Aalto University
School of Science

Department of Computer Science

Combinatorics of Efficient Computations

Approximation Algorithms

Lecture 9: An Approximation Scheme for Euclidean TSP

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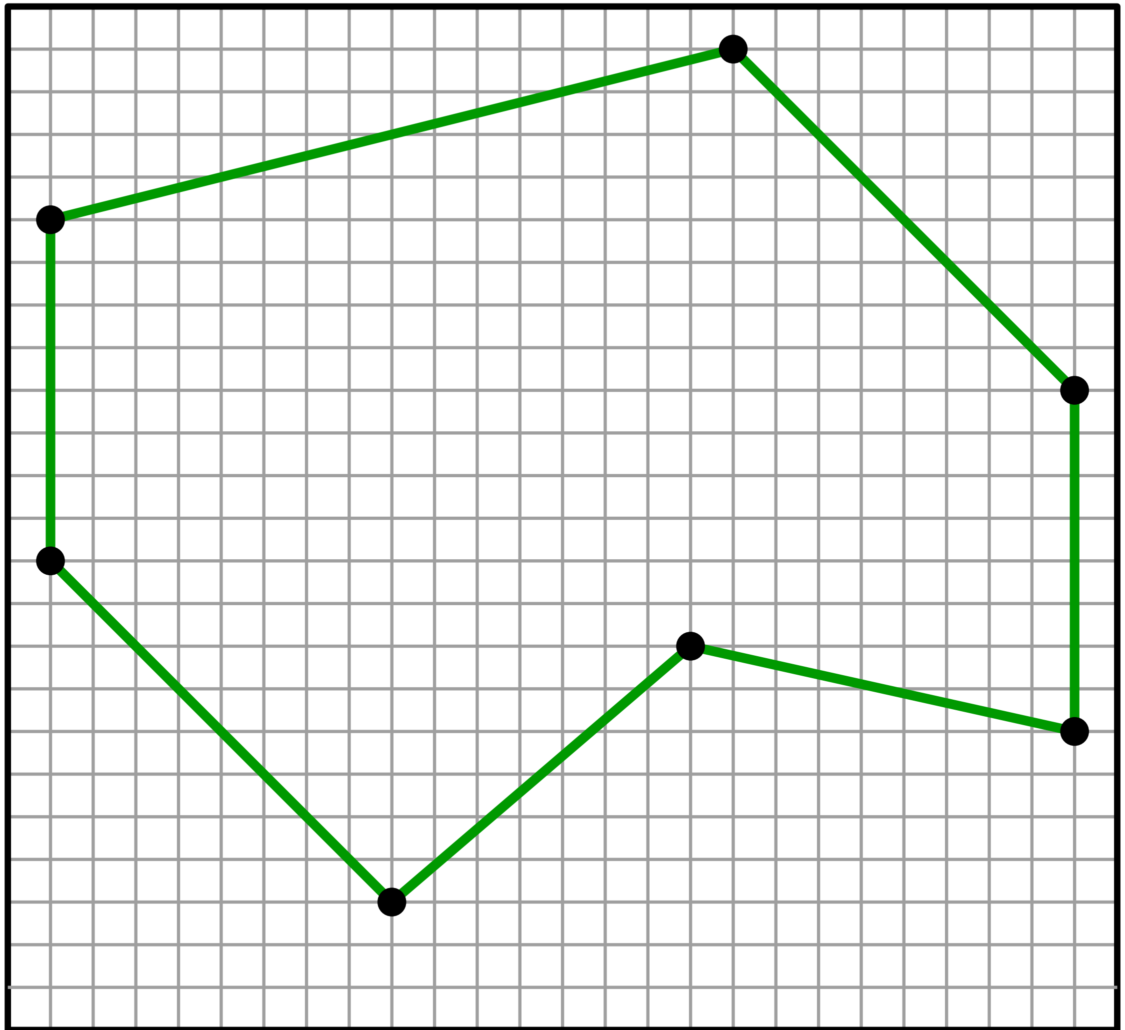
Euclidean TSP

Given: A set of n points in $\mathbb{R}^2$.

The distance between two points is the euclidean distance.

Find: A Hamiltonian cycle (tour) of minimum length.



