

Optimal Exploration of Terrains with Obstacles

Jurek Czyzowicz¹ David Ilcinkas²
Arnaud Labourel^{1,2} Andrzej Pelc¹

¹Université du Québec en Outaouais, Canada

²CNRS & Univ. de Bordeaux, France

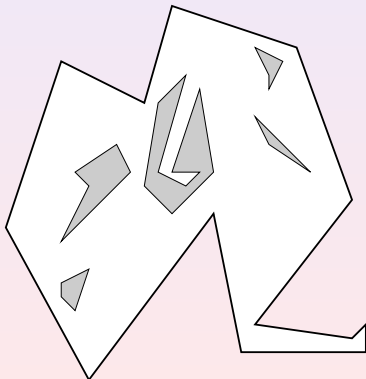
SWAT 2010

June 21, 2010

The problem

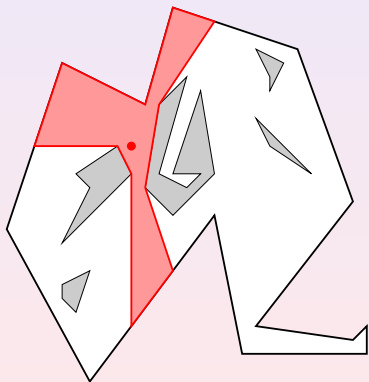
Exploration of terrains with obstacles

A mobile robot has to **explore/see all points** of an **unknown** bounded terrain, possibly with obstacles.



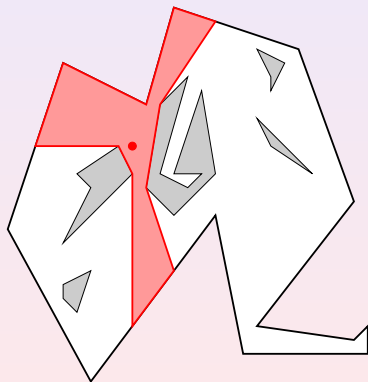
Vision

Unlimited vision

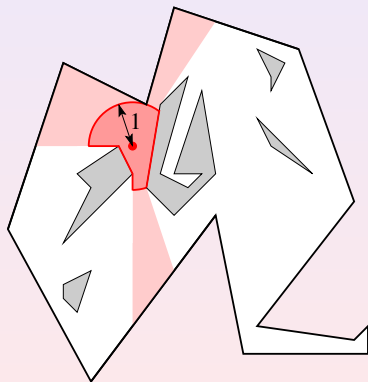


Vision

Unlimited vision



Limited vision



Motivations

Motivations / Applications

Exploration / searching / map drawing of

- unsafe environments
- unreachable environments

Related (off-line) problems

- with unlimited vision
 - Gallery tour problem (NP-hard)
 - Watchman's route (polynomial)
- with limited vision
 - Sweeper problem (NP-hard)
 - Pocket milling problem (NP-hard)
 - Lawn mowing problem (NP-hard)

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Performance measures

Algorithm \mathcal{A} having **no a priori knowledge** on the terrain.

Worst-case complexity

Worst-case length of \mathcal{A} 's trajectory in the family of terrains of bounded parameters

- P : total perimeter
- A : area of the terrain
- k : number of obstacles

Competitive ratio

$$\max_T \frac{\text{length of } \mathcal{A}'\text{s trajectory}}{\text{length of an optimal algorithm knowing the terrain } T}$$

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Related work (unlimited vision)

Rectilinear polygon without obstacles

- [Kleinberg, 1994]: (randomized) competitive ratio $\frac{5}{4}$
no deterministic algorithm with competitive ratio $< \frac{5}{4}$
- [Deng, Kameda, Papadimitriou, 1998]: competitive ratio 2
- [Hammar, Nilsson, Schuierer, 2002]: competitive ratio $\frac{5}{3}$
- [Hammar, Nilsson, Persson, 2006]: competitive ratio $\frac{3}{2}$

Polygonal terrain with obstacles

- [Kalyanasundaram, Pruhs, 1993]: competitive ratio $O(k)$
($O(\sqrt{k})$ in some special cases)
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Offline problem (sweeper problem)

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Restricted class of polygons

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Our results

We consider the **worst-case trajectory length** measure.

