Introduction to State-of-the-art Motion Planning Algorithms

Presented by

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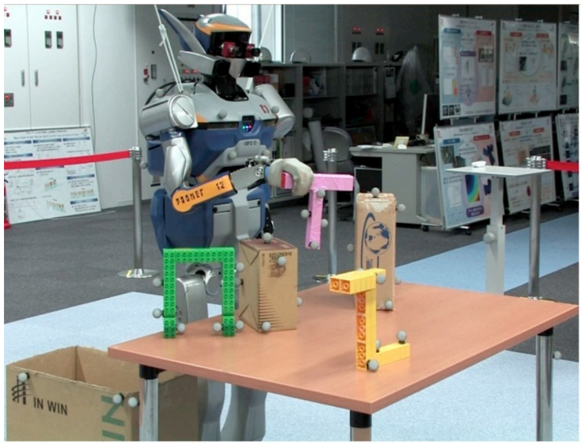
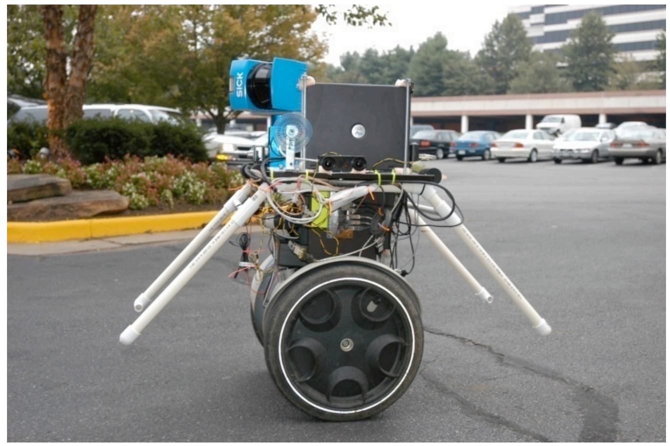
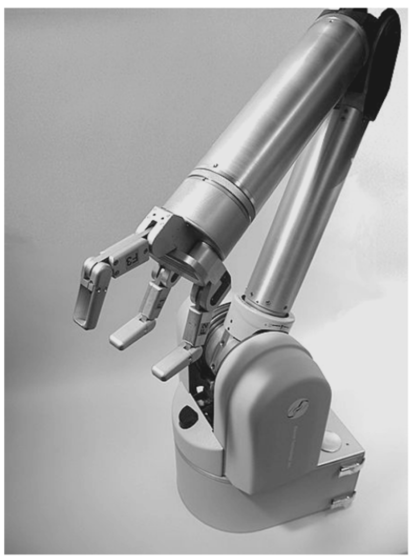
Robots need to move!



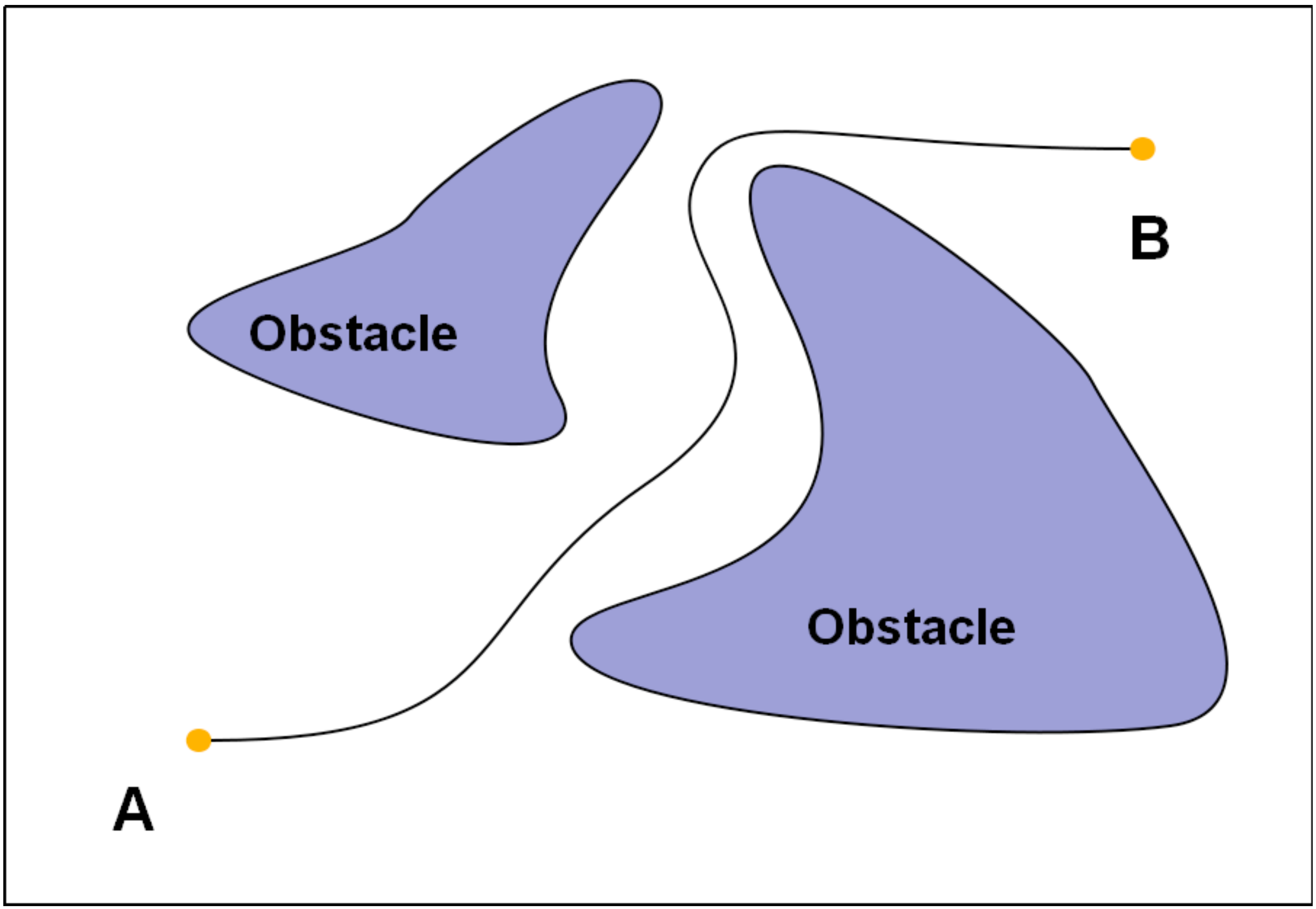




Motion

- Robot motion must be continuous
- Geometric constraints
- Dynamic constraints
- Safety constraints
- Execution constraints

Path planning – *A to B paradigm*



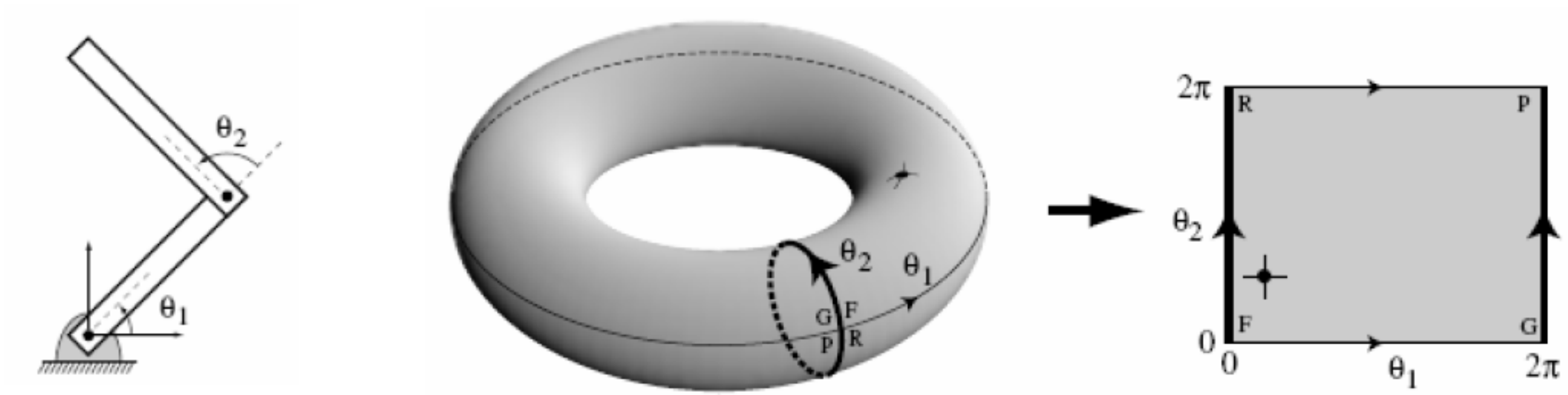
A real robot has a shape

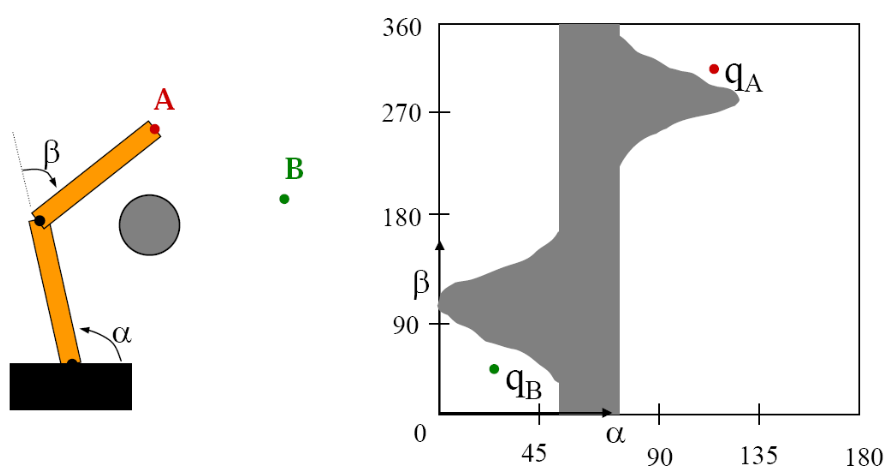
A robot as a point in its **Configuration Space**

- Given its geometry, a robot is fully specified by a minimal set of parameters $p_1, p_2, \ldots, p_n$
  - *Generalized coordinates*
  - *Degrees of freedom*
  - *Configurations space parameters*
- If $p_i \in X_i$, the configuration space (*C-Space*) is a manifold

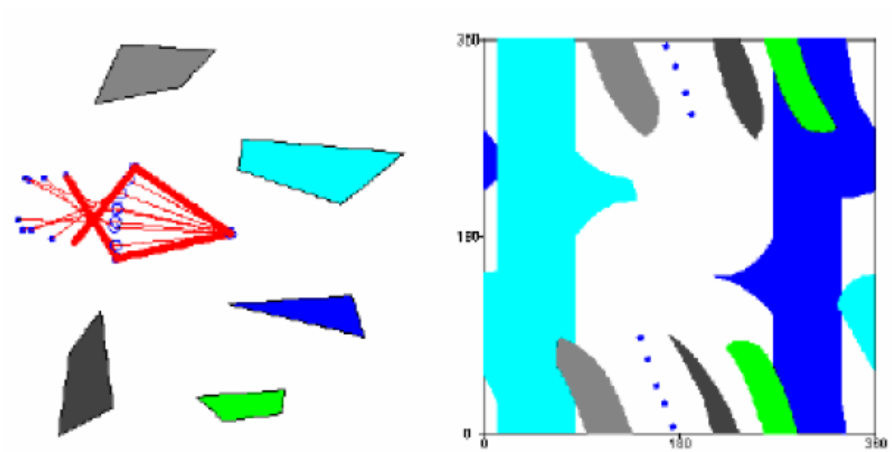
$$Q = X_1 \times X_2 \times \ldots \times X_n$$

