

DCGI

KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

DUALITY AND APPLICATIONS OF ARRANGEMENTS

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<https://cw.felk.cvut.cz/doku.php/courses/a4m39vg/start>

Based on [Berg], [Mount], and [Goswami]

Version from 5.2.2017

Talk overview

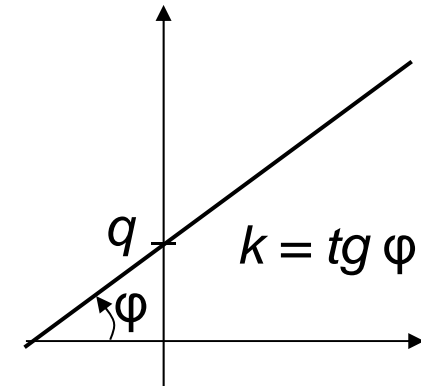
- Duality
 1. Points and lines
 2. Line segments
 3. Polar duality (different points and lines)
 4. Convex hull using duality
- Applications of duality and arrangements



1. Duality of lines and points in the plane

- Points and lines - both have 2 parameters:

- Points – coords x and y
- Lines – slope k and y -intercept q
 $y = kx + q$



- We can simply **map** points and lines 1:1
- Many mappings exist – it depends on the context



Why to use duality?

Some reasons why to use duality:

- Transforming a problem to dual plane may give a **new view on the problem**
- Looking from a different angle may **give the insight** needed to solve it
- Solution in dual space may be even simpler

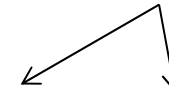


Definition of duality transformation D

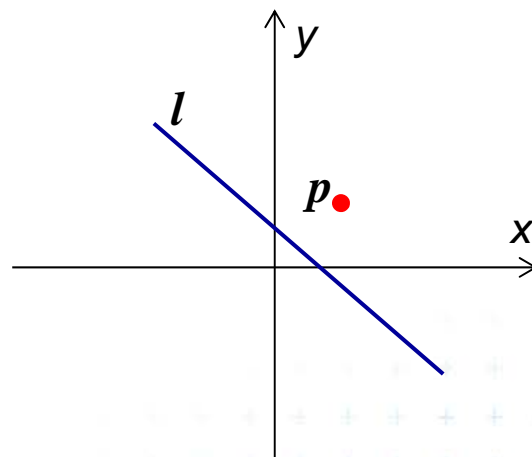
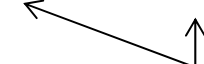
Let D be the duality transform:

- Point $p = [p_x, p_y]$ is transformed to line $D_p = p^* := (b = p_x a - p_y)$
- Line $l : (y = ax - b)$ is transformed to point $D_l = l^* := [a, b]$

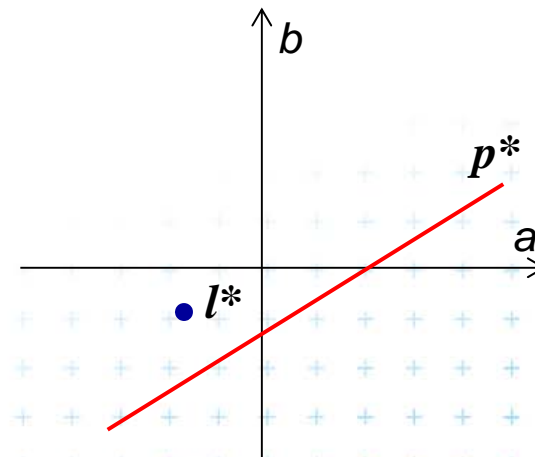
variables



constants



Primal plane (xy)



Dual plane (ab)



Example and more about duality D

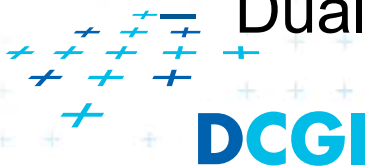
- Example:
line $y = 5x - 3$
can be represented as point $y^* = [5, 3]$

See the [applet]

- Duality D

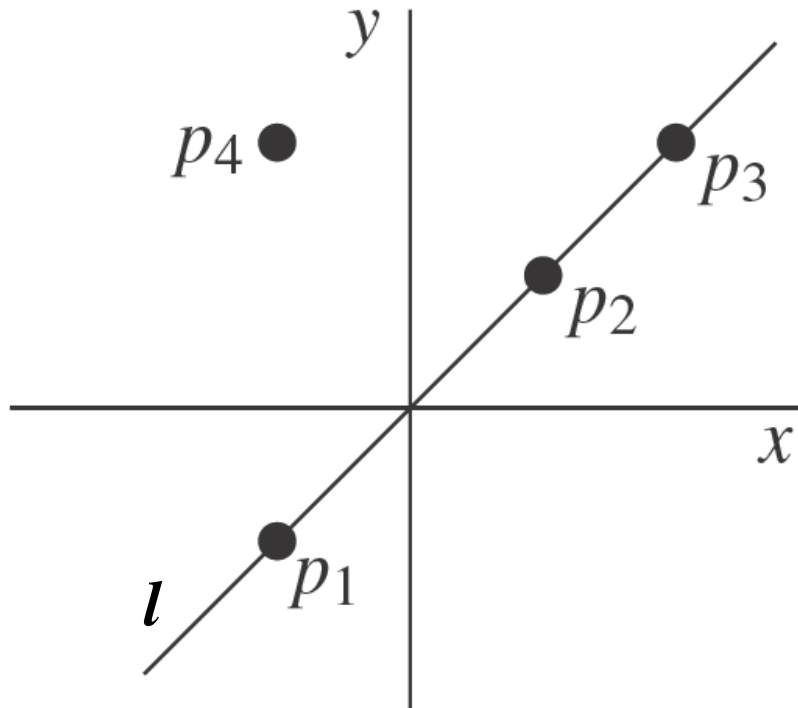
- is its own **inverse** $DD_p = p, DD_l = l$
- cannot represent **vertical lines**
=> Take vertical lines as special cases, use lexicographic order, or rotate the problem space slightly.

- Primal plane – plane with coordinates x, y
- Dual plane* – plane with coordinates a, b

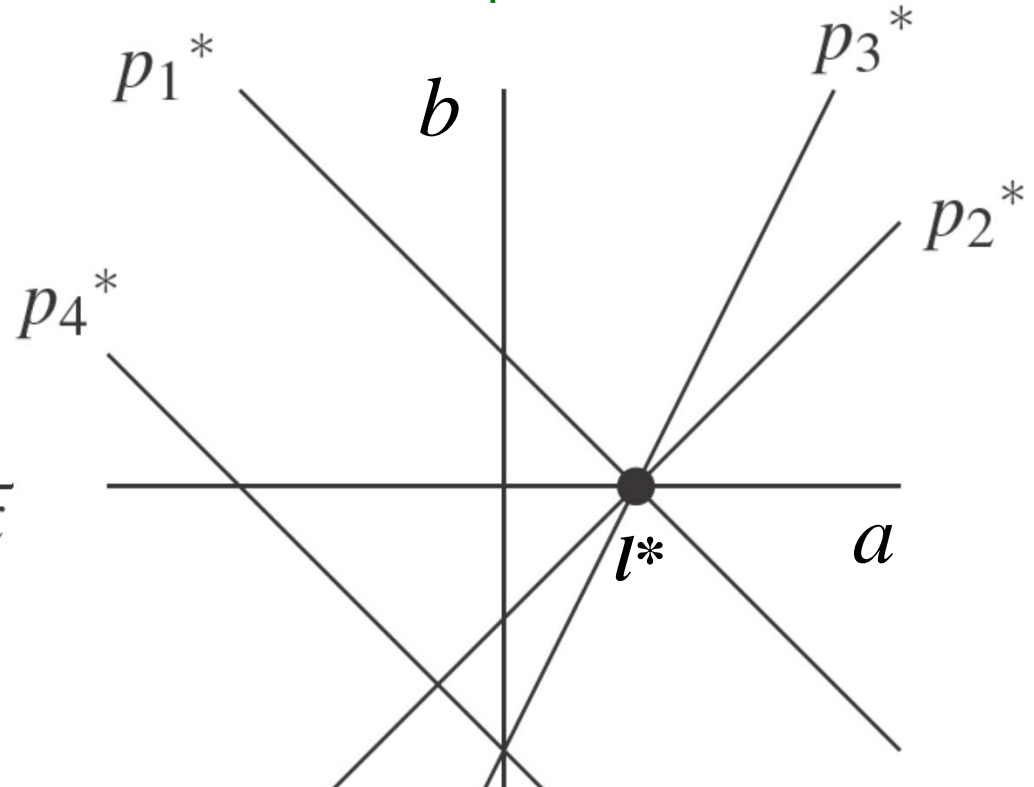


Duality of lines and points in the plane

Primal plane



Dual plane

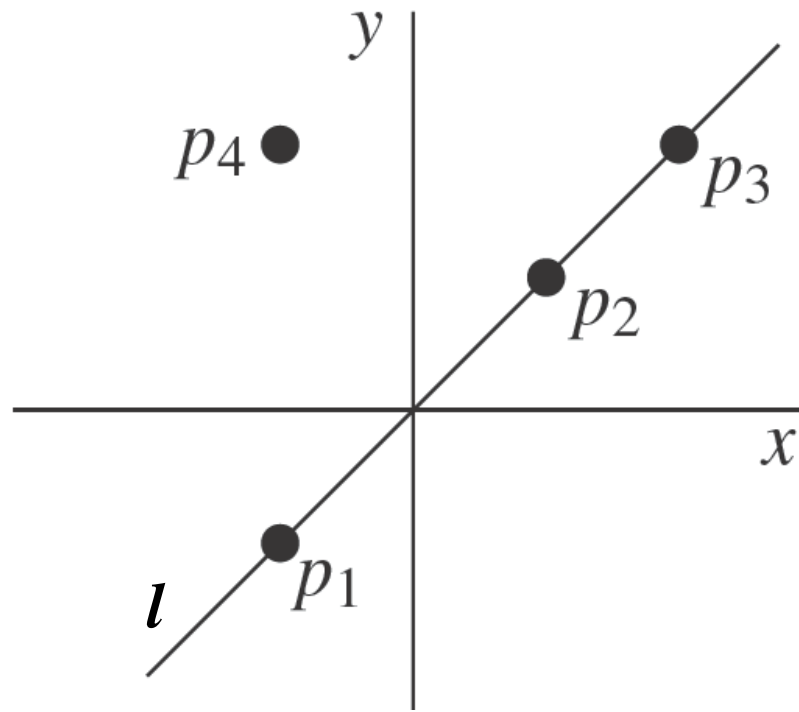


[Berg]



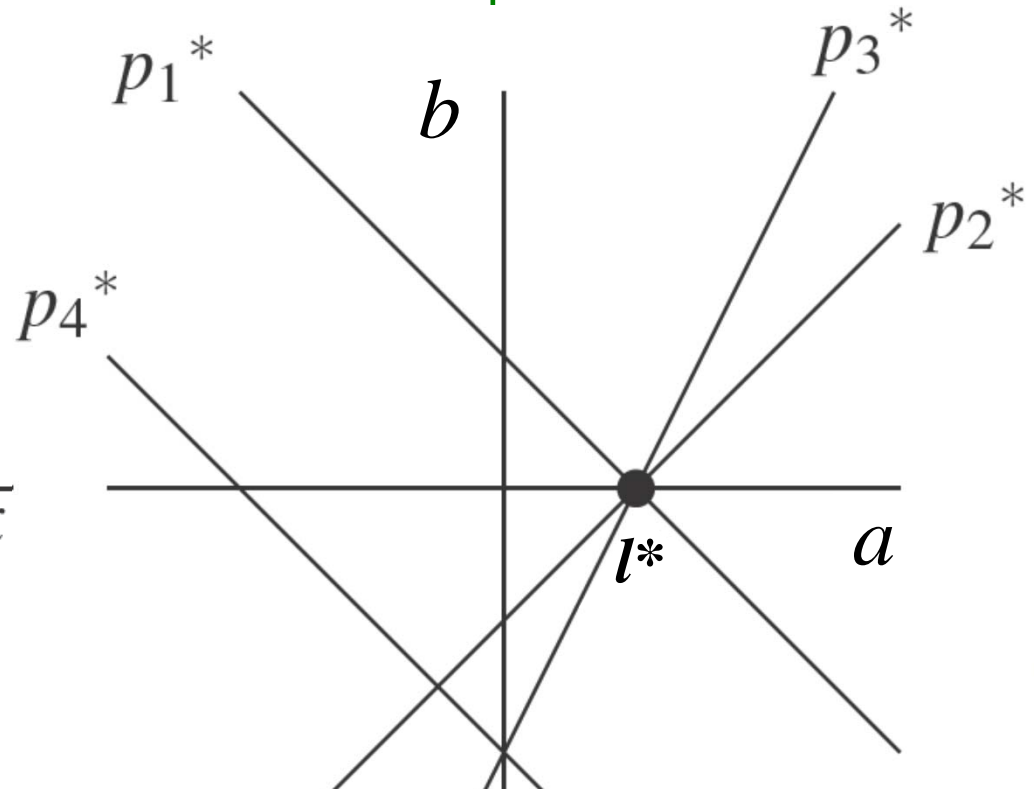
Duality of lines and points in the plane

Primal plane



point $p = [p_x, p_y]$

Dual plane

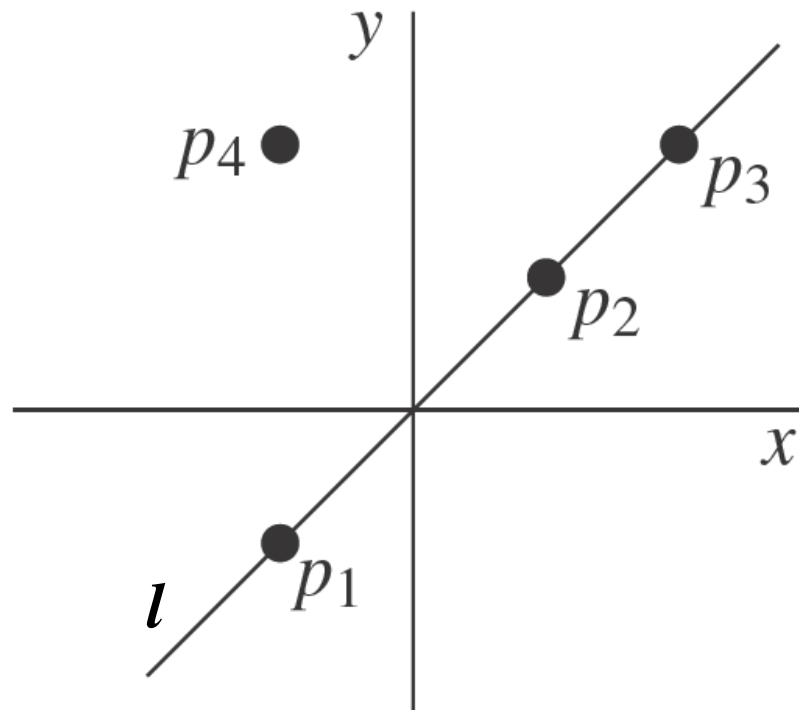


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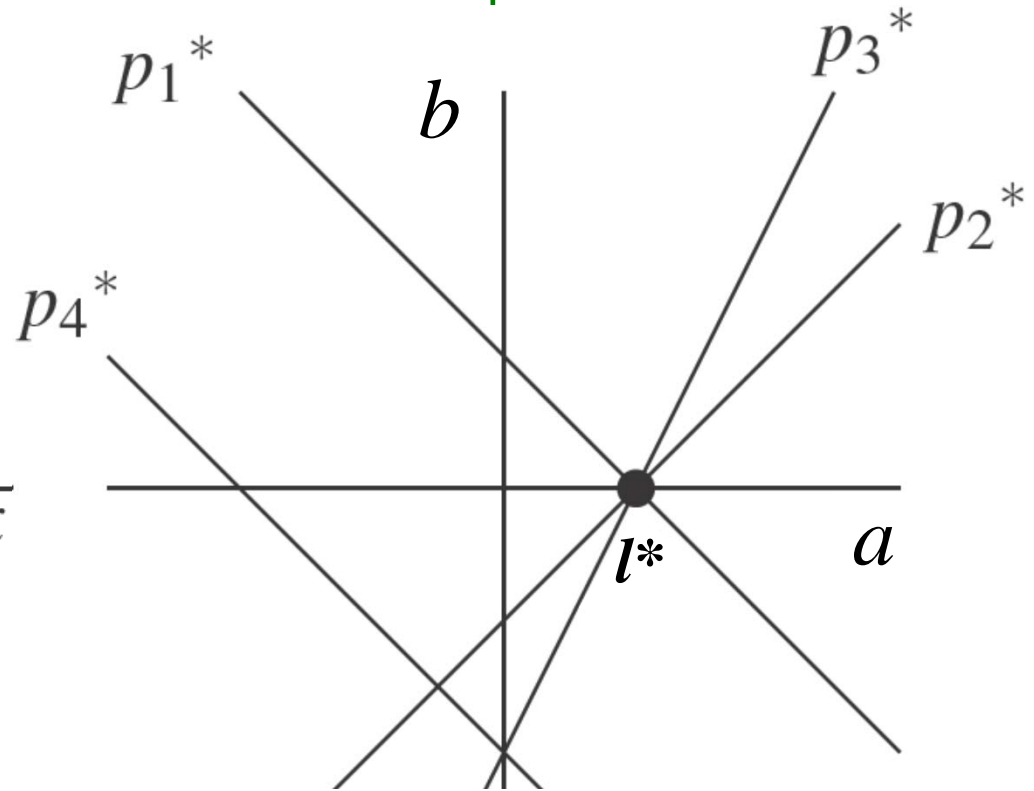
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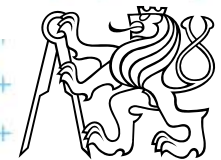
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Dual plane



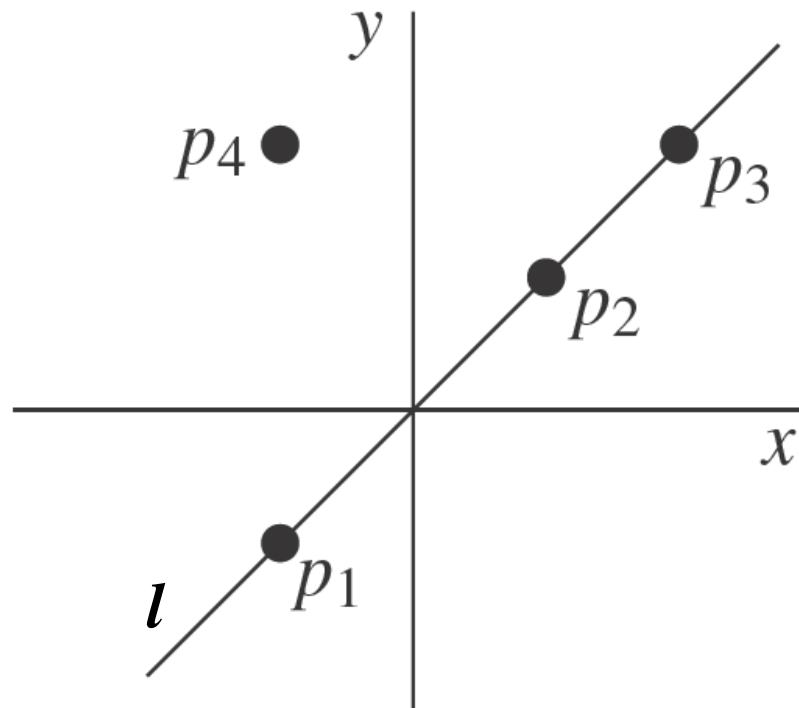
line $p^* := (b = p_x a - p_y)$

[Berg]



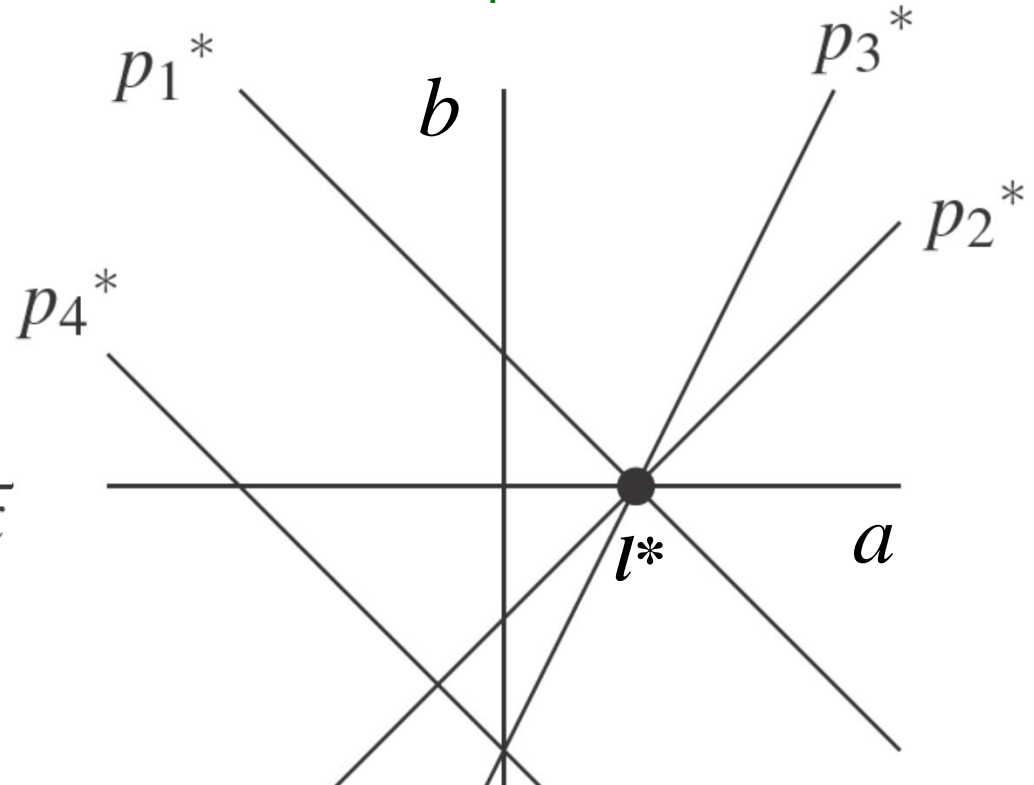
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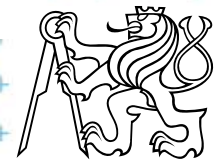
point $p = [p_x, p_y]$
 line $l := (y = ax + b)$

Dual plane



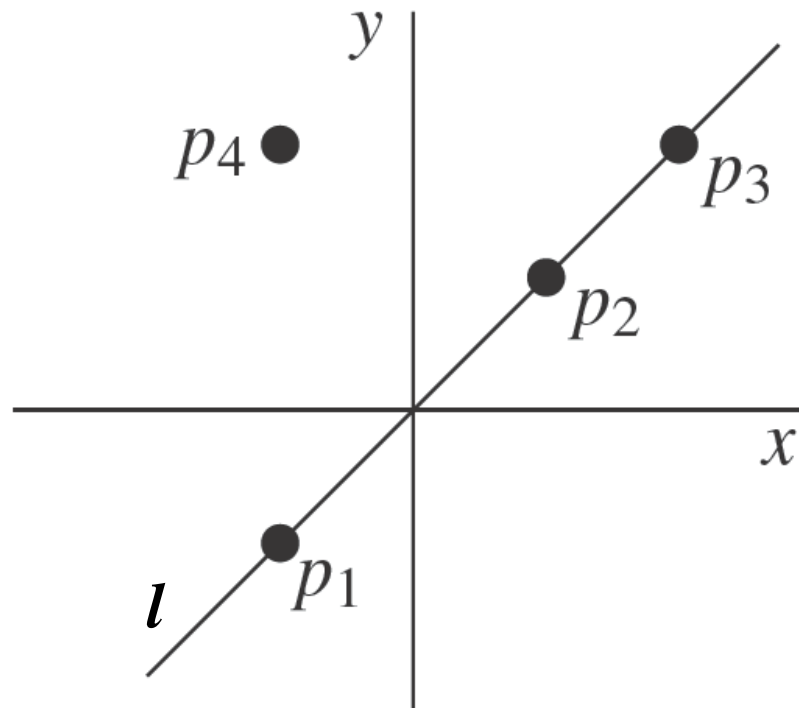
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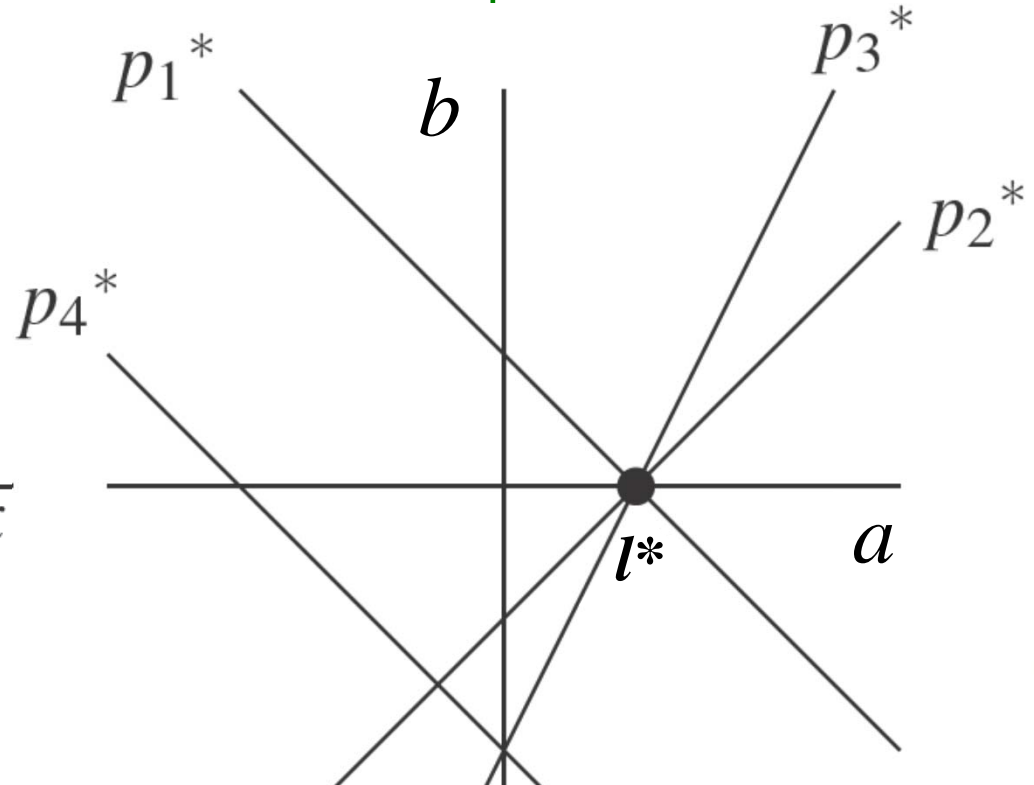
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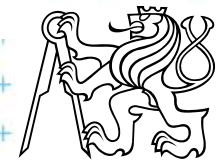
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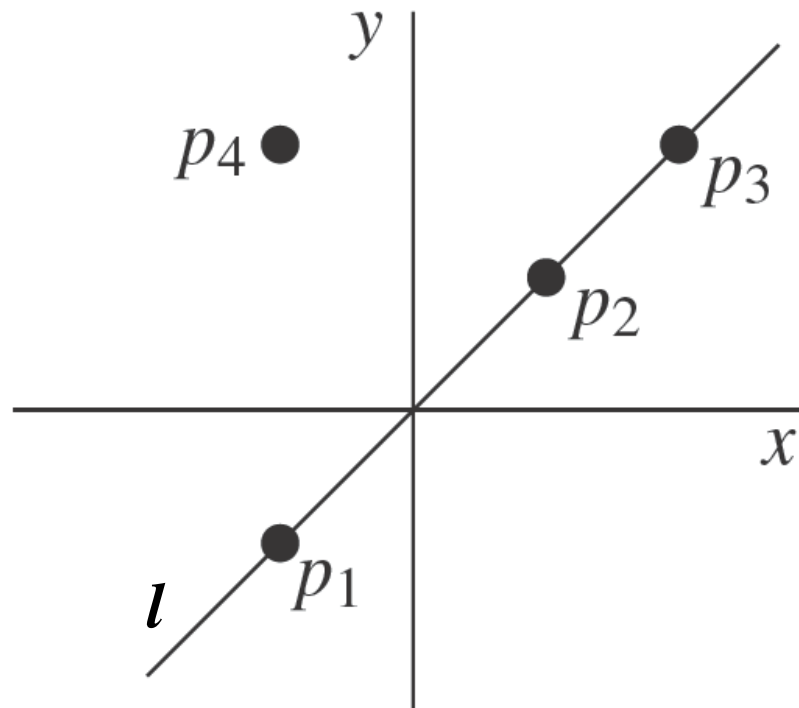
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 Point $l^* = [a, -b]$

[Berg]



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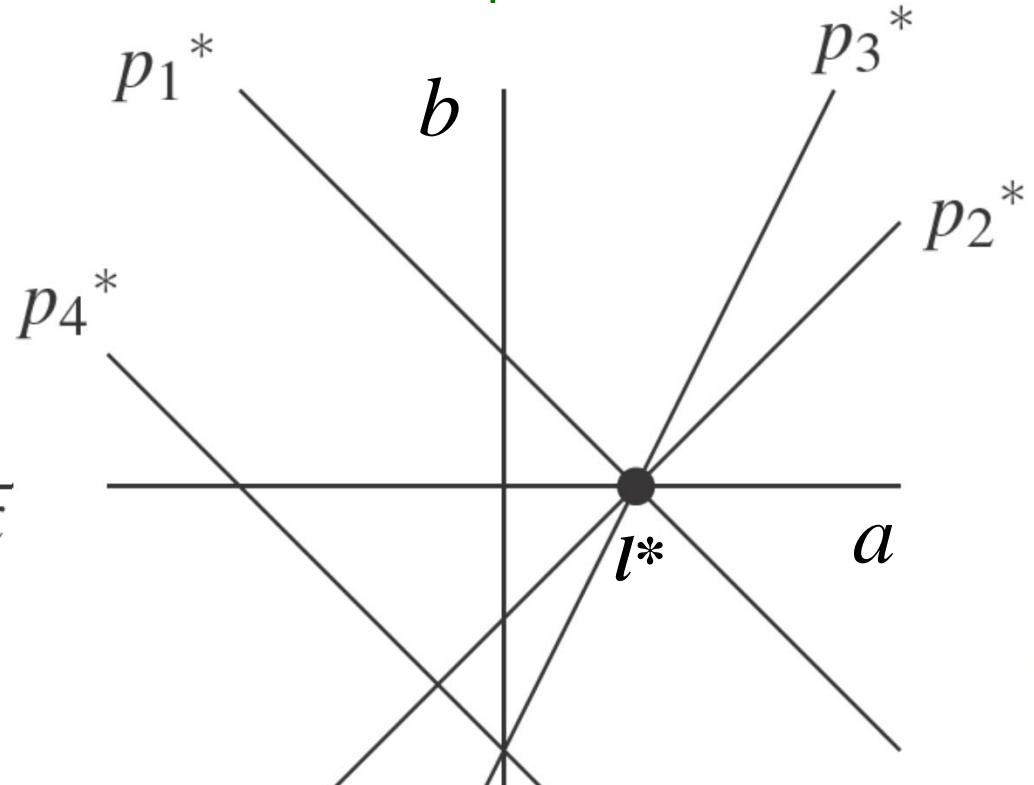
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Dual plane



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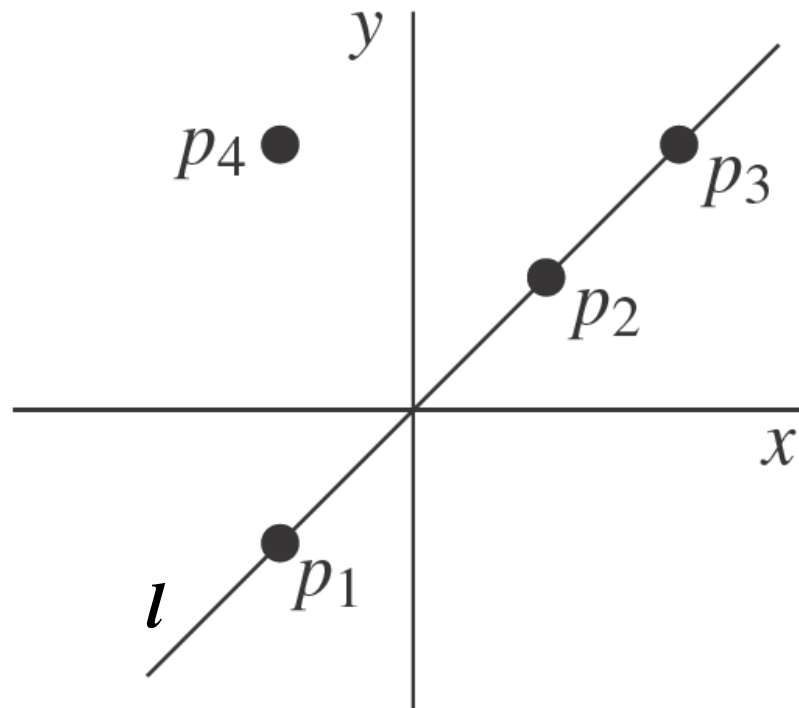
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Duality of lines and points in the plane

Primal plane

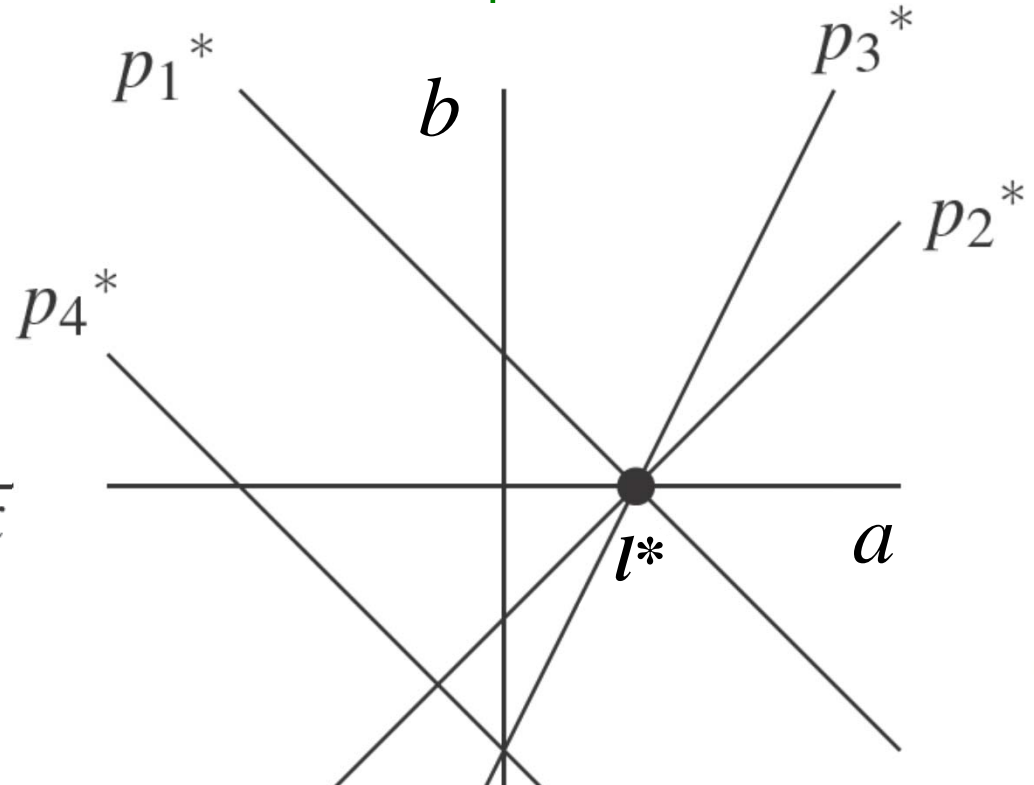


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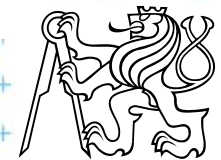
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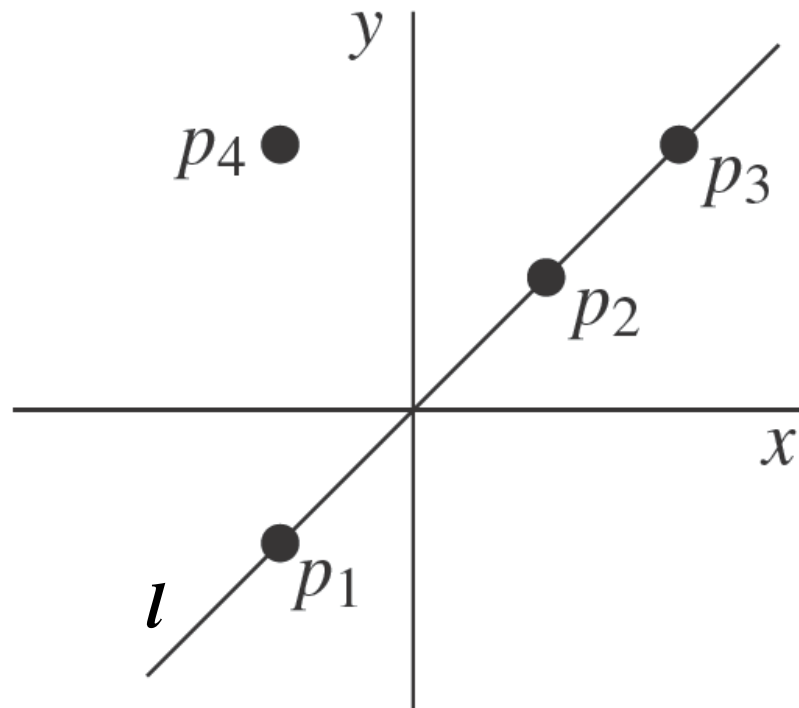
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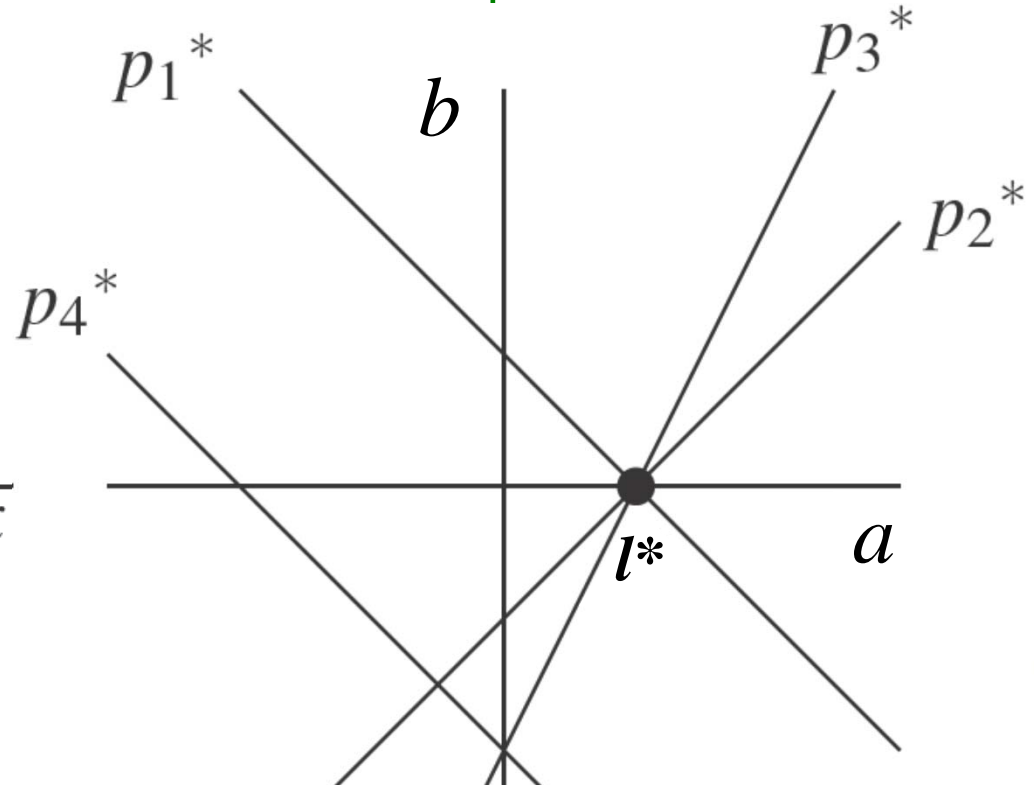


