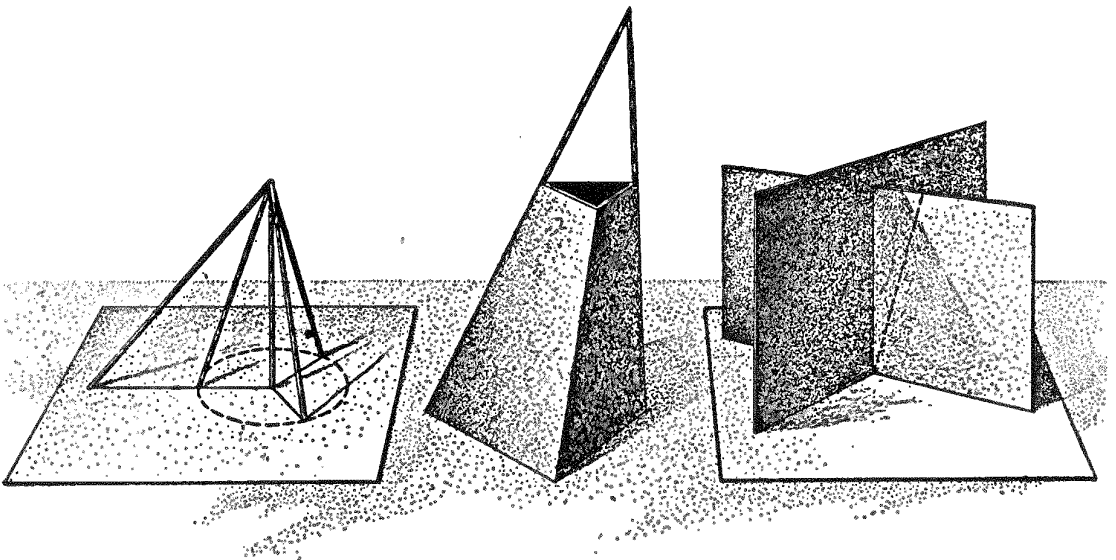
Ex. 1158. In measuring wheat with a half bushel measure, the measure is first heaped, then a straightedge is drawn across the top. Why is the measure then even full?

Ex. 1159. Why is a surveyor's transit or a photographer's camera always supported on three legs rather than on two or four?

Ex. 1160. How many planes are determined by four straight lines, no three of which lie in the same plane, if the four lines intersect: (1) at a common point? (2) at four different points?

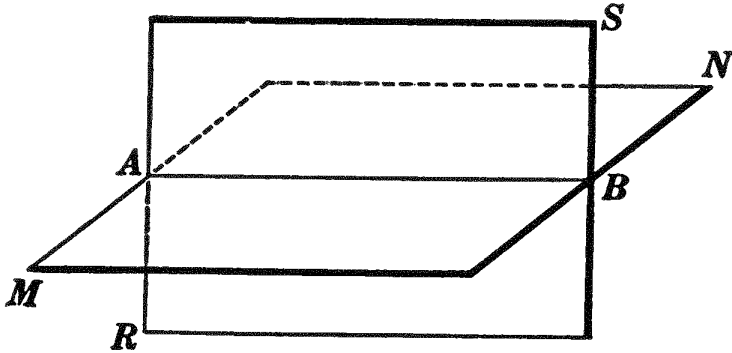
614. Def. The intersection of two surfaces is the locus of all points common to the two surfaces.

615. Assumption 21. Postulate. *Two planes having one point in common also have another point in common.*



PROPOSITION II. THEOREM

616. *If two planes intersect, their intersection is a straight line.*



Given intersecting planes MN and RS .

To prove the intersection of MN and RS a str. line.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Let A and B be any two points common to the two planes MN and RS . | 1. § 615. |
| 2. Draw str. line AB . | 2. § 54, 15. |
| 3. Since both A and B lie in plane MN , str. line AB lies in plane MN . | 3. § 603, <i>a</i> . |
| 4. Likewise str. line AB lies in plane RS . | 4. § 603, <i>a</i> . |
| 5. Furthermore no point outside of AB can lie in both planes. | 5. § 610. |
| 6. $\therefore AB$ is the intersection of planes MN and RS . | 6. § 614. |
| 7. But AB is a str. line. | 7. Arg. 2. |
| 8. \therefore the intersection of MN and RS is a str. line. Q.E.D. | 8. Args. 6 and 7. |

Ex. 1161. Is it possible for more than two planes to intersect in a straight line? Explain.

Ex. 1162. By referring to §§ 26 and 608, give the meaning of the expression, "Two planes determine a straight line."

Ex. 1163. Is the statement in Ex. 1162 always true? Give reasons for your answer.

PROPOSITION III. THEOREM

617. *If three planes, not passing through the same line, intersect each other, their three lines of intersection are concurrent, or else they are parallel, each to each.*

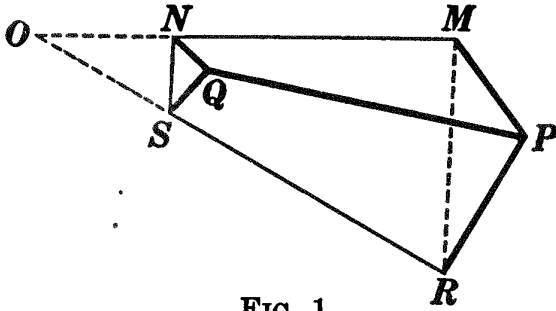


FIG. 1.

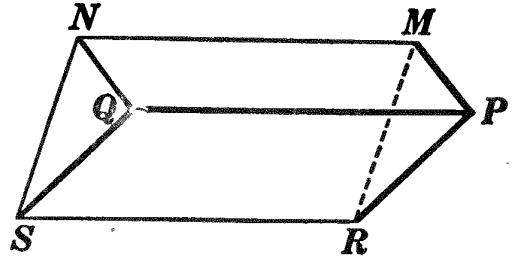


FIG. 2.

Given planes MQ , PS , and RN intersecting each other in lines MN , PQ , and RS ; also :

I. Given MN and RS intersecting at O (Fig. 1).

To prove MN , PQ , and RS concurrent.

| ARGUMENT | REASONS |
|---|----------------------|
| 1. $\because O$ is in line MN , it lies in plane MQ . | 1. § 603, <i>a</i> . |
| 2. $\because O$ is in line RS , it lies in plane PS . | 2. § 603, <i>a</i> . |
| 3. $\because O$, lying in planes MQ and PS , must lie in their intersection, PQ . | 3. § 614. |
| 4. $\therefore PQ$ passes through O ; <i>i.e.</i> MN , PQ , and RS are concurrent in O . Q.E.D. | 4. Arg. 3. |

II. Given $MN \parallel RS$ (Fig. 2).

To prove $PQ \parallel MN$ and RS .

| ARGUMENT | REASONS |
|---|-----------------------------|
| 1. PQ and MN are either \parallel or not \parallel . | 1. § 161, <i>a</i> . |
| 2. Suppose that PQ intersects MN ; then MN also intersects RS . | 2. § 617, I. |
| 3. But this is impossible, for $MN \parallel RS$. | 3. By hyp. |
| 4. $\therefore PQ \parallel MN$. | 4. § 161, <i>b</i> . |
| 5. Likewise $PQ \parallel RS$. Q.E.D. | 5. By steps similar to 1-4. |

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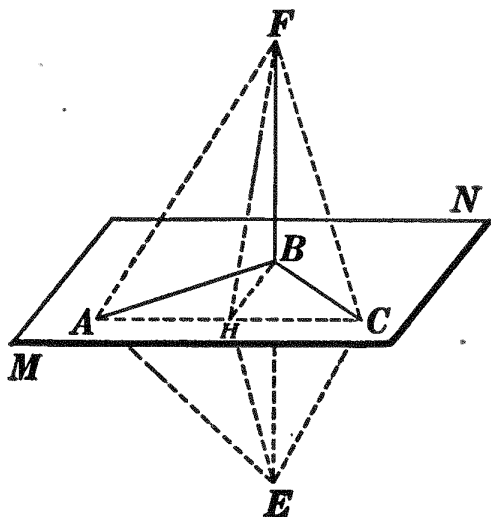
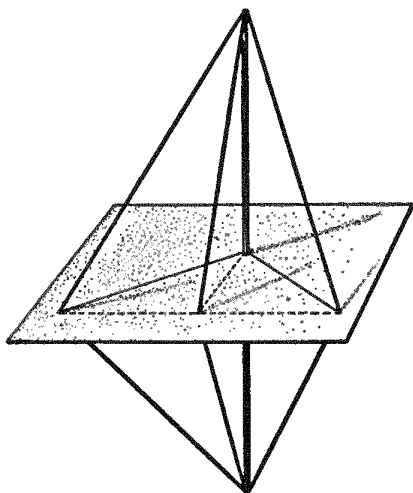
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PROPOSITION IV. THEOREM

622. *If a straight line is perpendicular to each of two intersecting straight lines at their point of intersection, it is perpendicular to the plane of those lines.*



Given str. line $FB \perp AB$ and to BC at B , and plane MN containing AB and BC .

To prove $FB \perp$ plane MN .

OUTLINE OF PROOF

1. In plane MN draw AC ; through B draw any line, as BH , meeting AC at H .
2. Prolong FB to E so that $BE = FB$; draw AF, HF, CF, AE, HE, CE .
3. AB and BC are then \perp bisectors of FE ; i.e. $FA = AE, FC = CE$.
4. Prove $\triangle AFC = \triangle EAC$; then $\angle HAF = \angle EAH$.
5. Prove $\triangle HAF = \triangle EAH$; then $HF = HE$.
6. $\therefore BH \perp FE$; i.e. $FB \perp BH$, any line in plane MN passing through B .
7. $\therefore FB \perp MN$.

623. **Cor.** *All the perpendiculars that can be drawn to a straight line at a given point in the line lie in a plane perpendicular to the line at the given point.*

PROPOSITION V. PROBLEM

624. Through a given point to construct a plane perpendicular to a given line.

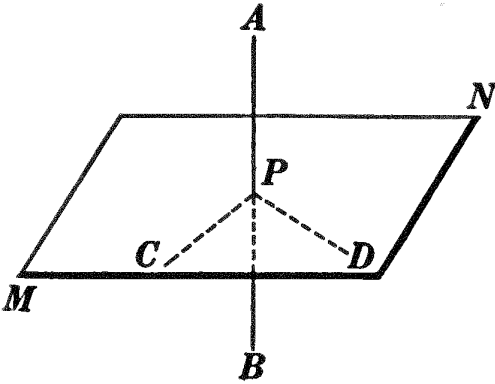


FIG. 1.

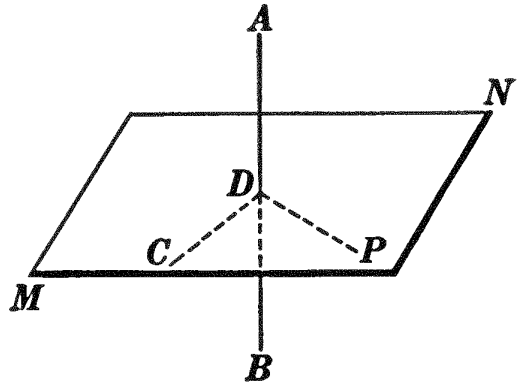


FIG. 2.

Given point P and line AB .

To construct, through P , a plane $\perp AB$.

I. Construction

1. Through line AB and point P pass a plane, as APD (in Fig. 1, any plane through AB). §§ 607, 610.
2. In plane APD construct PD , through P , $\perp AB$. §§ 148, 149.
3. Through AB pass a second plane, as ABC . § 607.
4. In plane ABC , through the foot of PD , construct a \perp to AB (PC in Fig. 1, DC in Fig. 2). § 148.
5. Plane MN , determined by C , D , and P , is the plane required.

II. The proof is left as an exercise for the student.

HINT. Apply § 623.

III. The discussion will be given in § 625.

Ex. 1164. Tell how to test whether or not a flag pole is erect.

Ex. 1165. Lines AB and CD are each perpendicular to line EF . Are AB and CD necessarily parallel? Explain. Do they necessarily lie in the same plane? why or why not?

PROPOSITION VI. THEOREM

625. *Through a given point there exists only one plane perpendicular to a given line.*

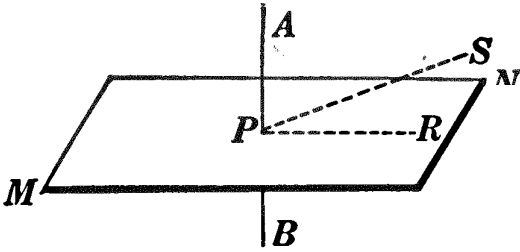


FIG. 1.

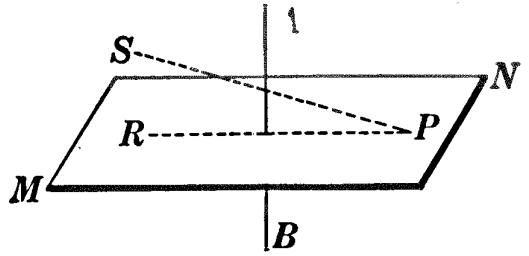


FIG. 2.

Given plane MN , through P , $\perp AB$.

To prove MN the only plane through $P \perp AB$.

ARGUMENT ONLY

1. Either MN is the only plane through $P \perp AB$ or it is not.
2. In MN draw a line through P intersecting line AB , as PR .
3. Let plane determined by AB and PR be denoted by APR .
4. Suppose that there exists another plane through $P \perp AB$; let this second plane intersect plane APR in line PS .
5. Then $AB \perp PR$ and also PS ; i.e. PR and PS are $\perp AB$.
6. This is impossible.
7. $\therefore MN$ is the only plane through $P \perp AB$. Q.E.D.

626. Question. In Fig. 2, explain why $AB \perp PS$.

627. §§ 624 and 625 may be combined in one statement:

Through a given point there exists one and only one plane perpendicular to a given line.

628. Cor. I. *The locus of all points in space equidistant from the extremities of a straight line segment is the plane perpendicular to the segment at its mid-point.*

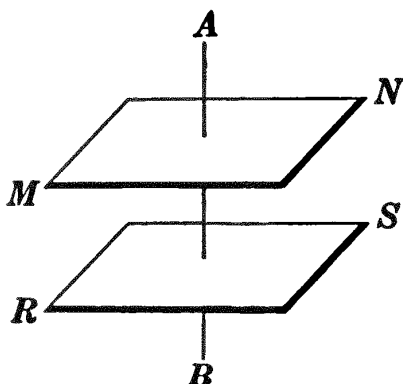
629. Def. A straight line is parallel to a plane if the straight line and the plane cannot meet.

630. Def. A straight line is oblique to a plane if it is neither perpendicular nor parallel to the plane.

631. Def. Two planes are parallel if they cannot meet.

PROPOSITION VII. THEOREM

632. *Two planes perpendicular to the same straight line are parallel.*



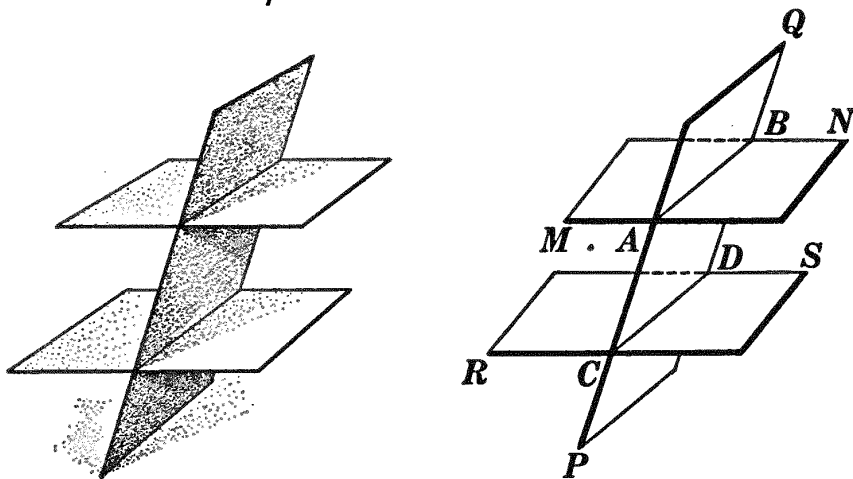
Given planes MN and RS , each \perp line AB .

To prove $MN \parallel RS$.

HINT. Use indirect proof. Compare with § 187.

PROPOSITION VIII. THEOREM

633. *If a plane intersects two parallel planes, the lines of intersection are parallel.*



Given \parallel planes MN and RS , and any plane PQ intersecting MN and RS in AB and CD , respectively.

To prove $AB \parallel CD$.

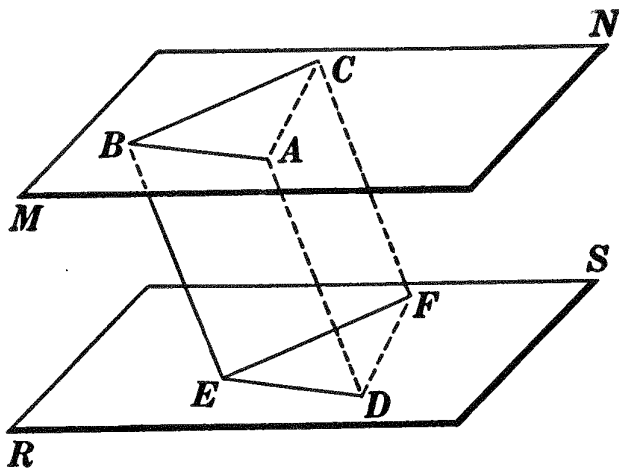
HINT. Show that AB and CD cannot meet.

634. Cor. I. *Parallel lines intercepted between the same parallel planes are equal.* (HINT. Compare with § 234.)

Ex. 1166. State the converse of Prop. VIII. Is it true?

PROPOSITION IX. THEOREM

635. *If two angles, not in the same plane, have their sides parallel respectively, and lying on the same side of the line joining their vertices, they are equal.**



Given $\angle ABC$ in plane MN and $\angle DEF$ in plane RS with BA and $BC \parallel$ respectively to ED and EF , and lying on the same side of line BE .

To prove $\angle ABC = \angle DEF$.

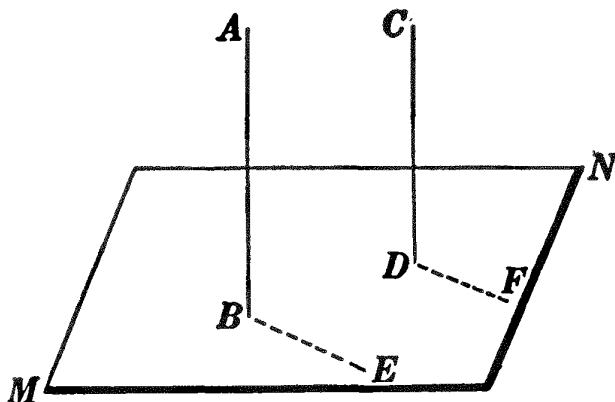
| ARGUMENT | REASONS |
|--|--------------|
| 1. Measure off $BA = ED$ and $BC = EF$. | 1. § 122. |
| 2. Draw AD , CF , AC , and DF . | 2. § 54, 15. |
| 3. $BA \parallel ED$ and $BC \parallel EF$. | 3. By hyp. |
| 4. Then $ADEB$ and $CFEB$ are \square . | 4. § 240. |
| 5. $\therefore AD = BE$ and $CF = BE$. | 5. § 232. |
| 6. $\therefore AD = CF$. | 6. § 54, 1. |
| 7. Also $AD \parallel BE$ and $CF \parallel BE$. | 7. § 220. |
| 8. $\therefore AD \parallel CF$. | 8. § 618. |
| 9. $\therefore ACFD$ is a \square . | 9. § 240. |
| 10. $\therefore AC = DF$. | 10. § 232. |
| 11. But $BA = ED$ and $BC = EF$. | 11. Arg. 1. |
| 12. $\therefore \triangle ABC = \triangle DEF$. | 12. § 116. |
| 13. $\therefore \angle ABC = \angle DEF$. Q.E.D. | 13. § 110. |

Ex. 1167. Prove Prop. IX if the angles lie on opposite sides of BE .

* It will also be seen (§ 645) that the planes of these angles are parallel.

PROPOSITION X. THEOREM

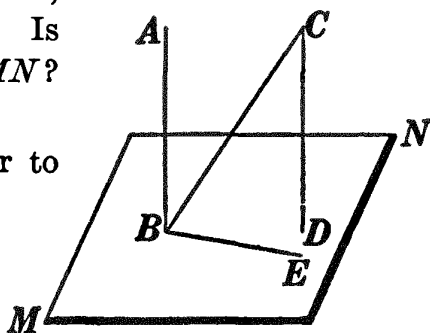
636. *If one of two parallel lines is perpendicular to a plane, the other also is perpendicular to the plane.*



Given $AB \parallel CD$ and $AB \perp$ plane MN .
To prove $CD \perp$ plane MN .

| ARGUMENT | REASONS |
|--|--------------|
| 1. Through D draw any line in plane MN , as DF . | 1. § 54, 15. |
| 2. Through B draw BE in plane $MN \parallel DF$. | 2. § 179. |
| 3. Then $\angle ABE = \angle CDF$. | 3. § 635. |
| 4. But $\angle ABE$ is a rt. \angle . | 4. § 619. |
| 5. $\therefore \angle CDF$ is a rt. \angle ; i.e. $CD \perp DF$, any line in plane MN through D . | 5. § 54, 1. |
| 6. $\therefore CD \perp$ plane MN . Q.E.D. | 6. § 619. |

Ex. 1168. In the accompanying diagram AB and CD lie in the same plane. Angle $CBA = 35^\circ$, angle $BCD = 35^\circ$, angle $ABE = 90^\circ$, BE lying in plane MN . Is CD necessarily perpendicular to plane MN ? Prove your answer.



Ex. 1169. Can a line be perpendicular to each of two intersecting planes? Prove.

Ex. 1170. If one of two planes is perpendicular to a given line, but the other is not, the planes are not parallel.

Ex. 1171. If a straight line and a plane are each perpendicular to the same straight line, they are parallel to each other.

PROPOSITION XI. PROBLEM

637. Through a given point to construct a line perpendicular to a given plane.

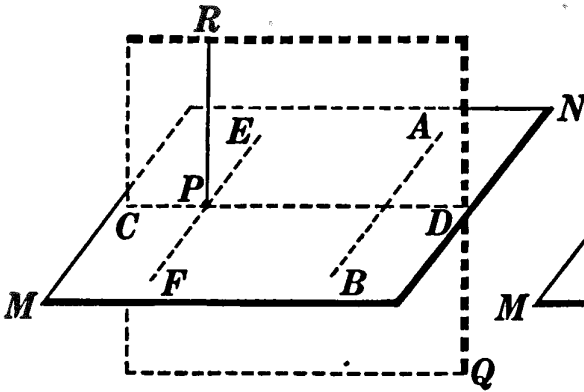


FIG. 1.

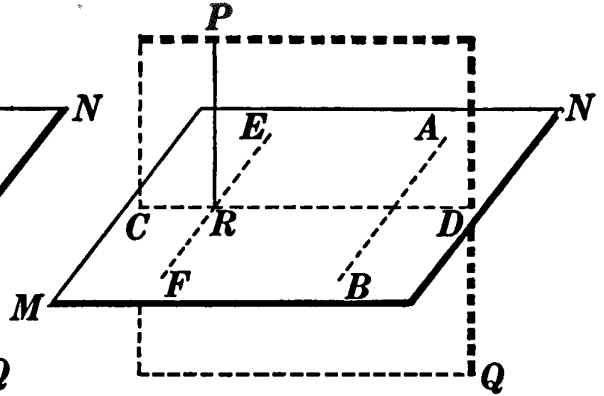


FIG. 2.

Given point P and plane MN .

To construct, through P , a line \perp plane MN .

I. Construction

1. In plane MN draw any convenient line, as AB .
2. Through P construct plane $PQ \perp AB$. § 624.
3. Let plane PQ intersect plane MN in CD . § 616.
4. In plane PQ construct a line through $P \perp CD$, as PR . §§ 148, 149.
5. PR is the perpendicular required.

II. Proof

| ARGUMENT | REASONS |
|--|-------------|
| 1. Through the foot of PR (P in Fig. 1, R in Fig. 2) in plane MN , draw $EF \parallel AB$. | 1. § 179. |
| 2. $AB \perp$ plane PQ . | 2. By cons. |
| 3. $\therefore EF \perp$ plane PQ . | 3. § 636. |
| 4. $\therefore EF \perp PR$; i.e. $PR \perp EF$. | 4. § 619. |
| 5. But $PR \perp CD$. | 5. By cons. |
| 6. $\therefore PR \perp$ plane MN . Q.E.D. | 6. § 622. |

III. The discussion will be given in § 639.

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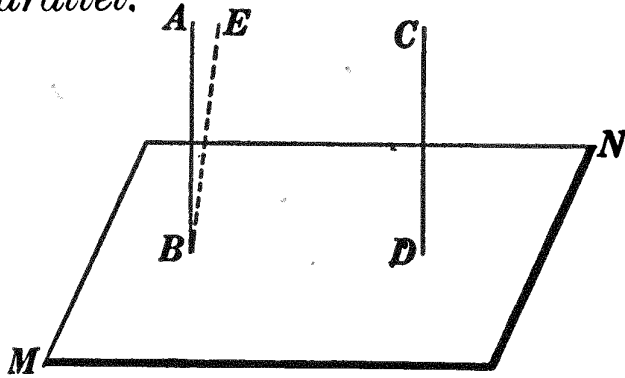
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PROPOSITION XIII. THEOREM

640. *Two straight lines perpendicular to the same plane are parallel.*



Given str. lines AB and $CD \perp$ plane MN .

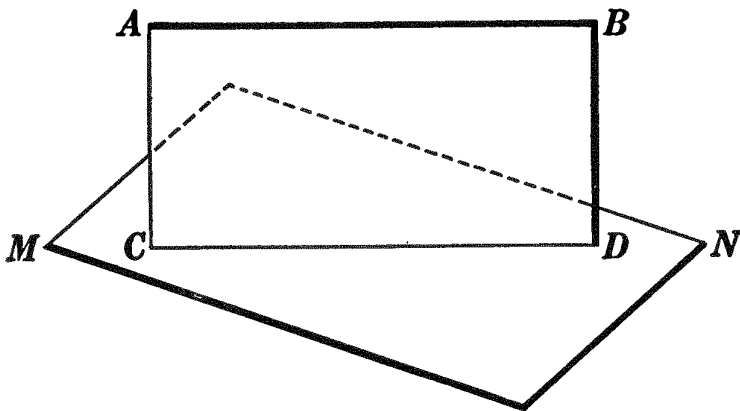
To prove $AB \parallel CD$.

The proof is left as an exercise for the student.

HINT. Suppose that AB is not $\parallel CD$, but that some other line through B , as BE , is $\parallel CD$. Use § 638.

PROPOSITION XIV. THEOREM

641. *If a straight line is parallel to a plane, the intersection of the plane with any plane passing through the given line is parallel to the given line.*



Given line $AB \parallel$ plane MN , and plane AD , through AB , intersecting plane MN in line CD .

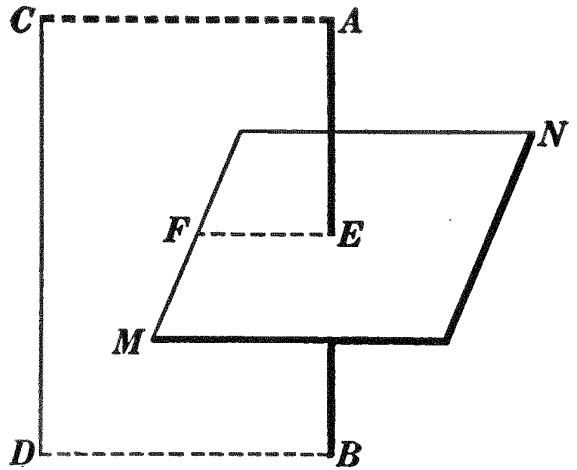
To prove $AB \parallel CD$.

The proof is left as an exercise for the student.

HINT. Suppose that AB is not $\parallel CD$. Show that AB will then meet plane MN .

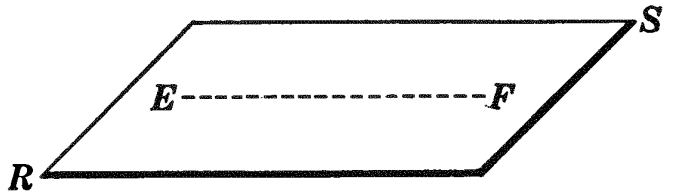
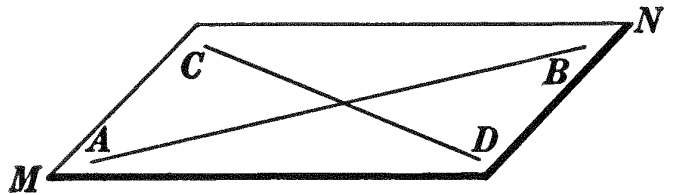
642. Cor. I. *If a plane intersects one of two parallel lines, it must, if sufficiently extended, intersect the other also.*

HINT. Pass a plane through AB and CD and let it intersect plane MN in EF . Now if MN does not intersect CD , but is \parallel to it, then $EF \parallel CD$, § 641. Apply § 178.



643. Cor. II. *If two intersecting lines are each parallel to a given plane, the plane of these lines is parallel to the given plane.*

HINT. If plane MN , determined by AB and CD , is not \parallel to plane RS , it will intersect it in some line, as EF . What is the relation of EF to AB and CD ?



644. Cor. III. Problem. *Through a given point to construct:*

- (a) *A line parallel to a given plane.*
- (b) *A plane parallel to a given plane.*

HINT. (a) Let A be a point outside of plane MN . Through A construct any plane intersecting plane MN in line CD . Complete the construction.

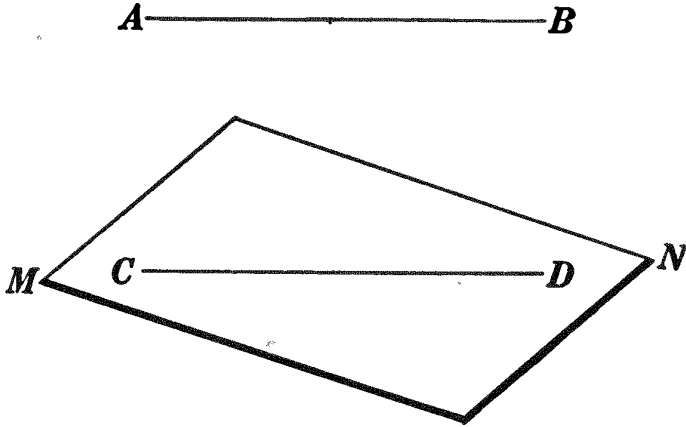
645. Cor. IV. *If two angles, not in the same plane, have their sides parallel respectively, their planes are parallel.*

Ex. 1173. Hold a pointer parallel to the blackboard. Is its shadow on the blackboard parallel to the pointer? why?

Ex. 1174. Find the locus of all straight lines passing through a given point and parallel to a given plane.

PROPOSITION XV. THEOREM

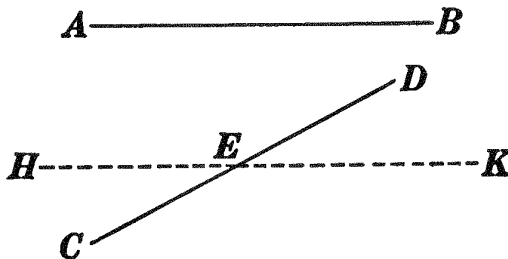
646. *If two straight lines are parallel, a plane containing one of the lines, and only one, is parallel to the other.*



Given \parallel lines AB and CD , and plane MN containing CD .
To prove plane $MN \parallel AB$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Either plane MN is $\parallel AB$ or it is not. | 1. § 161, a. |
| 2. Suppose MN is not $\parallel AB$; then plane MN will intersect AB . | 2. § 629. |
| 3. Then plane MN must also intersect CD . | 3. § 642. |
| 4. This is impossible, for MN contains CD . | 4. By hyp. |
| 5. \therefore plane $MN \parallel AB$. Q.E.D. | 5. § 161, b. |

647. **Cor. I. Problem.** *Through a given line to construct a plane parallel to another given line.*

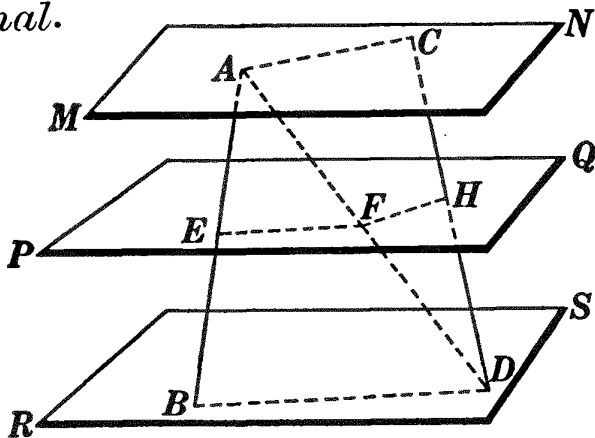


HINT. Through E , any point in CD , construct a line $HK \parallel AB$.

648. **Cor. II. Problem.** *Through a given point to construct a plane parallel to any two given straight lines in space.*

PROPOSITION XVI. THEOREM

649. *If two straight lines are intersected by three parallel planes, the corresponding segments of these lines are proportional.*



Given \parallel planes MN , PQ , and RS intersecting line AB in A , E , B and line CD in C , H , D , respectively.

To prove $\frac{AE}{EB} = \frac{CH}{HD}$.

| ARGUMENT | REASONS |
|---|-----------------|
| 1. Draw AD intersecting plane PQ in F . | 1. § 54, 15. |
| 2. Let the plane determined by AB and AD intersect PQ in EF and RS in BD . | 2. §§ 612, 616. |
| 3. Let the plane determined by AD and DC intersect PQ in FH and MN in AC . | 3. §§ 612, 616. |
| 4. $\therefore EF \parallel BD$ and $FH \parallel AC$. | 4. § 633. |
| 5. $\therefore \frac{AE}{EB} = \frac{AF}{FD}$ and $\frac{CH}{HD} = \frac{CF}{FD}$. | 5. § 410. |
| 6. $\therefore \frac{AE}{EB} = \frac{CH}{HD}$. Q.E.D. | 6. § 54, 1. |

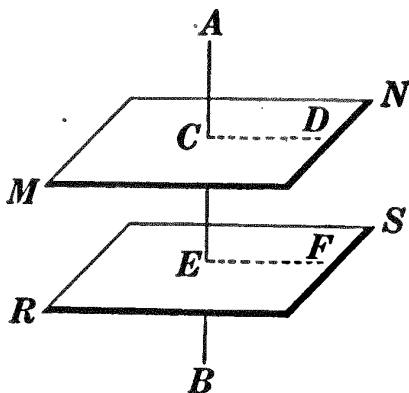
650. *Cor. If two straight lines are intersected by three parallel planes, the lines are divided proportionally.*

Ex. 1175. If any number of lines passing through a common point are cut by two or more parallel planes, their corresponding segments are proportional.

Ex. 1176. In the figure for Prop. XVI, $AE = 6$, $EB = 8$, $AD = 21$, $CD = 28$. Find AF and HD .

PROPOSITION XVII. THEOREM

651. *A straight line perpendicular to one of two parallel planes is perpendicular to the other also.*



Given plane $MN \parallel$ plane RS and line $AB \perp$ plane RS .
To prove line $AB \perp$ plane MN .

ARGUMENT ONLY

1. In plane MN , through C , draw any line CD , and let the plane determined by AC and CD intersect plane RS in EF .
2. Then $CD \parallel EF$.
3. But $AB \perp EF$.
4. $\therefore AB \perp CD$, any line in plane MN passing through C .
5. \therefore line $AB \perp$ plane MN . Q.E.D.

652. Cor. I. *Through a given point there exists only one plane parallel to a given plane. (HINT. Apply §§ 638, 644b, 651, 625.)*

653. §§ 644b and 652 may be combined in one statement:

Through a given point there exists one and only one plane parallel to a given plane.

654. Cor. II. *If two planes are each parallel to a third plane, they are parallel to each other. (HINT. See § 180.)*

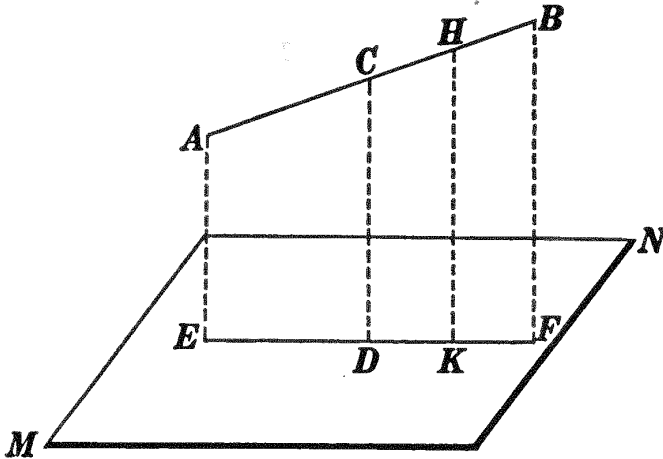
655. Def. The projection of a point upon a plane is the foot of the perpendicular from the point to the plane.

656. Def. The projection of a line upon a plane is the locus of the projections of all points of the line upon the plane.



PROPOSITION XVIII. THEOREM

657. *The projection upon a plane of a straight line not perpendicular to the plane is a straight line.*



Given str. line AB not \perp plane MN .

To prove the projection of AB upon MN a str. line.

| ARGUMENT | REASONS |
|---|-------------------|
| 1. Through C , any point in AB , draw $CD \perp$ plane MN . | 1. § 639. |
| 2. Let the plane determined by AB and CD intersect plane MN in the str. line EF . | 2. §§ 612, 616. |
| 3. From H , any point in AB , draw HK , in plane AF , $\parallel CD$. | 3. § 179. |
| 4. Then $HK \perp$ plane MN . | 4. § 636. |
| 5. $\therefore K$ is the projection of H upon plane MN . | 5. § 655. |
| 6. $\therefore EF$ is the projection of AB upon plane MN . | 6. § 656. |
| 7. \therefore the projection of AB upon plane MN is a str. line. | 7. Args. 2 and 6. |

Q.E.D.

Ex. 1177. Compare the length of the projection of a line upon a plane with the length of the line itself :

(a) If the line is parallel to the plane.

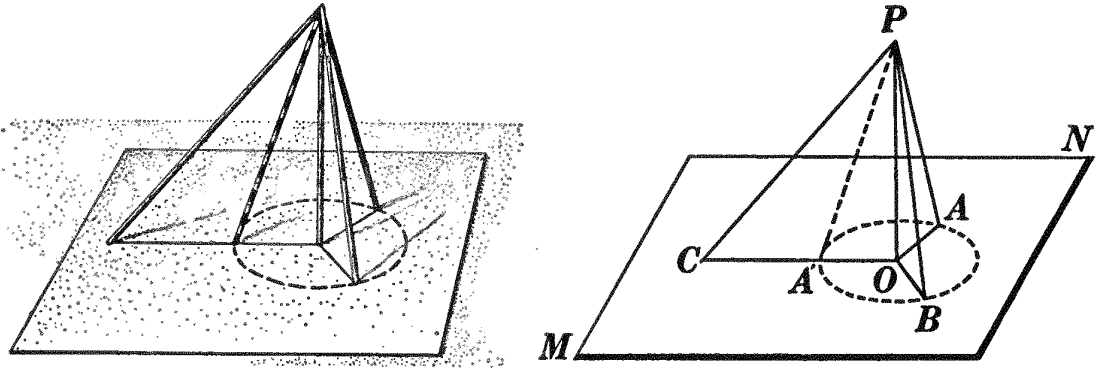
(b) If the line is neither parallel nor perpendicular to the plane.

(c) If the line is perpendicular to the plane.

PROPOSITION XIX. THEOREM

658. *Of all oblique lines drawn from a point to a plane:*

- I. *Those having equal projections are equal.*
- II. *Those having unequal projections are unequal, and the one having the greater projection is the longer.*



Given line $PO \perp$ plane MN and:

- I. Oblique lines PA and PB with projection $OA =$ projection OB .
- II. Oblique lines PA and PC with projection $OC >$ projection OA .

To prove: I. $PB = PA$; II. $PC > PA$.

The proof is left as an exercise for the student.

659. Cor. I. (Converse of Prop. XIX). *Of all oblique lines drawn from a point to a plane:*

- I. *Equal oblique lines have equal projections.*
- II. *Unequal oblique lines have unequal projections, and the longer line has the greater projection.*

660. Cor. II. *The locus of a point in space equidistant from all points in the circumference of a circle is a straight line perpendicular to the plane of the circle and passing through its center.*

661. Cor. III. *The shortest line from a point to a given plane is the perpendicular from that point to the plane.*

662. Def. The distance from a point to a plane is the length of the perpendicular from the point to the plane.

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DIHEDRAL ANGLES

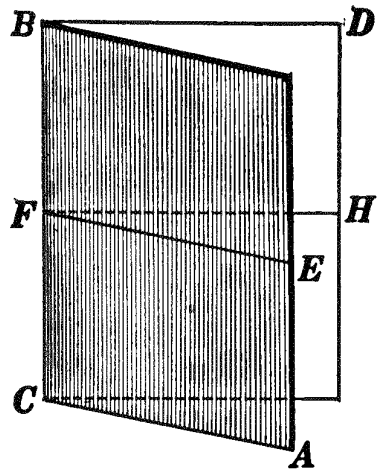
666. Defs. A **dihedral angle** is the figure formed by two planes that diverge from a line. The planes forming a dihedral angle are called its **faces**, and the intersection of these planes, its **edge**.

667. A dihedral angle may be designated by reading in order the two planes forming the angle; thus, an angle formed by planes AB and CD is angle $AB-CD$, and is usually written angle $A-BC-D$. If there is no other dihedral angle having the same edge, the line forming the edge is a sufficient designation, as dihedral angle BC .

668. Def. Points, lines, or planes lying in the same plane are said to be **coplanar**.

669. A clear notion of the *magnitude* of a dihedral angle may be obtained by imagining that its two faces, considered as finite portions of planes, were at first coplanar and that one of them has *revolved* about a line common to the two. Thus in the figure we may imagine face CD first to have been in the position of face AB and then to have revolved about BC as an axis to the position of face CD .

670. Def. The **plane angle** of a dihedral angle is the angle formed by two straight lines, one in each face of the dihedral angle, perpendicular to its edge at the same point. Thus if EF , in face AB , is $\perp BC$ at F , and FH , in face CD , is $\perp BC$ at F , then $\angle EFH$ is the plane \angle of the dihedral $\angle A-BC-D$.

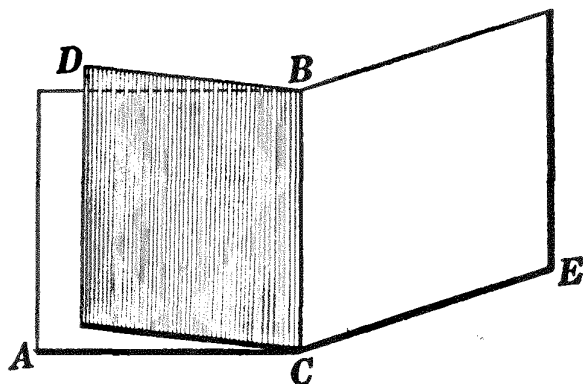


Ex. 1188. All plane angles of a dihedral angle are equal.

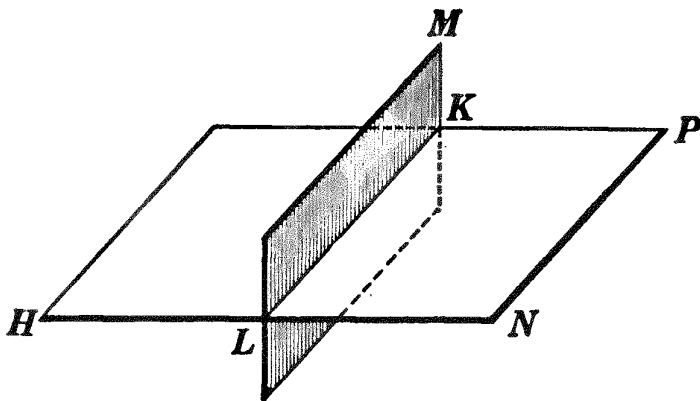
Ex. 1189. Is the plane of angle EFH (§ 667) perpendicular to the edge BC ? Prove. State your result in the form of a theorem.

Ex. 1190. Is Ex. 309 true if the quadrilateral is a quadrilateral in space, *i.e.* if the vertices of the quadrilateral are not all in the same plane? Prove.

671. Def. Two dihedral angles are **adjacent** if they have a common edge and a common face which lies between them; thus $\angle A-BC-D$ and $\angle D-CB-E$ are adj. dihedral \sphericalangle s.



672. Def. If one plane meets another so as to make two adjacent dihedral angles equal, each of these angles is a **right dihedral angle**, and the planes are said to be **perpendicular** to each other. Thus if plane HP meets plane LM so that dihedral $\sphericalangle H-KL-M$ and $M-LK-N$ are equal, each \sphericalangle is a rt. dihedral \sphericalangle , and planes HP and LM are \perp to each other.



