Math Level 2 Handouts Week 04

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Online Classes Season 3

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§ 1 Circles

Definition 1 (Radius). The distance from the center to any point on a circle is the **radius**.

This of course means this distance is constant.

Definition 2 (Diameter). The largest distance between two points on a circle is the **diameter**

As it turns out, the largest distance d is $2r$.

§ 1.1 Perimeter

Theorem 1 (Perimeter of a Circle). The perimeter of a circle, also known as the **circumference**, is given by $2\pi r$, where r is the radius.

§ 1.2 Area

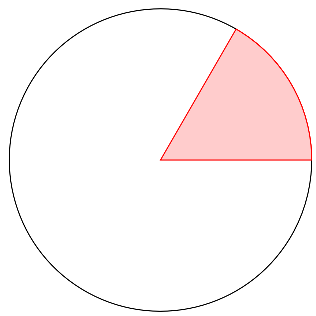
Theorem 2 (Area of a Circle). The area of a circle is given by πr^2, where r is the radius.

Example 1. Find the area of a circle with diameter 12.

Solution. The radius is $\frac{12}{6}$. Therefore, the area is $(6^2)\pi = \boxed{36\pi}$. $\square$

Definition 3 (Sector). A **sector** is the area bounded between an arc and the radii that connect the ends of that arc.

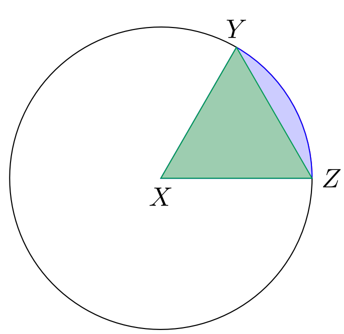
Below is an example of a sector.



Example 2. $\triangle XYZ$ is equilateral with side length 10. A circle is constructed with center X and radius 10, therefore passing through Y and Z. Find the area of sector YXZ of the circle.

Solution. To find the area of the sector, we need to first find what portion the sector is of the whole circle. Since $\triangle XYZ$ is equilateral, we must have $\angle X = 60^\circ$. This implies sector XYZ makes up $60^\circ/360^\circ = 1/6$ of the circle. Therefore, its area must also be $1/6$ the circle! Our answer is therefore

$$\frac{1}{6}(10^2\pi) = \boxed{\frac{50\pi}{3}}.$$

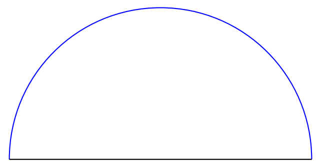


$\square$

Theorem 3. We can apply the above method to find the area of any sector. For a given sector AOB, we have

$$\text{Area of sector } AOB = \frac{\angle AOB}{360^\circ} r^2\pi.$$

Example 3. Farmer Tim has 50 feet of fence. He wants to enclose a semicircular area adjacent to his barn, using his barn as one side of the enclosure. What is the area of the space Farmer Tim can enclose?



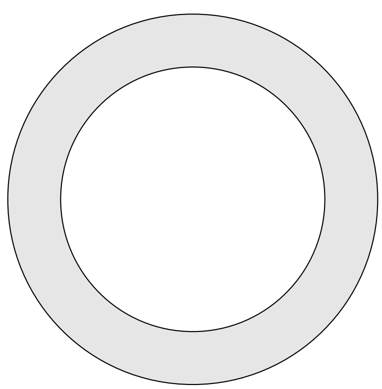
Solution. We know that if half the semicircle has perimeter 50 feet, then the whole circle must have a perimeter of 100 feet. We know that $2\pi r = C$, or $r = \frac{C}{2\pi} = \frac{100}{2\pi} = 50/\pi$. We also know the area of the semicircle is half the area of a whole circle. Therefore, our answer is

$$\frac{1}{2}\pi\left(\frac{50}{\pi}\right)^2 = \boxed{\frac{1250}{\pi}} \text{ square feet.}$$

□

Example 4. A man is standing on a lawn is wearing a circular sombrero of radius 3 feet. Unfortunately, the hat blocks the sunlight so effectively that the grass under it dies instantly. If the man walks in a circle of radius 5 feet, what is the area of the dead grass?

