

EGMO Solutions

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1 Angle Chasing

Problem 1.5

Solve the first part of Example 1.1.

Let the intersections of the diagonals of $WXYZ$ be A . Then, we have that

$$\angle ZY = 180 - (90 + \angle AYZ) = 40^\circ.$$

Hence,

$$\angle Z = \angle AZW + \angle ZY = \boxed{70^\circ}.$$

Problem 1.6

Let ABC be a triangle inscribed in a circle ω . Show that $\overline{AC} \perp \overline{CB}$ if and only if \overline{AB} is a diameter of ω .

Let the center of ω be O . We start with the if direction. Given that \overline{AB} is a diameter of ω , we know that

$$\angle AOB = 180^\circ.$$

Thus, because of the Inscribed Angle Theorem, we know that $\angle ACB$ must be equal to 90° as desired.

Now for the only if direction. If $\overline{AC} \perp \overline{CB}$, then we know that

$$\angle ACB = 90^\circ.$$

By the Inscribed Angle Theorem, this implies that

$$\angle AOB = 180^\circ$$

which means that \overline{AB} is a diameter of ω as desired. \square

Problem 1.7

Let O and H denote the circumcenter and orthocenter of an acute $\triangle ABC$, respectively. Show that $\angle BAH = \angle CAO$.

By the Inscribed Angle Theorem,

$$2\angle ABC = \angle AOC.$$

Negating both sides and adding 180, we get that

$$\begin{aligned} 180 - 2\angle ABC &= 2(90 - \angle ABC) \\ &= 2\angle BAH \end{aligned}$$

and

$$180 - \angle AOC = 2\angle CAO$$

since $\triangle AOC$ is isosceles ($OA = OC$). Finally, this means that $\angle BAH = \angle CAO$ as desired. \square

Problem 1.10

Show that a trapezoid is cyclic if and only if it is isosceles.

Let the aforementioned trapezoid be $ABCD$ where $\overline{BC} \parallel \overline{AD}$. We start with the if direction. Since $ABCD$ is isosceles, we know that

$$\angle BAD = \angle CDA = 180 - \angle BCD$$

so the opposite angles add up to 180° , implying that $ABCD$ is cyclic.

Now, we do the only if direction. Since $ABCD$ is cyclic, we know that

$$\angle BAD = 180 - \angle BCD = \angle CDA$$

which means that $ABCD$ is isosceles as desired. \square

Problem 1.11

Quadrilateral $ABCD$ has $\angle ABC = \angle ADC = 90^\circ$. Show that $ABCD$ is cyclic, and that $(ABCD)$ (that is, the circumcircle of $ABCD$) has diameter \overline{AC} .

Since

$$\angle ABC + \angle ADC = 180^\circ$$

we know that $ABCD$ is cyclic. In addition, by Problem 1.6, we know that $(ABCD)$ has diameter \overline{AC} as desired. \square

Problem 1.16

In Figure 1.3A, show that $\triangle AEF$, $\triangle BFD$, and $\triangle CDE$ are each similar to $\triangle ABC$.

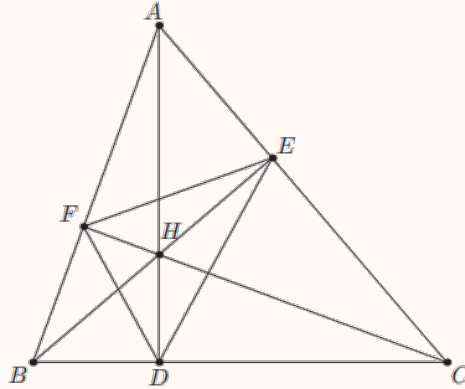


Figure 1.3A

We will show the necessary result for one of them ($\triangle AEF$), as it easily generalizes. Clearly, we know that $\triangle ABC$ and $\triangle AEF$ share $\angle A$. In addition,

$$\begin{aligned} \angle B &= 90 - \angle BAD \\ &= \angle AHF \\ &= \angle AEF. \end{aligned}$$

Thus, we know that two of the angles are equal, so

$$\triangle ABC \sim \triangle AEF$$

as required. \square

Problem 1.17

Let H be the orthocenter of $\triangle ABC$, as in the diagram below. Let X be the reflection of H over \overline{BC} and Y the reflection over the midpoint of \overline{BC} .

- (a) Show that X lies on (ABC) .
- (b) Show that \overline{AY} is a diameter of (ABC) .

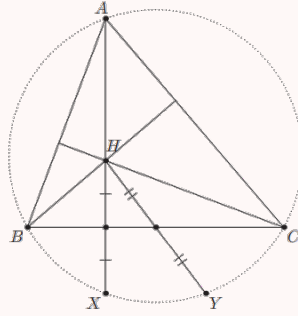


Figure 1.3B

We start with part (a). Let the foot of the altitude from A be D , from B be E , and the foot from C be F . Then, we can write the following equations:

$$\begin{aligned}\angle A + \angle BXC &= \angle A + \angle BHC \\ &= \angle A + \angle FHE \\ &= 180\end{aligned}$$

so $ABXC$ is cyclic, implying that X lies on (ABC) as desired.

We proceed with part (b). Define M to be the midpoint of \overline{BC} . Then, we know that

$$\triangle HDM \sim \triangle HXY.$$

This means that

$$\angle HXY = \angle AXY = 90.$$

Next, we show that Y lies on (ABC) , by showing that $AXYC$ is cyclic. We can say that:

$$\begin{aligned}\angle BCY + \angle C &= \angle HBC + \angle C \\ &= 90\end{aligned}$$

where $\angle BCY = \angle HBC$ since $\triangle HBM \cong \triangle YCM$. This, in conjunction with the fact that $\angle AXY = 90$ means that $AXYC$ is cyclic. So, Y lies on (ABC) as desired. Finally, this means that \overline{AY} is the diameter of (AXY) or equivalently (ABC) , as required. \square

Remark

The complex number proof can be found as Problem 6.14.

Problem 1.28

We claimed that $\angle FKD + \angle DKE + \angle EKF = 0$ in the above proof. Verify this.

Let P be a point that is collinear with D and K . Then, we know that

$$\angle DKE + \angle EKP = 0$$

and

$$\angle PKF + \angle FKD = 0.$$

Adding these gives the desired conclusion. \square

Remark

Throughout this text, we will use \angle to denote directed angles.

Problem 1.29

Show that for any distinct points A, B, C, D we have $\angle ABC + \angle BCD + \angle CDA + \angle DAB = 0$.

We know that:

$$\begin{aligned}\angle BAD + \angle ADB + \angle DBA &= 0 \\ \angle BDC + \angle DCB + \angle CBD &= 0.\end{aligned}$$

Adding these gives that

$$\angle BAD + (\angle ADB + \angle BDC) + (\angle DBA + \angle CBD) + \angle DCB = 0$$

and simplifying, we have that

$$\angle BAD + \angle ADC + \angle CBA + \angle DCB = 0.$$

Finally, negating the entire equation gives the desired conclusion. \square

Problem 1.30

Points A, B, C lie on a circle with center O . Show that $\angle OAC = 90^\circ - \angle CBA$.

Let A' be the reflection of A across O . Then, we know that since AA' is a diameter,

$$\angle ACA' = 90^\circ.$$

This implies the following:

$$\begin{aligned}\angle ABC &= \angle AA'C \\ &= -\angle A'CA - \angle CAA' \\ &= 90 + \angle A'AC \\ &= 90 + \angle OAC.\end{aligned}$$

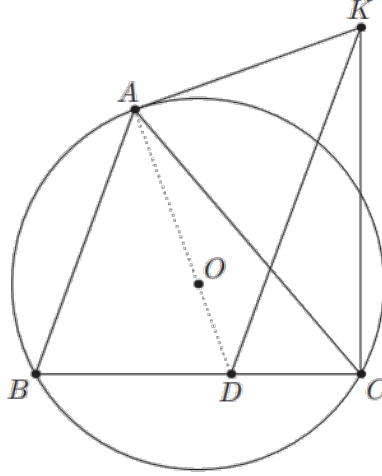
This implies that

$$\angle OAC = 90 + \angle ABC$$

as desired. \square

Problem 1.33

Let ABC be a triangle and let ray AO meet \overline{BC} at D . Point K is selected so that \overline{KA} is tangent to (ABC) and $\angle KCB = 90^\circ$. Prove that $\overline{KD} \parallel \overline{AB}$.



Since

$$\angle KAD = \angle KCD = 90^\circ$$

we know that quadrilateral $KADC$ is cyclic. Because of this, we can write that:

$$\begin{aligned}\angle KDB &= 180 - \angle KDC \\ &= 180 - \angle KAC \\ &= 180 - \angle B\end{aligned}$$

which implies that $\overline{KD} \parallel \overline{AB}$, as required. \square

Problem 1.34

In scalene triangle ABC , let K be the intersection of the angle bisector of $\angle A$ and the perpendicular bisector of \overline{BC} . Prove that the points A, B, C, K are concyclic.

Let K' be the intersection of the angle bisector of $\angle A$ and (ABC) not at A . We wish to show that $K' = K$. By the Incenter-Excenter Lemma, we know that

$$K'B = K'C$$

implying that K' lies on the perpendicular bisector of \overline{BC} . Hence, K' is the same point as K , and since $ABK'C$ is cyclic, we have the required result. \square

Problem 1.36

Let $ABCDE$ be a convex pentagon such that $BCDE$ is a square with center O and $\angle A = 90^\circ$. Prove that \overline{AO} bisects $\angle BAE$.

Clearly, $ABOE$ is cyclic since $\angle BOE = 90^\circ$. This means that

$$\angle BAO = \angle BEO = 45^\circ.$$

So, \overline{AO} bisects $\angle BAE$ as desired. \square

Problem 1.37 (BAMO 1999/2)

Let $O = (0, 0)$, $A = (0, a)$, and $B = (0, b)$, where $0 < a < b$ are reals. Let Γ be a circle with diameter \overline{AB} and let P be any other point on Γ . Line \overline{PA} meets the x-axis again at Q . Prove that $\angle BQP = \angle BOP$.

We wish to show that quadrilateral $BPOQ$ is cyclic. We can write the following:

$$\begin{aligned}\angle PQO &= \angle AQO \\ &= 90 - \angle OAQ \\ &= 90 - \angle BAP \\ &= \angle PBA \\ &= \angle PBO\end{aligned}$$

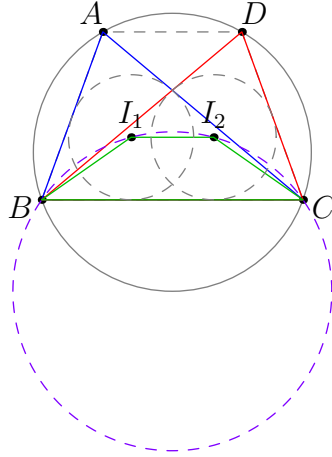
so $BPOQ$ is indeed cyclic. This implies that

$$\angle BQP = \angle BOP$$

as desired. \square

Problem 1.38

In cyclic quadrilateral $ABCD$, let I_1 and I_2 denote the incenters of ABC and DBC , respectively. Prove that I_1I_2BC is cyclic.



Firstly, since $ABCD$ is cyclic, we know that

$$\angle BAC = \angle BDC.$$

Dividing by two and adding 90, we get that $90 + \frac{\angle BAC}{2} = 90 + \frac{\angle BDC}{2}$, which is equivalent to

$$\angle BI_1C = \angle BI_2C$$

so BI_1I_2C is cyclic, as desired. \square

Problem 1.39 (CGMO 2012/5)

Let ABC be a triangle. The incircle of $\triangle ABC$ is tangent to \overline{AB} and \overline{AC} at D and E respectively. Let O denote the circumcenter of $\triangle BCI$. Prove that $\angle ODB = \angle OEC$.



We know that $AEID$ is cyclic since

$$\angle AEI + \angle ADI = 180^\circ.$$

In addition, we know that \overline{AI} bisects $\angle EID$, and since A , I , and O are collinear (by the Incenter-Excenter Lemma), we know that $\angle EIO = \angle DIO$. This implies that

$$\triangle EIO \sim \triangle DIO$$

since $DI = EI$, which means that

$$\angle IEO = \angle IDO.$$

Finally, this implies that $\angle ADO = \angle AEO$, which result in the desired claim after negating and adding 180. \square

Problem 1.40 (Canada 1991/3)

Let P be a point inside circle ω . Consider the set of chords of ω that contain P . Prove that their midpoints all lie on a circle.

We claim that all the midpoints lie on the circle with diameter \overline{OP} .

Let M be any one of these midpoints. We must show that $\angle OMP = 90^\circ$ for any M . Let A be one endpoint of the chord, and B , the other. Then, we know that

$$\triangle OMA \sim \triangle OMB$$

since all the corresponding sides are equal ($OA = OB$ as well). Thus, this means that

$$\angle OMA = \angle OMB = 90^\circ$$

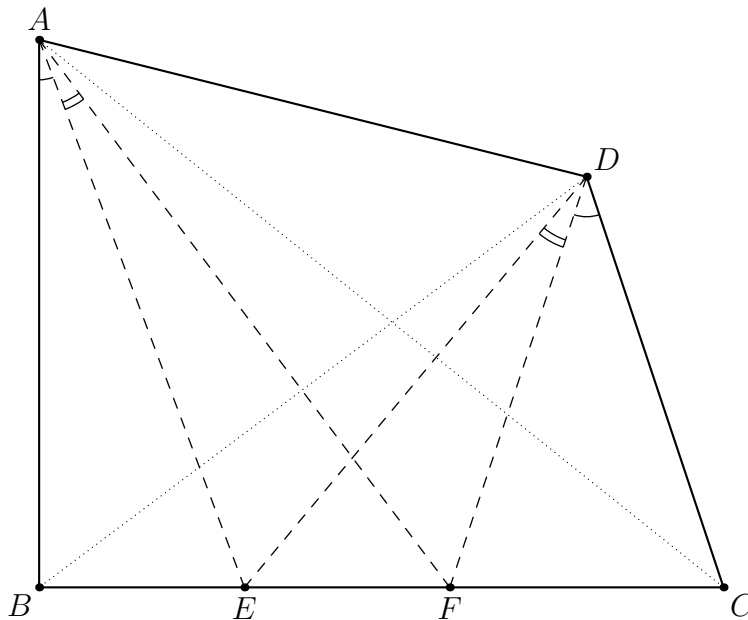
as desired. \square

Remark

Note that there are a few exceptions. If $O = M$, then obviously M lies on the circle with diameter \overline{OP} . Similarly, if $P = M$, then M obviously lies on that circle.

Problem 1.42 (Russian Olympiad 1996)

Points E and F are on side \overline{BC} of convex quadrilateral $ABCD$ (with E closer than F to B). It is known that $\angle BAE = \angle CDF$ and $\angle EAF = \angle FDE$. Prove that $\angle FAC = \angle EDB$.



Clearly, quadrilateral $ADEF$ is cyclic. Thus, we can write the following:

$$\begin{aligned}
 \angle D &= \angle ADF + \angle FDC \\
 &= 180 - \angle AEF + \angle FDC \\
 &= \angle AEB + \angle FDC \\
 &= 180 - \angle BAE - \angle B + \angle FDC \\
 &= 180 - \angle B.
 \end{aligned}$$

Thus, $ABCD$ is cyclic. This implies that

$$\angle BAC = \angle CDB$$

which implies that

$$\angle FAC = \angle EDB$$

due to the congruent angles. \square

Problem 1.42

Let ABC be an acute triangle inscribed in circle Ω . Let X be the midpoint of the arc \widehat{BC} not containing A and define Y, Z similarly. Show that the orthocenter of $\triangle XYZ$ is the incenter I of $\triangle ABC$.



We will show that $\overline{XI} \perp \overline{YZ}$ since the result easily generalizes to the other sides. By the Incenter-Excenter Lemma, we know that A, I , and X are collinear, and similarly for the other points. This means that:

$$\begin{aligned}\angle ZXI &= \angle ZXA \\ &= \angle ZCA \\ &= \frac{\angle C}{2}.\end{aligned}$$

On the other hand,

$$\begin{aligned}\angle Z &= \frac{m \widehat{XY}}{2} \\ &= 90 - \frac{m \widehat{AB}}{4} \\ &= 90 - \frac{\angle C}{2}.\end{aligned}$$

Thus, we get that $\overline{IX} \perp \overline{YZ}$ as required. \square

Problem 1.43 (JMO 2011/5)

Points A, B, C, D, E lie on a circle ω and point P lies outside the circle. The given points are such that:

- (i) lines PB and PD are tangent to ω
- (ii) P, A, C are collinear
- (iii) $\overline{DE} \parallel \overline{AC}$

Prove that \overline{BE} bisects \overline{AC} .



Let O be the center of ω . Since $\overline{DE} \parallel \overline{AC}$, we have that

$$m \widehat{AE} = m \widehat{CD}.$$

Then, we know that:

$$\begin{aligned} \angle BMP &= \angle BMC \\ &= \frac{m \widehat{AE}}{2} + \frac{m \widehat{BC}}{2} \\ &= \frac{m \widehat{CD}}{2} + \frac{m \widehat{BC}}{2} \\ &= \frac{m \widehat{BD}}{2} \\ &= \angle BOP. \end{aligned}$$

Thus, quadrilateral $POMB$ is cyclic. Thus, we have that

$$\angle OMC = \angle OMP = \angle OBP = 90^\circ$$

so M is the midpoint of \overline{AC} , as required. \square

Problem 1.44 (Three Tangents)

Let ABC be an acute triangle. Let \overline{BE} and \overline{CF} be altitudes of $\triangle ABC$, and denote by M the midpoint of \overline{BC} . Prove that \overline{ME} , \overline{MF} , and the line through A parallel to \overline{BC} are all tangents to (AEF) .



We will show that \overline{ME} is tangent, and \overline{MF} can be derived easily using a similar method. We know that

$$\angle HAE = 90 - \angle C.$$

In addition, since $\triangle BEC$ is a right triangle, and \overline{EM} is the median, we know that $\triangle BME$ is isosceles, and so

$$\angle MEB = \angle MBE = 90 - \angle C.$$

So

$$\angle HAE = \angle MEB = \angle MEH$$

implying that \overline{ME} is tangent to (AEF) . The proof for \overline{MF} is similar, so we omit it. Now let P be a point on \overline{BC} on the side of B . Then, we have that

$$\angle FAP = \angle B$$

due to parallel lines. In addition, we can say that

$$\angle AHF = 90 - \angle HAF = \angle B.$$

So, we have that

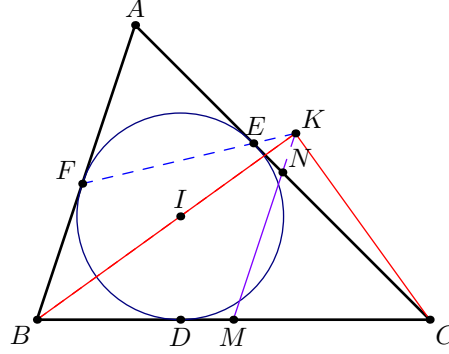
$$\angle FAP = \angle AHF$$

implying that \overline{AP} is tangent to (AEF) , as desired. \square

Problem 1.45 (Right Angles on Incircle Chord)

The incircle of $\triangle ABC$ is tangent to \overline{BC} , \overline{CA} , \overline{AB} at D , E , F , respectively. Let M and N be the midpoints of \overline{BC} and \overline{AC} , respectively. Ray BI meets line EF at K .

- (i) Show that $\overline{BK} \perp \overline{CK}$.
- (ii) Show K lies on line MN .



We start with the first part. Clearly, we know that $\triangle BMK$ is isosceles. This implies that

$$\angle BKM = \frac{\angle B}{2}.$$

In addition, this also implies that $\triangle KMC$ is isosceles. So, we know that

$$\angle MKC = 90 - \frac{\angle KMC}{2} = \frac{\angle BMK}{2} = 90 - \frac{\angle B}{2}.$$

Thus, we know that $\angle BKC$ is right, as required.

We proceed with the second part. All we must show is that

$$\angle KMC = \angle NMC = \angle B.$$

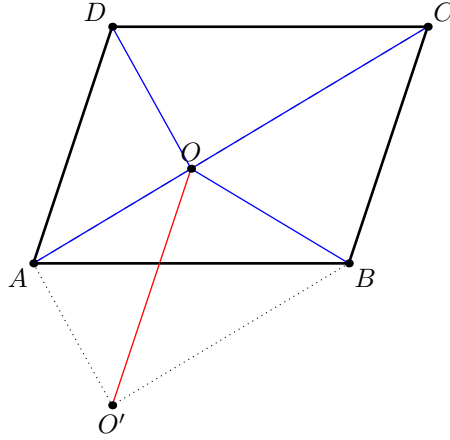
We already established that $\triangle KMC$ is isosceles. Hence, we know that

$$\angle KMC = 180 - 2\angle MKC = \angle B$$

as required. \square

Problem 1.46 (Canada 1997/4)

The point O is situated inside the parallelogram $ABCD$ such that $\angle AOB + \angle COD = 180^\circ$. Prove that $\angle OBC = \angle ODC$.



Let O' be defined as the translation of O using the vector \overrightarrow{DA} (or equivalently \overrightarrow{CB}). Now, we can write that

$$\begin{aligned}\triangle DOA &\cong \triangle O'AO \\ \triangle COB &\cong \triangle O'BO\end{aligned}$$

because of the parallelograms created. Because of this, we can write that

$$\begin{aligned}\angle AO'B &= \angle AO'O + \angle BO'O \\ &= \angle ADO + \angle BCO \\ &= 180 - \angle ODC - \angle OCD \\ &= \angle DOC \\ &= 180 - \angle AOB\end{aligned}$$

so quadrilateral $AO'BO$ is cyclic. Finally, we can say that:

$$\begin{aligned}\angle OBA &= \angle OO'A \\ &= \angle ODA\end{aligned}$$

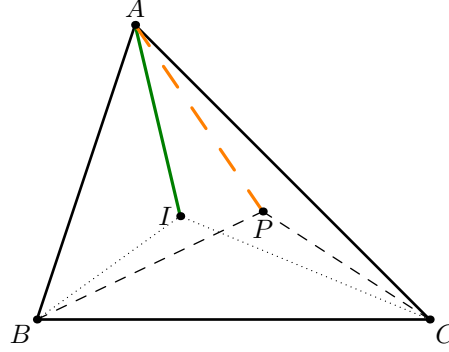
and since $\angle B = \angle D$ this implies that

$$\angle OBC = \angle OBA$$

as required. \square

Problem 1.47 (IMO 2006/1)

Let ABC be a 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 $P = I$.



We can rewrite the condition as

$$\angle PBA + \angle PCA = \angle B - \angle PBA + \angle C - \angle PCA$$

which simplifies to

$$\angle PBA + \angle PCA = \frac{\angle B}{2} + \frac{\angle C}{2}.$$

We can rearrange this to

$$\angle PBA - \frac{\angle B}{2} = \frac{\angle C}{2} - \angle PCA.$$

This implies that P must lie on (BIC) .

It is well known that the minimum distance from any point to a circle can be found by finding the distance from that point to intersection of the segment with endpoints of the center of the circle and that point. In addition, by the Incenter-Excenter Lemma, we know that A , I and the center of (BIC) are collinear, so the minimum distance from A to (BIC) is AI . Hence, we must have

$$AP \geq AI$$

for any P , with equality that holds if and only if $P = I$, as required. \square

Problem 1.48 (Simson Line)

Let ABC be a triangle and P be any point on (ABC) . Let X , Y , Z be the feet of the perpendiculars from P onto lines BC , CA , and AB . Prove that points X , Y , Z are collinear.

It suffices to show that

$$\angle PYX = \angle PYZ.$$

We can establish that $PYXC$ is cyclic since

$$\angle PYC = \angle PXC = 90^\circ.$$

Similarly, we know that $PZAY$ is cyclic since

$$\angle PYA = \angle PZA = 90^\circ.$$

Then, we can say that

$$\begin{aligned}
\angle PYX &= \angle PCX \\
&= \angle PCB \\
&= \angle PAB \\
&= \angle PAZ \\
&= \angle PYZ
\end{aligned}$$

where the third line follows because $PABC$ is cyclic. This is the desired conclusion. \square

Remark

A proof by complex numbers can be found as part (a) of Problem 6.22.

