CSCI 4560/6560 Computational Geometry

https://www.cs.rpi.edu/~cutler/classes/computationalgeometry/F23/

Lecture 13: Arrangements & Duality

Outline for Today

- Homework 5 Questions?
- Last Lecture: Problems that reduce to Voronoi Diagrams
- Duality: Points $\leftrightarrow$ Lines
- Arrangement of Lines
- Complexity of an Arrangement of Lines
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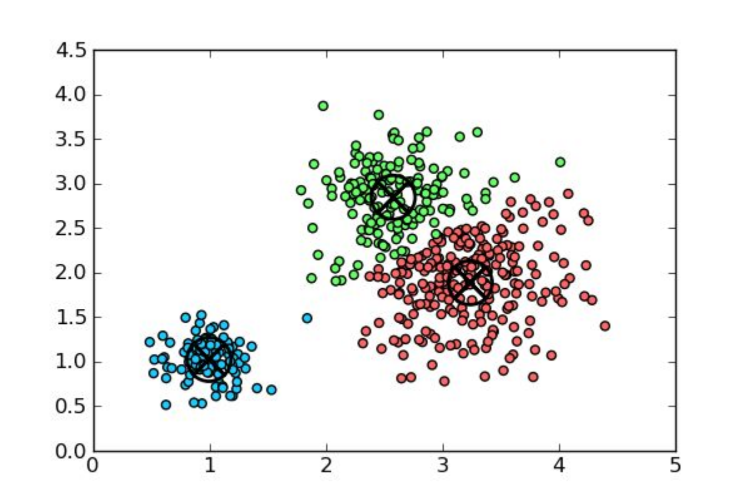
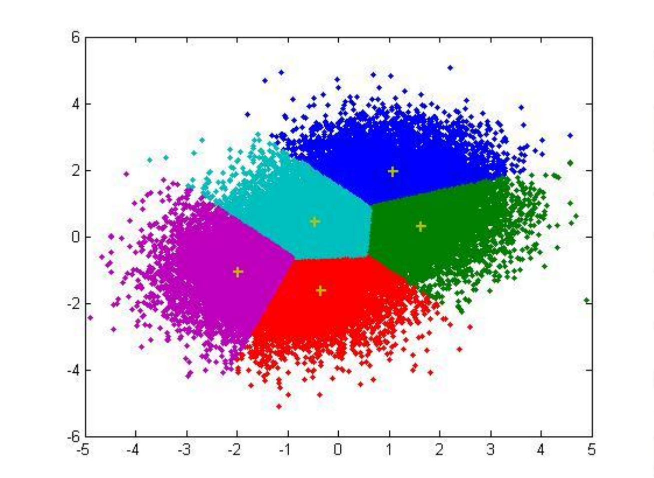
- Arrangement Application: Architectural Sketching
- Next Time: Delaunay Triangulations

K-Means Clustering

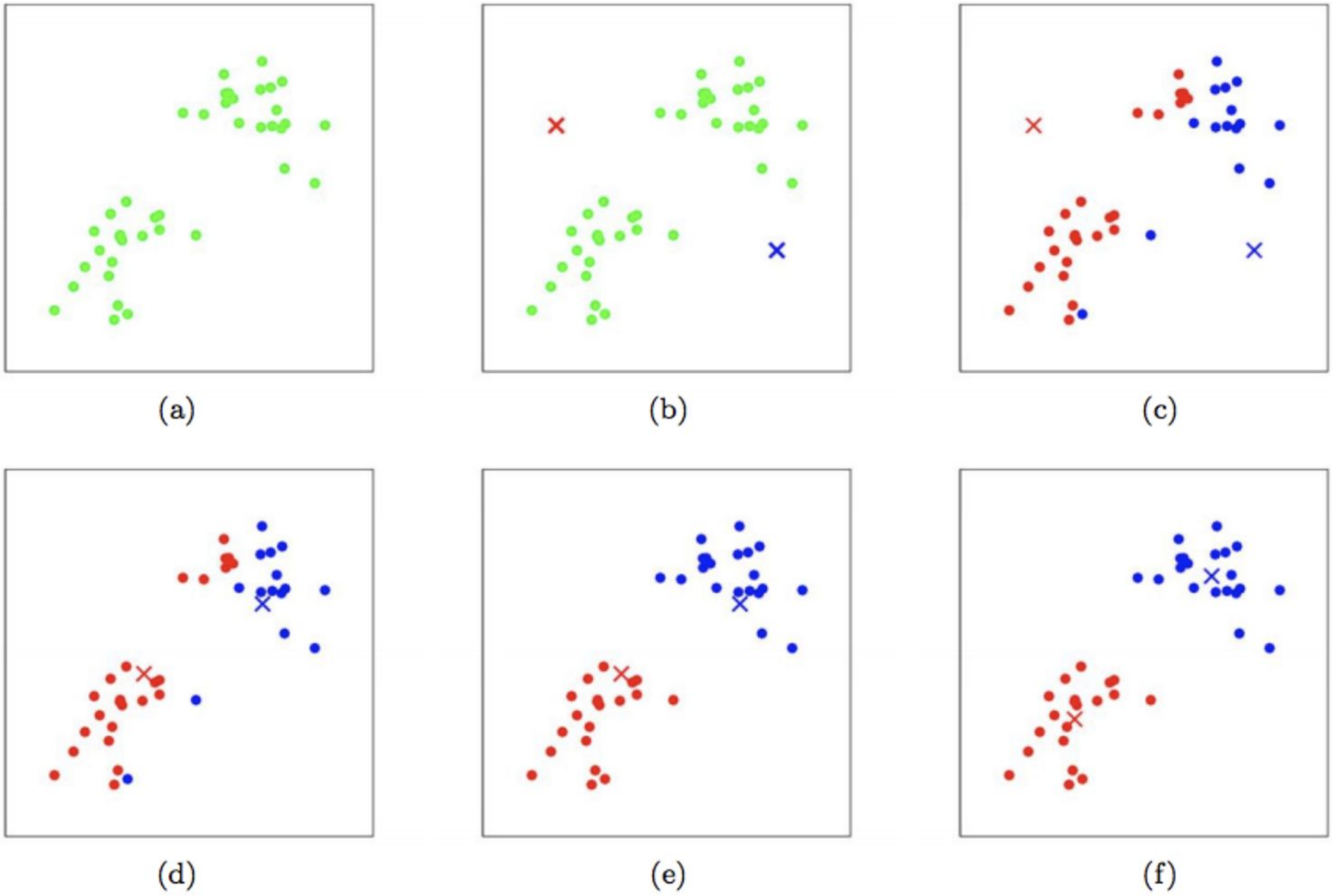
- Works quite well, when the data can be meaningfully classified (and we know how many clusters to use).
- With dense data, output is visually similar to Voronoi diagram (k-Means chooses the data points that define the cells)



http://blog.mpacula.com/2011/04/27/k-means-clustering-example-python/



"Efficient K-Means Clustering using JIT" Yi Cao



Wei Zhang
https://wei2624.github.io/MachineLearning/usv_kmeans/

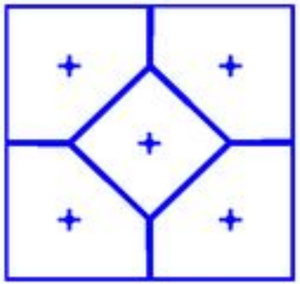
Centroidal Voronoi Diagram

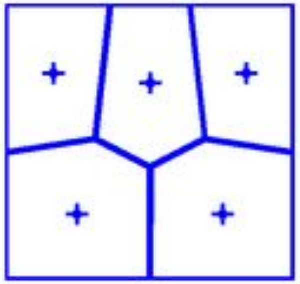
- *What if we could place all of the grocery stores?*
- Where should we place the grocery stores so that they are centrally located for all of their customers?
- But if you change the position of the store, the closest store will change for some customers…

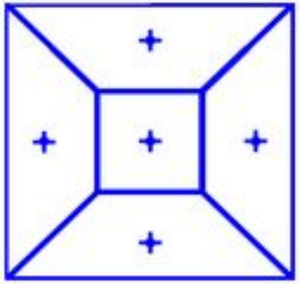
- Points are at the center of mass of their cell
- Constructed using k-means clustering / Lloyd's algorithm - an iterative relaxation algorithm

- *Note: May be multiple solutions!*

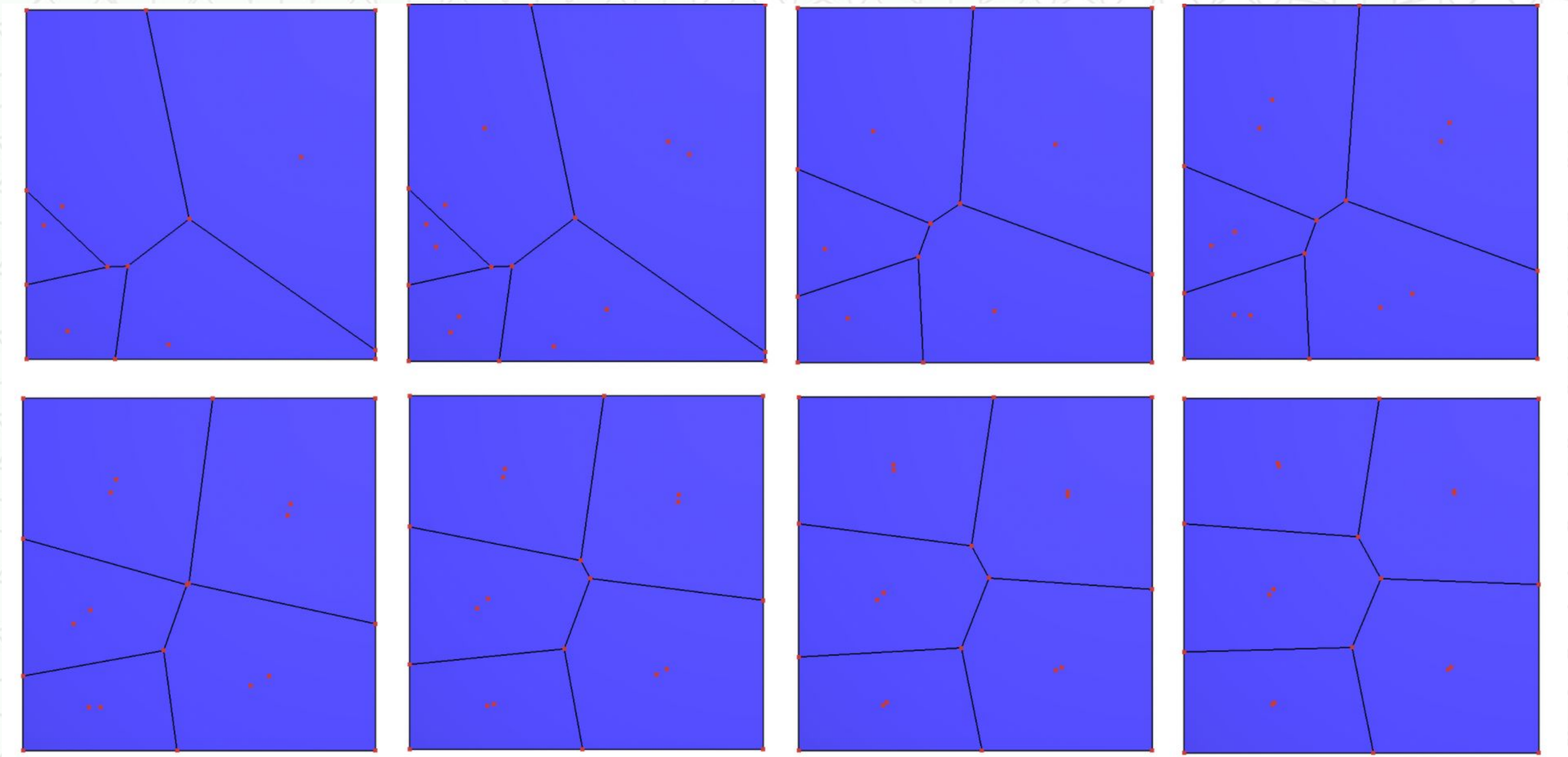
https://en.wikipedia.org/wiki/Centroidal_Voronoi_tessellation

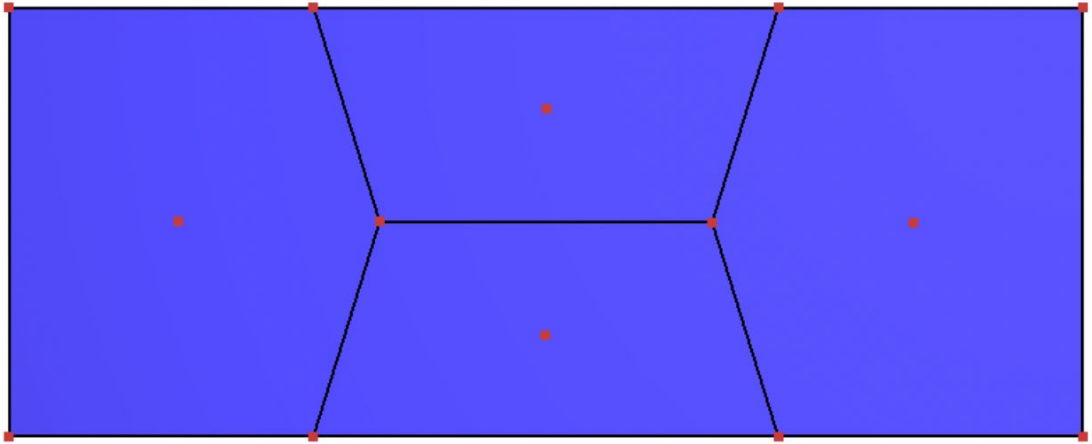
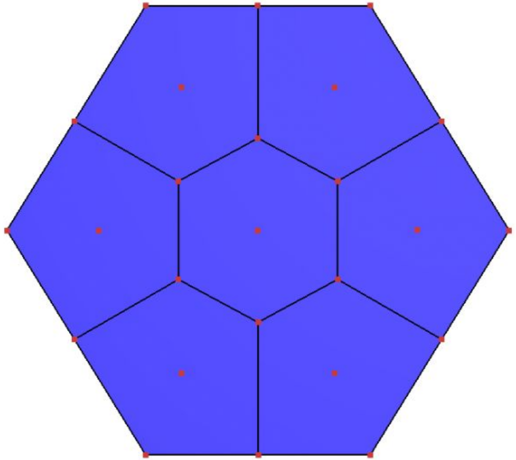
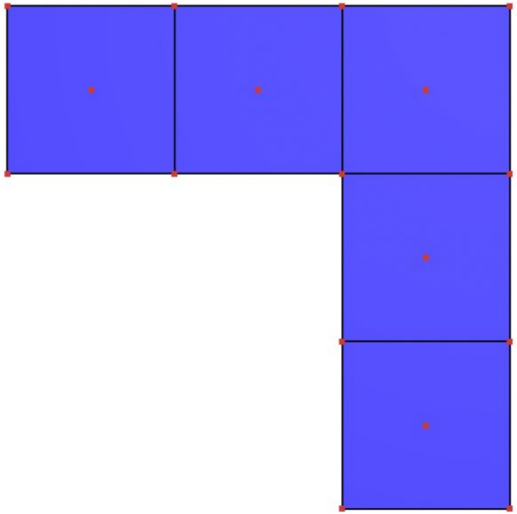
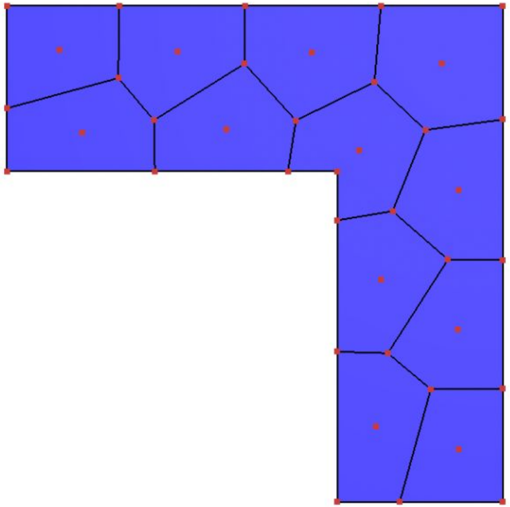
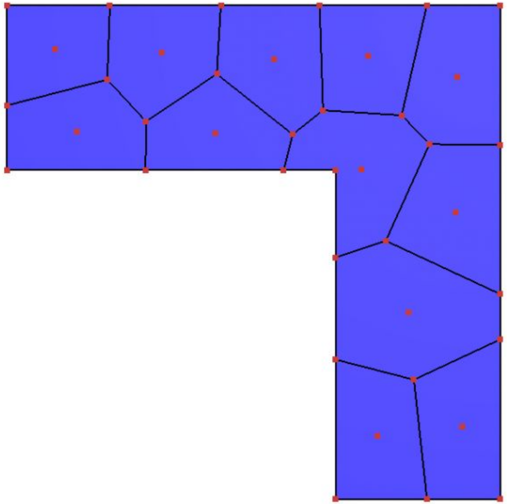






Homework 5 Questions?