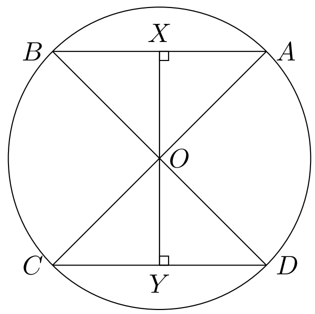
Solution. After the man walks in a circle, the resulting picture will look like this.



The outer ring is a total distance of $5+3 = 8$ feet from the center of the circle in which the man walks around. The small ring is a distance of $5-3 = 2$ feet from the center of the circle. Therefore, the area we want is the area of a circle with radius 8 minus the area of a circle with radius 2. This is just $8^2\pi - 2^2\pi = \boxed{60\pi}$. □

Example 5. A circle has two parallel chords of length x that are x units apart. If the part of the circle included between the chords has area $2+\pi$, find x.

Solution. We begin with a diagram.

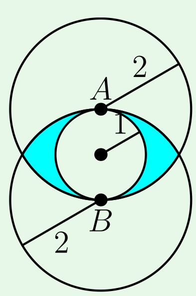


Let's show $\triangle BOA$ and $\triangle COA$ are right triangles. We note that $\triangle BOA$ and $\triangle COD$ are congruent because of SSS congruence. Thus, their corresponding altitudes are the same by CPCTC (congruent parts of corresponding triangles are congruent). Thus, $OY = OX = x/2$. Next, note that $\triangle BOX \cong \triangle AOX$ because of HL congruence (their hypotenuses are the radii and they share OX). Therefore, $\triangle BOX$ and $\triangle AOX$ are $45^\circ - 45^\circ - 90^\circ$ triangles. This means $\angle BOA$ must be a 90° angle. Notice that we can combine $\triangle BOA$ and $\triangle COD$ to create a square with side length r, where r is the radius of the circle. Thus, $\triangle BOA$ and $\triangle COD$ make up r^2. The other part region between the two segments BA and CD are sectors BOC and AOD, which comprise of $\frac{90+90}{360} = \frac{1}{2}$ the circle, or $\pi r^2/2$. Thus, we have

$$\frac{\pi r^2}{2} + r^2 = 2 + \pi.$$

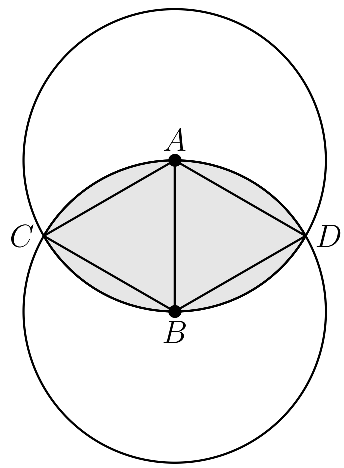
We notice that the $\pi r^2/2$ on the left side must correspond to the π on the right side, so $r = \sqrt{2}$. Using properties of $45^\circ - 45^\circ - 90^\circ$ triangles, we see $2AX = 2 \times \frac{\sqrt{2}}{\sqrt{2}}) = \boxed{2}$. □

Example 6. A circle of radius 1 is internally tangent to two circles of radius 2 at points A and B, where AB is a diameter of the smaller circle. What is the area of the region, shaded in the picture, that is outside the smaller circle and inside each of the two larger circles?



Solution. This seems like a tough problem, mostly because it seems difficult to find the area of the region inside of both big circles. However, if we can just find this region, we can simply subtract the area of the smaller circle to find the area of the shaded region. Thus, we shall focus on finding the overlapping region between the two big circles.

In geometry problems, it is often helpful to connect points of intersection. Thus, let C and D be the intersections of the two large circles. Connect them to A and B to get the picture below:



We now see that $AC = AB = BC = 2$ (they are all radii), so $\triangle ABC$ is equilateral! The same logic applies to $\triangle ABD$ as well. Therefore, $\angle CBA = 60^\circ$. We see that our shaded region is made up of two equilateral triangles and 4 regions that are 60° sectors minus an equilateral triangle. The area of the equilateral triangles are

$$2\left(\frac{2^2\sqrt{3}}{4}\right) = 2\sqrt{3}.$$

We can calculate the area of the 4 smaller regions by finding the area of 60° sector (which is just $1/6$ the area of a circle) and subtracting the area of the equilateral triangle within that sector and multiplying that area by 4.

$$4\left(\frac{2^2\pi}{6} - \frac{2^2\sqrt{3}}{4}\right) = \frac{8\pi}{3} - 4\sqrt{3}.$$

Therefore, the area of the overlapping regions between the two big circles is $8\pi/3 - 2\sqrt{3}$. However, we still need to subtract the area of the small circle of radius 1, which has area π. Therefore, our answer is $\boxed{5\pi/3 - 2\sqrt{3}}$. □

§ 1.3 Angles

We say that an angle is **inscribed** in an arc if its vertex is on the circumference of the circle and its sides hit the circle at the ends of the arc.