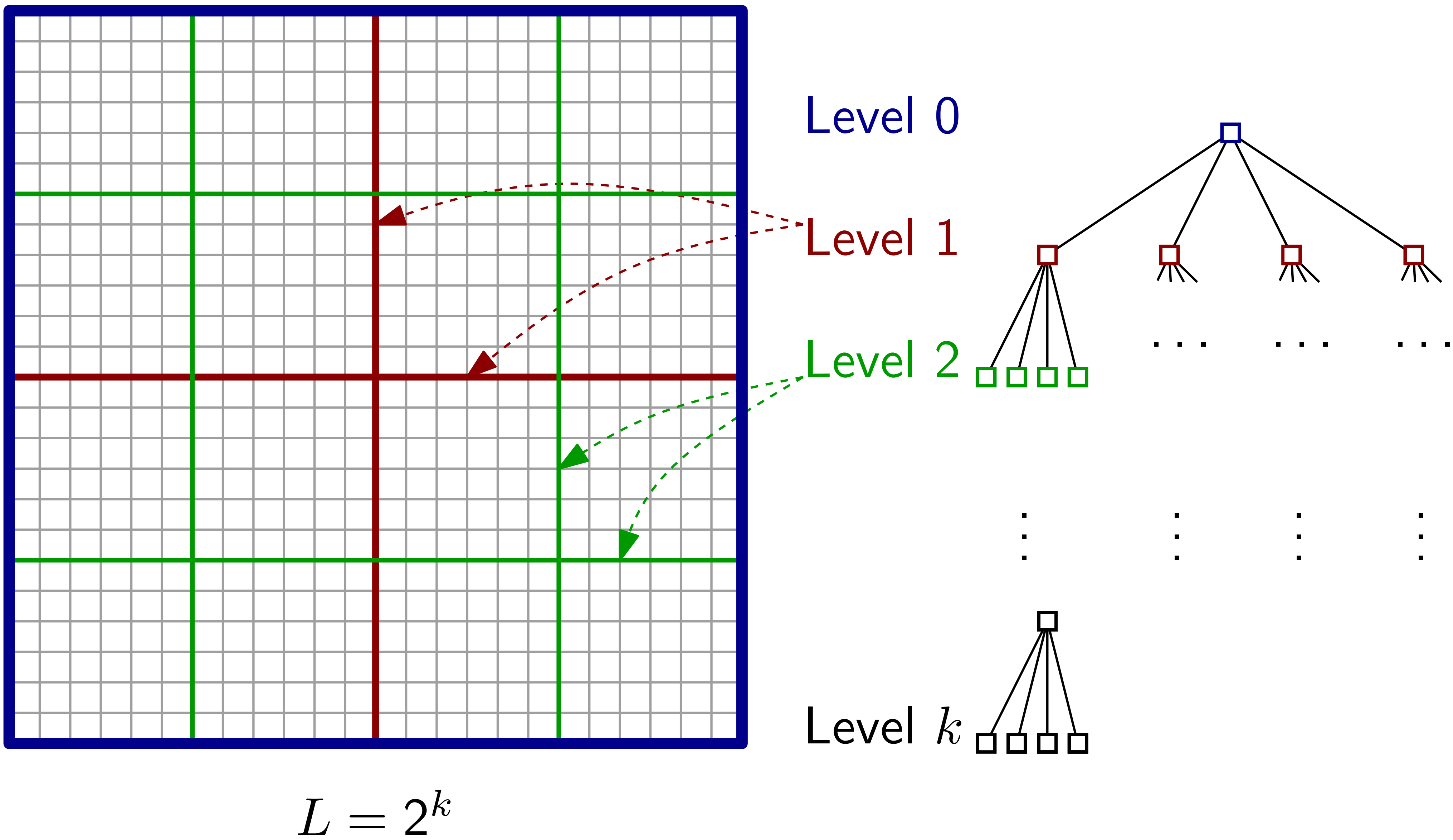
Goal: $(1 + \epsilon)$-Approximation!

