The Grid-Based Path Planning Competition

-or-

Contractions, contractions everywhere

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University of Denver

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UNIVERSITY of DENVER
DANIEL FELIX RITCHIE SCHOOL OF ENGINEERING & COMPUTER SCIENCE

Testing Heuristics: We Have It All Wrong

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Carnegie Mellon University
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May 1995

Testing Heuristics

- Suppose: bright idea for a new algorithm

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- Approach “spawns a host of evils”

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- The emphasis on competition is fundamentally antiintellectual
  - Does not build the sort of insight…(for)…more effective algorithms

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- The emphasis on competition is fundamentally antiintellectual
  - Does not build the sort of insight…(for)…more effective algorithms
- Competition diverts time and resources from productive investigation
  - Hours spent crafting the fastest possible code

Example

- 2nd DIMACS challenge
  - Studied SAT problems
  - Stimulated great interest
  - Difficult to know why one approach is better

- Studies which tease out why approaches work without performance increase are hard to publish, but important intellectually

Conclusion

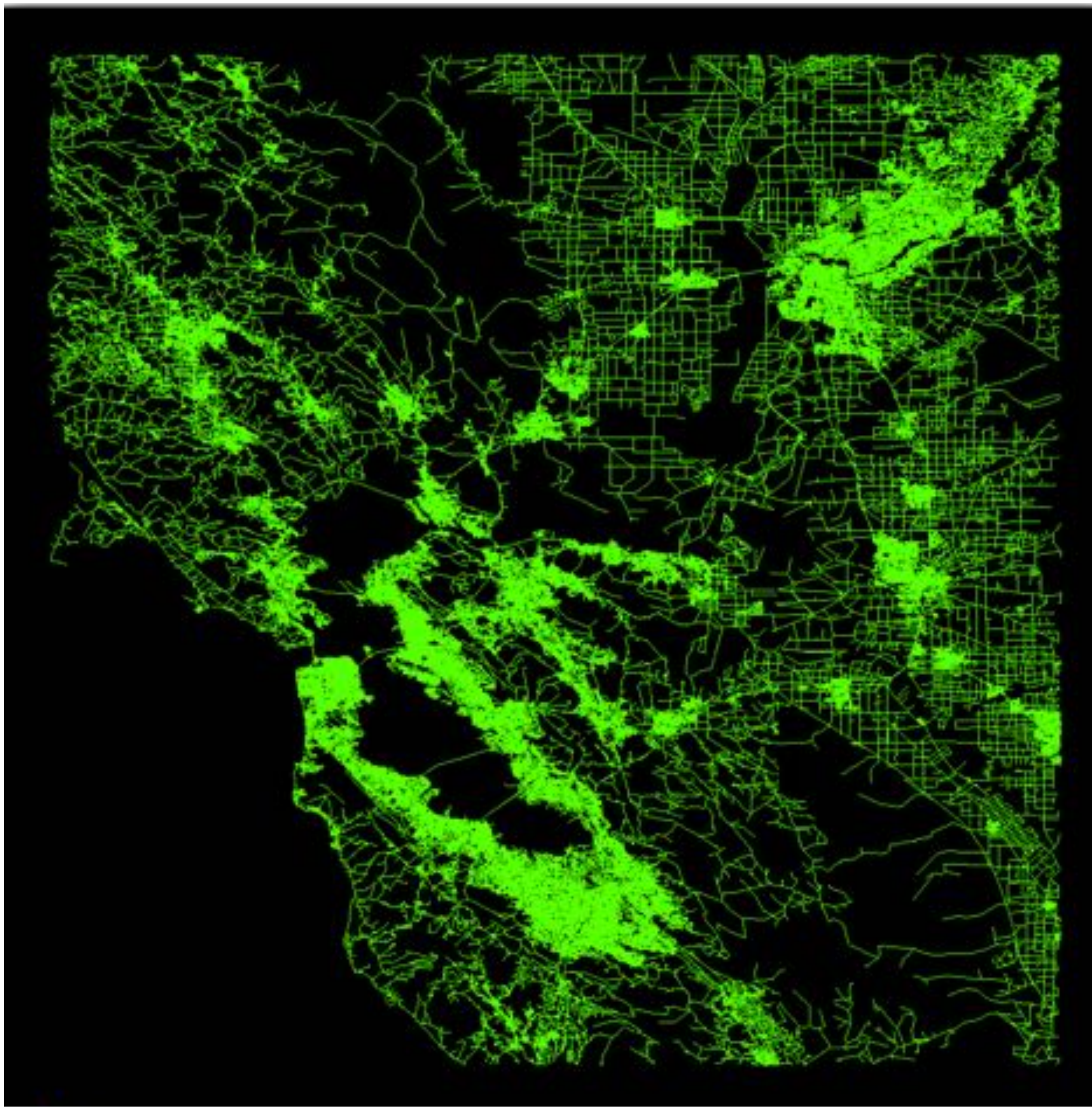
- New norms for research:
  - “That experimental results be evaluated on the basis of whether they contribute to our understanding rather than whether they show that the authors algorithm can win a race with the state of the art.”
  - Algorithm researchers shouldn’t have the “burden of exhibiting faster and better algorithms in each paper.”

Talk Goals

- Present latest GPPC results
- Present insights into commonalities in approaches
- Discuss future challenges

Recent (related) example

- 9th DIMACS challenge
  - Begun in 2005
  - Path planning on road networks



Result of Challenge

- Road networks for testing made available
  - 200k to 24 million nodes
  - 700k to 60 million edges

Result of Challenge

- **Better Heuristics:**
  - Computing the shortest path: A search meets graph theory [Goldberg & Harrelson, 2005]
- **Better Bounding:**
  - Better Landmarks Within Reach [Goldberg et. al., 2007]
- **Exploiting Structure:**
  - In Transit to Constant Time Shortest-Path Queries in Road Networks [Bast et. al. 2007]
  - Contraction Hierarchies: Faster and Simpler Hierarchical Routing in Road Networks [Geisberger et. al. 2008]
  - A Hub-Based Labeling Algorithm for Shortest Paths in Road Networks [Abraham et. al., 2011]
- **Theoretical Justification:**
  - Highway Dimension, Shortest Paths, and Provably Efficient Algorithms [Abraham et. al., 2010]

Observation

Benchmark data spurs research

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Imperfect benchmarks are better than no benchmarks.

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Imperfect benchmarks are better than no benchmarks.

You have to have (flawed) benchmarks before
you can fix/improve them.

Grid Map Benchmarks

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  - [Sturtevant, 2012]

Grid-Based Path Planning Competition

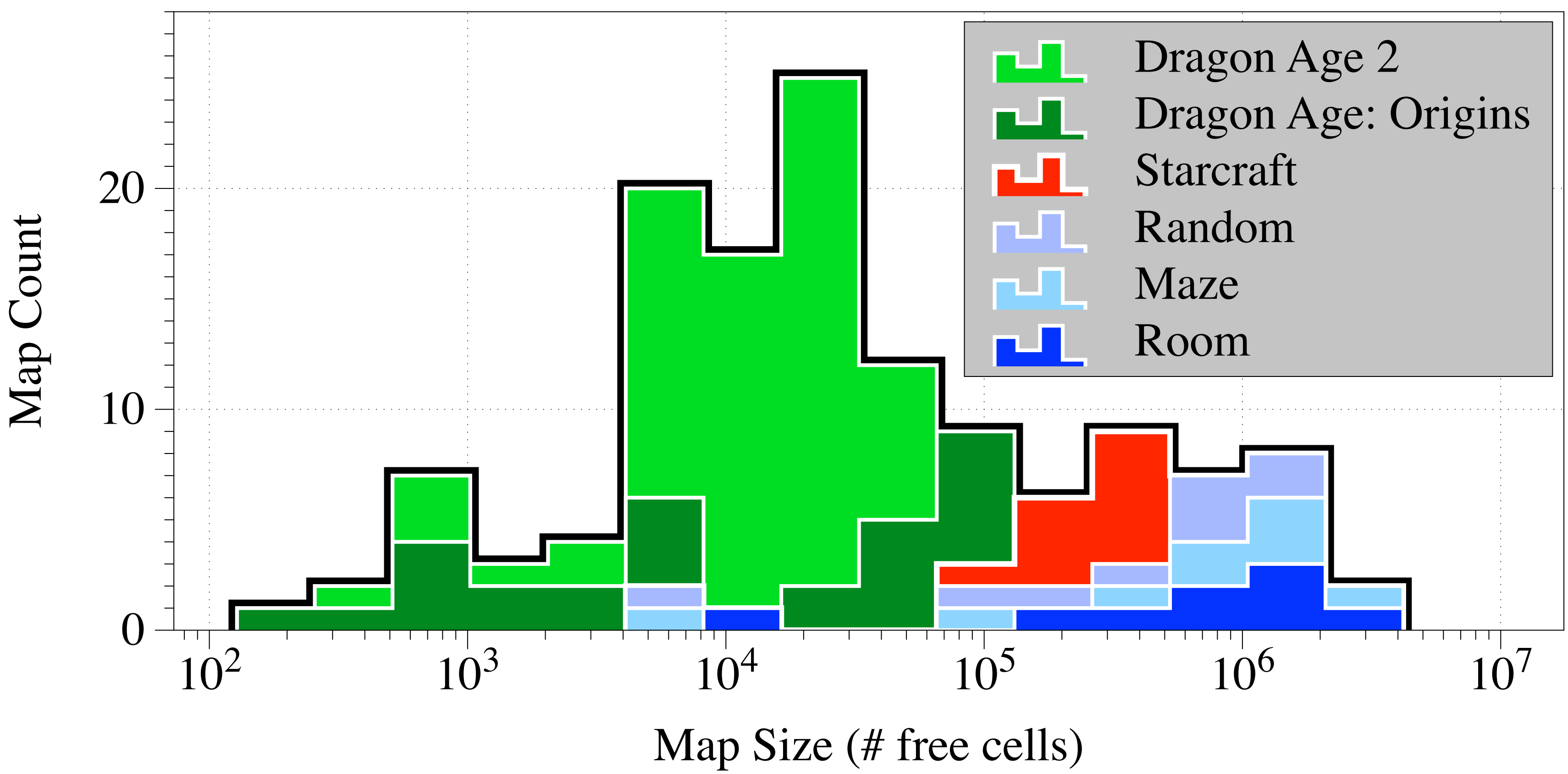
- Started in 2012; goals to:
  - Improve evaluation
  - Establish metrics
  - Improve comparisons

Entry Specification

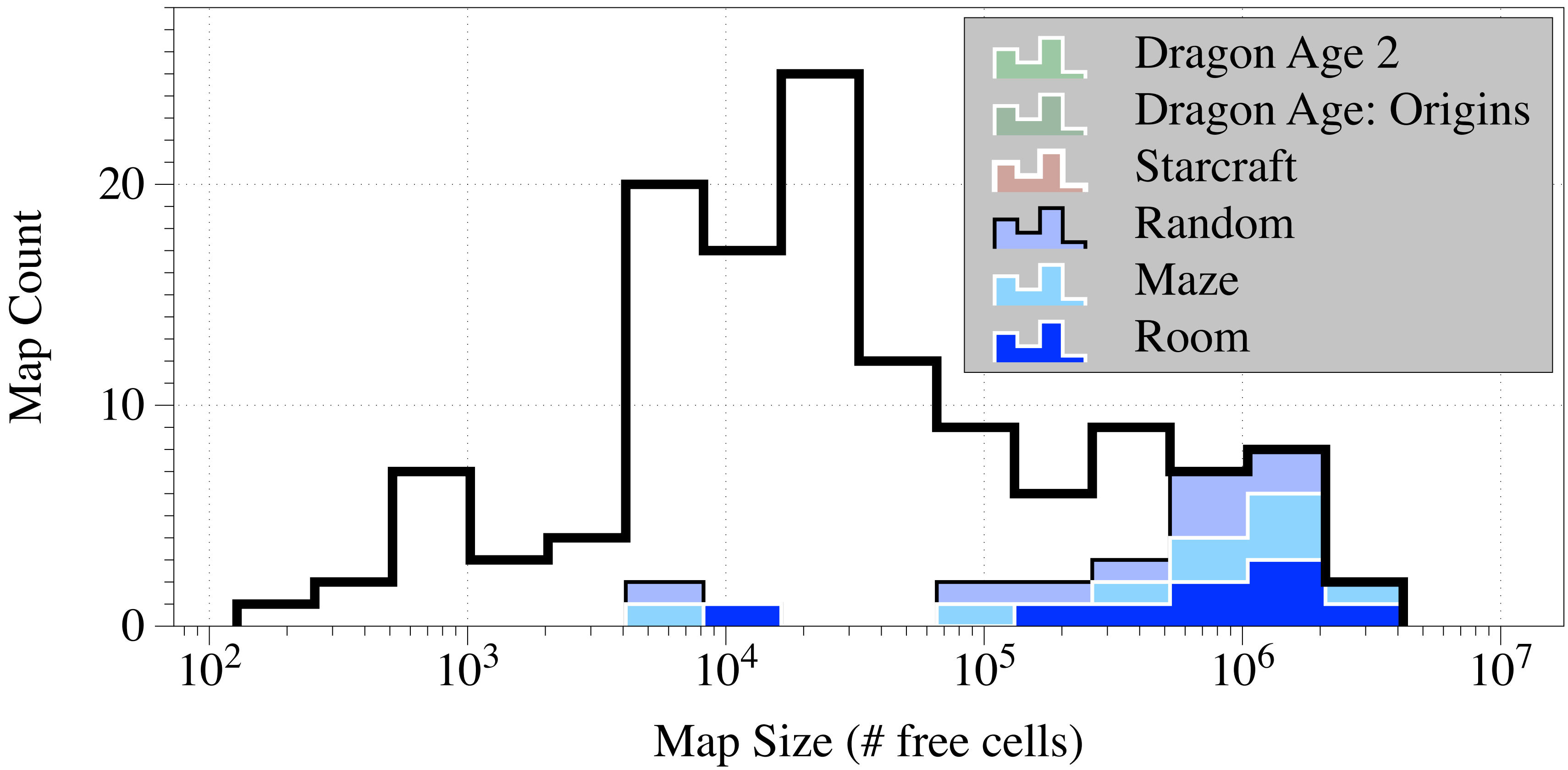
- Time allowed for pre-processing
- At runtime:
  - Load pre-processed data
  - Path query (start, goal) given to entry
    - Entry returns full or partial path
    - Query repeated until full path returned
- Run 5 times for statistical significance

Problem Setup

Source	# Maps	# Problems
Starcraft	11	29,970
Dragon Age: Origins	27	44,414
Dragon Age 2	57	54,360
Mazes	18	145,976
Random	18	32,228
Rooms	18	27,130
Total	132	347,868



Dragon Age 2
Dragon Age: Origins
Starcraft
Random
Maze
Room
Map Count
0
10
20
10^2
10^3
10^4
10^5
10^6
10^7
Map Size (# free cells)



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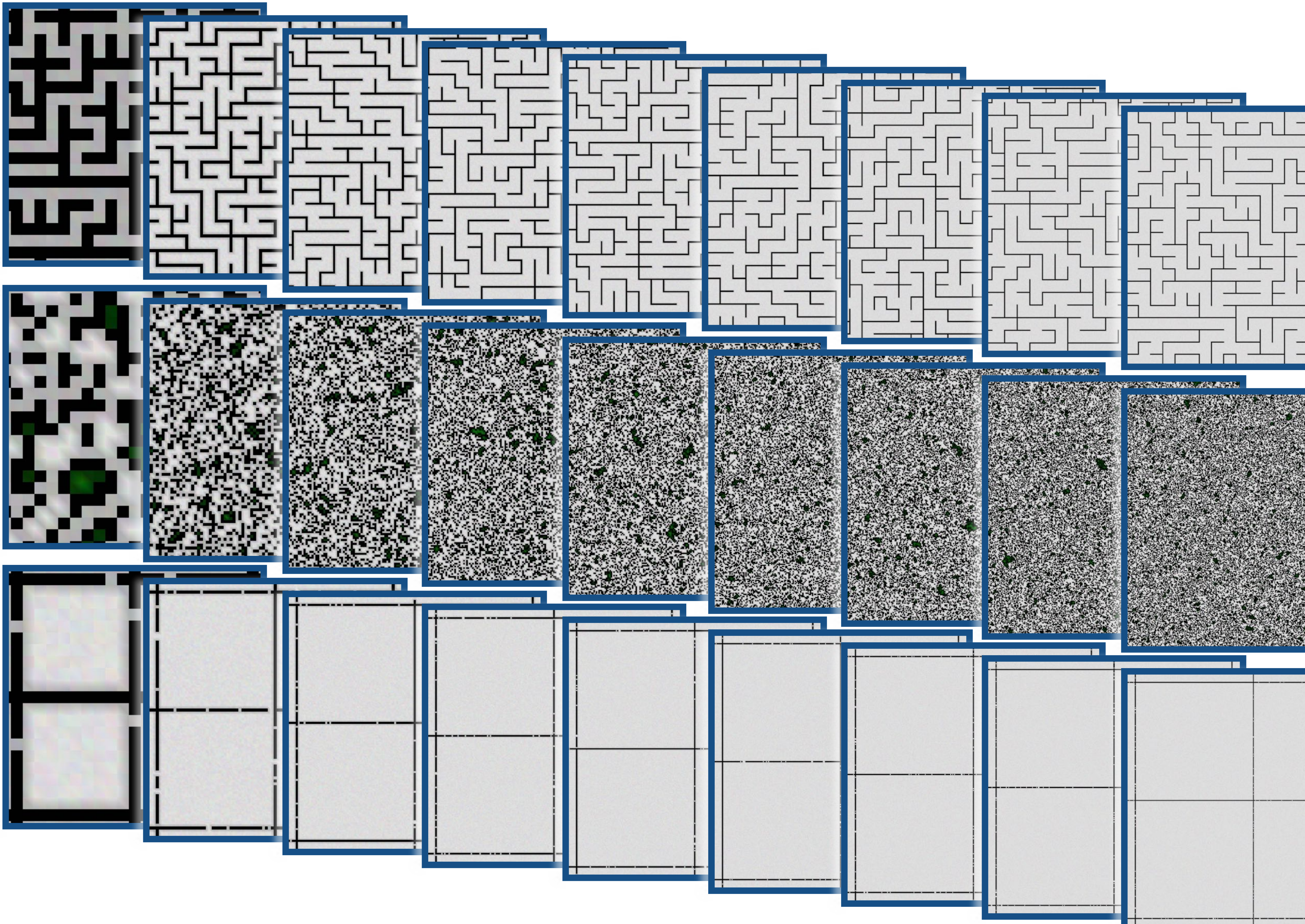

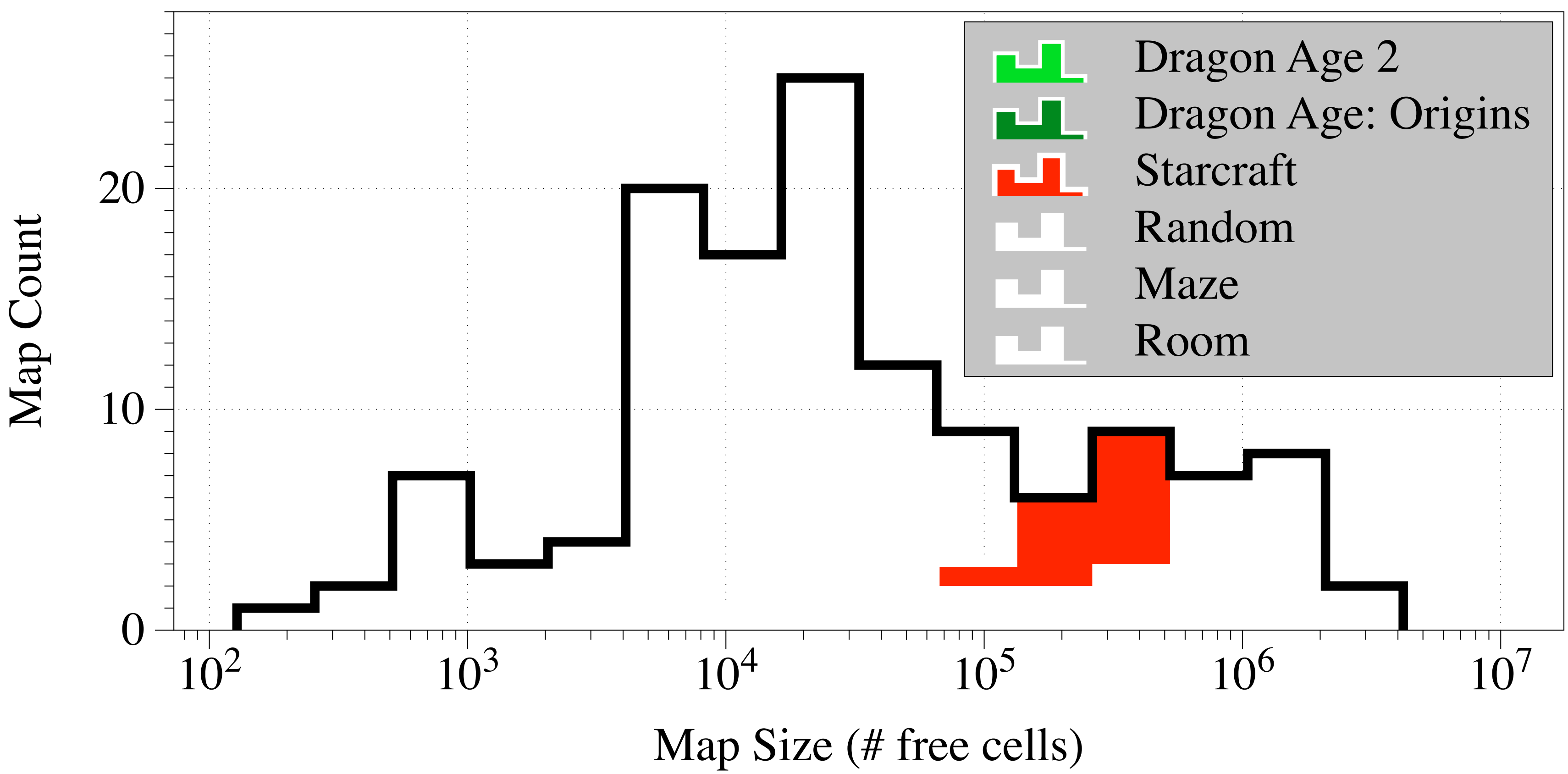

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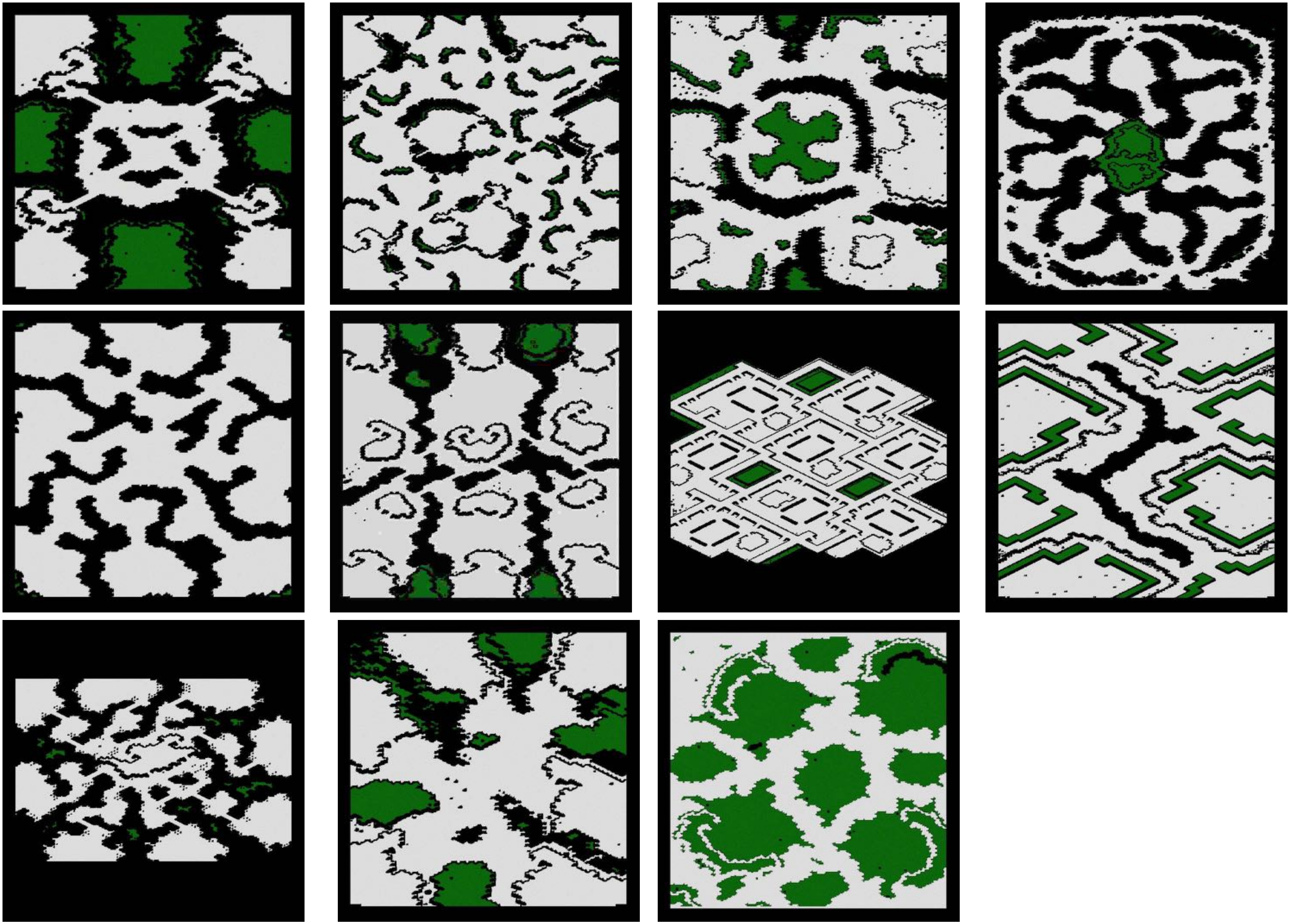

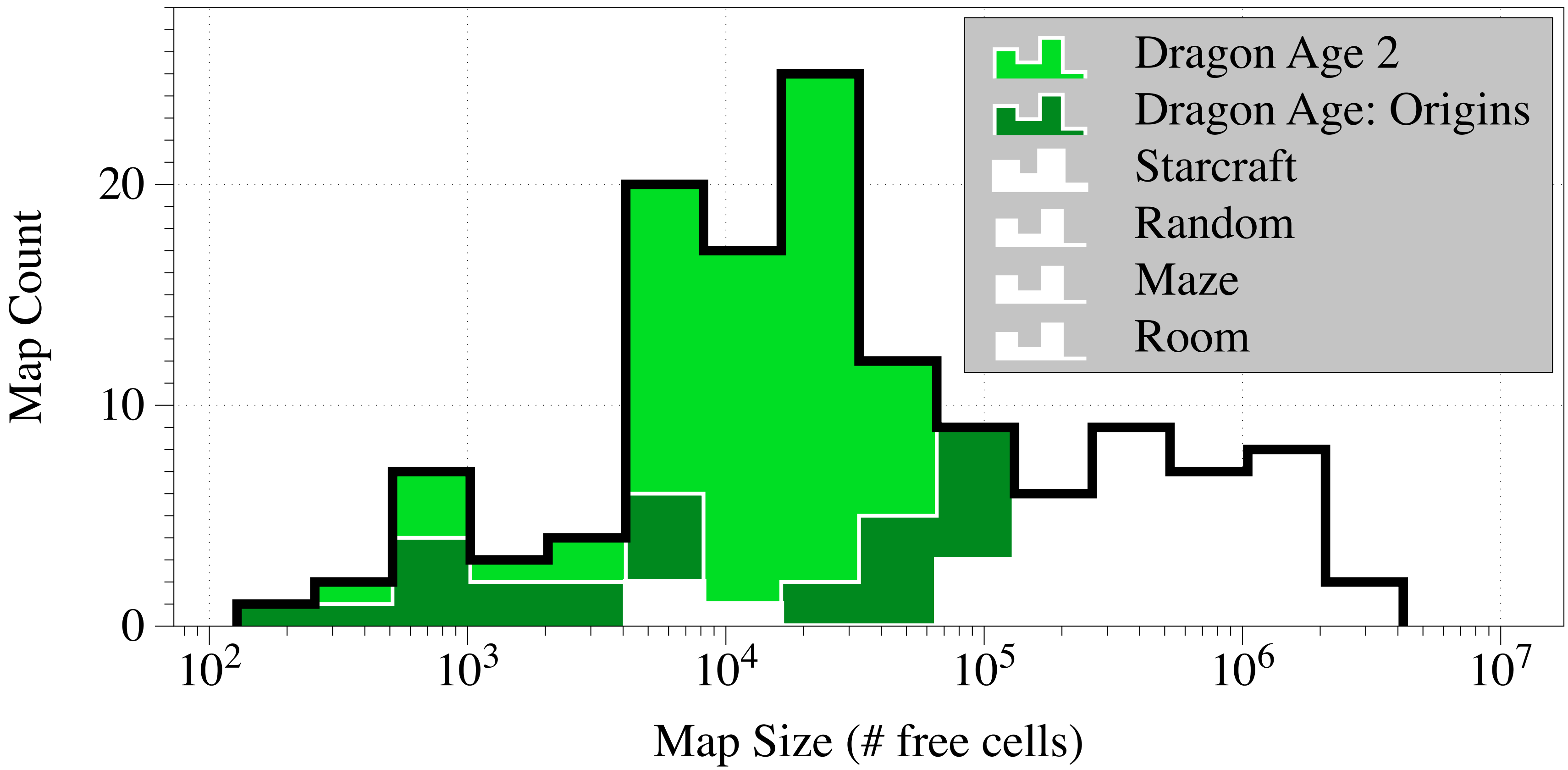

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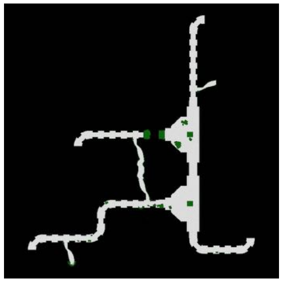 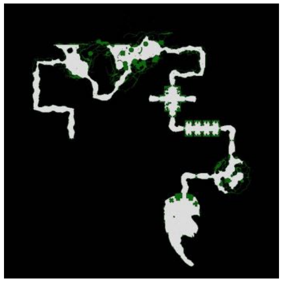 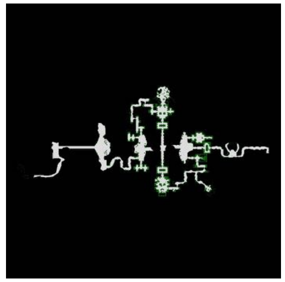 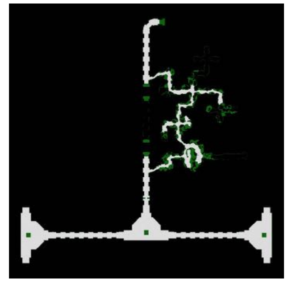 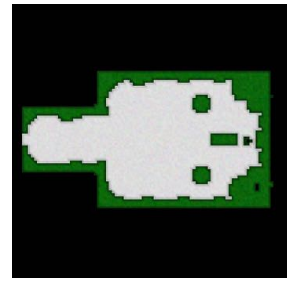 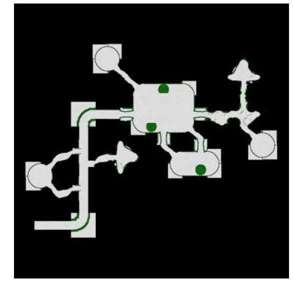
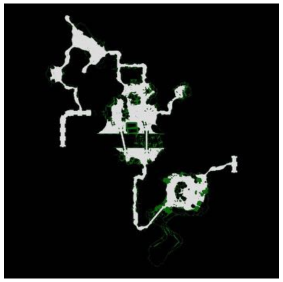 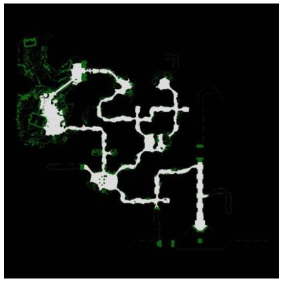 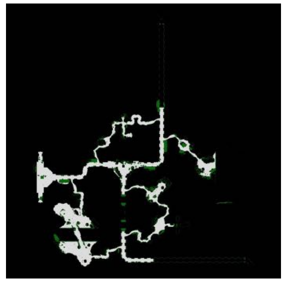 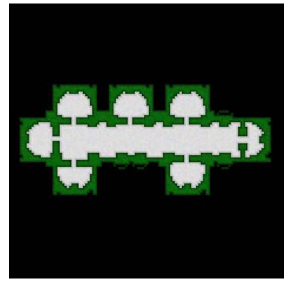 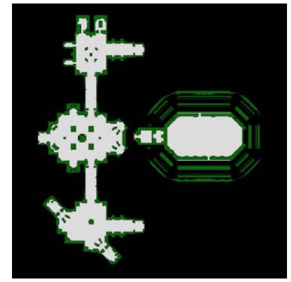 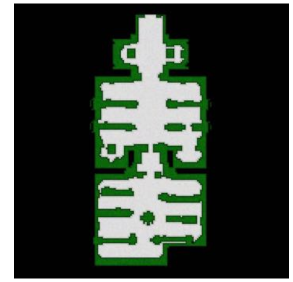
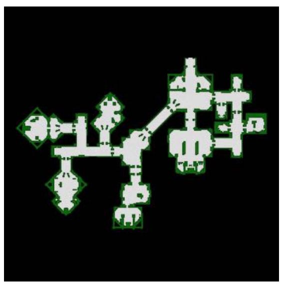 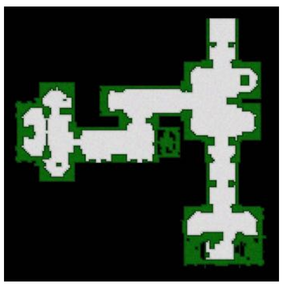 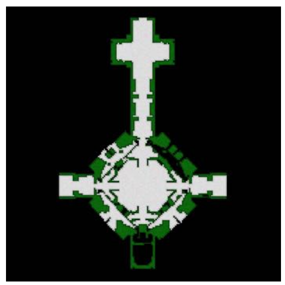 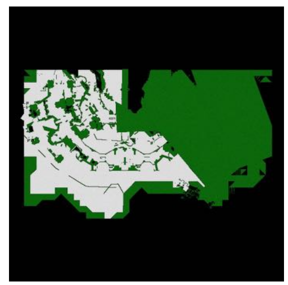 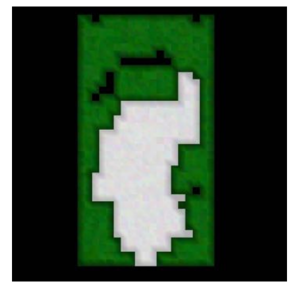 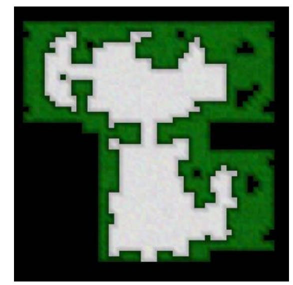
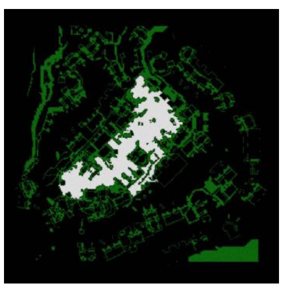 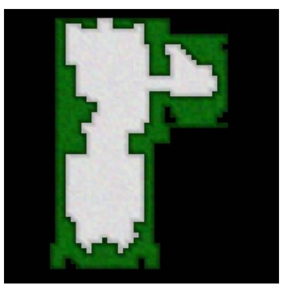 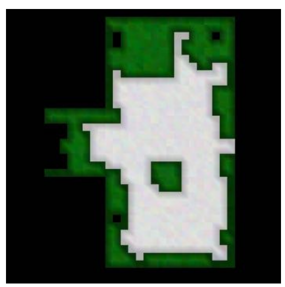  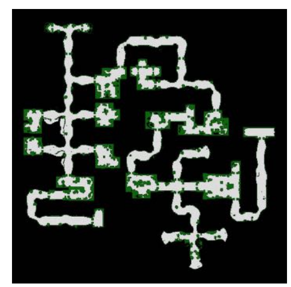 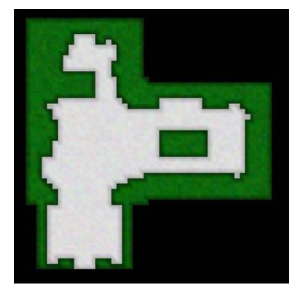
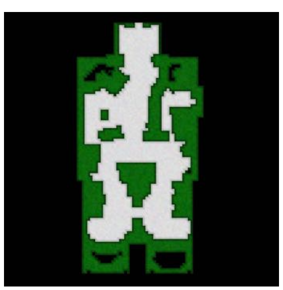 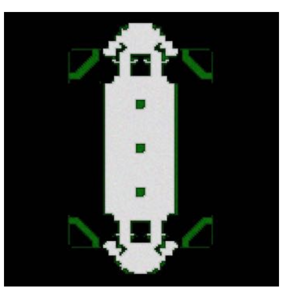 

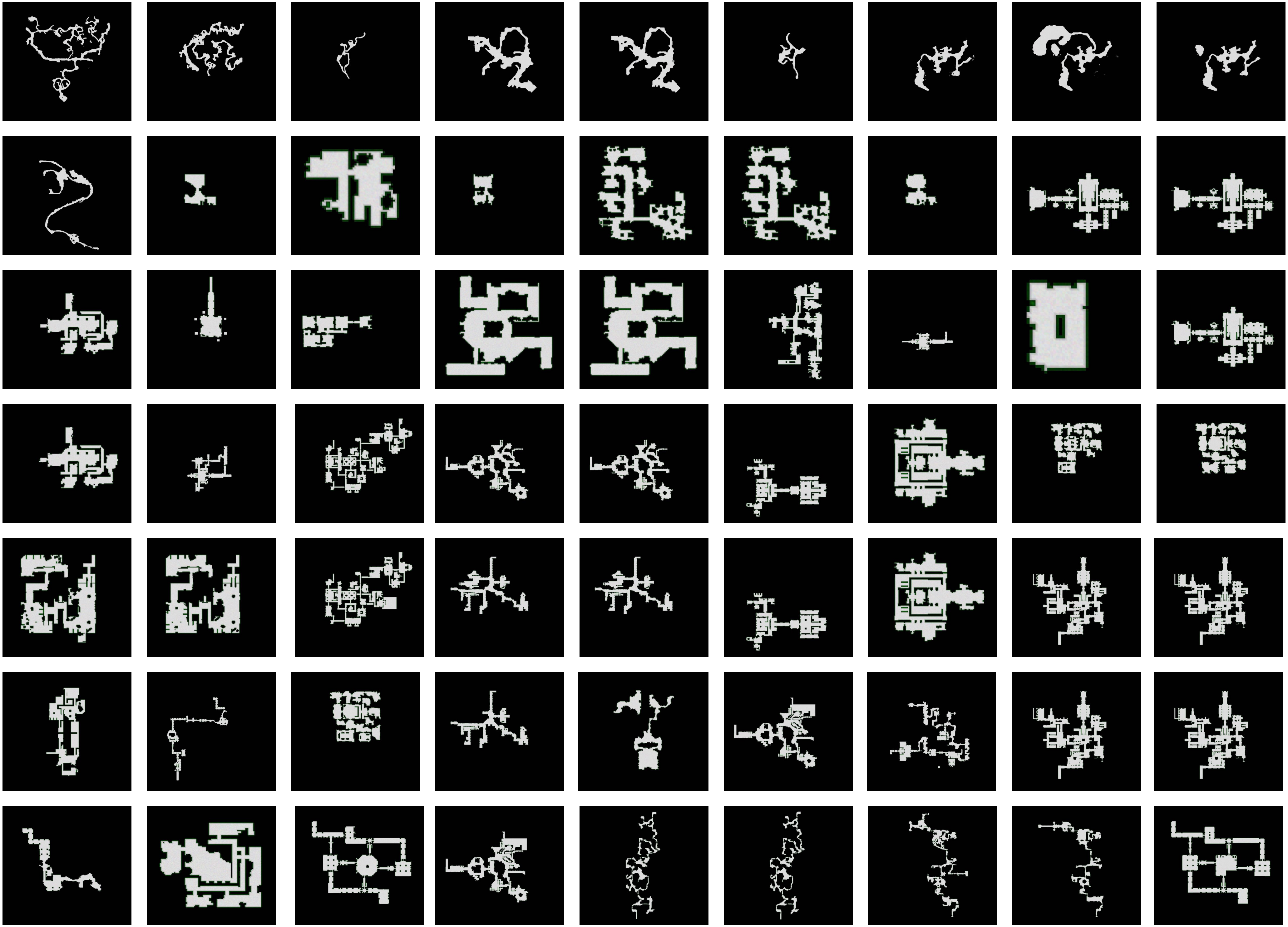

Metrics

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- Time for 20 steps (real-time startup)

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- RAM at runtime (before/after)
- Disk storage

Metrics

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- Time for 20 steps (real-time startup)
- Maximum segment time (real-time steady state)
- Suboptimality
- Correctness
- RAM at runtime (before/after)
- Disk storage
- Pre-computation

All 2014 Approaches

- Single-Row Compression (SRC) (4 variants)

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- BLJPS (2 variants), BLJPS_Subgoal
- Relaxed A*, Relaxed A* Subgoal

Single Row Compression

- Ben Strasser [KIT], Adi Botea [IBM Dublin], and Daniel Harabor [NICTA]
  - Build full all-pairs-shortest-path data
  - Run-length encoding to compress each row
  - Incremental or non-incremental path generation

- *Fast First-Move Queries through Run-Length Encoding, Strasser, Harabor and Botea (2014)*
- *Complexity Results for Compressing Optimal Paths, Botea, Strasser and Harabor (2015)*

Contraction Hierarchies

- Ben Strasser [KIT]
  - Originally developed by [Geisberger et. al. 2008]
  - Wasn't optimized for grids [Sturtevant and Geisberger, 2010]
  - Later optimization for grids [Storandt, 2013]

- *Contraction Hierarchies: Faster and Simpler Hierarchical Routing in Road Networks, Robert Geisberger, Peter Sanders, Dominik Schultes and Daniel Delling, 2008*

N-level Subgoals

- Tansel Uras and Sven Koenig [USC]
  - 3rd entry into GPPC
  - Builds a n-level hierarchy from the basic subgoal approach
  - Basic subgoals are built up from visibility graphs

- *Identifying Hierarchies for Fast Optimal Search, Uras and Koenig, 2014*

JPS+

- Steve Rabin [Digipen & Games Industry*]
  - Independently invented JPS+
  - Based on Jump Point Search

- *Improving Jump Point Search, Daniel Harabor and Alban Grastien, 2014*
- *Online Graph Pruning for Pathfinding On Grid Maps, Daniel Harabor and Alban Grastien, 2011*

BLJPS

- Jason Traish and James Tulip [Charles Sturt University]
- Boundary Lookup JPS
- Alternate optimization similar to JPS+
  - Also applied ideas to subgoals

- *Optimization using Boundary Lookup Jump Point Search, Traish and Tulip, 2015*

Relaxed A*

- http://www.iroboapp.org/
- Doesn't perform A* re-expansions & other optimizations
  - Also applied to subgoal search

