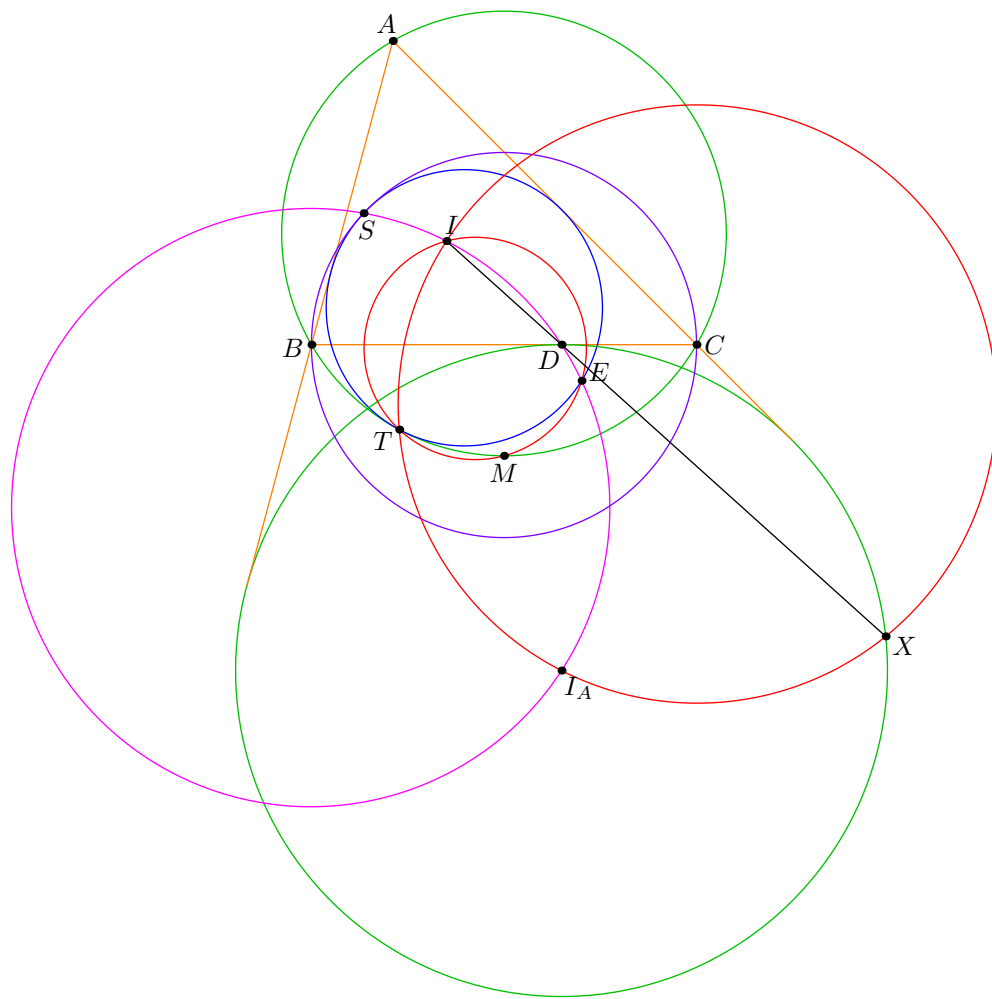


*PREVIEW OF* Dennis Chen's

# Exploring Euclidean Geometry



**Dennis Chen**

*Last updated July 23, 2020*

# Exploring Euclidean Geometry V2

Dennis Chen

July 23, 2020

## Introduction

This is a preview of Exploring Euclidean Geometry V2. It contains the first four chapters, which constitute the entirety of the first part.

This should be a good introduction for those training for computational geometry questions. This book may be somewhat rough on beginners, so I do recommend using some slower-paced books as a supplement, but I believe the explanations should be concise and clear enough to understand. In particular, a lot of other texts have unnecessarily long proofs for basic theorems, while this book will try to prove it as clearly and succinctly as possible.

There aren't a ton of worked examples in this section, but the check-ins should suffice since they're just direct applications of the material.

## Contents

**Part A**

**The Basics**

# Chapter 1

## Triangle Centers

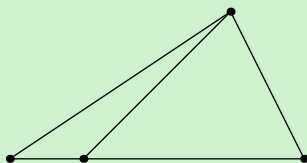
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Empty your mind of any theories,  
'Til all the facts are in.

*Death Note Musical*

We define the primary four triangle centers, their corresponding lines, and define a cevian.

**Definition 1.1 (Cevian)** In a triangle, a cevian is a line segment with a vertex of the triangle as an endpoint and its other endpoint on the opposite side.



### ♣ 1.1 Incenter

The corresponding cevian is the *interior* angle bisector.

**Definition 1.2 (Interior Angle Bisector)** The interior angle bisector of  $\angle CAB$  is the line that bisects acute  $\angle CAB$ .

The interior angle bisector of  $\angle CAB$  is also the locus of points inside  $\angle CAB$  equidistant from lines  $AB$  and  $AC$ .

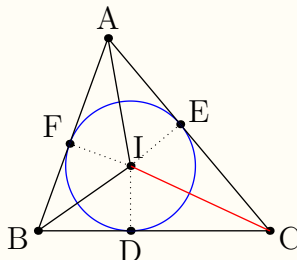
**Fact 1.1 (Angle Bisector Equidistant from Both Sides)** In  $\angle CAB$ ,  $\angle PAB = \angle PAC$  if and only if  $\delta(P, AB) = \delta(P, AC)$ .

**Proof:** Let the feet of the altitudes from  $P$  to  $AB, AC$  be  $X, Y$ . Then note that either of these conditions imply  $\triangle APX \cong \triangle APY$ , which in turn implies the other condition. ■

**Theorem 1.1 (Incenter)** There is a point  $I$  that the angle bisectors of  $\triangle ABC$  concur at. Furthermore,  $I$  is equidistant from sides  $AB, BC, CA$ .

**Proof:** Recall that a point is on the angle bisector of  $\angle CAB$  if and only if  $\delta(P, AB) = \delta(P, AC)$ . Let the angle bisectors of  $\angle CAB$  and  $\angle ABC$  intersect at  $I$ . Then  $\delta(P, CA) = \delta(P, AB)$  and  $\delta(P, AB) = \delta(P, BC)$ , so  $\delta(P, BC) = \delta(P, CA)$ , implying that  $I$  lies on the angle bisector of  $\angle BCA$ .

Since  $\delta(P, AB) = \delta(P, BC) = \delta(P, CA)$ , the circle with radius  $\delta(P, AB)$  centered at  $I$  is inscribed in  $\triangle ABC$ .



■

## ❖ 1.2 Centroid

The corresponding cevian is the median.

**Definition 1.3 (Midpoint)** The midpoint of segment  $AB$  is the unique point  $M$  that satisfies the following:

- (a)  $M$  is on  $AB$ .
- (b)  $AM = MB$ .

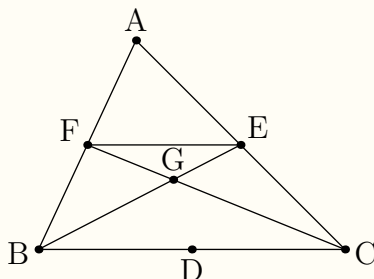
**Definition 1.4 (Median)** The  $A$ -median of  $\triangle ABC$  is the line segment that joins  $A$  with the midpoint of  $BC$ .

**Theorem 1.2 (Centroid)** The medians  $AD, BE, CF$  of  $\triangle ABC$  concur at a point  $G$ . Furthermore, the following two properties hold:

- (a)  $\frac{AG}{GD} = \frac{BG}{GE} = \frac{CG}{GF} = 2$ .
- (b)  $[BGD] = [CGD] = [CGE] = [AGE] = [AGF] = [BGF]$ .

**Proof:** Let  $BE$  intersect  $CF$  at  $G$ . Since  $\triangle AFE \sim \triangle ABC$ ,  $FE \parallel BC$ . Thus  $\triangle BCG \sim \triangle EFG$  with a ratio of  $\frac{BC}{EF} = 2$ , so  $\frac{BG}{GE} = 2$ .

Similarly let  $BE$  intersect  $AD$  at  $G'$ . Repeating the above yields  $\frac{BG'}{G'E} = 2$ . Thus  $G$  and  $G'$  are the same point, and the medians are concurrent.



■

### ❖ 1.3 Circumcenter

A perpendicular bisector is not a cevian, but it is still a special line in triangles.

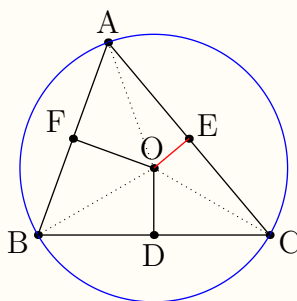
**Definition 1.5 (Perpendicular Bisector)** The perpendicular bisector of a line segment  $AB$  is the locus of points  $X$  such that  $AX = BX$ .

The circumcenter is the unique circle that contains points  $A, B, C$ .

**Theorem 1.3 (Circumcenter)** There is a point  $O$  that the perpendicular bisectors of  $BC, CA, AB$  concur at. Furthermore,  $O$  is the center of  $(ABC)$ .

**Proof:** Let the perpendicular bisectors of  $AB, BC$  intersect at  $O$ . By the definition of a perpendicular bisector,  $AO = BO$  and  $BO = CO$ . But this implies  $CO = AO$ , so  $O$  lies on the perpendicular bisector of  $CA$ .

Since  $AO = BO = CO$ , the circle centered at  $O$  with radius  $AO$  circumscribes  $\triangle ABC$ .



■

### ❖ 1.4 Orthocenter

The corresponding cevian is the altitude.

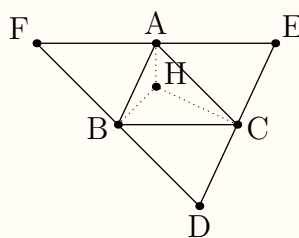
**Definition 1.6 (Altitude)** The  $A$ -altitude of  $\triangle ABC$  is the line through  $A$  perpendicular to  $BC$ .

**Definition 1.7 (Foot of Altitude)** The foot of the altitude from  $A$  to  $BC$  is the point  $H$  where the  $A$ -altitude intersects  $BC$ .

**Theorem 1.4 (Orthocenter)** The altitudes of  $\triangle ABC$  concur.

**Proof:** We will be piggybacking on the proof for the circumcenter.

Let the line through  $B$  parallel to  $AC$  and the line through  $C$  parallel to  $AB$  intersect at  $D$ . Define  $E, F$  similarly. Note that  $FA = BC = AE$ , so the  $A$  altitude of  $\triangle ABC$  is the perpendicular bisector of  $DE$ . Since the circumcenter exists, the orthocenter must too.



## ♠ 1.5 Summary

### 1.5.1 Theory

#### 1. Angle Bisector

- ◆ The angle bisector bisects the angle, as the name suggests.
- ◆ It is also the locus of points equidistant from two lines.

#### 2. Incenter

- ◆ The incenter is the center of the incircle.
- ◆ The incenter is equidistant from all sides.
- ◆ The incenter is the concurrence point of the angle bisectors.

#### 3. Median

- ◆ The median joins the vertex to the midpoint of the opposite side.

#### 4. Centroid

- ◆ The centroid is the center of mass.
- ◆ The centroid is the concurrence point of the medians.
- ◆ The centroid  $G$  splits the medians in the ratio  $\frac{AG}{GD} = 2$ .

#### 5. Perpendicular Bisector

- ◆ The perpendicular bisector is the locus of points equidistant from the endpoints of a line segment.



- ◆ The perpendicular bisector perpendicularly bisects the segment.

#### 6. Circumcenter

- ◆ The circumcenter is the center of the circumcircle.
- ◆ The circumcenter is equidistant from all vertices.
- ◆ The circumcenter is the concurrence point of the perpendicular bisectors.

#### 7. Altitude

- ◆ The altitude is the perpendicular line through one vertex to the opposite side.
- ◆ The foot of the altitude is the intersection of the altitude with the side.

#### 8. Orthocenter

- ◆ The orthocenter is the concurrence point of the altitudes.

### 1.5.2 Tips and Strategies

#### 1. Incenter

- ◆ Just remember that the angle bisector bisects angles.

#### 2. Centroid

- ◆ Length chase with the length condition.
- ◆ Take homotheties from the midpoint of a side with scale factor  $\frac{1}{3}$  to send the opposite vertex to the centroid.
- ◆ Remember that the medians split the triangle into six triangles of equal area.

#### 3. Circumcenter

- ◆ Use  $AO = BO = CO$  to find isosceles triangles - this will help a lot with angle chasing.