Simplifying Assumptions

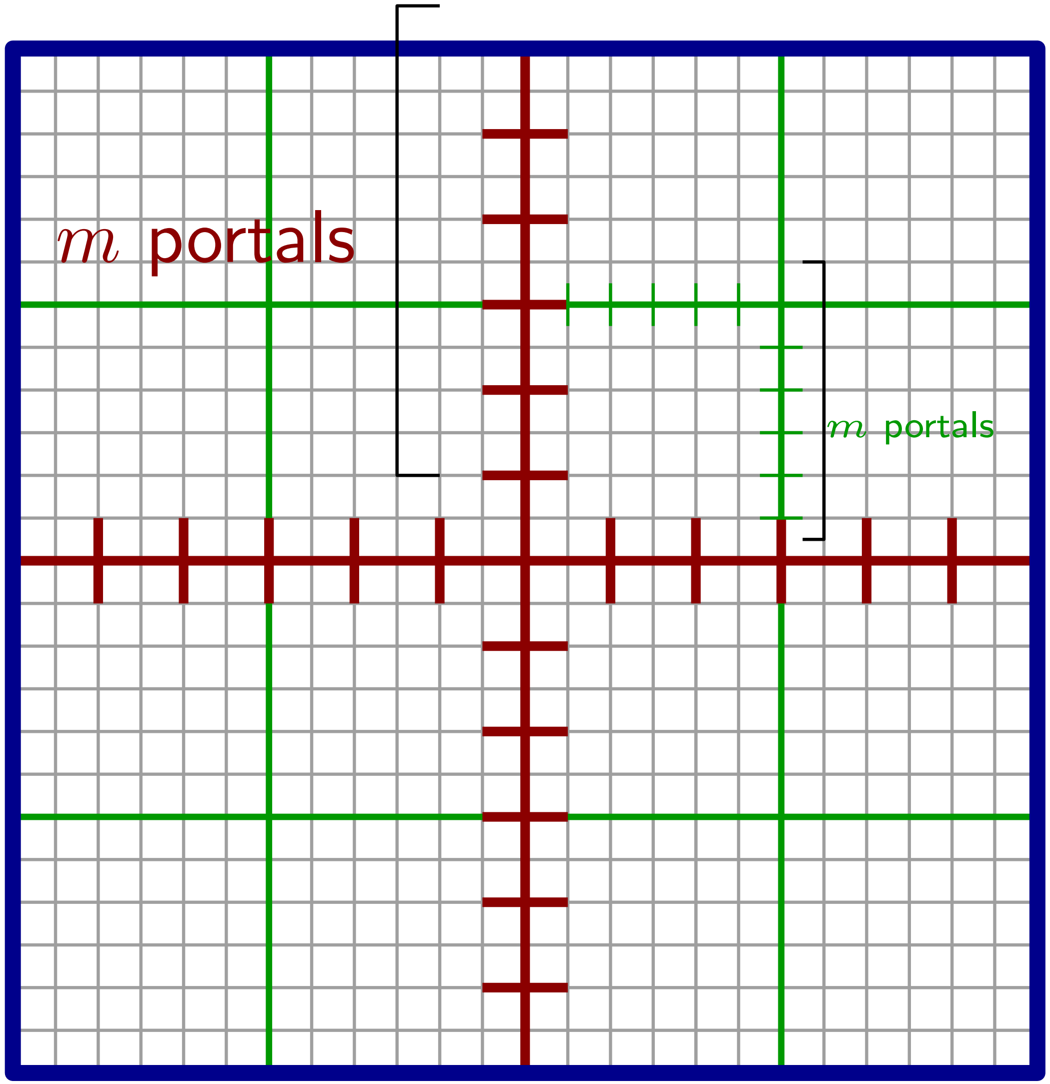
- points belong to an $L \times L$-square
- $L := 4n^2 = 2^k$; $k = 2 + 2 \log_2 n$
- integer coordinates