Theorem 4 (Thale's Theorem). Any angle inscribed in a semicircle is a right angle.

Example 7. Points A, B, and C, are on circle O such that $\overset{\frown}{AC} = 80^\circ$ and $\overset{\frown}{ACB} = 130^\circ$. Find $\angle ABC$.

Solution. We know that the measure of an arc equals the angle formed by the radii that cut off the arc (we call such an angle a **central angle**). Therefore, we draw radii to A, B, and C, thus forming some isosceles triangles. Since $\angle BOC = \overset{\frown}{BC} = \overset{\frown}{AB} - \overset{\frown}{AC} = 50^\circ$, we have

$$\angle OBC = \angle OCB = \frac{180^\circ - 50^\circ}{2} = 65^\circ$$

Similarly, $\angle AOB = \overset{\frown}{AB} = 130^\circ$, so

$$\angle OAB = \angle OBA = \frac{180^\circ - 130^\circ}{2} = 25^\circ$$

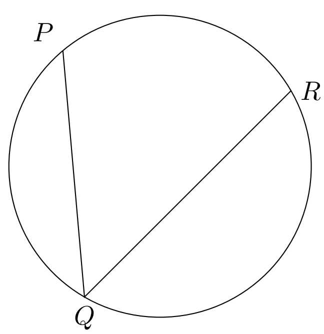
Therefore, $\angle ABC = \overset{\frown}{AC}/2$ and we wonder if this is always the case. We can try changing BC to see if that matters. If we let $\overset{\frown}{BC} = 64^\circ$, we can go through the same series of calculations as above to find that, indeed, $\angle ABC$ is still 40°. □

Now that we have a specific case as a guideline, we'll try to prove that an inscribed angle is always half the arc it intercepts. Unfortunately, to completely prove this, we'll need a number of cases. We'll try one of these cases here.

Theorem 5 (Inscribed Angle Theorem). The measure of an inscribed angle is one half the measure of the arc it intercepts.

For example,

$$\angle PQR = \frac{\overset{\frown}{PR}}{2}.$$



Example 8. Find x given that $\angle APB = 2x$, $\angle ACD = x$, and $\widehat{BC} = x$.

Solution. Since $\angle B$ and $\angle C$ are inscribed in the same arc, they must be equal (since each equals half of the arc). Therefore, $\angle B = \angle C = x$. Since $\angle A$ is inscribed in $\widehat{BC}$, we have $\angle A = \widehat{BC}/2 = x/2$. Now we can use $\triangle APB$ to write an equation for x.

$$\angle A + \angle APB + \angle B = 180^\circ$$

We have,

$$\frac{x}{2} + 2x + x = 180^\circ$$

Solving this equation gives $x = 51\frac{3}{7}^\circ$. □

Solving this problem also illustrates another important principle that will be a crucial step in many problems when you move on to more advanced geometry.

Corollary 6. Any two angles that are inscribed in the same arc are equal.

Theorem 7. The measure of an angle formed by two secants which intersect outside the circle is equal to one-half the difference of the arcs intercepted by the secants.

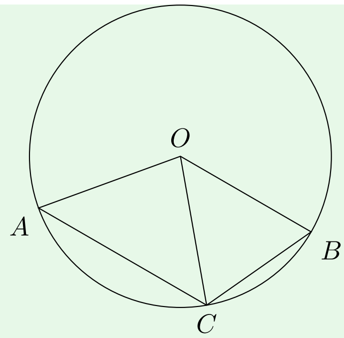
Theorem 8. Let BC be a chord of a circle and A be a point outside the circle such that AB is **tangent** (touching at only one point) to the circle. If D is a point on the opposite side of BC to A, then $\angle ABC = \angle BDC$.

Theorem 9. The measure of the angle formed by two chords is one-half the sum of the intercepted arcs.