Duality of lines and points in the plane

Primal plane



Dual plane



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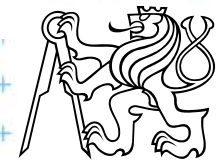
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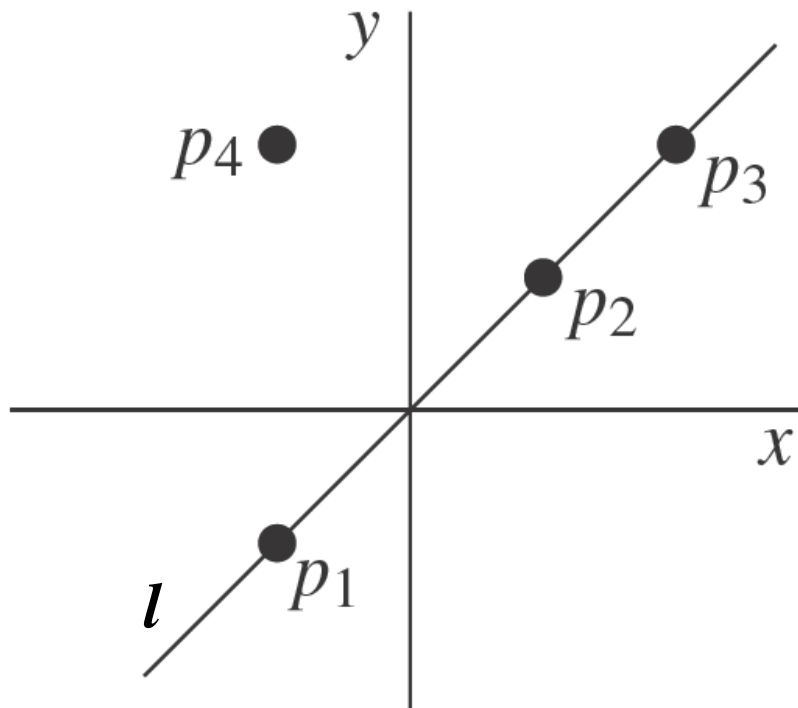
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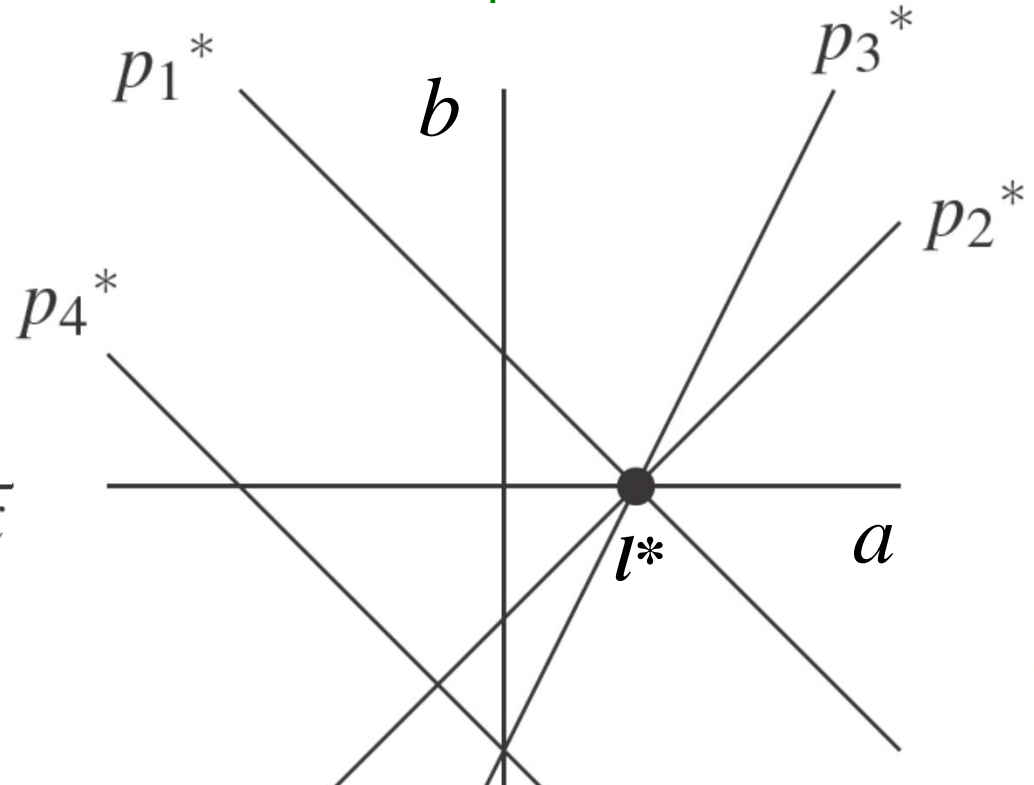


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Primal plane



Dual plane



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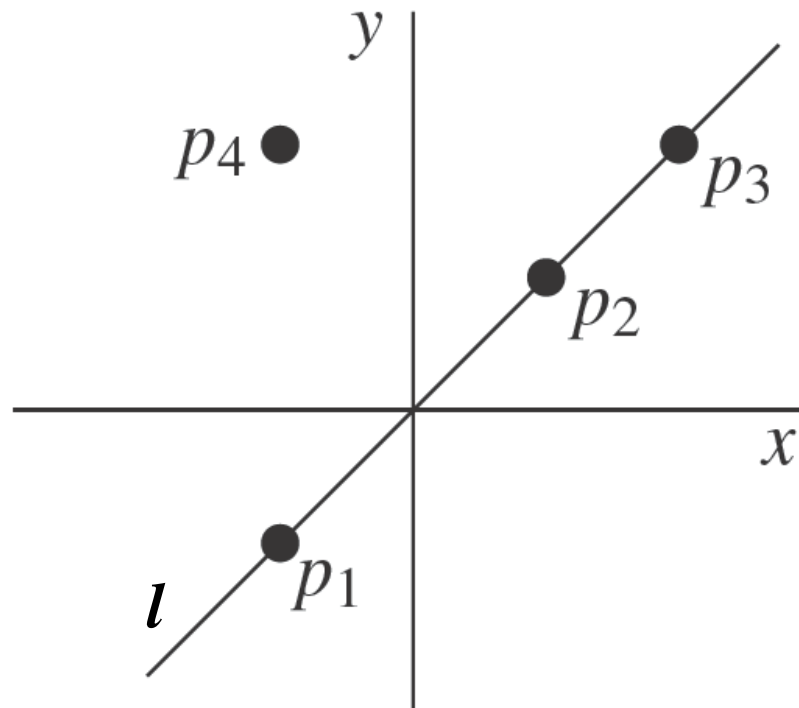
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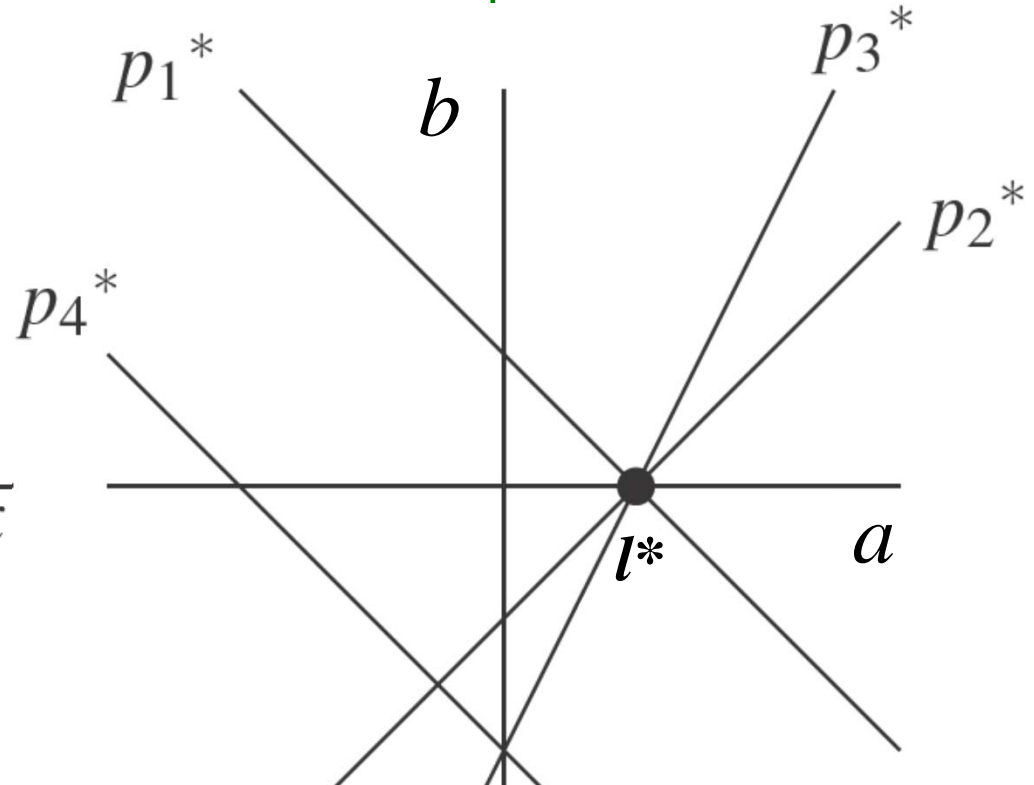


Duality of lines and points in the plane

Primal plane



Dual plane



point $p = [p_x, p_y]$

~~line $l := (y = ax + b)$~~

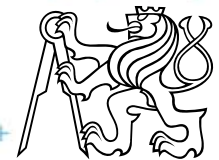
line $l := (y = ax - b)$

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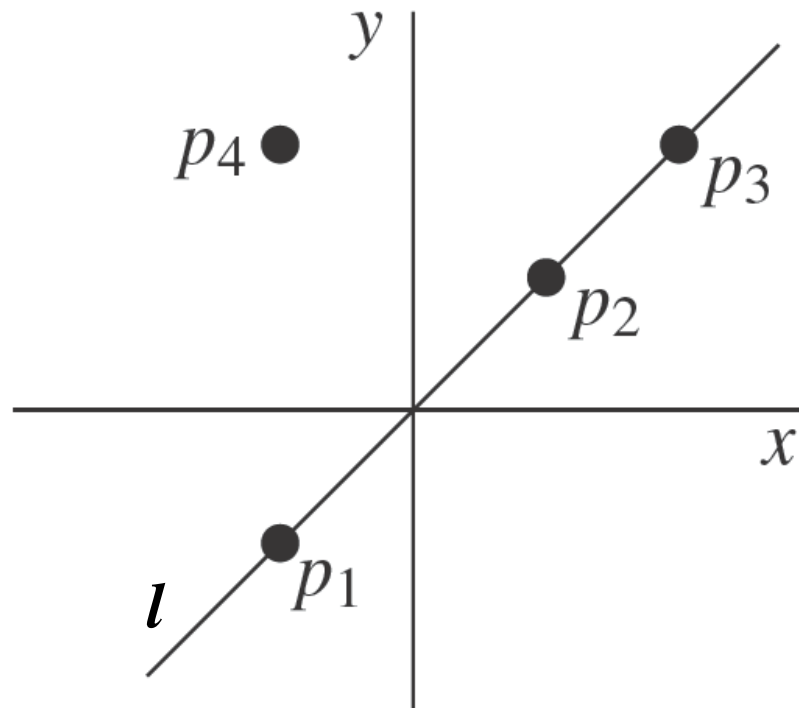
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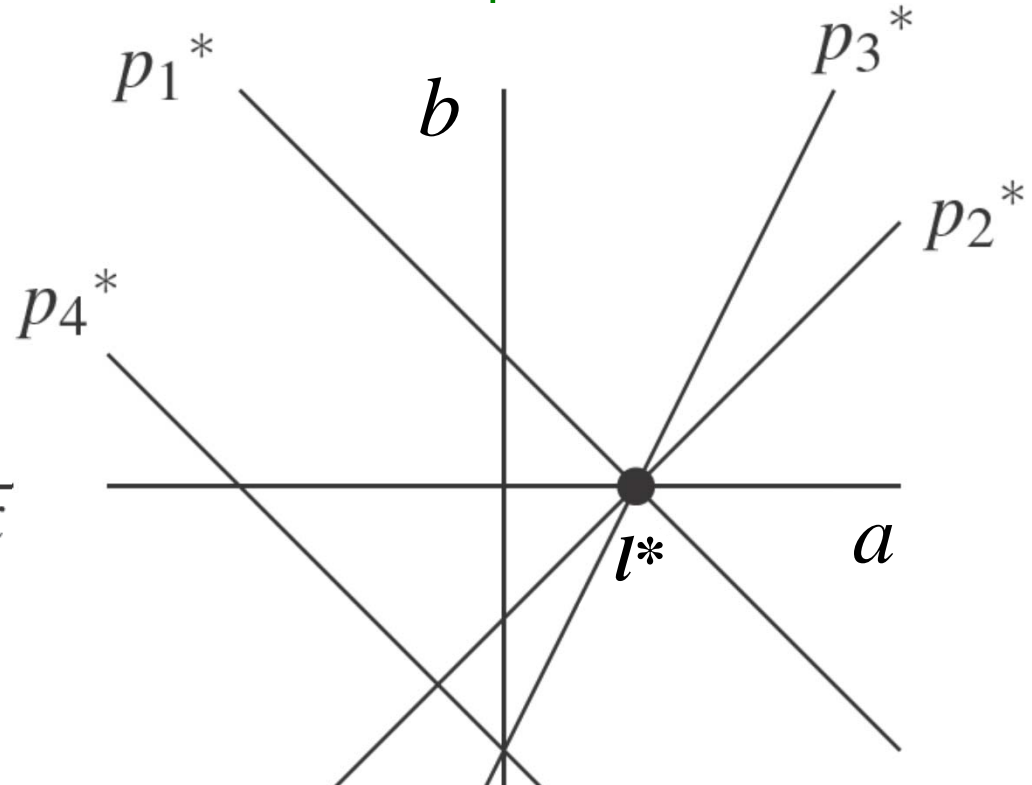


Duality of lines and points in the plane

Primal plane



Dual plane



point $p = [p_x, p_y]$

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Point $l^* = [a, -b]$

Point $l^* = [a, b]$

[Berg]

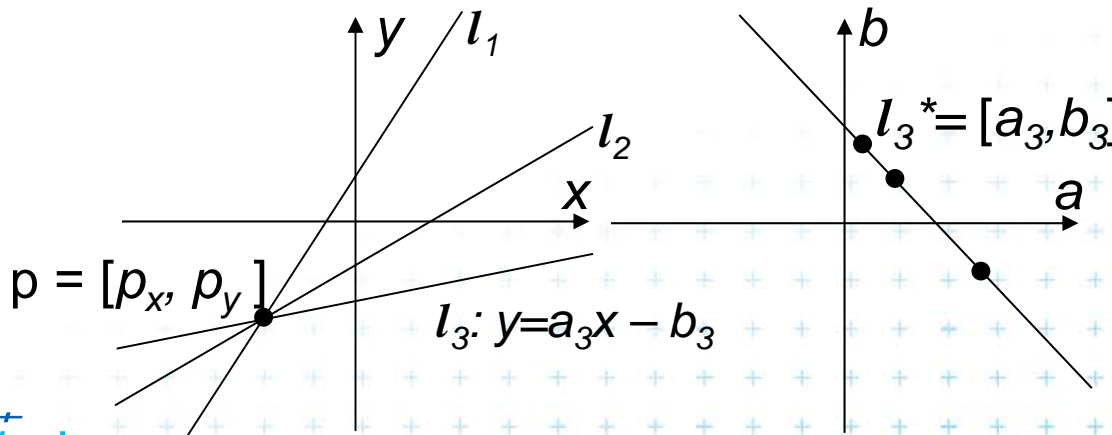
Same form => **It is convenient** to negate b in the line equation



Why is b negated in the line equation?

- In primal plane, consider
 - point $p = [p_x, p_y]$ and
 - set of non-vertical lines $l_i : y = a_i x - b_i$ passing through p satisfy the equation $p_y = a_i p_x - b_i$ (each line with different constants a_i, b_i)
- In dual plane, these lines transform to collinear points

$$\{ l_i^* = [a_i, b_i] : b_i = p_x a_i - p_y \}$$



Same form =>
It is convenient to negate b in the line equation



If b not negated in the line equation...

Lines l_i have equation $l_i : y = a_i x - b_i$ OR $y = a_i x + b_i$

Passing through point $p = [p_x, p_y]$:

- With minus

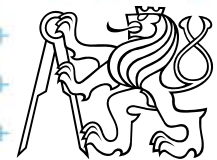
- equation l_i : $p_y = a_i p_x - b_i$

- dual points $\{l_i^* = [a_i, b_i] : b_i = p_x a_i - p_y\}$... same form

- With plus

- equation l_i : $p_y = a_i p_x + b_i$

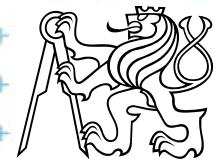
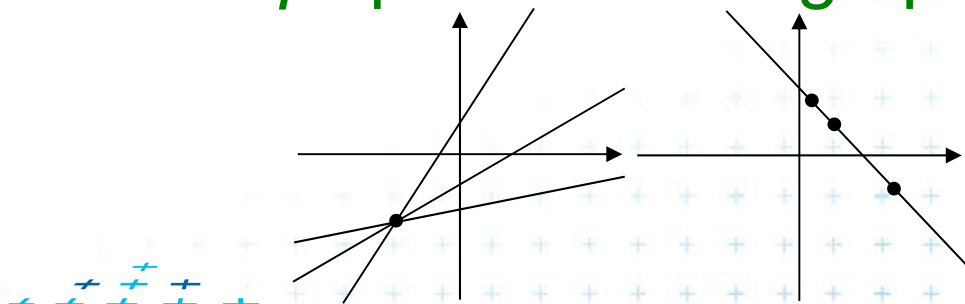
- dual $\{l_i^* = [a_i, b_i] : b_i = -p_x a_i + p_y\}$... different form



Properties of points and lines duality

Incidence is preserved

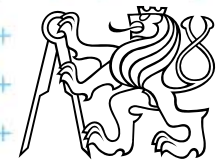
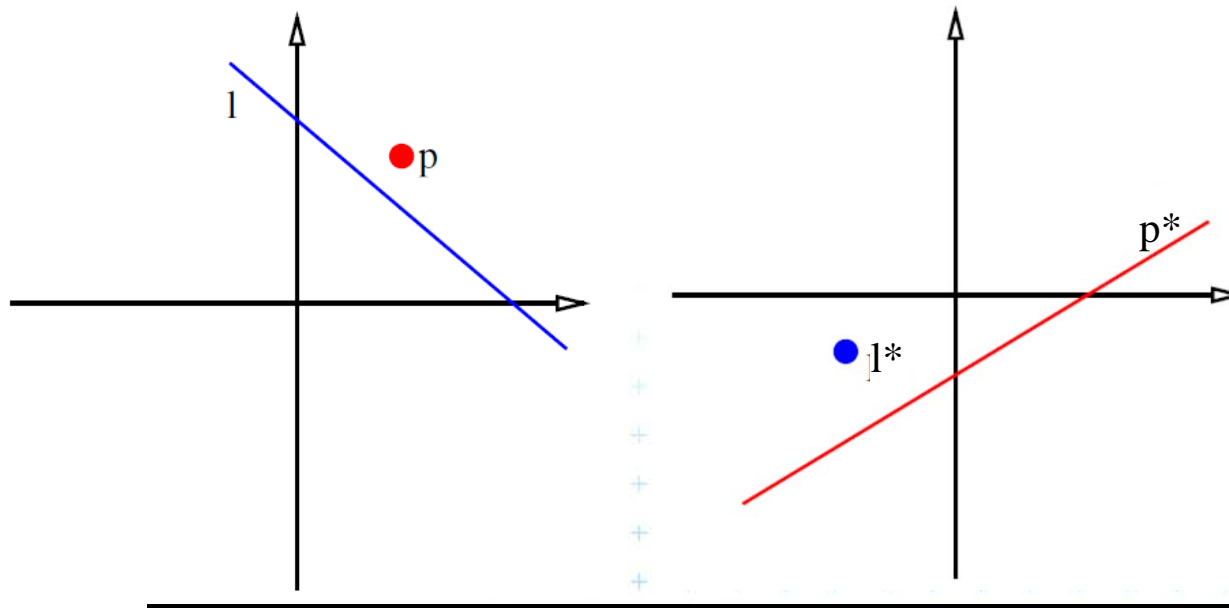
- Point p is incident to the line l in primal plane
iff
point l^* is incident to the line p^* in the dual plane.
- Lines l_1, l_2 intersects at point p
iff
line p^* passes through points l_1^*, l_2^* .



Properties of points and lines duality

But **order is reversed**

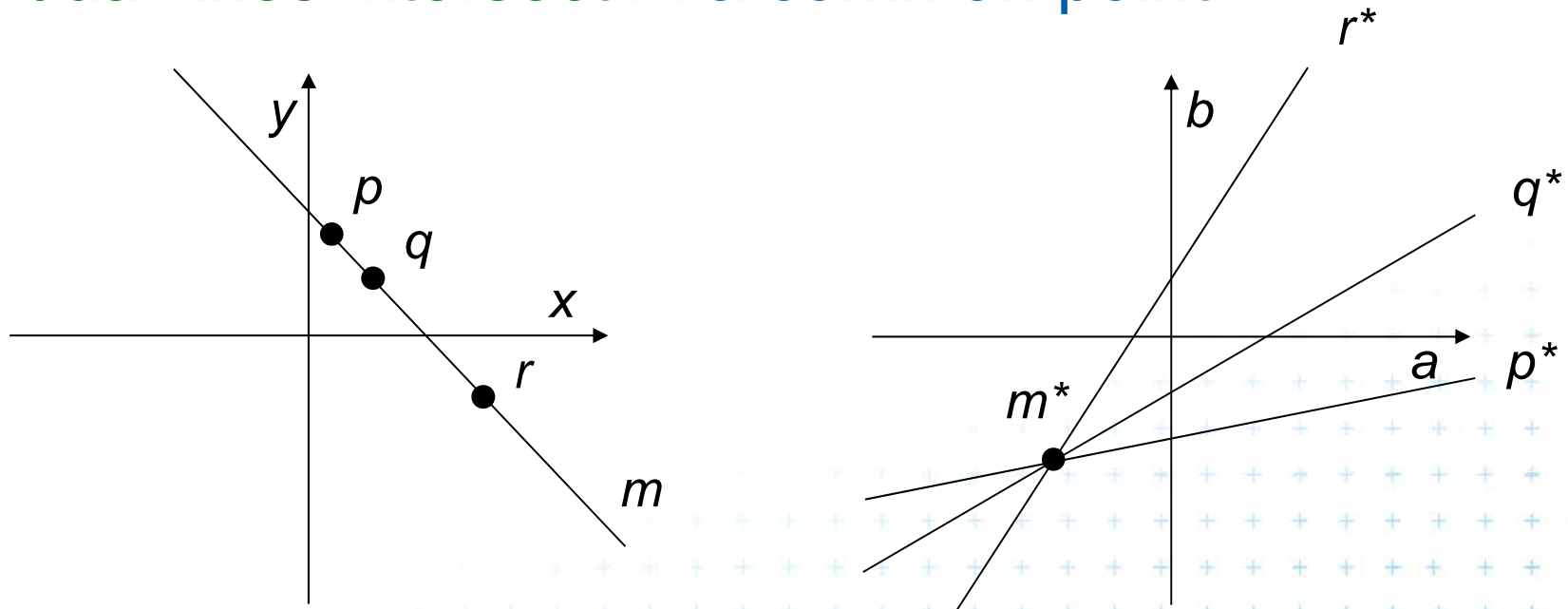
- Point p lies **above (below)** line l in the primal plane **iff** line p^* passes **below (above)** point l^* in the dual plane Or said order is preserved: ... **iff** Point l^* lies **above (below)** line p^*



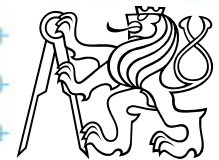
Properties of points and lines duality

Collinearity

- Points are **collinear** in the primal plane **iff** their dual lines intersect in a common point

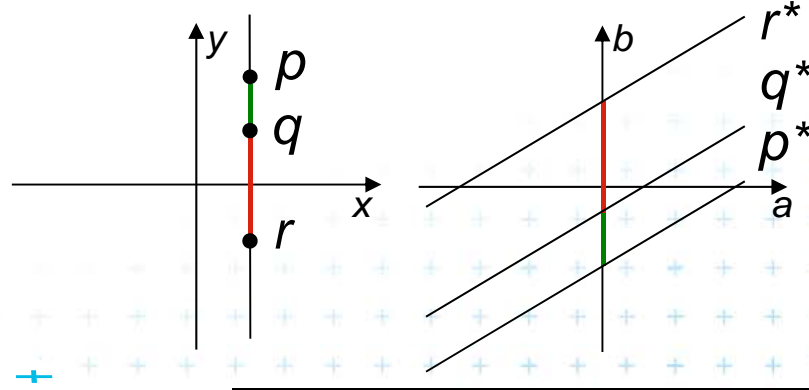


- This does not hold for points on vertical line



Handling of vertical lines

- Dual transform is undefined for vertical lines
 - Points with the same x coordinate dualize to lines with the same slope (parallel lines) and therefore
 - These dual lines do not intersect (as should for collinear points)
 - **Vertical line** through these points **does not dualize to an intersection point**
 - For detection of vertically collinear points use other method - $O(n)$ vertical lines $\rightarrow O(n^2)$ brute force 3|| lines s.



$\rightarrow O(n)$ after $O(n \log n)$ sorting by x

Vertical distances of such duals are "preserved". For $p_x = q_x$

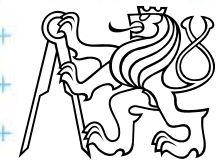
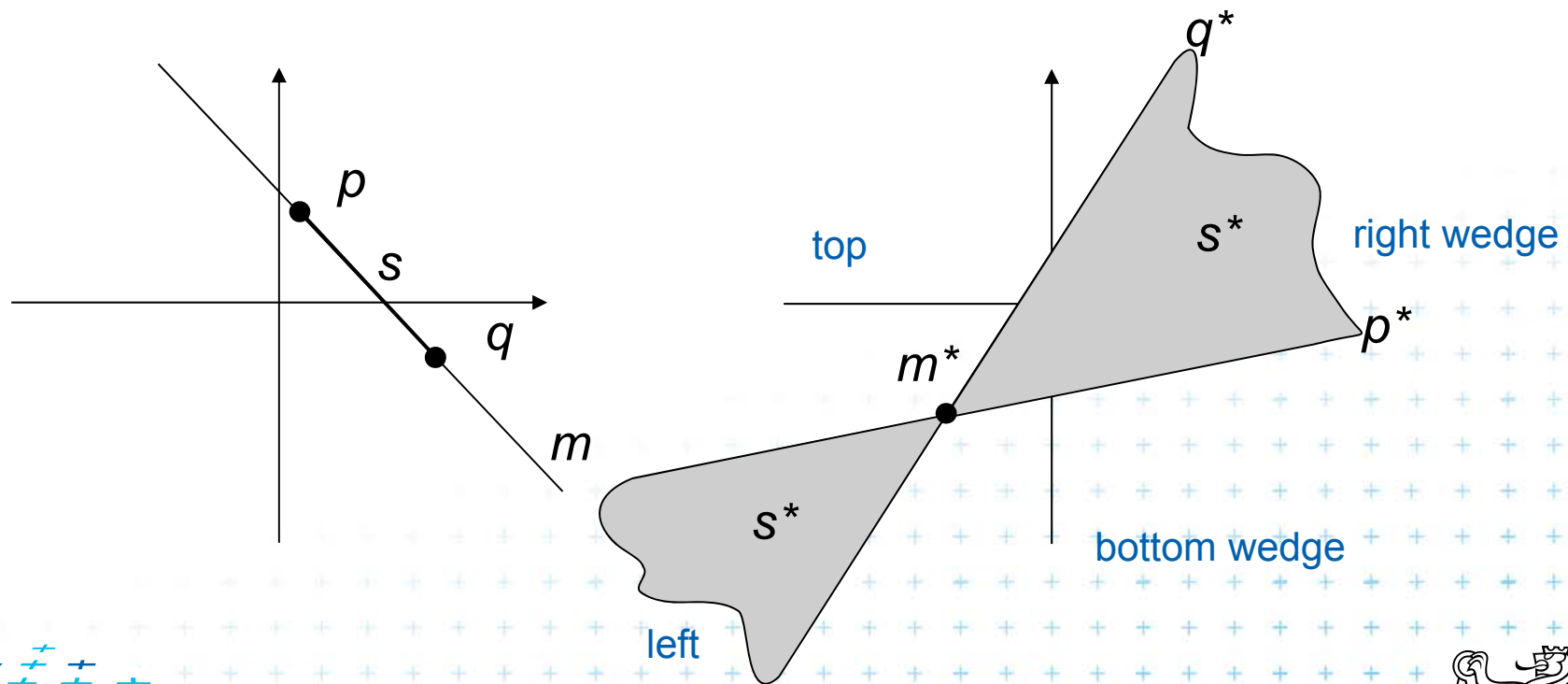
$$\text{vertDist}(q^*_b, p^*_b) = p_y - q_y$$



2. Duality of line segments

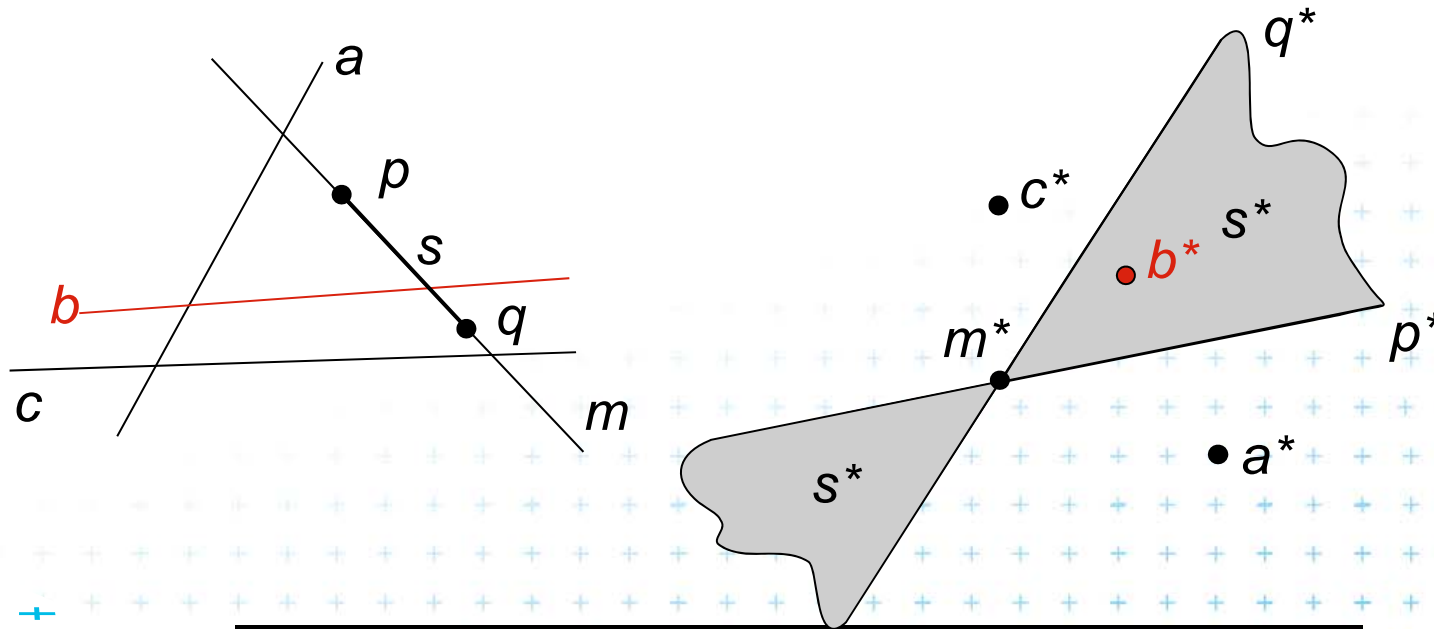
- Line segment s

- = set of collinear points $\xrightarrow{\text{dual}}$ set of lines passing one point
- union of these lines is a (left-right) **double wedge** s^*



Intersection of line and line segment

- Line b intersects line segment s
 - if point b^* lays in the double wedge s^* ,
i.e., between the duals p^*, q^* of segment endpoints p, q
 - point p lies above line b and q lies below line b
 - point b^* lies above line p^* and b^* lies below line q^*



3. Polar duality (Polarity)

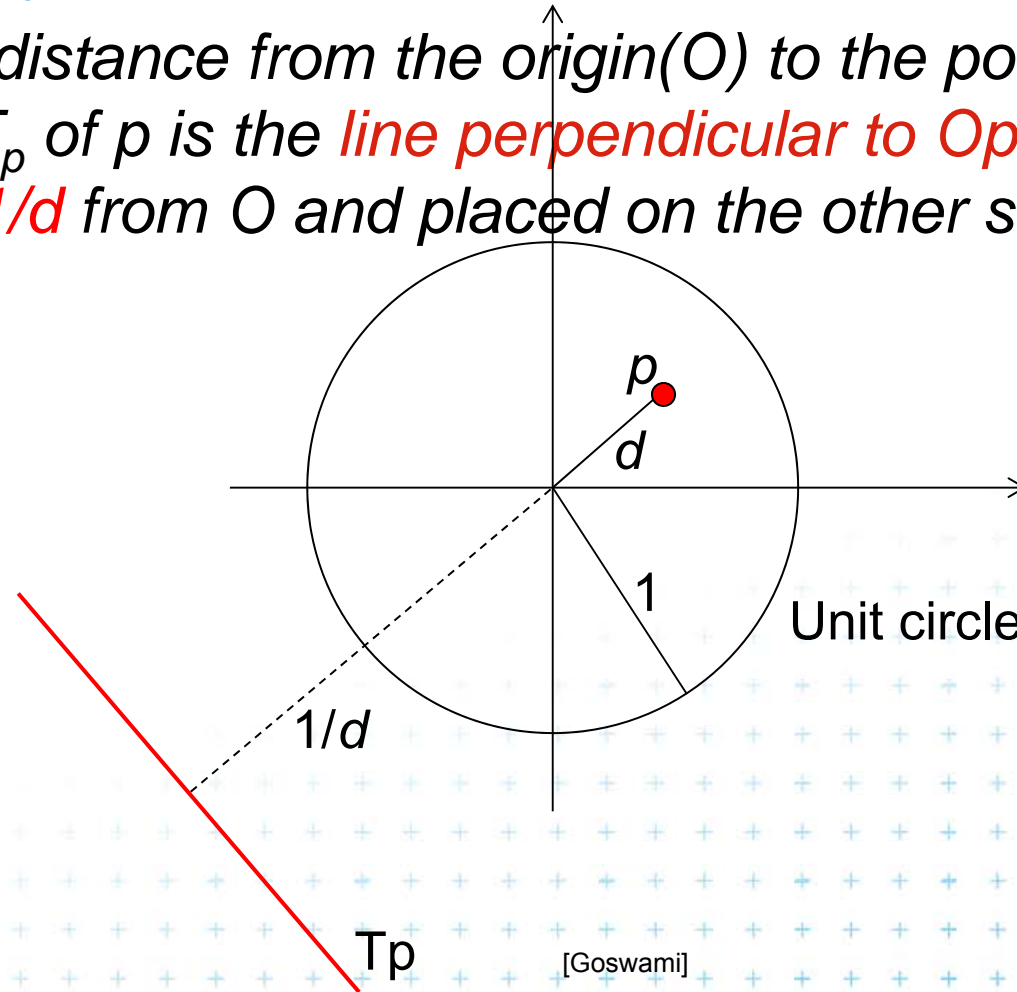
- Another example of **point-line duality**
- In 2D: Point $p = (p_x, p_y)$ in the primal plane corresponds to a line T_p with equation $ax + by = 1$ in the dual plane and vice versa $p_x x + p_y y = 1$
- In dD: Point p is taken as a radius-vector (starts in origin O). The **dot product** $(p \cdot x) = 1$ defines a **polar hyperplane** $p^* = T_p = \{ x \in R^d : (p \cdot x) = 1 \}$
- Used in theory of polytopes



Polar duality (Polarity)

- Geometrically in 2D, this means that

- if d is the distance from the origin(O) to the point p , the dual T_p of p is the **line perpendicular to Op** at distance $1/d$ from O and placed on the other side of O .