Configuration space of a 2-link arm



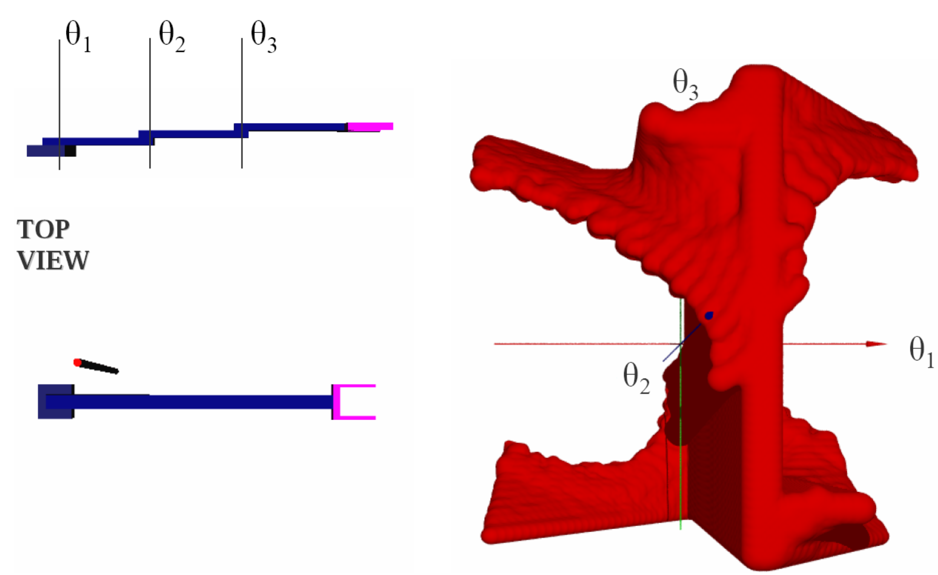


Some more examples



2-link planar arm
among 5 obstacles

3-link
planar arm



workspace

C-space

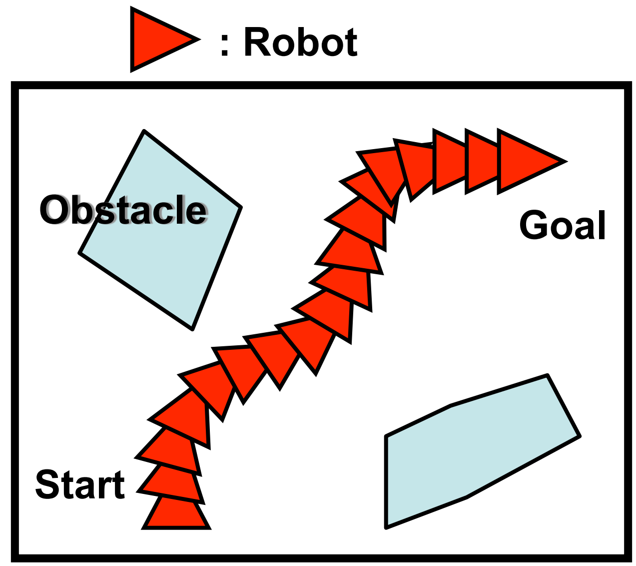
Path Planning

<u>Given:</u>

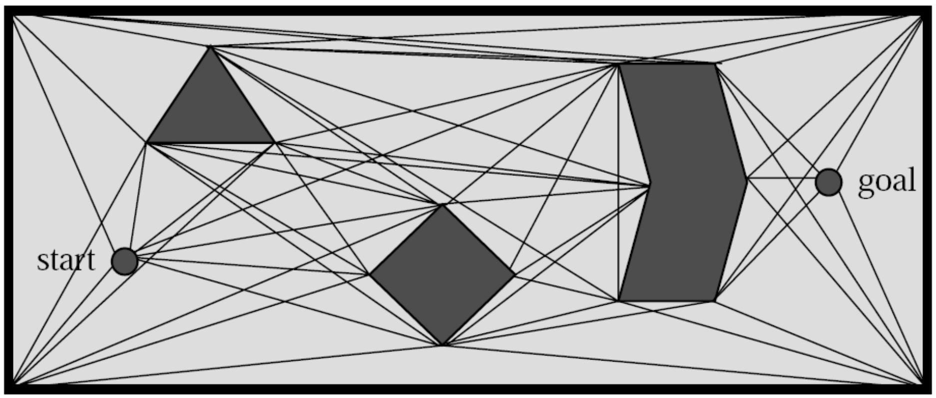
- World geometry
- Robot's geometry
- Start and goal configuration

<u>Compute:</u>

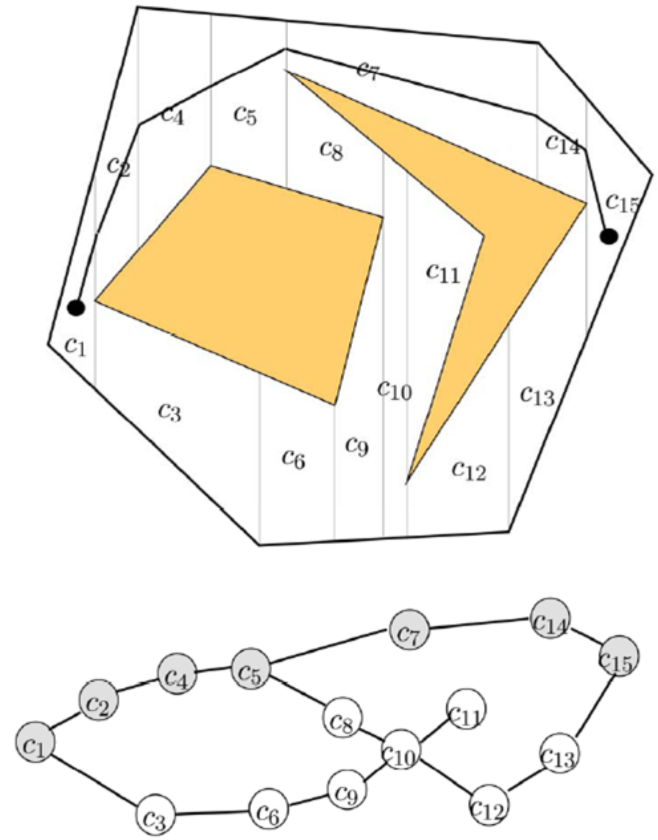
A collision-free, feasible path to the goal



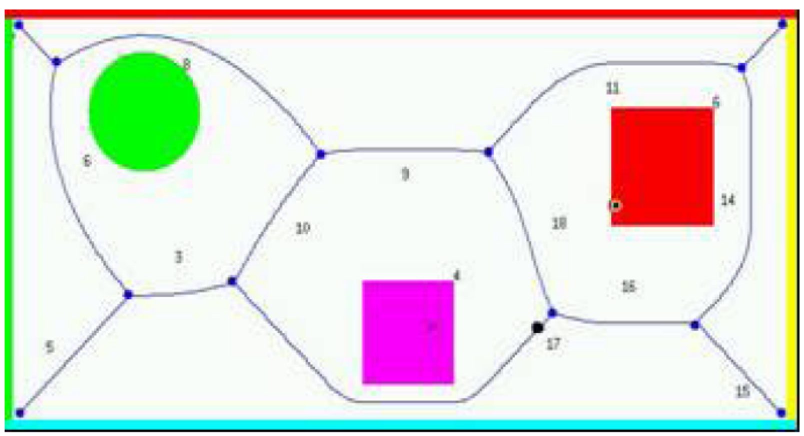
Complete planners - Examples



Visibility roadmap



Trapezoidal decomposition



Voronoi diagram

Path planning is hard..

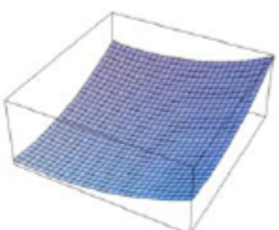
PROBLEM	COMPLEXITY
Sofa Mover (3DOF)	$O(n^{2+\varepsilon})$ - not implemented [HS96]
Piano Mover (6DOF)	Polynomial – no practical algorithm [SS83]
n Disks in the Plane	NP-Hard [SS83]
n Link Chain in 3D	PSPACE-Complete [HSS87]
Generalized Mover	PSPACE-Complete [Canny88]

- Understanding the structure of C-spaces is a very hard mathematical challenge
- C-spaces for most interesting problems are high dimensional

Potential field planners

$$U(q) = U_{\text{att}}(q) + U_{\text{rep}}(q)$$

$$F(q) = -\nabla U(q)$$



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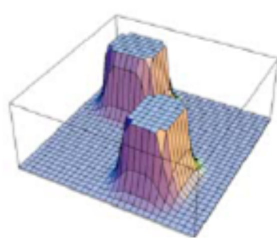

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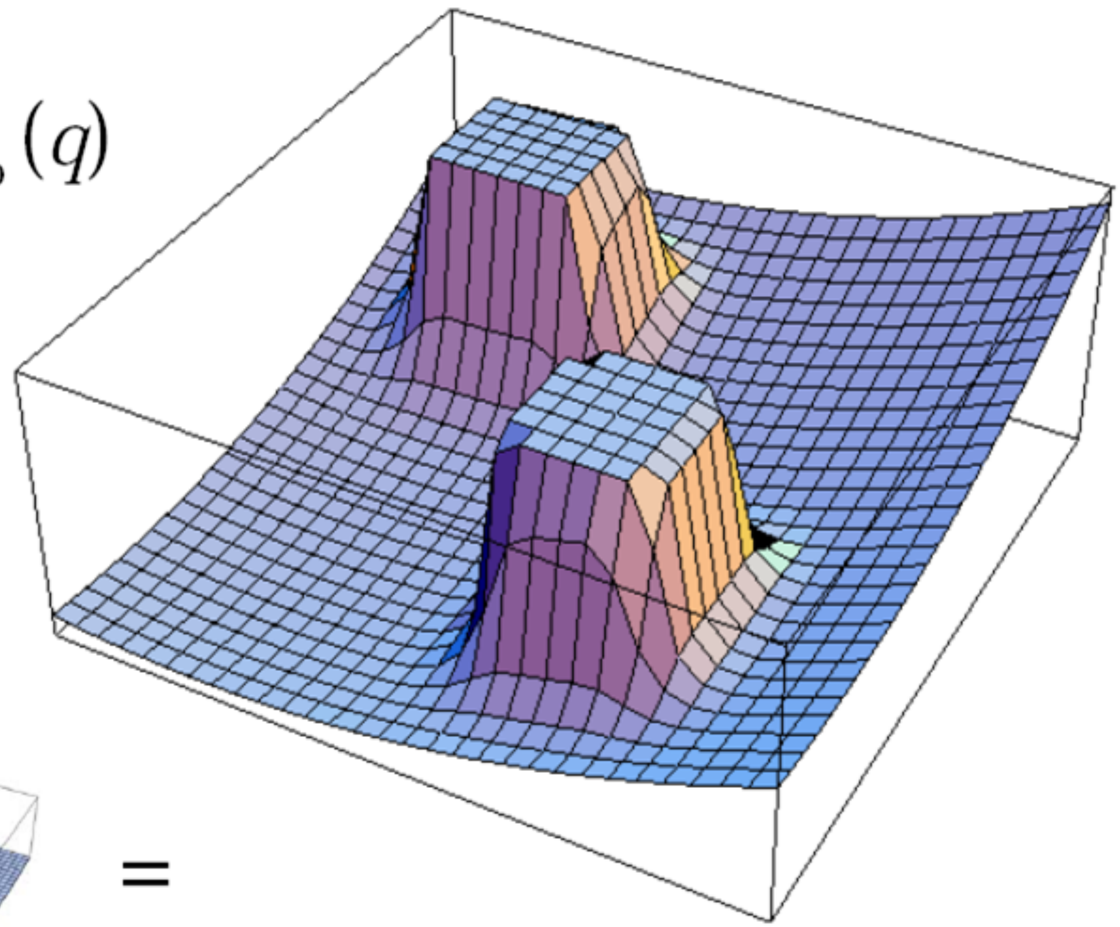
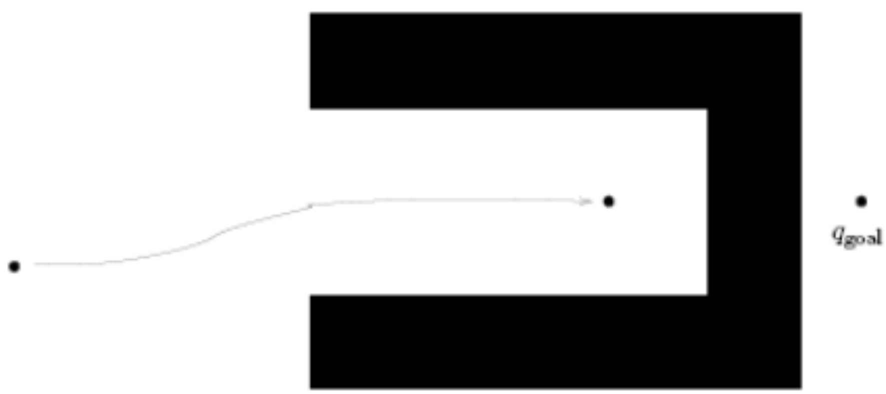
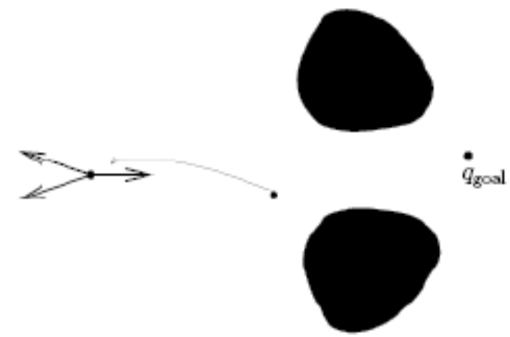


