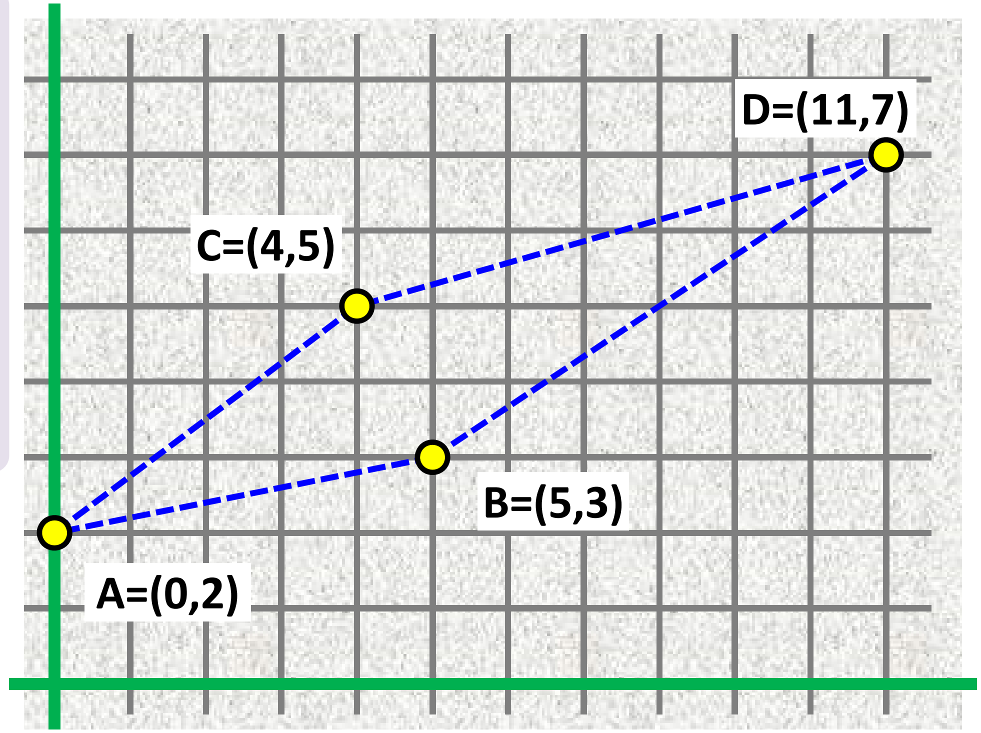
Distance (A, B) =

= sqrt((Ax–Bx)^2 + (Ay–By)^2)

= distance (B, A)



Comparing distances

Compare squares of distances
(faster, integer coordinates → no floats!)

dist(A, B) < dist(B, C) ⇔ dist(A, C)^2 < dist(B, C)^2

dist(A, B)^2 = (0–5)^2 + (2–3)^2 = 26

dist(A, C)^2 = (0–4)^2 + (2–5)^2 = 25

dist(C, D)^2 = (4–11)^2 + (5–7)^2 = 53

dist(B, D)^2 = (5–11)^2 + (3–7)^2 = 52

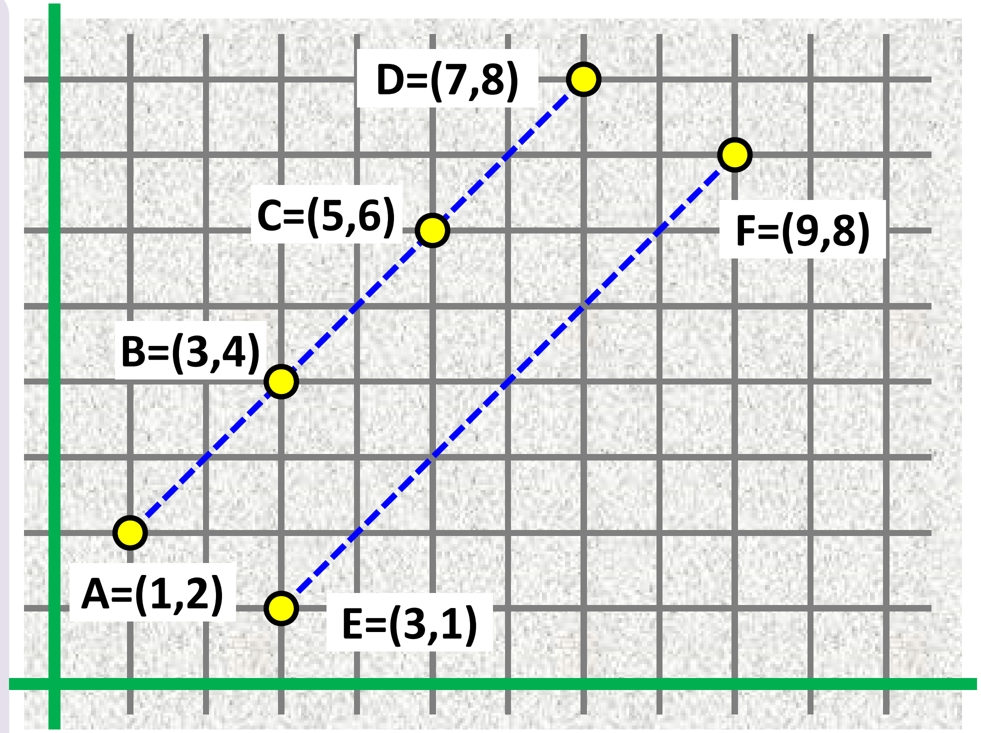
Comparing distances example

dist(A, D) = dist(A,B) + dist(B,C) + dist(D,E)

= sqrt(8) + sqrt(8) + sqrt(8)

dist(E, F) = sqrt(72)

theoretically: dist(E, F) = dist(A, D)



Implementation with double (IEEE 754 floating-point standard):

sqrt(8) + sqrt(8) + sqrt(8) = 8.48528137423857**1**
sqrt(72) = 8.48528137423857**0**

Bits in double representations:
01000000001000001111100001110110110011001101111101101100110110**10**
01000000001000001111100001110110110011001101111101101100110110**01**

AB = vector (A,B) = B – A

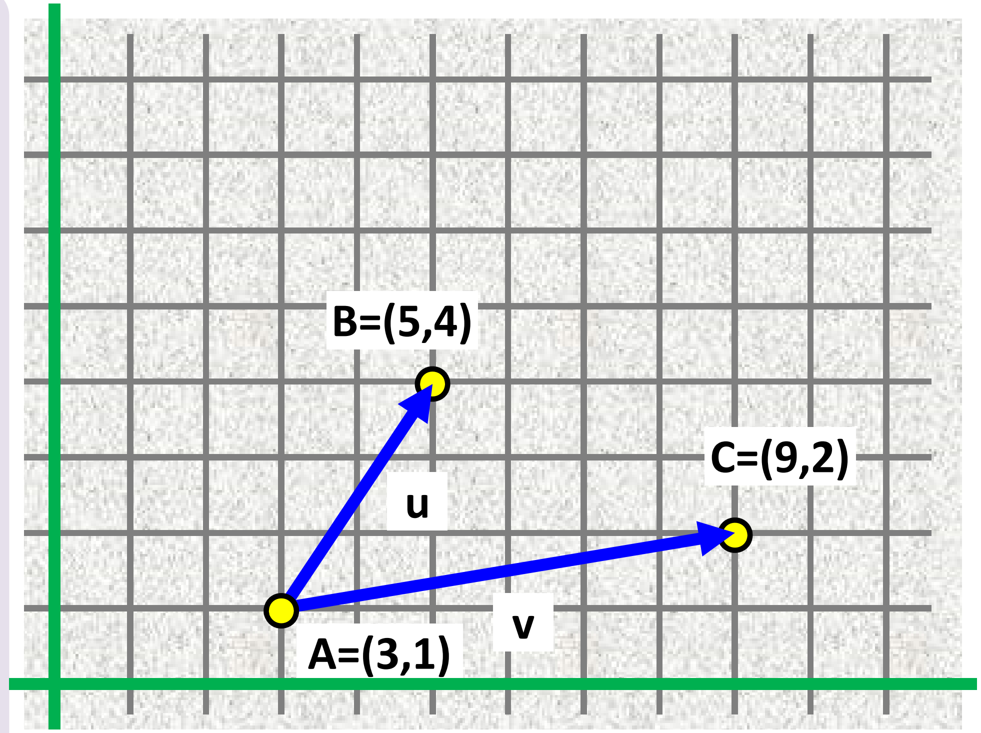
AB = $(Bx–Ax, By–Ay)^T$

Vector **norm** = vector **length**

‖**AB**‖ = ‖**BA**‖

‖**AB**‖ = sqrt($(Bx–Ax)^2 + (By–Ay)^2$)