4. Convex hull using duality – definitions

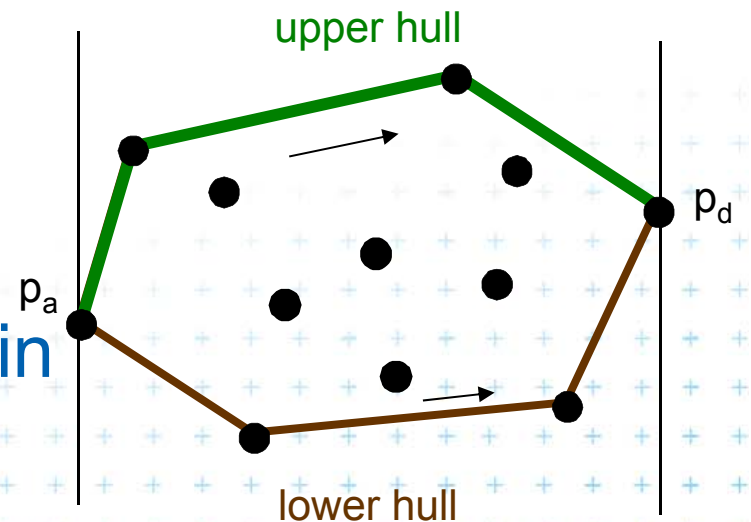
- An optimal algorithm
 - Let P be the given set of n points in the plane.
 - Let $p_a \in P$ be the point with smallest x-coordinate
 - Let $p_d \in P$ be the point with largest x-coordinate
- Both p_a and $p_d \in CH(P)$

Upper hull = CW polygonal chain

p_a, \dots, p_d along the hull

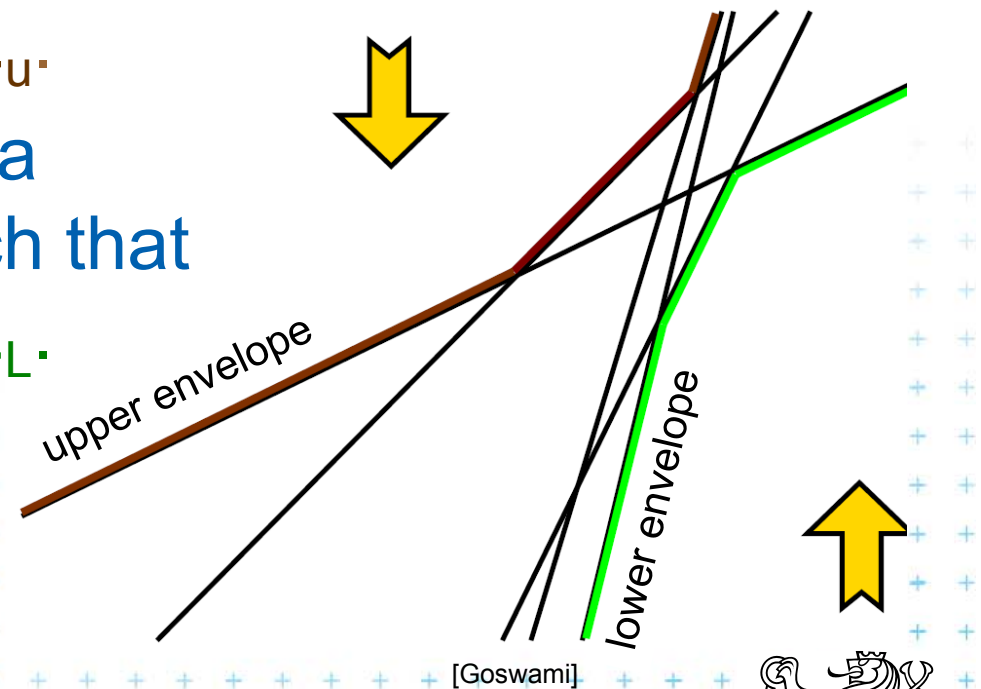
Lower hull = CCW polygonal chain

p_a, \dots, p_d along the hull

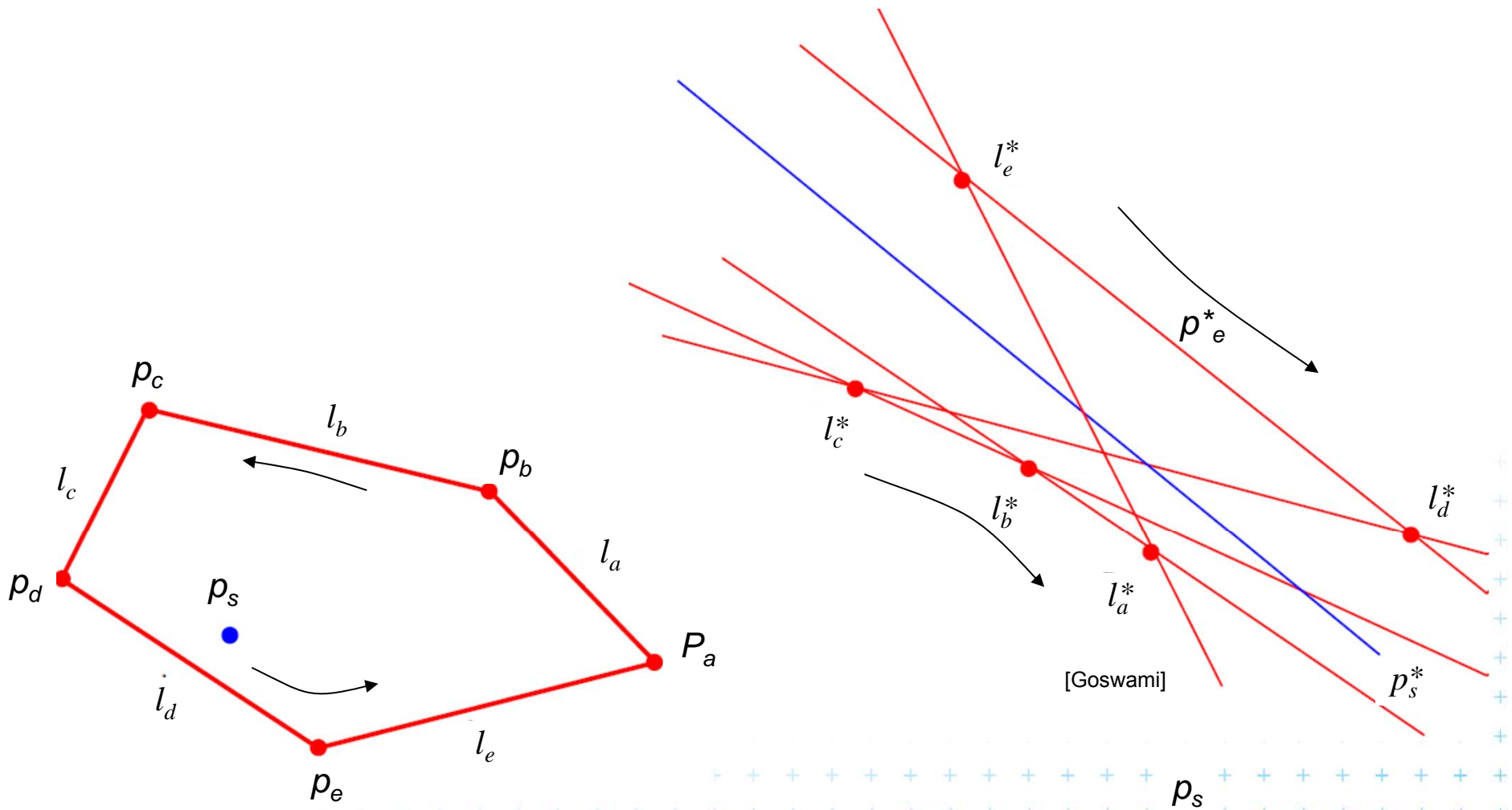


Definitions

- Let L be a set of lines in the plane
- The upper envelope is a polygonal chain E_u such that no line $l \in L$ is above E_u .
- The lower envelope is a polygonal chain E_L such that no line $l \in L$ is below E_L .

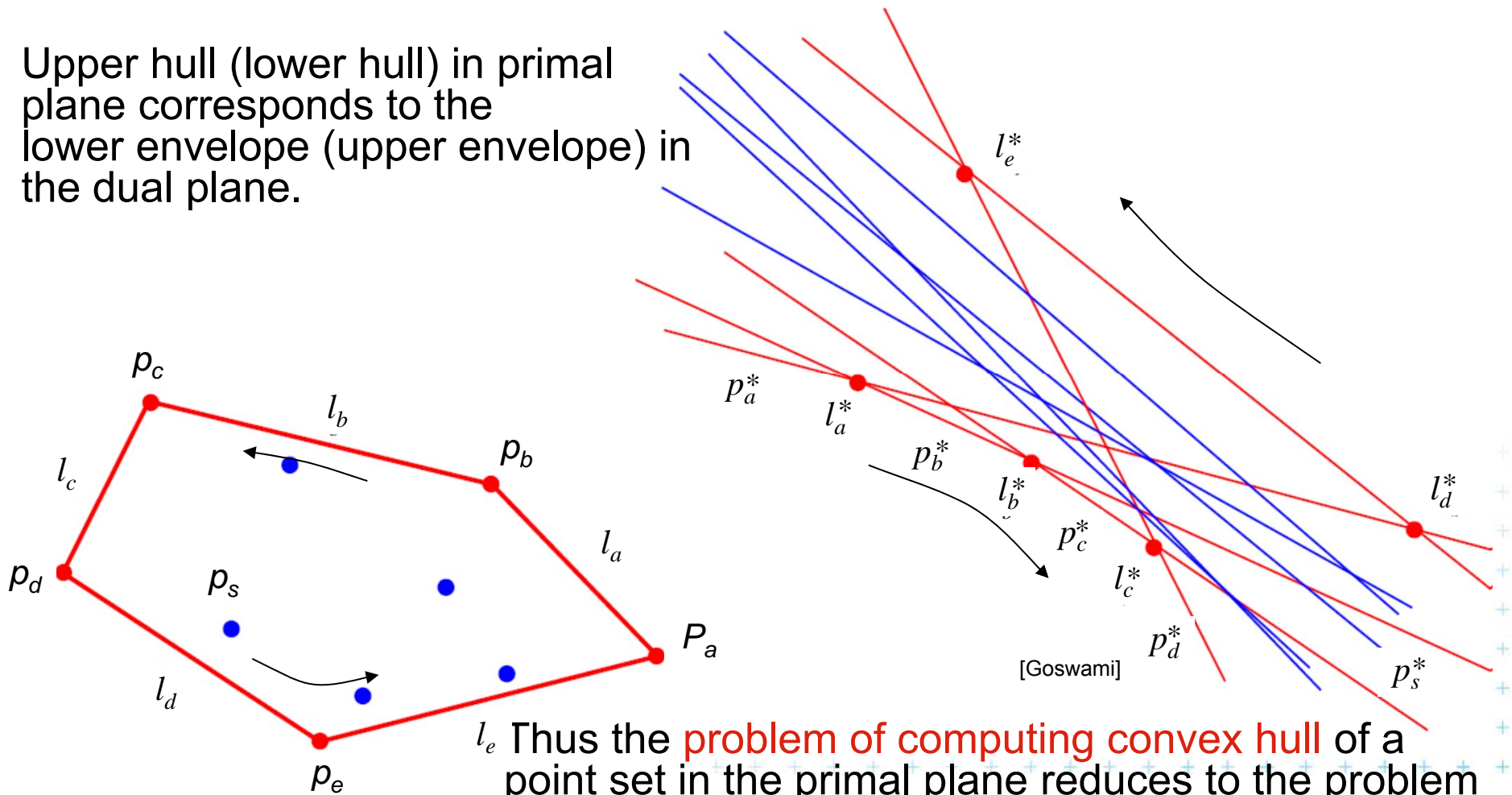


Connection between Hull and Envelope

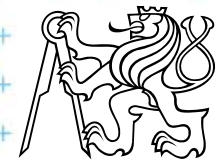


Connection between Hull and Envelope

Upper hull (lower hull) in primal plane corresponds to the lower envelope (upper envelope) in the dual plane.

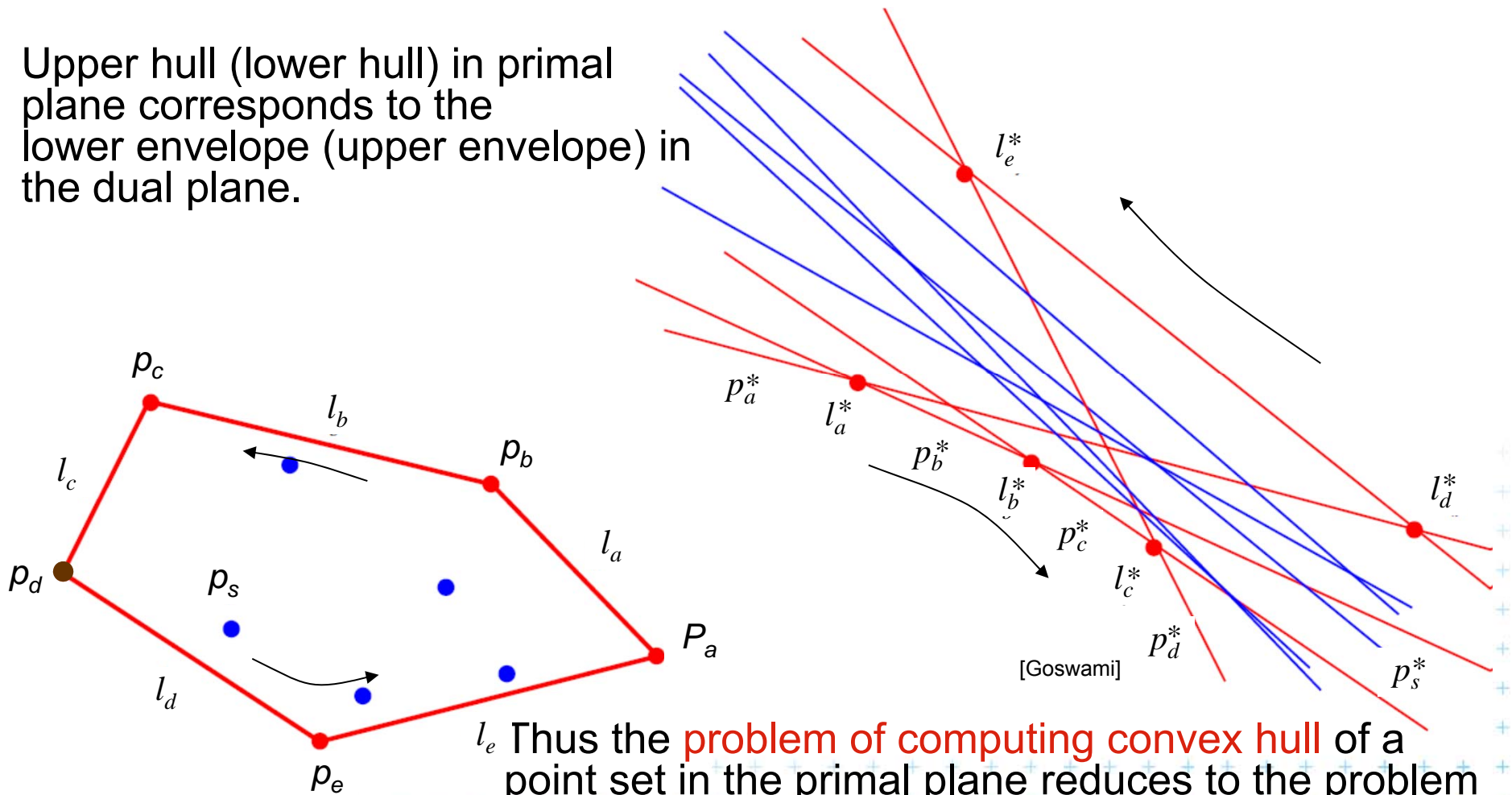


Thus the **problem of computing convex hull** of a point set in the primal plane reduces to the problem of computing **upper and lower envelopes** of the line set in the dual plane.



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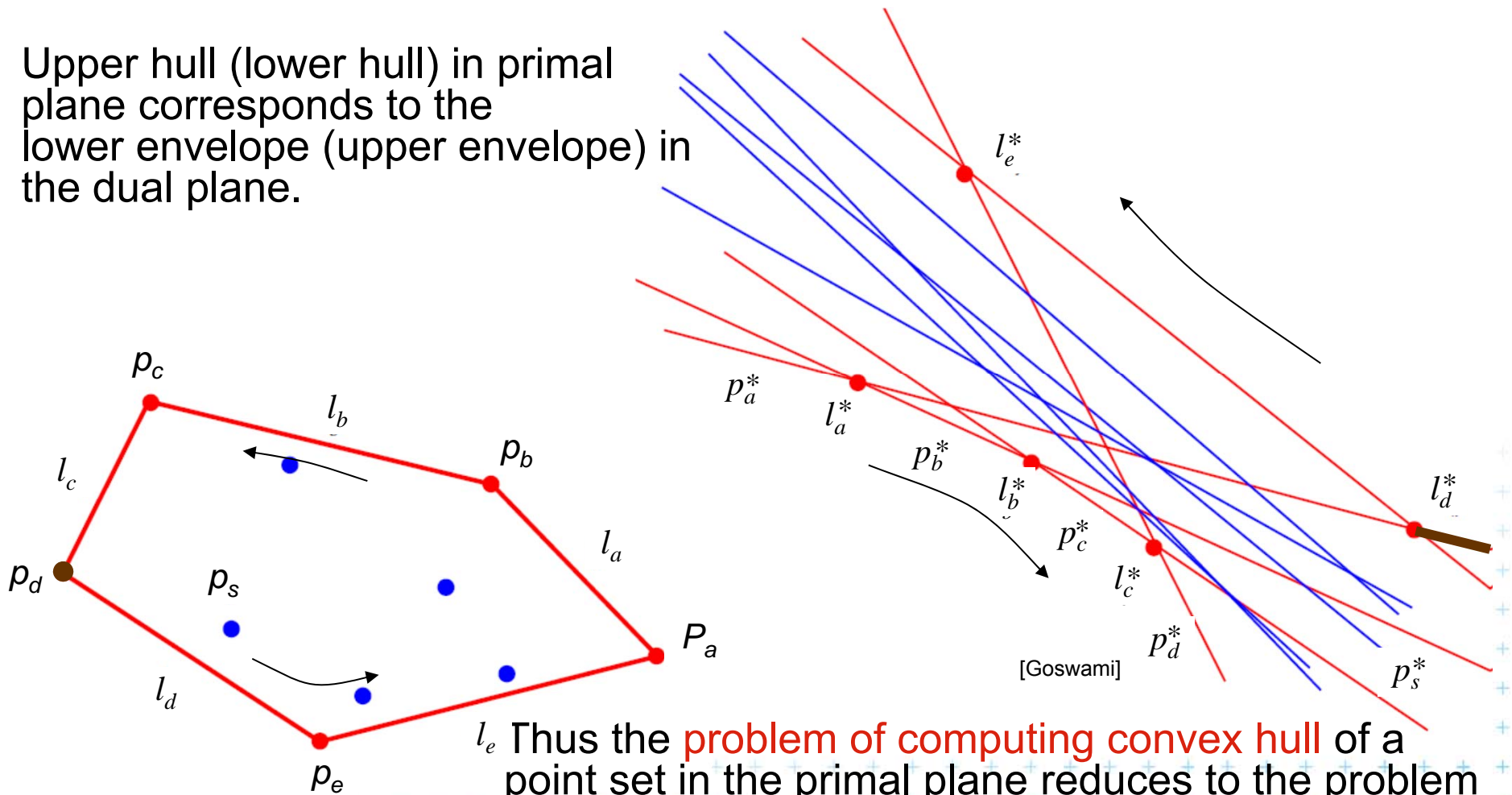


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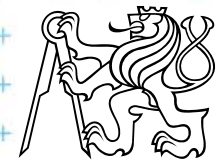


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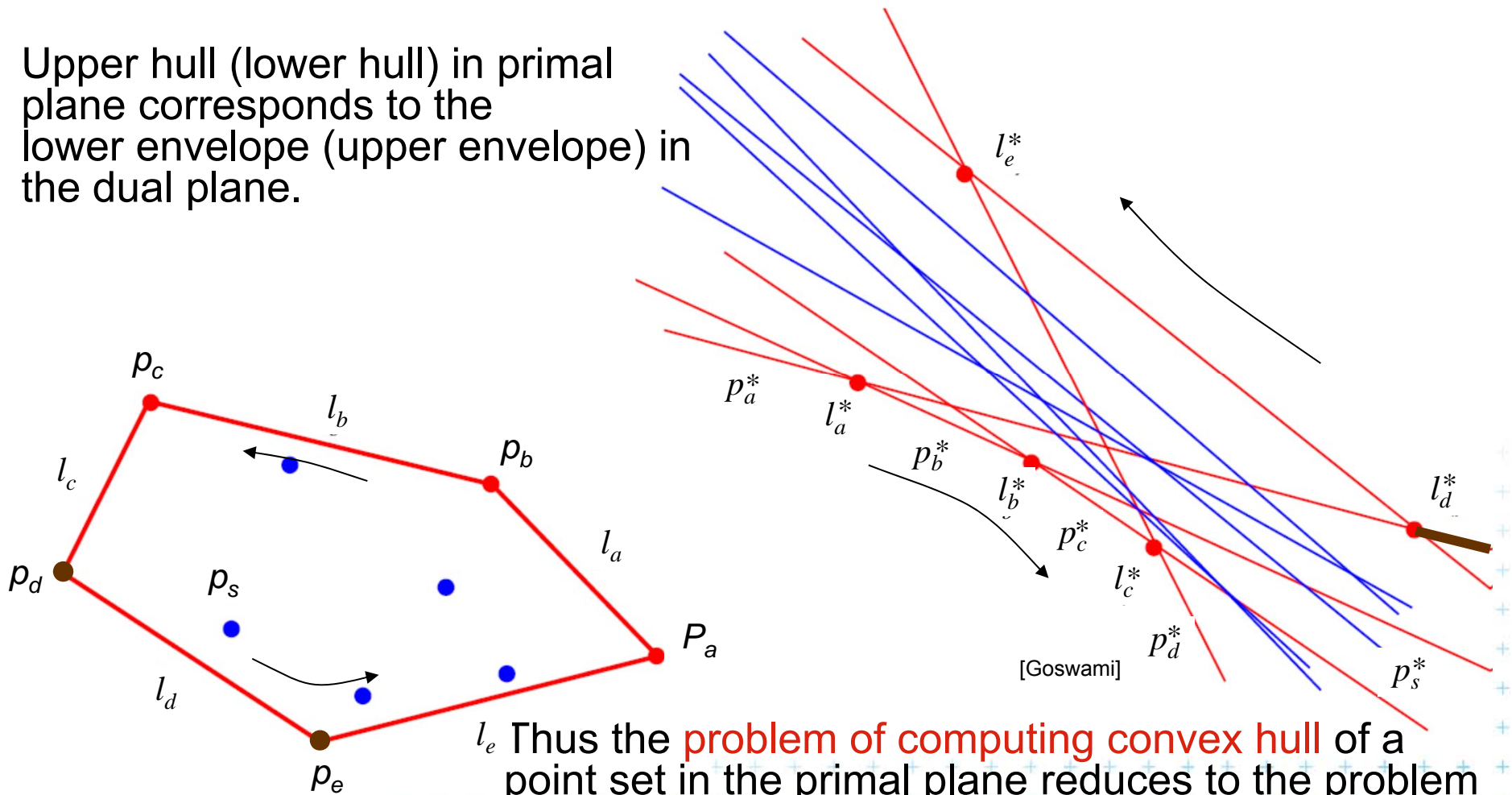


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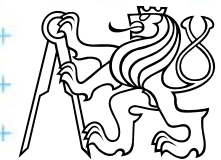


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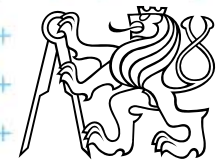
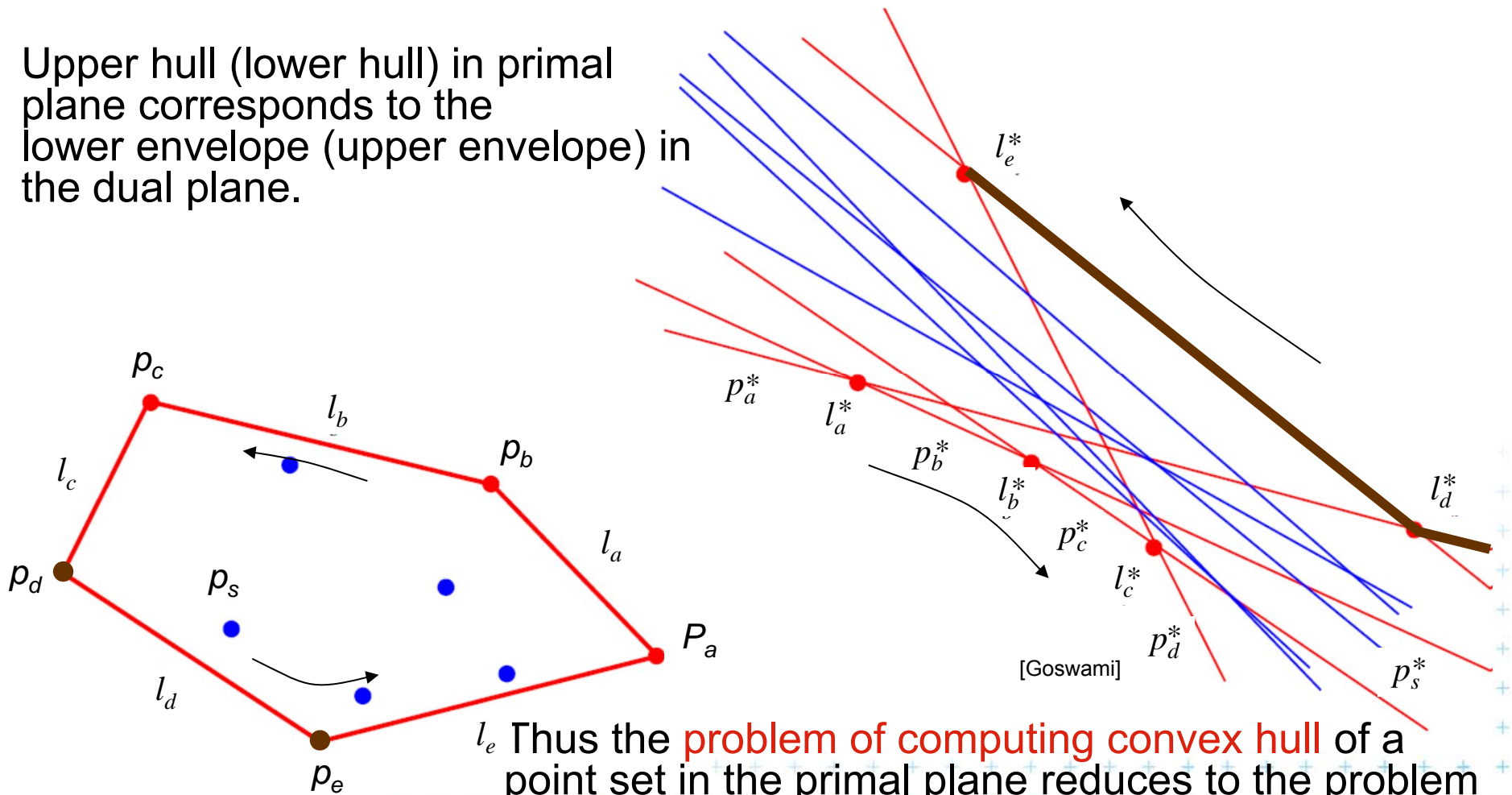


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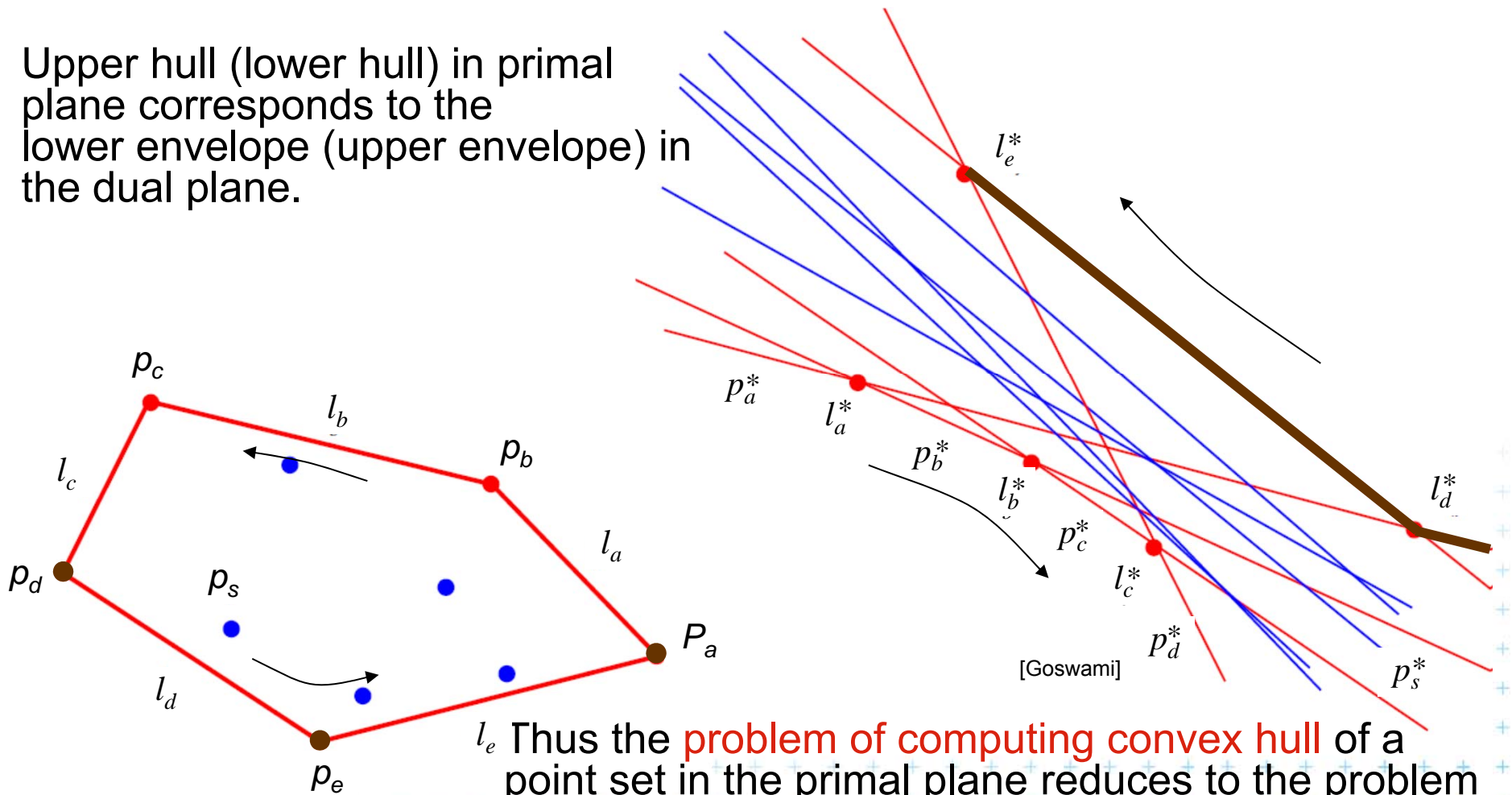
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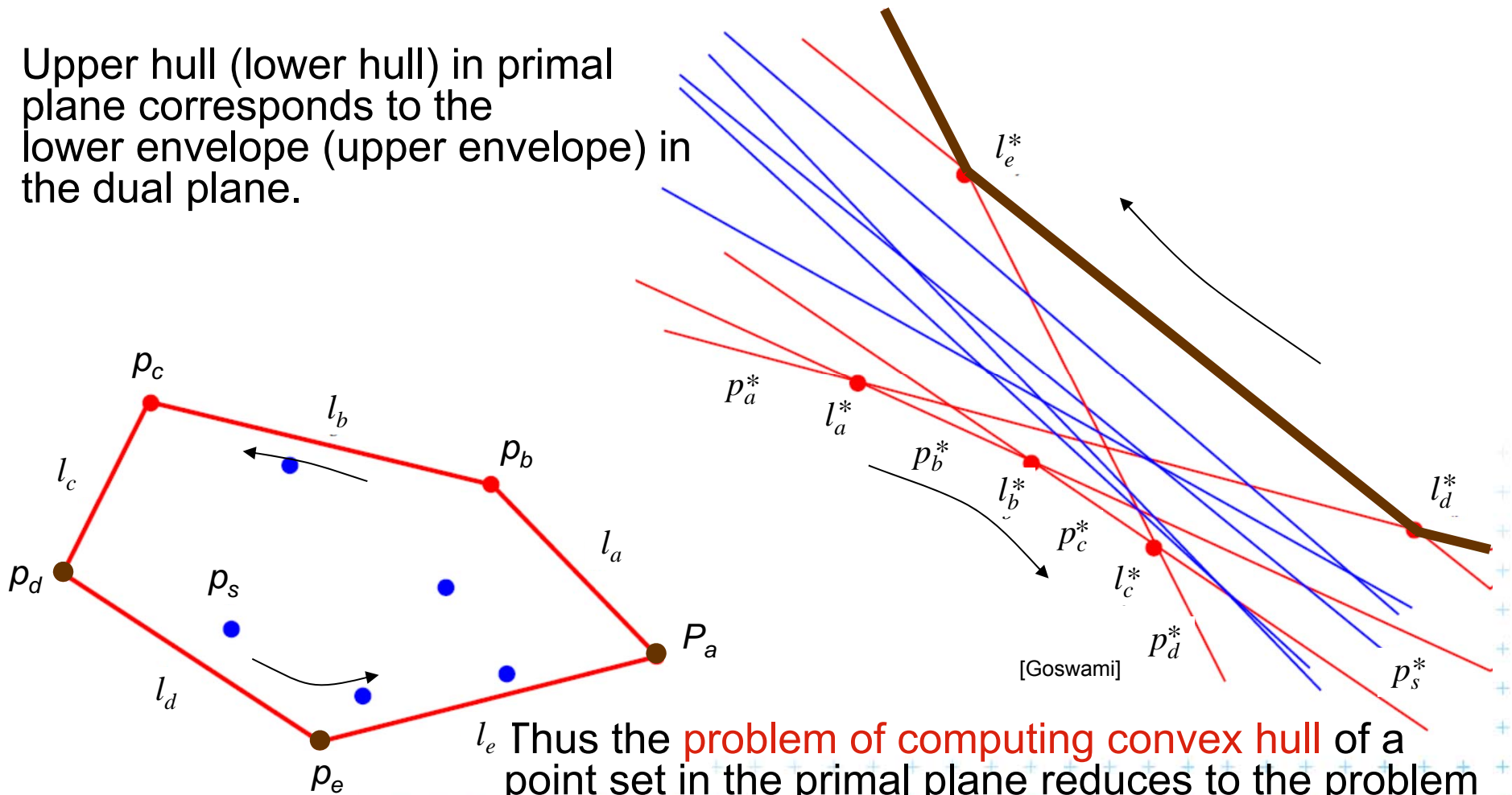


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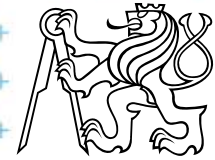


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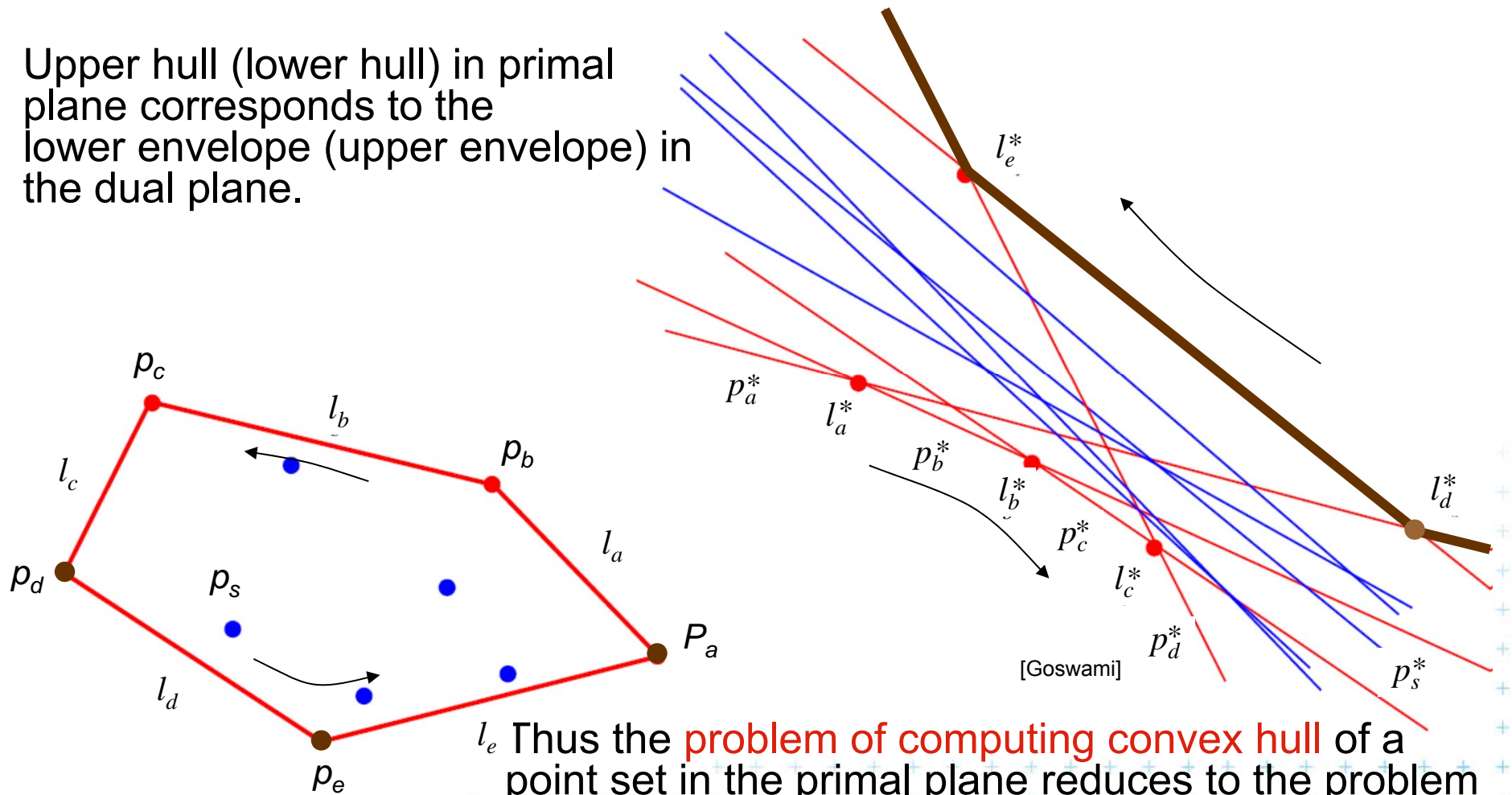