Example 9. Given that $\triangle ABC$ is inscribed in a circle, $\angle A = 70^\circ$, and $\widehat{AC} = 130^\circ$, find $\angle C$.

Solution. Since $\angle B$ is inscribed in $\widehat{AC}$, we have $\angle B = AC/2 = 65^\circ$. Therefore, $\angle C = 180^\circ - \angle A - \angle B = 45^\circ$. □

Example 10. Points A, B, and C, are on circle O such that $\widehat{AC} = 80^\circ$ and $\widehat{ACB} = 130^\circ$. Find $\angle ABC$.



Solution. We know that the measure of an arc equals the angle formed by the radii that cut off the arc (we call such an angle a **central angle**). Therefore, we draw radii to A, B, and C, thus forming some isosceles triangles. Since $\angle BOC = \widehat{BC} = \widehat{AB} - \widehat{AC} = 50^\circ$, we have

$$\angle OBC = \angle OCB = \frac{180^\circ - 50^\circ}{2} = 65^\circ$$

Similarly, $\angle AOB = \widehat{AB} = 130^\circ$, so

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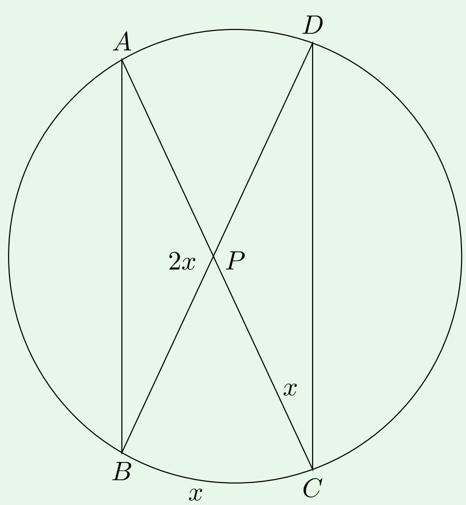
Therefore, $\angle ABC = \widehat{AC}/2$ and we wonder if this is always the case. We can try changing BC to see if that matters. If we let $\widehat{BC} = 64^\circ$, we can go through the same series of calculations as above to find that, indeed, $\angle ABC$ is still 40°. □

Let's use this in some problems.

Example 11. Find x given that $\angle APB = 2x$, $\angle ACD = x$, and $\widehat{BC} = x$.



Solution. Since $\angle B$ and $\angle C$ are inscribed in the same arc, they must be equal (since each equals half of the arc). Therefore, $\angle B = \angle C = x$. Since $\angle A$ is inscribed in $\widehat{BC}$, we have $\angle A = \widehat{BC}/2 = x/2$. Now we can use $\triangle APB$ to write an equation for x.

$$\angle A + \angle APB + \angle B = 180^\circ$$

We have,

$$\frac{x}{2} + 2x + x = 180^\circ$$

Solving this equation gives $x = 51\frac{3}{7}^\circ$. □

Solving this problem also illustrates another important principle that will be a crucial step in many problems when you move on to more advanced geometry.

§ 1.4 Power of a Point

Theorem 10 (Power of a Point). Let A, B, C, D be points on a circle, and let AB and CD intersect at P. Then $PA \cdot PB = PC \cdot PD$.

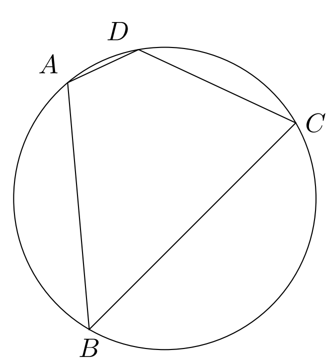
There are two possibilities of this arrangement: the order of the points is A, B, C, D, or the order of the points is A, C, B, D. In either case, the theorem is the same.

Corollary 11. Let P be a point outside the circle, and one line through P intersects the circle at A and B, whereas another is tangent to the circle at C. Then $PC^2 = PA \cdot PB$.

Power of a Point is best seen through problems, and they will be introduced in the problems section.