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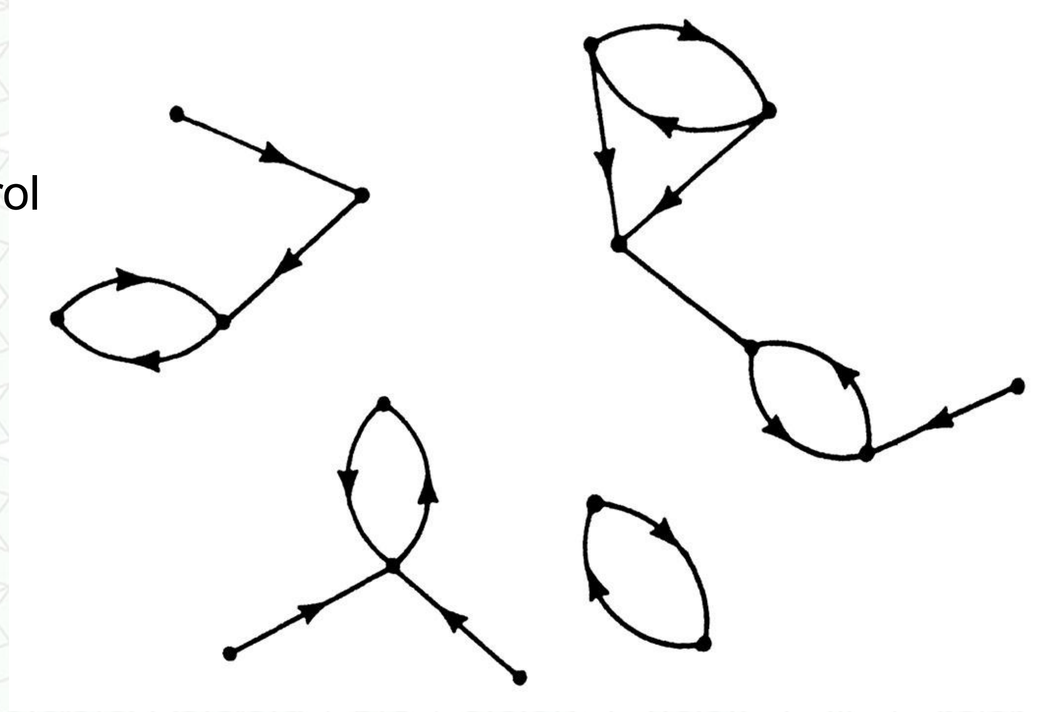
Problem: Closest Pair

- Which two points are the closest?
- Applications - Collision Detection & Air Traffic Control
- Which two objects have soonest potential for collision?

- Linear loop over all edges in the All Nearest Neighbors solution to find the shortest edge
- Will be a reciprocal pair



Computational Geometry: An Introduction,
Preparata & Shamos, 1985, Figure 5.1

Problem: Euclidean Minimum Spanning Tree

- Given *n* points
- Draw *n-1* edges to create a tree, connecting all points without creating any cycles.
- Pick edges to minimize the sum of their lengths.

- *Application: Minimize cost of physical telephone lines*

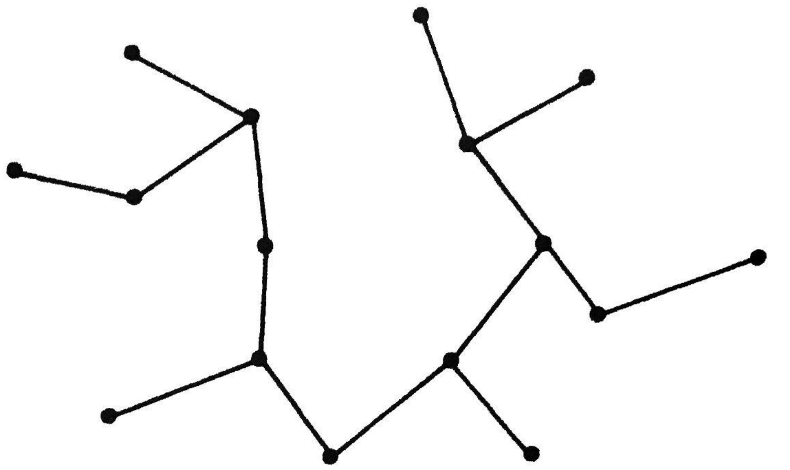


Figure 5.2 A minimum spanning tree on a planar point set.

Computational Geometry: An Introduction, Preparata & Shamos, 1985, Figure 5.2

Reduce Convex Hull to Voronoi Diagram

- Theorem: Voronoi polygon V_i is unbounded if and only if Voronoi site *i* is on the convex hull of all sites. (proved in Preparata & Shamos)

- O(n) to convert Voronoi Diagram to Convex Hull:
  - Start with any unbounded cell
  - Walk edges clockwise to find adjacent unbounded cell
  - Voronoi sites will trace convex hull in counter-clockwise order

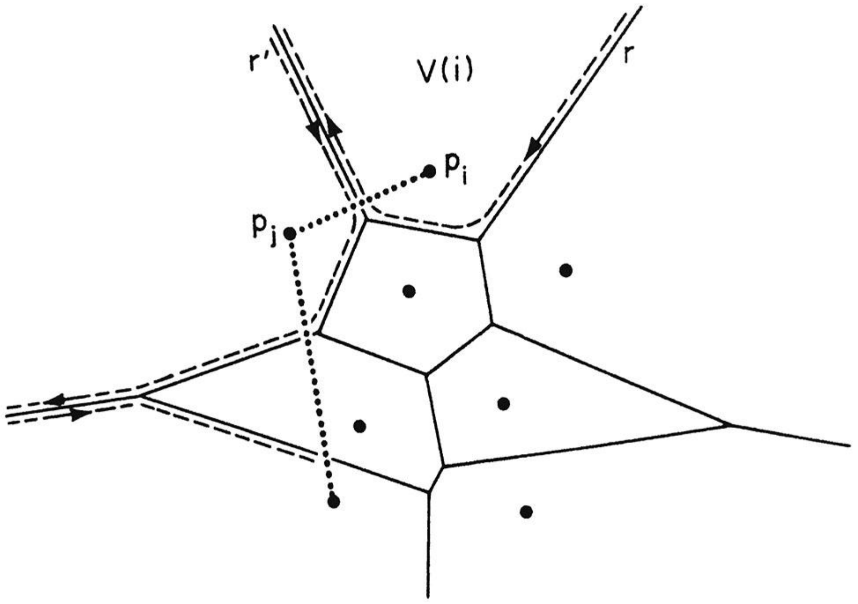
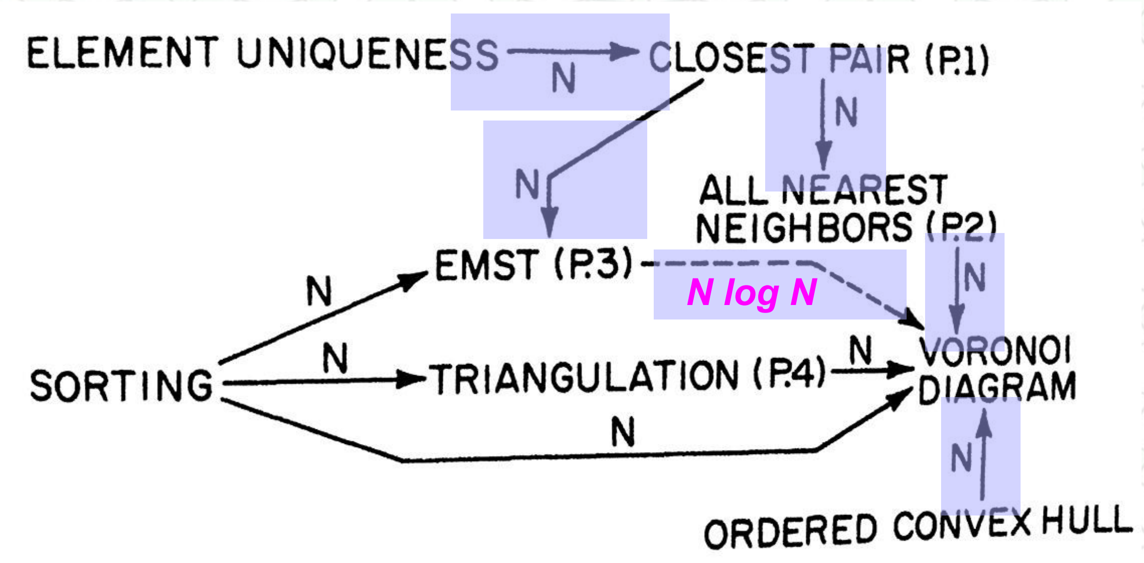


Figure 5.31 Construction of the convex hull from the Voronoi diagram.

Computational Geometry: An Introduction, Preparata & Shamos, 1985, Figure 5.31

Problems that Reduce to Voronoi Diagram

- We can compute the Voronoi Diagram of *n* points in *O(n log n)* time and *O(n)* space.
- These other problems can be computed in *O(n)* additional time if given the Voronoi Diagram.



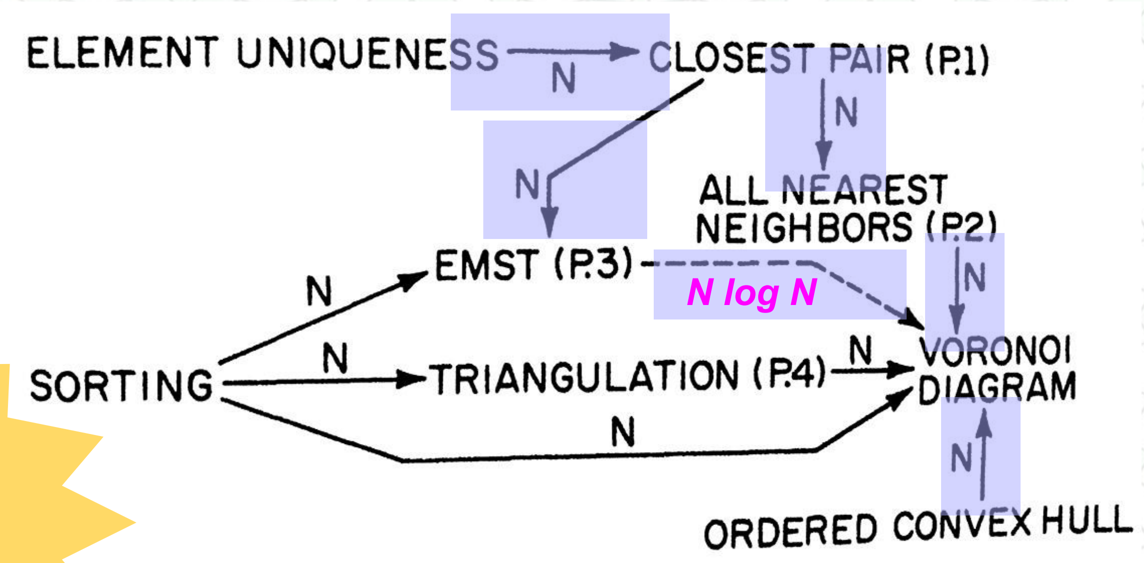
Computational Geometry: An Introduction,
Preparata & Shamos,1985 Figure 5.30

- *Therefore they are also O(n log n) time and O(n) space.*

Problems that Reduce to Voronoi Diagram

- We can compute the Voronoi Diagram of *n* points in *O(n log n)* time and *O(n)* space.
- The … Vor…

Because UNIQUENESS and SORTING are lower bound Ω(n log n)... VORONOI DIAGRAM is also Ω(n log n)



Computational Geometry: An Introduction, Preparata & Shamos,1985, Figure 5.30

- *Therefore they are also O(n log n) time and O(n) space.*

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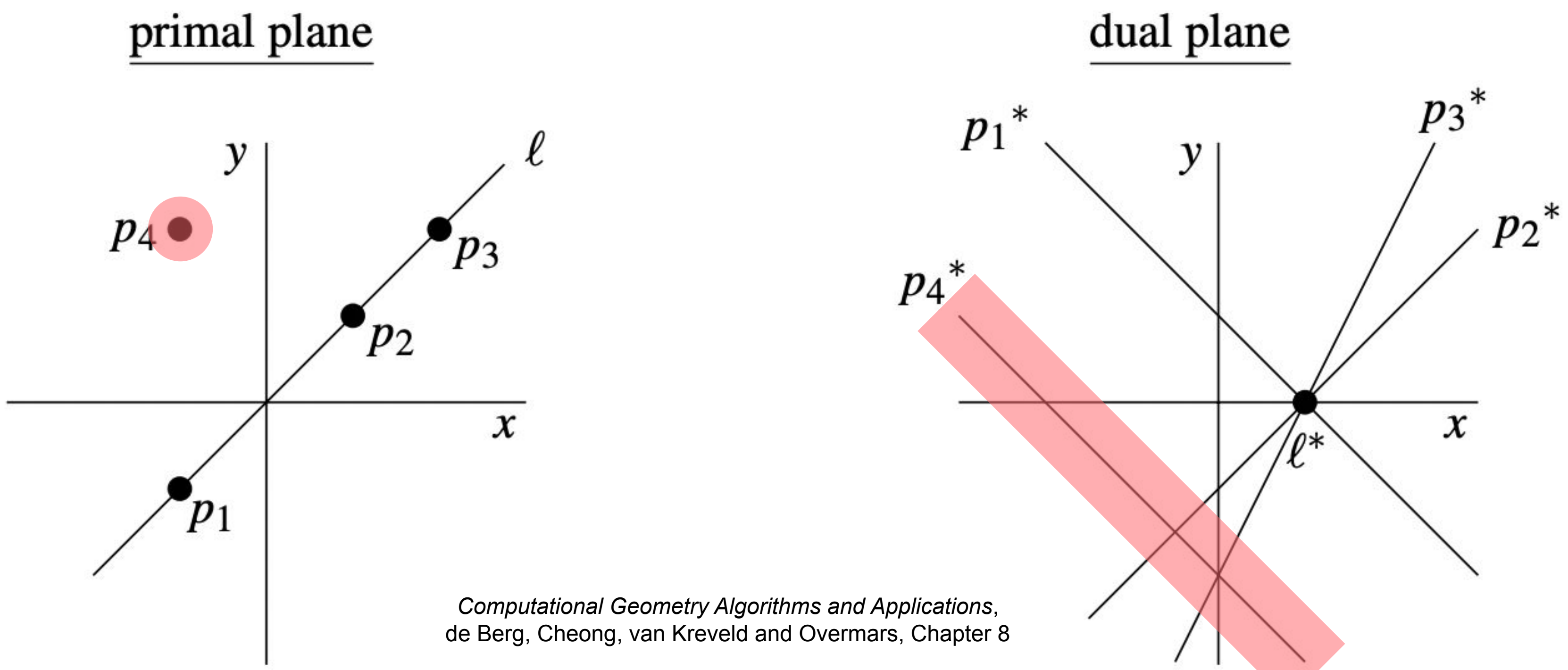
Duality: Points ↔ Lines