- P : total **perimeter**
- D : **diameter** of the (convex hull of the) terrain
- A : **area** of the terrain
- k : number of **obstacles**

Unlimited vision

- $\Omega(P + D\sqrt{k})$, even if the terrain is a priori known
- $O(P + D\sqrt{k})$, constructive proof (algorithm)

Limited vision

- $\Omega(P + A + \sqrt{Ak})$, even if the terrain is a priori known
- $O(P + A + \sqrt{Ak})$, if k or A is known (algorithm)
- $O(\min\{\log A, \log k\}(P + A + \sqrt{Ak}))$, nothing known

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Outline

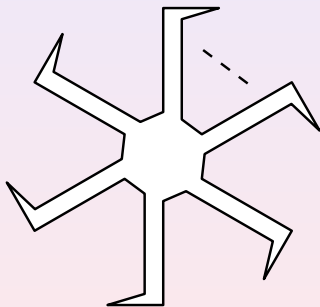
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- 2 Unlimited vision**
 - Lower bound
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Lower bound

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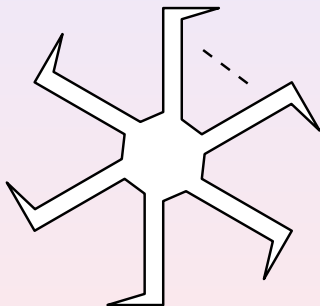
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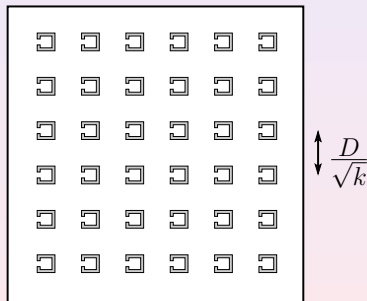
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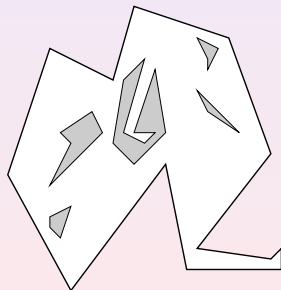
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Upper bound (optimal)

Upper bound $O(P + D\sqrt{k})$, without a priori knowledge.
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Our algorithm

- Apply the *naive algorithm* but **only approaching "close" obstacles**

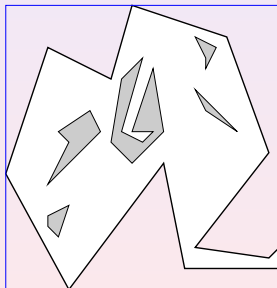


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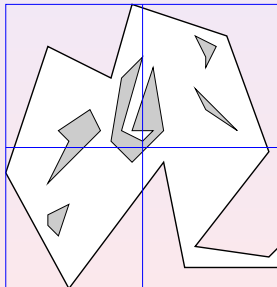


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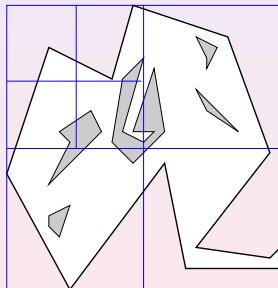


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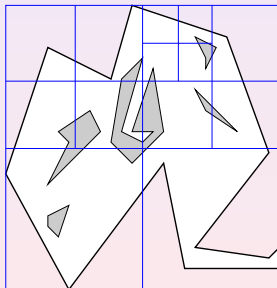


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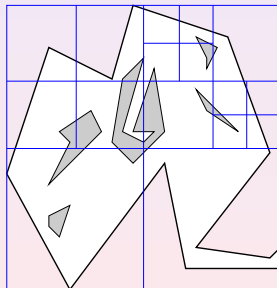