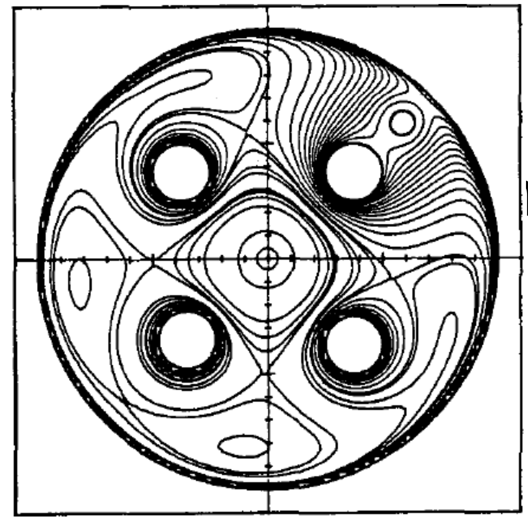
Local minima problem





Navigation functions

- Exact navigation functions are mathematically challenging in general (RK91)



- Approximate navigation functions are intractable in many dimensions

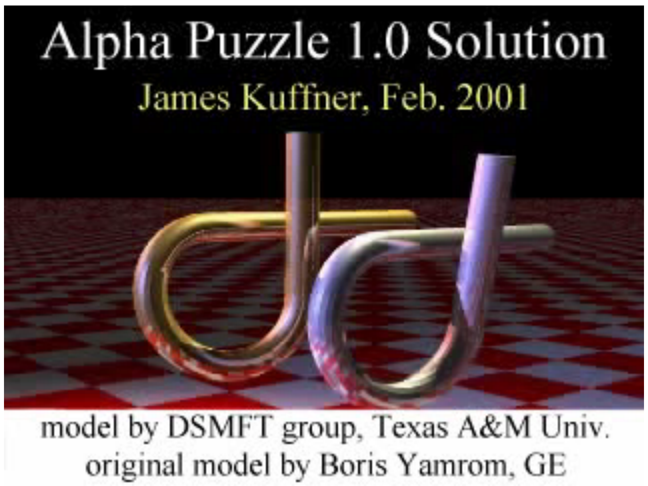
7	**18**	17	16	15	14	13	12	11	10	9	9	9	9	9	9	9
6	17	17	16	15	14	13	12	11	10	9	8	8	8	8	8	8
5	17	16	16	15	14	13	12	11	10	9	8	7	7	7	7	7
4	17	16	15	15	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	6	6	6	6
3	17	16	15	14	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	5	5	5	5
2	17	16	15	14	13	12	11	10	9	8	7	6	5	4	4	4
1	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	3
0	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	**2**
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

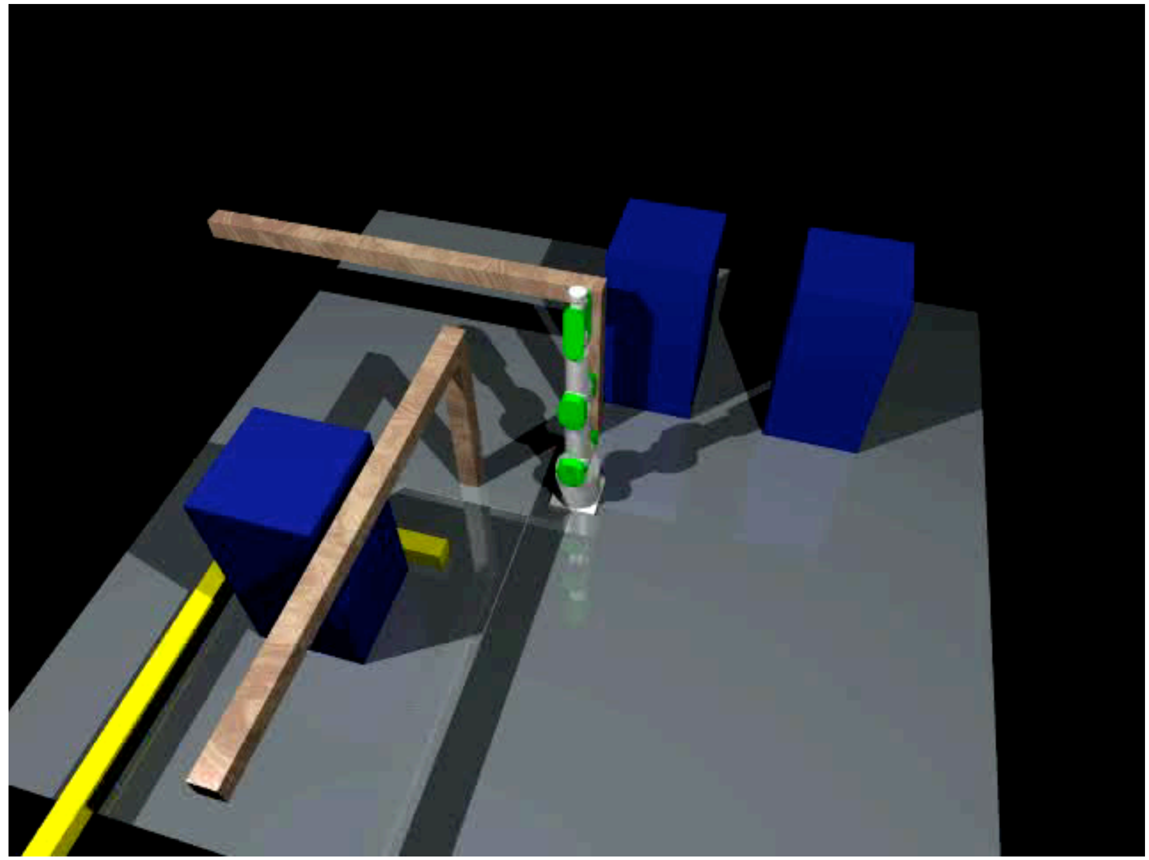
Planning does not require understanding the structure of the configuration space!

Sampling-based Planners

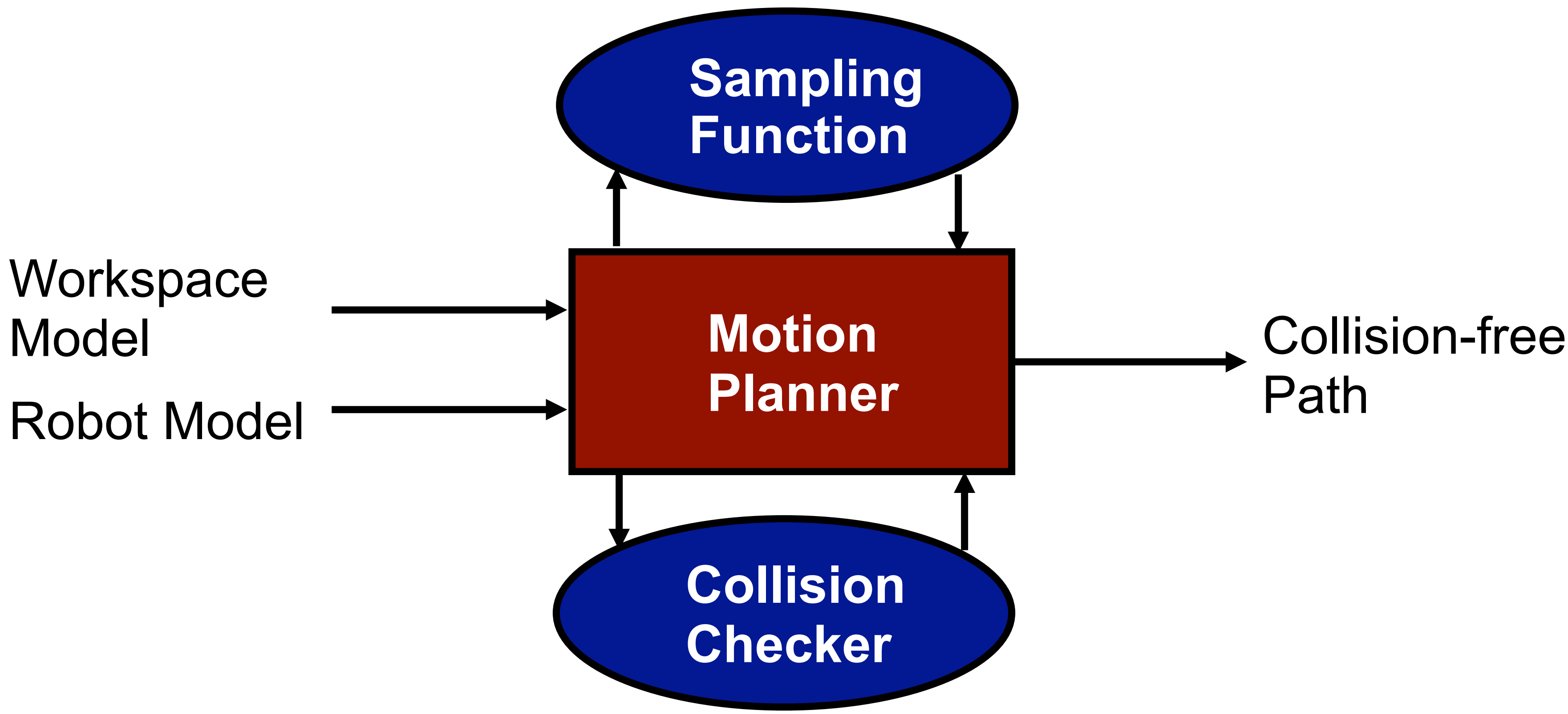
- Try to capture the connectivity of the C-Space without explicitly constructing it
- Use sampling – possible due to development of fast collision checking algorithms
- Result in very efficient algorithms that showed solutions to many previously intractable geometric planning problems

Two difficult examples

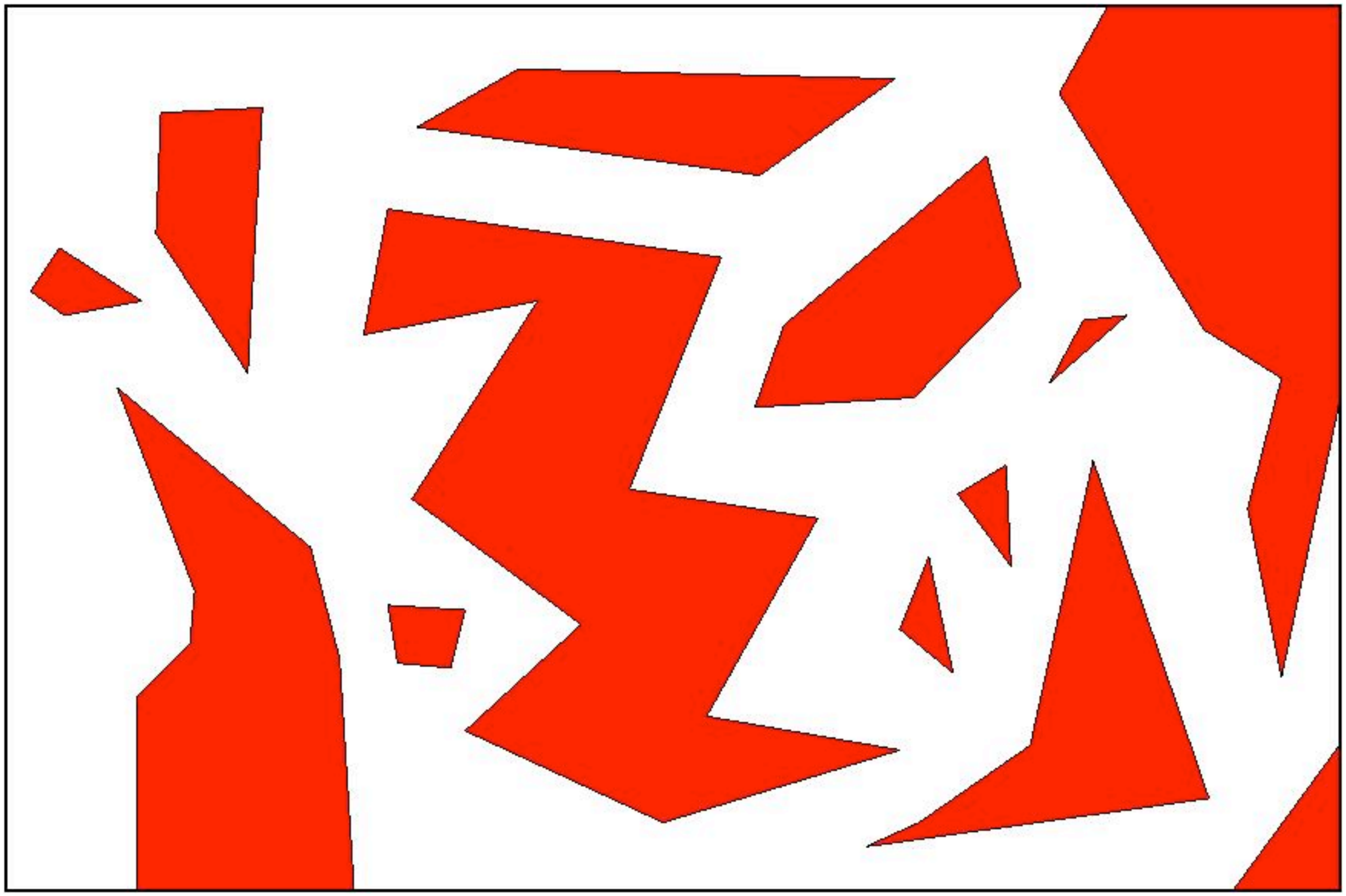




Sampling-based planning



Probabilistic Roadmap (PRM)