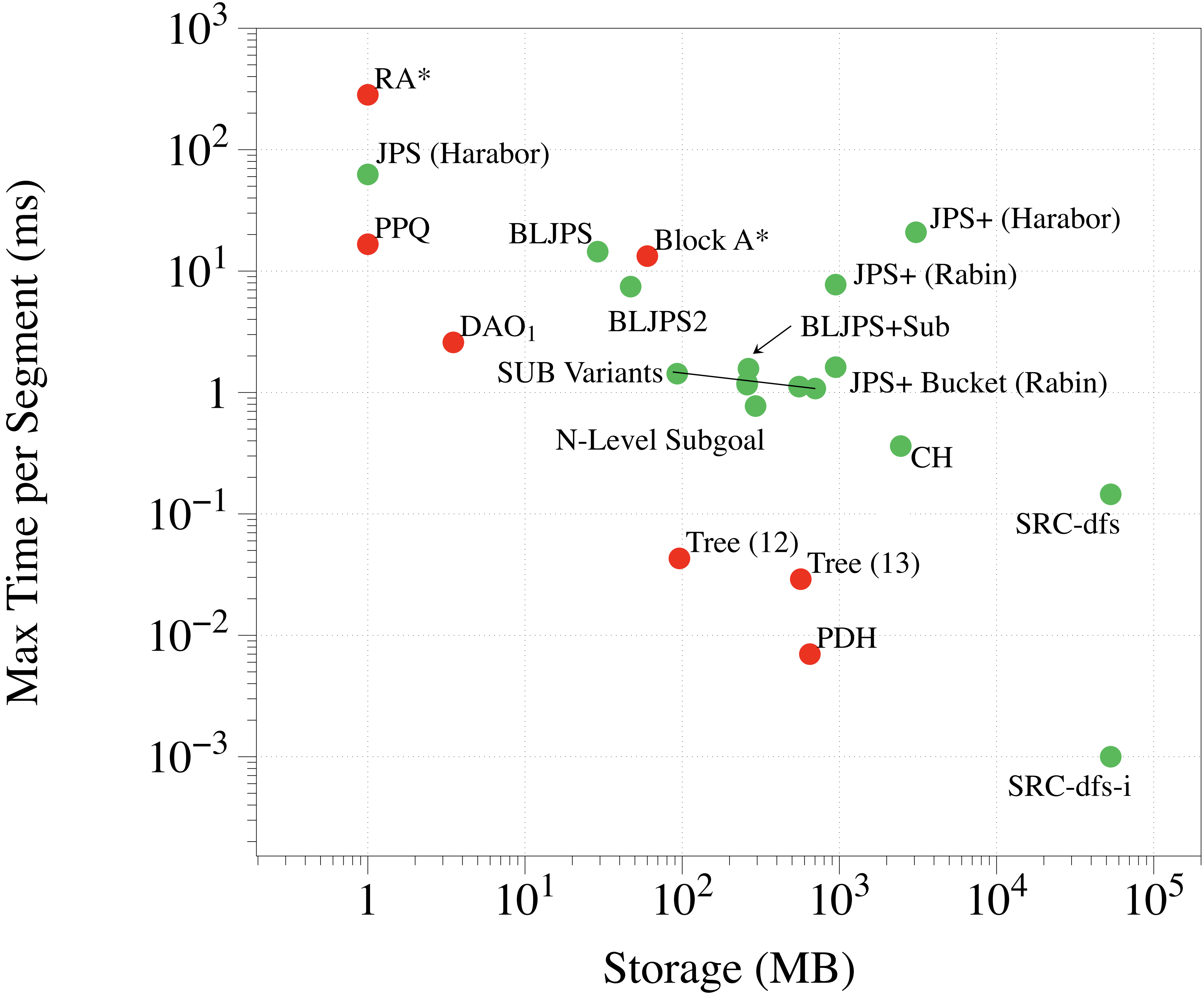
Results

Non-Dominated Approaches

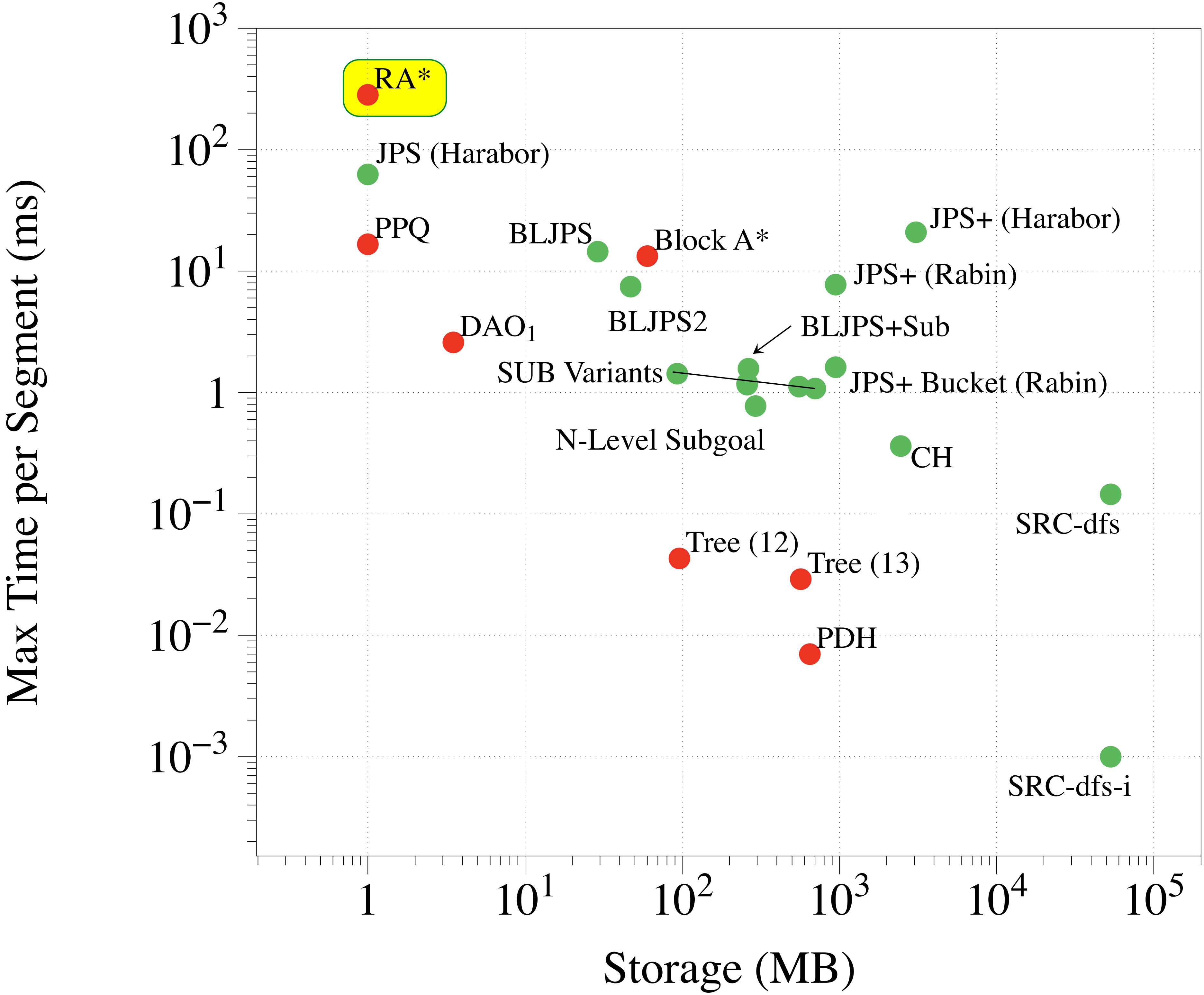
- RA*, RA* Subgoal
- BLJPS, BLJPS2
- N-level Subgoals
- Contraction Hierarchies (CH)
- Single-Row Compression (SRC) (2 variants)

Speed vs Storage (2014)

Entry	Average (ms)	Storage
RA*	282.995	0
BLJPS	14.453	20 MB
BLJPS2	7.444	47 MB
RA* Subgoal	1.688	264 MB
NSubgoal	0.773	293 MB
CH	0.362	2.4 GB
SRC-dfs	0.145	28 GB



Max Time per Segment (ms)
Storage (MB)
RA*
JPS (Harabor)
PPQ
BLJPS
Block A*
JPS+ (Harabor)
JPS+ (Rabin)
BLJPS2
DAO1
BLJPS+Sub
SUB Variants
JPS+ Bucket (Rabin)
N-Level Subgoal
CH
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i



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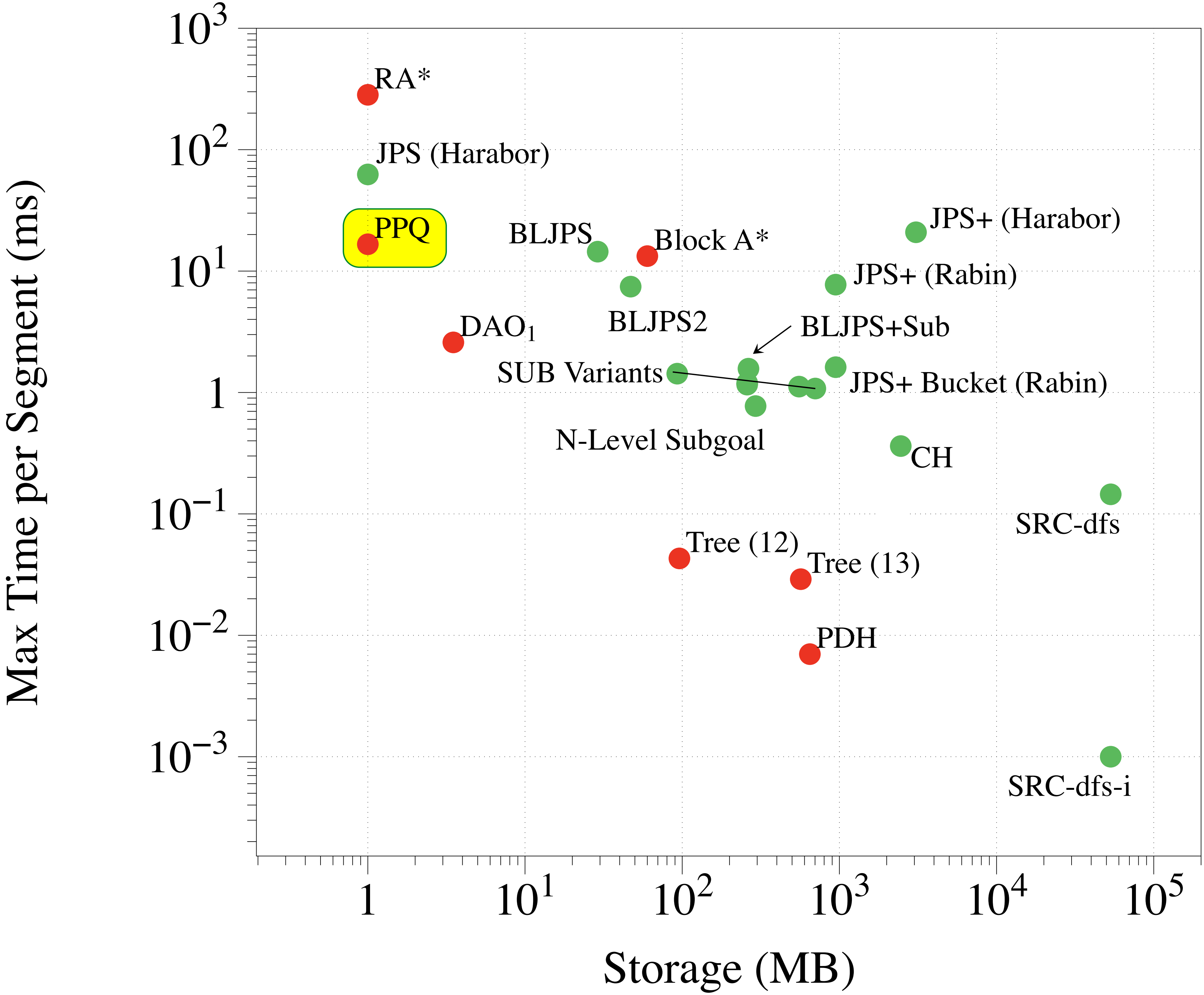
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DAO$_1$
BLJPS+Sub
SUB Variants
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N-Level Subgoal
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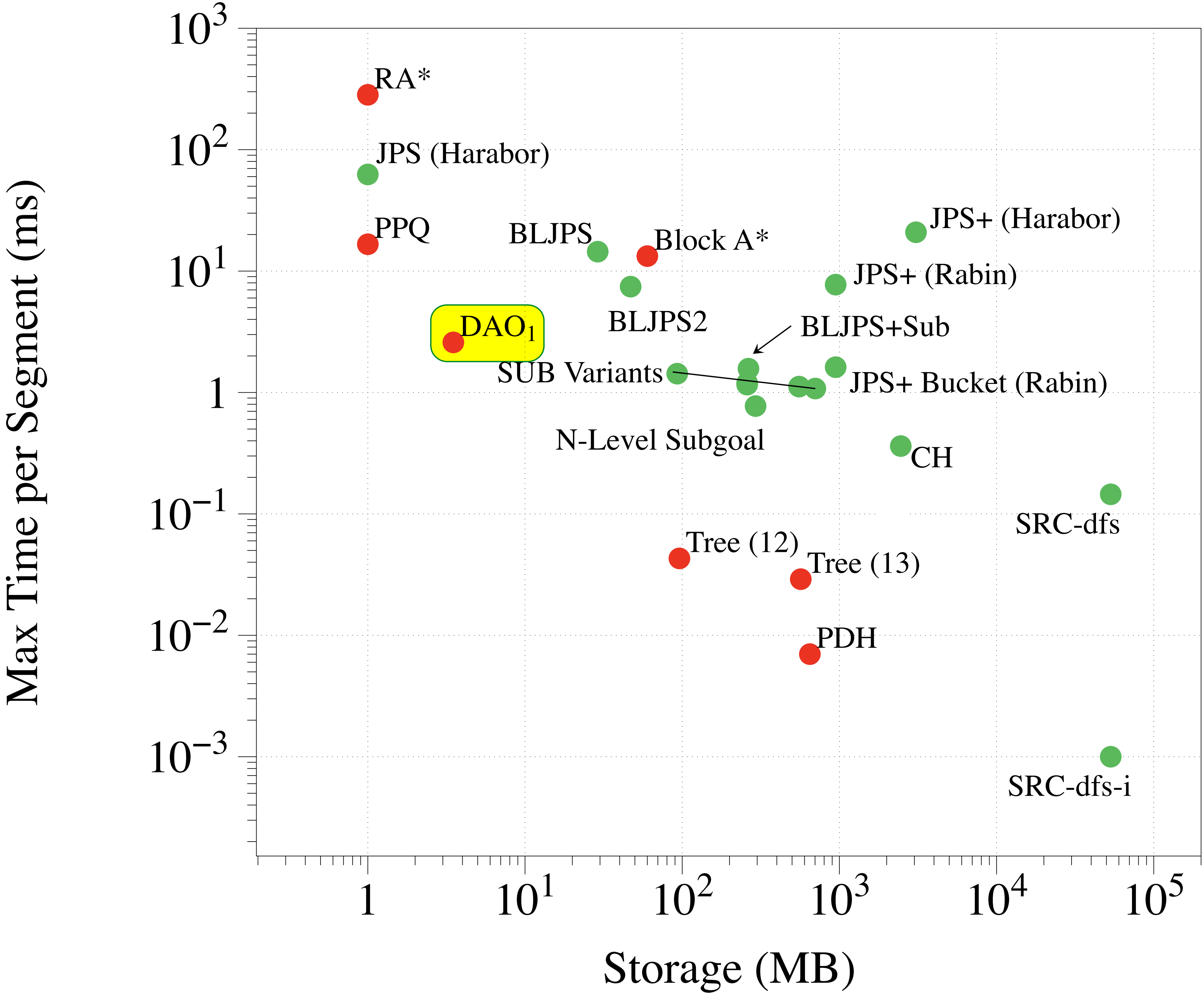
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i
Max Time per Segment (ms)
Storage (MB)
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
1
10^1
10^2
10^3
10^4
10^5



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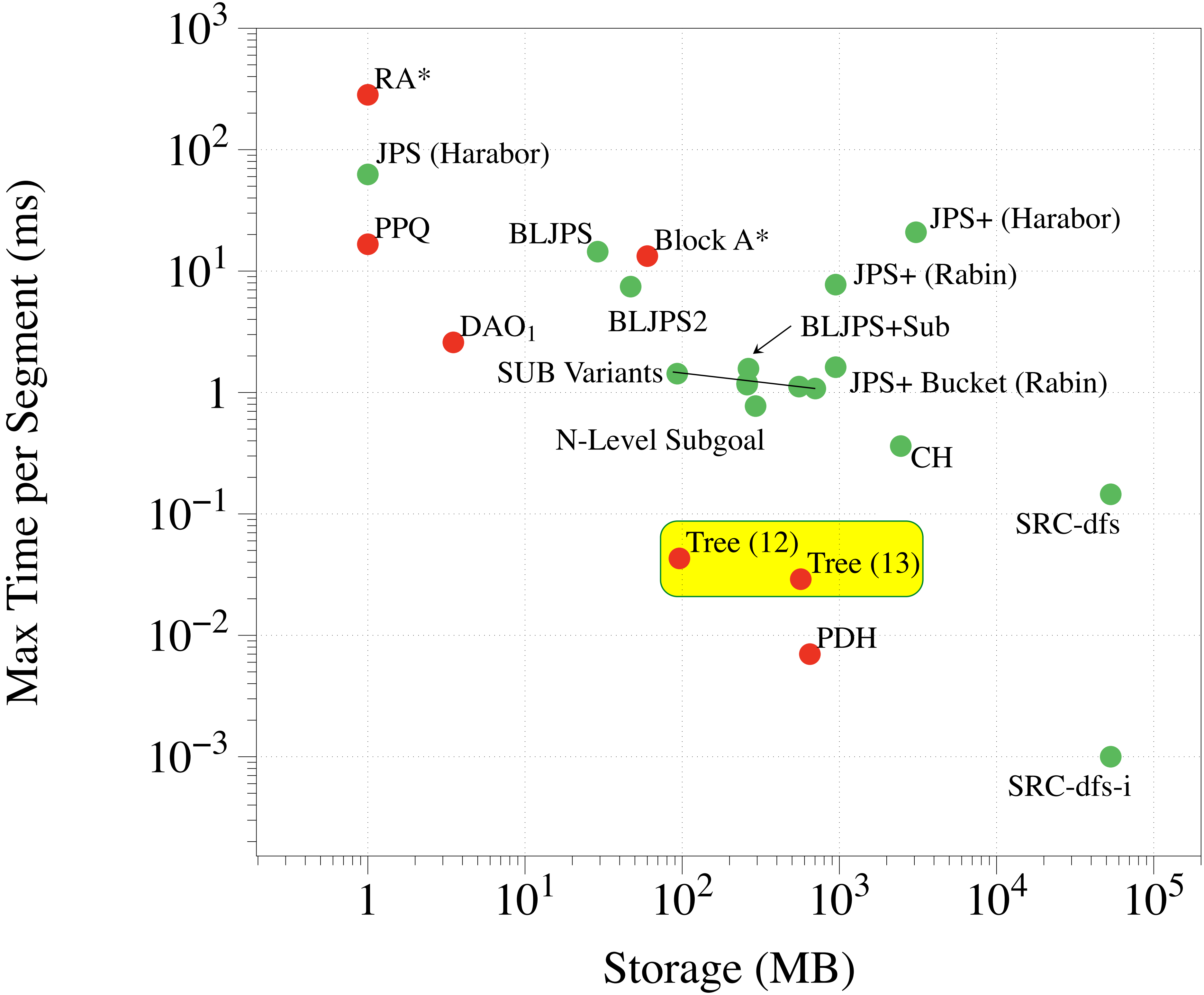

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Storage (MB)
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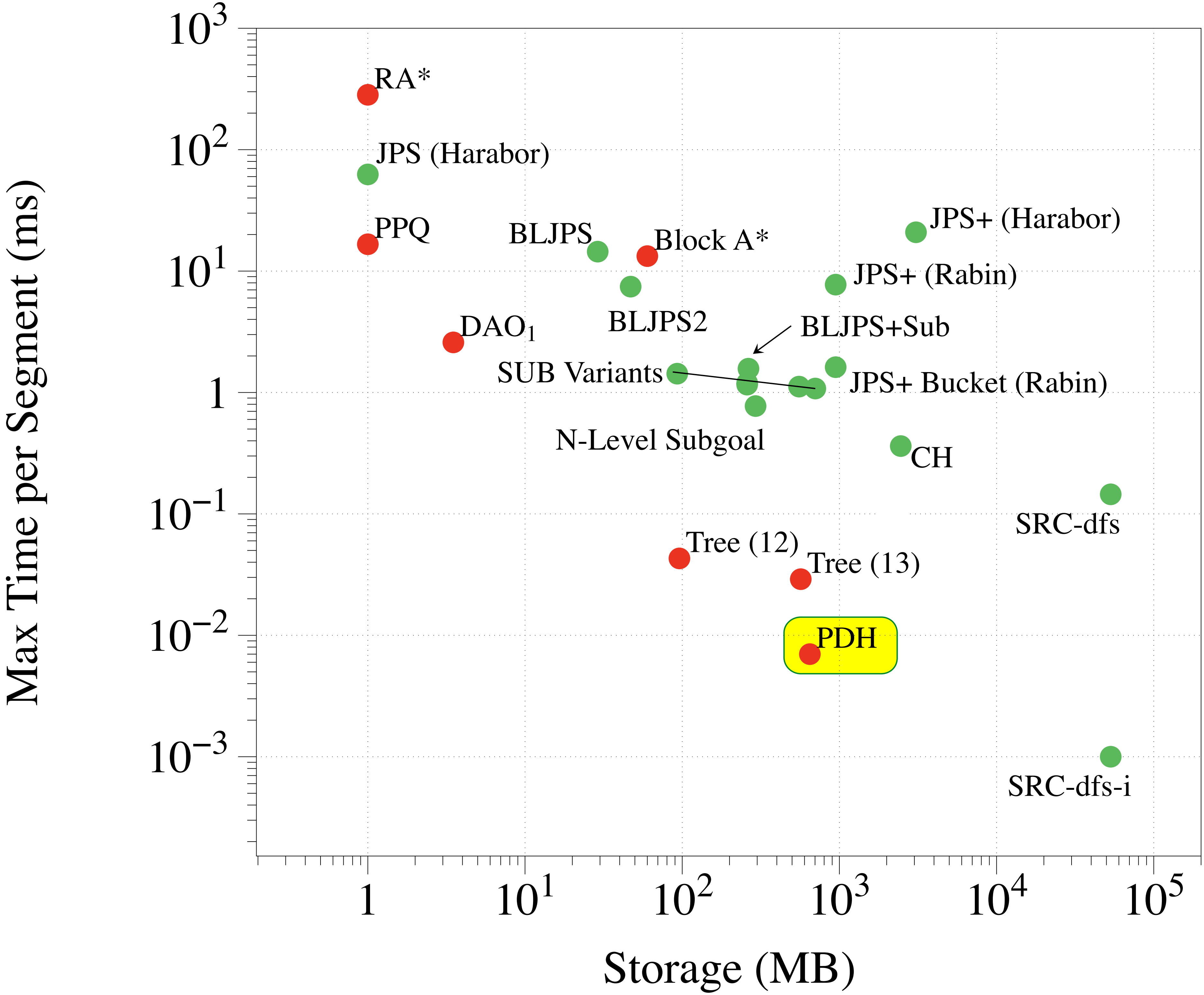

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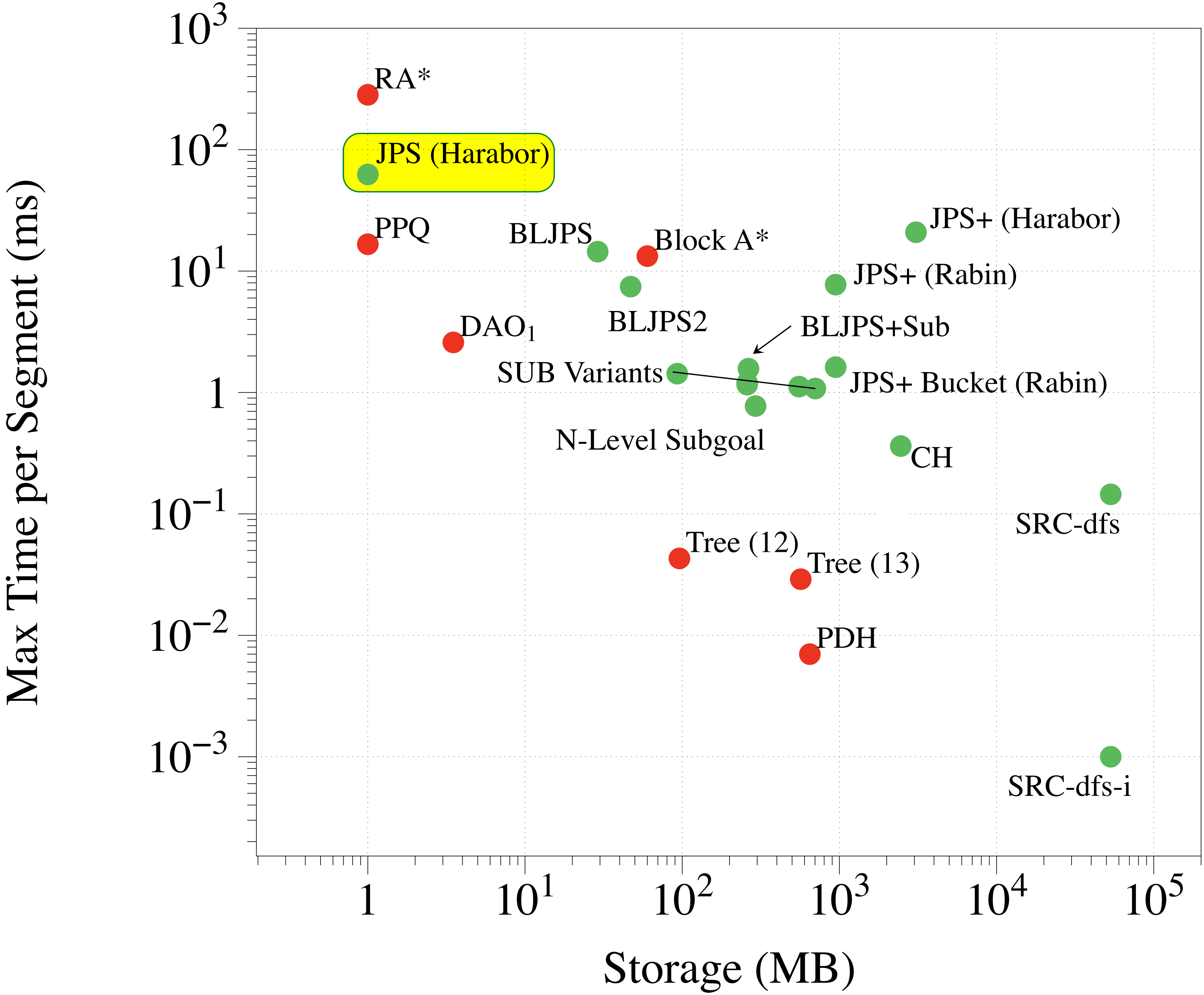
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
1
10^1
10^2
10^3
10^4
10^5
Max Time per Segment (ms)
Storage (MB)



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PPQ
BLJPS
Block A*
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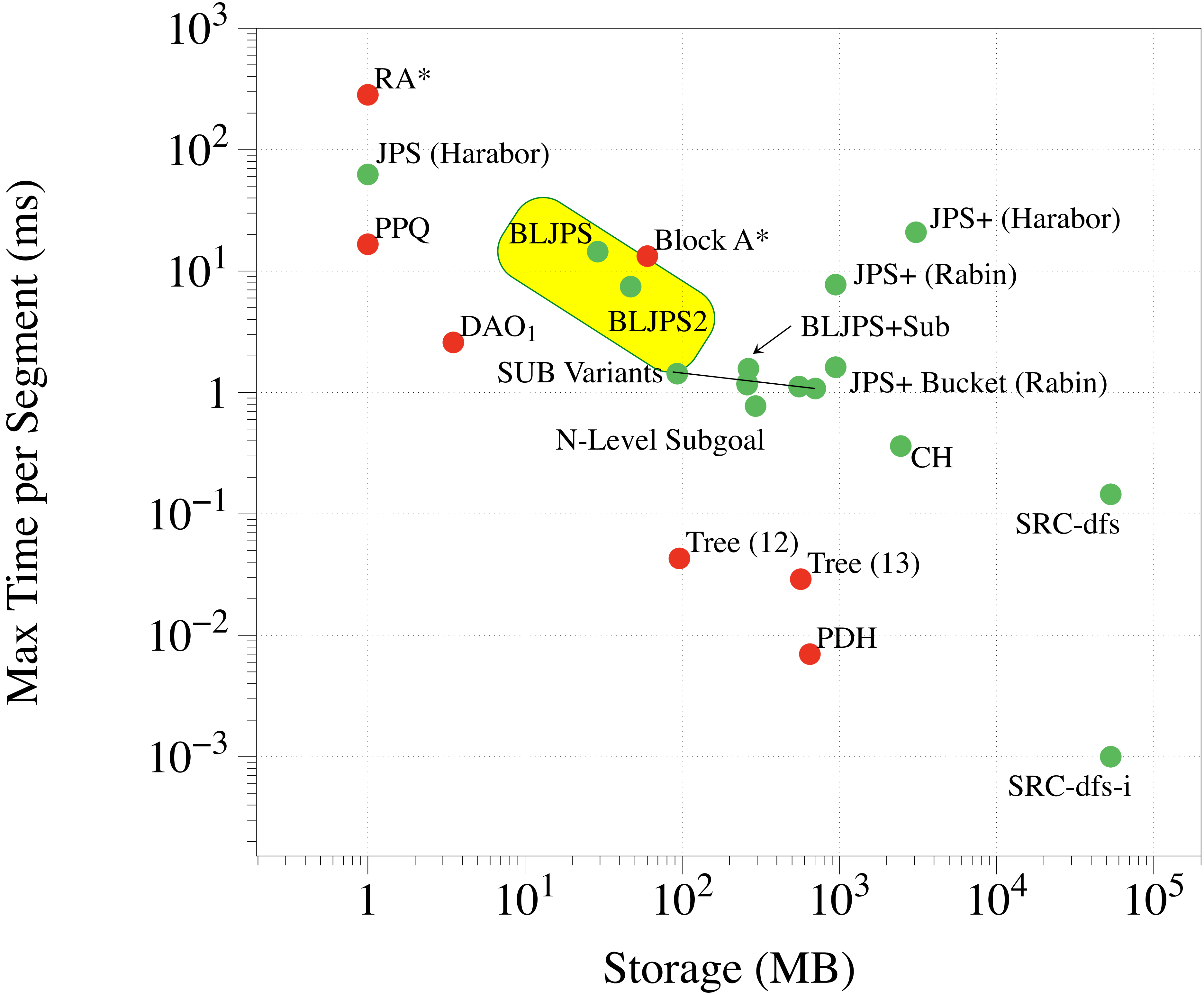
JPS+ (Rabin)
BLJPS2
DAO1
BLJPS+Sub
SUB Variants
JPS+ Bucket (Rabin)
N-Level Subgoal
CH
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i
Max Time per Segment (ms)
Storage (MB)



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10^3
10^4
10^5
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JPS (Harabor)
PPQ
BLJPS
Block A*
BLJPS2
DAO1
SUB Variants
BLJPS+Sub
JPS+ (Harabor)
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N-Level Subgoal
CH
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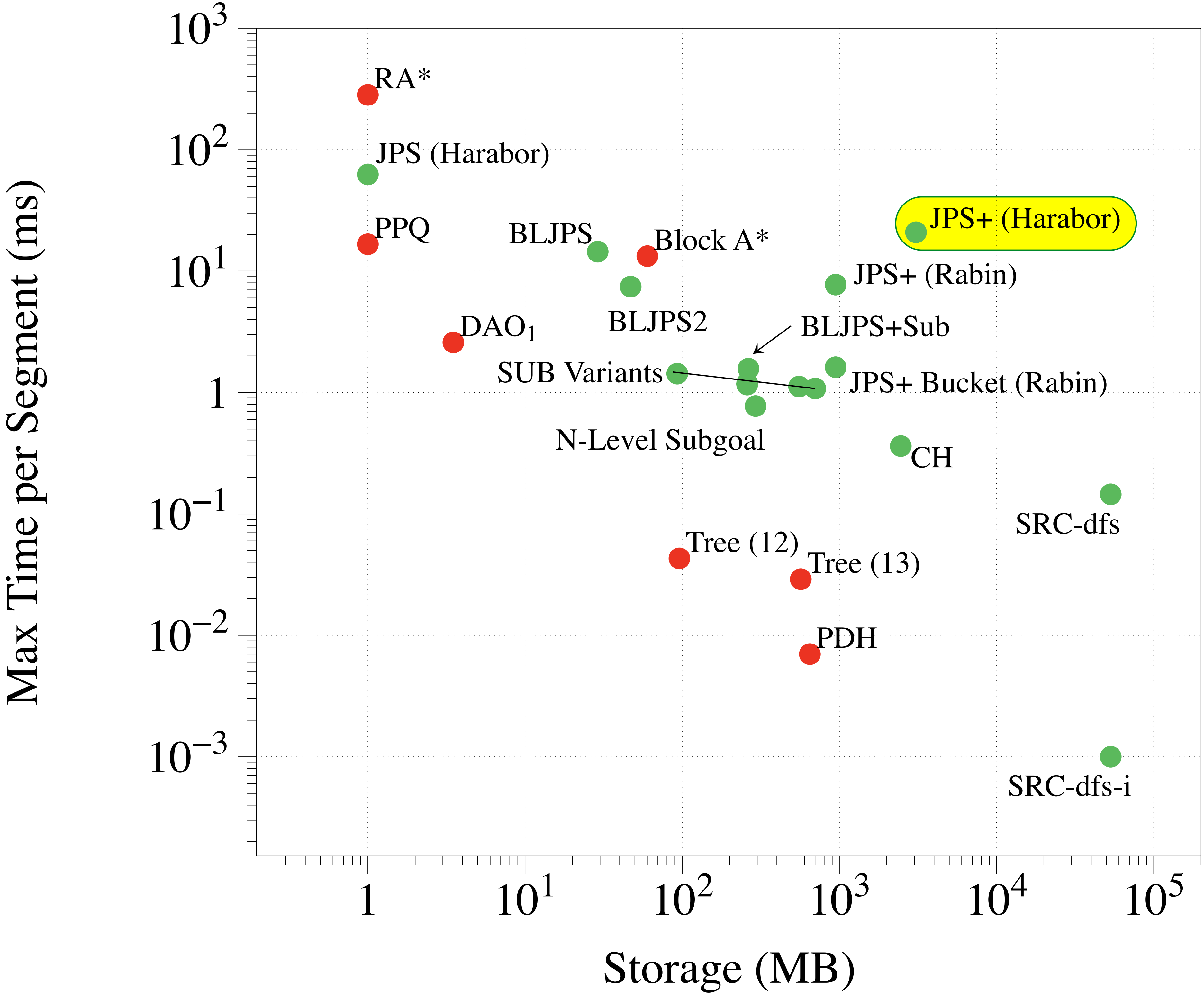

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DAO$_1$
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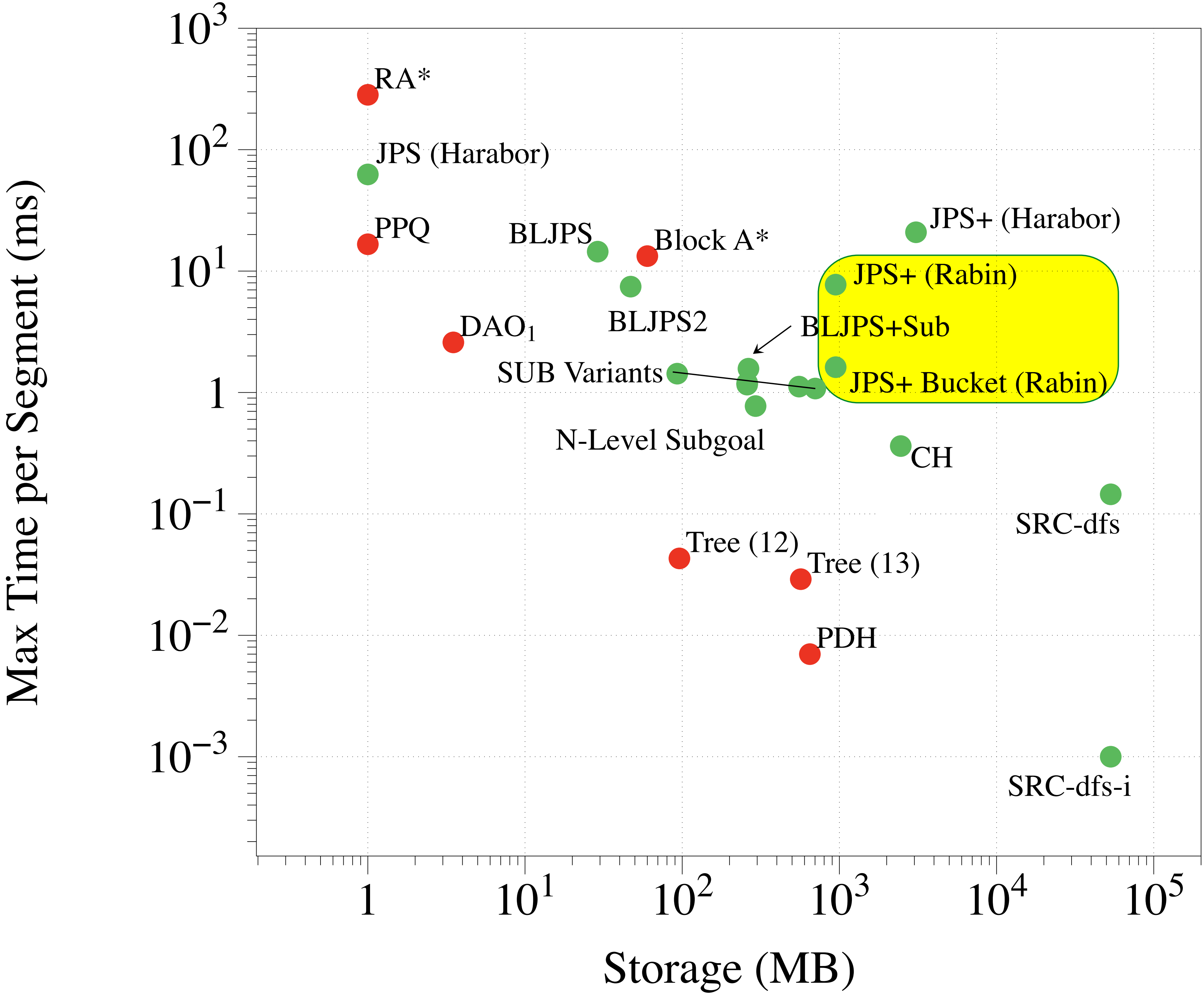

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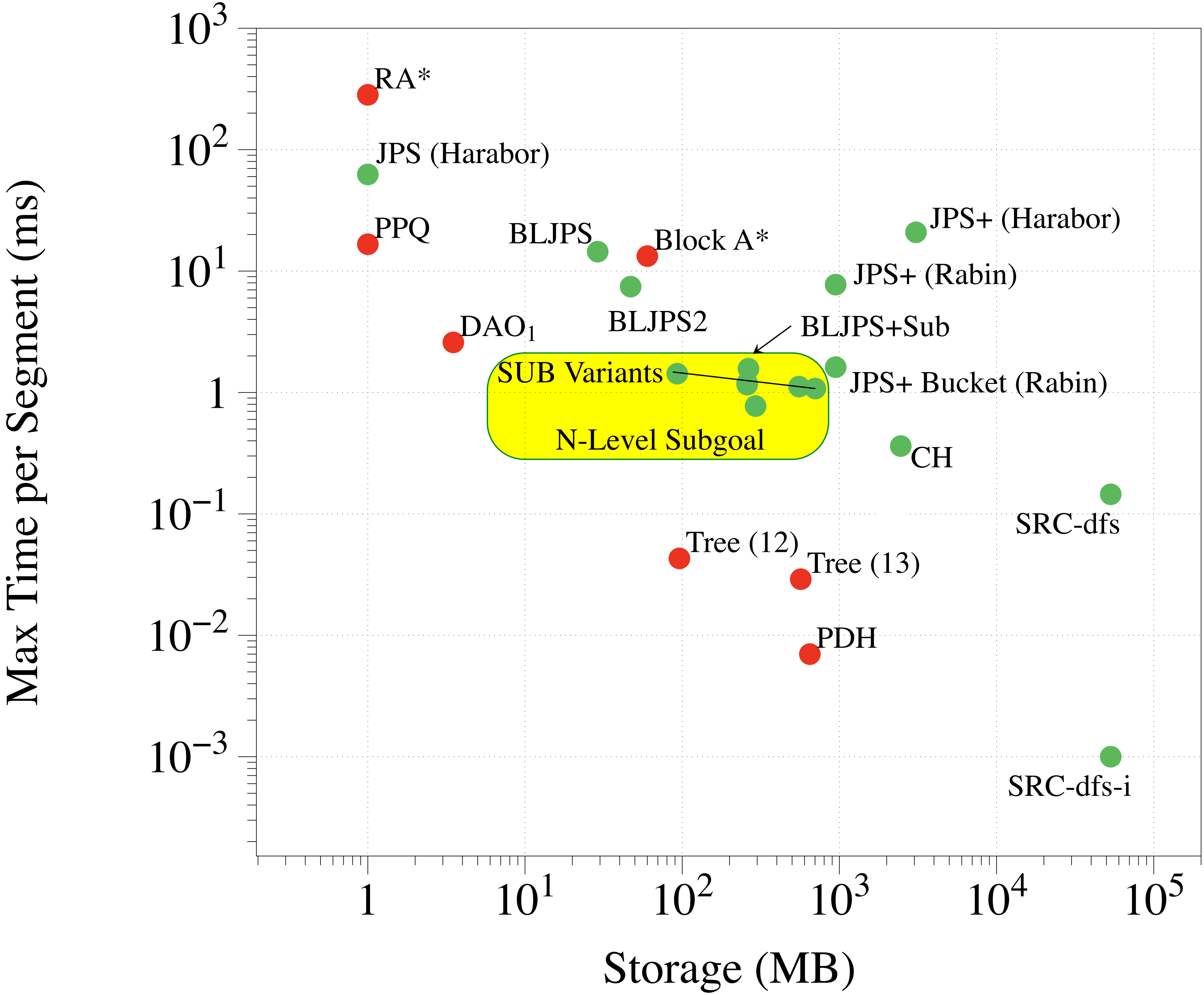