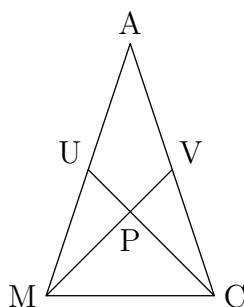
#### 4. Orthocenter

- ◆ Watch out for right triangles and right angles.

## ❖ 1.6 Exercises

### 1.6.1 Check-ins

1. Prove that a triangle is equilateral if and only if its incenter is the same point as its circumcenter.
2. Consider  $\triangle ABC$  with incenter  $I$ . Prove that  $\angle BIC = 90^\circ + \frac{1}{2}\angle BAC$ . **Hints:** ??
3. Prove that the perpendicular bisector of line segment  $AB$  is perpendicular to and bisects  $AB$ , if the perpendicular bisector is defined as the locus of points  $X$  such that  $AX = BX$ .
4. Consider  $\triangle ABC$  with circumcenter  $O$ . If  $AO = 20$  and  $BC = 32$ , find  $[BOC]$ .
5. (AMC 10A 2020/12) Triangle  $AMC$  is isosceles with  $AM = AC$ . Medians  $\overline{MV}$  and  $\overline{CU}$  are perpendicular to each other, and  $MV = CU = 12$ . What is the area of  $\triangle AMC$ ?



### 1.6.2 Problems

1. (AMC 10B 2018/12) Line segment  $\overline{AB}$  is a diameter of a circle with  $AB = 24$ . Point  $C$ , not equal to  $A$  or  $B$ , lies on the circle. As point  $C$  moves around the circle, the centroid (center of mass) of  $\triangle ABC$  traces out a closed curve missing two points. To the nearest positive integer, what is the area of the region bounded by this curve? **Solution:** ??
2. Consider  $\triangle ABC$  with medians  $BE, CF$ . If  $BE$  and  $CF$  are perpendicular, find  $\frac{b^2+c^2}{a^2}$ . **Hints:** ?? ?? **Solution:** ??
3. (Brazil 2007) Let  $ABC$  be a triangle with circumcenter  $O$ . Let  $P$  be the intersection of straight lines  $BO$  and  $AC$  and  $\omega$  be the circumcircle of triangle  $AOP$ . Suppose that  $BO = AP$  and that the measure of the arc  $OP$  in  $\omega$ , that does not contain  $A$ , is  $40^\circ$ . Determine the measure of the angle  $\angle OBC$ . **Hints:** ?? ?? **Solution:** ??

### 1.6.3 Challenges

1. Three congruent circles  $\omega_1, \omega_2, \omega_3$  concur at  $P$ . Let  $\omega_1$  intersect  $\omega_2$  at  $A \neq P$ , let  $\omega_2$  intersect  $\omega_3$  at  $B \neq P$ , and let  $\omega_3$  intersect  $\omega_1$  at  $C \neq P$ . What triangle center is  $P$  with respect to  $\triangle ABC$ ?
2. Let  $ABC$  be an isosceles triangle with  $AB = AC$ . If  $\omega$  is inscribed in  $ABC$  and the orthocenter of  $ABC$  lies on  $\omega$ , find  $\frac{AB}{BC}$ .
3. Let  $G$  be the centroid of  $\triangle ABC$ . If  $\angle BGC = 90^\circ$ , find the maximum value  $\sin A$  can take. **Hints:** ??

## Chapter 2

# Angle Chasing

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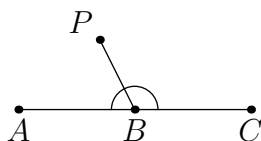
‘Think simple’ as my old master used to say — meaning reduce the whole of its parts into the simplest terms, getting back to first principles.

*Frank Lloyd Wright*

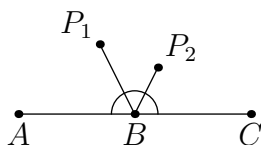
You can angle chase to show points are collinear or lines are concurrent, lines are parallel, a line is tangent to a circle, or four points are cyclic. In computational contests, you may be asked to find an angle for easier problems and angle chasing can reveal more about the configuration for harder problems.

### ❖ 2.1 Collinearity and Concurrency

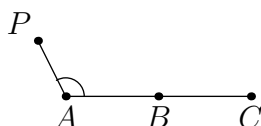
**Fact 2.1 (Collinearity Condition)** A line has measure  $180^\circ$ . This means  $A, B, C$ , are collinear if and only if for any point  $P$ ,  $\angle ABP + \angle PBC = 180^\circ$ . This is one of the main ways to prove points are collinear.



This holds for more than one point too. For the right configuration,  $A, B, C$  are collinear if and only if for points  $P_1, P_2, \dots, P_n$ ,  $\angle ABP_1 + \angle P_1BP_2 + \dots + \angle P_nBC = 180^\circ$ . (Directed angles can be used to avoid configuration issues.)



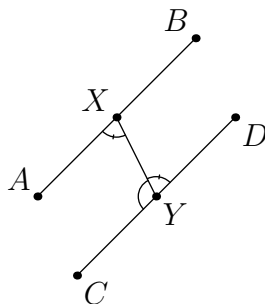
A similar condition is that  $A, B, C$  are collinear if and only if for any point  $P$ ,  $\angle PAB = \angle PAC$ .



## ❖ 2.2 Parallel Lines

**Fact 2.2 (Parallel Lines)** Consider parallel lines  $AB$  and  $CD$ . Then for  $X$  on segment  $AB$  and  $Y$  on segment  $CD$ ,

$$\angle AXY = 180^\circ - \angle CXY = \angle DXY.$$



## ❖ 2.3 Angle Chasing in Circles

We begin with some definitions.

**Definition 2.1 (Chord)** A chord is a line segment formed by two distinct points on a circle.

**Definition 2.2 (Secant)** A secant is a line that intersects a circle twice.

**Definition 2.3 (Tangent)** A tangent is a line that intersects a circle once.

Sometimes, it will be more convenient to think of a tangent as intersecting a circle twice at the same point, such as with Power of a Point.

**Definition 2.4 (Measure of an Arc)** The measure of  $\widehat{AB}$  of circle with center  $O$  is the measure of  $\angle AOB$ . Unless specified, this means the minor arc, or the smaller arc.

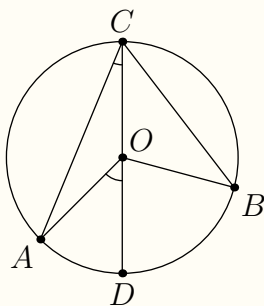
Now we present three important theorems.

**Theorem 2.1 (Inscribed Angle)** Let  $A, B$  be points on a circle with center  $O$ .

If  $C$  is a point on minor arc  $AB$ , then  $\angle ACB = \frac{\angle AOB}{2}$ .

If  $C$  is a point on major arc  $AB$ , then  $\angle ACB = 180^\circ - \frac{\angle AOB}{2}$ .

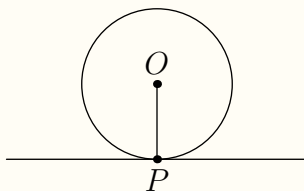
**Proof:** Let  $D$  be the antipode of  $C$ . Then  $\angle ACD = \frac{180^\circ - \angle AOC}{2} = \frac{\angle AOD}{2}$ . Thus addition or subtraction, depending on whether  $O$  is inside acute angle  $\angle ACB$ , of  $\angle ACD$  and  $\angle BCD$  will yield the result.



■

**Theorem 2.2 (Tangent Perpendicular to Radius)** Consider circle  $\omega$  with center  $O$  and point  $P$  on  $\omega$ . If  $\ell$  is the tangent to  $\omega$  through  $P$ , then  $\ell$  is perpendicular to  $OP$ .

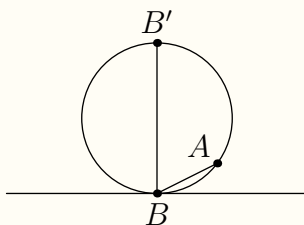
**Proof:** This is identical to the claim that  $P$  is the point on  $\ell$  with the smallest distance to  $O$ . We prove this is true by contradiction. Assume this is not true. Then there is some point  $X$  on  $\ell$  such that  $OX < OP$ , implying that  $\ell$  intersects  $\omega$  twice, contradiction.



■

**Theorem 2.3 (Tangent Angle)** Consider circle  $\omega$  with center  $O$  and points  $A, B$  on  $\omega$ . Let  $\ell$  be the tangent to  $\omega$  through  $B$  and let  $\theta$  be the acute angle between  $AB$  and  $\ell$ . Then  $\theta = \frac{\angle AOB}{2}$ .

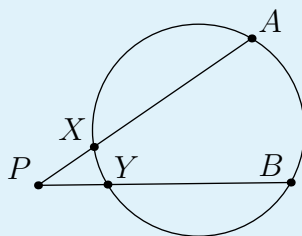
**Proof:** Let  $B'$  be the antipode of  $B$ . Then note that  $\theta = 90^\circ - \angle ABB' = \frac{180^\circ - \angle AOB'}{2} = \frac{\angle AOB}{2}$ .



■

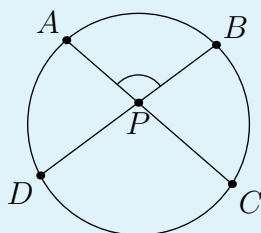
A corollary of this theorem is that if  $C$  is some point on  $\widehat{AB}$ , then  $\theta = \angle ACB$ . With the Inscribed Angle Theorem in mind, try to prove these two theorems.

**Theorem 2.4 (Angle of Secants/Tangents)** Let lines  $AX$  and  $BY$  intersect at  $P$  such that  $A, X, P$  and  $B, Y, P$  are collinear in that order. Then  $\angle APB = \frac{\angle AOB - \angle XOY}{2}$ .



Hints: ?? ?? ??

**Theorem 2.5 (Angle of Chords)** Let chords  $AC, BD$  intersect at  $P$ . Then  $\angle APB = \frac{\angle AOB + \angle COD}{2}$ .



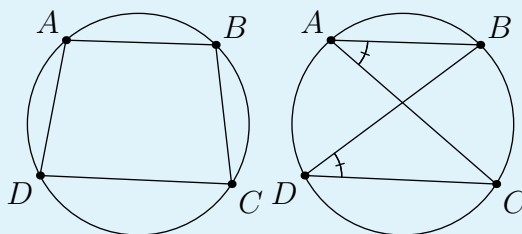
Hints: ??

## ♣ 2.4 Cyclic Quadrilaterals

Here's a very important application of the Inscribed Angle Theorem.

**Theorem 2.6 (Cyclic Quadrilaterals)** Any one of the three implies the other two:

1. Quadrilateral  $ABCD$  is cyclic.
2.  $\angle ABC + \angle ADC = 180^\circ$ .
3.  $\angle BAC = \angle BDC$ .



## ♣ 2.5 Summary

### 2.5.1 Theory

1. Supplementary Angles

♦  $A, B, C$ , are collinear if and only if for any point  $P$ ,  $\angle ABP + \angle PBC = 180^\circ$ .

- ◆ This is generalizable to more points.
- ◆  $A, B, C$  are collinear if and only if for any point  $P$ ,  $\angle PAB = \angle PAC$ .

## 2. Parallel Lines

- ◆ For parallel lines  $AB, CD$  and points  $X$  and  $Y$  on  $AB$  and  $CD$  respectively,  $\angle AXY = 180^\circ - \angle CXY = \angle DXY$ .

## 3. Inscribed Angle Theorem

- ◆ The measure of an angle is half the measure of the subtended arc.
- ◆ Proved by considering the case where one leg of the angle is a diameter and angle chasing, and generalizing.
- ◆ Thale's Theorem: In the special case where the feet of the angle form a diameter of the circle, the angle is  $90^\circ$ . The converse also holds.

## 4. Tangent Perpendicular to Radius

- ◆ This is important. Remember it.

## 5. Tangent Angle

- ◆ When you see circles and an angle condition with a tangent, keep this in mind.
- ◆ This proves points are concyclic.

## 6. Cyclic Quadrilaterals

- ◆ Angles on opposite sides are supplementary.
- ◆ Angles on the same side are congruent.

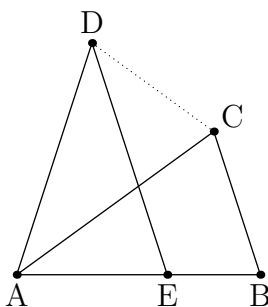
### 2.5.2 Tips and Strategies

1. Proving collinearity and concurrency for lines can basically be switched around at will.
2. One way to prove concurrency of three figures is to let two of them intersect at a point  $P$ , and prove the third passes through  $P$ .
3. If two lines are parallel, then it's probably an important part of the problem.