‖**AB**‖ = distance(A, B)



u = **AB** = B – A = $(5 – 3, 4 – 1)^T = (2, 3)^T$

v = **AC** = C – A = $(9 – 3, 2 – 1)^T = (6, 1)^T$

‖**u**‖ = sqrt($2^2 + 3^2$) = sqrt(13)

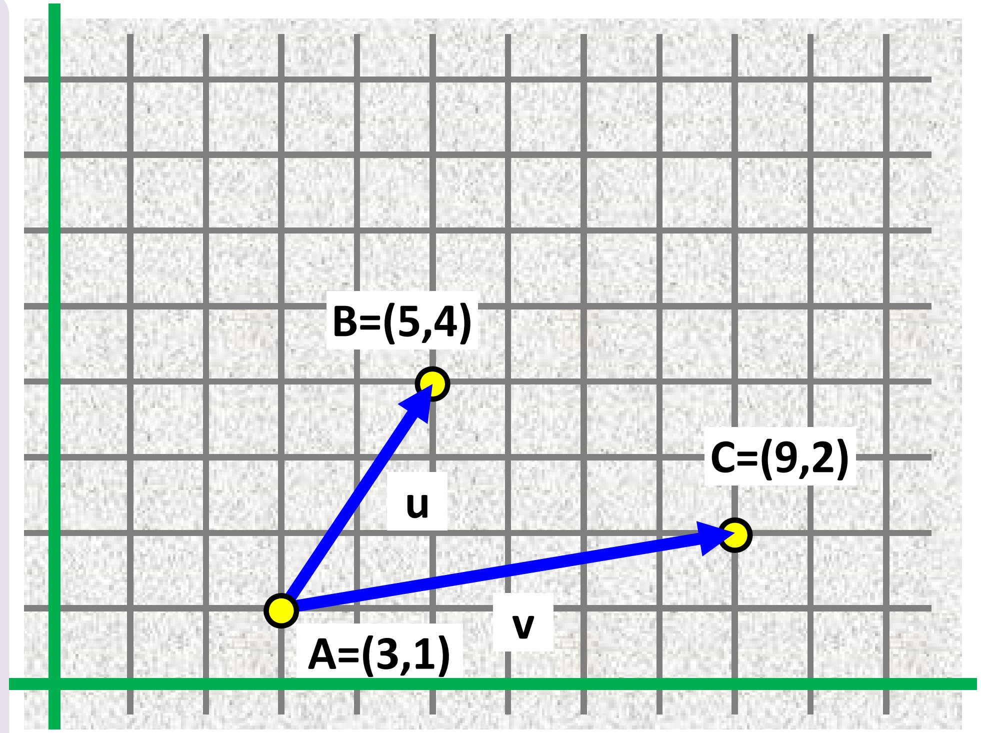
‖**v**‖ = sqrt($6^2 + 1^2$) = sqrt(37) in Euclidean space

Dot product ≡ scalar product

$\langle \mathbf{u}, \mathbf{v} \rangle = \langle \mathbf{v}, \mathbf{u} \rangle = \mathbf{u} \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{u}$
// commutative

sum(i = 1..dimension, **u**[i]***v**[i])

$= \mathbf{u_x\, v_x + u_y\, v_y}$ **// in 2D**



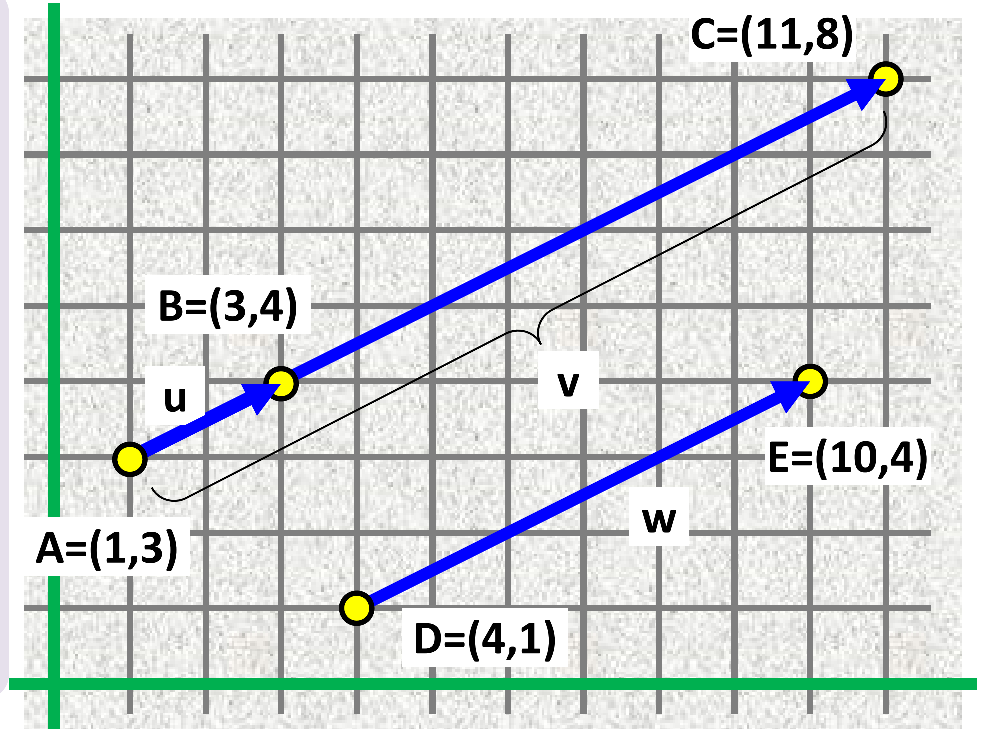
$\mathbf{u} = \mathbf{AB} = B - A = (5 - 3, 4 - 1)^T = (2, 3)^T$

$\mathbf{v} = \mathbf{AC} = C - A = (9 - 3, 2 - 1)^T = (6, 1)^T$

$\langle \mathbf{u}, \mathbf{v} \rangle = 2*6 + 3*1 = 15$

Vectors **u** and **v** are **collinear**
if and only if
u is a non-zero multiple of **v**
(and vice versa)
or equivalently:

determinant $\begin{vmatrix} u_x & v_x \\ u_y & v_y \end{vmatrix} = 0$



u = $(2, 1)^T$
v = $(10, 5)^T$
w = $(6, 3)^T$

det(**u**, **v**) = $\det((2, 1)^T, (10, 5)^T) = \det\begin{pmatrix} 2, & 10 \\ 1, & 5 \end{pmatrix} = 2*5 - 1*10 = 0$

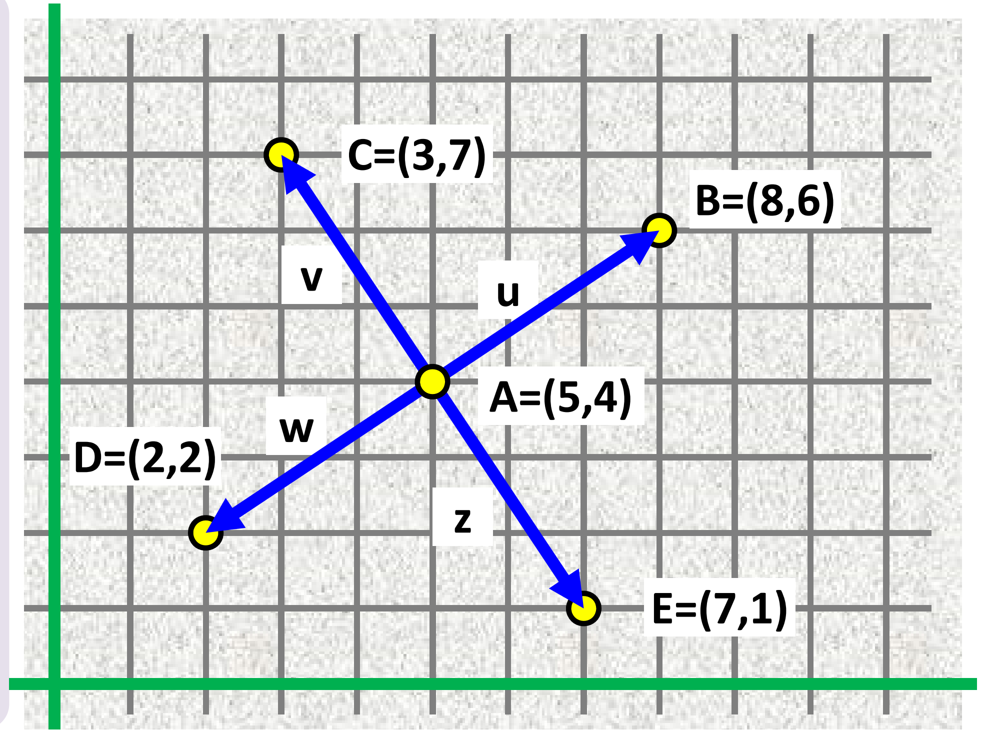
det(**u**, **w**) = $\det((2, 1)^T, (6, 3)^T) = \det\begin{pmatrix} 2, & 6 \\ 1, & 3 \end{pmatrix} = 2*3 - 1*6 = 0$

det(**v**, **w**) = $\det((10, 5)^T, (6, 3)^T) = \det\begin{pmatrix} 10, & 6 \\ 5, & 3 \end{pmatrix} = 10*3 - 5*6 = 0$