Ex. 1191. By comparison with the definitions of the corresponding terms in plane geometry, frame exact definitions of the following terms: acute dihedral angle; obtuse dihedral angle; reflex dihedral angle; oblique dihedral angle; vertical dihedral angles; complementary dihedral angles; supplementary dihedral angles; bisector of a dihedral angle; alternate interior dihedral angles; corresponding dihedral angles. Illustrate as many of these as you can with an open book.

Ex. 1192. If one plane meets another plane, the sum of the two adjacent dihedral angles is two right dihedral angles.

HINT. See proof of § 65.

Ex. 1193. If the sum of two adjacent dihedral angles is equal to two right dihedral angles, their exterior faces are coplanar.

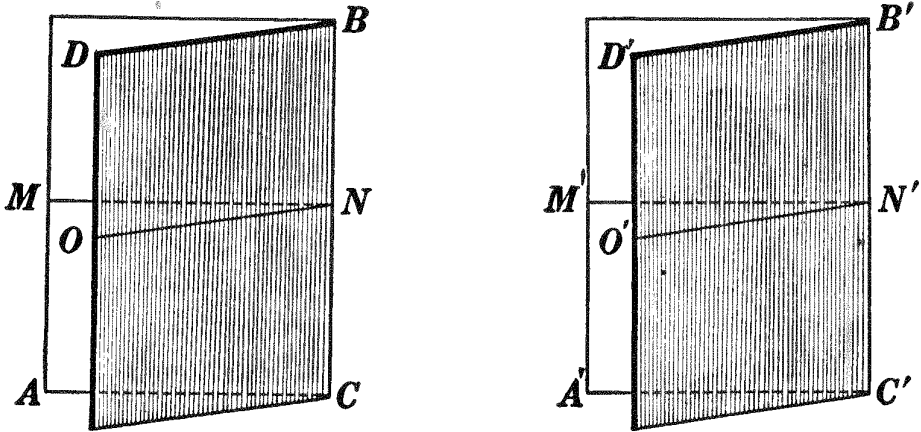
HINT. See proof of § 76.

Ex. 1194. If two planes intersect, the vertical dihedral angles are equal.

HINT. See proof of § 77.

PROPOSITION XX. THEOREM

673. *If two dihedral angles are equal, their plane angles are equal.*



Given two equal dihedral \sphericalangle s BC and $B'C'$ whose plane \sphericalangle s are \sphericalangle s MNO and $M'N'O'$, respectively.

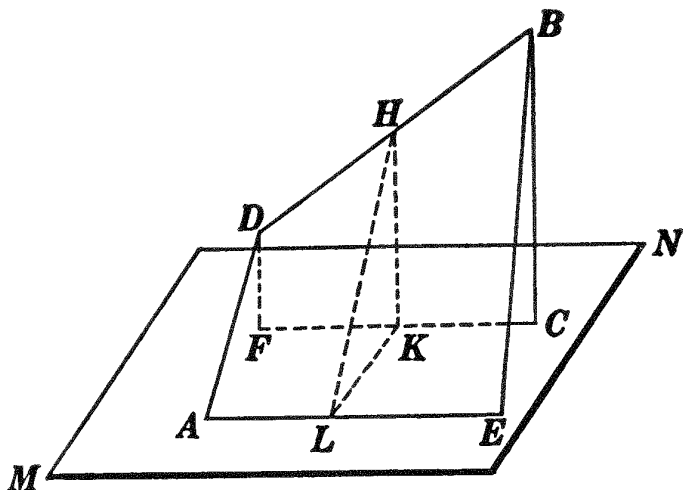
To prove $\sphericalangle MNO = \sphericalangle M'N'O'$.

| ARGUMENT | REASONS |
|---|----------------|
| 1. Superpose dihedral $\sphericalangle BC$ upon its equal, dihedral $\sphericalangle B'C'$, so that point N of edge BC shall fall upon point N' of edge $B'C'$. | 1. § 54, 14. |
| 2. Then MN and $M'N'$, two lines in plane AB , are $\perp BC$ at point N . | 2. § 670. |
| 3. $\therefore MN$ and $M'N'$ are collinear. | 3. § 62. |
| 4. Likewise NO and $N'O'$ are collinear. | 4. §§ 670, 62. |
| 5. $\therefore \sphericalangle MNO = \sphericalangle M'N'O'$. Q.E.D. | 5. § 18. |

674. **Cor. I.** *The plane angle of a right dihedral angle is a right angle.*

675. **Cor. II.** *If two intersecting planes are each perpendicular to a third plane, their intersections with the third plane intersect each other.*

Given planes AB and $CD \perp$ plane MN and intersecting each other in line DB ; also let AE and FC be the intersections of planes AB and CD with plane MN .



To prove that AE and FC intersect each other.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Either $AE \parallel FC$ or AE and FC intersect each other. | 1. 161, a. |
| 2. Suppose $AE \parallel FC$. Then through H , any point in DB , pass a plane $HKL \perp FC$, intersecting FC in K and AE in L . | 2. § 627. |
| 3. Then plane HKL is $\perp AE$ also. | 3. § 636. |
| 4. $\therefore \angle HKL$ is the plane \angle of dihedral $\angle FC$, and $\angle KLH$ is the plane \angle of dihedral $\angle AE$. | 4. § 670. |
| 5. But dihedral $\sphericalangle FC$ and AE are rt. dihedral \sphericalangle . | 5. § 672. |
| 6. $\therefore \sphericalangle HKL$ and KLH are rt. \sphericalangle . | 6. § 674. |
| 7. $\therefore \triangle HKL$ contains two rt. \sphericalangle . | 7. Arg. 6. |
| 8. But this is impossible. | 8. § 206. |
| 9. $\therefore AE$ and FC intersect each other. Q.E.D. | 9. § 161, b. |

Ex. 1195. Find the locus of all points equidistant from two given points in space.

Ex. 1196. Find the locus of all points equidistant from three given points in space.

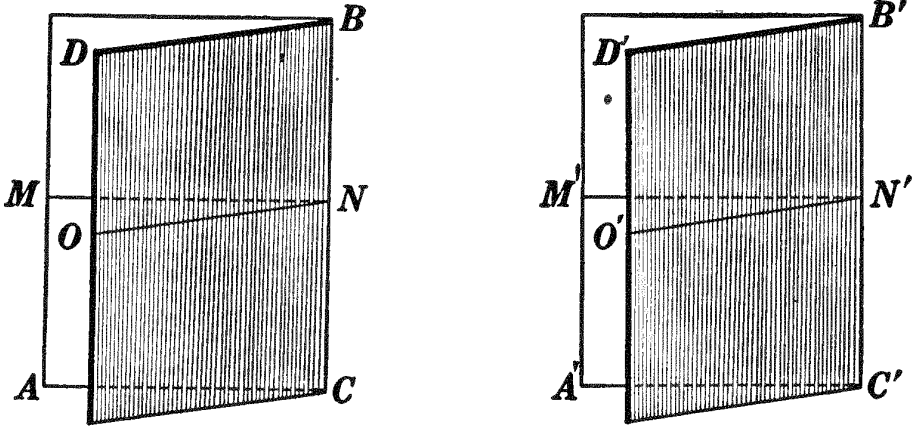
Ex. 1197. Are the supplements of equal dihedral angles equal? complements? Prove your answer.

Ex. 1198. If two planes are each perpendicular to a third plane, can they be parallel to each other? Explain. If they are parallel to each other, prove their intersections with the third plane parallel.

PROPOSITION XXI. THEOREM

(Converse of Prop. XX)

676. *If the plane angles of two dihedral angles are equal, the dihedral angles are equal.*



Given two dihedral $\angle BC$ and $B'C'$ whose plane $\angle MNO$ and $M'N'O'$ are equal.

To prove dihedral $\angle BC =$ dihedral $\angle B'C'$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Place dihedral $\angle BC$ upon dihedral $\angle B'C'$ so that plane $\angle MNO$ shall be superposed upon its equal, plane $\angle M'N'O'$. | 1. § 54, 14. |
| 2. Then BC and $B'C'$ are both $\perp MN$ and NO at N . | 2. § 670. |
| 3. $\therefore BC$ and $B'C'$ are both \perp plane MNO at N . | 3. § 622. |
| 4. $\therefore BC$ and $B'C'$ are collinear. | 4. § 638. |
| 5. \therefore planes AB and $A'B'$, determined by MN and BC , are coplanar; also planes CD and $C'D'$, determined by BC and NO , are coplanar. | 5. § 612. |
| 6. \therefore dihedral $\angle BC =$ dihedral $\angle B'C'$. | 6. § 18. |

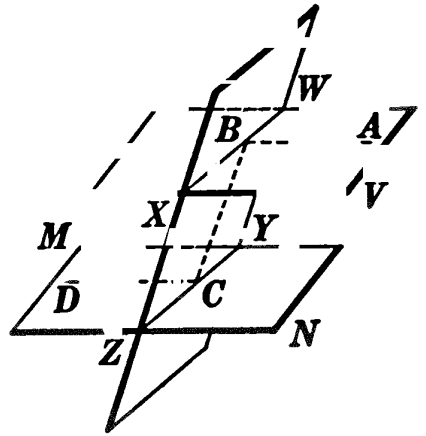
Q.E.D.

677. Cor. *If the plane angle of a dihedral angle is a right angle, the dihedral angle is a right dihedral angle.*

Ex. 1199. Prove Ex. 1194 by applying § 676.

Ex. 1200. If two parallel planes are cut by a transversal plane, the alternate interior dihedral angles are equal.

HINT. Let $\angle ABC$ be the plane \angle of dihedral $\angle V-WX-Y$. Let the plane determined by AB and BC intersect plane MN in CD . Then AB and CD lie in the same plane and are \parallel (§ 633). Prove that $\angle DCB$ is the plane \angle of dihedral $\angle M-ZY-X$.



Ex. 1201. State the converse of Ex. 1200, and prove it by the indirect method.

Ex. 1202. If two parallel planes are cut by a transversal plane, the corresponding dihedral angles are equal. (**HINT.** See proof of § 190.)

Ex. 1203. State the converse of Ex. 1202, and prove it by the indirect method.

Ex. 1204. If two parallel planes are cut by a transversal plane, the sum of the two interior dihedral angles on the same side of the transversal plane is two right dihedral angles. (**HINT.** See proof of § 192.)

Ex. 1205. Two dihedral angles whose faces are parallel, each to each, are either equal or supplementary dihedral angles. (**HINT.** See proof of § 198.)

Ex. 1206. A dihedral angle has the same numerical measure as its plane angle. (**HINT.** Proof similar to that of § 358.)

Ex. 1207. Two dihedral angles have the same ratio as their plane angles.

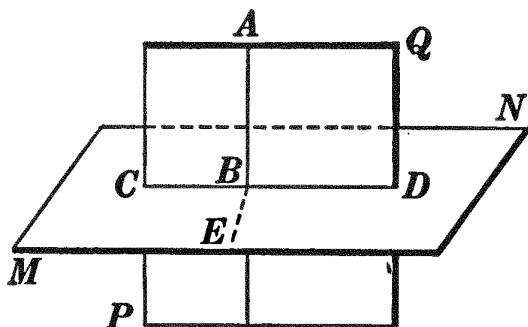
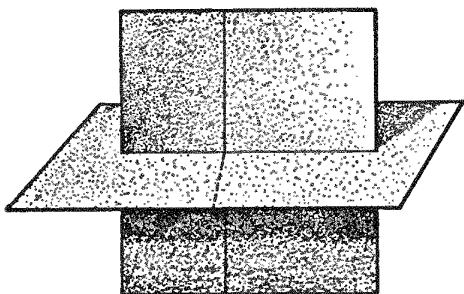
Ex. 1208. Find a point in a plane equidistant from three given points not lying in the plane.

Ex. 1209. If a straight line intersects one of two parallel planes, it must, if sufficiently prolonged, intersect the other also. (**HINT.** Use the indirect method and apply §§ 663 and 664.)

Ex. 1210. If a plane intersects one of two parallel planes, it must, if sufficiently extended, intersect the other also. (**HINT.** Use the indirect method and apply § 652.)

PROPOSITION XXII. THEOREM

678. *If a straight line is perpendicular to a plane, every plane containing this line is perpendicular to the given plane.*



Given str. line $AB \perp$ plane MN and plane PQ containing line AB and intersecting plane MN in CD .

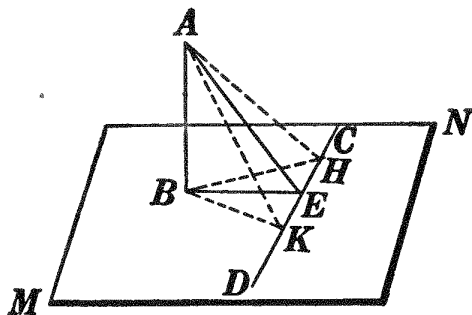
To prove plane $PQ \perp$ plane MN .

ARGUMENT

REASONS

- | | |
|---|---|
| <p>1. $AB \perp CD$.</p> <p>2. Through B, in plane MN, draw $BE \perp CD$.</p> <p>3. Then $\angle ABE$ is the plane \angle of dihedral $\angle Q-CD-M$.</p> <p>4. But $\angle ABE$ is a rt. \angle.</p> <p>5. \therefore dihedral $\angle Q-CD-M$ is a rt. dihedral \angle, and plane $PQ \perp$ plane MN. Q.E.D.</p> | <p>1. § 619.</p> <p>2. § 63.</p> <p>3. § 670.</p> <p>4. § 619.</p> <p>5. § 677.</p> |
|---|---|

Ex. 1211. If from the foot of a perpendicular to a plane a line is drawn at right angles to any line in the plane, the line drawn from the point of intersection so formed to any point in the perpendicular is perpendicular to the line of the plane.



HINT. Make $KE = EH$. Prove $AK = AH$, and apply § 142.

Ex. 1212. In the figure of Ex. 1211, if $AB = 20$, $BE = 4\sqrt{11}$, and $EK = 10$, find AK .

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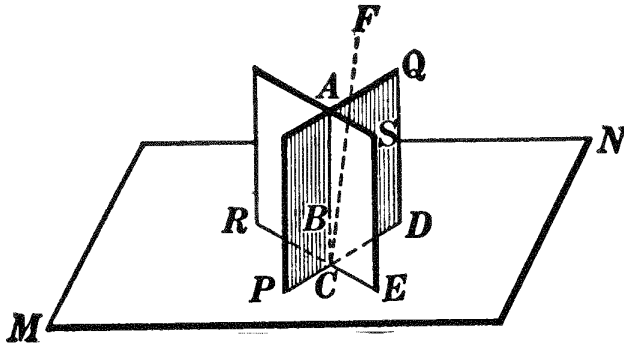
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PROPOSITION XXIV. THEOREM

681. *If each of two intersecting planes is perpendicular to a third plane:*

- I. *Their line of intersection intersects the third plane.*
- II. *Their line of intersection is perpendicular to the third plane.*



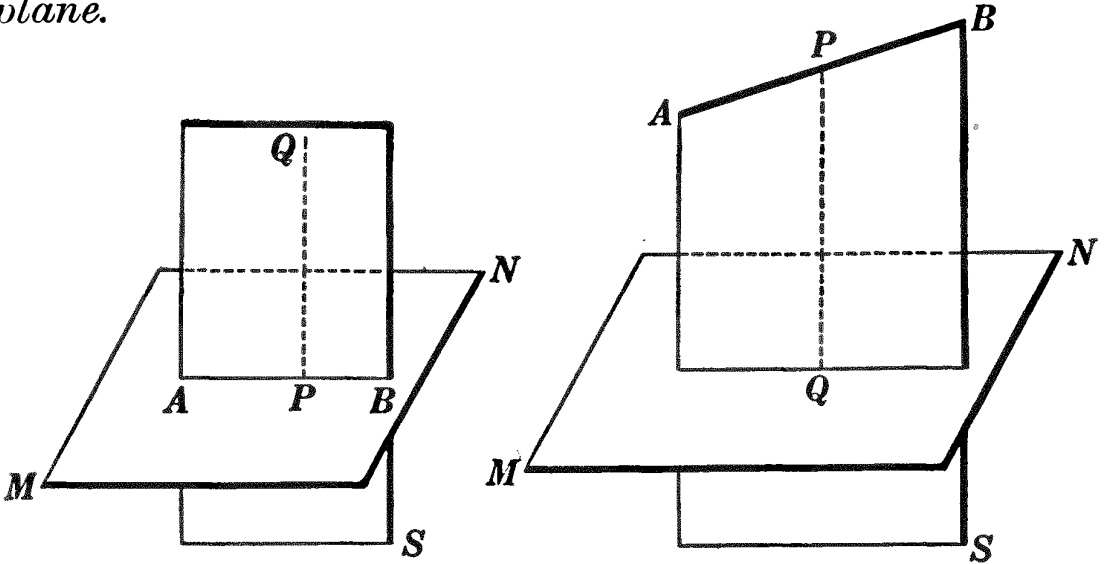
Given planes PQ and $RS \perp$ plane MN and intersecting each other in line AB .

- To prove:**
- I. That AB intersects plane MN .
 - II. $AB \perp$ plane MN .

| I. | ARGUMENT | REASONS |
|-----|--|----------------------|
| 1. | Let planes PQ and RS intersect plane MN in lines PD and RE , respectively. | 1. § 616. |
| 2. | Then PD and RE intersect in a point as C . | 2. § 675. |
| 3. | $\therefore AB$ passes through C ; <i>i.e.</i> AB intersects plane MN . Q.E.D. | 3. § 617, I. |
| II. | ARGUMENT | REASONS |
| 1. | Either $AB \perp$ plane MN or it is not. | 1. § 161, <i>a</i> . |
| 2. | Suppose AB is not \perp plane MN , but that some other line through C , the point common to the three planes, is \perp plane MN , as line CF . | 2. § 639. |
| 3. | Then CF lies in plane PQ , also in plane RS . | 3. § 680. |
| 4. | $\therefore CF$ is the intersection of planes PQ and RS . | 4. § 614. |
| 5. | \therefore planes PQ and RS intersect in two str. lines, which is impossible. | 5. § 616. |
| 6. | $\therefore AB \perp$ plane MN . Q.E.D. | 6. § 161, <i>b</i> . |

PROPOSITION XXV. PROBLEM

682. *Through any straight line, not perpendicular to a plane, to construct a plane perpendicular to the given plane.*



Given line AB not \perp plane MN .

To construct, through AB , a plane \perp plane MN .

The construction, proof, and discussion are left as an exercise for the student.

HINT. Apply § 678. For discussion, see § 683.

683. Cor. *Through a straight line, not perpendicular to a plane, there exists only one plane perpendicular to the given plane.*

HINT. Suppose there should exist another plane through $AB \perp$ plane MN . What would you know about AB ?

684. §§ 682 and 683 may be combined in one statement as follows :

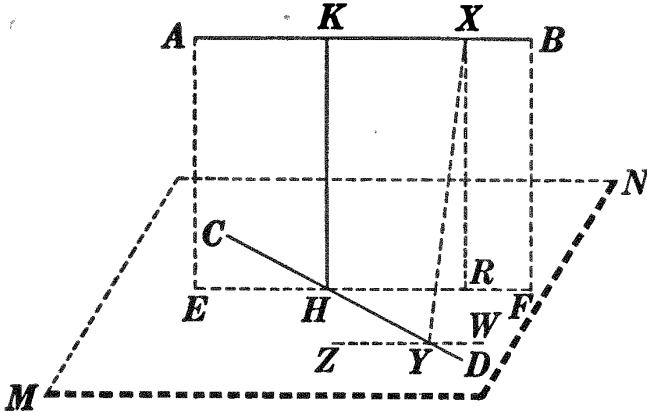
Through a straight line, not perpendicular to a plane, there exists one and only one plane perpendicular to the given plane.

Ex. 1216. Apply the truth of Prop. XXIV: (a) to the planes that intersect at the corner of a room ; (b) to the planes formed by an open book placed perpendicular to the top of the desk.

Ex. 1217. If a plane is perpendicular to each of two intersecting planes, it is perpendicular to their intersection.

PROPOSITION XXVI. PROBLEM

685. To construct a common perpendicular to any two straight lines in space.



Given AB and CD , any two str. lines in space.

To construct a line \perp both to AB and to CD .

I. Construction

1. Through CD construct plane $MN \parallel AB$. § 647.
2. Through AB construct plane $AF \perp$ plane MN intersecting MN in EF , and CD in H . § 682.
3. Through H construct HK , in plane AF , $\perp EF$. § 148.
4. HK is \perp to both AB and CD and is the line required.

II. Proof

| ARGUMENT | REASONS |
|---|-------------------|
| 1. $AB \parallel$ plane MN . | 1. By cons. |
| 2. $\therefore EF \parallel AB$. | 2. § 641. |
| 3. But $HK \perp EF$. | 3. By cons. |
| 4. $\therefore HK \perp AB$. | 4. § 193. |
| 5. Also $HK \perp$ plane MN . | 5. § 679. |
| 6. $\therefore HK \perp CD$. | 6. § 619. |
| 7. $\therefore HK \perp$ to both AB and CD . q.e.d. | 7. Args. 4 and 6. |

III. The discussion will be given in § 686.

686. Cor. Between two straight lines in space (not in the same plane) there exists only one common perpendicular.

HINT. Suppose XY , in figure of § 685, a second \perp to AB and CD . Through Y draw $ZW \parallel AB$. What is the relation of XY to AB ? to ZW ? to CD ? to plane MN ? Through X draw $XR \perp EF$. What is the relation of XR to plane MN ? Complete the proof.

687. §§ 685 and 686 may be combined in one statement as follows:

Between two straight lines in space (not in the same plane) there exists one and only one common perpendicular.

Ex. 1218. A room is 20 feet long, 15 feet wide, and 10 feet high. Find the length of the shortest line that can be drawn on floor and walls from a lower corner to the diagonally opposite corner. Find the length of the line that extends diagonally across the floor, then along the intersection of two walls to the ceiling.

Ex. 1219. If two equal lines are drawn from a given point to a given plane, the inclinations of these lines to the given plane are equal. If two unequal lines are thus drawn, which has the greater inclination? Prove.

Ex. 1220. The two planes determined by two parallel lines and a point not in their plane, intersect in a line which is parallel to each of the given parallels.

Ex. 1221. If two lines are parallel, their projections on a plane are either the same line, or parallel lines.

Ex. 1222. If each of three planes is perpendicular to the other two: (a) the intersection of any two of the planes is perpendicular to the third plane; (b) each of the three lines of intersection is perpendicular to the other two. Find an illustration of this exercise in the classroom.

Ex. 1223. If two planes are parallel, no line in the one can meet any line in the other.

Ex. 1224. Find all points equidistant from two parallel planes and equidistant from three points: (a) if the points lie in neither plane; (b) if the points lie in one of the planes.

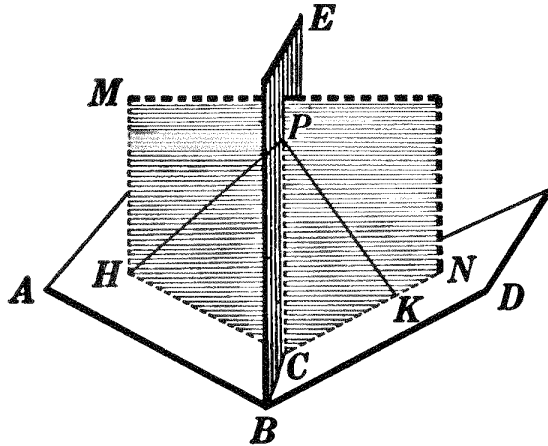
Ex. 1225. Find all points equidistant from two given points, equidistant from two parallel planes, and at a given distance d from a third plane.

Ex. 1226. If each of two intersecting planes is parallel to a given line, the intersection of the planes is parallel to the line.

Ex. 1227. Construct, through a point in space, a straight line that shall be parallel to two intersecting planes.

PROPOSITION XXVII. THEOREM

688. *Every point in the plane that bisects a dihedral angle is equidistant from the faces of the angle.*



Given plane BE bisecting the dihedral \angle formed by planes AC and CD ; also PH and $PK \perp$ s from P , any point in plane BE , to faces AC and CD , respectively.

To prove $PH = PK$.

| ARGUMENT | REASONS |
|---|----------------|
| 1. Through PH and PK pass plane MN intersecting plane AC in CH , plane CD in CK , plane BE in PC , and edge BC in C . | 1. § 612, 616. |
| 2. Then plane $MN \perp$ planes AC and CD ; <i>v.e.</i> planes AC and CD are \perp plane MN . | 2. § 678. |
| 3. $\therefore BC \perp$ plane MN . | 3. § 681, II. |
| 4. $\therefore BC \perp CH, CP,$ and CK . | 4. § 619. |
| 5. $\therefore \sphericalangle PCH$ and KCP are the plane \sphericalangle of the dihedral $\sphericalangle E-BC-A$ and $D-CB-E$. | 5. § 670. |
| 6. But dihedral $\angle E-BC-A =$ dihedral $\angle D-CB-E$. | 6. By hyp. |
| 7. $\therefore \angle PCH = \angle KCP$. | 7. § 673. |
| 8. Also $PC = PC$. | 8. By iden. |
| 9. \therefore rt. $\triangle PCH =$ rt. $\triangle KCP$. | 9. § 209. |
| 10. $\therefore PH = PK$. | 10. § 110. |

Q.E.D.

689. Cor. I. *Every point equidistant from the two faces of a dihedral angle lies in the plane bisecting the angle.*

690. Cor. II. *The plane bisecting a dihedral angle is the locus of all points in space equidistant from the faces of the angle.*

691. Cor. III. Problem. *To construct the bisector of a given dihedral angle.*

Ex. 1228. Prove that a dihedral angle can be bisected by only one plane.

HINT. See proof of § 599.

Ex. 1229. Find the locus of all points equidistant from two intersecting planes. Of how many planes does this locus consist?

Ex. 1230. Find the locus of all points in space equidistant from two intersecting lines. Of how many planes does this locus consist?

Ex. 1231. Find the locus of all points in space equidistant from two parallel lines.

Ex. 1232. Find the locus of all points in space equidistant from two intersecting planes and equidistant from all points in the circumference of a circle.

Ex. 1233. Find the locus of all points in space equidistant from two intersecting planes and equidistant from two fixed points.

Ex. 1234. Find the locus of all points in space equidistant from two intersecting planes, equidistant from two parallel planes, and equidistant from two fixed points.

Ex. 1235. If from any point within a dihedral angle lines are drawn perpendicular to the faces of the angle, the angle formed by the perpendiculars is supplementary to the plane angle of the dihedral angle.

Ex. 1236. Given two points, P and Q , one in each of two intersecting planes, M and N . Find a point X in the intersection of planes M and N such that $PX + XQ$ is a minimum.

Ex. 1237. Given two points, P and Q , on one side of a given plane MN . Find a point X in plane MN such that $PX + XQ$ shall be a minimum.

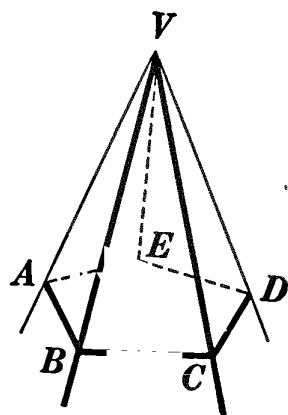
HINT. See Ex. 175.

POLYHEDRAL ANGLES

692. Def. A polyhedral angle is the figure generated by a moving straight line segment that continually intersects the boundary of a fixed polygon and one extremity of which is a fixed point not in the plane of the given polygon. A polyhedral angle is sometimes called a **solid angle**.

693. Defs. The moving line is called the **generatrix**, as VA ; the fixed polygon is called the **directrix**, as polygon $ABCDE$; the fixed point is called the **vertex** of the polyhedral angle, as V .

694. Defs. The generatrix in any position is an **element** of the polyhedral angle; the elements through the vertices of the polygon are the **edges**, as VA , VB , etc.; the portions of the planes determined by the edges of the polyhedral angle, and limited by them are the **faces**, as AVB , BVC , etc.; the angles formed by the edges are the **face angles**, as $\sphericalangle AVB$, BVC , etc.; the dihedral angles formed by the faces are called the **dihedral angles** of the polyhedral angle, as dihedral $\sphericalangle VA$, VB , etc.



695. Def. The face angles and the dihedral angles taken together are sometimes called the **parts of a polyhedral angle**.

696. A polyhedral angle may be **designated** by a letter at the vertex and one on each edge, as $V-ABCDE$. If there is no other polyhedral angle having the same vertex, the letter at the vertex is a sufficient designation, as V .

697. Def. A **convex polyhedral angle** is a polyhedral angle whose directrix is a convex polygon, *i.e.* a polygon no side of which, if prolonged, will enter the polygon; as $V-ABCDE$. In this text only convex polyhedral angles will be considered.

698. Defs. A **trihedral angle** is a polyhedral angle whose directrix is a triangle (*tri*-gon); a **tetrahedral angle**, a polyhedral angle whose directrix is a quadrilateral (*tetra*-gon); etc.

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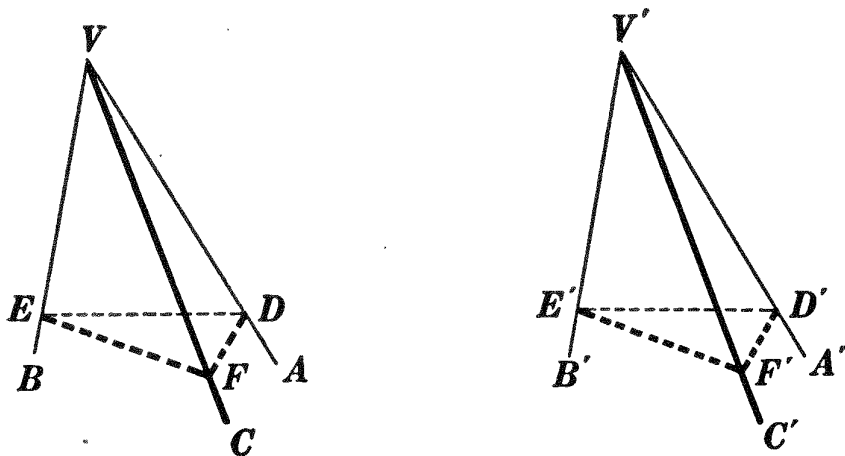
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PROPOSITION XXIX. THEOREM

704. *Two trihedral angles are equal if the three face angles of one are equal respectively to the three face angles of the other, and the equal parts are arranged in the same order.*



Given trihedral $\angle V-ABC$ and $V'-A'B'C'$, $\angle AVB = \angle A'V'B'$, $\angle BVC = \angle B'V'C'$, $\angle CVA = \angle C'V'A'$, and the equal face angles arranged in the same order.

To prove trihedral $\angle V-ABC =$ trihedral $\angle V'-A'B'C'$.

OUTLINE OF PROOF

1. Since, by hyp., any two face \angle s of $V-ABC$, as $\angle AVB$ and BVC , are equal, respectively, to the two corresponding face \angle s of $V'-A'B'C'$, it remains only to prove the included dihedral $\angle VB$ and $V'B'$ equal. § 702, II. (See also § 705.)

2. Let face $\angle AVB$ and BVC be oblique \angle s; then from any point E in VB , draw ED and EF , in planes AVB and BVC , respectively, and $\perp VB$.

3. Since $\angle AVB$ and BVC are oblique \angle s, ED and EF will meet VA and VC in D and F , respectively. Draw FD .

4. Similarly, lay off $V'E' = VE$ and draw $\triangle D'E'F'$.

5. Prove $\text{rt. } \triangle DVE = \text{rt. } \triangle D'V'E'$; then $VD = V'D'$, $ED = E'D'$.

6. Prove $\text{rt. } \triangle EVF = \text{rt. } \triangle E'V'F'$; then $VF = V'F'$, $EF = E'F'$.

7. Prove $\triangle FVD = \triangle F'V'D'$; then $FD = F'D'$.

8. $\therefore \triangle DEF = \triangle D'E'F'$: then $\angle DEF = \angle D'E'F'$.

9. But $\sphericalangle DEF$ and $D'E'F'$ are the plane \sphericalangle s of dihedral $\sphericalangle VB$ and $V'B'$, respectively.

10. \therefore dihedral $\sphericalangle VB =$ dihedral $\sphericalangle V'B'$.

11. \therefore trihedral $\sphericalangle V-ABC =$ trihedral $\sphericalangle V'-A'B'C'$. Q.E.D.

705. Note. If all the face \sphericalangle s are rt. \sphericalangle s, show that all the dihedral \sphericalangle s are rt. dihedral \sphericalangle s and hence that all are equal. If two face \sphericalangle s of a trihedral \sphericalangle are rt. \sphericalangle s, show that the third face \sphericalangle is the plane \sphericalangle of the included dihedral \sphericalangle , and hence that two homologous dihedral \sphericalangle s, as VB and $V'B'$, are equal. It remains to prove that Prop. XXIX is true if only one face \sphericalangle of the first trihedral \sphericalangle and its homologous face \sphericalangle of the other are rt. \sphericalangle s, or if all face \sphericalangle s are oblique.

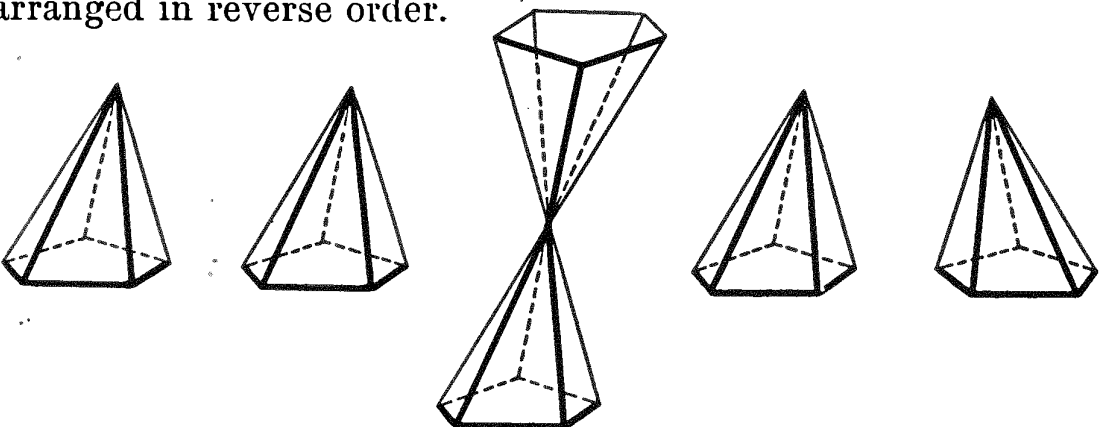
706. Questions. State the proposition in Bk. I that corresponds to § 704. What was the main step in the proof of that proposition? Did that correspond to proving dihedral $\sphericalangle VB$ of § 704 = dihedral $\sphericalangle V'B'$?

707. Def. Two polyhedral angles are said to be **symmetrical** if their corresponding parts are equal but arranged in reverse order.

By making symmetrical polyhedral angles and comparing them, the student can easily satisfy himself that in general they cannot be made to coincide.

708. Def. Two polyhedral angles are said to be **vertical** if the edges of each are the prolongations of the edges of the other.

It will be seen that two vertical, like two symmetrical, polyhedral angles have their corresponding parts equal but arranged in reverse order.



Two Equal Polyhedral Angles

Two Vertical Polyhedral Angles

Two Symmetrical Polyhedral Angles

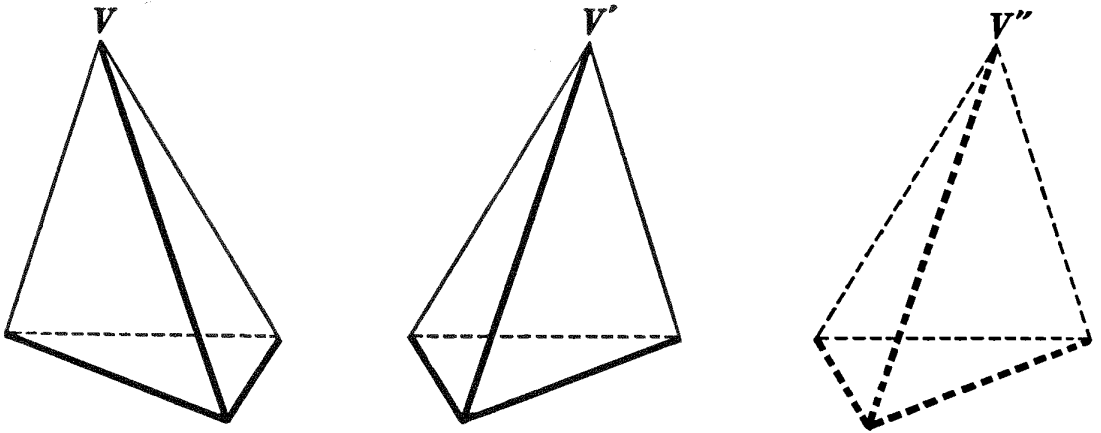
PROPOSITION XXX. THEOREM

709. *Two trihedral angles are symmetrical:*

I. *If a face angle and the two adjacent dihedral angles of one are equal respectively to a face angle and the two adjacent dihedral angles of the other;*

II. *If two face angles and the included dihedral angle of one are equal respectively to two face angles and the included dihedral angle of the other;*

III. *If the three face angles of one are equal respectively to the three face angles of the other: provided the equal parts are arranged in reverse order.*



The proofs are left as exercises for the student.

HINT. Let V and V' be the two trihedral \sphericalangle with parts equal but arranged in reverse order. Construct trihedral $\sphericalangle V''$ symmetrical to V . Then what will be the relation of V'' to V' ? of V' to V ?

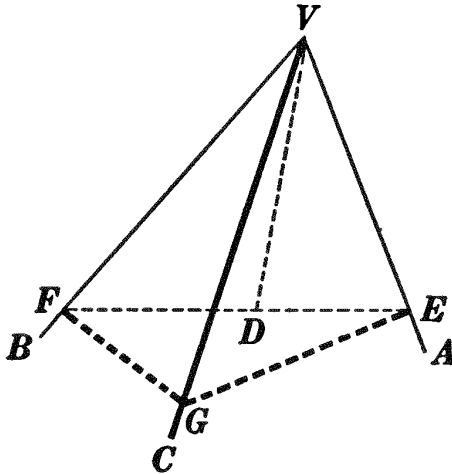
Ex. 1240. Can two polyhedral angles be symmetrical and equal? vertical and equal? symmetrical and vertical? If two polyhedral angles are vertical, are they necessarily symmetrical? if symmetrical, are they necessarily vertical?

Ex. 1241. Are two trirectangular trihedral angles necessarily equal? Are two birectangular trihedral angles equal? Prove your answers.

Ex. 1242. If two trihedral angles have three face angles of one equal respectively to three face angles of the other, the dihedral angles of the first are equal respectively to the dihedral angles of the second.

PROPOSITION XXXI. THEOREM

710. *The sum of any two face angles of a trihedral angle is greater than the third face angle.*



Given trihedral $\angle V-ABC$ in which the greatest face \angle is AVB .

To prove $\angle BVC + \angle CVA > \angle AVB$.

OUTLINE OF PROOF

1. In face AVB draw VD making $\angle DVB = \angle BVC$, and through D draw any line intersecting VA in E and VB in F .
2. On VC lay off $VG = VD$ and draw FG and GE .
3. Prove $\triangle FVG = \triangle DVF$; then $FG = FD$.
4. But $FG + GE > FD + DE$; $\therefore GE > DE$.
5. In $\triangle GVE$ and EVD , prove $\angle GVE > \angle EVD$.
6. But $\angle FVG = \angle DVF$.
7. $\therefore \angle FVG + \angle GVE > \angle EVD + \angle DVF$;
i.e. $\angle BVC + \angle CVA > \angle AVB$. Q.E.D.

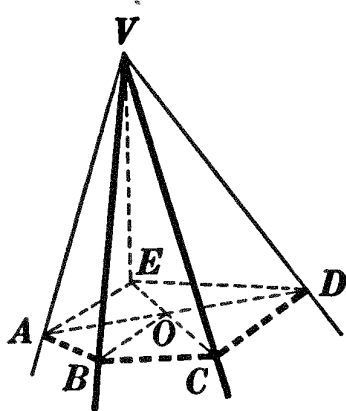
711. Question. State the theorem in Bk. I that corresponds to Prop. XXXI. Can that theorem be proved by a method similar to the one used here? If so, give the proof.

Ex. 1243. If, in trihedral angle $V-ABC$, angle $BVC = 60^\circ$, and angle $CVA = 80^\circ$, make a statement as to the number of degrees in angle AVB .

Ex. 1244. Any face angle of a trihedral angle is greater than the difference of the other two.

PROPOSITION XXXII. THEOREM

712. *The sum of all the face angles of any convex polyhedral angle is less than four right angles.*



Given polyhedral $\angle V$ with n faces.

To prove the sum of the face \sphericalangle s at $V < 4$ rt. \sphericalangle s.

HINT. Let a plane intersect the edges of the polyhedral \angle in $A, B, C,$ etc. From $O,$ any point in polygon $ABCD \dots,$ draw $OA, OB, OC,$ etc. How many \triangle have their vertices at $V?$ at $O?$ What is the sum of all the \sphericalangle s of all the \triangle with vertices at $V?$ at $O?$ Which is the greater, $\angle ABV + \angle VBC$ or $\angle ABO + \angle OBC?$ Then which is the greater, the sum of the base \sphericalangle s of \triangle with vertices at $V,$ or the sum of the base \sphericalangle s of \triangle with vertices at $O?$ Then which is greater, the sum of the face \sphericalangle s about $V,$ or the sum of the \sphericalangle s about $O?$

713. Question. Is there a proposition in plane geometry corresponding to Prop. XXXII? If so, state it. If not, state the one that most nearly corresponds to it.

Ex. 1245. Can a polyhedral angle have for its faces three equilateral triangles? four? five? six?

Ex. 1246. Can a polyhedral angle have for its faces three squares? four?

Ex. 1247. Can a polyhedral angle have for its faces three regular pentagons? four?

Ex. 1248. Show that the greatest number of polyhedral angles that can possibly be formed with regular polygons as faces is five.

Ex. 1249. Can a trihedral angle have for its faces a regular decagon and two equilateral triangles? a regular decagon, an equilateral triangle, and a square? two regular octagons and a square?

BOOK VII

POLYHEDRONS

714. Def. A surface is said to be closed if it separates a finite portion of space from the remaining space.

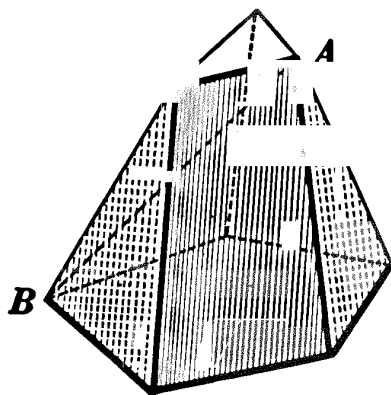
715. Def. A solid closed figure is a figure in space composed of a closed surface and the finite portion of space bounded by it.

716. Def. A polyhedron is a solid closed figure whose bounding surface is composed of planes only.

717. Defs. The intersections of the bounding planes are called the edges; the intersections of the edges, the vertices; and the portions of the bounding planes bounded by the edges, the faces, of the polyhedron.

718. Def. A diagonal of a polyhedron is a straight line joining any two vertices not in the same face, as AB .

719. Defs. A polyhedron of four faces is called a tetrahedron; one of six faces, a hexahedron; one of eight faces, an octahedron; one of twelve faces, a dodecahedron; one of twenty faces, an icosahedron; etc.



Po'yhedron

Ex. 1250. How many diagonals has a tetrahedron? a hexahedron?

Ex. 1251. What is the least number of faces that a polyhedron can have? edges? vertices?

Ex. 1252. How many edges has a tetrahedron? a hexahedron? an octahedron?

Ex. 1253. How many vertices has a tetrahedron? a hexahedron? an octahedron?

Ex. 1254. If E represents the number of edges, F the number of faces, and V the number of vertices in each of the polyhedrons mentioned in Exs. 1252 and 1253, show that in each case $E + 2 = V + F$. This result is known as Euler's theorem.