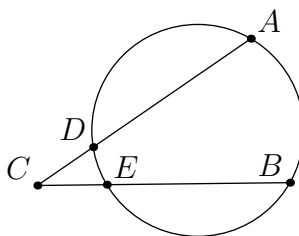
## 2.6 Exercises

### 2.6.1 Check-ins

1. Prove  $\triangle ABC$  satisfies  $\angle A + \angle B + \angle C = 180^\circ$ . **Hints:** ??
2. Prove that the sum of the interior angles of an  $n$ -gon is  $180(n - 2)$ . **Hints:** ?? ??
3. (Brazil 2004) In the figure,  $ABC$  and  $DAE$  are isosceles triangles ( $AB = AC = AD = DE$ ) and the angles  $BAC$  and  $ADE$  have measures  $36^\circ$ .
  - (a) Using geometric properties, calculate the measure of angle  $\angle EDC$ .
  - (b) Knowing that  $BC = 2$ , calculate the length of segment  $DC$ .
  - (c) Calculate the length of segment  $AC$ .



4. If  $\angle ABC = 60^\circ$  and  $\angle CAB = 70^\circ$ , find  $\widehat{AB} - \widehat{DE}$ .

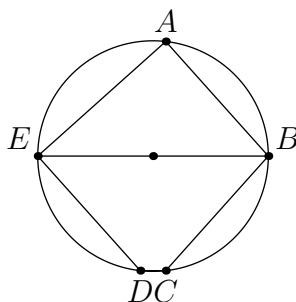


5.
  - (a) Given that  $A, B, C$ , and  $D$  are all on the same circle, that  $BE$  is the angle bisector of  $\angle ABC$ , that  $\angle AEB = \angle CEB$ , and that  $\angle ADC = 50^\circ$ , find  $\angle BAC$ .
  - (b) Given points  $A, B, C, D, E$  such that  $BE$  is the angle bisector of  $\angle ABC$ ,  $\angle AEB = \angle CEB$ ,  $\angle BAC + \angle BDC = \angle ABD + \angle ACD$ , and  $\angle ADC = 48^\circ$ , find  $\angle BCA$ .
6. Consider any cyclic pentagon  $ABCDE$ . If  $P$  is the center of  $(ABCDE)$ , then prove that  $ABCP$  is never cyclic.
7. Two circles  $\omega_1, \omega_2$  intersect at  $P, Q$ . If a line intersects  $\omega_1$  at  $A, B$  and  $\omega_2$  at  $C, D$  such that  $A, B, C, D$  lie on the line in that order, and  $P$  and  $Q$  lie on the same side of the line, compute  $\angle APC + \angle BQD$ .  
**Solution:** ??



## 2.6.2 Problems

1. Consider rectangle  $ABCD$  with  $AB = 6$ ,  $BC = 8$ . Let  $M$  be the midpoint of  $AD$  and let  $N$  be the midpoint of  $CD$ . Let  $BM$  and  $BN$  intersect  $AC$  at  $X$  and  $Y$  respectively. Find  $XY$ .
2. (AMC 10A 2019/13) Let  $\triangle ABC$  be an isosceles triangle with  $BC = AC$  and  $\angle ACB = 40^\circ$ . Construct the circle with diameter  $\overline{BC}$ , and let  $D$  and  $E$  be the other intersection points of the circle with the sides  $\overline{AC}$  and  $\overline{AB}$ , respectively. Let  $F$  be the intersection of the diagonals of the quadrilateral  $BCDE$ . What is the degree measure of  $\angle BFC$ ? **Hints:** ??
3. (Miquel's Theorem) Consider  $\triangle ABC$  with  $D$  on  $BC$ ,  $E$  on  $CA$ , and  $F$  on  $AB$ . Prove that  $(AEF)$ ,  $(BFD)$ , and  $(CDE)$  concur. **Hints:** ??
4. Consider  $\triangle ABC$  with  $D$  on segment  $BC$ ,  $E$  on segment  $CA$ , and  $F$  on segment  $AB$ . Let the circumcircles of  $\triangle FBD$  and  $\triangle DCE$  intersect at  $P \neq D$ . If  $\angle A = 50^\circ$ ,  $\angle B = 35^\circ$ , find  $\angle DPE$ .
5. Let circles  $\omega_1$  and  $\omega_2$  intersect at  $X, Y$ . Let line  $\ell_1$  passing through  $X$  intersect  $\omega_1$  at  $A$  and  $\omega_2$  at  $C$ , and let line  $\ell_2$  passing through  $Y$  intersect  $\omega_1$  at  $B$  and  $\omega_2$  at  $D$ . If  $\ell_1$  intersects  $\ell_2$  at  $P$ , prove that  $\triangle PAB \sim \triangle PCD$ . **Hints:** ??
6. (Reim's Theorem) Let circles  $\omega_1, \omega_2$  intersect at  $P, Q$ . Let line  $\ell_1$  passing through  $P$  intersect  $\omega_1$  again at  $A_1$  and  $\omega_2$  again at  $A_2$ . Let  $B_1$  be a point on  $\omega_1$  and  $B_2$  be a point on  $\omega_2$ . Then prove that  $A_1B_1 \parallel A_2B_2$  if and only if  $Q$  lies on  $B_1B_2$ .
7. (Simson's Theorem) Consider  $\triangle ABC$  and point  $P$ , and let  $X, Y, Z$  be the feet of the altitudes from  $P$  to  $BC, CA, AB$ . Prove that  $X, Y, Z$  are collinear if and only if  $P$  is on  $(ABC)$ . **Hints:** ??
8. (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  $BCD$ ?



9. (Formula of Unity 2018) A point  $O$  is the center of an equilateral triangle  $ABC$ . A circle that passes through points  $A$  and  $O$  intersects the sides  $AB$  and  $AC$  at points  $M$  and  $N$  respectively. Prove that  $AN = BM$ . **Solution:** ??
10. (Australia Math Olympiad 2019/3) Let  $A, B, C, D, E$  be five points in order on a circle  $K$ . Suppose that  $AB = CD$  and  $BC = DE$ . Let the chords  $AD$  and  $BE$  intersect at the point  $P$ . Prove that the circumcentre of triangle  $AEP$  lies on  $K$ . **Hints:** ?? ?? ?? **Solution:** ??
11. Consider square  $ABCD$  and some point  $P$  outside  $ABCD$  such that  $\angle APB = 90^\circ$ . Prove that the angle bisector of  $\angle APB$  also bisects the area of  $ABCD$ . **Hints:** ?? **Solution:** ??
12. (USAJMO 2020/4) Let  $ABCD$  be a convex quadrilateral inscribed in a circle and satisfying  $DA < AB = BC < CD$ . Points  $E$  and  $F$  are chosen on sides  $CD$  and  $AB$  such that  $BE \perp AC$  and  $EF \parallel BC$ . Prove that  $FB = FD$ .

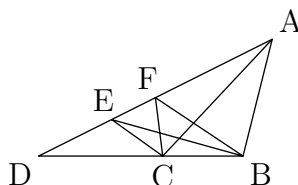
13. (IMO 2006/1) Let  $ABC$  be triangle with incenter  $I$ . A point  $P$  in the interior of the triangle satisfies

$$\angle PBA + \angle PCA = \angle PBC + \angle PCB.$$

Show that  $AP \geq AI$ , and that equality holds if and only if  $P = I$ .

### 2.6.3 Challenges

- (MAST Diagnostic 2020) Consider parallelogram  $ABCD$  with  $AB = 7$ ,  $BC = 6$ . Let the angle bisector of  $\angle DAB$  intersect  $BC$  at  $X$  and  $CD$  at  $Y$ . Let the line through  $X$  parallel to  $BD$  intersect  $AD$  at  $Q$ . If  $QY = 6$ , find  $\cos \angle DAB$ . **Hints:** ?? ?? **Solution:** ??
- (Memorial Day Mock AMC 10 2018/21) In the following diagram,  $m\angle BAC = m\angle BFC = 40^\circ$ ,  $m\angle ABF = 80^\circ$ , and  $m\angle FEB = 2m\angle DBE = 2m\angle FBE$ . What is  $m\angle ADB$ ?



**Hints:** ?? ??

- (FARML 2012/6) In triangle  $ABC$ ,  $AB = 7$ ,  $AC = 8$ , and  $BC = 10$ .  $D$  is on  $AC$  and  $E$  is on  $BC$  such that  $\angle AEC = \angle BED = \angle B + \angle C$ . Compute the length  $AD$ . **Hints:** ?? ?? **Solution:** ??
- (ISL 1994/G1)  $C$  and  $D$  are points on a semicircle. The tangent at  $C$  meets the extended diameter of the semicircle at  $B$ , and the tangent at  $D$  meets it at  $A$ , so that  $A$  and  $B$  are on opposite sides of the center. The lines  $AC$  and  $BD$  meet at  $E$ .  $F$  is the foot of the perpendicular from  $E$  to  $AB$ . Show that  $EF$  bisects angle  $CFD$ . **Hints:** ?? ?? ?? **Solution:** ??
- Consider  $\triangle ABC$  with  $D$  on line  $BC$ . Let the circumcenters of  $\triangle ABD$  and  $\triangle ACD$  be  $M, N$ , respectively. Let the circumcircle of  $\triangle MND$  intersect the circumcircle of  $\triangle ACD$  again at  $H \neq D$ . Prove that  $A, M, H$  are collinear. **Hints:** ?? ??
- (APMO 1999/3) Let  $\Gamma_1$  and  $\Gamma_2$  be two circles intersecting at  $P$  and  $Q$ . The common tangent, closer to  $P$ , of  $\Gamma_1$  and  $\Gamma_2$  touches  $\Gamma_1$  at  $A$  and  $\Gamma_2$  at  $B$ . The tangent of  $\Gamma_1$  at  $P$  meets  $\Gamma_2$  at  $C$ , which is different from  $P$ , and the extension of  $AP$  meets  $BC$  at  $R$ . Prove that the circumcircle of triangle  $PQR$  is tangent to  $BP$  and  $BR$ . **Hints:** ?? ?? ?? ?? **Solution:** ??
- Let  $K_1$  and  $K_2$  be circles that intersect at two points  $A$  and  $B$ . The tangents to  $K_1$  at  $A$  and  $B$  intersect at a point  $P$  inside  $K_2$ , and the line  $BP$  intersects  $K_2$  again at  $C$ . The tangents to  $K_2$  at  $A$  and  $C$  intersect at a point  $Q$ , and the line  $QA$  intersects  $K_1$  again at  $D$ .  
Prove that  $QP$  is perpendicular to  $PD$  if and only if the centre of  $K_2$  lies on  $K_1$ . **Hints:** ?? ?? **Solution:** ??
- (IMO 2000/1) Two circles  $G_1$  and  $G_2$  intersect at two points  $M$  and  $N$ . Let  $AB$  be the line tangent to these circles at  $A$  and  $B$ , respectively, so that  $M$  lies closer to  $AB$  than  $N$ . Let  $CD$  be the line parallel to  $AB$  and passing through the point  $M$ , with  $C$  on  $G_1$  and  $D$  on  $G_2$ . Lines  $AC$  and  $BD$  meet at  $E$ ; lines  $AN$  and  $CD$  meet at  $P$ ; lines  $BN$  and  $CD$  meet at  $Q$ . Show that  $EP = EQ$ . **Hints:** ?? ?? **Solution:** ??

## Chapter 3

# Power of a Point

---

You're a wizard, Harry.

*Harry Potter and the Philosopher's Stone*

There's only one theorem, so this will be a short chapter. The only prerequisites are angle chasing theorems in circles.

### ♣ 3.1 Power of a Point

The Power of a Point theorem helps us length chase in circles. The proof is a result of similar triangles, and its uses are numerous in lower-level competitions. If you already know this theorem, feel free to skip this section.

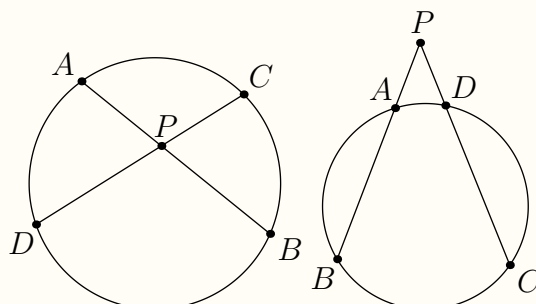
**Theorem 3.1 (Power of a Point)** Let line  $\ell_1$  intersect circle  $\omega$  at  $A, B$  and line  $\ell_2$  intersect  $\omega$  at  $C, D$ . Then  $PA \cdot PB = PC \cdot PD$ .