Problem 1.49 (USAMO 2010/1)

Let $AXYZB$ be a convex pentagon inscribed in a semicircle of diameter \overline{AB} . Denote by P, Q, R, S the feet of the perpendiculars from Y onto lines AX, BX, AZ, BZ , respectively. Prove that the acute angle formed by lines PQ and RS is half the size of $\angle XOZ$, where O is the midpoint of segment \overline{AB} .



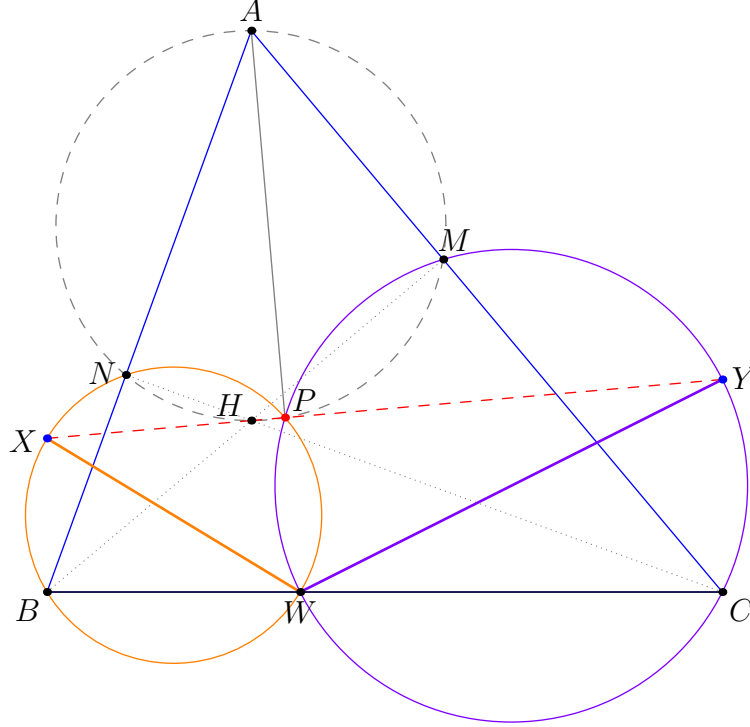
Let T be the intersection between lines PQ and RS . Notice that we can write $\angle QTR$ as

$$\begin{aligned}
\angle QTR &= \angle PQY - \angle QYT + \angle SRY - \angle RYT \\
&= \angle PQY + \angle SRY - \angle QYR \\
&= \angle PXY + \angle SZY - \angle QYR \\
&= 180 - \angle AXY + 180 - \angle YZB - \angle ZAB - \angle XBA \\
&= \angle ABY + \angle YAB - \angle ZAB - \angle XBA \\
&= \angle XBY + \angle YAZ \\
&= \frac{\angle XOZ}{2}
\end{aligned}$$

as required. \square

Problem 1.50 (IMO 2013/4)

Let ABC be an acute triangle with orthocenter H , and let W be a point on the side \overline{BC} , between B and C . The points M and N are the feet of the altitudes drawn from B and C , respectively. ω_1 is the circumcircle of triangle BWN and X is a point such that \overline{WX} is a diameter of ω_1 . Similarly, ω_2 is the circumcircle of triangle CWM and Y is a point such that \overline{WY} is a diameter of ω_2 . Show that the points X , Y , and H are collinear.



Let P be the second intersection between the two circumcircles (other than W). We will show that X , H , and P are collinear, and the same result can easily be replicated for Y . First, note that by the Miquel Point, $ANPM$ is cyclic, and because

$$\angle ANH = \angle AMH = 90^\circ$$

$ANHM$ is also cyclic. This implies that pentagon $ANHPM$ is cyclic. Next, we prove that A , P , and W are collinear. This is equivalent to show that

$$\angle APM + \angle WPM = 180^\circ.$$

We can do this as follows:

$$\begin{aligned} \angle APM &= \angle AHM \\ &= 90 - \angle HAM \\ &= \angle C \\ &= 180 - \angle WPM \end{aligned}$$

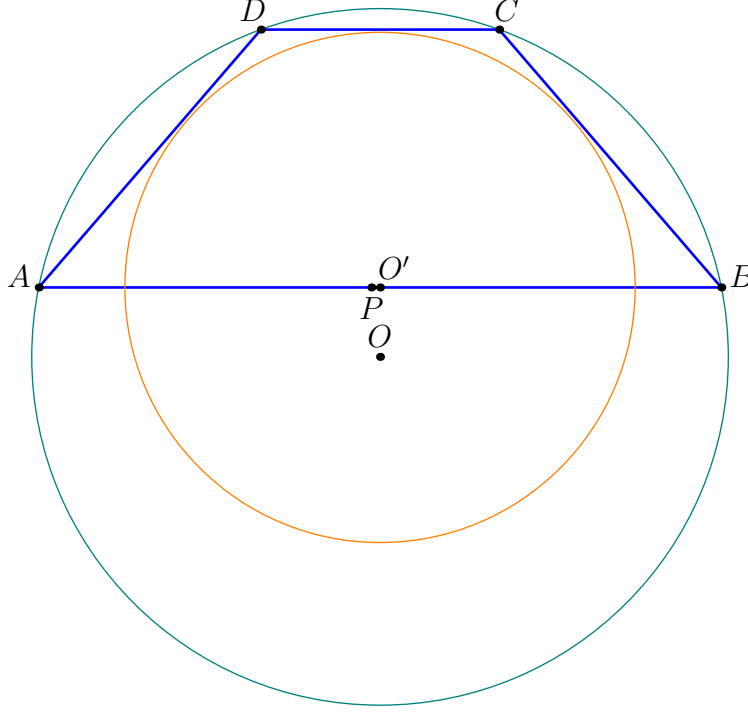
as required. Now, we can say that

$$\angle APH = \angle XPW = 90^\circ$$

so X , H , and P are collinear. We repeat this with Y to get a similar result, which implies that X , H , and Y are collinear, as required. \square

Problem 1.51 (IMO 1985/1)

A circle has center on the side \overline{AB} of the cyclic quadrilateral $ABCD$. The other three sides are tangent to the circle. Prove that $AD + BC = AB$.



Let P be the point on \overline{AB} such that

$$AD = AP.$$

We wish to show that

$$BC = BP.$$

We can first notice that $DPO'C$ is cyclic since

$$\begin{aligned} \angle DPO' &= 180 - \angle DPA \\ &= 90 + \frac{\angle DAP}{2} \\ &= 90 + \frac{180 - \angle C}{2} \\ &= 180 - \angle DCO'. \end{aligned}$$

Next, we will show that $\triangle PBC$ is isosceles. We can say that:

$$\begin{aligned} \angle CPB &= \angle CPO' \\ &= \angle CDO' \\ &= \frac{\angle D}{2} \\ &= 90 - \frac{\angle B}{2} \end{aligned}$$

so $\triangle PBC$ is indeed isosceles, implying that

$$BP = BC$$

as desired. \square

2 Circles

Problem 2.5

Prove the following (Theorem 2.3): Consider a circle ω and an arbitrary point P .

- (a) The quantity $\text{Pow}_\omega(P)$ is positive, zero, or negative according to whether P is outside, on, or inside ω , respectively.
- (b) If l is a line through P intersecting ω at two distinct points X and Y , then

$$PX \cdot PY = |\text{Pow}_\omega(P)|.$$

- (c) If P is outside ω and \overline{PA} is a tangent to ω at a point A on ω , then

$$PA^2 = \text{Pow}_\omega(P).$$

For completeness, we define Pow .

Definition

Let O be the center of ω . We define $\text{Pow}_\omega(P)$ as the quantity $OP^2 - r^2$ if r is the radius of ω .

We start with part (a). If P is inside ω , then $OP < r$, so $\text{Pow}_\omega(P)$ is negative. If P is on ω , then $OP = r$, so $\text{Pow}_\omega(P)$ is zero. Similarly, if P is outside ω , then $OP > r$, so $\text{Pow}_\omega(P)$ is positive.

We continue with part (b). Let the diameter through P intersect ω at A and B . Then, we know that

$$\triangle APX \sim \triangle YPB.$$

Then, we know that

$$\frac{AP}{YP} = \frac{PX}{PB}.$$

So, we know that

$$PX \cdot PY = PA \cdot PB = (OP + r)(OP - r) = |\text{Pow}_\omega(P)|$$

as required.

We finish with part (c). We already know that

$$PA \cdot PB = PX \cdot PY.$$

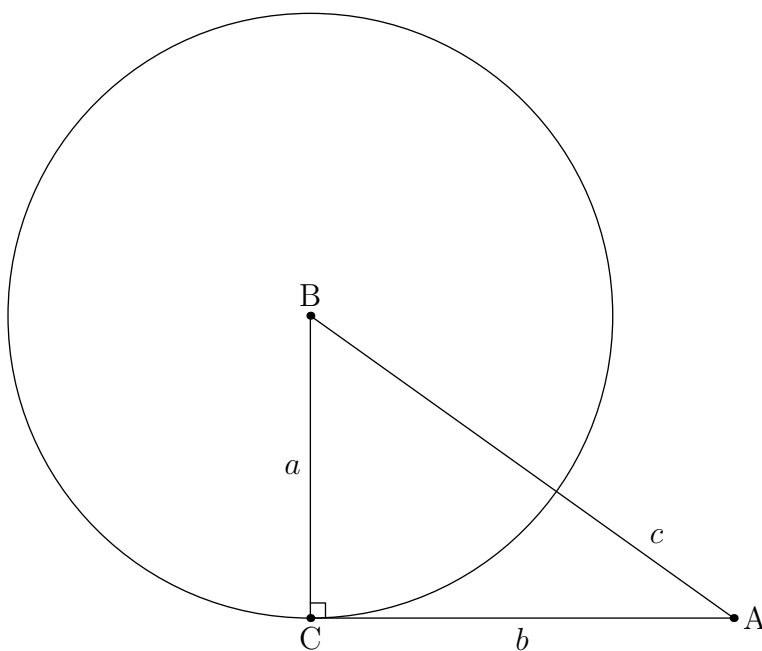
Now, move the line creating A and B closer and closer to the circumference. Consider the limiting case, when $A = B$. In this case, we can write that

$$PA^2 = PX \cdot PY = \text{Pow}_\omega(P)$$

as required. \square

Problem 2.6

Let ABC be a right triangle with $\angle ACB = 90^\circ$. Give a proof of the Pythagorean theorem.



Note that by Power of a Point, we have that

$$b^2 = c(c + 2a).$$

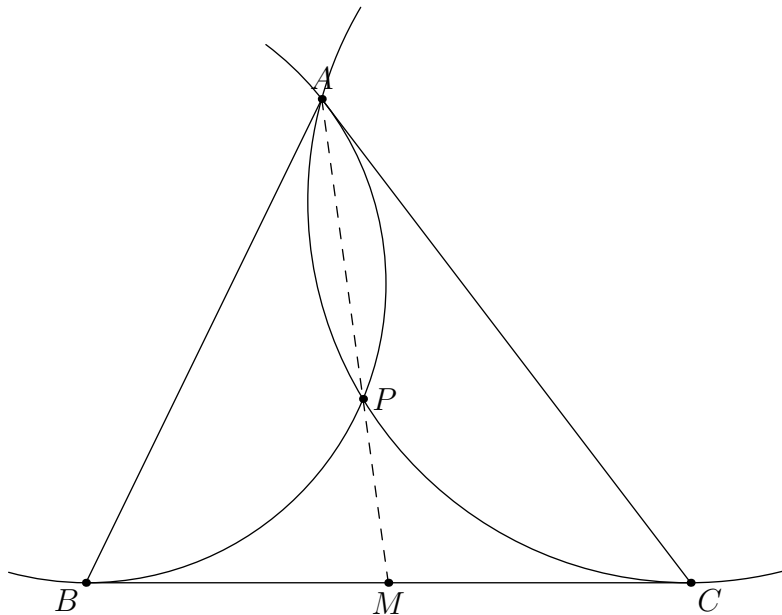
Solving this equation yields the following:

$$\begin{aligned} b^2 &= c^2 + 2ac \\ a^2 + b^2 &= (a + c)^2 \end{aligned}$$

which is equivalent to the Pythagorean Theorem in the given diagram.

Problem 2.11

Let ABC be a triangle and consider a point P in its interior. Suppose that \overline{BC} is tangent to the circumcircles of triangles ABP and ACP . Prove that ray AP bisects \overline{BC} .



We know that the midpoint of \overline{BC} (which we call M) lies on the radical axis of (ABP) and (ACP) because

$$\text{Pow}_{(ABP)}(M) = \text{Pow}_{(ACP)}(M)$$

which is due to the fact that the length of the tangents to those circles are equal. \square

Problem 2.12

Show that the orthocenter of a triangle exists using radical axes. That is, if \overline{AD} , \overline{BE} , and \overline{CF} are altitudes of a triangle ABC , show that the altitudes are concurrent.

Consider the circles with diameters \overline{AB} , \overline{AC} , and \overline{BC} . These circles' common chords (considered pairwise) are the aforementioned altitudes. Thus, since the radical center exists, so does the orthocenter. \square

Problem 2.18

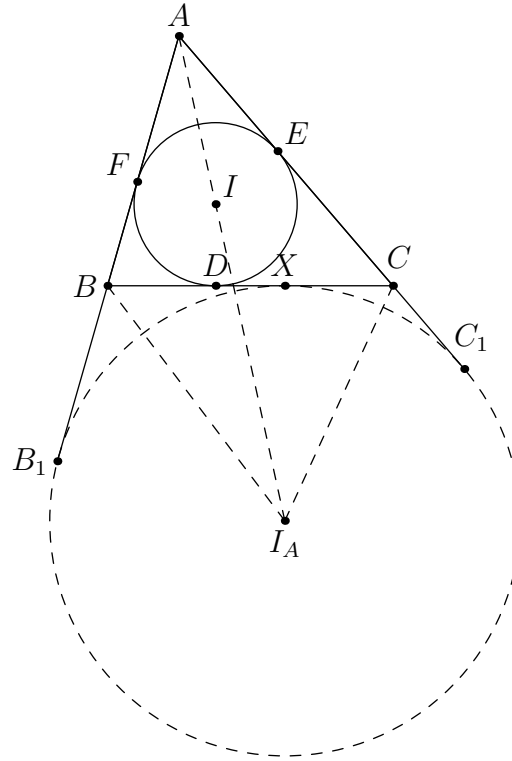
Let the external angle bisectors of B and C in a triangle ABC intersect at I_A . Show that I_A is the center of a circle tangent to \overline{BC} , the extension of \overline{AB} through B , and the extension of \overline{AC} through C . Furthermore, show that I_A lies on ray AI .

Clearly, the circle tangent to \overline{BC} , the extension of \overline{AB} through B , and the extension of \overline{AC} through C exists. Now, since this circle is tangent to \overline{BC} and the extension of \overline{AB} through B , we know that the center lies on the external angle bisector of B . Similarly, the center also lies on the external angle bisector of C , as desired. Finally, by the Incenter-Excenter Lemma, A , I , and I_A are collinear. \square

Problem 2.19

Prove that the A-exradius has length

$$r_a = \frac{s}{s-a}r.$$



Clearly,

$$\triangle AFI \sim \triangle AB_1I_A.$$

Thus, we have that

$$\frac{AB_1}{B_1I_A} = \frac{AF}{FI} = \frac{s-a}{r}.$$

So, we know that

$$\frac{s-a}{r} = \frac{AB_1}{B_1I_A} = \frac{s}{r_a}$$

as required. \square

Problem 2.20

Let ABC be a triangle. Suppose its incircle and A -excircle are tangent to \overline{BC} at X and D , respectively. Show that $BX = CD$ and $BD = CX$.

Refer to the diagram in Problem 2.19.

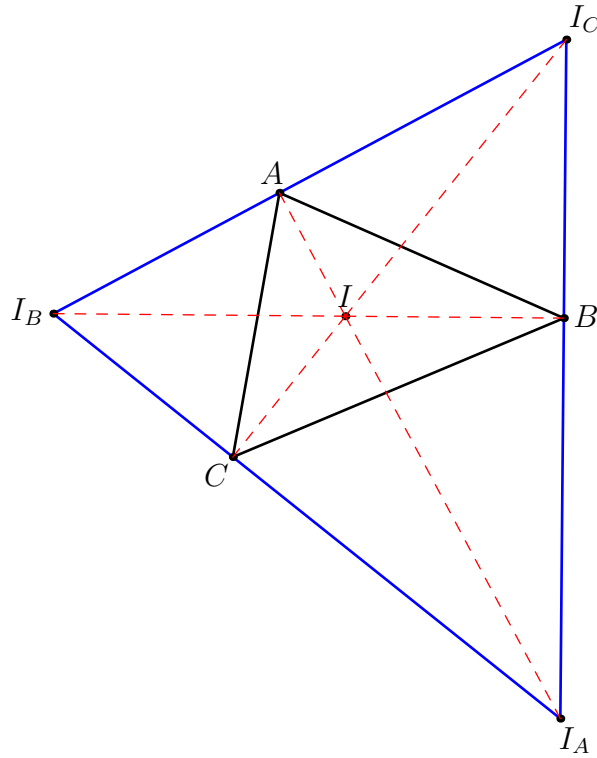
We will show the former, and that will imply the latter. We know that:

$$\begin{aligned} BX &= BB_1 \\ &= AB_1 - AB \\ &= s - c \\ &= DC \end{aligned}$$

as required. \square

Problem 2.24

Let ABC be a triangle with I_A , I_B , and I_C as excenters. Prove that triangle $I_AI_BI_C$ has orthocenter I and that triangle ABC is its orthic triangle.



We already know that any vertex is collinear with the incenter and its corresponding excenter (by the Incenter-Excenter Lemma). Thus, all we must prove is that the segment from any vertex to the corresponding excenter is perpendicular to the segment formed by the other two excenters. If we prove that

$$\overline{I_B B} \perp \overline{I_A I_C}$$

then we can easily generalize this to the other sides.

$$\begin{aligned}
\angle I_B B I_A &= \angle I_B B C + \angle C B I_A \\
&= \angle I B C + \frac{180 - \angle B}{2} \\
&= \frac{\angle B}{2} + \frac{180 - \angle B}{2} \\
&= 90
\end{aligned}$$

as claimed. \square

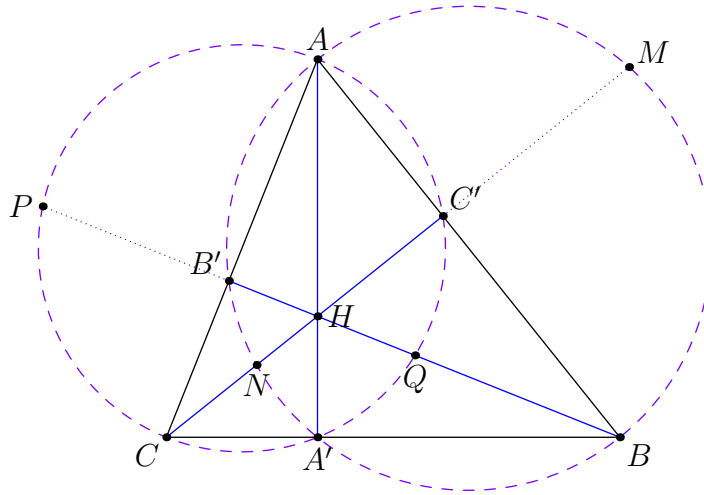
Problem 2.25 (Pitot's Theorem)

Let $ABCD$ be a quadrilateral. If a circle can be inscribed in it, prove that $AB + CD = BC + DA$.

We leave many details to the reader, as this proof is relatively elementary. The circle tangent to $ABCD$ will divide up the sides into two parts, each of which will have a corresponding congruent side on the side adjacent to it. Adding up the opposite sides, will then result in equality.

Problem 2.26 (USAMO 1990/5)

An acute-angled triangle ABC is given in the plane. The circle with diameter \overline{AB} intersects altitude $\overline{CC'}$ and its extension at points M and N , and the circle with diameter \overline{AC} intersects altitude $\overline{BB'}$ and its extensions at P and Q . Prove that the points M, N, P, Q lie on a common circle.



Clearly, lines MN and PQ intersect on the radical axis of the two circles ($\overline{AA'}$), since they intersect at H . Thus, we know that M, N, P , and Q lie on a common circle by the Radical Center of Intersecting Circles.

We can write this out if necessary: Let ω_1 be the circle with diameter \overline{AB} , and ω_2 the circle with diameter \overline{AC} . Then,

$$HP \cdot HQ = \text{Pow}_{\omega_2}(H) = \text{Pow}_{\omega_1}(H) = HM \cdot HN$$

so M, N, P , and Q are indeed concyclic by the Converse of Power of a Point. \square

Problem 2.27 (BAMO 2012/4)

Given a segment \overline{AB} in the plane, choose on it a point M different from A and B . Two equilateral triangles AMC and BMD in the plane are constructed on the same side of segment \overline{AB} . The circumcircles of the two triangles intersect in point M and another point N .

- (a) Prove that \overline{AD} and \overline{BC} pass through point N .
- (b) Prove that no matter where one chooses the point M along segment \overline{AB} , all lines MN will pass through some fixed point K in the plane.



We start with part (a). Clearly, quadrilaterals $ACNM$ and $BDNM$ are cyclic. Now, we just need to show that N lies on both \overline{AD} and \overline{BC} . We can do this as follows:

$$\begin{aligned}\angle AND &= \angle ANM + \angle MND \\ &= \angle ACM + \angle MBD \\ &= 0\end{aligned}$$

so N lies on \overline{AD} . We can do the same for \overline{BC} and get that N lies on \overline{BC} as well, as required.

We proceed with part (b). We wish to show that this point K is the point on the opposite side of \overline{AB} such that $\triangle AKB$ is equilateral. Hence, we can show that line NM always passes through K . Now, since \overline{NM} is the radical axis of the two circumcircles, it suffices to show that the tangents to the two circles are always equal in length.

We start by showing that \overline{KA} is tangent to (ACM) . Let the center of (ACM) be O_1 . Then, we know that:

$$\begin{aligned}\angle O_1AK &= \angle O_1AM + \angle MAK \\ &= 90.\end{aligned}$$

We can show something similar for the other circle as well. Thus, \overline{AK} is tangent to (ACM) and

\overline{BK} is tangent to (BDM) . Finally, since

$$AK = BK$$

we know that

$$\text{Pow}_{(ACM)}(K) = \text{Pow}_{(BDM)}(K).$$

So, K lies on line NM , as desired. \square

Problem 2.28 (JMO 2012/1)

Given a triangle ABC , let P and Q be points on segments \overline{AB} and \overline{AC} , respectively, such that $AP = AQ$. Let S and R be distinct points on segment \overline{BC} such that S lies between B and R , $\angle BPS = \angle PRS$, and $\angle CQR = \angle QSR$. Prove that P, Q, R, S are concyclic.



Assume for the sake of contradiction that the circumcircles (PRS) and (QRS) are distinct. Then, the given condition tells us that \overline{AC} is tangent to (QRS) at Q and \overline{AB} is tangent to (PRS) at P . In addition, we know that A must lie on the radical axis of (PRS) and (QRS) . However, we know that the radical axis is line BC , so if the two circles are distinct, then $\triangle ABC$ is degenerate, which cannot happen. Hence, (PRS) and (QRS) are the same circle, implying that P, Q, R , and S are cyclic. \square

Problem 2.29 (IMO 2008/1)

Let H be the orthocenter of an acute-angled triangle ABC . The circle Γ_A centered at the midpoint of \overline{BC} and passing through H intersects the sideline BC at points A_1 and A_2 . Similarly, define the points B_1, B_2, C_1 , and C_2 . Prove that six points A_1, A_2, B_1, B_2, C_1 , and C_2 are concyclic.