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N-Level Subgoal
CH
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i
Max Time per Segment (ms)
Storage (MB)
10^3
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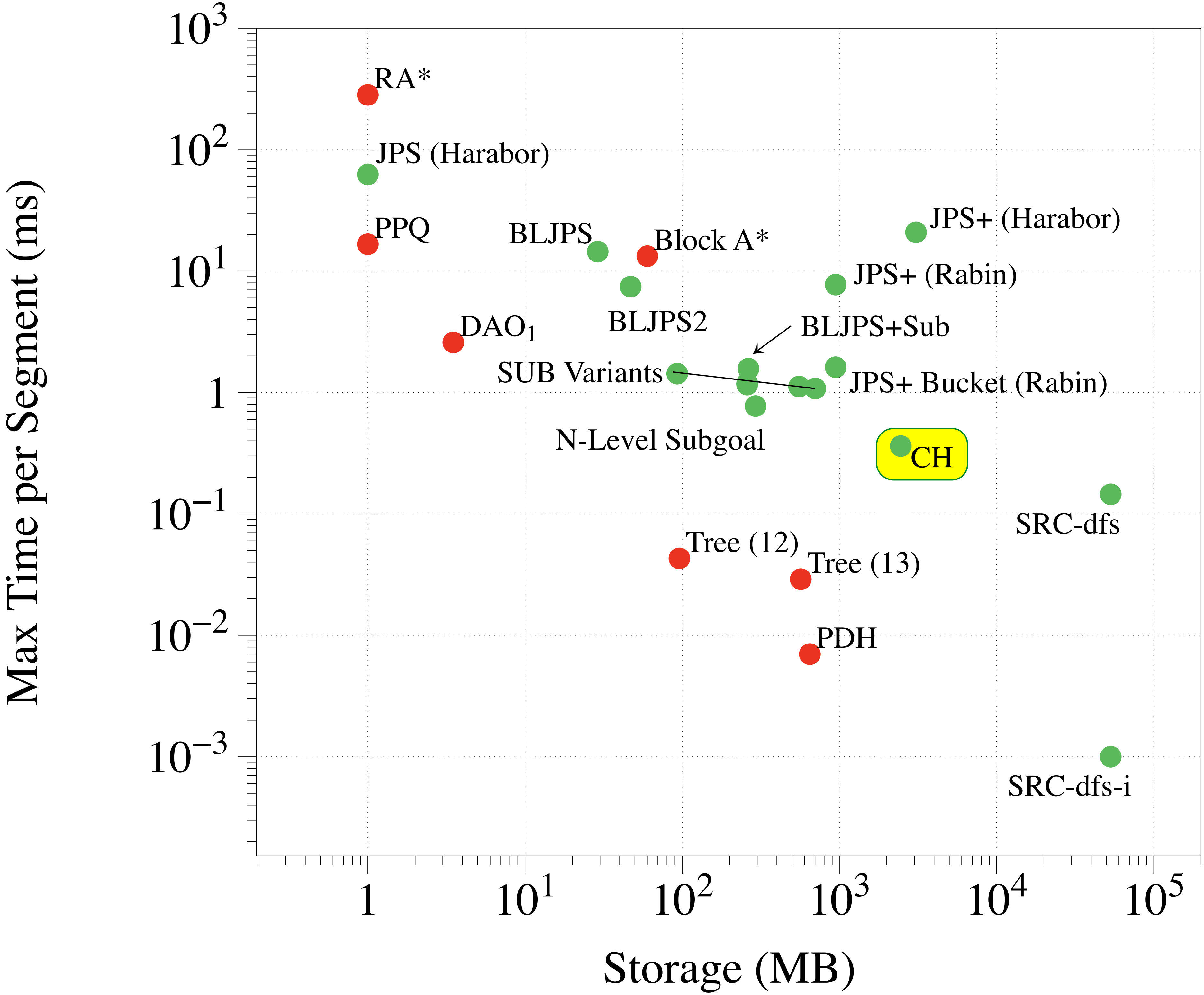
10^4
10^5



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SRC-dfs
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PDH
SRC-dfs-i
Max Time per Segment (ms)
Storage (MB)
10^3
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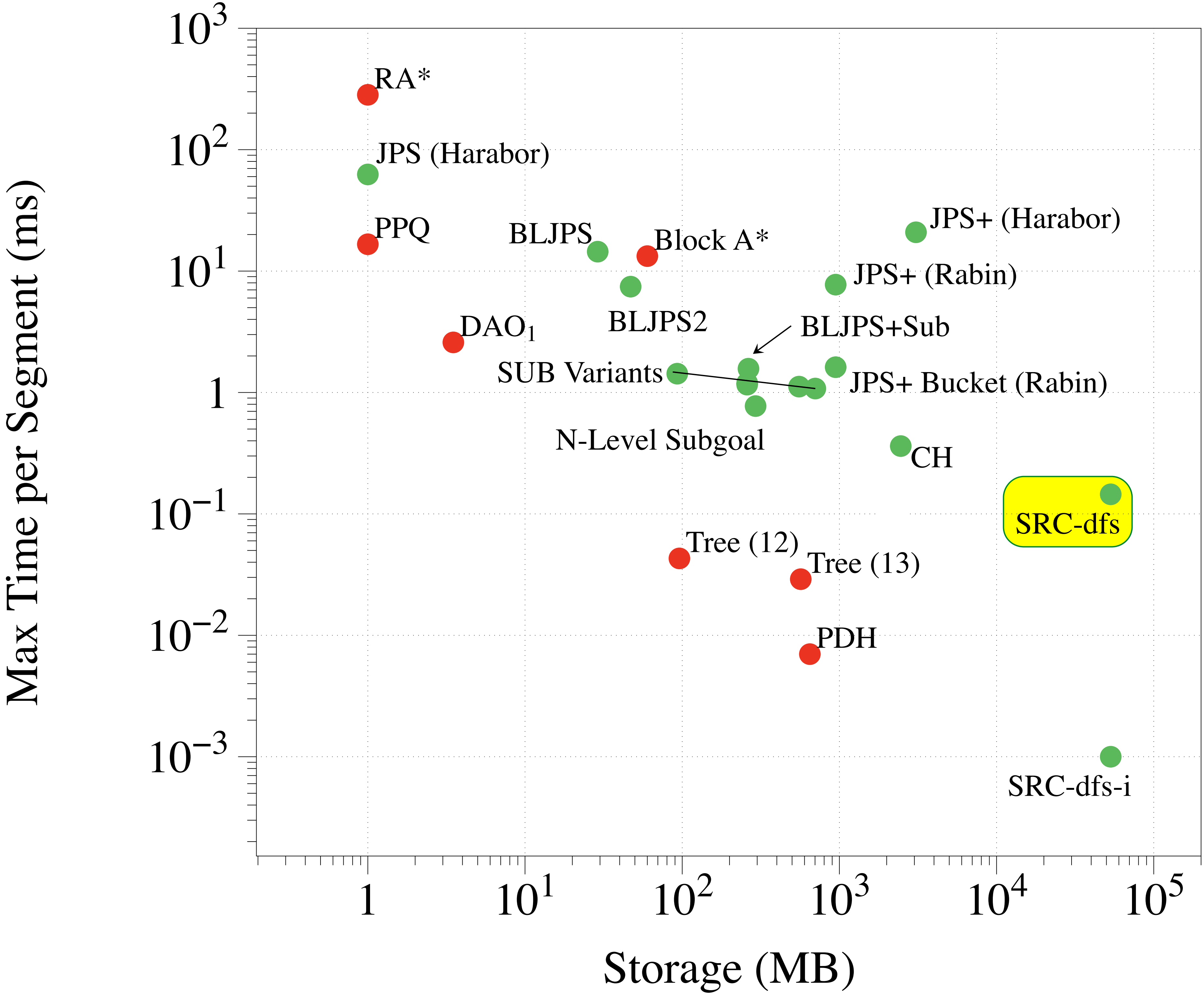

Max Time per Segment (ms)
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JPS+ (Rabin)
BLJPS2
DAO1
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N-Level Subgoal
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Tree (12)
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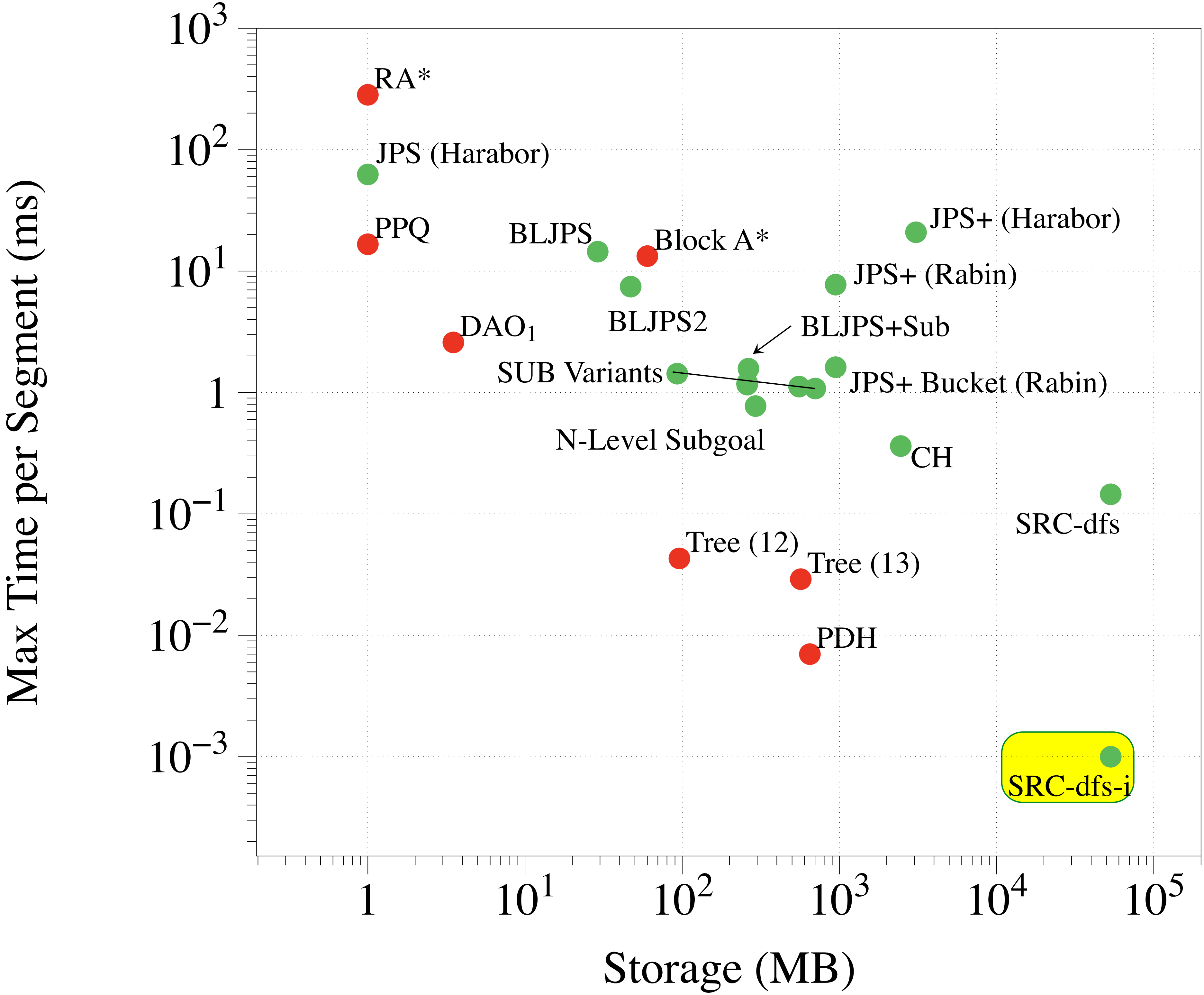
SRC-dfs-i



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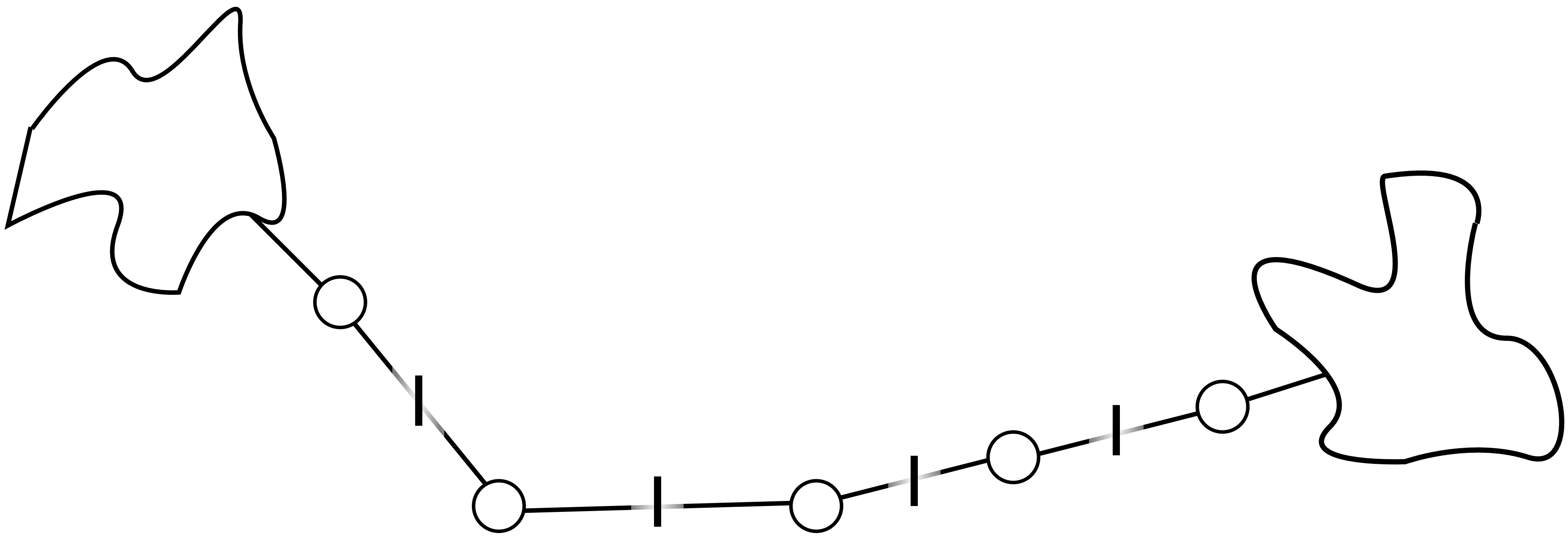
DAO_1
BLJPS+Sub
SUB Variants
JPS+ Bucket (Rabin)
N-Level Subgoal
CH
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i
Max Time per Segment (ms)
Storage (MB)
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
1
10^1
10^2
10^3
10^4
10^5

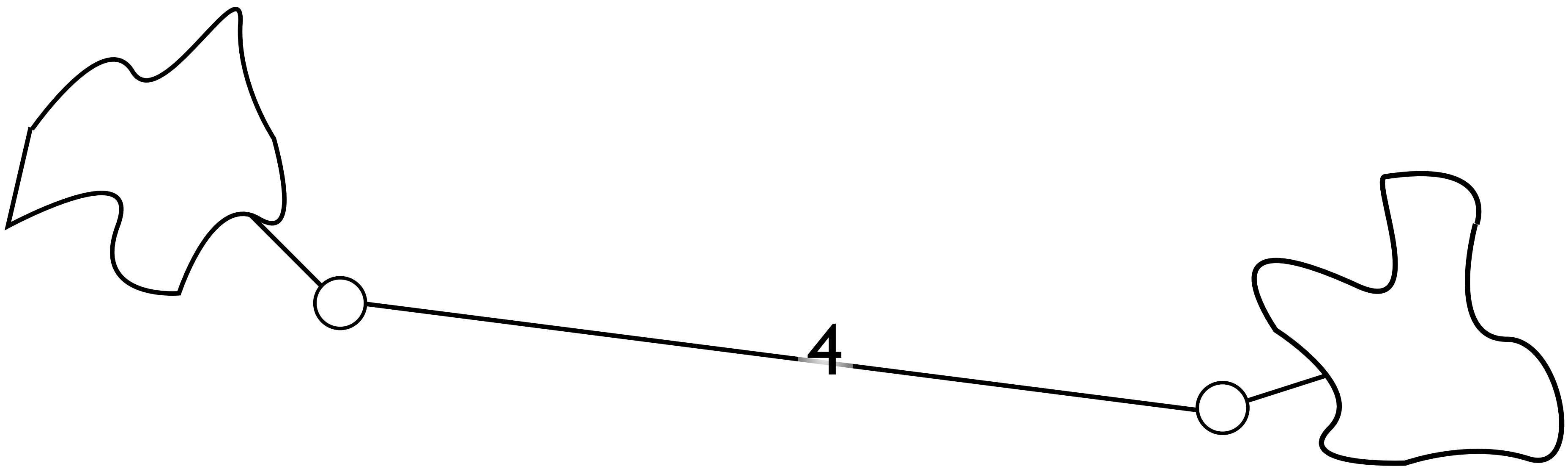
Contractions everywhere!

- Describe majority of approaches as contraction:
  - Contraction Hierarchies
  - DAO abstraction
  - Subgoal Graphs
  - Jump Point Search

Graph Contraction

- Remove a set S of states from a graph G
- Optimal:
  - Ensure that the shortest path between all states G \ S are not changed
  - Add edges (shortcuts) to preserve shortest paths
- Suboptimal:
  - Ensure that completeness is not lost

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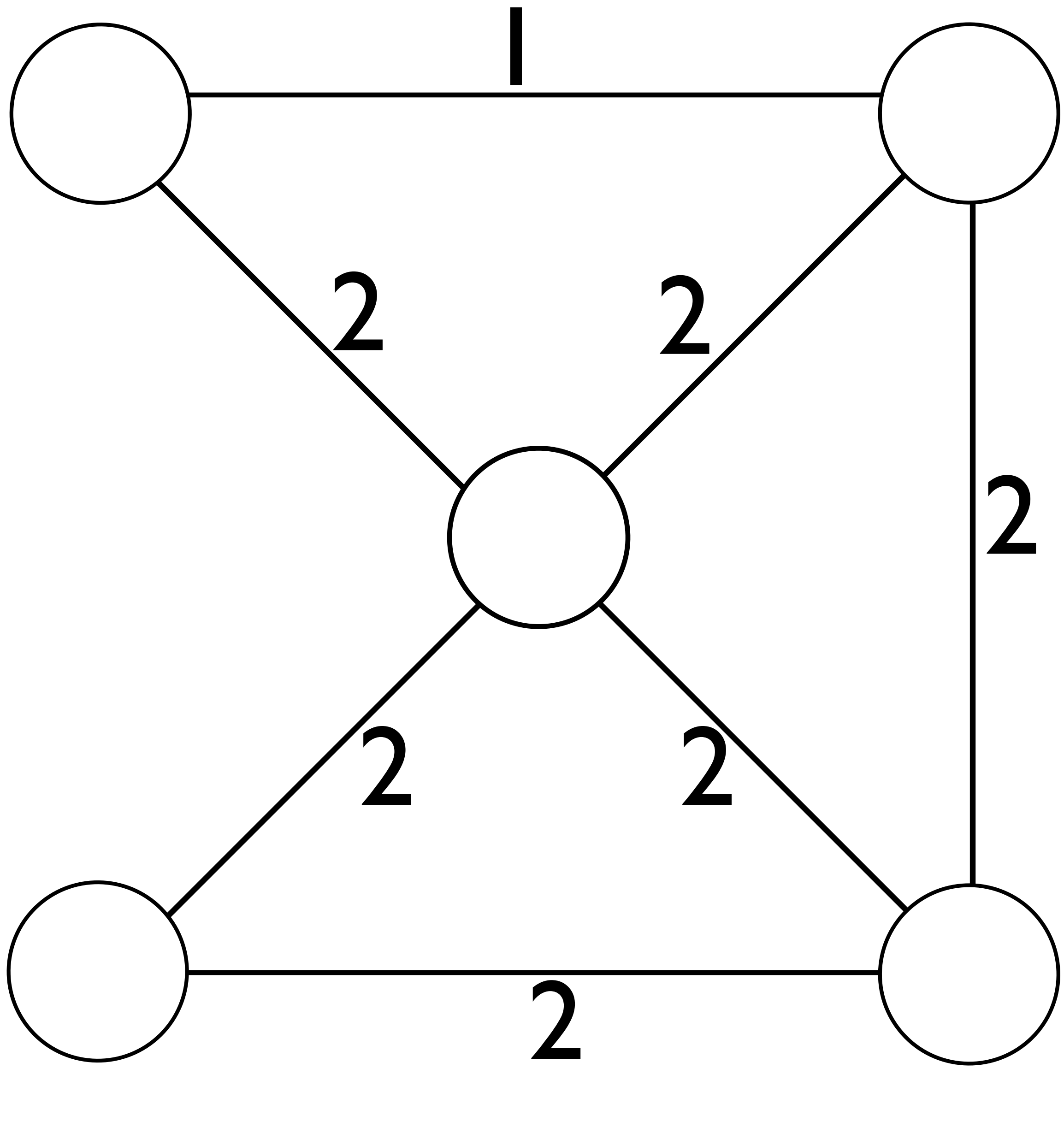
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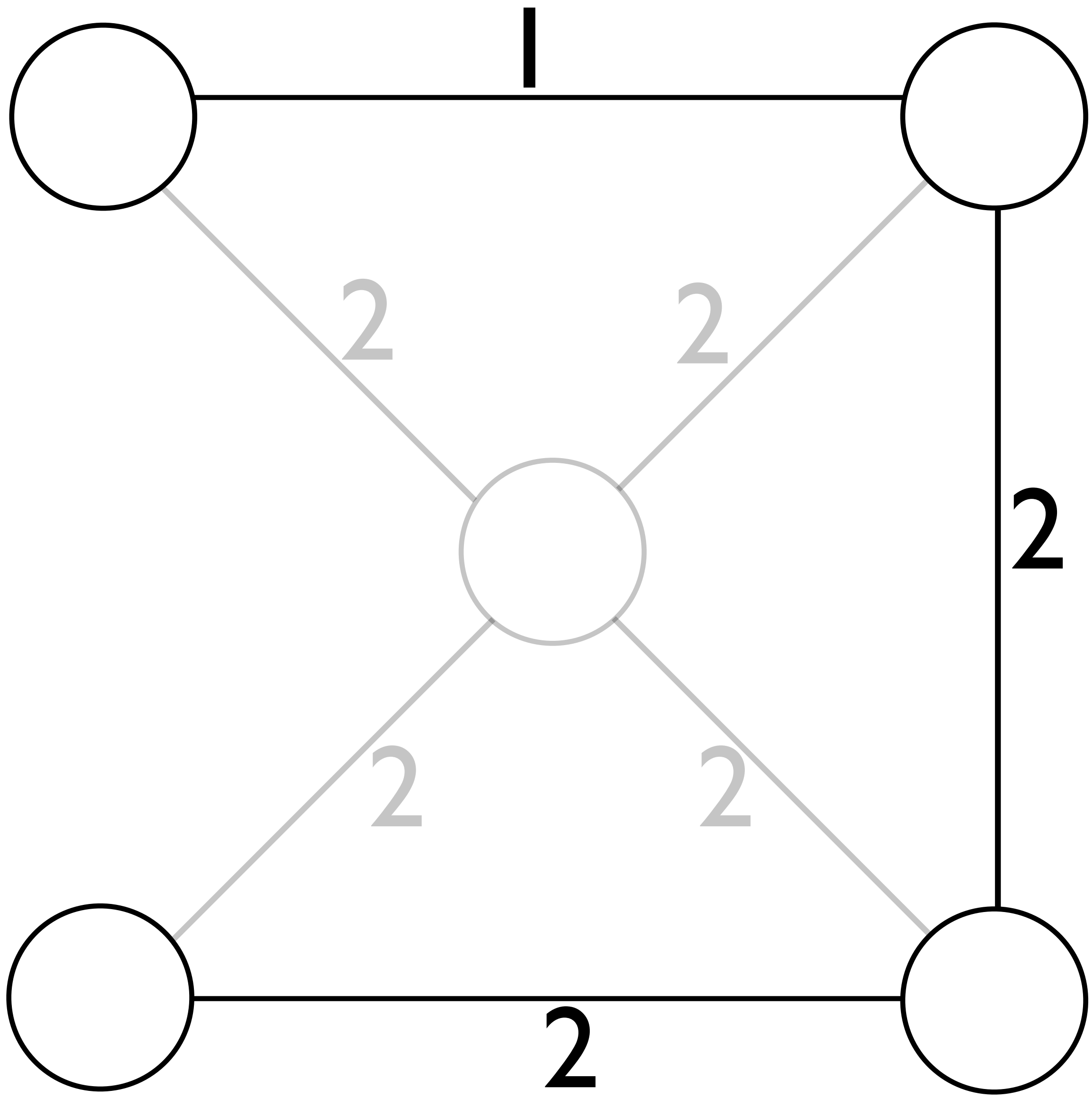
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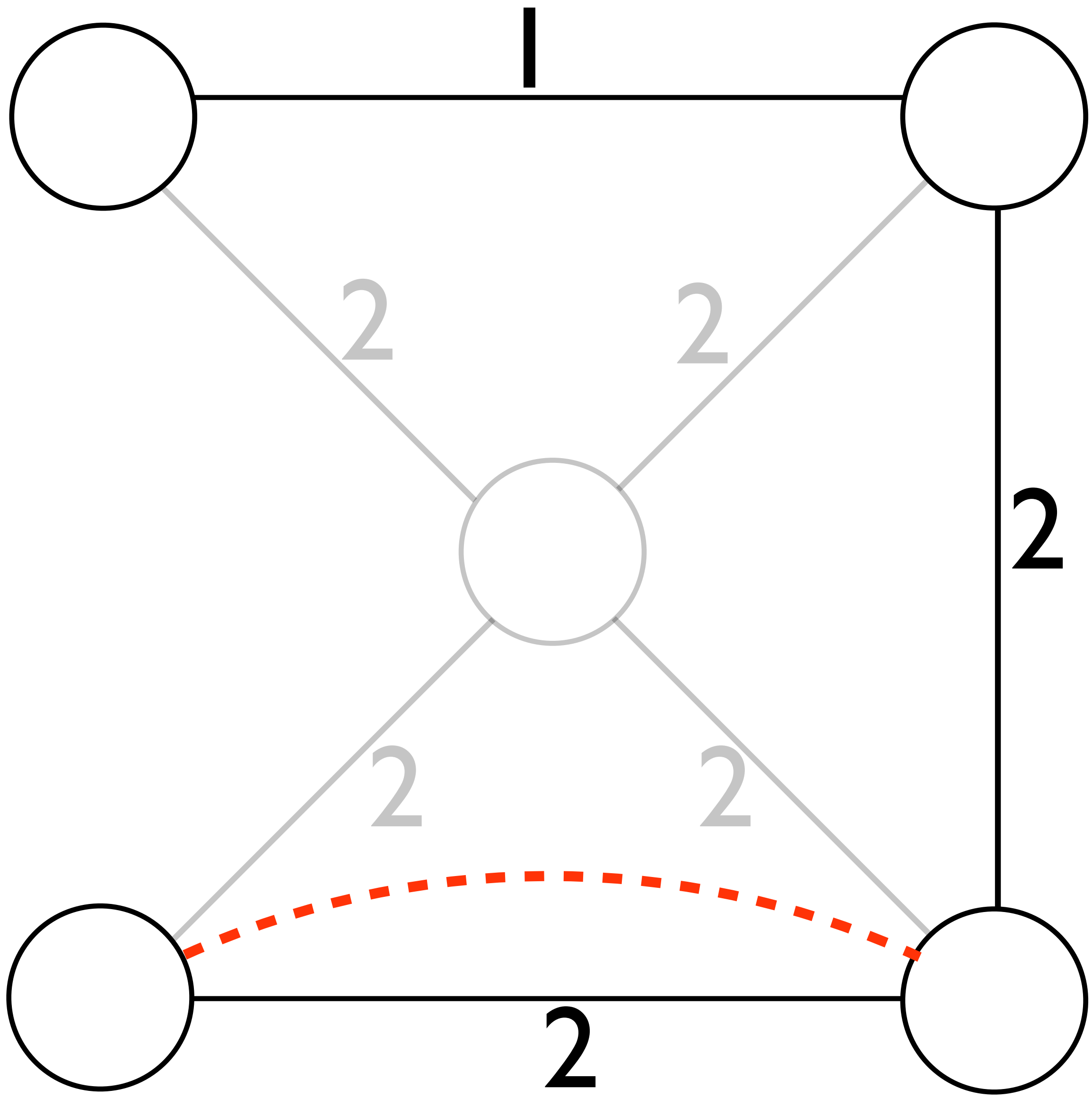
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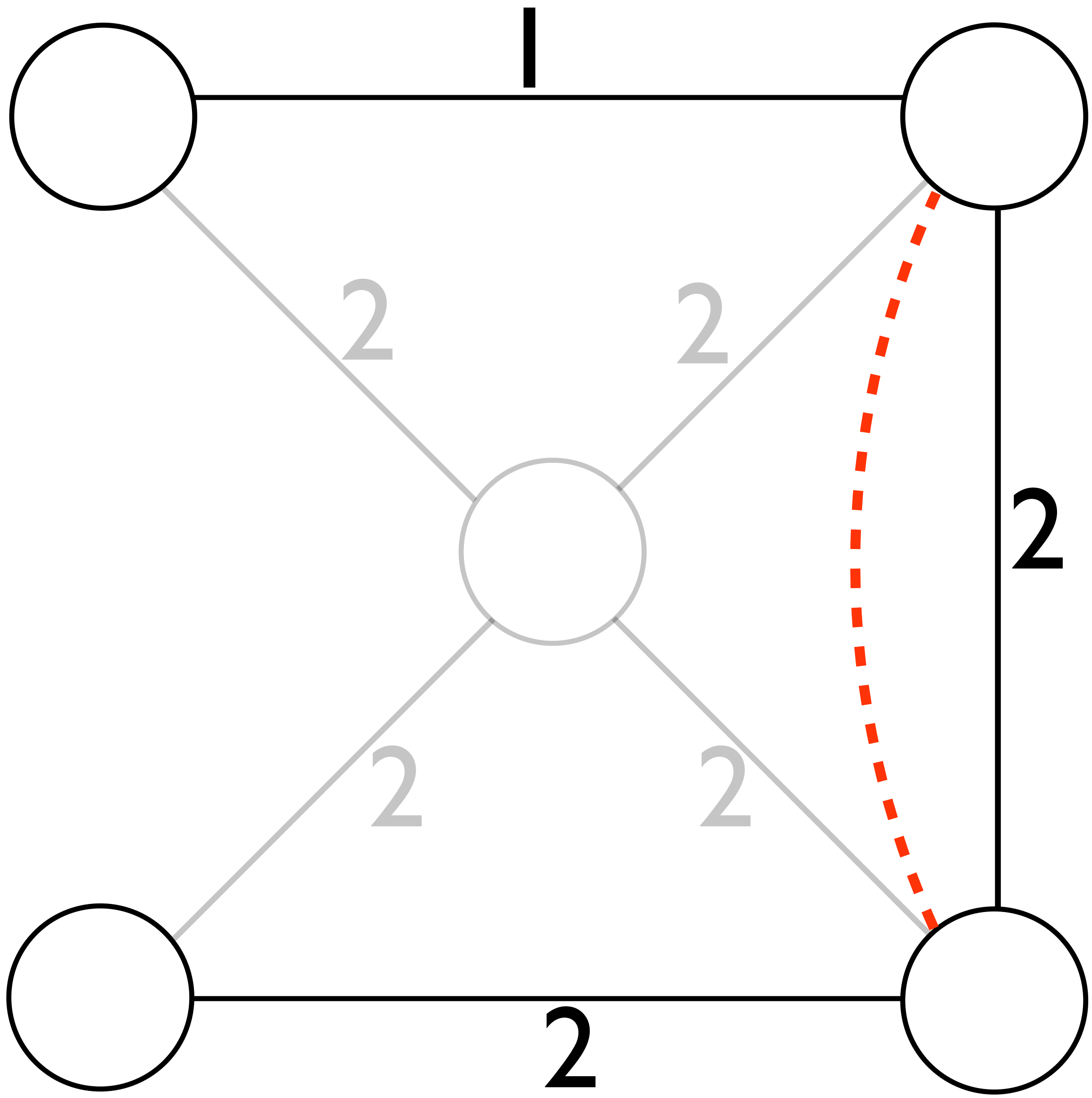

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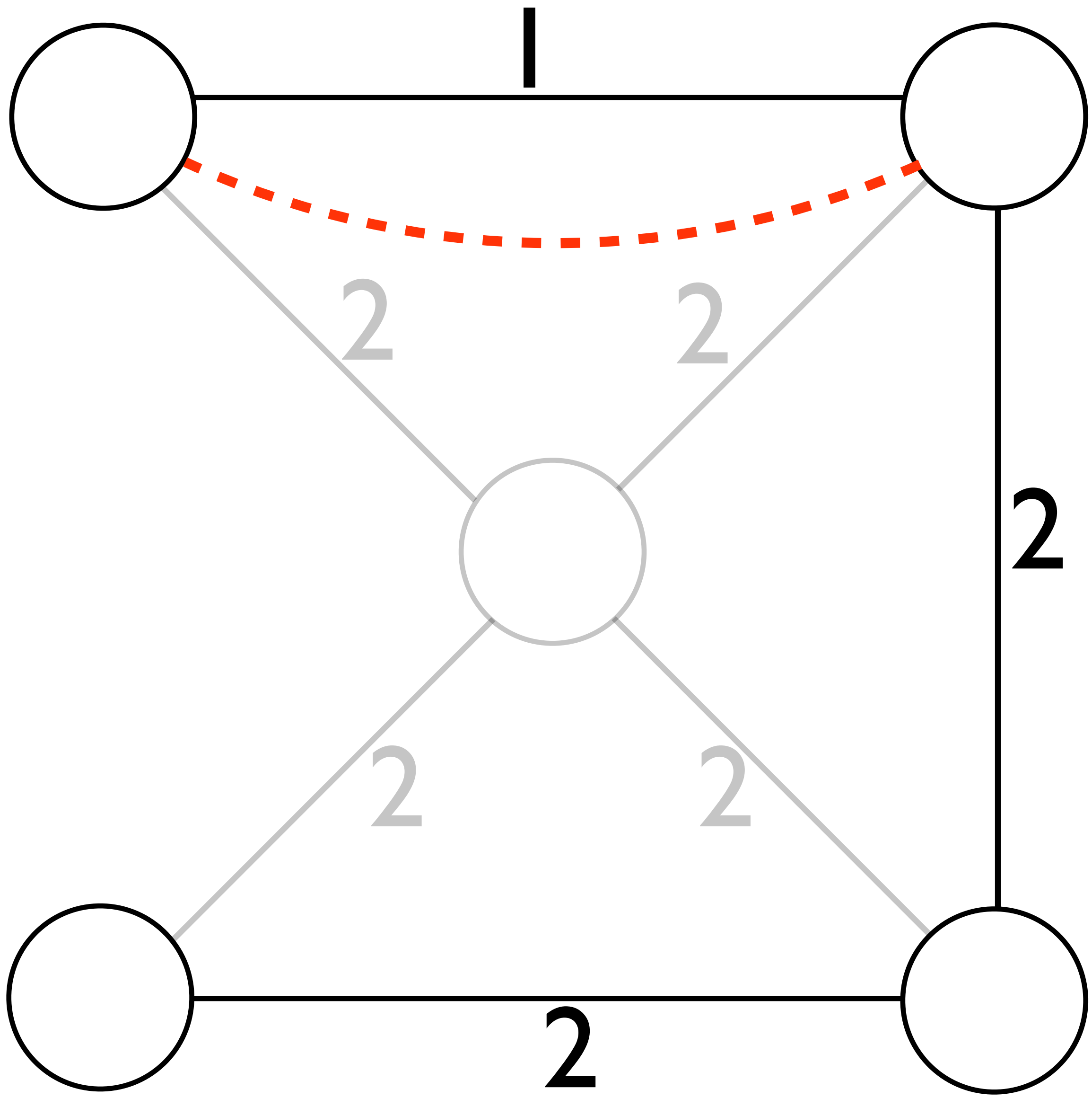
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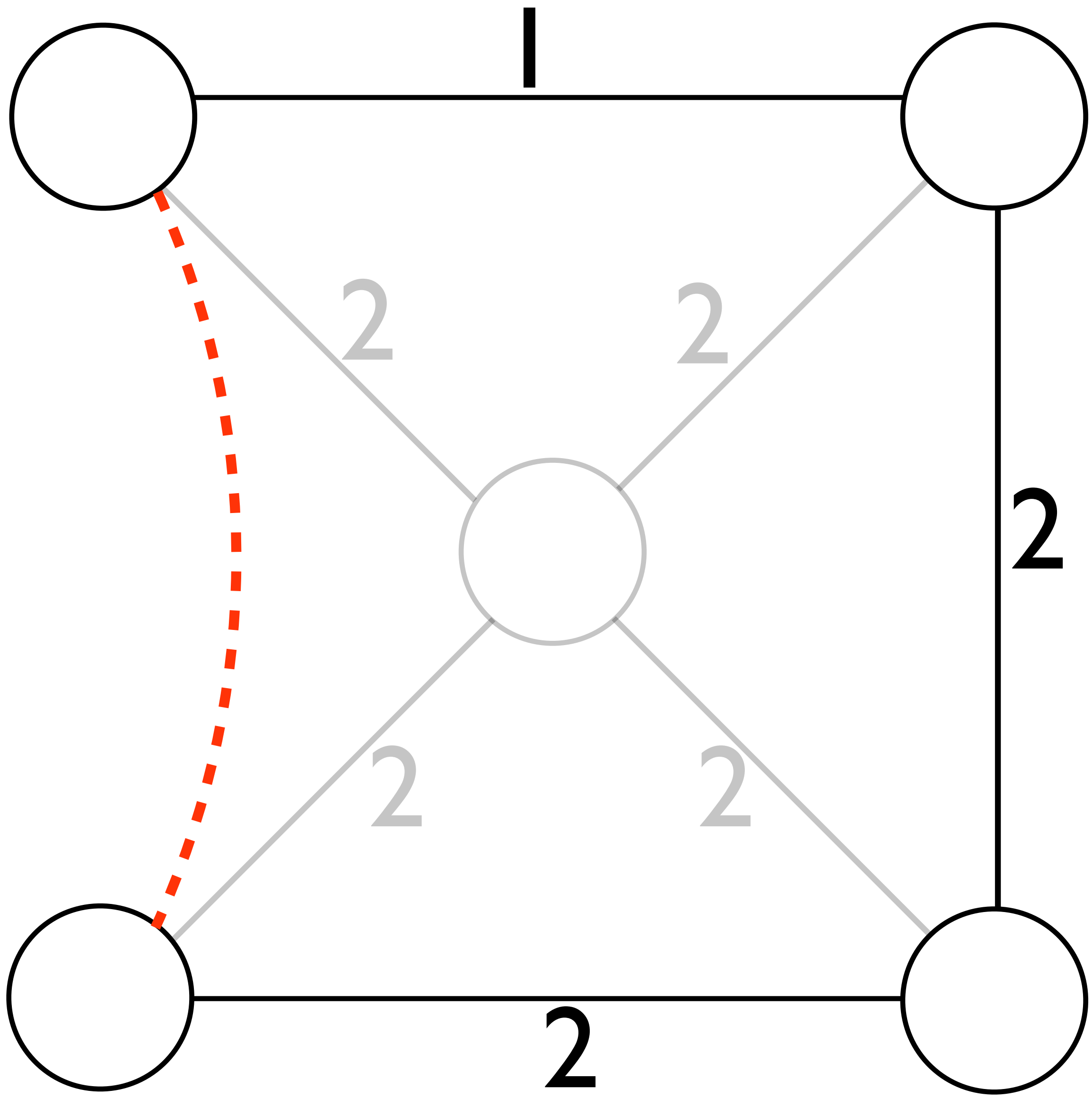