**Proof:** There are two cases here: Either  $P$  is inside of  $\omega$  or outside of  $\omega$ .

If  $P$  is inside of  $\omega$ , then note that by Inscribed Angle,  $\angle PAC = \angle PDB$  and  $\angle = \angle PAB$ , so  $\triangle PAC \sim \triangle PDB$ .

If  $P$  is outside of  $\omega$ , then without loss of generality, let  $PA \leq PB$  and  $PC \leq PD$ . Then note  $\angle PAC = 180^\circ - \angle CAB = \angle PDB$  and  $\angle PCA = 180^\circ - \angle ACD = \angle PBD$ , so  $\triangle PAC \sim \triangle PDB$ .

To finish, note that the similarity implies  $\frac{PA}{PC} = \frac{PD}{PB}$ , or  $PA \cdot PB = PC \cdot PD$ .



*P inside  $\omega$  and P outside  $\omega$ .*

■

In the case of tangency,  $A = B$  is the point of tangency. (You can think of a tangent line intersecting a circle twice at the same point.)

The Two Tangent Theorem is a corollary of Power of a Point. It states that the lengths of the two tangents from a point to a circle are equal.

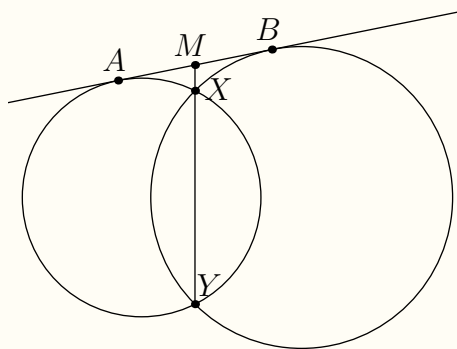
**Fact 3.1 (Two Tangent Lemma)** Let the tangents from point  $P$  to circle  $\omega$  intersect  $\omega$  at  $A, B$ . Then  $PA = PB$ . **Hints:** ?? **Solution:** ??

## ♣ 3.2 Bisector Lemma

This is a very powerful fact that kills a lot of earlier computational geometry problems involving circles.

**Fact 3.2 (Bisector Lemma)** Let  $\omega_1$  and  $\omega_2$  intersect at  $X$  and  $Y$ , and let  $\ell$  be a line tangent to  $\omega_1$  and  $\omega_2$ . If  $\ell$  intersects  $\omega_1$  at  $A$  and  $\omega_2$  at  $B$ , then  $XY$  bisects  $AB$ .

**Proof:** Let  $XY$  intersect  $AB$  at  $P$ . Then by Power of a Point,  $PX^2 = PA \cdot PB = PY^2$ .



## ♣ 3.3 Summary

### 3.3.1 Theory

#### 1. Power of a Point

- ◆ If lines  $\ell_1, \ell_2$  through  $P$  intersect circle  $\omega$  at  $A, B$  and  $C, D$ , respectively, then  $PA \cdot PB = PC \cdot PD$ .
- ◆ This is a consequence of similar triangles.

#### 2. Bisector Lemma

- ◆ The common chord of two circles bisects the common external tangent.

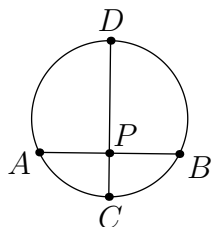
### 3.3.2 Tips and Strategies

1. If there are two circles and you're in doubt, use Bisector Lemma. (This even applies for some easier olympiad problems.)

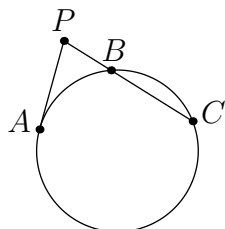
# ❖ 3.4 Exercises

## 3.4.1 Check-ins

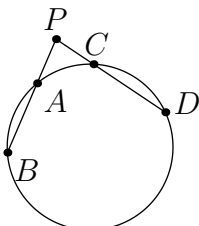
- Let chords  $AB$  and  $CD$  in circle  $\omega$  intersect at  $P$ . If  $AP = BP = 4$  and  $CP = 2$ , find  $DP$ .



- Let the tangent through  $A$  to circle  $\omega$  intersect line  $\ell$  that passes through  $B, C$  on  $\omega$  at  $P$ . If  $BP < CP$ ,  $AP = 4$ , and  $BC = 6$ , find  $BP$ .



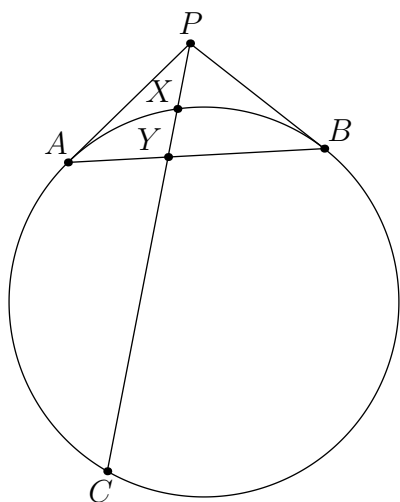
- Let line  $\ell_1$  that passes through  $A, B$  on circle  $\omega$  intersect line  $\ell_2$  that passes through  $C, D$  on  $\omega$  at  $P$ . If  $PA = 6$ ,  $AB = 12$ , and  $PC = 3$ , find  $CD$ .



- Let  $\triangle ABC$  have a right angle at  $C$  and let  $P$  be the foot of the altitude from  $C$  to  $AB$ . If the foot of the altitude from  $P$  to  $AC$  is  $X$  and the foot from  $P$  to  $BC$  is  $Y$ , then prove that  $AXYB$  is cyclic.

## 3.4.2 Problems

- Let  $PA$  and  $PB$  be tangents to circle  $\omega$ , and let line  $\ell$  through  $P$  intersect  $\omega$  at  $X$  and  $C$  and  $AB$  at  $Y$ . If  $PA = 4$ ,  $PC = 8$ ,  $AY = 1$ , and  $XY = 1$ , find the area of  $\triangle PAB$ .



2. Consider two externally tangent circles  $\omega_1, \omega_2$ . Let them have common external tangents  $AC, BD$  such that  $A, B$  are on  $\omega_1$  and  $C, D$  are on  $\omega_2$ . Let  $AC$  intersect  $BD$  at  $P$ , and let the common internal tangent intersect  $AC$  and  $BD$  at  $X$  and  $Y$ . If  $\frac{[PCD]}{[PAB]} = \frac{1}{25}$ , find  $\frac{[PCD]}{[PXY]}$ .
3. (Mandelbrot 2012) Let  $A$  and  $B$  be points on the lines  $y = 3$  and  $y = 12$ , respectively. There are two circles passing through  $A$  and  $B$  that are also tangent to the  $x$  axis, say at  $P$  and  $Q$ . Suppose that  $PQ = 2012$ . Find  $AB$ .
4. (Parody) Consider a coordinate plane with two circles tangent to the  $x$  axis at  $X, Y$ , respectively. If the circles intersect at  $P, Q$ , and  $XY = 8$ , is it possible for  $P$  to lie on  $y = 3$  and  $Q$  to lie on  $y = 12$ ?
5. (e-dchen Mock MATHCOUNTS) Consider chord  $AB$  of circle  $\omega$  centered at  $O$ . Let  $P$  be a point on segment  $AB$  such that  $AP = 2$  and  $BP = 8$ . If  $\angle APO = 150^\circ$ , what is the area of  $\omega$ ?

### ♣ 3.5 Challenges

1. (Geometry Bee 2019) Circles  $O_1$  and  $O_2$  are constructed with  $O_1$  having radius of 2,  $O_2$  having radius of 4, and  $O_2$  passing through the point  $O_1$ . Lines  $\ell_1$  and  $\ell_2$  are drawn so they are tangent to both  $O_1$  and  $O_2$ . Let  $O_1$  and  $O_2$  intersect at points  $P$  and  $Q$ . Segment  $\overline{EF}$  is drawn through  $P$  and  $Q$  such that  $E$  lies on  $\ell_1$  and  $F$  lies on  $\ell_2$ . What is the length of  $\overline{EF}$ ?
2. (AMC 10B 2013/23) In triangle  $ABC$ ,  $AB = 13$ ,  $BC = 14$ , and  $CA = 15$ . Distinct points  $D$ ,  $E$ , and  $F$  lie on segments  $\overline{BC}$ ,  $\overline{CA}$ , and  $\overline{DE}$ , respectively, such that  $\overline{AD} \perp \overline{BC}$ ,  $\overline{DE} \perp \overline{AC}$ , and  $\overline{AF} \perp \overline{BF}$ . The length of segment  $\overline{DF}$  can be written as  $\frac{m}{n}$ , where  $m$  and  $n$  are relatively prime positive integers. What is  $m + n$ ? **Solution:** ??

## Chapter 4

# Lengths and Areas in Triangles

---

Again, you can't connect the dots looking forward; you can only connect them looking backward. So you have to trust that the dots will somehow connect in your future. You have to trust in something — your gut, destiny, life, karma, whatever. This approach has never let me down, and it has made all the difference in my life.

*Steve Jobs*

### ♣ 4.1 Lengths

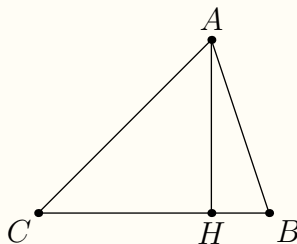
There are a couple of important lengths in a triangle. These are the lengths of cevians, the inradius/exradius, and the circumradius.

#### 4.1.1 Law of Cosines and Stewart's

We discuss how to find the third side of a triangle given two sides and an included angle, and use this to find a general formula for the length of a cevian.

**Theorem 4.1 (Law of Cosines)** Given  $\triangle ABC$ ,  $a^2 + b^2 - 2ab \cos C = c^2$ .

**Proof:** Let the foot of the altitude from  $A$  to  $BC$  be  $H$ . Then note that  $AH = b \sin C$ ,  $CH = b \cos C$ , and  $BH = |a - b \cos C|$ . (The absolute value is because  $\angle B$  can either be acute or obtuse.) Then note by the Pythagorean Theorem,  $(b \sin C)^2 + (a - b \cos C)^2 = a^2 + b^2 - 2ab \cos C = c^2$ .



■

**Theorem 4.2 (Stewart's Theorem)** Consider  $\triangle ABC$  with cevian  $AD$ , and denote  $BD = m$ ,  $CD = n$ , and  $AD = d$ . Then  $man + dad = bmb + cnc$ .

**Proof:** We use the Law of Cosines. Note that

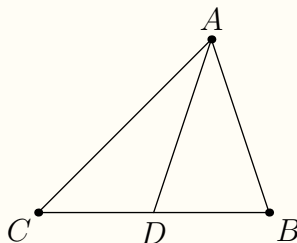
$$\cos \angle ADB = \frac{d^2 + m^2 - c^2}{2dm} = -\frac{d^2 + n^2 - b^2}{2dn} = -\cos \angle ADC.$$

Multiplying both sides by  $2dmn$  yields

$$c^2n - d^2n - m^2n = -bm^2 + d^2m + mn^2$$

$$b^2m + c^2n = mn(m + n) + d^2(m + n)$$

$$bmb + cnc = man + dad.$$



■

Here are two corollaries that will save you a lot of time in computational contests.

**Fact 4.1 (Length of Angle Bisector)** In  $\triangle ABC$  with angle bisector  $AD$ , denote  $BD = x$  and  $CD = y$ . Then

$$AD = \sqrt{bc - xy}.$$

**Fact 4.2 (Length of Median)** In  $\triangle ABC$  with median  $AD$ ,

$$AD = \frac{\sqrt{2b^2 + 2c^2 - a^2}}{2}.$$

### 4.1.2 Law of Sines and the Circumradius

The Law of Sines is a good way to length chase with a lot of angles.

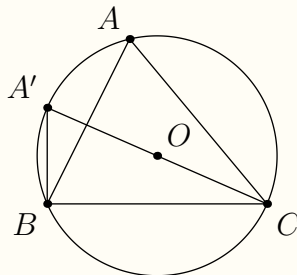
**Theorem 4.3 (Law of Sines)** In  $\triangle ABC$  with circumradius  $R$ ,

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} = 2R.$$



**Proof:** We only need to prove that  $\frac{a}{\sin A} = 2R$ , and the rest will follow.

Let the line through  $B$  perpendicular to  $AC$  intersect  $(ABC)$  again at  $A'$ . Then note that  $A'C = 2R$  by Thale's. By the Inscribed Angle Theorem,  $\sin \angle CA'B = \sin A$ , so  $\frac{a}{\sin A} = \frac{a}{\sin \angle CA'B} = \frac{a}{\frac{a}{2R}} = 2R$ .