"justification" $\rightsquigarrow$ exercise

Basic Dissection



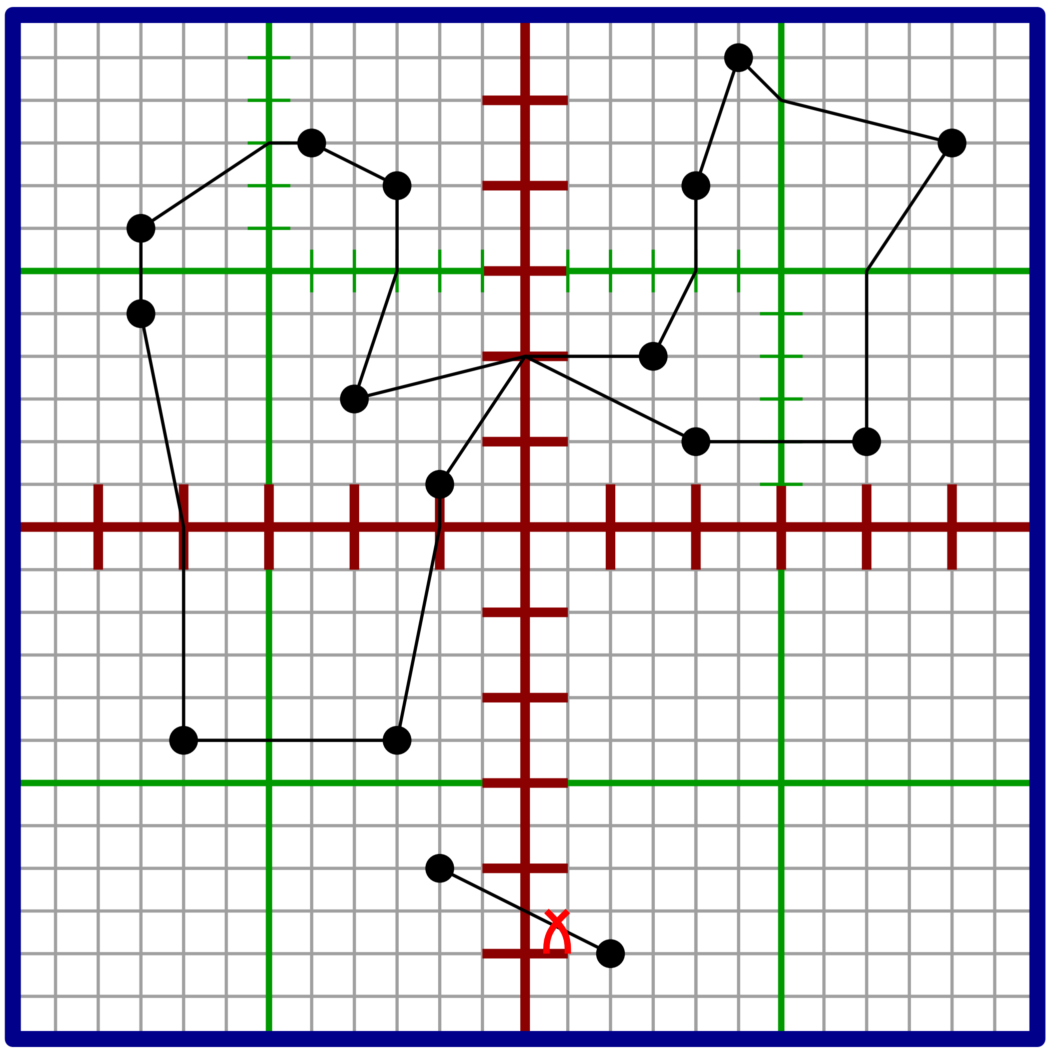
Portals



$$L := 4n^2 = 2^k.$$

- $k = O(\log n)$
- m is a power of two in the interval $[k/\epsilon, 2k/\epsilon]$
- $m = \Theta(\log n/\epsilon)$
- **Portals** on a level-i-line have distance $L/(2^i m)$
- each level-i-square has at most $4m$ boundary portals

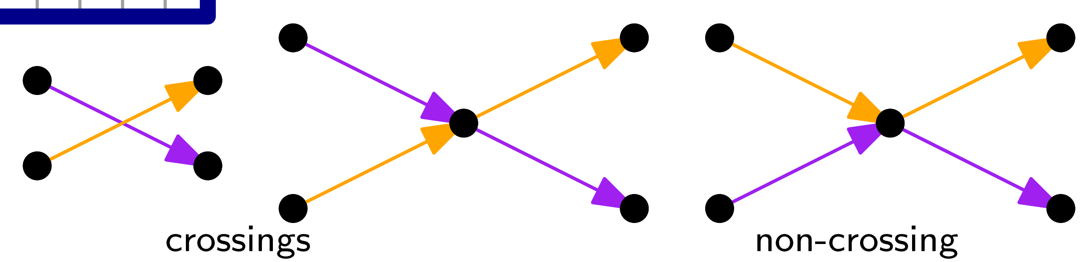
Well Behaved Tours



A tour is **well behaved**, when

- it involves all points and a subset of the portals,
- no edge of the tour crosses a line of the basic dissection
- it is crossing-free.

Without loss of generality (exercise): no portal is visited more than twice.