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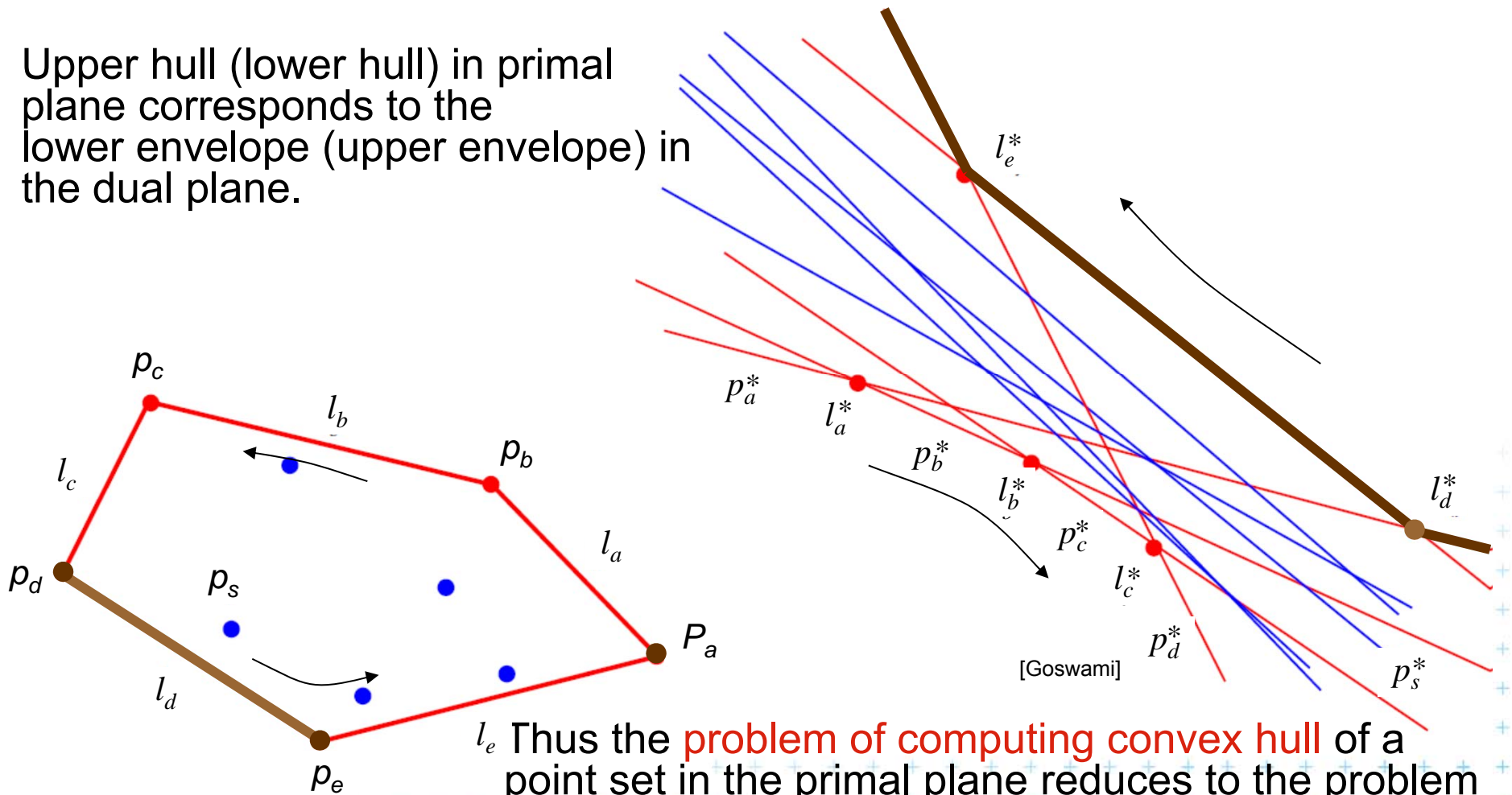
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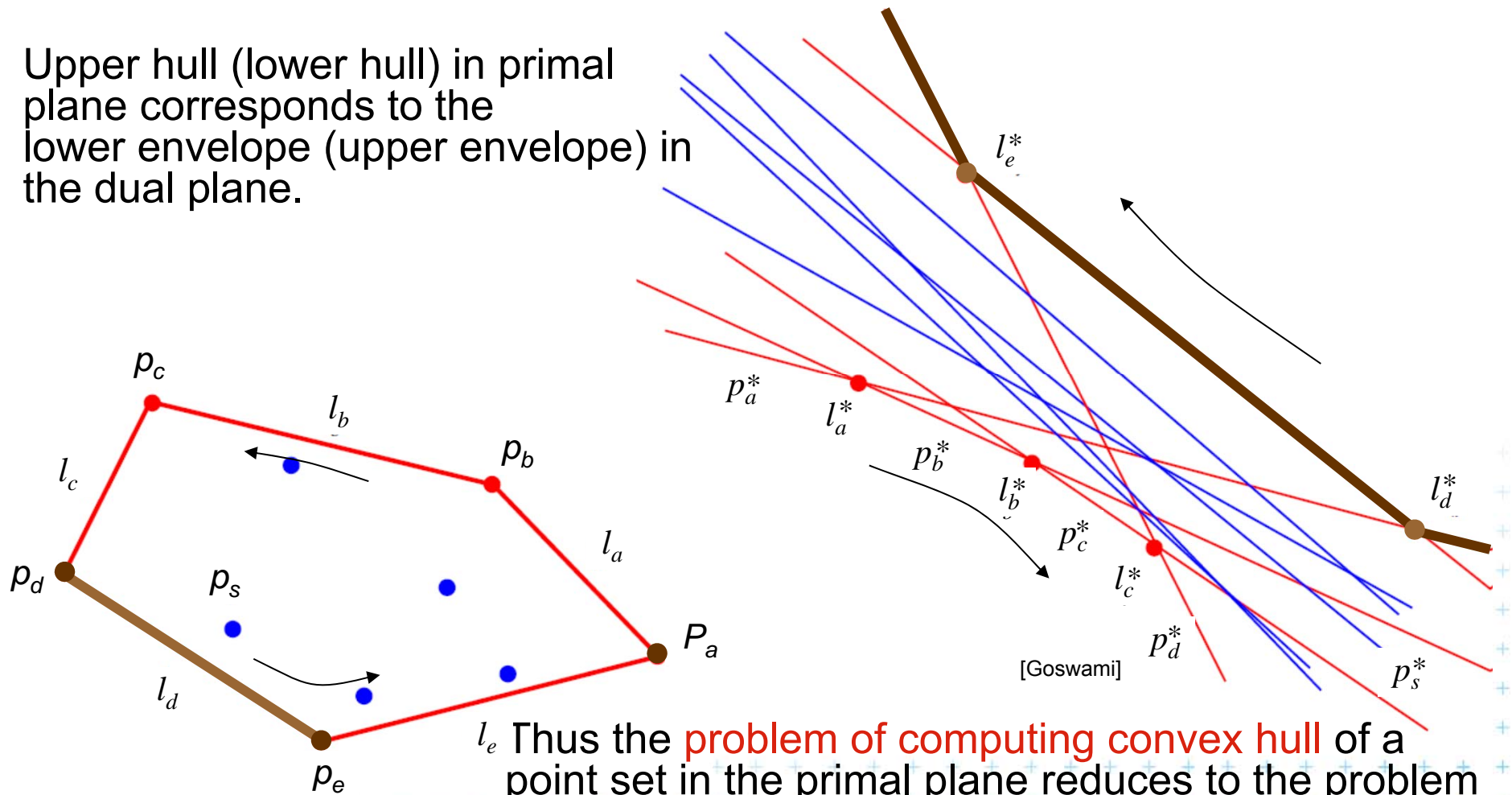


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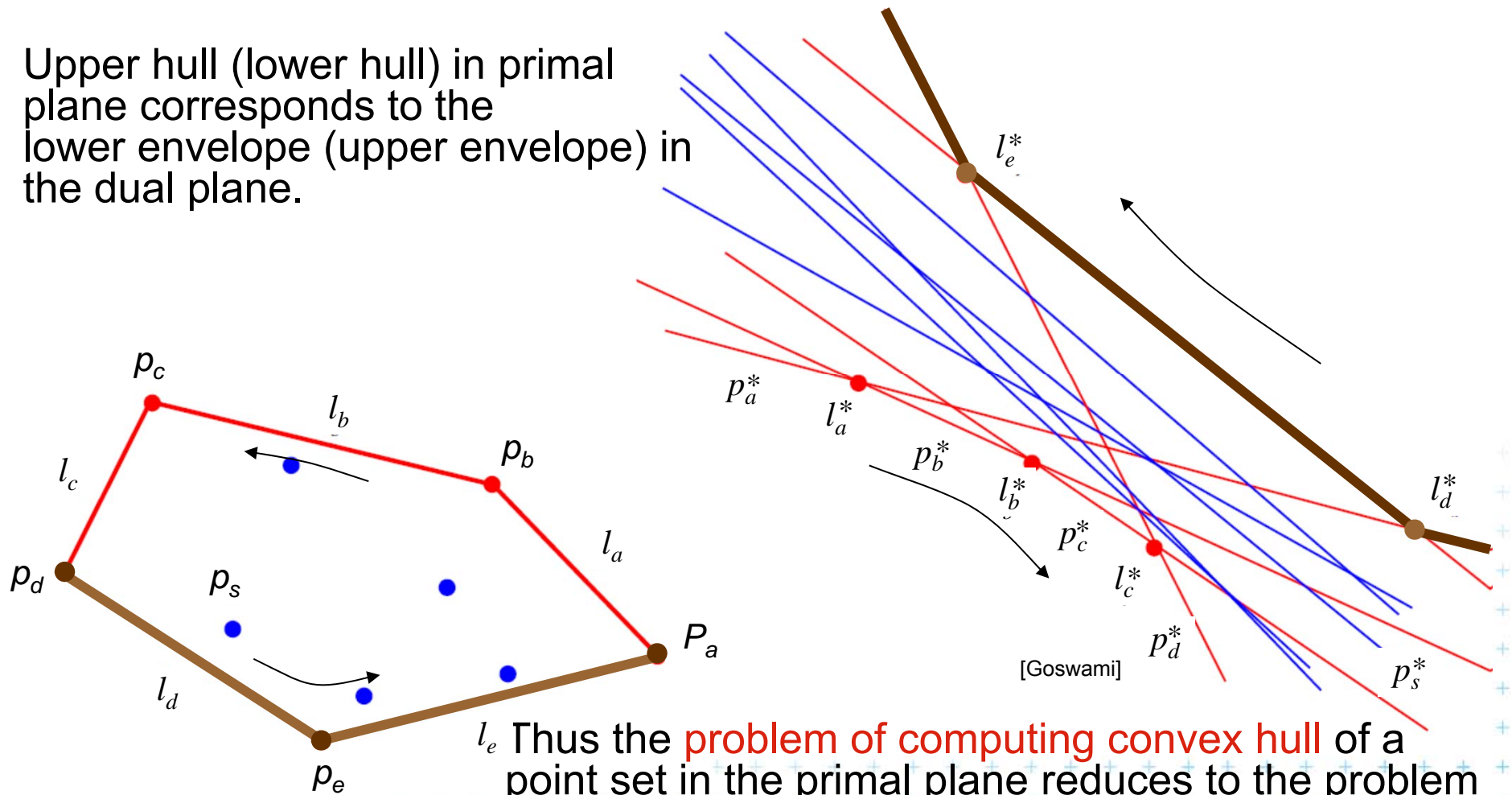


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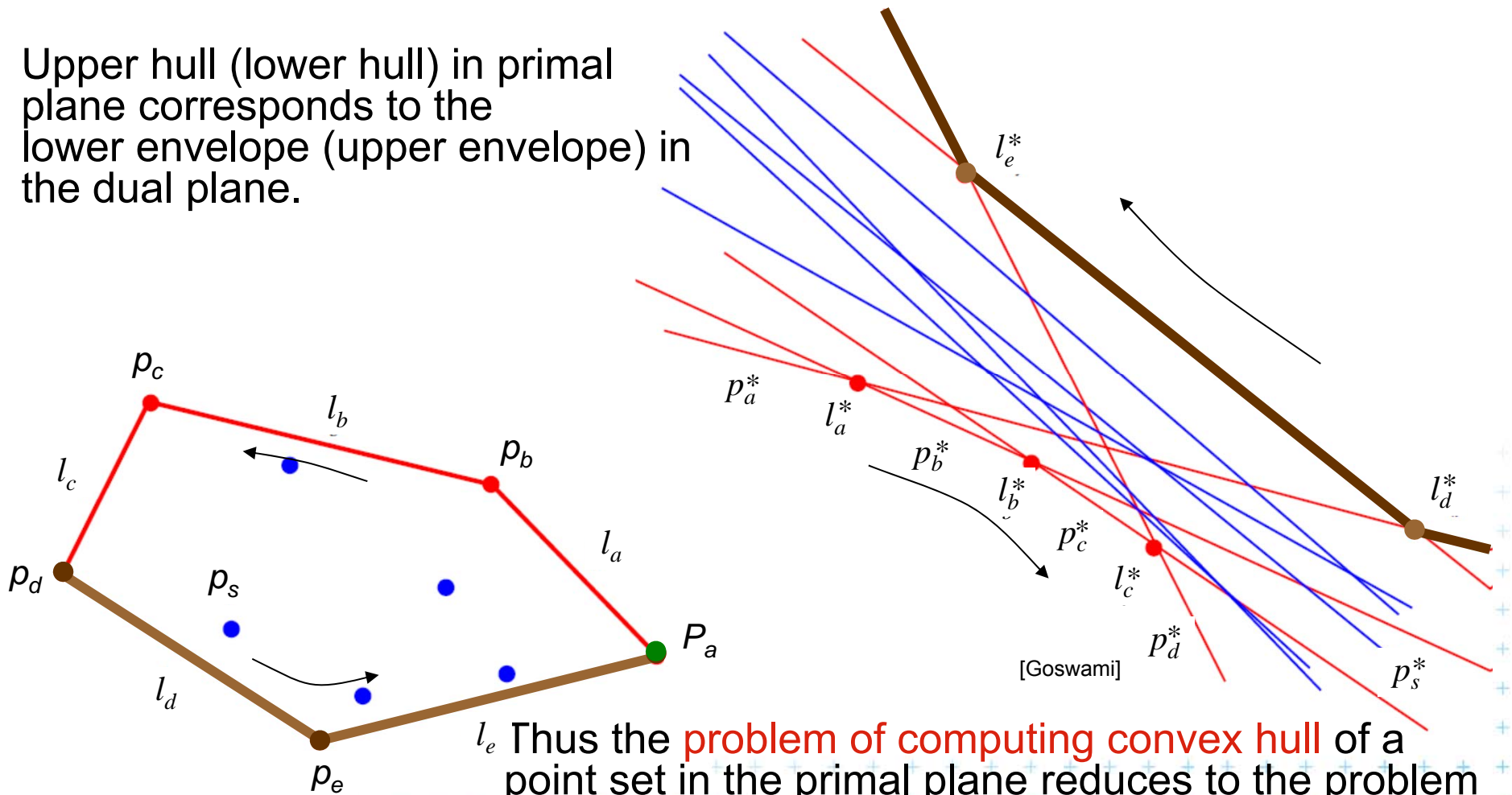


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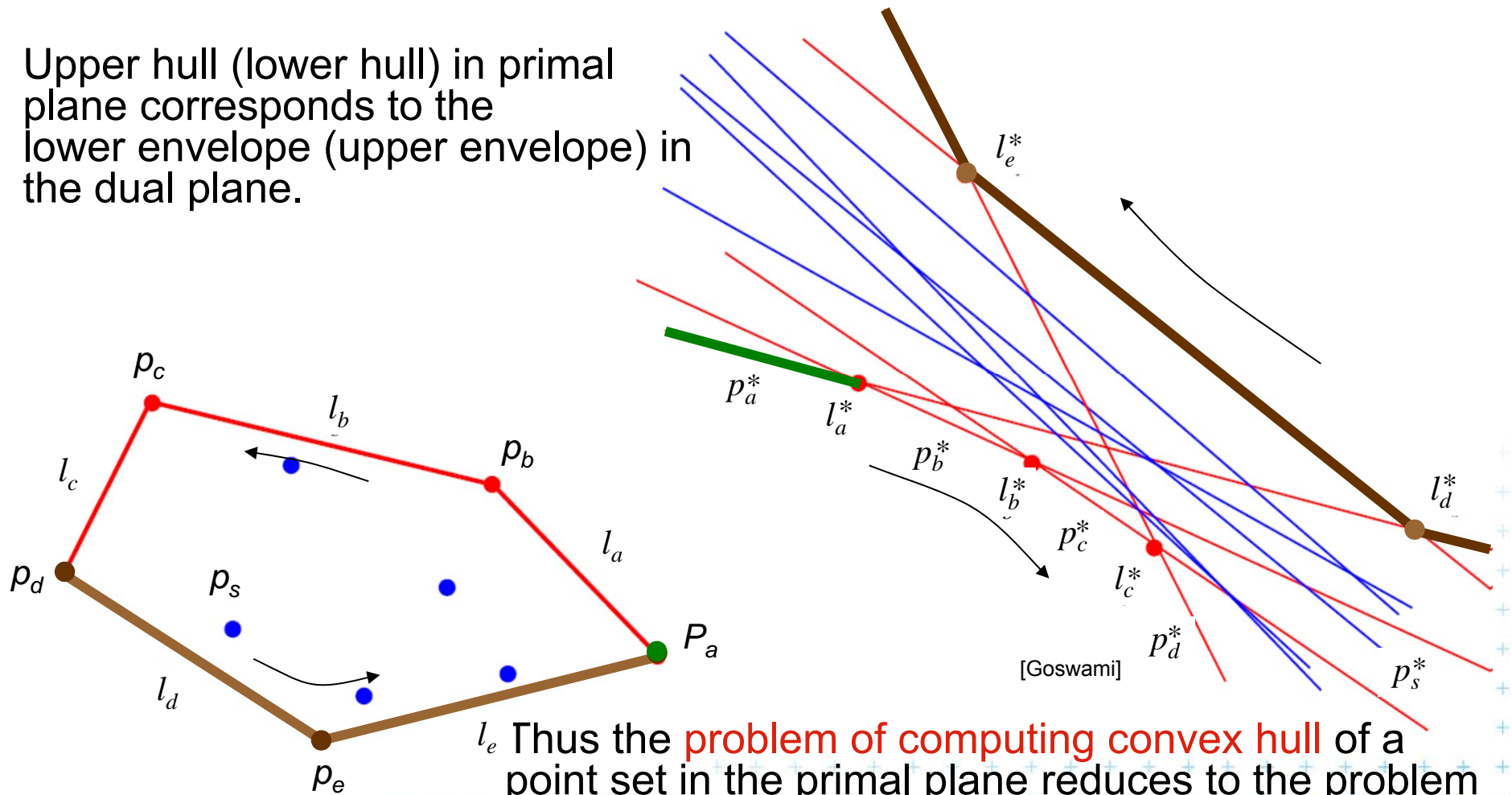


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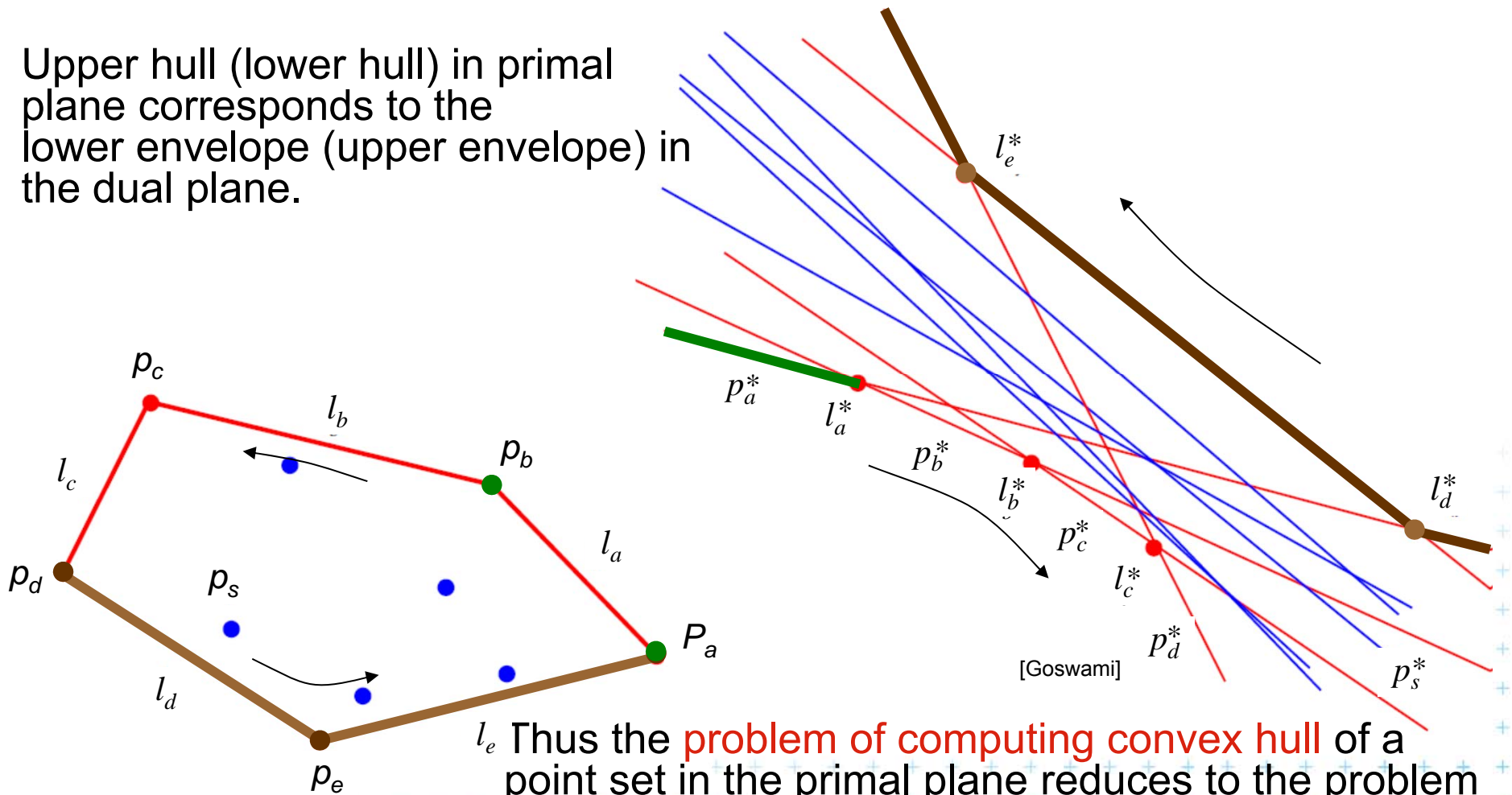


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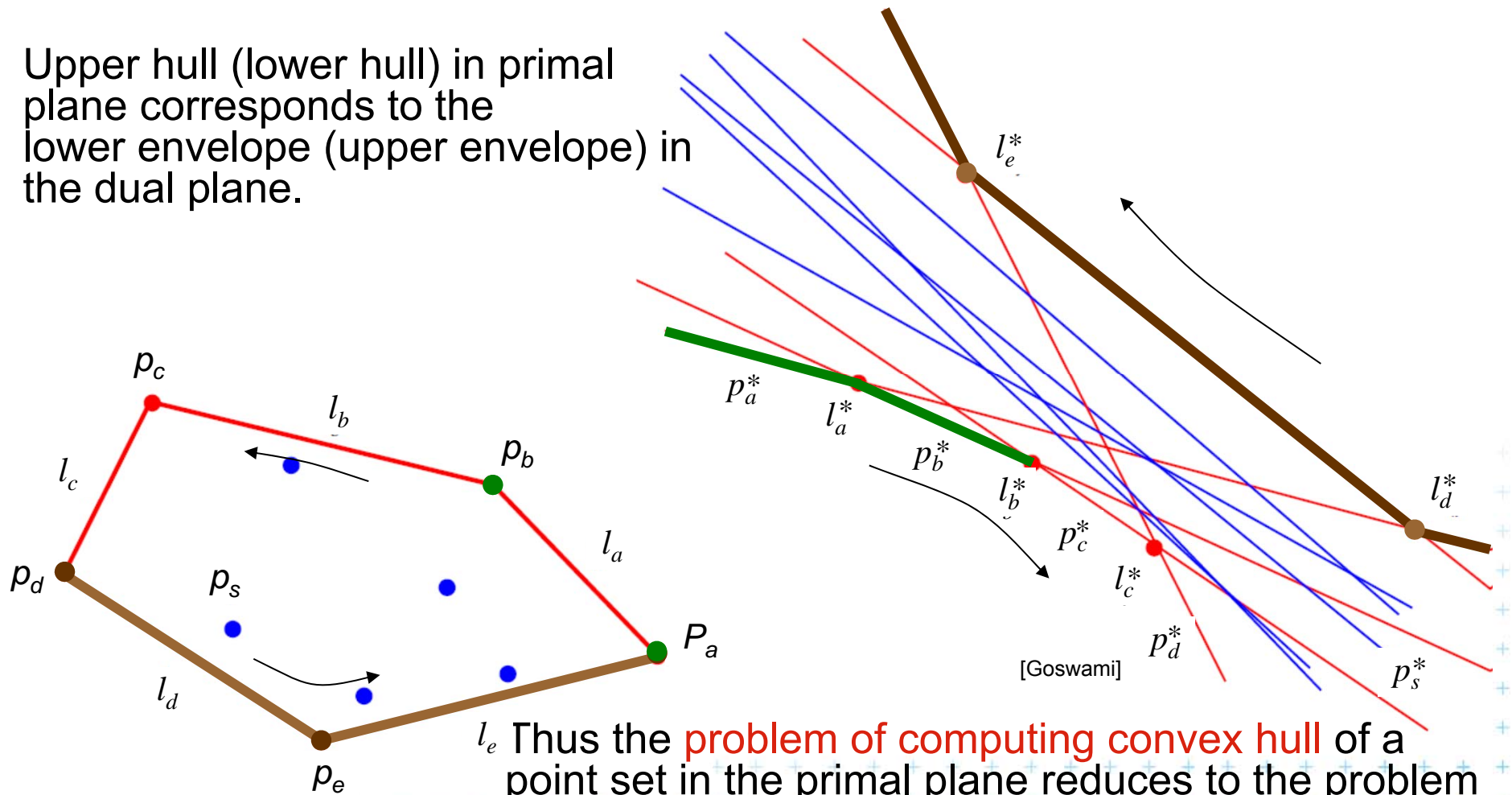


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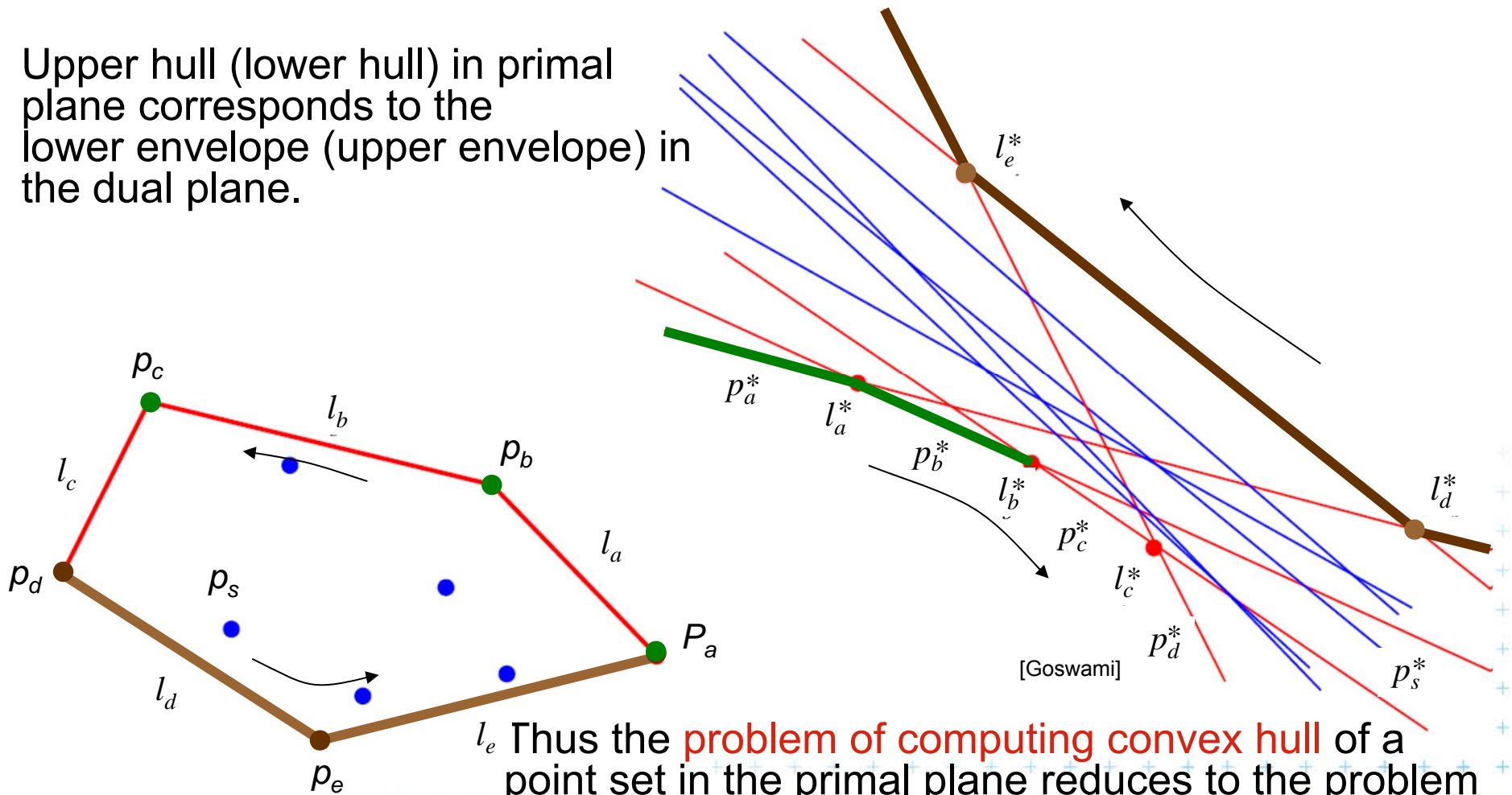


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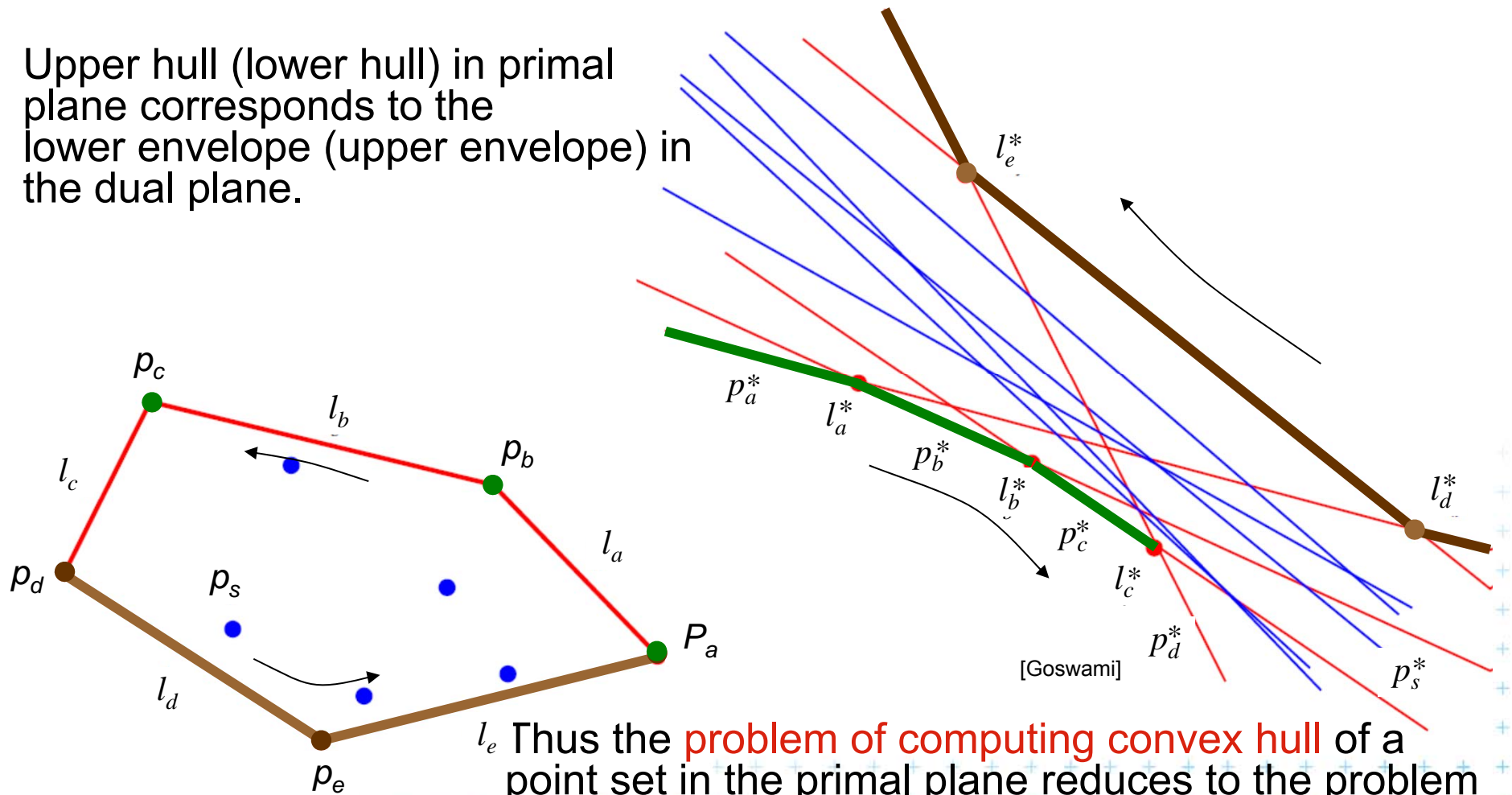


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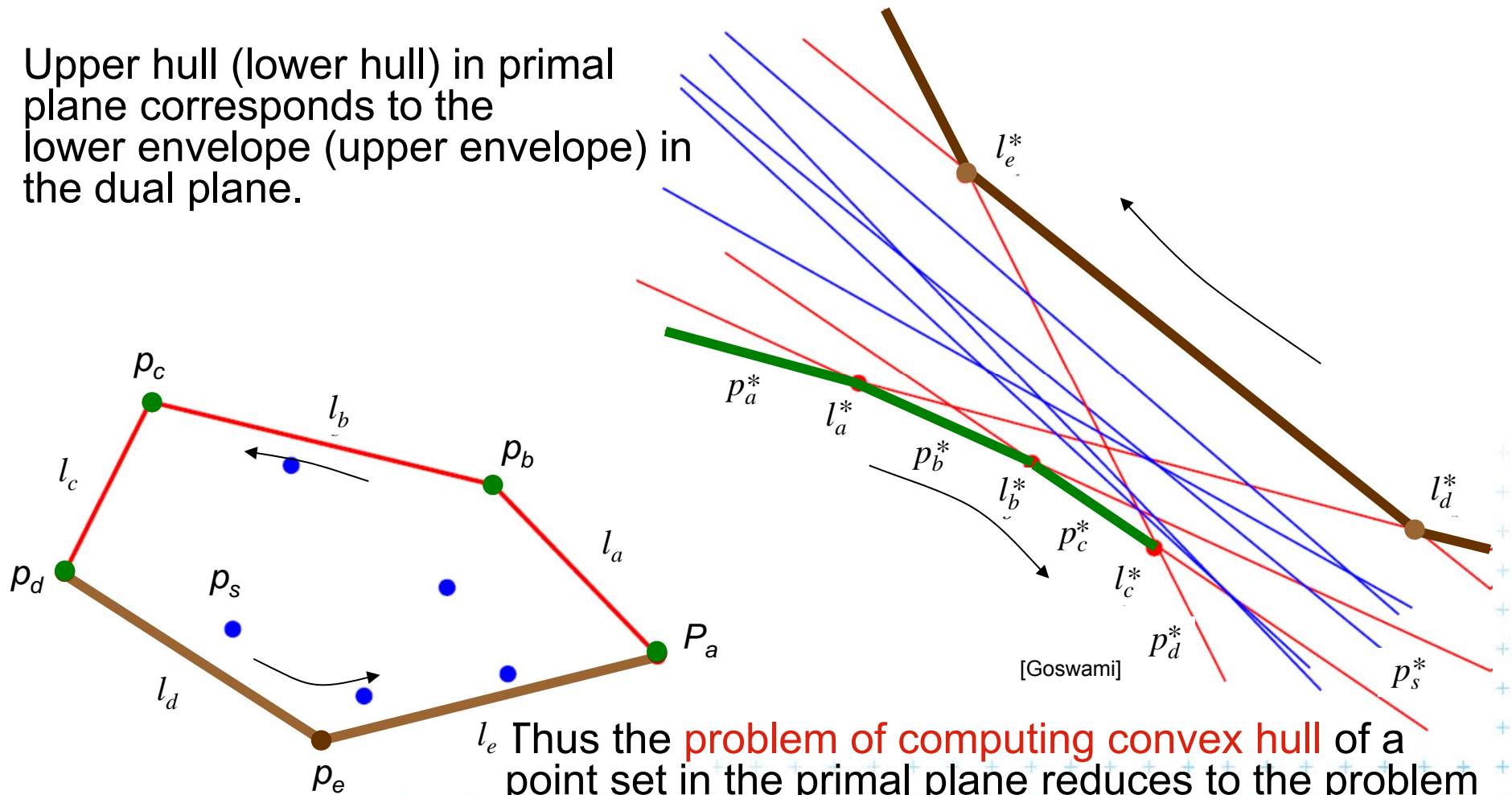


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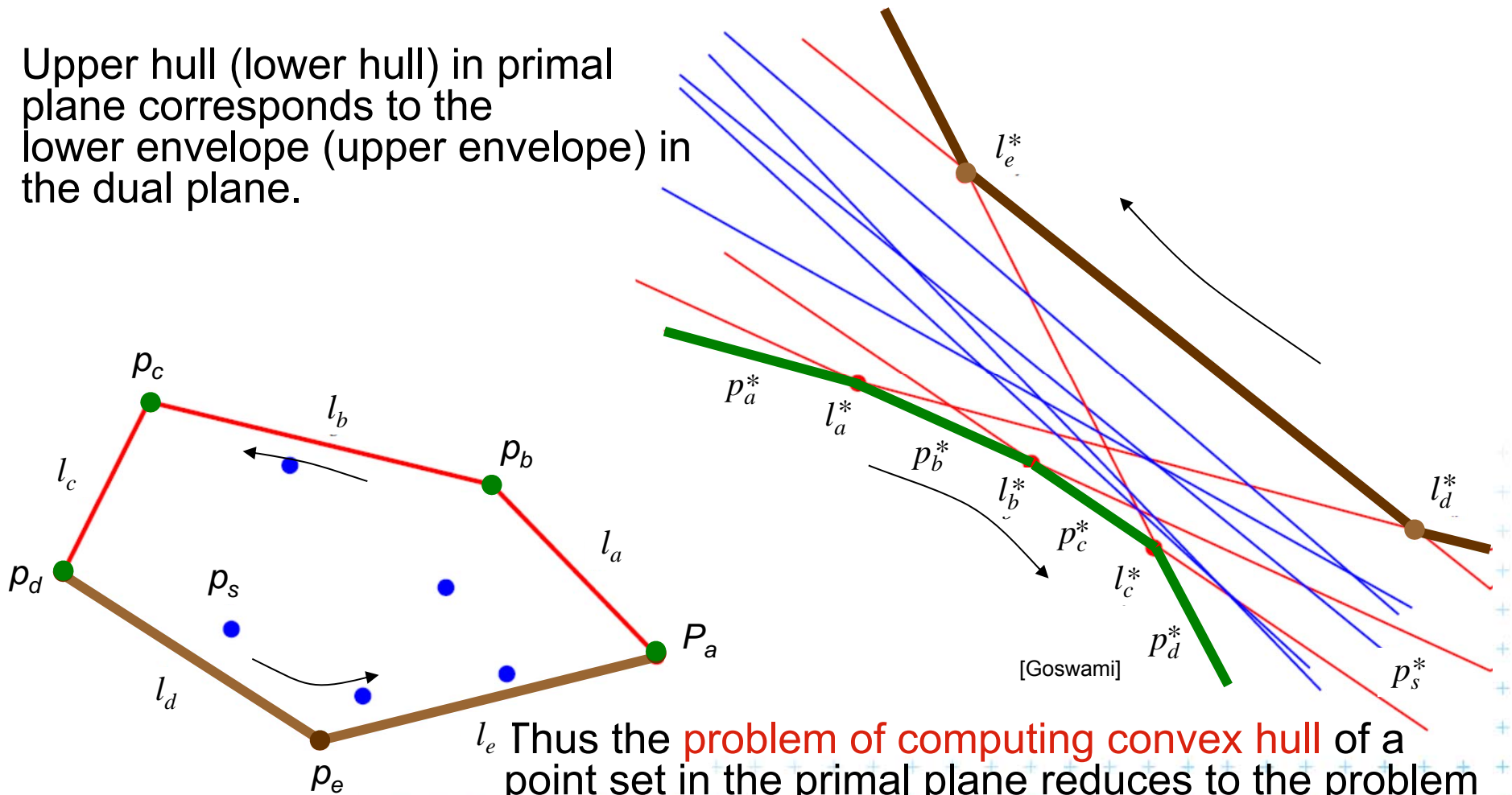