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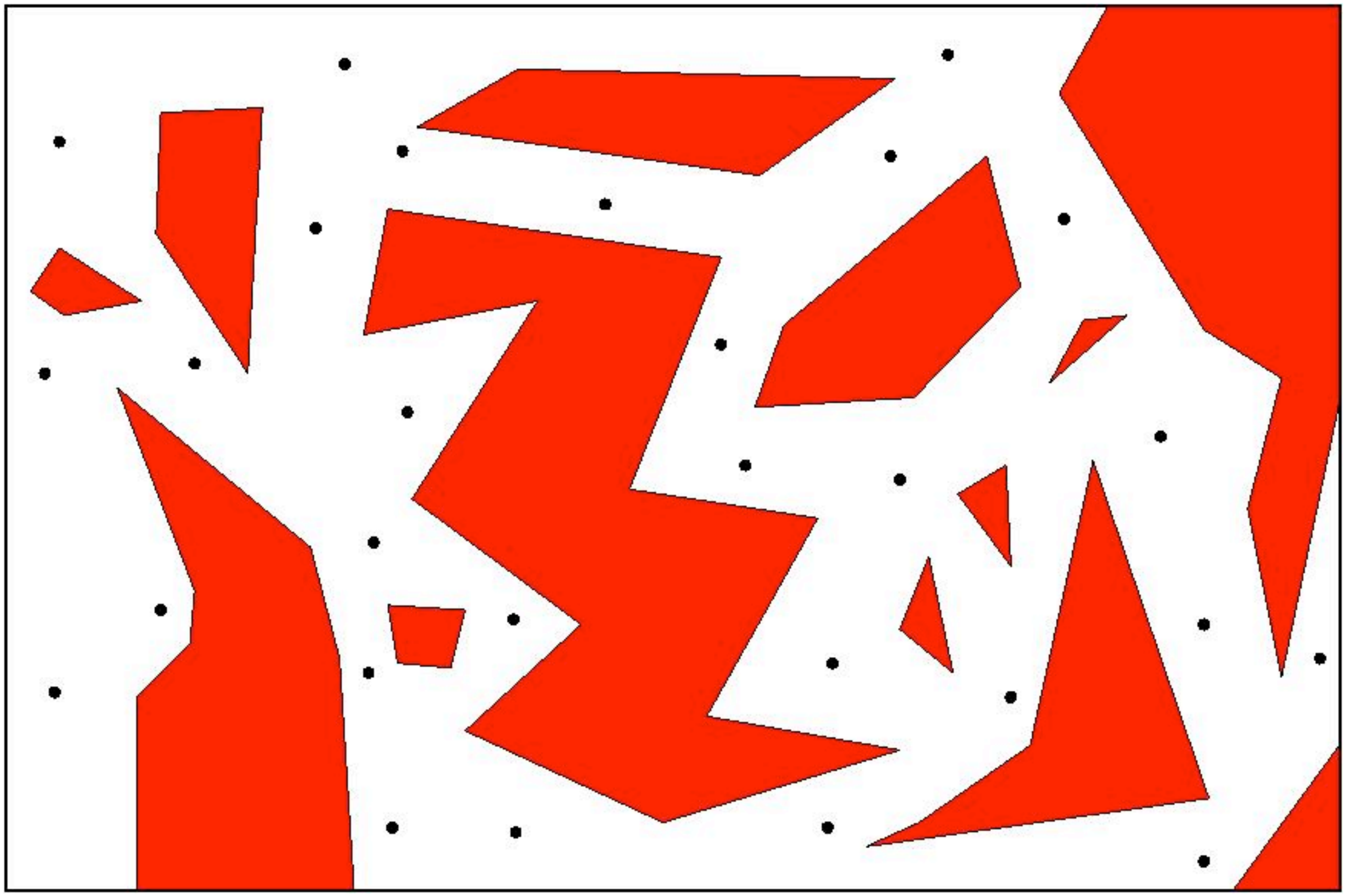

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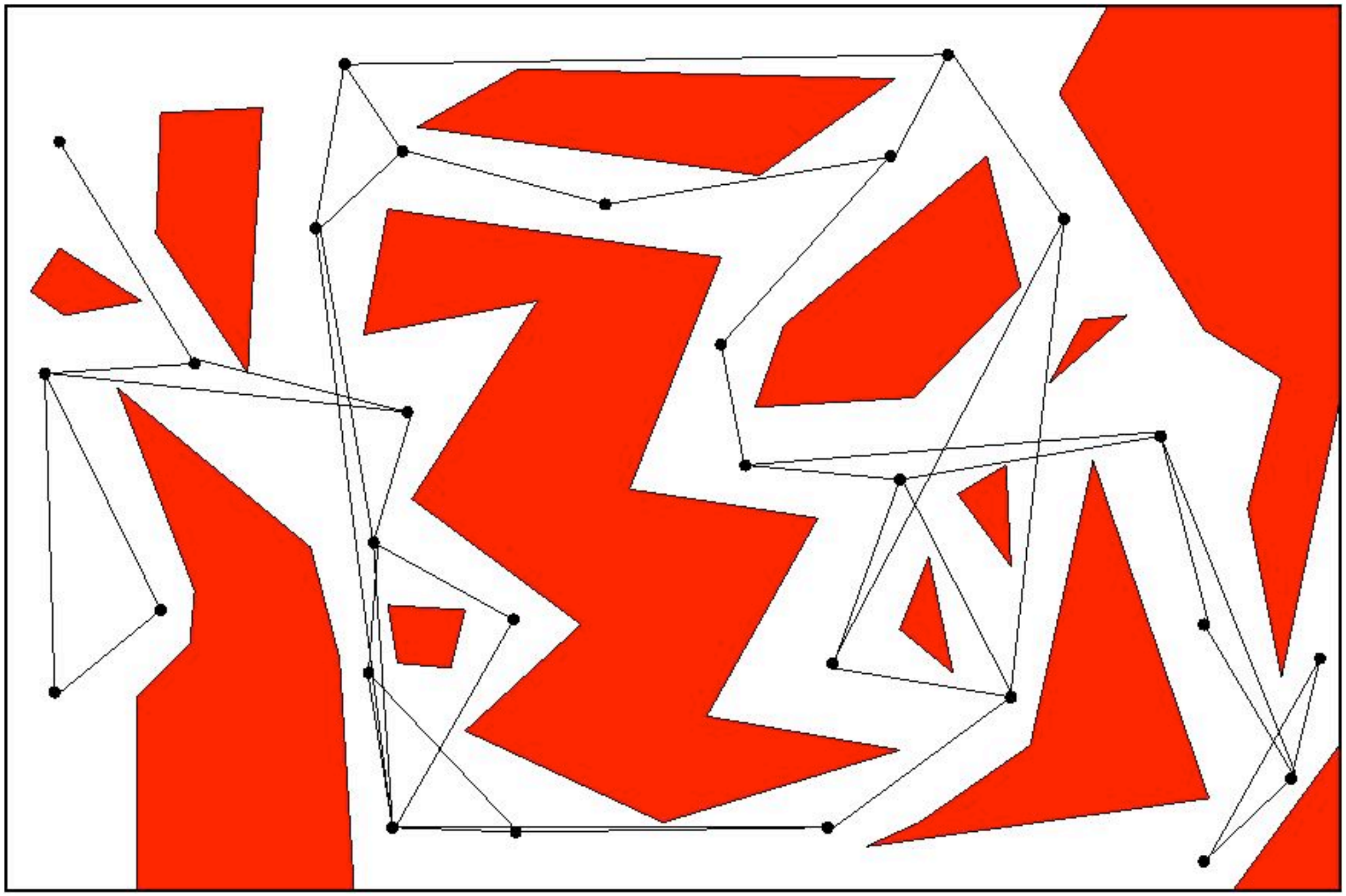

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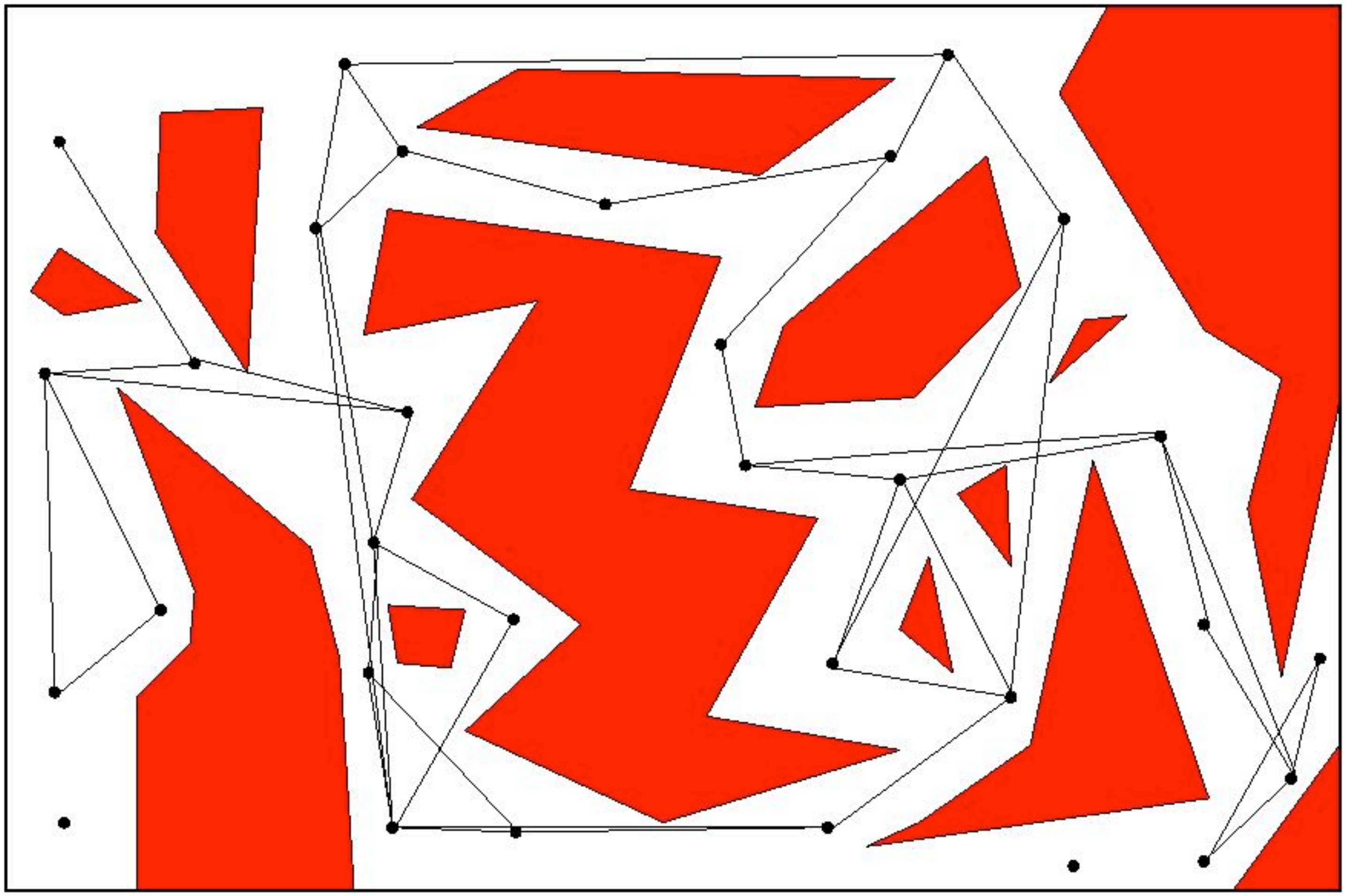

