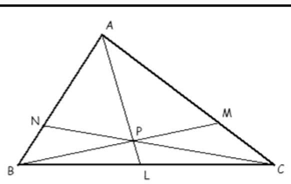
Ceva's Theorem

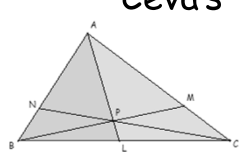
MA 341 – Topics in Geometry
Lecture 11

Ceva's Theorem

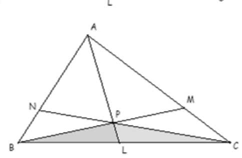
The three lines containing the vertices A, B, and C of $\triangle ABC$ and intersecting opposite sides at points L, M, and N, respectively, are concurrent if and only if $\frac{AN}{NB} \bullet \frac{BL}{LC} \bullet \frac{CM}{MA} = 1$



Ceva's Theorem

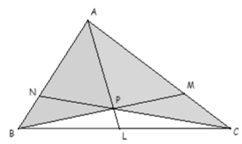


$$\frac{K(\triangle ABL)}{K(\triangle ACL)} = \frac{BL}{LC}$$



$$\frac{K(\triangle PBL)}{K(\triangle PCL)} = \frac{BL}{LC}$$

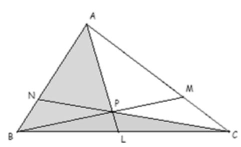
Ceva's Theorem



$$\frac{BL}{LC} = \frac{K(\triangle ABL) - K(\triangle PBL)}{K(\triangle ACL) - K(\triangle PCL)} = \frac{K(\triangle ABP)}{K(\triangle ACP)}$$

21-Sept-2011 MA 341 001 4

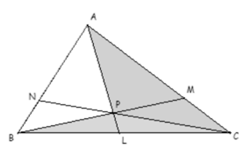
Ceva's Theorem



$$\frac{CM}{MA} = \frac{K(\triangle BMC) - K(\triangle PMC)}{K(\triangle BMA) - K(\triangle PMA)} = \frac{K(\triangle BCP)}{K(\triangle BAP)}$$

21-Sept-2011 MA 341 001 5

Ceva's Theorem



$$\frac{AN}{NB} = \frac{K(\triangle ACN) - K(\triangle APN)}{K(\triangle BCN) - K(\triangle BPN)} = \frac{K(\triangle ACP)}{K(\triangle BCP)}$$

21-Sept-2011 MA 341 001 6

Ceva's Theorem

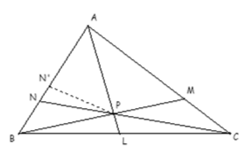
$$\frac{AN}{NB}\cdot\frac{BL}{LC}\cdot\frac{CM}{MA}=\frac{K(\triangle ACP)}{K(\triangle BCP)}\cdot\frac{K(\triangle ABP)}{K(\triangle ACP)}\cdot\frac{K(\triangle BCP)}{K(\triangle ABP)}=1$$

Ceva's Theorem

Now assume that

$$\frac{AN}{NB}\cdot\frac{BL}{LC}\cdot\frac{CM}{MA}=1$$

Let BM and AL intersect at P and construct CP intersecting AB at N', N' different from N.



Ceva's Theorem

Then AL, BM, and CN' are concurrent and

$$\frac{AN'}{N'B}\cdot\frac{BL}{LC}\cdot\frac{CM}{MA}=1$$

From our hypothesis it follows that

$$\frac{AN'}{N'B}=\frac{AN}{NB}$$

So N and N' must coincide.

Medians

In ΔABC, let M, N, and P be midpoints of AB, BC, AC.

Medians: CM, AN, BP

> Theorem: In any triangle the three medians meet in a single point, called the centroid.

M – midpoint $\Rightarrow$ AM=BM, N - midpoint $\Rightarrow$ BN=CN
P - midpoint $\Rightarrow$ AP=CP

$$\frac{AM}{MB} \cdot \frac{BN}{NC} \cdot \frac{CP}{PA} = 1$$

By Ceva's Theorem they are concurrent.

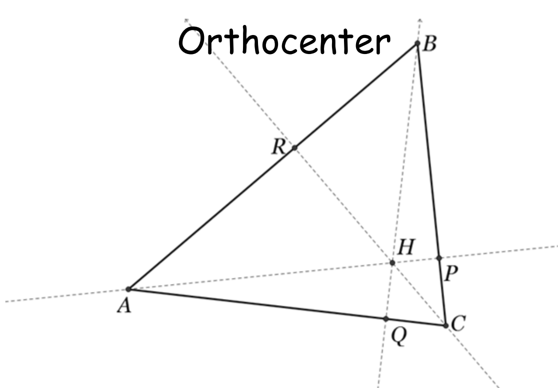
Orthocenter

Let ΔABC be a triangle and let P, Q, and R be the feet of A, B, and C on the opposite sides.

AP, BQ, and CR are the altitudes of ΔABC.