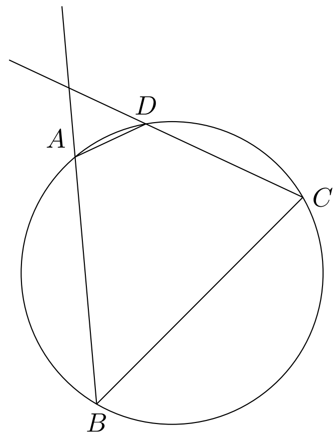
§ 1.5 Cyclic Quadrilaterals

Consider the following quadrilateral:



Theorem 12 (Cyclic Quadrilateral Angle Condition). In a cyclic quadrilateral, $\angle A + \angle C = \angle B + \angle D = 180^\circ$.

Let's extend a few lengths:



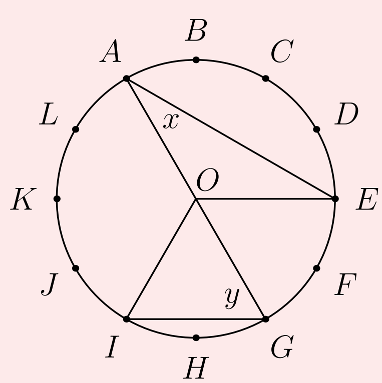
Let the two lines meet at P. Then $\triangle PAD \sim \triangle PCB$. Furthermore, many angles in this configuration are equal. One pair is $\angle BAC = \angle BDC$, using our knowledge of inscribed angles. This is sometimes useful in solving problems.

§ 1.6 Problems

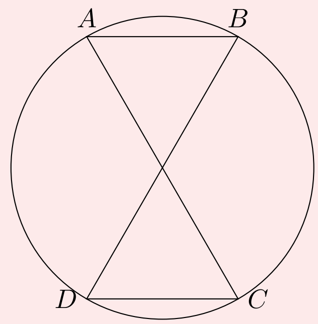
Problem 1 (AHSME 1950/33). The number of circular pipes with an inside diameter of 1 inch which will carry the same amount of water as a pipe with an inside diameter of 6 inches is n. Find n.

Problem 2 (AHSME 1973/25). A circular grass plot 12 feet in diameter is cut by a straight gravel path 3 feet wide, one edge of which passes through the center of the plot. What is the number of square feet in the remaining grass area?

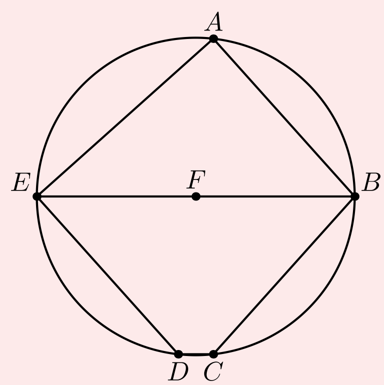
Problem 3 (AMC 8 2014/15). The circumference of the circle with center O is divided into 12 equal arcs, marked the letters A through L as seen below. What is the number of degrees in the sum of the angles x and y?



Problem 4. Chords $\overline{AC}$ and $\overline{BD}$ of a circle meet at P as shown. Given $AP = PB$, show that $\overline{AB} \parallel \overline{CD}$.

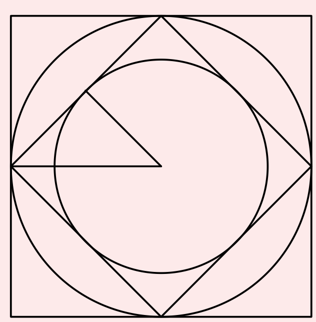


Problem 5 (AMC 10B 2011/17). In the given circle, the diameter $\overline{EB}$ is parallel to $\overline{DC}$, and $\overline{AB}$ is parallel to $\overline{ED}$. The angles AEB and ABE are in the ratio $4 : 5$. What is the degree measure of angle BCD?

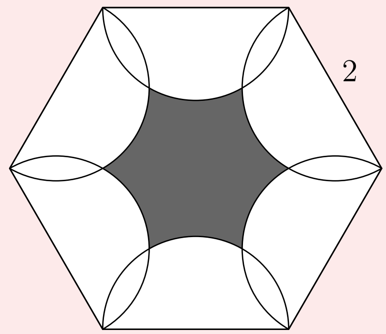


Problem 6 (AMC 12A 2002/7). A $45°$ arc of circle A is equal in length to a $30°$ arc of circle B. What is the ratio of circle A's area and circle B's area?