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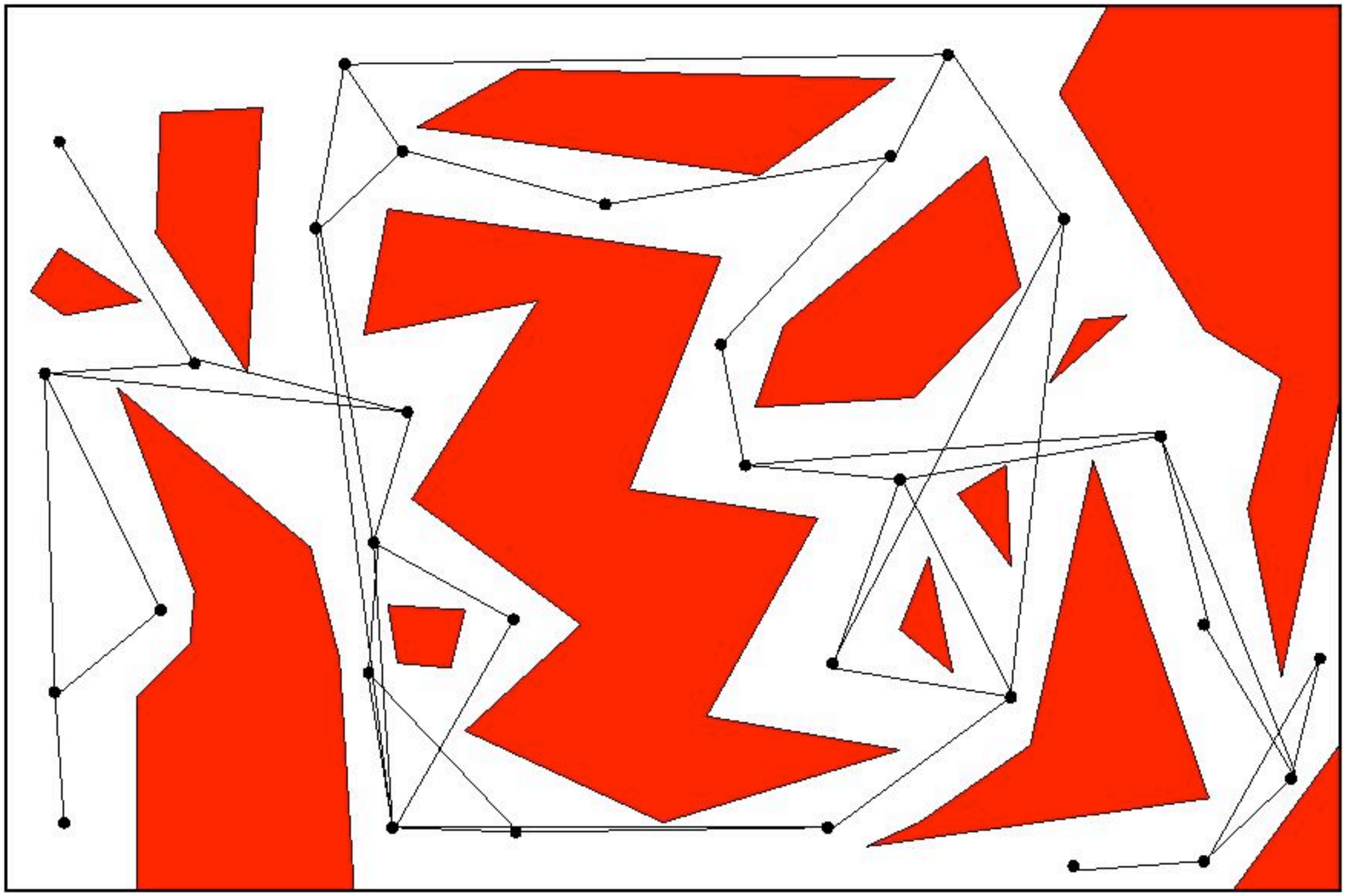

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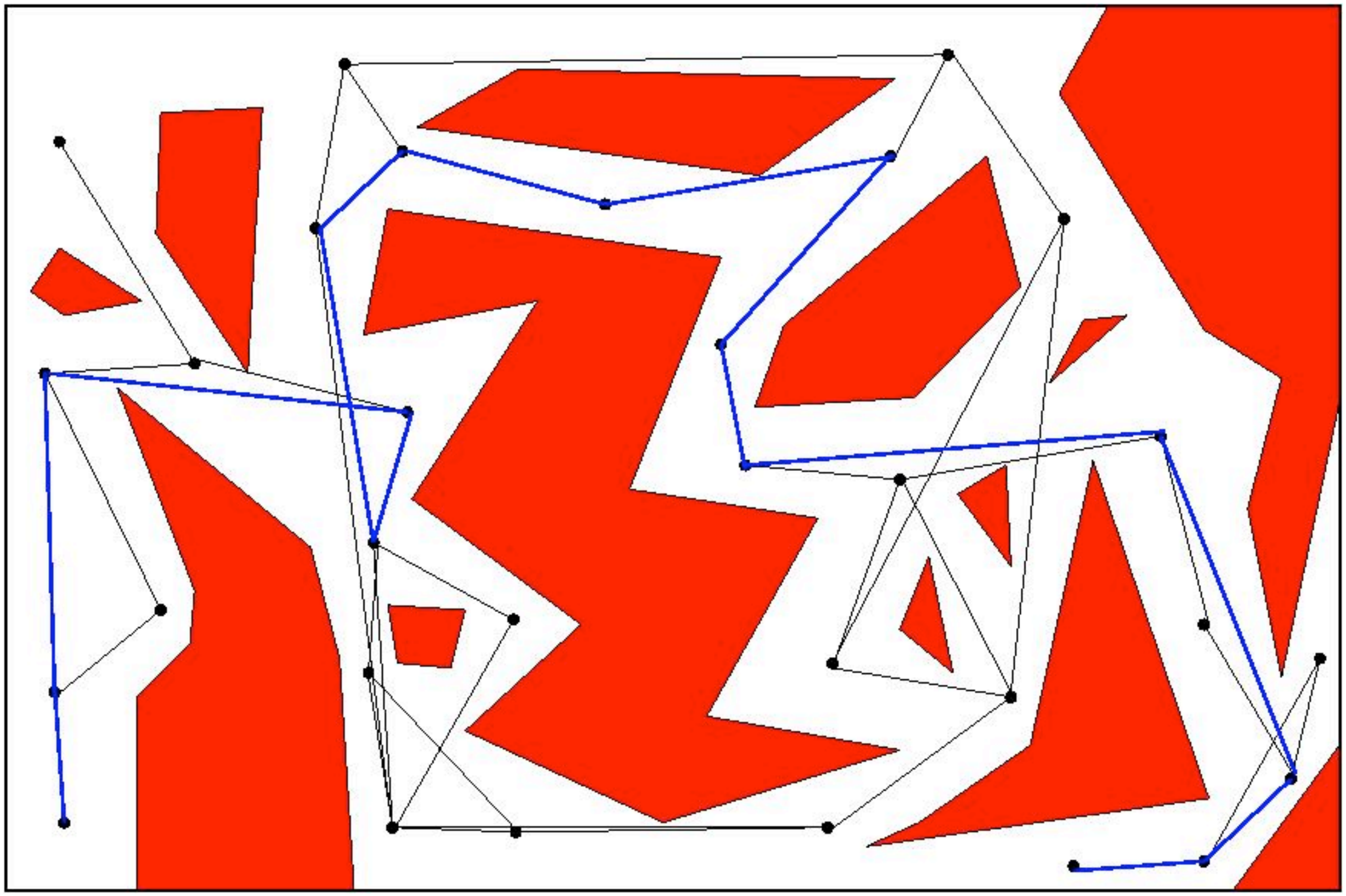
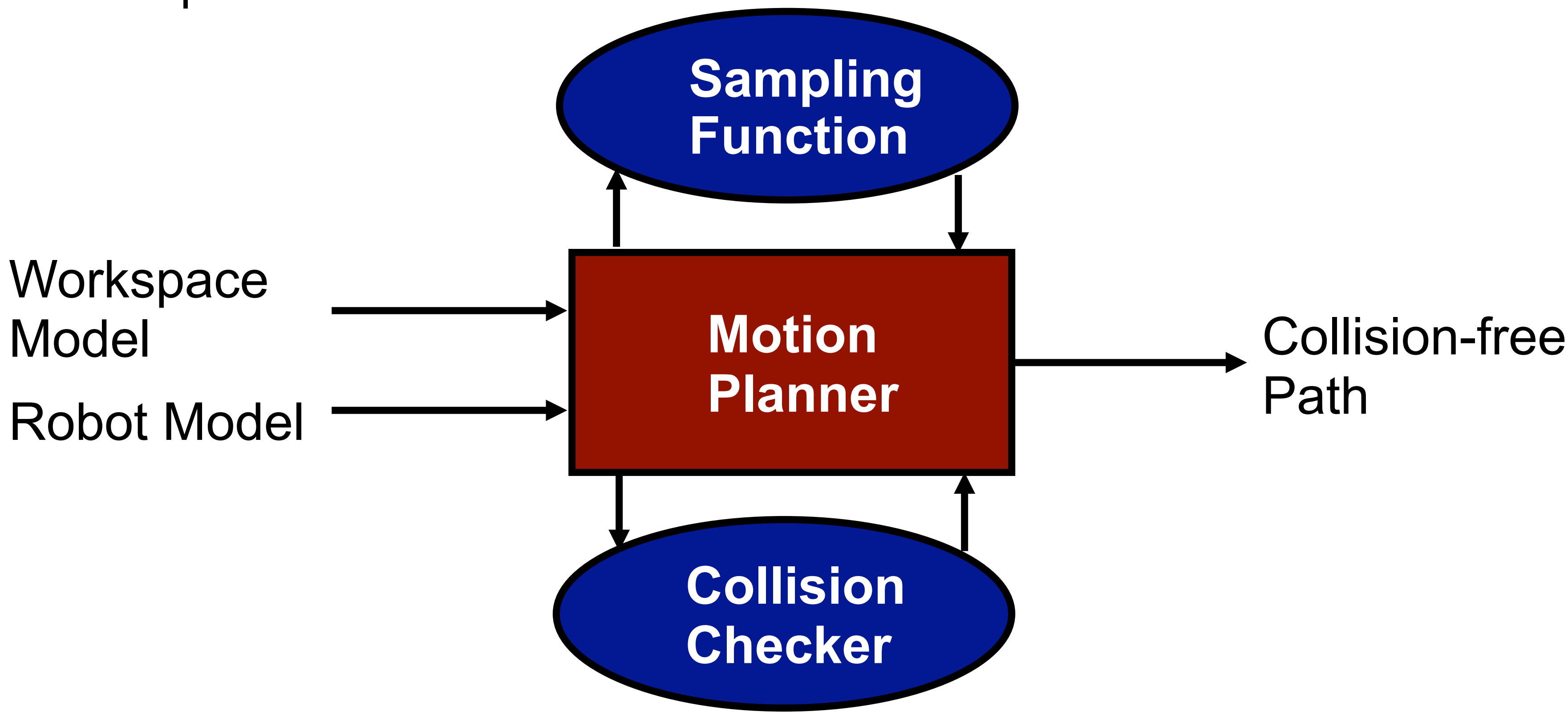
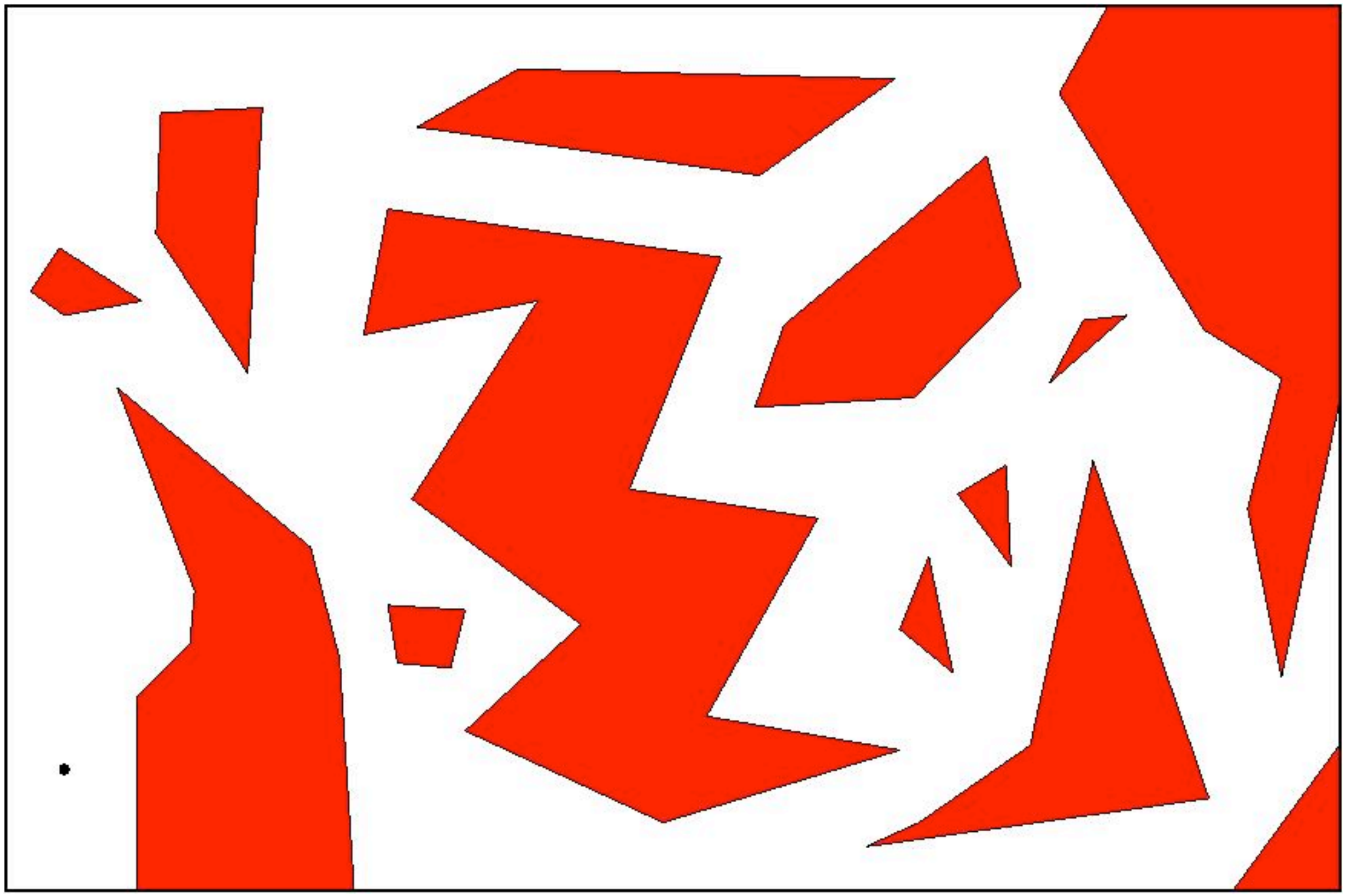