> Theorem: The altitudes of a triangle ΔABC meet in a single point, called the orthocenter, H.

Orthocenter



Orthocenter

By AA

$\Delta BRC \sim \Delta BPA$ (a right angle and $\angle B$)

$\Rightarrow BR/BP=BC/BA$

$\Delta AQB \sim \Delta ARC$ (a right angle and $\angle A$)

$\Rightarrow AQ/AR=AB/AC$

$\Delta CPA \sim \Delta CQB$ (a right angle and $\angle C$)

$\Rightarrow CP/CQ=AC/BC$

$$\frac{BR}{BP}\bullet\frac{AQ}{AR}\bullet\frac{CP}{CQ}=\frac{BC}{AB}\bullet\frac{AB}{AC}\bullet\frac{AC}{BC}=1$$

Orthocenter

By Ceva's Theorem, the altitudes meet at a single point.

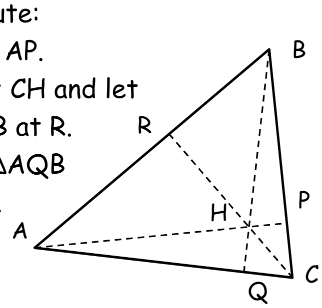
Orthocenter

Traditional route:

BQ intersects AP.

Now construct CH and let it intersect AB at R.

Prove $\Delta ARC \sim \Delta AQB$ making $\angle R=90$.



Incenter

Let ΔABC be a triangle and let AP, BQ, and CR be the angle bisectors of ∠A, ∠B, and ∠C.

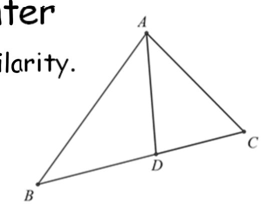
Angle Bisector Theorem: If AD is the angle bisector of ∠A with D on BC, then

$$\frac{AB}{AC} = \frac{BD}{CD}$$

21-Sept-2011 MA 341 001 16

Incenter

Proof: Want to use similarity. Where is similarity?

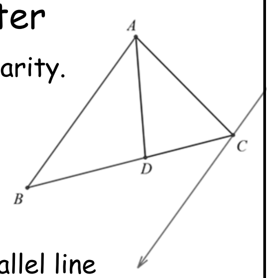


Construct line through C parallel to AB

21-Sept-2011 MA 341 001 17

Incenter

Proof: Want to use similarity. Where is similarity?



Construct line through C parallel to AB

Extend AD to meet parallel line through C at point E.

21-Sept-2011 MA 341 001 18

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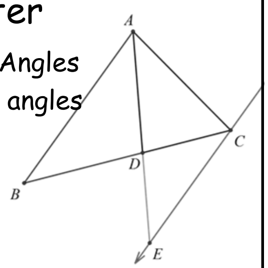


$\angle BAE \cong \angle CEA$ – Alt Int Angles

$\angle BDA \cong \angle CDE$ – vertical angles

$\Delta BAD \sim \Delta CDE$ – AA

Therefore

$$\frac{AB}{CE} = \frac{BD}{CD}$$

Note that $\angle CEA \cong \angle BAE \cong \angle CAE$

$\Rightarrow \Delta ACE$ isosceles $\Rightarrow CE = AC$ and $\frac{AB}{AC} = \frac{BD}{CD}$

21-Sept-2011 MA 341 001 19

Incenter

Let ΔABC be a triangle and let AP, BQ, and CR be the angle bisectors of $\angle A$, $\angle B$, and $\angle C$.

Theorem: The angle bisectors of a triangle ΔABC meet in a single point, called the incenter, I.

21-Sept-2011 MA 341 001 20

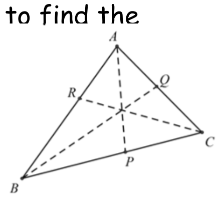
Incenter

Proof: Angle bisector means:

$$\frac{AB}{AC} = \frac{BP}{PC} \quad \frac{BA}{BC} = \frac{AQ}{QC} \quad \frac{CA}{CB} = \frac{AR}{RB}$$

By Ceva's Theorem we need to find the product:

$$\frac{AR}{RB} \bullet \frac{BP}{PC} \bullet \frac{CQ}{QA}$$

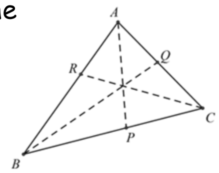


21-Sept-2011 MA 341 001 21

Incenter

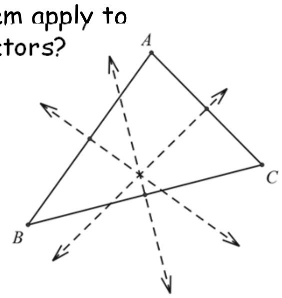
$$\frac{AR}{RB} \bullet \frac{BP}{PC} \bullet \frac{CQ}{QA} = \frac{AC}{BC} \bullet \frac{AB}{AC} \bullet \frac{BC}{AB} = 1$$

Thus by Ceva's Theorem the angle bisectors are concurrent.