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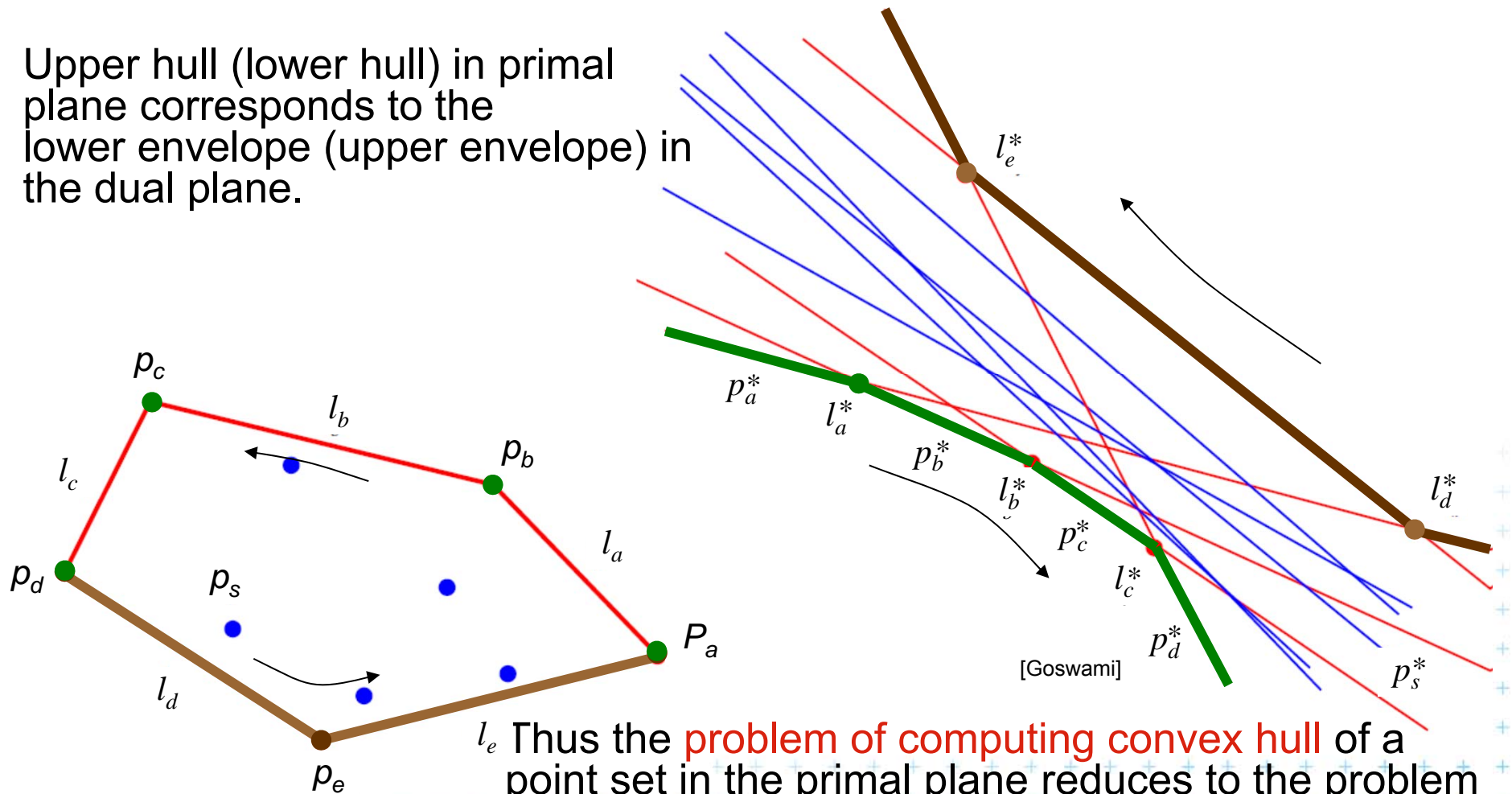


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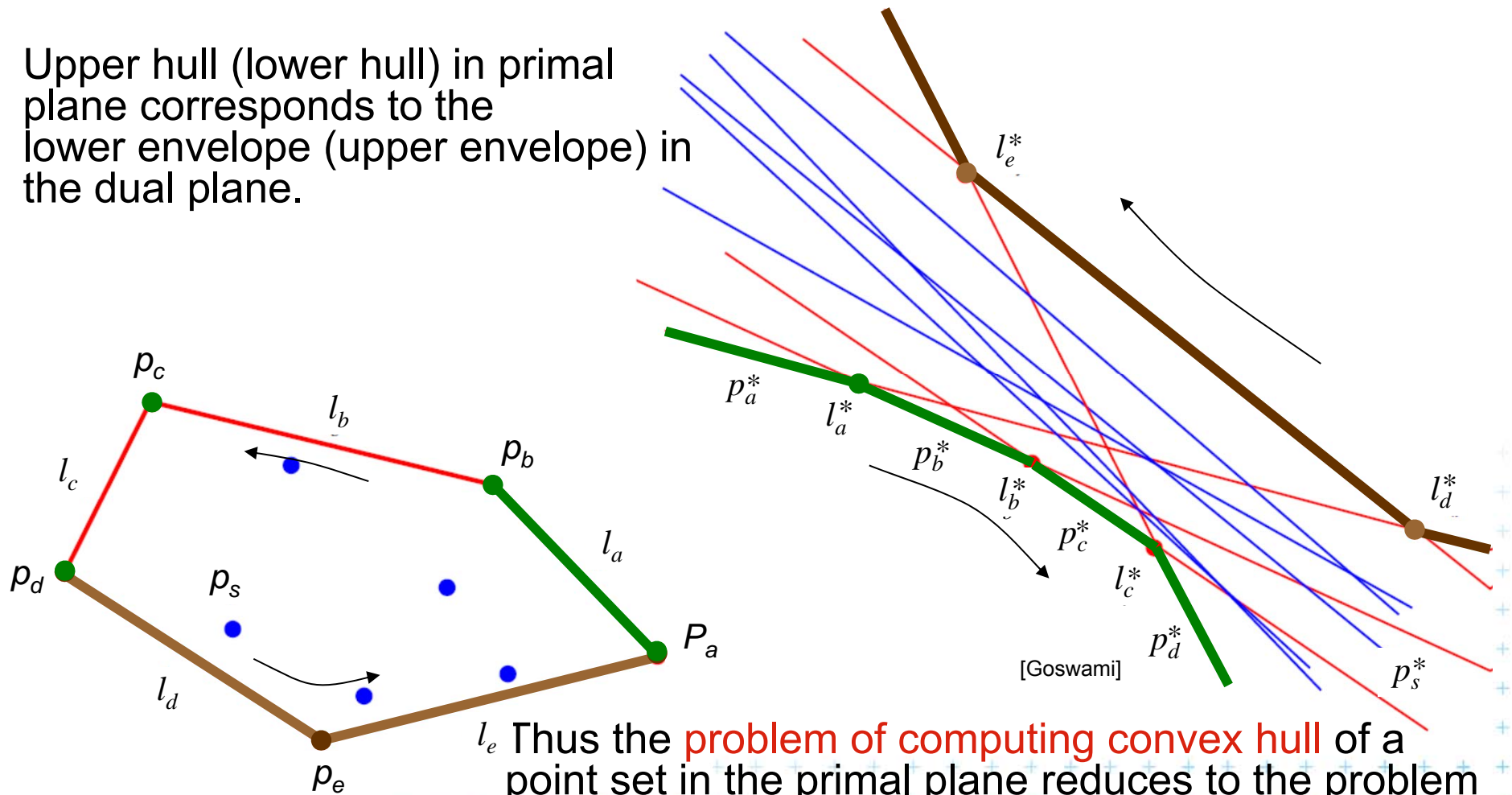


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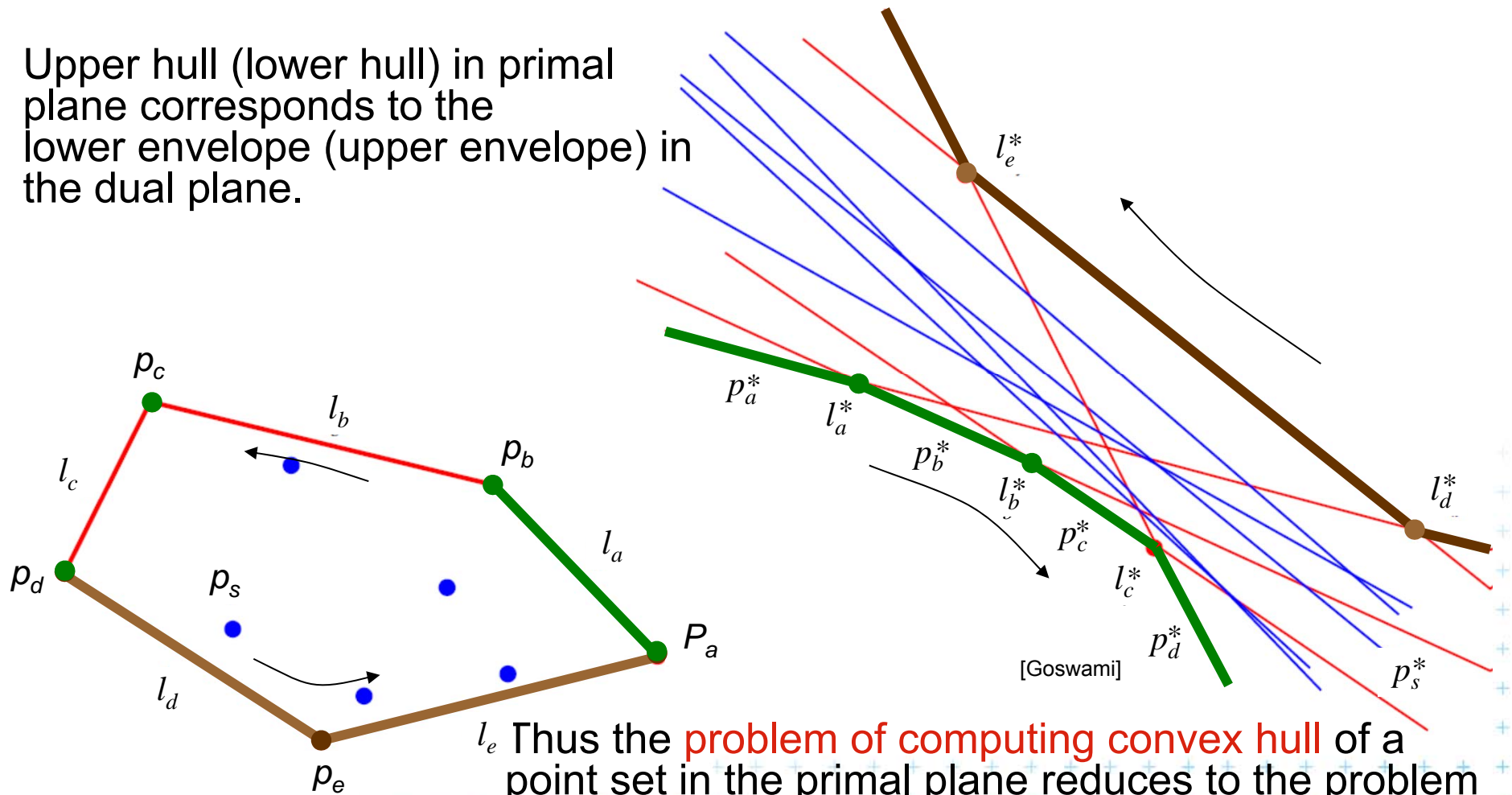


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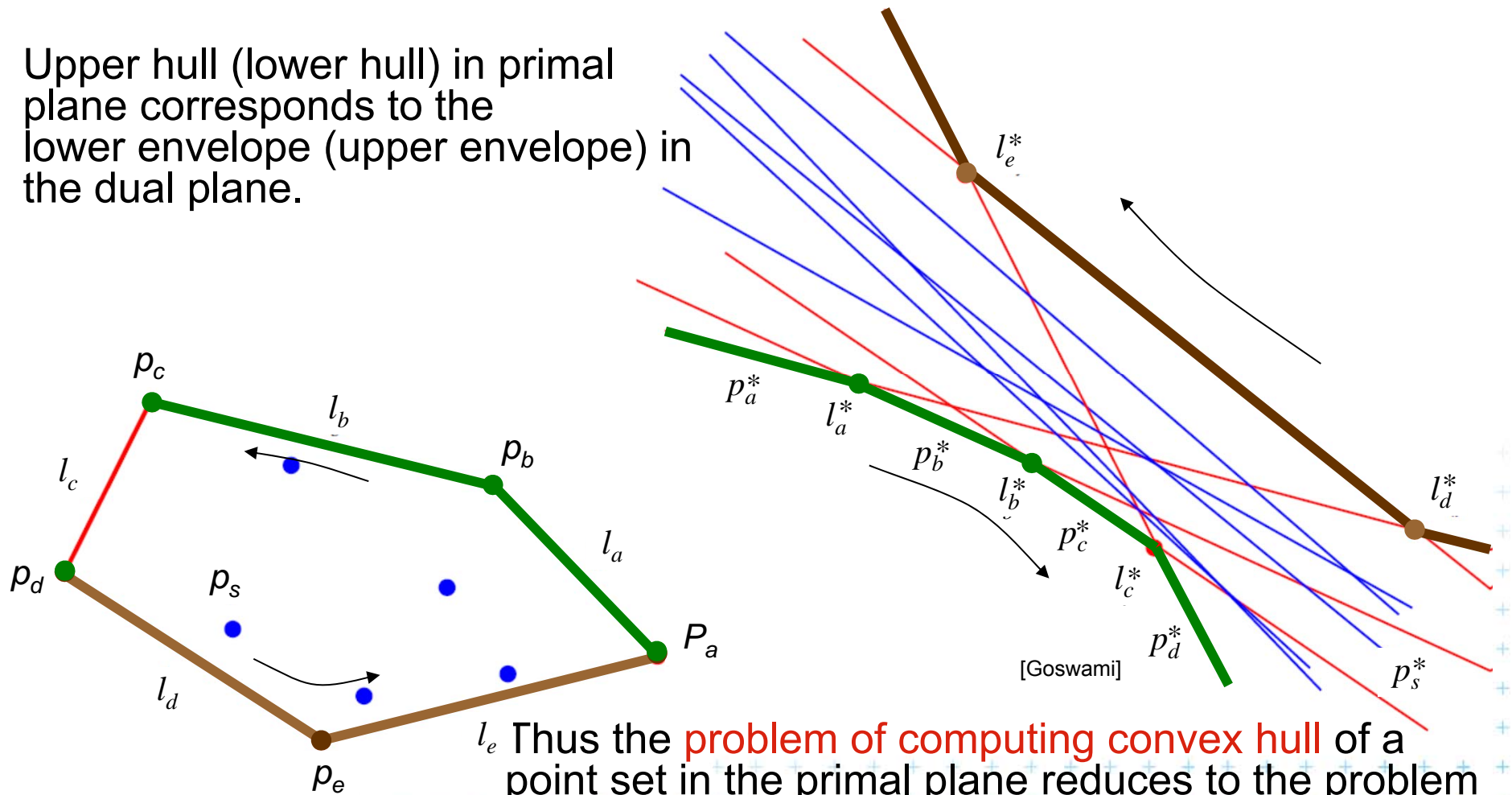


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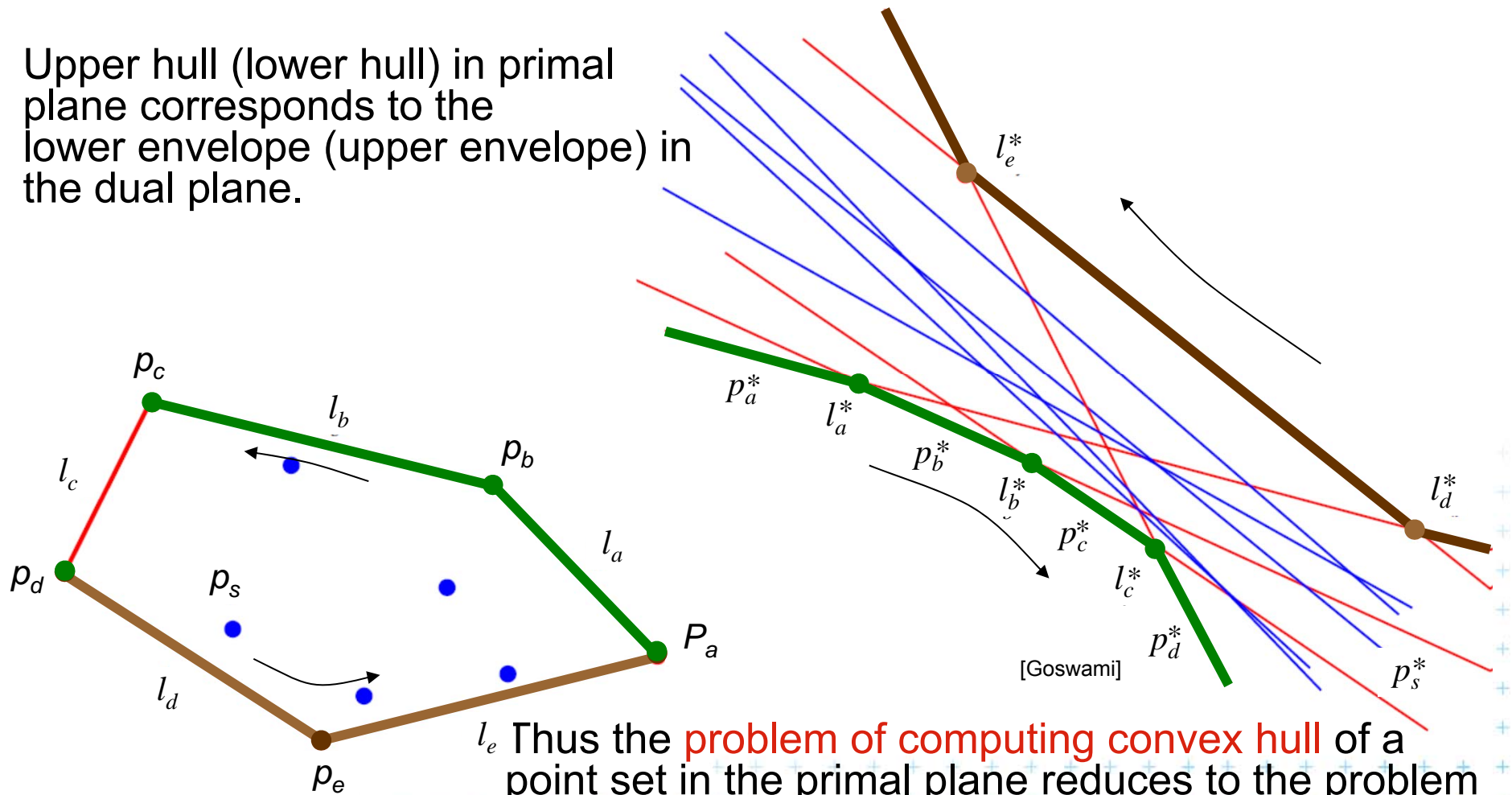


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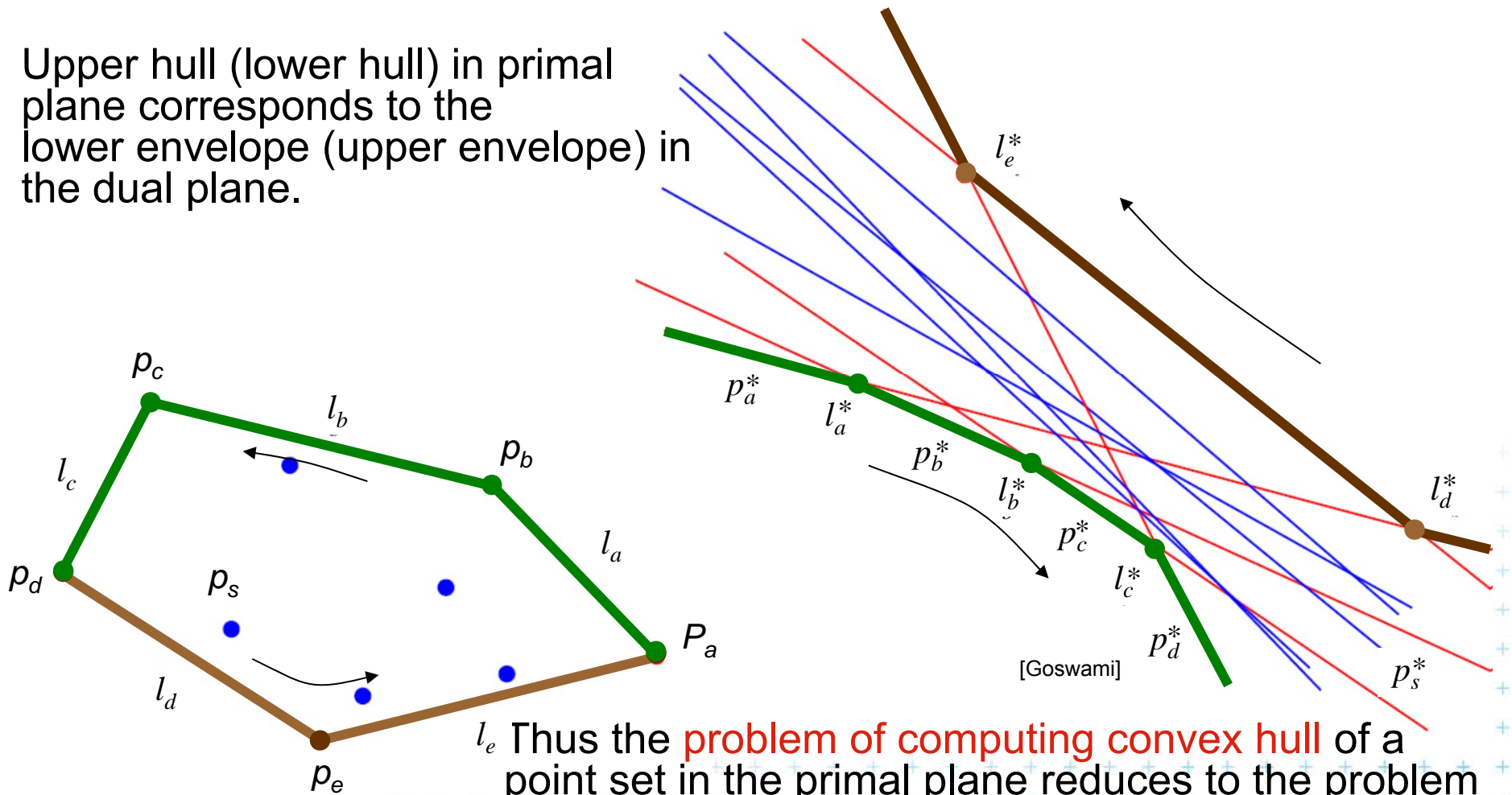


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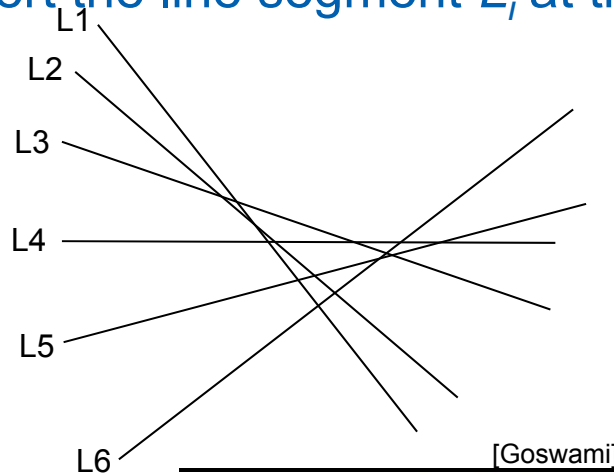
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Set of lines L sorted by **increasing** order of slopes (-90° to 90°)