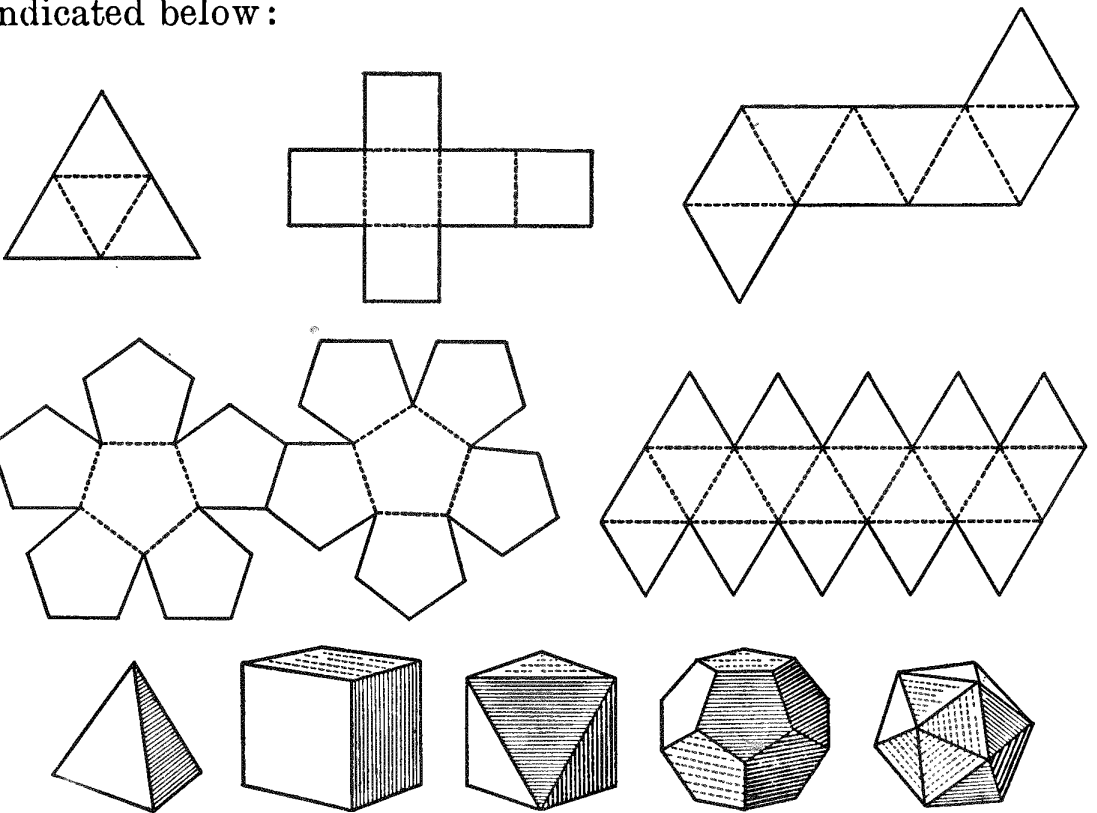
Ex. 1255. Show that in a tetrahedron $S = (V - 2) 4$ right angles, where S is the sum of the face angles and V is the number of vertices.

Ex. 1256. Does the formula, $S = (V - 2) 4$ right angles, hold for a hexahedron? an octahedron? a dodecahedron?

720. Def. A **regular polyhedron** is a polyhedron all of whose faces are equal regular polygons, and all of whose polyhedral angles are equal.

721. Questions. How many equilateral triangles can meet to form a polyhedral angle (§ 712)? Then what is the greatest number of regular polyhedrons possible having equilateral triangles as faces? What is the greatest number of regular polyhedrons possible having squares as faces? having regular pentagons as faces? Can a regular polyhedron have as faces regular polygons of more than five sides? why? What, then, is the maximum number of kinds of regular polyhedrons possible?

722. From the questions in § 721, the student has doubtless drawn the conclusion that *not more than five kinds of regular polyhedrons exist.* He should convince himself that these five *are* possible by actually making them from cardboard as indicated below:



Tetrahedron Hexahedron Octahedron Dodecahedron Icosahedron

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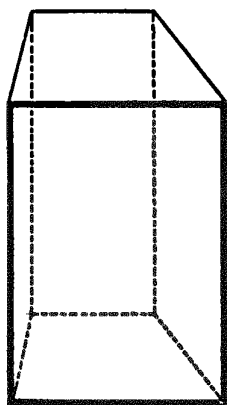
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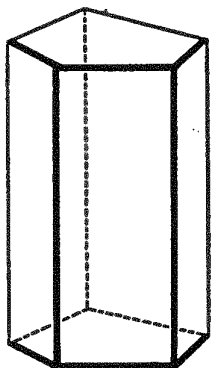
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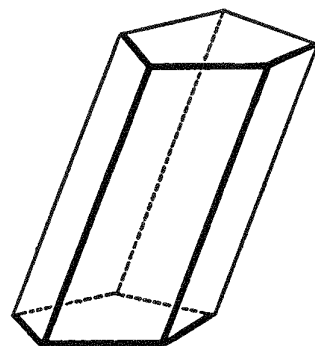
728. Def. A right section of a prism is a section formed by a plane which is perpendicular to a lateral edge of the prism and which cuts the lateral edges or the edges prolonged.



Right Prism



Regular Prism



Oblique Prism

729. Def. A right prism is a prism whose lateral edges are perpendicular to the bases.

730. Def. A regular prism is a right prism whose bases are regular polygons.

731. Def. An oblique prism is a prism whose lateral edges are oblique to the bases.

732. Defs. A prism is triangular, quadrangular, etc., according as its bases are triangles, quadrilaterals, etc.

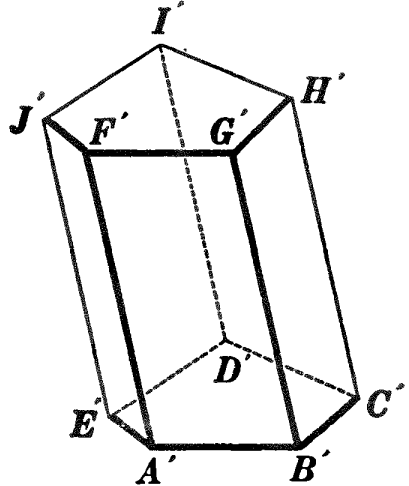
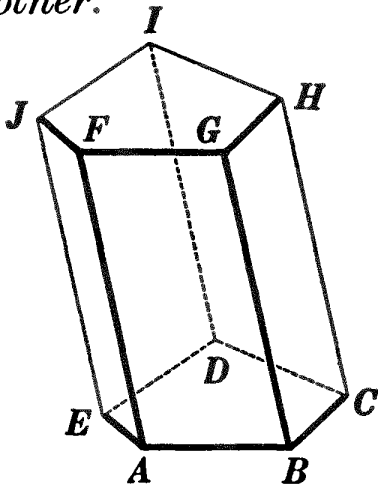
733. Def. The altitude of a prism is the perpendicular from any point in the plane of one base to the plane of the other base.

734. The following are some of the properties of a prism; the student should prove the correctness of each:

- (a) *Any two lateral edges of a prism are parallel.*
- (b) *The lateral edges of a prism are equal.*
- (c) *Any lateral edge of a right prism is equal to the altitude.*
- (d) *The lateral faces of a prism are parallelograms.*
- (e) *The lateral faces of a right prism are rectangles.*
- (f) *The bases of a prism are equal polygons.*
- (g) *The sections of a prism made by two parallel planes cutting all the lateral edges are equal polygons.*
- (h) *Every section of a prism made by a plane parallel to the base is equal to the base.*

PROPOSITION I. THEOREM

735. Two prisms are equal if three faces including a trihedral angle of one are equal respectively, and similarly placed, to three faces including a trihedral angle of the other.



Given prisms AI and $A'I'$, face $AJ = \text{face } A'J'$, face $AG = \text{face } A'G'$, face $AD = \text{face } A'D'$.

To prove prism $AI = \text{prism } A'I'$.

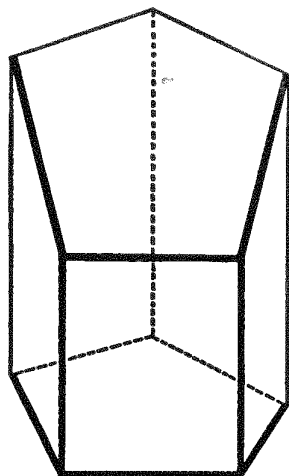
ARGUMENT

REASONS

- | | | | |
|--|--|---|---------------|
| <ol style="list-style-type: none"> 1. $\angle BAF, FAE,$ and BAE are equal, respectively, to $\angle B'A'F', F'A'E',$ and $B'A'E'$. 2. \therefore trihedral $\angle A = \text{trihedral } \angle A'$. 3. Place prism AI upon prism $A'I'$ so that trihedral $\angle A$ shall be superposed upon its equal, trihedral $\angle A'$. 4. Faces $AJ, AG,$ and AD are equal, respectively, to faces $A'J', A'G',$ and $A'D'$. 5. $\therefore J, F,$ and G will fall upon $J', F',$ and $G',$ respectively. 6. CH and $C'H'$ are both $\parallel BG$. 7. $\therefore CH$ and $C'H'$ are collinear. 8. $\therefore H$ will fall upon H'. 9. Likewise I will fall upon I'. 10. \therefore prism $AI = \text{prism } A'I'$. | <table border="0"> <tr> <td style="vertical-align: top;"> <ol style="list-style-type: none"> 1. § 110. 2. § 704. 3. § 54, 14. 4. By hyp. 5. § 18. 6. § 734, a. 7. § 179. 8. § 603, b. 9. By steps similar to 6–8. 10. § 18. </td> <td style="vertical-align: bottom; padding-top: 10px;"> <p>Q.E.D.</p> </td> </tr> </table> | <ol style="list-style-type: none"> 1. § 110. 2. § 704. 3. § 54, 14. 4. By hyp. 5. § 18. 6. § 734, a. 7. § 179. 8. § 603, b. 9. By steps similar to 6–8. 10. § 18. | <p>Q.E.D.</p> |
| <ol style="list-style-type: none"> 1. § 110. 2. § 704. 3. § 54, 14. 4. By hyp. 5. § 18. 6. § 734, a. 7. § 179. 8. § 603, b. 9. By steps similar to 6–8. 10. § 18. | <p>Q.E.D.</p> | | |

736. Def. A truncated prism is the portion of a prism included between the base and a section of the prism made by a plane oblique to the base, but which cuts all the edges of the prism.

737. Cor. I. *Two truncated prisms are equal if three faces including a trihedral angle of one are equal respectively to three faces including a trihedral angle of the other, and the faces are similarly placed.*



738. Cor. II. *Two right prisms are equal if they have equal bases and equal altitudes.*

Ex. 1257. Two triangular prisms are equal if their lateral faces are equal, each to each.

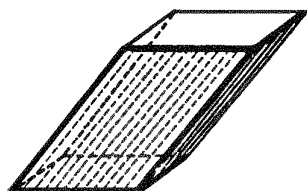
Ex. 1258. Classify the polyhedrons whose faces are: (a) four triangles; (b) two triangles and three parallelograms; (c) two quadrilaterals and four parallelograms; (d) two quadrilaterals and four rectangles; (e) two squares and four rectangles.

Ex. 1259. Find the sum of the plane angles of the dihedral angles whose edges are the lateral edges of a triangular prism; a quadrangular prism. (HINT. Draw a rt. section of the prism.)

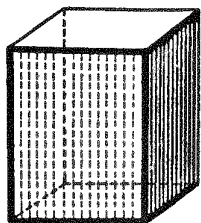
Ex. 1260. Every section of a prism made by a plane parallel to a lateral edge is a parallelogram.

Ex. 1261. Every section of a prism made by a plane parallel to a lateral face is a parallelogram.

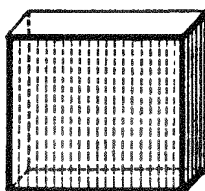
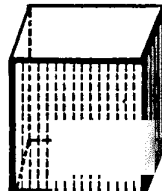
Ex. 1262. The section of a parallelepiped made by a plane passing through two diagonally opposite edges is a parallelogram.



Oblique Parallelepiped



Right Parallelepiped

Rectangular
Parallelepiped

Cube

739. Def. A parallelepiped is a prism whose bases are parallelograms.

740. Def. A **right parallelopiped** is a parallelopiped whose lateral edges are perpendicular to the bases.

741. Def. A **rectangular parallelopiped** is a right parallelopiped whose bases are rectangles.

742. Def. A **cube** (*i.e.* a regular hexahedron) is a rectangular parallelopiped whose edges are all equal.

743. The following are some of the properties of a parallelopiped; the student should prove the correctness of each:

(a) *All the faces of a parallelopiped are parallelograms.*

(b) *All the faces of a rectangular parallelopiped are rectangles.*

(c) *All the faces of a cube are squares.*

(d) *Any two opposite faces of a parallelopiped are equal and parallel.*

(e) *Any two opposite faces of a parallelopiped may be taken as the bases.*

Ex. 1263. Classify the polyhedrons whose faces are: (a) six parallelograms; (b) six rectangles; (c) six squares; (d) two parallelograms and four rectangles; (e) two rectangles and four parallelograms; (f) two squares and four rectangles.

Ex. 1264. Find the sum of all the face angles of a parallelopiped.

Ex. 1265. Find the diagonal of a cube whose edge is 8; 12; e .

Ex. 1266. Find the diagonal of a rectangular parallelopiped whose edges are 6, 8, and 12; whose edges are a , b , and c .

Ex. 1267. The edge of a cube: the diagonal of a face: the diagonal of the cube = $1 : x : y$; find x and y .

Ex. 1268. Find the edge of a cube whose diagonal is $20\sqrt{3}$; d .

Ex. 1269. The diagonals of a rectangular parallelopiped are equal.

Ex. 1270. The diagonals of a parallelopiped bisect each other.

Ex. 1271. The diagonals of a parallelopiped meet in a point.

This point is sometimes called the **center** of the parallelopiped.

Ex. 1272. Any straight line through the center of a parallelopiped, with its extremities in the surface, is bisected at the center.

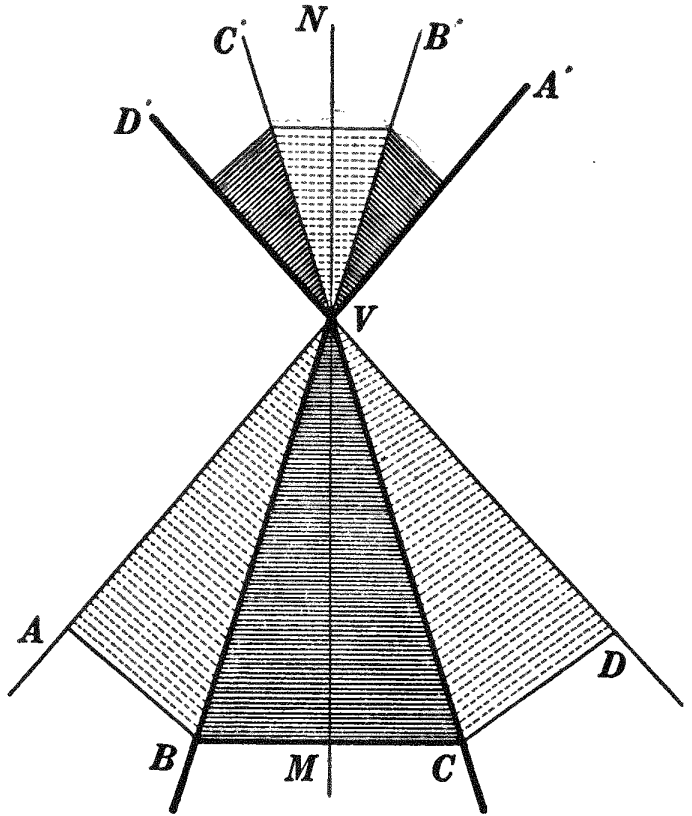
Ex. 1273. The sum of the squares of the four diagonals of a rectangular parallelopiped is equal to the sum of the squares of the twelve edges.

Ex. 1274. Is the statement in Ex. 1273 true for any parallelopiped?

Pyramidal
PYRAMIDS

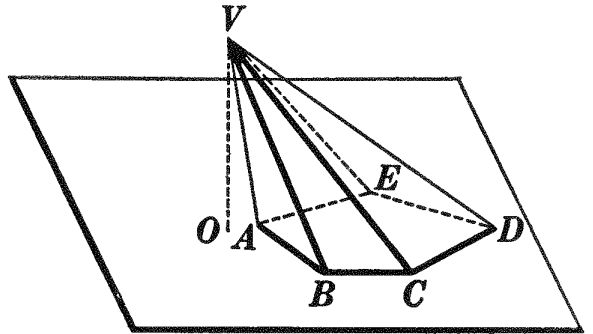
744. Def. A **pyramidal surface** is a surface generated by a moving straight line that continually intersects a fixed broken line and that passes through a fixed point not in the plane of the broken line.

745. Defs. By referring to §§ 693 and 694, give the definitions of **generatrix**, **directrix**, **vertex**, and **element** of a pyramidal surface. Point these out in the figure.



746. Def. A pyramidal surface consists of two parts lying on opposite sides of the vertex, called the **upper and lower nappes**.

747. Def. A **pyramid** is a polyhedron whose boundary consists of the portion of a pyramidal surface extending from its vertex to a plane cutting all its elements, and the section formed by this plane.



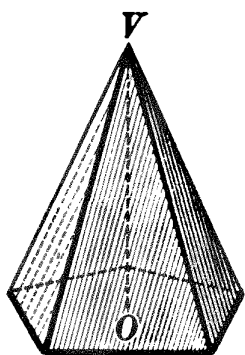
748. Defs. By referring to § 727, the student may give the definitions of **base**, **lateral faces**, and **lateral edges** of a pyramid. The vertex of the pyramidal surface is called the **vertex** of the pyramid, as V . Point these out in the figure.

In this text only pyramids whose bases are convex polygons will be considered.

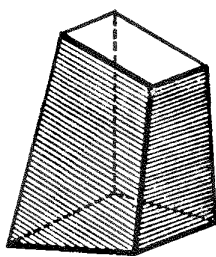
749. Defs. A pyramid is **triangular, quadrangular, etc.**, according as its base is a triangle, a quadrilateral, etc.

750. Questions. How many faces has a triangular pyramid? a tetrahedron? Can these terms be used interchangeably? How many different bases may a triangular pyramid have?

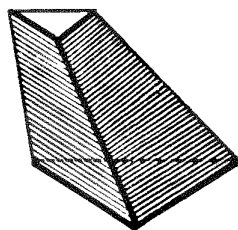
751. Def. The **altitude** of a pyramid is the perpendicular from the vertex to the plane of the base, as VO in the figure below, and in the figure on preceding page.



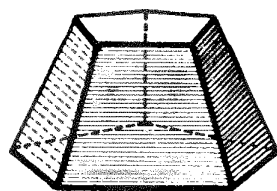
Regular
Pyramid



Truncated
Pyramid



Frustum of
Triangular Pyramid



Frustum of
Regular Pyramid

752. Def. A **regular pyramid** is a pyramid whose base is a regular polygon, and whose vertex lies in the perpendicular erected to the base at its center.

753. Def. A **truncated pyramid** is the portion of a pyramid included between the base and a section of the pyramid made by a plane cutting all the edges.

754. Def. A **frustum of a pyramid** is the portion of a pyramid included between the base and a section of the pyramid made by a plane parallel to the base.

755. The following are some of the properties of a pyramid; the student should prove the correctness of each:

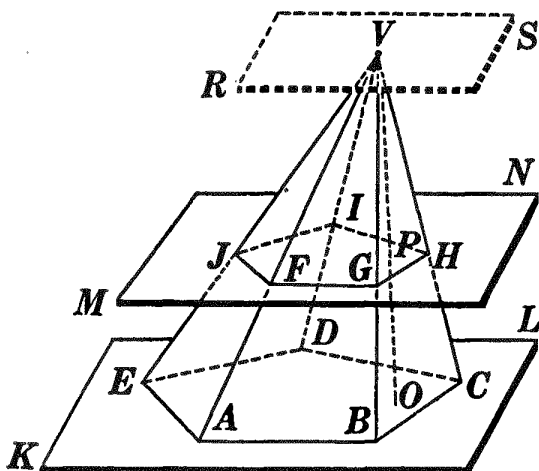
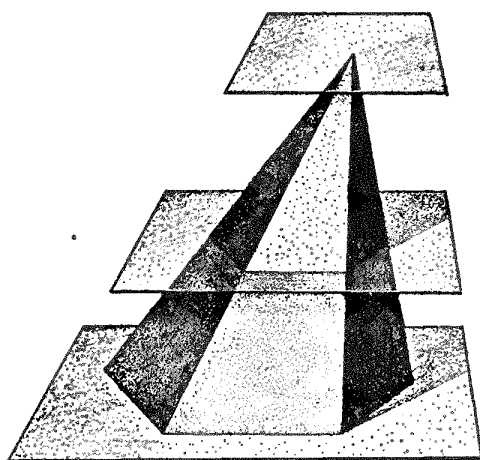
- (a) *The lateral edges of a regular pyramid are equal.*
- (b) *The lateral edges of a frustum of a regular pyramid are equal.*
- (c) *The lateral faces of a regular pyramid are equal isosceles triangles.*

(d) *The lateral faces of a frustum of a regular pyramid are equal isosceles trapezoids.*

PROPOSITION II. THEOREM

756. *If a pyramid is cut by a plane parallel to the base :*

- I. *The edges and altitude are divided proportionally.*
- II. *The section is a polygon similar to the base.*



Given pyramid $V-ABCDE$ and plane $MN \parallel$ base AD cutting the lateral edges in $F, G, H, I,$ and J and the altitude in P .

To prove: I. $\frac{VA}{VF} = \frac{VB}{VG} = \frac{VC}{VH} = \dots = \frac{VO}{VP}$.

II. $FGHIJ \sim ABCDE$.

I.

ARGUMENT

1. Through V pass plane $RS \parallel$ plane KL .
2. Then plane $RS \parallel$ plane MN .
3. $\therefore \frac{VA}{VF} = \frac{VB}{VG}, \frac{VB}{VG} = \frac{VC}{VH}, \frac{VC}{VH} = \frac{VO}{VP}$, etc.
4. $\therefore \frac{VA}{VF} = \frac{VB}{VG} = \frac{VC}{VH} = \dots = \frac{VO}{VP}$. Q.E.D.

REASONS

1. § 652.
2. § 654.
3. § 650.
4. § 54, 1.

II. The proof of II is left as an exercise for the student.

757. Cor I. *Any section of a pyramid parallel to the base is to the base as the square of its distance from the vertex is to the square of the altitude of the pyramid.*

HINT. Prove $\frac{FG^2}{AB^2} = \frac{VG^2}{VB^2} = \frac{VP^2}{VO^2}$.

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Ex. 1281. Prove that parallel sections of a pyramid are to each other as the squares of their distances from the vertex of the pyramid. Do the results obtained in Ex. 1280 fulfill this condition?

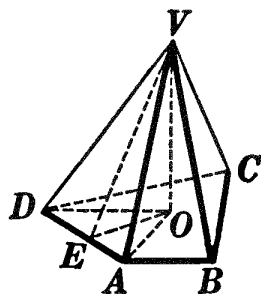
Ex. 1282. Each side of the base of a regular hexagonal pyramid is 6; the altitude is 15. How far from the vertex must a plane be passed parallel to the base to form a section whose area is $12\sqrt{3}$?

Ex. 1283. The areas of the bases of a frustum of a pyramid are 288 square feet and 450 square feet; the altitude of the frustum is 3 feet. Find the altitude of the pyramid of which the given figure is a frustum.

Ex. 1284. The bases of a frustum of a regular pyramid are equilateral triangles whose sides are 10 inches and 18 inches, respectively; the altitude of the frustum is 8 inches. Find the altitude of the pyramid of which the given figure is a frustum.

Ex. 1285. The sum of the lateral faces of any pyramid is greater than the base.

HINT. In the figure, let VE be the altitude of face VAD and VO the altitude of the pyramid. Which is the greater, VE or OE ?



MENSURATION OF THE PRISM AND PYRAMID

AREAS

760. Def. The lateral area of a prism, a pyramid, or a frustum of a pyramid is the sum of the areas of its lateral faces.

761. In the mensuration of the prism and pyramid the following notation will be used:

a, b, c = dimensions of a rectangular parallelepiped.

B = area of base in general or of lower base of a frustum.

b = area of upper base of a frustum.

E = lateral edge, or element, or edge of a tetrahedron in general.

H = altitude of a solid.

h = altitude of a surface.

L = slant height.

O = vertex of a pyramid.

P = perimeter of right section or of the lower base of a frustum.

p = perimeter of upper base of a frustum.

S = lateral area.

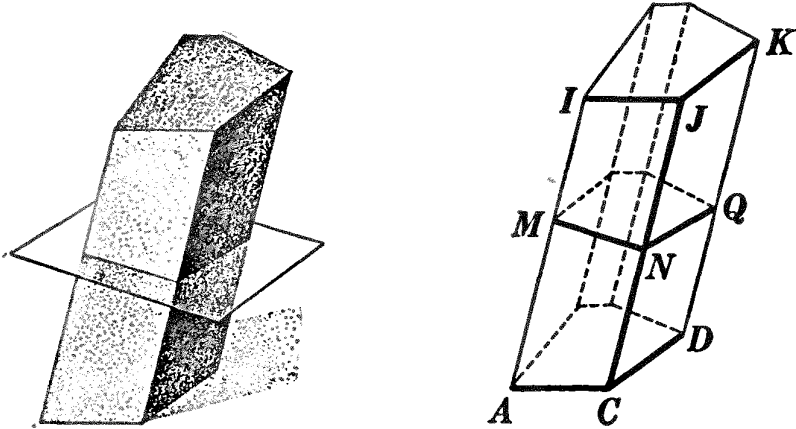
T = total area.

V = volume in general.

$v_1, v_2 \dots$ = volumes of smaller solids into which a larger solid is divided.

PROPOSITION III. THEOREM

762. *The lateral area of a prism is equal to the product of the perimeter of a right section and a lateral edge.*



Given prism AK with MQ a rt. section, E a lateral edge, S the lateral area, and P the perimeter of rt. section MQ .

To prove $S = P \cdot E$.

| ARGUMENT | REASONS |
|--|-------------|
| 1. Rt. section $MQ \perp AI, CJ$, etc. | 1. § 728. |
| 2. $\therefore MN \perp AI; NQ \perp CJ$; etc. | 2. § 619. |
| 3. $\therefore MN$ is the altitude of $\square AJ$; NQ is the altitude of $\square CK$; etc. | 3. § 228. |
| 4. \therefore area of $\square AJ = MN \cdot AI = MN \cdot E$; area of $\square CK = NQ \cdot CJ = NQ \cdot E$; etc. | 4. § 481. |
| 5. $\square AJ + \square CK + \dots = (MN + NQ + \dots)E$. | 5. § 54, 2. |
| 6. $\therefore S = P \cdot E$. | 6. § 309. |

763. Cor. *The lateral area of a right prism is equal to the product of the perimeter of its base and its altitude.*

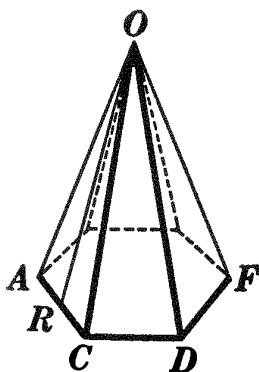
HINT. Thus, if $P =$ perimeter of base and $H =$ altitude, $S = P \cdot H$.

764. Def. The slant height of a regular pyramid is the altitude of any one of its triangular faces.

765. Def. The slant height of a frustum of a regular pyramid is the altitude of any one of its trapezoidal faces.

PROPOSITION IV. THEOREM

766. *The lateral area of a regular pyramid is equal to one half the product of the perimeter of its base and its slant height.*



Given regular pyramid $O-ACD \dots$ with the perimeter of its base denoted by P , its slant height by L , and its lateral area by S .

To prove $S = \frac{1}{2} P \cdot L$.

ARGUMENT

REASONS

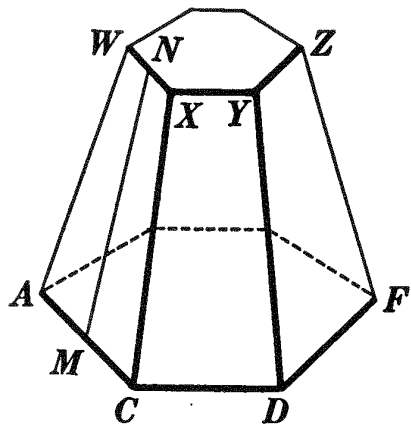
| | |
|---|--|
| <p>1. Area of $\triangle AOC = \frac{1}{2} AC \cdot OR = \frac{1}{2} AC \cdot L$; area of $\triangle COD = \frac{1}{2} CD \cdot L$; etc.</p> <p>2. $\therefore \triangle AOC + \triangle COD + \dots$ $= \frac{1}{2} (AC + CD + \dots)L$.</p> <p>3. $\therefore S = \frac{1}{2} P \cdot L$. Q.E.D.</p> | <p>1. § 485.</p> <p>2. § 54, 2.</p> <p>3. § 309.</p> |
|---|--|

767. **Cor.** *The lateral area of a frustum of a regular pyramid is equal to one half the product of the sum of the perimeters of its bases and its slant height.*

HINT. Prove $S = \frac{1}{2}(P + p)L$.

Ex. 1286. Find the lateral area and the total area of a regular pyramid each side of whose square base is 24 inches, and whose altitude is 16 inches.

Ex. 1287. The sides of the bases of a frustum of a regular octagonal pyramid are 15 centimeters and 24 centimeters, respectively, and the slant height is 30 centimeters. Find the number of square decimeters in the lateral area of the frustum.



Ex. 1288. Find the lateral area of a prism whose right section is a quadrilateral with sides 5, 7, 9, and 13 inches, and whose lateral edge is 15 inches.

Ex. 1289. Find the lateral area of a right prism whose altitude is 16 inches and whose base is a triangle with sides 8, 11, and 13 inches.

Ex. 1290. The perimeter of a right section of a prism is 45 decimeters; its altitude is $10\sqrt{3}$ decimeters; and a lateral edge makes with the base an angle of 60° . Find the lateral area.

Ex. 1291. Find the altitude of a regular prism, one side of whose triangular base is 5 inches and whose lateral area is 195 square inches.

Ex. 1292. Find the total area of a regular hexagonal prism whose altitude is 20 inches and one side of whose base is 10 inches.

Ex. 1293. Find the total area of a cube whose diagonal is $8\sqrt{3}$.

Ex. 1294. Find the edge of a cube if its total area is 294 square centimeters; if its total area is T .

Ex. 1295. Find the total area of a regular tetrahedron whose edge is 6 inches.

Ex. 1296. Find the lateral area and total area of a regular tetrahedron whose slant height is 8 inches.

Ex. 1297. Find the lateral area and total area of a regular hexagonal pyramid, a side of whose base is 6 inches and whose altitude is 10 inches.

Ex. 1298. Find the total area of a rectangular parallelepiped whose edges are 6, 8, and 12; whose edges are a , b , and c .

Ex. 1299. Find the total area of a right parallelepiped, one side of whose square base is 4 inches, and whose altitude is 6 inches.

Ex. 1300. The balcony of a theater is supported by four columns whose bases are regular hexagons. Find the cost, at 2 cents a square foot, of painting the columns if they are 20 feet high and the apothems of the bases are 10 inches.

Ex. 1301. In a frustum of a regular triangular pyramid, the sides of the bases are 8 and 4 inches, respectively, and the altitude is 10 inches. Find the slant height and a lateral edge.

Ex. 1302. In a frustum of a regular hexangular pyramid, the sides of the bases are 12 and 8, respectively, and the altitude is 16. Find the lateral area.

Ex. 1303. In a regular triangular pyramid, the side of the base is 8 inches, and the altitude is 12 inches; a lateral face makes with the base an angle of 60° . Find the lateral area.

VOLUMES

768. Note. The student should compare carefully §§ 769–776 with the corresponding discussion of the rectangle, §§ 466–473.

769. A solid may be **measured** by finding how many times it contains a *solid unit*. The solid unit most frequently chosen is a cube whose edge is of unit length. If the unit length is an inch, the solid unit is a cube whose edge is an inch. Such a unit is called a **cubic inch**. If the unit length is a foot, the solid unit is a cube whose edge is a foot, and the unit is called a **cubic foot**.

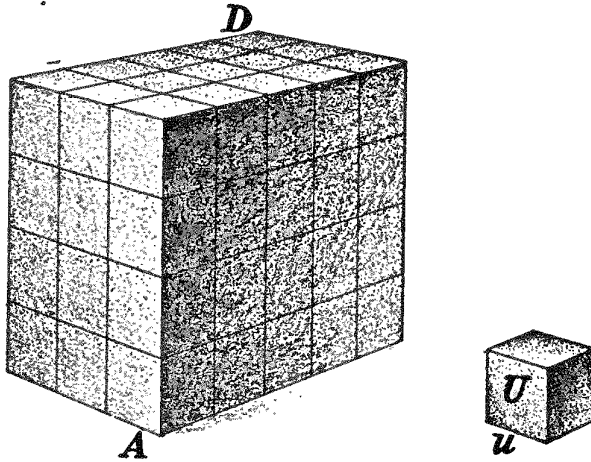


FIG. 1. Rectangular Parallelepiped $AD = 60 U$.

770. Def. The result of the measurement is a *number*, which is called the **measure-number**, or **numerical measure**, or **volume** of the solid.

771. Thus, if the unit cube U is contained in the rectangular

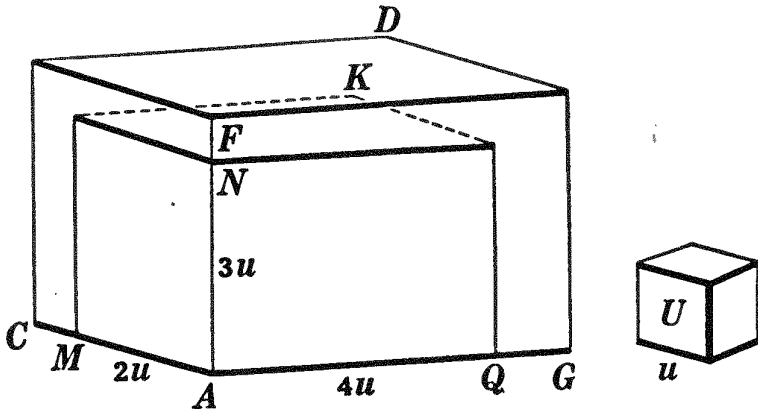


FIG. 2. Rectangular Parallelepiped $AD = 24 U+$.

parallelepiped AD (Fig. 1) 60 times, then the measure-number or volume of rectangular parallelepiped AD , in terms of U , is 60.

If the given unit cube is not contained in the given rectangular parallelepiped an integral number of times without a remainder (Fig. 2), then by taking a cube that is an aliquot part of U , as one eighth of U , and applying it as a measure to the rectangular parallelepiped (Fig. 3), a number will be obtained

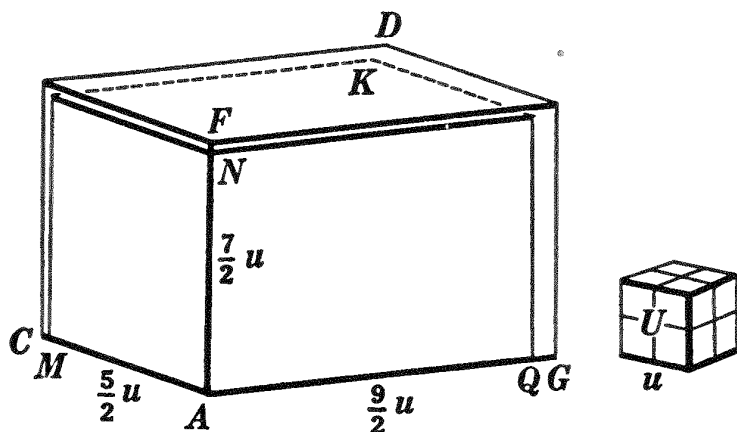


FIG. 3. Rectangular Parallelepiped $AD = 3\frac{1}{8} U^+ = 39\frac{3}{8} U^+$.

which, divided by 8,* will give another (and usually closer) approximate volume of the given rectangular parallelepiped. By proceeding in this way (Fig. 4), closer and closer approximations to the true volume may be obtained.

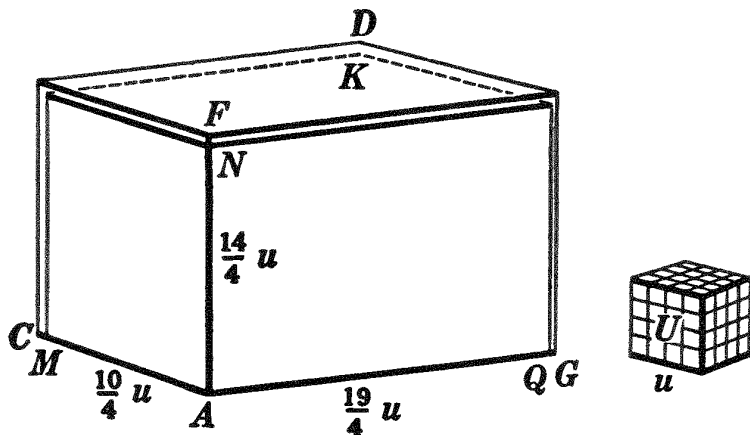


FIG. 4. Rectangular Parallelepiped $AD = \frac{2660}{64} U^+ = 41\frac{9}{16} U^+$.

* It takes eight of the small cubes to make the *unit cube* itself.

772. If the edges of the given rectangular parallelopiped and the edge of the unit cube are *commensurable*, a cube may be found which is an aliquot part of U , and which will be contained in the rectangular parallelopiped an integral number of times.

773. If the edges of the given rectangular parallelopiped and the edge of the unit cube are *incommensurable*, then closer and closer approximations to the volume may be obtained, but no cube which is an aliquot part of U will be also an aliquot part of the rectangular parallelopiped (by definition of incommensurable magnitudes).

There is, however, a definite *limit* which is approached more and more closely by the approximations obtained by using smaller and smaller subdivisions of the unit cube, as these subdivisions approach zero as a limit.

774. Def. The **volume** of a rectangular parallelopiped which is incommensurable with the chosen unit cube is the *limit* which successive approximate volumes of the rectangular parallelopiped *approach* as the subdivisions of the unit cube approach zero as a limit.

For brevity the expression *the volume of a solid*, or simply *the solid*, is used to mean the volume of the solid with respect to a chosen unit.

775. Def. The **ratio** of any two solids is the ratio of their measure-numbers, or volumes (based on the same unit).

776. Def. Two solids are **equivalent** if their volumes are equal.

777. Historical Note. The determination of the volumes of polyhedrons is found in a document as ancient as the Rhind papyrus, which is thought to be a copy of a manuscript dating back possibly as far as 3400 B.C. (See § 474.) In this manuscript Ahmes calculates the contents of an Egyptian barn by means of the formula, $V = a \cdot b \cdot (c + \frac{1}{2} c)$, where a , b , and c are supposed to be linear dimensions of the barn. But unfortunately the exact shape of these barns is unknown, so that the accuracy of the formula cannot be tested.

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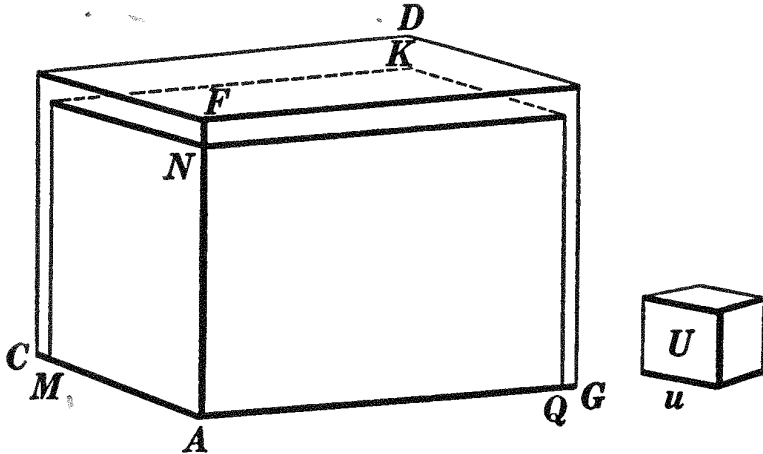
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(b) Suppose that u is not a measure of AC , AF , and AG , respectively, but that some aliquot part of u is such a measure.

The proof is left as an exercise for the student.



II. If AC , AF , and AG are each incommensurable with u .

ARGUMENT

REASONS

- | | |
|--|--------------|
| 1. Let m be a measure of u . Apply m as a measure to AC , AF , and AG , respectively, as many times as possible. There will be remainders, as MC , NF , and QG , each less than m . | 1. § 339. |
| 2. Through M draw plane $MK \perp AC$, through N draw plane $NK \perp AF$, and through Q draw plane $QK \perp AG$. | 2. § 627. |
| 3. Now AM , AN , and AQ are each commensurable with the measure m , and hence with u , the linear unit. | 3. § 337. |
| 4. \therefore the volume of rectangular parallelepiped $AK = AM \cdot AN \cdot AQ$. | 4. § 778, I. |
| 5. Now take a smaller measure of u . No matter how small a measure of u is taken, when it is applied as a measure to AC , AF , and AG , the remainders, MC , NF , and QG , will be smaller than the measure taken. | 5. § 335. |

| ARGUMENT | REASONS |
|--|-------------|
| 6. \therefore the difference between AM and AC , the difference between AN and AF , and the difference between AQ and AG , may each be made to become and remain less than any previously assigned segment, however small. | 6. Arg. 5. |
| 7. \therefore AM approaches AC as a limit, AN approaches AF as a limit, and AQ approaches AG as a limit. | 7. § 349. |
| 8. \therefore $AM \cdot AN \cdot AQ$ approaches $AC \cdot AF \cdot AG$ as a limit. | 8. § 593. |
| 9. Again, the difference between rectangular parallelepiped AK and rectangular parallelepiped AD may be made to become and remain less than any previously assigned volume, however small. | 9. Arg. 5. |
| 10. \therefore the volume of rectangular parallelepiped AK approaches the volume of rectangular parallelepiped AD as a limit. | 10. § 349. |
| 11. But the volume of AK is always equal to $AM \cdot AN \cdot AQ$. | 11. Arg. 4. |
| 12. \therefore the volume of $AD = AC \cdot AF \cdot AG$. Q.E.D. | 12. § 355. |

III. If AC is commensurable with u but AF and AG are incommensurable with u .

IV. If AC and AF are commensurable with u but AG is incommensurable with u .

The proofs of III and IV are left as exercises for the student.

779. Cor I. *The volume of a cube is equal to the cube of its edge.*

HINT. Compare with § 478.

780. Cor. II. *Any two rectangular parallelepipeds are to each other as the products of their three dimensions.* (HINT. Compare with § 479.)

781. Note. By the product of a surface and a line is meant the product of the measure-numbers of the surface and the line.

782. Cor. III. *The volume of a rectangular parallelepiped is equal to the product of its base and its altitude.*

783. Cor. IV. *Any two rectangular parallelepipeds are to each other as the products of their bases and their altitudes.* (HINT. Compare with § 479.)

784. Cor. V. (a) *Two rectangular parallelepipeds having equivalent bases are to each other as their altitudes;* (b) *two rectangular parallelepipeds having equal altitudes are to each other as their bases.* (HINT. Compare with § 480.)

785. Cor. VI. (a) *Two rectangular parallelepipeds having two dimensions in common are to each other as their third dimensions, and* (b) *two rectangular parallelepipeds having one dimension in common are to each other as the products of their other two dimensions.*

786. Questions. What is it in Book IV that corresponds to volume in Book VII? to rectangular parallelepiped? State the theorem and corollaries in Book IV that correspond to §§ 778, 779, 782, 783, and 784. Will the proofs given there, with the corresponding changes in terms, apply here? Compare the entire discussion of §§ 466–480 with §§ 769–785.

Ex. 1304. Find the volume of a cube whose diagonal is $5\sqrt{3}$; d .

Ex. 1305. The volume of a rectangular parallelepiped is V ; each side of the square base is one third the altitude of the parallelepiped. Find the side of the base. Find the side of the base if $V = 192$ cubic feet.

Ex. 1306. The dimensions of two rectangular parallelepipeds are 6, 8, 10 and 5, 12, 16, respectively. Find the ratio of their volumes.

Ex. 1307. The total area of a cube is 300 square inches; find its volume.

Ex. 1308. The volume of a certain cube is V ; find the volume of a cube whose edge is twice that of the given cube.

Ex. 1309. The edge of a cube is a ; find the edge of a cube twice as large; *i.e.* containing twice the volume of the given cube.

787. Historical Note. Plato (429–348 B.C.) was one of the first to discover a solution to that famous problem of antiquity, the *duplication of a cube*, i.e. the finding of the edge of a cube whose volume is double that of a given cube.

There are two legends as to the origin of the problem. The one is that an old tragic poet represented King Minos as wishing to erect a tomb for his son Glaukus. The king being dissatisfied with the dimensions (100 feet each way) proposed by his architect, exclaimed: "The inclosure is too small for a royal tomb; double it, but fail not in the cubical form."



PLATO

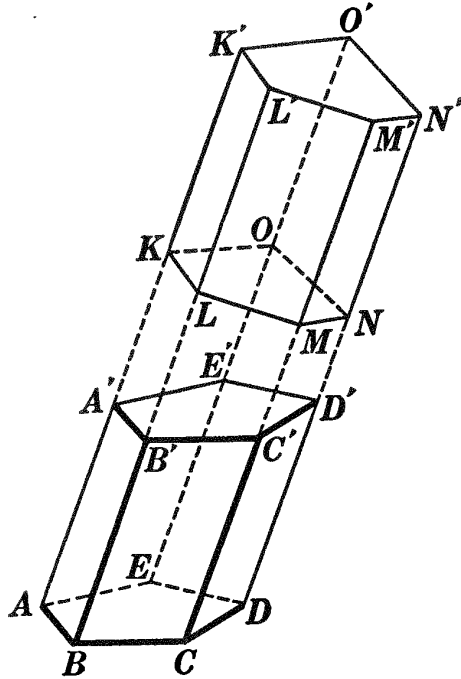
The other legend asserts that the Athenians, who were suffering from a plague of typhoid fever, consulted the oracle at Delos as to how to stop the plague. Apollo replied that the Delians would have to double the size of his altar, which was in the form of a cube. A new altar was constructed having its edge twice as long as that of the old one. The pestilence became worse than before, whereupon the Delians appealed to Plato. It is therefore known as the Delian problem.