Key components of the planner

- Nearest neighbor datastructures
- Sampling strategy [AB98,HR03,OS99,BL01]
- Connection strategy
- Collision checking [LM97,LM03]
- Graph search



Tree-based planner (RRT)



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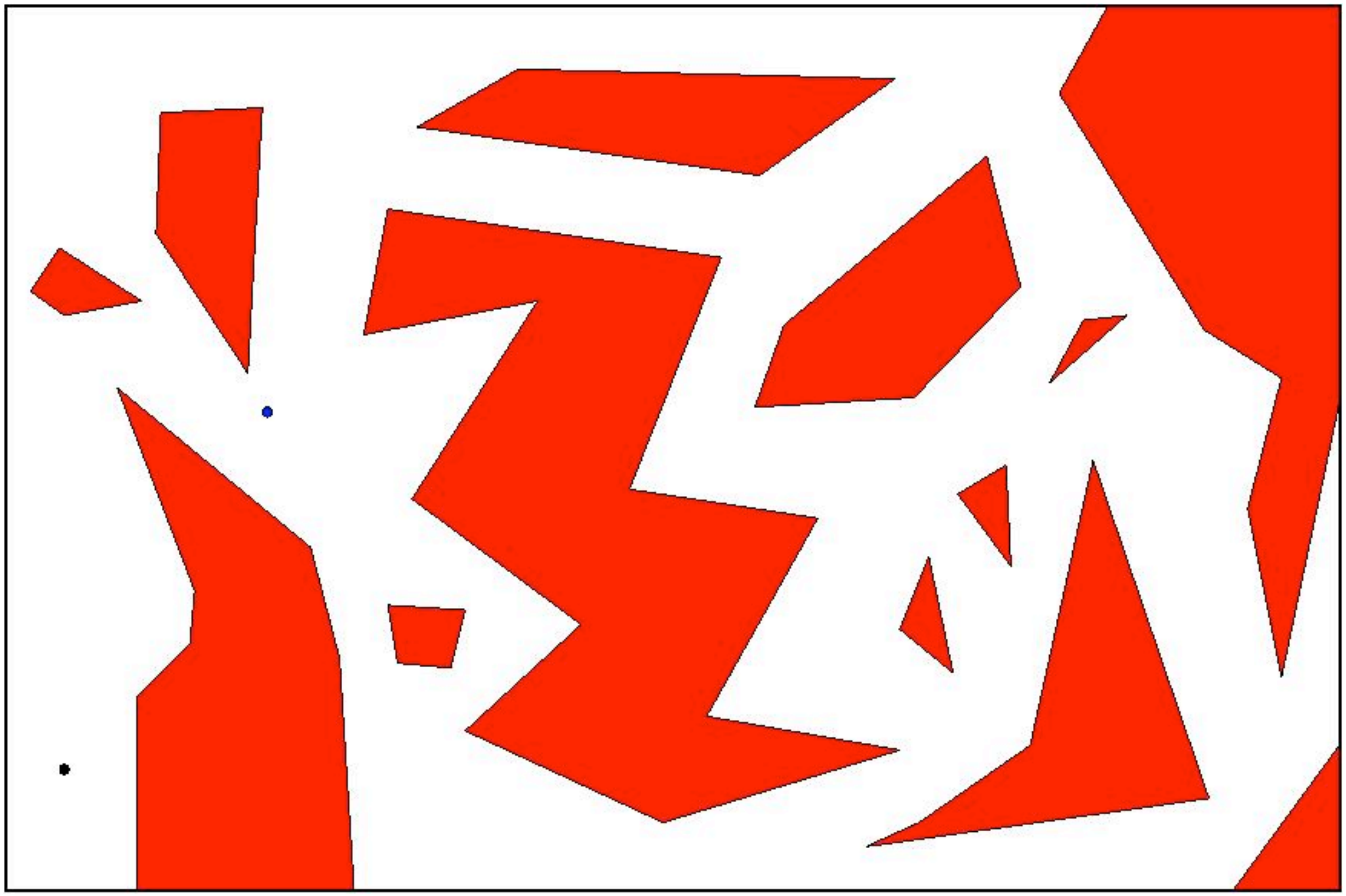

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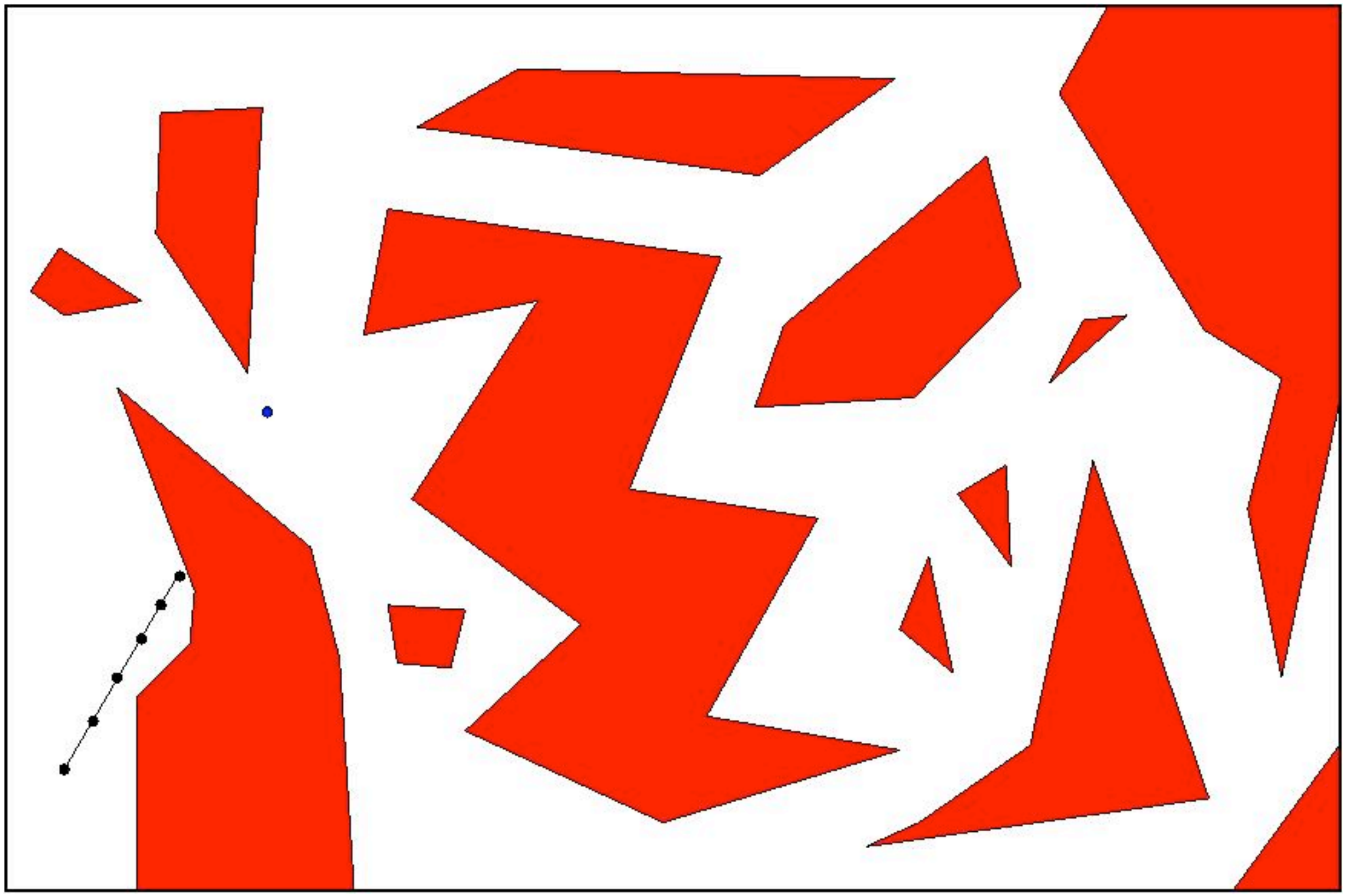

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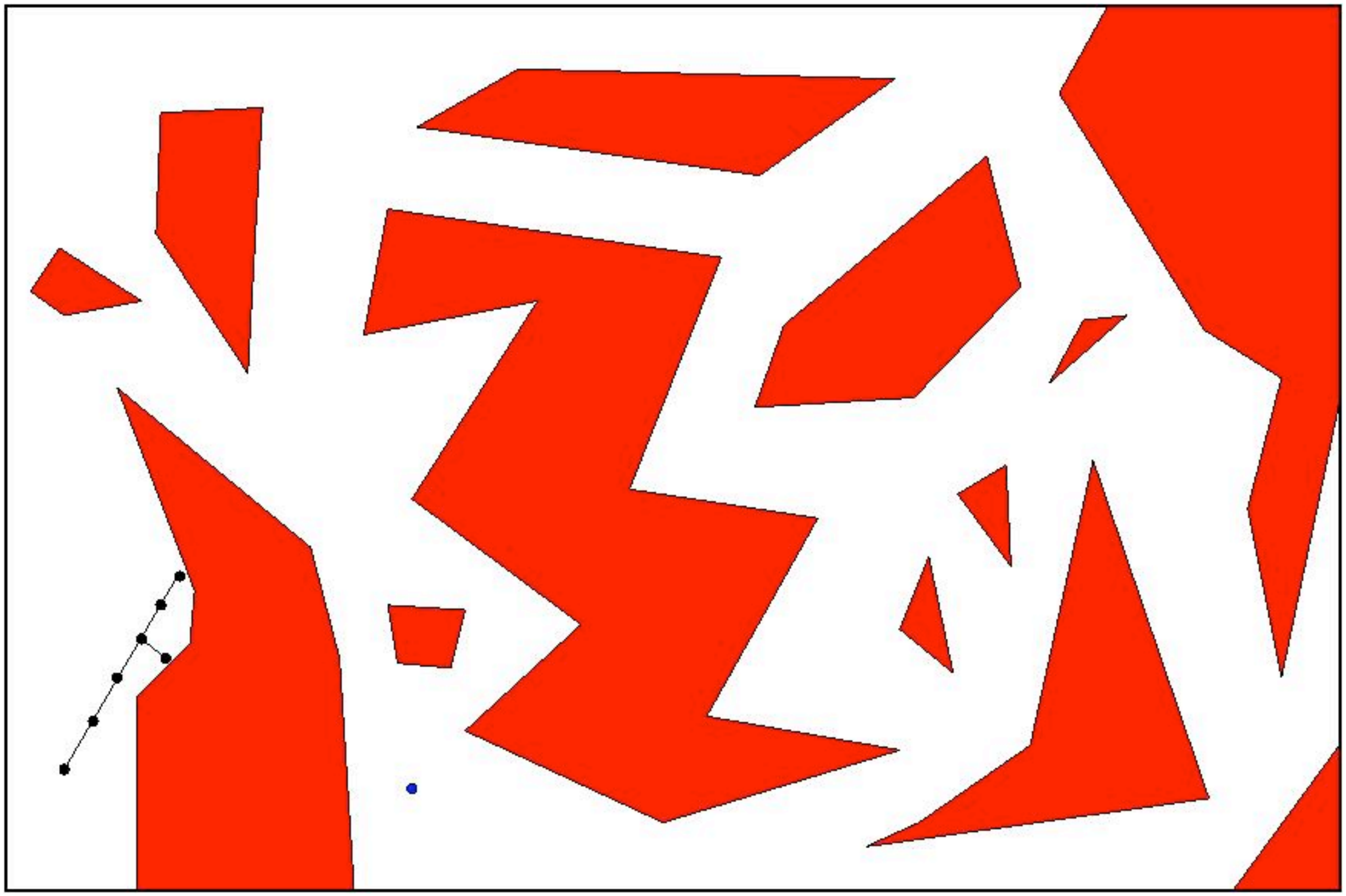