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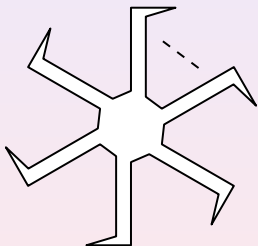


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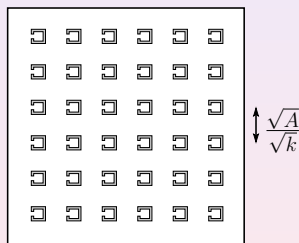
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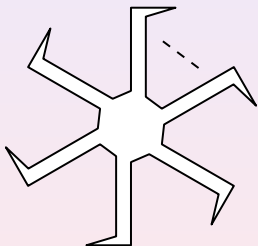
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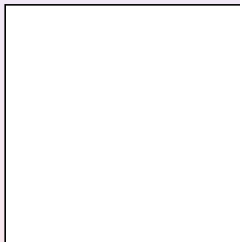
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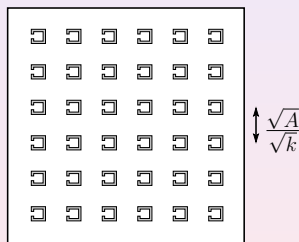
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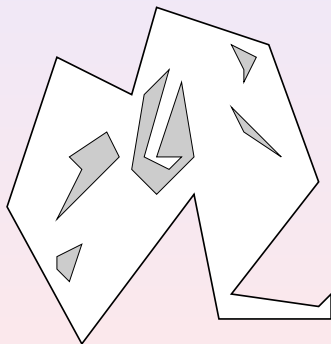
Upper bound (1)

Basic idea: re-use the unlimited vision algorithm

$F \leq 1$: length of square side

Algorithm LET(F)

- Reach the boundary
- Follow/explore the boundary
- **Partition** the terrain **in cells**
- \forall cell in **DFS** order
 - Explore the cell



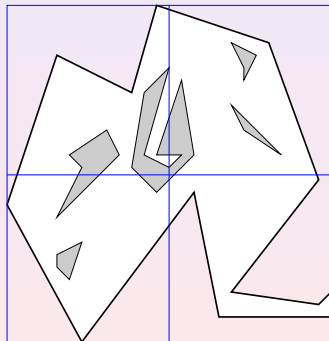
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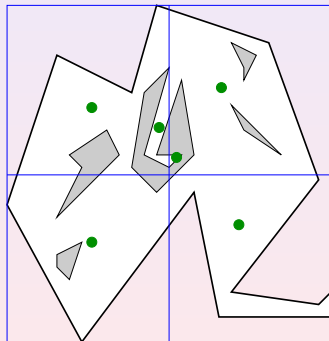
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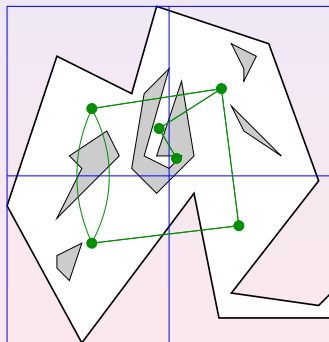
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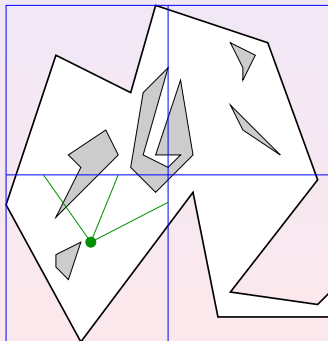
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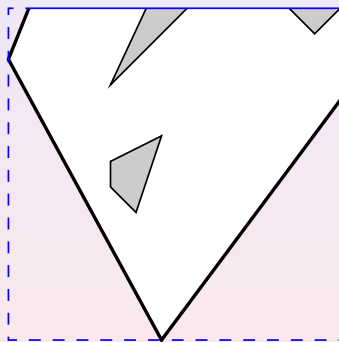