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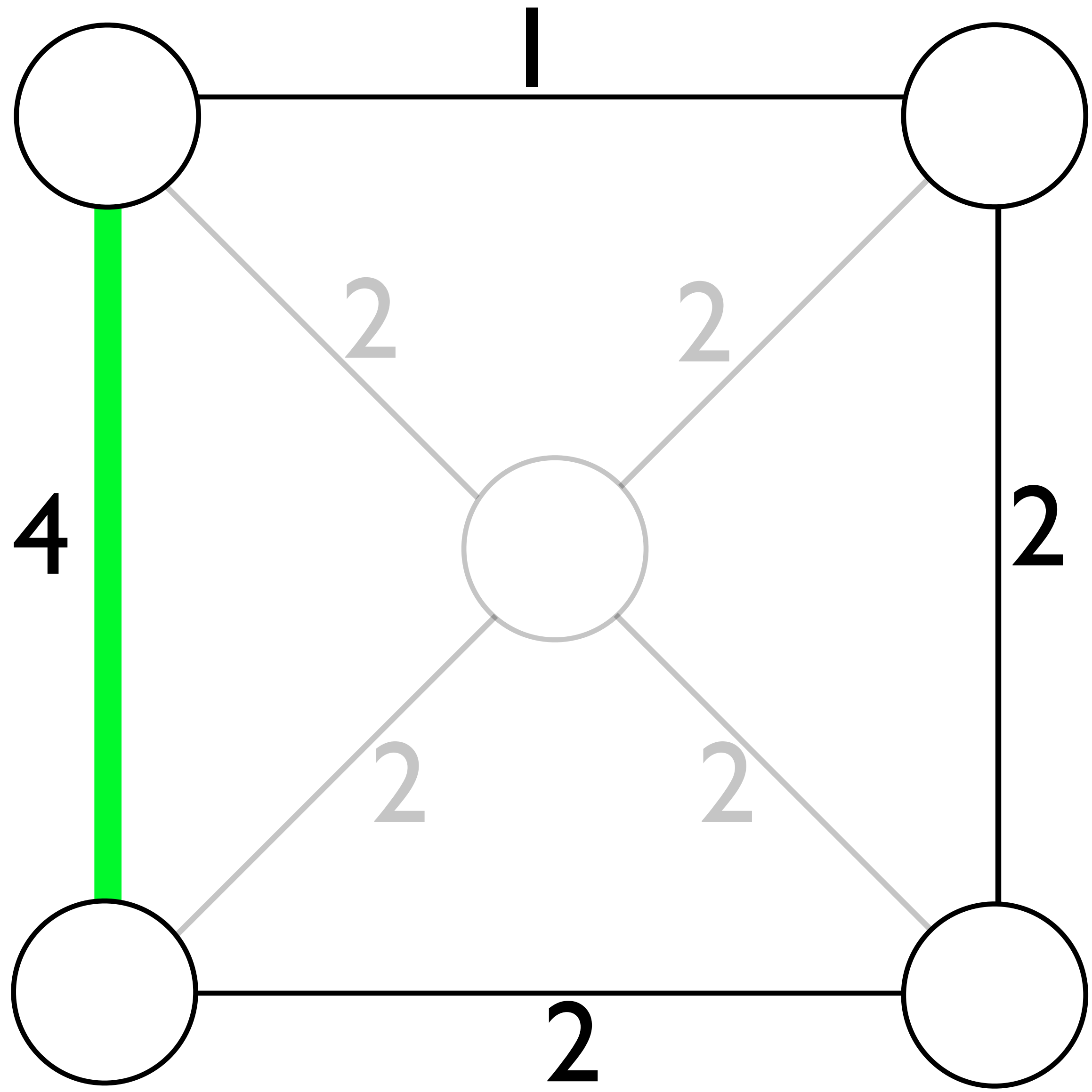
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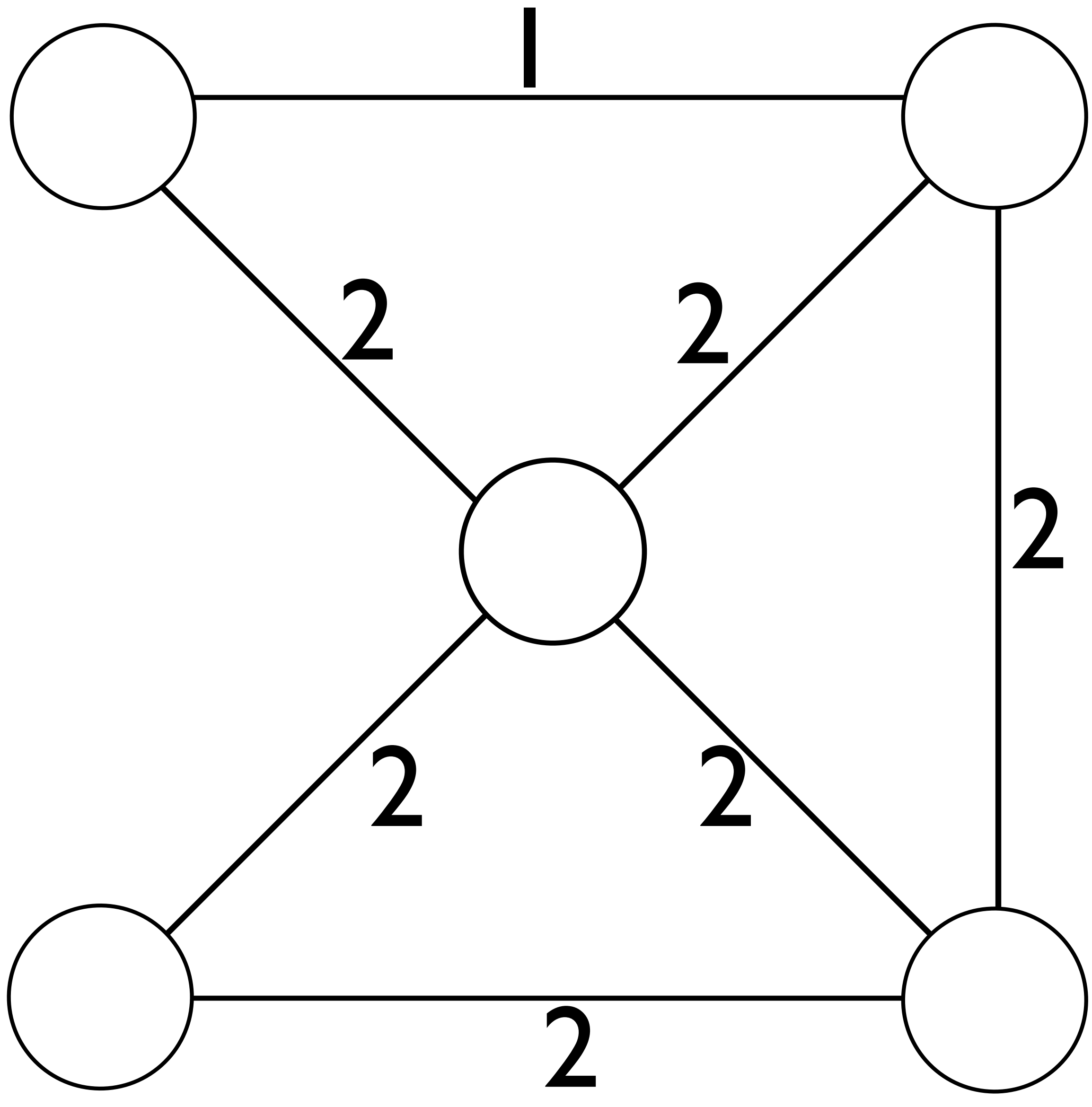
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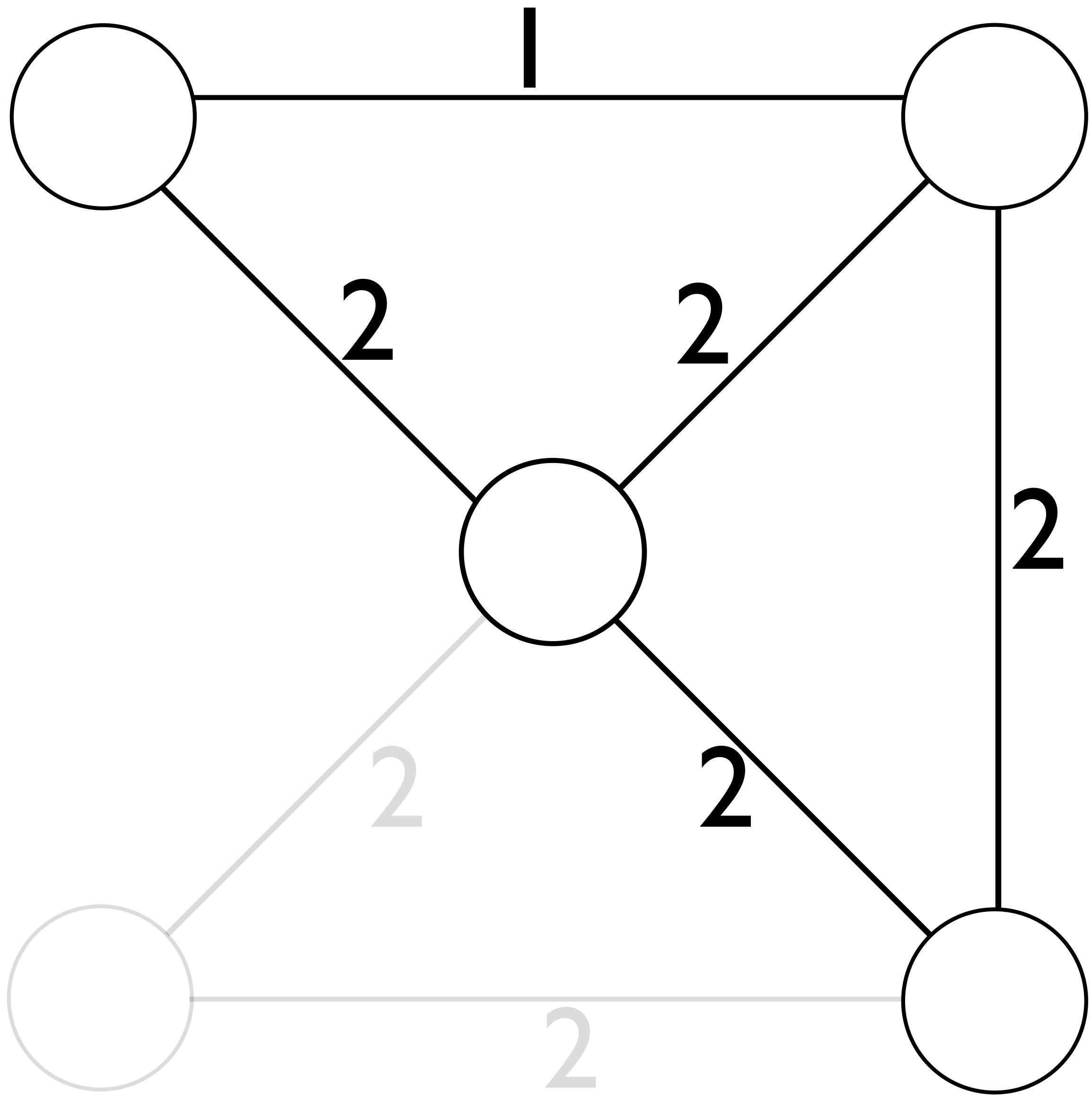

1
2
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2
2
2

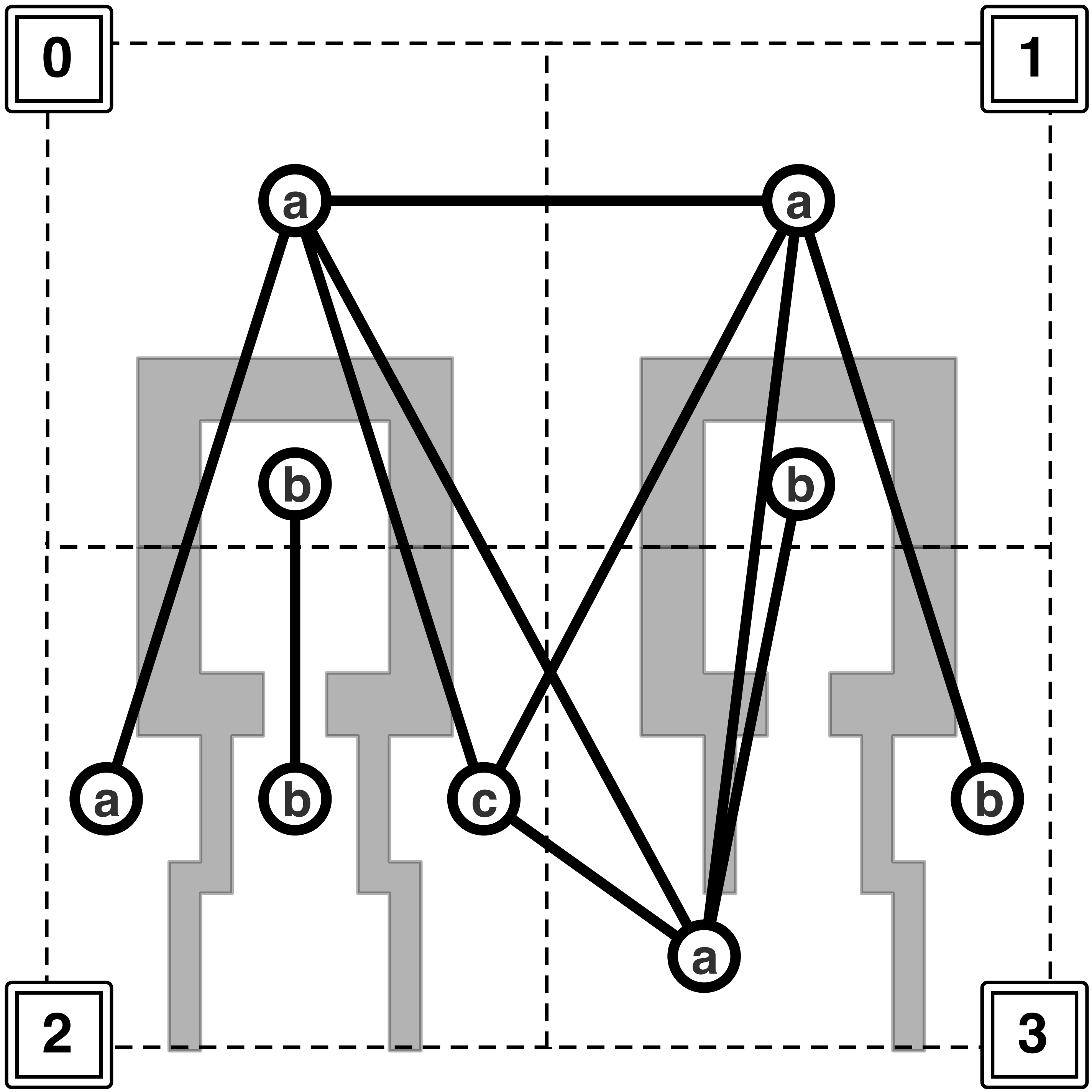
Contraction Hierarchies

- Optimal approach
- Key idea is finding good orderings for contracting nodes from the graph

- Contract one node at a time
  - Add shortcut edges

Traditional Abstraction/ Refinement

- Find strongly connected components
  - Abstract them together into a single abstract state
  - (Holte et al, 1996), (Fernández, & González, 2002), (Botea et. at., 2004), (Sturtevant & Buro, 2005), (Sturtevant 2007)
  - *Downward refinement property*
- Approach discarded in road networks after optimal approaches discovered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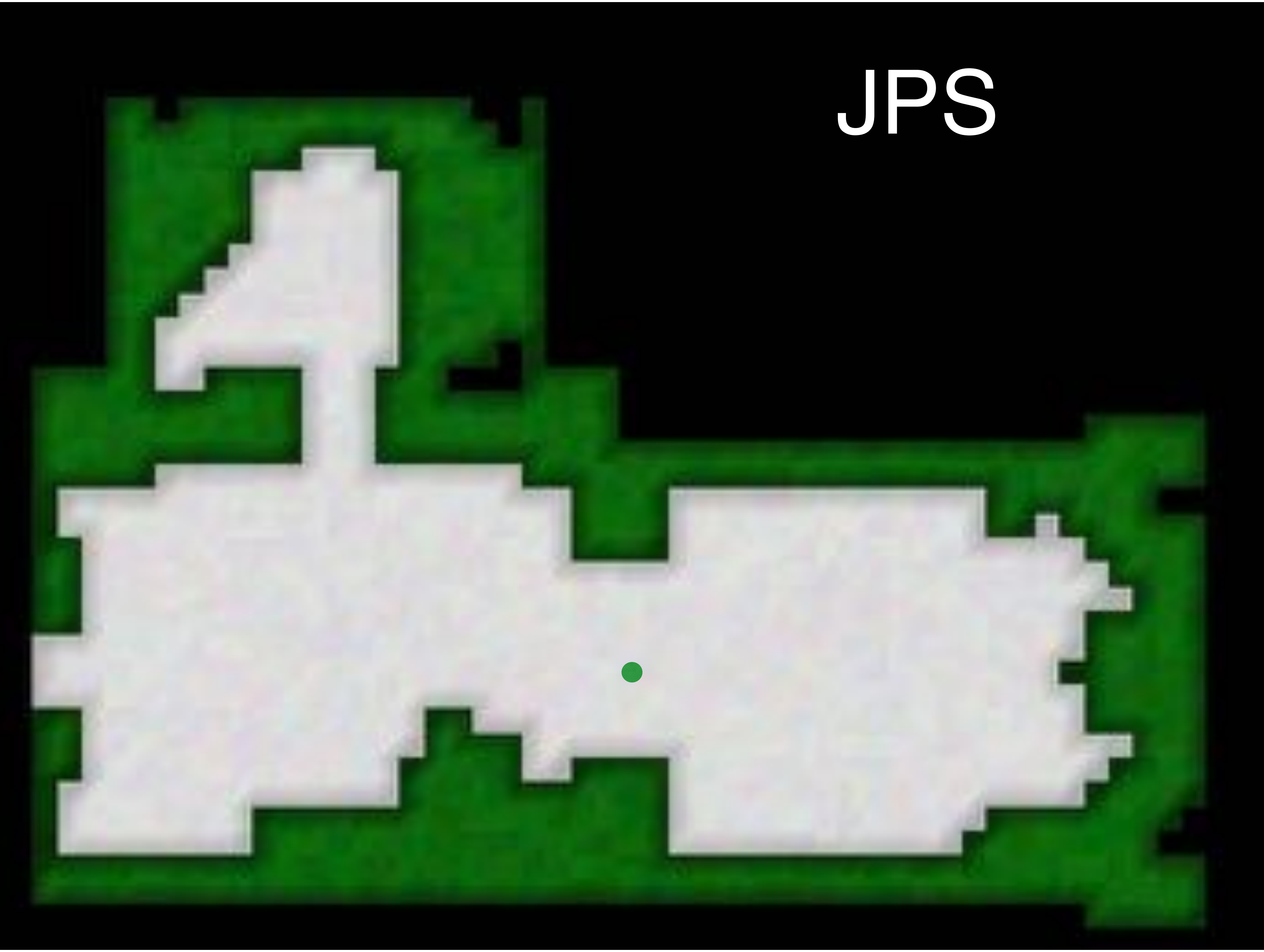
b
a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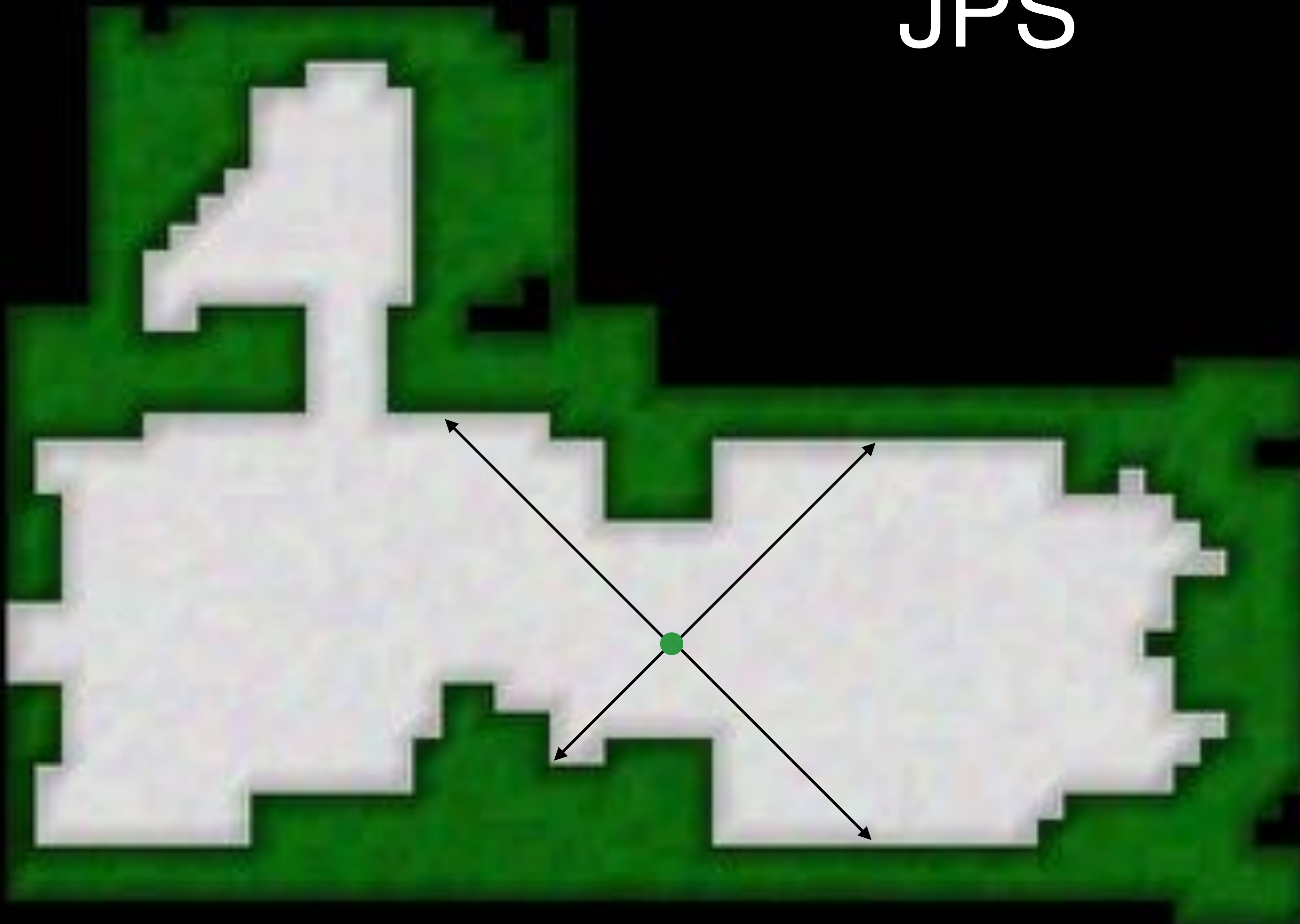
JPS



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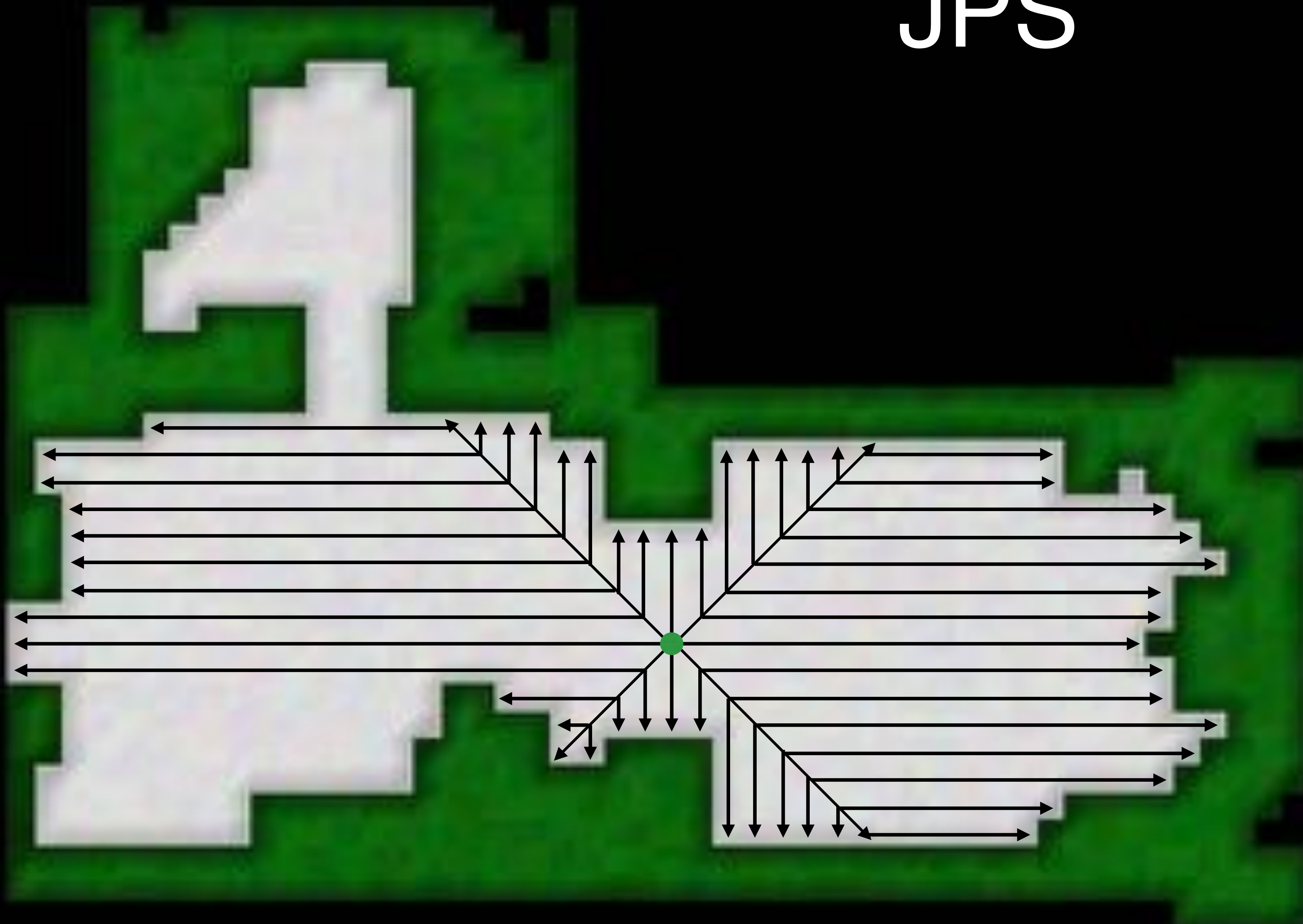

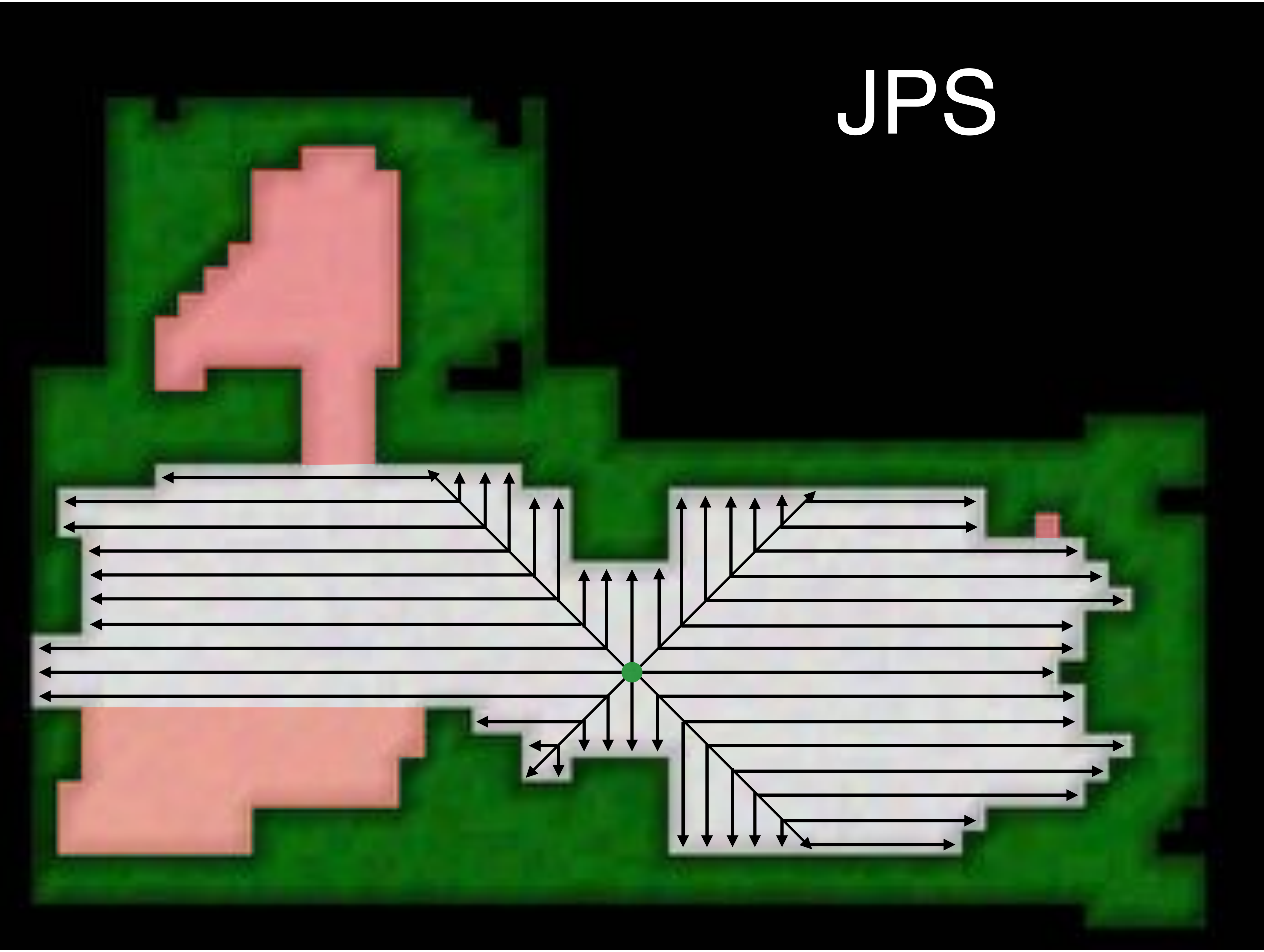

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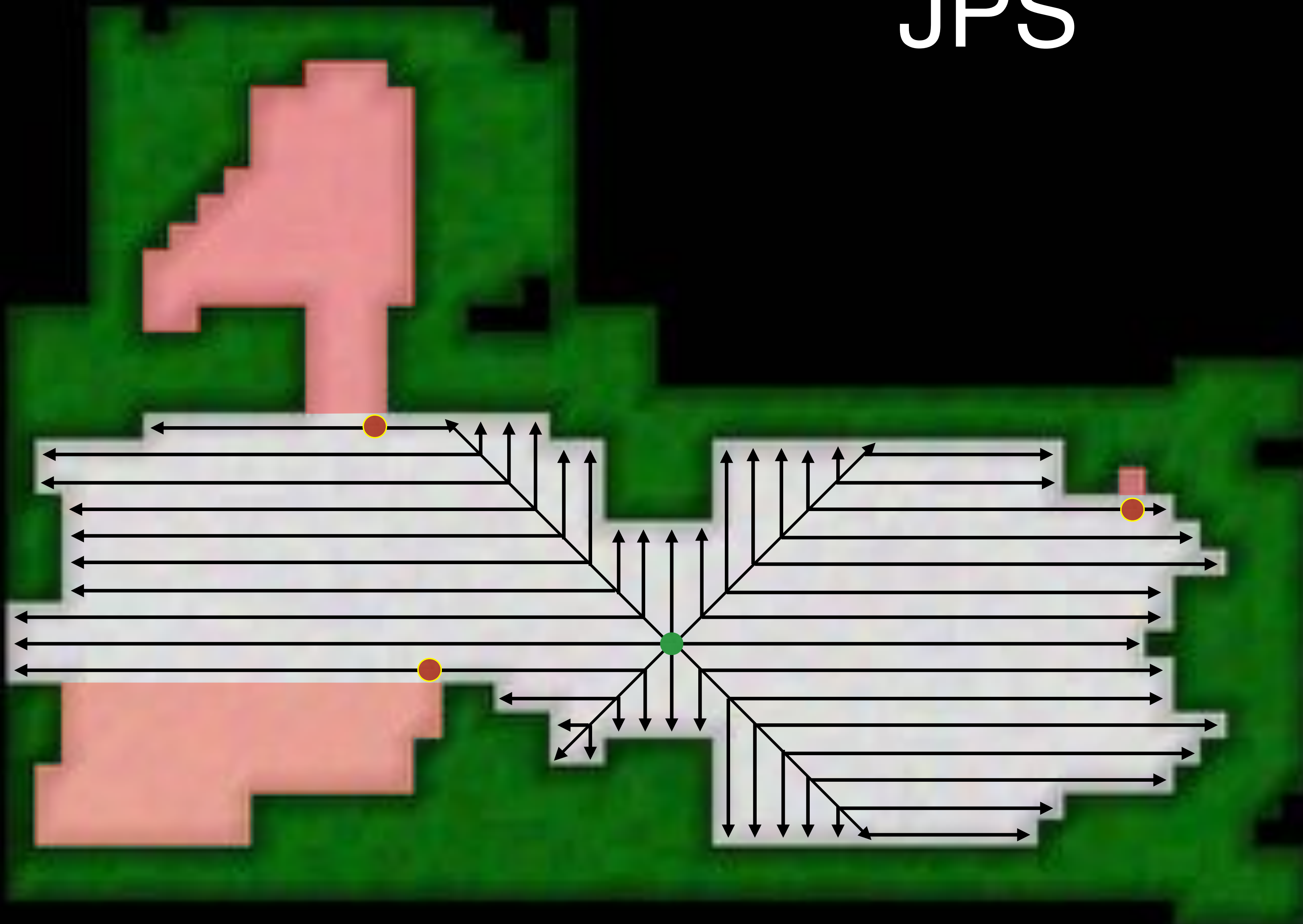

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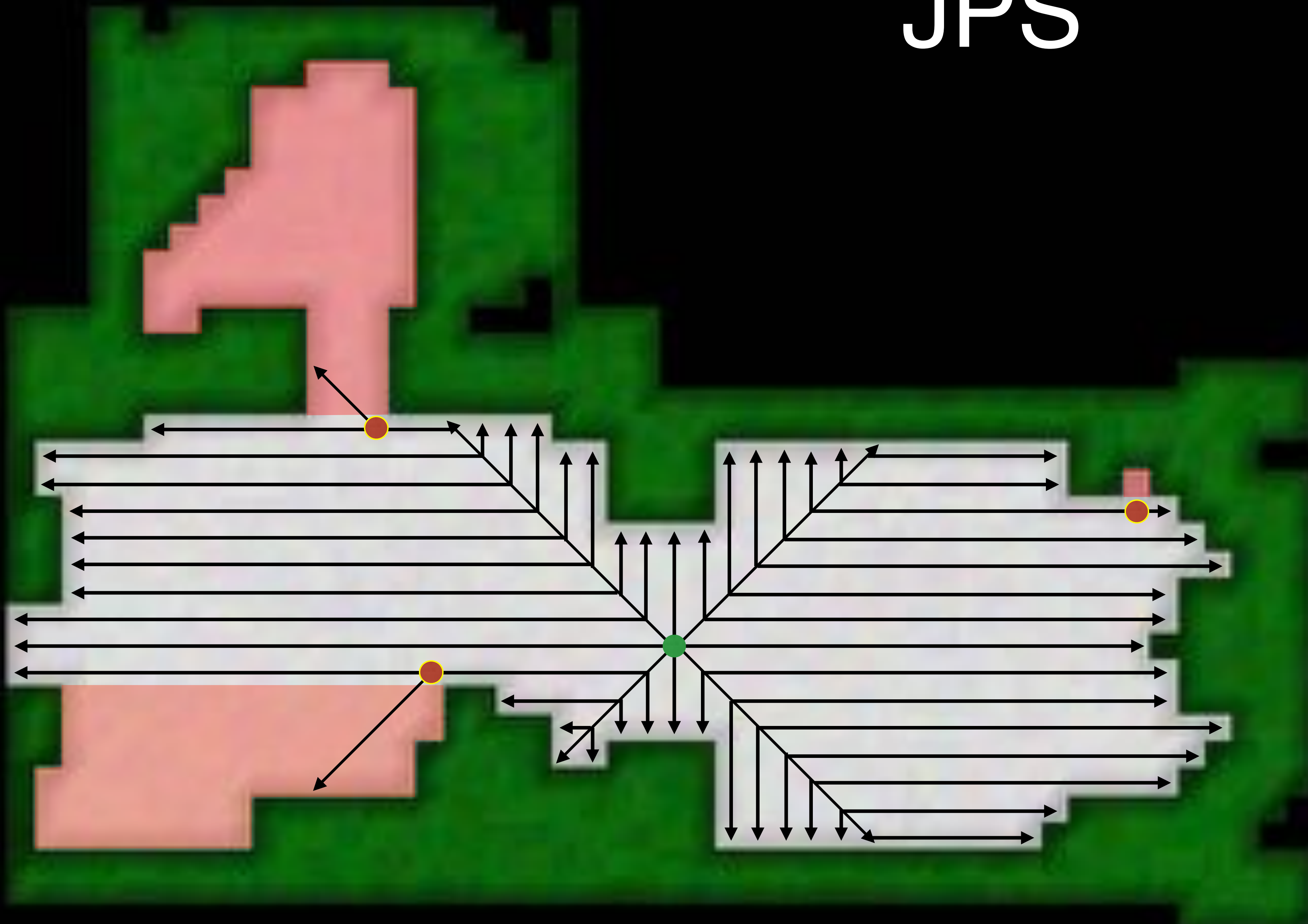

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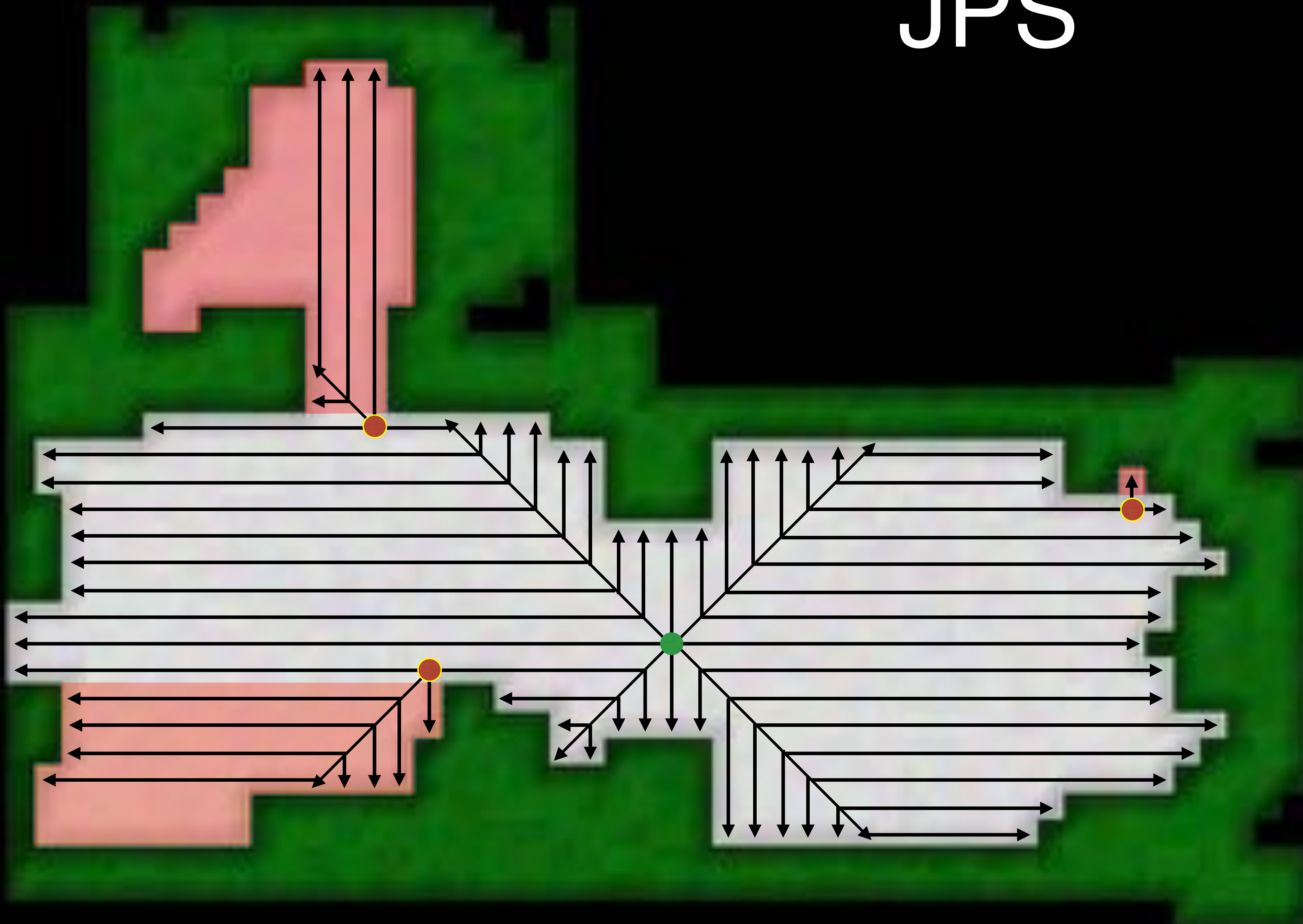

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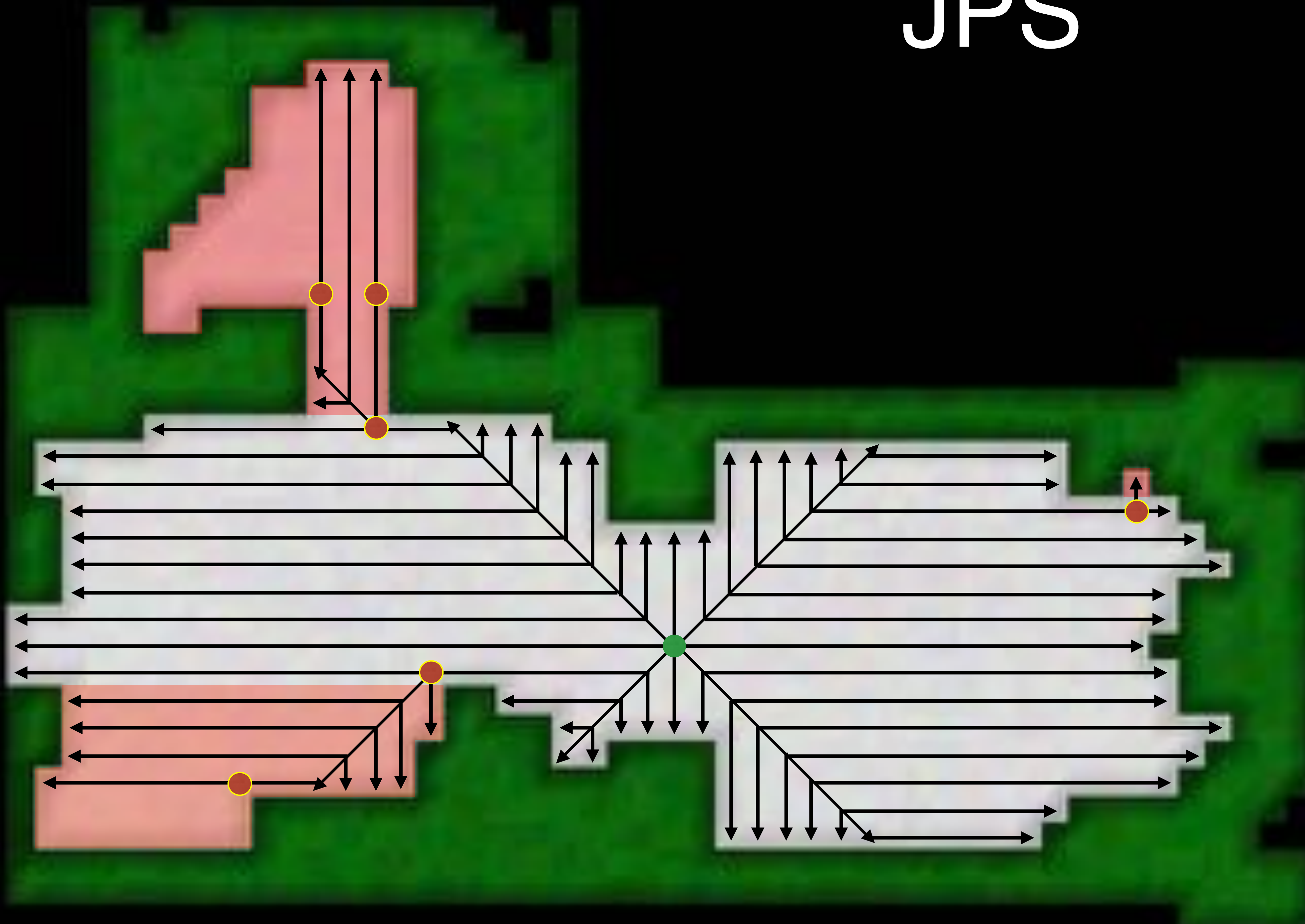