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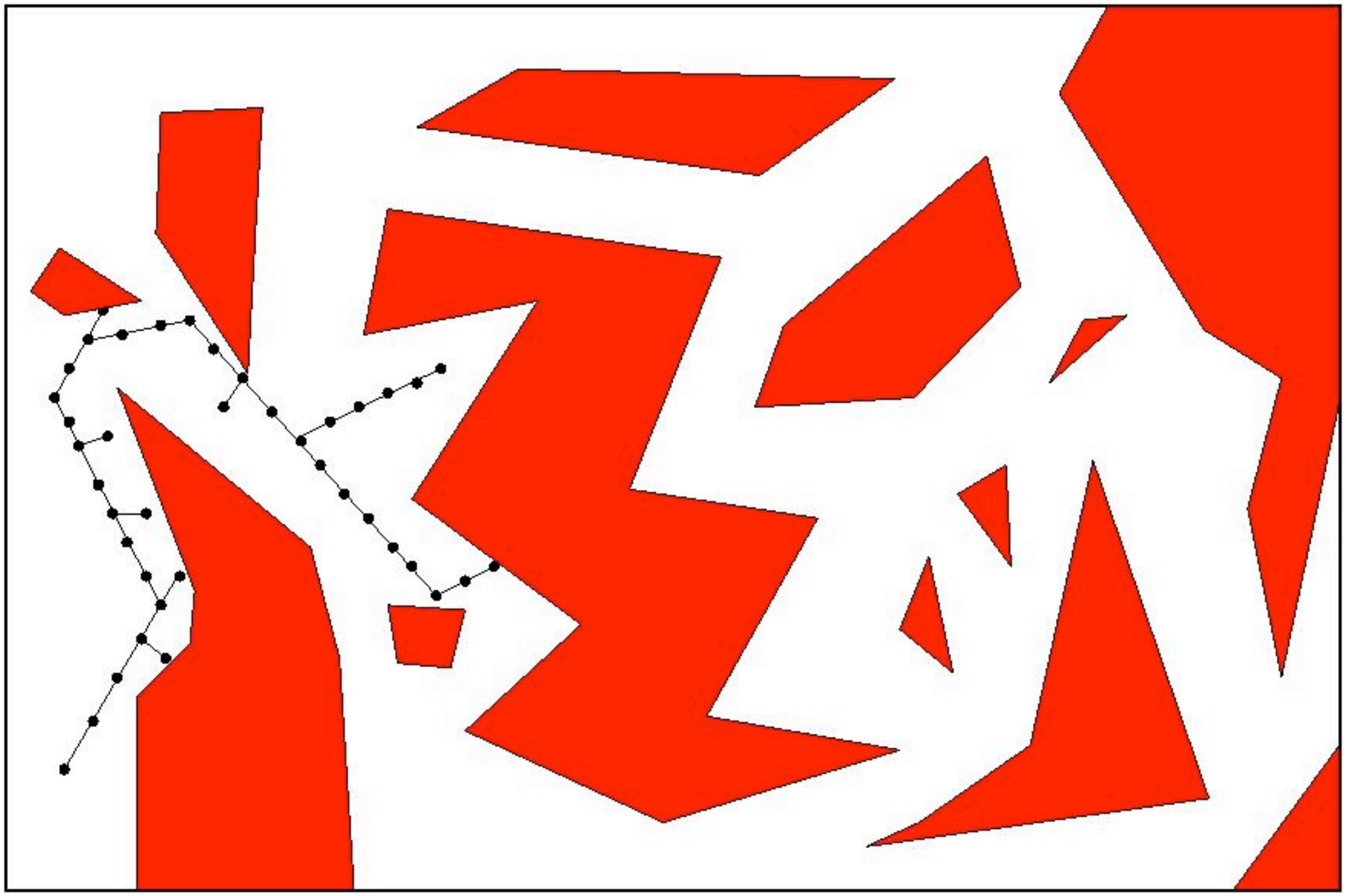


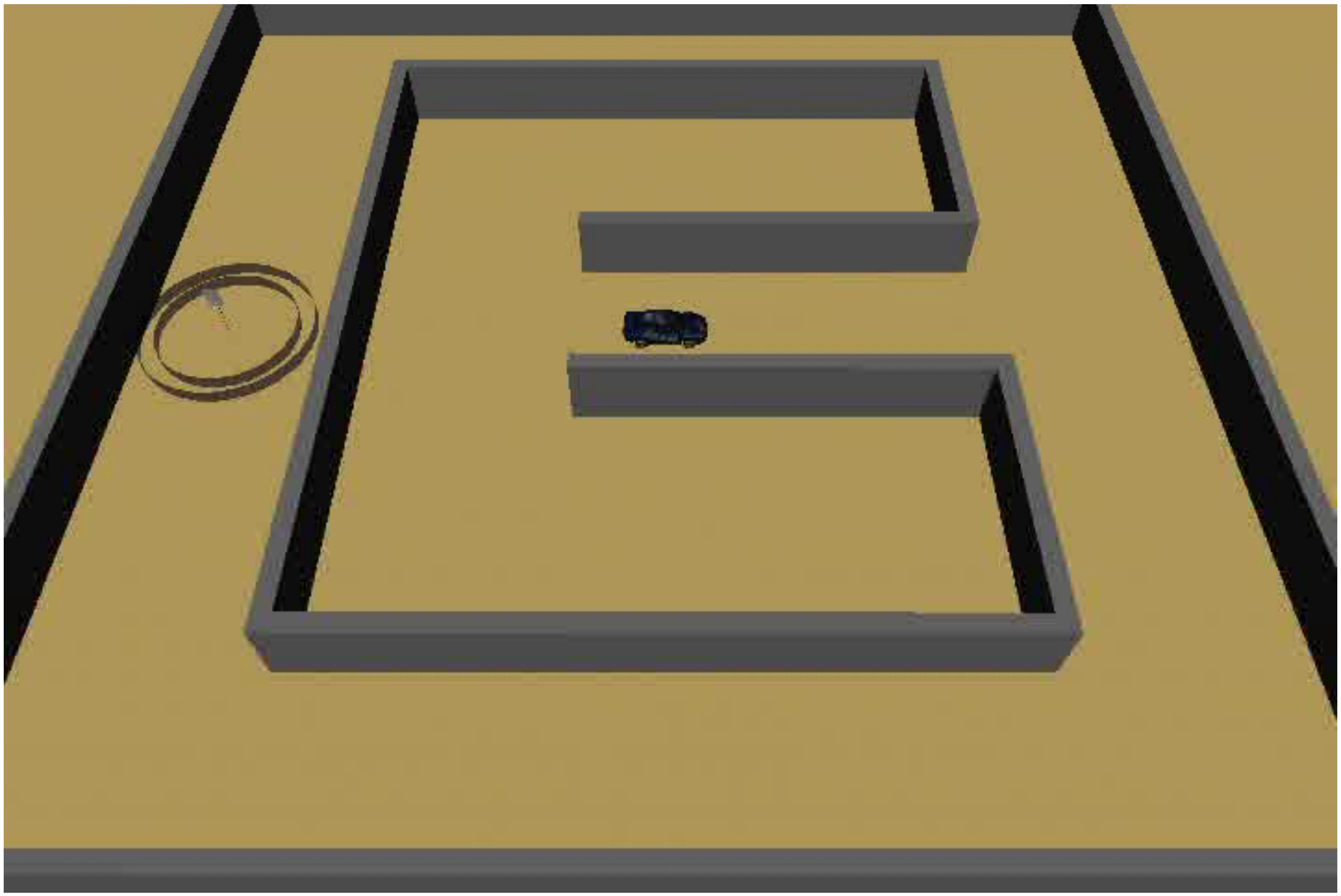
Tree-based planners

- Rapidly-exploring Random Tree (RRT) [KL99,LK01]
- Expansive Space Tree (EST) [H97,H00]
- Single Query Bidirectional Lazy Tree (SBL) [SL01]
- Guided Expansive Space Tree [PK03]
- Adaptive Dynamic Domain RRT [Y05]
- Utility-guided RRT [BB07]
- Particle RRT [NR07]
- …

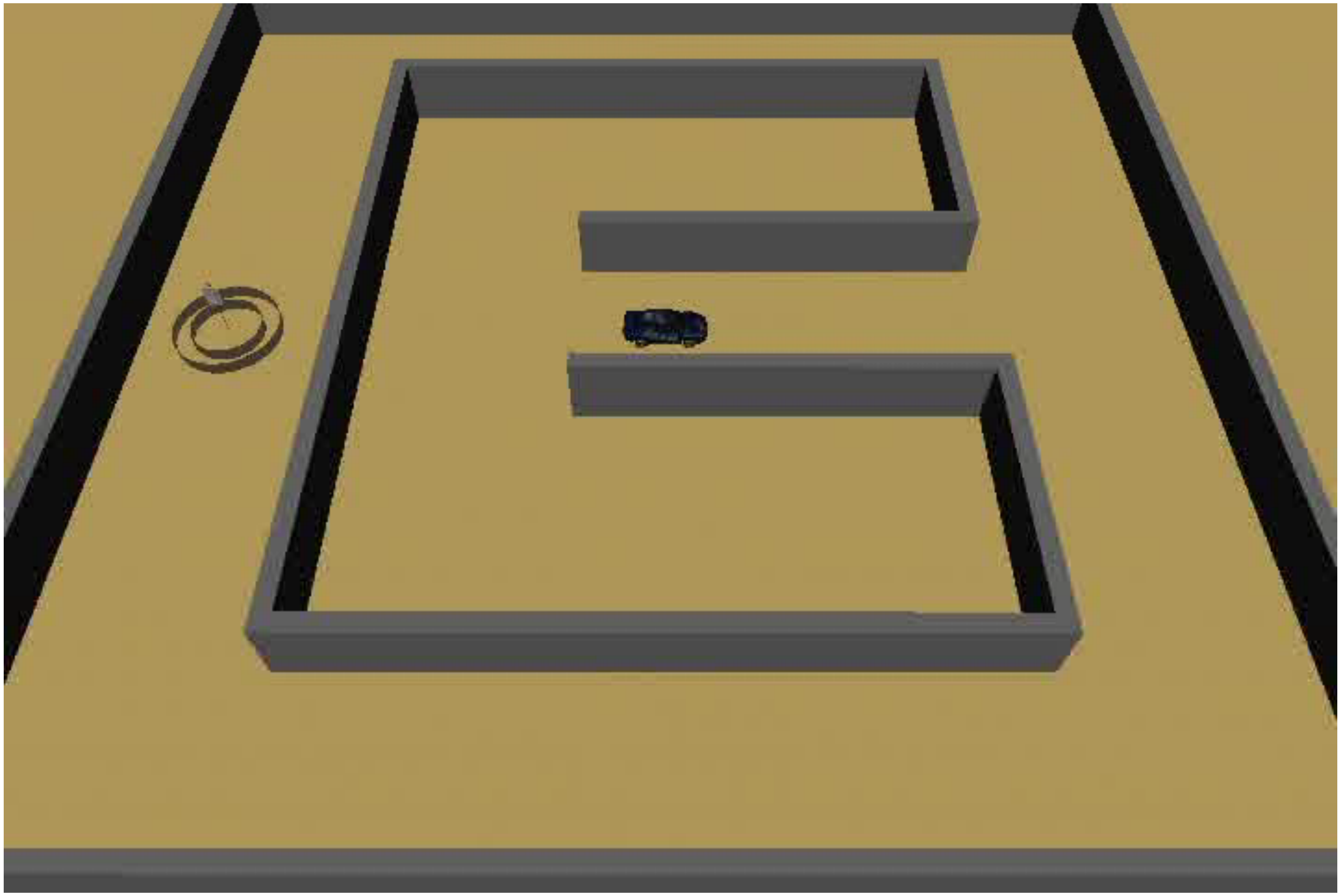
Non-holonomic and Kinodynamic planning

- Real robots have dynamic and actuation constraints
- Tree-based planners can easily accommodate a forward dynamics simulator to plan under realistic motion constraints
- Trees are directed data structures that nicely encode the notion of time
- Propagation is control based