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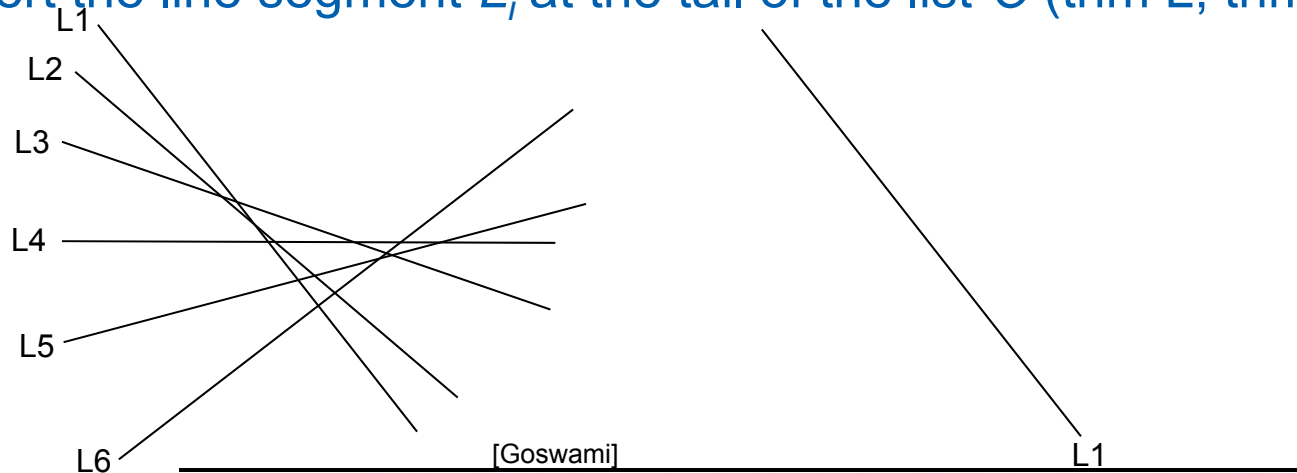
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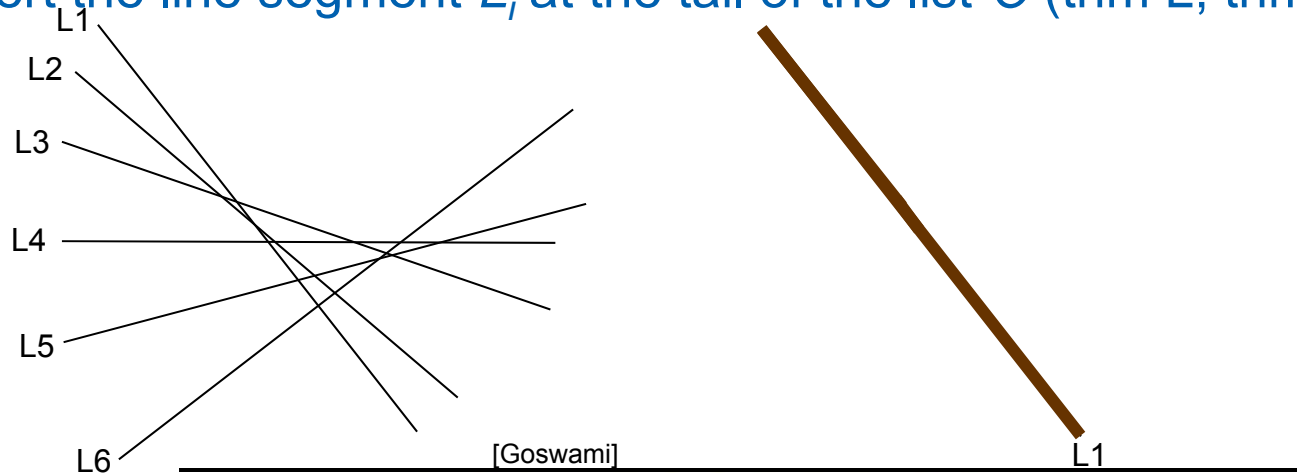
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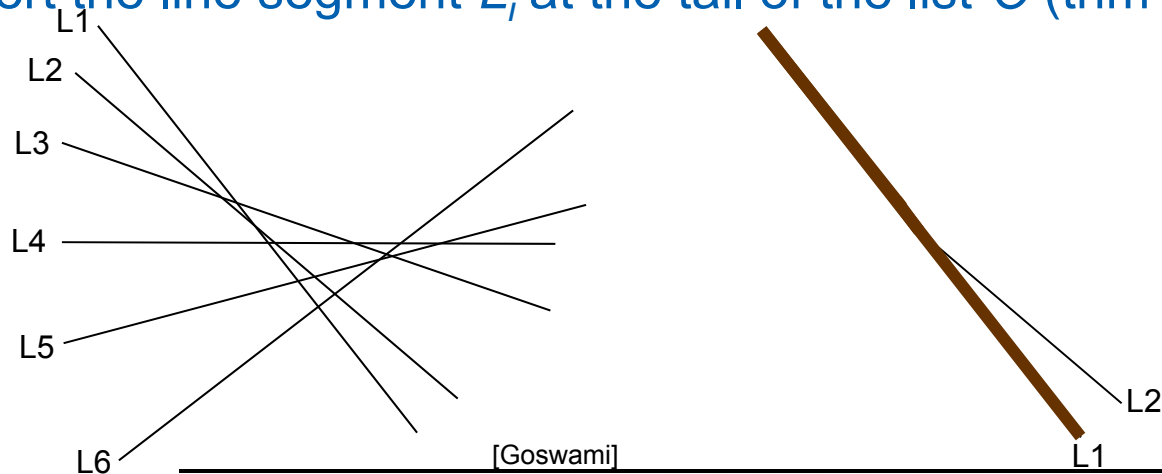
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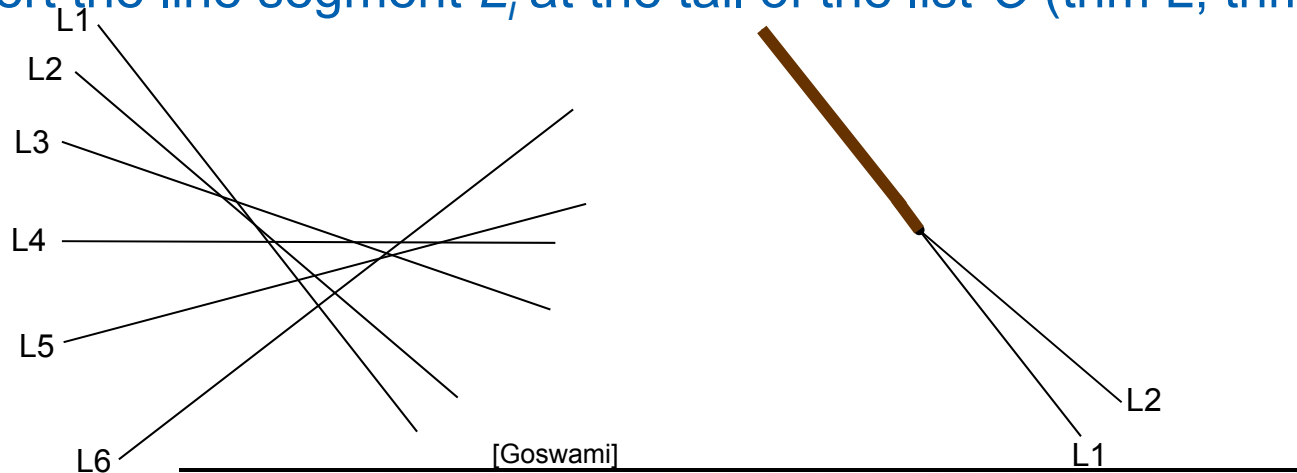
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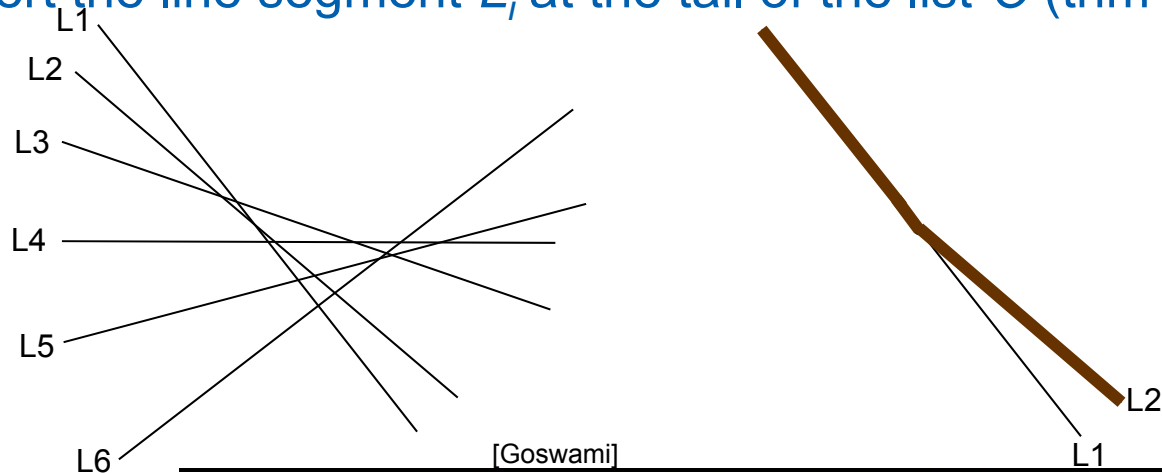
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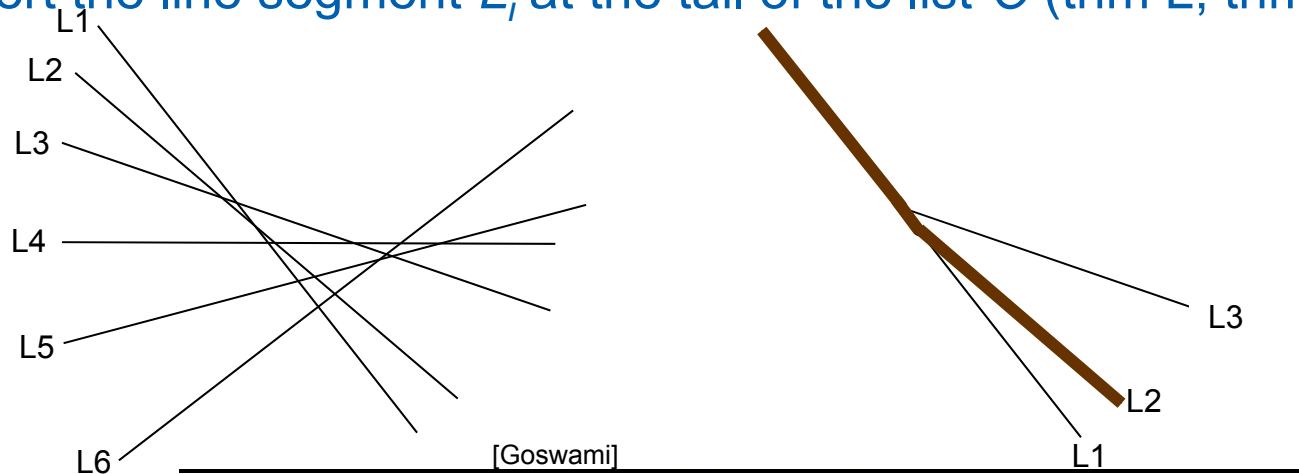
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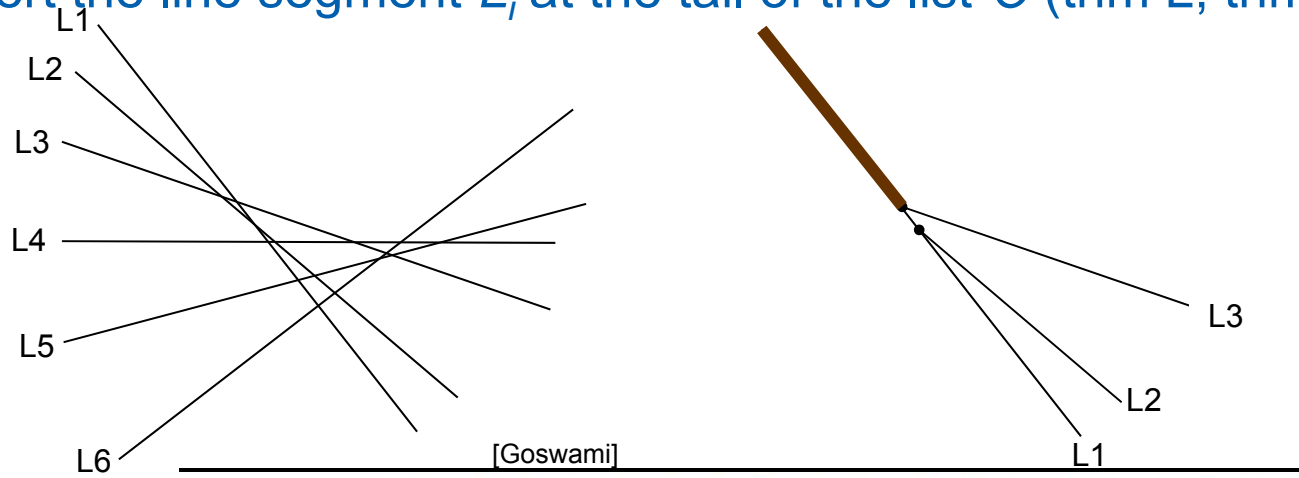
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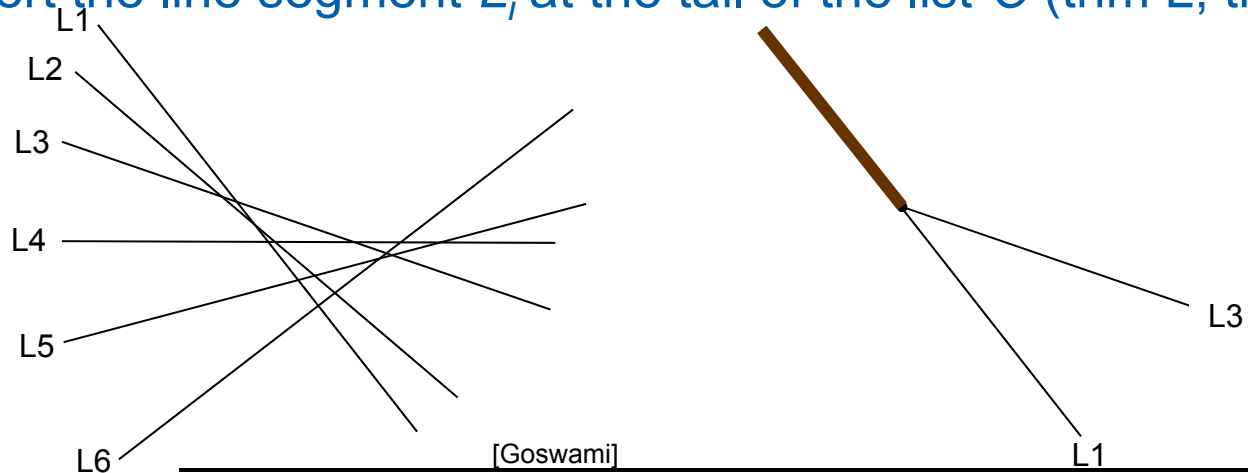
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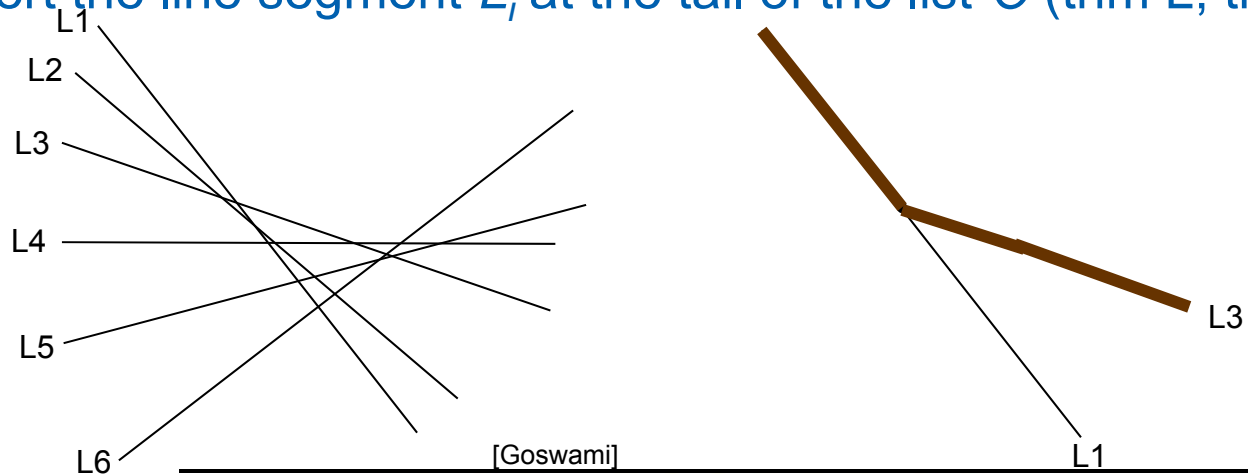
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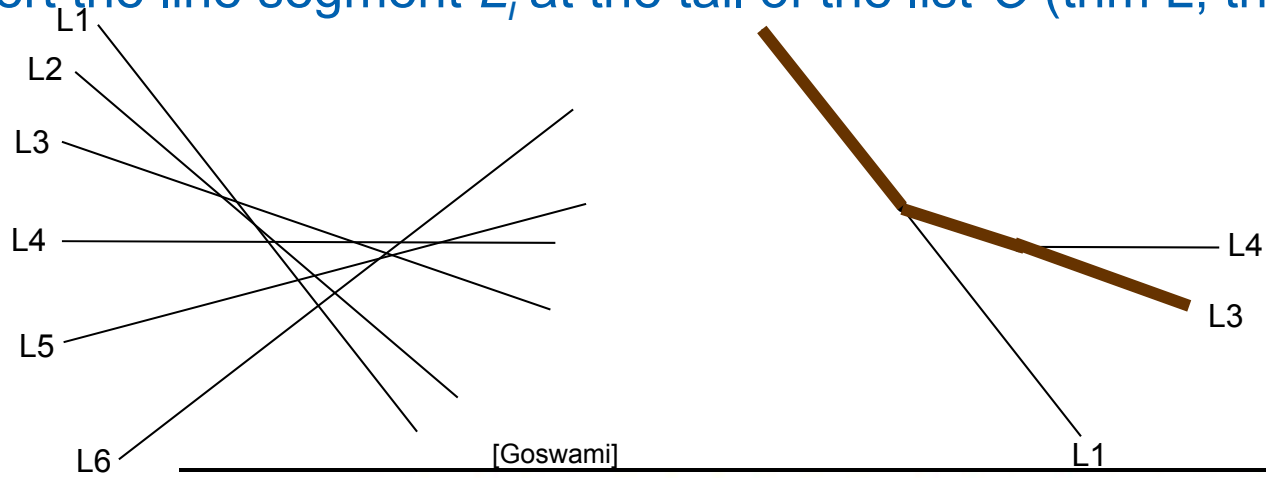
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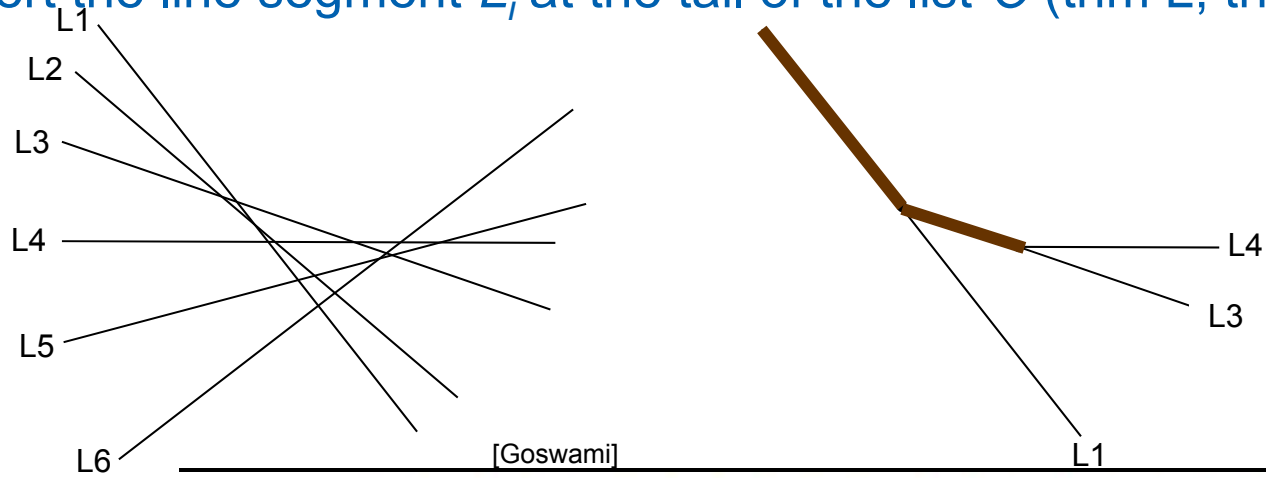
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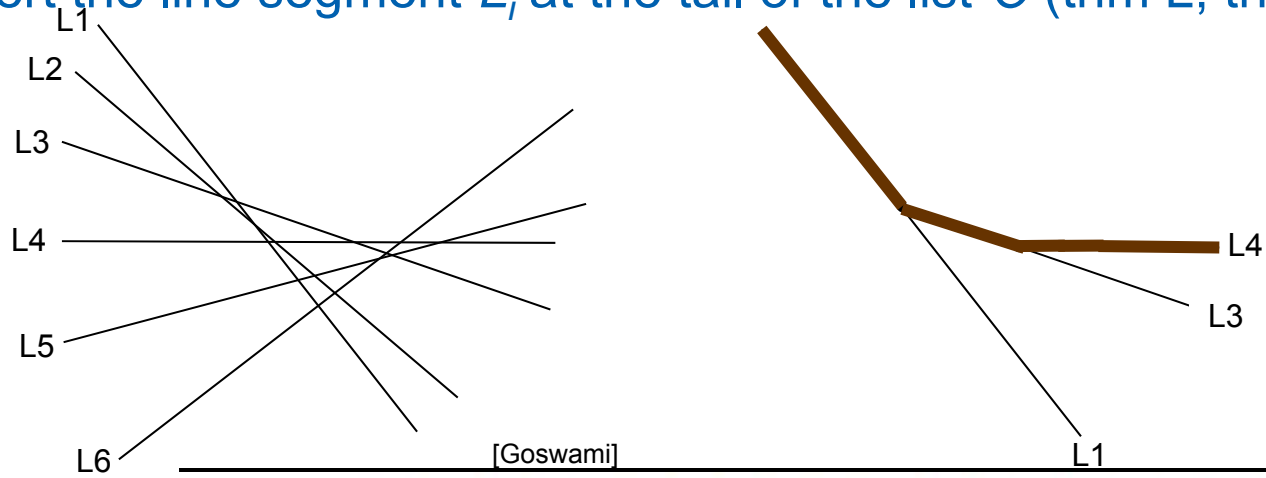
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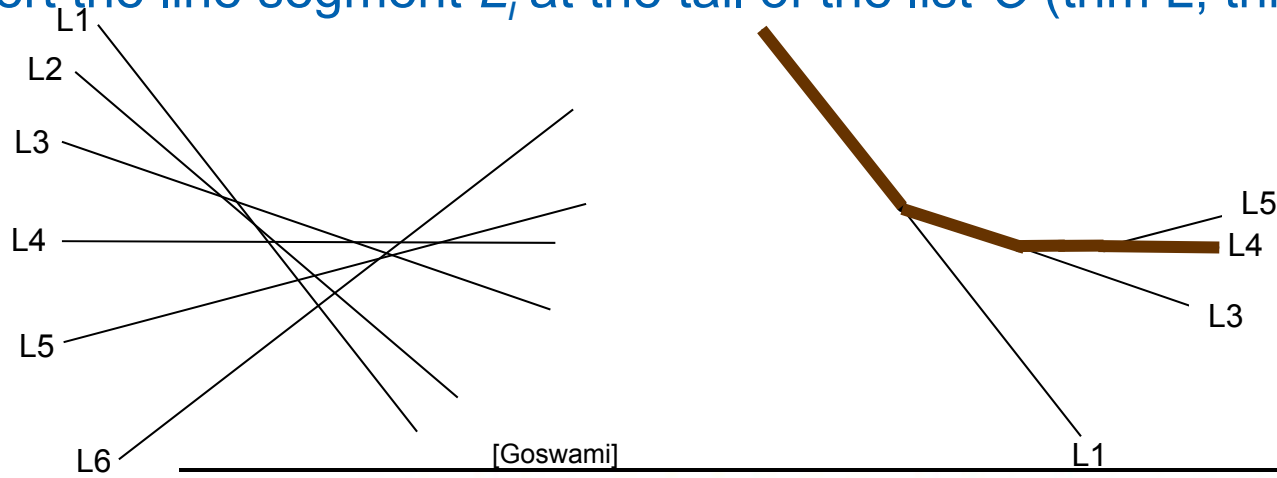
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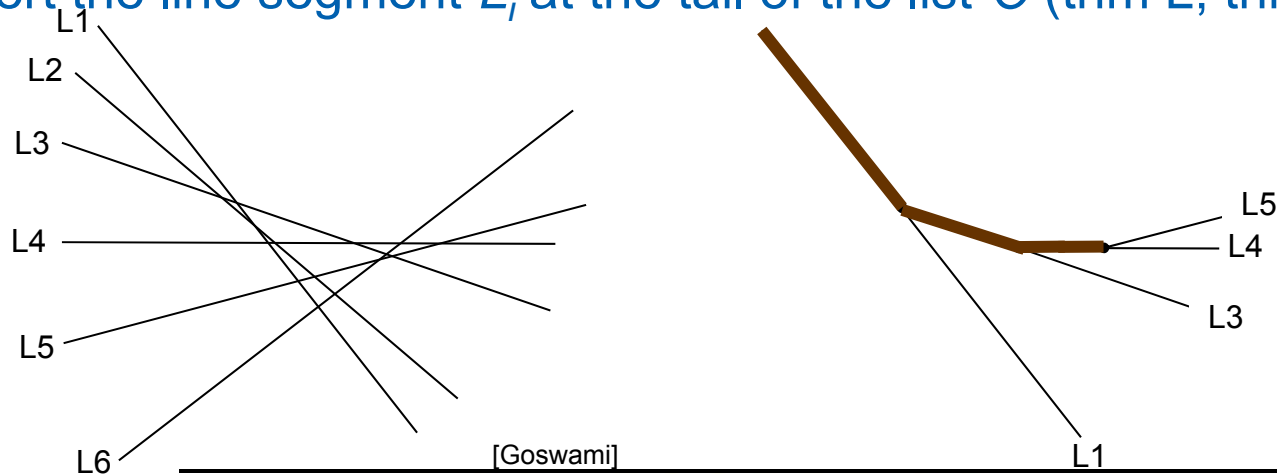
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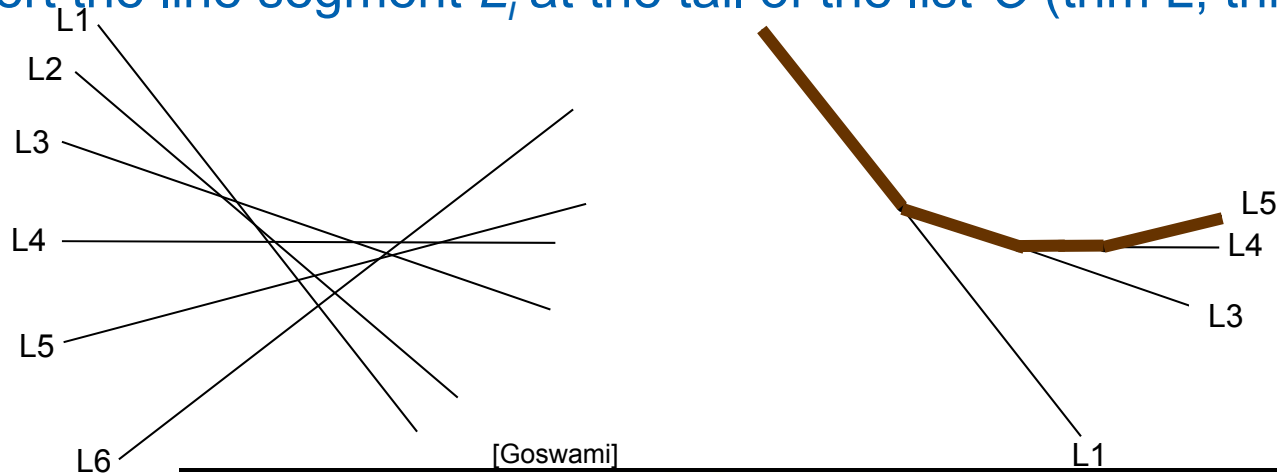
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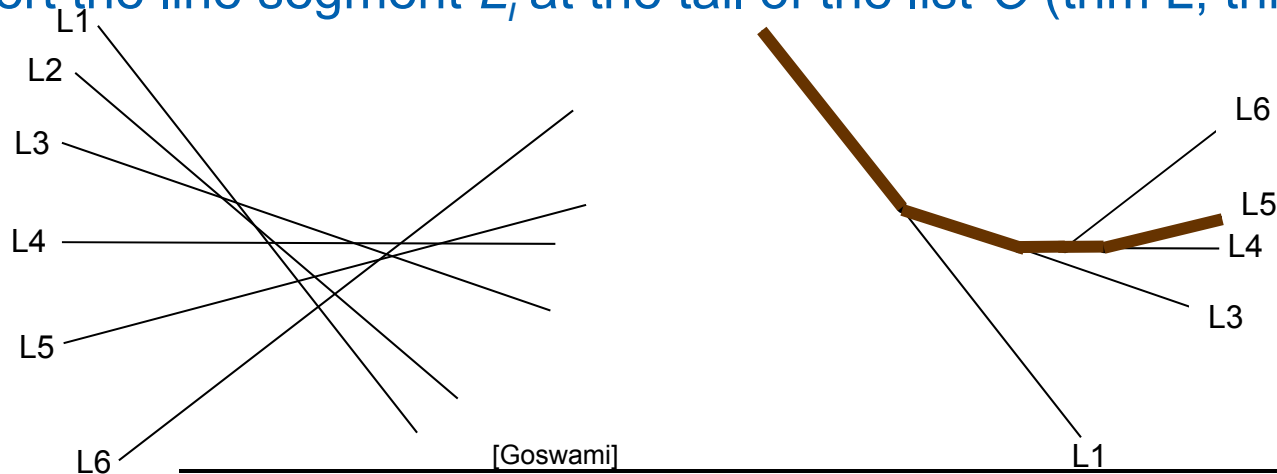
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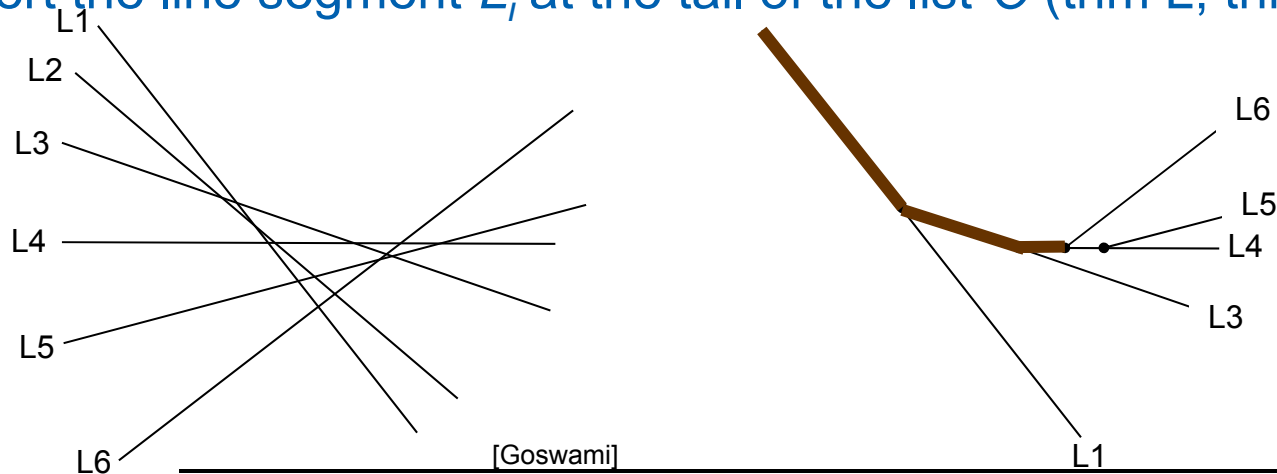
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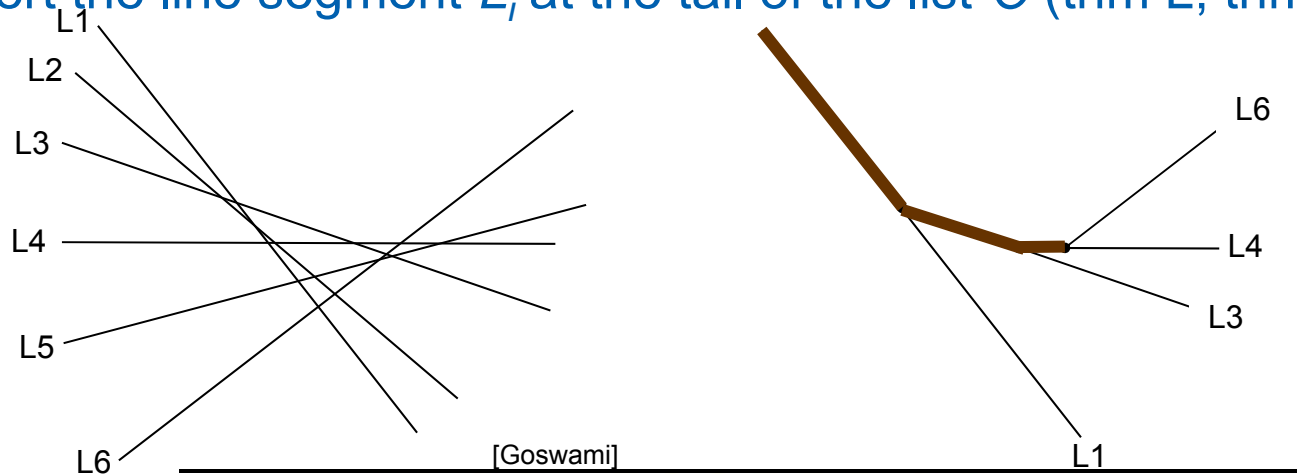
Upper envelope algorithm

UpperEnvelope(L)

Set of lines L sorted by **increasing** order of slopes (-90° to 90°)

Polygonal chain O representing the upper hull

1. $O = L_1$ // the only complete line in O
2. **for** $i = 2$ to n
3. $L =$ last entry in O // O contains half-lines, or line segments, // except of complete line L_1
4. **while**(the line segment L does not intersect line L_i)
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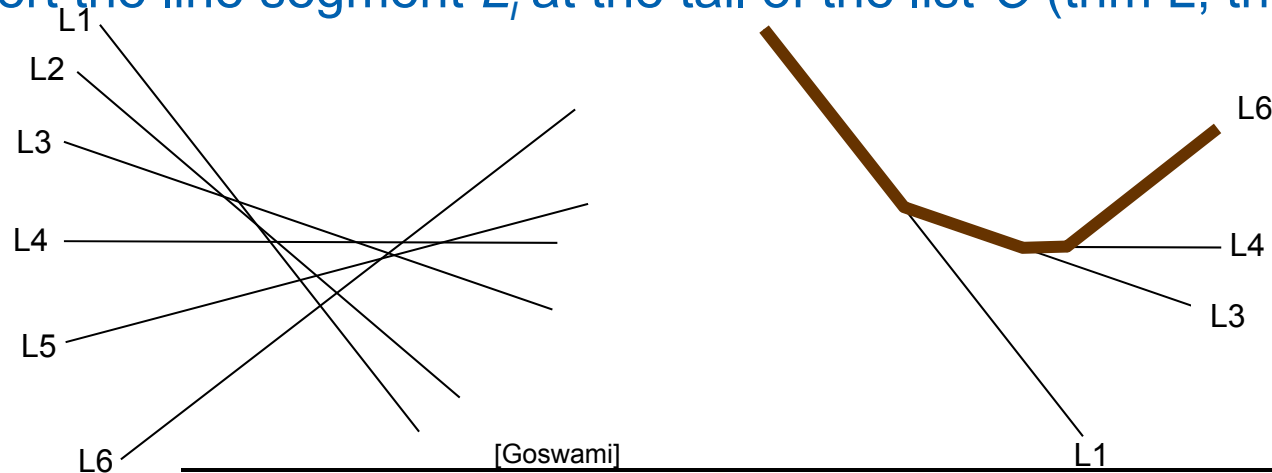
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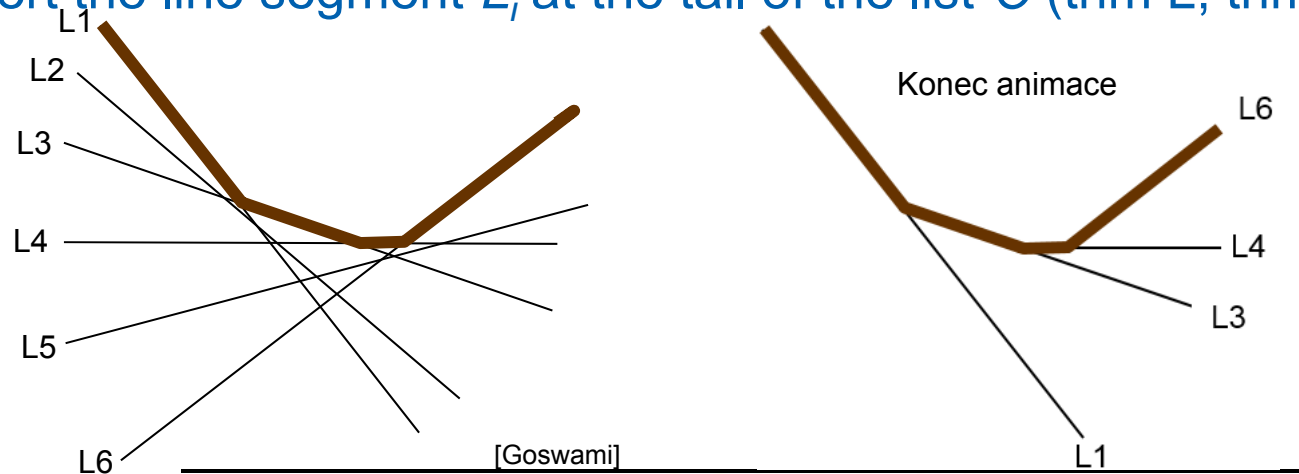
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Convex hull via upper and lower envelope

■ Upper envelope complexity

- After sorting n lines by their slopes in $O(n \log n)$ time, the upper envelope can be obtained in $O(n)$ time
- Proof: It may check more than one line segment when inserting a new line, but those ones checked are all removed except the last one.
($O(n)$ insertions, max $O(n)$ removals
=> $O(n)$ all steps. Average step $O(1)$ amortized time)

■ Convex hull complexity

- Given a set P of n points in the plane, $\text{CH}(P)$ can be computed in $O(n \log n)$ time using $O(n)$ space.



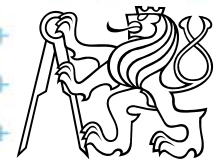
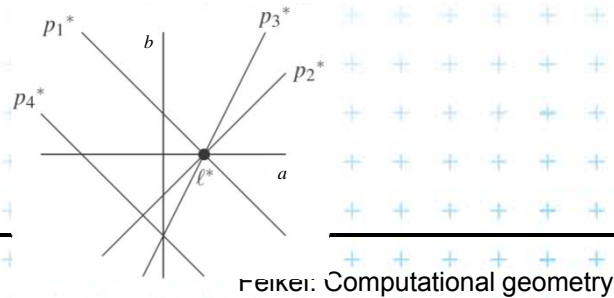
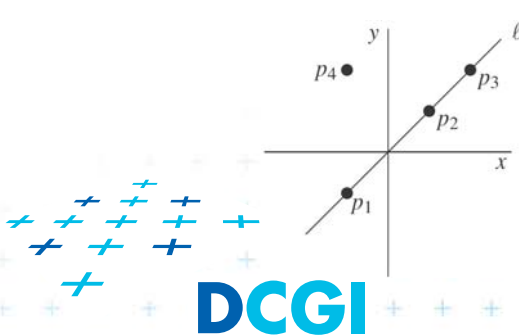
Applications of line arrangement

Examples of applications – solved in $O(n^2)$ and
↙ $O(n^2)$ space by constructing a line arrangement or
 $O(n)$ space through topological plain sweep.

a) General position test:

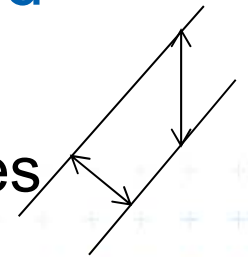
Given a set of n points in the plane, determine whether any three are collinear.

- Construct an arrangement in dual plane
- Report intersections of more than 2 lines



b) Minimum k-corridor

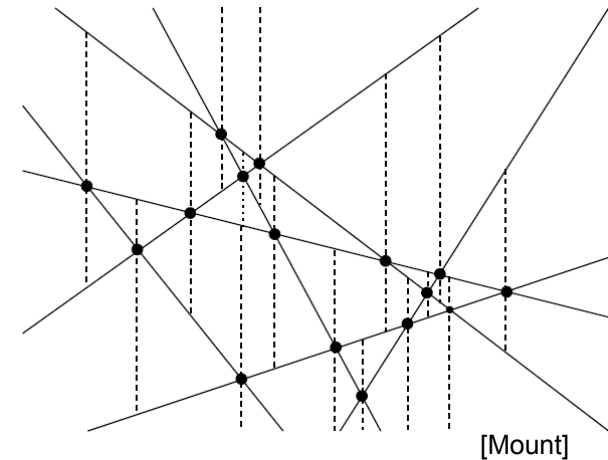
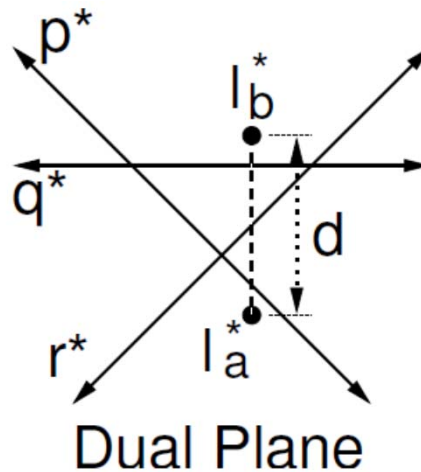
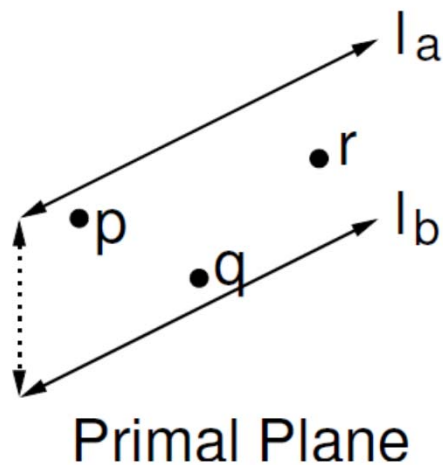
- Given a set of n points, and an integer $k \in [1 : n]$, determine the **narrowest pair of parallel lines** that **enclose at least k points** of the set.
- The distance between the lines can be defined
 - either as the **vertical distance** between the lines
 - or as the **perpendicular distance** between the lines
- Simplifications
 - Assume $k = 3$ and **no 3 points are collinear**
=> narrowest corridor - contains exactly 3 points
- has width > 0
 - No 2 points have the same x coordinate (avoid I duals)



vertical



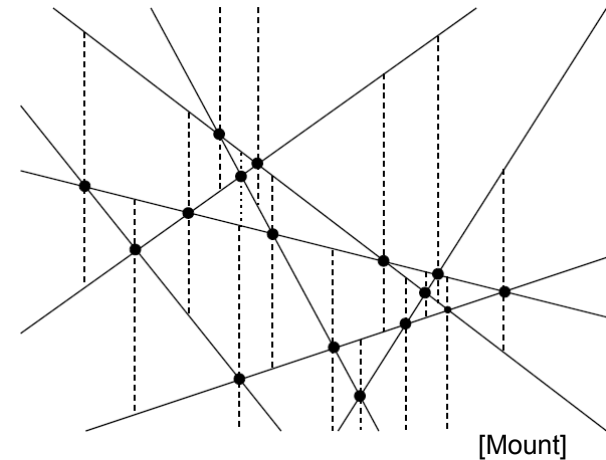
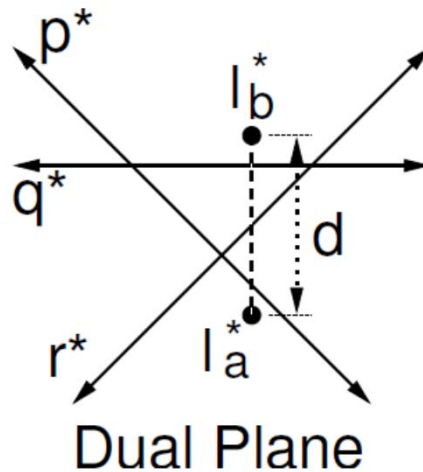
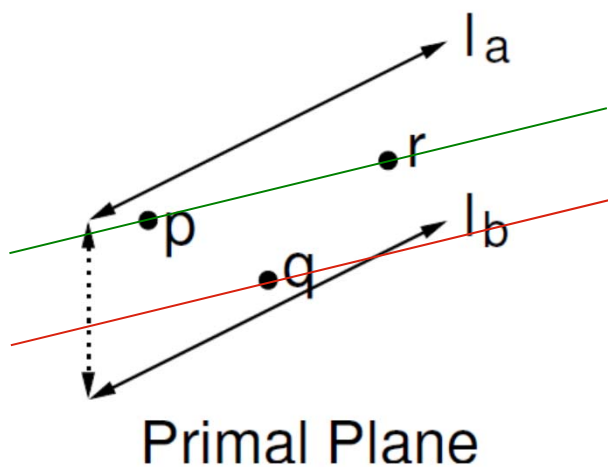
b) Minimum k-corridor



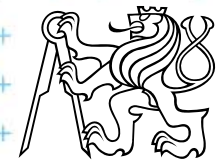
- **Vertical distance** of $l_a, l_b = (-)$ distance of l_a^*, l_b^*
- Nearest lines – one passes 2 vertices, e.g., p & r
- In dual plane are represented as intersection $p^* \times r^*$
- Find nearest 3-stabber similarly as trapezoidal map
- $O(n^2)$ time and $O(n)$ space – topological line sweep



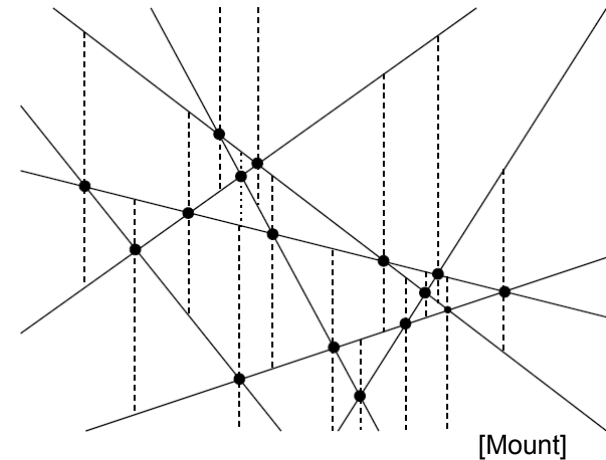
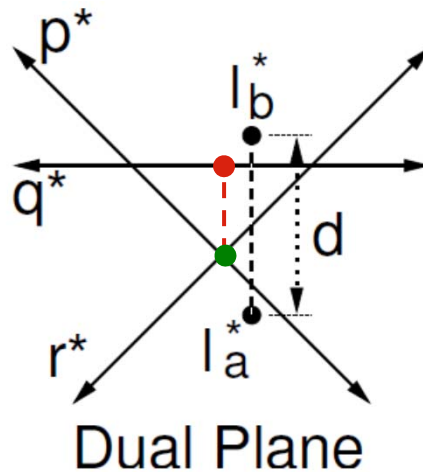
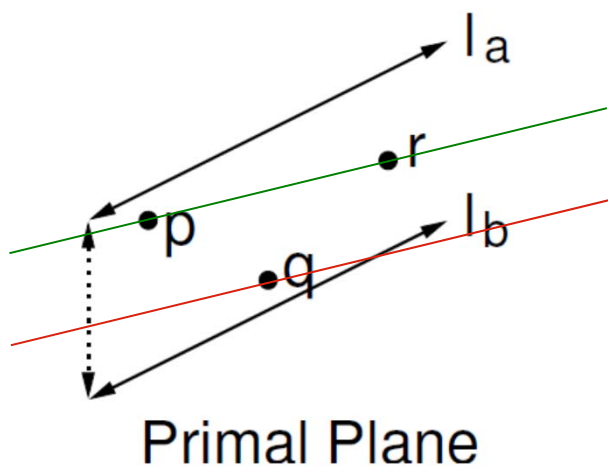
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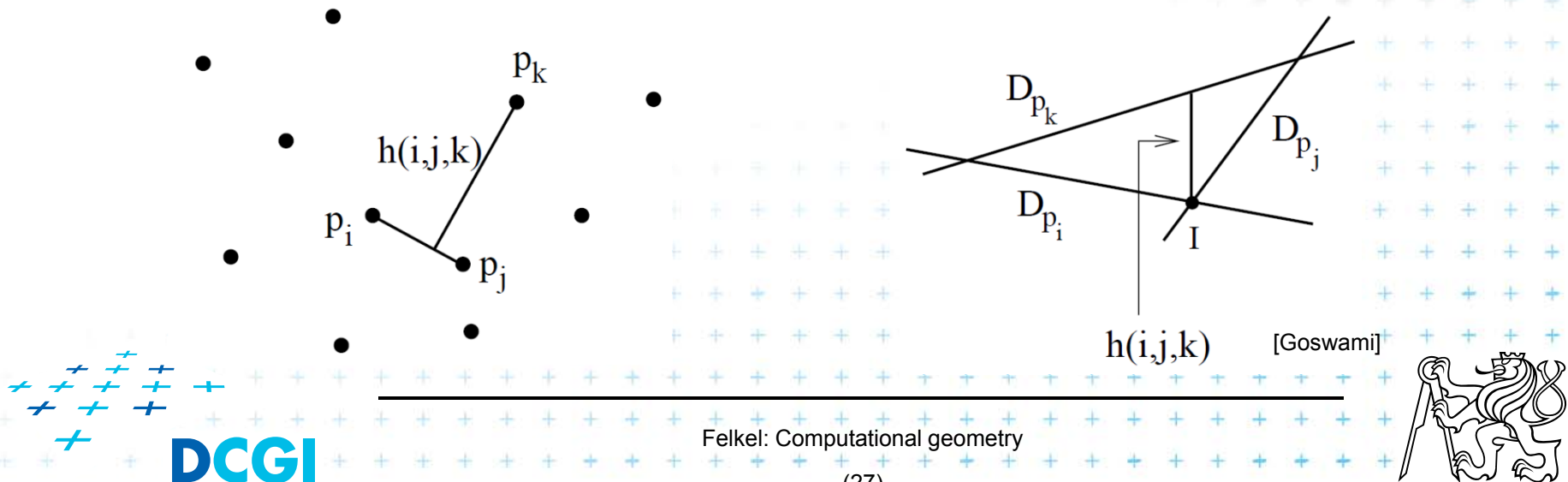
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c) Minimum area triangle

[Goswami]

- Given a set of n points in the plane, determine the minimum area triangle whose vertices are selected from these points
- Construct “trapezoids” as in the nearest corridor
- Minimize perpendicular distances (converted from vertical) multiplied by the distance from p_i to p_j



d) Sorting all angular sequences – naïve

- Natural application of duality and arrangements
- Important for **visibility graph** computation
- Set of n points in the plane
- For **each point** perform an **CCW angular sweep**
- Naïve: for each point compute angles to remaining $n - 1$ points and sort them
- $\Rightarrow O(n \log n)$ time per point
- $O(n^2 \log n)$ time overall
- Arrangements can get rid of $O(\log n)$ factor