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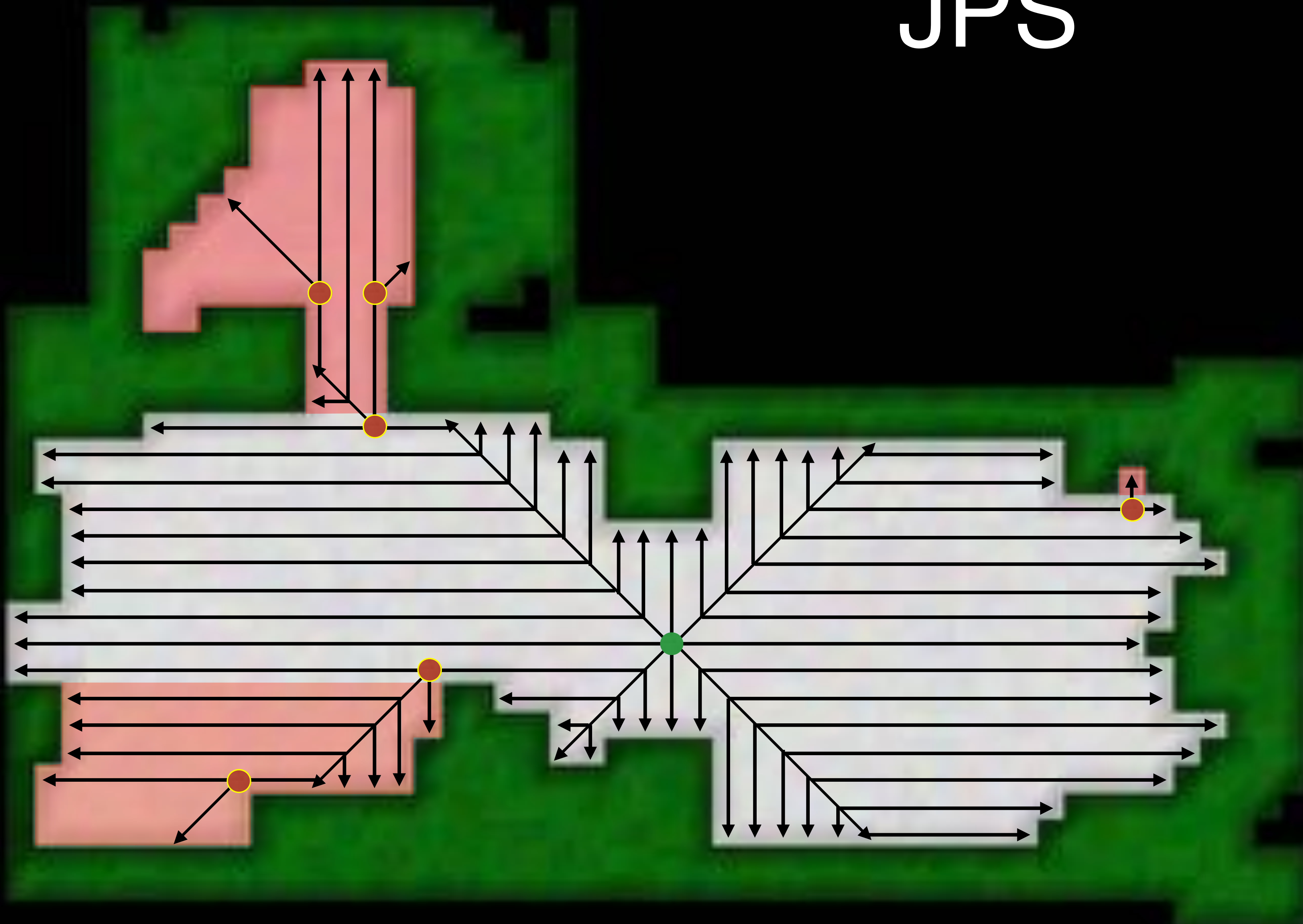

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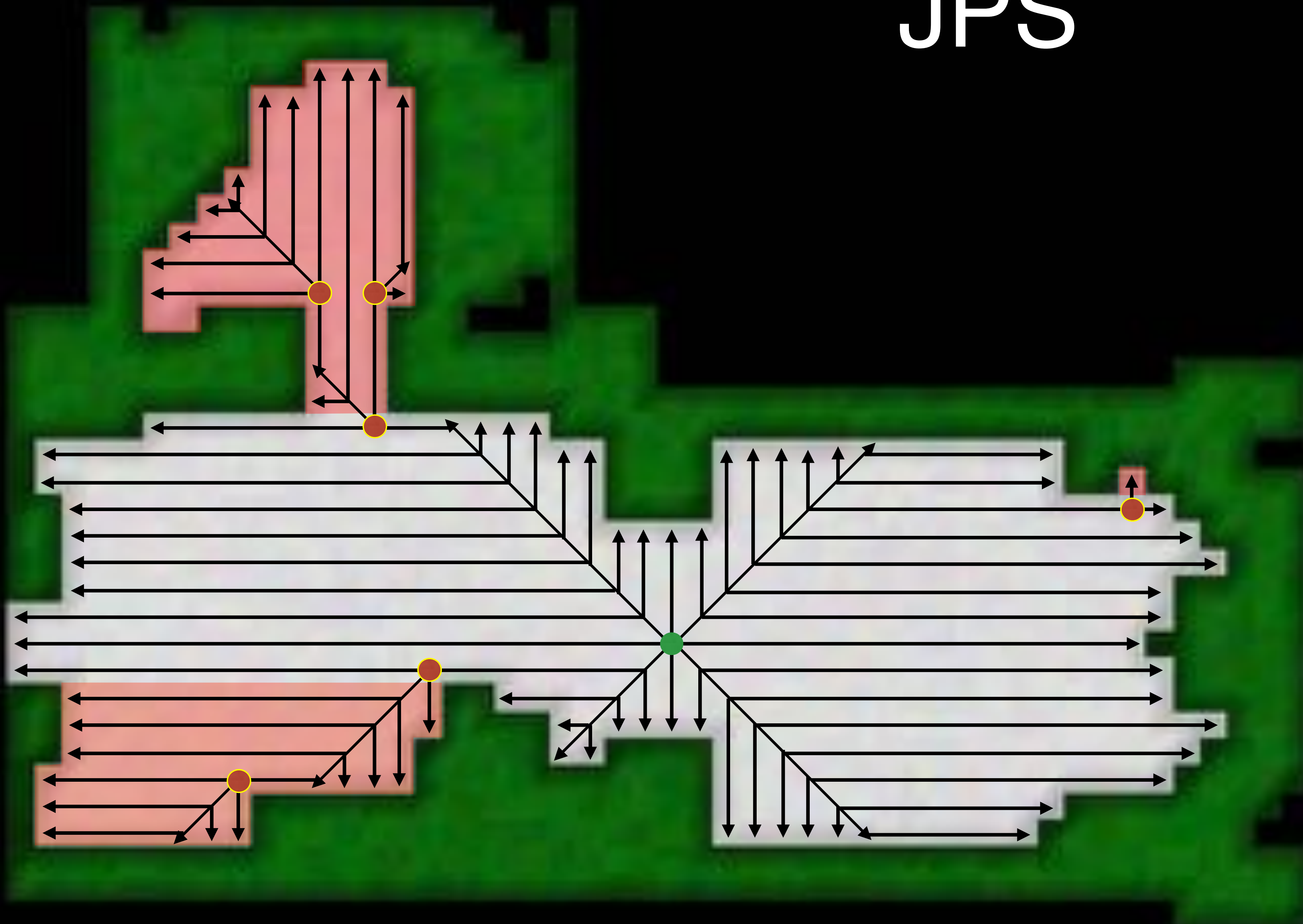

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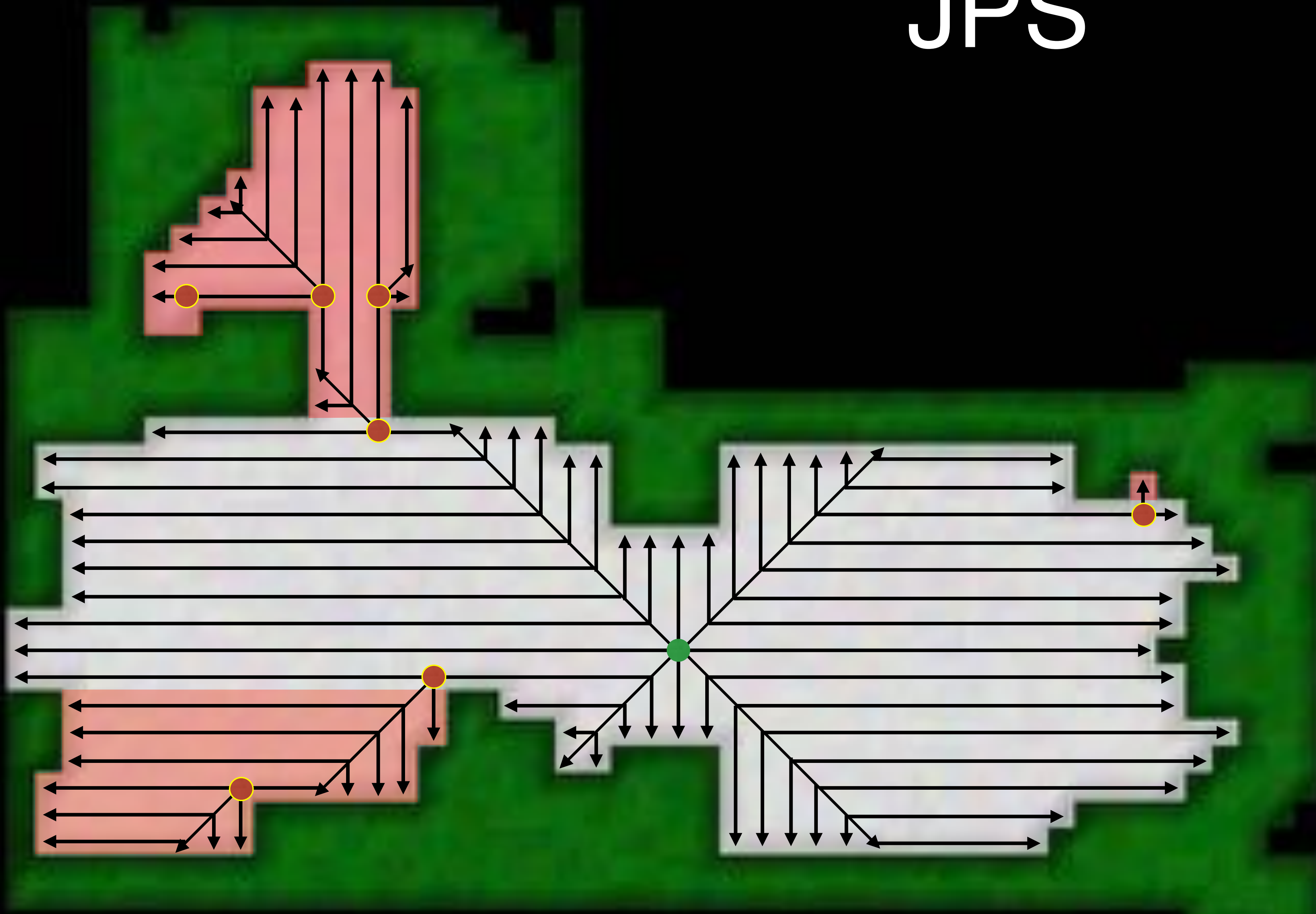

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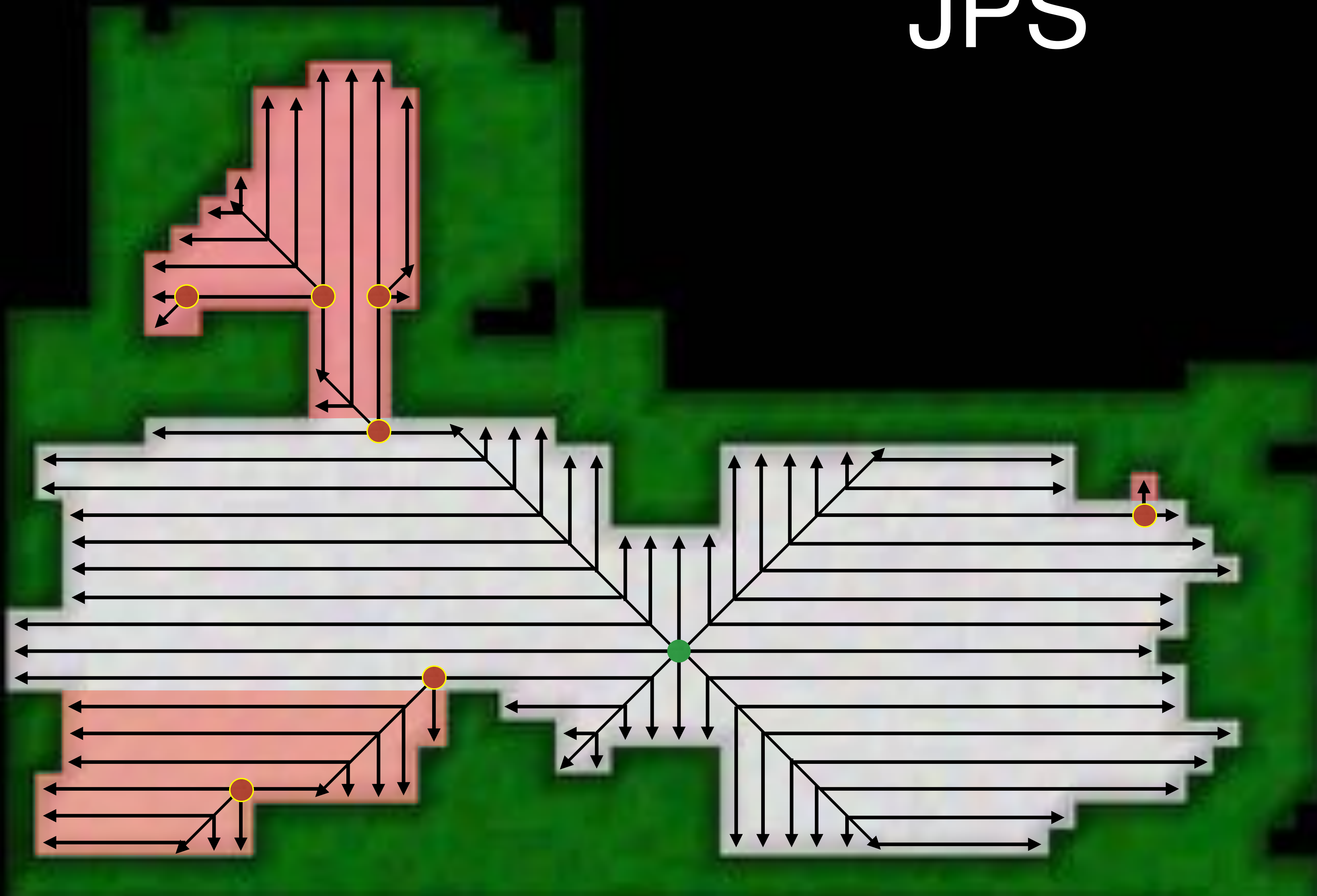

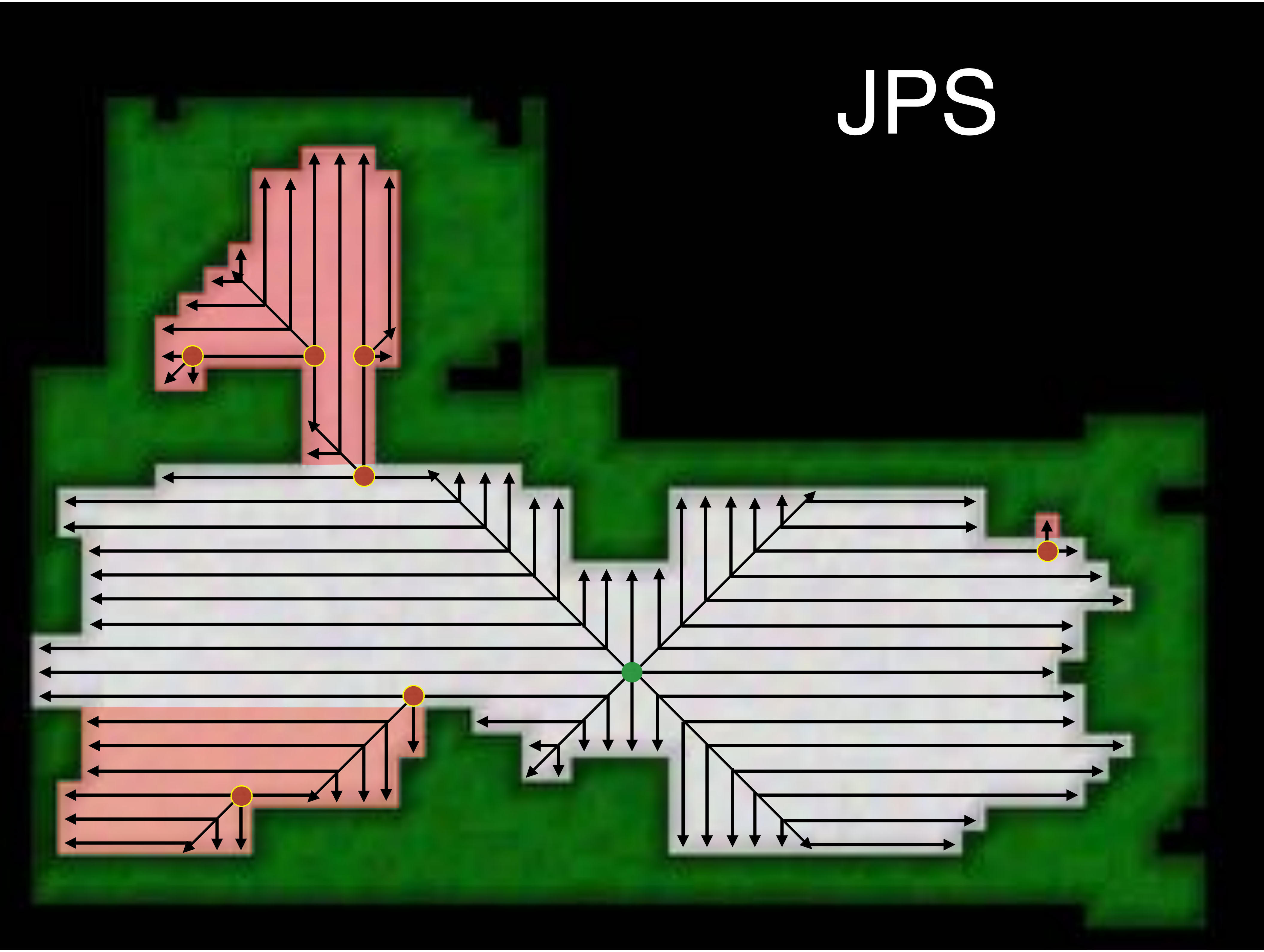
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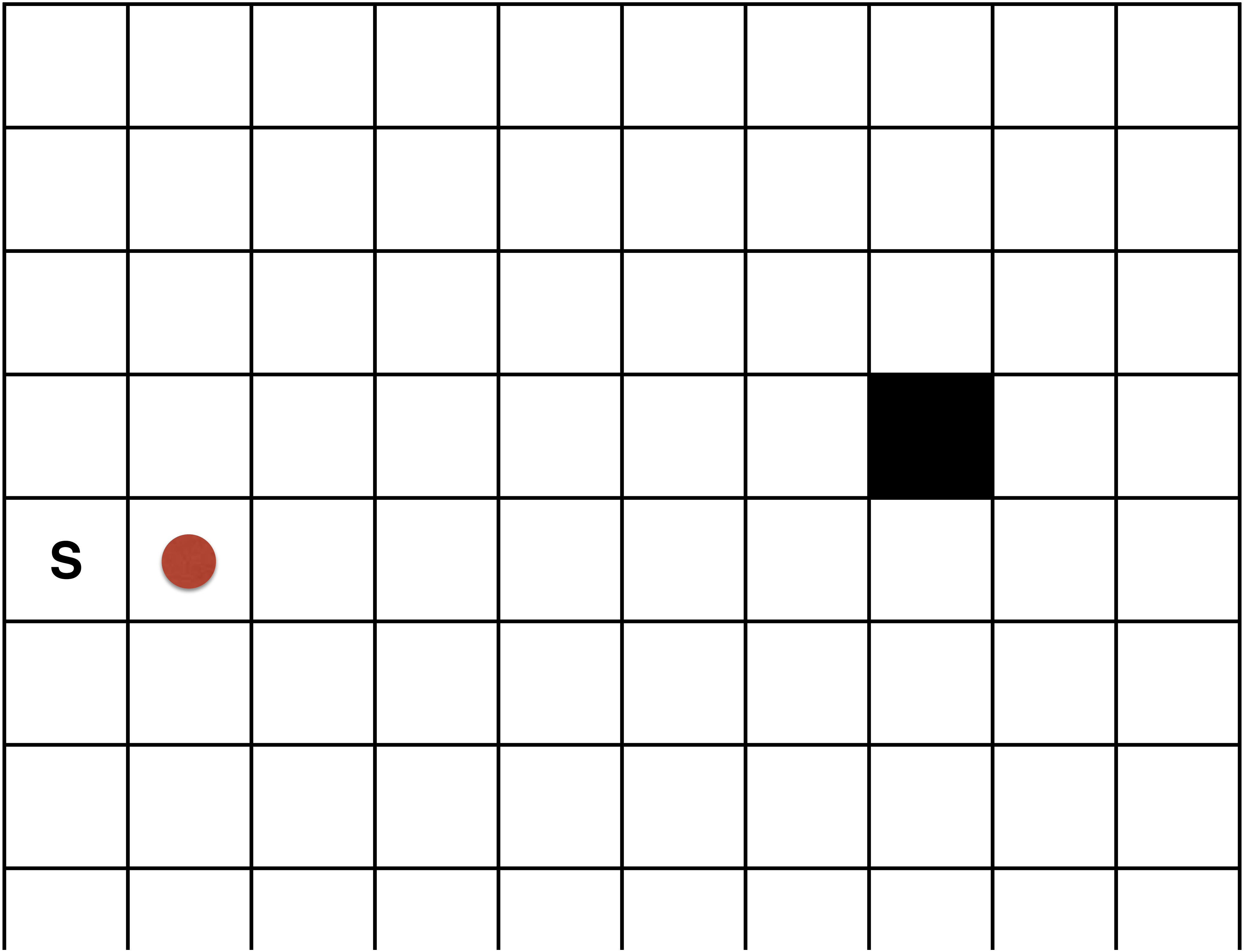
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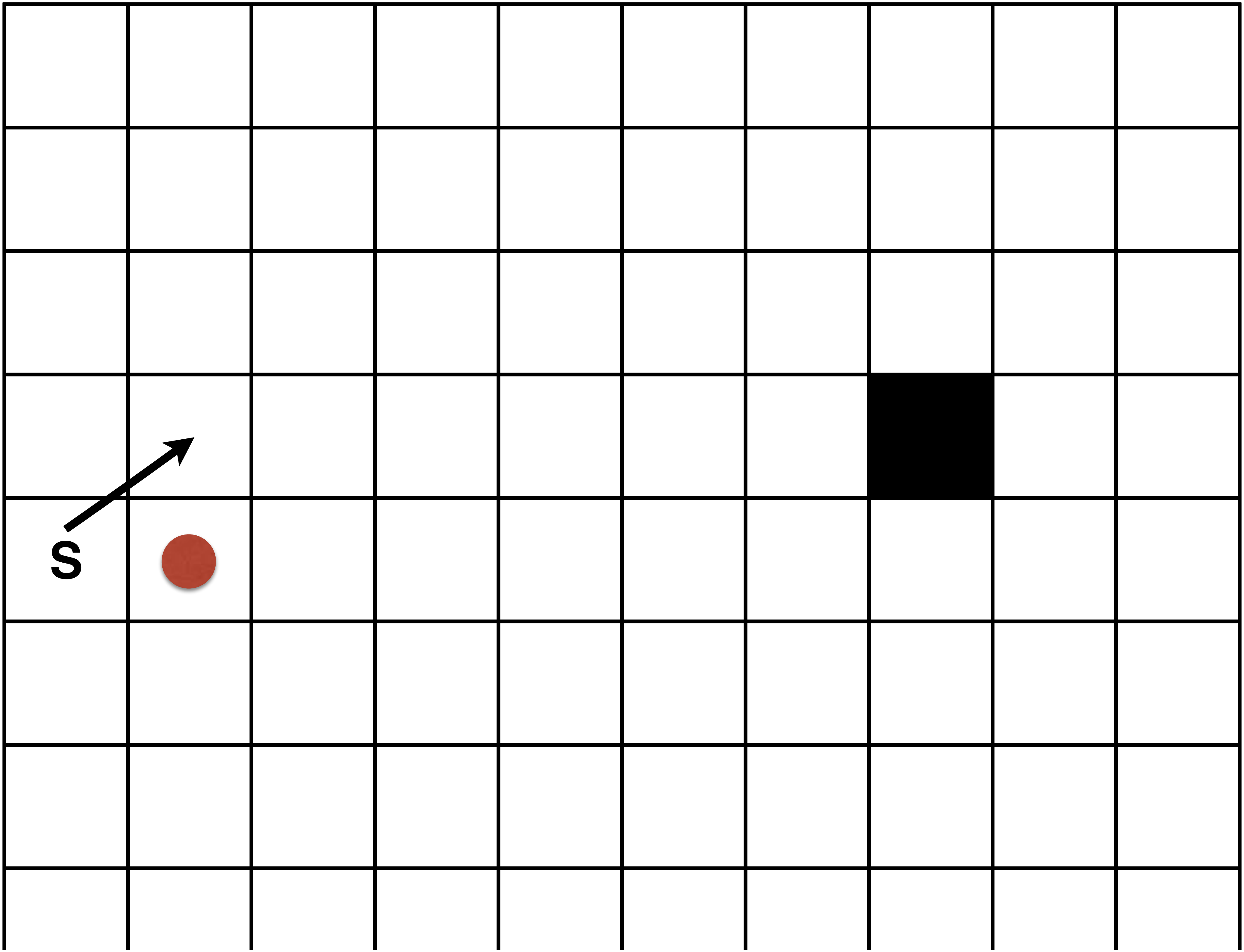
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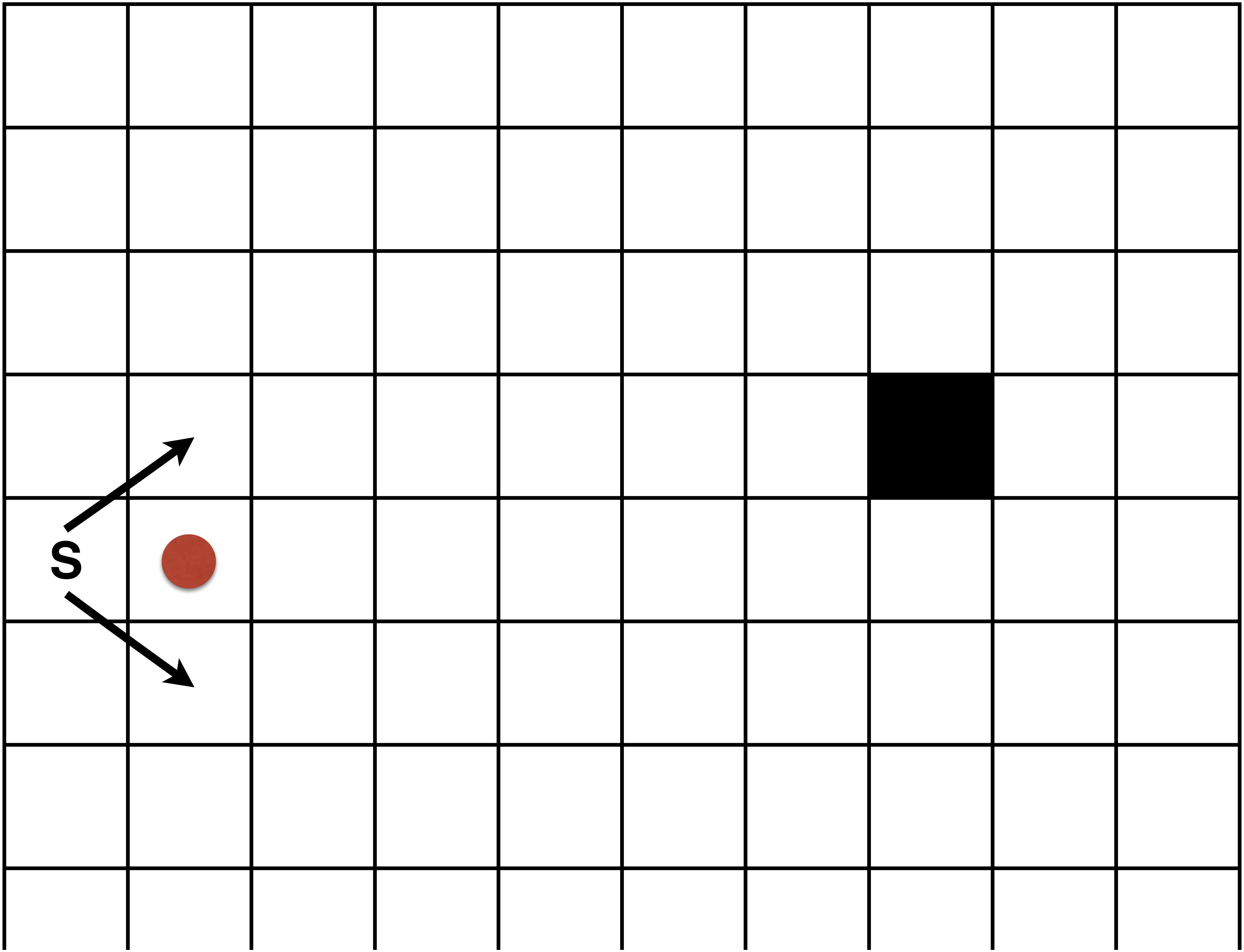
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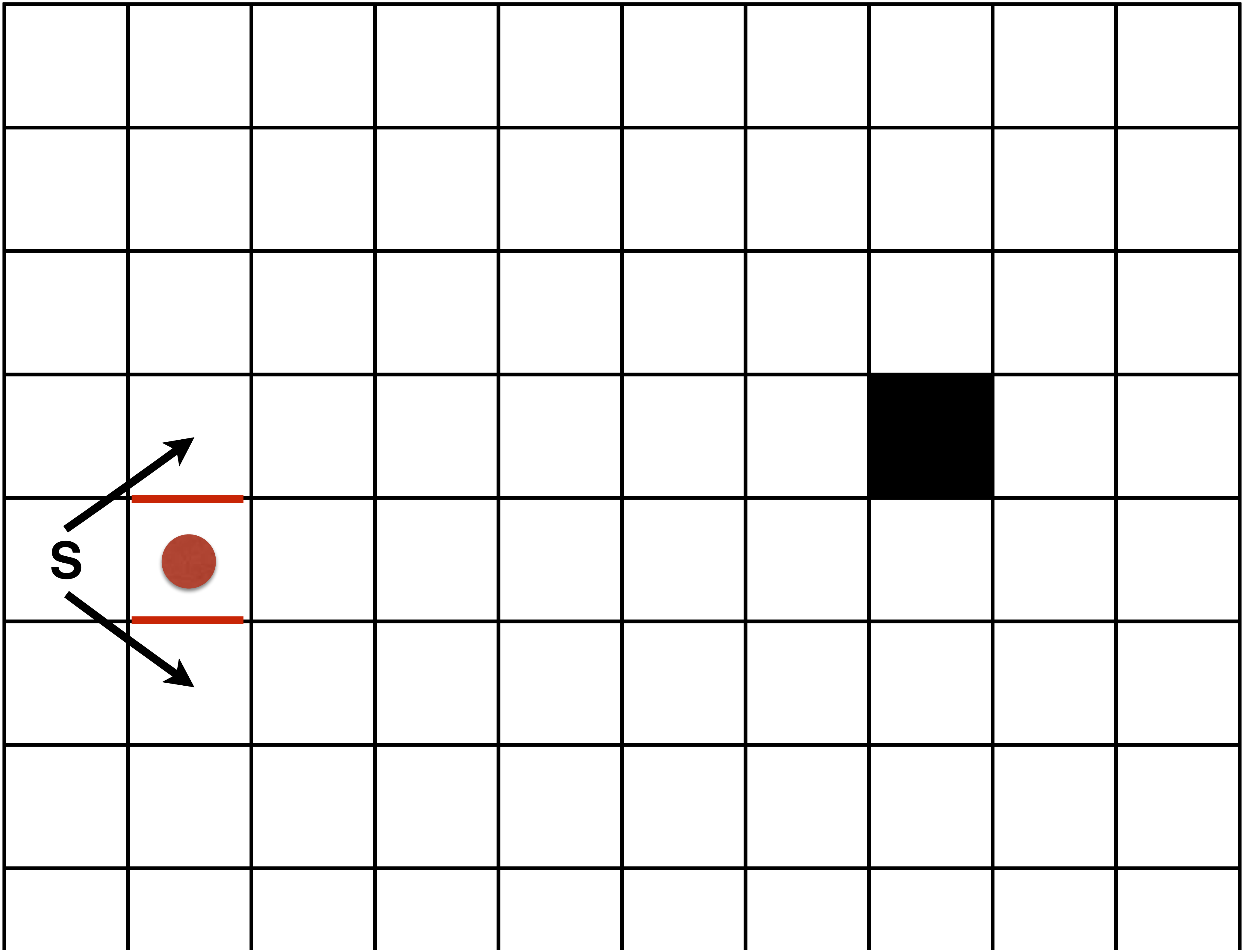
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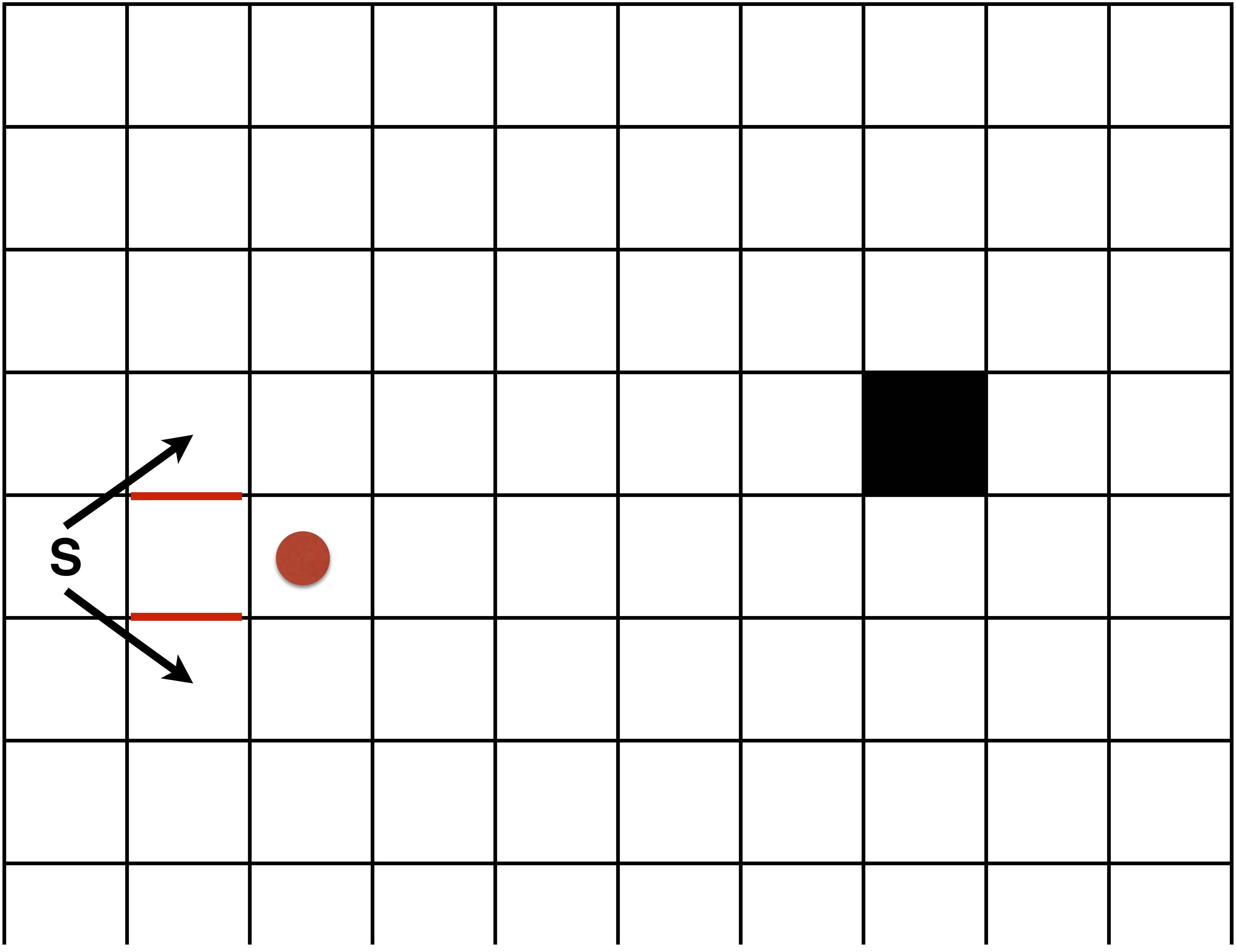
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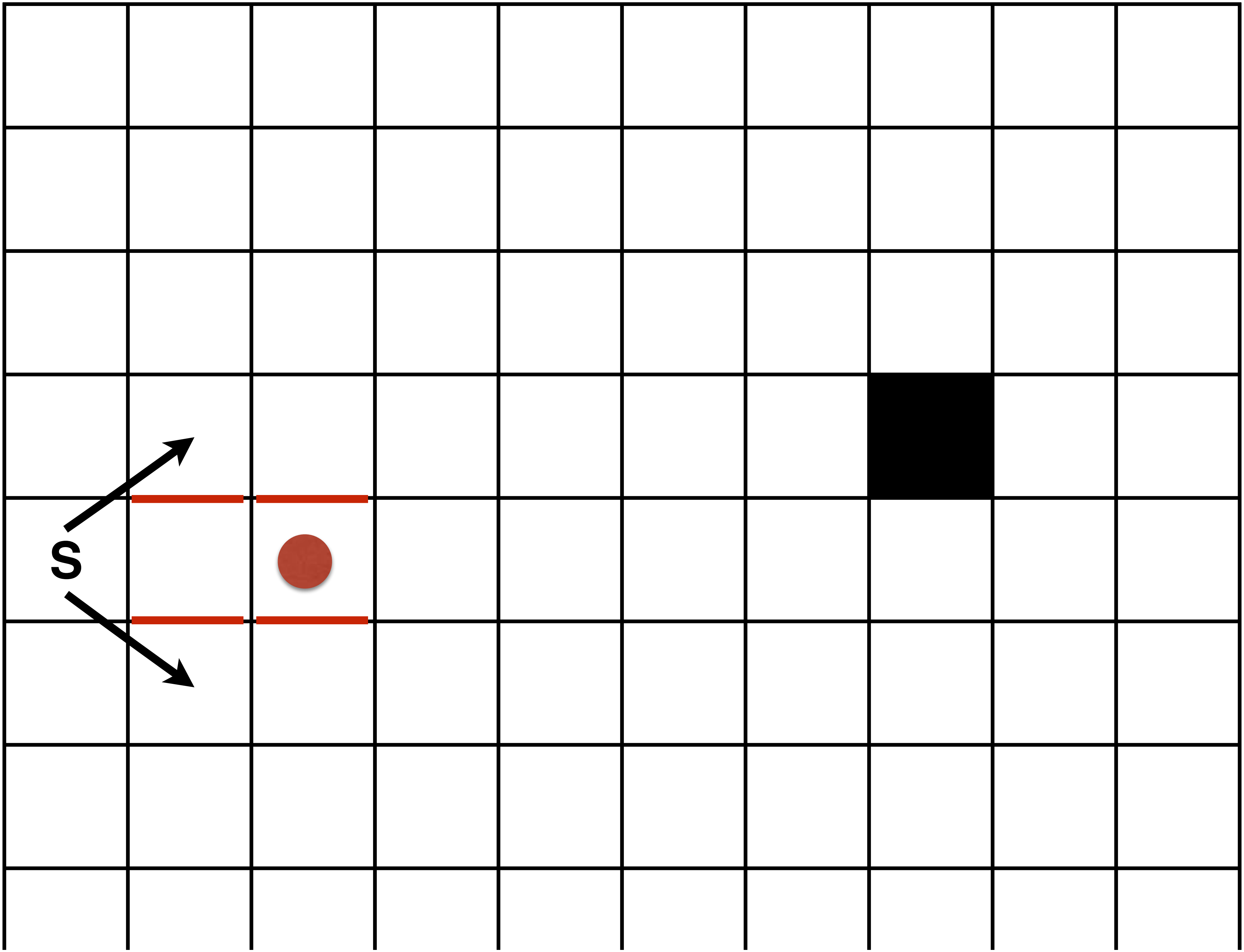
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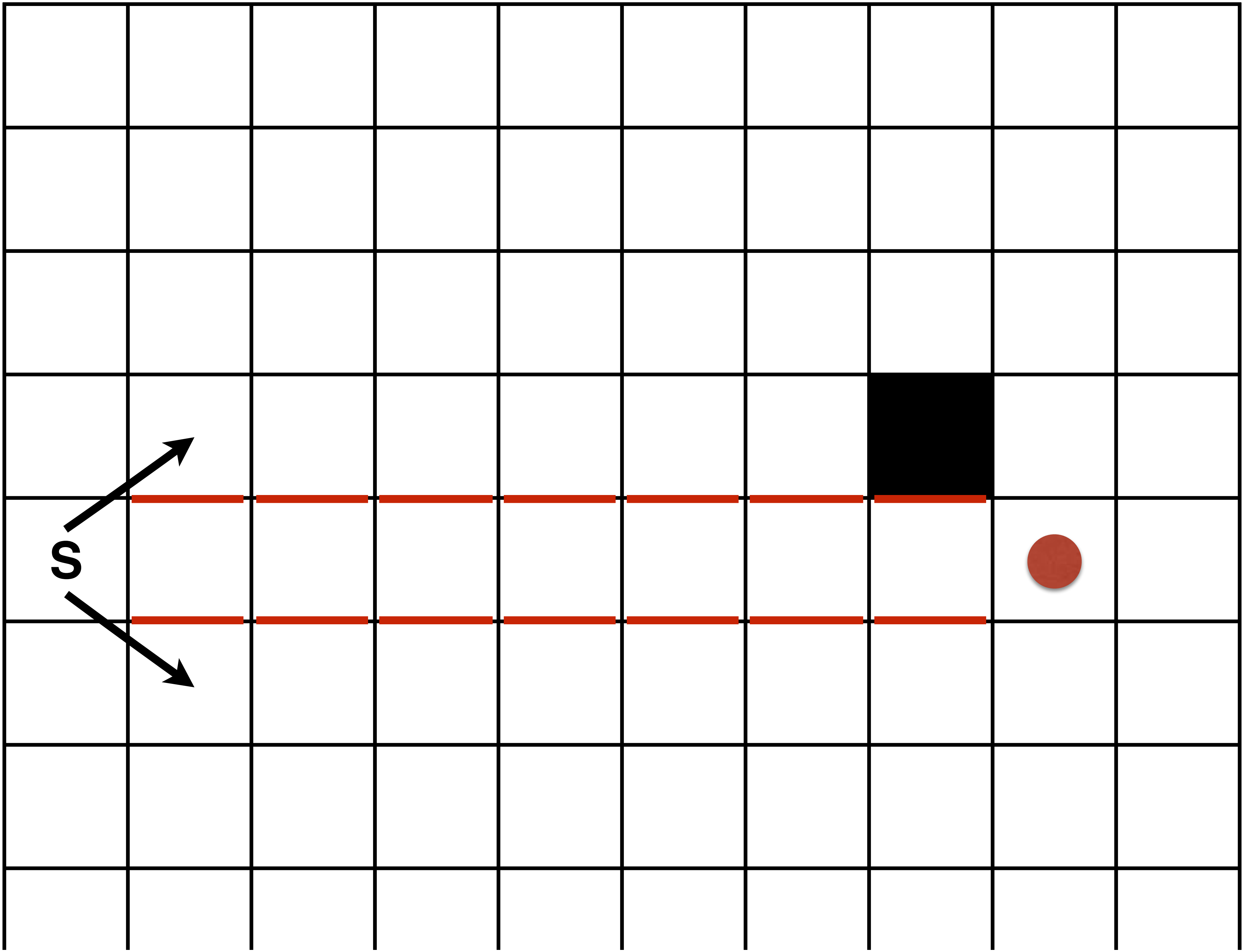
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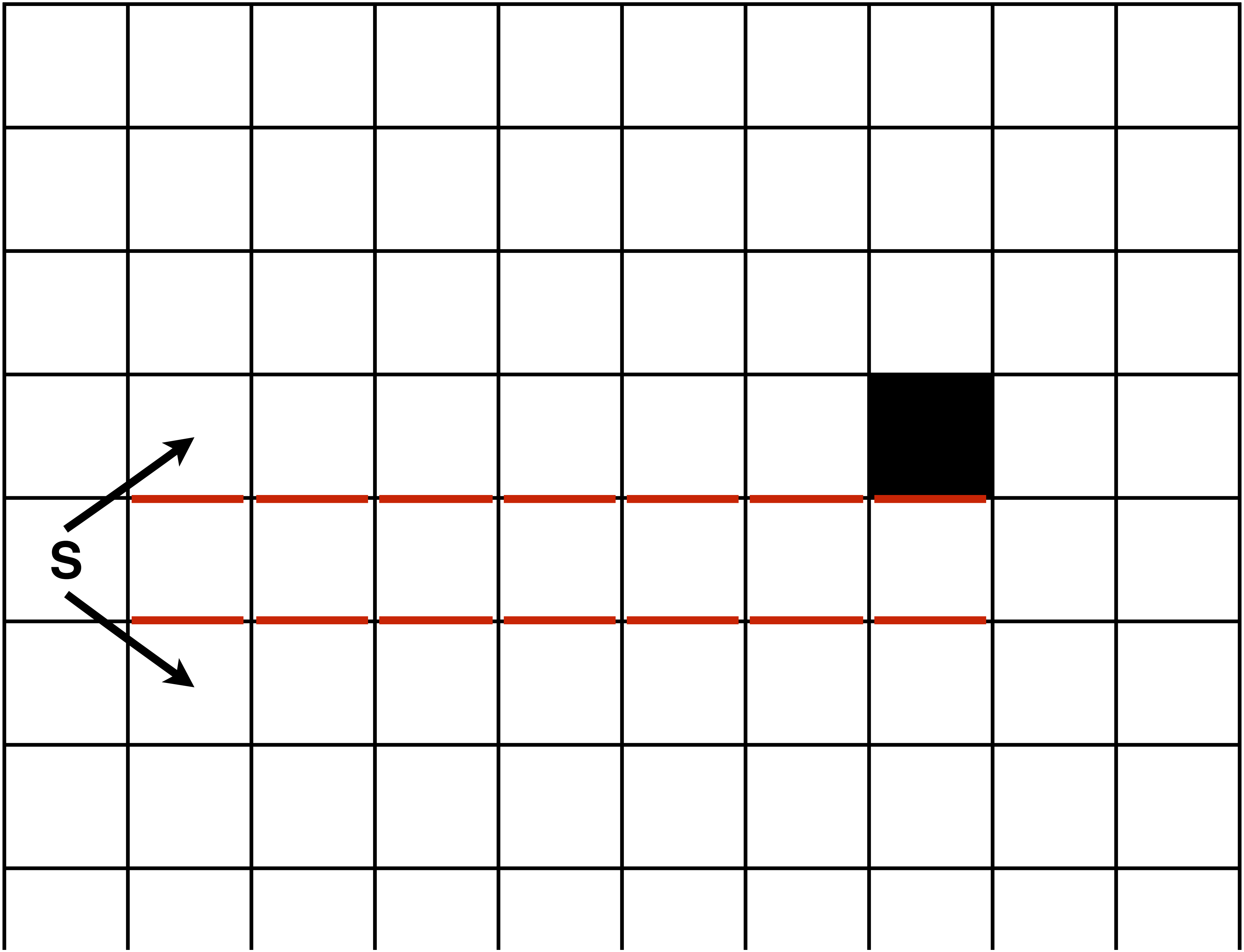
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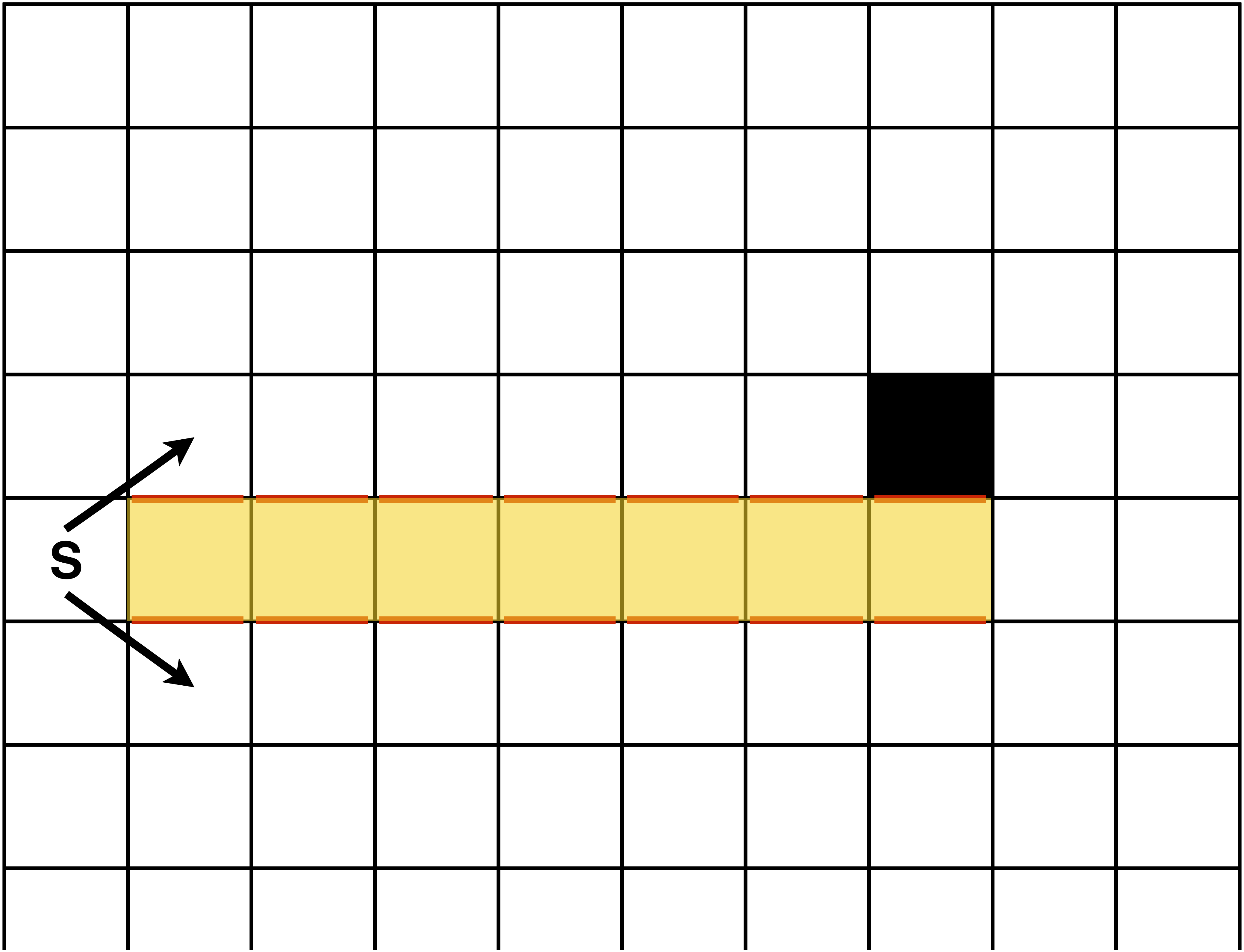
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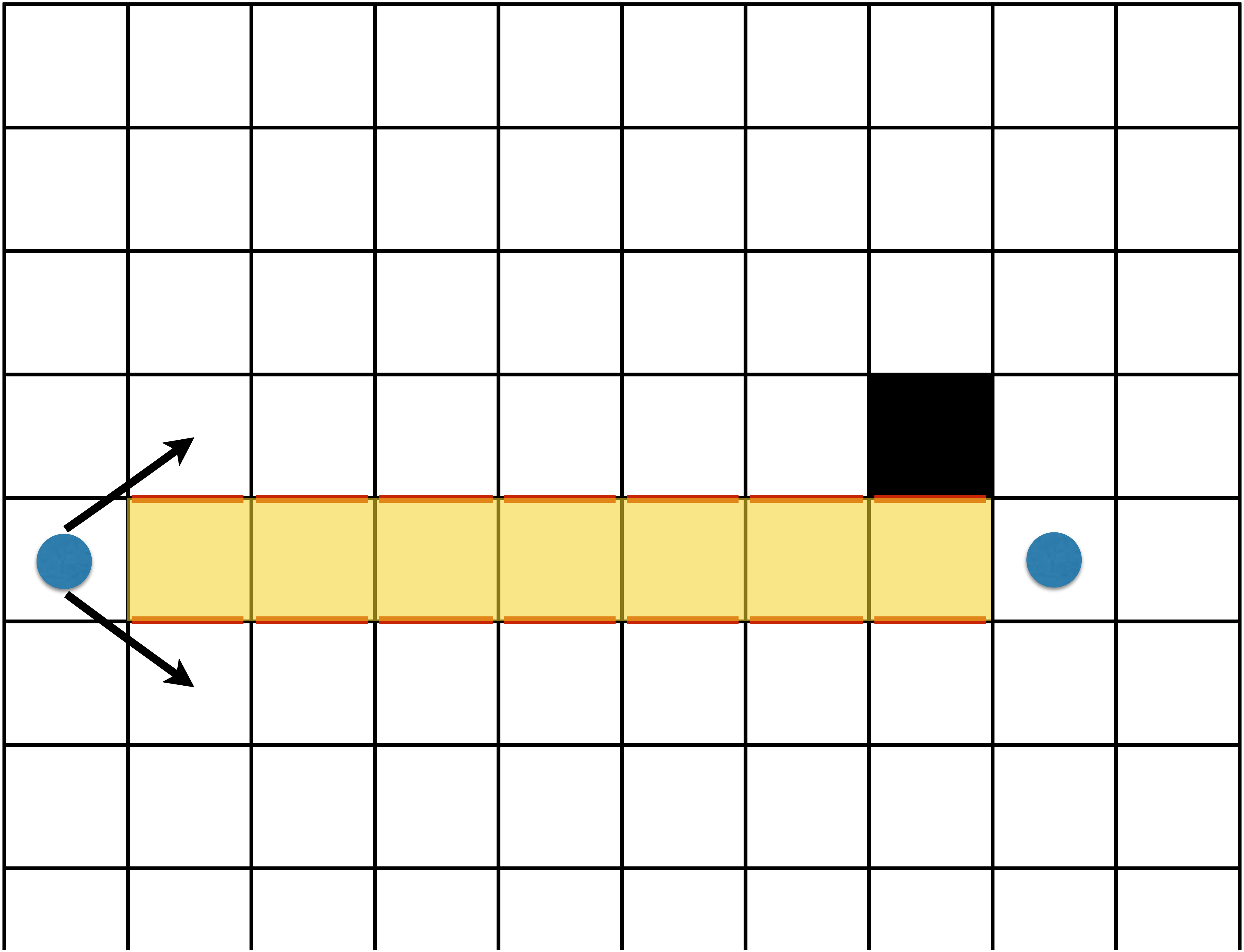