If we show that B_1, B_2, C_1 , and C_2 are cyclic, then we can apply the same reasoning to get that any other pair of pairs (A_i, B_i, C_i) for $i = 1, 2$ are cyclic as well, which would imply that they are all concyclic. Thus, we will show that the circle through B_1, B_2, C_1 , and C_2 exists. Now, let N be the other intersection of (C_1C_2H) and (B_1B_2H) . Then, we know that \overline{NH} is perpendicular to the segment formed by the centers of these two circles, since it is the radical axis. However, this implies that line

$$NH \perp \overline{BC}$$

since the segment formed by the centers of these two circles is parallel to \overline{BC} . Finally, because

$$AH \perp \overline{BC}$$

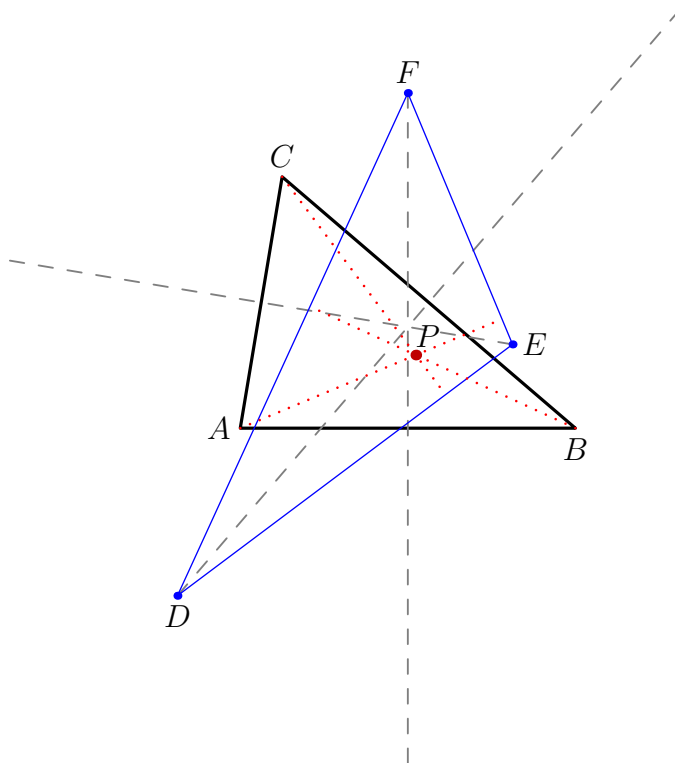
we know that A lies on the radical axis. Thus, since lines C_1C_2 and B_1B_2 concur at A , we know that they are concyclic, as desired. \square

Remark

The center of the circle through A_1, A_2, B_1, B_2, C_1 , and C_2 is actually O , the circumcenter of $\triangle ABC$.

Problem 2.30 (USAMO 1997/2)

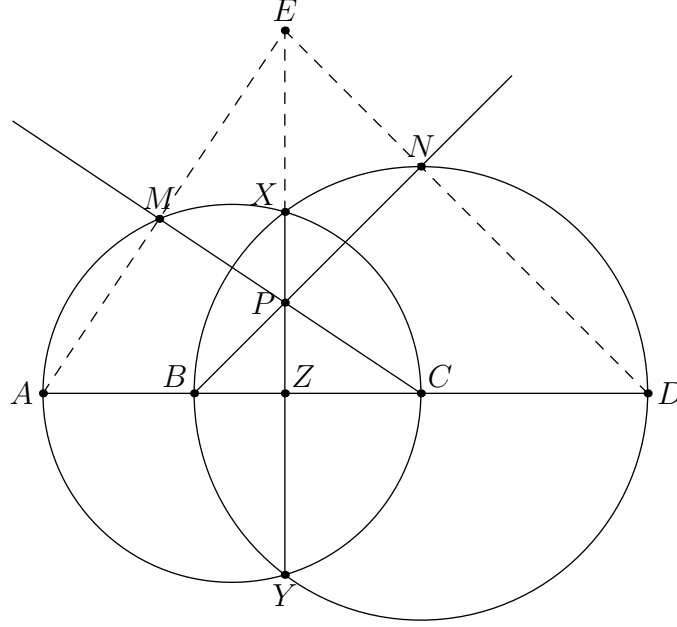
Let ABC be a triangle. Take points D, E, F on the perpendicular bisectors of \overline{BC} , \overline{CA} , \overline{AB} respectively. Show that the lines through A, B, C perpendicular to \overline{EF} , \overline{FD} , \overline{DE} respectively are concurrent.



Clearly, since D is on the perpendicular bisector of \overline{BC} and similarly for the others, we can define a circle Γ_D centered at D through B and C , and likewise for the other two points. Then, since the lines in question mentioned in the problem are perpendicular to the sides of $\triangle DEF$, and go through vertices of $\triangle ABC$, we know that they are the radical axes of the circles. Thus, the point in question (labeled P in the diagram) is just the radical center of Γ_D , Γ_E , and Γ_F , which we know to exist. \square

Problem 2.31 (IMO 1995/1)

Let A, B, C, D be four distinct points on a line, in that order. The circles with diameters \overline{AC} and \overline{BD} intersect at X and Y . The line XY meets \overline{BC} at Z . Let P be a point on the line XY other than Z . The line CP intersects the circle with diameter \overline{AC} at C and M , and the line BP intersects the circle with diameter \overline{BD} at B and N . Prove that the lines AM, DN, XY are concurrent.



We wish to show that the intersection of lines AM and DN , denoted E lies on the radical axis of the two circles in the diagram. Note that E has the property that

$$\text{Pow}_{(AMC)}(E) = EM \cdot EA$$

and

$$\text{Pow}_{(BND)}(E) = EN \cdot ED.$$

We wish to show that these quantities are equal. Now, we know that $\triangle EMP \sim \triangle EZA$ due to the shared angle and the fact that they are both right. Then, we know that

$$\frac{EM}{EP} = \frac{EZ}{EA}.$$

In addition, we know that $\triangle ENP \sim \triangle EZD$ for similar reasons, so

$$\frac{EN}{EP} = \frac{EZ}{ED}.$$

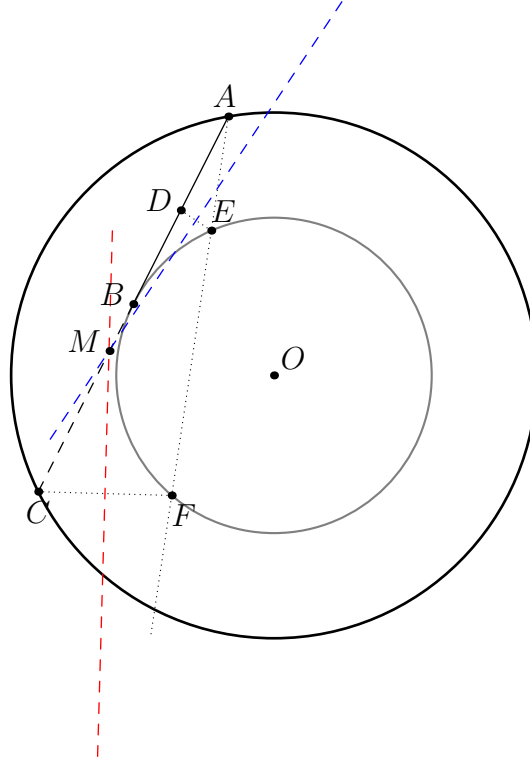
Thus:

$$\begin{aligned} \text{Pow}_{(AMC)}(E) &= EM \cdot EA \\ &= EZ \cdot EP \\ &= EN \cdot ED \\ &= \text{Pow}_{(BND)}(E) \end{aligned}$$

as required. So, E lies on the radical axis of the two circles, and hence lies on line XY . \square

Problem 2.32 (USAMO 1998/2)

Let \mathcal{C}_1 and \mathcal{C}_2 be concentric circles, with \mathcal{C}_2 in the interior of \mathcal{C}_1 . From a point A on \mathcal{C}_1 one draws the tangent \overline{AB} to \mathcal{C}_2 ($B \in \mathcal{C}_2$). Let C be the second point of intersection of ray AB and \mathcal{C}_1 , and let D be the midpoint of \overline{AB} . A line passing through A intersects \mathcal{C}_2 at E and F in such a way that the perpendicular bisectors of \overline{DE} and \overline{CF} intersect at a point M on AB . Find, with proof, the ratio $\frac{AM}{MC}$.



We claim that $\frac{AM}{MC} = \frac{5}{3}$.

We wish to show that quadrilateral $CDEF$ is cyclic. We can write that

$$AE \cdot AF = AB^2 = AD \cdot AC$$

by Power of a Point. Thus, we know that

$$\triangle ADE \sim \triangle AFC.$$

This then implies that $\angle ADE = \angle EFC$, so we know that

$$\angle EFC = \angle ADE = \angle EFC$$

implying that quadrilateral $CDEF$ is indeed cyclic. Now, we know that

$$MC = MF$$

and

$$MD = ME$$

because of the perpendicular bisectors, and so M is the center of $(CDEF)$. This means that we can write:

$$\begin{aligned}
 \frac{AM}{MC} &= \frac{AM}{MD} \\
 &= \frac{MD + AD}{MD} \\
 &= 1 + \frac{AD}{MD} \\
 &= 1 + \frac{AB}{AC - AD} \\
 &= 1 + \frac{AB}{2AB - \frac{AB}{2}} \\
 &= \boxed{\frac{5}{3}}
 \end{aligned}$$

as required. \square

Problem 2.33 (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 $EP = EQ$.



Because of \overline{AB} is tangent to the two circles, we know that line MN bisects \overline{AB} , and since

$$\triangle NPQ \sim \triangle NAB$$

we know that

$$MP = MQ.$$

Now, we know that

$$\triangle AEB \cong \triangle AMB$$

because of the tangency at A and B . Thus, we know that they are just reflections of each other across \overline{AB} . This means that $\overline{EM} \perp \overline{AB}$, and so

$$\overline{EM} \perp \overline{CD}$$

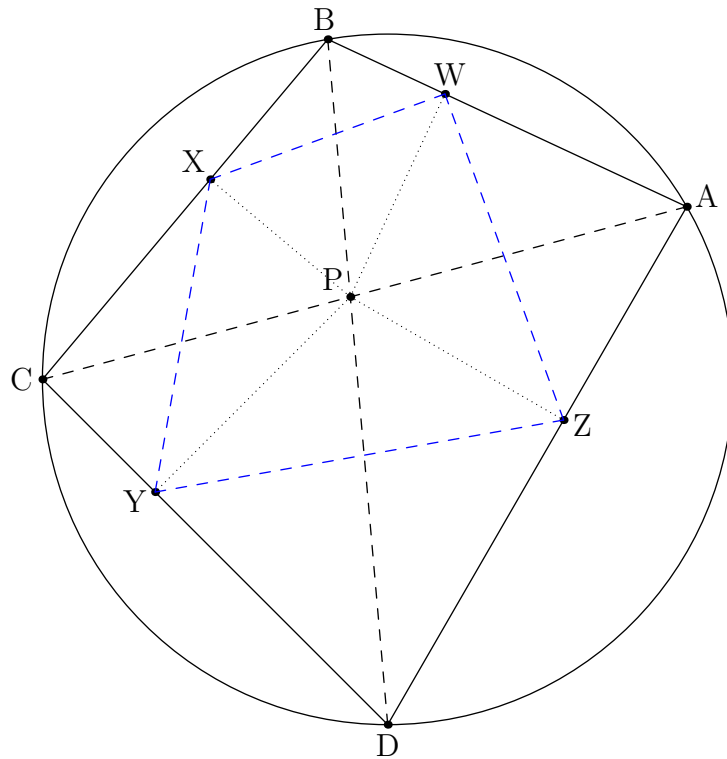
implying that

$$\overline{EM} \perp \overline{PQ}.$$

This, in conjunction with the fact that $MP = MQ$ implies that $\triangle EPQ$ is isosceles, so $EP = EQ$, as required. \square

Problem 2.34 (Canada 1990/3)

Let $ABCD$ be a cyclic quadrilateral whose diagonals meet at P . Let W, X, Y, Z be the feet of P onto $\overline{AB}, \overline{BC}, \overline{CD}, \overline{DA}$, respectively. Show that $WX + YZ = XY + WZ$.



By the Converse of Pitot's Theorem, we just have to show that there exists a point which is equidistant to all the sides of quadrilateral $WXYZ$.

Claim

The point P is equidistant to all the sides of $WXYZ$.

We can prove this by showing that P lies on the angle bisectors of quadrilateral $WXYZ$. We will show that for one angle bisector, and the result easily follows by replicating it for the others.

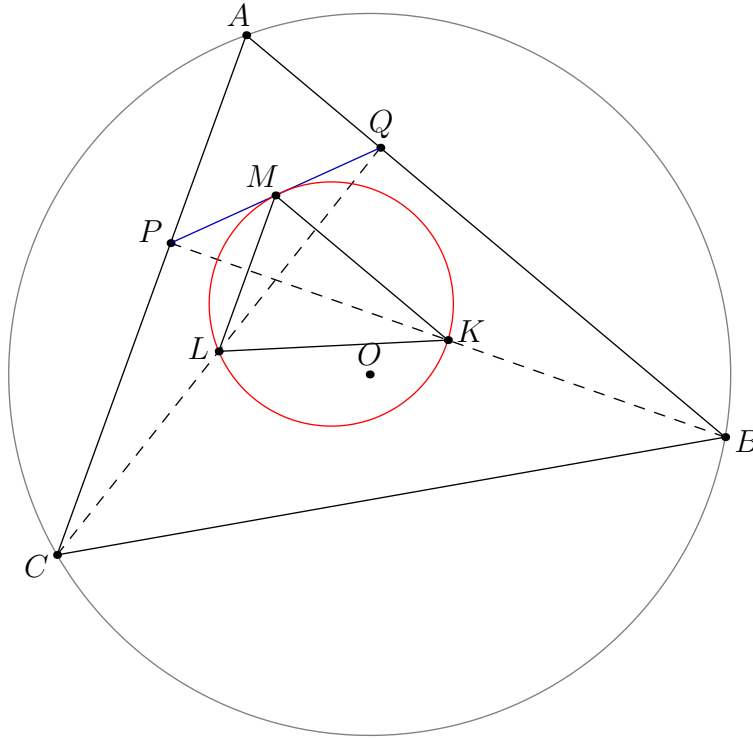
We can say that:

$$\begin{aligned}
\angle PYX &= \angle PCX \\
&= \angle ACB \\
&= \angle ADB \\
&= \angle PDZ \\
&= \angle PYZ
\end{aligned}$$

so P does indeed lie on the angle bisector of $\angle Y$, as desired. \square

Problem 2.35 (IMO 2009/2, synthetic)

Let ABC be a triangle with circumcenter O . The points P and Q are interior points of the sides \overline{CA} and \overline{AB} , respectively. Let K , L , and M be the midpoints of the segments \overline{BP} , \overline{CQ} , and \overline{PQ} , respectively, and let be the circle passing through K , L , and M . Suppose that the line PQ is tangent to the circle. Prove that $OP = OQ$.



Claim

We claim that

$$AP \cdot PC = AQ \cdot QB.$$

Proof. First, we know that

$$\triangle CQP \sim \triangle LQM$$

and

$$\triangle BPQ \sim \triangle KPM$$

for obvious reasons (note that they are both in the ratio 2 : 1). Next, we can say that

$$\angle APQ = 180 - \angle CPQ = 180 - \angle LMQ = \angle K$$

and similarly,

$$\angle AQP = 180 - \angle BQP = 180 - \angle KMP = \angle L.$$

Thus, we know that

$$\triangle APQ \sim \triangle MKL.$$

Finally, we can write that

$$\frac{AP}{AQ} = \frac{MK}{ML} = \frac{QB}{PC}$$

so the claim is indeed true, as required. \square

Thus, we know that

$$\text{Pow}_{(ABC)}(P) = \text{Pow}_{(ABC)}(Q)$$

which implies that

$$OP^2 - R^2 = OQ^2 - R^2$$

which gives the necessary result. \square

Remark

A solution by complex numbers can be found as Problem 6.41.

Problem 2.36

Let \overline{AD} , \overline{BE} , \overline{CF} be the altitudes of a scalene triangle ABC with circumcenter O . Prove that (AOD) , (BOE) , and (COF) intersect at point X other than O .

Claim

The circles (AOD) , (BOE) , and (COF) are coaxial.

Proof. We already know that the circles share the point O . If we show that there exists another point (call it H) such that

$$\text{Pow}_{(AOD)}(H) = \text{Pow}_{(BOE)}(H) = \text{Pow}_{(COF)}(H)$$

then the point line OH is the radical axis of all the circles, and thus they will be coaxial. We claim that the orthocenter satisfies the conditions of point H .

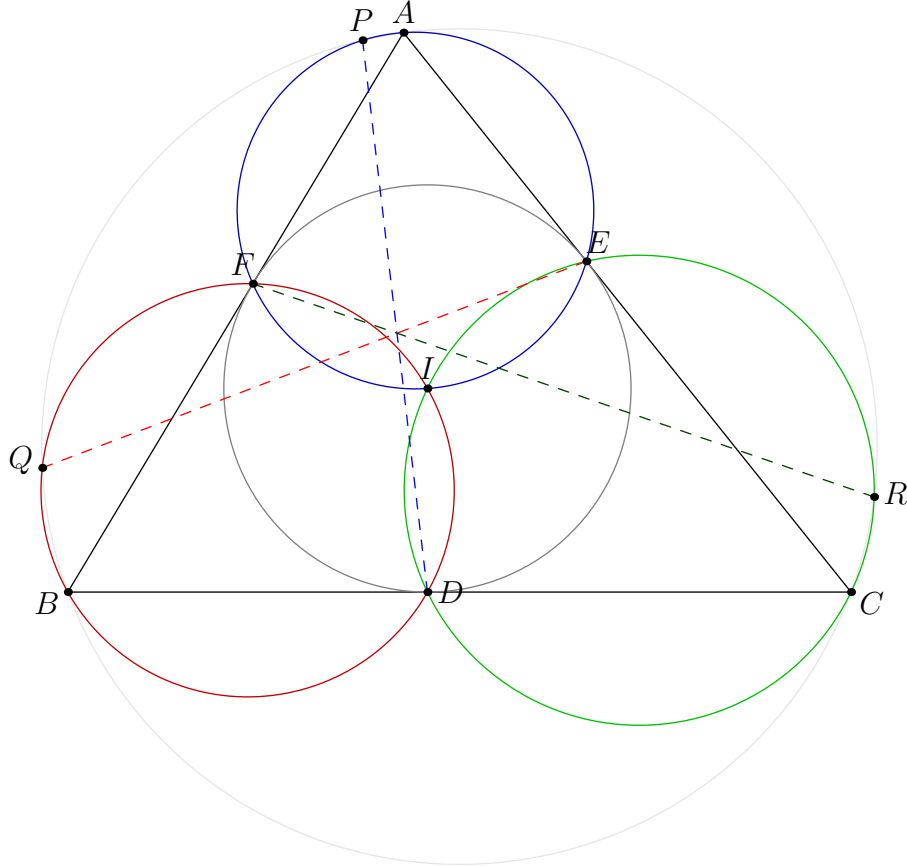
Consider any two of those circles. The chords of those circles that do not contain O will intersect at H , and since the quadrilateral formed by those four points is cyclic, we know that H lies on the radical axis of those two circles. Hence, H lies on the radical axis of *all* the three circles, as required. \square

Since the circles are coaxial, they intersect at the same two points, and so there exists another point X where all the three circumcircles intersect, as desired. \square

Problem 2.37 (Canada 2007/5)

Let the incircle of triangle ABC touch sides BC , CA and AB at D , E and F , respectively. Let ω , ω_1 , ω_2 and ω_3 denote the circumcircles of triangles ABC , AEF , BDF and CDE respectively. Let ω and ω_1 intersect at A and P , ω and ω_2 intersect at B and Q , ω and ω_3 intersect at C and R .

- (a) Prove that ω_1 , ω_2 and ω_3 intersect in a common point.
- (b) Show that lines PD , QE and RF are concurrent.



We start with part (a). We claim that the common point is I ; the incenter of $\triangle ABC$. Obviously, quadrilaterals $BFID$, $AEIF$ and $CDIE$ are cyclic due to the tangency, hence I must lie on all of their circumcircles, as desired.

We continue with part (b). We claim that the lines all intersect at point H . We will first show that quadrilateral $PEDQ$ is cyclic. Let the lines QD and PE intersect at K . Then, we know that

$$KD \cdot KQ = \text{Pow}_{(BQFID)}(K) = KI \cdot KF = \text{Pow}_{(APFIE)}(K) = KE \cdot KP.$$

Thus, K lies on the radical axis of the two circles, so $PEDQ$ is cyclic, as desired. Similarly, we get that $PRDF$, and $QFER$ are cyclic. Thus, since the radical center exists, we know that there exists a point where all the lines intersect. Thus, H exists, as required. \square

Remark

The point H is actually the orthocenter of $\triangle ABC$.

Problem 2.38 (Iran TST 2011/1)

In acute triangle ABC , $\angle B$ is greater than $\angle C$. Let M be the midpoint of \overline{BC} and let E and F be the feet of the altitudes from B and C , respectively. Let K and L be the midpoints of \overline{ME} and \overline{MF} , respectively, and let T be on line KL such that $\overline{TA} \parallel \overline{BC}$. Prove that $TA = TM$.



Consider the circle (AEF) . By the Three Tangents Lemma (proved in Problem 1.44 above), we know that lines AT , MF , and ME are tangent to (AEF) at A , F and E respectively. In addition, define ω to be a circle with radius zero centered at M . Clearly, we know that line LK is the radical axis of ω and (AEF) , and since T lies on this radical axis, we know that

$$\text{Pow}_{(AEF)}(T) = \text{Pow}_{\omega}(T)$$

implying that

$$TA = TM$$

as required. \square

3 Lengths and Ratios

Problem 3.2 (Angle Bisector Theorem)

Let ABC be a triangle and D a point on \overline{BC} so that \overline{AD} is the internal angle bisector of $\angle BAC$. Show that

$$\frac{AB}{AC} = \frac{DB}{DC}.$$

By the Law of Sines, we know that

$$\frac{BD}{\sin(\angle BAD)} = \frac{AB}{\sin(\angle BDA)}$$

and

$$\frac{CD}{\sin(\angle CAD)} = \frac{AC}{\sin(\angle CDA)}.$$

Dividing the first equation by the second, we get that

$$\frac{BD \sin(\angle CAD)}{CD \sin(\angle BAD)} = \frac{BD}{CD} = \frac{AB \sin(\angle CDA)}{AC \sin(\angle BDA)} = \frac{AB \sin(\angle CDA)}{AC \sin(\angle CDA)} = \frac{AB}{AC}$$

as required. \square

Problem 3.5

Show the trigonometric form of Ceva holds.

We state Ceva's Theorem for completeness.

Theorem (Ceva's Theorem)

Let \overline{AX} , \overline{BY} , and \overline{CZ} be cevians of $\triangle ABC$. They concur if and only if

$$\frac{BX}{XC} \cdot \frac{CY}{YA} \cdot \frac{AZ}{ZB} = 1.$$

By the Law of Sines, we know that

$$\frac{BX}{\sin(\angle BAX)} = \frac{AX}{\sin(\angle B)}$$

and

$$\frac{CX}{\sin(\angle CAX)} = \frac{AX}{\sin(\angle C)}.$$

Taking the first equation and dividing it by the second, we get that

$$\frac{BX \sin(\angle CAX)}{CX \sin(\angle BAX)} = \frac{\sin(\angle C)}{\sin(\angle B)}.$$

If we take this for all the sides and multiply them together, we get that

$$\begin{aligned} \frac{CX \sin(\angle BAX)}{BX \sin(\angle CAX)} \cdot \frac{CY \sin(\angle CBY)}{AY \sin(\angle ABY)} \cdot \frac{AZ \sin(\angle ACZ)}{BZ \sin(\angle BCZ)} &= \frac{\sin(\angle BAX) \sin(\angle CBY) \sin(\angle ACZ)}{\sin(\angle CAX) \sin(\angle ABY) \sin(\angle BCZ)} \\ &= \frac{\sin(\angle B)}{\sin(\angle C)} \cdot \frac{\sin(\angle C)}{\sin(\angle A)} \cdot \frac{\sin(\angle A)}{\sin(\angle B)} \\ &= 1 \end{aligned}$$

as required. \square

Problem 3.6

Let \overline{AM} , \overline{BE} , and \overline{CF} be concurrent cevians of a triangle ABC . Show that $\overline{EF} \parallel \overline{BC}$ if and only if $BM = MC$.