Nonzero vectors **u**, **v**
are **perpendicular** to each other

$\mathbf{u} \square \mathbf{v}$

iff scalar product $\langle \mathbf{u}, \mathbf{v} \rangle = 0$



$\mathbf{u} = (3,\ 2)^T$ $\quad$ $\mathbf{u} \square \mathbf{v}$: $\langle (3,\ 2)^T, (-2,\ 3)^T \rangle = 3*(-2) + 2*3 = 0$

$\mathbf{v} = (-2,\ 3)^T$ $\quad$ $\mathbf{v} \square \mathbf{w}$: $\langle (-2,\ 3)^T, (-3,\ -2)^T \rangle = (-2)*(-3) + 3*(-2) = 0$

$\mathbf{w} = (-3,\ -2)^T$ $\quad$ $\mathbf{w} \square \mathbf{z}$: $\langle (-3,\ -2)^T, (2,\ -3)^T \rangle = (-3)*2 + (-2)*(-3) = 0$

$\mathbf{z} = (2,\ -3)^T$ $\quad$ $\mathbf{z} \square \mathbf{u}$: $\langle (2,\ -3)^T, (3,\ 2)^T \rangle = 2*3 + (-3)*2 = 0$

Area of a triangle given by vectors **u, v = AB**, **AC**

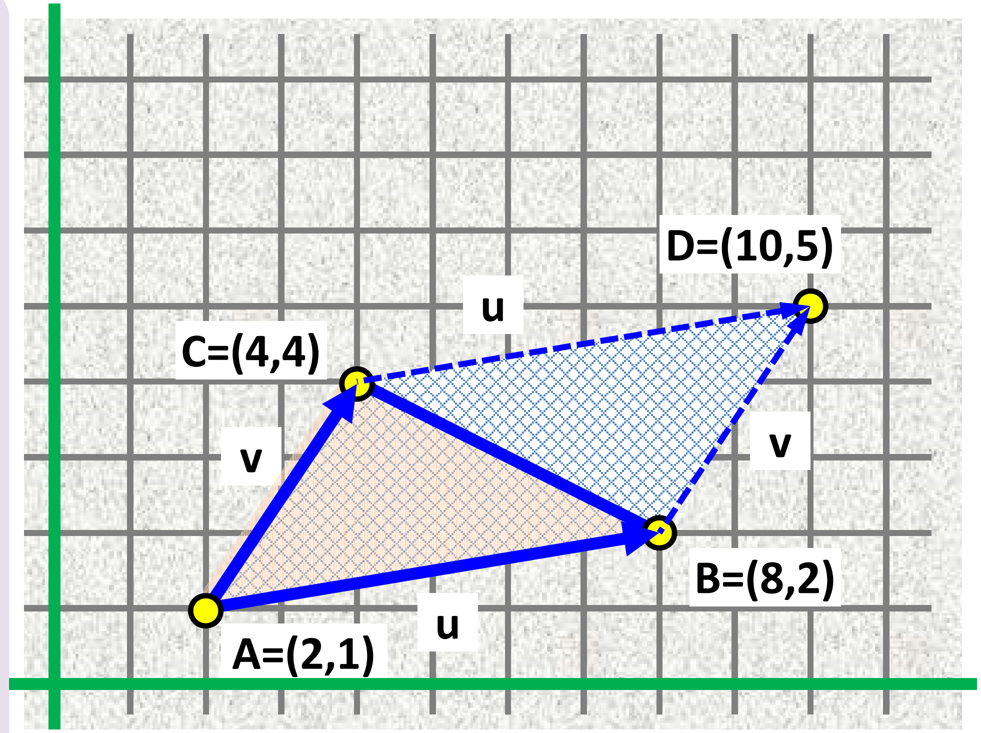
$\frac{1}{2} \cdot |\det(\mathbf{u}, \mathbf{v})|$

Area of parallelogram ABCD
(D = B + **v** = C + **u**)

$|\det(\mathbf{u}, \mathbf{v})|$

Vector mutual position matters:

$\det(\mathbf{v}, \mathbf{u}) = -\det(\mathbf{u}, \mathbf{v})$



Triangle ABC **area** =

= abs (det ($(6, 1)^T$, $(2, 3)^T$)) / 2 = abs(6*3 – 1*2) / 2 = 8 // vectors **AB**, **AC**

= abs (det ($(-6, -1)^T$, $(-4, 2)^T$)) / 2 = abs((–6)*2 – (–4)*(–1)) / 2 = 8 // vectors **BA**, **BC**

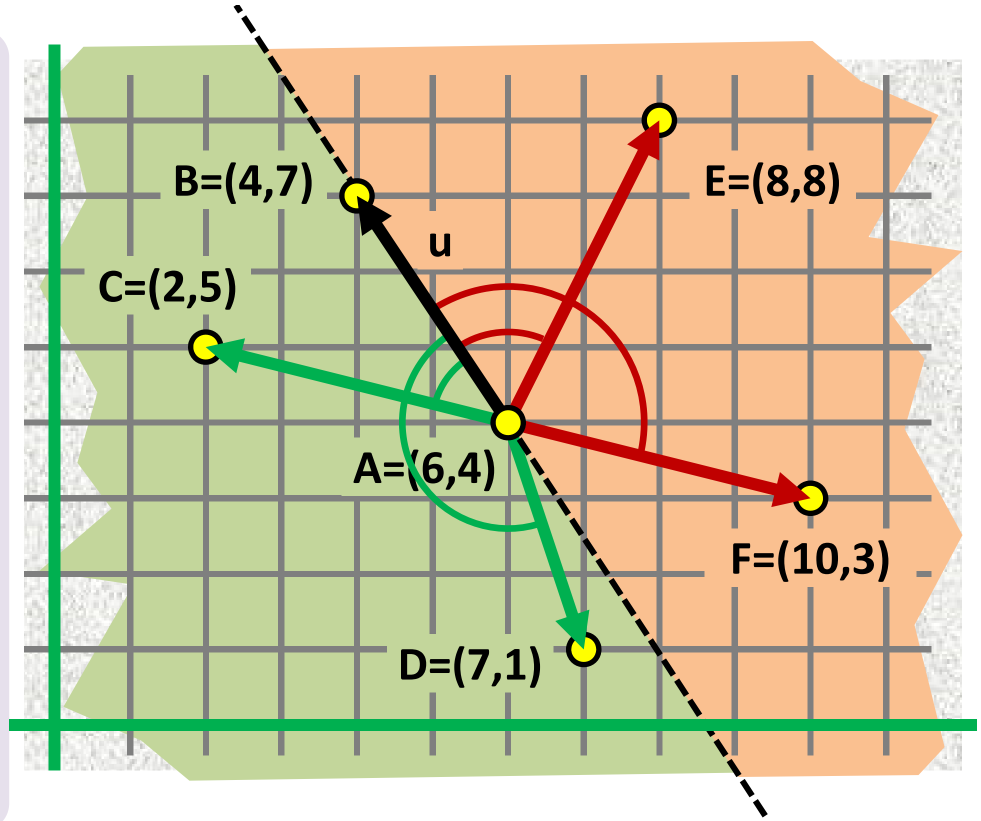
= abs (det ($(-2, -3)^T$, $(4, -2)^T$)) / 2 = abs((–2)*(–2) – (–3)*4)) / 2 = 8 // vectors **CA**, **CB**