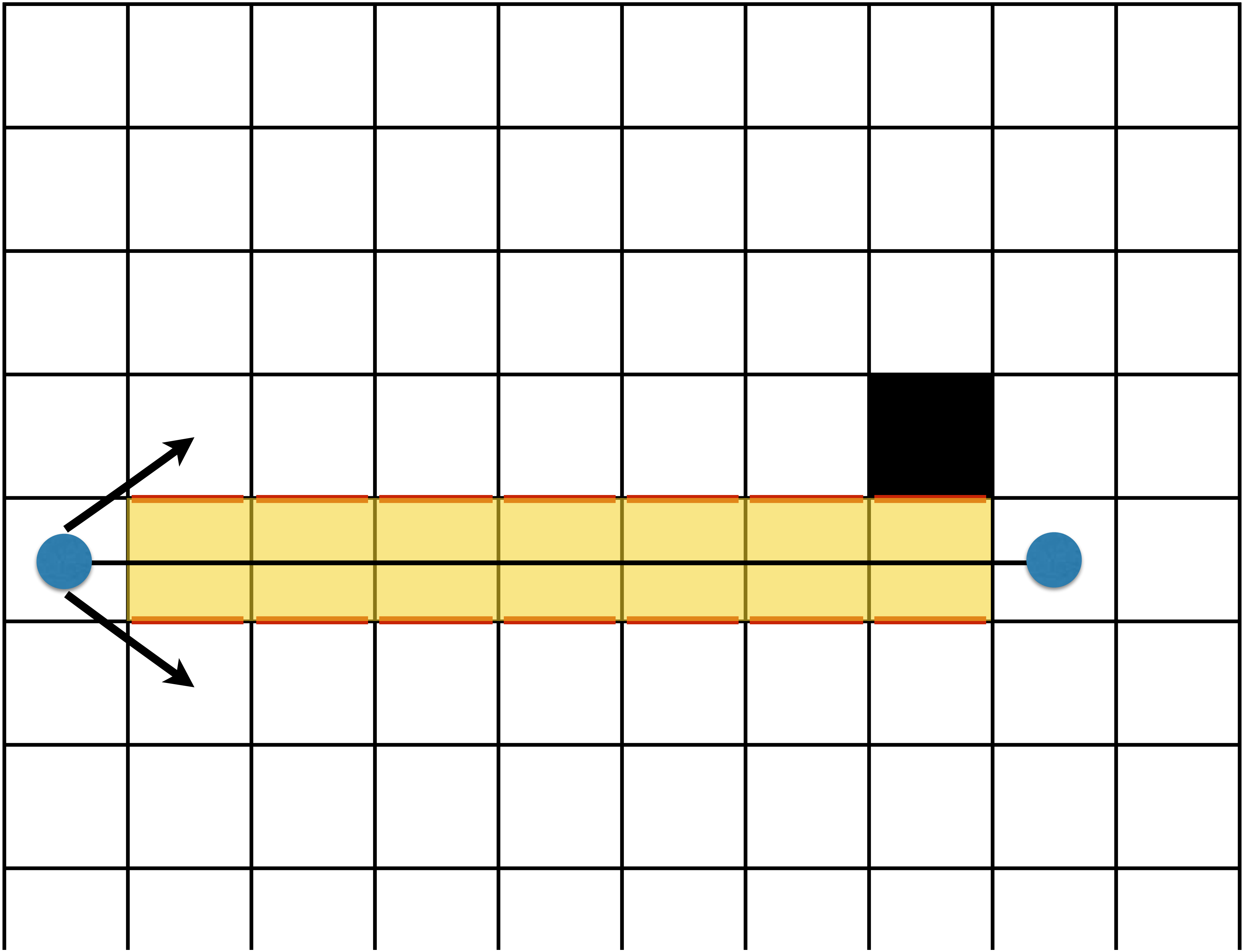

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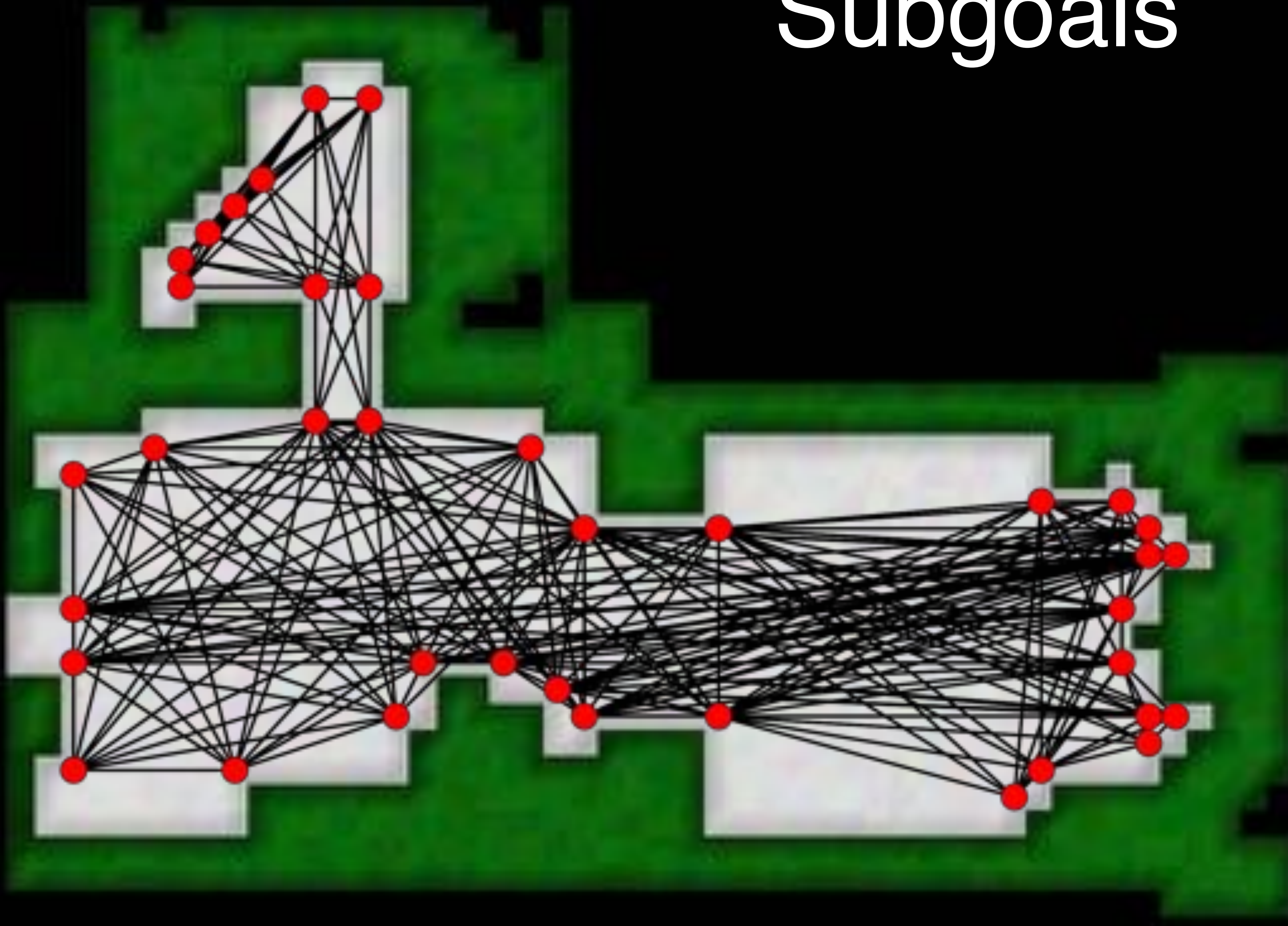
Subgoals

Subgoals



Subgoals

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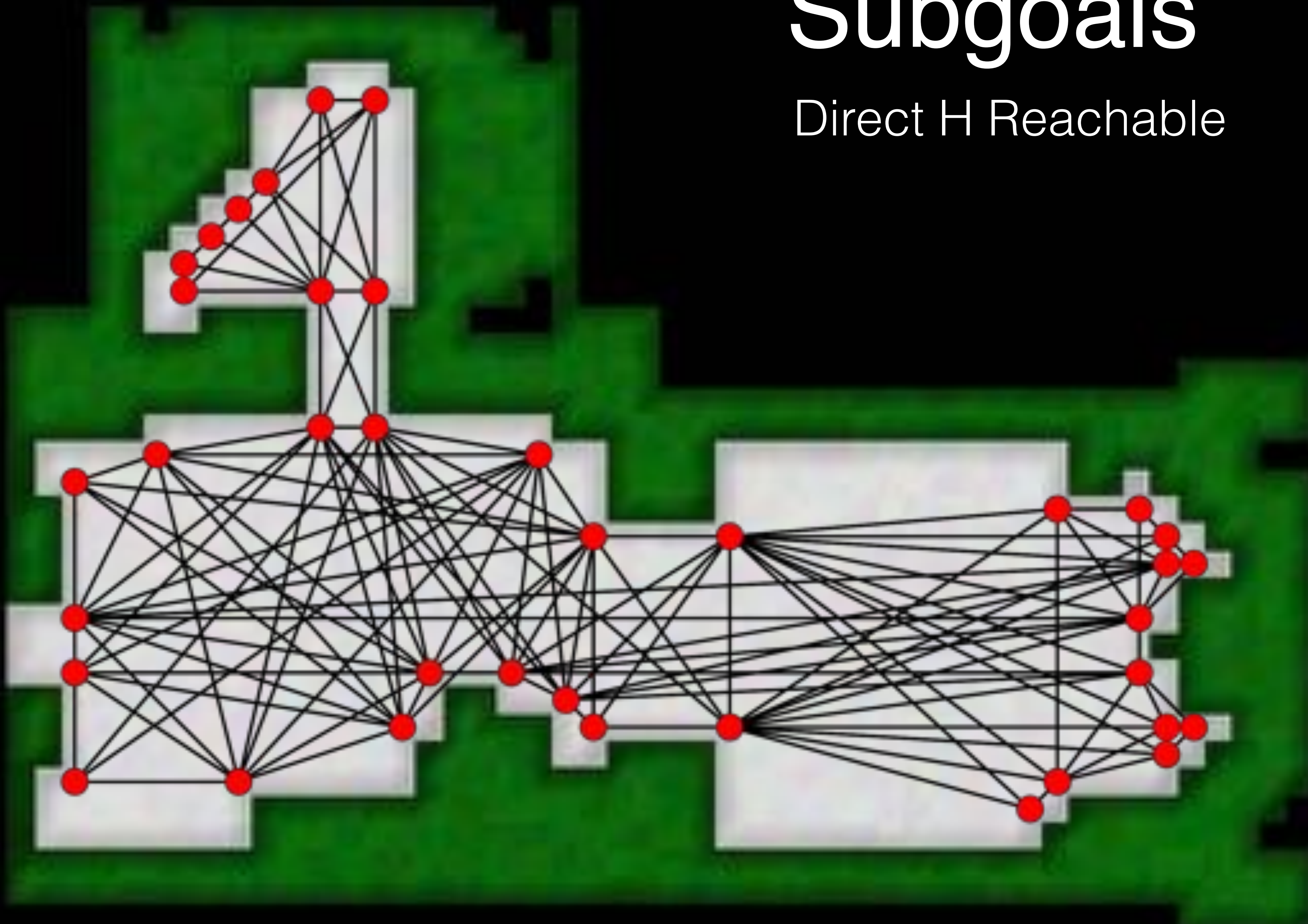

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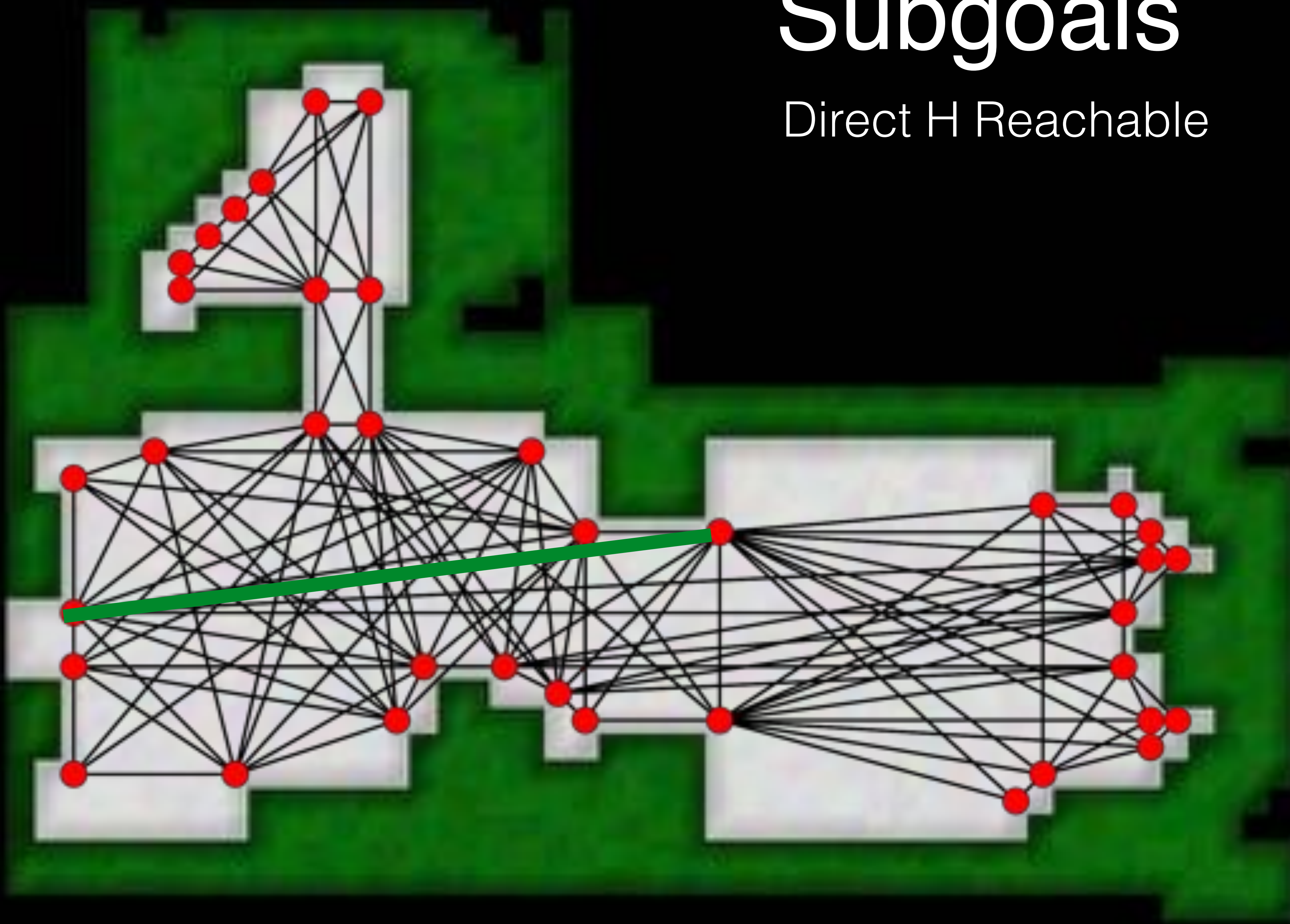

Subgoals

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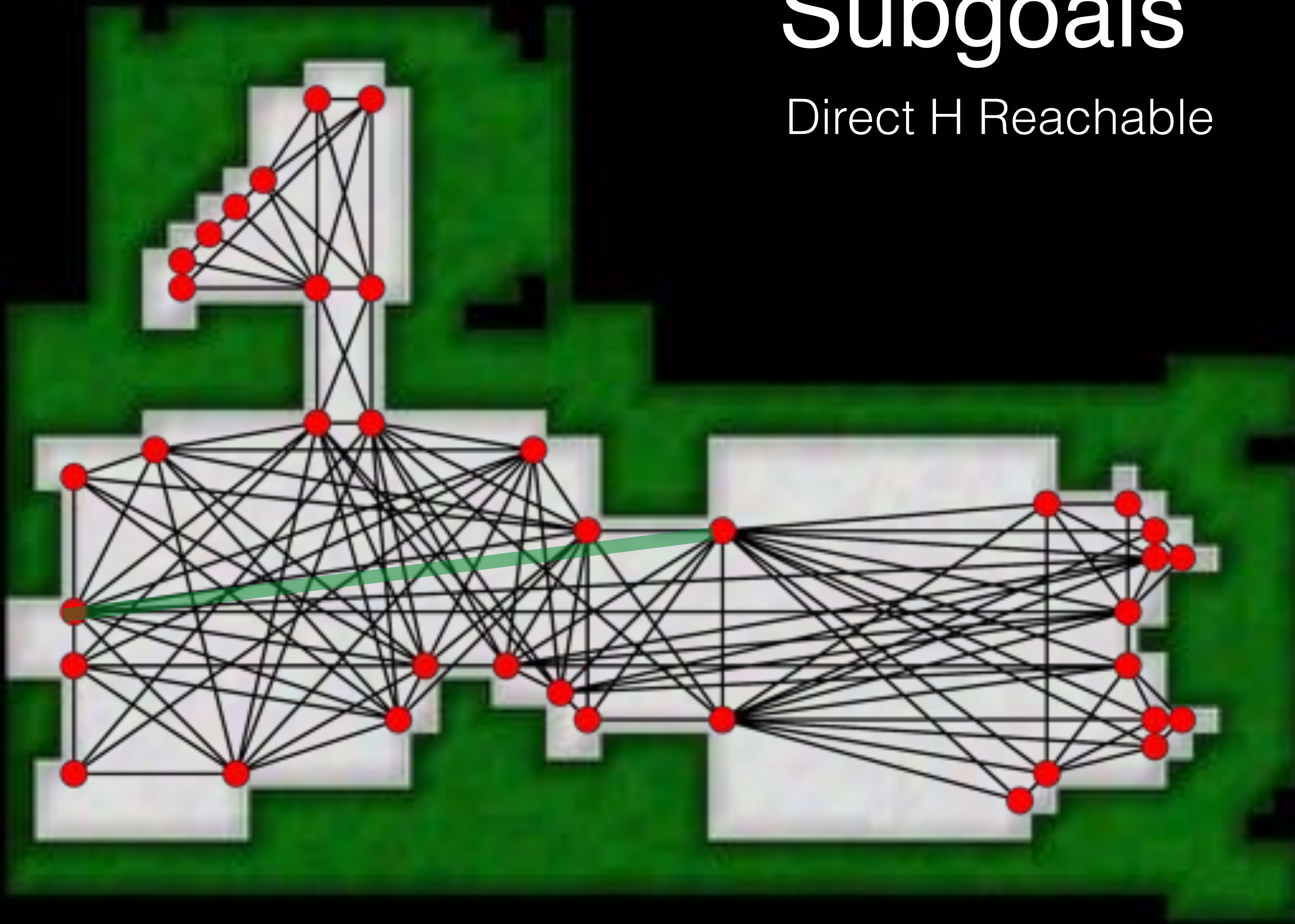

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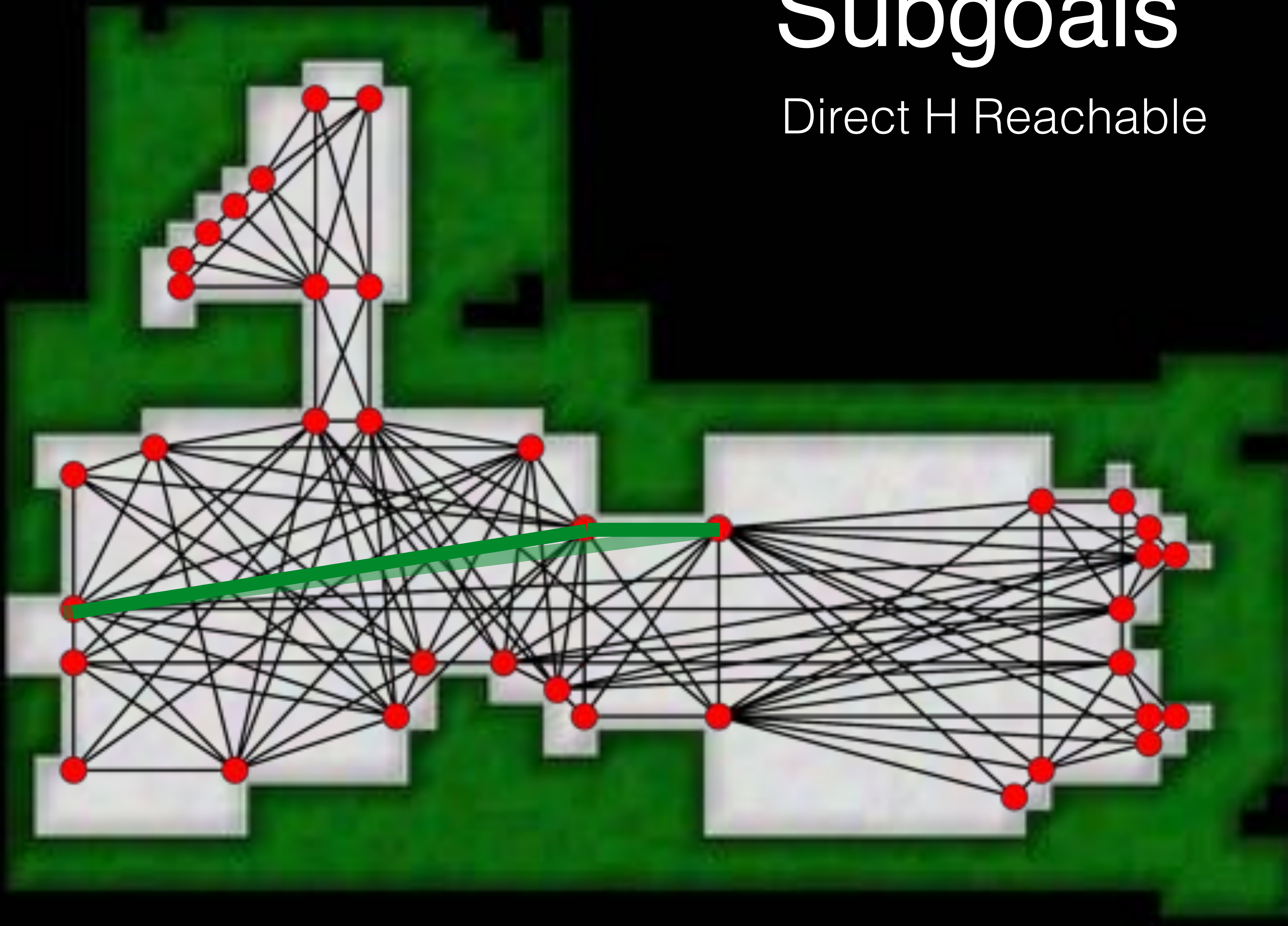
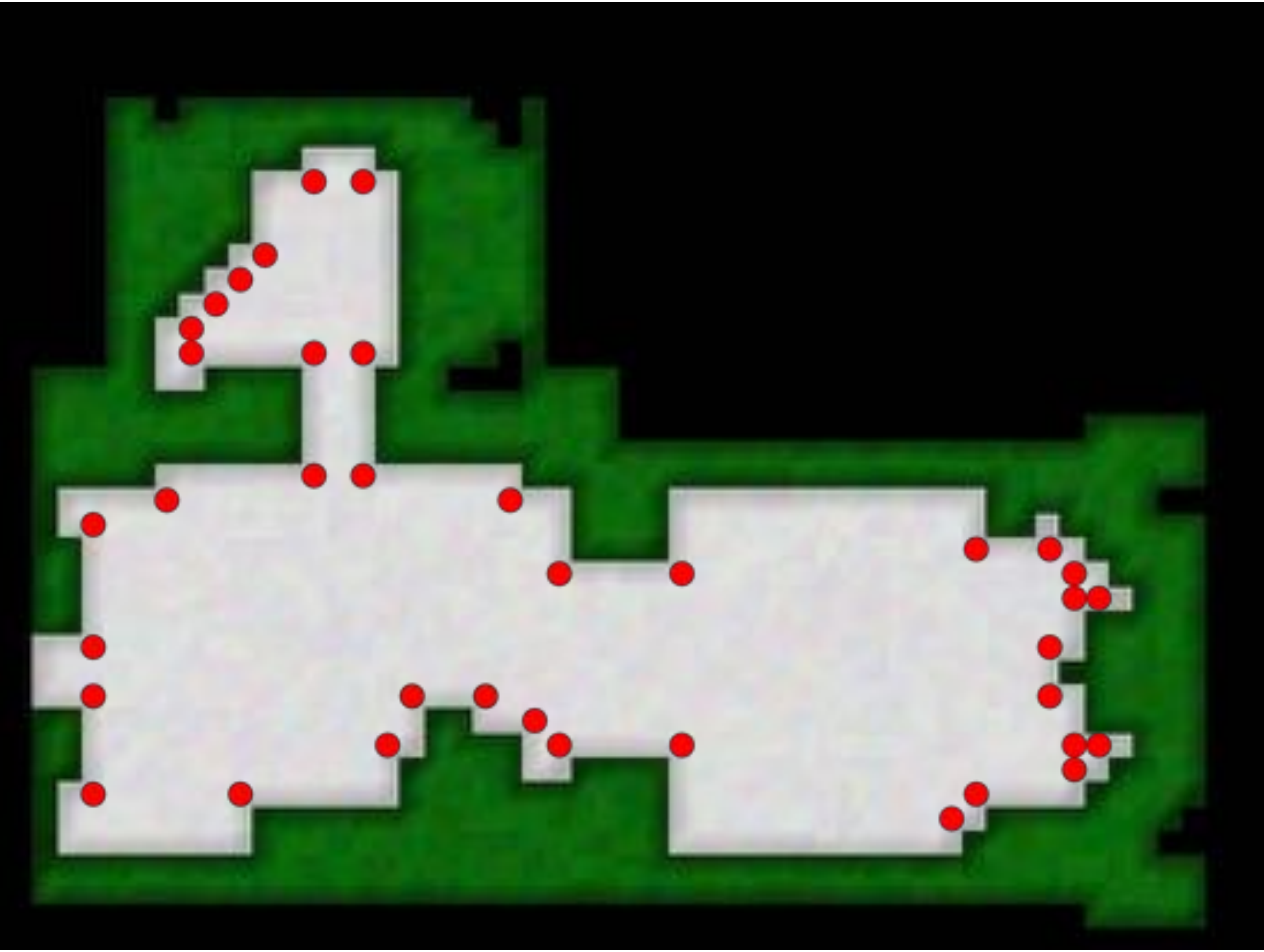
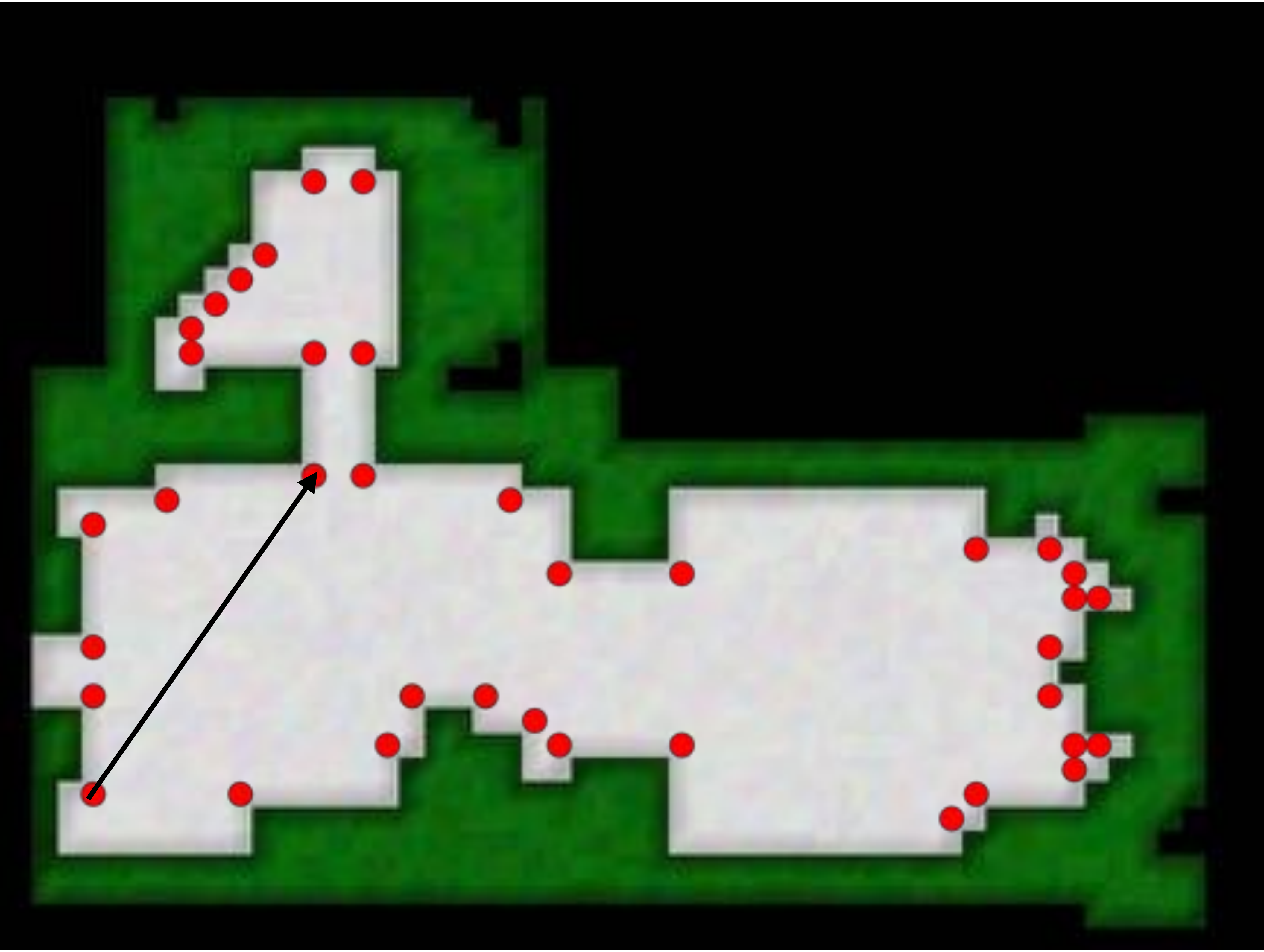
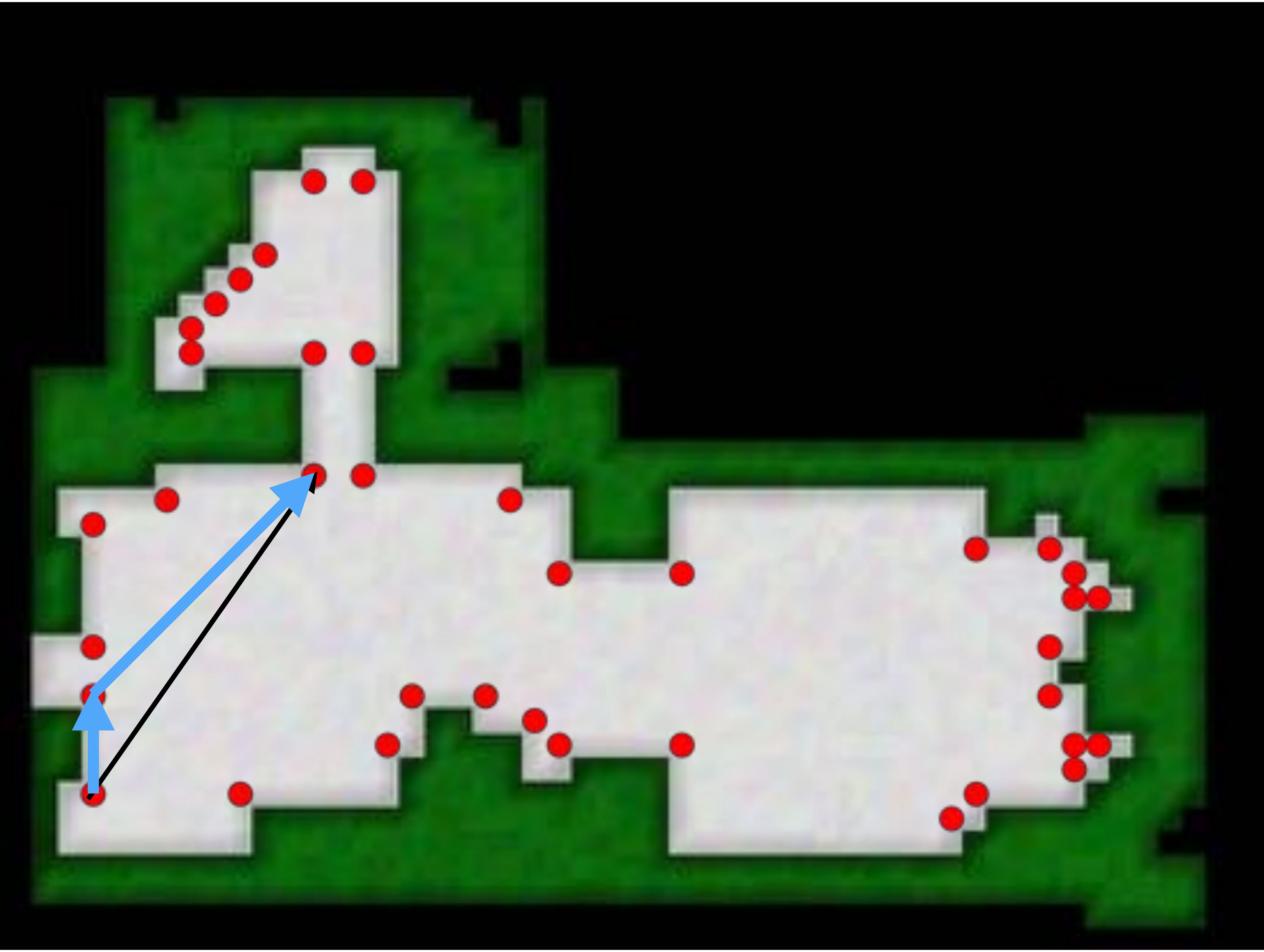
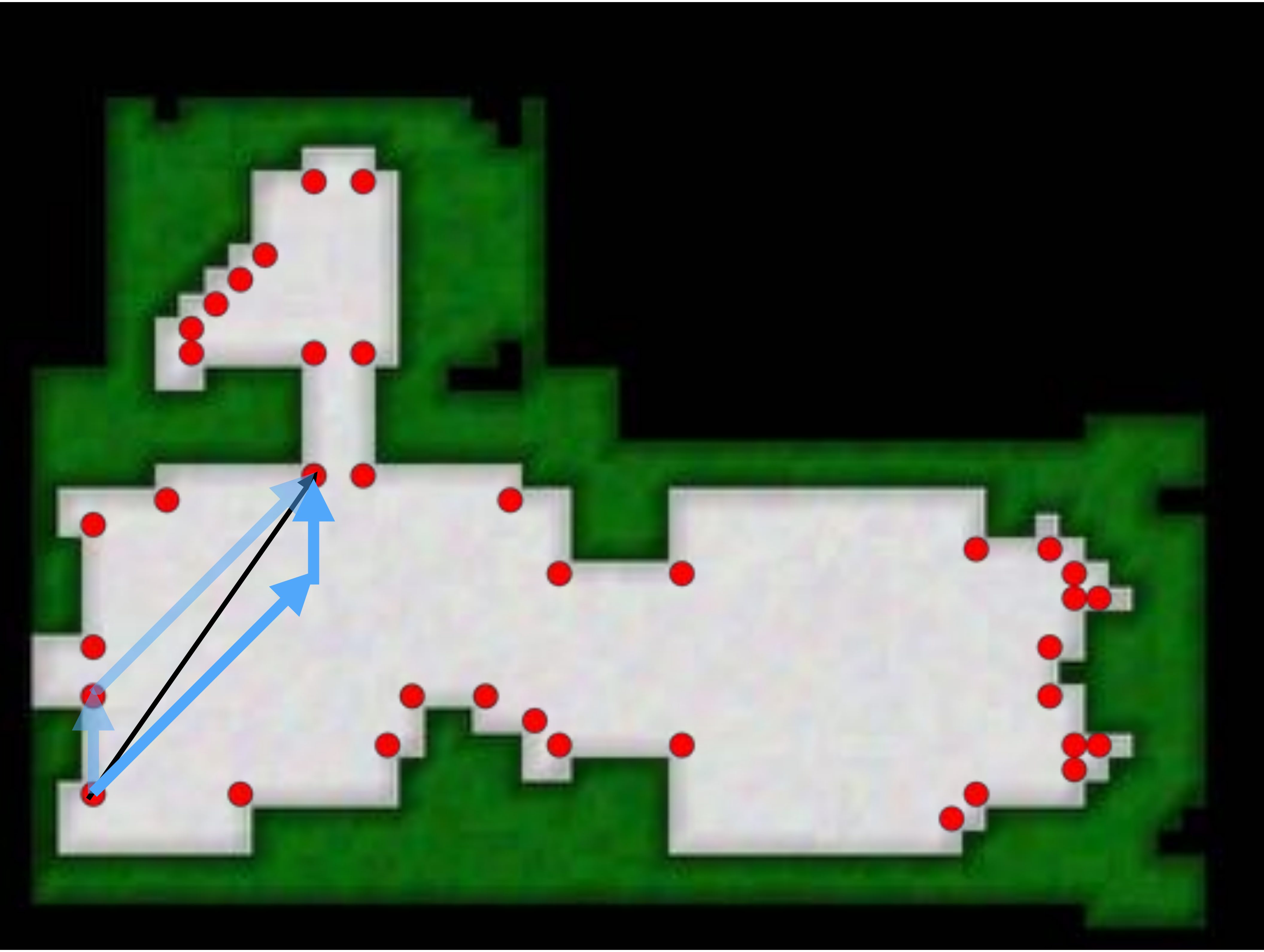
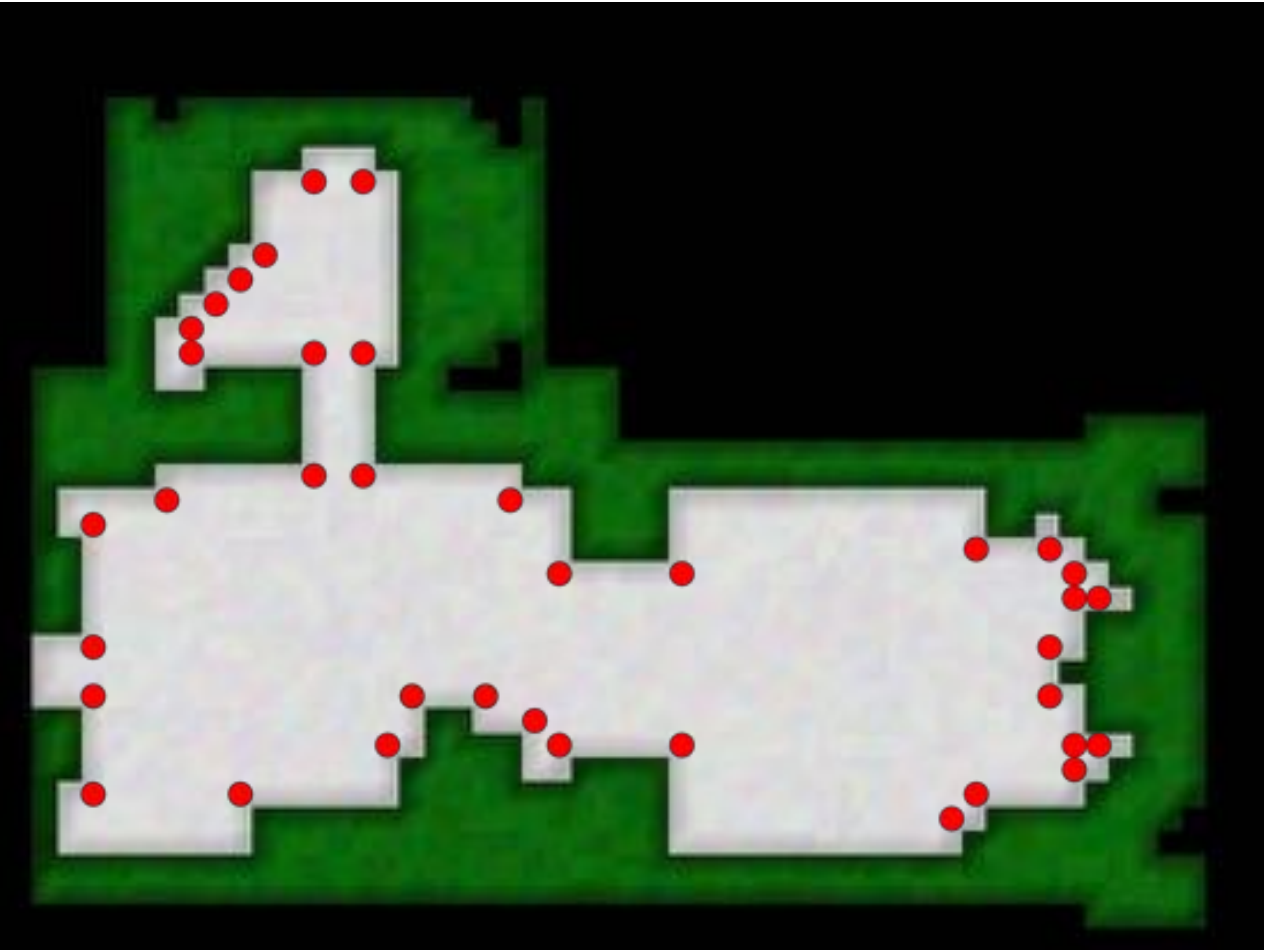