We start by showing the if direction. Since $BM = MC$, by Ceva's Theorem, we know that

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

so

$$\frac{AF}{AE} = \frac{FB}{CE} = \frac{AF + FB}{AE + CE} = \frac{AB}{AC}.$$

Thus, we know that

$$\triangle FAE \sim \triangle BAC.$$

Hence, $\angle AFE = \angle ABC$, so $\overline{EF} \parallel \overline{BC}$, as desired.

Now we show the only if direction. Since $\overline{EF} \parallel \overline{BC}$, we know that

$$\triangle FAE \sim \triangle BAC.$$

Hence,

$$\frac{AF}{AE} = \frac{FB}{CE}.$$

Thus, by Ceva's Theorem,

$$\frac{BM}{MC} = 1$$

and so $BM = MC$, as required. \square

Problem 3.12

Prove, by taking a negative homothety that the centroid of a triangle divides the median into a 2 : 1 ratio.

Let there exist a triangle $\triangle ABC$, which has medians \overline{AD} , \overline{BE} , and \overline{CF} . Then, take a homothety centered at G with scale factor -2 . Then, we know that $\triangle DEF$ maps to $\triangle ABC$, so we know that

$$\frac{GD}{GA} = \frac{GE}{GB} = \frac{GF}{GC} = \frac{1}{2}$$

as desired. \square

Problem 3.13 (Euler Line)

In triangle ABC , prove that O , G , H (with their usual meanings) are collinear and that G divides OH in a 2 : 1 ratio.

We begin with the following claim:

Claim

Let there exist a triangle ABC . The orthocenter of the medial triangle of $\triangle ABC$ is the circumcenter of $\triangle ABC$.

Proof. The perpendicular bisectors of $\triangle ABC$ are clearly the altitudes of its medial triangle. Hence, the intersection of the perpendicular bisectors of $\triangle ABC$, is the same as the intersection of the altitudes of the medial triangle. However, these are clearly the definition of the circumcenter and orthocenter respectively, so we have the desired conclusion. \square

Thus, taking a homothety centered at G with scale factor $-\frac{1}{2}$, $\triangle ABC$ maps to its medial triangle. In addition, H will map to the orthocenter of the medial triangle, which is the same as the circumcenter (O) of $\triangle ABC$ by the claim. Thus, O , G , and H are collinear, and $\frac{HG}{GO} = 2$, as required. \square

Problem 3.16 (Gergonne point)

Let ABC be a triangle with contact triangle DEF . Prove that \overline{AD} , \overline{BE} , \overline{CF} concur. The point of concurrency is the Gergonne point of triangle ABC .

We can write that

$$\frac{AF}{FC} \cdot \frac{CD}{DB} \cdot \frac{BE}{EA} = \frac{AF}{FC} \cdot \frac{FC}{BD} \cdot \frac{BD}{AF} = 1.$$

Thus, by Ceva's Theorem, we know that they are concurrent, so we are done. \square

Problem 3.17

In cyclic quadrilateral $ABCD$, points X and Y are the orthocenters of $\triangle ABC$ and $\triangle BCD$. Show that $AXYD$ is a parallelogram.



Let X' be the reflection of X across line BC , and analogously for Y .

Claim

Quadrilateral $Y'AX'D$ is an isosceles trapezoid.

Proof. Since a trapezoid is cyclic if and only if it's isosceles, we just have to show that $Y'AX'D$ is a trapezoid. However, we know that $\overline{AX'} \parallel \overline{Y'D}$ because they are both perpendicular to \overline{BC} . Hence, we have the desired claim. \square

Now, by the claim, we know that

$$AD = X'Y' = XY.$$

In addition, we know that $XA \parallel YD$, so $AXYD$ is indeed a parallelogram, as desired. \square

Problem 3.18

Let \overline{AD} , \overline{BE} , \overline{CF} be concurrent cevians in a triangle, meeting at P . Prove that

$$\frac{PD}{AD} + \frac{PE}{BE} + \frac{PF}{CF} = 1.$$

We can write that:

$$\frac{PD}{AD} = \frac{[PBD]}{[PBA]} = \frac{[PCD]}{[PCA]} = \frac{[PBC]}{[ABC]}$$

where the last equality is by the identity $\frac{a}{b} + \frac{c}{d} = \frac{a+c}{b+d}$. In fact, we can write similar statements for the other ratios as well. Hence, we get that

$$\frac{PD}{AD} + \frac{PE}{BE} + \frac{PF}{CF} = \frac{[PBC]}{[ABC]} + \frac{[PAC]}{[ABC]} + \frac{[PAB]}{[ABC]} = 1$$

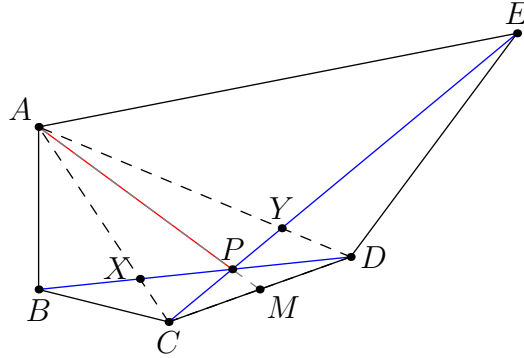
as required. \square

Problem 3.19 (ISL 2006/G3)

Let $ABCDE$ be a convex pentagon such that

$$\angle BAC = \angle CAD = \angle DAE \quad \text{and} \quad \angle ABC = \angle ACD = \angle ADE.$$

The diagonals BD and CE meet at P . Prove that the line AP bisects the side CD .



Let M be the point at which ray AP intersects \overline{CD} . By Ceva's Theorem, we know that

$$\frac{AX}{XC} \cdot \frac{CM}{MD} \cdot \frac{DY}{YA} = 1.$$

However, because

$$ABCD \sim ACDE$$

we know that

$$\frac{AX}{XC} = \frac{AY}{YD}.$$

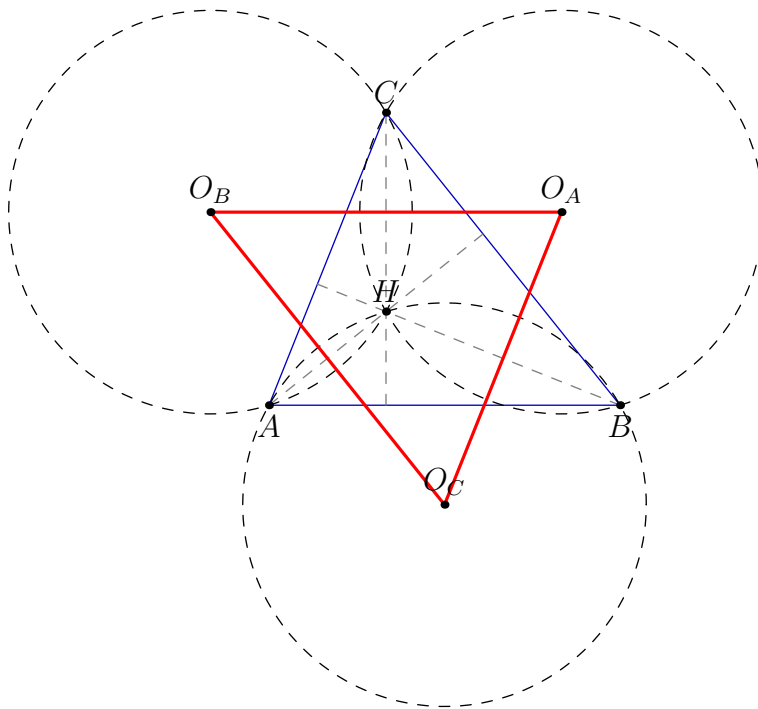
Hence, we know that

$$\frac{CM}{MD} = 1$$

so M is indeed the midpoint of \overline{CD} , as required.

Problem 3.20 (BAMO 2013/3)

Let H be the orthocenter of an acute triangle ABC . Consider the circumcenters of triangles ABH , BCH , and CAH . Prove that they are the vertices of a triangle that is congruent to ABC .



Define points O_A , O_B , and O_C as described in the figure; the centers of the given circumcircles. Then, we have the following claim:

Claim

The circles (AHC) , (AHB) , and (BHC) are congruent.

Proof. We wish to show that they have equal radii. However, let H_B be the reflection of H across \overline{AC} . Then, we know that

$$(ABC) = (AH_B C) \cong (AHC).$$

Hence, all the required circumcircles are congruent to (ABC) , proving the claim. \square

Now, take a homothety h with scale factor $\frac{1}{2}$ centered at H . Then, let $B' = h(B)$ and $C' = h(C)$. Then, we know that C' is the midpoint of $\overline{O_B O_A}$, and B' is the midpoint of $\overline{O_A O_C}$ because of the congruent circles. Hence, let g be a homothety centered at O_A with scale factor 2. Then, we know that $g(C')$ sends C' to O_C , and $g(B') = O_B$. Hence, we know that

$$O_B O_C = 2(\frac{1}{2} BC) = BC.$$

We get similar statements for the other sides, implying that

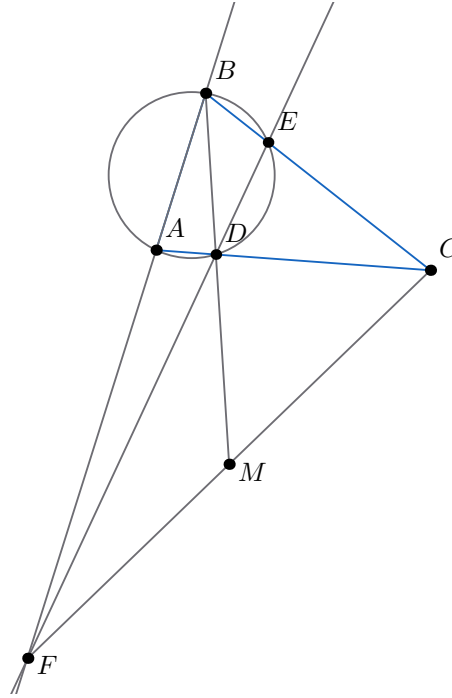
$$\triangle ABC \cong \triangle O_A O_B O_C.$$

Remark

Triangle $O_A O_B O_C$ is infact a rotation of $\triangle ABC$ around N_9 .

Problem 3.21 (USAMO 2003/4)

Let ABC be a triangle. A circle passing through A and B intersects segments AC and BC at D and E , respectively. Lines AB and DE intersect at F , while lines BD and CE intersect at M . Prove that $MF = MC$ if and only if $MB \cdot MD = MC^2$.



We will start with the if direction. Since $\frac{MB}{MC} = \frac{MC}{MD}$, and they share an angle, we know that

$$\triangle MBC \sim \triangle MCD.$$

Now, we can write that

$$\angle AEB = \angle ADB = \angle MDC = \angle MCB = \angle C.$$

Hence, we know that $AE \parallel FC$. This means that

$$\triangle BAE \sim \triangle BFC \implies \frac{BA}{BE} = \frac{BF}{BC} = \frac{AF}{EC}$$

due to the property that $\frac{a}{b} = \frac{c}{d} = \frac{c-a}{d-b}$. This means that

$$\frac{BA}{AF} \cdot \frac{FM}{MC} \cdot \frac{CE}{EB} = \frac{FM}{MC} = 1$$

by Ceva's Theorem. This is the necessary conclusion.

We now prove the only if direction. Since $MF = MC$, we know that

$$\frac{BA}{AF} \cdot \frac{CE}{EB} = 1$$

by Ceva. This implies that $AE \parallel FC$. Hence, we know that

$$\angle C = \angle MCB = \angle AEB = \angle ADB = \angle MDC.$$

Hence, we know that $\triangle MBC \sim \triangle MCD$, implying that $\frac{MB}{MC} = \frac{MC}{MD}$, as required. \square

Problem 3.22 (Monge's Theorem)

Consider disjoint circles $\omega_1, \omega_2, \omega_3$ in the plane, no two congruent. For each pair of circles, we construct the intersection of their common external tangents. Prove that these three intersections are collinear.

By Menelaus' Theorem, it suffices to show that the product of the ratios of the circles centers to the point at which they intersect is -1 . However, by similar triangles, this is equivalent to the product of the ratio of the radii, so we are done. \square

Problem 3.23 (Cevian Nest)

Let $\overline{AX}, \overline{BY}, \overline{CZ}$ be concurrent cevians of $\triangle ABC$. Let $\overline{XD}, \overline{YE}, \overline{ZF}$ be concurrent cevians in triangle XYZ . Prove that rays AD, BE, CF concur.

By Ceva's Theorem, we know that

$$\frac{ZD}{YD} \cdot \frac{YF}{FX} \cdot \frac{XE}{EZ} = 1.$$

In addition, by the Law of Sines, we can write that

$$\begin{aligned} \frac{\sin(\angle ZAD)}{\sin(\angle YAD)} &= \frac{ZD}{YD} \\ \frac{\sin(\angle YCF)}{\sin(\angle XCF)} &= \frac{YF}{XF} \\ \frac{\sin(\angle XBE)}{\sin(\angle ZBE)} &= \frac{XE}{ZE}. \end{aligned}$$

Multiplying these equations gives that:

$$\frac{\sin(\angle ZAD)}{\sin(\angle YAD)} \cdot \frac{\sin(\angle YCF)}{\sin(\angle XCF)} \cdot \frac{\sin(\angle XBE)}{\sin(\angle ZBE)} = \frac{ZD}{YD} \cdot \frac{YF}{FX} \cdot \frac{XE}{EZ} = 1.$$

So, by Trig Ceva, we know that the rays AD, BE , and CF concur, as required. \square

Problem 3.24

Let ABC be an acute triangle and suppose X is a point on (ABC) with $\overline{AX} \parallel \overline{BC}$ and $X \neq A$. Denote by G the centroid of triangle ABC , and by K the foot of the altitude from A to \overline{BC} . Prove that K, G, X are collinear.



Let h be the homothety centered at G with scale factor $-\frac{1}{2}$. This homothety will send $\triangle ABC$ to its medial triangle DEF . Note that G is both the centroid of $\triangle ABC$, and $\triangle DEF$. All that we need to show that is that K satisfies the same properties with respect to $\triangle DEF$ as X does with respect to $\triangle ABC$.

Claim

We claim that $\overline{DK} \parallel \overline{EF}$.

Proof. Clear, from the fact that X and D both lie on line BC and $BC \parallel \overline{EF}$. □

Claim

We claim that quadrilateral $DEFK$ is cyclic.

Proof. Clearly, we have that

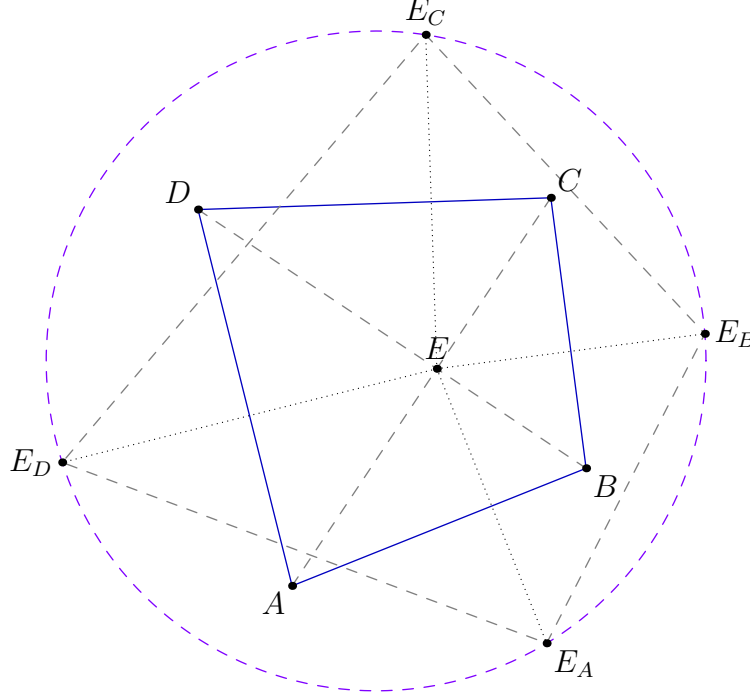
$$\angle FKD = 90 + \angle FKA = 90 + \angle KAF = 90 + \angle KAB = \angle KBA = \angle DBF = \angle FED$$

as required. □

These two claims in conjunction, show that $h(X) = K$, so K, G , and X are collinear, as desired.

Problem 3.25 (USAMO 1993/2)

Let $ABCD$ be a quadrilateral whose diagonals \overline{AC} and \overline{BD} are perpendicular and intersect at E . Prove that the reflections of E across \overline{AB} , \overline{BC} , \overline{CD} , \overline{DA} are concyclic.

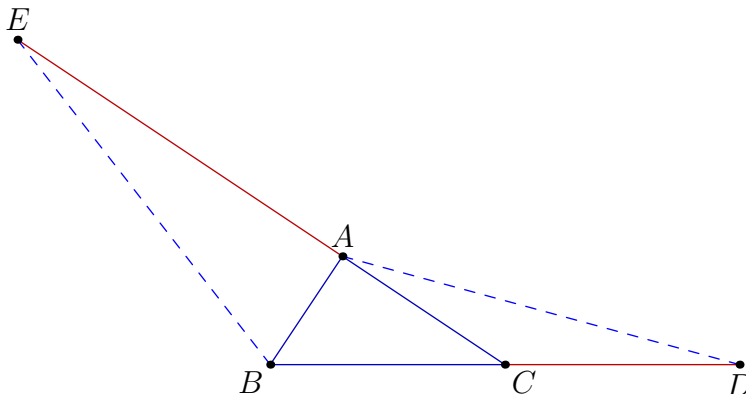


Define E_A , E_B , E_C , and E_D as shown in the diagram. Take a homothety h with scale factor $\frac{1}{2}$, centered at E , and let $h(E_A) = E'_A$ and similarly for the other points. Then, we know that:

$$\begin{aligned}
 \angle E'_D E'_A E'_B + \angle E'_D E'_C E'_B &= \angle E'_D E'_A E + \angle E E'_A E'_B + \angle E'_D E'_C E + \angle E E'_C E'_B \\
 &= \angle E'_D A E + \angle E'_B B E + \angle E'_D D E + \angle E'_B C E \\
 &= (\angle E'_D A E + \angle E'_D D E + \angle D E A) + (\angle E'_B B E + \angle E'_B C E + \angle C E B) \\
 &\quad - \angle D E A - \angle C E B \\
 &= 180 + 180 - 90 - 90 \\
 &= 180
 \end{aligned}$$

where the second line is due to the fact that the quadrilateral $EE'_D AE'_A$ is cyclic, as well as the other analogous quadrilaterals. This means that $E'_A E'_B E'_C E'_D$ is cyclic, so $E_A E_B E_C E_D$ is also cyclic, as desired. \square

The side BC of the triangle ABC is extended beyond C to D so that $CD = BC$. The side CA is extended beyond A to E so that $AE = 2CA$. Prove that if $AD = BE$ then the triangle ABC is right-angled.


$$AM = \frac{1}{2}AD = \frac{1}{2}BE = BM = EM.$$

Remark

For a computational method, look to Problem 5.19.

Let O be the circumcenter and H the orthocenter of an acute triangle ABC . Prove that the area of one of the triangles AOH , BOH , and COH is equal to the sum of the areas of the other two.



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BC outside \overline{BC} . This means that we can write that

$$[BHO] + [CHO] = 2[MHO]$$

because M is the midpoint of that segment, hence the altitude to line HO will be the average of BB' and CC' . This means that

$$[BHO] + [CHO] = 2[MHO] = [AHO]$$

as required. \square

Problem 3.28 (ISL 2001/G1)

Let A_1 be the center of the square inscribed in acute triangle ABC with two vertices of the square on side \overline{BC} . Thus one of the two remaining vertices of the square is on side \overline{AB} and the other is on \overline{AC} . Points B_1 and C_1 are defined in a similar way for inscribed squares with two vertices on sides \overline{AC} and \overline{AB} , respectively. Prove that lines AA_1 , BB_1 , CC_1 are concurrent.

For each of the A_1 , B_1 , and C_1 , take a homothety centered at its respective point (for example for A_1 , it would be A) sending one of the sides of its square to the side of the triangle opposite its respective point. Call the new centers A_2 , B_2 , and C_2 respectively. Then, we need to show that

$$\frac{\sin(\angle BAA_2)}{\sin(\angle CAA_2)} \cdot \frac{\sin(\angle ACC_2)}{\sin(\angle BCC_2)} \cdot \frac{\sin(\angle CBB_2)}{\sin(\angle ABB_2)} = 1.$$

However, by the Law of Sines, we know that

$$\frac{\sin(\angle BAA_2)}{BA_2} = \frac{\sin(\angle ABA_2)}{AA_2}$$

and

$$\frac{CA_2}{\sin(\angle CAA_2)} = \frac{AA_2}{\sin(\angle ACA_2)}.$$

Multiplying the two gives that

$$\frac{\sin(\angle BAA_2)}{\sin(\angle CAA_2)} = \frac{\sin(\angle ABA_2)}{\sin(\angle ACA_2)} = \frac{\sin(\angle B + 45)}{\sin(\angle C + 45)}.$$

We get similar equations for the other points, and multiplying them all gives that

$$\frac{\sin(\angle BAA_2)}{\sin(\angle CAA_2)} \cdot \frac{\sin(\angle ACC_2)}{\sin(\angle BCC_2)} \cdot \frac{\sin(\angle CBB_2)}{\sin(\angle ABB_2)} = \frac{\sin(\angle B + 45)}{\sin(\angle C + 45)} \cdot \frac{\sin(\angle C + 45)}{\sin(\angle A + 45)} \cdot \frac{\sin(\angle A + 45)}{\sin(\angle B + 45)} = 1$$

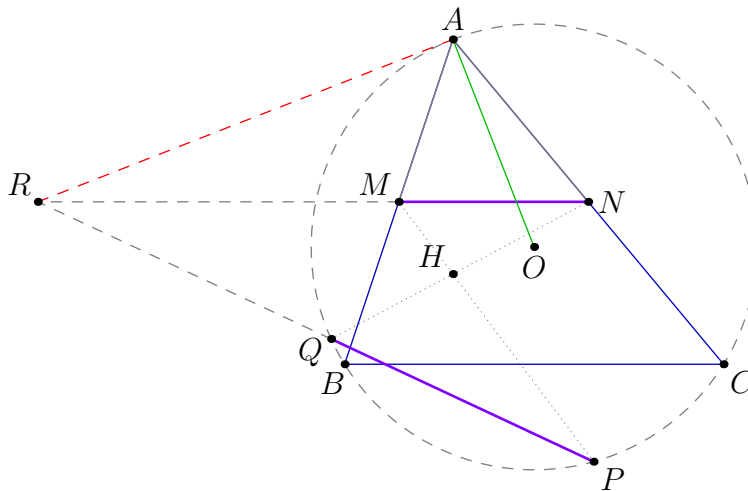
as required. \square

Problem 3.29 (TSTST 2011/4)

Acute triangle ABC is inscribed in circle ω . Let H and O denote its orthocenter and circumcenter, respectively. Let M and N be the midpoints of sides \overline{AB} and \overline{AC} , respectively. Rays \overline{MH} and \overline{NH} meet ω at P and Q , respectively. Lines MN and PQ meet at R . Prove that $\overline{OA} \perp \overline{RA}$.

Problem 3.29 (TSTST 2011/4)

Acute triangle ABC is inscribed in circle ω . Let H and O denote its orthocenter and circumcenter, respectively. Let M and N be the midpoints of sides \overline{AB} and \overline{AC} , respectively. Rays \overline{MH} and \overline{NH} meet ω at P and Q , respectively. Lines MN and PQ meet at R . Prove that $\overline{OA} \perp \overline{RA}$.



We begin with the following claim:

Claim

Quadrilateral $MNPQ$ is cyclic.