Point p: (p_x, p_y) in primal plane ↔ Line p^*: $y = p_x x - p_y$ in dual plane

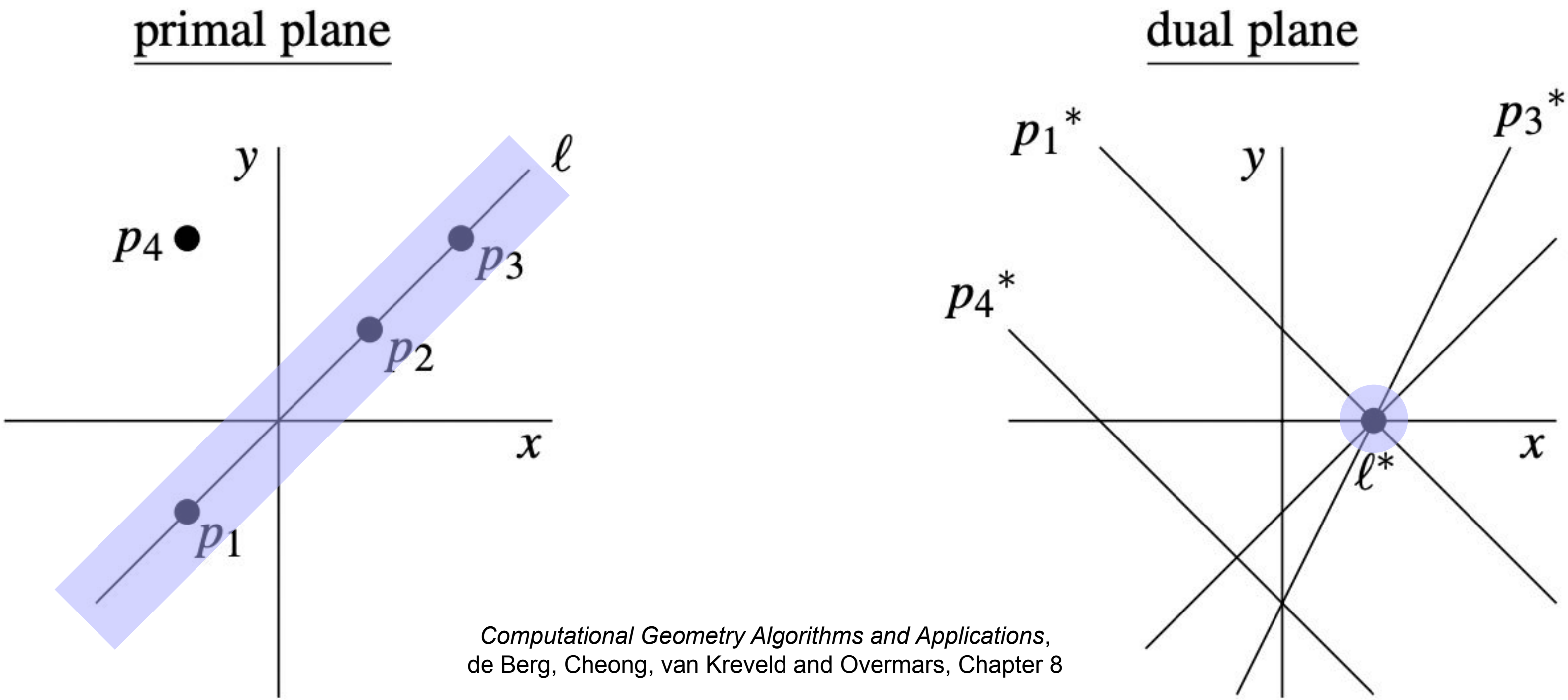


Computational Geometry Algorithms and Applications,
de Berg, Cheong, van Kreveld and Overmars, Chapter 8

Duality: Points ↔ Lines

Line ℓ: $y = mx + b$ in primal plane ↔ Point ℓ^*: (m,b) in dual plane

slope → m ; **y-intercept** → b



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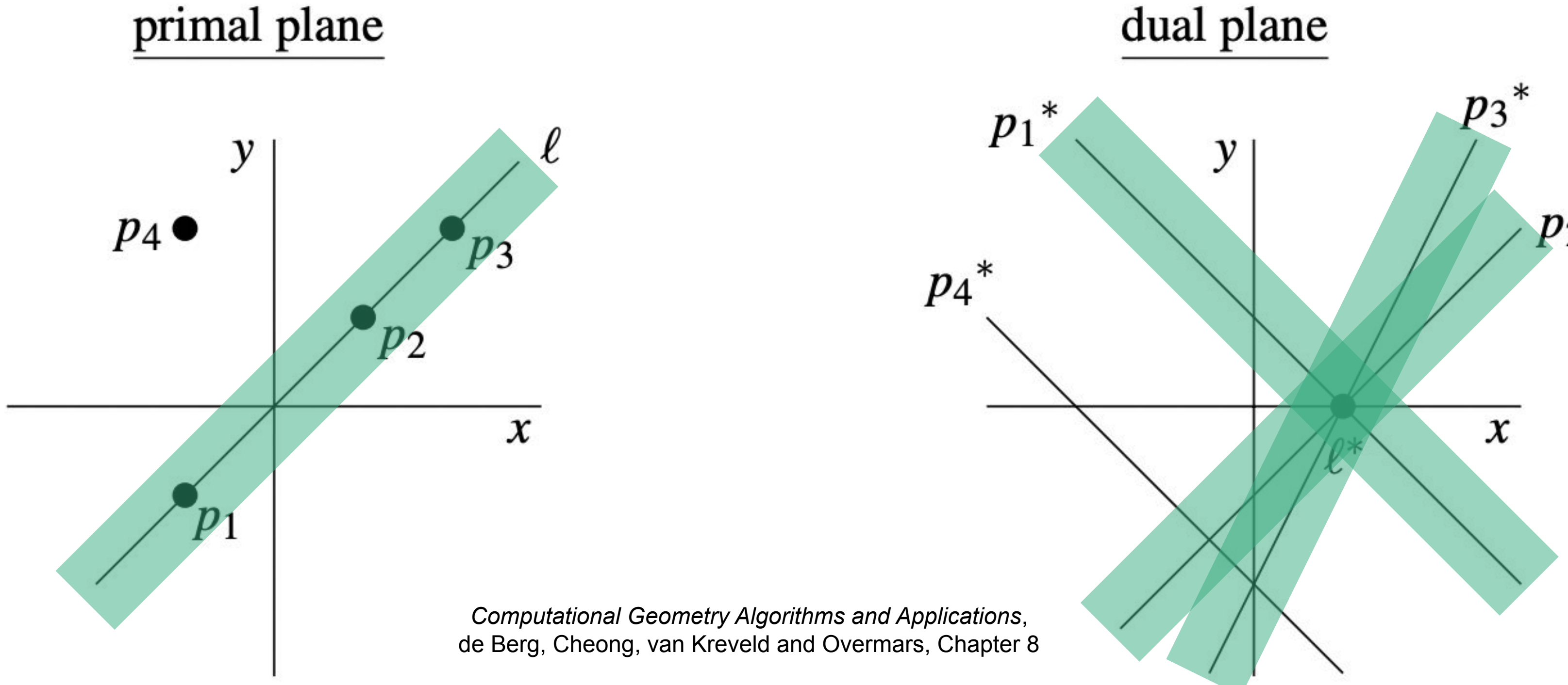
Duality: Points ↔ Lines

Points p_1, p_2, p_3 on line ℓ in primal plane,
are lines p_1*, p_2*, p_3* that pass through point ℓ* in dual plane.



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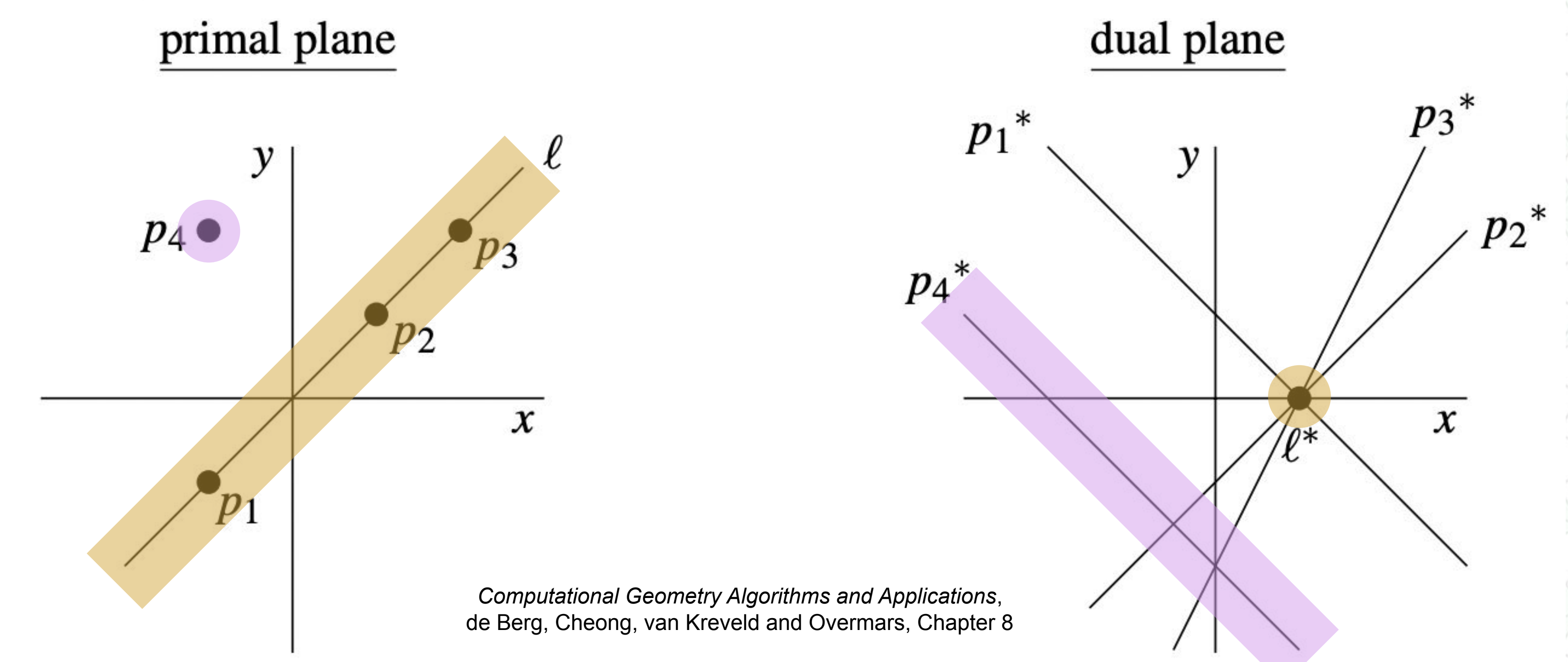
Duality: Points ↔ Lines

Point p_4 that lines above line ℓ in primal plane,
Is line p_4* that lies beneath point ℓ* in dual plane.



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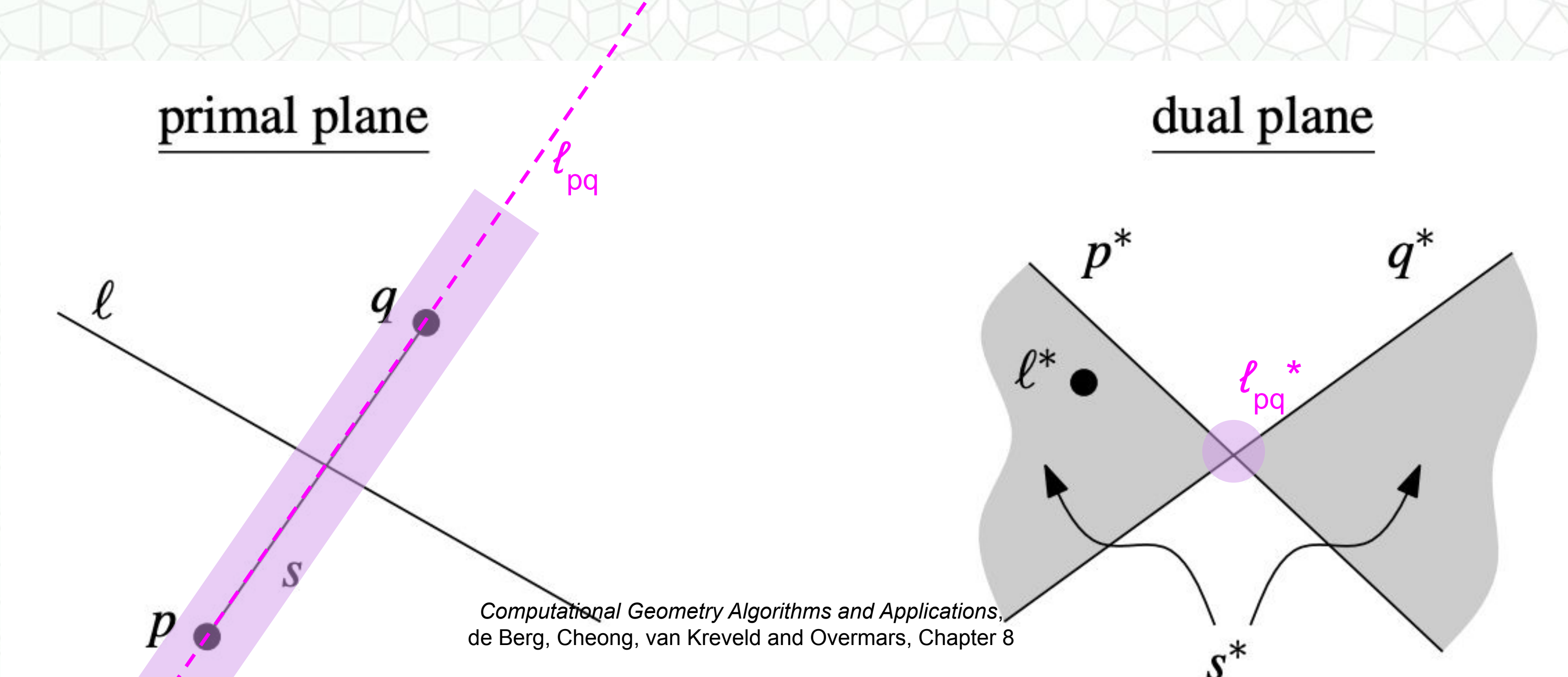
Duality: Line Segment ↔ Double Wedge

Line segment s between points p and q, which lies on line ℓ_{pq}, in primal plane