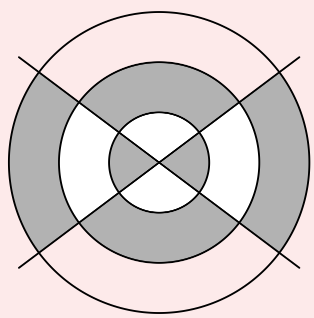
Problem 7 (AMC 10B 2005/7). A circle is inscribed in a square, then a square is inscribed in this circle, and finally, a circle is inscribed in this square. What is the ratio of the area of the smaller circle to the area of the larger square?



Problem 8 (AMC 10B 2020/14). As shown in the figure below, six semicircles lie in the interior of a regular hexagon with side length 2 so that the diameters of the semicircles coincide with the sides of the hexagon. What is the area of the shaded region — the area inside the hexagon but outside all of the semicircles?

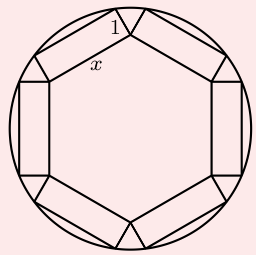


Problem 9 (AMC 10A 2004/21). Two distinct lines pass through the center of three concentric circles of radii 3, 2, and 1. The area of the shaded region in the diagram is $\frac{8}{13}$ of the area of the unshaded region. What is the radian measure of the acute angle formed by the two lines? (Note: π radians is 180 degrees.)

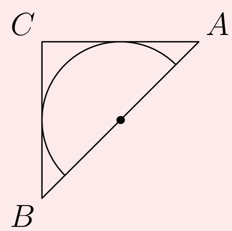


Problem 10 (AMC 10A 2008/17). An equilateral triangle has side length 6. What is the area of the region containing all points that are outside the triangle but not more than 3 units from a point of the triangle?

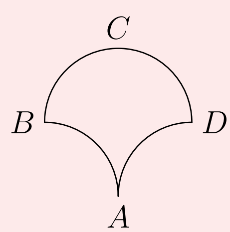
Problem 11 (AMC 12A 2008/22). A round table has radius 4. Six rectangular place mats are placed on the table. Each place mat has width 1 and length x as shown. They are positioned so that each mat has two corners on the edge of the table, these two corners being end points of the same side of length x. Further, the mats are positioned so that the inner corners each touch an inner corner of an adjacent mat. What is the area of the 6 rectangular mats?



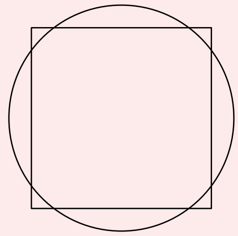
Problem 12 (AMC 8 2005/23). Isosceles right triangle ABC encloses a semicircle of area 2π. The circle has its center O on hypotenuse $\overline{AB}$ and is tangent to sides $\overline{AC}$ and $\overline{BC}$. What is the area of triangle ABC?



Problem 13. Three circular arcs of radius 5 units bound the region shown. Arcs AB and AD are quarter-circles, and arc BCD is a semicircle. What is the area, in square units, of the region?



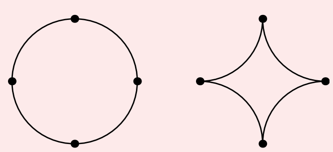
Problem 14. A square with side length 2 and a circle share the same center. The total area of the regions that are inside the circle and outside the square is equal to the total area of the regions that are outside the circle and inside the square. What is the radius of the circle?



Problem 15 (AMC 8 2006/7). Circle X has a radius of π. Circle Y has a circumference of 8π. Circle Z has an area of 9π. List the circles in order from smallest to largest radius.

Problem 16 (AMC 8 2008/25). Margie's winning art design is shown. The smallest circle has radius 2 inches, with each successive circle's radius increasing by 2 inches. Which of the following is closest to the percent of the design that is black?

Problem 17 (AMC 8 2012/24). A circle of radius 2 is cut into four congruent arcs. The four arcs are joined to form the star figure shown. What is the ratio of the area of the star figure to the area of the original circle?



Problem 18. In a circle, chords AB and CD intersect at E. If $AE : BE = 1 : 4$ and $CE : DE = 4 : 9$, find $\frac{AB}{CD}$.

Problem 19. Chords AB and CD of a given circle are perpendicular to each other and intersect at a right angle. Given that $BE = 16, DE = 4$, and $AD = 5$, find CE.