Proof. Let the reflection of H across M and N be denoted X and Y respectively. Then, we know that

$$HQ \cdot HX = \frac{1}{2}HQ \cdot HN = \frac{1}{2}HP \cdot HM$$

so by the Converse of Power of a Point, we know that $MNPQ$ is cyclic, as required. \square

Now, consider the circles (ABC) , (AMN) , and $(MNPQ)$. Clearly, the radical center is R , and so because \overline{AR} is tangent to (AMN) , we know that $\overline{AR} \perp \overline{OA}$, as required. \square

Problem 3.30 (USAMO 2015/2, synthetic)

Quadrilateral $APBQ$ is inscribed in circle ω with $\angle P = \angle Q = 90^\circ$ and $AP = AQ < BP$. Let X be a variable point on segment \overline{PQ} . Line AX meets ω again at S (other than A). Point T lies on arc AQB of ω such that XT is perpendicular to AX . Let M denote the midpoint of chord \overline{ST} . As X varies on segment \overline{PQ} , show that M moves along a circle.



Let N_9 be the nine-point circle of $\triangle AST$, and N be the midpoint of \overline{AS} . Then, we know that

$$\text{Pow}_{N_9}(A) = AN \cdot AX = \frac{AS \cdot AX}{2} = \frac{AQ^2}{2}.$$

In addition since the radius of N_9 is constant (it is equal to $\frac{AO}{2}$), we know that the center of N_9 always lies on a circle centered at A . In addition, there exists a homothety taking N_9 to G centered at O (with scale factor $\frac{2}{3}$), so G also lies on some circle. Finally, there exists a homothety with scale factor $\frac{3}{2}$ sending G to M , centered at A . Hence, M always lies on a circle, as required. \square

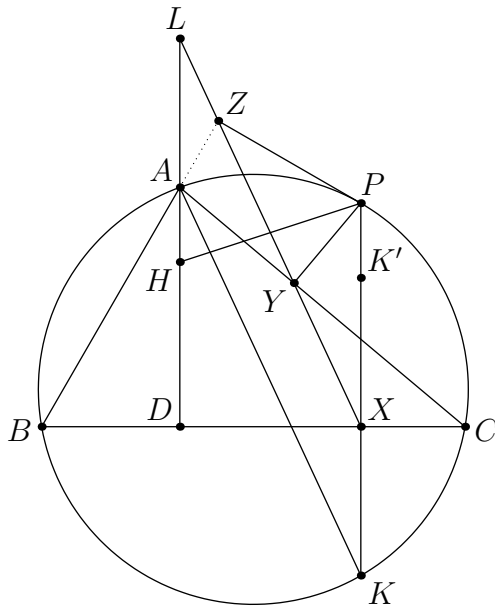
Remark

A complex bash can be found as Problem 6.35.

4 Assorted Configurations

Problem 4.1

Prove that the Simson line is parallel to \overline{AK} in the notation of the figure below.



Clearly, $PYXC$ is cyclic. Hence,

$$\angle AKP = \angle ACP = \angle YCP = \angle YXP$$

so line $XY \parallel \overline{AK}$, and we are done. \square

Problem 4.2

Let K' be the reflection of K across \overline{BC} . Show that K' is the orthocenter of $\triangle PBC$.

Refer to the diagram above. The desired result follows from the fact that $PK' \perp BC$ and the reflection of K' lies on K . \square

Problem 4.3

Show that $LHXP$ is a parallelogram.

We have that

$$LH = LA + AH = XK + K'P = XK' + K'P = XP$$

and $LH \parallel PX$ so we are done. \square

Problem 4.5

Check $\angle IAI_B = 90^\circ$ and $\angle IAI_C = 90^\circ$ where I_B denotes the B -excenter and similarly for I_C .

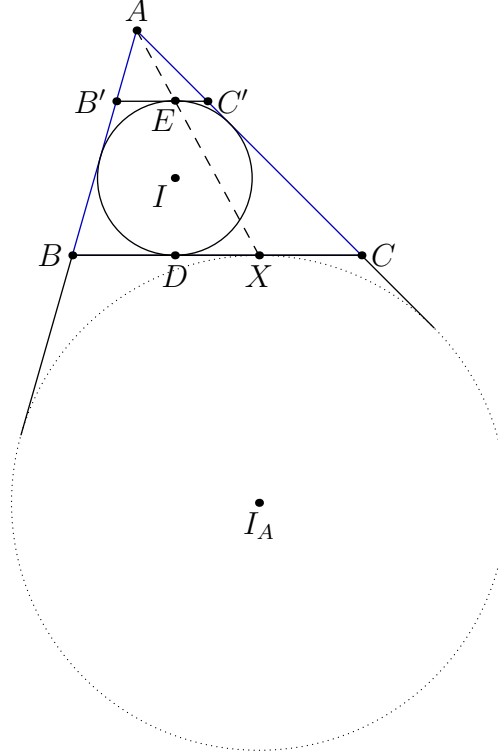
Since I_CA bisects the external angle at A , we know that

$$\angle IAI_C = \angle I_CAB + \angle BAI = 90 - \frac{\angle A}{2} + \frac{\angle A}{2} = 90^\circ.$$

A similar computation gives the result for I_B , as required. \square

Problem 4.8

Prove that A , E , and X are collinear and that \overline{DE} is a diameter of the incircle.



Clearly, there exists a homothety at A sending $\triangle AB'C'$ to $\triangle ABC$. This homothety would also send E to X , so they are collinear, as required.

In addition, we know that E , I , D are collinear because:

$$\angle EID = \angle EC'C + \angle C'CD = 0$$

since they $C'C$ is a transversal. Hence, we know that \overline{DE} is a diameter of the incircle, so we are done. \square

Problem 4.10

In the notation of the figure above, suppose \overline{XY} is a diameter of the A -excicle. Show that D lies on \overline{AY} .

Clearly, there exists a homothety taking the incircle of $\triangle ABC$ to the excircle of $\triangle ABC$ centered at A . Hence, this homothety will take D to Y , so A , D , Y are collinear, implying the necessary claim. \square

Problem 4.11

If M is the midpoint of \overline{BC} , prove that $\overline{AE} \parallel \overline{IM}$.

Obviously, there exists a homothety of scale factor 2 centered at D taking I to E and M to X . Hence,

$$\overline{IM} \parallel \overline{EX} \implies \overline{IM} \parallel \overline{AE}$$

as desired. \square

Problem 4.12

In the diagram below, prove that points X , I , M are collinear, if M is the midpoint of the altitude \overline{AK} .



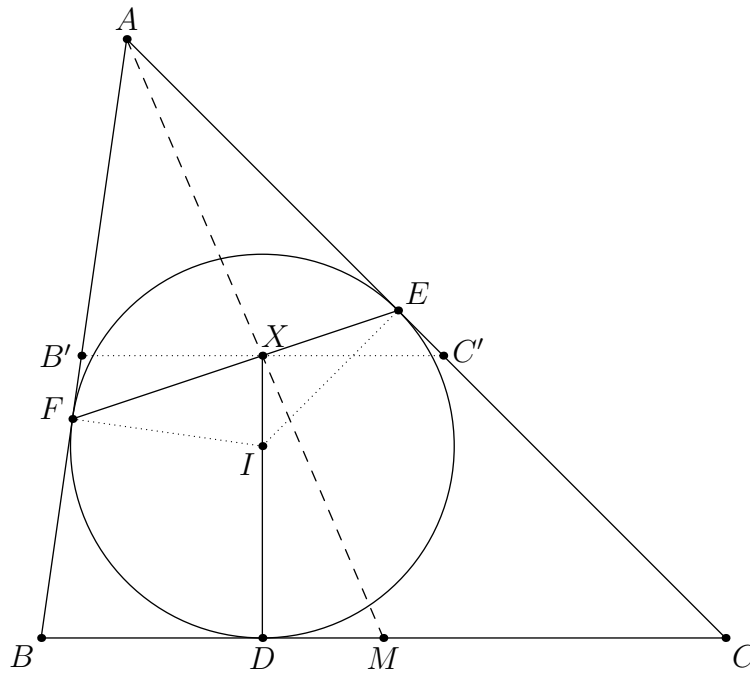
Clearly, there exists a homothety sending $\triangle IDX$ to $\triangle MKX$ centered at X since they are similar. Hence, M , I , and X are collinear. \square

Problem 4.13

Show that D , I_A , M are collinear.

There exists a homothety centered at D sending $\triangle AKD$ to $\triangle YXD$. This homothety will also send M to I_A since they are both the midpoints of \overline{AK} and \overline{XY} , respectively. Hence, M , D , and I_A are collinear. \square

Show that I must lie on $(AB'C')$.



Problem 4.16

Since $XB'FI$ and $xEC'I$ are cyclic, we can say that

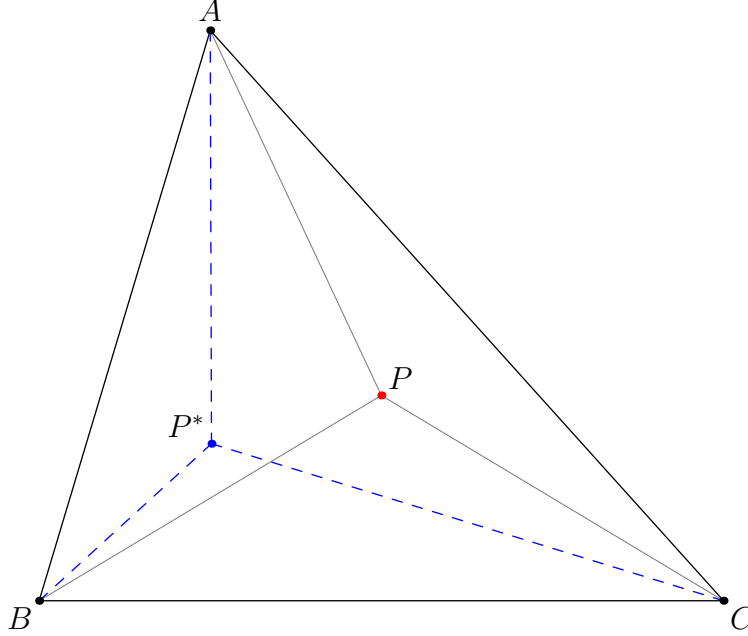
$$\angle IB'X = \angle IFX = \angle IEX = \angle IC'X.$$

Hence, $\triangle IB'X \cong \triangle IC'X$, from which the conclusion can easily be derived. \square

Problem 4.19

Show that if two of the angle relations below hold, then so does the third:

$$\angle BAP = \angle P^*AC, \quad \angle CBP = \angle P^*BA, \quad \angle ACP = \angle P^*CB.$$



WLOG say that we know the first two are true. By Trig Ceva, we know that

$$\frac{\sin(\angle BAP^*)}{\sin(\angle CAP^*)} \cdot \frac{\sin(\angle ACP^*)}{\sin(\angle BCP^*)} \cdot \frac{\sin(\angle CBP^*)}{\sin(\angle ABP^*)} = \frac{\sin(\angle CAP)}{\sin(\angle BAP)} \cdot \frac{\sin(\angle ACP^*)}{\sin(\angle BCP^*)} \cdot \frac{\sin(\angle ABP)}{\sin(\angle CBP)} = 1$$

and

$$\frac{\sin(\angle BAP)}{\sin(\angle CAP)} \cdot \frac{\sin(\angle ACP)}{\sin(\angle BCP)} \cdot \frac{\sin(\angle CBP)}{\sin(\angle ABP)} = 1.$$

Multiplying the two, we get that

$$\frac{\sin(\angle ACP^*)}{\sin(\angle BCP^*)} = \frac{\sin(\angle BCP)}{\sin(\angle ACP)}.$$

Now since they add to the same amount, and $\frac{\sin(a-x)}{\sin(x)}$ is monotonically decreasing, we must have $\angle ACP^* = \angle BCP$ and $\angle BCP^* = \angle ACP$, as required. \square

Problem 4.20

For a point P and triangle ABC , let X, Y, Z be the feet of the cevians through P . Let X' be the reflection of X about the midpoint of \overline{BC} and define Y' and Z' similarly. Prove that the cevians $\overline{AX'}$, $\overline{BY'}$, and $\overline{CZ'}$ concur at a point P^t , the isotomic conjugate of P .

By Ceva's Theorem, we know that

$$\frac{AZ}{ZB} \cdot \frac{BX}{XC} \cdot \frac{CY}{YA} = 1.$$

This is equivalent to

$$1 = \frac{ZB}{AZ} \cdot \frac{XC}{BX} \cdot \frac{YA}{CY} = \frac{AZ'}{Z'B} \cdot \frac{BX'}{X'C} \cdot \frac{CY'}{Y'A}$$

so by Ceva's Theorem, they do concur. \square

Problem 4.21

Check that if Q is the isogonal conjugate of P , then P is the isogonal conjugate of Q .

The isogonal conjugate of P can be found by reflecting the cevians through P across the angle bisectors, so obviously repeating this again (finding Q^*) will take Q back to P . \square

Problem 4.22 (Isogonal Ratios)

Let D and E be points on \overline{BC} so that \overline{AD} and \overline{AE} are isogonal. Then

$$\frac{BD}{DC} \cdot \frac{BE}{EC} = \left(\frac{AB}{AC} \right)^2.$$

By the Law of Sines, we know that

$$\frac{AB}{\sin(\angle BEA)} = \frac{BE}{\sin(\angle BAE)}$$

and

$$\frac{\sin(\angle AEC)}{AC} = \frac{\sin(\angle BEA)}{AC} = \frac{\sin(\angle EAC)}{EC}.$$

In addition, we have that

$$\frac{AB}{\sin(\angle BDA)} = \frac{BD}{\sin(\angle BAD)}$$

and

$$\frac{\sin(\angle ADC)}{AC} = \frac{\sin(\angle BDA)}{AC} = \frac{\sin(\angle DAC)}{DC}.$$

Multiplying the four equations together, we get that

$$\left(\frac{AB}{AC} \right)^2 = \frac{BD}{DC} \cdot \frac{BE}{EC} \cdot \frac{\sin(\angle EAC) \sin(\angle DAC)}{\sin(\angle BAE) \sin(\angle BAD)} = \frac{BD}{DC} \cdot \frac{BE}{EC} \cdot \frac{\sin(\angle BAD) \sin(\angle BAE)}{\sin(\angle BAE) \sin(\angle BAD)} = \frac{BD}{DC} \cdot \frac{BE}{EC}$$

as desired. \square

Problem 4.23

What is the isogonal conjugate of a triangle's circumcenter?

By Problem 1.7, it is the orthocenter. \square

Problem 4.25

Let X be the intersection of the tangents to (ABC) at B and C . In addition, let M be the intersection of the isogonal of \overline{AX} on \overline{BC} . Show that

$$\frac{BM}{MC} = \frac{\sin(\angle B) \sin(\angle BAX)}{\sin(\angle C) \sin(\angle CAX)} = 1.$$

Due to the properties of tangents, we know that

$$\frac{\sin(\angle BAX)}{\sin(\angle CAX)} = \frac{\sin(\angle C)}{\sin(\angle B)}.$$

In addition, by the Law of Sines, we know that:

$$\frac{\sin(\angle BAM)}{BM} = \frac{\sin(\angle B)}{AM}$$

$$\frac{\sin(\angle CAM)}{CM} = \frac{\sin(\angle C)}{AM}.$$

Dividing the second equation by the first, we get that

$$\frac{BM \sin(\angle CAM)}{MC \sin(\angle BAM)} = \frac{BM \sin(\angle BAX)}{MC \sin(\angle CAX)} = \frac{\sin(\angle C)}{\sin(\angle B)}$$

as required. \square

Problem 4.28

Let ABC be a triangle, and let the tangents to its circumcircle at B and C meet at point X . Let \overline{AX} meet (ABC) again at K and \overline{BC} at D . In addition, let M be the midpoint of \overline{BC} . Show that

$$\frac{AB}{BK} = \frac{AC}{CK}.$$

We know by angle chasing that

$$\triangle ABK \sim \triangle AMC$$

and

$$\triangle ACK \sim \triangle AMB.$$

Hence, we know that

$$\frac{AB}{BK} = \frac{AM}{MC} = \frac{AM}{MB} = \frac{AC}{CK}$$

so we are done. \square

Problem 4.29

Use the configuration in Problem 4.28. Show that \overline{BC} is the B -symmedian of $\triangle BAK$, and the C -symmedian of $\triangle CAK$.

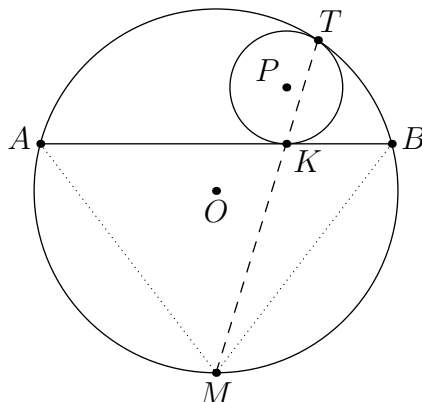
Clearly, we have that

$$\frac{BK}{KC} = \frac{BA}{AC}$$

and there can only be one point C that satisfies this on (ABC) , so the first part is proved. The second part can easily be replicated with similar logic. \square

Problem 4.31

Show that the homothety centered at T taking P to O , also takes K to M , and in particular that T , K , and M are collinear.



We know that

$$\triangle TPK \sim \triangle TOM$$

because they are both isosceles and share an angle. Hence, the same homothety taking P to O centered at T , takes K to M , as required. \square

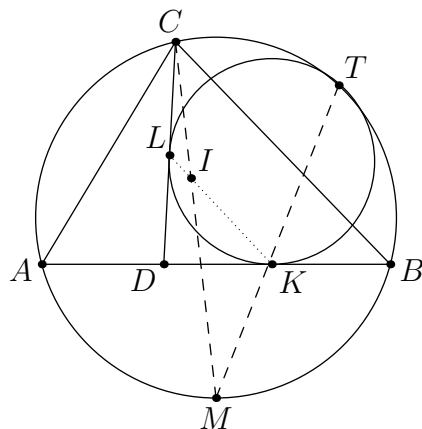
Problem 4.32

Show that $\triangle TMB \sim \triangle BMK$ in the diagram above.

Clearly, they share an angle, and we know that $\angle KBM = \angle BTM$ because of inscribed angles. Hence, they are similar, as required. \square

Problem 4.34

Prove that the points C , L , I , T are concyclic.



Consider the homothety centered at T sending the smaller circle to the bigger circle. We know that K will go to M , and so

$$\angle TCM = \angle TLK.$$

Hence,

$$\angle TLI = \angle TLK = \angle TCM = \angle TCI$$

implying that $CLIT$ is cyclic. \square

Problem 4.35

Show that $\triangle MKI \sim \triangle MIT$, in the diagram above.

They share an angle, and also

$$\angle MIT = \angle CIT = \angle CLT = \angle LKT = -\angle MKI$$

so they are similar, and oppositely oriented.

Problem 4.37

Let ω_A refer to this A -mixtilinear circle. Let K and L the tangency points of ω_A on \overline{AB} and \overline{AC} . Using the fact that I lies on \overline{KL} , check that I is in fact the midpoint of \overline{KL} .

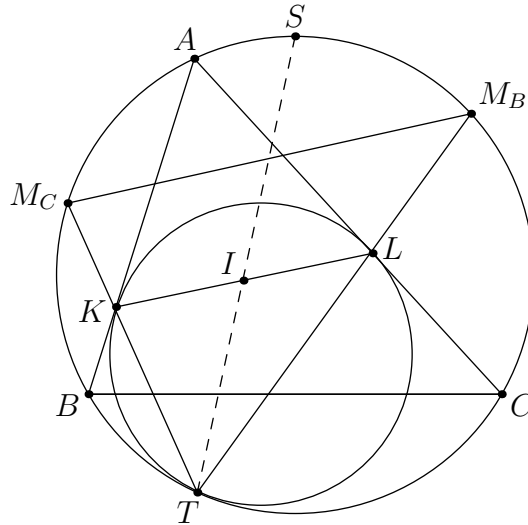
Because of the tangency, we know that

$$\triangle KIA \sim \triangle LIA.$$

Hence, we know that $KI = LI$, as desired. \square

Problem 4.38

Prove that $\angle ATK = \angle LTI$ in the diagram below.



We know that line TA is a symmedian of $\triangle KTL$ because of tangents at K and L intersect at A . Hence, lines TA and TI are isogonal, since \overline{TI} is a median. This directly implies the necessary result due to the definition of isogonal. \square

Problem 4.39

Prove that S is the midpoint of the arc \widehat{BC} containing A in the diagram above.

We know from Problem 4.34 that $BKIT$ is cyclic, and so is $CLIT$. Hence,

$$\angle BTS = \angle BTI = \angle BKI = \angle AKI = \angle ALI = \angle CLI = \angle CTI = \angle CTS.$$

Thus, we are done. \square

Problem 4.41 (Hong Kong 1998)

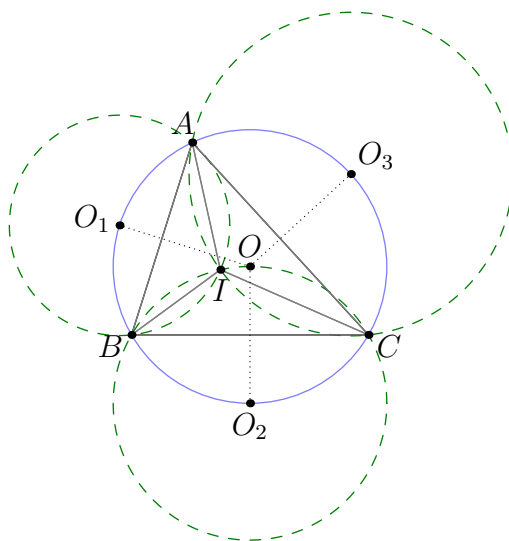
Let $PQRS$ be a cyclic quadrilateral with $\angle PSR = 90^\circ$ and let H and K be the feet of the altitudes from Q to lines PR and PS . Prove that \overline{HK} bisects \overline{QS} .



Since $\triangle PSR$ is right, we know that S is its orthocenter. Now since HK is a Simson Line, we know that \overline{HK} bisects \overline{QS} because of the Simson Lines properties. \square

Problem 4.42 (USAMO 1988/4)

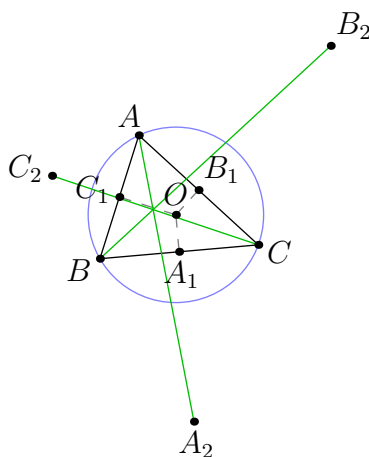
Suppose ABC is a triangle with incenter I . Show that the circumcenters of $\triangle IAB$, $\triangle IBC$, and $\triangle ICA$ lie on a circle whose center is the circumcenter of $\triangle ABC$.



Let the centers of the aforementioned circumcircles be denoted O_1 , O_2 , and O_3 , as in the figure above. By the Incenter-Excenter Lemma, we know that these centers O_1 , O_2 , and O_3 lie on the midpoints of the arcs \widehat{AB} , \widehat{BC} , and \widehat{AC} respectively. Hence, they lie on (ABC) , as required. \square

Problem 4.43 (USAMO 1995/3)

Given a nonisosceles, nonright triangle ABC , let O denote its circumcenter, and let A_1 , B_1 , and C_1 be the midpoints of sides \overline{BC} , \overline{CA} , and \overline{AB} , respectively. Point A_2 is located on the ray $\overrightarrow{OA_1}$ so that $\triangle OAA_1$ is similar to $\triangle OA_2A$. Points B_2 and C_2 on rays $\overrightarrow{OB_1}$ and $\overrightarrow{OC_1}$, respectively, are defined similarly. Prove that lines AA_2 , BB_2 , and CC_2 are concurrent.



We begin with the following claim:

Claim

The lines AA_2 , BB_2 , and CC_2 are symmedians.