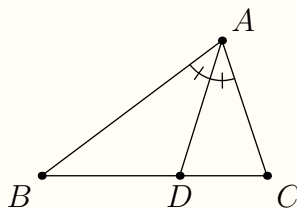
■

Other texts will call this the Extended Law of Sines. But the Extended Law of Sines has a better proof than the "normal" Law of Sines, and redundancy is bad.

The Law of Sines gives us the Angle Bisector Theorem.

**Theorem 4.4 (Angle Bisector Theorem)** Let  $D$  be the point on  $BC$  such that  $\angle BAD = \angle DAC$ . Then  $\frac{AB}{BD} = \frac{AC}{CD}$ .

**Proof:** By the Law of Sines,  $\frac{\sin \angle ADB}{\sin \angle BAD} = \frac{AB}{BD}$  and  $\frac{\sin \angle ADC}{\sin \angle CAD} = \frac{AC}{CD}$ . But note that  $\angle BAD = \angle CAD$  and  $\angle ADB + \angle ADC = 180^\circ$ , so  $\frac{AD}{BD} = \frac{AD}{CD}$ .



■

In fact, the Angle Bisector Theorem can be generalized in what is known as the ratio lemma.

**Theorem 4.5 (Ratio Lemma)** Consider  $\triangle ABC$  with point  $P$  on  $BC$ . Then  $\frac{BP}{CP} = \frac{c \sin \angle BAP}{b \sin \angle CAP}$ .

The proof is pretty much identical to the proof for Angle Bisector Theorem.

**Proof:** By the Law of Sines,  $BP = \frac{c \sin \angle BAP}{\sin \angle APB}$  and  $CP = \frac{b \sin \angle CAP}{\sin \angle APC}$ . Since  $\sin \angle APB = \sin \angle APC$ ,

$$\frac{BP}{CP} = \frac{c \sin \angle BAP}{b \sin \angle CAP}.$$

■

Note that this remains true even if  $P$  is on the *extension* of  $BC$ .

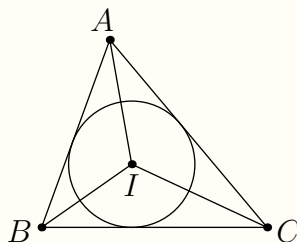
### 4.1.3 The Incircle, Excircle, and Tangent Chasing

We provide formulas for the inradius, exradii, and take a look at some uses of the Two Tangent Theorem. Recall that the Two Tangent Theorem states that if the tangents from  $P$  to  $\omega$  intersect  $\omega$  at  $A, B$ , then  $PA = PB$ .

**Theorem 4.6** ( $rs$ ) In  $\triangle ABC$  with inradius  $r$ ,

$$[ABC] = rs.$$

**Proof:** Note that  $[ABC] = r \cdot \frac{a+b+c}{2} = rs$ .



■

A useful fact of the incircle is that the length of the tangents from  $A$  is  $s - a$ . Similar results hold for the  $B, C$  tangents to the incircle.

**Fact 4.3 (Tangents to Incircle)** Let the incircle of  $\triangle ABC$  be tangent to  $BC, CA, AB$  at  $D, E, F$ . Then

$$AE = AF = s - a$$

$$BF = BD = s - b$$

$$CD = CE = s - c.$$

**Proof:** Note that by the Two Tangent Theorem,  $AE = AF = x$ ,  $BF = BD = y$ , and  $CD = CE = z$ . Also note that

$$BD + CD = y + z = a$$

$$CE + EA = z + x = b$$

$$AF + FB = x + y = c.$$

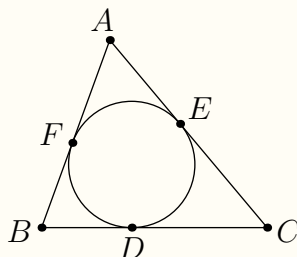
Adding these equations gives  $2x + 2y + 2z = a + b + c = 2s$ , implying  $x + y + z = s$ . Thus

$$x = AE = AF = s - a$$

$$y = BF = BD = s - b$$

$$z = CD = CE = s - c,$$

as desired.

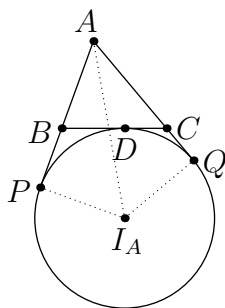


■

**Theorem 4.7** ( $r_a(s - a)$ ) In  $\triangle ABC$  with  $A$  exradius  $r_a$ ,

$$[ABC] = r_a(s - a).$$

**Proof:** Let  $AB, AC$  be tangent to the  $A$  excircle at  $P, Q$ , respectively, and let  $BC$  be tangent to the  $A$  excircle at  $D$ . Then note that by the Two Tangent Theorem,  $PB = BD$  and  $DC = CQ$ . Thus  $[ABC] = [API_A] + [AQI_A] - 2[B I_A C] = r_a \cdot \frac{s+s-2a}{2} = r_a(s - a)$ . ■

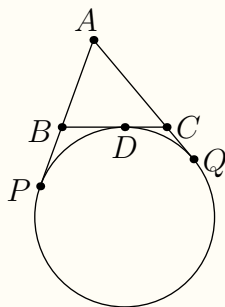


The proof also implies the following corollary.

**Fact 4.4 (Tangents to Excircle)** Let the  $A$  excircle of  $\triangle ABC$  be tangent to  $BC$  at  $D$ . Then  $BD = s - c$  and  $CD = s - b$ .

Analogous equations hold for the  $B$  and  $C$  excircles.

**Proof:** Let the  $A$  excircle be tangent to line  $AB$  at  $P$  and line  $AC$  at  $Q$ . Note that  $AP = AB + BP = c + BD$  and  $AQ = AC + CQ = b + CD$  by the Two Tangent Theorem. Applying the Two Tangent Theorem again gives  $AP = AQ$ , or  $c + BD = b + CD$ . Also note that  $AP + AQ = b + c + BD + DC = 2s$ , so  $AP = AQ = s$  and  $s = c + BD = b + CD$ . Thus  $BD = s - c$  and  $CD = s - b$ .



Keep these area and length conditions in mind when you see incircles and excircles.

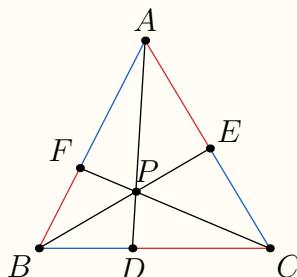
#### 4.1.4 Concurrency with Cevians

We discuss Ceva's Theorem, Menelaus Theorem, and mass points, three ways to look at concurrent cevians. Very rarely do problems involving concurrency with cevians appear on higher level contests, but they're fairly common in the AMC 8 and MATHCOUNTS. This is also a good tool to have for when you need it.

**Theorem 4.8 (Ceva's Theorem)** In  $\triangle ABC$  with cevians  $AD, BE, CF$ , they concur if and only if  $\frac{AF}{FB} \cdot \frac{BD}{DC} \cdot \frac{CE}{EA} = 1$ .

**Proof:** Let the point of concurrency be  $P$ . Note that  $\frac{[ABD]}{[ADC]} = \frac{[PBD]}{[PDC]} = \frac{BD}{DC}$ , so  $\frac{[BPA]}{[APC]} = \frac{BD}{DC}$ . Thus,

$$\frac{CE}{EA} \cdot \frac{AF}{FB} \cdot \frac{BD}{DC} = \frac{[CPB]}{[BPA]} \cdot \frac{[APC]}{[CPB]} \cdot \frac{[BPA]}{[APC]} = 1.$$



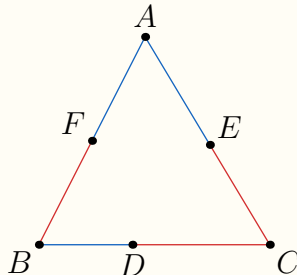
■

A good way to remember what goes in the numerator and denominator is by looking at the colors and thinking about them alternating.

We present an example of what not to do.

**Example 4.1 (Order Mixed Up)** Consider  $\triangle ABC$  with  $D, E, F$  on  $BC, CA, AB$  respectively, such that  $BD = 4$ ,  $DC = 6$ ,  $AE = 6$ ,  $EC = 4$ , and  $AF = BF = 5$ . Are  $AD$ ,  $BE$ , and  $CF$  concurrent?

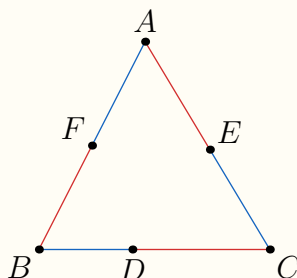
**Solution (Bogus):** Yes. Note that  $\frac{4}{6} \cdot \frac{6}{4} \cdot \frac{5}{5} = 1$ .



■

This is not right, as the order of the lengths is messed up (intentionally) in the problem statement. (Also note the colors are messed up.) We now present the correct solution.

**Solution (Correct):** No. Note that  $\frac{BD}{DC} \cdot \frac{CE}{EA} \cdot \frac{AF}{FB} = \frac{4}{6} \cdot \frac{4}{6} \cdot \frac{5}{5} = \frac{4}{9}$ , which is not 1.



■

**Theorem 4.9 (Menelaus)** Consider  $\triangle ABC$  with  $D, E, F$  on lines  $BC, CA, AB$ , respectively. Then  $D, E, F$  are collinear if  $\frac{DB}{BF} \cdot \frac{FA}{AE} \cdot \frac{EC}{CD} = 1$ .

This looks very similar to Ceva - in fact, the letters just switched. Instead of the line segments cycling through  $D, E, F$ , they now cycle through  $A, B, C$ .

**Proof:** Draw a line through  $A$  parallel to  $DE$  and let it intersect  $BC$  at  $P$ . Then note that  $\triangle ABP \sim \triangle FBD$  and  $\triangle ECD \sim \triangle ACP$ , so

$$\frac{AF}{FB} = \frac{PD}{DB}$$

$$\frac{EC}{EA} = \frac{DC}{DP}$$

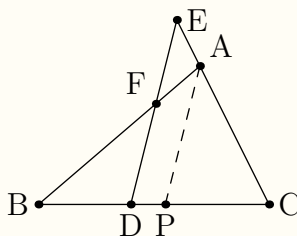
Multiplying the two together yields

$$\frac{AF}{FB} \cdot \frac{BD}{DC} = \frac{EA}{CE},$$

which implies that

$$\frac{AF}{FB} \cdot \frac{BD}{DC} \cdot \frac{CE}{EA} = 1,$$

as desired. ■

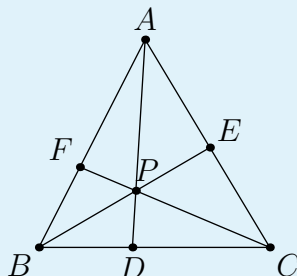


The converse states that  $\frac{DB}{BF} \cdot \frac{FA}{AE} \cdot \frac{EC}{CD} = -1$ , where all lengths are directed. (The directed lengths are necessary. In the original theorem, fixing  $D, E$  leaves two possible locations for  $F$ , only one of which actually lies on  $DE$ .)

**Theorem 4.10 (Mass Points)** Consider segment  $XY$  with  $P$  on  $XY$ . Then assign masses  $\diamond X, \diamond Y$  to points  $X, Y$  such that  $\frac{XP}{YP} = \frac{\diamond Y}{\diamond X}$ .



Now consider cevians  $AD, BE, CF$  of  $\triangle ABC$  that concur at some point  $P$ . Then  $\frac{AP}{PD} = \frac{\diamond B + \diamond C}{\diamond A}$ . This means that for  $P$  on  $XY$ , we can define  $\diamond P = \diamond X + \diamond Y$ .

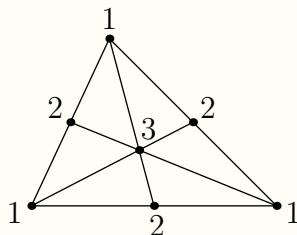


This is a direct application of Ceva's and Menelaus. This is somewhat abstract without an example, so we present the centroid as an example.

**Example 4.2 (Centroid)** Assign masses to  $\triangle ABC$ , its midpoints, and its centroid.

**Solution:** Note  $\diamond A = \diamond B = \diamond C$ . Without loss of generality, let  $\diamond A = 1$ .

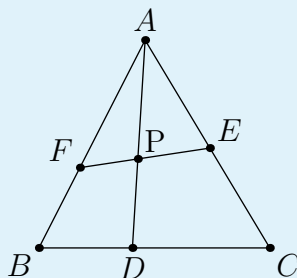
Then note that since  $\diamond X + \diamond Y = \diamond P$  for  $P$  on segment  $XY$ ,  $\diamond D = \diamond B + \diamond C = 2$ . Similarly,  $\diamond E = \diamond F = 2$ , and  $\diamond G = \diamond A + \diamond D = 1 + 2 = 3$ .