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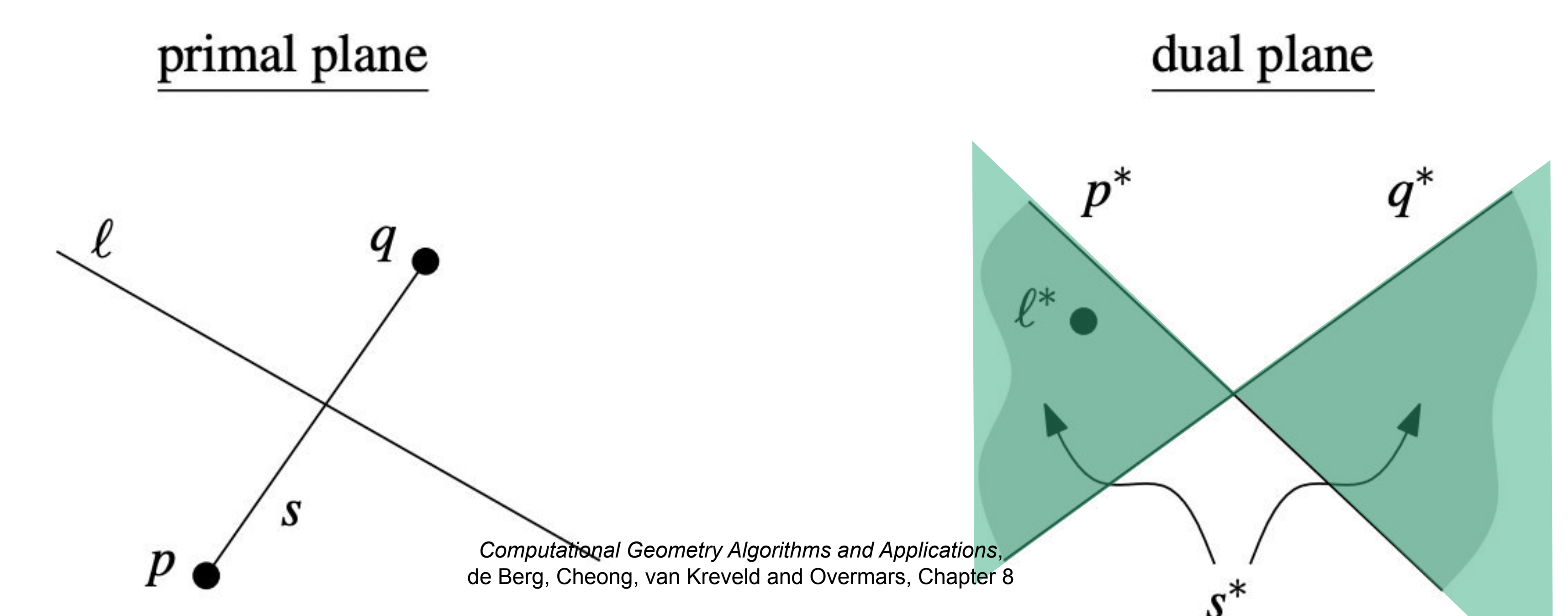
Duality: Line Segment ↔ Double Wedge

Line segment s between points p and q, which lies on line ℓ_{pq}, in primal plane
Is a double wedge s^* of area between lines p^* and q^* in the dual plane



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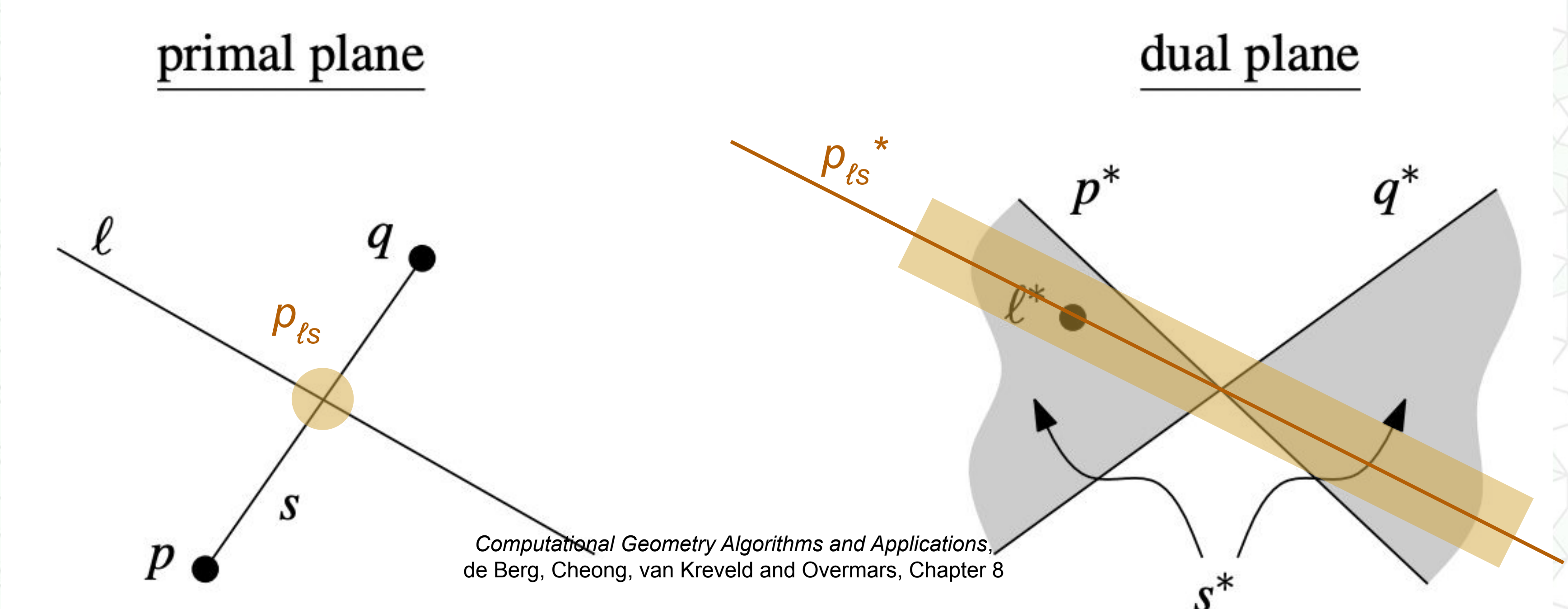
Duality: Line Segment ↔ Double Wedge

The intersection point $p_{\ell s}$ of segment s and line ℓ in primal plane,
Is line $p_{\ell s}{}^*$ that lies inside double wedge s^* *and crosses* ℓ^* *and* $\ell_{pq}{}^*$ *in the dual plane*



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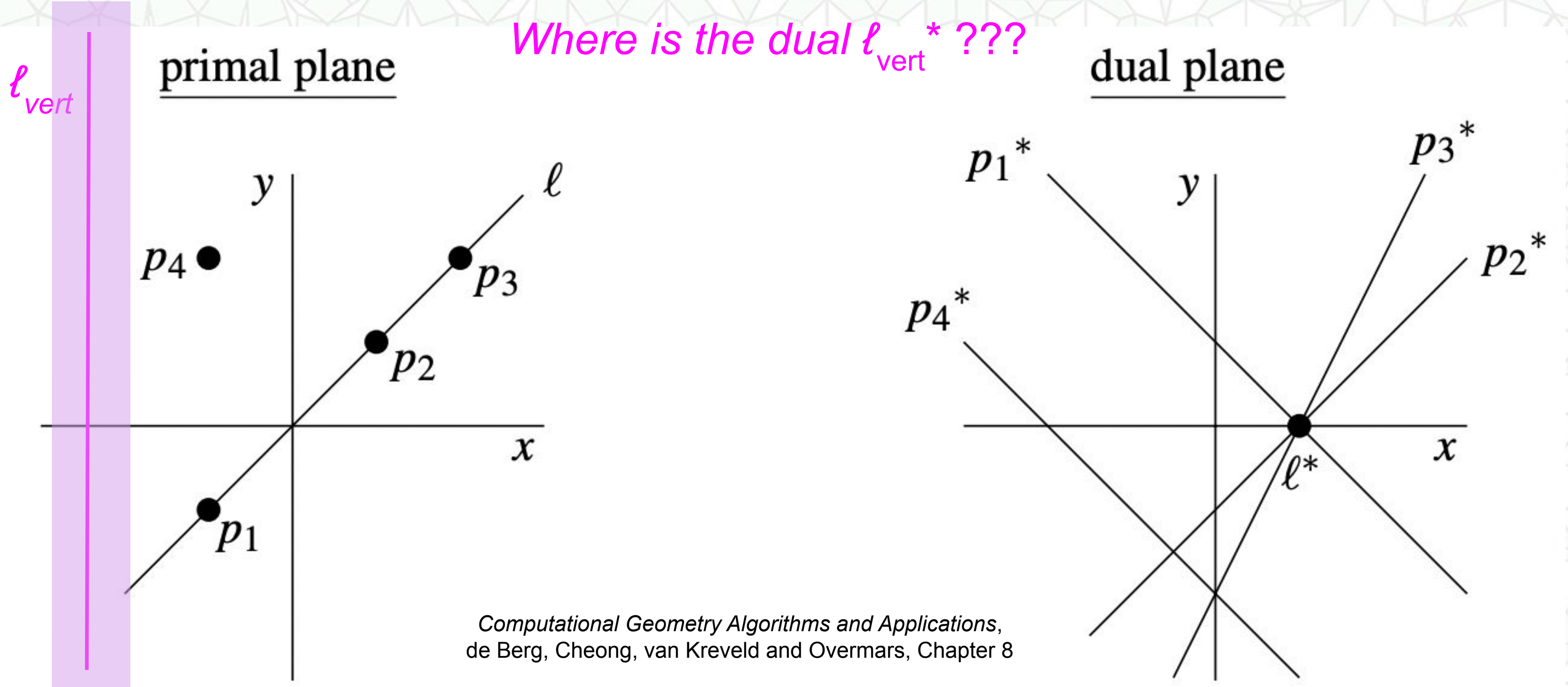
Duality: Assumptions / Special Cases

A vertical line segment ℓ_{vert} in the primal plane has slope $m = \infty$, *and* b = *undefined*



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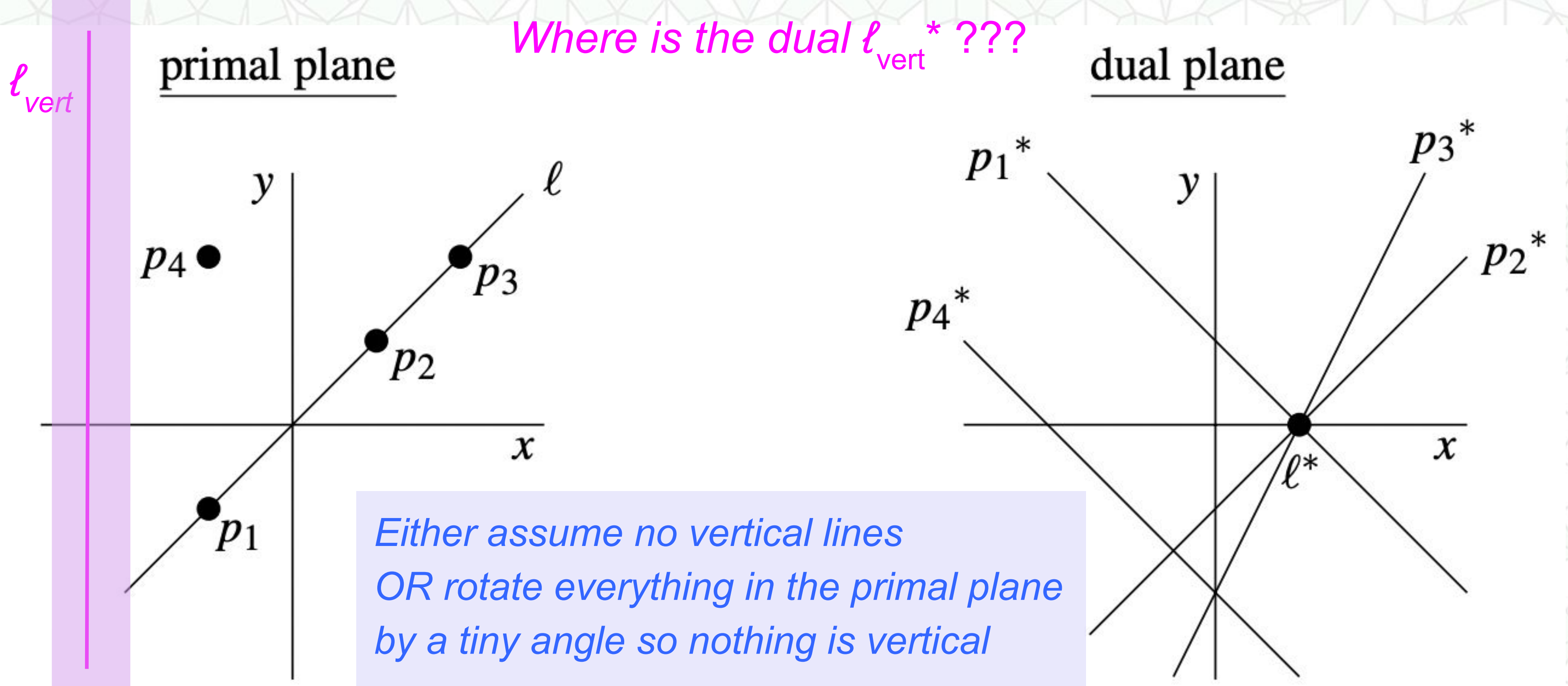
Duality: Assumptions / Special Cases

A vertical line segment ℓ_{vert} in the primal plane has slope $m = \infty$, *and* b = *undefined*

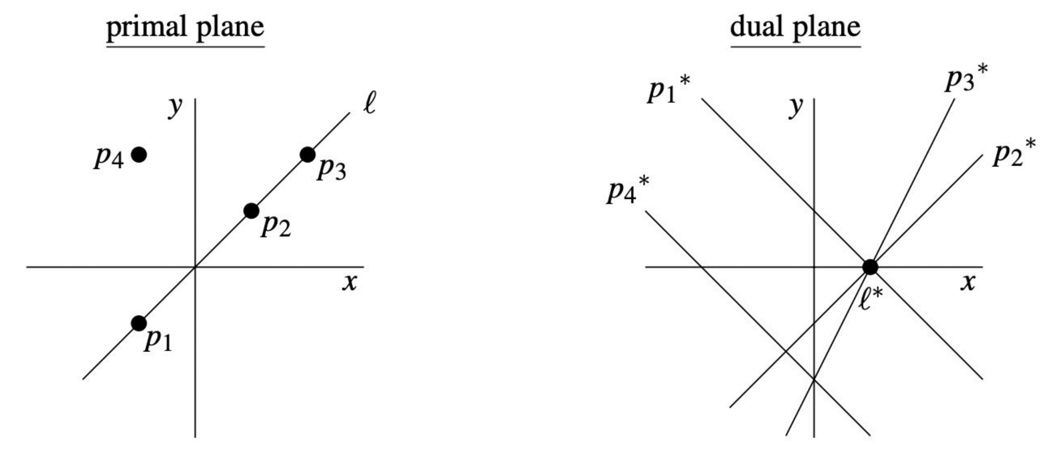
Where is the dual ℓ_{vert}^* ???



Either assume no vertical lines
OR rotate everything in the primal plane
by a tiny angle so nothing is vertical

Duality: Why Bother?