Proof. We will show that AA_2 is a symmedian. Similar methods can easily show the other two. By the similarity criterion, we know that

$$OA^2 = OA_1 \cdot OA_2.$$

Now, by the Law of Sines, we know that

$$\frac{OA_2}{\sin(\angle OCA_2)} = \frac{A_2C}{\sin(\angle A_2OC)}.$$

Substitution yields that

$$OA^2 = \frac{OA_1 \cdot A_2C}{\sin(\angle OCA_2) \sin(\angle A_2OC)} = \frac{OA_1 \cdot A_2C}{\sin(\angle OCA_2) \frac{A_1C}{OC}}.$$

Hence,

$$\frac{OA}{A_2C} = \frac{OC}{A_2C} = \frac{OA_1}{A_1C}.$$

Thus, we have that

$$\triangle OA_1C \sim \triangle OCA_2.$$

This means that $\angle OCA_2 = 90^\circ$ implying tangency. Hence, by the definition of symmedian, we can get that AA_2 is one. \square

We know that the symmedians concur at the symmedian point, so the existence of this point gives the required answer. \square

Problem 4.44 (USA TST 2014/1)

Let ABC be an acute triangle and let X be a variable interior point on the minor arc \widehat{BC} . Let P and Q be the feet of the perpendiculars from X to lines CA and CB , respectively. Let R be the intersection of line PQ and the perpendicular from B to \overline{AC} . Let ℓ be the line through P parallel to XR . Prove that as X varies along minor arc \widehat{BC} , the line ℓ always passes through a fixed point.



We claim the following:

Claim

The mentioned fixed point is H ; the orthocenter of $\triangle ABC$.

Proof. Since PQ is a Simson Line, Simson Line properties tell us that $RXPH$ is a parallelogram, implying that the fixed point is indeed H . \square

Clearly, we have shown the existence of the fixed point by declaring what it is, so we are done. \square

Problem 4.45 (USA TST 2011/1)

In an acute scalene triangle ABC , points D, E, F lie on sides BC, CA, AB , respectively, such that $AD \perp BC, BE \perp CA, CF \perp AB$. Altitudes AD, BE, CF meet at orthocenter H . Points P and Q lie on segment EF such that $AP \perp EF$ and $HQ \perp EF$. Lines DP and QH intersect at point R . Compute HQ/HR .



We claim that $\frac{HQ}{HR} = 1$. Note that H is the incenter of $\triangle DEF$, and Q is one of the contact points of the incircle. In addition, we know that A is the D -excenter of $\triangle DEF$, and P is the point of tangency of that circle with the triangle. Finally, we know that QR is a diameter of the incircle, because of the properties of the excircle. Hence, since H is the center of that incircle, we get the desired result. \square

Problem 4.46 (ELMO Shortlist 2012/G4)

Circles Ω and ω are internally tangent at point C . Chord AB of Ω is tangent to ω at E , where E is the midpoint of AB . Another circle, ω_1 is tangent to Ω, ω , and AB at D, Z , and F respectively. Rays CD and AB meet at P . If M is the midpoint of major arc AB , show that

$$\tan \angle ZEP = \frac{PE}{CM}.$$



Clearly, we can write that

$$\angle ZEP = \angle ZCE$$

due to the tangency. Hence, we just have to show that

$$\frac{EZ}{ZC} = \frac{PE}{CM}.$$

We will do this by showing that

$$\triangle CZM \sim \triangle EZP.$$

We already have one set of angles from the first line, thus we just need to show that

$$\angle CZM = \angle EZP \implies \angle CZE = 90^\circ = \angle PZM.$$

Let G be the point at which CP intersects ω_1 . We know that

$$\triangle CPE \sim \triangle GPF$$

implying that there exists a homothety centered at P taking one triangle to the other. In addition, since CE and FG are both diameters, these homotheties also take the circles to each other. Hence, PZ passes through the centers of these circles. This means that

$$PZ \perp ZM$$

implying the necessary claim. \square

Problem 4.47 (USAMO 2011/5)

Let P be a given point inside quadrilateral $ABCD$. Points Q_1 and Q_2 are located within $ABCD$ such that

$$\angle Q_1BC = \angle ABP, \quad \angle Q_1CB = \angle DCP, \quad \angle Q_2AD = \angle BAP, \quad \angle Q_2DA = \angle CDP.$$

Prove that $\overline{Q_1Q_2} \parallel \overline{AB}$ if and only if $\overline{Q_1Q_2} \parallel \overline{CD}$.

If $AB \parallel CD$ then it is obvious.

Suppose that AB is not parallel to CD . Then, let R be the intersection of the two. Then, from the given conditions, we know that Q_1 and P are isogonal conjugates of $\triangle RBC$, and Q_2 and P are isogonal conjugates of $\triangle RAD$. Hence, Q_1 , Q_2 , and R are collinear, so neither of the statements can be true. \square

Problem 4.48 (Japan Olympiad 2009)

Triangle ABC is inscribed in circle ω . A circle with center O is drawn, tangent to side \overline{BC} at a point P , and internally tangent to the arc BC not containing A at a point Q . Show that if $\angle BAO = \angle CAO$ then $\angle PAO = \angle QAO$.



We know that O must lie on the angle bisector of $\angle A$. In addition, extend AO to meet ω again at M . We know that M is the midpoint of arc BC .

Claim

Quadrilateral $APOQ$ is cyclic.

Proof. Let M_1 be the midpoint of arc BC containing A . Then, because of a homothety that sends both P to M_1 and O to the center of ω (call it O_1), we know that $PM_1 \parallel OO_1$.

Thus,

$$\angle QAO = \angle QAM = \angle QM_1M = \angle QM_1O = \angle QPO.$$

\square

This implies that because $OP = OQ$, we have the desired result. \square

Problem 4.49

Let ABC be a triangle and let its incircle touch \overline{BC} at D . Let T be the tangency point of the A -mixtilinear incircle with (ABC) . Prove that $\angle BTA = \angle CTD$.



Let I be the incenter of $\triangle ABC$, E be a point on \overline{BC} such that $BD = CE$, O be the circumcenter of $\triangle ABC$, and P be the reflection of A over the perpendicular bisector of \overline{BC} . In addition, define T' as the reflection of T over that same line. Then we can write that

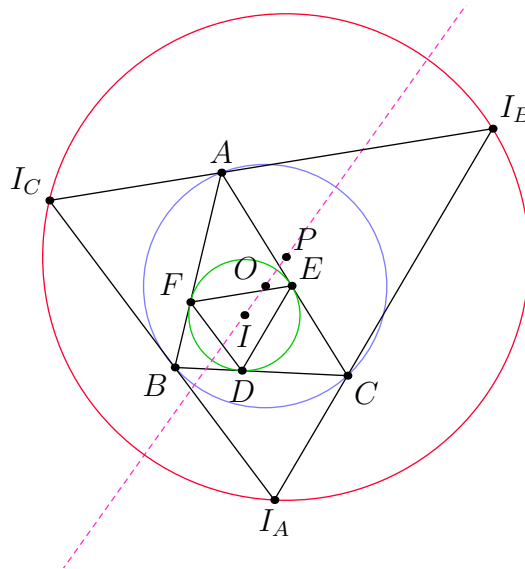
$$\angle EAC = \angle BAT = \angle T'AC$$

due to symmetry. Hence, A , E , and T' are collinear. In addition, by symmetry, we now know that arcs $AB = PC$, hence

$$\angle BTA = \angle BCA = \angle PBC = \angle PTC = \angle DTC$$

as required. \square

Given a triangle ABC . Let O be the circumcenter of this triangle ABC . Let H, K, L be the feet of the altitudes of triangle ABC from the vertices A, B, C , respectively. Denote by A_0, B_0, C_0 the midpoints of these altitudes AH, BK, CL , respectively. The incircle of triangle ABC has center I and touches the sides BC, CA, AB at the points D, E, F , respectively. Prove that the four lines A_0D, B_0E, C_0F and OI are concurrent.


$$\Delta DEF \sim \Delta I_A I_B I_C$$

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Problem 4.51 (Sharygin 2013)

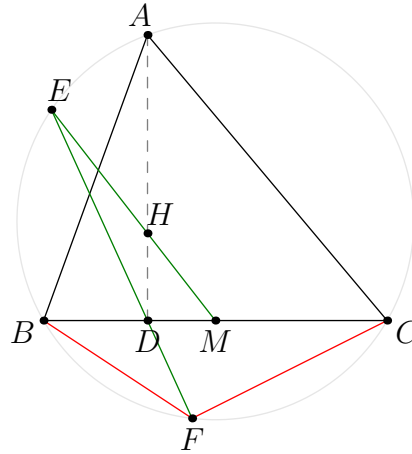
The incircle of triangle ABC touches \overline{BC} , \overline{CA} , \overline{AB} at points A_1 , B_1 , C_1 , respectively. The perpendicular from the incenter I to the median from vertex C meets the line A_1B_1 in point K . Prove that $CK \parallel AB$.



Let $H = CM \cap B_1K$. Then, we know that H is the orthocenter of $\triangle CIK$. However, since $HC_1 \perp AB$ and $IC \perp CK$, we have the required conclusion since it is well known that C_1 , I , and H are collinear.

Problem 4.52 (APMO 2012/4)

Let ABC be an acute triangle. Denote by D the foot of the perpendicular line drawn from the point A to the side \overline{BC} , by M the midpoint of \overline{BC} , and by H the orthocenter of $\triangle ABC$. Let E be the point of intersection of the circumcircle Γ of the triangle ABC and the half line MH , and $F \neq E$ be the point of intersection of the line ED and the circle Γ . Prove that $\frac{BF}{CF} = \frac{AB}{AC}$.



We begin with the following claim:

Claim

Quadrilateral $AEDM$ is cyclic.

Proof. Consider the triangle formed by taking a homothety of scale factor two centered at H of

$\triangle HDM$. Clearly, this triangle is similar to $\triangle HEA$. Hence,

$$\triangle AEH \sim \triangle MDH$$

and we are done. \square

Because of this, we may now write that

$$\angle AMC = \angle AMD = \angle AED = \angle AEF = \angle ABF$$

and

$$\angle AFB = \angle ACB = \angle ACM.$$

hence, this implies that

$$\triangle ABF \sim \triangle AMC$$

and since there can only be one point F on arc BC that satisfies this, we know that AF is a symmedian, implying the necessary result. \square

Problem 4.53 (ISL 2002/G7)

The incircle Ω of the acute-angled triangle ABC is tangent to its side \overline{BC} at a point K . Let \overline{AD} be an altitude of triangle ABC , and let M be the midpoint of the segment \overline{AD} . If $N \neq K$ is the common point of the circle Ω and the line KM , then prove that the incircle Ω and (BCN) are tangent to each other at the point N .



It is well known that M , K and I_A are collinear. Hence, define T to be the intersection of the perpendicular bisector of \overline{BC} and $\overline{KI_A}$.

Claim

Quadrilateral $BNCT$ is cyclic.

Proof. Let r be the inradius and r_a the A -exradius. Then, we have that

$$KN \cdot KI_A = KI_A(KI_A + KN) - KI_A^2 = KI_A \cdot NI_A - KI_A^2 = \text{Pow}_{\Omega}(I_A) - KI_A^2 = II_A^2 - r^2 - KI_A^2.$$

Now let X_A be the point of tangency of the A -excircle and \overline{BC} . Then, we can write that

$$KI_A^2 = KX_A^2 + X_AI_A^2 = (BC - 2BK)^2 + r_a^2$$

and

$$II_A^2 = KX_A^2 + (IK + XI_A)^2 = (BC - 2BK)^2 + (r + r_a)^2.$$

Hence,

$$KN \cdot KI_A = II_A^2 - r^2 - KI_A^2 = (r + r_a)^2 - r^2 - r_a^2 = 2rr_a.$$

This means that

$$KN \cdot KT = rr_a = (s - b)(s - c) = BK \cdot CK$$

implying the necessary result. \square

Finally, we can say that Ω and (BCT) are homothetic about N since T is the midpoint of arc BC and Ω is tangent to \overline{BC} at K , implying the necessary conclusion. \square

5 Computational Geometry

Problem 5.5

Show that $[ABC] = sr$.

We have that

$$[ABC] = 2 \cdot \frac{r(s-a)}{2} + 2 \cdot \frac{r(s-b)}{2} + 2 \cdot \frac{r(s-c)}{2} = 3sr - r(a+b+c) = sr$$

as required. \square

Problem 5.6

In $\triangle ABC$ we have $AB = 13$, $BC = 14$, $CA = 15$. Find the length of the altitude from A onto \overline{BC} .

We may find that $[ABC] = 84$, and so the desired answer is $2 \cdot \frac{84}{14} = \boxed{12}$.

Problem 5.12

Complete the synthetic proof above of the stronger version of Ptolemy's theorem.

Let there be a cyclic quadrilateral $ABCD$ with $AB = a$, $BC = b$, $CD = c$, $DA = d$. Then by Ptolemy's, if $x = BD$, $y = AC$, and z is a third diagonal, we have that $xy = ac + bd$, $yz = ad + bc$, and $zx = ab + cd$. Hence,

$$x^2 = BD^2 = \frac{(ac + bd)(ab + cd)}{ad + bc}$$

and

$$y^2 = AC^2 = \frac{(ac + bd)(ad + bc)}{ab + cd}$$

as required. \square

Problem 5.16 (Star Theorem)

Let $A_1A_2A_3A_4A_5$ be a convex pentagon. Suppose rays A_2A_3 and A_4A_5 meet at X_1 . Define X_2, X_3, X_4, X_5 similarly. Prove that

$$\prod_{i=1}^5 X_i A_{i+2} = \prod_{i=1}^5 X_i A_{i+3}$$

where indices are taken modulo 5.

By the Law of Sines, we know that

$$\frac{X_i A_{i+2}}{\sin(\angle X_i A_{i+3} A_{i+2})} = \frac{X_i A_{i+3}}{\sin(\angle X_i A_{i+2} A_{i+3})}.$$

In addition, note that

$$\angle X_i A_{i+3} A_{i+2} = \angle X_{i+1} A_{i+3} A_{i+4}.$$

Hence, taking the product of the first equation over all $i = 1, 2, \dots, 5$ gives the required result. \square

Problem 5.17

Let ABC be a triangle with inradius r . If the exradii of ABC are r_A, r_B, r_C , show that the triangle has area $\sqrt{r \cdot r_A \cdot r_B \cdot r_C}$.

We may write that:

$$\begin{aligned}
 [ABC] &= \sqrt{s(s-a)(s-b)(s-c)} \\
 &= \sqrt{\frac{[ABC]}{r} \cdot \frac{[ABC]}{r_a} \cdot \frac{[ABC]}{r_b} \cdot \frac{[ABC]}{r_c}} \\
 &= [ABC]^2 \sqrt{\frac{1}{r \cdot r_a \cdot r_b \cdot r_c}} \\
 \implies [ABC] &= \sqrt{r \cdot r_a \cdot r_b \cdot r_c}
 \end{aligned}$$

so we are done. \square

Problem 5.18 (APMO 2013/1)

Let ABC be an acute triangle with altitudes AD, BE , and CF , and let O be the center of its circumcircle. Show that the segments OA, OF, OB, OD, OC, OE dissect the triangle ABC into three pairs of triangles that have equal areas.

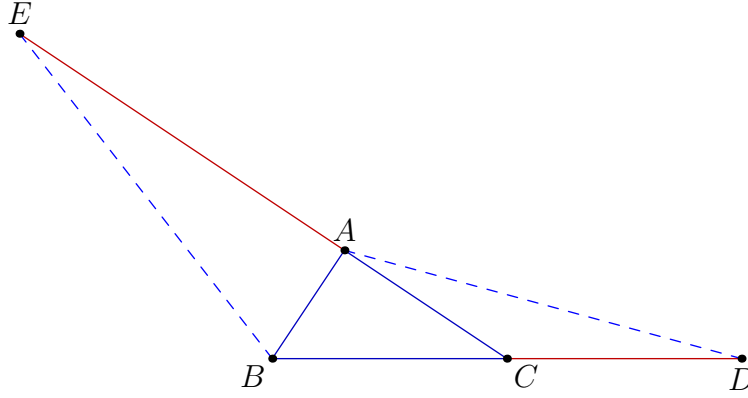
We claim that $[AOE] = [BOD]$. As required,

$$\begin{aligned}
 [AOE] &= \frac{1}{2} \cdot \sin(\angle OAE) \cdot OA \cdot AE \\
 &= \frac{1}{2} \cdot \sin(\angle BAD) \cdot OB \cdot AE \\
 &= \frac{1}{2} \cdot \frac{BD}{AB} \cdot OB \cdot AE \\
 &= \frac{1}{2} \cdot \frac{AE}{AB} \cdot OB \cdot BD \\
 &= \frac{1}{2} \cdot \sin(\angle EBA) \cdot OB \cdot BD \\
 &= \frac{1}{2} \cdot \sin(\angle OBD) \cdot OB \cdot BD \\
 &= [BOD]
 \end{aligned}$$

where the angle equalities follow from the fact that AO and AH (the orthocenter of $\triangle ABC$) are isogonal. Similarly, we get that $[AFO] = [CDO]$, and $[BFO] = [COE]$. \square

Problem 5.19 (EGMO 2013/1, computational)

The side BC of the triangle ABC is extended beyond C to D so that $CD = BC$. The side CA is extended beyond A to E so that $AE = 2CA$. Prove that if $AD = BE$ then the triangle ABC is right-angled.



By the Law of Cosines, we have that

$$\frac{EC^2 + BC^2 - BE^2}{2 \cdot EC \cdot BC} = \cos(\angle ACB)$$

and also

$$\frac{AD^2 - AC^2 - CD^2}{2 \cdot AC \cdot CD} = \cos(\angle ACB).$$

Equating the two, we get that

$$\begin{aligned} \frac{EC^2 + BC^2 - BE^2}{2 \cdot EC \cdot BC} &= \frac{AD^2 - AC^2 - CD^2}{2 \cdot AC \cdot CD} \\ \frac{EC^2 + BC^2 - BE^2}{3} &= AD^2 - AC^2 - CD^2 \\ 9AC^2 + BC^2 - AD^2 &= 3(AD^2 - AC^2 - BC^2) \\ 12AC^2 &= 4AD^2 - 4BC^2 \\ 3AC^2 &= AD^2 - BC^2 \end{aligned}$$

However by Stewarts Theorem, we have that

$$AB^2 + AD^2 = 2BC^2 + 2AC^2.$$

Thus, adding this to the equation above, we have that

$$3AC^2 + AB^2 + AD^2 = AD^2 + BC^2 + 2AC^2 \implies AC^2 + AB^2 = BC^2$$

so we are done. \square

Remark

The synthetic method can be found in Problem 3.26.

Problem 5.20 (HMMT 2013)

Let triangle ABC satisfy $2BC = AB + AC$ and have incenter I and circumcircle ω . Let D be the intersection of AI and ω (with A, D distinct). Prove that I is the midpoint of \overline{AD} .

By Ptolemy, we have that

$$AC \cdot BD + AB \cdot DC = AD \cdot BC.$$

However, by the Incenter-Excenter Lemma, we know that

$$BD = CD = ID.$$

Hence,

$$\begin{aligned} AD \cdot BC &= AC \cdot BD + AB \cdot DC \\ &= AC \cdot ID + AB \cdot ID \\ &= 2 \cdot BC \cdot ID \\ \implies AD &= 2ID \end{aligned}$$

so we are done. \square

Problem 5.21 (USAMO 2010/4)

Let ABC be a triangle with $\angle A = 90^\circ$. Points D and E lie on sides AC and AB , respectively, such that $\angle ABD = \angle DBC$ and $\angle ACE = \angle ECB$. Segments BD and CE meet at I . Determine whether or not it is possible for segments AB, AC, BI, ID, CI, IE to all have integer lengths.

Assume for the sake of contradiction that it is possible. We know that

$$\angle BIC = 90 + \frac{\angle A}{2} = 135.$$

Now by the Law of Cosines, we know that

$$\begin{aligned} BI^2 + CI^2 - 2BI \cdot CI \cos(\angle BIC) &= BI^2 + CI^2 + BI \cdot CI\sqrt{2} \\ &= BC^2 \\ &= AC^2 + AB^2. \end{aligned}$$

However, in order for

$$BI^2 + CI^2 + BI \cdot CI\sqrt{2} = AC^2 + AB^2$$

we cannot have all of them be integer, contradiction. Thus, it is not possible for all of them to have integer lengths. \square

Problem 5.22 (Iran Olympiad 1999)

Let I be the incenter of triangle ABC and let ray AI meet the circumcircle of $\triangle ABC$ at D . Denote the feet of the perpendiculars from I to lines BD and CD by E and F , respectively. If $IE + IF = \frac{1}{2}AD$, calculate $\angle BAC$.

We have that

$$IE = ID \sin(\angle C)$$

and

$$IF = ID \sin(\angle B).$$

Hence, since $\sin(\angle B) = \frac{AC}{2R}$ and $\sin(\angle C) = \frac{AB}{2R}$ we may write that

$$\begin{aligned} IE + IF &= ID \sin(\angle C) + ID \sin(\angle B) \\ &= \frac{AB \cdot CD}{2R} + \frac{AC \cdot BD}{2R} \\ &= \frac{AD \cdot BC}{2R} \\ &= \frac{1}{2}AD. \end{aligned}$$

Hence, $BC = R$, implying that $\angle BOC = 60^\circ$ if O is the circumcenter of $\triangle ABC$. Finally, Inscribed Angle Theorem tells us that $\angle BAC = \boxed{30^\circ}$ or $\boxed{150^\circ}$ as required. \square

Problem 5.23 (CGMO 2002/4)

Circles O_1 and O_2 intersect at two points B and C , and \overline{BC} is the diameter of circle O_1 . Construct a tangent line of circle O_1 at C and intersecting circle O_2 at another point A . We join AB to intersect circle O_1 at point E , then join CE and extend it to intersect circle O_2 at point F . Assume H is an arbitrary point on line segment AF . We join HE and extend it to intersect circle O_1 at point G , and then join BG and extend it to intersect the extend line of AC at point D . Prove that

$$\frac{AH}{HF} = \frac{AC}{CD}.$$



We can write that

$$\frac{AH}{HF} = \frac{AE \sin(\angle AEH)}{EF \sin(\angle FEH)} = \frac{EC \sin(\angle BEG)}{EB \sin(\angle CEG)} = \frac{EC \cdot BG}{EB \cdot CG}.$$

In addition,

$$AC = \frac{BC \cdot CE}{BE}$$

and

$$CD = \frac{GC \cdot BC}{BG}$$

by similar triangles, and dividing gives the necessary result. \square

Problem 5.24 (IMO 2007/4)

In triangle ABC the bisector of angle BCA intersects the circumcircle again at R , the perpendicular bisector of \overline{BC} at P , and the perpendicular bisector of \overline{AC} at Q . The midpoint of \overline{BC} is K and the midpoint of \overline{AC} is L . Prove that the triangles RPK and RQL have the same area.