**Theorem 4.11 (Mass Points with Transversals)** Consider  $\triangle ABC$  with points  $D, E, F$  on sides  $BC, CA, AB$ , and let  $AD$  intersect  $FE$  at  $P$ . Then  $\diamond A = \diamond B \cdot \frac{BF}{FA} + \diamond C \cdot \frac{CE}{EA}$ .

This is equivalent to

$$\frac{AP}{PD} = \frac{\diamond B + \diamond C}{\diamond B \cdot \frac{BF}{FA} + \diamond C \cdot \frac{CE}{EA}} = \frac{BC}{CD \cdot \frac{BF}{FA} + BD \cdot \frac{CE}{EA}}.$$



The classic analogy is having  $A_1$  on  $AB$  and  $A_2$  on  $AC$ , and adding  $\diamond A_1 + \diamond A_2$  where the masses are taken with respect to  $AB$  and  $AC$  individually.

You can prove this with Law of Cosines. We present the outline of the proof (the actual algebraic manipulations are very long; this is just a demonstration that it can be proven true).

**Proof:** There is exactly one value of  $AP$  such that

$$FP + PE = FE,$$

where

$$FP = \sqrt{AF^2 + AP^2 - 2 \cdot AF \cdot AP \cos \angle BAD}$$

$$PE = \sqrt{AE^2 + AP^2 - 2 \cdot AE \cdot AP \cos \angle CAD}$$

$$FE = \sqrt{AE^2 + AF^2 - 2 \cdot AE \cdot AF \cos \angle BAC},$$

and all you have to do is verify

$$AG = \frac{BC \cdot GD}{CD \cdot \frac{BF}{FA} + BD \cdot \frac{CE}{EA}}$$

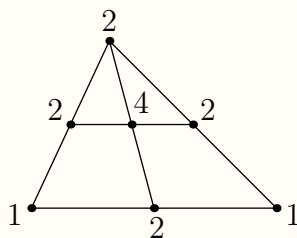
indeed works.

As an example, we use a midsegment and a median.

**Example 4.3 (Midsegment)** Assign masses to  $\triangle ABC$ ,  $A$ -midsegment  $EF$ , median  $AD$ , and the point  $P$  that lies on  $AD$  and  $EF$ .

**Solution:** Note  $\diamond A = \diamond B \cdot \frac{BF}{FA} + \diamond C \cdot \frac{CE}{EA} = \diamond B + \diamond C$ . Without loss of generality, let  $\diamond B = \diamond C = 1$ . Then  $\diamond A = 2$ .

Also note that  $\diamond D = \diamond B + \diamond C = 2$  and  $\diamond P = \diamond A + \diamond D = 4$ .

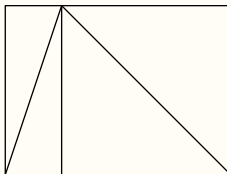


## 4.2 Areas

There are a variety of methods to find area. For harder problems, computing the area in two different ways can give useful information about the configuration.

**Theorem 4.12** ( $\frac{bh}{2}$ ) The area of a triangle is  $\frac{bh}{2}$ .

**Proof:** The area of each right triangle is half of the area of the rectangle it is in.

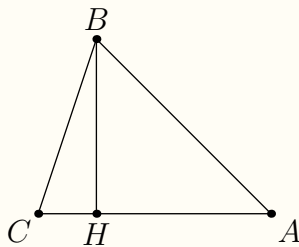


**Theorem 4.13** ( $rs$ ) The area of a triangle is  $rs$ , where  $r$  is the inradius and  $s$  is the semiperimeter.

We have already proved this in Length Chasing - but we mention this theorem again because it is useful for area too.

**Theorem 4.14** ( $\frac{1}{2}ab \sin C$ ) The area of a triangle is  $\frac{1}{2}ab \sin C$ , where  $a, b$  are side lengths and  $C$  is the included angle.

**Proof:** Drop an altitude from  $B$  to  $AC$  and let it have length  $h$ . Then note  $\frac{1}{2} \cdot a \sin C \cdot b = \frac{1}{2} \cdot hb = \frac{bh}{2}$ .



■

We present a useful corollary of this theorem.

**Fact 4.5** ( $\frac{[PAB]}{[PXY]} = \frac{PA \cdot PB}{PX \cdot PY}$ ) Let  $P, A, X$  be on  $\ell_1$  and  $P, B, Y$  be on  $\ell_2$ . Then  $\frac{[PAB]}{[PXY]} = \frac{PA \cdot PB}{PX \cdot PY}$ .

**Proof:** Note  $\frac{[PAB]}{[PXY]} = \frac{\frac{1}{2} \cdot PA \cdot PB \cdot \sin \theta}{\frac{1}{2} \cdot PX \cdot PY \cdot \sin \theta} = \frac{PA \cdot PB}{PX \cdot PY}$ , where  $\theta = \angle APB$ .

This works for all configurations since  $\sin \theta = \sin(180 - \theta)$ .

■

**Theorem 4.15** ( $\frac{abc}{4R}$ ) In  $\triangle ABC$  with side lengths  $a, b, c$  and circumradius  $R$ ,

$$[ABC] = \frac{abc}{4R}.$$

**Proof:** Note that  $[ABC] = \frac{1}{2}ab \sin C = \frac{1}{2}ab \cdot \frac{c}{2R} = \frac{abc}{4R}$ .

■

Heron's Formula can find the area of a triangle with *only* the side lengths.

**Theorem 4.16 (Heron's Formula)** In  $\triangle ABC$  with sidelengths  $a, b, c$  such that  $s = \frac{a+b+c}{2}$ ,

$$[ABC] = \sqrt{s(s-a)(s-b)(s-c)}.$$

**Proof:** Since  $\cos C = \frac{a^2+b^2-c^2}{2ab}$ , the Pythagorean Identity gives us

$$\sin C = \sqrt{\frac{4a^2b^2 - (a^2 + b^2 - c^2)^2}{4a^2b^2}} = \sqrt{\frac{(a+b+c)(-a+b+c)(a-b+c)(a+b-c)}{4a^2b^2}}.$$

So

$$\frac{1}{2}ab \sin C = \sqrt{\left(\frac{a+b+c}{2}\right)\left(\frac{-a+b+c}{2}\right)\left(\frac{a-b+c}{2}\right)\left(\frac{a+b-c}{2}\right)} = \sqrt{s(s-a)(s-b)(s-c)}.$$

■

Heron's Formula has a reputation for being notoriously tricky to prove, but the proof isn't too bad if you consider what we're actually doing.

1. Use the Law of Cosines to find  $\cos C$ .



2. Use the Pythagorean Identity to find  $\sin C$ .
3. Use  $\frac{1}{2}ab\sin C$  to find  $[ABC]$ .
4. Clean the expression up.

**Fact 4.6 (Heron's with Altitudes)** If  $x, y, z$  are the lengths of the altitudes of  $\triangle ABC$ ,

$$\frac{1}{[ABC]} = \sqrt{\left(\frac{1}{x} + \frac{1}{y} + \frac{1}{z}\right) \left(-\frac{1}{x} + \frac{1}{y} + \frac{1}{z}\right) \left(\frac{1}{x} - \frac{1}{y} + \frac{1}{z}\right) \left(\frac{1}{x} + \frac{1}{y} - \frac{1}{z}\right)}.$$

Hints: ??

## ♠ 4.3 Summary

### 4.3.1 Theory

1. Law of Cosines

$$\blacklozenge a^2 + b^2 - 2ab \cos C = c^2.$$

2. Stewart's Theorem

$$\blacklozenge man + dad = bmb + cnc.$$

$$\blacklozenge \sqrt{bc - xy} \text{ gives the length of angle bisector } AD.$$

$$\blacklozenge \frac{\sqrt{2b^2 + 2c^2 - a^2}}{2} \text{ gives the length of median } AD.$$

3. Law of Sines

$$\blacklozenge \frac{a}{\sin A} = 2R.$$

4. Angle Bisector Theorem and Ratio Lemma

$$\blacklozenge \text{ If } AD \text{ bisects } \angle BAC, \text{ then } \frac{AB}{BD} = \frac{AC}{CD}.$$

$$\blacklozenge \text{ Generally, } \frac{BP}{CP} = \frac{c \sin \angle BAP}{b \sin \angle CAP}.$$

5. Tangents

$$\blacklozenge \text{ Two Tangent Theorem}$$

$$\blacklozenge \text{ The tangent is perpendicular to the radius.}$$

$$\blacklozenge [ABC] = rs.$$

$$\blacklozenge [ABC] = r_a(s - a).$$

$$\blacklozenge \text{ Lengths of tangents to the incircle from the vertices are } s - a, s - b, s - c.$$

$$\blacklozenge \text{ Lengths of tangents to the excircles from the vertices are also } s - a, s - b, s - c \text{ (but in a different order).}$$

6. Concurrency and Collinearity

$$\blacklozenge \text{ Ceva's states } \frac{AF}{FB} \cdot \frac{BE}{EC} \cdot \frac{CD}{DA} = 1.$$

$$\blacklozenge \text{ Menelaus states } \frac{DB}{BF} \cdot \frac{FA}{AE} \cdot \frac{EC}{CD} = 1.$$

## 7. Mass Points

- ◆  $\frac{XP}{YP} = \frac{\diamond Y}{\diamond X}$ .
- ◆  $\diamond X + \diamond Y = \diamond P$ .

## 8. Area

- ◆  $\frac{bh}{2}$
- ◆  $rs$
- ◆  $\frac{1}{2}ab \sin C$
- ◆  $\frac{abc}{4R}$
- ◆ Heron's ( $\sqrt{s(s-a)(s-b)(s-c)}$ )

**4.3.2 Tips and Strategies**

1. Use the Law of Sines and Law of Cosines when convenient angles exist.
  - ◆ These can be supplementary, congruent, special, etc.
  - ◆ Use Stewart's when angles are not explicitly present but you need to find a cevian's length anyway.
2. If you have tangents, do length chasing. You will need it.
3.  $\frac{1}{2}ab \sin C$  gives ratios of areas. (In general, whenever angles are the same or supplementary, use  $\frac{1}{2}ab \sin C$  to get information.)
4. Use two methods to calculate area.
  - ◆ This can give you information about a problem; after all, area doesn't change. So now you can set two seemingly unrelated things equal.

## 4.4 Exercises

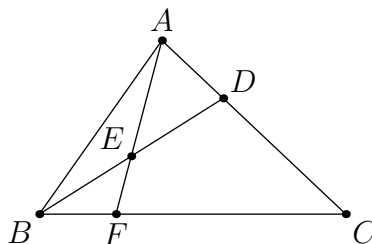
### 4.4.1 Check-ins

- Find the inradius of the triangles with the following lengths:

- 3, 4, 5
- 5, 12, 13
- 13, 14, 15
- 5, 7, 8

(These are arranged by difficulty. All of these are good to know.)

- Prove that in a right triangle with legs of length  $a, b$  and hypotenuse with length  $c$ ,  $r = \frac{a+b-c}{2}$ .
- In  $\triangle ABC$ ,  $AB = 5$ ,  $BC = 12$ , and  $CA = 13$ . Points  $D, E$  are on  $BC$  such that  $BD = DC$  and  $\angle BAE = \angle CAE$ . Find  $[ADE]$ . **Hints:** ?? **Solution:** ??
- (Gergonne Point) Let the incircle of  $\triangle ABC$  be tangent to  $BC, CA, AB$  at  $D, E, F$ , respectively. Prove that  $AD, BE, CF$  concur. **Hints:** ??
- (Nagel Point) Let the  $A$  excircle of  $\triangle ABC$  be tangent to  $BC$  at  $D$ , and define  $E, F$  similarly. Prove that  $AD, BE, CF$  concur. **Hints:** ??
- (AMC 8 2019/24) In triangle  $ABC$ , point  $D$  divides side  $\overline{AC}$  so that  $AD : DC = 1 : 2$ . Let  $E$  be the midpoint of  $\overline{BD}$  and let  $F$  be the point of intersection of line  $BC$  and line  $AE$ . Given that the area of  $\triangle ABC$  is 360, what is the area of  $\triangle EBF$ ?