Relative orientation of vectors

angle (**u**, **v**) ... how much to turn **u** *to the* ***left*** to obtain a vector parallel to **v**

det(**u**, **v**) > 0 ⇔ 0 < angle (**u**, **v**) < 180

det(**u**, **v**) < 0 ⇔ 180 < angle (**u**, **v**) < 360



$\mathbf{u} = (B - A)^T = (-2, 3)^T$

det (**u**, **AC**) = det($(-2, 3)^T, (-4, 1)^T$) = –2*1 – 3*(–4) = 10 > 0

det (**u**, **AD**) = det($(-2, 3)^T, (1, -3)^T$) = –2*(–3) – 3*1 = 3 > 0

det (**u**, **AE**) = det($(-2, 3)^T, (2, 4)^T$) = –2*4 – 3*2 = –14 < 0

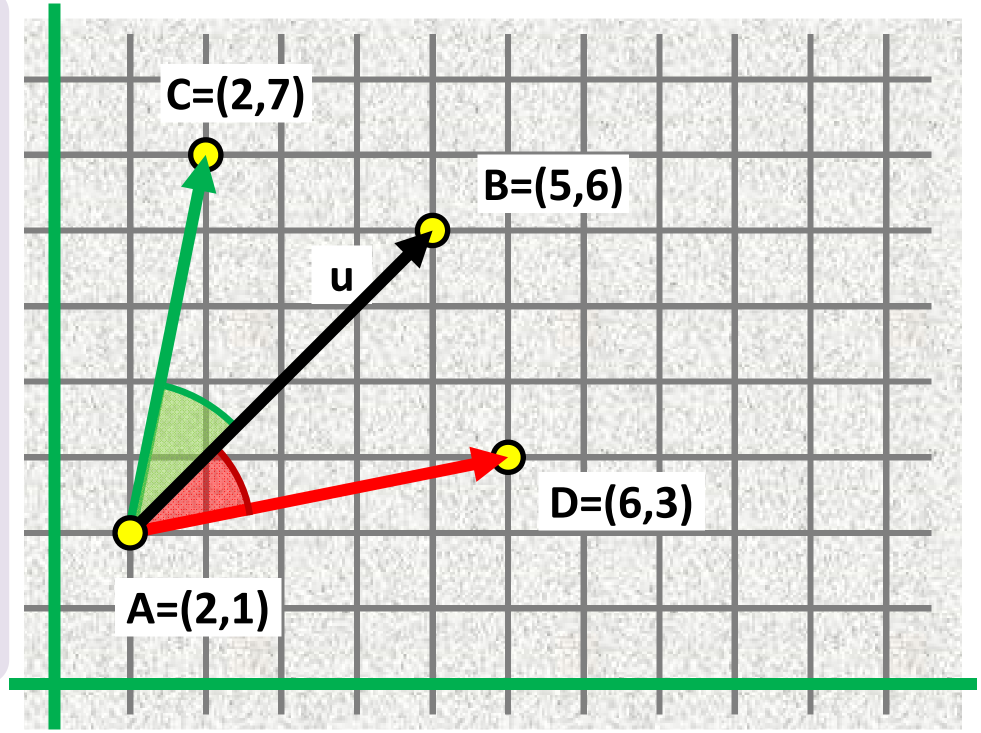
det (**u**, **AF**) = det($(-2, 3)^T, (4, -1)^T$) = –2*(–1) – 3*4 = –10 < 0

Angle of vectors

$\cos \text{angle} = \langle \mathbf{u}, \mathbf{v} \rangle / (\|\mathbf{u}\| \, \|\mathbf{v}\|)$

$\text{angle} = \arccos (\langle \mathbf{u}, \mathbf{v} \rangle / (\|\mathbf{u}\| \, \|\mathbf{v}\|))$

Relative orientation of **u** and **v**
is **not** calculated



$\mathbf{u} = (4, 4)^T$

$\cos \angle BAC = \langle \mathbf{u}, \mathbf{AC} \rangle / (\|\mathbf{u}\| \, \|\mathbf{AC}\|) \quad = \quad \cos \angle CAB = \langle \mathbf{AC}, \mathbf{u} \rangle / (\|\mathbf{AC}\| \, \|\mathbf{u}\|)$

$= \langle (4, 4)^T, (1, 5)^T \rangle / (\|(4, 4)^T\| \, \|(1, 5)^T\|)$

$= (4*1 + 4*5) / (\text{sqrt}(32) * \text{sqrt}(26)) = 24 / (8*\text{sqrt}(13)) = 3/\text{sqrt}(13)$

$\cos \angle BAD = \langle \mathbf{u}, \mathbf{AD} \rangle / (\|\mathbf{u}\| \, \|\mathbf{AD}\|) \quad = \quad \cos \angle DAB = \langle \mathbf{AD}, \mathbf{u} \rangle / (\|\mathbf{AD}\| \, \|\mathbf{u}\|)$

$= \langle (4, 4)^T, (5, 1)^T \rangle / (\|(4, 4)^T\| \, \|(5, 1)^T\|)$

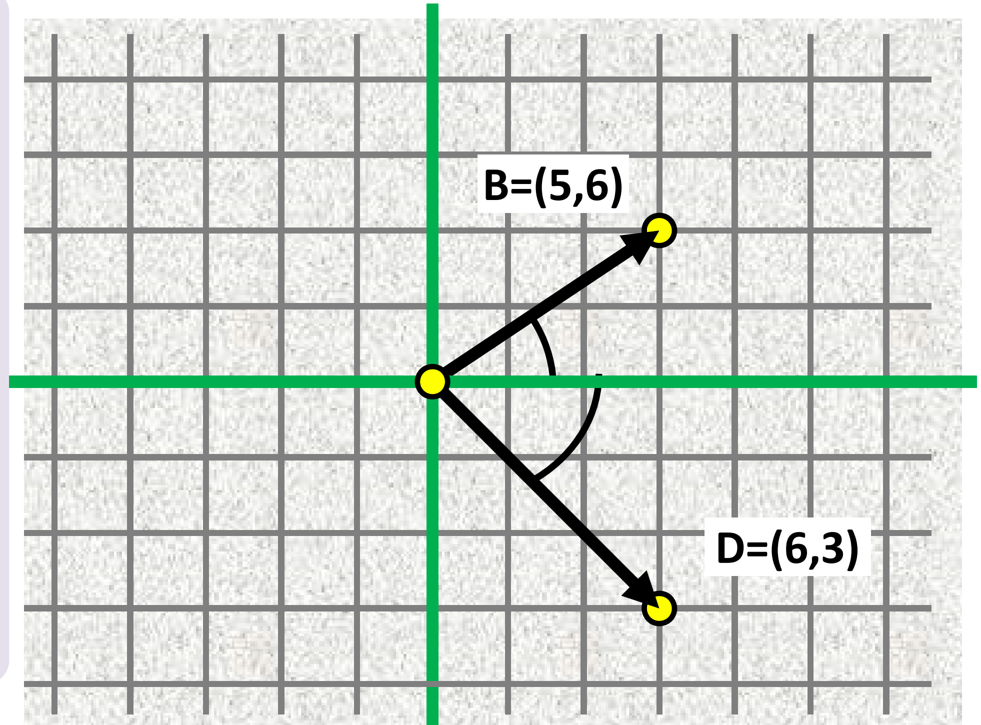
$= (4*5 + 4*1) / (\text{sqrt}(32) * \text{sqrt}(26)) = 24 / (8*\text{sqrt}(13)) = 3/\text{sqrt}(13)$

$\angle BAC = \angle BAD = \arccos (3/ \text{sqrt}(13)) = 0.588 \text{ rad} = 33.69^\circ$

$\pi \text{ rad} = 180 \text{ deg}$
$1 \text{ rad} = 180/\pi \text{ deg}$
$1 \text{ deg} = \pi/180 \text{ rad}$

Angle of vector (x, y)
in quadrant I and IV

angle = arc tan(y/ x)



double atan2(double y, double x);
Returns the **principal value** of the arc tangent of y/x, expressed in radians.

```
dot =  x1*x2 + y1*y2       // dot product between [x1, y1] and [x2, y2]
det = x1*y2 - y1*x2        // determinant
angle = atan2(det, dot)    // atan2(y, x) or atan2(sin, cos)
```

Note that the documentation does not mention the case x == 0.0. (??)
(y/0.0 is undefined, or ⁺/- inf right?). However, the function returns correct value.
E.g. `cout << atan2( 1, 0 ) * 2 << endl;` **// prints 3.14159, as one would expect.**

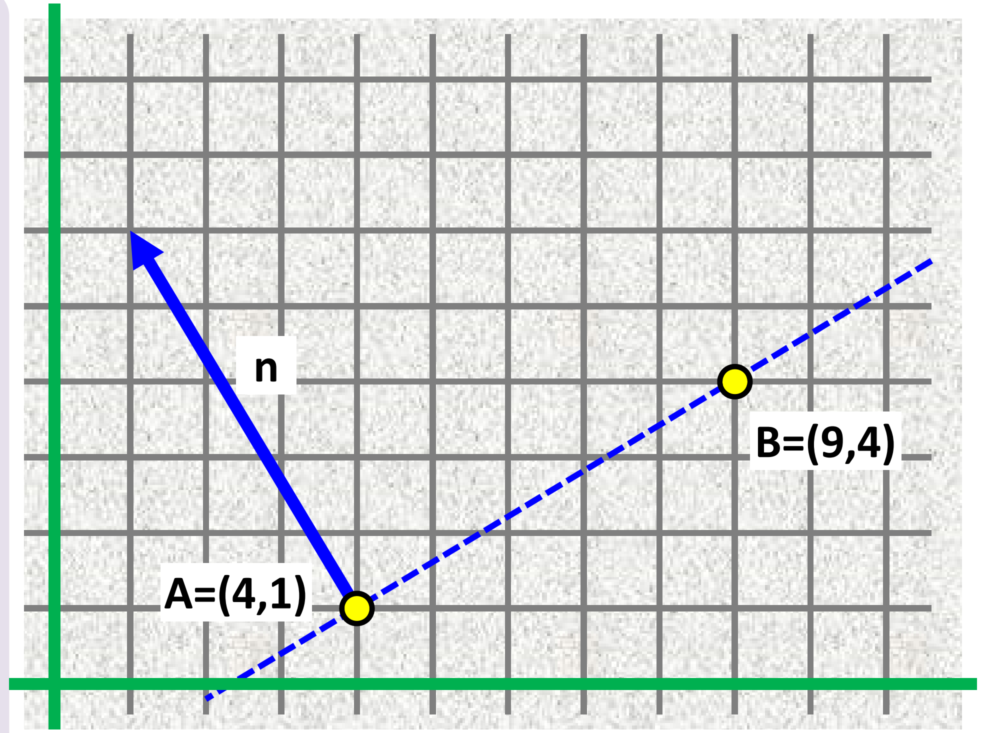
Two points **A** = (A_x, A_y), **B** = (B_x, B_y)