We can write that

$$\frac{[RPK]}{[RQL]} = \frac{\frac{1}{2} \cdot RP \cdot PK \sin(\angle RPK)}{\frac{1}{2} \cdot RQ \cdot QL \sin(\angle RQL)} = \frac{RP \cdot PK}{RQ \cdot QL} = \frac{RP \cdot BC}{RQ \cdot AC}.$$

Now, since $\triangle ARB$ is isosceles, we know that

$$RA = \frac{AB}{2 \cos\left(\frac{\angle C}{2}\right)}.$$

Hence, by Ptolemy, we have that

$$RA \cdot BC + RB \cdot AC = RA(BC + AC) = RC \cdot AB.$$

So,

$$RC = \frac{BC + AC}{2 \cos\left(\frac{\angle C}{2}\right)}.$$

Finally,

$$\begin{aligned}
\frac{RP}{RQ} &= \frac{RC - PC}{RC - QC} \\
&= \frac{\frac{BC + AC}{2 \cos\left(\frac{\angle C}{2}\right)} - \frac{KC}{\cos\left(\frac{\angle C}{2}\right)}}{\frac{BC + AC}{2 \cos\left(\frac{\angle C}{2}\right)} - \frac{LC}{\cos\left(\frac{\angle C}{2}\right)}} \\
&= \frac{\frac{BC + AC}{2 \cos\left(\frac{\angle C}{2}\right)} - \frac{BC}{2 \cos\left(\frac{\angle C}{2}\right)}}{\frac{BC + AC}{2 \cos\left(\frac{\angle C}{2}\right)} - \frac{AC}{2 \cos\left(\frac{\angle C}{2}\right)}} \\
&= \frac{\frac{AC}{2 \cos\left(\frac{\angle C}{2}\right)}}{\frac{BC}{2 \cos\left(\frac{\angle C}{2}\right)}} \\
&= \frac{AC}{BC}.
\end{aligned}$$

Hence,

$$\frac{[RPK]}{[RQL]} = \frac{RP \cdot BC}{RQ \cdot AC} = \frac{AC \cdot BC}{BC \cdot AC} = 1$$

so we are done. \square

Problem 5.25 (JMO 2013/5)

Quadrilateral $XABY$ is inscribed in the semicircle ω with diameter XY . Segments AY and BX meet at P . Point Z is the foot of the perpendicular from P to line XY . Point C lies on ω such that line XC is perpendicular to line AZ . Let Q be the intersection of segments AY and XC . Prove that

$$\frac{BY}{XP} + \frac{CY}{XQ} = \frac{AY}{AX}.$$

Let $\angle AYX = \alpha$ and $\angle BXY = \beta$. Then, we know that $\triangle BXY \sim \triangle ZXP$, so by the Law of Sines,

$$\frac{BY}{XP} = \frac{XY \sin(\beta)}{XP} = \frac{XY \sin(\beta)}{\frac{XY \sin(\alpha)}{\sin(\alpha + \beta)}} = \frac{\sin(\alpha + \beta) \sin(\beta)}{\sin(\alpha)}.$$

Now, we know that $AXPZ$ is cyclic, so

$$\angle CXY = \angle AXY - \angle AXC = 90 - \alpha - (90 - \angle XAZ) = 90 - \alpha - (90 - \angle XPZ) = 90 - \alpha - (90 - (90 - \beta)) = 90 - \alpha - \beta.$$

Hence,

$$CY = XY \sin(\angle CXY) = XY \sin(90 - \alpha - \beta) = XY \cos(\alpha + \beta).$$

In addition,

$$\frac{XQ}{\sin(\alpha)} = \frac{XY}{\sin(90 + \beta)} = \frac{XY}{\cos(\beta)}$$

by the Law of Sines. Hence,

$$\frac{CY}{XQ} = \frac{XY \cos(\alpha + \beta)}{\frac{XY \sin(\alpha)}{\cos(\beta)}} = \frac{\cos(\alpha + \beta)}{\frac{\sin(\alpha)}{\cos(\beta)}} = \frac{\cos(\alpha + \beta) \cos(\beta)}{\sin(\alpha)}.$$

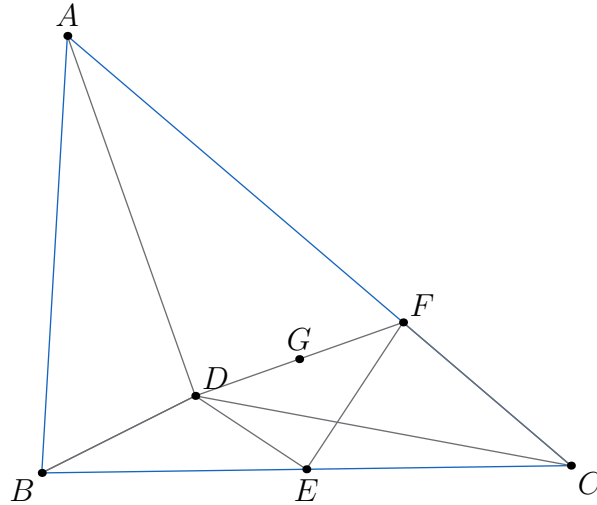
Finally, we can write that:

$$\begin{aligned}
\frac{BY}{XP} + \frac{CY}{XQ} &= \frac{\sin(\alpha + \beta) \sin(\beta)}{\sin(\alpha)} + \frac{\cos(\alpha + \beta) \cos(\beta)}{\sin(\alpha)} \\
&= \frac{\sin(\alpha + \beta) \sin(\beta) + \cos(\alpha + \beta) \cos(\beta)}{\sin(\alpha)} \\
&= \frac{\cos(\alpha + \beta - \beta)}{\sin(\alpha)} \\
&= \tan(\alpha) \\
&= \frac{AY}{AX}
\end{aligned}$$

as required. \square

Problem 5.26 (CGMO 2007/5)

Point D lies inside triangle ABC such that $\angle DAC = \angle DCA = 30^\circ$ and $\angle DBA = 60^\circ$. Point E is the midpoint of segment \overline{BC} . Point F lies on segment \overline{AC} with $AF = 2FC$. Prove that $\overline{DE} \perp \overline{EF}$.



Let G be the midpoint of \overline{DF} . Scale the figure down so that $AC = 3$. Then, we have that $AD = CD = \sqrt{3}$. In addition, since $AF = 2$ as well, we know that $\triangle ADF$ is right, and $DF = 1$.

Claim

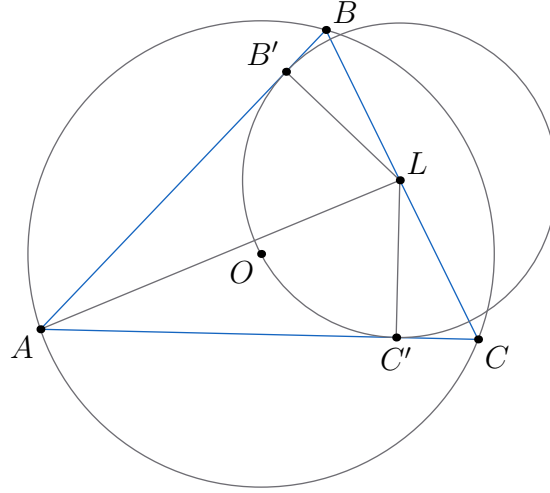
Quadrilateral $ODFC$ is a parallelogram.

Proof. Let O be the circumcenter of $\triangle ABD$. Then, $\angle ODC = 150^\circ$ and since $\angle ACD = 30^\circ$, we know that $OD \parallel FC$. In addition, we know that $OD = FC = 1$, so $ODFC$ is a parallelogram, as required. \square

Hence, since G is the midpoint of DF and OC , we know that $GE = \frac{BO}{2} = 0.5$, and since $DG = DF = 0.5$, we are done. \square

Problem 5.27 (ISL 2011/G1)

Let ABC be an acute triangle. Let ω be a circle whose center L lies on the side \overline{BC} . Suppose that ω is tangent to \overline{AB} at B' and \overline{AC} at C' . Suppose also that the circumcenter O of triangle ABC lies on the shorter arc BC of ω . Prove that the circumcircle of $\triangle ABC$ and ω meet at two points.



We rephrase into the following claim:

Claim

We claim that

$$OL > \frac{1}{2}R.$$

Proof. Let the midpoint of \overline{BC} be M . Then, we will show that

$$OL \geq OM > \frac{1}{2}R.$$

We know that $OM = \sqrt{R^2 - \frac{1}{4}BC^2}$ by the Pythagorean Theorem. Now, since

$$\angle B'OC' = 180 - \frac{\angle B'LC'}{2} = 90 + \frac{\angle A}{2} > \angle BOC = 2\angle A$$

Hence, $\angle A < 60^\circ$.

We will now try to find the maximum value of $\frac{BC}{R}$. By the Law of Sines, we know that $\frac{BC}{R} = 2\sin(A)$, so

$$\max\left(\frac{BC}{R}\right) = \max(2\sin(A)) = 2\sin(60) = \sqrt{3}.$$

Hence,

$$\begin{aligned} BC^2 &< 3R^2 \\ \frac{R^2}{4} + \frac{BC^2}{4} &< R^2 \\ \frac{R^2}{4} &< R^2 - \frac{BC^2}{4} \\ \frac{1}{2}R &< \sqrt{R^2 - \frac{1}{4}BC^2} \\ \frac{1}{2}R &< OM \end{aligned}$$

so we have proved the claim. \square

With this, it is clear to see that this directly implies the required result. \square

Problem 5.28 (IMO 2001/1)

Consider an acute-angled triangle ABC . Let P be the foot of the altitude of triangle ABC issuing from the vertex A , and let O be the circumcenter of triangle ABC . Assume that $\angle C \geq \angle B + 30^\circ$. Prove that $\angle A + \angle COP < 90^\circ$.

We begin with a claim.

Claim

We claim that $CP < PO$.

Proof. We know that $CP = AC \cos(C)$. In addition, by the Law of Cosines,

$$OP^2 = R^2 + CP^2 - 2R \cdot CP \cos(90 - A) = R^2 + AC^2 \cos^2(C) - 2R \cdot AC \cos(C) \cos(90 - A).$$

Thus,

$$\begin{aligned} CP^2 &< OP^2 \\ AC^2 \cos^2(C) &< R^2 + AC^2 \cos^2(C) - 2R \cdot AC \cos(C) \cos(90 - A) \\ 0 &< R^2 - 2R \cdot AC \cos(C) \cos(90 - A) \\ 2 \cdot AC \cos(C) \cos(90 - A) &< R \\ &= \frac{AC}{2 \sin(B)} \\ 4 \cos(C) \sin(B) \cos(90 - A) &< 1 \\ 4 \cos(C) \sin(B) \cos(90 - (180 - B - C)) &< 1 \\ 4 \cos(C) \sin(B) \sin(B + C) &< 1. \end{aligned}$$

However, we can write that

$$4 \cos(C) \sin(B) \sin(B + C) < 4 \cos(C) \sin(B) = 2(\sin(B + C) - \sin(C - B)) \leq 2(\sin(B + C) - \frac{1}{2}) \leq 1$$

and since all steps are reversible, we have proved the result. \square

From here, it is obvious that this implies that

$$\angle COP < \angle OCP = 90 - \angle A$$

so we are done. \square

Problem 5.29 (IMO 2001/5)

Let ABC be a triangle. Let AP bisect $\angle BAC$ and let BQ bisect $\angle ABC$, with P on \overline{BC} and Q on \overline{AC} . If $AB + BP = AQ + QB$ and $\angle BAC = 60^\circ$, what are the angles of the triangle?

Let $\angle ABQ = \alpha$. Then, we know from the given condition

$$AB + \frac{AB}{2 \sin(150 - 2\alpha)} = \frac{AB \sin(\alpha)}{\sin(120 - \alpha)} + \frac{AB \sin(60)}{\sin(120 - \alpha)}$$

so

$$1 + \frac{1}{2 \sin(150 - 2\alpha)} = \frac{\sin(\alpha) + \sin(60)}{\sin(60 + \alpha)} = \frac{2 \sin(\frac{60+\alpha}{2}) \cos(\frac{60-\alpha}{2})}{2 \sin(\frac{60+\alpha}{2}) \cos(\frac{60+\alpha}{2})} = \frac{\cos(\frac{60-\alpha}{2})}{\cos(\frac{60+\alpha}{2})}.$$

Now,

$$\frac{\cos(\frac{60-\alpha}{2})}{\cos(\frac{60+\alpha}{2})} - 1 = \frac{\cos(\frac{60-\alpha}{2}) - \cos(\frac{60+\alpha}{2})}{\cos(\frac{60+\alpha}{2})} = \frac{2 \sin(30) \sin(\frac{\alpha}{2})}{\cos(\frac{60+\alpha}{2})} = \frac{\sin(\frac{\alpha}{2})}{\cos(\frac{60+\alpha}{2})}.$$

Hence,

$$\frac{1}{2 \sin(150 - 2\alpha)} = \frac{\sin(\frac{\alpha}{2})}{\cos(\frac{60+\alpha}{2})} \implies \cos(30 + \frac{\alpha}{2}) = 2 \sin(\frac{\alpha}{2}) \sin(150 - 2\alpha) = \cos(\frac{5}{2}\alpha - 150) - \cos(150 - \frac{3}{2}\alpha)$$

so

$$\cos(\frac{1}{2}\alpha + 30) + \cos(\frac{5}{2}\alpha + 30) = \cos(\frac{3}{2}\alpha + 30).$$

Now, by sum to product, we know that

$$\frac{\cos(\frac{1}{2}\alpha + 30) + \cos(\frac{5}{2}\alpha + 30)}{2} = \cos(\frac{3}{2}\alpha + 30) \cos(\alpha) = \frac{\cos(\frac{3}{2}\alpha + 30)}{2} \implies \cos(\alpha) = \frac{1}{2} \text{ or } \cos(\frac{3}{2}\alpha + 30) = 0.$$

It clearly must be the latter since we cannot have $\angle B = 120$, so we know that $\alpha = 40$, giving angles:

$$(\angle A, \angle B, \angle C) = \boxed{(60^\circ, 80^\circ, 40^\circ)}. \quad \square$$

Problem 5.30 (IMO 2001/6)

Let $a > b > c > d$ be positive integers and suppose that

$$ac + bd = (b + d + a - c)(b + d - a + c).$$

Prove that $ab + cd$ is not prime.

Expanding, we get that

$$\begin{aligned} ac + bd &= (b + d + a - c)(b + d - a + c) \\ &= b^2 + bd - ab + bc + bd + d^2 - ad + cd + ab + ad - a^2 + ac - bc - cd + ac - c^2 \\ &= b^2 + bd + bd + d^2 - a^2 + ac + ac - c^2 \end{aligned}$$

so

$$a^2 + c^2 - ac = b^2 + d^2 + bd. \quad (1)$$

Now construct a quadrilateral $WXYZ$ with side lengths a, c, b, d in that order (define $WX = a$, $XY = c$, $YZ = b$, $ZW = d$).

Clearly, this quadrilateral is cyclic because the Law of Cosines on (1) tells us that the opposite angles are indeed supplementary. Now by Ptolemy's,

$$WY^2 = \frac{(ab + cd)(ad + bc)}{ac + bd}.$$

Now assume for the sake of contradiction that $ab + cd$ is prime. Then, by the rearrangement inequality,

$$ab + cd > ac + bd > ad + bc.$$

However, this implies that the quantity above is not an integer, which is a contradiction. \square

6 Complex Numbers

Problem 6.3

Show that the foot of the altitude from Z to \overline{AB} is given by

$$\frac{(\bar{a} - \bar{b})z + (a - b)\bar{z} + \bar{a}b - a\bar{b}}{2(\bar{a} - \bar{b})}.$$

Make the transformation $z \rightarrow \frac{z-a}{b-a}$. Then, the required answer is

$$\frac{\frac{z-a}{b-a} + \frac{\bar{z}-\bar{a}}{\bar{b}-\bar{a}}}{2}.$$

We then revert the transformation. Hence, the answer is:

$$\begin{aligned} \frac{(b-a)(\frac{z-a}{b-a} + \frac{\bar{z}-\bar{a}}{\bar{b}-\bar{a}})}{2} + a &= \frac{z + a + (b-a)(\frac{\bar{z}-\bar{a}}{\bar{b}-\bar{a}})}{2} \\ &= \frac{(z+a)(\bar{b}-\bar{a}) + (b-a)(\bar{z}-\bar{a})}{2(\bar{b}-\bar{a})} \\ &= \frac{z\bar{b} - z\bar{a} + a\bar{b} - a\bar{a} + \bar{z}b - \bar{z}a - \bar{a}b + a\bar{a}}{2(\bar{b}-\bar{a})} \\ &= \frac{(\bar{b}-\bar{a})z + (b-a)\bar{z} + a\bar{b} - \bar{a}b}{2(\bar{b}-\bar{a})} \\ &= \boxed{\frac{(\bar{a}-\bar{b})z + (a-b)\bar{z} + \bar{a}b - a\bar{b}}{2(\bar{a}-\bar{b})}} \end{aligned}$$

so we are done. \square

Problem 6.8

Prove that complex numbers z, a, b are collinear if and only if

$$\frac{z-a}{z-b} = \overline{\left(\frac{z-a}{z-b}\right)}.$$

If they are collinear, then we know that the quantity

$$\frac{z-a}{z-b}$$

is real, since it describes sending the point a to 0, and sending z, b onto the real axis (if and only if they are collinear). The finish is clear. \square

Problem 6.14

Let H be the orthocenter of $\triangle ABC$. Let X be the reflection of H over \overline{BC} and Y the reflection over the midpoint of \overline{BC} . Prove that X and Y lie on (ABC) , and \overline{AY} is a diameter.

We can express X as:

$$\begin{aligned}
X &= 2 \cdot \frac{1}{2}(a + b + (a + b + c) - ab(\overline{a + b + c})) - (a + b + c) \\
&= a + b - ab(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}) \\
&= a + b - a - b - \frac{ab}{c} \\
&= -\frac{ab}{c}.
\end{aligned}$$

which indeed has magnitude 1. \square

Now, we can also express Y as

$$Y = 2 \cdot (\frac{b+c}{2}) - (a + b + c) = -a$$

so we are done. \square

Remark

The synthetic solution can be found as Problem 1.17.

Problem 6.20

Let a, b, c, d be distinct complex numbers, not all collinear. Then A, B, C, D are concyclic if and only if

$$\frac{b-a}{c-a} \div \frac{b-d}{c-d}$$

is a real number.

This is equivalent to $\angle BAC = \angle BDC$, which is the criterion for a cyclic quadrilateral. \square

Remark

It is stated in the EGMO errata that this is supposed to be the correct statement, not Theorem 6.16.

Problem 6.21

Show that if a, b, c are complex numbers, then the signed area of triangle ABC is given by

$$\frac{i}{4} \begin{vmatrix} a & \bar{a} & 1 \\ b & \bar{b} & 1 \\ c & \bar{c} & 1 \end{vmatrix}.$$

We may write that:

$$\begin{aligned}
\frac{i}{4} \begin{vmatrix} a & \bar{a} & 1 \\ b & \bar{b} & 1 \\ c & \bar{c} & 1 \end{vmatrix} &= \frac{i}{4} \begin{vmatrix} 2\Re(a) & \bar{a} & 1 \\ 2\Re(b) & \bar{b} & 1 \\ 2\Re(c) & \bar{c} & 1 \end{vmatrix} \\
&= \frac{i}{4} \begin{vmatrix} 2\Re(a) & -i\Im(a) & 1 \\ 2\Re(b) & -i\Im(b) & 1 \\ 2\Re(c) & -i\Im(c) & 1 \end{vmatrix} \\
&= \frac{1}{2} \begin{vmatrix} \Re(a) & \Im(a) & 1 \\ \Re(b) & \Im(b) & 1 \\ \Re(c) & \Im(c) & 1 \end{vmatrix}
\end{aligned}$$

which is the so called “Shoelace Formula”. \square

Problem 6.22

Let ABC be a triangle with orthocenter H and let P be a point on (ABC) .

- (a) Show that the Simson line exists.
- (b) Show that the Simson line at P bisects \overline{PH} .

We begin with part (a). Let the foot of P to \overline{AB} be X , to \overline{AC} be Y , and analogously for Z . Then, we may write that

$$x = \frac{1}{2}(a + b + p - ab\bar{p}) = \frac{1}{2}(a + b + p - \frac{ab}{p})$$

and similarly,

$$y = \frac{1}{2}(a + c + p - \frac{ac}{p})$$

$$z = \frac{1}{2}(b + c + p - \frac{bc}{p}).$$

Now, x , y , and z are collinear if and only if

$$\frac{x - y}{x - z}$$

is real. Hence,

$$\begin{aligned} \frac{x - y}{x - z} &= \frac{\frac{1}{2}(a + b + p - \frac{ab}{p}) - \frac{1}{2}(a + c + p - \frac{ac}{p})}{\frac{1}{2}(a + b + p - \frac{ab}{p}) - \frac{1}{2}(b + c + p - \frac{bc}{p})} \\ &= \frac{a + b + p - \frac{ab}{p} - (a + c + p - \frac{ac}{p})}{a + b + p - \frac{ab}{p} - (b + c + p - \frac{bc}{p})} \\ &= \frac{b - \frac{ab}{p} - c + \frac{ac}{p}}{a - \frac{ab}{p} - c + \frac{bc}{p}} \\ &= \frac{bp - ab - cp + ac}{ap - ab - cp + bc} \\ &= \frac{(b - c)(p - a)}{(a - b)(p - c)} \end{aligned}$$

however we know that this quantity is real since this is exactly the criteria for the points being concyclic, so we are done. \square

We now continue with part (b). We will show that the midpoint of \overline{PH} , X and Y are collinear:

$$\begin{aligned}
\begin{vmatrix} x & \bar{x} & 1 \\ y & \bar{y} & 1 \\ \frac{h+p}{2} & \frac{\bar{h}+\bar{p}}{2} & 1 \end{vmatrix} &= \begin{vmatrix} \frac{1}{2}(a+b+p-\frac{ab}{p}) & \frac{1}{2}(\frac{1}{a}+\frac{1}{b}+\frac{1}{p}-\frac{p}{ab}) & 1 \\ \frac{1}{2}(a+c+p-\frac{ac}{p}) & \frac{1}{2}(\frac{1}{a}+\frac{1}{c}+\frac{1}{p}-\frac{p}{ac}) & 1 \\ \frac{1}{2}(a+b+c+p) & \frac{1}{2}(\frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{p}) & 1 \end{vmatrix} \\
&= \frac{1}{4} \begin{vmatrix} a+b+p-\frac{ab}{p} & \frac{1}{a}+\frac{1}{b}+\frac{1}{p}-\frac{p}{ab} & 1 \\ a+c+p-\frac{ac}{p} & \frac{1}{a}+\frac{1}{c}+\frac{1}{p}-\frac{p}{ac} & 1 \\ a+b+c+p & \frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{p} & 1 \end{vmatrix} \\
&= \frac{1}{4} \begin{vmatrix} -c-\frac{ab}{p} & -\frac{1}{c}-\frac{p}{ab} & 1 \\ -b-\frac{ac}{p} & -\frac{1}{b}-\frac{p}{ac} & 1 \\ 0 & 0 & 1 \end{vmatrix} \\
&= \frac{1}{4} \begin{vmatrix} c+\frac{ab}{p} & \frac{1}{c}+\frac{p}{ab} & 1 \\ b+\frac{ac}{p} & \frac{1}{b}+\frac{p}{ac} & 1 \\ 0 & 0 & 1 \end{vmatrix} \\
&= \frac{1}{4} \left(\left(c+\frac{ab}{p} \right) \left(\frac{1}{b}+\frac{p}{ac} \right) - \left(\frac{1}{c}+\frac{p}{ab} \right) \left(b+\frac{ac}{p} \right) \right) \\
&= 0
\end{aligned}$$

so we are done. \square

Remark

A synthetic proof of part (a) can be found as Problem 1.48. In addition, a synthetic proof of part (b) can be found as a consequence of Problem 4.3.

Problem 6.29

Give a proof of the inscribed angle theorem using complex numbers.

Let A , B , and C be points on the unit circle with center O . Then, we wish to show that

$$\arg\left(\frac{a}{b}\right) = 2 \arg\left(\frac{a-c}{b-c}\right) = \arg\left(\left(\frac{a-c}{b-c}\right)^2\right).$$

This is equivalent to showing that 0 , $\frac{a}{b}$, and $\left(\frac{a-c}{b-c}\right)^2$ are collinear. Indeed,

$$\begin{aligned}
\overline{\left(\frac{\left(\frac{a-c}{b-c}\right)^2}{\frac{a}{b}}\right)} &= \overline{\left(\frac{b(a-c)^2}{a(b-c)^2}\right)} \\
&= \frac{\frac{1}{b}\left(\frac{1}{a}-\frac{1}{c}\right)^2}{\frac{1}{a}\left(\frac{1}{b}-\frac{1}{c}\right)^2} \\
&= \frac{a\left(\frac{1}{a}-\frac{1}{c}\right)^2}{b\left(\frac{1}{b}-\frac{1}{c}\right)^2} \\
&= \frac{a\left(\frac{1}{a^2}-\frac{2}{ac}+\frac{1}{c^2}\right)}{b\left(\frac{1}{b^2}-\frac{2}{bc}+\frac{1}{c^2}\right)} \\
&= \frac{ab^2c^2(c^2-2ac+a^2)}{a^2bc^2(c^2-2bc+b^2)} = \frac{b(a-c)^2}{a(b-c)^2}
\end{aligned}$$

so we are done. \square

Problem 6.30 (Complex Chord)

Show that a point P lies on a chord \overline{AB} of the unit circle if and only if $p + ab\bar{p} = a + b$.