Plato was born in Athens, and for eight years was a pupil of Socrates. Plato possessed considerable wealth, and after the death of Socrates in 399 B.C. he spent some years in traveling and in the study of mathematics. It was during this time that he became acquainted with the members of the Pythagorean School, especially with Archytas, who was then its head. No doubt it was his association with these people that gave him his passion for mathematics. About 380 B.C. he returned to his native city, where he established a school. Over the entrance to his school was this inscription: "Let none ignorant of geometry enter my door." Later an applicant who knew no geometry was actually turned away with the statement: "Depart, for thou hast not the grip of philosophy."

Plato is noted as a teacher, rather than an original discoverer, and his contributions to geometry are improvements in its method rather than additions to its matter. He valued geometry mainly as a "means of education in right seeing and thinking and in the conception of imaginary processes." It is stated on good authority that "Plato was almost as important as Pythagoras to the advance of Greek geometry."

PROPOSITION VI. THEOREM

788. *An oblique prism is equivalent to a right prism, whose base is a right section of the oblique prism, and whose altitude is equal to a lateral edge of the oblique prism.*



Given oblique prism AD' ; also rt. prism KN' with base KN a rt. section of AD' , and with KK' , LL' , etc., lateral edges of KN' , equal to AA' , BB' , etc., lateral edges of AD' .

To prove oblique prism $AD' \cong$ rt. prism KN' .

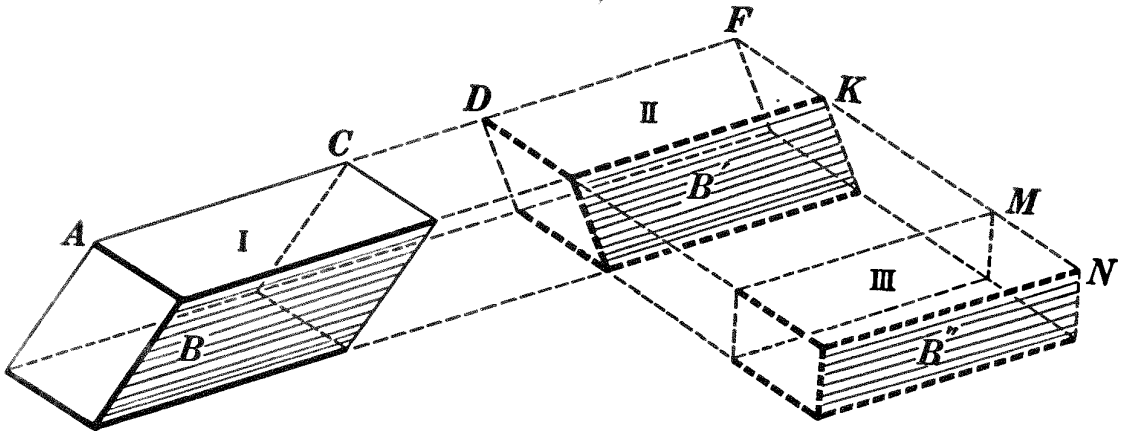
OUTLINE OF PROOF

1. In truncated prisms AN and $A'N'$, prove the \sphericalangle of face BK equal, respectively, to the \sphericalangle of face $B'K'$.
2. Prove the sides of face BK equal, respectively, to the sides of face $B'K'$.
3. \therefore face $BK =$ face $B'K'$.
4. Similarly face $BM =$ face $B'M'$, and face $BE =$ face $B'E'$.
5. \therefore truncated prism $AN =$ truncated prism $A'N'$ (§ 737).
6. But truncated prism $A'N =$ truncated prism $A'N$.
7. \therefore oblique prism $AD' \cong$ rt. prism KN' . Q.E.D.

789. Question. Is there a theorem in Book IV that corresponds to Prop. VI? If not, formulate one and see if you can prove it true.

PROPOSITION VII. THEOREM

790. *The volume of any parallelopiped is equal to the product of its base and its altitude.*



Given parallelopiped I with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = B \cdot H$.

| ARGUMENT | REASONS |
|---|--------------|
| 1. Prolong edge AC and all edges of $I \parallel AC$. | 1. § 54, 16. |
| 2. On the prolongation of AC take $DF = AC$, and through D and F pass planes $\perp AF$, forming rt. parallelopiped II . | 2. § 627. |
| 3. Then $I \cong II$. | 3. § 788. |
| 4. Prolong edge FK and all edges of $II \parallel FK$. | 4. § 54, 16. |
| 5. On the prolongation of FK take $MN = FK$, and through M and N pass planes $\perp FN$, forming rectangular parallelopiped III . | 5. § 627. |
| 6. Then $II \cong III$. | 6. § 788. |
| 7. $\therefore I \cong III$. | 7. § 54, 1. |
| 8. Again, $B \cong B' = B''$. | 8. § 482. |
| 9. Also H , the altitude of I , = the altitude of III . | 9. § 663. |
| 10. But the volume of $III = B'' \cdot H$. | 10. § 782. |
| 11. $\therefore V = B \cdot H$. | 11. § 309. |

Q.E.D.

791. Cor. I. *Parallelopipeds having equivalent bases and equal altitudes are equivalent.*

792. Cor. II. *Any two parallelopipeds are to each other as the products of their bases and their altitudes.*

793. Cor. III. (a) *Two parallelopipeds having equivalent bases are to each other as their altitudes, and* (b) *two parallelopipeds having equal altitudes are to each other as their bases.*

794. Questions. What expression in Book IV corresponds to *volume of a parallelopiped*? Quote the theorem and corollaries in Book IV that correspond to §§ 790–793. Will the proofs given there, with the corresponding changes, apply here?

Ex. 1310. Prove Prop. VI by subtracting the equal truncated prisms of Arg. 5 from the entire figure.

Ex. 1311. The base of a parallelopiped is a parallelogram two adjacent sides of which are 8 and 15, respectively, and they include an angle of 30° . If the altitude of the parallelopiped is 10, find its volume.

Ex. 1312. Four parallelopipeds have equivalent bases and equal lateral edges. In the first the lateral edge makes with the base an angle of 30° ; in the second an angle of 45° ; in the third an angle of 60° ; and in the fourth an angle of 90° . Find the ratio of the volumes of the four parallelopipeds.

Ex. 1313. Find the edge of a cube equivalent to a rectangular parallelopiped whose edges are 6, 10, and 15; whose edges are a , b , and c .

Ex. 1314. Find the diagonal of a cube whose volume is 512 cubic inches; a cubic inches.

Ex. 1315. The edge of a cube is a . Find the area of a section made by a plane through two diagonally opposite edges.

Ex. 1316. How many cubic feet of cement will be needed to make a box, including lid, if the inside dimensions of the box are 2 feet 6 inches, 3 feet, and 4 feet 6 inches, if the cement is 3 inches thick?

HINT. In a problem of this kind, always find the volume of the whole solid, and the volume of the inside solid, then subtract.

Ex. 1317. The volume of a rectangular parallelopiped is 2430 cubic inches, and its edges are in the ratio of 3, 5, and 6. Find its edges.

Ex. 1318. In a certain cube the area of the surface and the volume have the same numerical value. Find the volume of the cube.

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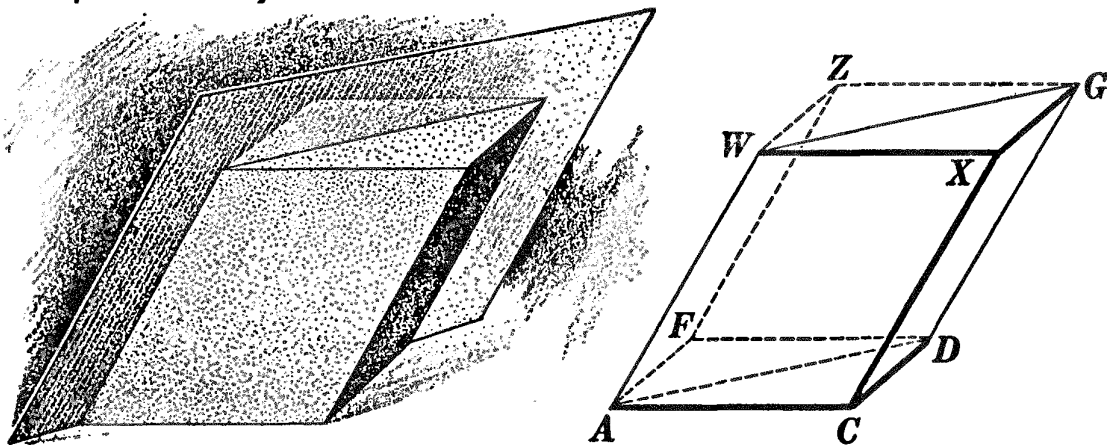
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PROPOSITION IX. THEOREM

797. *The volume of a triangular prism is equal to the product of its base and its altitude.*



Given triangular prism $ACD-X$ with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = B \cdot H$.

The proof is left as an exercise for the student.

798. Questions. What proposition in Book IV corresponds to Prop. IX above? Can you apply the proof there given? What is the name of the figure CZ in § 797? What is its volume? What part of CZ is $ACD-X$ (§ 795)?

Ex. 1319. The volume of a triangular prism is equal to one half the product of any lateral face and the perpendicular from any point in the opposite edge to that face.

HINT. The triangular prism is one half of a certain parallelepiped (§ 795).

Ex. 1320. The base of a coal bin which is 8 feet deep is a triangle with sides 10 feet, 15 feet, and 20 feet, respectively. How many tons of coal will the bin hold considering 35 cubic feet of coal to a ton?

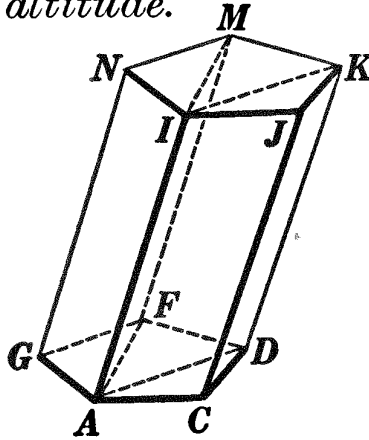
Ex. 1321. One face of a triangular prism contains 45 square inches; the perpendicular to this face from a point in the opposite edge is 6 inches. Find the volume of the prism.

Ex. 1322. During a rainfall of $\frac{1}{2}$ inch, how many barrels of water will fall upon a ten-acre field, counting $7\frac{1}{2}$ gallons to a cubic foot and $31\frac{1}{2}$ gallons to a barrel?

Ex. 1323. The inside dimensions of an open tank before lining are 6 feet, 2 feet 6 inches, and 2 feet, respectively, the latter being the height. Find the number of pounds of zinc required to line the tank with a coating $\frac{1}{4}$ inch thick, a cubic foot of zinc weighing 6860 ounces.

PROPOSITION X. THEOREM

799. *The volume of any prism is equal to the product of its base and its altitude.*



Given prism AM with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = B \cdot H$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. From any vertex of the lower base, as A , draw diagonals AD, AF , etc. | 1. § 54, 15. |
| 2. Through edge AI and these diagonals pass planes AK, AM , etc. | 2. § 612. |
| 3. Prism AM is thus divided into triangular prisms. | 3. § 732. |
| 4. Denote the volume and base of triangular prism $ACD-J$ by v_1 and b_1 ; of $ADF-K$ by v_2 and b_2 ; etc. Then $v_1 = b_1H; v_2 = b_2H; \text{ etc.}$ | 4. § 797. |
| 5. $\therefore v_1 + v_2 + \dots = (b_1 + b_2 + \dots)H$. | 5. § 54, 2. |
| 6. $\therefore V = B \cdot H$. Q.E.D. | 6. § 309. |

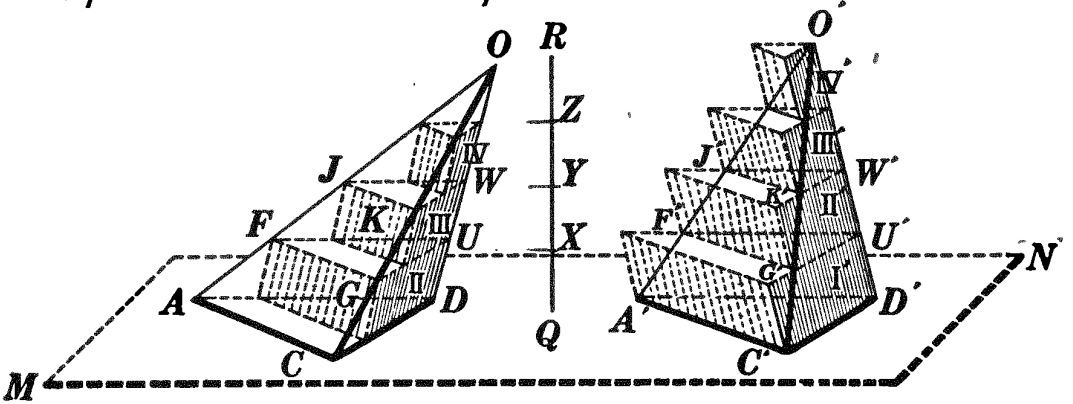
800. Cor. I. *Prisms having equivalent bases and equal altitudes are equivalent.*

801. Cor. II. *Any two prisms are to each other as the products of their bases and their altitudes.*

802. Cor. III. (a) *Two prisms having equivalent bases are to each other as their altitudes;* (b) *two prisms having equal altitudes are to each other as their bases.*

PROPOSITION XI. THEOREM

803. *Two triangular pyramids having equivalent bases and equal altitudes are equivalent.*



Given triangular pyramids $O-ACD$ and $O'-A'C'D'$ with base $ACD \cong$ base $A'C'D'$, with altitudes each equal to QR , and with volumes denoted by V and V' , respectively.

To prove $V = V'$.

ARGUMENT

REASONS

- | | |
|---|--|
| <ol style="list-style-type: none"> 1. $V = V', V < V',$ or $V > V'.$ 2. Suppose $V < V',$ so that $V' - V = k,$ a constant. For convenience, place the two pyramids so that their bases are in the same plane, $MN.$ 3. Divide the common altitude QR into n equal parts, as $QX, XY,$ etc., and through the several points of division pass planes \parallel plane $MN.$ 4. Then section $FGU \cong$ section $F'G'U',$ section $JKW \cong$ section $J'K'W',$ etc. 5. On $FGU, JKW,$ etc., as upper bases, construct prisms with edges $\parallel DO$ and with altitudes $= QX.$ Denote these prisms by $II, III,$ etc. 6. On $A'C'D', F'G'U',$ etc., as lower bases, construct prisms with edges $\parallel D'O'$ and with altitudes $= QX.$ Denote these prisms by $I', II',$ etc. | <ol style="list-style-type: none"> 1. 161, $\alpha.$ 2. § 54, 14. 3. § 653. 4. § 759. 5. § 726. 6. § 726. |
|---|--|

| ARGUMENT | REASONS |
|--|-------------------------------|
| 7. Then prism II \cong prism II', prism III \cong prism III', etc. | 7. § 800. |
| 8. Now denote the sum of the volumes of prisms II, III, etc., by S ; the sum of the volumes of prisms I', II', III', etc., by S' ; and the volume of prism I' by v' . Then $S' - S = v'$. | 8. § 54, 3. |
| 9. But $v' < S'$ and $S < v$. | 9. § 54, 12. |
| 10. $\therefore v' + S < v + S'$. | 10. § 54, 9. |
| 11. $\therefore v' - v < S' - S$; <i>i.e.</i> $v' - v < v'$. | 11. § 54, 5. |
| 12. By making the divisions of the altitude QR smaller and smaller, prism I', and hence v' may be made less than any previously assigned volume, however small. | 12. 802, <i>a</i> . |
| 13. $\therefore v' - v$, which is $< v'$, may be made less than any previously assigned volume, however small. | 13. § 54, 10. |
| 14. \therefore the supposition that $v' - v = k$, a constant, is false; <i>i.e.</i> v is not $< v'$. | 14. Arg. 13. |
| 15. Similarly it may be proved that v' is not $< v$. | 15. By steps similar to 2-14. |
| 16. $\therefore v = v'$. Q.E.D. | 16. § 161, <i>b</i> . |

Ex. 1324. The volume of an oblique prism is equal to the product of its right section and a lateral edge.

HINT. Apply § 788.

Ex. 1325. The volume of a regular prism is equal to the product of its lateral area and one half the apothem of its base.

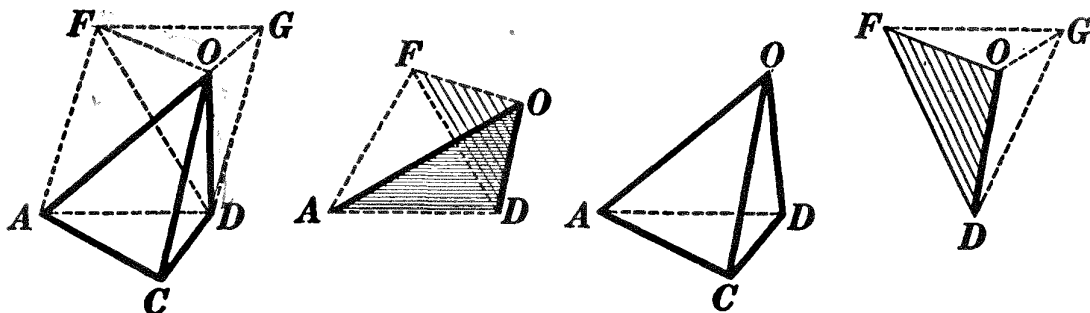
HINT. See Ex. 1319.

Ex. 1326. The base of a prism is a rhombus having one side 29 inches and one diagonal 42 inches. If the altitude of the prism is 25 inches, find its volume.

Ex. 1327. In a certain cube the area of the surface and the combined lengths of its edges have the same numerical value. Find the volume of the cube.

PROPOSITION XII. THEOREM

804. *The volume of a triangular pyramid is equal to one third the product of its base and its altitude.*



Given triangular pyramid $O-ACD$ with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = \frac{1}{3} B \cdot H$.

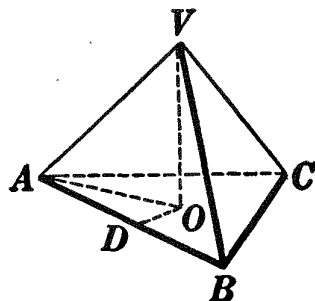
ARGUMENT ONLY

1. Construct prism AG with base ACD and lateral edge CO .
2. The prism is then composed of triangular pyramid $O-ACD$ and quadrangular pyramid $O-ADGF$.
3. Through OD and OF pass a plane, intersecting $ADGF$ in DF and dividing quadrangular pyramid $O-ADGF$ into two triangular pyramids $O-ADF$ and $O-DGF$.
4. $ADGF$ is a \square ; $\therefore \triangle ADF = \triangle DGF$.
5. $\therefore O-ADF \cong O-DGF$.
6. But in triangular pyramid $O-DGF$, OGF may be taken as base and D as vertex; then $O-DGF = D-OGF \cong O-ACD$.
7. But $O-ACD + O-ADF + O-DGF \cong$ prism AG .
8. \therefore 3 times the volume of $O-ACD =$ the volume of prism AG .
9. $\therefore V = \frac{1}{3}$ the volume of prism AG .
10. But prism $AG = B \cdot H$; $\therefore V = \frac{1}{3} B \cdot H$. Q.E.D.

Ex. 1328. Find the volume of a regular tetrahedron whose edge is 6.

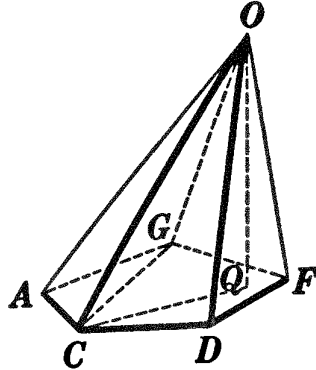
HINT. O , the foot of the \perp from V to the plane of base ABC , is the center of $\triangle ABC$ (§ 752). Hence $OA = \frac{2}{3}$ of the altitude of $\triangle ABC$, and a \perp from O to any edge of the base, as $OD = \frac{1}{2}$ of OA .

Ex. 1329. Find the volume of a regular tetrahedron with slant height $2\sqrt{3}$; with altitude a .



PROPOSITION XIII. THEOREM

805. *The volume of any pyramid is equal to one third the product of its base and its altitude.*



Given pyramid $O-ACDFG$ with its volume denoted by V , its base by B , and its altitude, OQ , by H .

To prove $V = \frac{1}{3} B \cdot H$.

The proof is left as an exercise for the student.

HINT. See proof of Prop. X.

806. **Cor. I.** *Pyramids having equivalent bases and equal altitudes are equivalent.*

807. **Cor. II.** *Any two pyramids are to each other as the products of their bases and their altitudes.*

808. **Cor. III.** (a) *Two pyramids having equivalent bases are to each other as their altitudes, and (b) two pyramids having equal altitudes are to each other as their bases.*

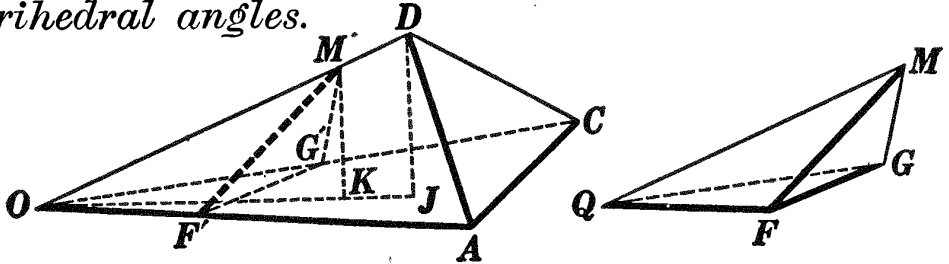
Ex. 1330. In the figure of § 805, if the base = 250 square inches, $OC = 18$ inches, and the inclination of OC to the base is 60° , find the volume.

Ex. 1331. A pyramid and a prism have equivalent bases and equal altitudes; find the ratio of their volumes.

809. **Historical Note.** The proof of the proposition that "every pyramid is the third part of a prism on the same base and with the same altitude" is attributed to Eudoxus (408–355 B.C.), a great mathematician of the Athenian School. In a noted work written by Archimedes (287–212 B.C.), called *Sphere and Cylinder*, there is also found an expression for the surface and volume of a pyramid. (For a further account of Archimedes, see §§ 542, 896, and 973.) Later a solution of this problem was given by Brahmagupta, a noted Hindoo writer born about 598 A.D.

PROPOSITION XIV. THEOREM

810. *Two triangular pyramids, having a trihedral angle of one equal to a trihedral angle of the other, are to each other as the products of the edges including the equal trihedral angles.*



Given triangular pyramids $O-ACD$ and $Q-FGM$ with trihedral $\angle O =$ trihedral $\angle Q$, and with volumes denoted by V and V' , respectively.

To prove
$$\frac{V}{V'} = \frac{OA \cdot OC \cdot OD}{QF \cdot QG \cdot QM}.$$

ARGUMENT

REASONS

- | | |
|---|---|
| <p>1. Place pyramid $Q-FGM$ so that trihedral $\angle Q$ shall coincide with trihedral $\angle O$. Represent pyramid $Q-FGM$ in its new position by $O-F'G'M'$.</p> <p>2. From D and M' draw DJ and $M'K \perp$ plane OAC.</p> <p>3. Then $\frac{V}{V'} = \frac{\Delta OAC \cdot DJ}{\Delta OF'G' \cdot M'K} = \frac{\Delta OAC}{\Delta OF'G'} \cdot \frac{DJ}{M'K}.$</p> <p>4. But $\frac{\Delta OAC}{\Delta OF'G'} = \frac{OA \cdot OC}{OF' \cdot OG'}.$</p> <p>5. Again let the plane determined by DJ and $M'K$ intersect plane OAC in line OKJ.</p> <p>6. Then rt. $\Delta DJO \sim$ rt. $\Delta M'KO$.</p> <p>7. $\therefore \frac{DJ}{M'K} = \frac{OD}{OM'}.$</p> <p>8. $\therefore \frac{V}{V'} = \frac{OA \cdot OC}{OF' \cdot OG'} \cdot \frac{OD}{OM'} = \frac{OA \cdot OC \cdot OD}{QF \cdot QG \cdot QM}.$ Q.E.D.</p> | <p>1. § 54, 14.</p> <p>2. § 639.</p> <p>3. § 807.</p> <p>4. § 498.</p> <p>5. §§ 613, 616.</p> <p>6. § 422.</p> <p>7. § 424, 2.</p> <p>8. § 309.</p> |
|---|---|

811. Def. Two polyhedrons are similar if they have the same number of faces similar each to each and similarly placed, and have their corresponding polyhedral angles equal.

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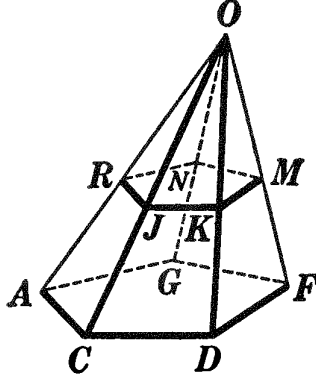
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PROPOSITION XVI. THEOREM

815. *The volume of a frustum of any pyramid is equal to one third the product of its altitude and the sum of its lower base, its upper base, and the mean proportional between its two bases.*



Given frustum AM , of pyramid $O-AF$, with its volume denoted by V , its lower base by B , its upper base by b , and its altitude by H .

To prove $V = \frac{1}{3} H(B + b + \sqrt{B \cdot b})$.

ARGUMENT

REASONS

1. Frustum $AM =$ pyramid $O-AF$ minus pyramid $O-RM$.
2. Let H' denote the altitude of $O-RM$.
Then $V = \frac{1}{3} B(H + H') - \frac{1}{3} b \cdot H'$
 $= \frac{1}{3} HB + \frac{1}{3} H'(B - b)$.
It now remains to find the value of H' .

3.
$$\frac{b}{B} = \frac{H'^2}{(H + H')^2}$$

4.
$$\therefore \frac{\sqrt{b}}{\sqrt{B}} = \frac{H'}{H + H'}$$

5. Whence $H' = \frac{H\sqrt{b}}{\sqrt{B} - \sqrt{b}}$.

6.
$$\therefore V = \frac{1}{3} HB + \frac{1}{3} \frac{H\sqrt{b}}{\sqrt{B} - \sqrt{b}} (B - b)$$

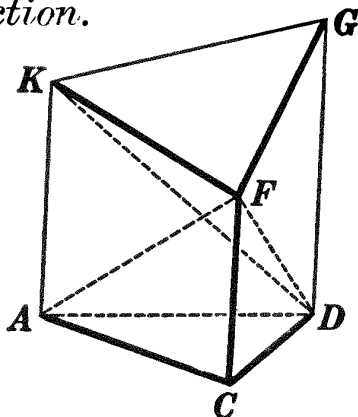
$$= \frac{1}{3} HB + \frac{1}{3} Hb + \frac{1}{3} H\sqrt{B \cdot b};$$

i.e. $V = \frac{1}{3} H(B + b + \sqrt{B \cdot b})$. Q.E.D.

1. § 54, 11.
2. § 805.
3. § 757.
4. § 54, 13.
5. Solving for H' .
6. § 309.

PROPOSITION XVII. THEOREM

816. *A truncated triangular prism is equivalent to three triangular pyramids whose bases are the base of the frustum and whose vertices are the three vertices of the inclined section.*



Given truncated triangular prism $ACD-FGK$.

To prove $ACD-FGK \cong F-ACD + G-ACD + K-ACD$.

ARGUMENT

REASONS

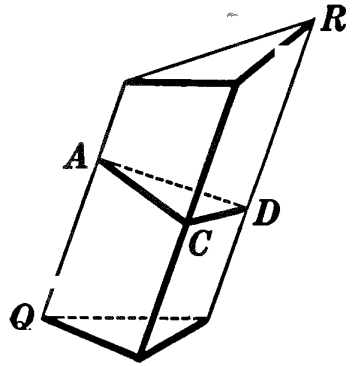
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|---|--|
| <p>1. Through A, D, F and K, D, F pass planes dividing frustum $ACD-FGK$ into three triangular pyramids $F-ACD$, $F-ADK$, and $F-DGK$. Since $F-ACD$ is one of the required pyramids, it remains to prove $F-ADK \cong K-ACD$ and $F-DGK \cong G-ACD$.</p> <p>2. $CF \parallel$ plane AG.</p> <p>3. \therefore the altitude of pyramid $F-ADK =$ the altitude of pyramid $C-ADK$.</p> <p>4. $\therefore F-ADK \cong C-ADK$.</p> <p>5. But in $C-ADK$, ACD may be taken as base and K as vertex.</p> <p>6. $\therefore F-ADK \cong K-ACD$.</p> <p>7. Likewise $F-DGK \cong C-DGK = K-CDG$; and $K-CDG \cong A-CDG = G-ACD$.</p> <p>8. $\therefore F-DGK \cong G-ACD$.</p> <p>9. $\therefore ACD - FGK \cong F-ACD + G-ACD + K-ACD$.</p> | <p>1. § 611.</p> <p>2. § 646.</p> <p>3. § 664.</p> <p>4. § 806.</p> <p>5. §§ 749, 750.</p> <p>6. § 309.</p> <p>7. By steps similar to 3-7.</p> <p>8. § 54, 1.</p> <p>9. § 309.</p> |
|---|--|

Q.E.D.

817. Cor. I. *The volume of a truncated right triangular prism is equal to one third the product of its base and the sum of its lateral edges.*

818. Cor. II. *The volume of any truncated triangular prism is equal to one third the product of a right section and the sum of its lateral edges.*

HINT. Rt. section ACD divides truncated triangular prism QR into two truncated right triangular prisms.



Ex. 1334. The base of a truncated right triangular prism has for its sides 13, 14, and 15 inches; its lateral edges are 8, 11, and 13 inches. Find its volume.

Ex. 1335. In the formula of § 815: (1) put $b = 0$ and compare result with formula of § 805; (2) put $b = B$ and compare result with formula of § 799.

Ex. 1336. A frustum of a square pyramid has an altitude of 13 inches; the edges of the bases are $2\frac{1}{2}$ inches and 4 inches, respectively. Find the volume.

Ex. 1337. The edges of the bases of a frustum of a square pyramid are 3 inches and 5 inches, respectively, and the volume of the frustum is $204\frac{1}{4}$ cubic inches. Find the altitude of the frustum.

Ex. 1338. The base of a pyramid contains 144 square inches, and its altitude is 10 inches. A section of the pyramid parallel to the base divides the altitude into two equal parts. Find: (a) the area of the section; (b) the volume of the frustum formed.

Ex. 1339. A section of a pyramid parallel to the base cuts off a pyramid similar to the given pyramid.

Ex. 1340. The total areas of two similar tetrahedrons are to each other as the squares of any two homologous edges.

Ex. 1341. The altitude of a pyramid is 6 inches. A plane parallel to the base cuts the pyramid into two equivalent parts. Find the altitude of the frustum thus formed.

Ex. 1342. Two wheat bins are similar in shape; the one holds 1000 bushels, and the other 800 bushels. If the first is 15 feet deep, how deep is the second?

Ex. 1343. A plane is passed parallel to the base of a pyramid cutting the altitude into two equal parts. Find: (a) the ratio of the section to the base; (b) the ratio of the pyramid cut off to the whole pyramid.

MISCELLANEOUS EXERCISES

Ex. 1344. Find the locus of all points equidistant from the three edges of a trihedral angle.

Ex. 1345. Find the locus of all points equidistant from the three faces of a trihedral angle.

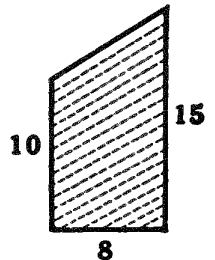
Ex. 1346. (a) Find the ratio of the volumes and the ratio of the total areas of two similar tetrahedrons whose homologous edges are in the ratio of 2 to 5. (b) Find the ratio of their homologous edges and the ratio of their total areas if their volumes are in the ratio of 1 to 27.

Ex. 1347. (a) Construct three or more equivalent pyramids on the same base. (b) Find the locus of the vertices of all pyramids equivalent to a given pyramid and standing on the same base.

HINT. Compare with Exs. 821 and 822.

Ex. 1348. The altitude of a pyramid is 12 inches. Its base is a regular hexagon whose side is 5 inches. Find the area of a section parallel to the base and 4 inches from the base ; 4 inches from the vertex.

Ex. 1349. A farmer has a corncrib 20 feet long, a cross section of which is represented in the figure, the numbers denoting feet. If the crib is entirely filled with corn in the ear, how many bushels of corn will it contain, counting 2 bushels of corn in the ear for 1 bushel of shelled corn. (Use the approximation, 1 bushel = $1\frac{1}{4}$ cubic feet. For the exact volume of a bushel, see Ex. 1439.)



Ex. 1350. A wheat elevator in the form of a frustum of a square pyramid is 30 feet high ; the edges of its bases are 12 feet and 6 feet, respectively. How many bushels of wheat will it hold ? (Use the approximation given in Ex. 1349.)

Ex. 1351. A frustum of a regular square pyramid has an altitude of 12 inches, and the edges of its bases are 4 inches and 10 inches, respectively. Find the volume of the pyramid of which the frustum is a part.

Ex. 1352. In a frustum of a regular quadrangular pyramid, the sides of the bases are 10 and 6, respectively, and the slant height is 14. Find the volume.

Ex. 1353. Find the lateral area of a regular triangular pyramid whose altitude is 8 inches, and each side of whose base is 6 inches.

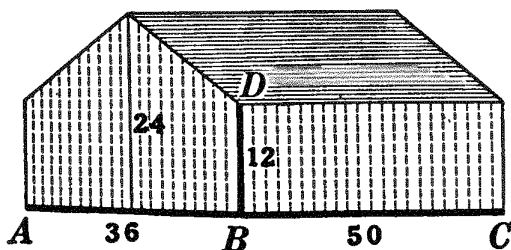
Ex. 1354. The edge of a cube is a . Find the edge of a cube 3 times as large ; n times as large.

Ex. 1355. A berry box supposed to contain a quart of berries is in the form of a frustum of a pyramid 5 inches square at the top, $4\frac{1}{2}$ inches square at the bottom, and $2\frac{7}{8}$ inches deep. The United States dry quart contains 67.2 cubic inches. Does the box contain more or less than a quart?

Ex. 1356. The space left in a basement for a coal bin is a rectangle 8×10 feet. How deep must the bin be made to hold 10 tons of coal?

Ex. 1357. The figure represents a barn, the numbers denoting the dimensions in feet. Find the number of cubic feet in the barn.

Ex. 1358. Let AB , BC , and BD , the dimensions of the barn in Ex. 1357, be denoted by a , b , and c , respectively. Substitute the values of a , b , and c in Ahmes' formula given in § 777. Compare your result with the result obtained in Ex. 1357.



Would Ahmes' formula have been correct if the Egyptian barns had been similar in shape to the barn in Ex. 1357?

Ex. 1359. How much will it cost to paint the barn in Ex. 1357 at 1 cent per square foot for lateral surfaces and 2 cents per square foot for the roof?

Ex. 1360. The barn in Ex. 1357 has a stone foundation 18 inches wide and 3 feet deep. Find the number of cubic feet of masonry if the outer surfaces of the walls are in the same planes as the sides of the barn.

Ex. 1361. The volume of a regular tetrahedron is $\frac{1}{3}\sqrt{2}$. Find its edge, slant height, and altitude.

Ex. 1362. The edge of a regular octahedron is a . Prove that the volume equals $\frac{a^3}{3}\sqrt{2}$.

Ex. 1363. The planes determined by the diagonals of a parallelepiped divide the parallelepiped into six equivalent pyramids.

Ex. 1364. A dam across a stream is 40 feet long, 12 feet high, 7 feet wide at the bottom, and 4 feet wide at the top. How many cubic feet of material are there in the dam? how many loads, counting 1 cubic yard to a load? Give the name of the geometrical solid represented by the dam.

Ex. 1365. Given S the lateral area, and H the altitude, of a regular square pyramid, find the volume.

Ex. 1366. Find the volume V , of a regular square pyramid, if its total surface is T , and one edge of the base is a .

BOOK VIII

CYLINDERS AND CONES

CYLINDERS

819. Def. A cylindrical surface is a surface generated by a moving straight line that continually intersects a fixed curve and remains parallel to a fixed straight line not coplanar with the given curve.

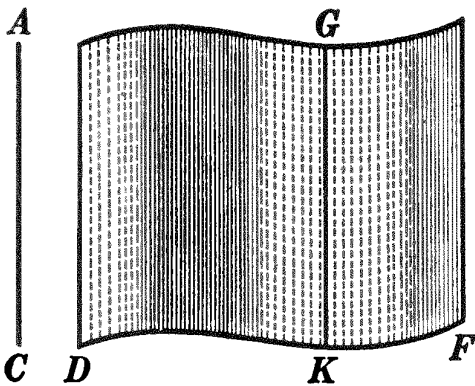


FIG. 1. Cylindrical Surface

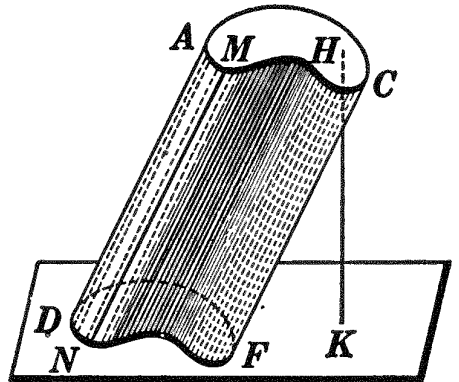


FIG. 2. Cylinder

820. Defs. By referring to §§ 693 and 694, the student may give the definitions of **generatrix**, **directrix**, and **element** of a cylindrical surface. Point these out in the figure.

The student should note that by changing the directrix from a broken line to a curved line, a prismatic surface becomes a cylindrical surface.

821. Def. A **cylinder** is a solid closed figure whose boundary consists of a cylindrical surface and two parallel planes cutting the generatrix in each of its positions, as *DC*.

822. Defs. The two parallel plane sections are called the **bases** of the cylinder, as AC and DF (Fig. 4); the portion of the cylindrical surface between the bases is the **lateral surface** of the cylinder; and the portion of an element of the cylindrical surface included between the bases is an **element** of the cylinder, as MN .

823. Def. A **right cylinder** is a cylinder whose elements are perpendicular to the bases.

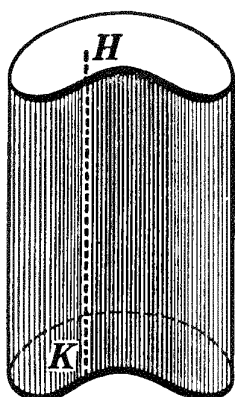


FIG. 3. Right Cylinder

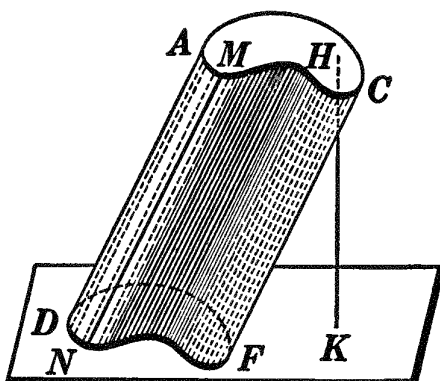


FIG. 4. Oblique Cylinder

824. Def. An **oblique cylinder** is a cylinder whose elements are not perpendicular to the bases.

825. Def. The **altitude** of a cylinder is the perpendicular from any point in the plane of one base to the plane of the other base, as HK in Figs. 3 and 4.

826. The following are some of the properties of a cylinder; the student should prove the correctness of each:

(a) *Any two elements of a cylinder are parallel and equal (§§ 618 and 634).*

(b) *Any element of a right cylinder is equal to its altitude.*

(c) *A line drawn through any point in the lateral surface of a cylinder parallel to an element, and limited by the bases, is itself an element (§§ 822 and 179).*

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Ex. 1367. Every section of a cylinder made by a plane parallel to its base is a circle, if the base is a circle.

Ex. 1368. If a line joins the centers of the bases of a cylinder, this line passes through the center of every section of the cylinder parallel to the bases, if the bases are circles.

830. Def. A right section of a cylinder is a section formed by a plane perpendicular to an element, as section EF .

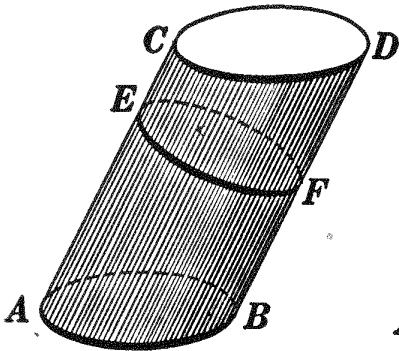


FIG. 1. Cylinder with Circular Base AB

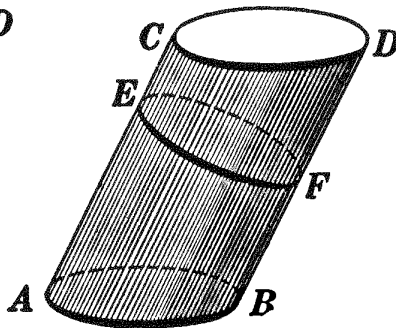


FIG. 2. Circular Cylinder

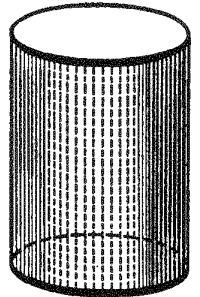


FIG. 3. Right Circular Cylinder

831. Def. A circular cylinder is a cylinder in which a right section is a circle; thus, in Fig. 2, if rt. section EF is a \odot , cylinder AD is a circular cylinder.

832. Def. A right circular cylinder is a right cylinder whose base is a circle (Fig. 3).

833. Questions. In Fig. 1, is rt. section EF a \odot ? In Fig. 2, is base AB a \odot ? In Fig. 3, would a rt. section be a \odot ?

834. Note. The theorems and exercises on the cylinder that follow will be limited to cases in which the bases of the cylinders are circles. When the term *cylinder* is used, therefore, it must be understood to mean a *cylinder with circular bases*. See also § 846.

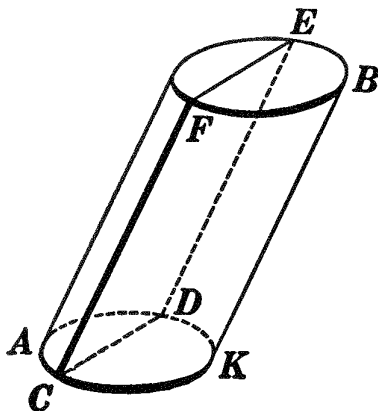
Ex. 1369. Find the locus of all points at a distance of 6 inches from a straight line 2 feet long.

Ex. 1370. Find the locus of all points: (a) 2 inches from the lateral surface of a right circular cylinder whose altitude is 12 inches and the radius of whose base is 5 inches; (b) 2 inches from the entire surface.

Ex. 1371. A log is 20 feet long and 30 inches in diameter at the smaller end. Find the dimensions of the largest piece of square timber, the same size at each end, that can be cut from the log.

PROPOSITION II. THEOREM

835. *Every section of a cylinder made by a plane passing through an element is a parallelogram.* (See § 834.)



Given cylinder AB with base AK , and $CDEF$ a section made by a plane through element CF and some point, as D , not in CF , but in the circumference of the base.

To prove $CDEF$ a \square .

| ARGUMENT | REASONS |
|---|----------------------|
| 1. Through D draw a line in plane $DF \parallel CF$. | 1. § 179. |
| 2. Then the line so drawn is an element; <i>i.e.</i> it lies in the cylindrical surface. | 2. § 826, <i>c</i> . |
| 3. But this line lies also in plane DF . | 3. Arg. 1. |
| 4. \therefore it is the intersection of plane DF with the cylindrical surface, and coincides with DE . | 4. § 614. |
| 5. $\therefore DE$ is a str. line and is \parallel and $= CF$. | 5. § 826, <i>a</i> . |
| 6. Also CD and EF are str. lines. | 6. § 616. |
| 7. $\therefore CDEF$ is a \square . • | 7. § 240. |

Q.E.D.

836. Cor. *Every section of a right circular cylinder made by a plane passing through an element is a rectangle.*

Ex. 1372. In the figure of Prop. II, the radius of the base is 4 inches, element CF is 12 inches, CD is 1 inch from the center of the base, and CF makes with CD an angle of 60° . Find the area of section $CDEF$.

Ex. 1373. Every section of a cylinder, parallel to an element, is a parallelogram. How is the base of this cylinder restricted? (See § 834.)

CONES

837. Def. A conical surface is a surface generated by a moving straight line that continually intersects a fixed curve and that passes through a fixed point not in the plane of the curve.