$\rightarrow$ **line equation**

$$ax + by + c = 0$$

1. Normal vector **n** = (a, b)^T
2. A lies on the line AB $\Rightarrow$
   $a \cdot A_x + b \cdot A_y + c = 0 \Rightarrow$
   $c = -a \cdot A_x - b \cdot A_y \Rightarrow$

$$a \cdot x + b \cdot y - a \cdot A_x - b \cdot A_y = 0$$



AB = (5,3)^T
n = (–3, 5), equation: $-3x + 5y + c = 0$

c = – (–3)*4 – 5*1 = 7 equation: $-3x + 5y + 7 = 0$

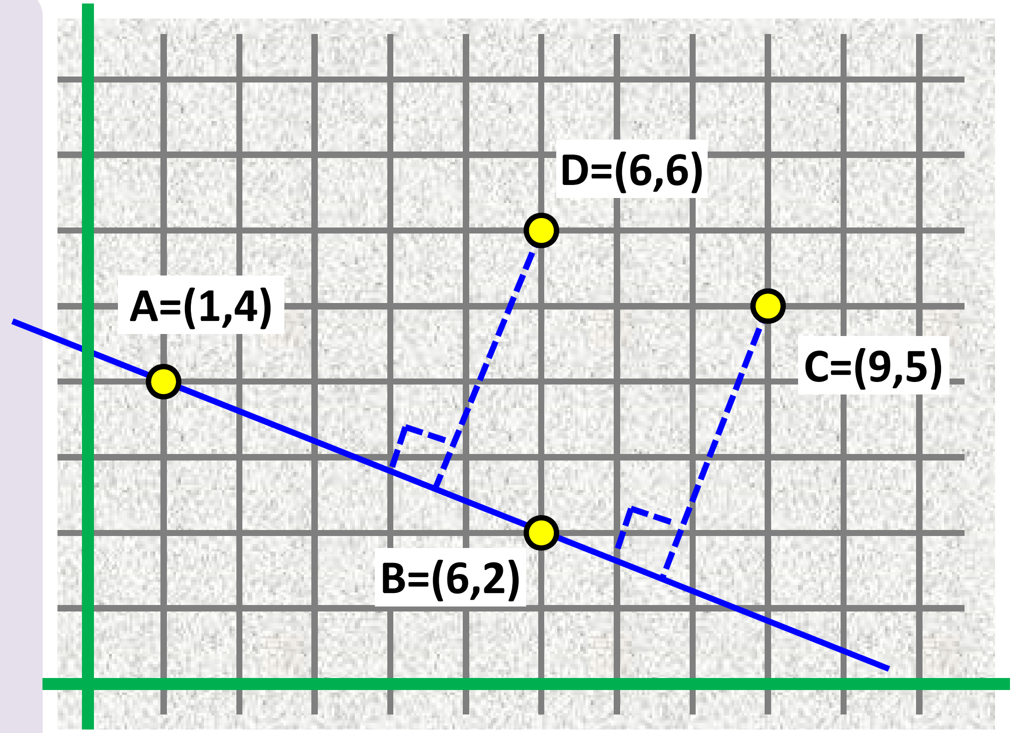
(Check: plug coords of B = (9, 4) into the equation: –3*9 + 5*4 + 7 = –27+20+7 = 0)

Distance point to line

Point P: (Px, Py)
Line: ax + by + c = 0

Distance(P, line) =

$| a \cdot Px + b \cdot Py + c | \; / \; \| (a, b)^T \|$



line AB: $2x + 5y - 22 = 0$
C = (9, 5)
D = (6, 6)

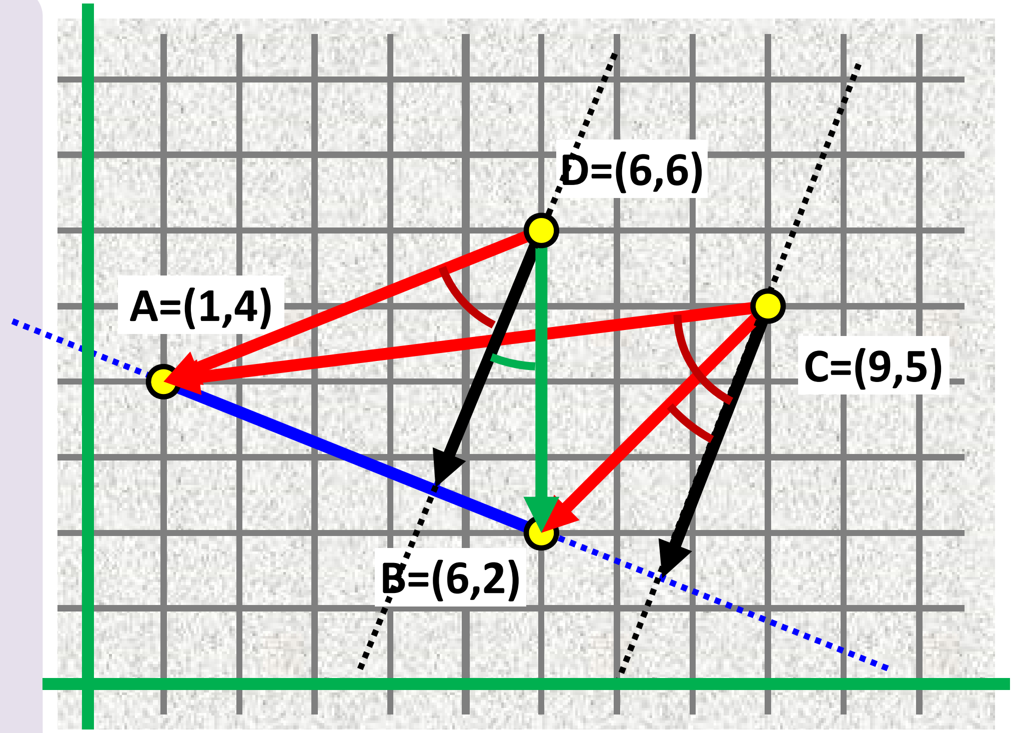
dist(C, AB) = abs(2*9 + 5*5 – 22) / sqrt(2*2 + 5*5) = 21/sqrt(29) ≈ 3.8996

dist(D, AB) = abs(2*6 + 5*6 – 22) / sqrt(2*2 + 5*5) = 20/sqrt(29) ≈ 3.7139

Distance point to segment

Point P: (Px, Py)
Segment: AB

Normal vector **n** to AB
If vectors **PA** and **PB**
are "on the same side" wrt **n**
then
dist(P, AB) = min (dist(P, A), dist(P, B))
else
dist(P, AB) = dist(P, line AB)



Being "on the same side" wrt **n** means
that the angle between **n** and **PA** and the angle between **n** and **PB**
are either both between 0° and 180° or both between 180° and 360°.
In other words, the sign of det (**n**, **PA**) and det (**n**, **PB**) is the same, or simply
det (**n**, **PA**) * det (**n**, **PB**) > 0.