- Solving a problem in the primal plane is ***equivalent*** to solving a problem in the dual space.
- Sometimes it is difficult to solve a problem in the primal plane, but relatively easy to solve the problem in the dual plane. (or vice versa)
- *Note: There are many forms of duality… not just 2D point ↔ line!*



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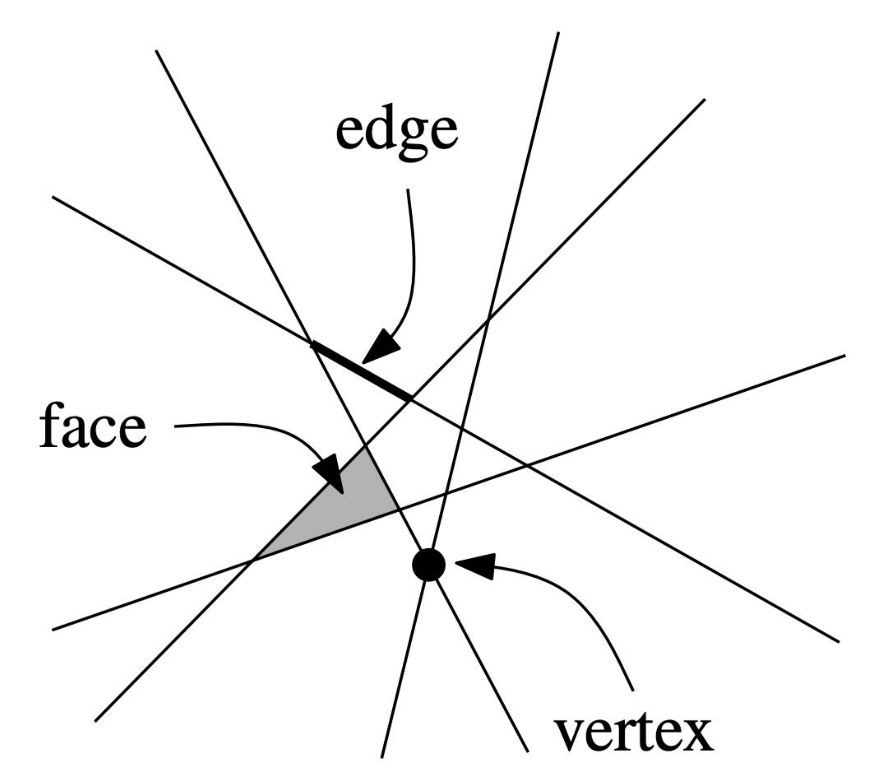
Arrangement of Lines

- A collection of *n* lines in the plane
- Creates a subdivision of the plane into vertices, edges, and faces



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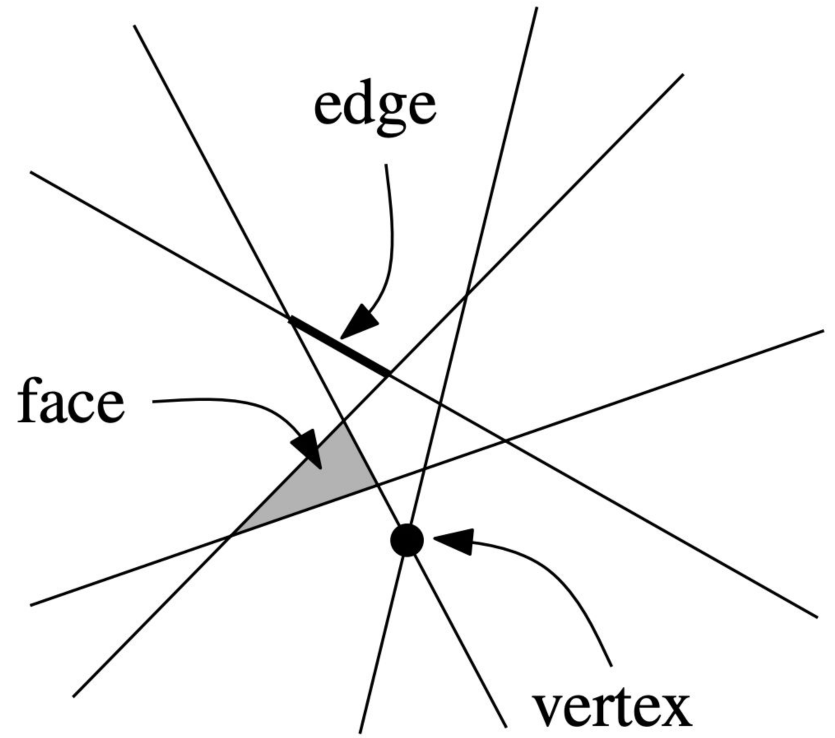
Arrangement of Lines

- A collection of *n* lines in the plane
- Creates a subdivision of the plane into vertices, edges, and faces

- Definition:
  A *simple arrangement* of lines
  - No three lines pass through the same point
  - No two lines are parallel



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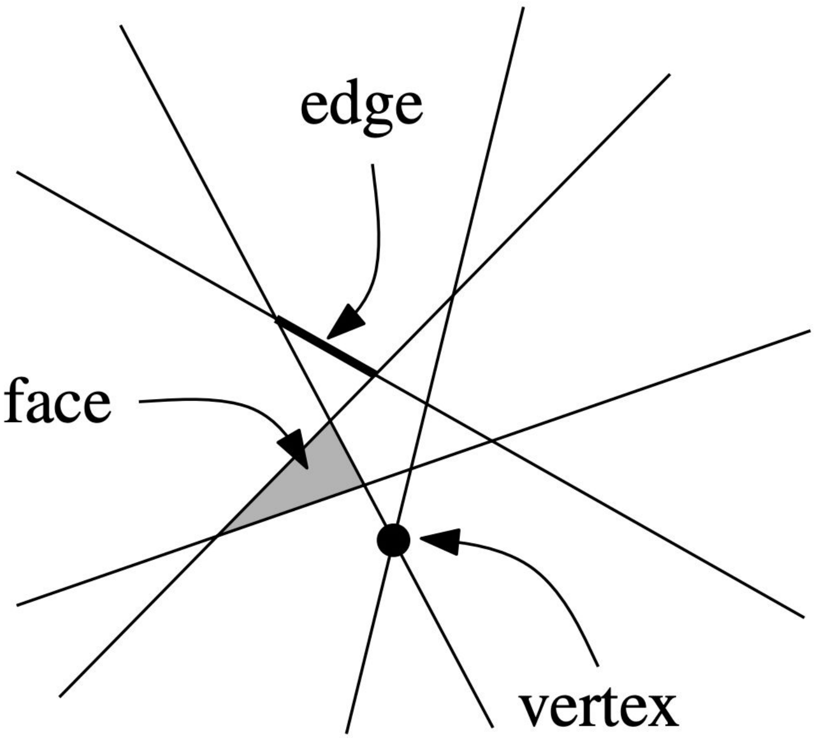
Complexity of an Arrangement of Lines

- A collection of *n* lines in the plane
- How many vertices?
  -
- How many edges?
  -
- How many faces?
  -



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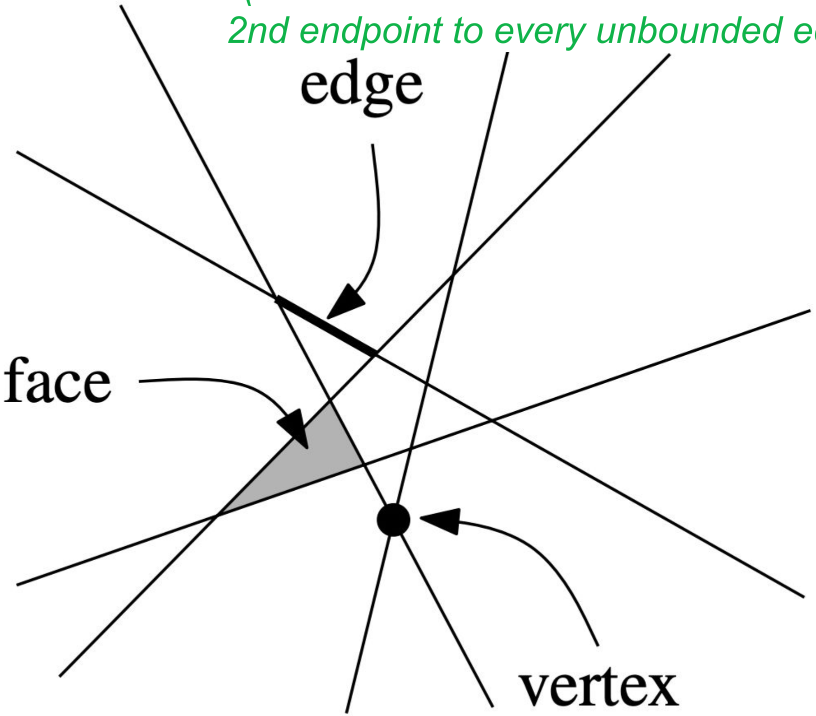
Complexity of an Arrangement of Lines

- A collection of *n* lines in the plane
- How many vertices?
  - $n * (n-1) / 2$
- How many edges?
  - n^2
- How many faces?
  - $n^2/2 + n/2 + 1$

Or fewer if not a *simple arrangement*

- 3 or more lines intersect at a point, or
- 2 or more lines are parallel

Confirm using Euler formula: $V - E + F = 2$
(Need to add an extra vertex to be the 2nd endpoint to every unbounded edge)



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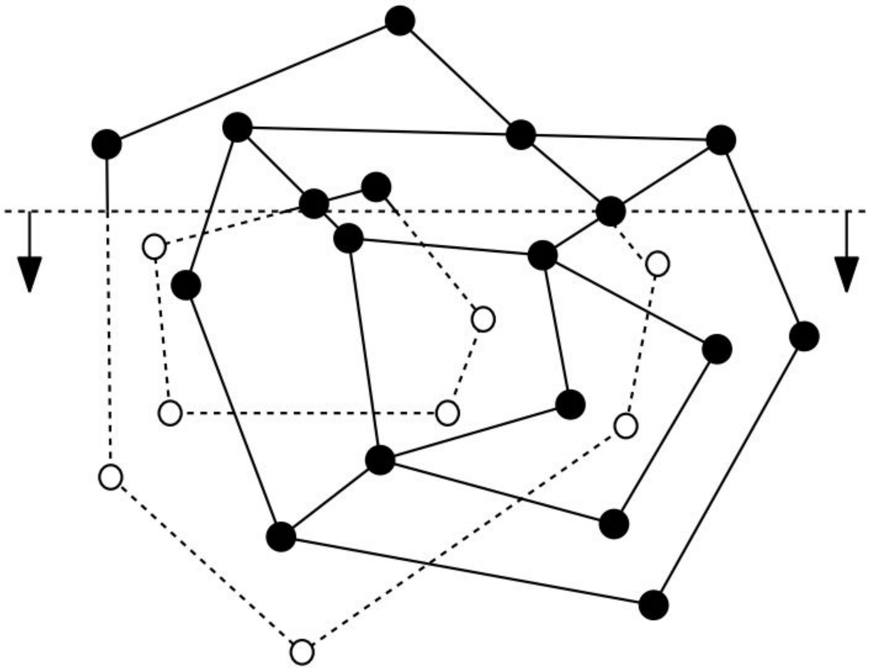
Map Overlay & Line Segment Intersection

- Line Sweep Algorithm covered in Lecture 3

- For *n* line segments
- With *k* overlay complexity (# of elements in output)

- Runtime Analysis:
  O(n log n + k log n)



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de Berg, Cheong, van Kreveld and Overmars, Chapter 2

Applied to (Unbounded) Lines…

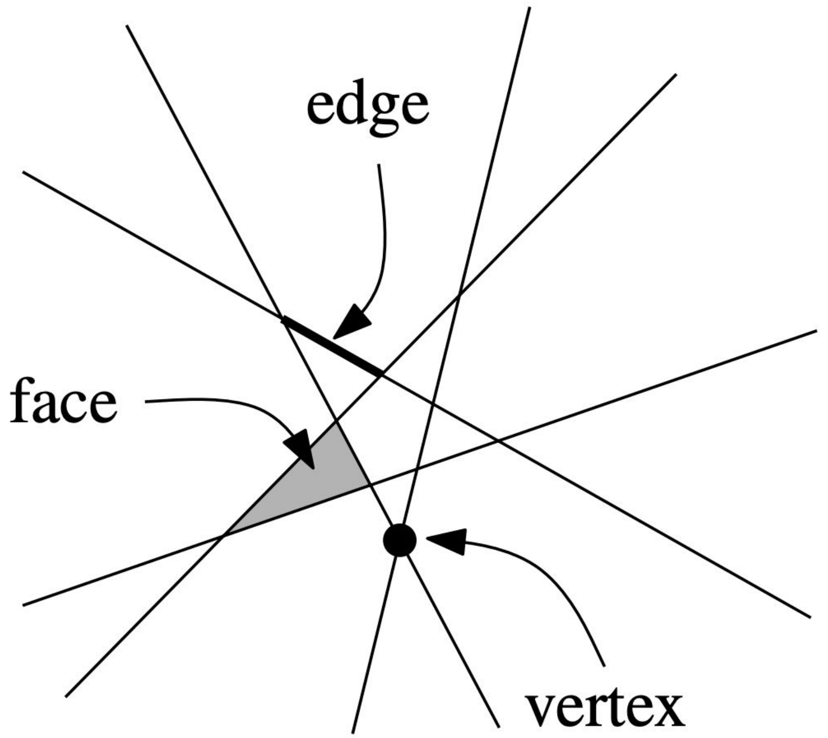
- For n ~~line segments~~ **lines**
- With k overlay complexity (# of elements in output)

  → $k = O(n^2)$

- Runtime Analysis: $O(n \log n + k \log n)$

  → $O(n^2 \log n)$

Can we do better?



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de Berg, Cheong, van Kreveld and Overmars, Chapter 8

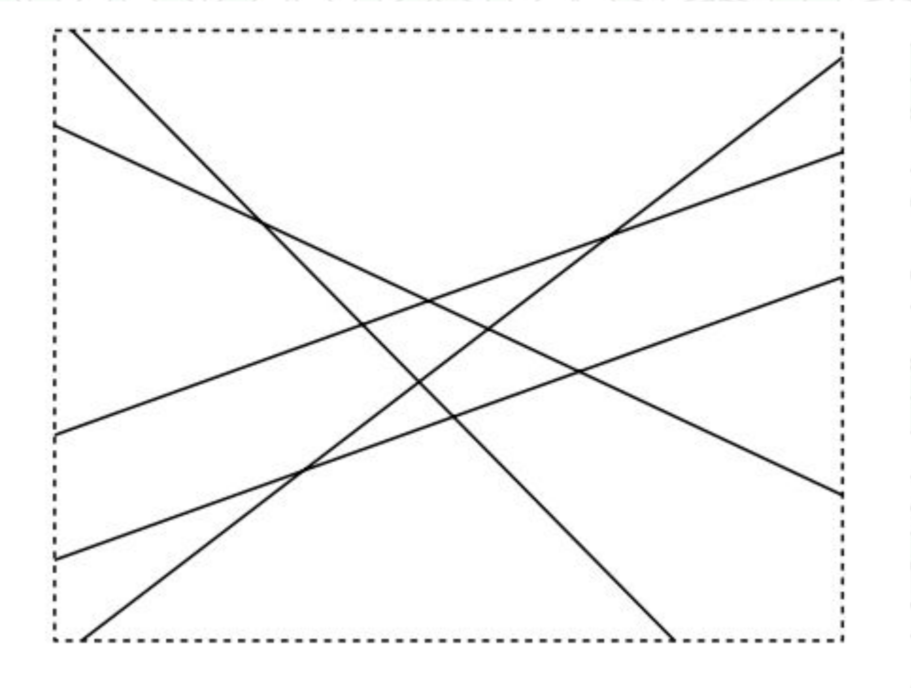
Construct an Arrangement

- Dealing with unbounded cells in a half-edge structure is impractical.

- Compute the bounding box for the arrangement.