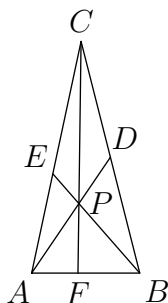
- Consider  $\triangle ABC$  where  $X, Y$  are on  $BC, CA$  such that  $\frac{BX}{CX} = \frac{1}{4}$ ,  $\frac{CY}{YA} = \frac{2}{3}$ . If  $AX, BY$  intersect at  $Z$ , find  $\frac{AZ}{ZX}$ .
- Given  $\triangle ABC$  with  $E, F$  on line segments  $AC, AB$  such that  $AE : EC = BF : FA = 1 : 3$  and median  $AD$  that intersects  $EF$  at  $G$ ,  $AG : GD$ .
- A triangle has side lengths 4, 8,  $x$  and area  $3\sqrt{15}$ . Find  $x$ .
- Find the sum of the altitudes of a triangle with side lengths 5, 7, 8.
- Let  $\angle BAC = 30^\circ$  and let  $P$  be the midpoint of  $AC$ . If  $\angle BPC = 45^\circ$ , what is  $\angle ABC$ ? **Hints:** ??
- Given  $\triangle ABC$ , find  $\sin A \sin B \sin C$  in terms of  $[ABC]$  and  $abc$ .

**4.4.2 Problems**

1. Consider  $\triangle ABC$  with  $AB = 7$ ,  $BC = 8$ ,  $AC = 6$ . Let  $AD$  be the angle bisector of  $\angle BAC$  and let  $E$  be the midpoint of  $AC$ . If  $BE$  and  $AD$  intersect at  $G$ , find  $AG$ .
2. Find the maximum area of a triangle with two of its sides having lengths 10, 11.
3. Consider trapezoid  $ABCD$  with bases  $AB$  and  $CD$ . If  $AC$  and  $BD$  intersect at  $P$ , prove the sum of the areas of  $\triangle ABP$  and  $\triangle CDP$  is at least half the area of trapezoid  $ABCD$ .
4. Consider rectangle  $ABCD$  such that  $AB = 2$  and  $BC = 1$ . Let  $X, Y$  trisect  $AB$ . Then let  $DX$  and  $DY$  intersect  $AC$  at  $P$  and  $Q$ , respectively. What is the area of quadrilateral  $XYQP$ ?
5. (Autumn Mock AMC 10) Equilateral triangle  $ABC$  has side length 6. Points  $D, E, F$  lie within the lines  $AB, BC$  and  $AC$  such that  $BD = 2AD$ ,  $BE = 2CE$ , and  $AF = 2CF$ . Let  $N$  be the numerical value of the area of triangle  $DEF$ . Find  $N^2$ .
6. Consider  $\triangle ABC$  such that  $AB = 8$ ,  $BC = 5$ , and  $CA = 7$ . Let  $AB$  and  $CA$  be tangent to the incircle at  $T_C, T_B$ , respectively. Find  $[AT_B T_C]$ . **Hints:** ??
7. Consider  $\triangle ABC$  with an area of 60, inradius of 3, and circumradius of  $\frac{17}{2}$ . Find the side lengths of the triangle.
8. (AIME I 2019/2) In  $\triangle PQR$ ,  $PR = 15$ ,  $QR = 20$ , and  $PQ = 25$ . Points  $A$  and  $B$  lie on  $\overline{PQ}$ , points  $C$  and  $D$  lie on  $\overline{QR}$ , and points  $E$  and  $F$  lie on  $\overline{PR}$ , with  $PA = QB = QC = RD = RE = PF = 5$ . Find the area of hexagon  $ABCDEF$ .
9. (PUMaC 2016) Let  $ABCD$  be a cyclic quadrilateral with circumcircle  $\omega$  and let  $AC$  and  $BD$  intersect at  $X$ . Let the line through  $A$  parallel to  $BD$  intersect line  $CD$  at  $E$  and  $\omega$  at  $Y \neq A$ . If  $AB = 10$ ,  $AD = 24$ ,  $XA = 17$ , and  $XB = 21$ , then the area of  $\triangle DEY$  can be written in simplest form as  $\frac{m}{n}$ . Find  $m + n$ .
10. (AIME I 2001/4) In triangle  $ABC$ , angles  $A$  and  $B$  measure 60 degrees and 45 degrees, respectively. The bisector of angle  $A$  intersects  $\overline{BC}$  at  $T$ , and  $AT = 24$ . The area of triangle  $ABC$  can be written in the form  $a + b\sqrt{c}$ , where  $a$ ,  $b$ , and  $c$  are positive integers, and  $c$  is not divisible by the square of any prime. Find  $a + b + c$ .

**4.4.3 Challenges**

1. (CIME 2020) An excircle of a triangle is a circle tangent to one of the sides of the triangle and the extensions of the other two sides. Let  $ABC$  be a triangle with  $\angle ACB = 90^\circ$  and let  $r_A, r_B, r_C$  denote the radii of the excircles opposite to  $A, B, C$ , respectively. If  $r_A = 9$  and  $r_B = 11$ , then  $r_C$  can be expressed in the form  $m + \sqrt{n}$ , where  $m$  and  $n$  are positive integers and  $n$  is not divisible by the square of any prime. Find  $m + n$ .
2. Consider  $ABC$  with  $\angle A = 45^\circ$ ,  $\angle B = 60^\circ$ , and with circumcenter  $O$ . If  $BO$  intersects  $CA$  at  $E$  and  $CO$  intersects  $AB$  at  $F$ , find  $\frac{[AFE]}{[ABC]}$ .
3. (AIME 1989/15) Point  $P$  is inside  $\triangle ABC$ . Line segments  $APD$ ,  $BPE$ , and  $CPF$  are drawn with  $D$  on  $BC$ ,  $E$  on  $AC$ , and  $F$  on  $AB$  (see the figure at right). Given that  $AP = 6$ ,  $BP = 9$ ,  $PD = 6$ ,  $PE = 3$ , and  $CF = 20$ , find the area of  $\triangle ABC$ .



4. (AIME II 2019/11) Triangle  $ABC$  has side lengths  $AB = 7$ ,  $BC = 8$ , and  $CA = 9$ . Circle  $\omega_1$  passes through  $B$  and is tangent to line  $AC$  at  $A$ . Circle  $\omega_2$  passes through  $C$  and is tangent to line  $AB$  at  $A$ . Let  $K$  be the intersection of circles  $\omega_1$  and  $\omega_2$  not equal to  $A$ . Then  $AK = \frac{m}{n}$ , where  $m$  and  $n$  are relatively prime positive integers. Find  $m + n$ . **Hints: ??**
5. (AIME II 2016/10) Triangle  $ABC$  is inscribed in circle  $\omega$ . Points  $P$  and  $Q$  are on side  $\overline{AB}$  with  $AP < AQ$ . Rays  $CP$  and  $CQ$  meet  $\omega$  again at  $S$  and  $T$  (other than  $C$ ), respectively. If  $AP = 4$ ,  $PQ = 3$ ,  $QB = 6$ ,  $BT = 5$ , and  $AS = 7$ , then  $ST = \frac{m}{n}$ , where  $m$  and  $n$  are relatively prime positive integers. Find  $m + n$ .
6. (AIME II 2005/14) In triangle  $ABC$ ,  $AB = 13$ ,  $BC = 15$ , and  $CA = 14$ . Point  $D$  is on  $\overline{BC}$  with  $CD = 6$ . Point  $E$  is on  $\overline{BC}$  such that  $\angle BAE \cong \angle CAD$ . Given that  $BE = \frac{p}{q}$  where  $p$  and  $q$  are relatively prime positive integers, find  $q$ .
7. (AIME I 2019/11) In  $\triangle ABC$ , the sides have integer lengths and  $AB = AC$ . Circle  $\omega$  has its center at the incenter of  $\triangle ABC$ . An excircle of  $\triangle ABC$  is a circle in the exterior of  $\triangle ABC$  that is tangent to one side of the triangle and tangent to the extensions of the other two sides. Suppose that the excircle tangent to  $\overline{BC}$  is internally tangent to  $\omega$ , and the other two excircles are both externally tangent to  $\omega$ . Find the minimum possible value of the perimeter of  $\triangle ABC$ .
8. (ART 2019/6) Consider unit circle  $O$  with diameter  $AB$ . Let  $T$  be on the circle such that  $TA < TB$ . Let the tangent line through  $T$  intersect  $AB$  at  $X$  and intersect the tangent line through  $B$  at  $Y$ . Let  $M$  be the midpoint of  $YB$ , and let  $XM$  intersect circle  $O$  at  $P$  and  $Q$ . If  $XP = MQ$ , find  $AT$ . **Hints: ?? ?? ?? ?? Solution: ??**
9. (AIME I 2020/13) Point  $D$  lies on side  $BC$  of  $\triangle ABC$  so that  $\overline{AD}$  bisects  $\angle BAC$ . The perpendicular bisector of  $\overline{AD}$  intersects the bisectors of  $\angle ABC$  and  $\angle ACB$  in points  $E$  and  $F$ , respectively. Given that  $AB = 4$ ,  $BC = 5$ ,  $CA = 6$ , the area of  $\triangle AEF$  can be written as  $\frac{m\sqrt{n}}{p}$ , where  $m$  and  $p$  are relatively prime positive integers, and  $n$  is a positive integer not divisible by the square of any prime. Find  $m + n + p$ .
10. (USAMO 1999/6) Let  $ABCD$  be an isosceles trapezoid with  $AB \parallel CD$ . The inscribed circle  $\omega$  of triangle  $BCD$  meets  $CD$  at  $E$ . Let  $F$  be a point on the (internal) angle bisector of  $\angle DAC$  such that  $EF \perp CD$ . Let the circumscribed circle of triangle  $ACF$  meet line  $CD$  at  $C$  and  $G$ . Prove that the triangle  $AFG$  is isosceles. **Hints: ??**
11. (ISL 2003/G1) Let  $ABCD$  be a cyclic quadrilateral. Let  $P$ ,  $Q$ ,  $R$  be the feet of the perpendiculars from  $D$  to the lines  $BC$ ,  $CA$ ,  $AB$ , respectively. Show that  $PQ = QR$  if and only if the bisectors of  $\angle ABC$  and  $\angle ADC$  are concurrent with  $AC$ .
12. (CIME 2019) Let  $\triangle ABC$  be a triangle with circumcenter  $O$  and incenter  $I$  such that the lengths of the three segments  $AB$ ,  $BC$  and  $CA$  form an increasing arithmetic progression in this order. If  $AO = 60$  and  $AI = 58$ , then the distance from  $A$  to  $BC$  can be expressed as  $\frac{m}{n}$ , where  $m$  and  $n$  are relatively prime positive integers. Find  $m + n$ .

## Chapter 5

## Hints

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If anyone tells me it's a mistake to have hope, well then, I'll just tell them, they're wrong. And I'll keep telling them until they believe. No matter how many times it takes.

*Puella Magi Madoka Magica*

1.  $R$  seems somewhat pesky. Can you find other stuff  $R$  is involved with?
2.  $F$  is a *specific* point.
3. There are three more cyclic quadrilaterals.
4. Draw  $AE$ .
5. Equal sides mean equal arclengths.
6. Find  $\frac{[AT_BTC]}{[ABC]}$ .
7. Look for similar and congruent triangles.
8. Draw a line through  $A$  parallel to  $BC$ .
9. Reduce the problem to a bunch of triangles.
10. We know the height. What else do we need?
11. Use power of a point to relate  $PA$  and  $PB$ .
12. Use the tangent angle condition to angle chase.
13. Note  $x = \frac{[ABC]}{2a}$ .
14. Look for collinear points.
15. How can you express  $\frac{\angle DOE}{2}$  and  $\frac{\angle AOB}{2}$ ?
16. Drop an altitude from  $B$  to  $CA$ .
17. Reflect  $P$  about the midpoint of  $AB$ .
18. How can you find the proportions of the lengths with the knowledge that  $OX = OM$ ?
19. Let  $MN$  intersect  $AB$  at  $O$ .
20. Look at  $\angle AEC$ .
21. Prove  $\triangle ABC \sim \triangle EDC \sim \triangle EBA$ .
22. Find the area of  $\triangle XYY'$  in two ways.
23.  $BCDP$  is a parallelogram.