Line-line intersection P

$a1 \cdot x + b \cdot 1y + c1 = 0,$

$a2 \cdot x + b2 \cdot y + c2 = 0$

Solution of syst. of two lin. eq. in x and y, using Cramer rule:

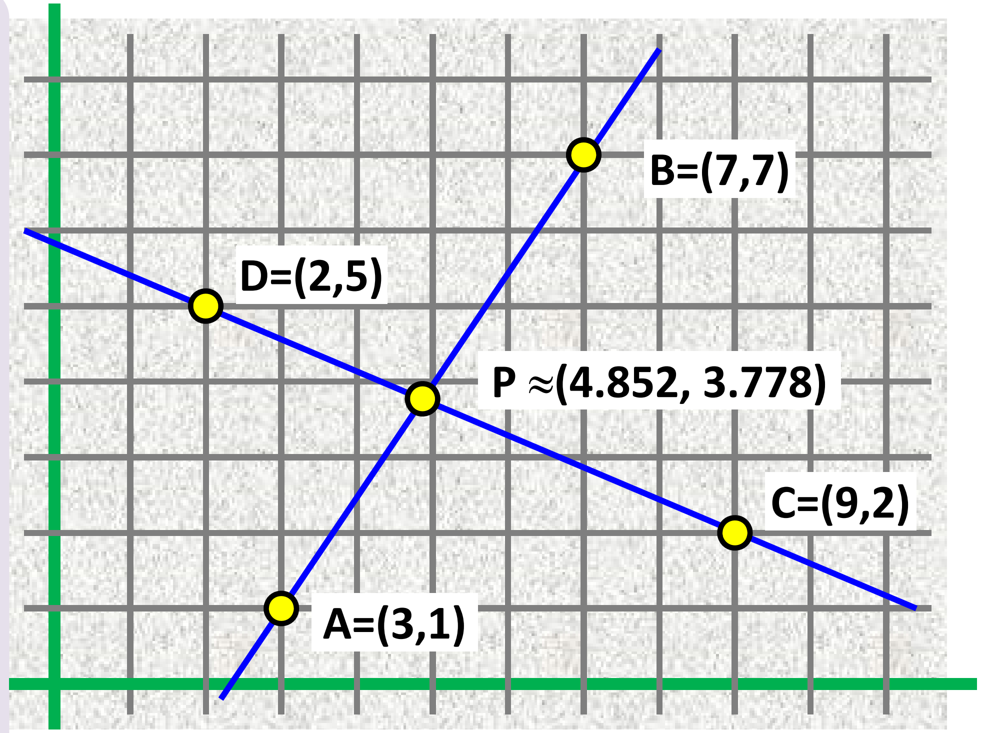
$\det(\mathbf{n1}^T, \mathbf{n2}^T) = a1*b2 - a2*b1$

if det $(\mathbf{n1}^T, \mathbf{n2}^T)$ == 0 then collinear

if det $(\mathbf{n1}^T, \mathbf{n2}^T)$!= 0 then

$Px = (b1*c2 - b2*c1) / \det(\mathbf{n1}^T, \mathbf{n2}^T)$

$Py = (c1*a2 - c2*a1) / \det(\mathbf{n1}^T, \mathbf{n2}^T)$



line eq: $\mathbf{n}^T = (a, b)$, $ax + by - a \cdot Ax - b \cdot Ay = 0$

line AB: $\mathbf{n1}^T = (-6, 4)$; $-6x + 4y + 14 = 0$

line CD: $\mathbf{n2}^T = (3, 7)$; $3x + 7y - 41 = 0$

$\det(\mathbf{n1}^T, \mathbf{n2}^T) = (-6)*7 - 4*3 = -54$

$Px = (4*(-41) - 7*14) / (-54) = -262 / -54 \approx 4.852$

$Py = (14*3 - (-41)(-6)) / (-54) = -204 / -54 \approx 3.778$

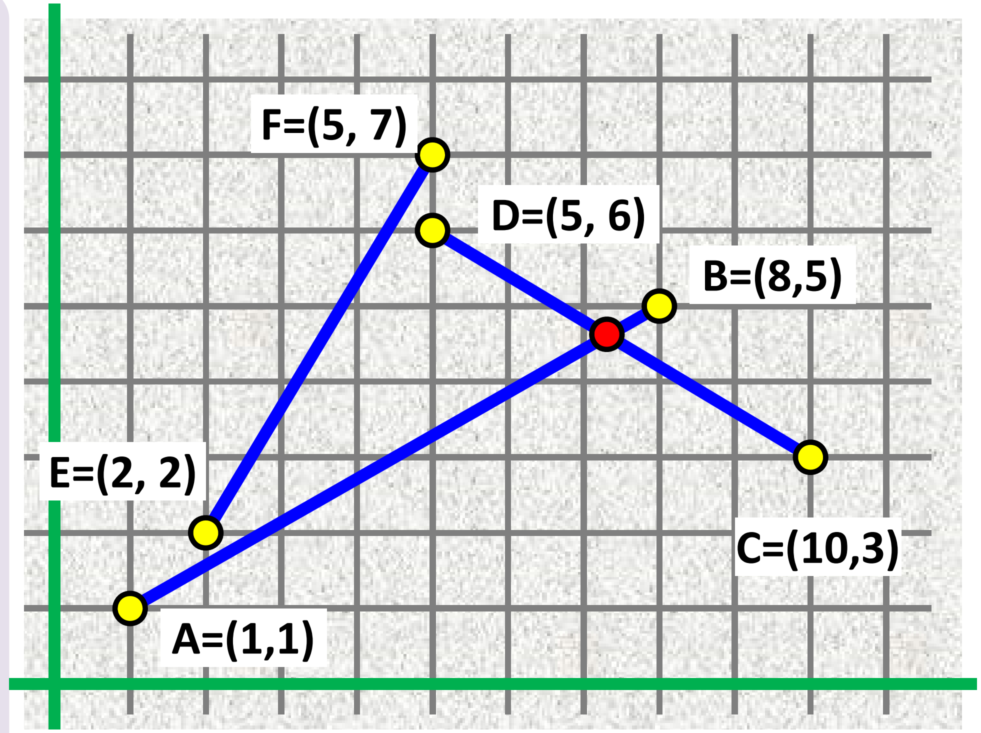
segment segment intersection

does (A,B) intersect (C, D) ?

Homework:
-- C and D should not lie on the same side of line (A, D)
-- A and B should not lie on the same side of line (C, D)
-- also check collinearity (A,B) and (C, D).

Another method:

if A and B are on different sides of CD
AND
C and D are on different sides of AB
then
X := line-line intersection of AB and CD
else
no intersection.



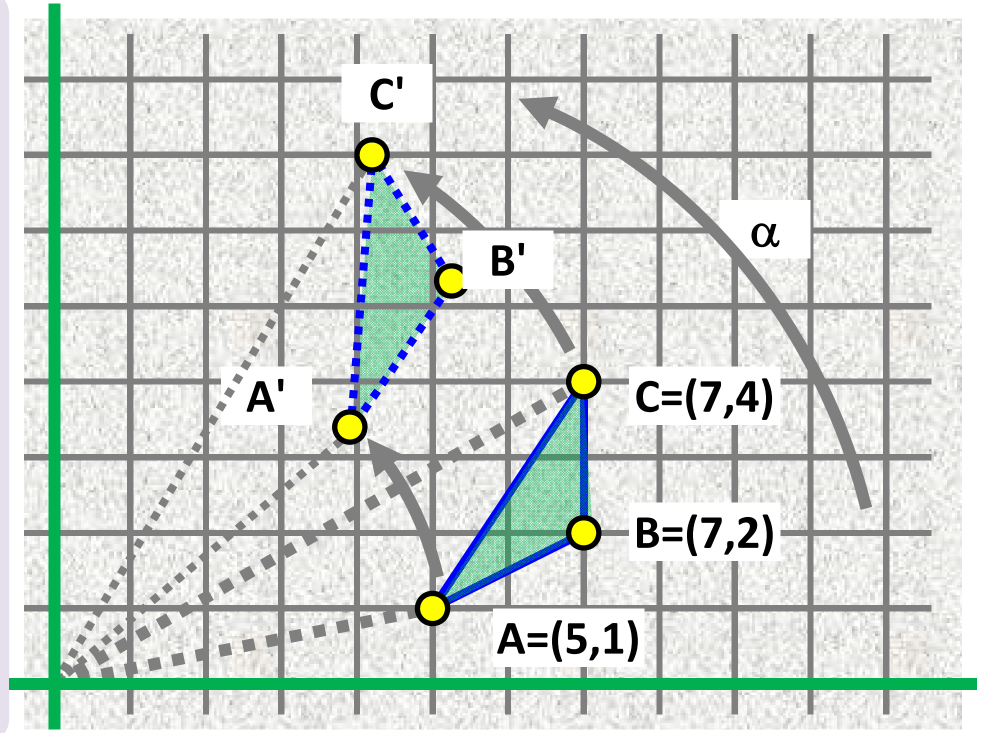
Rotate point A = (Ax, Ay)
counterclockwise (!) around origin
by a given angle α:

$$\begin{pmatrix} \cos\alpha, & -\sin\alpha \\ \sin\alpha, & \cos\alpha \end{pmatrix} \begin{pmatrix} Ax \\ Ay \end{pmatrix} =$$

(cosα*Ax – sinα*Ay, sinα*Ax + cosα*Ay)

rotate left by 90 deg, multiply by matrix

$$\begin{pmatrix} \cos 90^\circ, & -\sin 90^\circ \\ \sin 90^\circ, & \cos 90^\circ \end{pmatrix} = \begin{pmatrix} 0, & -1 \\ 1, & 0 \end{pmatrix}$$