- Find all n * (n-1) vertices (pairwise intersect all of the lines)

- Find the maximum and minimum x and y coordinates



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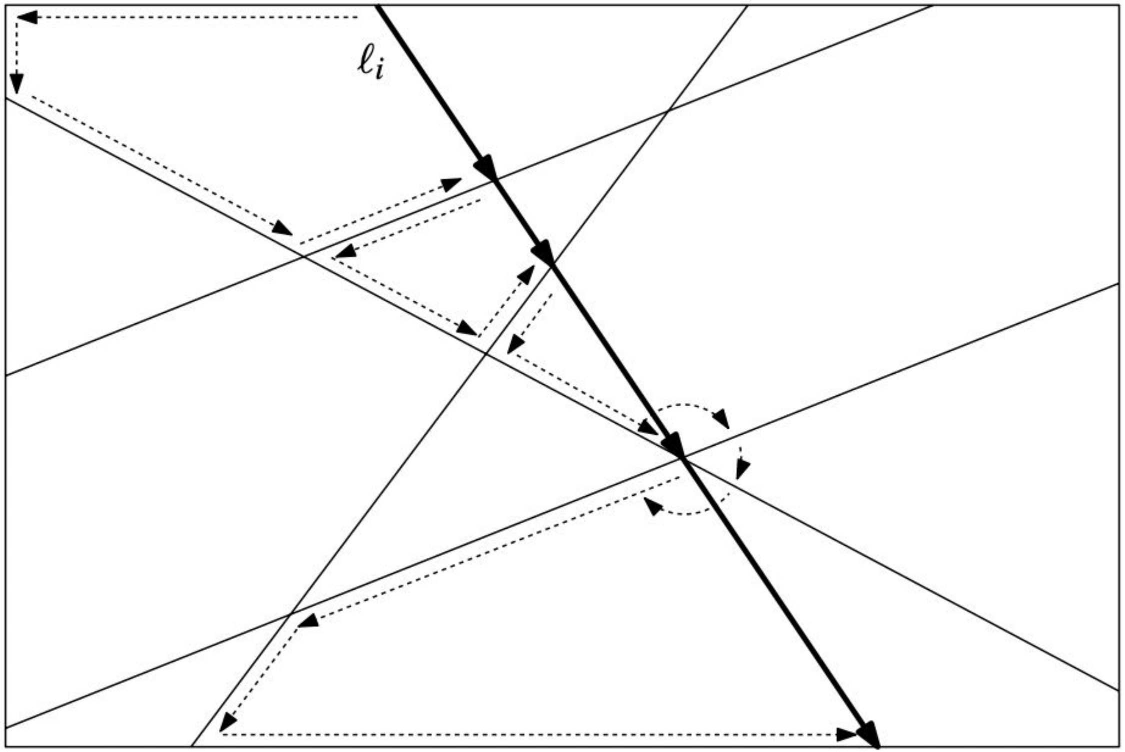
Construct an Arrangement

- Insert the lines one at a time
- Intersect the line with the bounding box
- Cut edge into two new edges
- Cut face into two new faces
- Walk the edges of the face to find the next face



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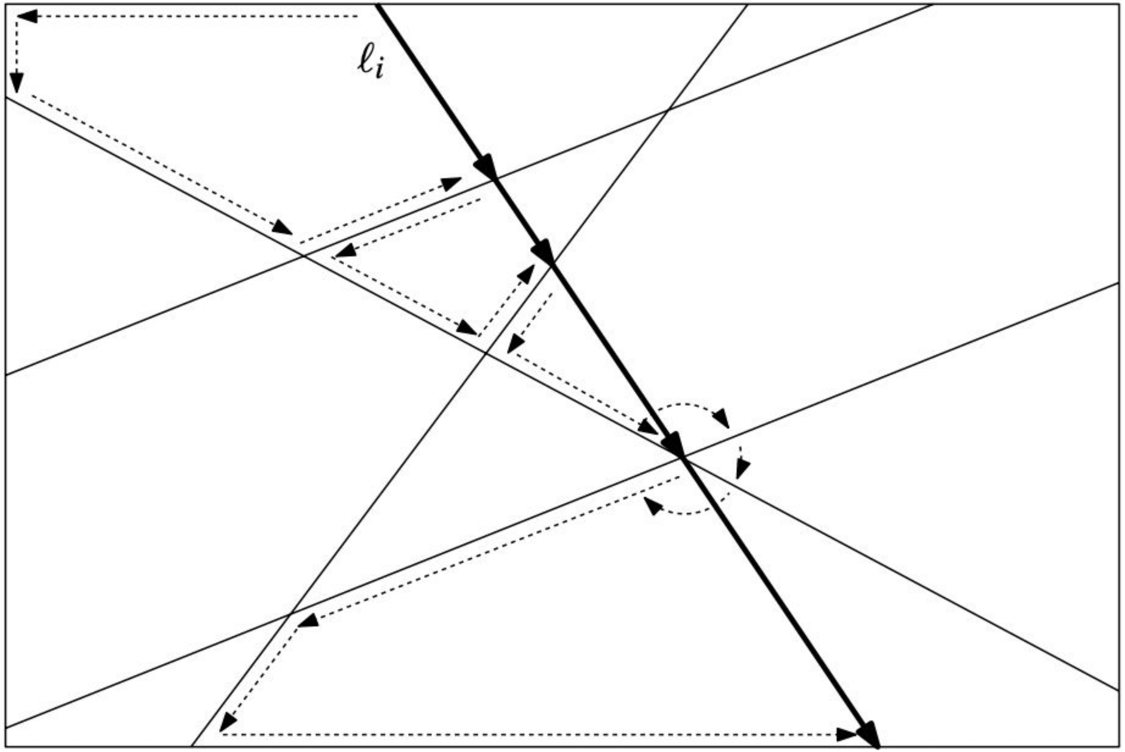
Construct an Arrangement

Runtime Analysis:

- linear cost to insert each line

- Overall:



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Construct an Arrangement

Runtime Analysis:

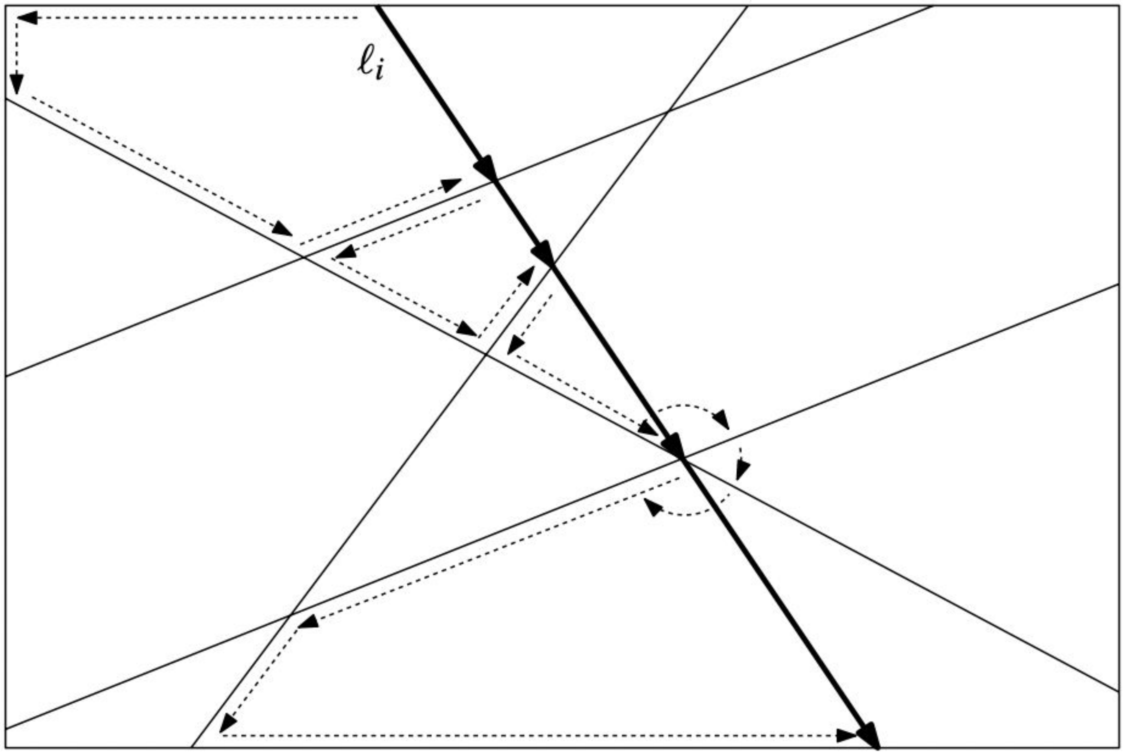
- linear cost to insert each line

  → ***O(n)***

- Overall:

  → ***O(n²)***

Line arrangements (& their computation) are quadratic…



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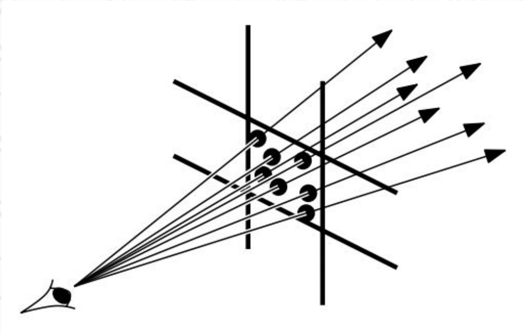
Ray Tracing Antialiasing – Supersampling

- Trace multiple rays per pixel



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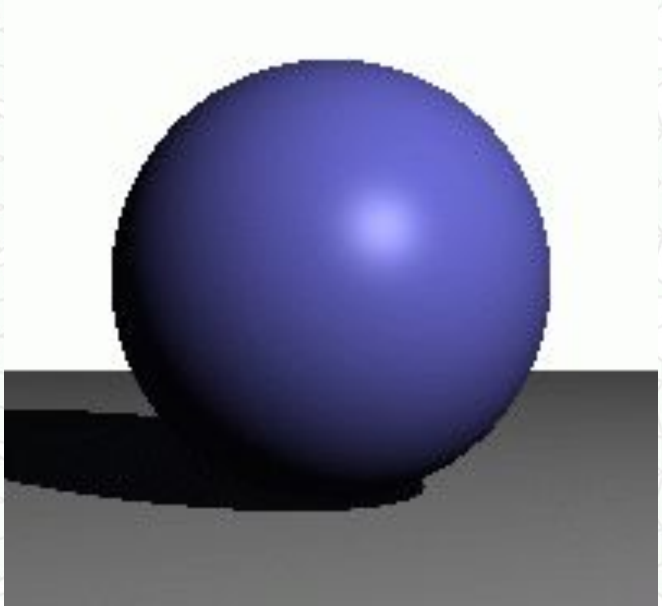
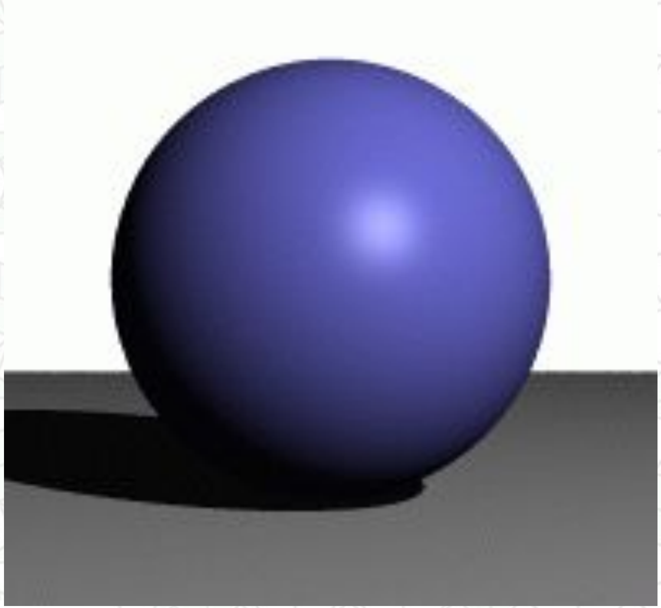




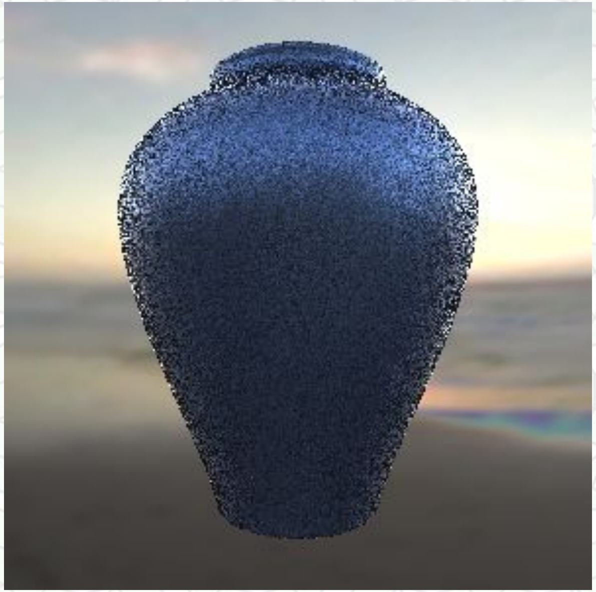
Noise from Insufficient Sampling

Can be very noticeable and distracting!

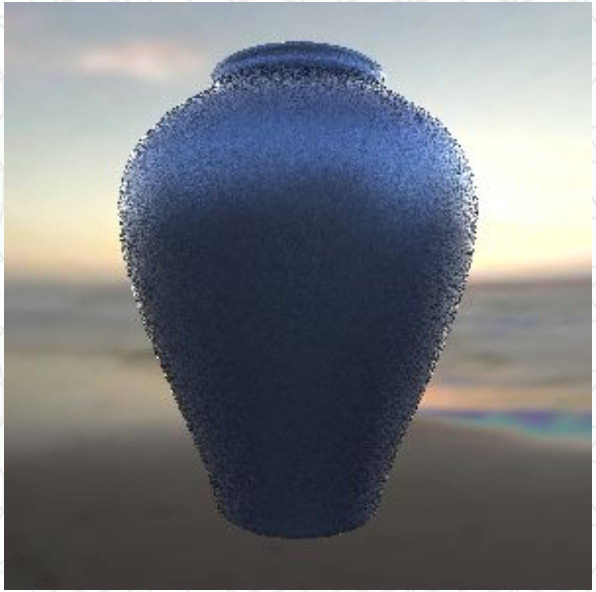
Henrik Wann Jensen

Noise from Insufficient Sampling

5 Samples/Pixel



25 Samples/Pixel

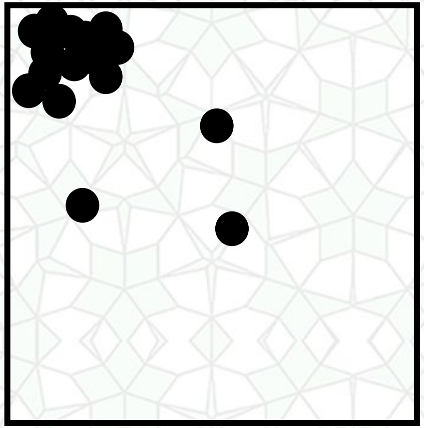


75 Samples/Pixel

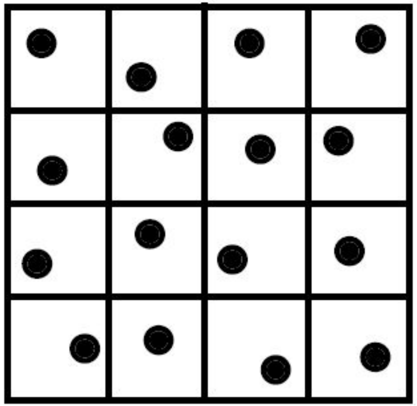
“Efficient BRDF Importance Sampling Using a Factored Representation”,
SIGGRAPH 2004, Lawrence, Rusinkiewicz, & Ramamoorthi

Noise also comes from Poor Sampling

- With uniform random sampling,
  we can get unlucky…
  e.g. all samples in a corner

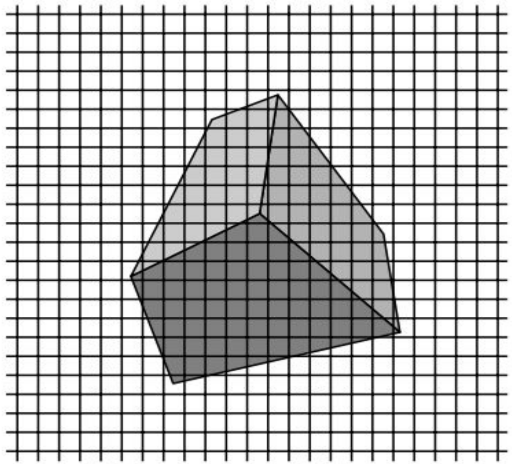


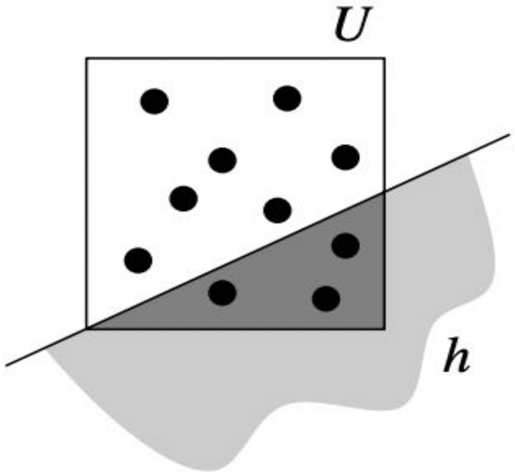
- *Stratified Sampling* can prevent it
  - Subdivide domain Ω into non-overlapping regions Ω_i
  - Each region is called a stratum
  - Take one random samples per Ω_i



Compute the Discrepancy of a Specific Pixel Sampling

- Generally we'll be ray tracing / sampling straight-edged geometric objects
- So our primary concern:
  Is the number of samples in the half space below a polygon edge proportional to the area of the square pixel below the edge?
- *Idea: Let's convert the problem to the dual plane! (samples → lines, polygon edge → point)*