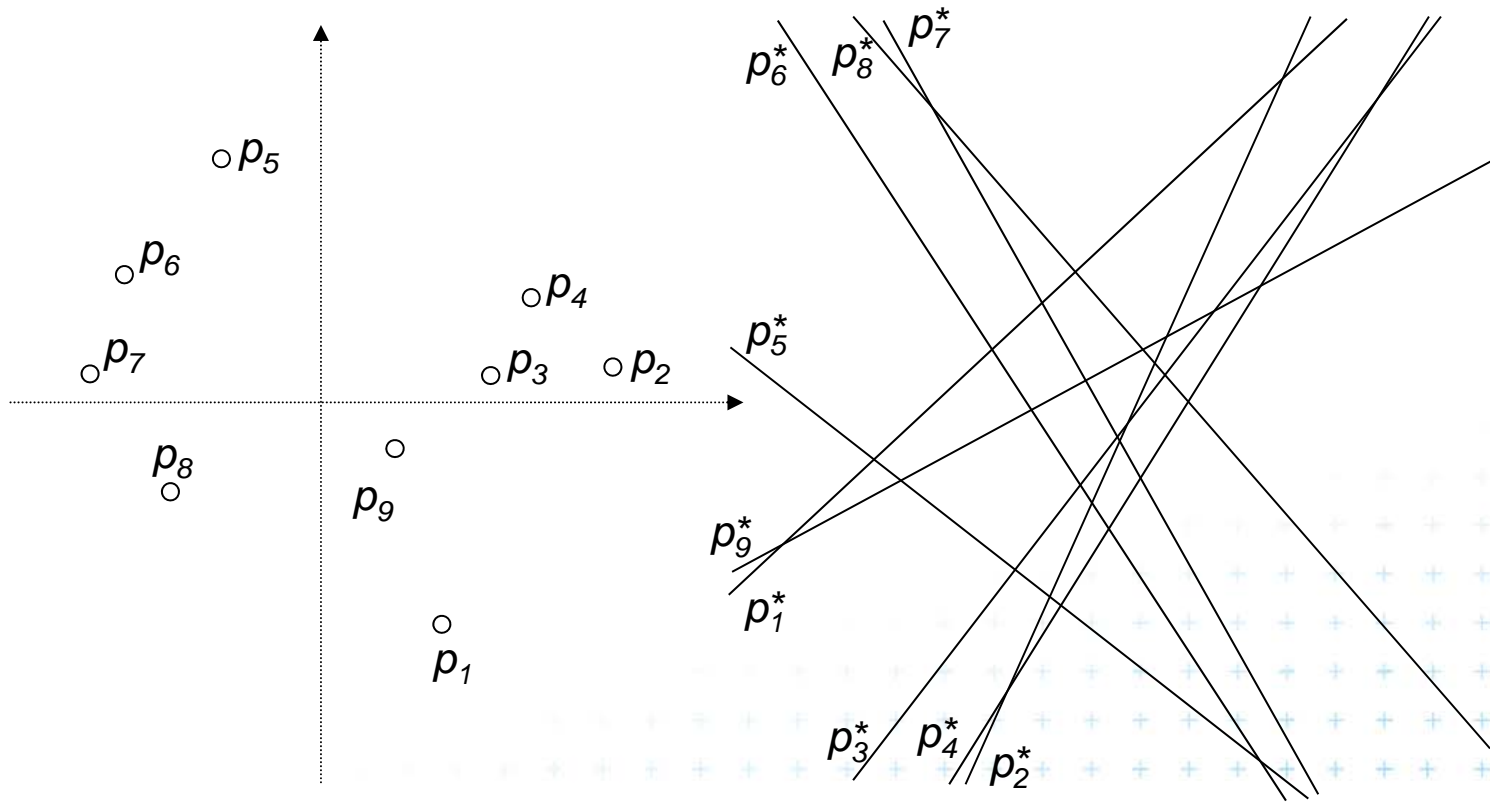


d) Sorting all angular sequences – optimal

- For point p_i
 - Dual of point p_i is line p_i^*
 - Line p_i^* intersects other dual lines in **order of slope**
(angles from -90° to 90°) (180°)
 - We need **order of angles around p_i**
(angles from -90° to 270°) (360°)
 - Split points in primal plane by vertical line through p_i
 - First, report intersections of points **right of p_i**
 - Second, report the intersections of points **left of p_i**
 - Once the arrangement is constructed:
 $O(n)$ time for point, **$O(n^2)$ time for all n points**



d) Angular sequence around p_9

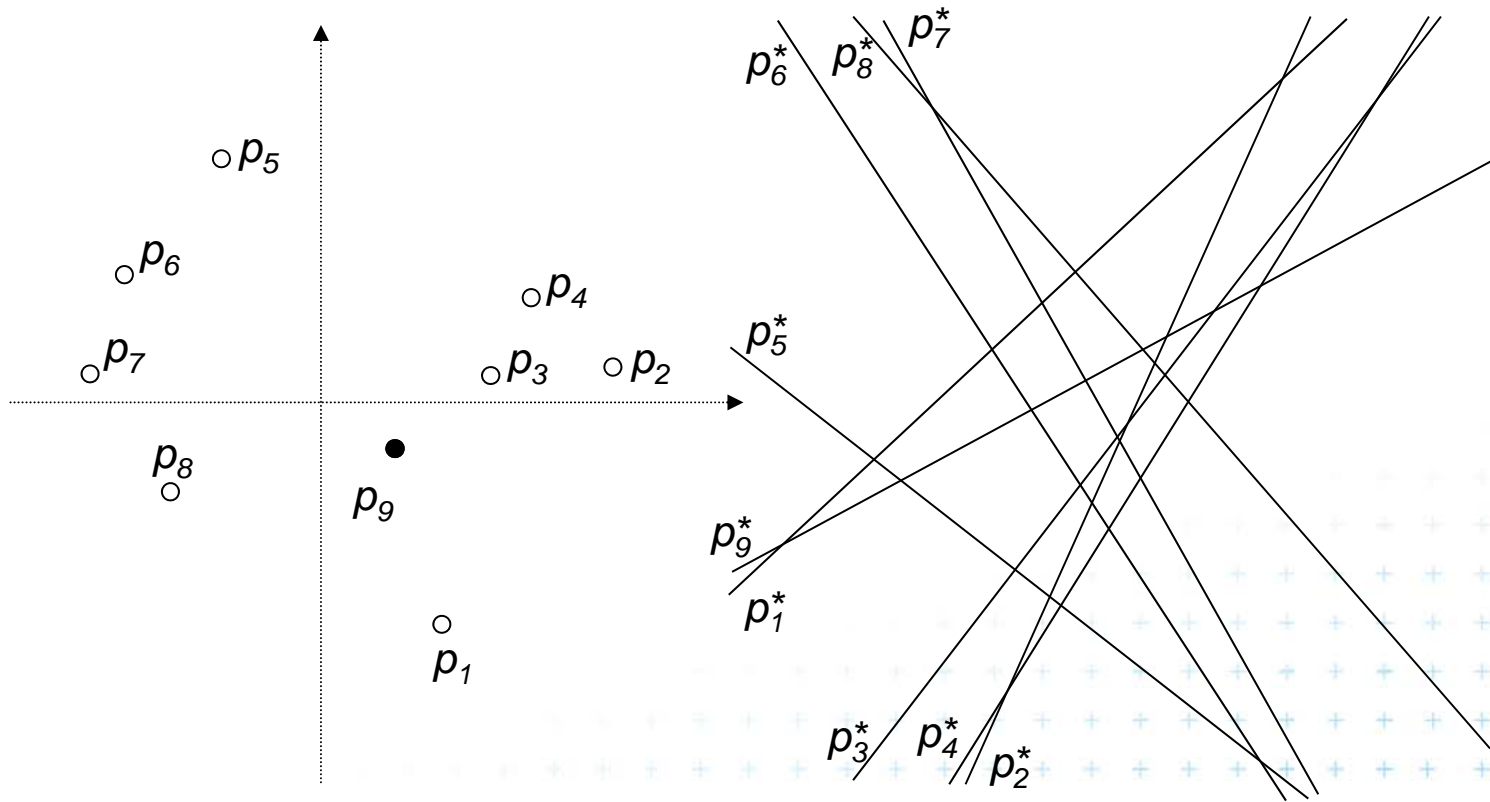


In primal plane

In dual plane

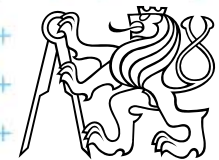


d) Angular sequence around p_9

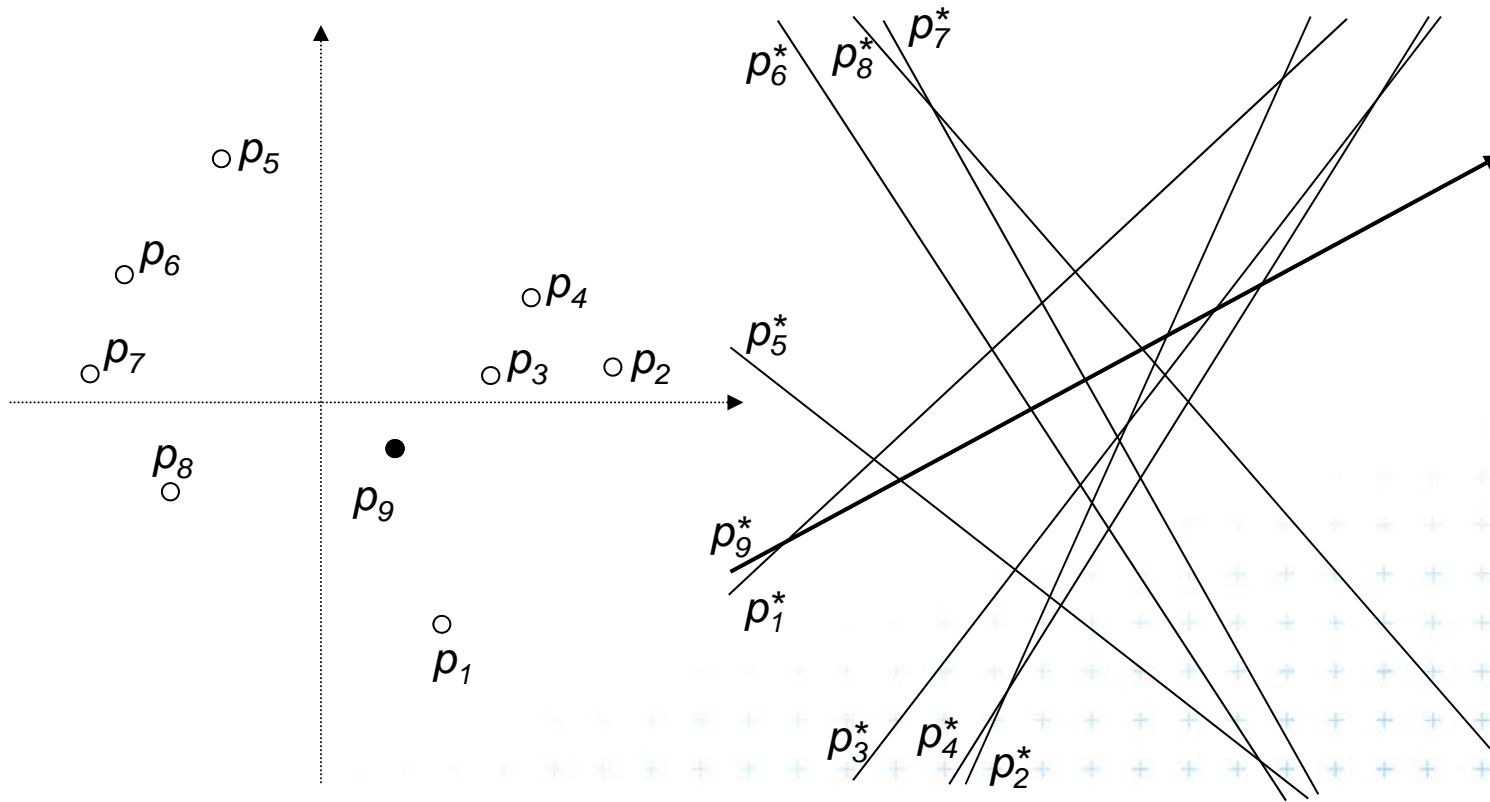


In primal plane

In dual plane



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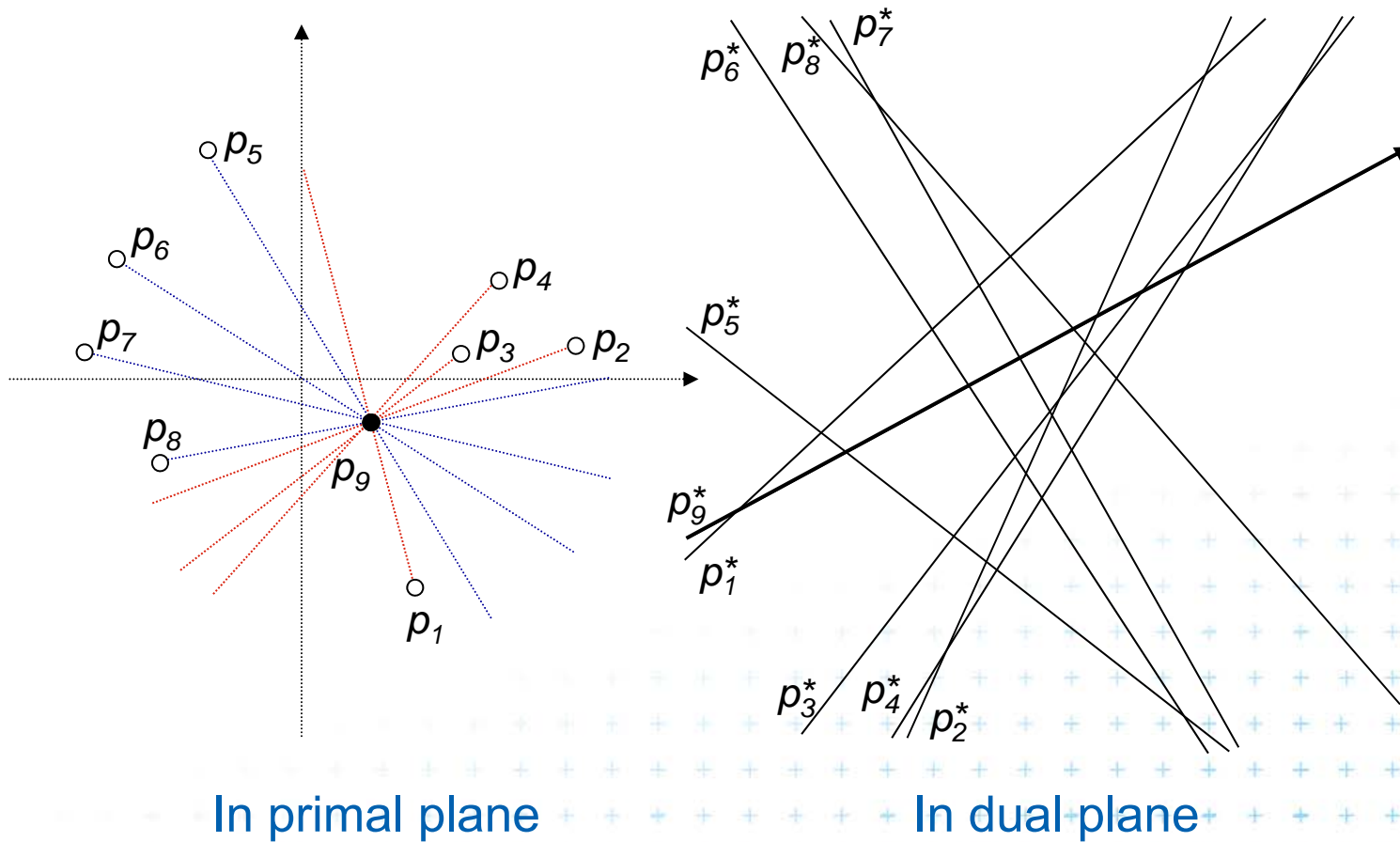


In primal plane

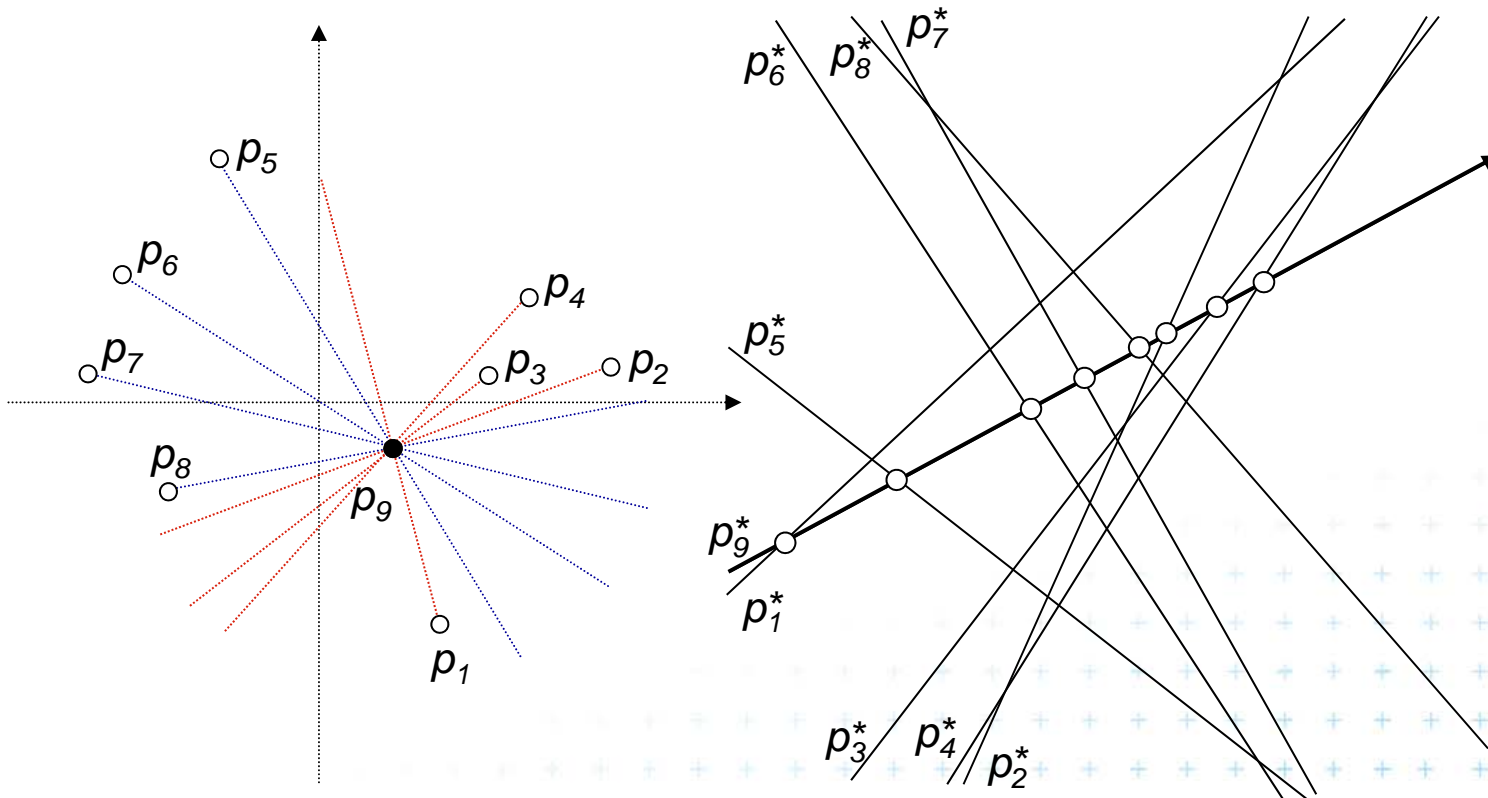
In dual plane



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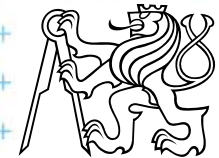
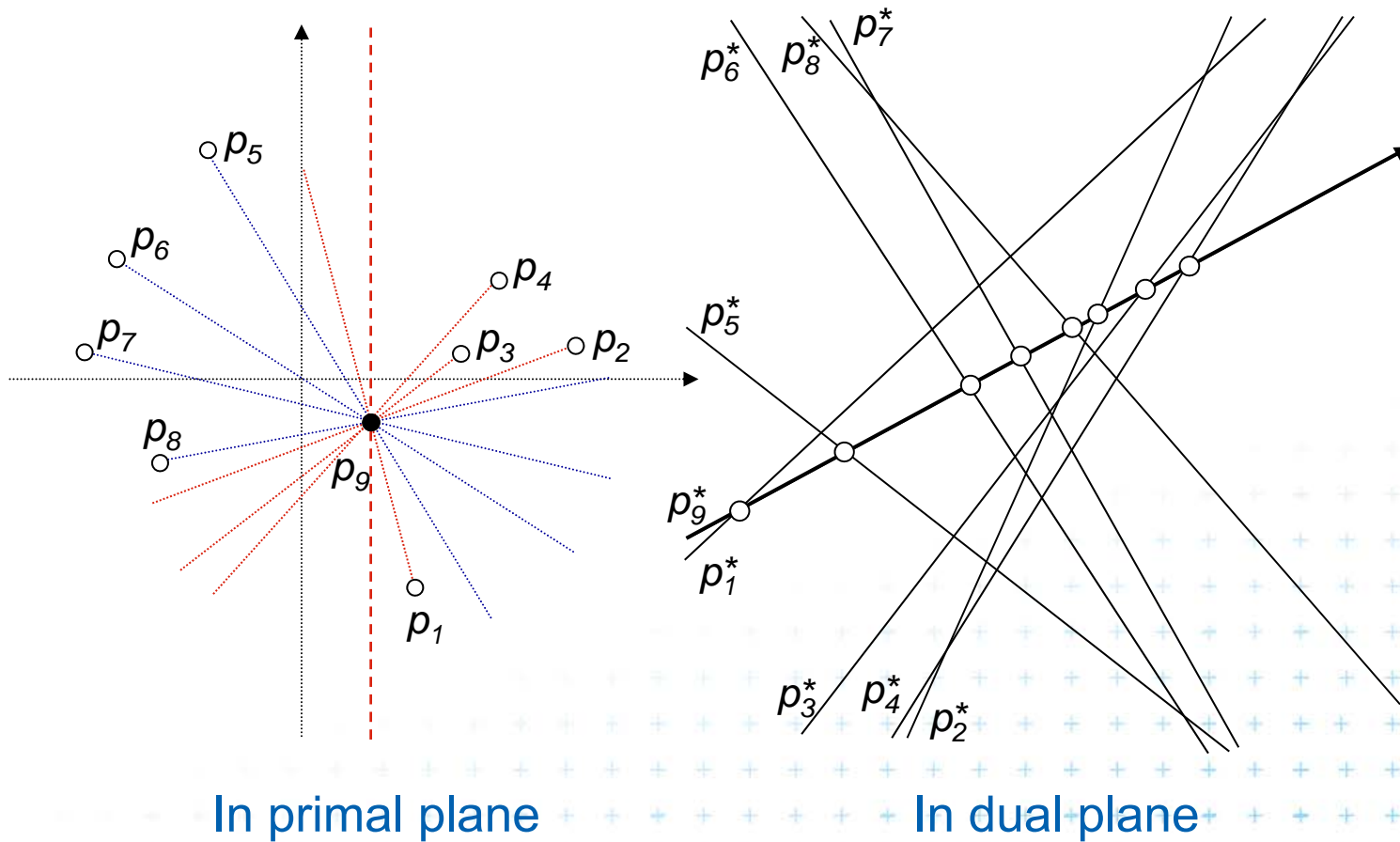


In primal plane

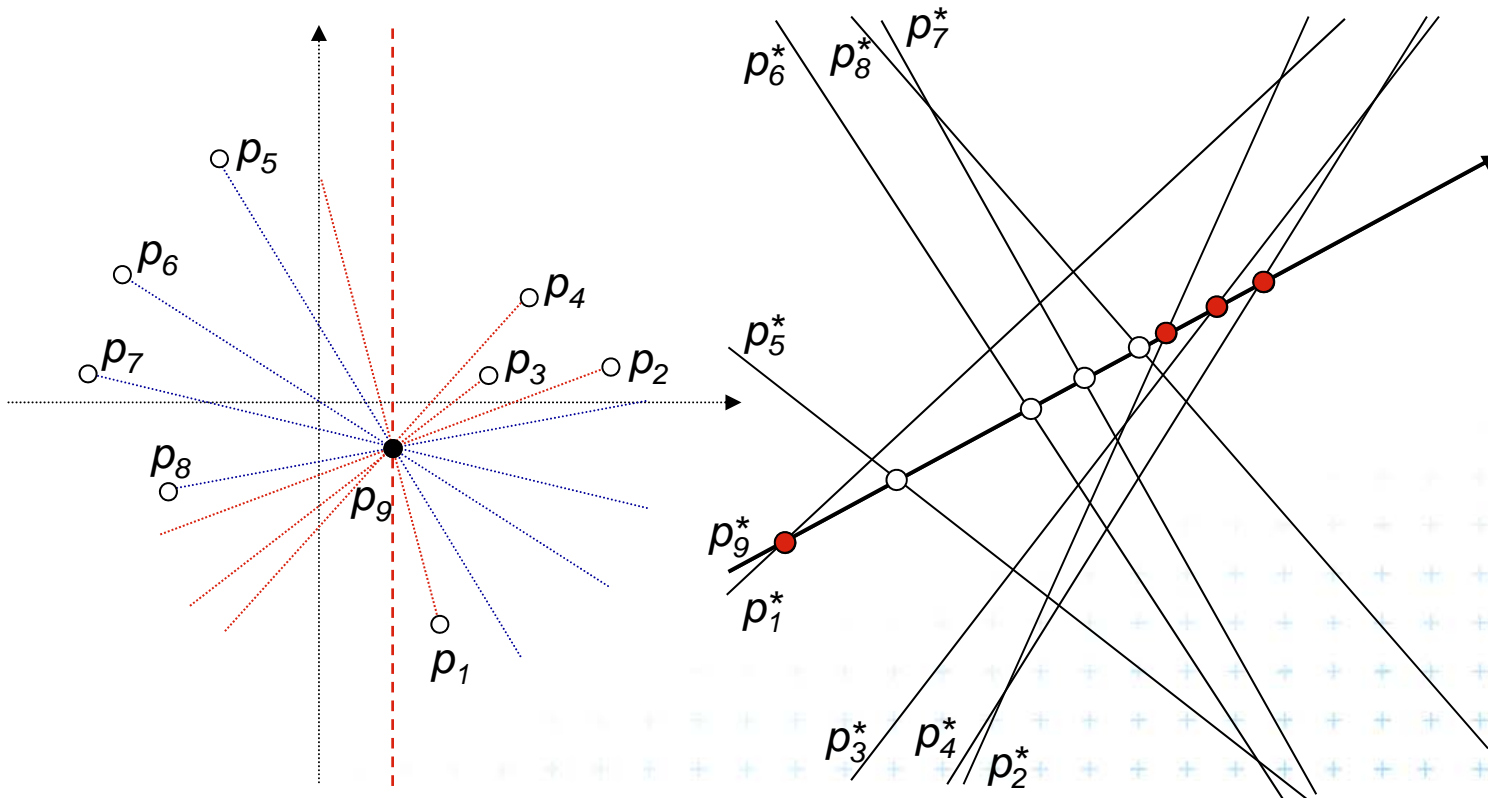
In dual plane



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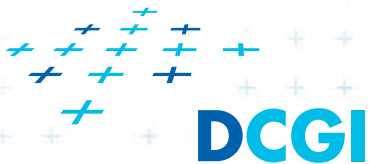


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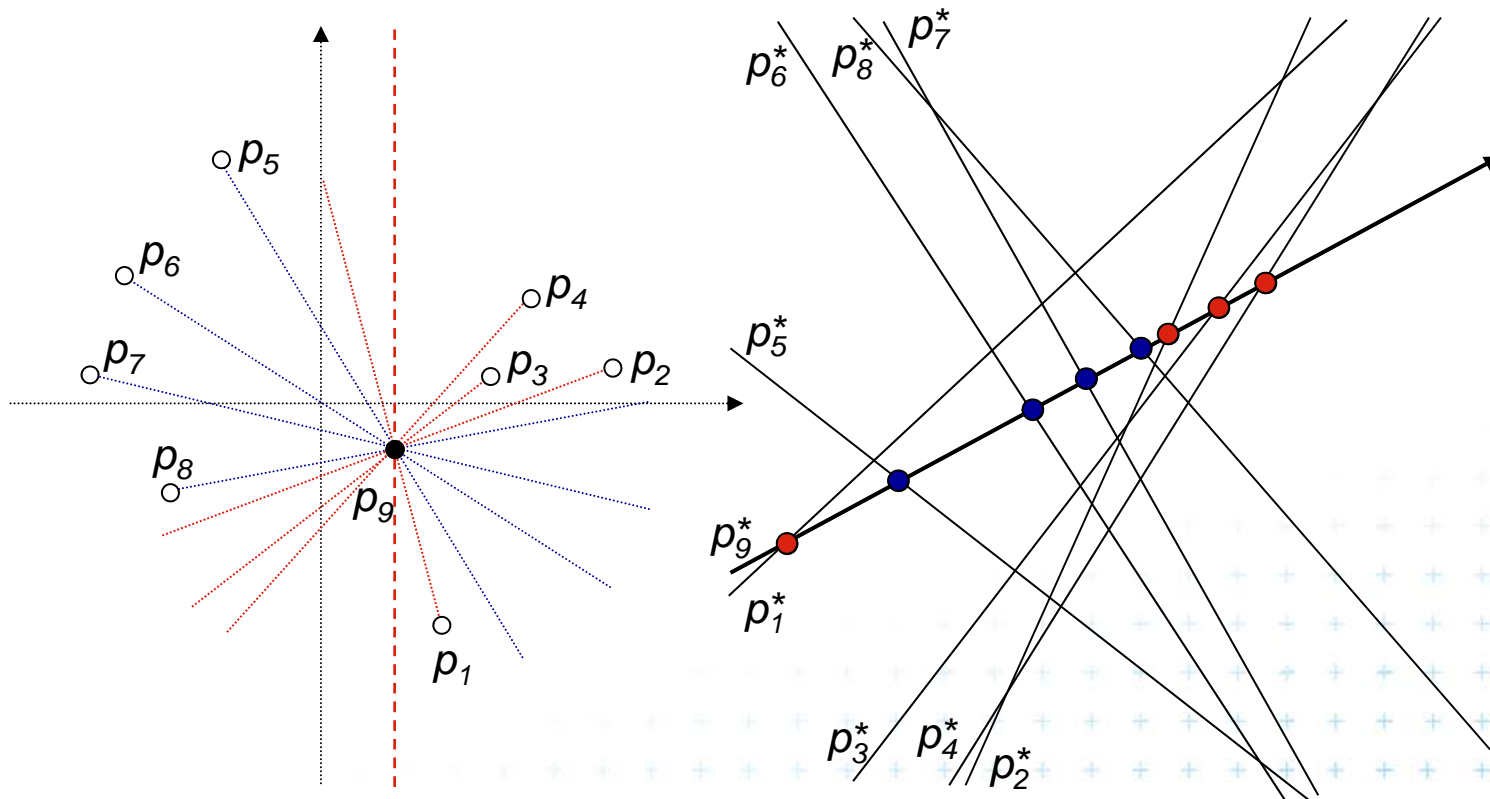


In primal plane

In dual plane

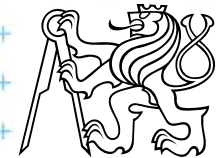


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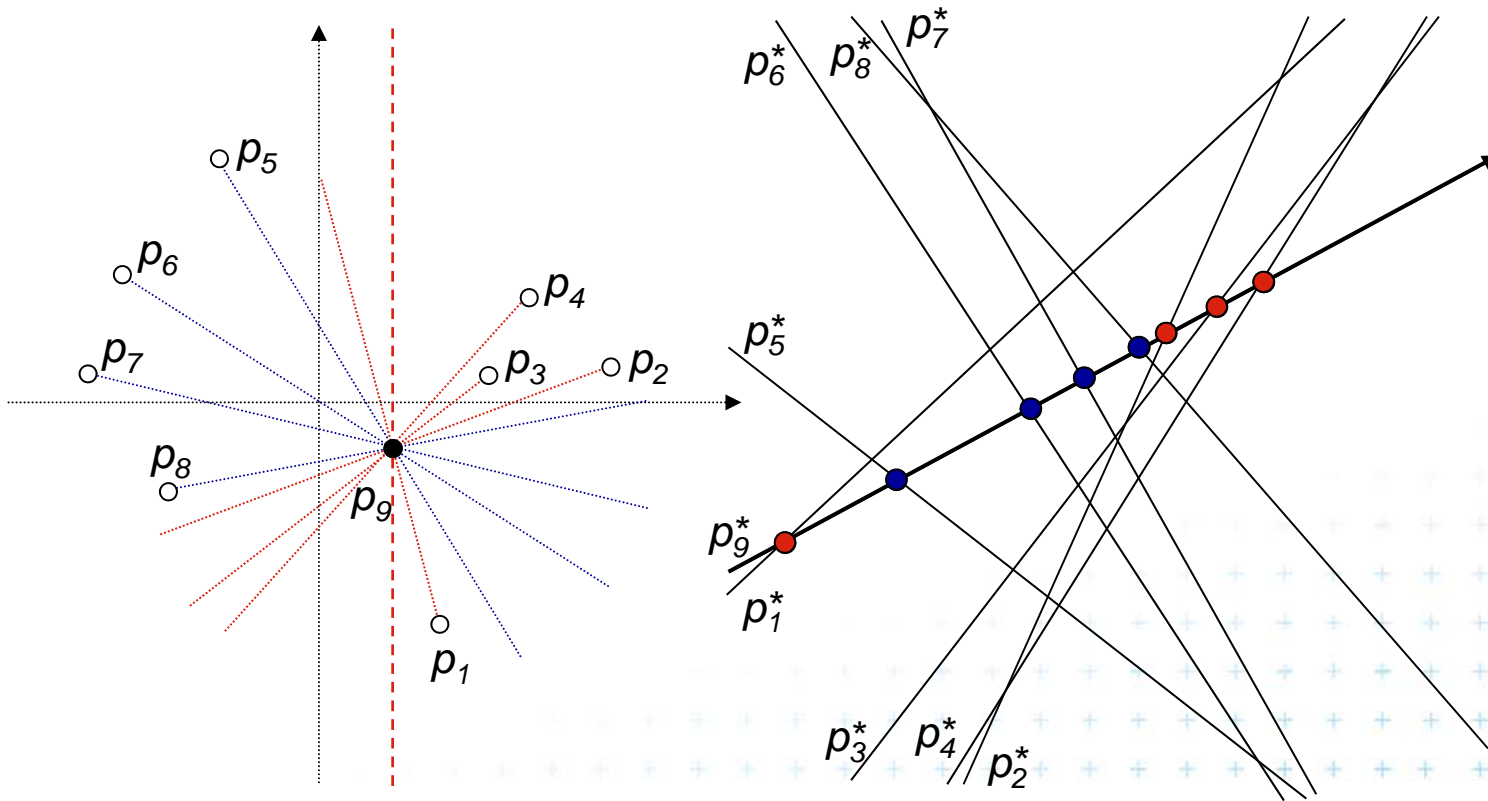


In primal plane

In dual plane



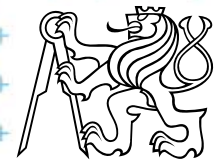
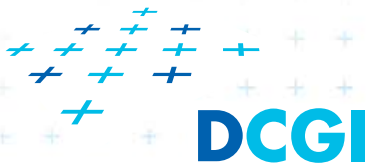
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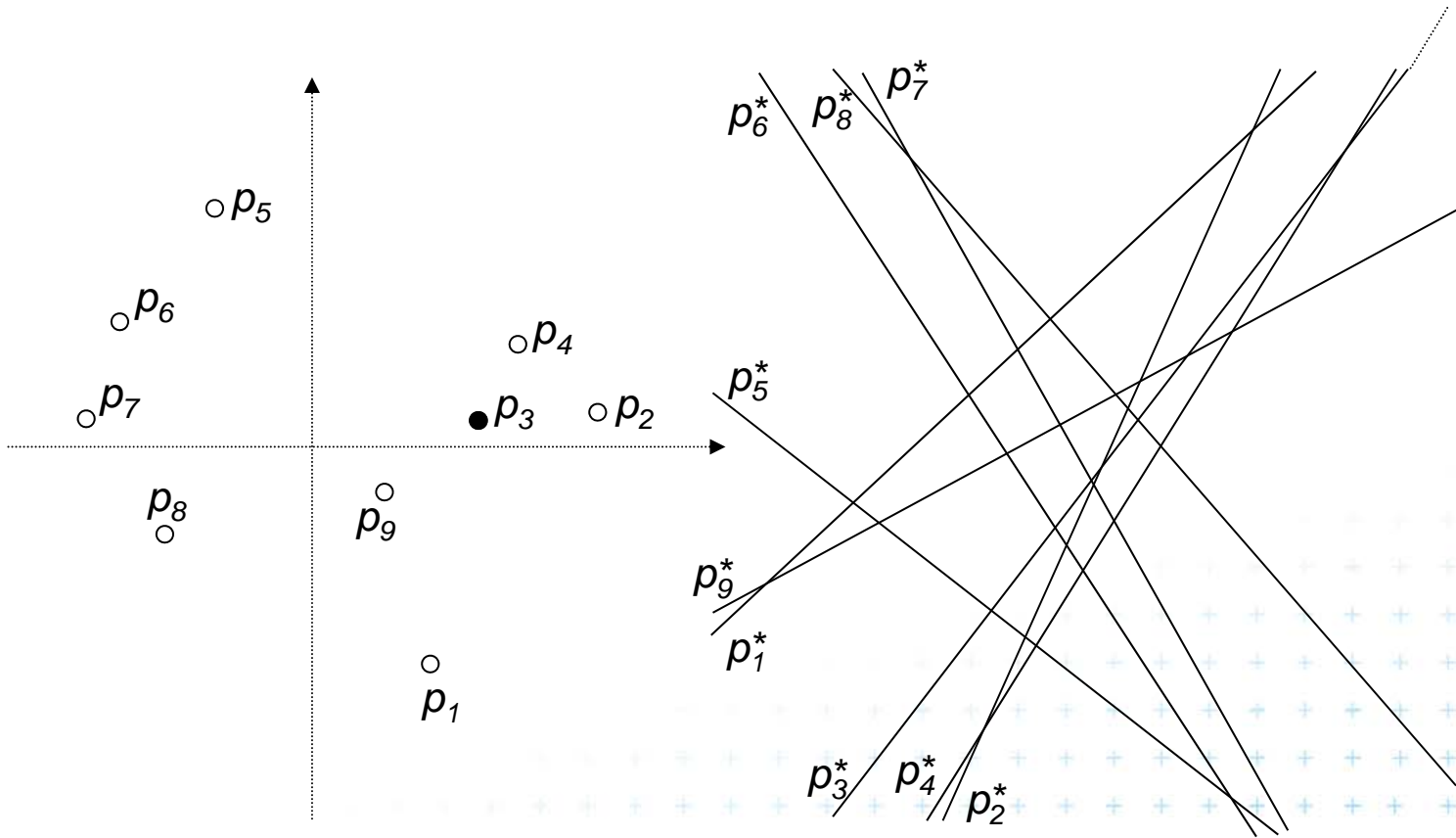
In primal plane