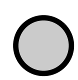
Other contractions

- Dead-end heuristic
  - Yngvi Björnsson and Kári Halldórsson, 2006
- Swamps
  - Nir Pochter, Aviv Zohar, Jeffrey S. Rosenschein, Ariel Felner [2008 - 2010]
- Dead/redundant states
  - N.R. Sturtevant, V. Bulitko and Y. Bjornsson, 2010

- What is the correct way to contract a map?

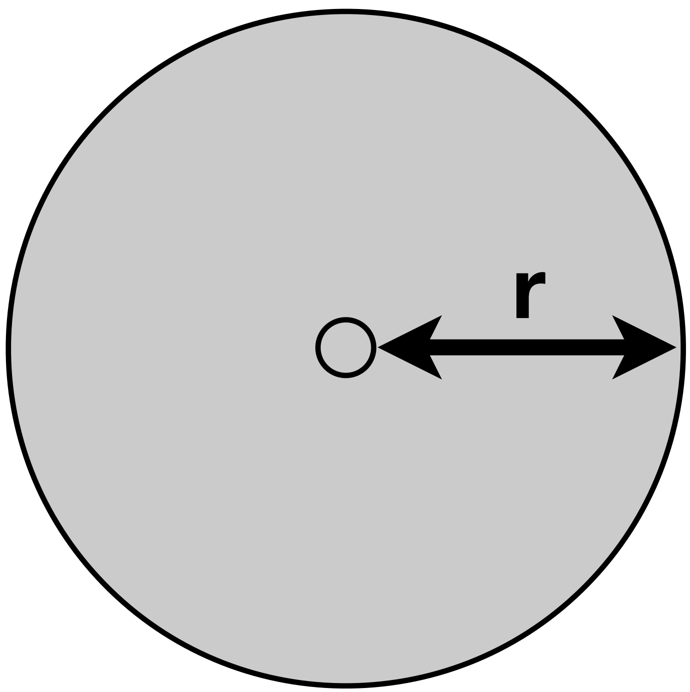
Highway Dimension

Highway Dimension, Shortest Paths, and Provably Efficient Algorithms [Abraham et. al., 2010]



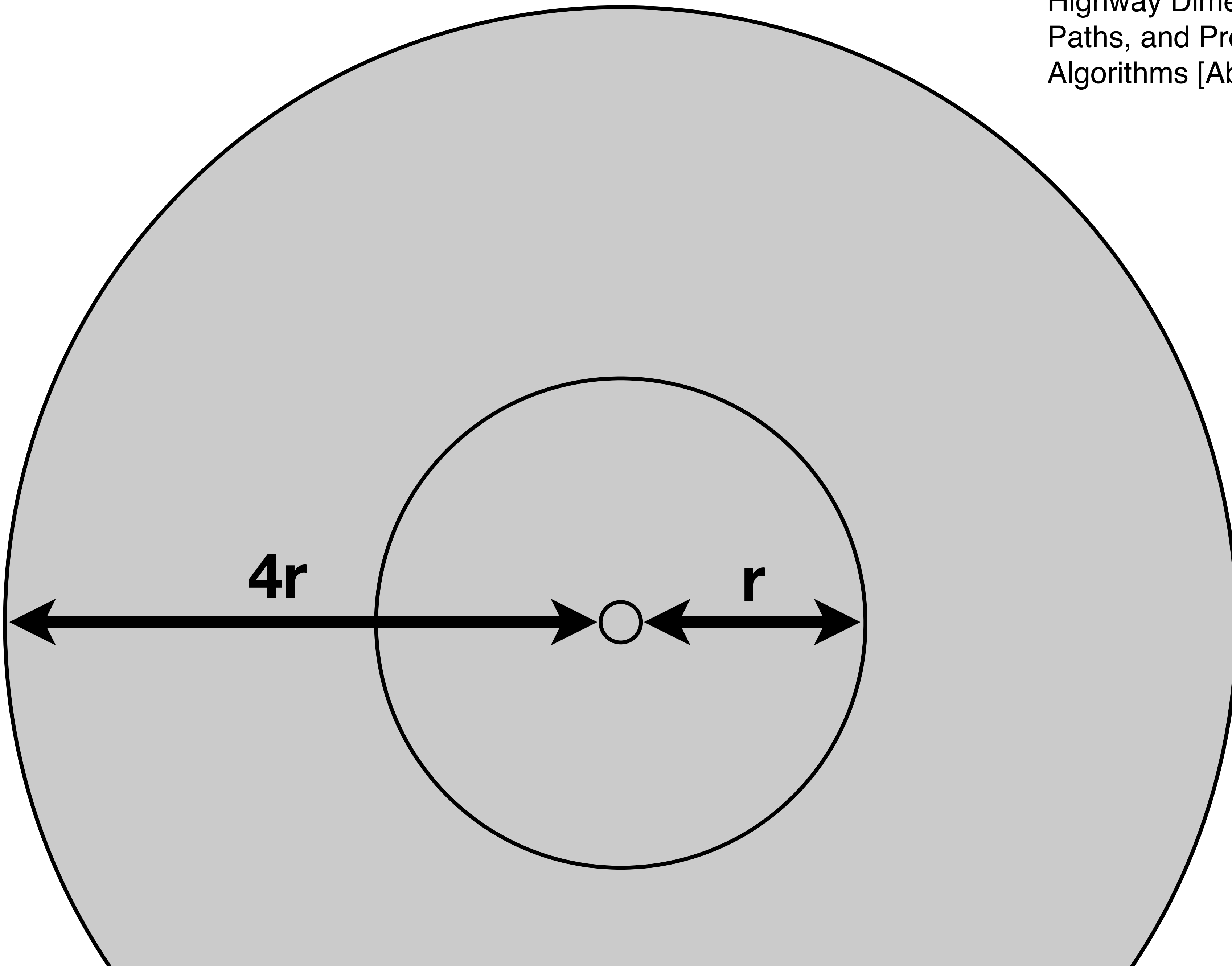
Highway Dimension

Highway Dimension, Shortest Paths, and Provably Efficient Algorithms [Abraham et. al., 2010]



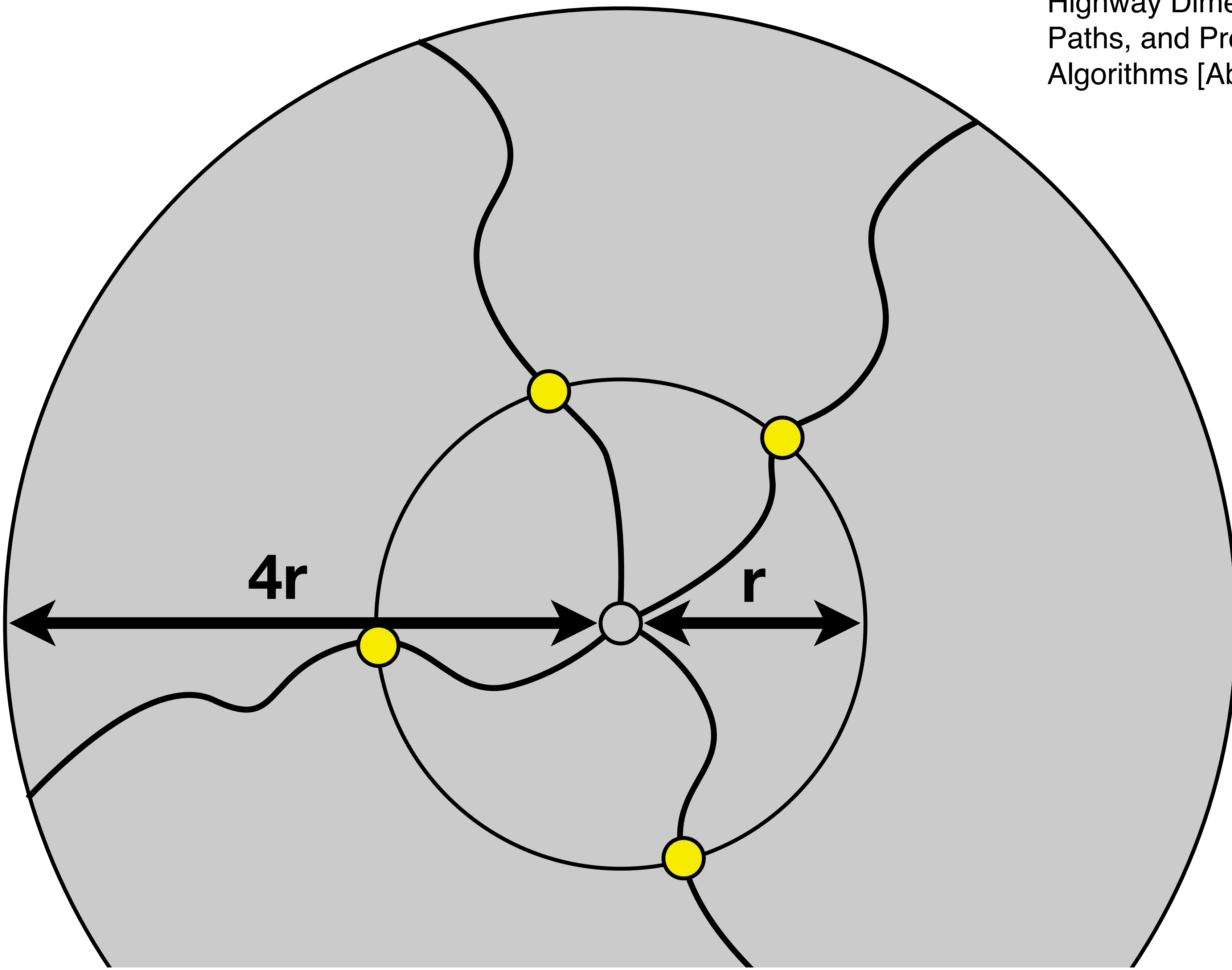
Highway Dimension

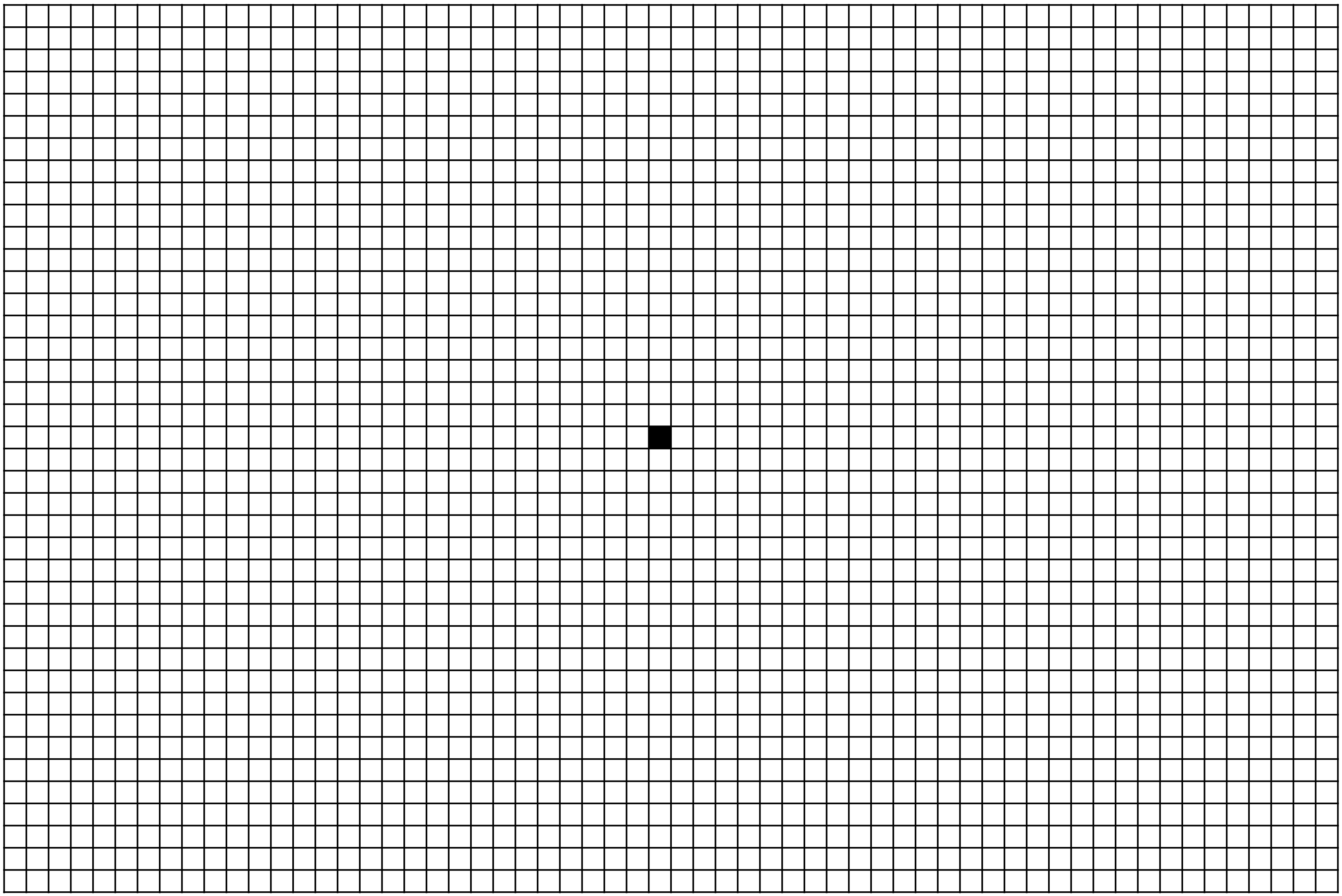
Highway Dimension, Shortest Paths, and Provably Efficient Algorithms [Abraham et. al., 2010]

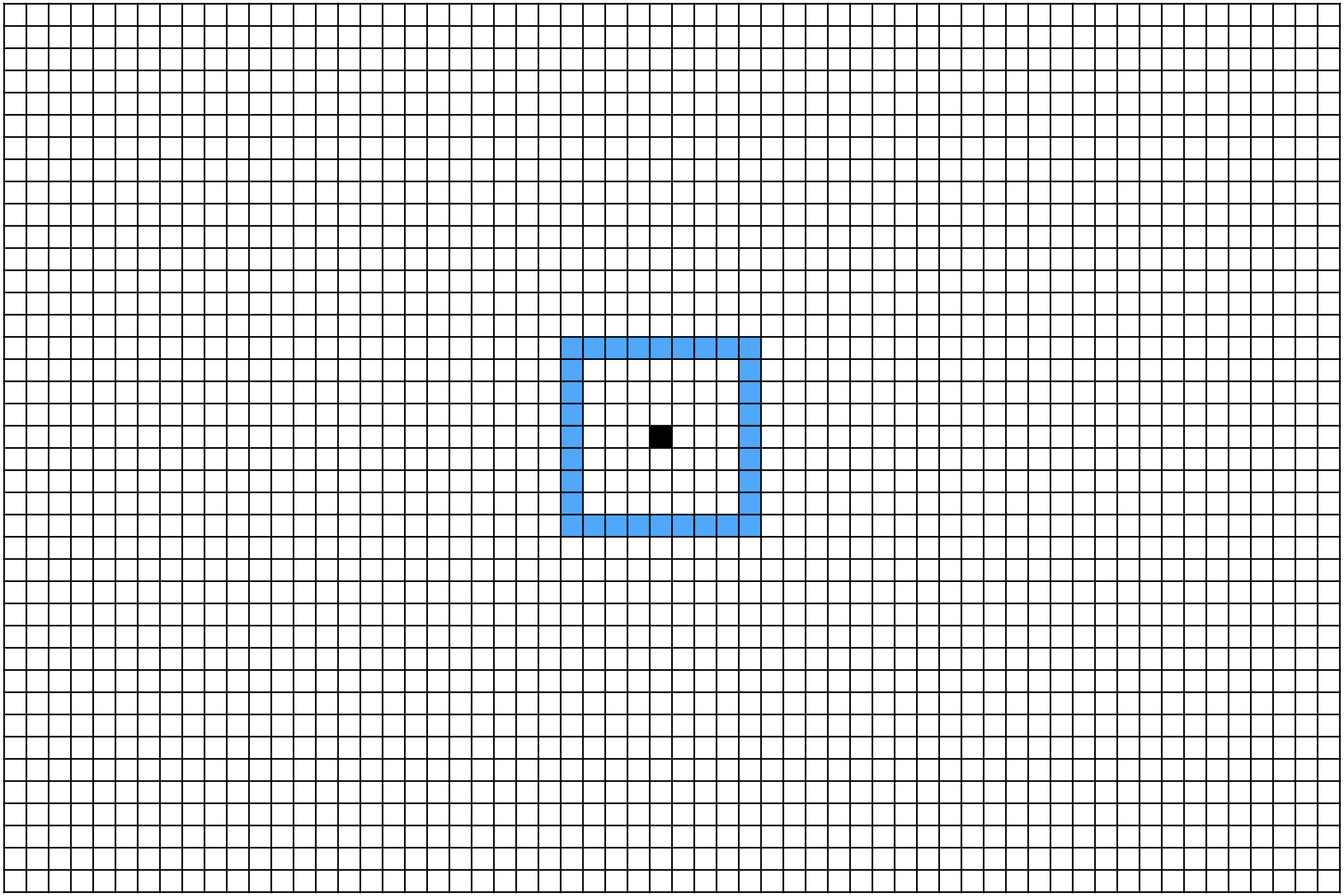


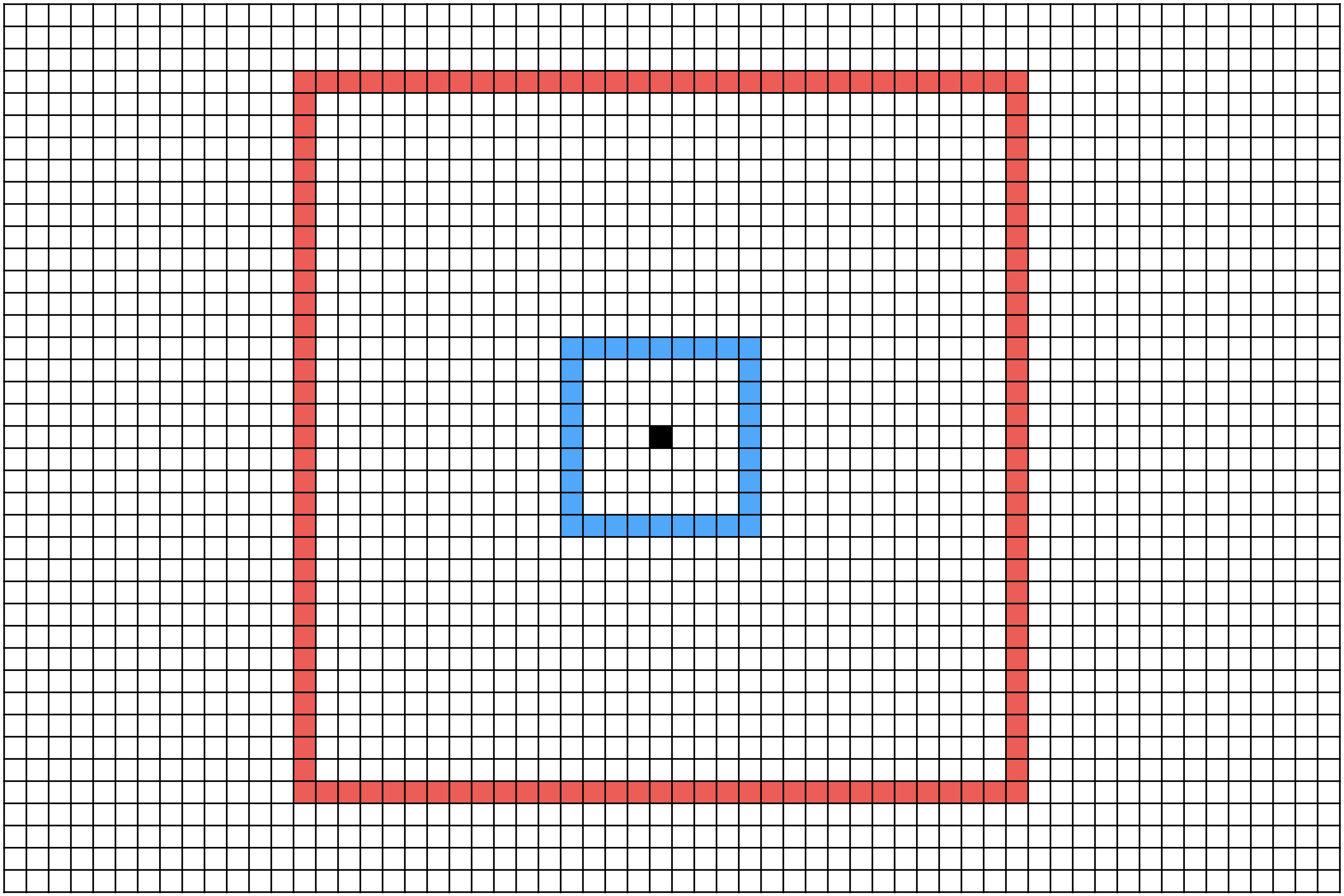
Highway Dimension

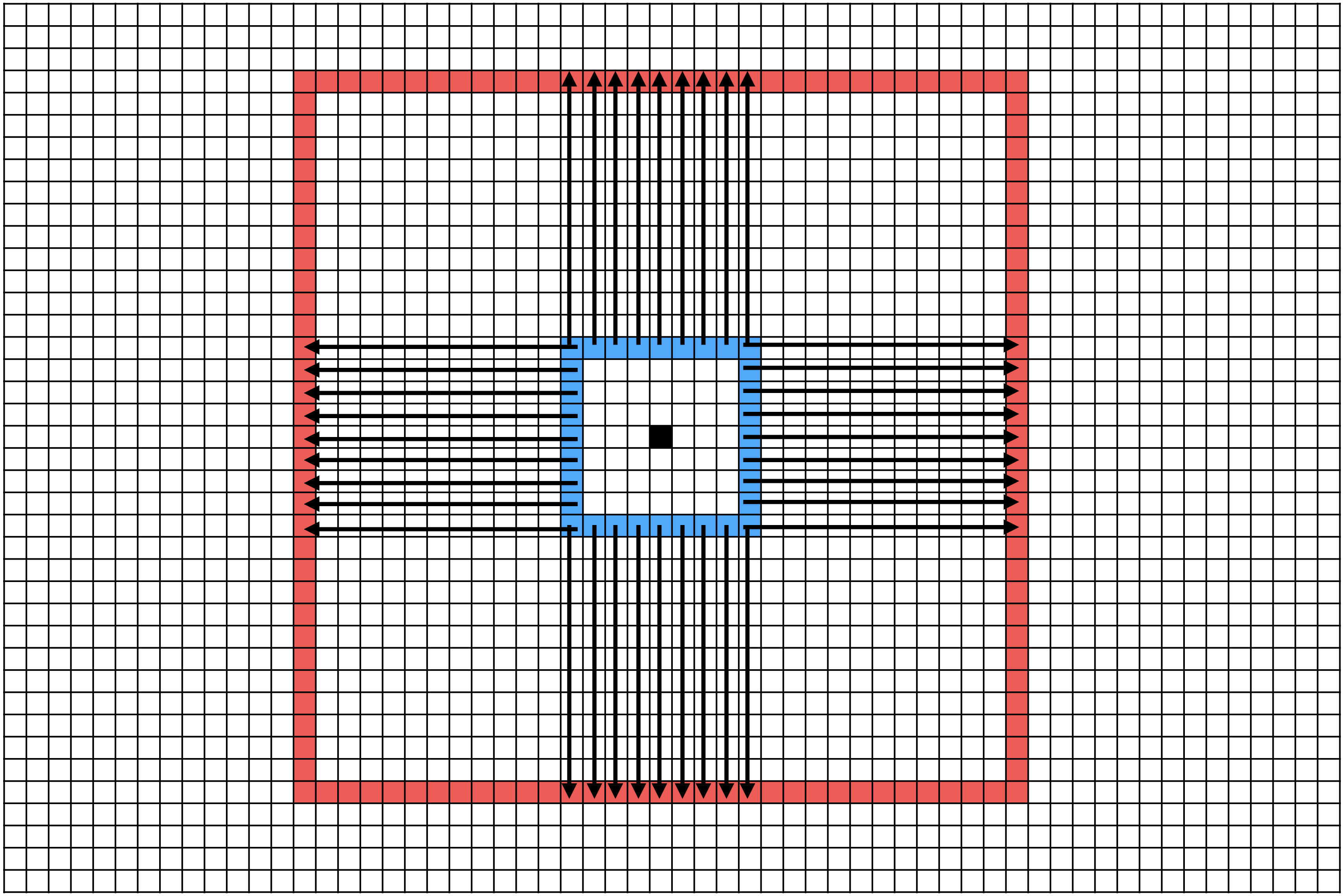
Highway Dimension, Shortest Paths, and Provably Efficient Algorithms [Abraham et. al., 2010]