838. Defs. By referring to §§ 693, 694, and 746, the student may give the definitions of **generatrix**, **directrix**, **vertex**, **element**, and **upper and lower nappes** of a conical surface. Point these out in the figure.

The student should observe that by changing the directrix from a broken line to a curved line, a pyramidal surface becomes a conical surface.

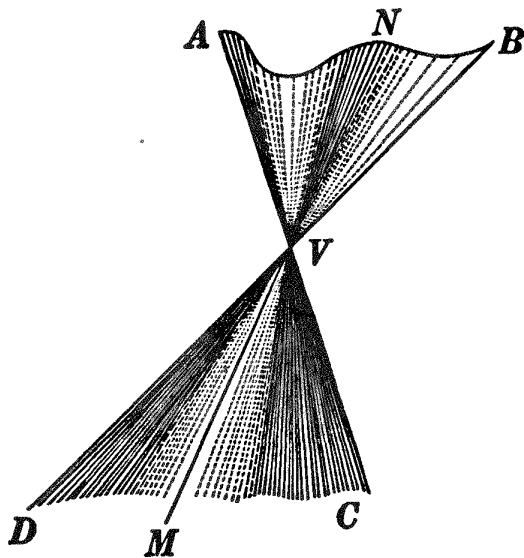


FIG. 1. Conical Surface

839. Def. A cone is a solid closed figure whose boundary consists of the portion of a conical surface extending from its vertex to a plane cutting all its elements, and the section formed by this plane.

840. Defs. By referring to §§ 748 and 822, the student may give the definitions of **vertex**, **base**, **lateral surface**, and **element** of a cone. Point these out in the figure.

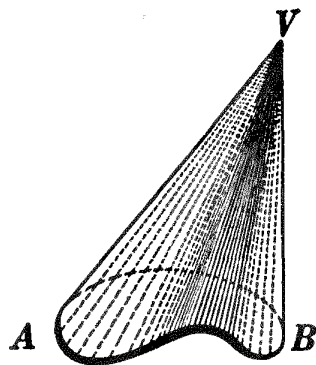


FIG. 2. Cone

841. Def. A circular cone is a cone containing a circular section such that a line joining the vertex of the cone to the center of the section is perpendicular to the section.

Thus in Fig. 4, if section AB of cone $V-CD$ is a \odot with center O , such that VO is \perp the section, cone $V-CD$ is a circular cone.

842. Def. The **altitude** of a cone is the perpendicular from its vertex to the plane of its base, as VC in Fig. 3 and VO in Fig. 5.

843. Defs. In a cone with a circular base, if the line joining its vertex to the center of its base is perpendicular to the

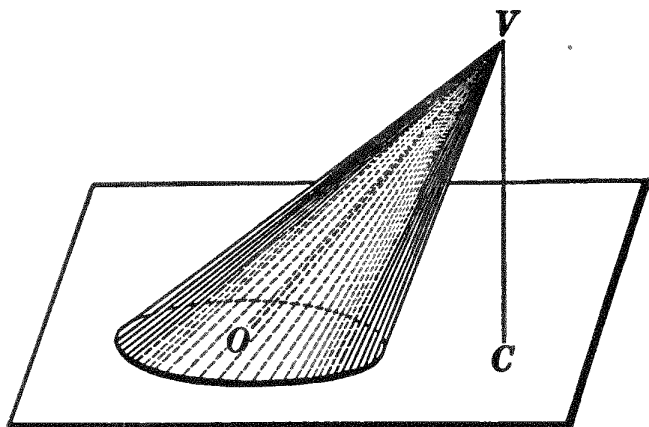


FIG. 3. Cone with Circular Base

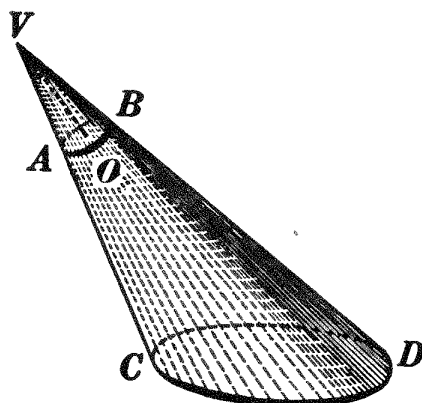


FIG. 4. Circular Cone

plane of the base, the cone is a **right circular cone** (Fig. 5).

If such a line is not perpendicular to the plane of the base, the cone is called an **oblique cone** (Fig. 3).

844. Def. The **axis** of a right circular cone is the line joining its vertex to the center of its base, as VO , Fig. 5.

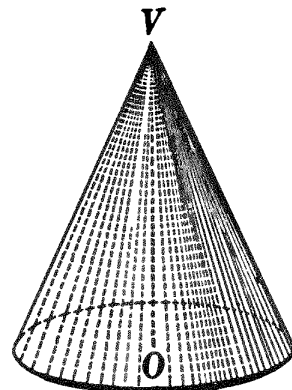


FIG. 5. Right Circular Cone

845. The following are some of the properties of a cone; the student should prove the correctness of each:

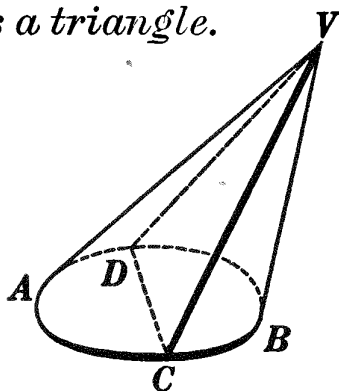
- (a) *The elements of a right circular cone are equal.*
- (b) *The axis of a right circular cone is equal to its altitude.*
- (c) *A straight line drawn from the vertex of a cone to any point in the perimeter of its base is an element.*

846. Note. The theorems and exercises on the cone that follow will be limited to cases in which the bases of the cones are circles, though not necessarily to *circular cones*. When the term *cone* is used, therefore, it must be understood to mean a *cone with circular base*. See also § 834.

Ex. 1374. What is the locus of all points 2 inches from the lateral surface, and 2 inches from the base, of a right circular cone whose altitude is 12 inches and the radius of whose base is 5 inches?

PROPOSITION III. THEOREM

847. *Every section of a cone made by a plane passing through its vertex is a triangle.*



Given cone $V-AB$ with base AB and section VCD made by a plane through V .

To prove VCD a Δ .

ARGUMENT

1. From V draw str. lines to C and D .
2. Then the lines so drawn are elements;
i.e. they lie in the conical surface.
3. But these lines lie also in plane VCD .
4. \therefore they are the intersections of plane VCD with the conical surface, and coincide with VC and VD , respectively.
5. Also CD is a str. line.
6. $\therefore VC$, VD , and CD are str. lines and VCD is a Δ .

Q.E.D.

REASONS

1. § 54, 15.
2. § 845, *c*.
3. § 603, *a*.
4. § 614.
5. § 616.
6. § 92.

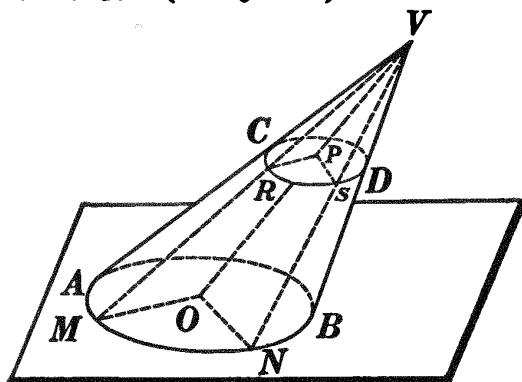
Ex. 1375. What kind of triangle in general is the section of a cone through the vertex, if the cone is oblique? if the cone is a right circular cone? Can any section of an oblique cone be perpendicular to the base of the cone? of a right circular cone? Explain.

Ex. 1376. Find the locus of all straight lines making a given angle with a given straight line, at a given point in the line. What will this locus be if the given angle is 90° ?

Ex. 1377. Find the locus of all straight lines making a given angle with a given plane at a given point. What will the locus be if the given angle is 90° ?

PROPOSITION IV. THEOREM

848. Every section of a cone made by a plane parallel to its base is a circle. (See § 846.)



Given CD a section of cone $V-AB$ made by a plane \parallel base AB .
 To prove section CD a \odot .

OUTLINE OF PROOF

1. Let R and S be any two points on the boundary of section CD ; pass planes through OV and points R and S .
2. Prove $\triangle VOM \sim \triangle VPR$ and $\triangle VON \sim \triangle VPS$.
3. Then $\frac{OM}{PR} = \frac{VO}{VP}$ and $\frac{ON}{PS} = \frac{VO}{VP}$; i.e. $\frac{OM}{PR} = \frac{ON}{PS}$.
4. But $OM = ON$; $\therefore PS = PR$; i.e. P is equidistant from any two points on the boundary of section CD .
5. \therefore section CD is a \odot . Q.E.D.

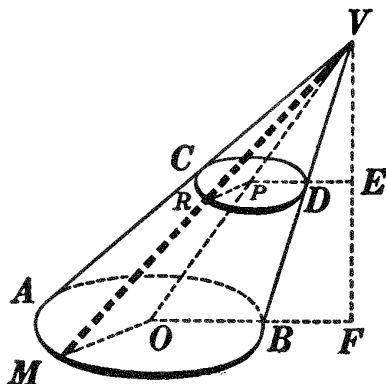
849. Cor. Any section of a cone parallel to its base is to the base as the square of its distance from the vertex is to the square of the altitude of the cone.

OUTLINE OF PROOF

By § 563, $\frac{\text{section } CD}{\text{base } AB} = \frac{\overline{PR}^2}{\overline{OM}^2}$.

Prove $\frac{PR}{OM} = \frac{VP}{VO} = \frac{VE}{VF}$.

Then $\frac{\text{section } CD}{\text{base } AB} = \frac{\overline{VE}^2}{\overline{VF}^2}$.



For applications of §§ 848 and 849, see Exs. 1380-1384.

MENSURATION OF THE CYLINDER AND CONE

AREAS

850. Def. A plane is tangent to a cylinder if it contains an element, but no other point, of the cylinder.

851. Def. A prism is inscribed in a cylinder if its lateral edges are elements of the cylinder, and the bases of the two figures lie in the same plane.

852. Def. A prism is circumscribed about a cylinder if its lateral faces are all tangent to the cylinder, and the bases of the two figures lie in the same plane.

Ex. 1378. How many planes can be tangent to a cylinder? If two of these planes intersect, the line of intersection is parallel to an element. How are the bases of the cylinders in §§ 850–852 restricted? (See § 834.)

853. Before proceeding further it might be well for the student to review the more important steps in the development of the area of a circle. In that development it was shown that:

(1) The area of a regular polygon circumscribed about a circle is greater, and the area of a regular polygon inscribed in a circle less, than the area of the regular circumscribed or inscribed polygon of twice as many sides (§ 541).

(2) By repeatedly doubling the number of sides of regular circumscribed and inscribed polygons of the same number of sides, and making the polygons always regular, their areas approach a common limit (§ 546).

(3) This common limit is defined as the area of the circle (§ 558).

(4) Finally follows the theorem for the area of the circle (§ 559).

It will be observed that precisely the same method is used throughout the mensuration of the cylinder and the cone.

Compare carefully the four articles just cited with §§ 854, 855, 857, and 858.

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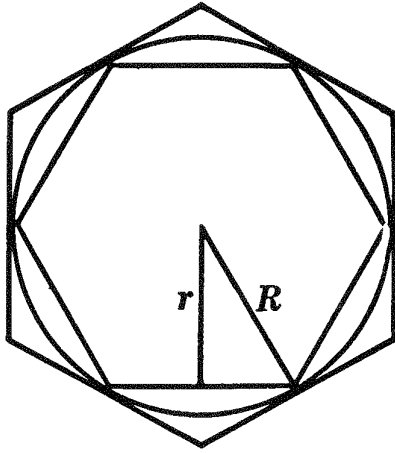
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PROPOSITION VI. THEOREM

855. *By repeatedly doubling the number of sides of the bases of regular prisms circumscribed about, and inscribed in, a right circular cylinder, and making the bases always regular polygons, their lateral areas approach a common limit.*



Given H the common attitude, R and r the apothems of the bases, P and p the perimeters of the bases, and S and s the lateral areas, respectively, of regular circumscribed and inscribed prisms whose bases have the same number of sides. Let the given figure represent the base of the actual figure.

To prove that by repeatedly doubling the number of sides of the bases of the prisms, and making them always regular polygons, S and s approach a common limit.

| ARGUMENT | | REASONS |
|----------|---|---------------|
| 1. | $S = P \cdot H$ and $s = p \cdot H.$ | 1. § 763. |
| 2. | $\therefore \frac{S}{s} = \frac{P}{p}.$ | 2. § 54, 8 a. |
| 3. | But $\frac{P}{p} = \frac{R}{r}.$ | 3. § 538. |
| 4. | $\therefore \frac{S}{s} = \frac{R}{r}.$ | 4. § 54, 1. |
| 5. | $\therefore \frac{S - s}{S} = \frac{R - r}{R}.$ | 5. § 399. |

| ARGUMENT | REASONS |
|--|---------------|
| 6. $\therefore S - s = S \frac{R - r}{R}$. | 6. § 54, 7 a. |
| 7. But by repeatedly doubling the number of sides of the bases of the prisms, and making them always regular polygons, $R - r$ can be made less than any previously assigned value, however small. | 7. § 543, I. |
| 8. $\therefore \frac{R - r}{R}$ can be made less than any previously assigned value, however small. | 8. § 586. |
| 9. $\therefore S \frac{R - r}{R}$ can be made less than any previously assigned value, however small, S being a decreasing variable. | 9. § 587. |
| 10. $\therefore S - s$, being always equal to $S \frac{R - r}{R}$, can be made less than any previously assigned value, however small. | 10. § 309. |
| 11. $\therefore S$ and s approach a common limit. | 11. § 594. |

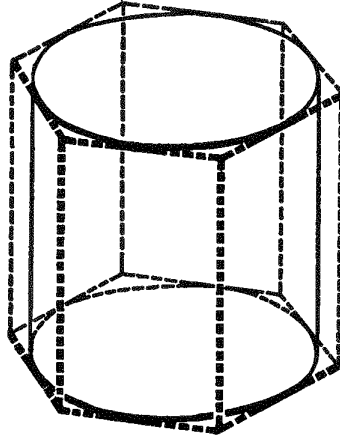
Q.E.D.

856. Note. The above proof is limited to *regular* prisms, but it can be shown that the limit of the lateral area of any inscribed (or circumscribed) prism is the same by whatever method the number of the sides of its base is successively increased, provided that each side approaches zero as a limit. (See also § 549.) Compare the proof of § 855 with that of § 546, I.

857. Def. The lateral area of a right circular cylinder is the common limit which the successive lateral areas of circumscribed and inscribed regular prisms (having bases containing 3, 4, 5, etc., sides) approach as the number of sides of the bases is successively increased and each side approaches zero as a limit.

PROPOSITION VII. THEOREM

858. *The lateral area of a right circular cylinder is equal to the product of the circumference of its base and its altitude.*



Given a rt. circular cylinder with its lateral area denoted by S , the circumference of its base by C , and its altitude by H .

To prove $S = C \cdot H$.

| ARGUMENT | REASONS |
|---|------------|
| 1. Circumscribe about the rt. circular cylinder a regular prism. Denote its lateral area by S' , the perimeter of its base by P , and its altitude by H . | 1. § 852. |
| 2. Then $S' = P \cdot H$. | 2. § 763. |
| 3. As the number of sides of the base of the regular circumscribed prism is repeatedly doubled, P approaches C as a limit. | 3. § 550. |
| 4. $\therefore P \cdot H$ approaches $C \cdot H$ as a limit. | 4. § 590. |
| 5. Also S' approaches S as a limit. | 5. § 857. |
| 6. But S' is always equal to $P \cdot H$. | 6. Arg. 2. |
| 7. $\therefore S = C \cdot H$. | 7. § 355. |

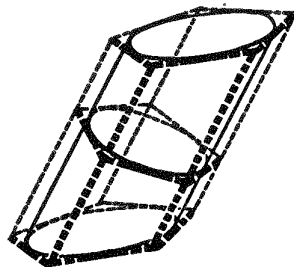
Q.E.D.

859. Cor. *If S denotes the lateral area, T the total area, H the altitude, and R the radius of the base, of a right circular cylinder,*

$$S = 2 \pi RH;$$

$$T = 2 \pi RH + 2 \pi R^2 = 2 \pi R(H + R).$$

860. Note. Since the lateral area of an oblique prism is equal to the product of the perimeter of a right section and a lateral edge (§ 762), the student would naturally infer that the lateral area of an oblique cylinder with circular bases is equal to the product of the perimeter of a right section and an element. This statement is true. But the right section of an oblique cylinder with circular base is not a circle. And since the only curve dealt with in elementary geometry is the circle, this theorem and its applications have been omitted here.



Ex. 1385. Find the lateral area and total area of a right circular cylinder whose altitude is 20 centimeters and the diameter of whose base is 10 centimeters.

Ex. 1386. How many square inches of tin will be required to make an open cylindrical pail 8 inches in diameter and 10 inches deep, making no allowance for waste?

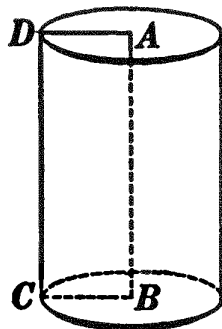
Ex. 1387. In a right circular cylinder, find the ratio of the lateral area to the sum of the two bases. What is this ratio if the altitude and the radius of base are equal?

Ex. 1388. Find the altitude of a right circular cylinder if its lateral area is S and the radius of its base R .

Ex. 1389. Find the radius of the base of a right circular cylinder if its total area is T and its altitude is H .

861. Def. Because it may be generated by a rectangle revolving about one of its sides as an axis, a right circular cylinder is sometimes called a **cylinder of revolution**.

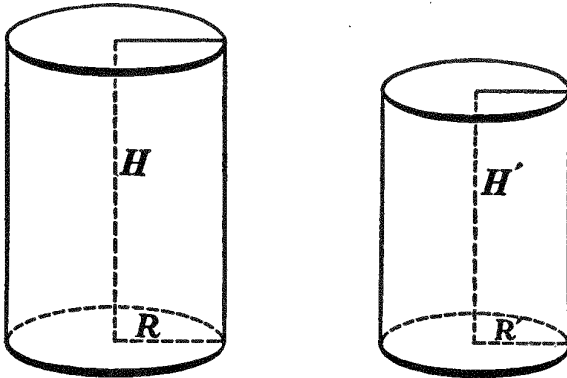
862. Questions. What part of the cylinder will side CD , opposite the axis AB , generate? What will AD and BC generate? What will the plane AC generate? What might CD in any one of its positions be called?



863. Def. Similar cylinders of revolution are cylinders generated by similar rectangles revolving about homologous sides as axes.

PROPOSITION VIII. THEOREM

864. *The lateral areas, and the total areas, of two similar cylinders of revolution are to each other as the squares of their altitudes, and as the squares of the radii of their bases.*



Given two similar cylinders of revolution with their lateral areas denoted by S and S' , their total areas by T and T' , their altitudes by H and H' , and the radii of their bases by R and R' , respectively.

To prove: (a) $\frac{S}{S'} = \frac{H^2}{H'^2} = \frac{R^2}{R'^2}$.

(b) $\frac{T}{T'} = \frac{H^2}{H'^2} = \frac{R^2}{R'^2}$.

ARGUMENT

1. $S = 2\pi RH$ and $S' = 2\pi R'H'$.
2. $\therefore \frac{S}{S'} = \frac{2\pi RH}{2\pi R'H'} = \frac{RH}{R'H'} = \frac{R}{R'} \cdot \frac{H}{H'}$.
3. But rectangle $RH \sim$ rectangle $R'H'$.
4. $\therefore \frac{H}{H'} = \frac{R}{R'}$.
5. $\therefore \frac{S}{S'} = \frac{R}{R'} \cdot \frac{H}{H'} = \frac{R^2}{R'^2}$.
6. Also $\frac{S}{S'} = \frac{R}{R'} \cdot \frac{R}{R'} = \frac{R^2}{R'^2}$.
7. Again, $T = 2\pi R(H + R)$
and $T' = 2\pi R'(H' + R')$.

REASONS

1. § 859.
2. § 54, 8 a.
3. § 863.
4. § 419.
5. § 309.
6. § 309.
7. § 859.

| ARGUMENT | REASONS |
|--|---------------|
| 8. $\therefore \frac{T}{T'} = \frac{R(H+R)}{R'(H'+R')} = \frac{R}{R'} \cdot \frac{H+R}{H'+R'}$ | 8. § 54, 8 a. |
| 9. But, from Arg. 4, $\frac{H+R}{H'+R'} = \frac{H}{H'} = \frac{R}{R'}$ | 9. § 401. |
| 10. $\therefore \frac{T}{T'} = \frac{R}{R'} \cdot \frac{R}{R'} = \frac{R^2}{R'^2}$ | 10. § 309. |
| 11. Also $\frac{T}{T'} = \frac{R}{R'} \cdot \frac{R}{R'} = \frac{R^2}{R'^2}$ Q.E.D. | 11. § 309. |

Ex. 1390. The altitudes of two similar cylinders of revolution are 5 inches and 7 inches, respectively, and the total area of the first is 675 square inches. Find the total area of the second.

Ex. 1391. The lateral areas of two similar cylinders of revolution are 320 square inches and 500 square inches, and the radius of the base of the larger is 10 inches. Find the radius of the base of the smaller.

Ex. 1392. Two adjacent sides of a rectangle are a and b ; find the lateral area of the cylinder generated by revolving the rectangle: (1) about a as an axis; (2) about b as an axis. Put the results in the form of a general statement. Have you proved this general statement?

865. Def. The **slant height** of a right circular cone is a straight line joining its vertex to any point in the circumference of its base. Thus any element of such a cone is its slant height.

866. Def. A plane is **tangent to a cone** if it contains an element, but no other point, of the cone.

867. Def. A **pyramid is inscribed in a cone** if its base is inscribed in the base of the cone and its vertex coincides with the vertex of the cone.

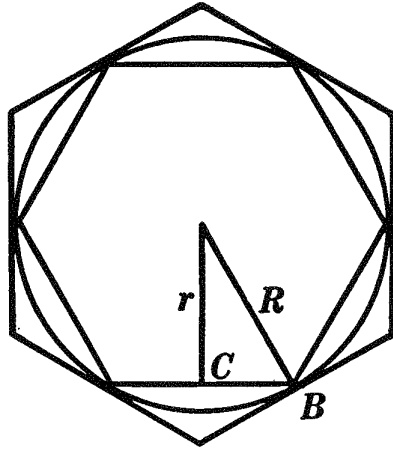
868. Def. A **pyramid is circumscribed about a cone** if its base is circumscribed about the base of the cone and its vertex coincides with the vertex of the cone.

869. The student may state and prove the theorems on the right circular cone corresponding to those mentioned in § 854.

Ex. 1393. How many planes can be tangent to a cone? Through what point must each of these planes pass? Prove. How are the bases of the cones in §§ 866–868 restricted? (See § 846.)

PROPOSITION IX. THEOREM

870. *By repeatedly doubling the number of sides of the bases of regular pyramids circumscribed about, and inscribed in, a right circular cone, and making the bases always regular polygons, their lateral areas approach a common limit.*



Given H the common altitude, L and l the slant heights, R and r the apothems of the bases, P and p the perimeters of the bases, and S and s the lateral areas, respectively, of regular circumscribed and inscribed pyramids whose bases have the same number of sides. Let the given figure represent the base of the actual figure.

To prove that by repeatedly doubling the number of sides of the bases of the pyramids, and making them always regular polygons, S and s approach a common limit.

| ARGUMENT | REASONS |
|---|---------------|
| 1. $S = \frac{1}{2} PL$ and $s = \frac{1}{2} pl$. | 1. § 766. |
| 2. $\therefore \frac{S}{s} = \frac{PL}{pl} = \frac{P}{p} \cdot \frac{L}{l}$. | 2. § 54, 8 a. |
| 3. But $\frac{P}{p} = \frac{R}{r}$. | 3. § 538. |
| 4. $\therefore \frac{S}{s} = \frac{R}{r} \cdot \frac{L}{l} = \frac{RL}{rl}$. | 4. § 309. |
| 5. $\therefore \frac{S - s}{S} = \frac{RL - rl}{RL}$. | 5. § 399. |

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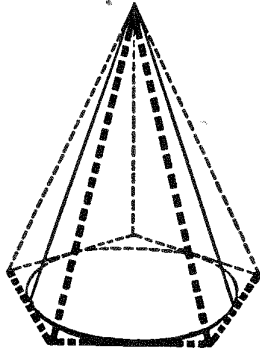
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PROPOSITION X. THEOREM

873. *The lateral area of a right circular cone is equal to one half the product of the circumference of its base and its slant height.*



Given a rt. circular cone with its lateral area denoted by S , the circumference of its base by C , and its slant height by L .

To prove $S = \frac{1}{2} C \cdot L$.

The proof is left as an exercise for the student.

874. Question. What changes are necessary in the proof of Prop. VII to make it the proof of Prop. X?

875. Cor. *If s denotes the lateral area, T the total area, L the slant height, and R the radius of the base, of a right circular cone,*

$$S = \pi RL;$$

$$T = \pi RL + \pi R^2 = \pi R(L + R).$$

Ex. 1394. The altitude of a right circular cone is 12 inches and the radius of the base 8 inches. Find the lateral area and the total area of the cone.

Ex. 1395. How many yards of canvas 30 inches wide will be required to make a conical tent 16 feet high and 20 feet in diameter, if 10% of the goods is allowed for cutting and fitting?

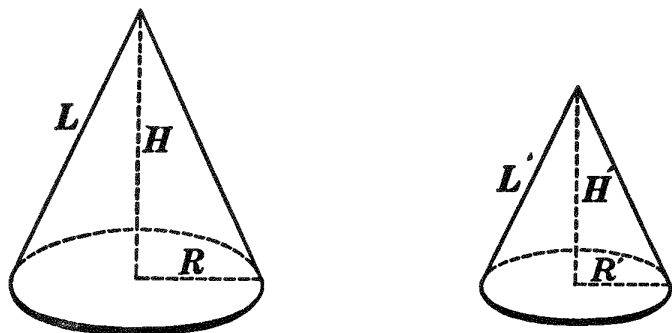
Ex. 1396. The lateral area of a right circular cone is $440\sqrt{89}$ square inches, and the radius of the base is 10 inches. Find the altitude.

876. Def. Because it may be generated by a right triangle revolving about one of its sides as an axis, a right circular cone is sometimes called a **cone of revolution**.

877. Def. **Similar cones of revolution** are cones generated by similar right triangles revolving about homologous sides as axes.

PROPOSITION XI. THEOREM

878. *The lateral areas, and the total areas, of two similar cones of revolution are to each other as the squares of their altitudes, as the squares of their slant heights, and as the squares of the radii of their bases.*



Given two similar cones of revolution with their lateral areas denoted by S and S' , their total areas by T and T' , their altitudes by H and H' , their slant heights by L and L' , and the radii of their bases by R and R' , respectively.

To prove :

$$(a) \quad \frac{S}{S'} = \frac{H^2}{H'^2} = \frac{L^2}{L'^2} = \frac{R^2}{R'^2}.$$

$$(b) \quad \frac{T}{T'} = \frac{H^2}{H'^2} = \frac{L^2}{L'^2} = \frac{R^2}{R'^2}.$$

The proof is left as an exercise for the student.

HINT. Apply the method of proof used in Prop. VIII.

879. Def. A **frustum of a cone** is the portion of the cone included between the base and a section of the cone made by a plane parallel to the base.

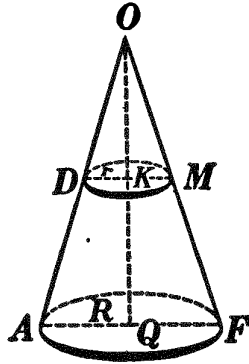
880. Questions. What are the upper and lower bases of a frustum of a cone? the altitude? What kind of a figure is the upper base of a frustum of a right circular cone (§ 848)?

881. Def. The **slant height** of a frustum of a right circular cone is the length of that portion of an element of the cone included between the bases of the frustum.

Ex. 1397. Every section of a frustum of a cone, made by a plane passing through an element, is a trapezoid.

PROPOSITION XII. THEOREM

882. *The lateral area of a frustum of a right circular cone is equal to one half the product of the sum of the circumferences of its bases and its slant height.*



Given frustum AM , of right circular cone $O-AF$, with its lateral area denoted by S , the circumferences of its bases by C and c , the radii of its bases by R and r , and its slant height by L .

To prove $S = \frac{1}{2}(C+c)L$.

ARGUMENT

REASONS

1. S = lateral area of cone $O-AF$ minus lateral area of cone $O-DM$.

1. § 54, 11.

2. Let L' denote the slant height of cone $O-DM$. Then $S = \frac{1}{2} C(L + L') - \frac{1}{2} cL'$
 $= \frac{1}{2} CL + \frac{1}{2} L'(C - c)$.

2. § 873.

It now remains to find the value of L' .

3. $\frac{C}{c} = \frac{R}{r}$.

3. § 556.

4. But $\triangle OKD \sim \triangle OQA$.

4. § 422.

5. $\therefore \frac{R}{r} = \frac{OA}{OD} = \frac{L + L'}{L'}$.

5. § 424, 2.

6. $\therefore \frac{C}{c} = \frac{L + L'}{L'}$.

6. § 54, 1.

7. $\therefore L' = \frac{cL}{C - c}$.

7. Solving for L' .

8. $\therefore S = \frac{1}{2} CL + \frac{1}{2} \cdot \frac{cL}{C - c} (C - c) = \frac{1}{2}(C + c)L$.

8. § 309.

Q.E.D.

883. Cor. I. *If S denotes the lateral area, T the total area, L the slant height, and R and r the radii of the bases, of a frustum of a right circular cone,*

$$S = \pi L(R + r);$$

$$T = \pi L(R + r) + \pi(R^2 + r^2).$$

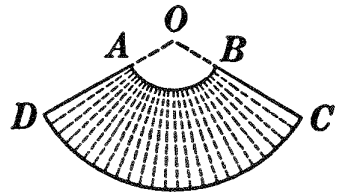
884. Cor. II. *The lateral area of a frustum of a right circular cone is equal to the product of its slant height and the circumference of a section midway between its bases.*

Ex. 1398. If S denotes the lateral area, L the slant height, and C the circumference of a section midway between the bases, of a frustum of a right circular cone, then $S = CL$.

Ex. 1399. In the formulas of § 883: (a) make $r = 0$ and compare results with formulas of § 875; (b) make $b = B$ and compare results with formulas of § 859.

Ex. 1400. The altitude of a frustum of a right circular cone is 16 inches, and the diameters of its bases are 20 inches and 30 inches, respectively. Find its lateral area and also its total area.

Ex. 1401. In the figure, AB and CD are arcs of circles; $OA = 2$ inches, $OD = 5$ inches, and $\angle DOC = 120^\circ$. Cut figure $ABCD$ out of paper and form it into a frustum of a cone. Find its lateral area and also its total area.



Ex. 1402. A frustum of a right circular cone whose altitude is 4 inches and radii of bases 4 inches and 7 inches, respectively, is made as indicated in Ex. 1401. Find the radius of the circle from which it must be cut.

Ex. 1403. The sum of the total areas of two similar cylinders of revolution is 216 square inches, and one altitude is $\frac{3}{4}$ of the other. Find the total area of each cylinder.

Ex. 1404. A regular triangular and a regular hexangular pyramid are inscribed in a right circular cone with altitude 20 inches and with radius of base 4 inches. Find the difference between their lateral areas.

Ex. 1405. Cut out of paper a semicircle whose radius is 4 inches, and find its area. Form a cone with this semicircle and find its lateral area by § 875. Do the two results agree?

Ex. 1406. The slant height, and the diameter of the base, of a right circular cone are each equal to L . Find the total area.

VOLUMES

PROPOSITION XIII. THEOREM

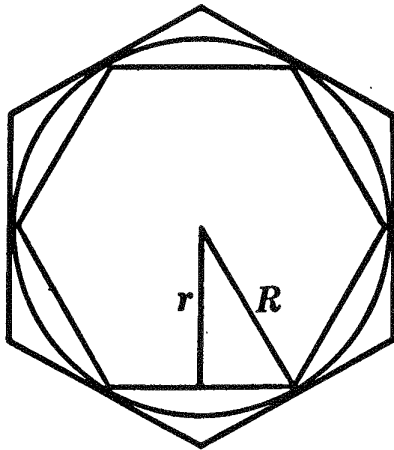
885. I. *The volume of a prism whose base is a regular polygon and which is circumscribed about a cylinder is greater than the volume of the circumscribed prism whose base is a regular polygon with twice as many sides.*

II. *The volume of a prism whose base is a regular polygon and which is inscribed in a cylinder is less than the volume of the inscribed prism whose base is a regular polygon with twice as many sides.*

The figures and proofs are left as exercises for the student.

PROPOSITION XIV. THEOREM

886. *By repeatedly doubling the number of sides of the bases of prisms circumscribed about, and inscribed in, a cylinder, and making the bases always regular polygons, their volumes approach a common limit.*



Given H the common altitude, B and b the areas of the bases, and V and v the volumes, respectively, of circumscribed and inscribed prisms whose bases are regular and have the same number of sides. Let the given figure represent the base of the actual figure.

To prove that by repeatedly doubling the number of sides of the bases of the prisms, and making them always regular polygons, V and v approach a common limit.

| ARGUMENT | REASONS |
|---|---------------|
| 1. $V = B \cdot H$ and $v = b \cdot H$. | 1. § 799. |
| 2. $\therefore \frac{V}{v} = \frac{B \cdot H}{b \cdot H} = \frac{B}{b}$. | 2. § 54, 8 a. |
| 3. $\therefore \frac{V - v}{V} = \frac{B - b}{B}$. | 3. § 399. |
| 4. $\therefore V - v = V \frac{B - b}{B}$. | 4. § 54, 7 a. |
| 5. Similar to Arg. 7, § 855. | 5. § 546, II. |
| 6. Similar to Arg. 8, § 855. | 6. § 586. |
| 7. Similar to Arg. 9, § 855. | 7. § 587. |
| 8. Similar to Arg. 10, § 855. | 8. § 309. |
| 9. $\therefore V$ and v approach a common limit. | 9. § 594. |
| Q.E.D. | |

887. Note. The proof of § 886 is limited in the same manner as the proof of § 855. Read § 856.

Ex. 1407. The total area of a right circular cone whose altitude is 10 inches is 280 square inches. Find the total area of the cone cut off by a plane parallel to the base and 6 inches from the base.

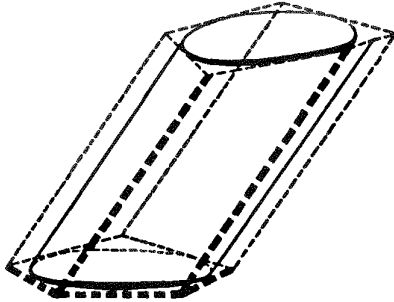
Ex. 1408. The altitude of a right circular cone is 12 inches. What part of the lateral surface is cut off by a plane parallel to the base and 6 inches from the vertex?

Ex. 1409. The altitude of a right circular cone is H . How far from the vertex must a plane be passed parallel to the base so that the lateral area and the total area of the cone cut off shall be one half that of the original cone? one third? one n th?

888. Def. The volume of a cylinder is the common limit which the successive volumes of circumscribed and inscribed prisms approach as the number of sides of the bases is successively increased, and each side approaches zero as a limit.

PROPOSITION XV. THEOREM

889. *The volume of a cylinder is equal to the product of its base and its altitude.*



Given a cylinder, with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = B \cdot H$.

| ARGUMENT | REASONS |
|--|------------|
| 1. Circumscribe about the cylinder a prism whose base is a regular polygon. Denote its volume by V' and the area of its base by B' . | 1. § 852. |
| 2. Then $V' = B' \cdot H$. | 2. § 799. |
| 3. As the number of sides of the base of the circumscribed prism is repeatedly doubled, B' approaches B as a limit. | 3. § 558. |
| 4. $\therefore B' \cdot H$ approaches $B \cdot H$ as a limit. | 4. § 590. |
| 5. Also V' approaches V as a limit. | 5. § 888. |
| 6. But V' is always equal to $B' \cdot H$. | 6. Arg. 2. |
| 7. $\therefore V = B \cdot H$. Q.E.D. | 7. § 355. |

890. Cor. *If V denotes the volume, H the altitude, and R the radius of the base, of a cylinder,*

$$V = \pi R^2 H.$$

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Ex. 1411. A cylinder of revolution has an altitude of 12 inches and a base with a radius of 5 inches. Find the total area of a similar cylinder whose volume is 8 times that of the given cylinder.

Ex. 1412. The dimensions of a rectangle are 6 inches and 8 inches, respectively. Find the volume of the solid generated by revolving the rectangle: (a) about its longer side as an axis; (b) about its shorter side. Compare the ratio of these volumes with the ratio of the sides of the rectangle.

Ex. 1413. Cylinders having equal bases and equal altitudes are equivalent.

Ex. 1414. Any two cylinders are to each other as the products of their bases and their altitudes.

Ex. 1415. (a) Two cylinders having equal bases are to each other as their altitudes, and (b) having equal altitudes are to each other as their bases.

Ex. 1416. The volume of a right circular cylinder is equal to the product of its lateral area and one half the radius of its base.

Ex. 1417. Cut out a rectangular piece of paper 6×9 inches. Roll this into a right circular cylinder and find its volume (two answers).

Ex. 1418. A cistern in the form of a right circular cylinder is to be 20 feet deep and 8 feet in diameter. How much will it cost to dig it at 5 cents a cubic foot?

Ex. 1419. Find the altitude of a right circular cylinder if its volume is V and the radius of its base R .

Ex. 1420. In a certain right circular cylinder the lateral area and the volume have the same numerical value. (a) Find the radius of the base. (b) Find the volume if the altitude is equal to the diameter of the base.

Ex. 1421. A cylinder is inscribed in a cube whose edge is 10 inches. Find: (a) the volume of each; (b) the ratio of the cylinder to the cube.

Ex. 1422. A cylindrical tin tomato can is $4\frac{9}{16}$ inches high, and the diameter of its base is 4 inches. Does it hold more or less than a liquid quart, *i.e.* $2\frac{3}{4}$ cubic inches? _____

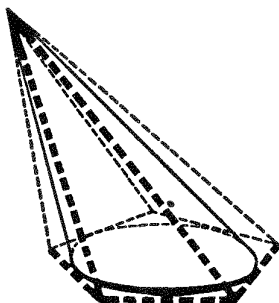
892. The student may:

(a) State and prove the theorems on the cone corresponding to those given in §§ 885 and 886.

(b) State, by aid of § 888, the definition of the volume of a

PROPOSITION XVII. THEOREM

893. *The volume of a cone is equal to one third the product of its base and its altitude.*



Given a cone with its volume denoted by V , its base by B , and its altitude by H .

To prove $V = \frac{1}{3} B \cdot H$.

The proof is left as an exercise for the student.

894. Question. What changes must be made in the proof of Prop. XV to make it the proof of Prop. XVII?

895. Cor. *If V denotes the volume, H the altitude, and R the radius of the base of a cone,*

$$V = \frac{1}{3} \pi R^2 H.$$

Ex. 1423. Any two cones are to each other as the products of their bases and altitudes.

Ex. 1424. The slant height of a right circular cone is 18 inches and makes with the base an angle of 60° ; the radius of the base is 8 inches. Find the volume of the cone.

Ex. 1425. The base of a cone has a radius of 12 inches; an element of the cone is 24 inches long and makes with the base an angle of 30° . Find the volume of the cone.

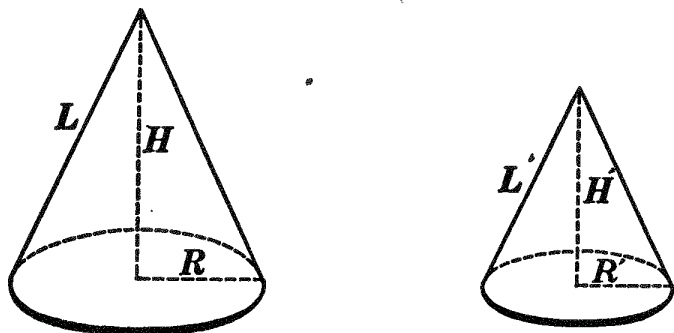
Ex. 1426. The hypotenuse of a right triangle is 17 inches and one side is 15 inches. Find the volume of the solid generated by revolving the triangle about its shortest side as an axis.

Ex. 1427. A cone and a cylinder have equal bases and equal altitudes. Find the ratio of their volumes.

896. Historical Note. To Eudoxus is credited the proof of the proposition that "every cone is the third part of a cylinder on the same base and with the same altitude." Proofs of this proposition were also given later by Archimedes and Brahmagupta. (Compare with § 809.)

PROPOSITION XVIII. THEOREM

897. *The volumes of two similar cones of revolution are to each other as the cubes of their altitudes, as the cubes of their slant heights, and as the cubes of the radii of their bases.*



Given two similar cones of revolution with their volumes denoted by V and V' , their altitudes by H and H' , their slant heights by L and L' , and the radii of their bases by R and R' , respectively.

To prove
$$\frac{V}{V'} = \frac{H^3}{H'^3} = \frac{L^3}{L'^3} = \frac{R^3}{R'^3}.$$

The proof is left as an exercise for the student.

HINT. Apply the method of proof used in Prop. XVI.

Ex. 1428. If the altitude of a cone of revolution is three fourths that of a similar cone, what other fact follows by definition? Compare the circumferences of the two bases; their areas. Compare the total areas of the two cones; their volumes.

Ex. 1429. If the lateral area of a right circular cone is $1\frac{9}{16}$ times that of a similar cone, what is the ratio of their volumes? of their altitudes?

Ex. 1430. Through a given cone X two planes are passed parallel to the base; let Y denote the cone cut off by the upper plane, and Z the entire cone cut off by the lower plane. Prove that Y and Z are to each other as the cubes of the distances of the planes from the vertex of the given cone X .

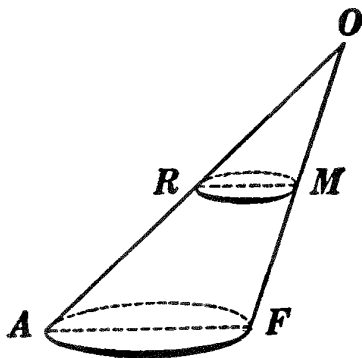
HINT. See Ex. 1381.

Ex. 1431. Show that § 897 is a special case of Ex. 1430.

Ex. 1432. The lateral area of a cone of revolution is 144 square inches and the total area 240 square inches. Find the volume.

PROPOSITION XIX. THEOREM

898. *The volume of a frustum of a cone is equal to one third the product of its altitude and the sum of its lower base, its upper base, and the mean proportional between its two bases.*



Given frustum AM , of cone $O-AF$, with its volume denoted by V , its lower base by B , its upper base by b , and its altitude by H .

To prove $V = \frac{1}{3} H(B + b + \sqrt{B \cdot b})$.

The proof is left as an exercise for the student.

HINT. In the proof of § 815, change "pyramid" to "cone."

899. Cor. *If V denotes the volume, H the altitude, and R and r the radii of the bases of a frustum of a cone,*

$$V = \frac{1}{3} \pi H(R^2 + r^2 + R \cdot r).$$

Ex. 1433. Make a frustum of a right circular cone as indicated in Ex. 1401, and of the same dimensions. Find its volume.

Ex. 1434. A tin pail is in the form of a frustum of a cone; the diameter of its upper base is 12 inches, of its lower base 10 inches. How high must the pail be to hold $2\frac{1}{2}$ gallons of water? (See Ex. 1422.)

Ex. 1435. A cone 6 feet high is cut by a plane parallel to the base and 4 feet from the vertex; the volume of the frustum formed is 456 cubic inches. Find the volume of the entire cone.

Ex. 1436. Find the ratio of the base to the lateral area of a right circular cone whose altitude is equal to the diameter of its base.

MISCELLANEOUS EXERCISES

Ex. 1437. The base of a cylinder is inscribed in a face of a cube whose edge is 10 inches. Find the altitude of the cylinder if its volume is equal to the volume of the cube.

Ex. 1438. A block of marble in the form of a regular prism is 10 feet long and 2 feet 6 inches square at the base. Find the volume of the largest cylindrical pillar that can be cut from it.

Ex. 1439. The Winchester bushel, formerly used in England, was the volume of a right circular cylinder $18\frac{1}{2}$ inches in internal diameter and 8 inches in depth. Is this the same volume as the bushel used in the United States (2150.42 cubic inches) ?

Ex. 1440. To determine the volume of an irregular body, it was immersed in a vessel containing water. The vessel was in the form of a right circular cylinder the radius of whose base was 8 inches. On placing the body in the cylinder, the surface of the water was raised $10\frac{1}{2}$ inches. Find the volume of the irregular solid.

Ex. 1441. In draining a certain pond a 4-inch tiling (*i.e.* a tiling whose inside diameter was 4 inches) was used. In draining another pond, supposed to contain half as much water, a 2-inch tiling was laid. It could not drain the pond. What was the error made ?

Ex. 1442. A grain elevator in the form of a frustum of a right circular cone is 25 feet high ; the radii of its bases are 10 feet and 5 feet, respectively ; how many bushels of wheat will it hold, counting $1\frac{1}{4}$ cubic feet to a bushel ?