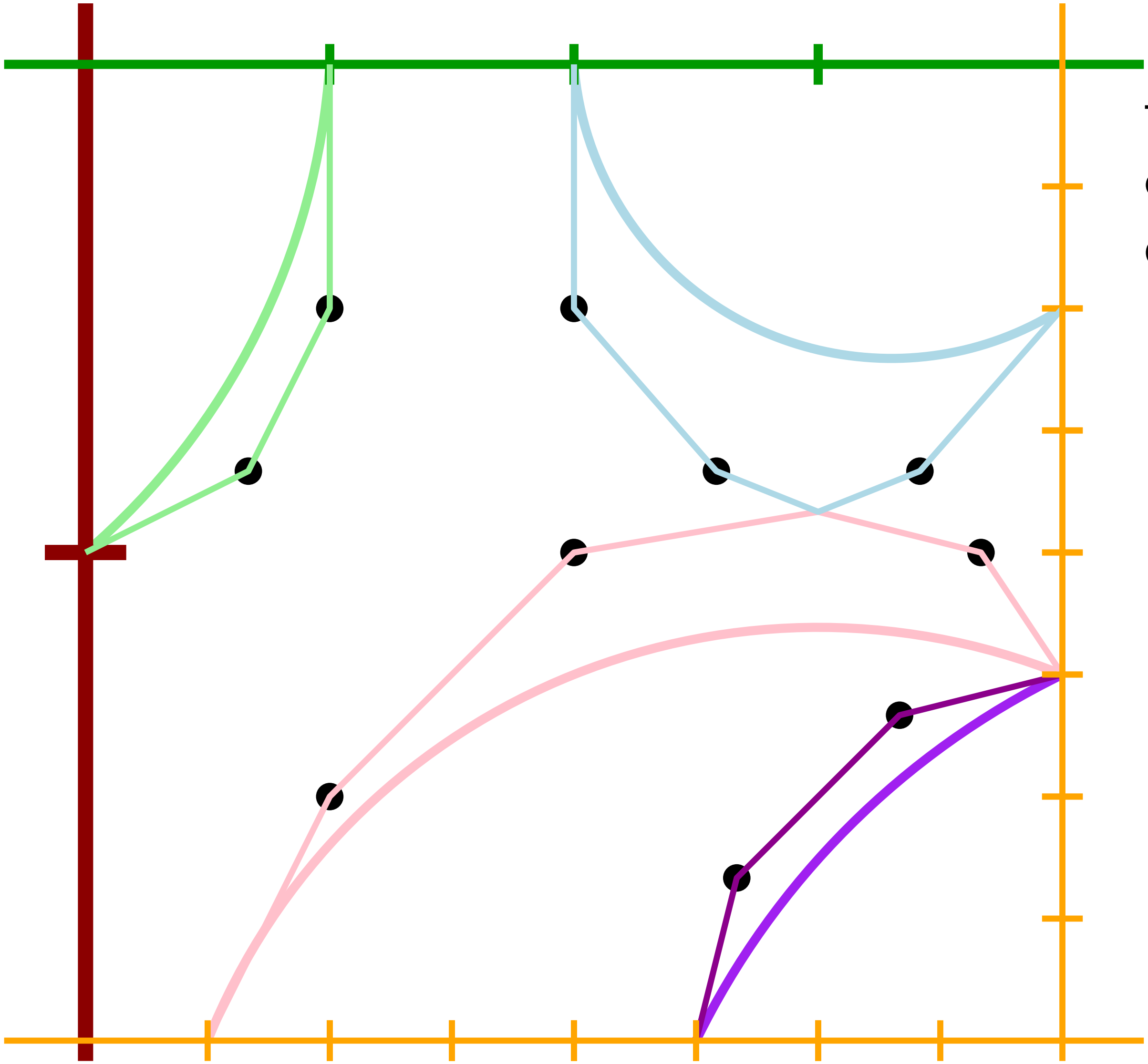


Computing a well behaved tour

Lem. An optimal well behaved tour can be computed in $2^{O(m)} = n^{O(1/\epsilon)}$ time.

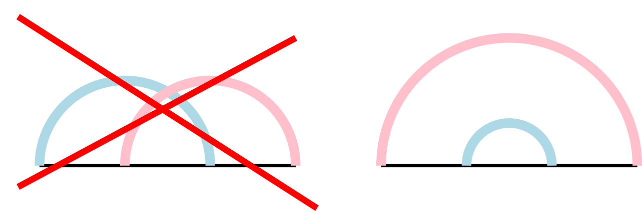
Proof.
- Dynamic Program.
- Compute sub-structure of an optimal tour for each square in the dissection tree.
- These solutions can be efficiently propagated bottom-up through the dissection tree.

Dynamic Program (I)



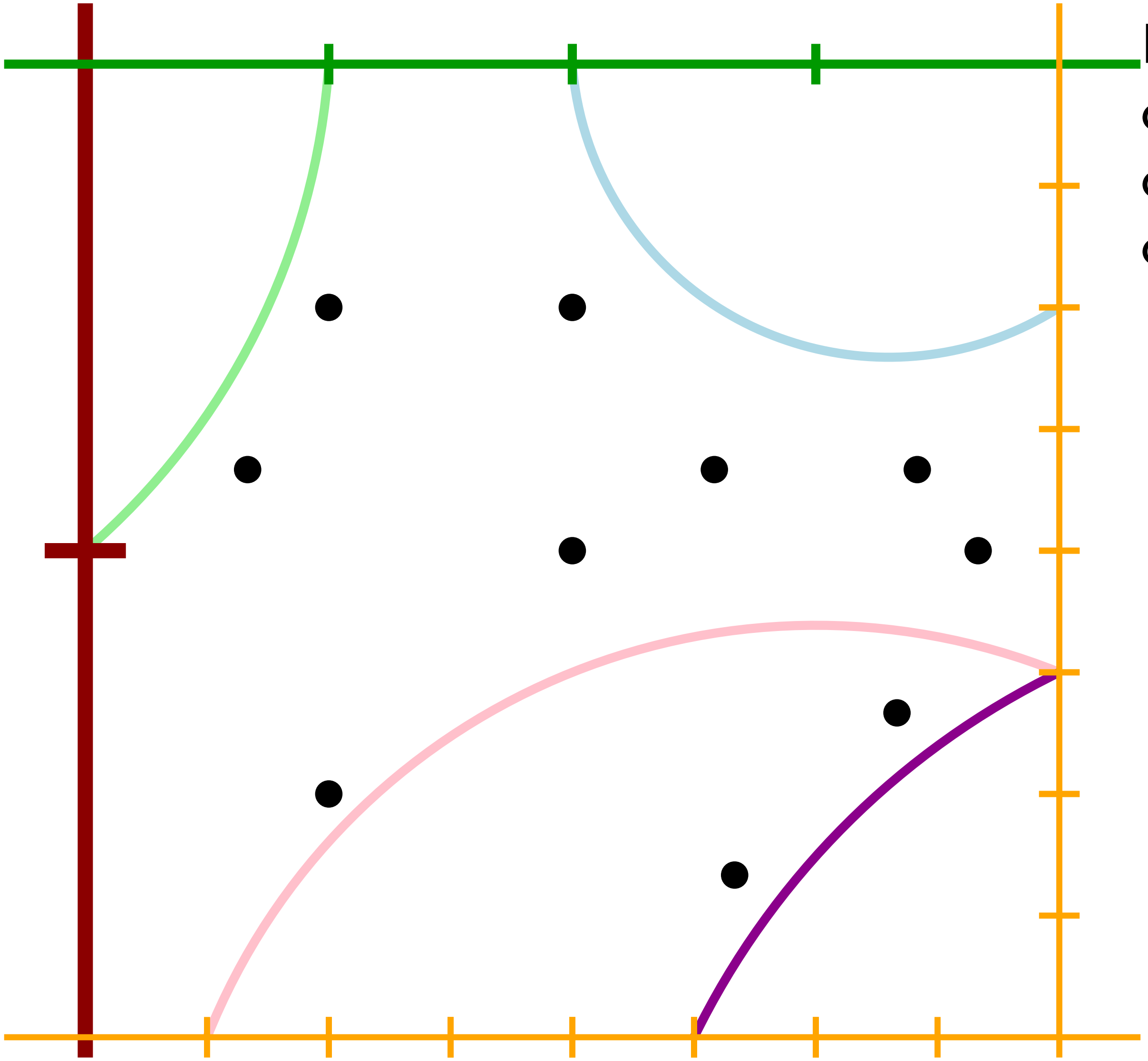
Each global well behaved tour induces the following in each square Q of the dissection:

- a path cover on the vertices in Q
- each portal of Q is visted 0,1 or 2 times by this path cover.
- a **crossing-free pairing** of the visited portals.



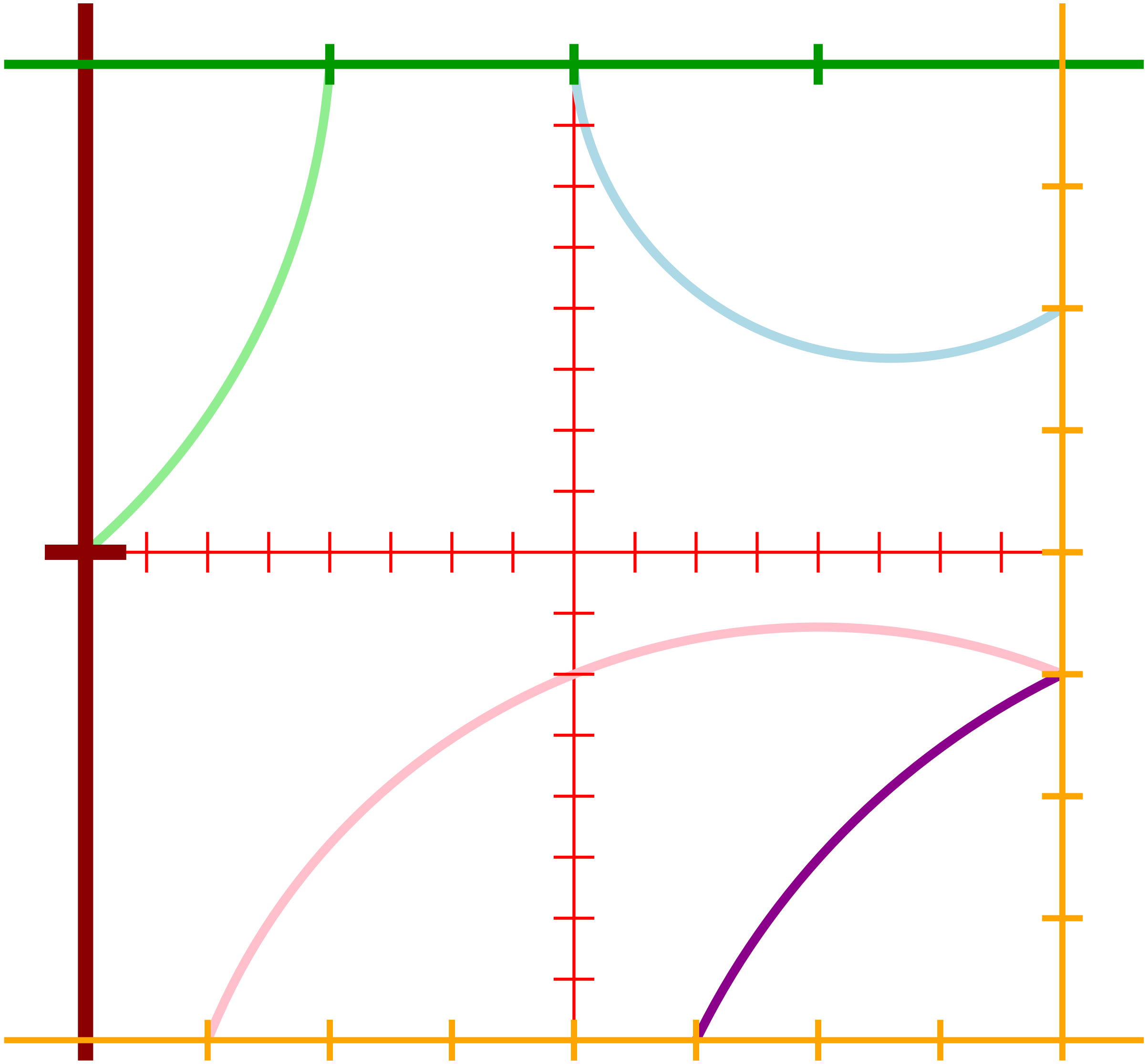
$$\text{max. } \underbrace{n^{O(1/\epsilon)}}_{\#\text{visit vectors}} \times \underbrace{2^{O(m)}}_{\#\text{real. pairings}} = n^{O(1/\epsilon)} \text{ total pairings}$$