In dual plane

Point order around p_9 : $p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8$



d) Angular sequences around p_3

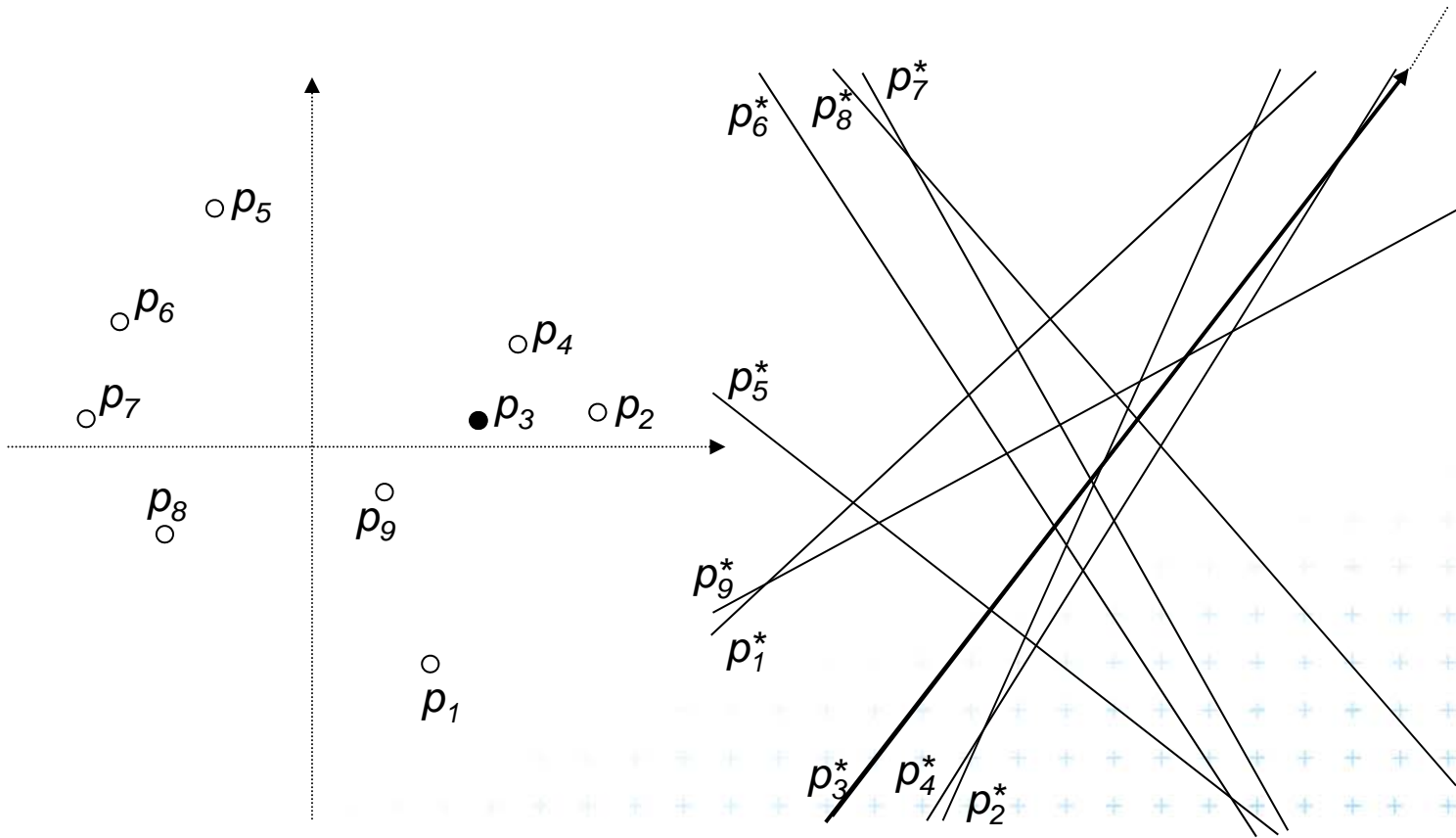


In primal plane

In dual plane



d) Angular sequences around p_3

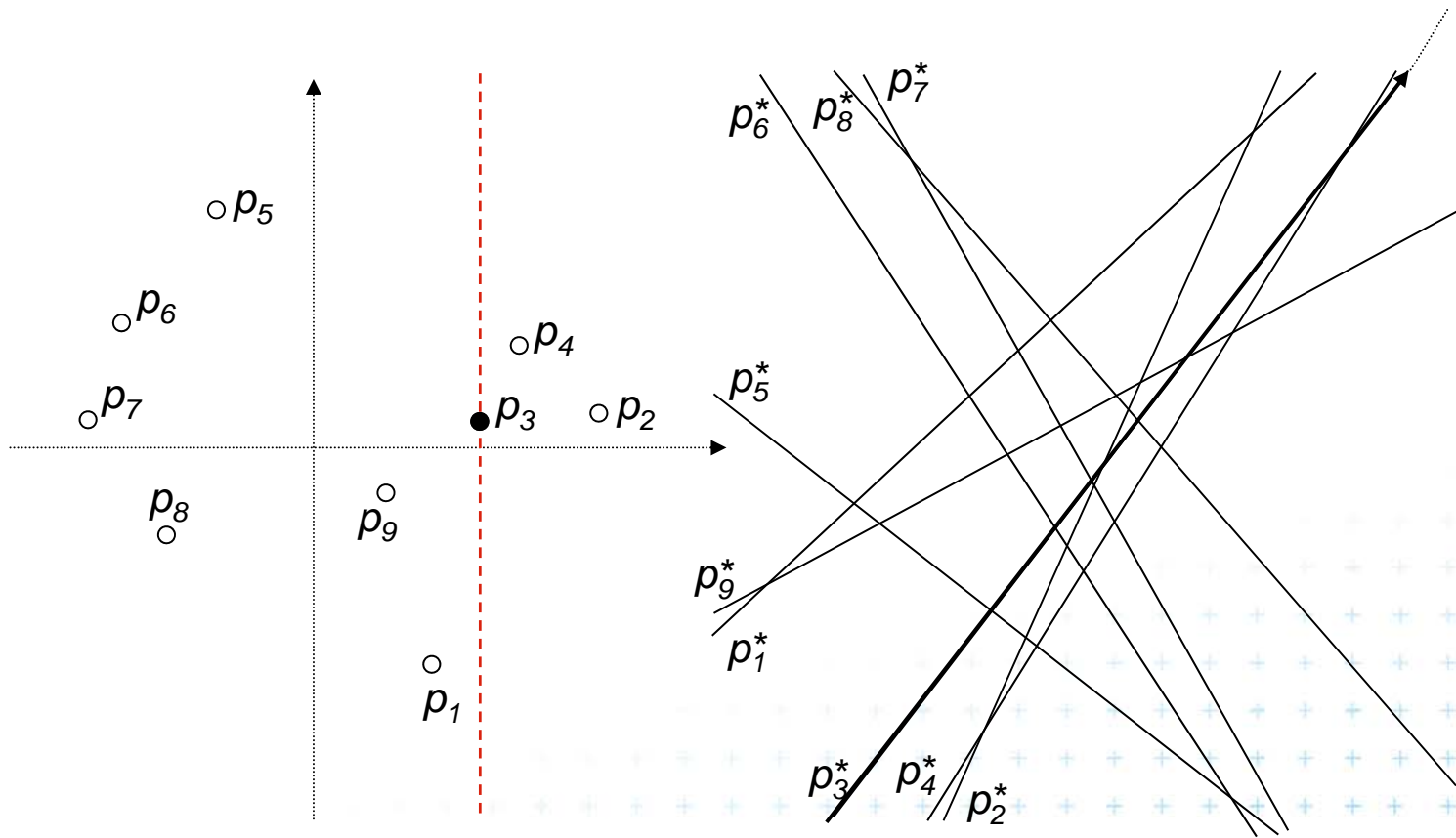


In primal plane

In dual plane



d) Angular sequences around p_3

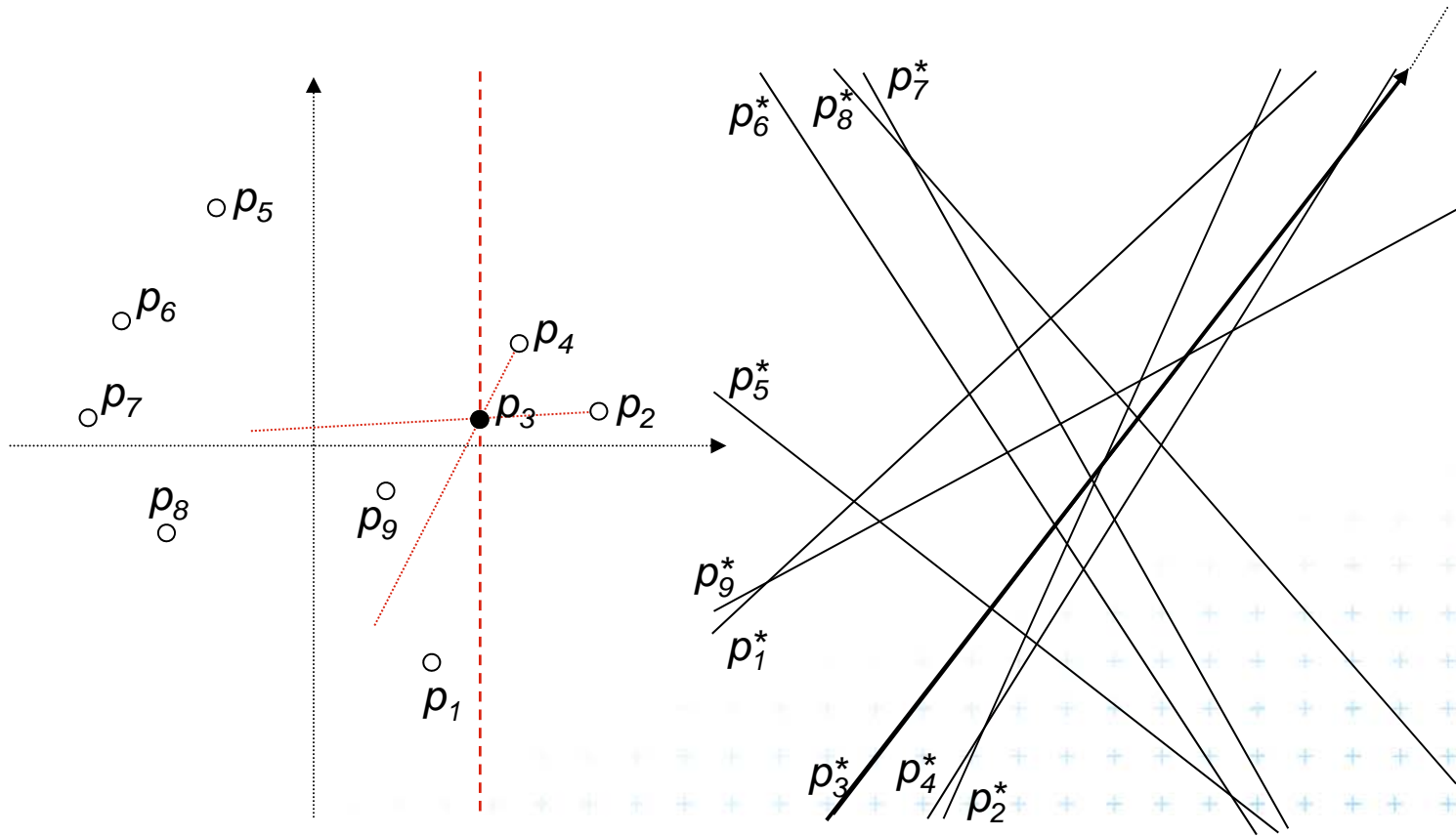


In primal plane

In dual plane

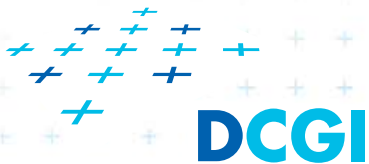


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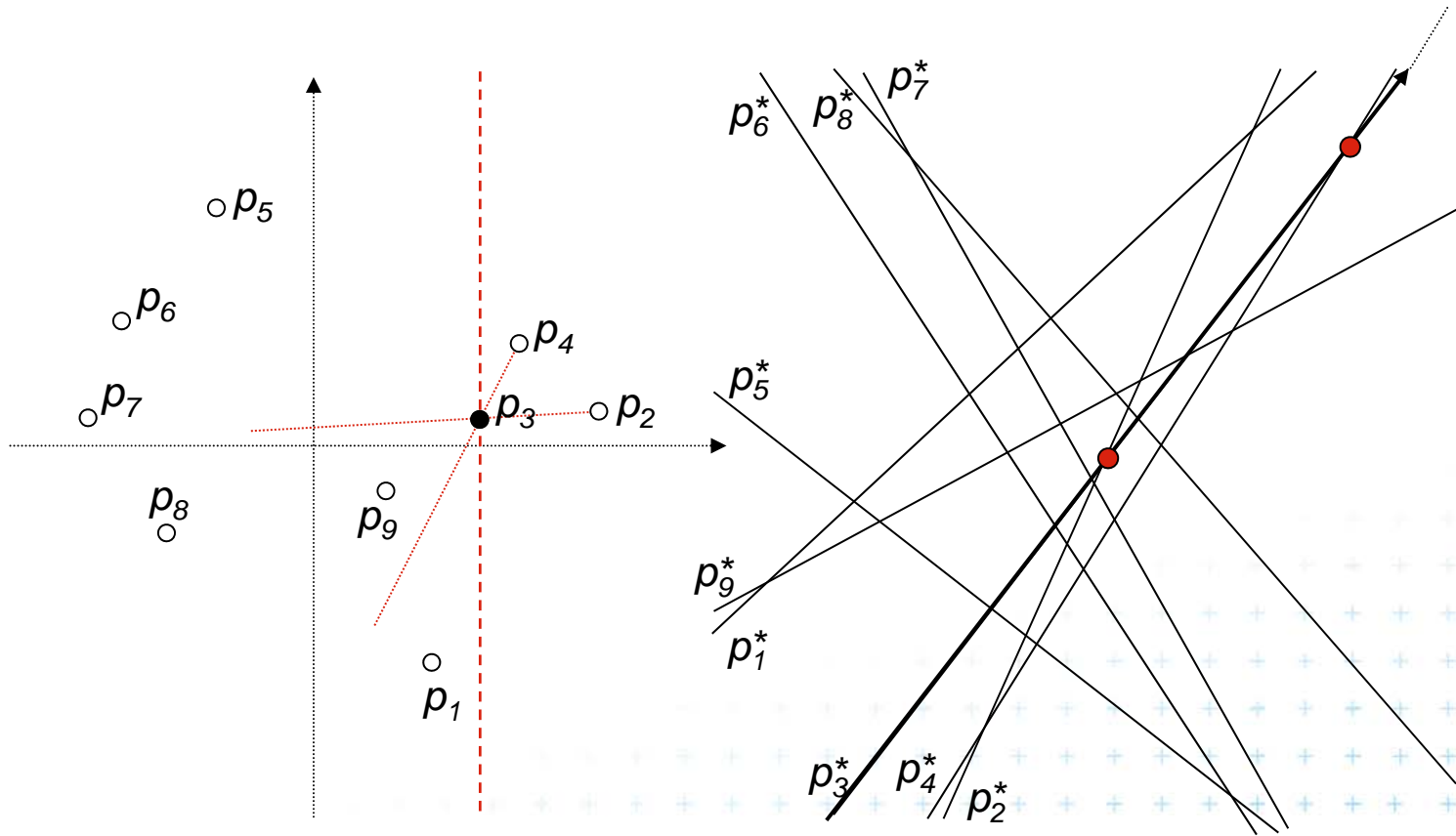


In primal plane

In dual plane

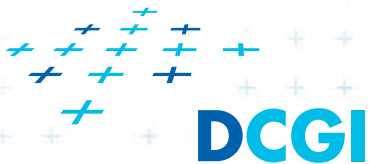


d) Angular sequences around p_3

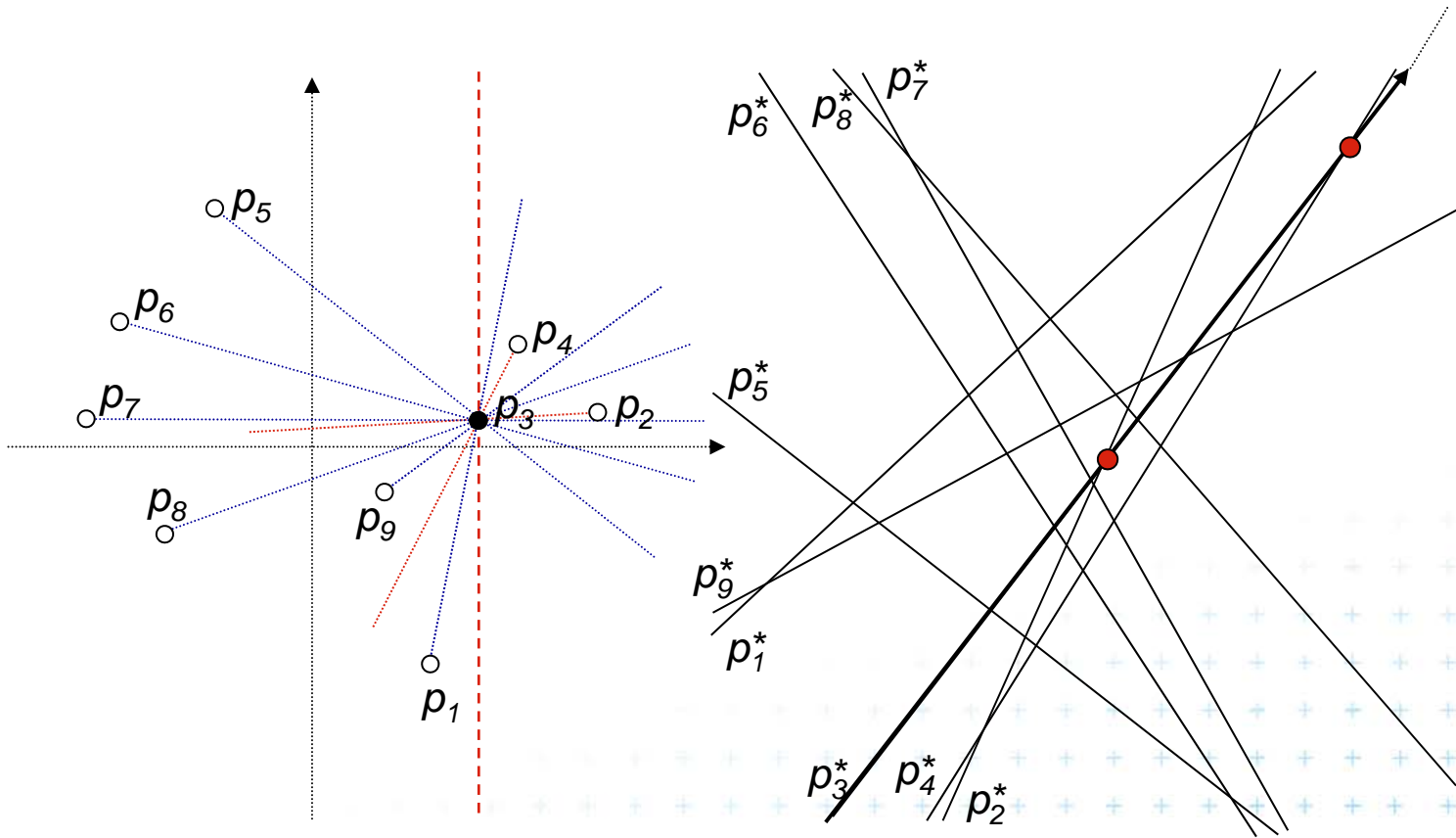


In primal plane

In dual plane



d) Angular sequences around p_3

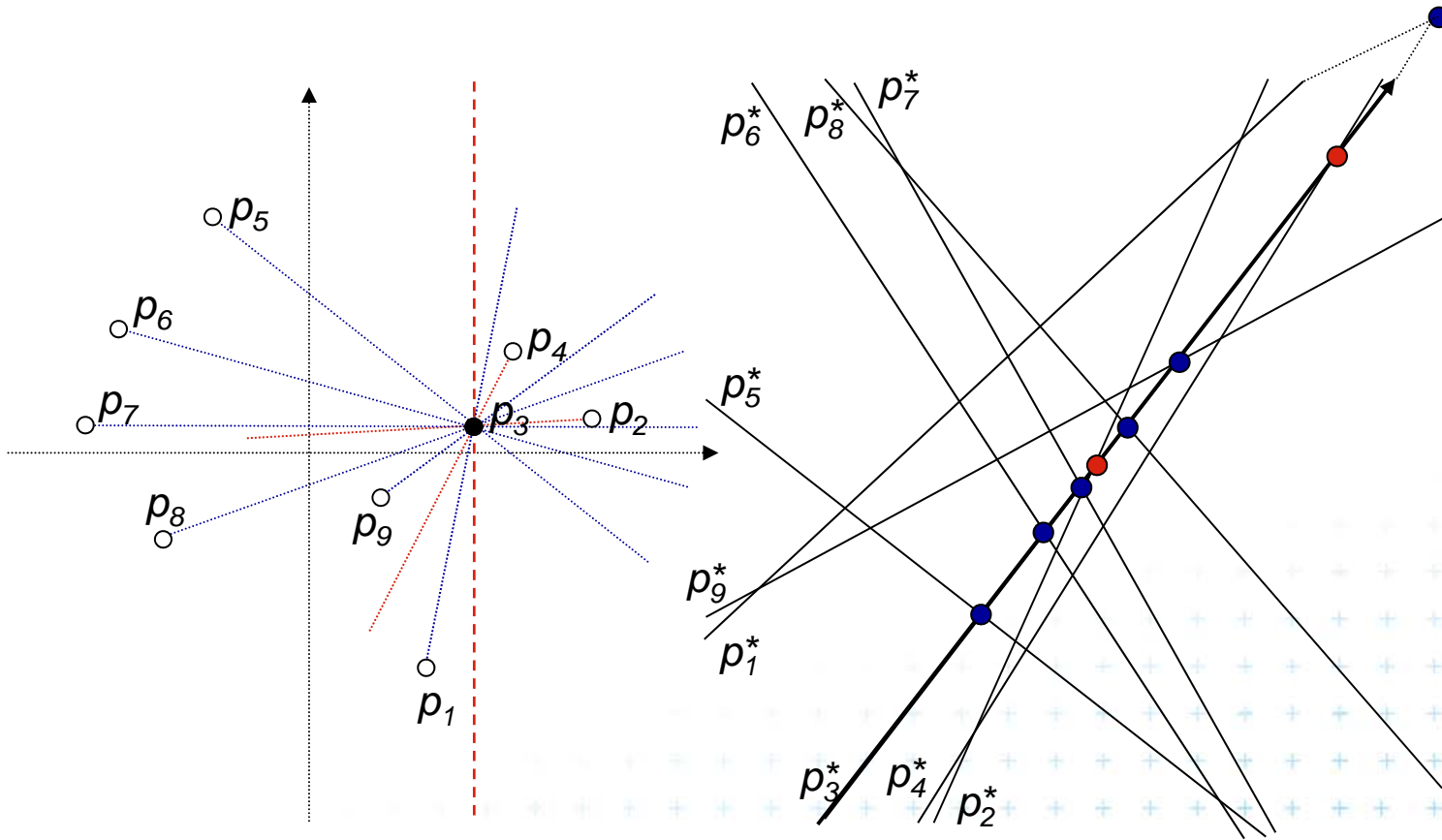


In primal plane

In dual plane



d) Angular sequences around p_3

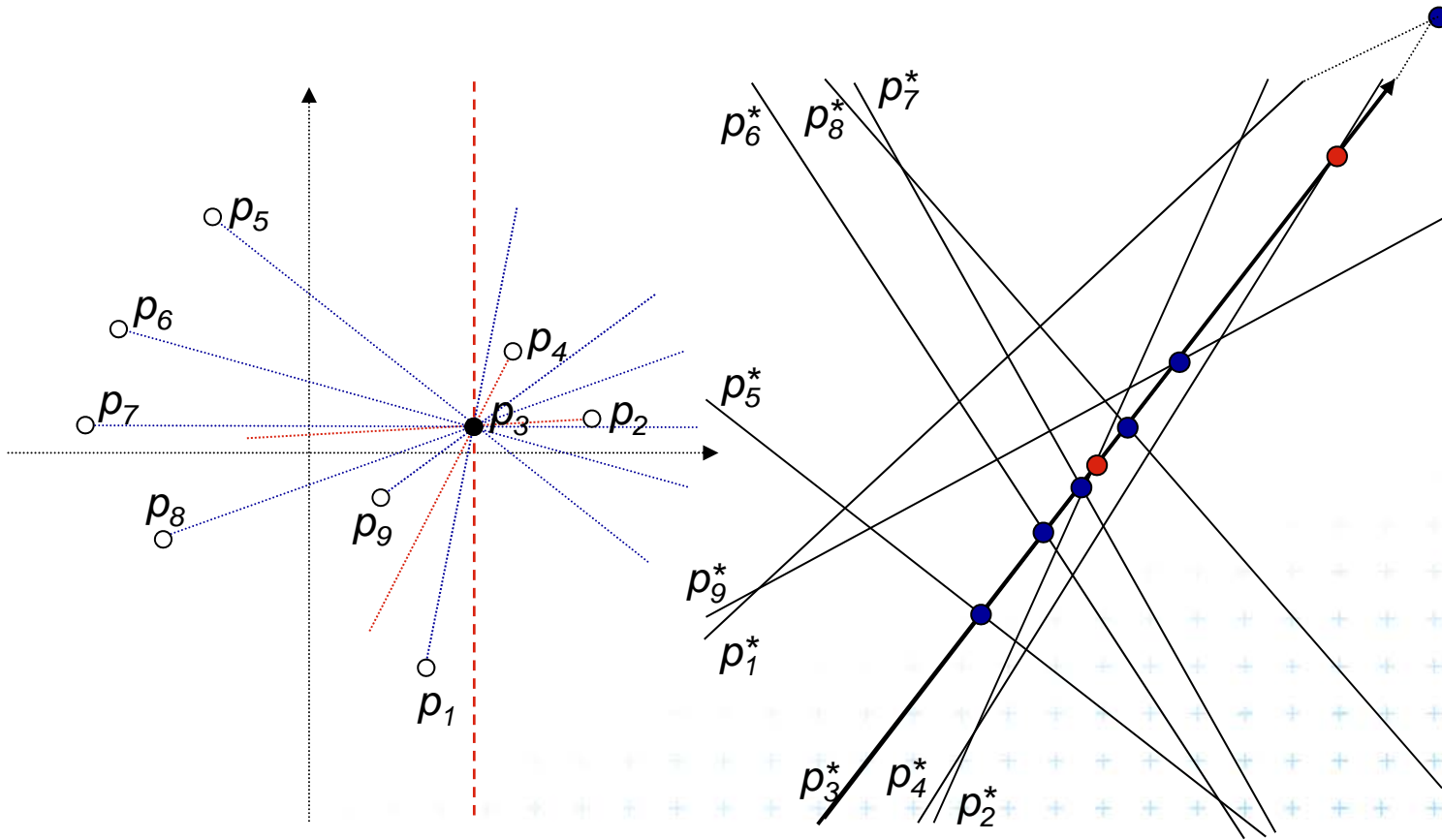


In primal plane

In dual plane



d) Angular sequences around p_3



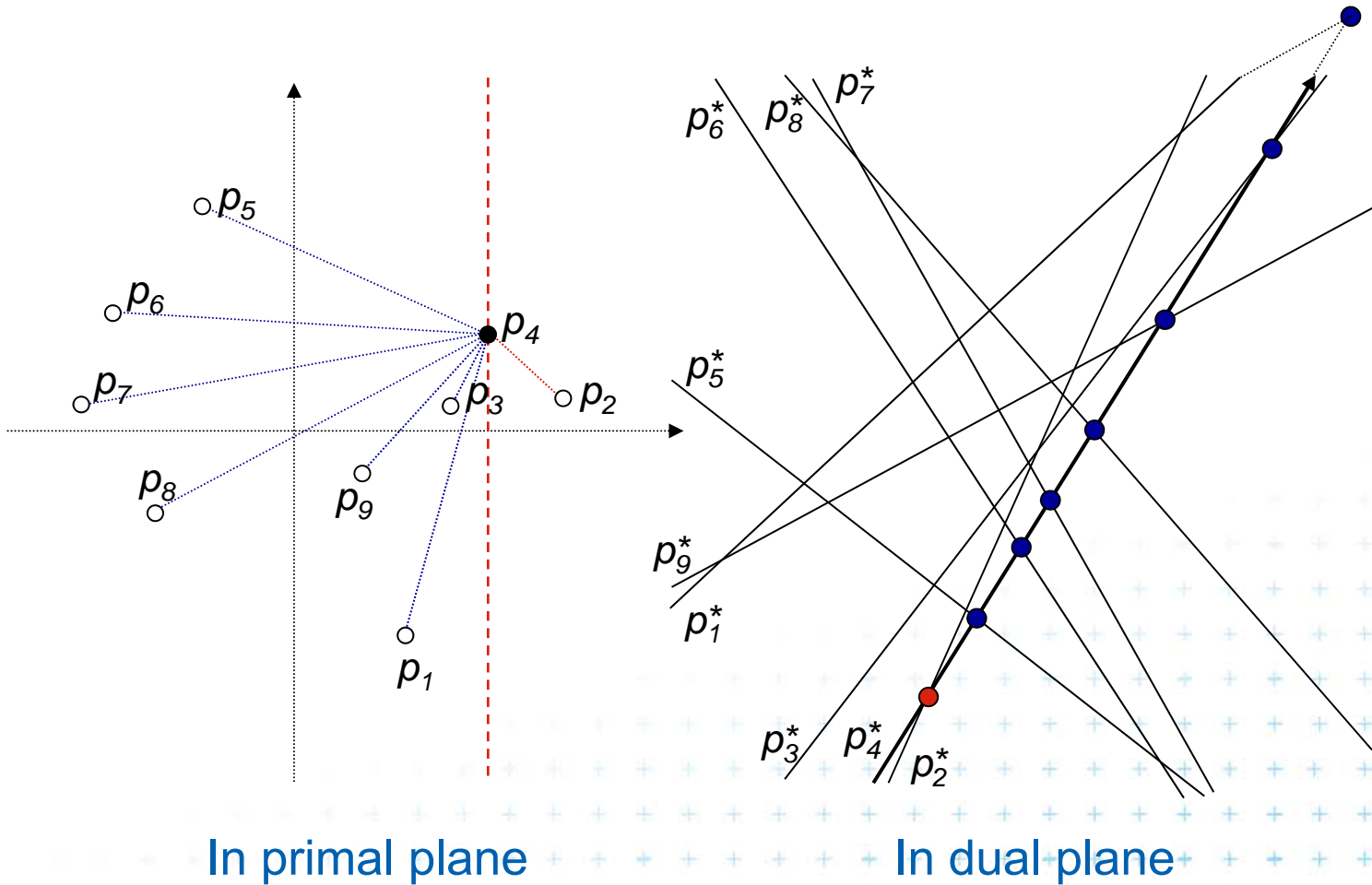
In primal plane

In dual plane

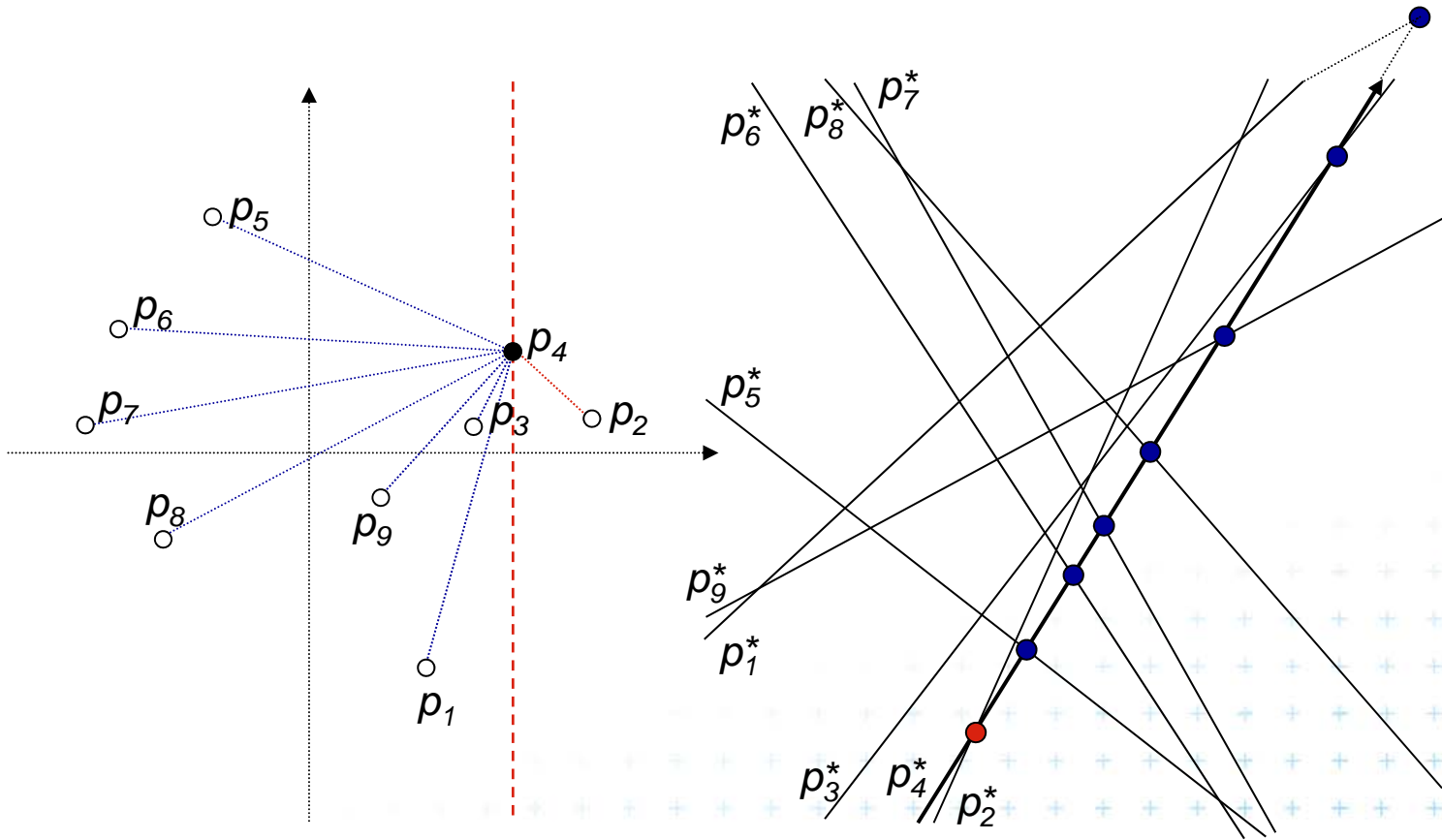
Point order around p_3 : $p_2, p_4, p_5, p_6, p_7, p_8, p_3, p_1$



d) Angular sequences around p_4



d) Angular sequences around p_4



In primal plane

In dual plane

Point order around p_4 : $p_2, p_5, p_6, p_7, p_8, p_9, p_3, p_1$



e) More applications of line arrangement

Visibility graph

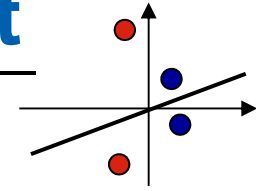
Given a set of n non-intersecting line segments, compute the *visibility graph*, whose vertices are the endpoints of the segments, and whose edges are pairs of visible endpoints (use angular sequences).

Maximum stabbing line

Given a set of n line segments in the plane, compute the line that stabs (intersects) the maximum number of these line segments.



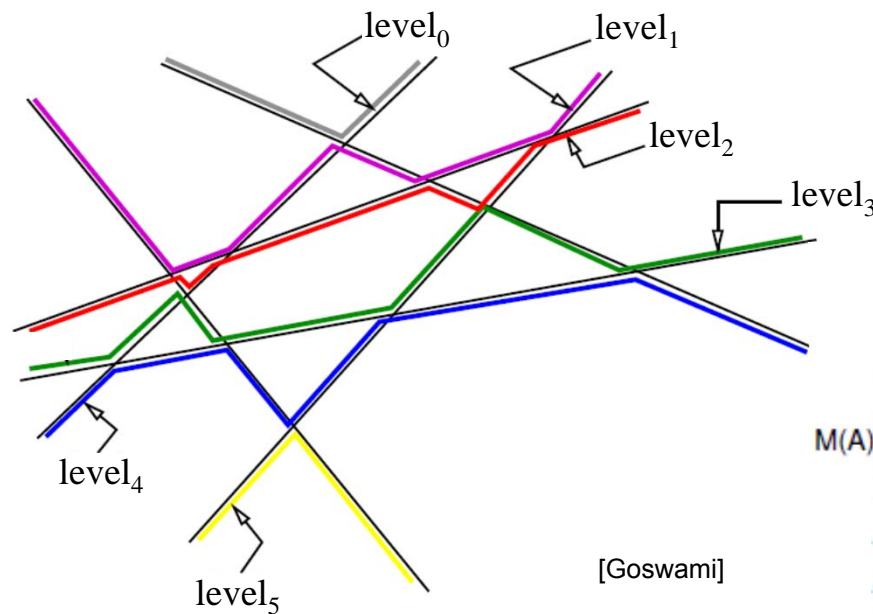
More applications of line arrangement



Ham-Sandwich cut

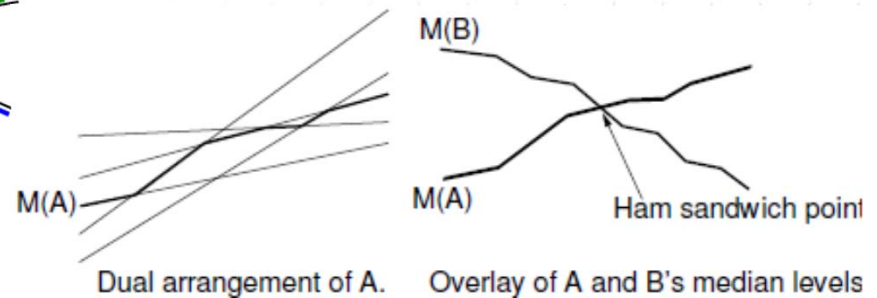
Given two sets of points, n red and m blue points compute a **single line that simultaneously bisects both sets**

Principle – intersect middle levels of arrangements



[Goswami]

Point at k -th level L_k has
at most k lines above and
at most $n - k - 1$ lines below



Dual arrangement of A.

Overlay of A and B's median levels

[Mount]



DCGI



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