Cell exploration

Basic idea: use the unlimited vision **naive** algorithm

Naive algorithm

- Reach the boundary of **cell c**
- Follow/explore the boundary
- **While** unvisited obstacles
 - Go to an unvisited obstacle
 - Go around it to explore it
 - Go around it again to look at other unvisited obstacles and to explore them recursively



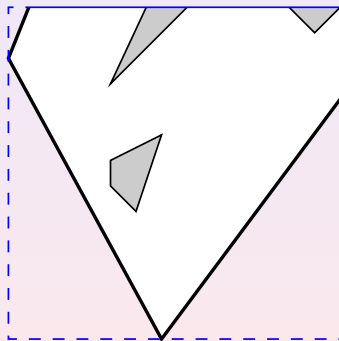
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Upper bound (2)

Complexity of $\text{LET}(F)$: $O(P + A/F + k \cdot F)$

Goal (lower bound): $\Omega(P + A + \sqrt{A \cdot k})$

Solutions intuition: choose $F = \min\{1, \sqrt{\frac{A}{k}}\}$

If only A is known (case when k known is similar):

Algorithm LET_A

- Set $F = 1$
- Apply $\text{LET}(F)$ until the error is “too” large
- Decrease F appropriately
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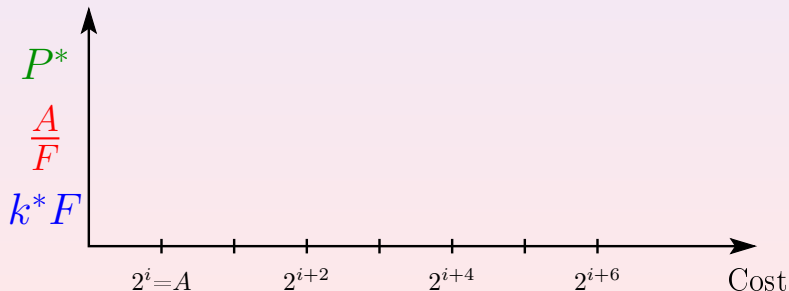
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Complexity analysis of LET_A (A known)

P^*, k^* : current discovered values of P and k

P_j, k_j : values of P^*, k^* at the end of Phase j

- $F_1 = 1$
- Stopping condition: $\{k^* F_j \geq 2 \frac{A}{F_j} \text{ and } k^* F_j \geq P^*\}$
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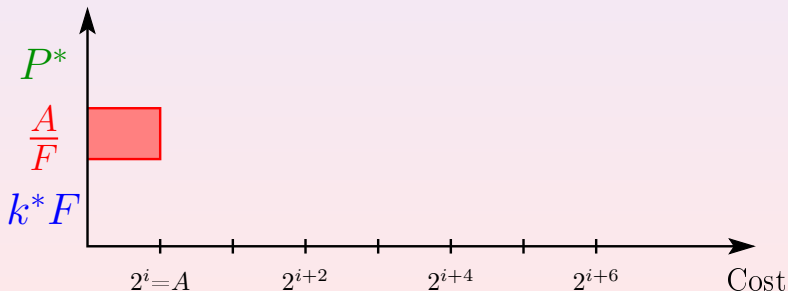


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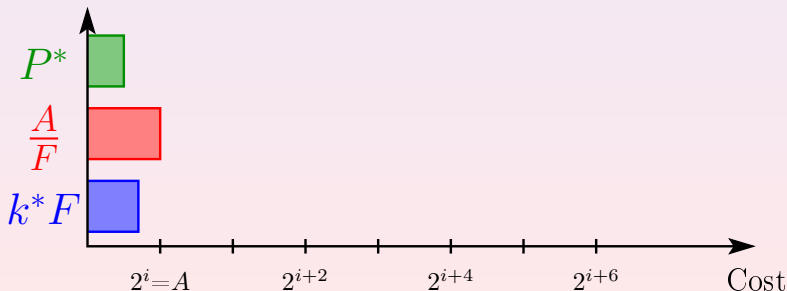