This is equivalent to showing that if the foot from P to \overline{AB} is P , then $p + ab\bar{p} = a + b$. However, it is well known that the foot can be expressed as $\frac{1}{2}(a + b + p - ab\bar{p})$. Hence, all we need to solve is:

$$\frac{1}{2}(a + b + p - ab\bar{p}) = p \implies p + ab\bar{p} = a + b$$

as required. \square

Problem 6.31

Let $ABCD$ be a cyclic quadrilateral. Let H_A, H_B, H_C, H_D denote the orthocenters of triangles BCD, CDA, DAB , and ABC , respectively. Prove that $\overline{AH_A}, \overline{BH_B}, \overline{CH_C}$, and $\overline{DH_D}$ concur.

Toss onto the complex plane. Note that the point $\frac{1}{2}(a + b + c + d)$ is the midpoint of all the aforementioned segments, so we are done. \square

Problem 6.32

Let $ABCD$ be a quadrilateral circumscribed around a circle with center I . Prove that I lies on the line joining the midpoints of \overline{AC} and \overline{BD} .

Toss onto the complex plane, let $I = 0$ and scale so that the circle has radius 1. In addition, let the tangency points of $\overline{AB}, \overline{BC}, \overline{CD}$, and \overline{DA} to the circle be W, X, Y , and Z , respectively. Then, we know that

$$\begin{aligned} A &= \frac{2wz}{w+z} \\ B &= \frac{2wx}{w+x} \\ C &= \frac{2xy}{x+y} \\ D &= \frac{2yz}{y+z}. \end{aligned}$$

Thus, all we need to show is that B, C , and $I = 0$ are collinear. Hence,

$$\begin{aligned} \frac{\frac{2wz}{w+z} + \frac{2xy}{x+y}}{\frac{2wx}{w+x} + \frac{2yz}{y+z}} &= \frac{\frac{wz}{w+z} + \frac{xy}{x+y}}{\frac{wx}{w+x} + \frac{yz}{y+z}} \\ &= \frac{\frac{1}{\frac{1}{w} + \frac{1}{z}} + \frac{1}{\frac{1}{x} + \frac{1}{y}}}{\frac{1}{\frac{1}{w} + \frac{1}{x}} + \frac{1}{\frac{1}{y} + \frac{1}{z}}} \\ &= \frac{1}{\left(\frac{1}{w} + \frac{1}{z}\right)\left(\frac{1}{x} + \frac{1}{y}\right)} \\ &= \frac{\left(\frac{1}{w} + \frac{1}{x}\right)\left(\frac{1}{y} + \frac{1}{z}\right)}{\left(\frac{1}{w} + \frac{1}{z}\right)\left(\frac{1}{x} + \frac{1}{y}\right)} = \frac{(w+x)(y+z)}{(w+z)(x+y)} \end{aligned}$$

and the last line implies that the expression is real, as required. \square

Problem 6.33 (China TST 2011)

Let ABC be a triangle, and let A', B', C' be points on its circumcircle, diametrically opposite A, B, C , respectively. Let P be any point inside $\triangle ABC$ and let D, E, F be the feet of the altitudes from P onto $\overline{BC}, \overline{CA}, \overline{AB}$, respectively. Let X, Y, Z denote the reflections of A', B', C' over D, E, F , respectively. Show that triangles XYZ and ABC are similar to each other.

Toss onto the complex plane so that the circumcircle is the unitcircle. Then, we know that $a' = -a, b' = -b$, and $c' = -c$. In addition,

$$\begin{aligned} d &= \frac{1}{2}(b + c + p - bc\bar{p}) \\ e &= \frac{1}{2}(a + c + p - ac\bar{p}) \\ f &= \frac{1}{2}(a + b + p - ab\bar{p}). \end{aligned}$$

Thus,

$$\begin{aligned} x &= a + b + c + p - bc\bar{p} \\ y &= a + b + c + p - ac\bar{p} \\ z &= a + b + c + p - ab\bar{p}. \end{aligned}$$

This means it suffices to show that the triangle formed by a, b, c and ab, ac, bc are similar. Now, the condition for oppositely similar triangles is the same as directly similar, but showing it is equal to the conjugate of the other side. Hence:

$$\frac{\overline{b-a}}{c-a} = \frac{\frac{1}{b} - \frac{1}{a}}{\frac{1}{c} - \frac{1}{a}} = \frac{ac(a-b)}{ab(a-c)} = \frac{c(a-b)}{b(a-c)} = \frac{ac-bc}{ab-bc} = \frac{bc-ac}{bc-ab}$$

so we are done. \square

Problem 6.34 (Napoleon's Theorem)

Let ABC be a triangle and erect equilateral triangles on sides $\overline{BC}, \overline{CA}, \overline{AB}$ outside of ABC with centers O_A, O_B, O_C . Prove that $\triangle O_A O_B O_C$ is equilateral and that its center coincides with the centroid of triangle ABC .

We may find that $\frac{o_c-b}{a-b} = \frac{1}{2} + \frac{\sqrt{3}}{6}i$ and similar equations for the others. Hence, we know that:

$$\begin{aligned} o_a &= \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i\right)(b-c) + c \\ o_b &= \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i\right)(c-a) + a \\ o_c &= \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i\right)(a-b) + b. \end{aligned}$$

Summing all of these equations and dividing by three gives that

$$\frac{o_a + o_b + o_c}{3} = \frac{a + b + c}{3}$$

so the centroids coincide. \square

Next, we will show that $\triangle O_A O_B O_C$ is equilateral. We will do this by showing that

$$(o_a + o_b + o_c)^2 = (a + b + c)^2 = 3(o_a o_b + o_a o_c + o_b o_c).$$

We know that

$$\begin{aligned} o_a o_b &= \left(\left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right) (b - c) + c \right) \left(\left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right) (c - a) + a \right) \\ &= \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right)^2 (bc - ab - c^2 + ac) + \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right) (c^2 + ab - 2ac) + ac. \end{aligned}$$

Cyclicly summing this gives that

$$\left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right)^2 (ab + ac + bc - a^2 - b^2 - c^2) + \left(\frac{1}{2} + \frac{\sqrt{3}}{6}i \right) (a^2 + b^2 + c^2 - ab - ac - bc) + ab + ac + bc = \frac{(a + b + c)^2}{3}$$

after expanding and collecting terms. Hence, we are done. \square

Problem 6.35 (USAMO 2015/2, complex)

Quadrilateral $APBQ$ is inscribed in circle ω with $\angle P = \angle Q = 90^\circ$ and $AP = AQ < BP$. Let X be a variable point on segment \overline{PQ} . Line AX meets ω again at S (other than A). Point T lies on arc AQB of ω such that XT is perpendicular to AX . Let M denote the midpoint of chord \overline{ST} . As X varies on segment \overline{PQ} , show that M moves along a circle.

Let the circumcircle of $APBQ$ be the unitcircle, $A = -1$, and $B = 1$. Then, we know that

$$x = \frac{1}{2}(a + s + t - \frac{as}{t}) = \frac{1}{2}(s + t - 1 + \frac{s}{t}).$$

Then, note that

$$4\Re(x) + 2 = s + \frac{1}{s} + t + \frac{1}{t} + \frac{s}{t} + \frac{t}{s}.$$

Now, note that

$$4 \left| \frac{1}{2} - \frac{s+t}{2} \right|^2 = |s + t - 1|^2 = (s + t - 1) \left(\frac{1}{s} + \frac{1}{t} - 1 \right) = 4\Re(x) + 5$$

which does not depend on X , so we are done. \square

Remark

A synthetic proof can be found as Problem 3.30.

Problem 6.36 (China TST 2006)

Point H is the orthocenter of triangle ABC . Points D , E , and F lie on the circumcircle of triangle ABC such that $\overline{AD} \parallel \overline{BE} \parallel \overline{CF}$. Points S , T , and U are the respective reflections of D , E , and F across the lines BC , CA , and AB . Prove that S , T , U , and H are concyclic.

Let the circumcircle be the unitcircle, and rotate so that the segments \overline{AD} , \overline{BE} , and \overline{CF} are perpendicular to the real axis. Then, we know that:

$$\begin{aligned} d &= \bar{a} = \frac{1}{a} \\ e &= \bar{b} = \frac{1}{b} \\ f &= \bar{c} = \frac{1}{c}. \end{aligned}$$

Thus, we can say that:

$$\begin{aligned} s &= b + c - \frac{bc}{d} = b + c - abc \\ t &= a + c - \frac{ac}{e} = a + c - abc \\ u &= a + b - \frac{ab}{f} = a + b - abc. \end{aligned}$$

Finally,

$$\begin{aligned} \frac{\frac{a+c-abc-(b+c-abc)}{a+b-abc-(b+c-abc)}}{\frac{a+c-abc-(a+b+c)}{a+b-abc-(a+b+c)}} &= \frac{\frac{a-b}{a-c}}{\frac{abc+b}{abc+c}} \\ &= \frac{(a-b)(abc+c)}{(a-c)(abc+b)}. \end{aligned}$$

The conjugate of this is

$$\frac{\left(\frac{1}{a} - \frac{1}{b}\right) \left(\frac{1}{abc} + \frac{1}{c}\right)}{\left(\frac{1}{a} - \frac{1}{c}\right) \left(\frac{1}{abc} + \frac{1}{b}\right)} = \frac{\left(\frac{1}{a} - \frac{1}{b}\right) (ab+1)}{\left(\frac{1}{a} - \frac{1}{c}\right) (ac+1)} = \frac{\left(\frac{b-a}{ab}\right) (ab+1)}{\left(\frac{c-a}{ac}\right) (ac+1)} = \frac{(a-b)(abc+c)}{(a-c)(abc+b)}$$

so we are done. \square

Remark

In the book, this is cited as MOP 2006, when it is more accurately from **China TST 2006**.

Problem 6.37 (USA January TST for IMO 2014)

Let $ABCD$ be a cyclic quadrilateral, and let E, F, G , and H be the midpoints of \overline{AB} , \overline{BC} , \overline{CD} , \overline{DA} , respectively. Let W, X, Y , and Z be the orthocenters of triangles AHE , BEF , CFG , and DGH , respectively. Prove that quadrilaterals $ABCD$ and $WXYZ$ have the same area.

Toss onto the complex plane so that the circumcircle of $ABCD$ is the unitcircle. Then, note that:

$$\begin{aligned} e &= \frac{a+b}{2} \\ f &= \frac{b+c}{2} \\ g &= \frac{c+d}{2} \\ h &= \frac{a+d}{2}. \end{aligned}$$

Hence, we can find w by taking a homothety of scale factor 2 centered at A . This homothety will send E to B and H to D . Hence, the orthocenter of $\triangle AHE$ is

$$w = a + \frac{1}{2}(b+d).$$

Similarly, we get that:

$$\begin{aligned} x &= b + \frac{1}{2}(a+c) \\ y &= c + \frac{1}{2}(b+d) \\ z &= d + \frac{1}{2}(a+c). \end{aligned}$$

We now begin the grueling task of expansion:

$$\begin{aligned} [ABCD] &= [ABC] + [CDA] \\ &= \begin{vmatrix} a & \frac{1}{a} & 1 \\ b & \frac{1}{b} & 1 \\ c & \frac{1}{c} & 1 \end{vmatrix} + \begin{vmatrix} c & \frac{1}{c} & 1 \\ d & \frac{1}{d} & 1 \\ a & \frac{1}{a} & 1 \end{vmatrix} \\ &= \left(\frac{a}{b} - \frac{a}{c} - \frac{b}{a} + \frac{c}{a} + \frac{b}{c} - \frac{c}{b}\right) + \left(\frac{c}{d} - \frac{c}{a} - \frac{d}{c} + \frac{a}{c} + \frac{d}{a} - \frac{a}{d}\right) \\ &= \left(\frac{a}{b} - \frac{b}{a} + \frac{b}{c} - \frac{c}{b}\right) + \left(\frac{c}{d} - \frac{d}{c} + \frac{d}{a} - \frac{a}{d}\right) \end{aligned}$$

and

$$\begin{aligned}
[WXYZ] &= [WXY] + [YZW] \\
&= \begin{vmatrix} a + \frac{1}{2}(b+d) & \frac{1}{a} + \frac{1}{2}\left(\frac{1}{b} + \frac{1}{d}\right) & 1 \\ b + \frac{1}{2}(a+c) & \frac{1}{b} + \frac{1}{2}\left(\frac{1}{a} + \frac{1}{c}\right) & 1 \\ c + \frac{1}{2}(b+d) & \frac{1}{c} + \frac{1}{2}\left(\frac{1}{b} + \frac{1}{d}\right) & 1 \end{vmatrix} + \begin{vmatrix} c + \frac{1}{2}(b+d) & \frac{1}{c} + \frac{1}{2}\left(\frac{1}{b} + \frac{1}{d}\right) & 1 \\ d + \frac{1}{2}(a+c) & \frac{1}{d} + \frac{1}{2}\left(\frac{1}{a} + \frac{1}{c}\right) & 1 \\ a + \frac{1}{2}(b+d) & \frac{1}{a} + \frac{1}{2}\left(\frac{1}{b} + \frac{1}{d}\right) & 1 \end{vmatrix} \\
&= \begin{vmatrix} \frac{1}{2}a - \frac{1}{2}c & \frac{1}{2} \cdot \frac{1}{a} - \frac{1}{2} \cdot \frac{1}{c} & 1 \\ \frac{1}{2}b - \frac{1}{2}d & \frac{1}{2} \cdot \frac{1}{b} - \frac{1}{2} \cdot \frac{1}{d} & 1 \\ \frac{1}{2}c - \frac{1}{2}a & \frac{1}{2} \cdot \frac{1}{c} - \frac{1}{2} \cdot \frac{1}{a} & 1 \end{vmatrix} + \begin{vmatrix} \frac{1}{2}c - \frac{1}{2}a & \frac{1}{2} \cdot \frac{1}{c} - \frac{1}{2} \cdot \frac{1}{a} & 1 \\ \frac{1}{2}d - \frac{1}{2}b & \frac{1}{2} \cdot \frac{1}{d} - \frac{1}{2} \cdot \frac{1}{b} & 1 \\ \frac{1}{2}a - \frac{1}{2}c & \frac{1}{2} \cdot \frac{1}{a} - \frac{1}{2} \cdot \frac{1}{c} & 1 \end{vmatrix} \\
&= \frac{1}{4} \left(\begin{vmatrix} a-c & \frac{1}{a} - \frac{1}{c} & 1 \\ b-d & \frac{1}{b} - \frac{1}{d} & 1 \\ c-a & \frac{1}{c} - \frac{1}{a} & 1 \end{vmatrix} + \begin{vmatrix} c-a & \frac{1}{c} - \frac{1}{a} & 1 \\ d-b & \frac{1}{d} - \frac{1}{b} & 1 \\ a-c & \frac{1}{a} - \frac{1}{c} & 1 \end{vmatrix} \right) \\
&= \frac{1}{2} \left(\frac{2a}{b} - \frac{2b}{a} + \frac{2b}{c} - \frac{2c}{b} - \frac{2a}{d} + \frac{2c}{d} + \frac{2d}{a} - \frac{2d}{c} \right) \\
&= \left(\frac{a}{b} - \frac{b}{a} + \frac{b}{c} - \frac{c}{b} \right) + \left(\frac{c}{d} - \frac{d}{c} + \frac{d}{a} - \frac{a}{d} \right)
\end{aligned}$$

so we are done. \square

Problem 6.38 (OMO Fall 2013)

Let ABC be a triangle with $AB = 13$, $AC = 25$, and $\tan A = \frac{3}{4}$. Denote the reflections of B , C across AC , AB by D , E , respectively, and let O be the circumcenter of triangle ABC . Let P be a point such that $\triangle DPO \sim \triangle PEO$, and let X and Y be the midpoints of the major and minor arcs BC of the circumcircle of triangle ABC . Find $PX \cdot PY$.

Toss onto the complex plane. Let $O = 0$ and (ABC) be the unitcircle. Then, we get that:

$$\begin{aligned}
d &= a + c - \frac{ac}{b} \\
e &= a + b - \frac{ab}{c}.
\end{aligned}$$

Now, we know that

$$p^2 = de$$

and

$$x + y = 0 \quad xy = -bc.$$

Hence,

$$\begin{aligned}
PX \cdot PY &= |p - x| |p - y| \\
&= \sqrt{|p - x|^2 |p - y|^2} \\
&= \sqrt{(p - x)(p - y)(\bar{p} - \bar{x})(\bar{p} - \bar{y})} \\
&= \sqrt{(p^2 - (x + y)p + xy)(\bar{p}^2 - (\bar{x} + \bar{y})\bar{p} + \bar{x}\bar{y})} \\
&= \sqrt{(de - bc)(\overline{de - bc})} \\
&= \sqrt{de \cdot \overline{de} - bc \cdot \overline{de} - \overline{bc} \cdot de + |bc|^2} \\
&= \sqrt{de(\overline{de} - bc) - \frac{de}{bc} + 1} \\
&= \sqrt{\left(a + c - \frac{ac}{b}\right) \left(a + b - \frac{ab}{c}\right) \left(\overline{\left(a + c - \frac{ac}{b}\right) \left(a + b - \frac{ab}{c}\right)} - bc\right) - \frac{de}{bc} + 1}
\end{aligned}$$

$$\begin{aligned}
&= \sqrt{\left(\frac{1}{a} + \frac{1}{c} - \frac{b}{ac}\right) \left(\frac{1}{a} + \frac{1}{b} - \frac{c}{ab}\right) \left((a+c-\frac{ac}{b}) \left(a+b-\frac{ab}{c}\right) - bc\right) - \frac{de}{bc} + 1} \\
&= \sqrt{\left(\frac{1}{a^2} + \frac{1}{ab} - \frac{c}{a^2b} + \frac{1}{ac} + \frac{1}{bc} - \frac{1}{ab} - \frac{b}{a^2c} - \frac{1}{ac} + \frac{1}{a^2}\right) \left((a+c-\frac{ac}{b}) \left(a+b-\frac{ab}{c}\right) - bc\right) - \frac{de}{bc} + 1} \\
&= \sqrt{\left(\frac{2}{a^2} - \frac{c}{a^2b} + \frac{1}{bc} - \frac{b}{a^2c}\right) \left(a^2 + ab - \frac{a^2b}{c} + ac + bc - ab - \frac{a^2c}{b} - ac + a^2 - bc\right) - \frac{de}{bc} + 1} \\
&= \sqrt{\left(\frac{2}{a^2} - \frac{c}{a^2b} + \frac{1}{bc} - \frac{b}{a^2c}\right) \left(2a^2 - \frac{a^2b}{c} - \frac{a^2c}{b}\right) - \frac{de}{bc} + 1} \\
&= \sqrt{4 - \frac{2b}{c} - \frac{2c}{b} - \frac{2c}{b} + 1 + \frac{c^2}{b^2} + \frac{2a^2}{bc} - \frac{a^2}{c^2} - \frac{a^2}{b^2} - \frac{2b}{c} + \frac{b^2}{c^2} + 1 - \frac{de}{bc} + 1} \\
&= \sqrt{7 - \frac{4b}{c} - \frac{4c}{b} + \frac{c^2}{b^2} + \frac{2a^2}{bc} - \frac{a^2}{c^2} - \frac{a^2}{b^2} + \frac{b^2}{c^2} - \frac{(a+c-\frac{ac}{b})(a+b-\frac{ab}{c})}{bc}} \\
&= \sqrt{7 - \frac{4b}{c} - \frac{4c}{b} + \frac{c^2}{b^2} + \frac{2a^2}{bc} - \frac{a^2}{c^2} - \frac{a^2}{b^2} + \frac{b^2}{c^2} - \left(\frac{a^2 - \frac{a^2b}{c} + bc - \frac{a^2c}{b} + a^2}{bc}\right)} \\
&= \sqrt{7 - \frac{4b}{c} - \frac{4c}{b} + \frac{c^2}{b^2} + \frac{2a^2}{bc} - \frac{a^2}{c^2} - \frac{a^2}{b^2} + \frac{b^2}{c^2} - \frac{a^2}{bc} + \frac{a^2}{c^2} - 1 + \frac{a^2}{b^2} - \frac{a^2}{bc}} \\
&= \sqrt{6 - \frac{4b}{c} - \frac{4c}{b} + \frac{c^2}{b^2} + \frac{b^2}{c^2}} \\
&= \frac{c}{b} + \frac{b}{c} - 2 \\
&= -(b-c)(\bar{b}-\bar{c}) \\
&= BC^2.
\end{aligned}$$

Now, we are in the final stretch:

$$\tan^2 A + 1 = \sec^2 A \implies \frac{25}{9} = \sec^2 A \implies \cos A = \pm \frac{3}{5}.$$

Finally, the Law of Cosines gives that

$$BC^2 = AB^2 + AC^2 - 2AB \cdot AC \cos(A) = 13^2 + 25^2 \mp 2 \cdot 13 \cdot 25 \cdot \frac{3}{5} = \boxed{404} \text{ or } \boxed{1184}$$

as required. \square

Problem 6.39 (Tangent Addition)

Consider angles A, B, C in the open interval $(-90^\circ, 90^\circ)$.

(a) Let $x = \tan A$, $y = \tan B$, $z = \tan C$. Prove that

$$\tan(A+B+C) = \frac{(x+y+z) - xyz}{1 - (xy + yz + zx)}$$

if $xy + yz + zx \neq 1$, and is undefined otherwise.

(b) Generalize to multiple variables.

We solve both problems at once by immediately generalizing to k variables. Let

$$a_n = 1 + \tan(r_n)i$$

for $1 \leq n \leq k$. Now let e_n denote the n th elementary symmetric sum (of k variables/tangents in this case). Then, note that

$$\arg(a_1 a_2 \dots a_k) = \arg((1 + \tan(r_1)i)(1 + \tan(r_2)i) \dots (1 + \tan(r_k)i)) = \arg((1 - e_2 + e_4 - \dots) + (e_1 - e_3 + e_5 - \dots)i).$$

Hence,

$$\tan\left(\sum_{n=1}^k r_n\right) = \tan(\arg(a_1 a_2 \dots a_k)) = \tan(\arg((1 - e_2 + e_4 - \dots) + (e_1 - e_3 + e_5 - \dots)i)) = \frac{e_1 - e_3 + e_5 - \dots}{1 - e_2 + e_4 - \dots}$$

so we are done. \square

Problem 6.40 (Schiffler Point)

Let ABC be a triangle with incenter I . Prove that the Euler lines of triangles AIB , BIC , CIA , and ABC are concurrent (called the Schiffler point of ABC).

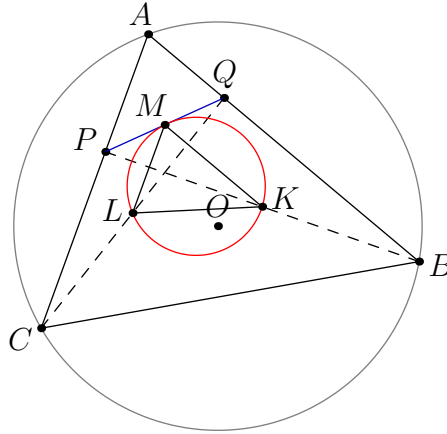
Toss onto the complex plane, with (ABC) as the unit circle. Denote $A = a^2$, and analogously for B and C . Then, we know by the Incenter-Excenter Lemma, that the circumcenter of $\triangle AIB$ is the midpoint of arc AB not containing C , or $-ab$. In addition, the centroid of $\triangle AIB$ is

$$\frac{a^2 + b^2 - ab - bc - ac}{3}$$

Now, we are trying to find the intersection of the line through 0 and $a + b + c$, and the former two points. We omit the routine (but very annoying) calculation using the intersection of lines formula, and state the result as a symmetric polynomial in a , b , c . Hence, we have the required result. \square

Problem 6.41 (IMO 2009/2, complex)

Let ABC be a triangle with circumcenter O . The points P and Q are interior points of the sides CA and AB , respectively. Let K , L , and M be the midpoints of the segments BP , CQ , and PQ , respectively, and let Γ be the circle passing through K , L , and M . Suppose that the line PQ is tangent to the circle Γ . Prove that $OP = OQ$.



Remark

A synthetic solution can be found as Problem 2.35.