Ex. 1443. The altitude of a cone with circular base is 16 inches. At what distance from the vertex must a plane be passed parallel to the base to cut the cone into two equivalent parts ?

Ex. 1444. Two sides of a triangle including an angle of 120° are 10 and 20, respectively. Find the volume of the solid generated by revolving the triangle about side 10 as an axis.

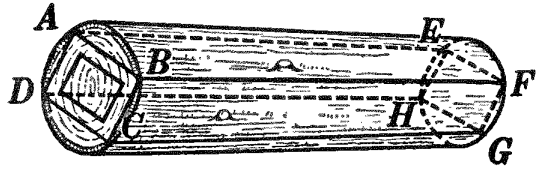
Ex. 1445. Find the volume of the solid generated by revolving the triangle of Ex. 1444 about side 20 as an axis.

Ex. 1446. Find the volume of the solid generated by revolving the triangle of Ex. 1444 about its longest side as an axis.

Ex. 1447. The slant height of a right circular cone is 20 inches, and the circumference of its base 4π inches. A plane parallel to the base cuts off a cone whose slant height is 8 inches. Find the lateral area and the volume of the frustum remaining.

Ex. 1448. A cone has an altitude of 12.5 feet and a base whose radius is 8.16 feet; the base of a cylinder having the same volume as the cone has a radius of 6.25 feet. Find the altitude of the cylinder.

Ex. 1449. A log 20 feet long is 3 feet in diameter at the top end and 4 feet in diameter at the butt end.



(a) How many cubic feet of wood does the log contain?

(b) How many cubic feet are there in the largest piece of square timber that can be cut from the log?

(c) How many cubic feet in the largest piece of square timber the same size throughout its whole length?

(d) How many board feet does the piece of timber in (c) contain, a board foot being equivalent to a board 1 foot square and 1 inch thick?

HINT. In (b) the larger end is square $ABCD$. What is the smaller end? In (c) one end is square $EFGH$. What is the other end?

Ex. 1450. The base of a cone has a radius of 16 inches. A section of the cone through the vertex, through the center of the base, and perpendicular to the base, is a triangle two of whose sides are 20 inches and 24 inches, respectively. Find the volume of the cone.

Ex. 1451. The hypotenuse of a right triangle is 10 inches and one side 8 inches; find the area of the surface generated by revolving the triangle about its hypotenuse as an axis.

Ex. 1452. A tin pail in the form of a frustum of a right circular cone is 8 inches deep; the diameters of its bases are $8\frac{1}{2}$ inches and $10\frac{1}{2}$ inches, respectively. How many gallons of water will it hold? (One liquid gallon contains 231 cubic inches.)

Ex. 1453. The altitude of a cone is 12 inches. At what distances from the vertex must planes be passed parallel to the base to divide the cone into four equivalent parts?

HINT. See Ex. 1430.

Ex. 1454. Find the volume of the solid generated by an equilateral triangle, whose side is a , revolving about one of its sides as an axis.

Ex. 1455. Regular hexagonal prisms are inscribed in and circumscribed about a right circular cylinder. Find (a) the ratio of the lateral areas of the three solids; (b) the ratio of their total areas; (c) the ratio of their volumes.

Ex. 1456. How many miles of platinum wire $\frac{1}{20}$ of an inch in diameter can be made from 1 cubic foot of platinum?

Ex. 1457. A tank in the form of a right circular cylinder is 5 feet long and the radius of its base is 8 inches. If placed so that its axis is horizontal and filled with gasoline to a depth of 12 inches, how many gallons of gasoline will it contain?

HINT. See Ex. 1024.

Ex. 1458. Find the weight in pounds of an iron pipe 10 feet long, if the iron is $\frac{1}{2}$ inch thick and the outer diameter of the pipe is 4 inches. (1 cubic foot of bar iron weighs 7780 ounces.)

Ex. 1459. In a certain right circular cone whose altitude and radius of base are equal, the total surface and the volume have the same numerical value. Find the volume of the cone.

Ex. 1460. Two cones of revolution lie on opposite sides of a common base. Their slant heights are 12 and 5, respectively, and the sum of their altitudes is 13. Find the radius of the common base.

Ex. 1461. The radii of the lower and upper bases of a frustum of a right circular cone are R and R' , respectively. Show that the area of a section midway between them is $\frac{\pi(R + R')^2}{4}$.

Ex. 1462. A plane parallel to the base of a right circular cone leaves three fourths of the cone's volume. How far from the vertex is this plane? How far from the vertex is the plane if it cuts off half the volume? Answer the same questions for a cylinder.

Ex. 1463. Is every cone cut from a right circular cone by a plane parallel to its base necessarily similar to the original cone? why? How is it with a cylinder? why?

Ex. 1464. Water is carried from a spring to a house, a distance of $\frac{1}{2}$ mile, in a cylindrical pipe whose inside diameter is 2 inches. How many gallons of water are contained in the pipe?

Ex. 1465. A square whose side is 6 inches is revolved about one of its diagonals as an axis. Find the surface and the volume of the solid generated. Can you find the volume of the solid generated by revolving a cube about one of its diagonals as an axis?

HINT. Make a cube of convenient size from pasteboard, pass a hat-pin through two diagonally opposite vertices, and revolve the cube *rapidly*.

Ex. 1466. Given V the volume, and R the radius of the base, of a right circular cylinder. Find the lateral area and total area.

Ex. 1467. Given the total area T , and the altitude H , of a right circular cylinder. Find the volume.

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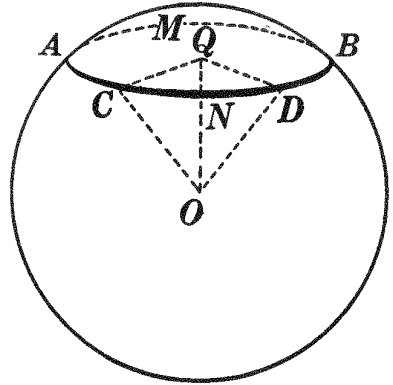
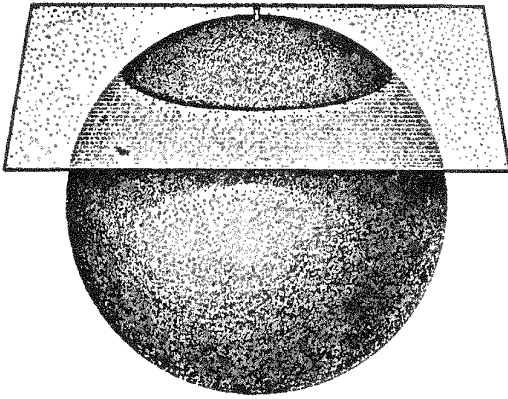
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PROPOSITION I. THEOREM

903. *Every section of a sphere made by a plane is a circle.*



Given AMB a section of sphere O made by a plane.
To prove section AMB a \odot .

ARGUMENT

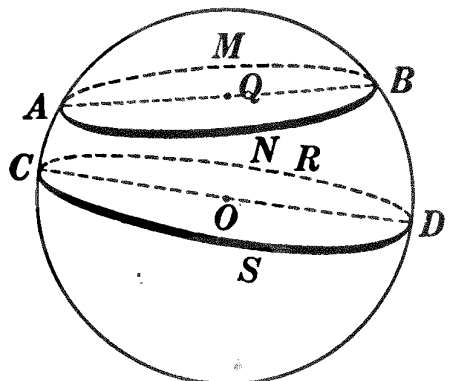
1. From O draw $OQ \perp$ section AMB .
2. Join Q to C and D , any two points on the perimeter of section AMB . Draw OC and OD .
3. In rt. $\triangle OQC$ and OQD , $OQ = OQ$.
4. $OC = OD$.
5. $\therefore \triangle OQC = \triangle OQD$.
6. $\therefore QC = QD$; i.e. any two points on the perimeter of section AMB are equidistant from Q .
7. \therefore section AMB is a \odot . Q.E.D.

REASONS

1. § 639.
2. § 54, 15.
3. By iden.
4. § 902, a.
5. § 211.
6. § 110.
7. § 276.

904. Def. A great circle of a sphere is a section made by a plane which passes through the center of the sphere, as $\odot CRDS$.

905. Def. A small circle of a sphere is a section made by a plane which does not pass through the center of the sphere, as $\odot AMB$.



906. Def. The **axis** of a circle of a sphere is the diameter of the sphere which is perpendicular to the plane of the circle.

907. Def. The **poles** of a circle of a sphere are the extremities of the axis of the circle.

Ex. 1472. Considering the earth as a sphere, what kind of circles are the parallels of latitude? the equator? the meridian circles? What is the axis of the equator? of the parallels of latitude? What are the poles of the equator? of the parallels of latitude?

Ex. 1473. The radius of a sphere is 17 inches. Find the area of a section made by a plane 8 inches from the center.

Ex. 1474. The area of a section of a sphere 45 centimeters from the center is 784π square centimeters. Find the radius of the sphere.

Ex. 1475. The area of a section of a sphere 7 inches from the center is 576π . Find the area of a section 8 inches from the center.

908. The following are some of the properties of a sphere; the student should prove the correctness of each:

(a) *In equal spheres, or in the same sphere, if two sections are equal, they are equally distant from the center, and conversely.*

HINT. Compare with § 307.

(b) *In equal spheres, or in the same sphere, if two sections are unequal, the greater section is at the less distance from the center, and conversely. (HINT. See §§ 308, 310.)*

(c) *In equal spheres, or in the same sphere, all great circles are equal. (HINT. See § 279, c.)*

(d) *The axis of a small circle of a sphere passes through the center of the circle, and conversely.*

(e) *Any two great circles of a sphere bisect each other.*

(f) *Every great circle of a sphere bisects the surface and the sphere.*

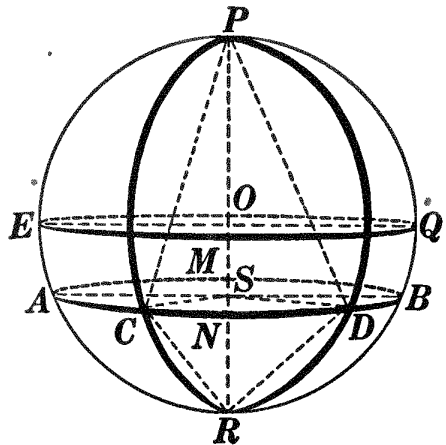
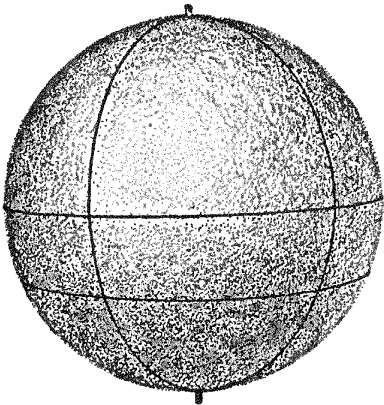
(g) *Through two points on the surface of a sphere, not the extremities of a diameter, there exists one and only one great circle.*

(h) *Through three points on the surface of a sphere there exists one and only one circle.*

909. Def. The **distance** between two points on the surface of a sphere is the length of the minor arc of the great circle joining them.

PROPOSITION II. THEOREM

910. *All points on the circumference of a circle of a sphere are equidistant from either pole of the circle.*



Given C and D any two points on the circumference, and P and R the poles, of $\odot AMBN$.

To prove $\text{arc } PC = \text{arc } PD$ and $\text{arc } RC = \text{arc } RD$.

The proof is left as an exercise for the student.

HINT. Apply § 298.

911. Def. The polar distance of a circle of a sphere is the distance between any point on its circumference and the nearer pole of the circle.

912. Cor. I. *The polar distance of a great circle is a quadrant.*

913. Cor. II. *In equal spheres, or in the same sphere, the polar distances of equal circles are equal.*

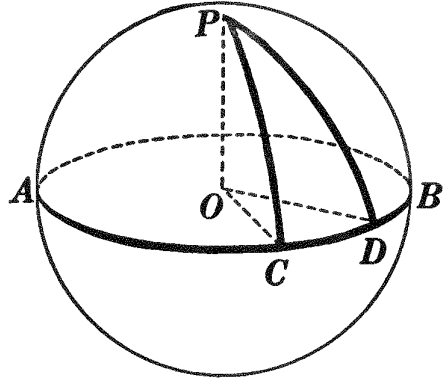
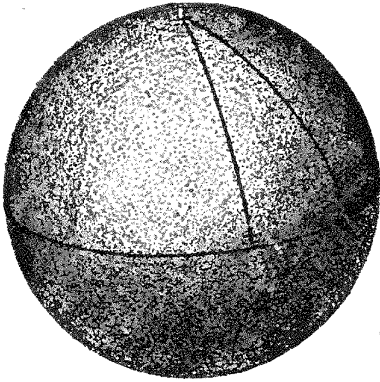
Ex. 1476. What is the locus of all points on the surface of the earth at a quadrant's distance from the north pole? from the south pole? from the equator? from a point P on the equator? at a distance of $23\frac{1}{2}^\circ$ from the south pole? $23\frac{1}{2}^\circ$ from the equator? 180° from the north pole?

Ex. 1477. Considering the earth as a sphere with a radius of 4000 miles, calculate in miles the polar distance of: (a) the Arctic Circle; (b) the Tropic of Cancer; (c) the equator.

Ex. 1478. State a postulate for the construction of a circle on the surface of a sphere corresponding to § 122, the postulate for the construction of a circle in a plane.

PROPOSITION III. THEOREM

914. *A point on the surface of a sphere at the distance of a quadrant from each of two other points (not the extremities of the same diameter) on the surface, is the pole of the great circle passing through these two points.*



Given PC and PD quadrants of great \odot of sphere O , and $ACDB$ a great \odot passing through points C and D .

To prove P the pole of great $\odot ACDB$.

| ARGUMENT | REASONS |
|--|--------------|
| 1. Draw OC , OD , and OP . | 1. § 54, 15. |
| 2. $\widehat{PC} = 90^\circ$ and $\widehat{PD} = 90^\circ$. | 2. By hyp |
| 3. $\therefore \angle POC$ and POD are rt. \angle s; i.e. $OP \perp OC$ and OD | 3. § 358. |
| 4. $\therefore OP \perp$ the plane of $\odot ACDB$. | 4. § 622. |
| 5. $\therefore OP$ is the axis of $\odot ACDB$. | 5. § 906. |
| 6. $\therefore P$ is the pole of great $\odot ACDB$. Q.E.D. | 6. § 907. |

Ex. 1479. Assuming the chord of a quadrant of a great circle of a sphere to be given, construct with compasses an arc of a great circle through two given points on the surface of the sphere.

Ex. 1480. If the planes of two great circles are perpendicular to each other, each passes through the poles of the other.

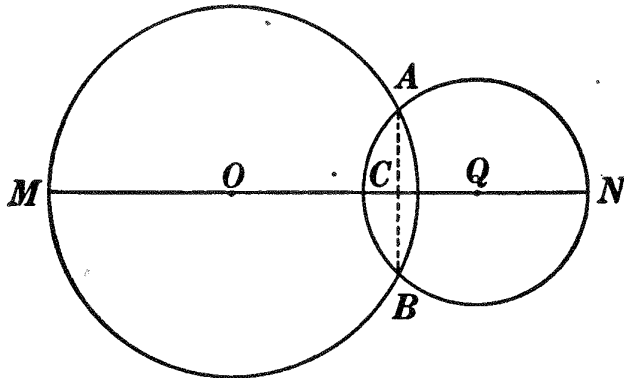
Ex. 1481. Find the locus of all points in space equidistant from two given points and at a given distance d from a third given point.

Ex. 1482. Find the locus of all points in space at a distance d from a given point and at a distance m from a given plane.

Ex. 1483. Find the locus of all points in space equidistant from two given points and also equidistant from two given parallel lines.

PROPOSITION IV. THEOREM

915. *The intersection of two spherical surfaces is the circumference of a circle.*



Given two spherical surfaces generated by intersecting circumferences O and Q revolving about line MN as an axis.

To prove the intersection of the two spherical surfaces the circumference of a \odot .

OUTLINE OF PROOF

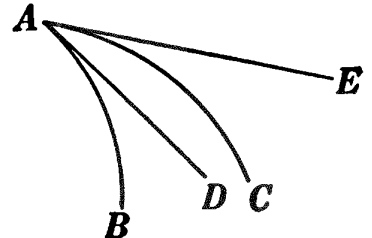
1. Show that $MN \perp AB$ at its mid-point C (§ 328).
2. Show that AC , revolving about axis MN , generates a plane.
3. Show that A generates the circumference of a \odot .
4. The locus of A is the intersection of what (§ 614)?
5. \therefore the intersection of the two spherical surfaces is the circumference of a \odot . Q.E.D.

Ex. 1484. Find the locus of all points in space 6 inches from a given point P and 10 inches from another given point Q .

Ex. 1485. The radii of two intersecting spheres are 12 inches and 16 inches, respectively. The line joining their centers is 24 inches. Find the circumference and area of their circle of intersection.

916. Def. An angle formed by two intersecting arcs of circles is the angle formed by tangents to the two arcs at their point of intersection; thus the \angle formed by arcs AB and AC is plane $\angle DAE$.

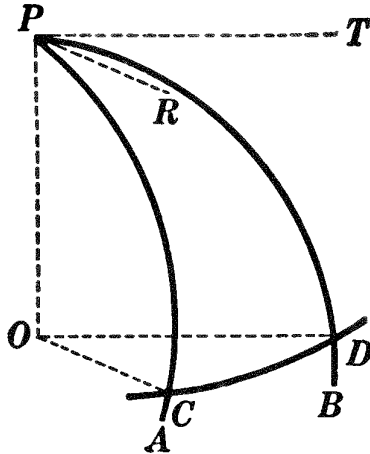
917. Def. A spherical angle is an angle formed by two intersecting arcs of great circles of a sphere.*



* A different meaning is sometimes attached to the expression "spherical angle" in advanced mathematics.

PROPOSITION V. THEOREM

918. *A spherical angle is measured by the arc of a great circle having the vertex of the angle as a pole and intercepted by the sides of the angle, prolonged if necessary.*



Given spherical $\angle APB$, with CD an arc of a great \odot whose pole is P and which is intercepted by sides PA and PB of $\angle APB$.

To prove that $\angle APB \propto \widehat{CD}$.

OUTLINE OF PROOF

1. Draw radii OP , OC , and OD .
2. From P draw PR tangent to \widehat{PA} and PT tangent to \widehat{PB} .
3. Prove OC and OD each $\perp OP$.
4. Prove $OC \parallel PR$, $OD \parallel PT$, and hence $\angle COD = \angle RPT$.
5. But $\angle COD \propto CD$; $\therefore \angle RPT$, i.e. $\angle APB \propto CD$. Q.E.D.

919. Cor. I. *A spherical angle is equal to the plane angle of the dihedral angle formed by the planes of the sides of the angle.*

920. Cor. II. *The sum of all the spherical angles about a point on the surface of a sphere equals four right angles.*

Ex. 1486. By comparison with the definitions of the corresponding terms in plane geometry, frame exact definitions of the following classes of spherical angles : acute, right, obtuse, adjacent, complementary, supplementary, vertical.

Ex. 1487. Any two vertical spherical angles are equal.

Ex. 1488. If one great circle passes through the pole of another great circle, the circles are perpendicular to each other.

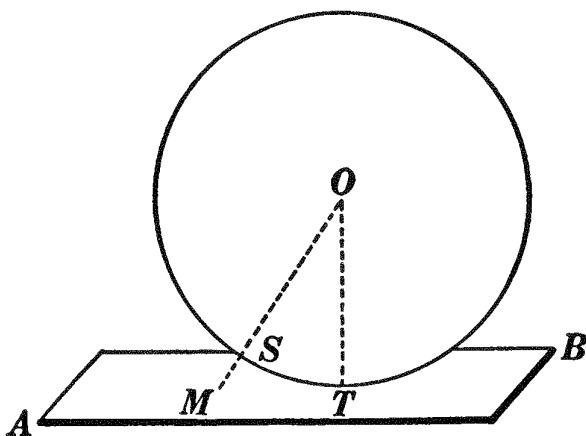
LINES AND PLANES TANGENT TO A SPHERE

921. Def. A straight line or a plane is tangent to a sphere if, however far extended, it meets the sphere in one and only one point.

922. Def. Two spheres are tangent to each other if they have one and only one point in common. They are tangent **internally** if one sphere lies within the other, and **externally** if neither sphere lies within the other.

PROPOSITION VI. THEOREM

923. *A plane tangent to a sphere is perpendicular to the radius drawn to the point of tangency.*



Given plane AB tangent to sphere O at T , and OT a radius drawn to the point of tangency.

To prove plane $AB \perp OT$.

The proof is left as an exercise for the student.

924. Question. What changes are necessary in the proof of § 313 to make it the proof of § 923?

925. Cor. I. (Converse of Prop. VI). *A plane perpendicular to a radius of a sphere at its outer extremity is tangent to the sphere.*

HINT. See § 314.

Ex. 1489. A straight line tangent to a sphere is perpendicular to the radius drawn to the point of tangency.

Ex. 1490. State and prove the converse of Ex. 1489.

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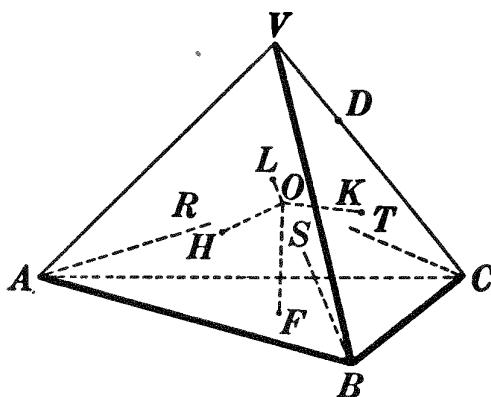
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PROPOSITION VII. PROBLEM

930. To inscribe a sphere in a given tetrahedron.



Given tetrahedron $V-ABC$.

To inscribe a sphere in tetrahedron $V-ABC$.

I. Construction

1. Construct planes $RABS$, $SBCT$, and $TCAR$ bisecting dihedral \angle s whose edges are AB , BC , and CA , respectively. § 691.
2. From O , the point of intersection of the three planes, construct $OF \perp$ plane ABC . § 637.
3. The sphere constructed with O as center and OF as radius will be inscribed in tetrahedron $V-ABC$.

II. Proof

| ARGUMENT | REASONS |
|---|-----------------------------|
| 1. Plane $RABS$, the bisector of dihedral $\angle AB$, lies between planes ABV and ABC ; <i>i.e.</i> it intersects edge VC in some point as D . | 1. By cons. |
| 2. \therefore plane $RABS$ intersects plane BCV in line BD and plane ACV in line AD . | 2. § 616. |
| 3. Plane $SBCT$ lies between planes BCV and ABC ; <i>i.e.</i> it intersects plane $RASB$ in a line through B between BA and BD , as BS . | 3. By cons. |
| 4. Similarly plane $TCAR$ intersects plane $RABS$ in a line through A between | 4. By steps similar to 1-3. |

| ARGUMENT | REASONS |
|--|------------------|
| AB and AD , as AR ; and plane $SBCT$ intersects plane $TCAR$ in a line through C as CT . | |
| 5. But AR and BS pass through the interior of $\triangle ABD$. | 5. Args. 3 & 4. |
| 6. $\therefore AR$ and BS intersect in some point as O , within $\triangle ABD$. | 6. § 194. |
| 7. $\therefore AR$, BS , and CT are concurrent in point O . | 7. § 617, I. |
| 8. From O draw OH , OK , and $OL \perp$ planes VAB , VBC , and VCA , respectively. | 8. § 639. |
| 9. $\therefore O$ is in plane OAB , $OF = OH$. | 9. § 688. |
| 10. $\therefore O$ is in plane OBC , $OF = OK$. | 10. § 688. |
| 11. $\therefore O$ is in plane OCA , $OF = OL$. | 11. § 688. |
| 12. $\therefore OF = OH = OK = OL$. | 12. § 54, 1. |
| 13. \therefore each of the four faces of the tetrahedron is tangent to sphere O . | 13. § 925. |
| 14. \therefore sphere O is inscribed in tetrahedron $V-ABC$. | 14. §§ 926, 927. |
| Q.E.D. | |

III. Discussion

The discussion is left as an exercise for the student.

Ex. 1501. The six planes bisecting the dihedral angles of a tetrahedron meet in a point which is equidistant from the four faces of the tetrahedron.

HINT. Compare with § 258.

Ex. 1502. Inscribe a sphere in a given cube.

Ex. 1503. The volume of any tetrahedron is equal to the product of its surface and one third the radius of the inscribed sphere.

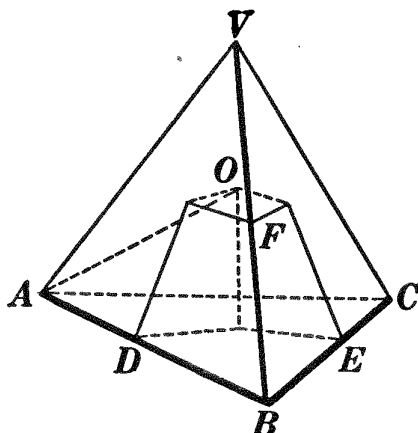
HINT. See §§ 491 and 492.

Ex. 1504. Find a point within a triangular pyramid such that the planes determined by the lines joining this point to the vertices shall divide the pyramid into four equivalent parts.

HINT. Compare with Ex. 1094.

PROPOSITION VIII. PROBLEM

931. *To circumscribe a sphere about a given tetrahedron.*



Given tetrahedron $V-ABC$.

To circumscribe a sphere about tetrahedron $V-ABC$.

I. Construction

1. Through D , the mid-point of AB , construct plane $DO \perp AB$; through E , the mid-point of BC , construct plane $EO \perp BC$; and through F , the mid-point of VB , construct plane $FO \perp VB$.
2. Join O , the point of intersection of the three planes, to A .
3. The sphere constructed with O as center and OA as radius will be circumscribed about tetrahedron $V-ABC$.

II. Outline of Proof

1. Prove that the three planes OD , OE , and OF intersect each other in three lines.
2. Prove that these three lines of intersection meet in a point, as O .
3. Prove that $OA = OB = OC = OV$.
4. \therefore sphere O is circumscribed about tetrahedron $V-ABC$.

Q.E.D.

932. Cor. *Four points not in the same plane determine a sphere.*

933. Questions. Are the methods used in §§ 930 and 931 similar to those used in §§ 321 and 323? In § 930 could the lines forming the edges of the dihedral angles bisected be three lines meeting in one vertex? In § 931 could the three edges bisected be three lines lying in the same face?

Ex. 1505. The six planes perpendicular to the edges of a tetrahedron at their mid-points meet in a point which is equidistant from the four vertices of the tetrahedron.

Ex. 1506. The four lines perpendicular to the faces of a tetrahedron, and erected at their centers, meet in a point which is equidistant from the four vertices of the tetrahedron.

Ex. 1507. Circumscribe a sphere about a given cube.

Ex. 1508. Circumscribe a sphere about a given rectangular parallelepiped. Can a sphere be inscribed in any rectangular parallelepiped? Explain.

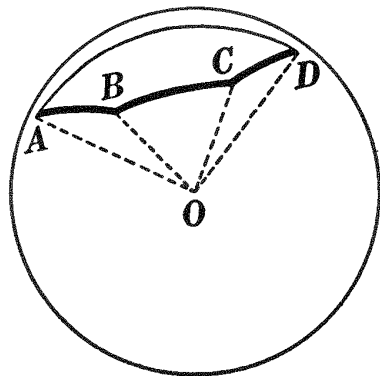
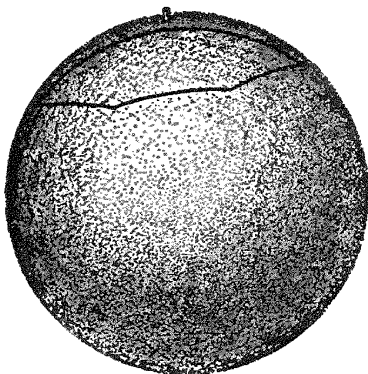
Ex. 1509. Find a point equidistant from four points in space not all in the same plane.

SPHERICAL POLYGONS

934. Def. A line on the surface of a sphere is said to be **closed** if it separates a portion of the surface from the remaining portion.

935. Def. A **closed figure** on the surface of a sphere is a figure composed of a portion of the surface of the sphere and its bounding line or lines.

936. Defs. A **spherical polygon** is a closed figure on the surface of a sphere whose boundary is composed of three or more arcs of great circles, as $ABCD$.



The bounding arcs are called the **sides** of the polygon, the points of intersection of the arcs are the **vertices** of the polygon, and the spherical angles formed by the sides are the **angles** of the polygon.

937. Def. A diagonal of a spherical polygon is an arc of a great circle joining any two non-adjacent vertices.

938. Def. A spherical triangle is a spherical polygon having three sides.

Ex. 1510. By comparison with the definitions of the corresponding terms in plane geometry, frame exact definitions of the following classes of spherical triangles: scalene, isosceles, equilateral, acute, right, obtuse, and equiangular.

Ex. 1511. With a given arc as one side, construct an equilateral spherical triangle.

HINT. Compare the cons., step by step, with § 124.

Ex. 1512. With three given arcs as sides, construct a scalene spherical triangle.

939. Since each side of a spherical polygon is an arc of a great circle (§ 936), the planes of these arcs meet at the center of the sphere and form at that point a polyhedral angle, as polyhedral $\angle O-ABCD$.

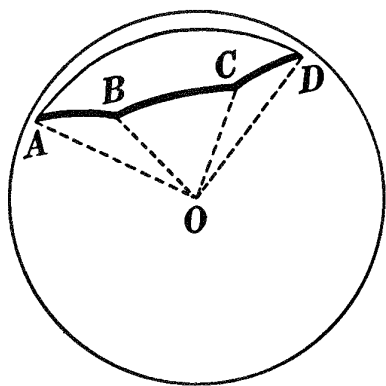
This polyhedral angle and the spherical polygon are very closely related. The following are some of the more important relations; the student should prove the correctness of each:

940. (a) *The sides of a spherical polygon have the same measures as the corresponding face angles of the polyhedral angle.*

(b) *The angles of a spherical polygon have the same measures as the corresponding dihedral angles of the polyhedral angle.*

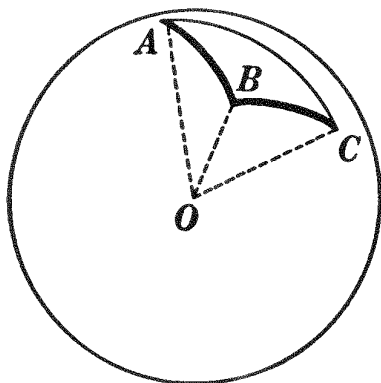
Thus, sides AB , BC , etc., of spherical polygon $ABCD$ have the same measures as face $\sphericalangle AOB$, $\sphericalangle BOC$, etc., of polyhedral $\angle O-ABCD$; and spherical $\sphericalangle ABC$, $\sphericalangle BCD$, etc., have the same measures as the dihedral \sphericalangle whose edges are OB , OC , etc.

These relations make it possible to establish certain properties of spherical polygons from the corresponding known properties of the polyhedral angle, as in §§ 941 and 942.



PROPOSITION IX. THEOREM

941. *The sum of any two sides of a spherical triangle is greater than the third side.*



Given spherical $\triangle ABC$.

To prove $\widehat{AB} + \widehat{BC} > \widehat{CA}$.

ARGUMENT

1. $\angle AOB + \angle BOC > \angle COA$.

2. $\angle AOB \propto \widehat{AB}$, $\angle BOC \propto \widehat{BC}$, $\angle COA \propto \widehat{CA}$.

3. $\therefore \widehat{AB} + \widehat{BC} > \widehat{CA}$.

Q.E.D.

REASONS

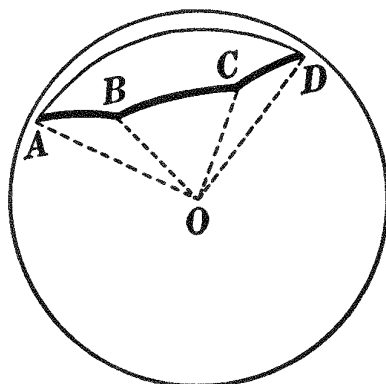
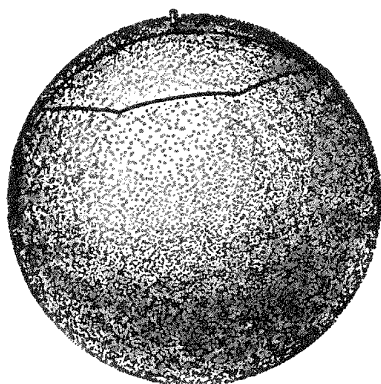
1. § 710.

2. § 940, a.

3. § 362, b.

PROPOSITION X. THEOREM

942. *The sum of the sides of any spherical polygon is less than 360° .*



Given spherical polygon $ABC \dots$ with n sides.

To prove $\widehat{AB} + \widehat{BC} + \dots < 360^\circ$.

HINT. See §§ 712 and 940, a.

Ex. 1513. In spherical triangle ABC , arc $AB = 40^\circ$ and arc $BC = 80^\circ$. Between what limits must arc CA lie?

Ex. 1514. Any side of a spherical polygon is less than the sum of the remaining sides.

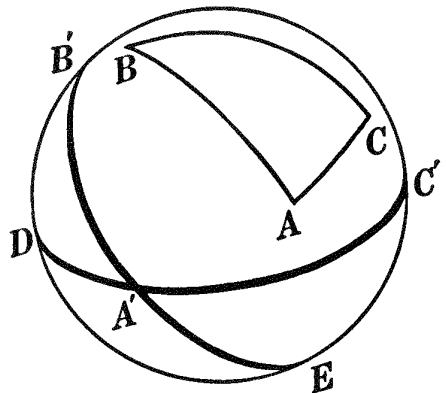
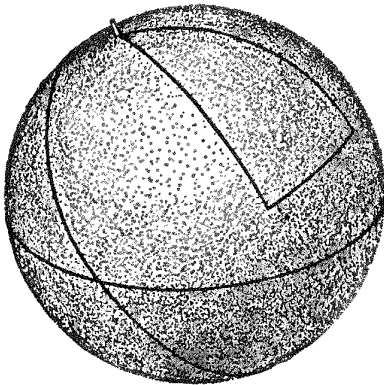
Ex. 1515. If arc AB is the perpendicular bisector of arc CD , every point on the surface of the sphere and not in arc AB is unequally distant from C and D .

Ex. 1516. In a spherical quadrilateral, between what limits must the fourth side lie if three sides are 60° , 70° , and 80° ? if three sides are 40° , 50° , and 70° ?

Ex. 1517. Any side of a spherical polygon is less than 180° .

HINT. See Ex. 1514.

943. If, with A , B , and C the vertices of any spherical triangle as poles, three great circles are constructed, as $B'C'ED$,



$C'A'D$, and $EA'B'$, the surface of the sphere will be divided into eight spherical triangles, four of which are seen on the hemisphere represented in the figure. Of these eight spherical triangles, $A'B'C'$ is the one and only one that is so situated that A and A' lie on the same side of BC , B and B' on the same side of AC , and C and C' on the same side of AB . This particular triangle $A'B'C'$ is called the **polar triangle** of triangle ABC .

944. Questions. In the figure above, $\triangle A'B'C'$, the polar of $\triangle ABC$, is entirely outside of $\triangle ABC$. Can the two \triangle be so constructed that :

- (a) $A'B'C'$ is entirely within ABC ?
- (b) $A'B'C'$ is partly outside of and partly within ABC ?

Ex. 1518. What is the polar triangle of a spherical triangle all of whose sides are quadrants?

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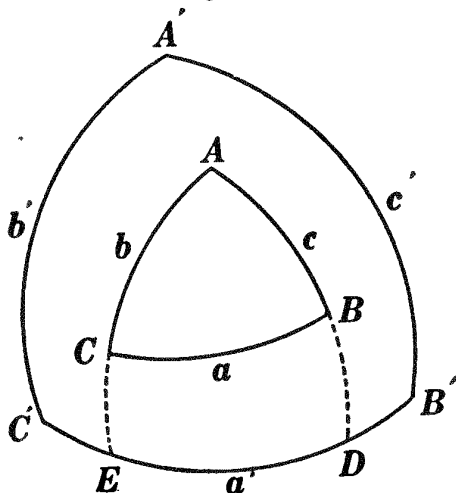
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PROPOSITION XII. THEOREM

947. *In two polar triangles each angle of one and that side of the other of which its vertex is the pole are together equal, numerically, to 180° .*



Given polar $\triangle ABC$ and $A'B'C'$, with sides denoted by a, b, c , and a', b', c' , respectively.

To prove: (a) $\angle A + a' = 180^\circ$, $\angle B + b' = 180^\circ$, $\angle C + c' = 180^\circ$;
 (b) $\angle A' + a = 180^\circ$, $\angle B' + b = 180^\circ$, $\angle C' + c = 180^\circ$.

(a) ARGUMENT ONLY

1. Let arcs AB and AC (prolonged if necessary) intersect arc $B'C'$ at D and E , respectively; then $C'D = 90^\circ$ and $EB' = 90^\circ$.

2. $\therefore C'D + EB' = 180^\circ$.

3. $\therefore C'E + ED + ED + DB' = 180^\circ$; i.e. $ED + a' = 180^\circ$.

4. But ED is the measure of $\angle A$.

5. $\therefore \angle A + a' = 180^\circ$.

6. Likewise $\angle B + b' = 180^\circ$, and $\angle C + c' = 180^\circ$. Q.E.D.

(b) The proof of (b) is left as an exercise for the student.

HINT. Let BC prolonged meet $A'B'$ at H and $A'C'$ at K .

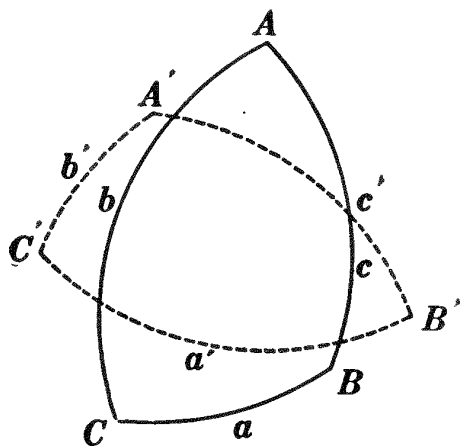
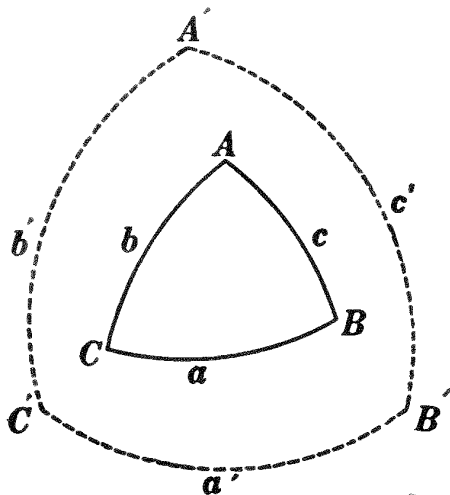
948. Question. In the history of mathematics, why are polar triangles frequently spoken of as **supplemental triangles**?

Ex. 1520. The angles of a spherical triangle are 75° , 85° , and 145° . Find the sides of its polar triangle.

Ex. 1521. If a spherical triangle is equilateral, its polar triangle is equiangular; and conversely.

PROPOSITION XIII. THEOREM

949. *The sum of the angles of a spherical triangle is greater than 180° and less than 540° .*



Given spherical $\triangle ABC$ with sides denoted by a , b , and c .
 To prove $\angle A + \angle B + \angle C > 180^\circ$ and $< 540^\circ$.

| ARGUMENT | REASONS |
|--|-------------|
| 1. Let $\triangle A'B'C'$, with sides denoted by a' , b' , and c' , be the polar of $\triangle ABC$. | 1. § 943. |
| 2. Then $\angle A + a' = 180^\circ$, $\angle B + b' = 180^\circ$, $\angle C + c' = 180^\circ$. | 2. § 947. |
| 3. $\therefore \angle A + \angle B + \angle C + (a' + b' + c') = 540^\circ$. | 3. § 54, 2. |
| 4. But $a' + b' + c' < 360^\circ$. | 4. § 942. |
| 5. $\therefore \angle A + \angle B + \angle C > 180^\circ$. | 5. § 54, 6. |
| 6. Again, $a' + b' + c' > 0^\circ$. | 6. § 938. |
| 7. $\therefore \angle A + \angle B + \angle C < 540^\circ$. Q.E.D. | 7. § 54, 6. |

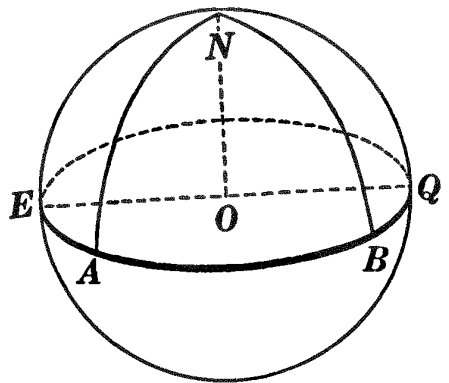
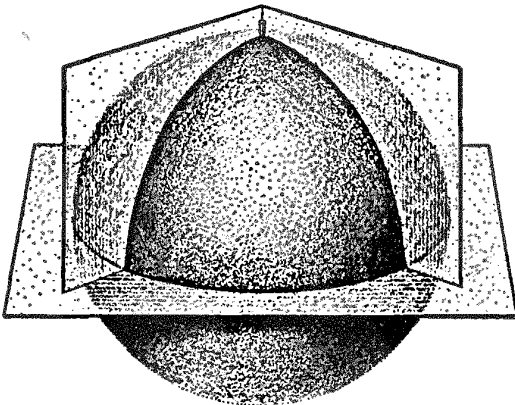
950. Cor. *In a spherical triangle there can be one, two, or three right angles; there can be one, two, or three obtuse angles.*

951. Note. Throughout the Solid Geometry the student's attention has constantly been called to the relations between definitions and theorems of solid geometry and the corresponding definitions and theorems of plane geometry. In the remaining portion of the geometry of the sphere there will likewise be many of these comparisons, but here the student must be particularly on his guard for contrasts as well as comparisons. For ex-

ample, while the sum of the angles of a plane triangle is equal to exactly 180° , he has learned (§ 949) that the sum of the angles of a spherical triangle may be any number from 180° to 540° ; while a plane triangle can have but one right or one obtuse angle, a spherical triangle may have one, two, or three right angles or one, two, or three obtuse angles (§ 950).

If the student will recall that, considering the earth as a sphere, the north and south poles of the earth are the poles of the equator, and that all meridian circles are great circles perpendicular to the equator, it will make his thinking about spherical triangles more definite.

952. Def. A spherical triangle containing two right angles is called a **birectangular spherical triangle**.



953. Def. A spherical triangle having all of its angles right angles is called a **trirectangular spherical triangle**.

Thus two meridians, as NA and NB , making at the north pole an acute or an obtuse \angle , form with the equator a birectangular spherical \triangle . If the \angle between NA and NB is made a rt. \angle , $\triangle ANB$ becomes a trirectangular spherical \triangle .

Ex. 1522. What kind of arcs are NA and NB ? Then what arc measures spherical angle ANB ? Are two sides of any birectangular spherical triangle quadrants? What is each side of a trirectangular spherical triangle?

Ex. 1523. If two sides of a spherical triangle are quadrants, the triangle is birectangular. (Hint. Apply § 947.)

Ex. 1524. What is the polar triangle of a trirectangular spherical triangle?

Ex. 1525. An exterior angle of a spherical triangle is less than the sum of the two remote interior angles. Compare this exercise with § 215. Make this new fact clear by applying it to a birectangular spherical triangle whose third angle is : (a) acute; (b) right; (c) obtuse.

PROPOSITION XIV. THEOREM

954. *In equal spheres, or in the same sphere, two spherical triangles are equal:*

I. *If a side and the two adjacent angles of one are equal respectively to a side and the two adjacent angles of the other;*

II. *If two sides and the included angle of one are equal respectively to two sides and the included angle of the other;*

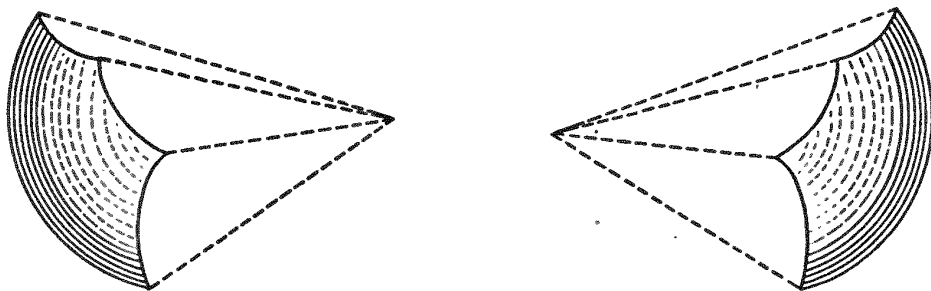
III. *If the three sides of one are equal respectively to the three sides of the other:
provided the equal parts are arranged in the same order.*

The proofs are left as exercises for the student.