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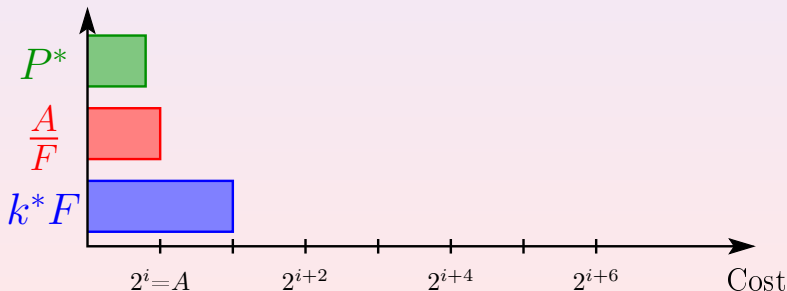


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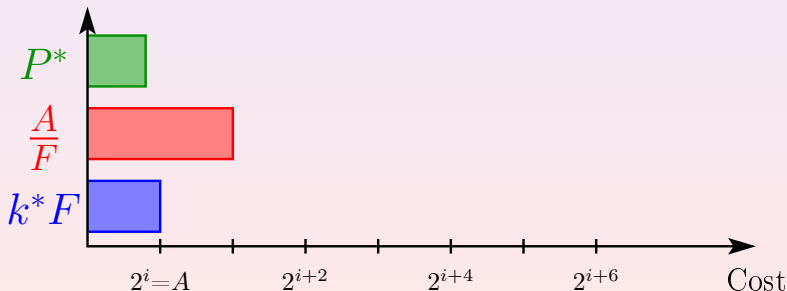


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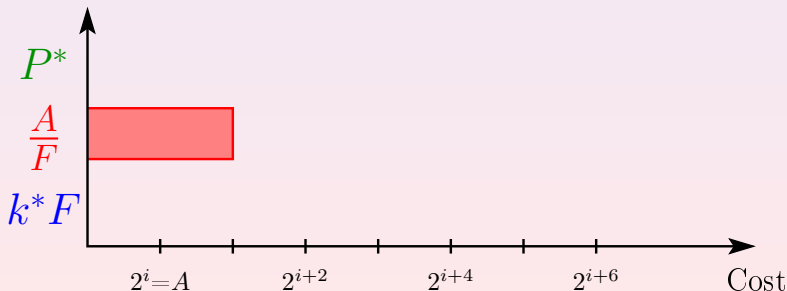


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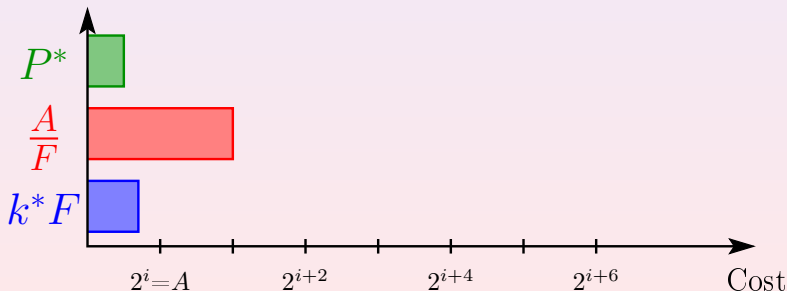


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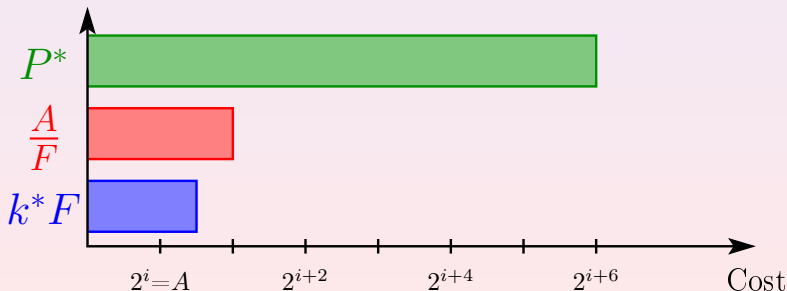