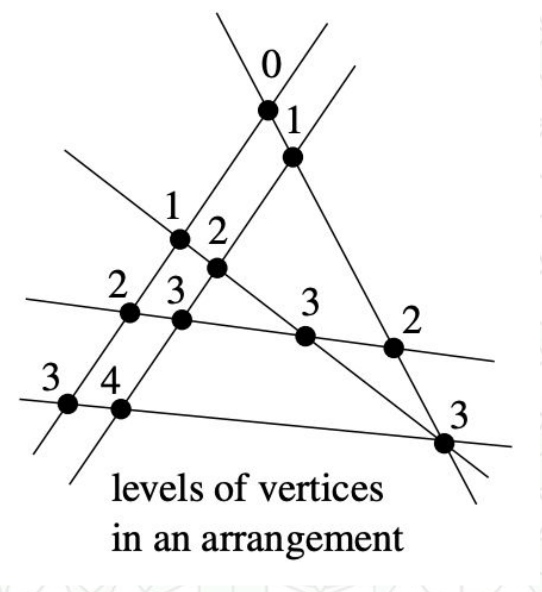


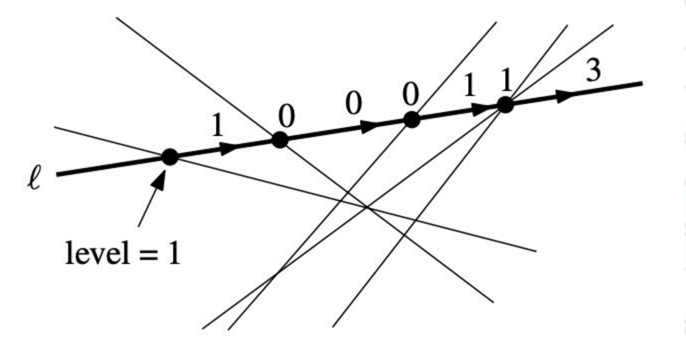


Computational Geometry Algorithms and Applications, de Berg, Cheong, van Kreveld and Overmars, Chapter 8

Compute the Discrepancy of a Specific Pixel Sampling

- Compute the arrangement of the samples [lines in the dual plane] → $O(n^2)$
- Using the arrangement, we can efficiently count the number of samples below the edge [lines above a point in the dual plane] → $O(n)$
- Determine the **maximal discrepancy** (edge whose area under the edge is least accurately estimated using these samples) → $O(n^2)$
- Goal: A set of samples with small maximal discrepancy.





Computational Geometry Algorithms and Applications, de Berg, Cheong, van Kreveld and Overmars, Chapter 8

Outline for Today

- Homework 5 Questions?
- Last Lecture: Problems that reduce to Voronoi Diagrams
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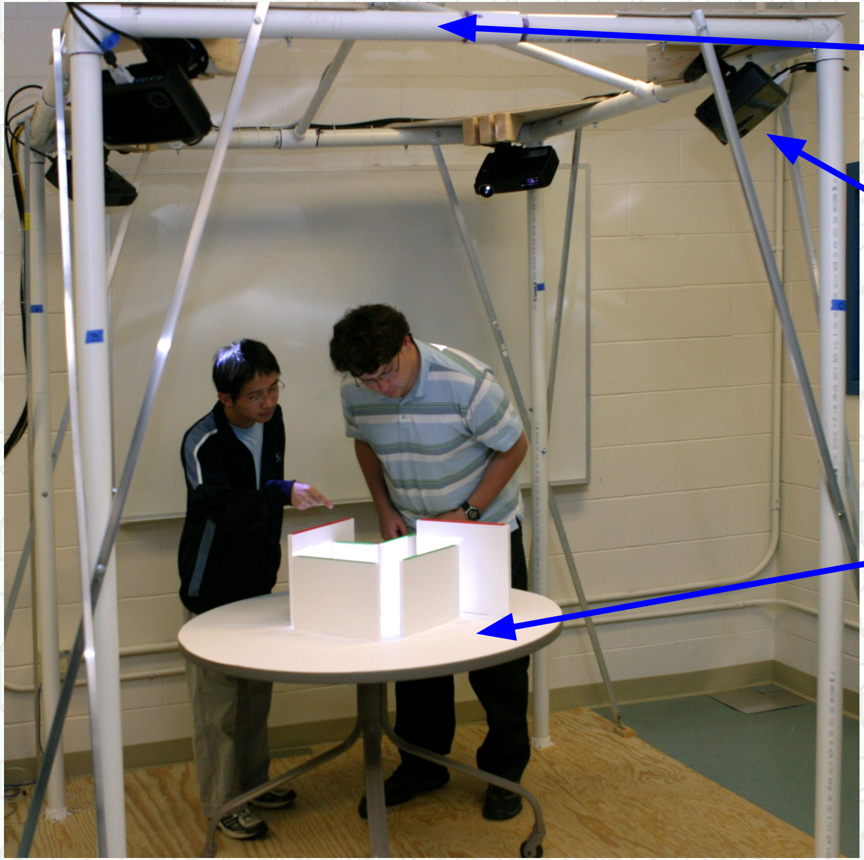
- Arrangement Application: Architectural Sketching
- Next Time: Delaunay Triangulations

Interpreting Physical Sketches as Architectural Models



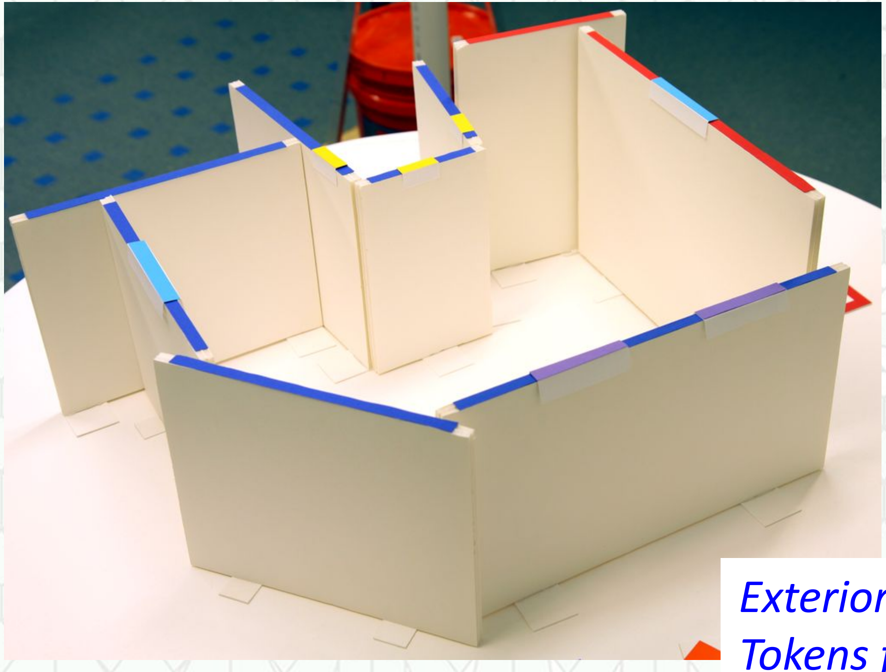
camera to detect geometry

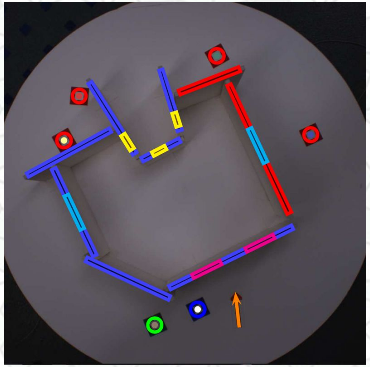
4 projectors to display solution

design sketched with foam-core walls

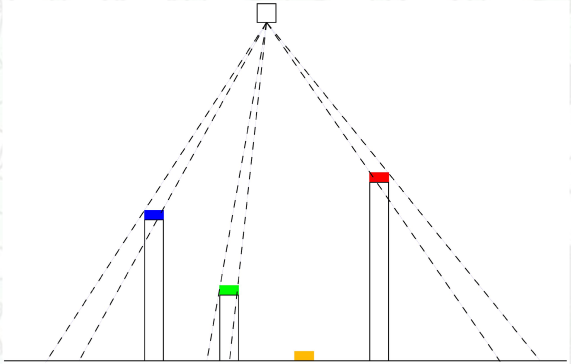
"Interpreting Physical Sketches as Architectural Models"
Advances in Architectural Geometry 2010
Cutler & Nasman

Tangible Interface for Architectural Design





Overhead camera

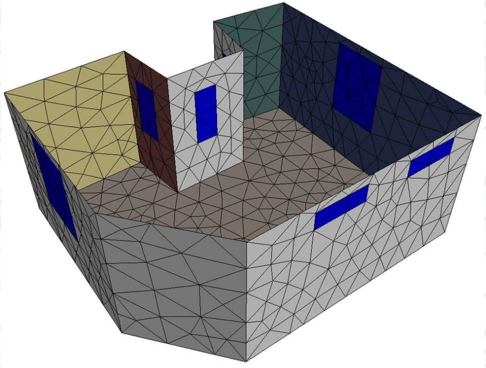


Projection geometry

Exterior & interior walls

Tokens for:

- *Windows*
- *Wall/floor colors*
- *North arrow*

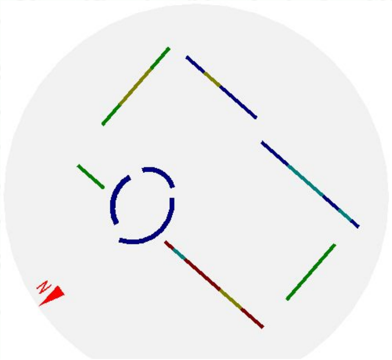


Inferred design

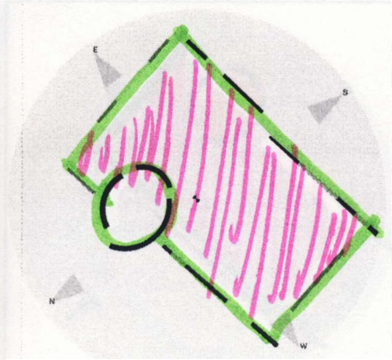
Our Contributions

- Algorithm for automatic interpretation of interior space vs. exterior space
- Construction of a watertight 3D mesh
- User study collected >300 example designs
- Validation of algorithm
    - Compare to annotations by the original designer
- Quantify design ambiguity
    - Compare annotations of a design by other users

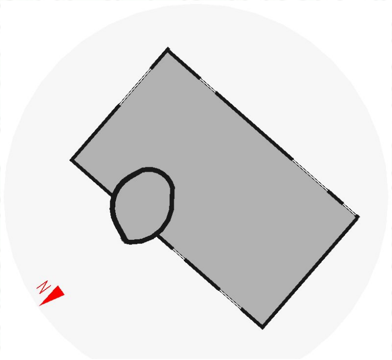
Physical Construction Tolerance: Collinearity



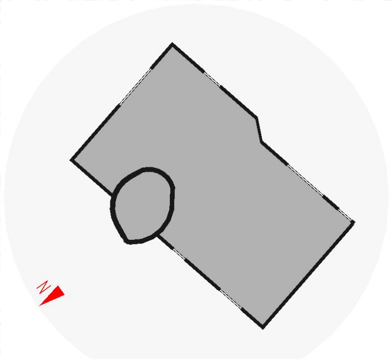
Detected Geometry



Designer's Intention



Favor Collinearity

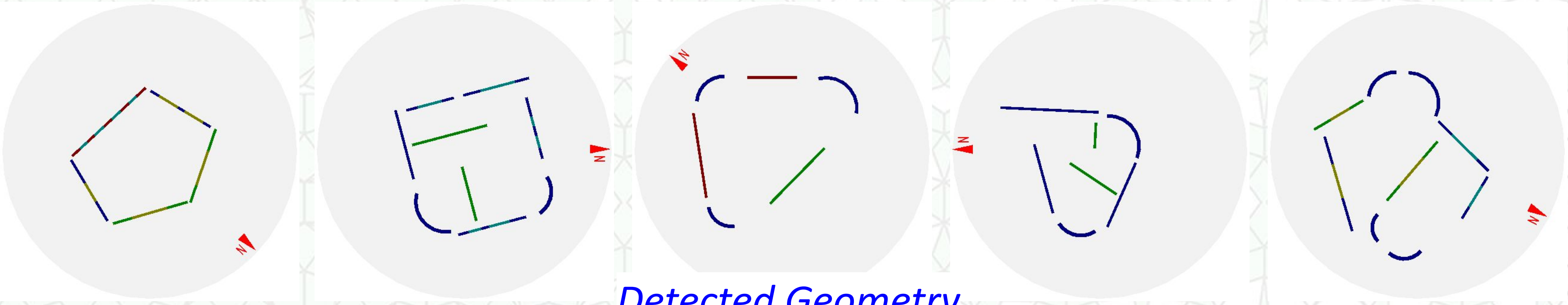


Favor Skew Lines

Other Users' Interpretations

Linking Elements to Form Chains

- Nearby walls with similar tangents can be joined into a chain

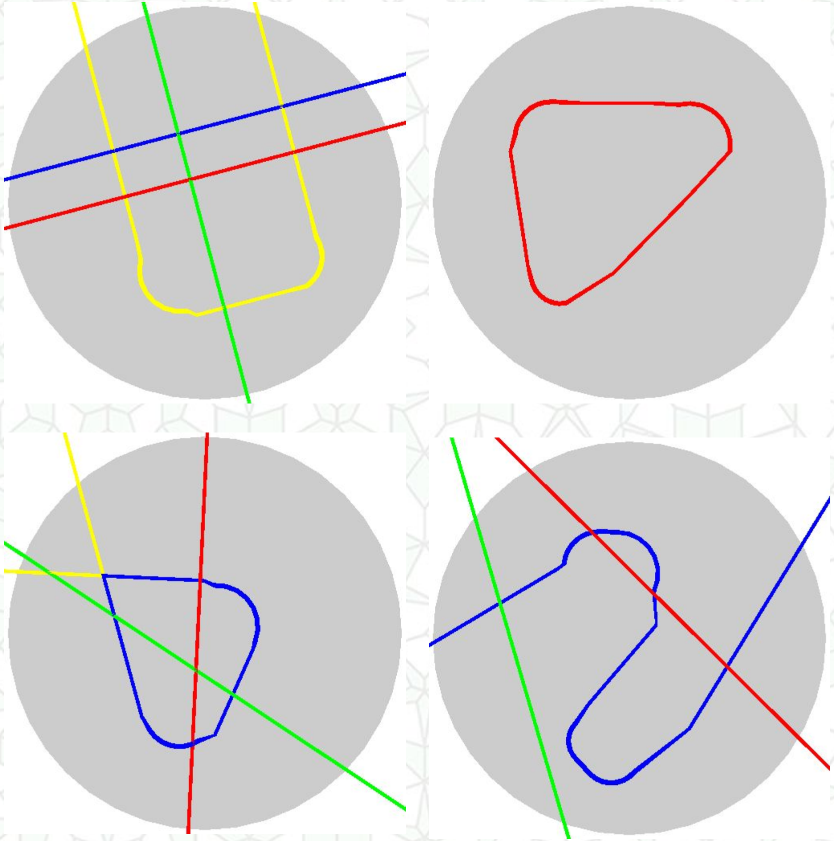


Detected Geometry

Wall Chains, Extended to Infinity

A Modified "Line Arrangement"

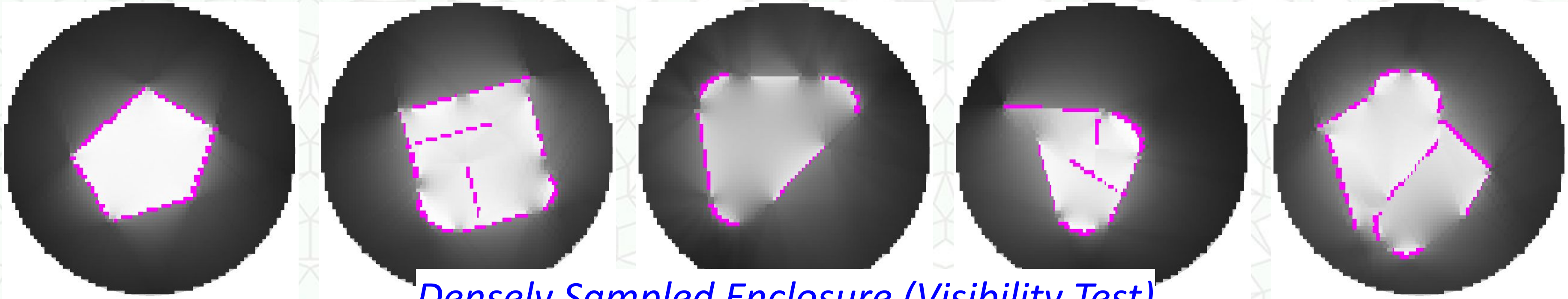
- In addition to infinite straight lines, a "wall chain" may:
    - Bend or be curved!
    - Be a closed loop!
    - Cross itself!
    - Cross another wall chain more than once!