Dynamic Program (II)



For each square Q, and each crossing-free pairing P in Q, compute an optimal path cover respecting P.

Dynamic Program (III)

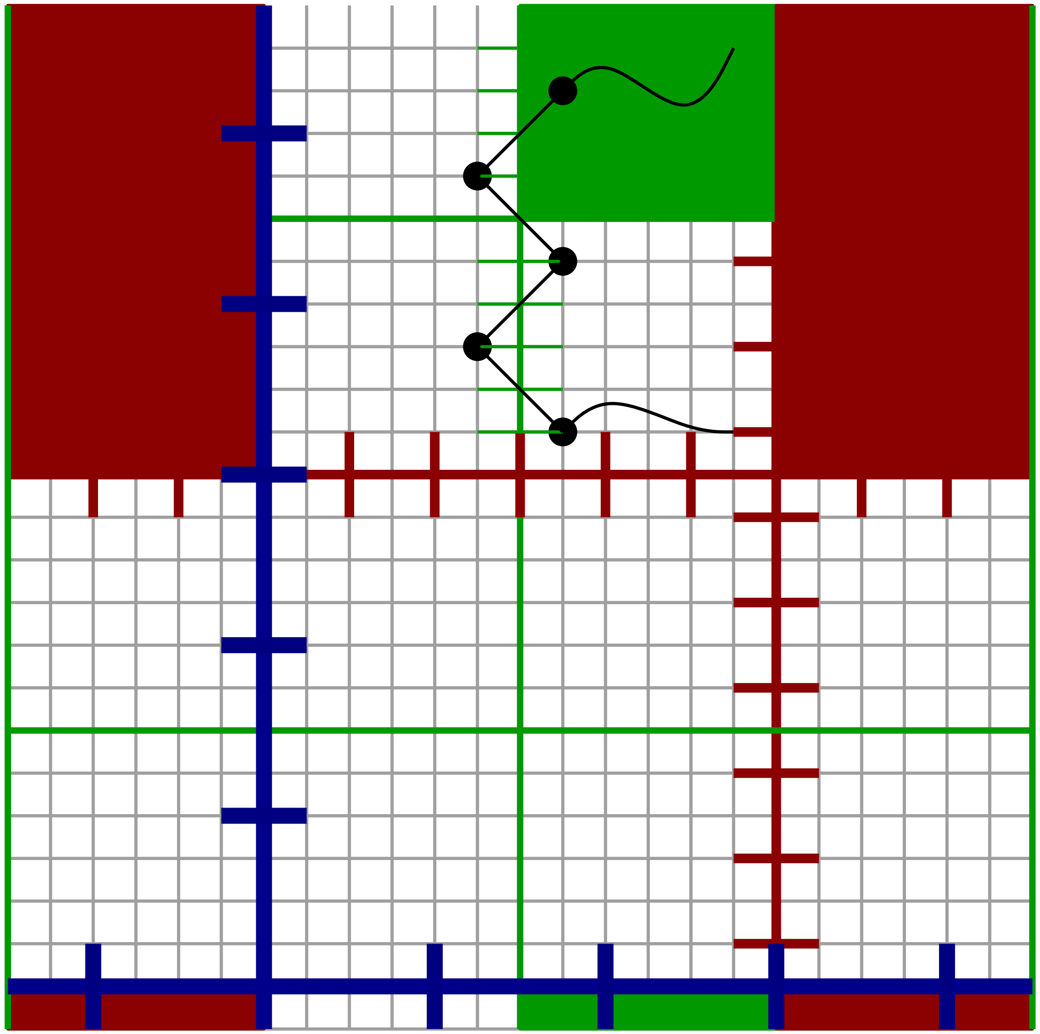


For a given square Q and pairing P:

- iterate over all $(n^{O(1/\epsilon)})^4 = n^{O(1/\epsilon)}$ crossing-free pairings of the child-squares
- choose a combination of such pairings which minimizes the cost and respects P.
- correctness by induction

$\square$

Shifted Dissections



- the best well behaved tour can be a poor approximation :-(
- Define an (a, b)-shifted dissection

  $$x \mapsto (x + a) \bmod L$$
  $$y \mapsto (y + b) \bmod L$$

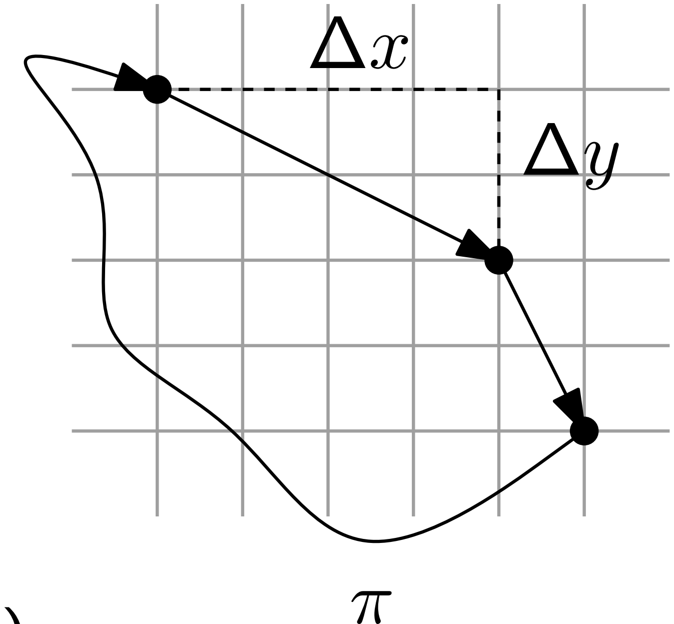
- Squares in the dissection tree are "wrapped around"
- dynamic program must be modified accordingly.

Shifted Dissections (II)

Lem. Let π be an optimal tour and $N(\pi)$ be the number of crossings with the lines of the $L \times L$-grid. Then we have $N(\pi) \leq \sqrt{2} \cdot \text{OPT}$

Proof.

- Consider a tour as an ordered cyclic sequence.
- Each edge generates $\leq \Delta x + \Delta y$ crossings.
- Crossings at the endpoint of an edge are counted for the next edge
- $(\Delta x + \Delta y)^2 \leq 2(\Delta x^2 + \Delta y^2)$ completes the proof.

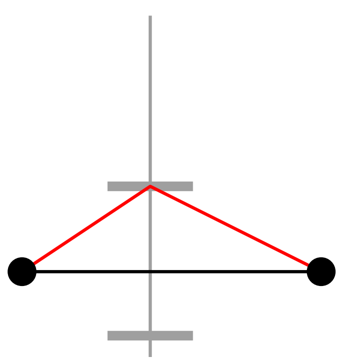


□

Shifted Dissections (III)

Thm. Let $a, b \in [0, L-1]$ be chosen independently and uniformaly at random. Then the expected cost of an optimal well behaved tour with respect to the (a,b)-shifted dissection is at most $(1+\sqrt{2}\epsilon)$OPT.

Proof. Consider an optimal tour π. Make π well behaved by moving each intersection point (with the $L \times L$-grid) to the nearest portal.



detour per intersection $\leq$ inter-portal distance.

Shifted Dissection (III)

- Consider an intersection point between π and a line l of the $L \times L$-grid.
- With probability *at most* $2^i/L$, l is a level-i-line $\rightsquigarrow$ an increase in tour length by a maximum of $L/(2^i m)$ (inter-portal distance).
- Thus, the expected increase in tour length due to this intersection is at most:

$$\sum_{i=0}^{k} \frac{L}{2^i m} \frac{2^i}{L} \leq \frac{k}{m} \leq \epsilon$$

- Summing over all $N(\pi) \leq \sqrt{2}\mathrm{OPT}$ intersection points, and applying linearity of expectation, provides the claim.

$\square$

Approximation Scheme.

Thm. There is a PTAS for euclidean TSP, i.e., for each $\epsilon > 0$ one can find a $(1+\epsilon)$-approximation in $n^{O(1/\epsilon)}$ time.

Proof. Try all L^2 different (a, b)-shifted dissections.
By the previous thm., one of these is good enough. $\square$