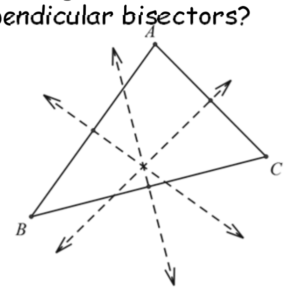
Circumcenter & Perp Bisectors

Does Ceva's Theorem apply to perpendicular bisectors?



Circumcenter & Perp Bisectors

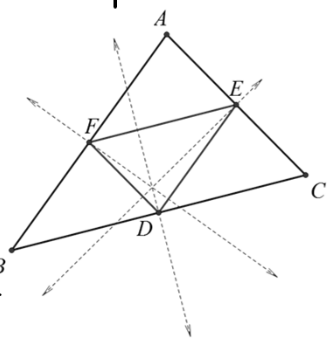
How can we get Ceva's Theorem to apply to perpendicular bisectors?



Circumcenter & Perp Bisectors

Draw in midsegments

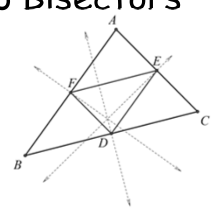
EF||BC ⇒ perpendicular bisector of BC is perpendicular to EF ⇒ is an altitude of ΔDEF



Circumcenter & Perp Bisectors

Perpendicular bisectors of AB, BC and AC are altitudes of ΔDEF.

Altitudes meet in a single point ⇒ perpendicular bisectors are concurrent.



Circumcircle

Theorem: There is exactly one circle through any three non-collinear points.

The circle = the circumcircle
The center = the circumcenter, O.
The radius = the circumradius, R.

Theorem: The circumcenter is the point of intersection of the three perpendicular bisectors.

Question

Where do the perpendicular bisectors of the sides intersect the circumcircle?

Question

Where do the perpendicular bisectors of the sides intersect the circumcircle?

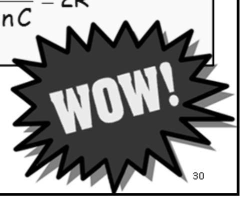
At one end is point of intersection of angle bisector with circumcircle

The other end is point of intersection of exterior angle bisector with circumcircle.

Extended Law of Sines

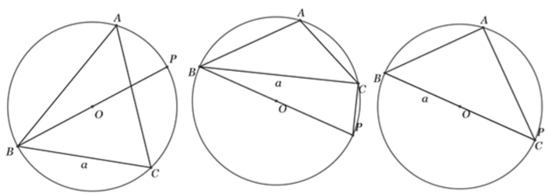
Theorem: Given ΔABC with circumradius R, let a, b, and c denote the lengths of the sides opposite angles $\angle A$, $\angle B$, and $\angle C$, respectively. Then

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



Proof

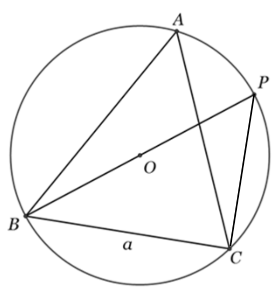
Three cases:



21-Sept-2011 MA 341 001 31

Proof

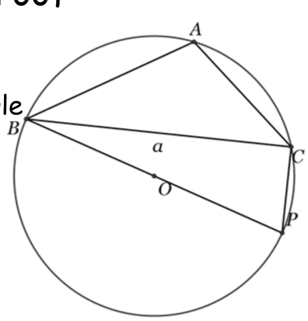
Case I: $\angle A < 90°$
BP = diameter
$\Rightarrow \Delta BCP$ right triangle
BP = 2R
$\Rightarrow$ sin P = a/2R
$\angle A = \angle P$
$\Rightarrow$ 2R = a/sin A



21-Sept-2011 MA 341 001 32

Proof

Case II: $\angle A > 90°$
BP = diameter
$\Rightarrow \Delta BCP$ right triangle
BP = 2R
$\Rightarrow$ sin P = a/2R
$\angle A = \angle P$
$\Rightarrow$ 2R = a/sin A



21-Sept-2011 MA 341 001 33

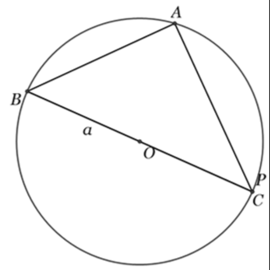
Proof

Case III: $\angle A = 90°$

BP = a = diameter

BP = 2R

2R = a = a/sin A



Circumradius and Area

Theorem: Let R be the circumradius and K be the area of ΔABC and let a, b, and c denote the lengths of the sides as usual. Then 4KR=abc

$$K = \frac{abc}{4R}$$

Proof

$K = \frac{1}{2}$ ab sin C

2K = ab sin C

c/sin C = 2R

sin C = c/2R

2K = abc/2R

4KR = abc