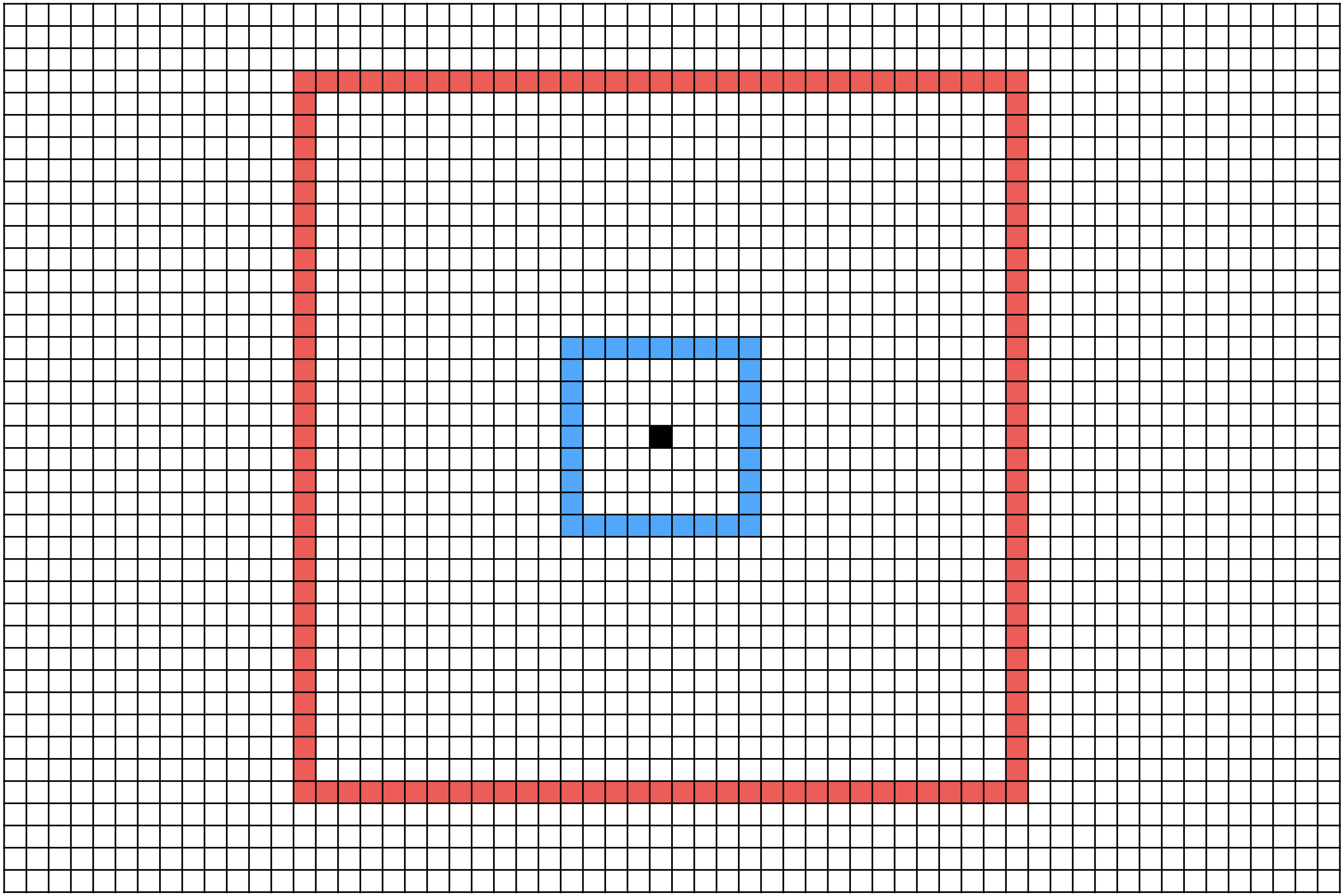


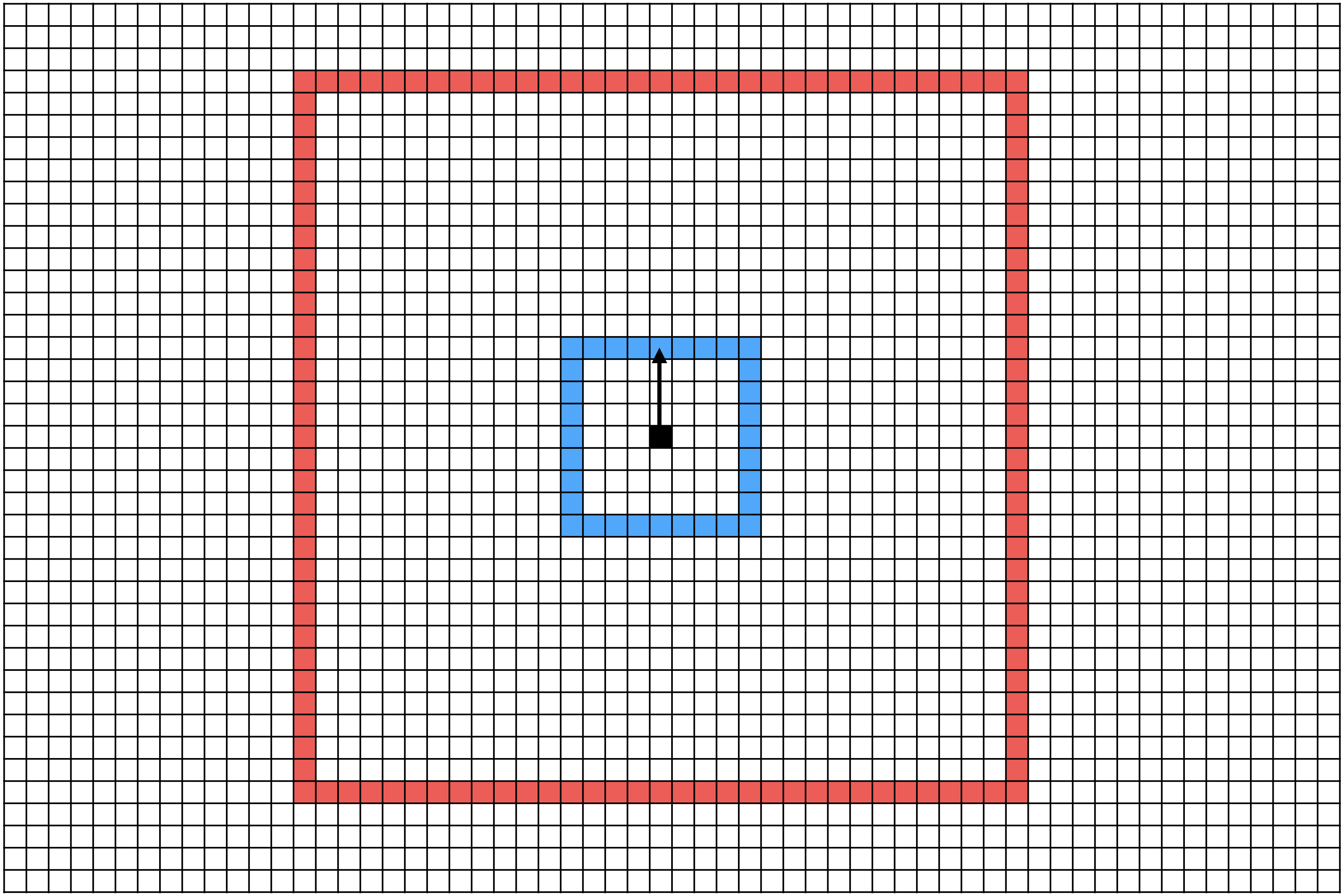


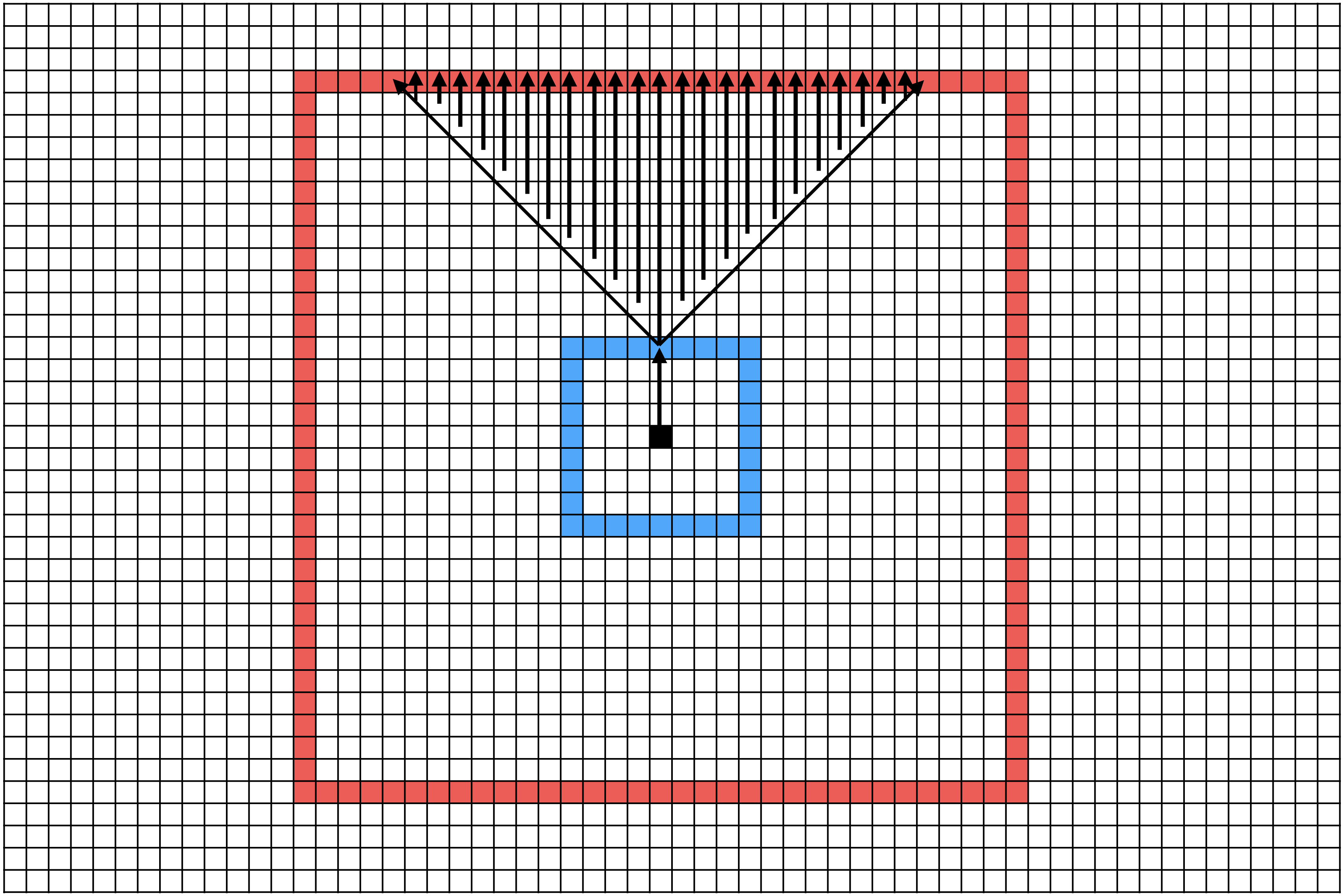


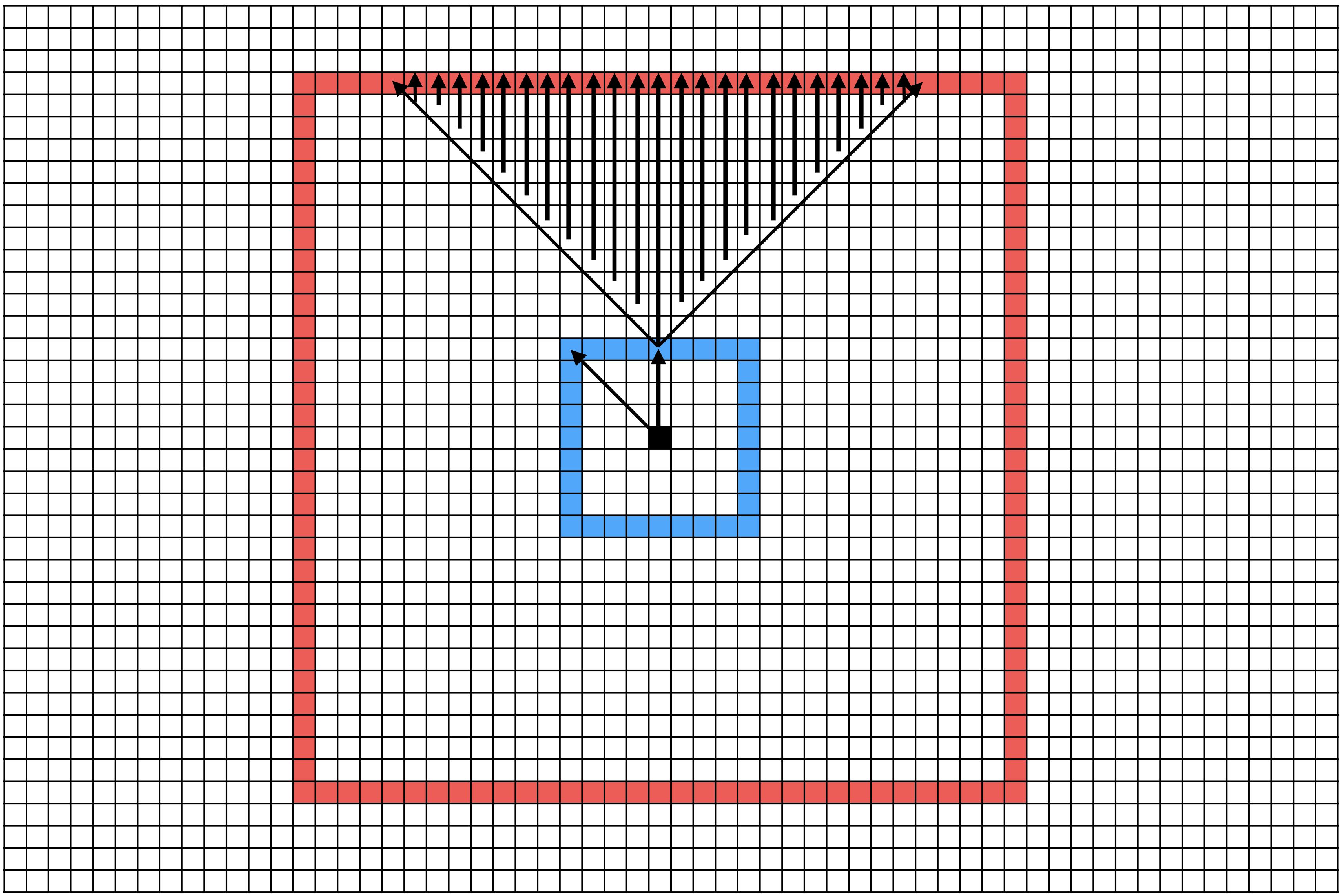


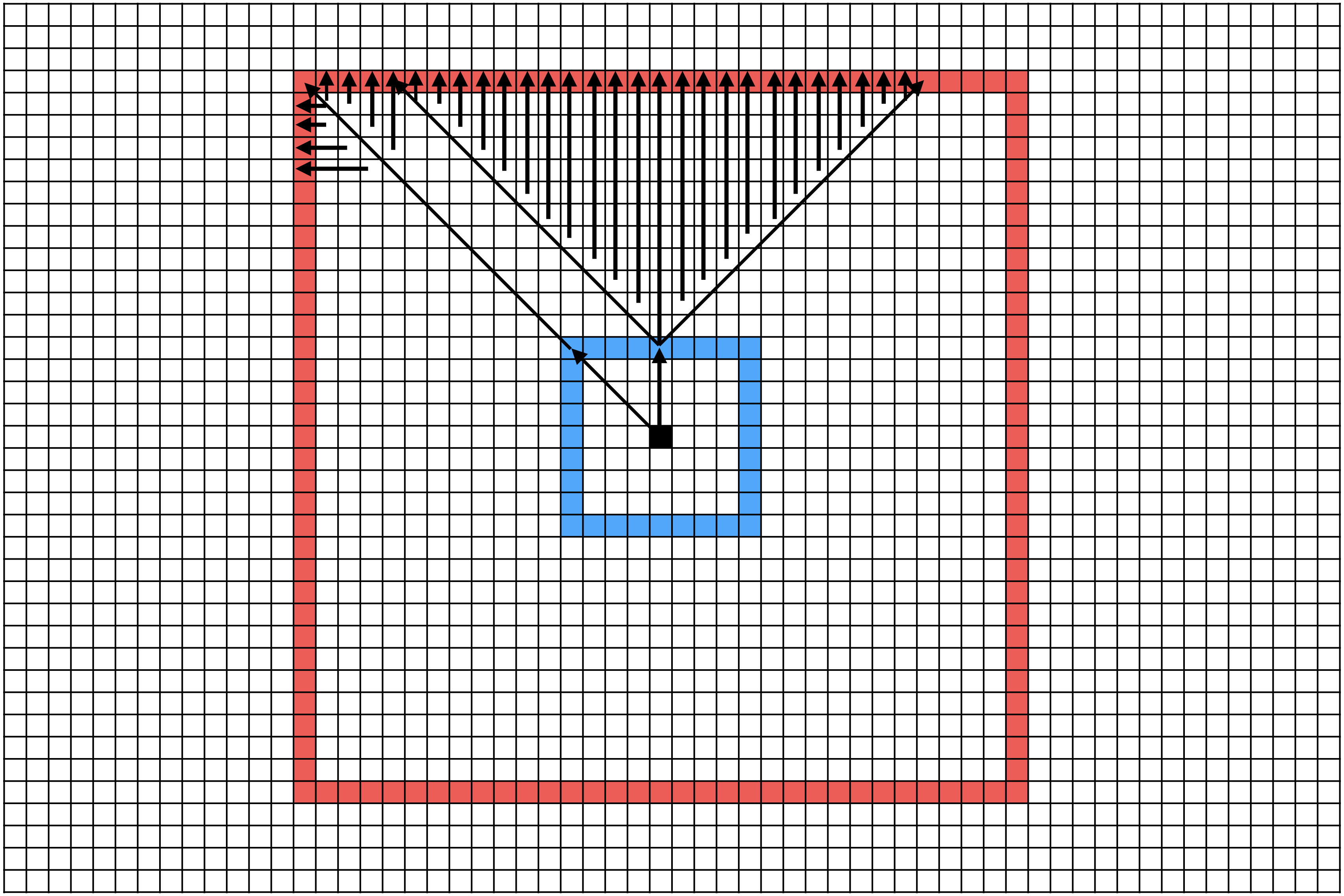


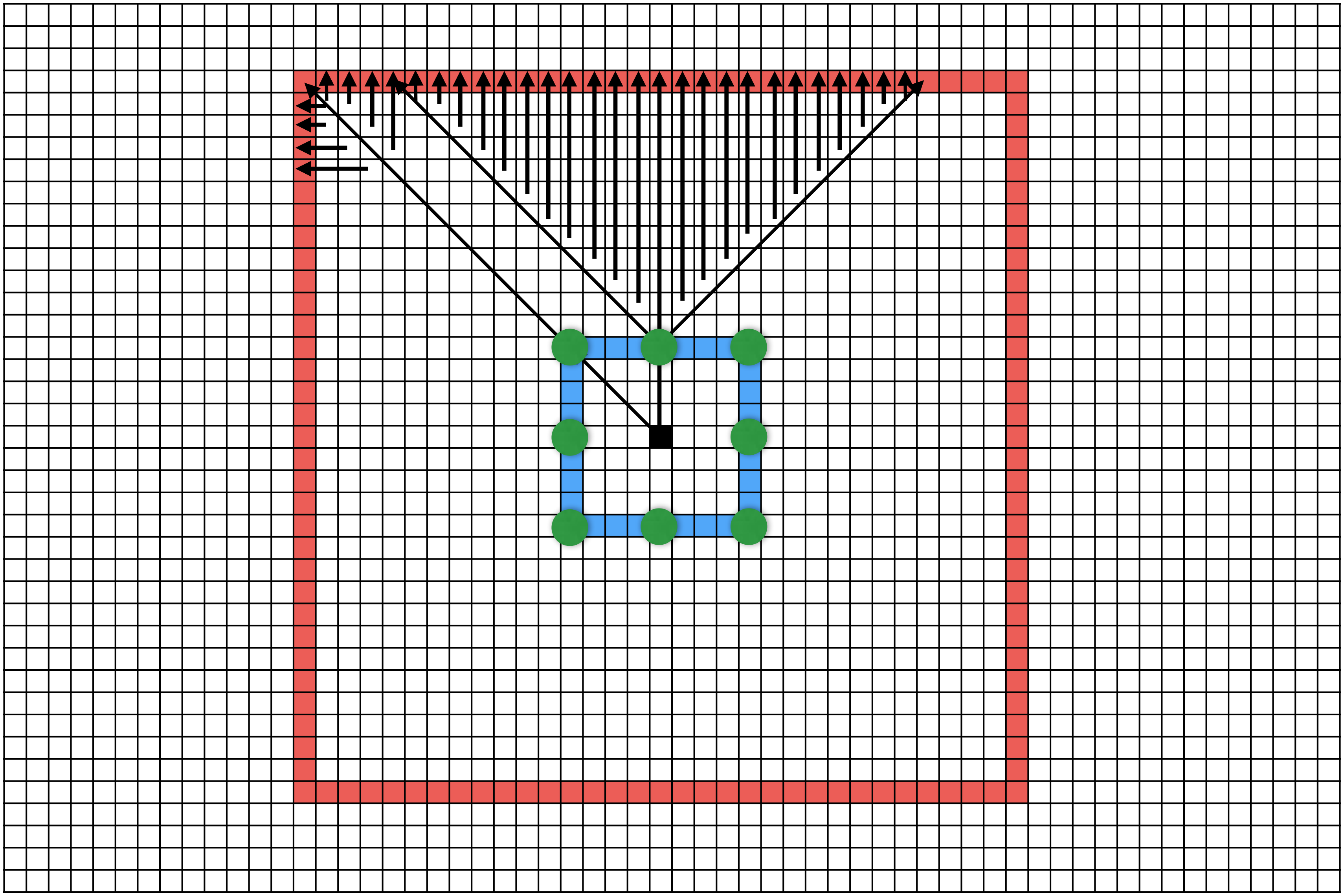












Cross-Fertilization

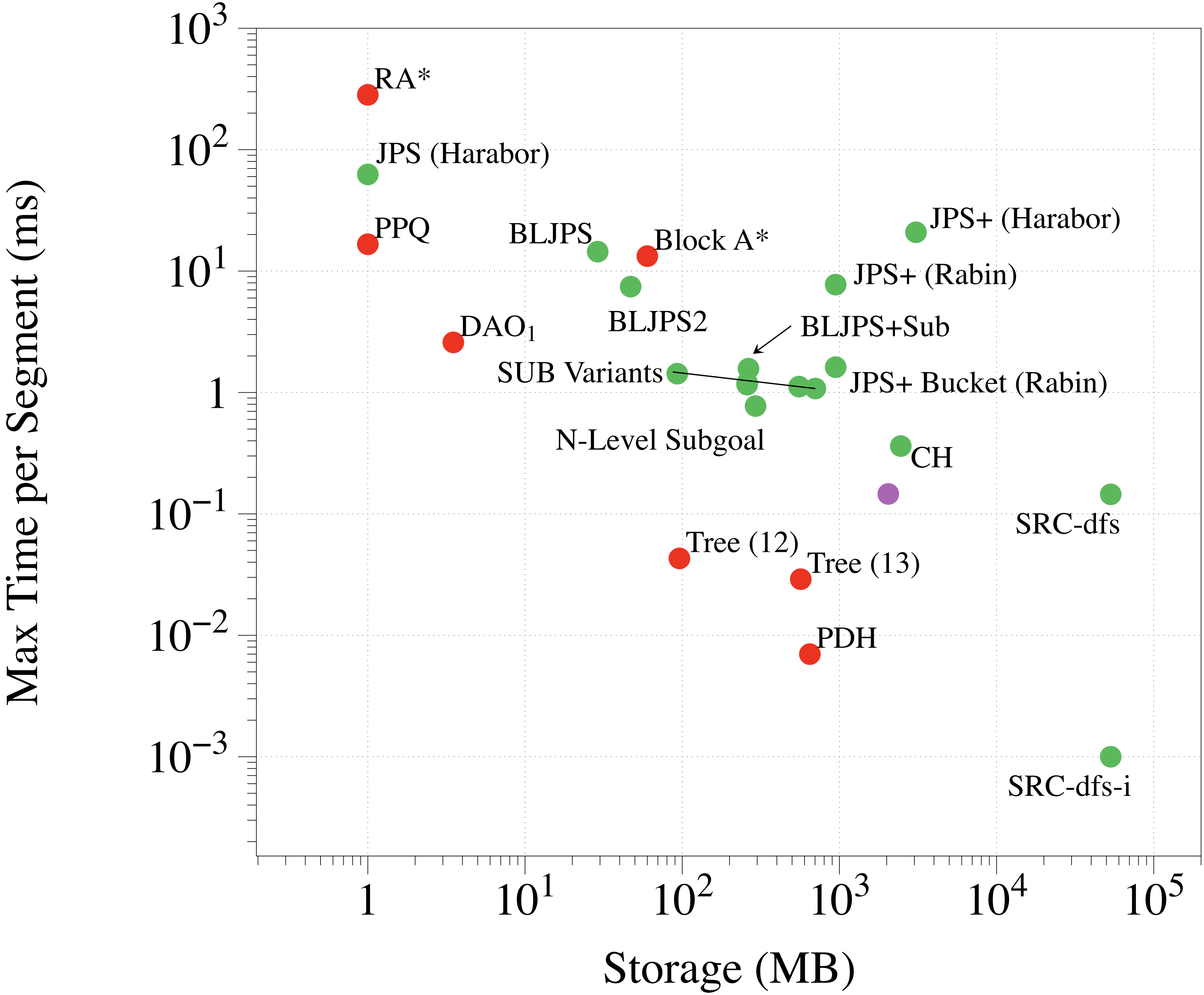
- Many road network ideas being used in grids
- Didn't originally know how to apply them properly
  - Contraction Hierarchies on Grid Graphs
    - Storandt, 2013
  - TRANSIT Routing on Video Game Maps
    - Antsfeld, Harabor, Kilby & Walsh, 2012

Further use of contractions?

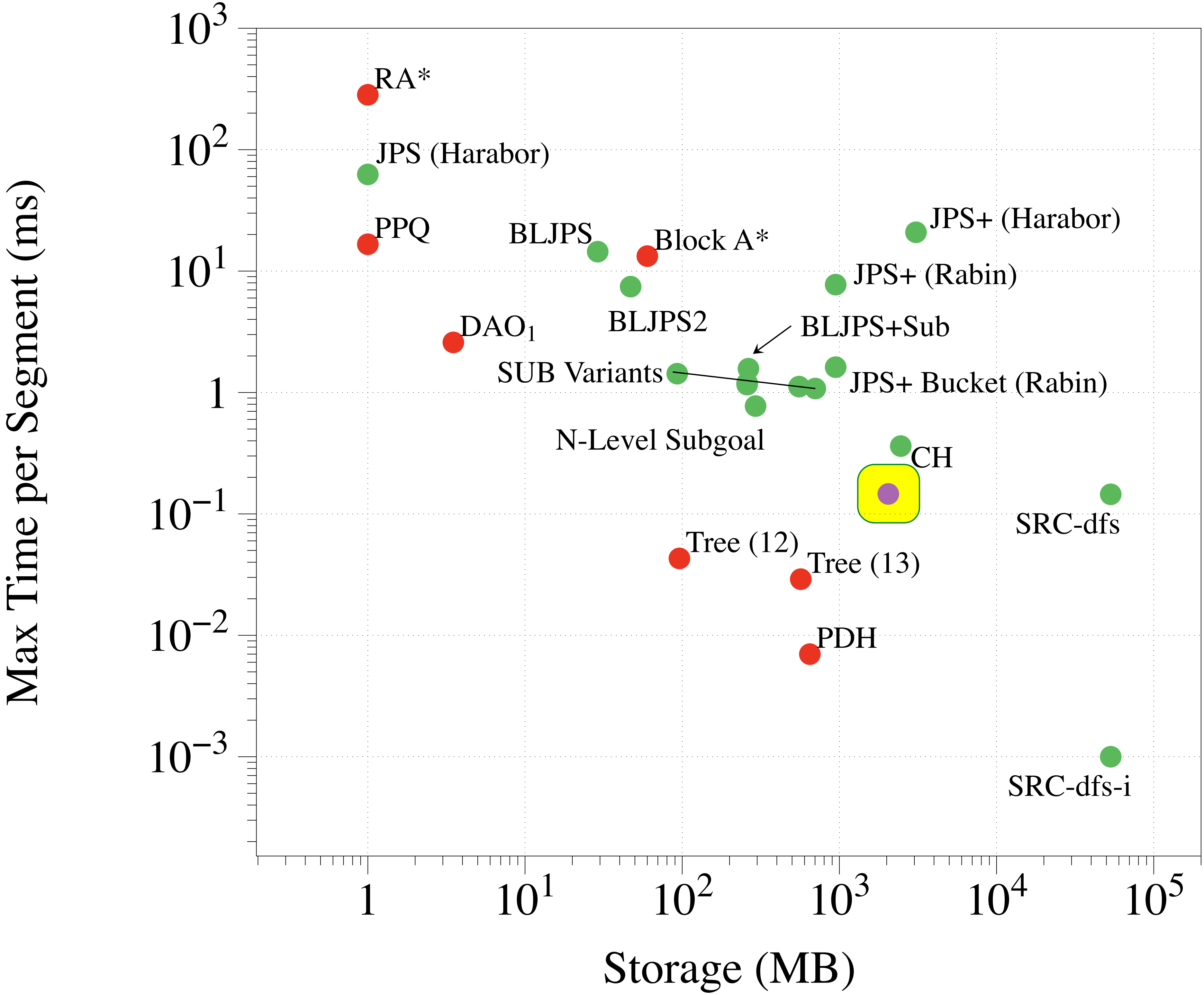
- Where else could we apply contractions?
    - Robotics?
    - 3D worlds?
    - Alternate representations? (polygons)

The Future

- Have we reached the limits of our performance?
- Where is there significant room for improvement?
- Other future directions?



Max Time per Segment (ms)
Storage (MB)
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
1
10^1
10^2
10^3
10^4
10^5
RA*
JPS (Harabor)
PPQ
BLJPS
Block A*
JPS+ (Harabor)
JPS+ (Rabin)
BLJPS2
DAO_1
BLJPS+Sub
SUB Variants
JPS+ Bucket (Rabin)
N-Level Subgoal
CH
SRC-dfs
Tree (12)
Tree (13)
PDH
SRC-dfs-i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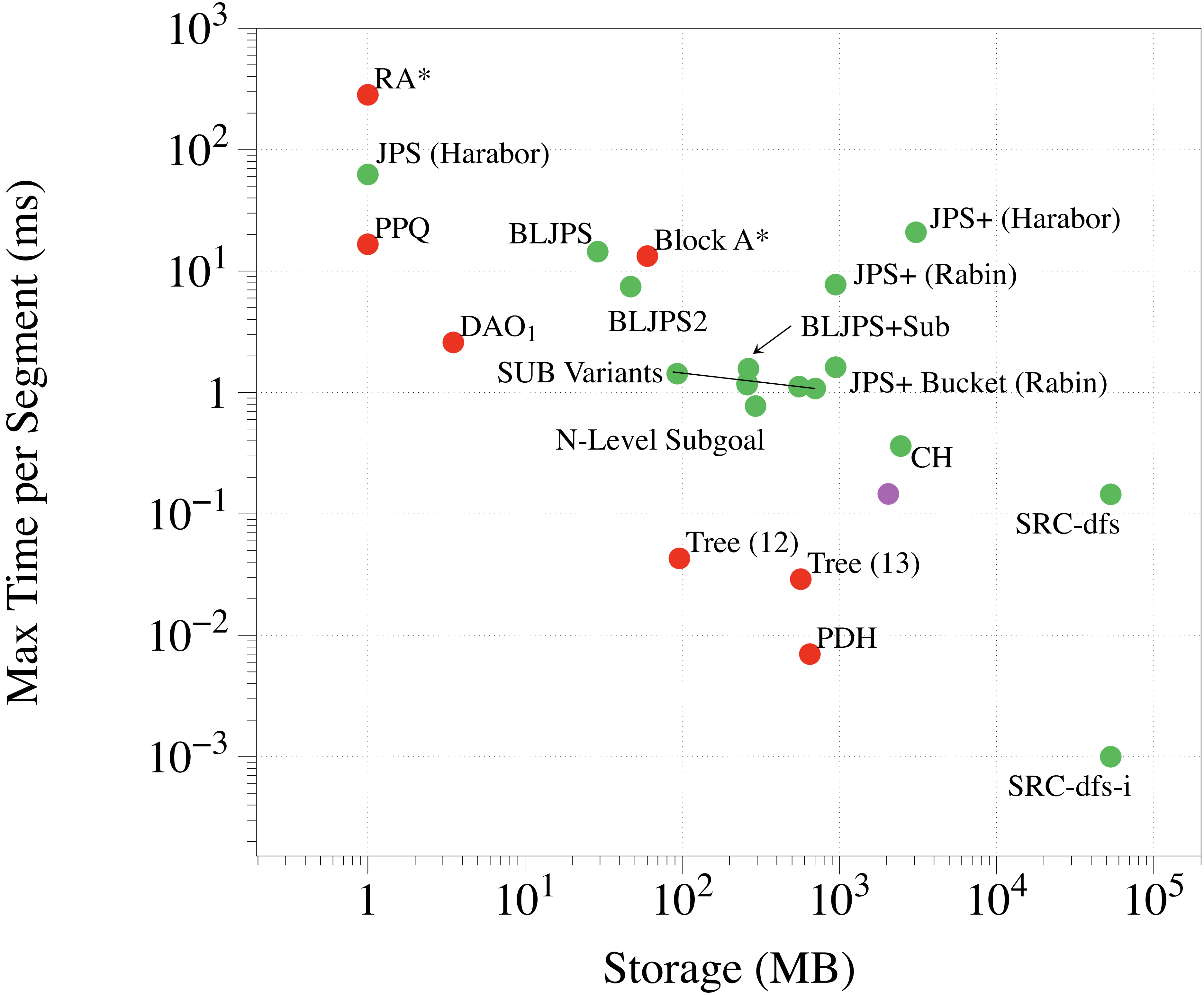
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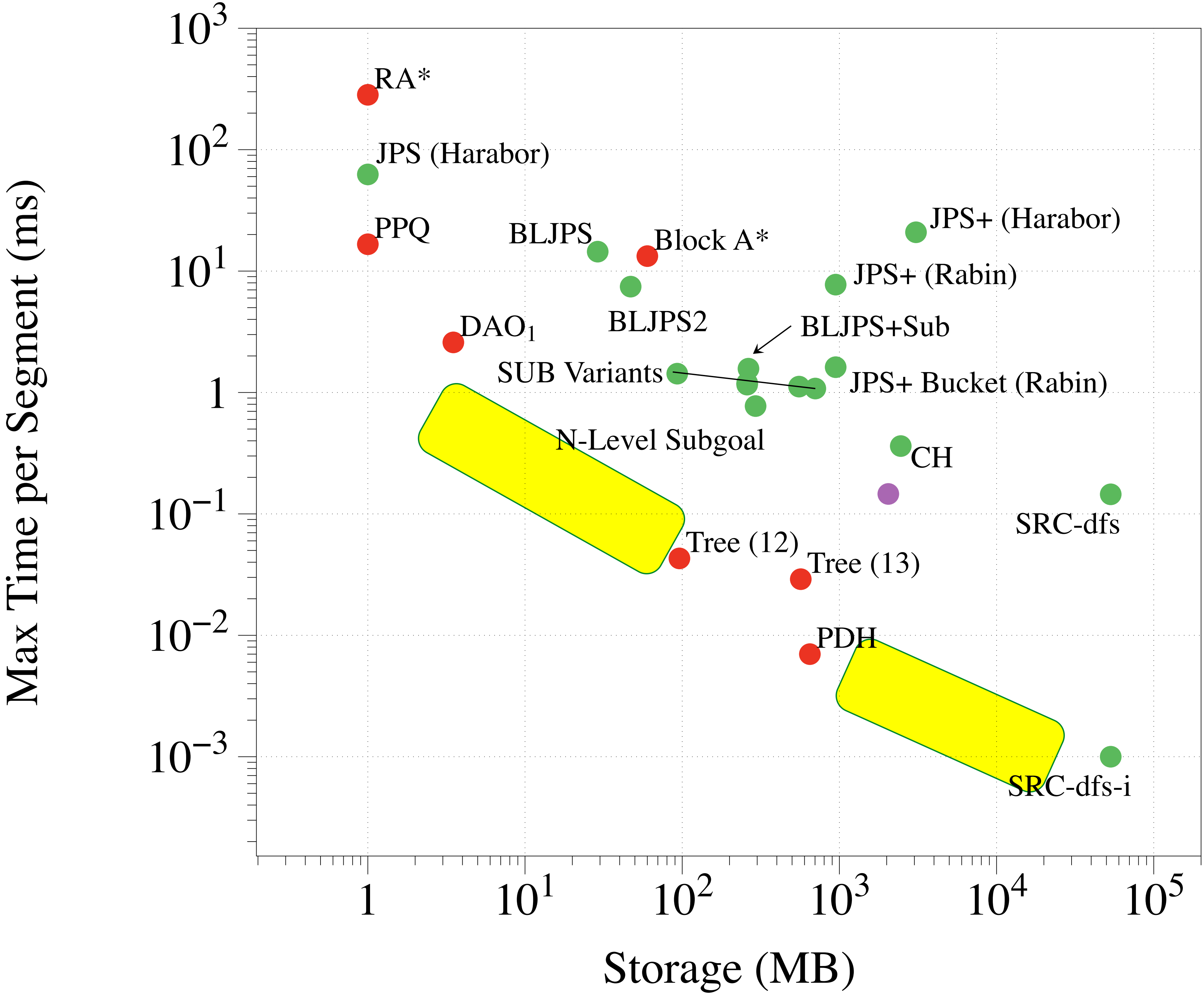

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Is this the real problem?

- Dynamic world
  - Costs change, connectivity changes
- Cell costs

Open Question

- Are we building insight?

Open Question

- Are we building insight?
  - The benchmarks are helping drive research

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  - Work is leading to new theoretical understanding

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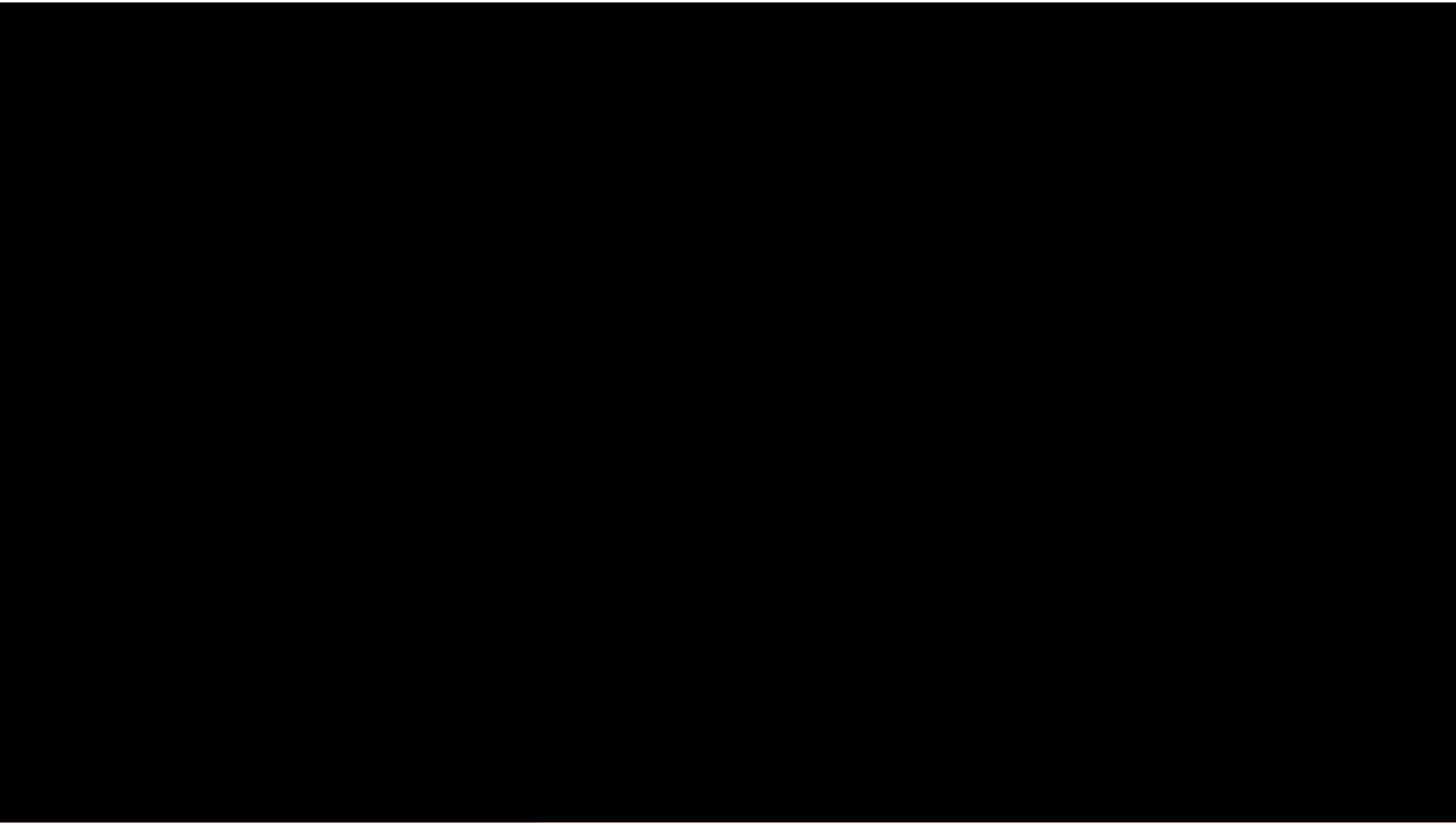
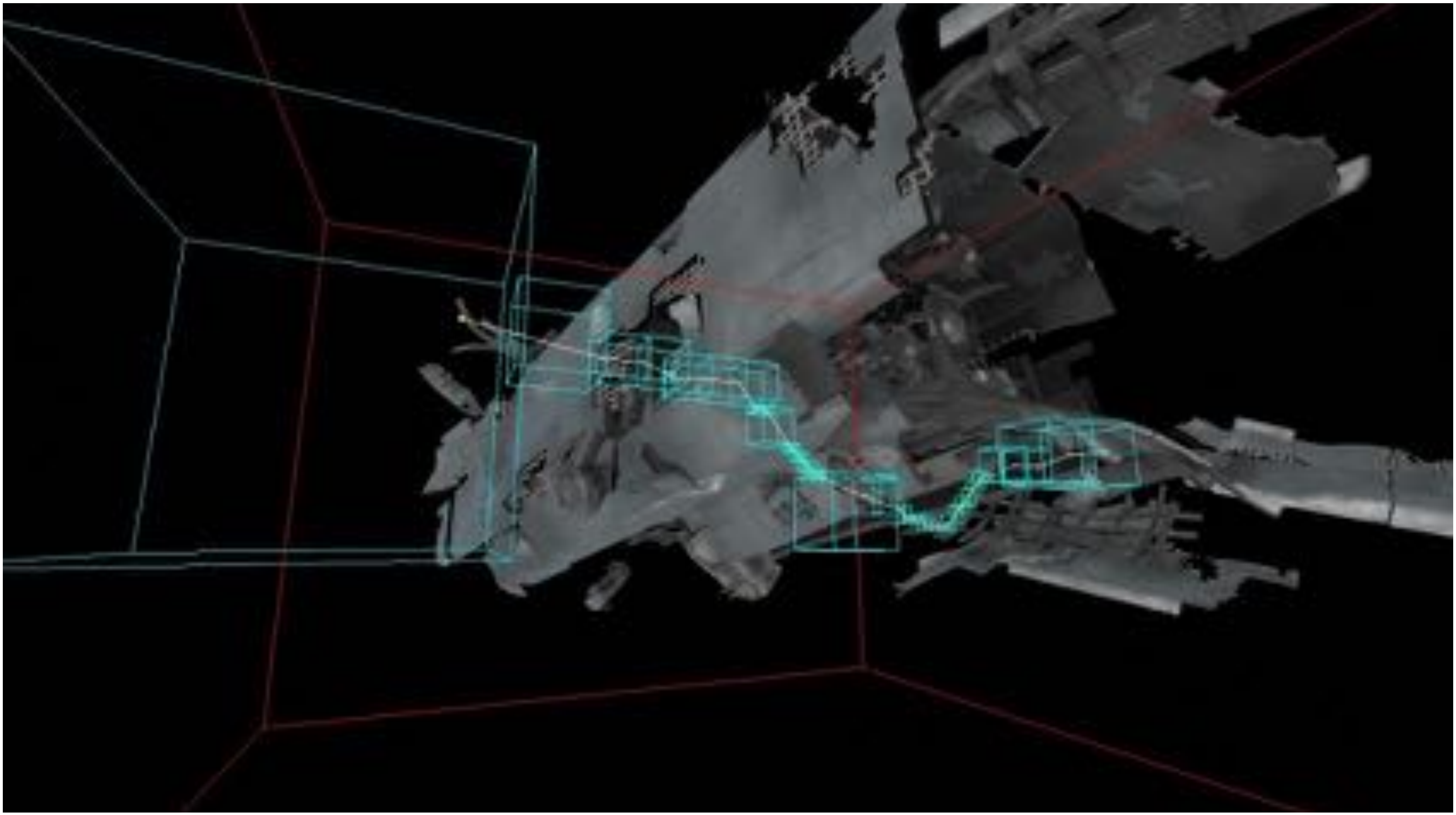
- Thanks to SoCS chairs for the chance to contribute to the understanding

One more thing!



Warframe - Digital Extremes



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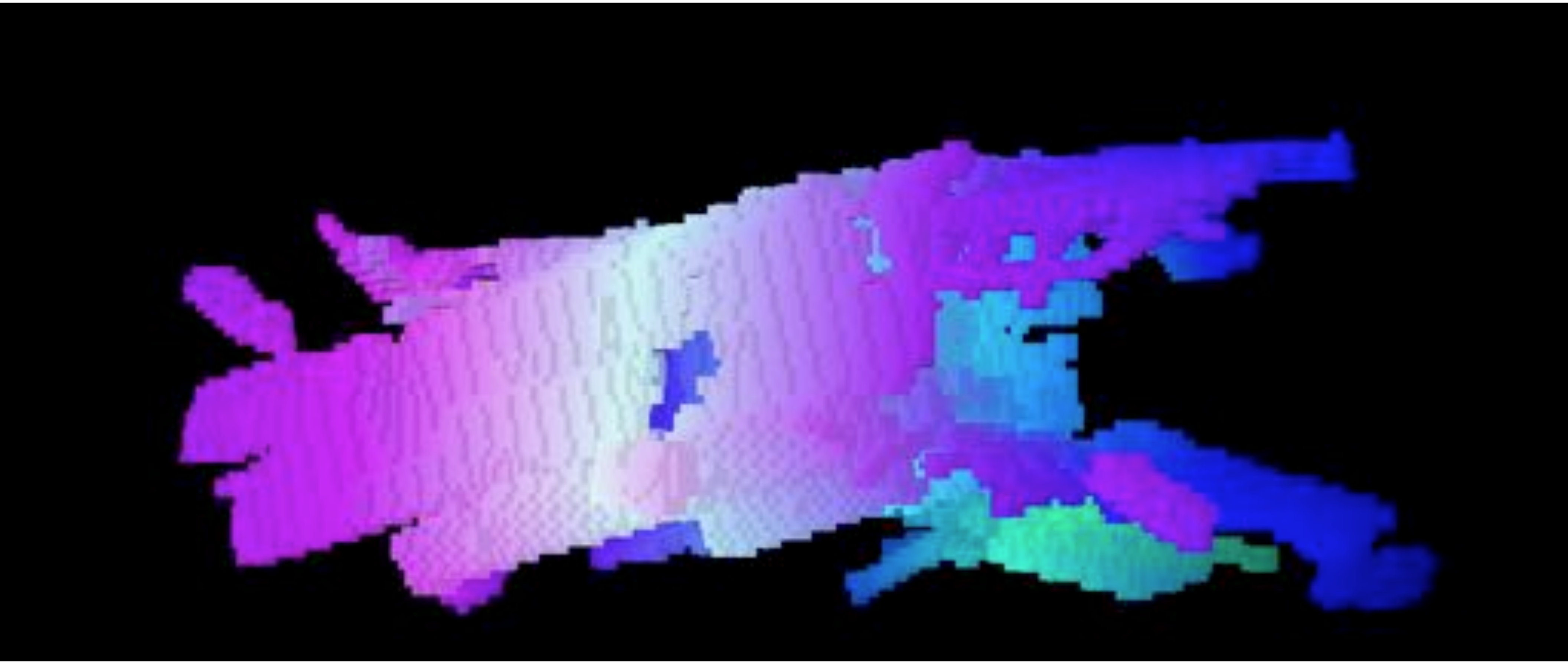
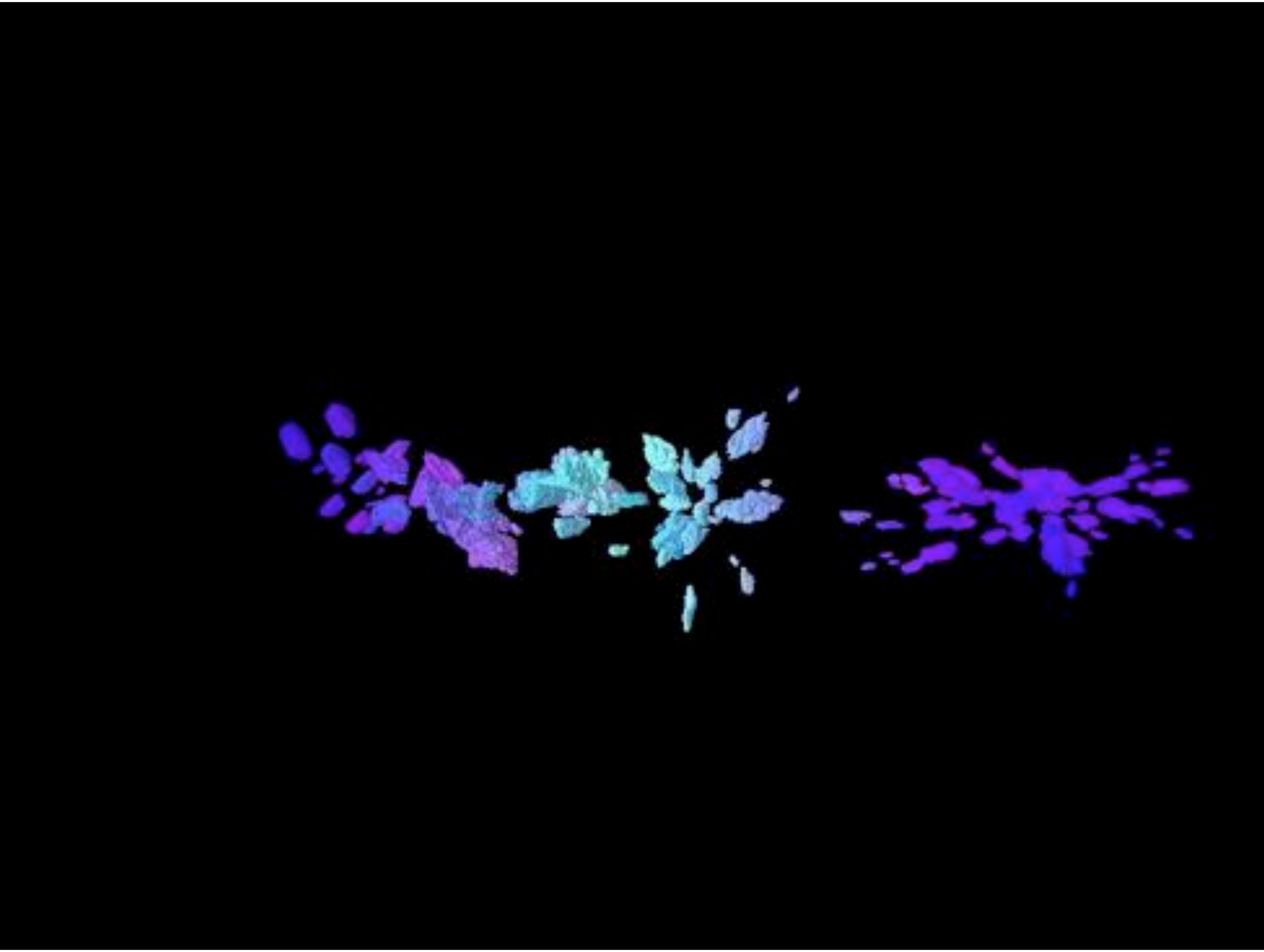
New repository coming

- 3D voxel world
- Challenging new path planning domain
- Thanks to Digital Extremes and Daniel Brewer!





Thanks

- Students/Collaborators
  - Renee Jansen
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  - Vadim Bulitko
  - Robert Geisberger
- http://movingai.com/GPPC/
- Games Industry
  - BioWare
  - Digital Extremes
    - Daniel Brewer
  - Troy Humphreys
- GPPC Participants
- SoCS Organizers