Halfspace Zones & Enclosure

- Further subdivided using GraphCuts (if needed)

Halfspace Zones



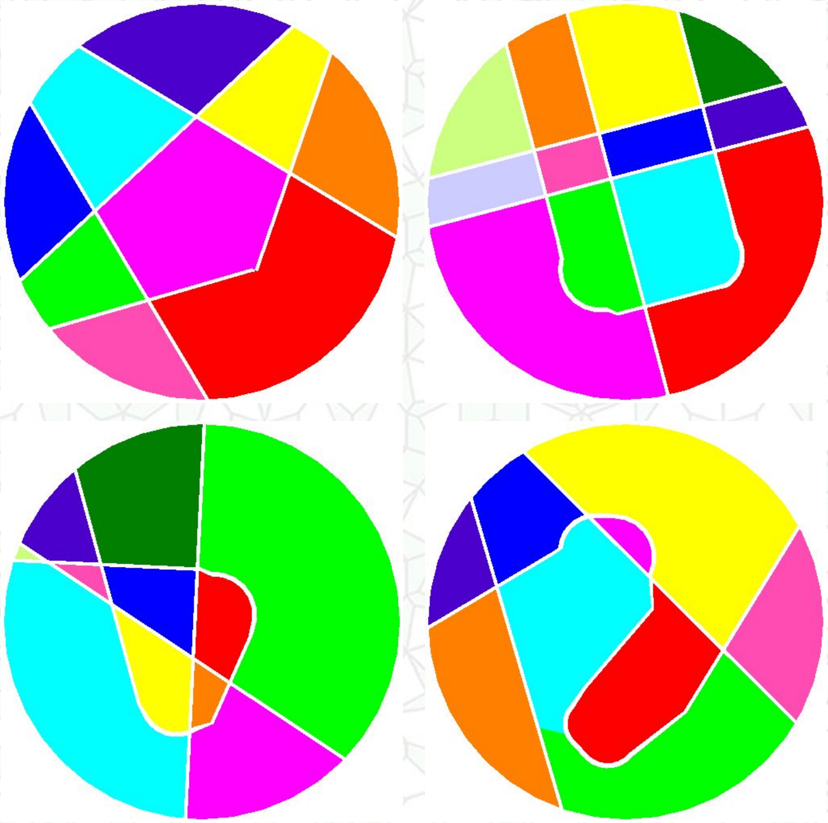
Densely Sampled Enclosure (Visibility Test)

Halfspace Zones & Enclosure

- For *n* wall chains
- *For simplicity, assume they are infinite straight lines*
- We will have *$O(n^2)$* faces/cells in the arrangement
- Each face/cell can be "interior" or "exterior"

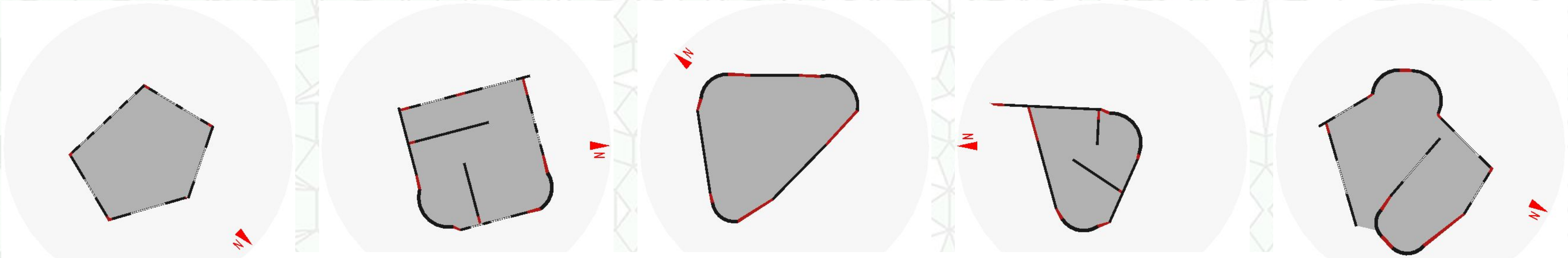
- *→ $2^{O(n^2)}$ possible buildings*

  Not feasible to check all of them!!



Interior/Exterior Enclosure Threshold

- There is no universal threshold – varies design-to-design, and *within-a-design*



Automatic Interior/Exterior Determination & Final Floorplan

Compare to Designer's Intention

Interior/Exterior Optimization

- Analyze histogram of point-sampled enclosure values
- Maximize usage of lengths of real wall elements
- Minimize length of inferred (added) walls
- Minimize area assigned in opposition of simple threshold metric

Interior/Exterior Optimization

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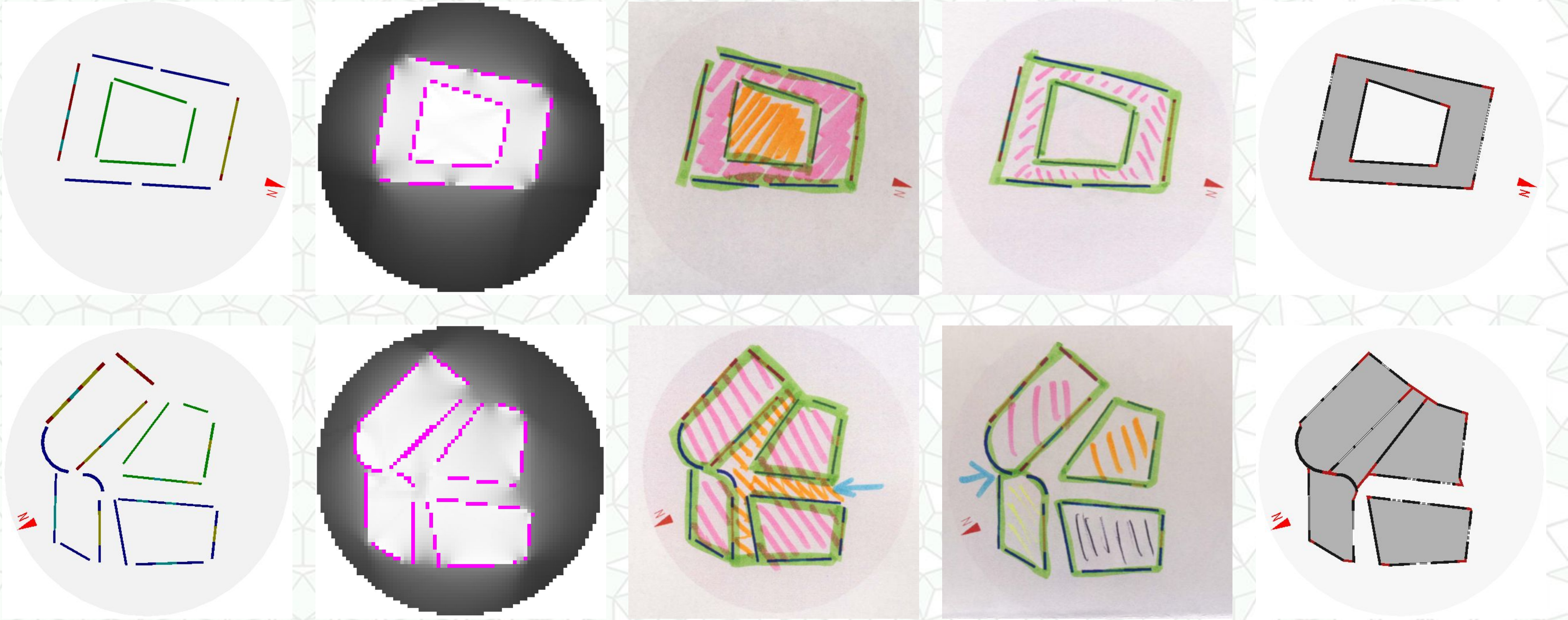
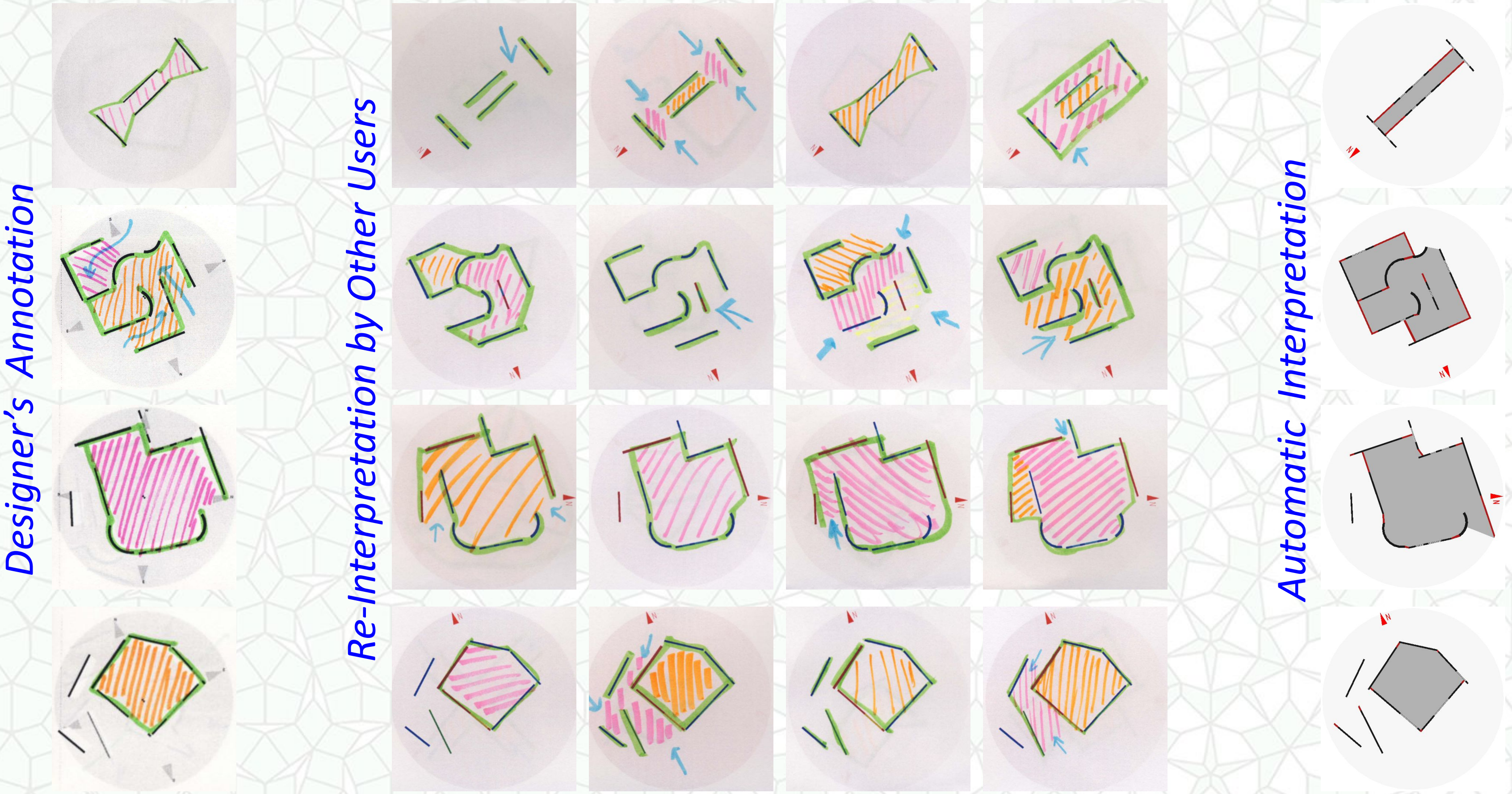
Interior/Exterior Optimization

- (Courtyard option) Minimize total enclosed area



User Study: Identify/Quantify Ambiguous Designs



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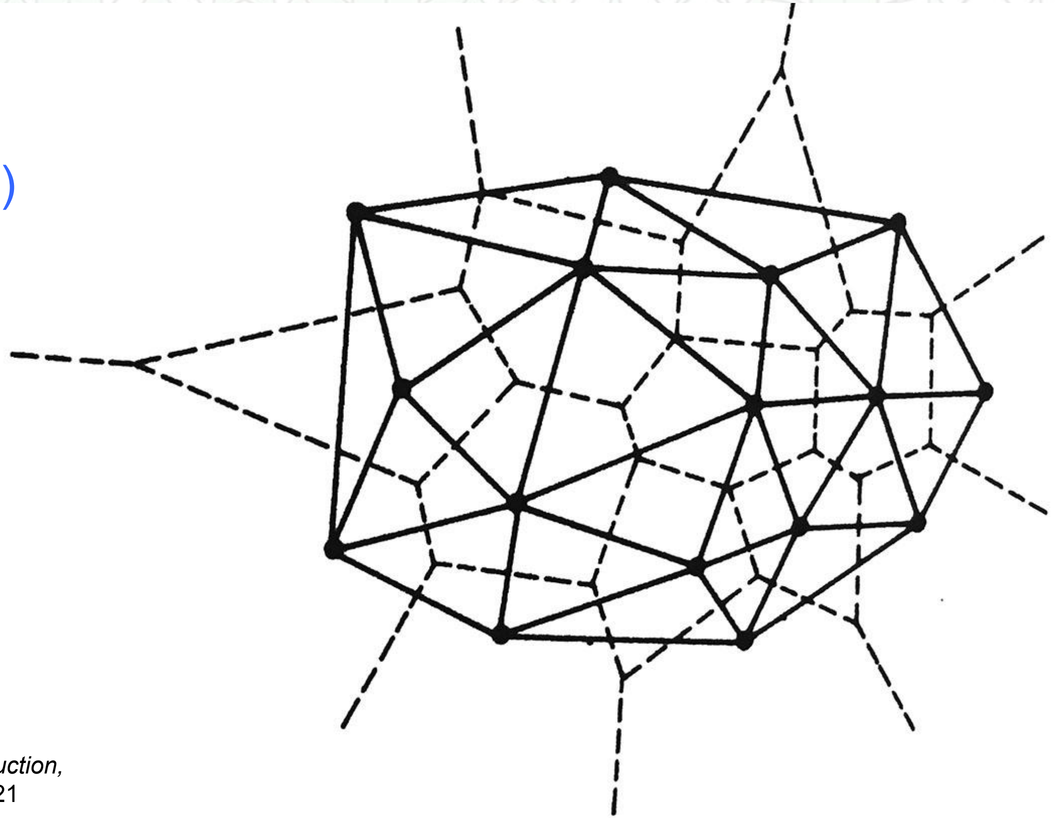
Next Time: Delaunay Triangulation!

- The Voronoi Diagram (VD) *is the dual of the* Delaunay Triangulation (DT)
- Every Voronoi Site is a face in Voronoi Diagram and a vertex in the DT
- Every Voronoi Edge is an edge in the DT
- Every Voronoi Vertex is a triangle in the DT



Computational Geometry: An Introduction,
Preparata & Shamos, Figure 5.21