HINT. In each of the above cases prove the corresponding trihedral \triangle equal (§§ 702, 704); and thus show that the spherical \triangle are equal.

955. Questions. Compare Prop. XIV, I and II, with § 702, I and II, and with §§ 105 and 107. Could the methods used there be employed in § 954? Is the method here suggested preferable? why?

956. Def. Two spherical polygons are symmetrical if the corresponding polyhedral angles are symmetrical.



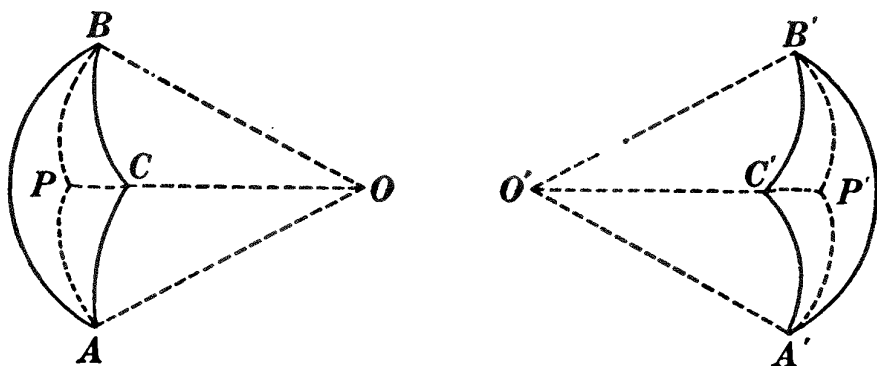
957. The following are some of the properties of symmetrical spherical triangles; the student should prove the correctness of each:

- (a) *Symmetrical spherical triangles have their parts respectively equal, but arranged in reverse order.*
- (b) *Two isosceles symmetrical spherical triangles are equal.*

HINT. Prove (b) by superposition or by showing that the corresponding trihedral \triangle are equal.

PROPOSITION XV. THEOREM

958. In equal spheres, or in the same sphere, two symmetrical spherical triangles are equivalent.



Given symmetrical spherical $\triangle ABC$ and $A'B'C'$ in equal spheres O and O' .

To prove spherical $\triangle ABC \cong$ spherical $\triangle A'B'C'$.

| ARGUMENT | REASONS |
|--|------------------------------|
| 1. Let P and P' be poles of small \odot through A, B, C , and A', B', C' , respectively. | 1. § 908, <i>h</i> . |
| 2. Arcs AB, BC, CA are equal, respectively, to arcs $A'B', B'C', C'A'$. | 2. § 957, <i>a</i> . |
| 3. \therefore chords AB, BC, CA , are equal, respectively, to chords $A'B', B'C', C'A'$. | 3. § 298, II. |
| 4. \therefore plane $\triangle ABC =$ plane $\triangle A'B'C'$. | 4. § 116. |
| 5. $\therefore \odot ABC = \odot A'B'C'$. | 5. § 324. |
| 6. Draw arcs of great \odot $PA, PB, PC, P'A', P'B'$, and $P'C'$. | 6. § 908, <i>g</i> . |
| 7. Then | 7. § 913. |
| $\widehat{PA} = \widehat{PB} = \widehat{PC} = \widehat{P'A'} = \widehat{P'B'} = \widehat{P'C'}$. | |
| 8. \therefore isosceles spherical $\triangle APB$ and $A'P'B'$ are symmetrical. | 8. § 956. |
| 9. $\therefore \triangle APB = \triangle A'P'B'$. | 9. § 957, <i>b</i> . |
| 10. Likewise $\triangle BPC = \triangle B'P'C'$ and $\triangle CPA = \triangle C'P'A'$. | 10. By steps similar to 8–9. |
| 11. \therefore spherical $\triangle ABC \cong$ spherical $\triangle A'B'C'$. | 11. § 54, 2. |

Q.E.D.

PROPOSITION XVI. THEOREM

959. *In equal spheres, or in the same sphere, two spherical triangles are symmetrical, and therefore equivalent:*

I. *If a side and the two adjacent angles of one are equal respectively to a side and the two adjacent angles of the other;*

II. *If two sides and the included angle of one are equal respectively to two sides and the included angle of the other;*

III. *If the three sides of one are equal respectively to the three sides of the other:*

provided the equal parts are arranged in reverse order.

The proofs are left as exercises for the student.

HINT. In each of the above cases prove the corresponding trihedral \triangle symmetrical (§ 709); and thus show that the spherical \triangle are symmetrical.

Ex. 1526. The bisector of the angle at the vertex of an isosceles spherical triangle is perpendicular to the base and bisects it.

Ex. 1527. The arc drawn from the vertex of an isosceles spherical triangle to the mid-point of the base bisects the vertex angle and is perpendicular to the base.

Ex. 1528. State and prove the theorems on the sphere corresponding to the following theorems on the plane:

(1) Every point in the perpendicular bisector of a line is equidistant from the ends of that line (§ 134).

(2) Every point equidistant from the ends of a line lies in the perpendicular bisector of that line (§ 139).

(3) Every point in the bisector of an angle is equidistant from the sides of the angle (§ 253).

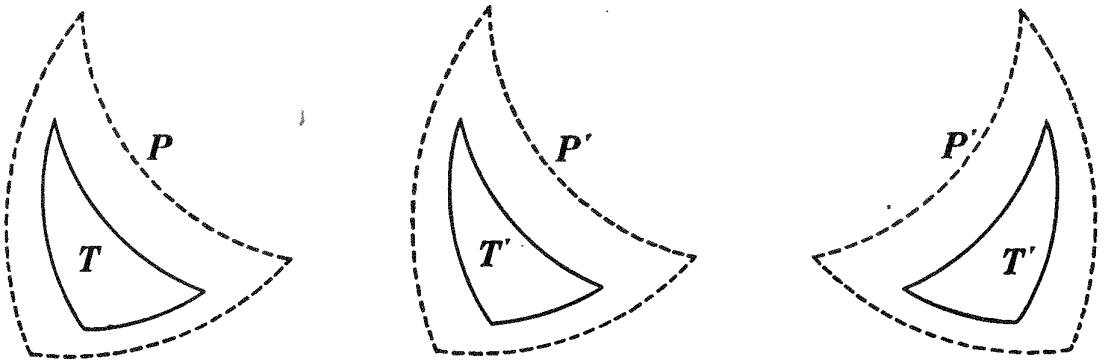
HINT. In the figure for (3), corresponding to the figure of § 252, draw $\widehat{PD} \perp \widehat{AB}$ and lay off $\widehat{BE} = \widehat{BD}$.

Ex. 1529. The diagonals of an equilateral spherical quadrilateral are perpendicular to each other. Prove. State the theorem in plane geometry that corresponds to this exercise.

Ex. 1530. In equal spheres, or in the same sphere, if two spherical triangles are mutually equilateral, their polar triangles are mutually equilateral; and conversely.

PROPOSITION XVII. THEOREM

960. *In equal spheres, or in the same sphere, if two spherical triangles are mutually equiangular, they are mutually equilateral, and are either equal or symmetrical.*



Given spherical $\triangle T$ and T' in equal spheres, or in the same sphere, and mutually equiangular.

To prove T and T' mutually equilateral and either equal or symmetrical.

| ARGUMENT | REASONS |
|---|-------------------------------|
| 1. Let $\triangle P$ and P' be the polars of $\triangle T$ and T' , respectively. | 1. § 943. |
| 2. T and T' are mutually equiangular. | 2. By hyp. |
| 3. Then P and P' are mutually equilateral. | 3. § 947. |
| 4. $\therefore P$ and P' are either equal or symmetrical, and hence are mutually equiangular. | 4. §§ 954, III, and 959, III. |
| 5. $\therefore T$ and T' are mutually equilateral. | 5. § 947. |
| 6. $\therefore T$ and T' are either equal or symmetrical. Q.E.D. | 6. Same reason as 4. |

Ex. 1531. In plane geometry, if two triangles are mutually equiangular, what can be said of them? Are they equal? equivalent?

Ex. 1532. Find the locus of all points of a sphere that are equidistant from two given points on the surface of the sphere; from two given points in space, not on the surface of the sphere.

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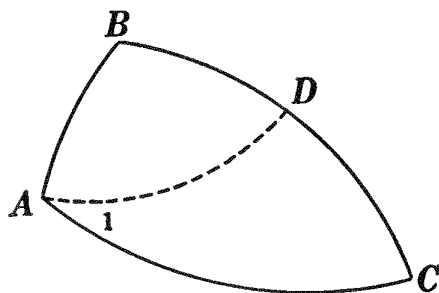
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PROPOSITION XX. THEOREM

963. *If two angles of a spherical triangle are unequal, the side opposite the greater angle is greater than the side opposite the less angle.*



Given spherical $\triangle ABC$ with $\angle A > \angle C$.

To prove $\widehat{BC} > \widehat{AB}$.

| ARGUMENT | REASONS |
|--|----------------------|
| 1. Draw an arc of a great $\odot AD$ making $\angle 1 = \angle C$. | 1. § 908, <i>g</i> . |
| 2. Then $\widehat{AD} = \widehat{DC}$. | 2. § 962. |
| 3. But $\widehat{BD} + \widehat{AD} > \widehat{AB}$. | 3. § 941. |
| 4. $\therefore \widehat{BD} + \widehat{DC} > \widehat{AB}$; i.e. $\widehat{BC} > \widehat{AB}$. Q.E.D. | 4. § 309. |

Ex. 1533. In a birectangular spherical triangle the side included by the two right angles is less than, equal to, or greater than, either of the other two sides, according as the angle opposite is less than, equal to, or greater than 90° .

Ex. 1534. An equilateral spherical triangle is also equiangular.

Ex. 1535. If two face angles of a trihedral angle are equal, the dihedral angles opposite are equal.

Ex. 1536. State and prove the converse of Ex. 1534.

Ex. 1537. State and prove the converse of Ex. 1535.

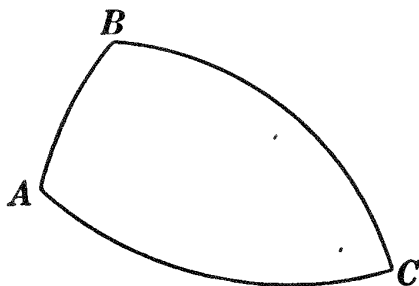
Ex. 1538. The arcs bisecting the base angles of an isosceles spherical triangle form an isosceles spherical triangle.

Ex. 1539. The bases of an isosceles trapezoid are 14 inches and 6 inches and the altitude 3 inches; find the total area and volume of the solid generated by revolving the trapezoid about its longer base as an axis.

Ex. 1540. Find the total area and volume of the solid generated by revolving the trapezoid of Ex. 1539 about its shorter base as an axis.

PROPOSITION XXI. THEOREM

964. *If two sides of a spherical triangle are unequal, the angle opposite the greater side is greater than the angle opposite the less side.*



Given spherical $\triangle ABC$ with $\widehat{BC} > \widehat{AB}$.

To prove $\angle A > \angle C$.

The proof is left as an exercise for the student.

HINT. Prove by the indirect method.

965. **Questions.** Could Prop. XXI have been proved by the method used in § 156? Does reason 4 of that proof hold in spherical \triangle ? See Ex. 1525.

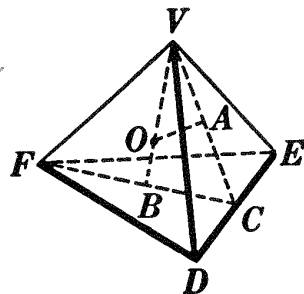
Ex. 1541. If two adjacent sides of a spherical quadrilateral are greater, respectively, than the other two sides, the spherical angle included between the two shorter sides is greater than the spherical angle between the two greater sides.

HINT. Compare with Ex. 153.

Ex. 1542. Find the total area and volume of the solid generated by revolving the trapezoid of Ex. 1539 about the perpendicular bisector of its bases as an axis.

Ex. 1543. Find the radius of the sphere inscribed in a regular tetrahedron whose edge is a .

HINT. Let O be the center of the sphere, A the center of face VED , and B the center of face EDF . Then $OA =$ radius of inscribed sphere. Show that rt. $\triangle VAO$ and VBC are similar. Then $VO : VC = VA : VB$. VC , VA , and VB can be found (Ex. 1328). Find VO , then OA .



Ex. 1544. Find the radius of the sphere circumscribed about a regular tetrahedron whose edge is a .

HINT. In the figure of Ex. 1543, draw AD and OD .

MENSURATION OF THE SPHERE

AREAS

PROPOSITION XXII. THEOREM

966. *If an isosceles triangle is revolved about a straight line lying in its plane and passing through its vertex but not intersecting its surface, the area of the surface generated by the base of the triangle is equal to the product of its projection on the axis and the circumference of a circle whose radius is the altitude of the triangle.*

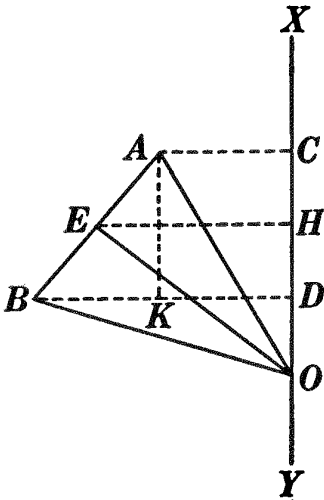


FIG. 1.

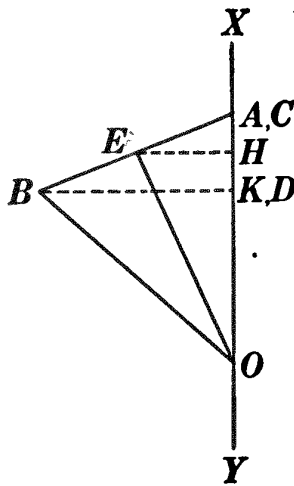


FIG. 2.

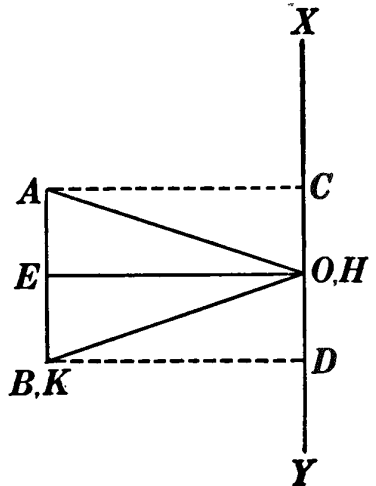


FIG. 3.

Given isosceles $\triangle AOB$ with base AB and altitude OE , a str. line XY lying in the plane of $\triangle AOB$ passing through O and not intersecting the surface of $\triangle AOB$, and CD the projection of AB on XY ; let the area of the surface generated by AB be denoted by area AB .

To prove $\text{area } AB = CD \cdot 2\pi OE$.

I. If AB is not $\parallel XY$ and does not meet XY (Fig. 1).

ARGUMENT ONLY

1. From E draw $EH \perp XY$.
2. Since the surface generated by AB is the surface of a frustum of a rt. circular cone, $\text{area } AB = AB \cdot 2\pi EH$.
3. From A draw $AK \perp BD$.
4. Then in rt. $\triangle BAK$ and OEH , $\angle BAK = \angle OEH$.

5. $\therefore \triangle BAK \sim \triangle OEH$.

6. $\therefore AB : AK = OE : EH$; i.e. $AB \cdot EH = AK \cdot OE$.

7. But $AK = CD$; $\therefore AB \cdot EH = CD \cdot OE$.

8. $\therefore \text{area } AB = CD \cdot 2\pi OE$.

Q.E.D.

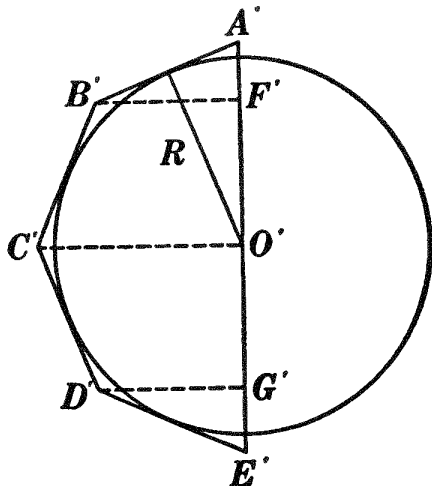
II. If AB is not $\parallel XY$ and point A lies in XY (Fig. 2).

III. If $AB \parallel XY$ (Fig. 3).

The proofs of II and III are left as exercises for the student.

HINT. See if the proof given for I will apply to Figs. 2 and 3.

967. Cor. I. *If half of a regular polygon with an even number of sides is circumscribed about a semicircle, the area of the surface generated by its semiperimeter as it revolves about the diameter of the semicircle as an axis, is equal to the product of the diameter of the regular polygon and the circumference of a circle whose radius is R , the radius of the given semicircle.*



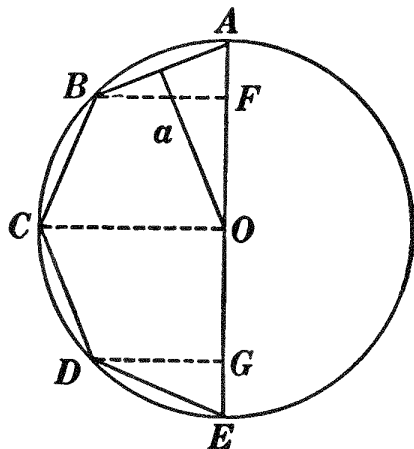
OUTLINE OF PROOF

1. Area $A'B' = A'F' \cdot 2\pi R$;

area $B'C' = F'O' \cdot 2\pi R$; etc.

2. $\therefore \text{area } A'B'C' \dots = (A'F' + F'O' + \dots) 2\pi R = A'E' \cdot 2\pi R$.

968. Cor. II. *If half of a regular polygon with an even number of sides is inscribed in a semicircle, the area of the surface generated by its semiperimeter as it revolves about the diameter of the semicircle as an axis, is equal to the product of the diameter of the semicircle and the circumference of a circle whose radius is the apothem of the regular polygon.*

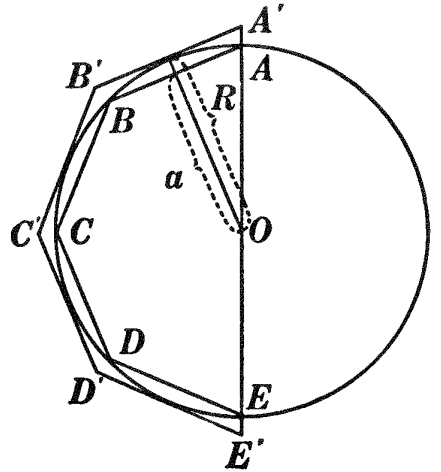


HINT. Prove area $ABC \dots = AE \cdot 2\pi a$.

969. Cor. III. *If halves of regular polygons with the same even number of sides are circumscribed about, and inscribed in, a semicircle, then by repeatedly doubling the number of sides of these polygons, and making the polygons always regular, the surfaces generated by the semiperimeters of the polygons as they revolve about the diameter of the semicircle as an axis approach a common limit.*

OUTLINE OF PROOF

1. If S and s denote the areas of the surfaces generated by the semiperimeters $A'B'C'\dots$ and $ABC\dots$ as they revolve about $A'E'$ as an axis, then $S = A'E' \cdot 2\pi R$ (§ 967); and $s = AE \cdot 2\pi a$ (§ 968).



$$2. \therefore \frac{S}{s} = \frac{A'E' \cdot 2\pi R}{AE \cdot 2\pi a} = \frac{A'E'}{AE} \cdot \frac{R}{a}$$

3. But polygon $A'B'C'\dots \sim$ polygon $ABC\dots$ (§ 438).

$$4. \therefore \frac{A'E'}{AE} = \frac{A'B'}{AB} = \frac{R}{a} \quad (\S\S 419, 435).$$

$$5. \therefore \frac{S}{s} = \frac{R}{a} \cdot \frac{R}{a} = \frac{R^2}{a^2}$$

$$6. \therefore \frac{S - s}{S} = \frac{R^2 - a^2}{R^2}$$

7. \therefore by steps similar to Args. 6–11 (§ 855), S and s approach a common limit. Q.E.D.

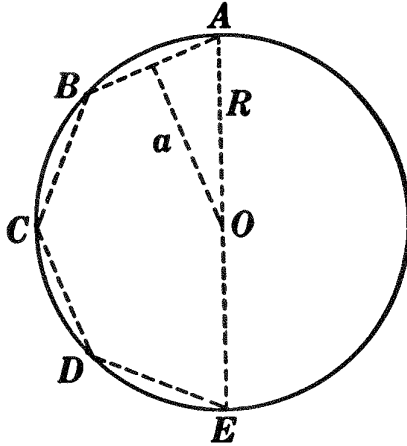
970. Def. The surface of a sphere is the common limit which the successive surfaces generated by halves of regular polygons with the same even number of sides approach, if these semipolygons fulfill the following conditions:

(1) They must be circumscribed about, and inscribed in, a great semicircle of the sphere;

(2) The number of sides must be successively increased, each side approaching zero as a limit.

PROPOSITION XXIII. THEOREM

971. *The area of the surface of a sphere is equal to four times the area of a great circle of the sphere.*



Given sphere O with its radius denoted by R , and the area of its surface denoted by S .

To prove $S = 4 \pi R^2$.

| ARGUMENT | REASONS |
|---|-----------------|
| 1. In the semicircle ACE inscribe $ABCDE$, half of a regular polygon with an even number of sides. Denote its apothem by a , and the area of the surface generated by the semiperimeter as it revolves about AE as an axis by S' . | 1. § 517, a . |
| 2. Then $S' = AE \cdot 2 \pi a$; <i>i.e.</i> $S' = 2 R \cdot 2 \pi a = 4 \pi Ra$. | 2. § 968. |
| 3. As the number of sides of the regular polygon, of which $ABCDE$ is half, is repeatedly doubled, S' approaches S as a limit. | 3. § 970. |
| 4. Also a approaches R as a limit. | 4. § 543, I. |
| 5. $\therefore 4 \pi R \cdot a$ approaches $4 \pi R \cdot R$, <i>i.e.</i> $4 \pi R^2$, as a limit. | 5. § 590. |
| 6. But S' is always equal to $4 \pi R \cdot a$. | 6. Arg. 2. |
| 7. $\therefore S = 4 \pi R^2$. Q.E.D. | 7. § 355. |

972. Cor. I. *The areas of the surfaces of two spheres are to each other as the squares of their radii and as the squares of their diameters.*

OUTLINE OF PROOF

$$1. \quad S = 4 \pi R^2 \text{ and } S' = 4 \pi R'^2; \therefore \frac{S}{S'} = \frac{4 \pi R^2}{4 \pi R'^2} = \frac{R^2}{R'^2}.$$

$$2. \text{ But } \frac{R^2}{R'^2} = \frac{4 R^2}{4 R'^2} = \frac{(2 R)^2}{(2 R')^2} = \frac{D^2}{D'^2}; \therefore \frac{S}{S'} = \frac{D^2}{D'^2}.$$

973. Historical Note. Prop. XXIII is given as Prop. XXXV in the treatise entitled *Sphere and Cylinder* by Archimedes, already spoken of in § 809.

Ex. 1545. Find the surface of a sphere whose diameter is 16 inches.

Ex. 1546. What will it cost to gild the surface of a globe whose radius is $1\frac{1}{2}$ decimeters, at an average cost of $\frac{2}{3}$ of a cent per square centimeter?

Ex. 1547. The area of a section of a sphere made by a plane 11 inches from the center is 3600π square inches. Find the surface of the sphere.

Ex. 1548. Find the surface of a sphere circumscribed about a cube whose edge is 12 inches.

Ex. 1549. The radius of a sphere is R . Find the radius of a sphere whose surface is twice the surface of the given sphere; one half; one n th.

Ex. 1550. Find the surface of a sphere whose diameter is $2 R$, and the total surface of a right circular cylinder whose altitude and diameter are each equal to $2 R$.

Ex. 1551. From the results of Ex. 1550 state, in the form of a theorem, the relation of the surface of a sphere to the total surface of the circumscribed cylinder.

Ex. 1552. Show that, in Ex. 1550, the surface of the sphere is exactly equal to the lateral surface of the cylinder.

974. Historical Note. The discovery of the remarkable property that the surface of a sphere is two thirds of the surface of the circumscribed cylinder (Exs. 1550 and 1551) is due again to Archimedes. The discovery of this proposition, and the discovery of the corresponding proposition for volumes (§ 1001), were the philosopher's chief pride, and he therefore asked that a figure of this proposition be inscribed on his tomb. His wishes were carried out by his friend Marcellus. (For a further account of Archimedes, read also § 542.)

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980. Cor. III. *In equal spheres, or in the same sphere, the areas of two zones are to each other as their altitudes.*

981. Question. In general, surfaces are to each other as the products of two lines. Is § 980 an exception to this rule? Explain.

Ex. 1553. The area of a zone of one base is equal to the area of a circle whose radius is the chord of the arc generating the zone.

HINT. Use §§ 979 and 444, II.

Ex. 1554. Show that the formula of § 971 is a special case of § 979.

Ex. 1555. Find the area of the surface of a zone if the distance between its bases is 8 inches and the radius of the sphere is 6 inches.

Ex. 1556. The diameter of a sphere is 16 inches. Three parallel planes divide this diameter into four equal parts. Find the area of each of the four zones thus formed.

Ex. 1557. Prove that one half of the earth's surface lies within 30° of the equator.

Ex. 1558. Considering the earth as a sphere with radius R , find the area of the zone adjoining the north pole, whose altitude is $\frac{R}{3}$; $\frac{2R}{3}$. Is the one area twice the other?

Ex. 1559. Considering the earth as a sphere with radius R , find the area of the zone extending 30° from the north pole; 60° from the north pole. Is the one area twice the other?

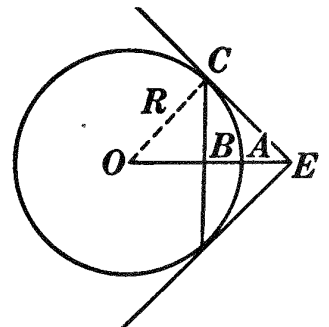
Ex. 1560. Considering the earth as a sphere with radius R , find the area of the zone whose bases are parallels of latitude: (a) 30° and 45° from the north pole; (b) 30° and 45° from the equator. Are the two areas equal? Explain your answer.

Ex. 1561. How far from the center of a sphere whose radius is R must the eye of an observer be so that one sixth of the surface of the sphere is visible?

HINT. Let E be the eye of the observer.

Then AB must be $\frac{R}{3}$. Find OB , then use § 443, II.

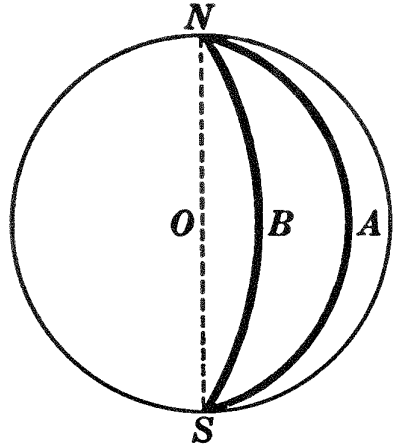
Ex. 1562. What portion of the surface of a sphere can be seen if the distance of the eye of the observer from the center of the sphere is $2R$? $3R$? nR ?



Ex. 1563. The radii of two concentric spheres are 6 inches and 10 inches. A plane is passed tangent to the inner sphere. Find: (a) the area of the section of the outer sphere made by the plane; (b) the area of the surface cut off of the outer sphere by the plane.

982. Def. A lune is a closed figure on the surface of a sphere whose boundary is composed of two semicircumferences of great circles, as $NASB$.

983. Defs. The two semicircumferences are called the **sides** of the lune, as NAS and NBS ; the points of intersection of the sides are called the **vertices** of the lune, as N and S ; the spherical angles formed at the vertices by the sides of the lune are called the **angles of the lune**, as $\sphericalangle ANB$ and BSA .



984. Prove, by superposition, the following property of lunes:
In equal spheres, or in the same sphere, two lunes are equal if their angles are equal.

985. So far, the surfaces considered in connection with the sphere have been measured in terms of square units, *i.e.* square inches, square feet, etc. For example, if the radius of a sphere is 6 inches, the surface of the sphere is $4\pi 6^2$, *i.e.* 144π square inches. But, as the sides and angles of a lune and a spherical polygon are given in degrees and not in linear units, it will be necessary to introduce some new unit for determining the areas of these figures. For this purpose the entire surface of a sphere is thought of as being divided into 720 equal parts, and each one of these parts is called a spherical degree. Hence:

986. Def. A **spherical degree** is $\frac{1}{720}$ of the surface of a sphere.
 Now if the area of a lune or of a spherical triangle can be obtained in spherical degrees, the area can easily be changed to square units. For example, if it is found that the area of a spherical triangle is 80 spherical degrees, its area is $\frac{80}{720}$, *i.e.* $\frac{1}{9}$ of the entire surface of the sphere. On the sphere whose radius is 6 inches, the area of the given triangle will be $\frac{1}{9}$ of 144π square inches, *i.e.* 16π square inches. The following theorems are for the purpose of determining the areas of figures on the surface of a sphere in terms of spherical degrees.

PROPOSITION XXIV. THEOREM

987. *The area of a lune is to the area of the surface of the sphere as the number of degrees in the angle of the lune is to 360.*

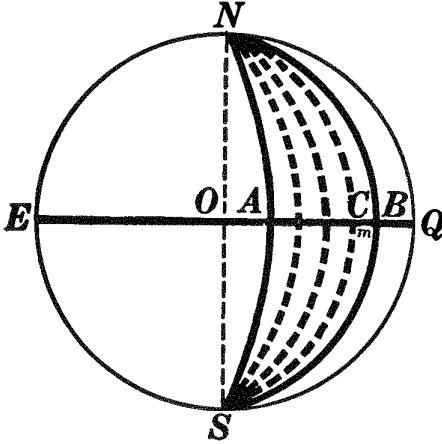


FIG. 1.

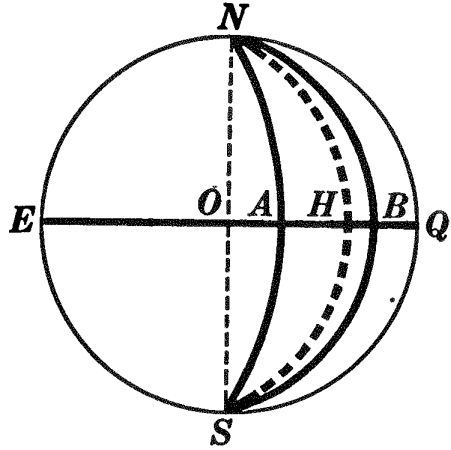


FIG. 2.

Given lune $NASB$ with the number of degrees in its \angle denoted by N , its area denoted by L , and the area of the surface of the sphere denoted by S ; let $\odot EQ$ be the great \odot whose pole is N .

To prove $\frac{L}{S} = \frac{N}{360}$

I. If arc AB and circumference EQ are commensurable (Fig. 1).

ARGUMENT

REASONS

1. Let m be a common measure of arc AB and circumference EQ , and suppose that m is contained in arc AB r times and in circumference EQ t times.
2. Then $\frac{\text{arc } AB}{\text{circumference } EQ} = \frac{r}{t}$.
3. Through the several points of division on circumference EQ pass semicircumferences of great circles from N to S .
4. Then lune $NASB$ is divided into r lunes and the surface of the sphere into t lunes, each equal to lune $NCSB$.

1. § 335.
2. § 341.
3. § 908, *h*.
4. § 984.

| ARGUMENT | REASONS |
|---|-------------|
| 5. $\therefore \frac{L}{S} = \frac{r}{t}$ | 5. § 341. |
| 6. $\therefore \frac{L}{S} = \frac{\text{arc } AB}{\text{circumference } EQ}$ | 6. § 54, 1. |
| 7. But arc AB is the measure of $\angle N$; <i>i.e.</i> it contains N degrees. | 7. § 918. |
| 8. And circumference EQ contains 360° . | 8. § 297. |
| 9. $\therefore \frac{L}{S} = \frac{N}{360}$ Q.E.D. | 9. § 309. |

II. If arc AB and circumference EQ are incommensurable (Fig. 2).

The proof is left as an exercise for the student.

HINT. The proof is similar to that of § 409, II.

988. Cor. I. *The area of a lune, expressed in spherical degrees, is equal to twice the number of degrees in its angle.*

OUTLINE OF PROOF

$$\frac{L}{S} = \frac{N}{360} \text{ (§ 987).} \quad \therefore \frac{L}{720} = \frac{N}{360} \quad \therefore L = 2N.$$

Ex. 1564. Find the area of a lune in spherical degrees if its angle is 35° . What part is the lune of the entire surface of the sphere?

Ex. 1565. Find the area of a lune in square inches if its angle is 42° and the radius of the sphere is 8 inches. (Use $\pi = \frac{22}{7}$.)

Ex. 1566. In equal spheres, or in the same sphere, two lunes are to each other as their angles.

Ex. 1567. Two lunes in unequal spheres, but with equal angles, are to each other as the squares of the radii of their spheres.

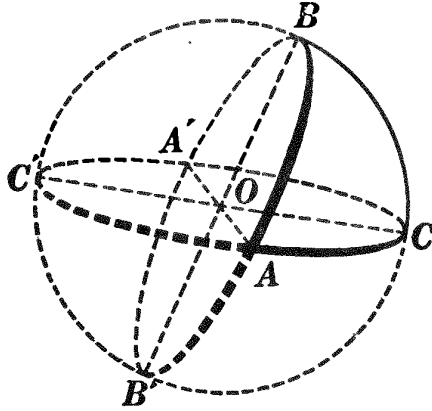
Ex. 1568. In a sphere whose radius is R , find the altitude of a zone equivalent to a lune whose angle is 45° .

Ex. 1569. Considering the earth as a sphere with radius R , find the area of the zone visible from a point at a height h above the surface of the earth.

989. Def. The **spherical excess** of a spherical triangle is the excess of the sum of its angles over 180° .

PROPOSITION XXV. THEOREM

990. *The area of a spherical triangle, expressed in spherical degrees, is equal to its spherical excess.*



Given spherical $\triangle ABC$ with its spherical excess denoted by E .

To prove area of $\triangle ABC = E$ spherical degrees.

| ARGUMENT | REASONS |
|--|-----------------------|
| 1. Complete the circumferences of which AB , BC , and CA are arcs. | 1. § 908, <i>g</i> . |
| 2. $\triangle AB'C'$ and $A'BC$ are symmetrical. | 2. § 956. |
| 3. $\therefore \triangle AB'C' \cong \triangle A'BC$. | 3. § 958. |
| 4. $\therefore \triangle ABC + \triangle AB'C' \cong \triangle ABC + \triangle A'BC$. | 4. § 54, 2. |
| 5. \therefore , expressed in spherical degrees, $\triangle ABC + \triangle AB'C' \cong$ lune $A = 2A$; $\triangle ABC + \triangle AB'C =$ lune $B = 2B$; $\triangle ABC + \triangle ABC' =$ lune $C = 2C$. | 5. § 988. |
| 6. $\therefore 2\triangle ABC + (\triangle ABC + \triangle AB'C' + \triangle AB'C + \triangle ABC') = 2(A + B + C)$. | 6. § 54, 2. |
| 7. But $\triangle ABC + \triangle AB'C' + \triangle AB'C + \triangle ABC' =$ surface of a hemisphere $= 360$. | 7. § 985. |
| 8. $\therefore 2\triangle ABC + 360 = 2(A + B + C)$. | 8. § 309. |
| 9. $\therefore \triangle ABC + 180 = A + B + C$. | 9. § 54, 8 <i>a</i> . |
| 10. $\therefore \triangle ABC = (A + B + C) - 180$, <i>i.e.</i> E spherical degrees. | 10. § 54, 3. |

Q.E.D.

991. In § 949 it was proved that the sum of the angles of a spherical triangle is greater than 180° and less than 540° . Hence the spherical excess of a spherical triangle may vary from 0° to 360° , from which it follows (§ 990) that the area of a spherical triangle may vary from $\frac{0}{720}$ to $\frac{360}{720}$ of the entire surface; *i.e.* the area of a spherical triangle may vary from nothing to $\frac{1}{2}$ the surface of the sphere. Thus in a spherical triangle whose angles are 70° , 80° , and 100° , respectively, the spherical excess is $(70^\circ + 80^\circ + 100^\circ) - 180^\circ = 70^\circ$; *i.e.* the area of the given triangle is $\frac{70}{720}$ of the surface of the sphere.

992. Historical Note. Menelaus of Alexandria (*circ.* 98 A.D.) wrote a treatise in which he describes the properties of spherical triangles, although there is no attempt at their solution. The expression for the area of a spherical triangle, as stated in § 990, was first given about 1626 A.D. by Girard. (See also § 946.) This theorem was also discovered independently by Cavalieri, a prominent Italian mathematician.

Ex. 1570. If three great circles are drawn, each perpendicular to the other two, into how many trirectangular spherical triangles is the surface divided? Then what is the area of a trirectangular spherical triangle in spherical degrees? Test your answer by applying Prop. XXV.

Ex. 1571. Find the area in spherical degrees of a birectangular spherical triangle one of whose angles is 70° ; of an equilateral spherical triangle one of whose angles is 80° . What part of the surface of the sphere is each triangle?

Ex. 1572. The angles of a spherical triangle in a sphere whose surface has an area of 216 square feet are 95° , 105° , and 130° . Find the number of square feet in the area of the triangle.

Ex. 1573. In a sphere whose diameter is 16 inches, find the area of a triangle whose angles are 70° , 86° , and 120° .

Ex. 1574. The angles of a spherical triangle are 60° , 120° , and 160° , and its area is $100\frac{4}{7}$ square inches. Find the radius of the sphere. (Use $\pi = \frac{22}{7}$.)

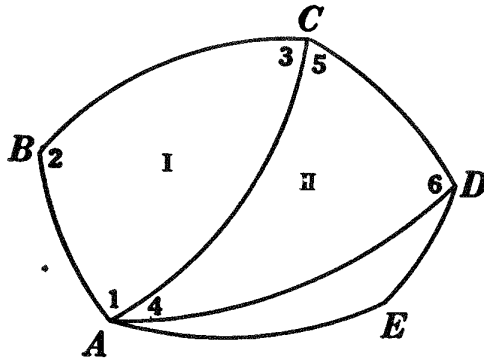
Ex. 1575. The area of a spherical triangle is 90 spherical degrees, and the angles are in the ratio of 2, 3, and 5. Find the angles.

Ex. 1576. Find the angle (1) of an equilateral spherical triangle, (2) of a lune, each equivalent to one third the surface of a sphere.

Ex. 1577. Find the angle of a lune equivalent to an equilateral spherical triangle one of whose angles is 84° .

PROPOSITION XXVI. THEOREM

993. *The area of a spherical polygon, expressed in spherical degrees, is equal to the sum of its angles diminished by 180° taken as many times less two as the polygon has sides.*



Given spherical polygon $ABCD \dots$ with n sides; denote the sum of its angles by T .

To prove area of polygon $ABCD \dots$, expressed in spherical degrees, $= T - (n - 2)180$.

| ARGUMENT | REASONS |
|--|-------------|
| 1. From any vertex such as A , draw all possible diagonals of the polygon, forming $n - 2$ spherical Δ , I, II, etc. | 1. § 937. |
| 2. Then, expressed in spherical degrees, $\Delta I = (\angle 1 + \angle 2 + \angle 3) - 180$; $\Delta II = (\angle 4 + \angle 5 + \angle 6) - 180$; etc. | 2. § 990. |
| 3. $\therefore \Delta I + \Delta II + \dots = T - (n - 2)180$. | 3. § 54, 2. |
| 4. \therefore area of polygon $ABCD \dots$ $= T - (n - 2)180$. | 4. § 309. |

Q.E.D.

Ex. 1578. Prove Prop. XXVI by using a figure similar to that used in § 216.

Ex. 1579. Find the area of a spherical polygon whose angles are 80° , 92° , 120° , and 140° , in a sphere whose radius is 8 inches.

Ex. 1580. Find the angle of an equilateral spherical triangle equivalent to a spherical pentagon whose angles are 90° , 100° , 110° , 130° , and 140° .

Ex. 1581. Find one angle of an equiangular spherical hexagon equivalent to six equilateral spherical triangles each with angles of 70° .

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PROPOSITION XXVII. THEOREM

995. *If an isosceles triangle is revolved about a straight line lying in its plane and passing through its vertex but not intersecting its surface, the volume of the solid generated is equal to the product of the surface generated by the base of the triangle and one third of its altitude.*

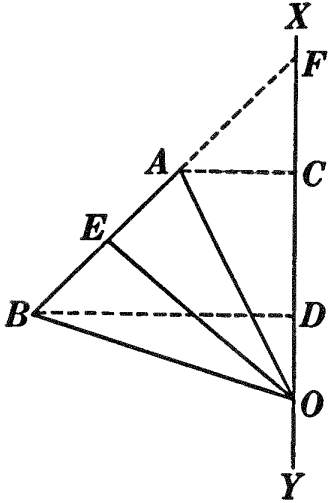


FIG. 1.

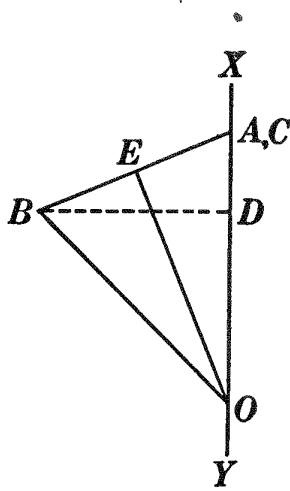


FIG. 2.

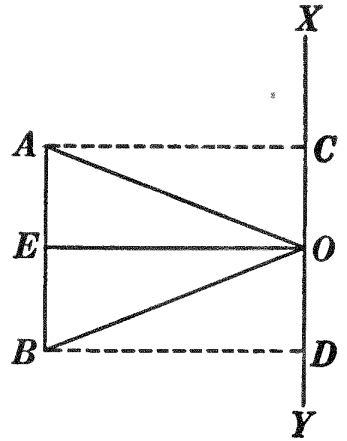


FIG. 3.

Given isosceles $\triangle AOB$ with altitude OE , and a str. line XY lying in the plane of $\triangle AOB$, passing through O and not intersecting the surface of $\triangle AOB$; let the volume of the solid generated by $\triangle AOB$ revolving about XY as an axis be denoted by volume AOB .

To prove $\text{volume } AOB = \text{area } AB \cdot \frac{1}{3} OE$.

I. If AB is not $\parallel XY$ and does not meet XY (Fig. 1).

ARGUMENT ONLY

1. Draw AC and $BD \perp XY$.
2. Prolong BA to meet XY at F .
3. Then $\text{volume } AOB = \text{volume } FOB - \text{volume } FOA$.
4. $\text{Volume } FOB = \text{volume } FDB + \text{volume } DOB$.
5. $\therefore \text{volume } FOB = \frac{1}{3} \pi \overline{BD}^2 \cdot FD + \frac{1}{3} \pi \overline{BD}^2 \cdot DO$
 $= \frac{1}{3} \pi \overline{BD}^2 (FD + DO) = \frac{1}{3} \pi \overline{BD} \cdot \overline{BD} \cdot FO$.
6. But $\overline{BD} \cdot FO = \text{twice area of } \triangle FOB = BF \cdot OE$.
7. $\therefore \text{volume } FOB = \frac{1}{3} \pi \overline{BD} \cdot BF \cdot OE = \pi \overline{BD} \cdot BF \cdot \frac{1}{3} OE$.
8. But $\pi \overline{BD} \cdot BF = \text{area } FB$.
9. $\therefore \text{volume } FOB = \text{area } FB \cdot \frac{1}{3} OE$.

10. Likewise volume $FOA = \text{area } FA \cdot \frac{1}{3} OE$.

$$\begin{aligned} 11. \therefore \text{volume } AOB &= \text{area } FB \cdot \frac{1}{3} OE - \text{area } FA \cdot \frac{1}{3} OE \\ &= (\text{area } FB - \text{area } FA) \frac{1}{3} OE \\ &= \text{area } AB \cdot \frac{1}{3} OE. \end{aligned}$$

Q.E.D.

II. If AB is not $\parallel XY$ and point A lies in XY (Fig. 2).

The proof is left as an exercise for the student.

HINT. See Arg. 9 or Arg. 10 of § 995, I.

III. If $AB \parallel XY$ (Fig. 3).

The proof is left as an exercise for the student.

HINT. Volume $AOB = \text{volume } ACDB - \text{twice volume } COA$.

996. The student may :

(a) State and prove the corollaries on the volume of a sphere corresponding to §§ 967 and 968.

(b) State and prove the theorem on the volume of a sphere corresponding to § 969.