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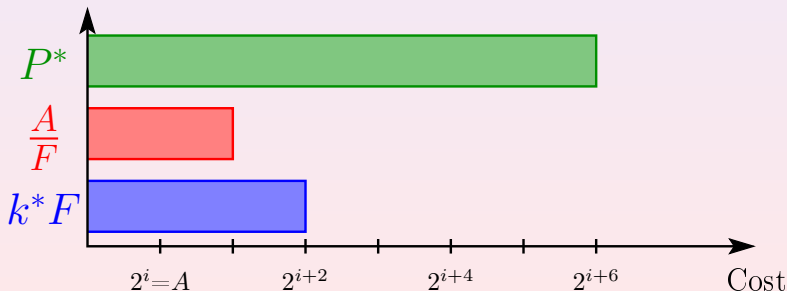


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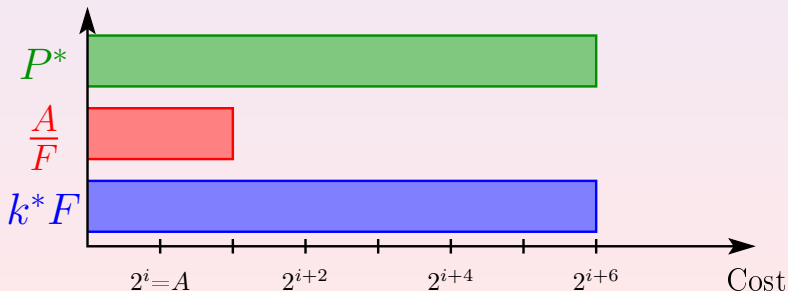


Complexity analysis of LET_A (A known)

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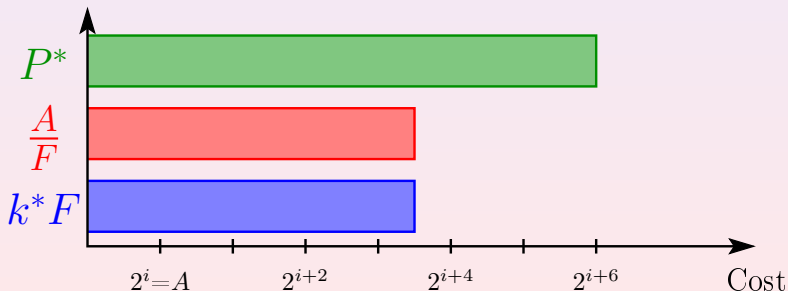


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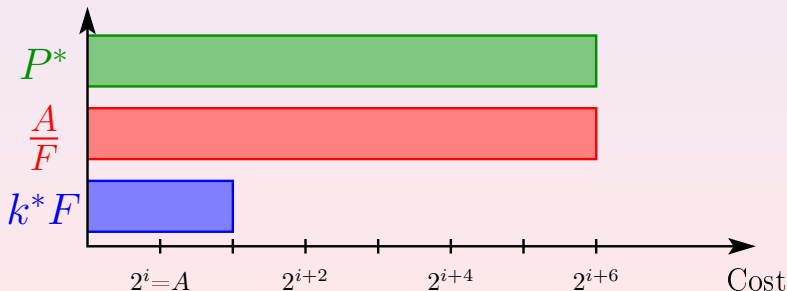


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Outline

- 1 Introduction
- 2 Unlimited vision
- 3 Limited vision
- 4 Conclusion**

Conclusion and perspectives

(Reminder: P = perimeter; A = area; k = # obstacles)

Limited vision

- $\Omega(P + A + \sqrt{Ak})$, even if the terrain is a priori known
- $O(P + A + \sqrt{Ak})$, if k or A is known (algorithm)
- $O(\min\{\log A, \log k\}(P + A + \sqrt{Ak}))$, nothing known

Open problem

- *Worst-case complexity without knowledge?*
- *Competitive ratio in any polygonal terrain with polygonal obstacles (limited and unlimited)?*

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Thank You
for your attention