Rotate ABC by 30°

$$\begin{pmatrix} \cos 30^\circ, & -\sin 30^\circ \\ \sin 30^\circ, & \cos 30^\circ \end{pmatrix} = \begin{pmatrix} \text{sqrt}(3)/2, & -1/2 \\ 1/2, & \text{sqrt}(3)/2 \end{pmatrix} \approx \begin{pmatrix} 0.886, & -0.5 \\ 0.5, & 0.886 \end{pmatrix}$$

A' = (0.886*5 – 0.5*1,   0.5*5 + 0.886*1) = (3.93, 3.386)

B' = (0.886*7 – 0.5*2,   0.5*7 + 0.886*2) = (5.202, 5.272)

C' = (0.886*7 – 0.5*4,   0.5*7 + 0.886*4) = (4.202, 7.044)

Simple polygon
(No two of its non-adjacent boundary segments touch or intersect each other)

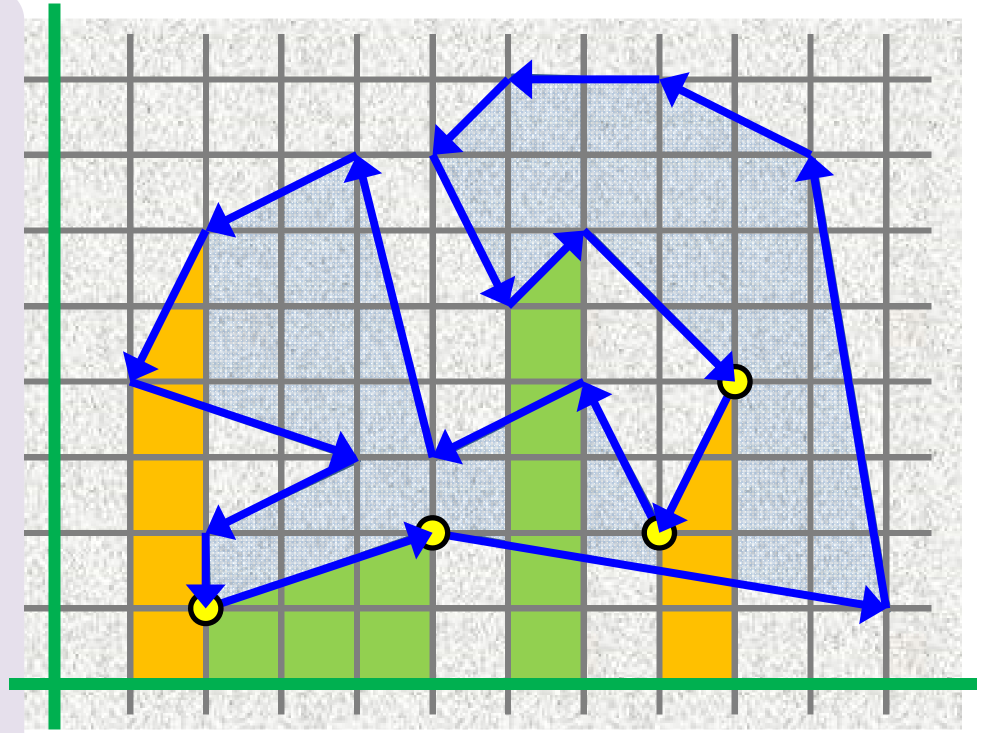
Area

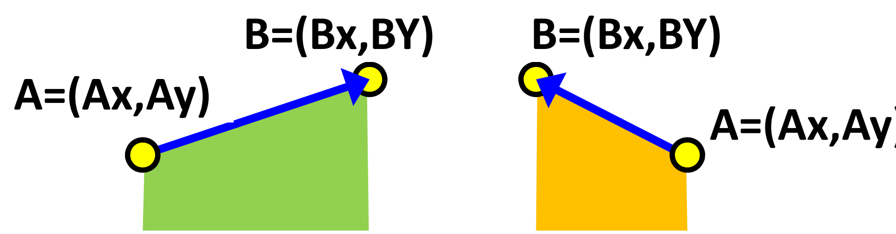
Choose boundary direction
consider forward and backward trapezoids

add all forward trapezoids area
subtract all backward trapezoids area

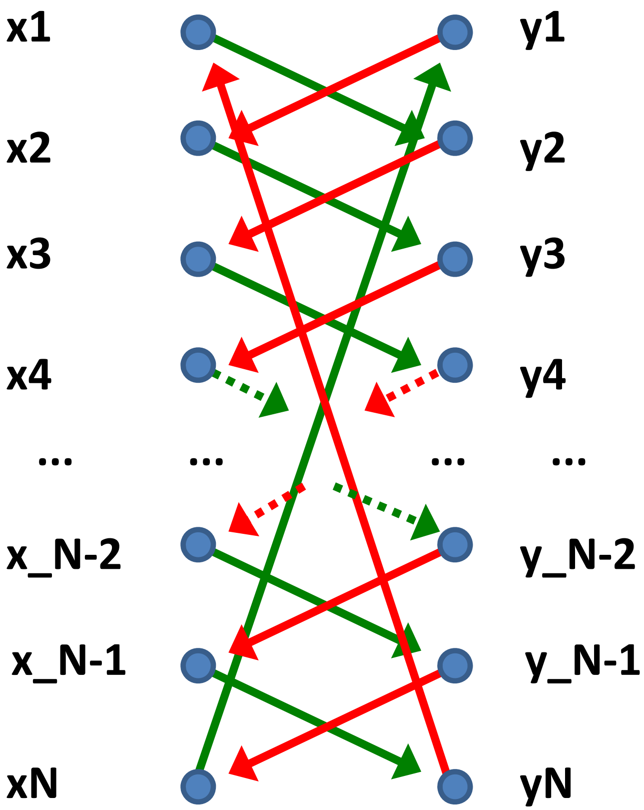
or equivalently

add all trapezoid areas
under assumption that the area of
backward trapezoids is negative

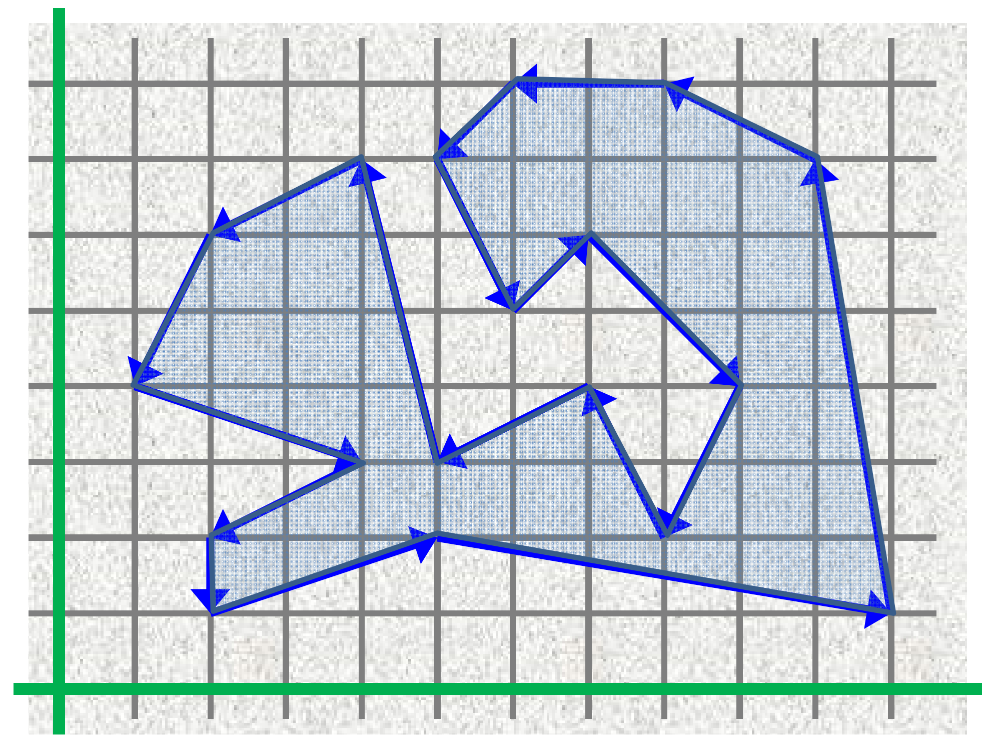




Trapezoid area $|(Ay+By)*(Bx-Ax)| / 2$



Simple polygon
(No two of its non-adjacent boundary segments touch or intersect each other)