OUTLINE OF PROOF

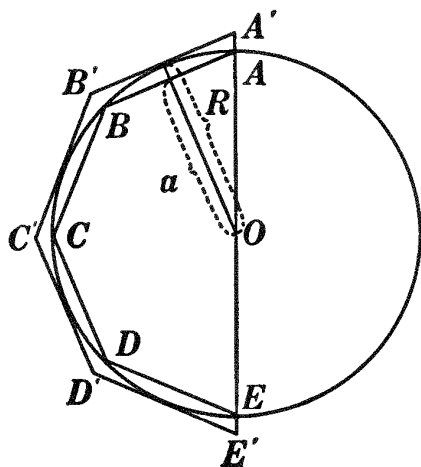
$$\begin{aligned} 1. \quad V &= (\text{area } A'B'C' \dots) \frac{1}{3} R \\ &= A'E' \cdot 2 \pi R \cdot \frac{1}{3} R \\ &= \frac{2}{3} \pi R^2 \cdot A'E' \\ &\quad (\S\S 996, a \text{ and } 967). \end{aligned}$$

$$\begin{aligned} 2. \quad v &= (\text{area } ABC \dots) \frac{1}{3} a \\ &= AE \cdot 2 \pi a \cdot \frac{1}{3} a \\ &= \frac{2}{3} \pi a^2 AE \\ &\quad (\S\S 996, a \text{ and } 968). \end{aligned}$$

$$3. \therefore \frac{V}{v} = \frac{\frac{2}{3} \pi R^2 \cdot A'E'}{\frac{2}{3} \pi a^2 \cdot AE} = \frac{R^2}{a^2} \cdot \frac{A'E'}{AE} = \frac{R^3}{a^3}.$$

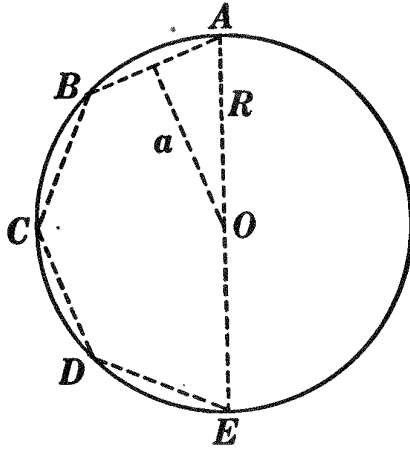
4. Proceed as in § 855, observing that since the limit of $a = R$ (§ 543, I), the limit of $a^3 = R^3$ (§ 593); *i.e.* $R^3 - a^3$ may be made less than any previously assigned value, however small.

(c) State, by aid of § 970, the definition of the volume of a



PROPOSITION XXVIII. THEOREM

997. *The volume of a sphere is equal to the product of the area of its surface and one third its radius.*



Given sphere O with its radius denoted by R , the area of its surface by S , and its volume by V .

To prove $V = S \cdot \frac{1}{3} R$.

ARGUMENT

1. In the semicircle ACE inscribe $ABCDE$, half of a regular polygon with an even number of sides. Denote its apothem by a , the area of the surface generated by the semiperimeter as it revolves about AE as an axis by S' , and the volume of the solid generated by semipolygon $ABCDE$ by V' .
2. Then $V' = S' \cdot \frac{1}{3} a$.
3. As the number of sides of the regular polygon, of which $ABCDE$ is half, is repeatedly doubled, V' approaches V as a limit.
4. Also S' approaches S as a limit.
5. And a approaches R as a limit.
6. $\therefore S' \cdot a$ approaches $S \cdot R$ as a limit.
7. $\therefore S' \cdot \frac{1}{3} a$ approaches $S \cdot \frac{1}{3} R$ as a limit.
8. But V' is always equal to $S' \cdot \frac{1}{3} a$.
9. $\therefore V = S \cdot \frac{1}{3} R$. Q.E.D.

REASONS

1. § 517, a .
2. § 996, a .
3. § 996, c .
4. § 970.
5. § 543, I.
6. § 592.
7. § 590.
8. Arg. 2.
9. § 355.

998. Cor. I. *If V denotes the volume, R the radius, and D the diameter of a sphere,*

$$V = \frac{4}{3} \pi R^3 = \frac{1}{6} \pi D^3.$$

999. Cor. II. *The volumes of two spheres are to each other as the cubes of their radii and as the cubes of their diameters.* (HINT. See § 972.)

1000. Historical Note. It is believed that the theorem of § 999 was proved as early as the middle of the fourth century B.C. by Eudoxus, a great Athenian mathematician already spoken of in §§ 809 and 896.

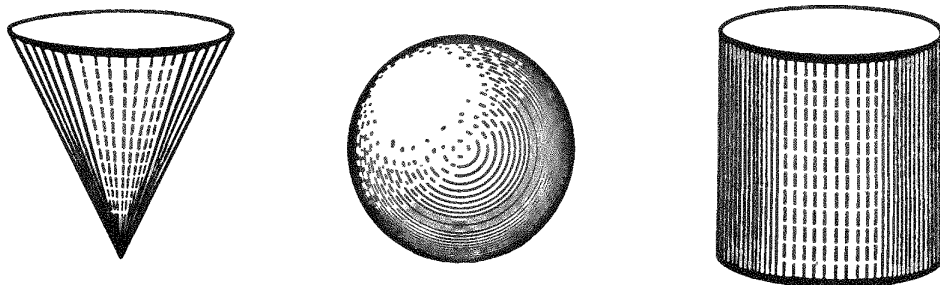
Ex. 1588. Find the volume of a sphere inscribed in a cube whose edge is 8 inches.

Ex. 1589. The volume of a sphere is $1774\frac{2}{3} \pi$ cubic centimeters. Find its surface.

Ex. 1590. Find the radius of a sphere equivalent to a cone with altitude a and radius of base b .

Ex. 1591. Find the radius of a sphere equivalent to a cylinder with the same dimensions as those of the cone in Ex. 1590.

Ex. 1592. The metal cone and cylinder in the figure have their altitude and diameter each equal to $2R$, the diameter of the sphere. Place



the sphere in the cylinder, then fill the cone with water and empty it into the cylinder. How nearly is the cylinder filled? Next fill the cone with water and empty it into the cylinder three times. Is the cylinder filled?

Ex. 1593. From the results of Ex. 1592 state, in the form of a theorem, the relation of the volume of a sphere: (a) to the volume of a circumscribed cylinder; (b) to the volume of the corresponding cone. Prove these statements.

1001. Historical Note. The problem "To find a sphere equivalent to a given cone or a given cylinder" (Exs. 1590 and 1591), as well as the properties that the volume of a sphere is two thirds of the volume of the circumscribed cylinder and twice the volume of the corresponding cone (Exs. 1592 and 1593), are due to Archimedes. The importance attached to this by the author himself is spoken of more fully in §§ 542 and 974.

Ex. 1594. A bowl whose inner surface is an exact hemisphere is made to hold $\frac{1}{2}$ gallon of water. Find the diameter of the bowl.

Ex. 1595. A sphere 12 inches in diameter weighs 93 pounds. Find the weight of a sphere of the same material 16 inches in diameter.

Ex. 1596. In a certain sphere the area of the surface and the volume have the same numerical value. Find the volume of the sphere.

Ex. 1597. Find the volume of a spherical shell 5 inches thick if the radius of its inner surface is 10 inches.

Ex. 1598. A pine sphere 24 inches in diameter weighs 175 pounds. Find the diameter of a sphere of the same material weighing 50 pounds.

Ex. 1599. The radius of a sphere is R . Find the radius of a sphere whose volume is one half the volume of the given sphere; twice the volume; n times the volume.

1002. Defs. A spherical sector is a solid closed figure generated by a sector of a circle revolving about a diameter of the circle as an axis.

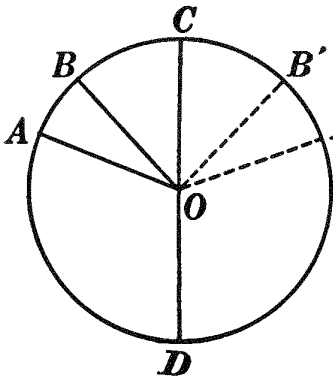


FIG. 1.

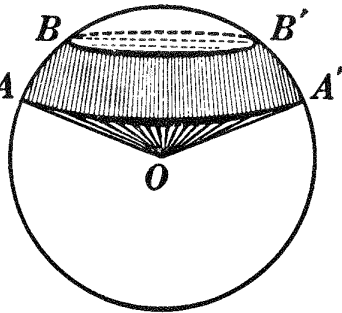


FIG. 2.

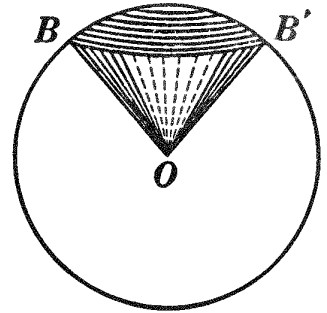


FIG. 3.

The zone generated by the arc of the circular sector is called the base of the spherical sector.

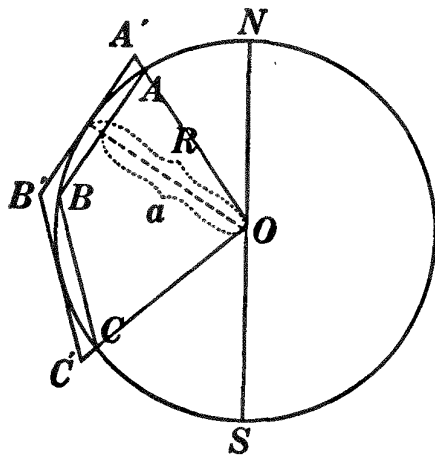
1003. Def. If one radius of the circular sector generating a spherical sector is a part of the axis, *i.e.* if the base of the spherical sector is a zone of one base, the spherical sector is sometimes called a spherical cone.

Thus if circular sector AOB (Fig. 1) revolves about diameter CD as an axis, arc AB will generate a zone which will be the base of the spherical sector generated by circular sector AOB (Fig. 2). If circular sector BOC revolves about diameter CD , the spherical sector generated, whose base is the zone generated by arc BC , will be a spherical cone (Fig. 3).

1004. Cor. III. *The volume of a spherical sector is equal to the product of its base and one third the radius of the sphere.*

OUTLINE OF PROOF

Let V denote the volume generated by polygon $OA'B'C'$, v the volume generated by polygon $OABC$, S the area of the surface generated by broken line $A'B'C'$, s the area of the surface generated by broken line ABC , and Z the base of the spherical sector generated by circular sector AOC .



Then $V = S \cdot \frac{1}{3} R$, and $v = s \cdot \frac{1}{3} a$.

$$\therefore \frac{V}{v} = \frac{S \cdot \frac{1}{3} R}{s \cdot \frac{1}{3} a} = \frac{S}{s} \cdot \frac{R}{a}$$

But $\frac{S}{s} = \frac{R^2}{a^2}$ (Args. 2-5, § 969).

$$\therefore \frac{V}{v} = \frac{R^2}{a^2} \cdot \frac{R}{a} = \frac{R^3}{a^3}$$

Then by steps similar to § 996, *b* and *c*, and § 997, the volume of the spherical sector generated by circular sector $AOC = Z \cdot \frac{1}{3} R$.

1005. Cor. IV. *If V denotes the volume of a spherical sector, Z the area of the zone forming its base, H the altitude of the zone, and R the radius of the sphere,*

$$V = Z \cdot \frac{1}{3} R \tag{§ 1004}$$

$$= (H \cdot 2 \pi R) \frac{1}{3} R \tag{§ 979}$$

$$= \frac{2}{3} \pi R^2 H.$$

Ex. 1600. Considering the earth as a sphere with radius R , find the volume of the spherical sector whose base is a zone adjoining the north pole and whose altitude is $\frac{R}{3}$; $\frac{2R}{3}$. Is the one volume twice the other?

Compare your results with those of Ex. 1558.

Ex. 1601. Considering the earth as a sphere with radius R , find the volume of the spherical sector whose base is a zone extending: (a) 30° from the north pole; (b) 60° from the north pole. Is the one volume twice the other? Compare your results with those of Ex. 1559.

Ex. 1602. Considering the earth as a sphere with radius R , find the volume of the spherical sector whose base is a zone lying between the parallels of latitude: (a) 30° and 45° from the north pole; (b) 30° and 45° from the equator. Are the two volumes equal? Compare your results with those of Ex. 1560.

Ex. 1603. Considering the earth as a sphere with radius R , find the area of the zone whose bases are the circumferences of small circles, one 30° north of the equator, the other 30° south of the equator. What part of the entire surface is this zone?

Ex. 1604. What part of the entire volume of the earth is that portion included between the planes of the bases of the zone in Ex. 1603?

HINT. This volume consists of two pyramids and a spherical sector.

Ex. 1605. A spherical shell 2 inches in thickness contains the same amount of material as a sphere whose radius is 6 inches. Find the radius of the outer surface of the shell.

Ex. 1606. A spherical shell 3 inches thick has an outer diameter of 16 inches. Find the volume of the shell.

Ex. 1607. Find the volume of a sphere circumscribed about a rectangular parallelepiped whose edges are 3, 4, and 12.

Ex. 1608. Find the volume of a sphere inscribed in a cube whose volume is 686 cubic centimeters.

Ex. 1609. The surface of a sphere and the surface of a cube are each equal to S . Find the ratio of their volumes. Which is the greater?

Ex. 1610. In a certain sphere the volume and the circumference of a great circle have the same numerical value. Find the surface and the volume of the sphere.

Ex. 1611. How many bullets $\frac{1}{4}$ of an inch in diameter can be made from a sphere of lead 10 inches in diameter? from a cube of lead whose edge is 10 inches?

1006. Defs. A **spherical wedge** is a solid closed figure whose bounding surface consists of a lune and the planes of the sides of the lune.

The lune is called the **base** of the spherical wedge, and the angle of the lune the **angle of the spherical wedge**.

1007. Prove, by superposition, the following property of wedges:

In equal spheres, or in the same sphere, two spherical wedges are equal if their angles are equal.

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1010. Defs. A **spherical pyramid** is a solid closed figure whose bounding surface consists of a spherical polygon and the planes of the sides of the spherical polygon. The spherical polygon is the **base**, and the center of the sphere the **vertex**, of the spherical pyramid.

1011. By comparison with § 957, *b* and § 958, prove the following property of spherical pyramids:

In equal spheres, or in the same sphere, two triangular spherical pyramids whose bases are symmetrical spherical triangles are equivalent.

1012. Cor. II. *The volume of a spherical triangular pyramid is equal to the product of its base and one third the radius of the sphere.*

OUTLINE OF PROOF

1. Pyramid $O-AB'C' \cong$ pyramid $O-A'BC$ (§ 1011).

2. \therefore pyramid $O-ABC +$ pyramid $O-AB'C' \cong$ wedge $A = 2A \cdot \frac{1}{3}R$ (§ 1009); pyramid $O-ABC +$ pyramid $O-AB'C =$ wedge $B = 2B \cdot \frac{1}{3}R$; pyramid $O-ABC +$ pyramid $O-ABC' =$ wedge $C = 2C \cdot \frac{1}{3}R$.

3. \therefore twice pyramid $O-ABC +$ hemisphere $= 2(A + B + C) \frac{1}{3}R$.

4. \therefore twice pyramid $O-ABC + 360 \cdot \frac{1}{3}R = 2(A + B + C) \frac{1}{3}R$.

5. \therefore pyramid $O-ABC = (A + B + C - 180) \frac{1}{3}R$

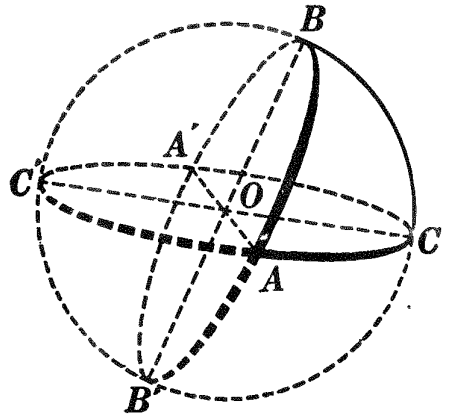
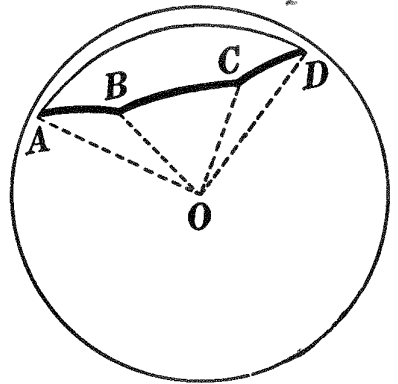
$$= \triangle ABC \cdot \frac{1}{3}R = K \cdot \frac{1}{3}R.$$

Q.E.D.

1013. Cor. III. *The volume of any spherical pyramid is equal to the product of its base and one third the radius of the sphere.* (HINT. Compare with § 805.)

Ex. 1613. Show that the formula of § 997 is a special case of §§ 1004, 1009 and 1013.

Ex. 1614. In a sphere whose radius is 12 inches, find the volume of a spherical pyramid whose base is a triangle with angles 70° , 80° , and 90° .



MISCELLANEOUS EXERCISES ON SOLID GEOMETRY

Ex. 1615. A spherical pyramid whose base is an equiangular pentagon is equivalent to a wedge whose angle is 30° . Find an angle of the base of the pyramid.

Ex. 1616. The volume of a spherical pyramid whose base is an equiangular spherical triangle with angles of 105° is 128π cubic inches. Find the radius of the sphere.

Ex. 1617. In a sphere whose radius is 10 inches, find the angle of a spherical wedge equivalent to a spherical sector whose base has an altitude of 12 inches.

Ex. 1618. Find the depth of a cubical tank that will hold 100 gallons of water.

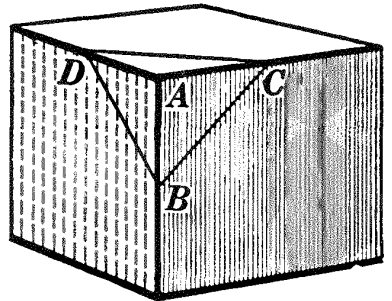
Ex. 1619. The altitude of a pyramid is H . At what distance from the vertex must a plane be passed parallel to the base so that the part cut off is one half of the whole pyramid? one third? one n th?

Ex. 1620. Allowing 550 pounds of copper to a cubic foot, find the weight of a copper wire $\frac{1}{8}$ of an inch in diameter and 2 miles long.

Ex. 1621. Disregarding quality, and considering oranges as spheres, *i.e.* as similar solids, determine which is the better bargain, oranges averaging $2\frac{3}{4}$ inches in diameter at 15 cents per dozen, or oranges averaging $3\frac{1}{2}$ inches in diameter at 30 cents per dozen.

Ex. 1622. In the figure, B , C , and D are the mid-points of the edges of the cube meeting at A . What part of the whole cube is the pyramid cut off by plane BCD ?

HINT. Consider ABC as the base and D as the vertex of the pyramid.



Ex. 1623. Is the result of Ex. 1622 the same if the figure is a rectangular parallelepiped? any parallelepiped?

Ex. 1624. It is proved in calculus that in order that a cylindrical tin can closed at the top and having a given capacity may require the smallest possible amount of tin for its construction, the diameter of the base must equal the height of the can. Find the dimensions of such a can holding 1 quart; 2 gallons.

Ex. 1625. A cylindrical tin can holding 2 gallons has its height equal to the diameter of its base. Another cylindrical tin can with the same capacity has its height equal to twice the diameter of its base. Find the ratio of the amount of tin required for making the two cans. Is your answer consistent with the fact contained in Ex. 1624?

Ex. 1626. A cannon ball 12 inches in diameter is melted, and the lead is cast in the form of a cube. Find the edge of the cube.

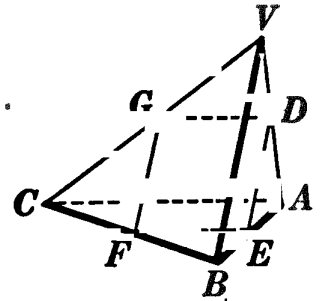
Ex. 1627. The cube of Ex. 1626 is melted, and the lead is cast in the form of a cone, the diameter of whose base is 12 inches. Find the altitude of the cone.

Ex. 1628. Find the weight of the cannon ball in Ex. 1626 if a cubic foot of iron weighs 450 pounds.

Ex. 1629. The planes determined by the diagonals of a cube divide the cube into six equal pyramids.

Ex. 1630. Let $D, E, F,$ and G be the mid-points of $VA, AB, BC,$ and $CV,$ respectively, of triangular pyramid $V-ABC$. Prove $DEFG$ a parallelogram.

Ex. 1631. In the figure, is plane $DEFG$ parallel to edge AC ? to edge VB ? Prove that any section of a triangular pyramid made by a plane parallel to two opposite edges is a parallelogram.



Ex. 1632. The three lines joining the mid-points of the opposite edges of a tetrahedron bisect each other and hence meet in a point.

HINT. Draw DF and EG . Are these two of the required lines?

Ex. 1633. In a White Mountain two-quart ice cream freezer, the can is $4\frac{5}{8}$ inches in diameter and $6\frac{1}{2}$ inches high; the tub is $6\frac{3}{4}$ inches in diameter at the bottom, 8 inches at the top, and $9\frac{3}{4}$ inches high, inside measurements. (a) Does the can actually hold 2 quarts? (b) How many cubic inches of ice can be packed about the can?

Ex. 1634. Find the total area of a regular tetrahedron whose altitude is a centimeters.

Ex. 1635. The lateral faces of a triangular pyramid are equilateral triangles, and the altitude of the pyramid is 6 inches. Find the total area.

Ex. 1636. In the foundation work of the Woolworth Building, a 55-story building on Broadway, New York City, it was necessary, in order to penetrate the sand and quicksand to bed rock, to sink the caissons that contain the huge shafts of concrete to a depth, in some instances, of 131 feet. If the largest circular caisson, 19 feet in diameter, is 130 feet deep and was filled with concrete to within 30 feet of the surface, how many loads of concrete were required, considering 1 cubic yard to a load?

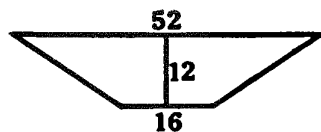
Ex. 1637. From A draw a line meeting line XY in B ; let C be the mid-point of AB . Find the locus of C as B moves in line XY .

Ex. 1638. In Ex. 1637, let XY be a plane. Find the locus of C as B moves arbitrarily in plane XY .

Ex. 1639. A granite shaft in the form of a frustum of a square pyramid contains $161\frac{3}{4}$ cubic feet of granite; the edges of the bases are 4 feet and $1\frac{1}{2}$ feet, respectively. Find the height of the shaft.

Ex. 1640. The volume of a regular square pyramid is $42\frac{2}{3}$ cubic feet; its altitude is twice one side of the base. (a) Find the total surface of the pyramid; (b) find the area of a section made by a plane parallel to the base and one foot from the base.

Ex. 1641. Allowing 1 cubic yard to a load, find the number of loads of earth in a railway cut $\frac{1}{2}$ mile in length, the average dimensions of a cross section being as represented in the figure, the numbers denoting feet. Give the name of the geometrical solid represented by the cut. Why is it not a frustum of a pyramid?

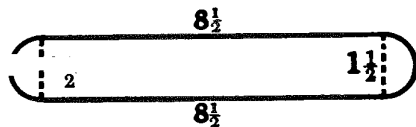


Ex. 1642. For protection against fire, a tank in the form of a frustum of a right circular cone was placed in the tower room of a certain public building. The tank is 16 feet in diameter at the bottom, 12 feet in diameter at the top, and 16 feet deep. If the water in the tank is never allowed to get less than 14 feet deep, how many cubic feet of water would be available in case of an emergency? how many barrels, counting $4\frac{1}{4}$ cubic feet to a barrel?

Ex. 1643. A sphere with radius R is inscribed in a cylinder, and the cylinder is inscribed in a cube. Find: (a) the ratio of the volume of the sphere to that of the cylinder; (b) the ratio of the cylinder to the cube; (c) the ratio of the sphere to the cube.

Ex. 1644. A cone has the same base and altitude as the cylinder in Ex. 1643. Find the ratio of the cone: (a) to the sphere; (b) to the cylinder; (c) to the cube.

Ex. 1645. In a steam-heated house the heat for a room was supplied by a series of 10 radiators each 3 feet high. The average cross section of a radiator is shown in the figure, the numbers denoting inches. It consists of a rectangle with a semicircle at each end. Find the total radiating surface in the room.



Ex. 1646. A coffee pot is 5 inches deep, $4\frac{1}{4}$ inches in diameter at the top, and $5\frac{1}{4}$ inches in diameter at the bottom. How many cups of coffee will it hold, allowing 6 cups to a quart? (Answer to nearest whole number.)

Ex. 1647. Any plane passing through the center of a parallelepiped divides it into two equivalent solids. Are these solids equal?

Ex. 1648. From two points, P and R , on the same side of plane AB , two lines are drawn to point O in plane AB , making equal angles with the plane. Find the locus of point O . (Hint. See Ex. 1237.)

Ex. 1649. A factory chimney is in the form of a frustum of a regular square pyramid. The chimney is 120 feet high, and the edges of its bases are 12 feet and 8 feet, respectively. The flue is 6 feet square throughout. How many cubic feet of material does the chimney contain?

Ex. 1650. Find the edge of the largest cube that can be cut from a regular square pyramid whose altitude is 10 inches and one side of whose base is 8 inches, if one face of the cube lies in the base of the pyramid.

Ex. 1651. Fig. 1 represents a granite monument, the numbers denoting inches. The main part of the stone is 5 feet high, the total height of the stone being 5 feet 6 inches. Fig. 2 represents a view of

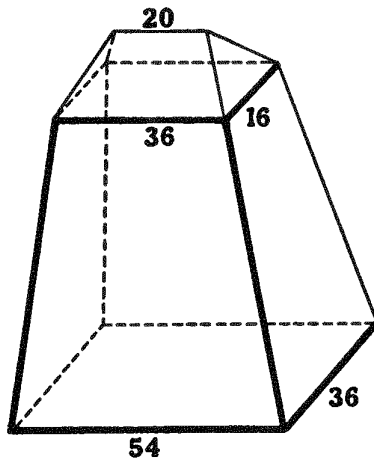


FIG. 1.

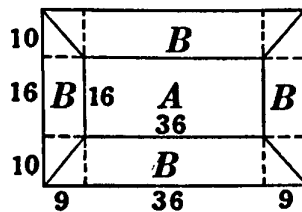


FIG. 2.

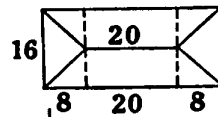


FIG. 3.

the main part of the stone looking directly from above. Fig. 3 represents a view of the top of the stone looking directly from above. Calculate the volume of the stone.

HINT. From Fig. 2 it is seen that the main part of the stone consists of a rectangular parallelepiped A , four right triangular prisms B , and a rectangular pyramid at each corner. Fig. 3 shows that the top consists of a right triangular prism and two rectangular pyramids.

Ex. 1652. The monument in Ex. 1651 was cut from a solid rock in the form of a rectangular parallelepiped. How many cubic feet of granite were wasted in the cutting?

Ex. 1653. In the monument of Ex. 1651 the two ends of the main part, and the top, have a rock finish, the front and rear surfaces of the main part being polished. Find the number of square feet of rock finish and of polished surface.

Ex. 1654. The base of a regular pyramid is a triangle inscribed in a circle whose radius is R , and the altitude of the pyramid is $2R$. Find the lateral area of the pyramid.

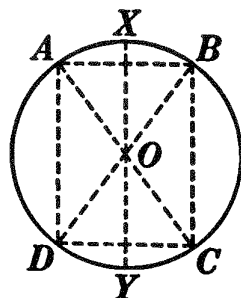
Ex. 1655. Find the weight in pounds of the water required to fill the tank in Ex. 1323, if a cubic foot of water weighs 1000 ounces.

Ex. 1656. By using the formula obtained in Ex. 1543, find the volume of the sphere inscribed in a regular tetrahedron whose edge is 12.

Ex. 1657. By using the formula obtained in Ex. 1544, find the volume of the sphere circumscribed about a regular tetrahedron whose edge is 12.

Ex. 1658. A hole 6 inches in diameter was bored through a sphere 10 inches in diameter. Find the volume of the part cut out.

HINT. The part cut out consists of two spherical cones and the solid generated by revolving isosceles $\triangle BOC$ about XY as an axis.



Ex. 1659. Check your result for Ex. 1658 by finding the volume of the part left.

Ex. 1660. Find the area of the spherical surface left in Ex. 1658.

Ex. 1661. Four spheres, each with a radius of 6 inches, are placed on a plane surface in a triangular pile, each one being tangent to each of the others. Find the total height of the triangular pile.

Ex. 1662. Find the total height of a triangular pile of spheres, each with radius of 6 inches, if there are three layers; four layers; n layers.

FORMULAS OF SOLID GEOMETRY

1014. In addition to the notation given in § 761, the following will be used :

| | |
|---|---|
| <p>A, B, C, \dots = number of degrees in the angles of a spherical polygon.</p> <p>a, b, c, \dots = sides of a spherical polygon.</p> <p>B = base of spherical sector, wedge, and pyramid.</p> <p>C = circumference of base in general or of lower base of frustum of cone.</p> <p>c = circumference of upper base of frustum of cone.</p> <p>D = diameter of a sphere.</p> <p>E = spherical excess of a spherical triangle.</p> | <p>H = altitude of zone or spherical sector.</p> <p>K = area of a spherical triangle or spherical polygon.</p> <p>L = area of lune.</p> <p>N = number of degrees in the angle of a lune or wedge.</p> <p>R = radius of base in general, of lower base of frustum of cone, or of sphere.</p> <p>r = radius of upper base of frustum of cone.</p> <p>S = area of surface of a sphere.</p> <p>T = sum of the angles of a spherical polygon.</p> <p>W = volume of a wedge.</p> <p>Z = area of a zone.</p> |
|---|---|

| FIGURE | FORMULA | REFERENCE |
|-----------------------------------|--|-----------|
| Prism. | $S = P \cdot E.$ | § 762. |
| Right prism. | $S = P \cdot H.$ | § 763. |
| Regular pyramid. | $S = \frac{1}{2} P \cdot L.$ | § 766. |
| Frustum of regular pyramid. | $S = \frac{1}{2} (P + p)L.$ | § 767. |
| Rectangular parallelepiped. | $V = a \cdot b \cdot c.$ | § 778. |
| Cube. | $V = E^3.$ | § 779. |
| Rectangular parallelepipeds. | $\frac{V}{V'} = \frac{a \cdot b \cdot c}{a' \cdot b' \cdot c'}.$ | § 780. |
| Rectangular parallelepiped. | $V = B \cdot H.$ | § 782. |
| Rectangular parallelepipeds. | $\frac{V}{V'} = \frac{B \cdot H}{B' \cdot H'}.$ | § 783. |
| Any parallelepiped. | $V = B \cdot H.$ | § 790. |
| Parallelepipeds. | $\frac{V}{V'} = \frac{B \cdot H}{B' \cdot H'}.$ | § 792. |
| Triangular prism. | $V = B \cdot H.$ | § 797. |
| Any prism. | $V = B \cdot H.$ | § 799. |
| Prisms. | $\frac{V}{V'} = \frac{B \cdot H}{B' \cdot H'}.$ | § 801. |
| Triangular pyramid. | $V = \frac{1}{3} B \cdot H.$ | § 804. |
| Any pyramid. | $V = \frac{1}{3} B \cdot H.$ | § 805. |
| Pyramids. | $\frac{V}{V'} = \frac{B \cdot H}{B' \cdot H'}.$ | § 807. |
| Similar tetrahedrons. | $\frac{V}{V'} = \frac{E^3}{E'^3}.$ | § 812. |
| Frustum of any pyramid. | $V = \frac{1}{3} H (B + b + \sqrt{B \cdot b}).$ | § 815. |
| Truncated right triangular prism. | $V = \frac{1}{3} B (E + E' + E'').$ | § 817. |
| Right circular cylinder. | $S = C \cdot H.$ | § 858. |
| | $S = 2 \pi R \cdot H.$ | § 859. |
| | $T = 2 \pi R (H + R).$ | § 859. |
| Similar cylinders of revolution. | $\frac{S}{S'} = \frac{H^2}{H'^2} = \frac{R^2}{R'^2}.$ | § 864. |
| | $\frac{T}{T'} = \frac{H^2}{H'^2} = \frac{R^2}{R'^2}.$ | § 864. |
| Right circular cone. | $S = \frac{1}{2} C \cdot L.$ | § 873. |
| | $S = \pi R \cdot L.$ | § 875. |
| | $T = \pi R (L + R).$ | § 875. |
| Similar cones of revolution. | $\frac{S}{S'} = \frac{H^2}{H'^2} = \frac{L^2}{L'^2} = \frac{R^2}{R'^2}.$ | § 878. |

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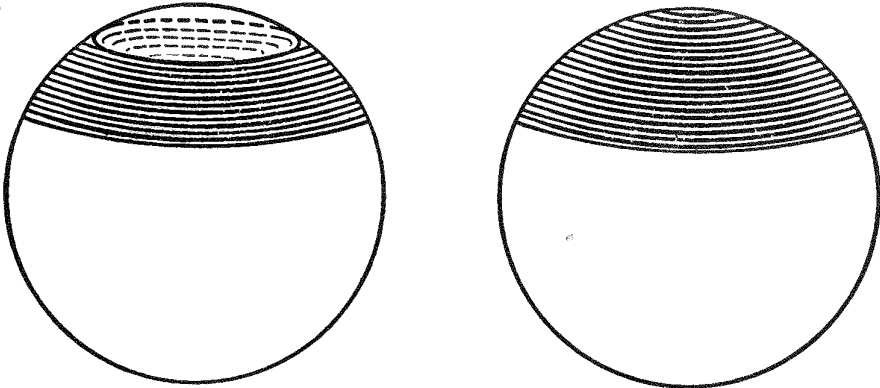
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APPENDIX TO SOLID GEOMETRY

SPHERICAL SEGMENTS

1015. Defs. A spherical segment is a solid closed figure whose bounding surface consists of a zone and two parallel planes.



Spherical Segment of Two Bases

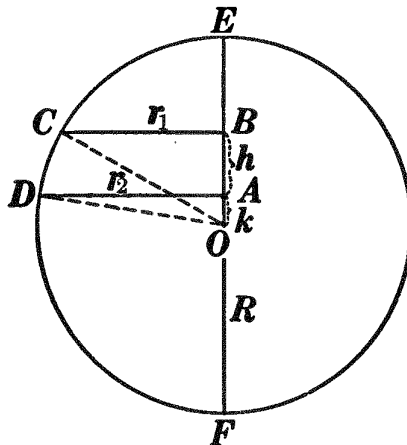
Spherical Segment of One Base

The sections of the sphere formed by the two parallel planes are called the **bases** of the spherical segment.

1016. Defs. State, by aid of §§ 976 and 977, definitions of:
 (a) **Altitude of a spherical segment.** (b) **Segment of one base.**

PROPOSITION I. PROBLEM

1017. *To derive a formula for the volume of a spherical segment in terms of the radii of its bases and its altitude.*



Given spherical segment generated by $ABCD$ revolving about EF as an axis, with its volume denoted by V , its altitude by h , and the radii of its bases by r_1 and r_2 , respectively.

To derive a formula for V in terms of r_1 , r_2 , and h .

∴ pyramid $P-ADC = \frac{1}{6} H \cdot m_1 + \frac{1}{6} H \cdot m_1 + \frac{2}{6} H \cdot m_1 = \frac{1}{6} H \cdot 4 m_1$.
 ∴ the volume of all lateral pyramids $= \frac{1}{6} H \cdot 4 M$.
 ∴ $V = \frac{1}{6} H \cdot B + \frac{1}{6} H \cdot b + \frac{1}{6} H \cdot 4 M = \frac{1}{6} H (B + b + 4 M)$. Q.E.F.

Ex. 1665. By substituting in the prismatoid formula, derive the formula for: (a) the volume of a prism (§ 799); (b) the volume of a pyramid (§ 805); (c) the volume of a frustum of a pyramid (§ 815).

Ex. 1666. Solve Ex. 1651 by applying the prismatoid formula to each part of the monument.

SIMILAR POLYHEDRONS *

1022. The student should prove the following:

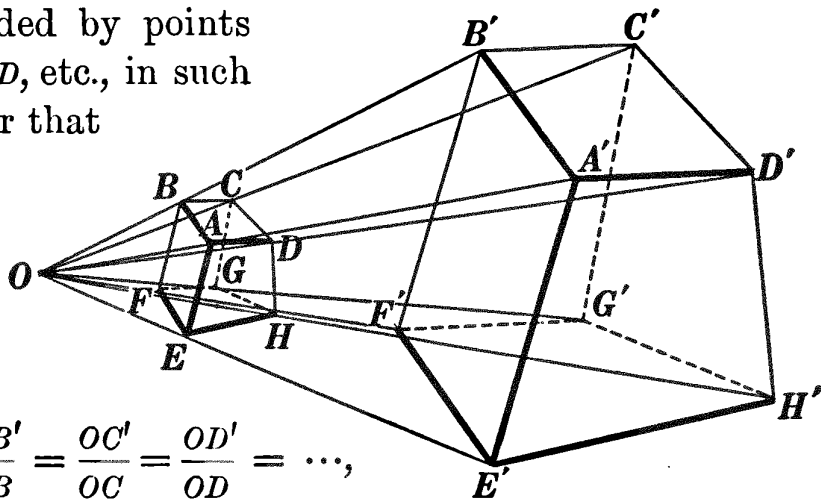
(a) *Any two homologous edges of two similar polyhedrons have the same ratio as any other two homologous edges.*

(b) *Any two homologous faces of two similar polyhedrons have the same ratio as the squares of any two homologous edges.*

(c) *The total surfaces of two similar polyhedrons have the same ratio as the squares of any two homologous edges.*

1023. Def. The ratio of similitude of two similar polyhedrons is the ratio of any two homologous edges.

1024. Def. If two polyhedrons $ABCD \dots$ and $A'B'C'D' \dots$ are so situated that lines from a point O to A', B', C', D', \dots , are divided by points A, B, C, D, \dots , in such a manner that



$$\frac{OA'}{OA} = \frac{OB'}{OB} = \frac{OC'}{OC} = \frac{OD'}{OD} = \dots,$$

the two polyhedrons are said to be radially placed.

Ex. 1667. Construct two polyhedrons radially placed and so that point O lies between the two polyhedrons; within the two polyhedrons.

* See § 811. In this discussion only convex polyhedrons will be considered.

PROPOSITION III. THEOREM

1025. *Any two radially placed polyhedrons are similar.* (See Fig. 2 below.)

Given polyhedrons EC and $E'C'$ radially placed with respect to point O .

To prove polyhedron $EC \sim$ polyhedron $E'C'$.

$AB, BC, CD,$ and DA are \parallel respectively to $A'B', B'C', C'D',$ and $D'A'$. § 415.

$\therefore ABCD \parallel A'B'C'D',$ and is similar to it. § 756, II.

Likewise each face of polyhedron EC is \sim to the corresponding face of polyhedron $E'C'$, and the faces are similarly placed.

Again, face $AII \parallel$ face $A'H',$ and face $AF \parallel$ face $A'F'.$

\therefore dihedral $\angle AE =$ dihedral $\angle A'E'.$

Likewise each dihedral \angle of polyhedron EC is equal to its corresponding dihedral \angle of polyhedron $E'C'.$

\therefore each polyhedral \angle of polyhedron EC is equal to its corresponding polyhedral \angle of polyhedron $E'C'.$ § 18.

\therefore polyhedron $EC \sim$ polyhedron $E'C'.$ § 811. Q.E.D.

PROPOSITION IV. THEOREM

1026. *Any two similar polyhedrons may be radially placed.*

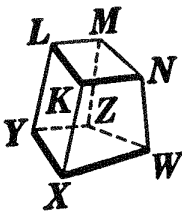


FIG. 1.

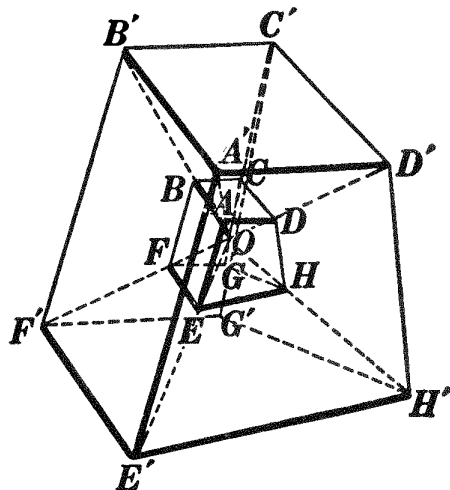


FIG. 2.

Given two similar polyhedrons XM and $E'C'.$

To prove that XM and $E'C'$ may be radially placed.

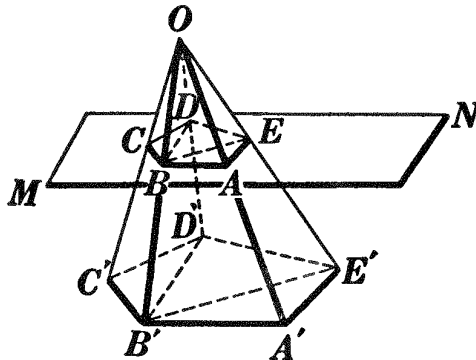
OUTLINE OF PROOF

1. Take any point O within polyhedron $E'C'$ and construct polyhedron EC so that it is radially placed with respect to $E'C'$ and so that $OA' : OA = OB' : OB = \dots = A'B' : KL$.
2. Then polyhedron $EC \sim$ polyhedron $E'C'$. § 1025.
3. Prove that the dihedral \sphericalangle of polyhedron EC are equal, respectively, to the dihedral \sphericalangle of polyhedron XM , each being equal, respectively, to the dihedral \sphericalangle of polyhedron $E'C'$.
4. Prove that the faces of polyhedron EC are equal, respectively, to the faces of polyhedron XM .
5. Prove, by superposition, that polyhedron $EC = XM$.
6. \therefore polyhedron XM may be placed in the position of EC .
7. But EC and $E'C'$ are radially placed.
8. $\therefore XM$ and $E'C'$ may be radially placed. Q.E.D.

PROPOSITION V. THEOREM

1027. *If a pyramid is cut by a plane parallel to its base:*

- I. *The pyramid cut off is similar to the given pyramid.*
- II. *The two pyramids are to each other as the cubes of any two homologous edges.*

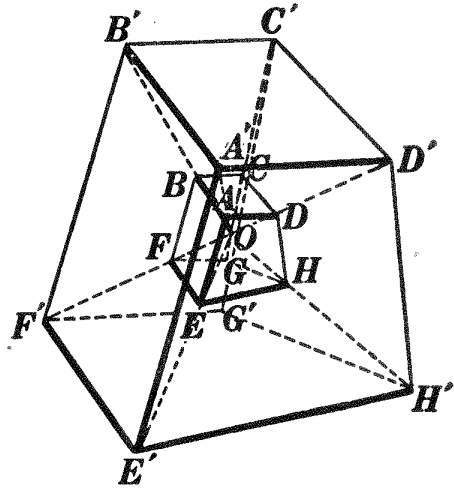
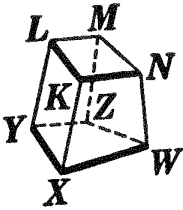


The proofs are left as exercises for the student.

HINT. For the proof of II, pass planes through OB' and diagonals $B'D'$, $B'E'$, etc., dividing each of the pyramids into triangular pyramids. Then pyramid $O-BCD \sim$ pyramid $O-B'C'D'$; pyramid $O-EBD \sim$ pyramid $O-E'B'D'$, etc. Use § 812 and a method similar to that used in § 505.

PROPOSITION VI. THEOREM.

1028. *Two similar polyhedrons are to each other as the cubes of any two homologous edges.*



Given two similar polyhedrons XM and $E'C'$, with their volumes denoted by V and V' , respectively, and with KL and $A'B'$ two homol. edges.

To prove $\frac{V}{V'} = \frac{\overline{KL}^3}{\overline{A'B'}^3}$.

Place XM in position EC , so that XM and $E'C'$ are radially placed with respect to point O within both polyhedrons. § 1026.

Denote the volumes of pyramids $O-ABCD$, $O-AEFB$, etc., by v_1 , v_2 , etc., and the volumes of pyramids $O-A'B'C'D'$, $O-A'E'F'B'$, etc., by v_1' , v_2' , etc.

Then $\frac{v_1}{v_1'} = \frac{\overline{AB}^3}{\overline{A'B'}^3}$; $\frac{v_2}{v_2'} = \frac{\overline{AE}^3}{\overline{A'E'}^3}$; etc. § 1027, II.

But $\frac{AB}{A'B'} = \frac{AE}{A'E'} = \dots$ (§ 1022, a); $\therefore \frac{\overline{AB}^3}{\overline{A'B'}^3} = \frac{\overline{AE}^3}{\overline{A'E'}^3} = \dots$

$\therefore \frac{v_1}{v_1'} = \frac{v_2}{v_2'} = \dots = \frac{\overline{AB}^3}{\overline{A'B'}^3}$; $\therefore \frac{v_1 + v_2 + \dots}{v_1' + v_2' + \dots} = \frac{\overline{AB}^3}{\overline{A'B'}^3}$. § 401.

$\therefore \frac{\text{polyhedron } EC}{\text{polyhedron } E'C'} = \frac{\overline{AB}^3}{\overline{A'B'}^3}$; i.e. $\frac{V}{V'} = \frac{\overline{KL}^3}{\overline{A'B'}^3}$. Q.E.D.

1029. Note. Since § 1028 was assumed early in the text (see § 814), the teacher will find plenty of exercises throughout Books VII, VIII, and IX illustrating this principle.

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