24. Look for similar triangles.
25. Use Tangent/Secant to set up a system of equations.
26. Reflect  $Y$  about  $XB$  to get  $Y'$ .
27. Look at  $\triangle BIC$ .
28. Two Tangent Theorem.
29. Where do  $BC$  and  $DA$  meet?
30. Look for similar triangles.
31.  $\triangle AOP$  is isosceles.
32. Look for parallel lines.
33. Show that  $BP = BR$ .
34. How would you find  $BX$  and  $DY$ ?
35. What is  $\angle BCD$ ?
36. What does  $XP = MQ$  really mean?
37. Add stuff so that the angle bisector of  $\angle APB$  the diagonal of a square as well.
38. What is the foot of the perpendicular from  $E$  to  $PQ$ ?
39. Note  $\angle APB = 180^\circ - \angle BAP - \angle ABP$ .
40. There is a cyclic quadrilateral with  $O_2$  on it.
41. Prove that  $ABRQ$  is cyclic.
42. Have you found  $\frac{b^2+c^2}{a^2}$  yet?
43. What does  $\triangle AMN \sim \triangle DMN \sim \triangle ABC$  tell you?
44. Look for cyclic quadrilaterals.
45. Two Tangent Theorem.
46. Note that  $BO = AO$ .
47. What information do cyclic quadrilaterals give you?
48. Look at  $\triangle GBC$ .
49. You can get  $BE$  and  $BF$  (via Stewart's), so you can get  $BG$  and  $CG$ .
50. Let  $(BFD)$  intersect  $(CDE)$  at  $P$ .
51. Draw in the center of the semicircle.
52. Pick a point. Draw all the diagonals connected to that point.
53. Remember that  $QX$  and  $DB$  are parallel. How does this help you find  $QD$ ?

## Chapter 6

# Solutions

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Regret your helplessness, and feel despair.

*Psycho-Pass*

1. Let  $O$  be the center of the circle. Notice that this implies that  $OM = OX$ . We claim that if  $BM = x$ , then  $XT = x$  as well.

By the Pythagorean Theorem,  $OM = \sqrt{x^2 + 1}$ . Since  $OM = OX$ ,  $AX = \sqrt{x^2 + 1} - 1$ . Then by Power of a Point,  $XT = \sqrt{XA \cdot XB} = (\sqrt{x^2 + 1} - 1)(\sqrt{x^2 + 1} + 1) = x$ , as desired.

Also, by the Pythagorean Theorem,  $BX = \sqrt{5}x$ .

We have a semicircle with a known radius inscribed within a right triangle. Knowing the proportions of the triangle motivates reflecting about  $BX$  to use  $[ABC] = rs$ .

Let the reflection of  $Y$  about  $BX$  be  $Y'$ . Then notice  $[YXY'] = 2\sqrt{5}x^2$ , by  $\frac{bh}{2}$ . But also notice by  $[ABC] = rs$ ,  $[YXY'] = 5x$ . Since the area of a triangle is the same no matter how it is computed,  $2\sqrt{5}x^2 = 5x$ , implying  $x = \frac{\sqrt{5}}{2}$ .

Drop an altitude from  $T$  to  $BX$ , and let the foot be  $T'$ . Notice that  $\triangle YBX \sim \triangle TT'X$  with a ratio of  $3 : 1$ . Thus  $TT' = \frac{\sqrt{5}}{3}$  and  $TX = \frac{5}{6}$ . Then notice  $T'A = T'X - AX$ . Since  $BX = \frac{5}{2}$  and  $BA = 2$ ,  $AX = \frac{1}{2}$ . Thus  $T'A = \frac{5}{6} - \frac{1}{2} = \frac{1}{3}$ . By the Pythagorean Theorem,  $TA = \sqrt{(\frac{1}{3})^2 + (\frac{\sqrt{5}}{3})^2} = \sqrt{\frac{6}{9}} = \frac{\sqrt{6}}{3}$ , which is our answer.

2. Without loss of generality, let  $P$  be closer to  $\ell$  than  $Q$ . Note

$$\angle APC = 180 - \angle PAB - \angle BCP = \angle DCP - \angle PAB$$

$$\angle BQD = \angle BQP + \angle DQP.$$

Since  $\angle PAB = \angle BDP$ , the sum is  $\angle DCP + \angle DQP = 180$ .

3. The central claim is that  $BCDP$  is a parallelogram. Note that  $ED = CB$  implies  $EB \parallel DC$ , and similarly,  $AB = CD$  implies  $AD \parallel BC$ .

Note  $\angle AKE = 180^\circ = 2\angle APE = 360^\circ - 2\angle BPD = 360^\circ - 2\angle BCD$ . Also note that  $2\angle BCD - \angle ACE = 180^\circ$ , so  $\angle ACE = 2\angle BCD - 180^\circ$ .

Thus  $\angle AKE + \angle ACE = 180^\circ$ , as desired.

4. Note that  $\angle MBO = 30^\circ = \angle NAO$ ,  $\angle ANO = 180^\circ - \angle AMO = \angle BMO$ , and  $AO = BO$ , so  $\triangle BMO \cong \triangle ANO$ . Thus  $AN = BM$ .

5. Notice  $\angle EAB = \angle ACM = \angle ANM = \angle BAM$  and  $\angle EBA = \angle ABM$ , so  $\triangle EAB \cong \triangle MAB$ , implying that  $AB$  is the perpendicular bisector of  $EM$ . So  $\angle EMP = \angle EMQ = 90^\circ$ , and it suffices to show that  $PM = MQ$ .

Let  $MN$  intersect  $AB$  at  $O$ . Note that  $AO = BO$ , so  $PM = MQ$  by similar triangles.



6. The key observation is that  $AD, BC, EF$  concur.

Let  $AD$  and  $BC$  intersect at  $P$  and let  $Q$  be the foot of the altitude from  $P$  to  $AB$ . Also let the semicircle have center  $O$ . Now note

$$\triangle PAQ \sim \triangle OAD$$

$$\triangle PBQ \sim \triangle OBC$$

so  $\frac{AQ}{QB} \cdot \frac{BC}{CP} \cdot \frac{PD}{DA} = 1$ . Since  $AC, BD, PQ$  concur,  $Q$  is actually  $F$ , and  $AC, BD, PF$  concur.

Now note

$$\angle OCP = \angle ODP = \angle OFP = 90^\circ,$$

so  $OFPCD$  is cyclic. Thus

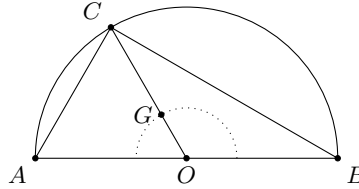
$$\angle COP = \angle DOP$$

$$\angle CFP = \angle DFP.$$

7. Angle chase to find  $\triangle ABC \sim \triangle EDC \sim \triangle EBA$ . So  $BE = 7 \cdot \frac{7}{10} = \frac{49}{10}$ , implying  $CE = 10 - \frac{49}{10} = \frac{51}{10}$ , and  $CD = \frac{10}{8} \cdot \frac{51}{10} = \frac{51}{8}$ , implying  $AD = 8 - \frac{51}{8} = \frac{13}{8}$ .

8. Note that  $BD = 6$  and  $BE = \frac{5}{5+13} \cdot 12 = \frac{10}{3}$ , so  $DE = 6 - \frac{10}{3} = \frac{8}{3}$ . Thus  $[ADE] = \frac{1}{2} \cdot 5 \cdot \frac{8}{3} = \frac{20}{3}$ .

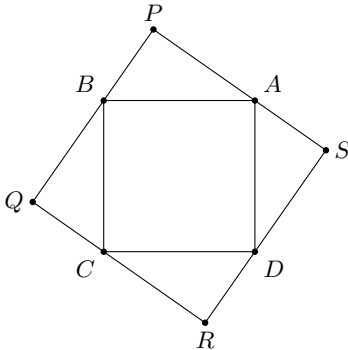
9. Let  $O$  be the center of the circle and  $G$  be the centroid of  $\triangle ABC$ . Since  $O$  is also the midpoint of  $AB$  and thus lies on  $CG$ , we're motivated to make use of the  $2:1$  ratio.  $CO$  always has length 12, so it follows that  $GO$  always has length 4. This means that the locus of  $G$  is a circle with center  $O$  and radius 4 by definition, so the area is  $16\pi \approx 50$ .



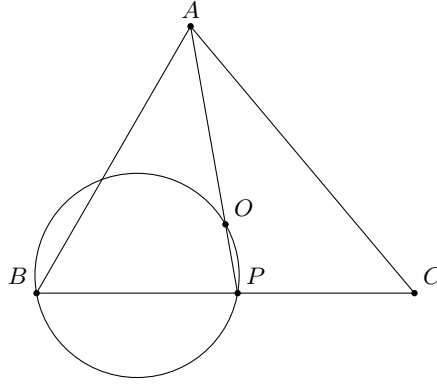
10. Let the circle with diameter  $AB$  be  $\omega$ . Note  $\omega$  intersects  $DE$  at  $D, F$  and  $AC$  at  $H$  where  $H$  is the foot of the altitude from  $B$  to  $AC$ .

Now note  $EF \cdot ED = EH \cdot EA$ , or  $EF \cdot \frac{36}{5} = 3 \cdot \frac{48}{5}$ . So  $EF = 4$  and  $DF = \frac{16}{5}$ , so the answer is 21.

11. Let  $Q, R, S$  be the rotations of  $P$  about  $O$  by  $90^\circ, 180^\circ, 270^\circ$  counterclockwise. Note that  $PR$  is the angle bisector of  $\angle APB$  and  $PR$  bisects the area of  $[PQRS]$ . Since the area we added to both halves of  $ABCD$  is the same,  $PR$  also bisects  $ABCD$ .



12. Note that  $BO = AO = AP$ , so  $\triangle AOP$  is isosceles. Thus  $\angle OAP = 20^\circ$ , implying  $\angle AOC = 140^\circ$ , and  $\angle AOP = \angle APO = 80^\circ$ , implying that  $\angle AOB = 100^\circ$ . So  $\angle OBC = 360^\circ - 140^\circ - 100^\circ = 120^\circ$ , or  $\angle OBC = 30^\circ$ .



13. Note that

$$\angle BPR = \angle BAP + \angle ABP = \angle AQP + \angle PBQ = \angle AQB$$

and that

$$\angle BRP = \angle RPC + \angle RCP = 180^\circ - \angle APC + \angle BCP = \angle AQP + \angle BQP = \angle AQB,$$

so  $\angle BPR = \angle BRP$ .

Now note

$$\angle AQB = \angle BAP + \angle ABP = 180^\circ - \angle APB = \angle BPR = \angle BRP,$$

so  $ABRQ$  is cyclic.

Now reflect  $P$  about the midpoint of  $AB$  to get  $P'$ . Then note

$$\angle PQR = \angle P'QR = \angle P'AR = \angle P'AB + \angle BAR = \angle ABR + \angle BAP = \angle BPR,$$

so  $BP$  is tangent to  $(PQR)$ , as desired.

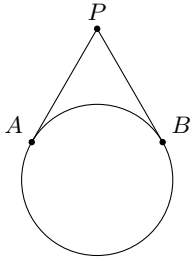
14. Note that  $\triangle ABX$  and  $\triangle ADY$  are isosceles, so  $BX = 7$  and  $DY = 6$ . Now also note that  $XQDB$  is a parallelogram, so  $QD = BX = 7$ . Now note  $\angle QDY = \angle DAB$ , so it suffices to find  $\cos \angle QDY$ .

Now note that  $QY = DY = 6$  and  $QD = 7$ . Thus dropping the altitude from  $Y$  to  $QD$  gives us  $\cos \angle QDY = \frac{7}{2} = \frac{7}{12}$ .

15. By Stewart's,  $BE = \frac{\sqrt{2c^2+2a^2-b^2}}{2}$  and  $CF = \frac{\sqrt{2a^2+2b^2-c^2}}{2}$ , so  $a^2 = BG^2 + CF^2 = \frac{4}{9} \left( \frac{2c^2+2a^2-b^2}{4} + \frac{2a^2+2b^2-c^2}{4} \right) = \frac{4a^2+b^2+c^2}{9}$ .

Thus,  $5a^2 = b^2 + c^2$  and  $\frac{b^2+c^2}{a^2} = 5$ .

16. Note that by Power of a Point,  $PA^2 = PB^2$ .



17. Say the center of  $K_1$  is  $O_1$  and the center of  $K_2$  is  $O_2$ . Obviously  $AO_2CQ$  is cyclic since  $\angle QAO_2 = \angle QCO_2 = 90^\circ$ . Now note  $\angle QCP = 180 - \angle BAC$ , and  $\angle PAB = \angle ABP = \angle ABC = \angle QAC$ , so  $P$  also lies on this circle. Thus  $\angle O_2PQ = 90^\circ$ . Note

$$\angle ABO_2 = \frac{180^\circ - \angle AO_2B}{2} = 90^\circ - \angle ACB = 90^\circ - \angle ACP = 90^\circ - \angle AQP = 90^\circ - \angle DQP,$$

and  $\angle O_2DA = \angle O_2BA$  if and only if  $O_2$  lies on  $(ABD)$ , or  $K_1$ . Then  $\angle O_2DA = \angle O_2BA$  implies that  $\angle DPQ = 90^\circ$ , as desired.