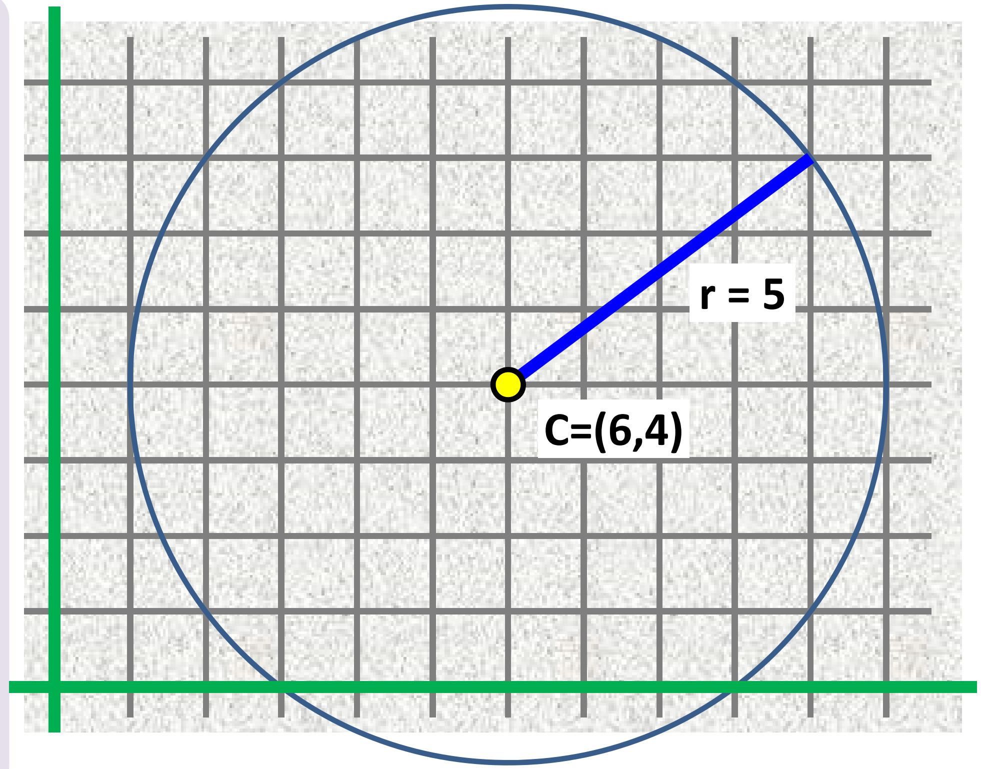


Area: Shoelace formula

$$\frac{1}{2} \left(x_1 y_2 + x_2 y_3 + \ldots + x_{N-1} y_N + x_N y_1 - x_2 y_1 - x_3 y_2 - \ldots - x_N y_{N-1} - x_1 y_N \right)$$

Circle equation

$(Cx - x)^2 + (Cy - y)^2 = r^2$



Circle tangent in point T

Circle eq: $(Cx - x)^2 + (Cy - y)^2 = r^2$

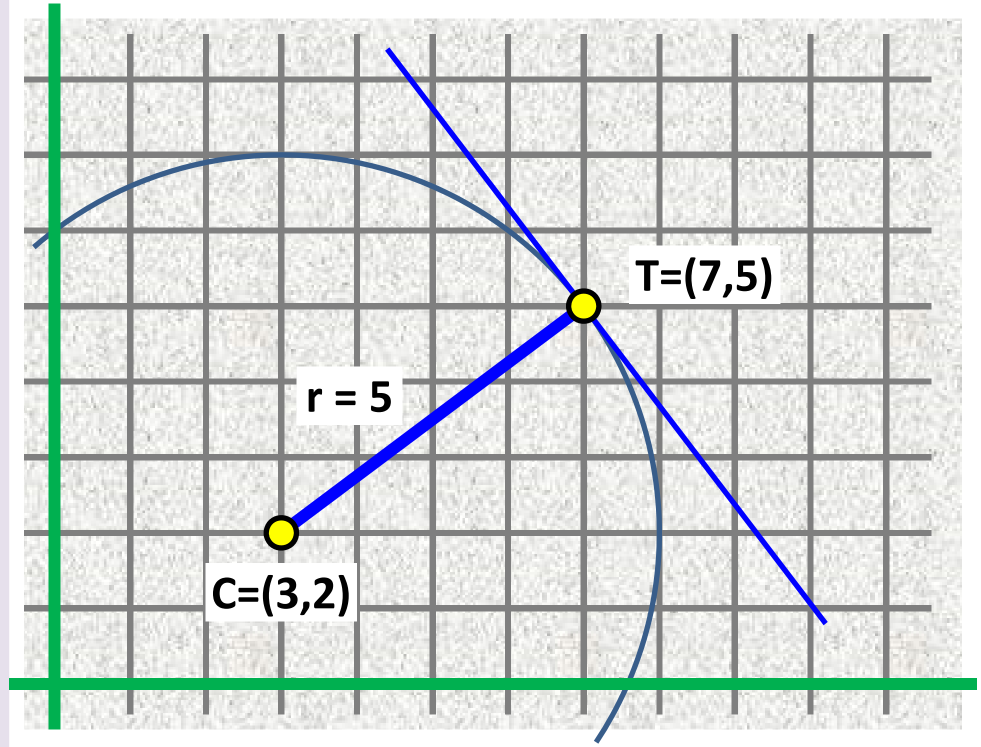
tangent line equation

$(Tx - Cx)(x - Cx) + (Ty - Cy)(y - Cy) = r^2$

tangent line equation

$ax + by + c = 0$

$a = Tx - Cx$
$b = Ty - Cy$
$c = Cx^2 + Cy^2 - r^2 - Cx \cdot Tx - Cy \cdot Ty$



tangent line equation,

$(7-3)(x-3) + (5-2)(y-2) = 25$
$4x - 12 + 3y - 6 = 25$
$4x + 3y - 43 = 0$

Polar of a point T wrt a circle

Polar line connects points T' and T''.
Lines TT' and TT'' are tangent lines
to the given circle

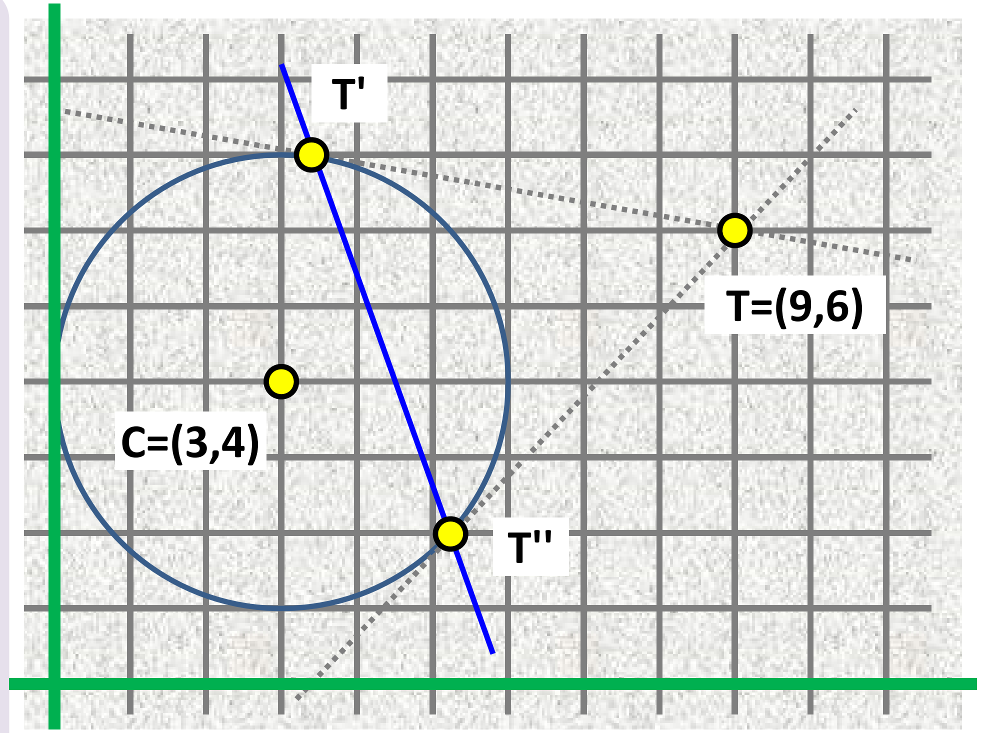
Circle eq: $(Cx - x)^2 + (Cy - y)^2 = r^2$

polar line equation

$$(Tx - Cx)(x - Cx) + (Ty - Cy)(y - Cy) = r^2$$

polar line equation
$ax + by + c = 0$

$a = Tx - Cx$
$b = Ty - Cy$
$c = Cx^2 + Cy^2 - r^2 - Cx \cdot Tx - Cy \cdot Ty$



polar line equation
wrt circle $(3 - x)^2 + (4 - y)^2 = 3^2$
T = (9, 6)

$$6x + 2y + 9 + 16 - 9 - 27 - 24 = 0$$
$$6x + 2y - 35 = 0$$