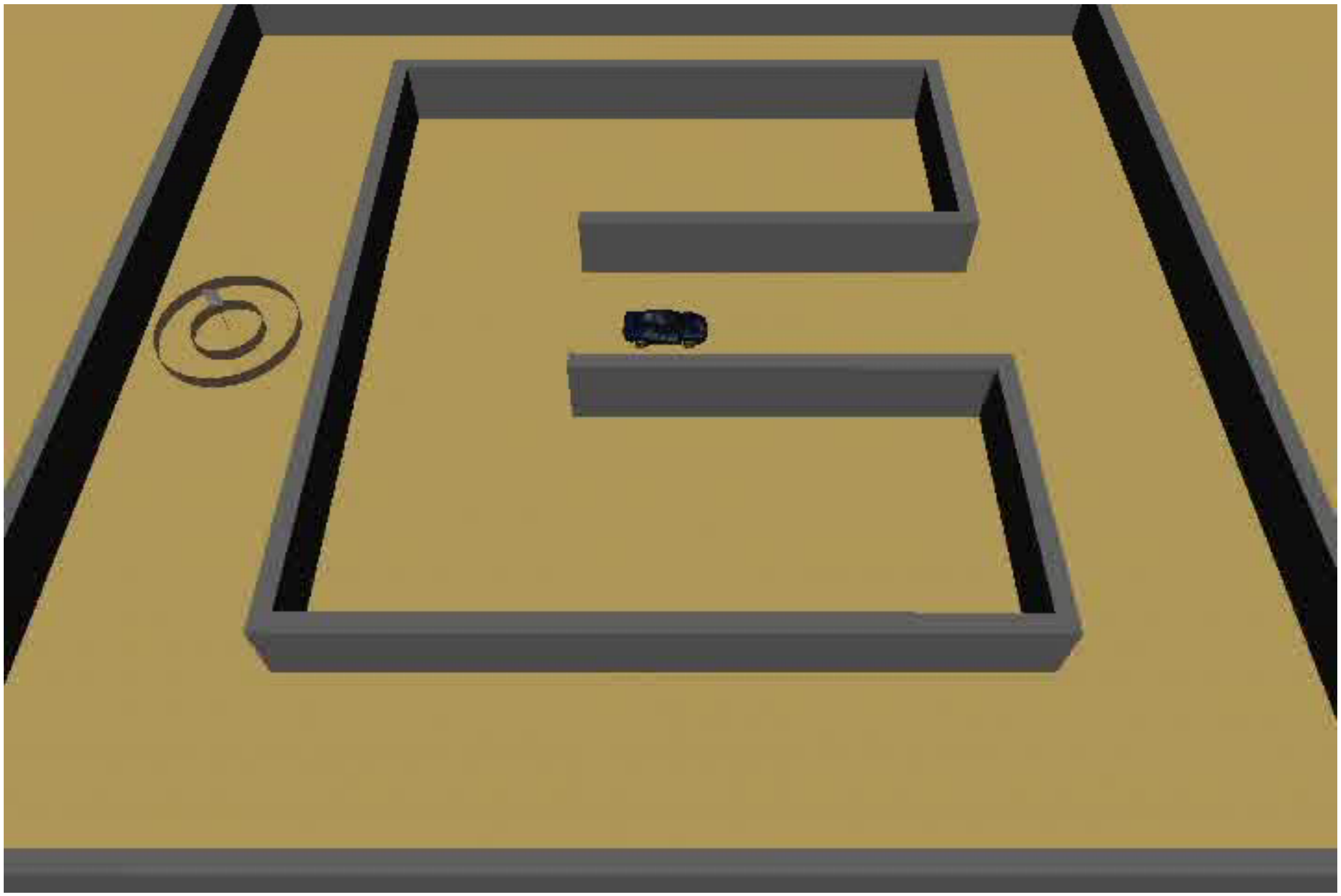
Path planning for a car (PRM)



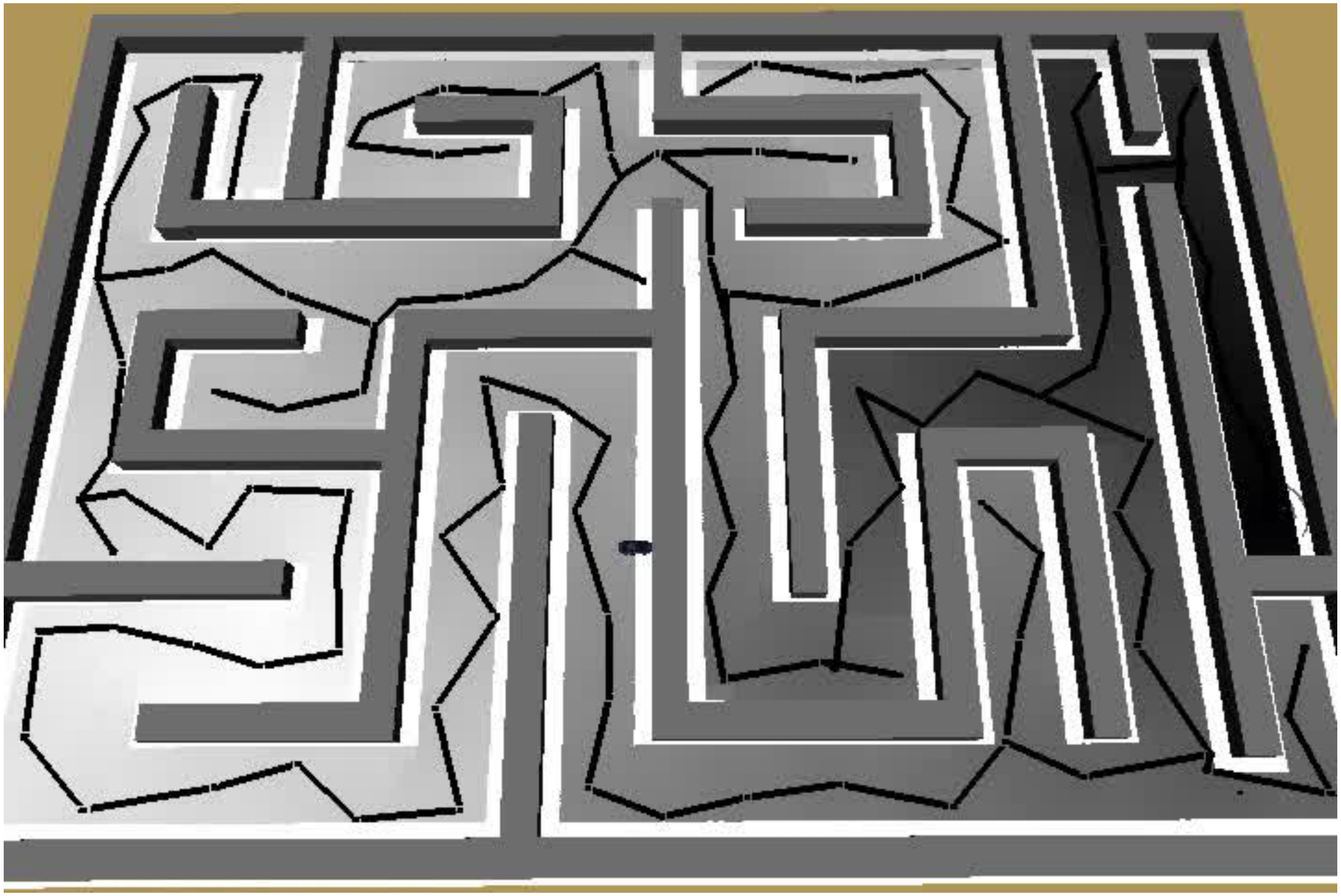
Planning with velocity control (IST)



Planning with acceleration control (IST)



Building a tree with IST

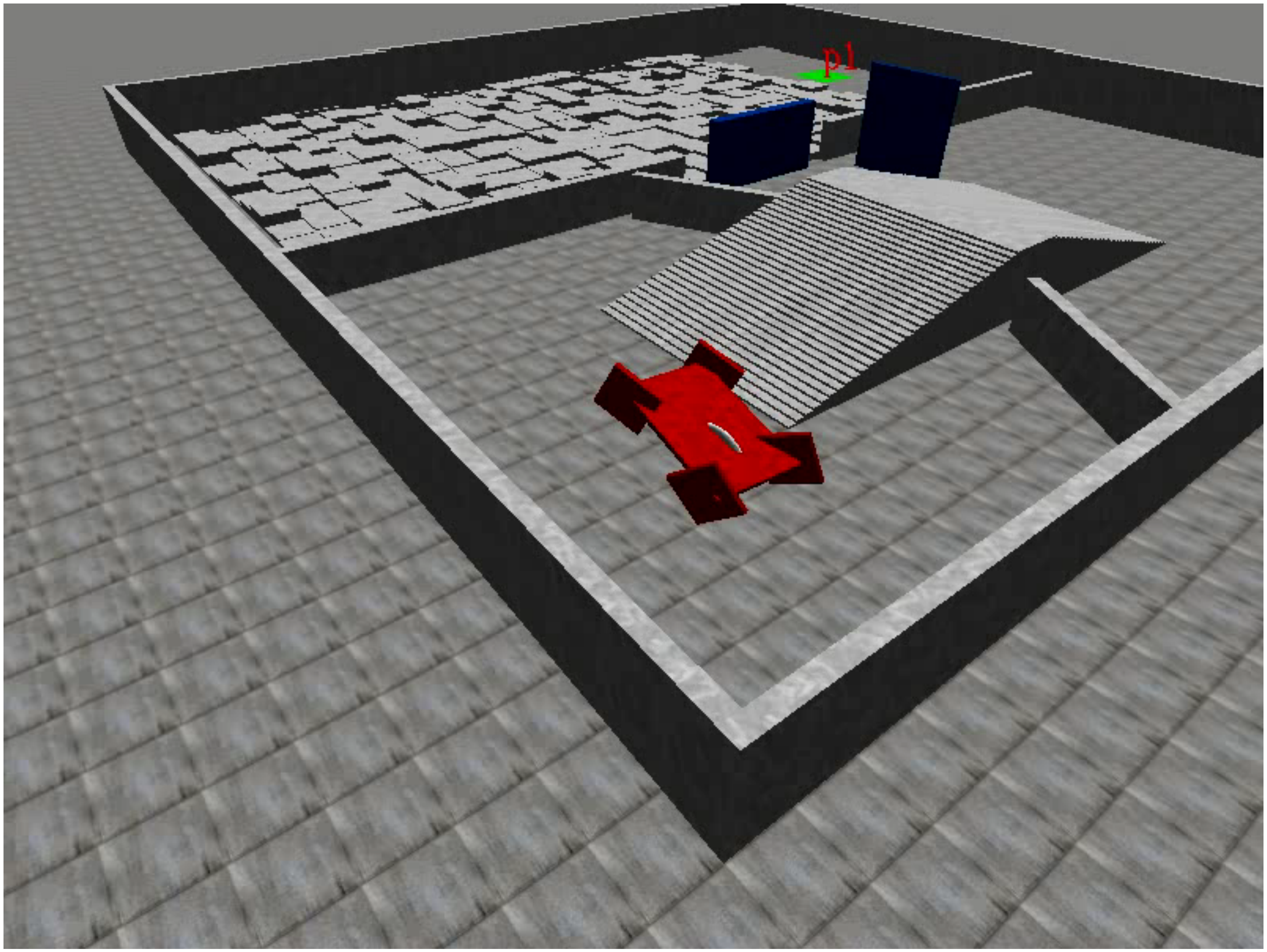


More examples from the latest planners

- DSLX
- KPIECE
- Real-time replanning
- Real-time multirobot exploration

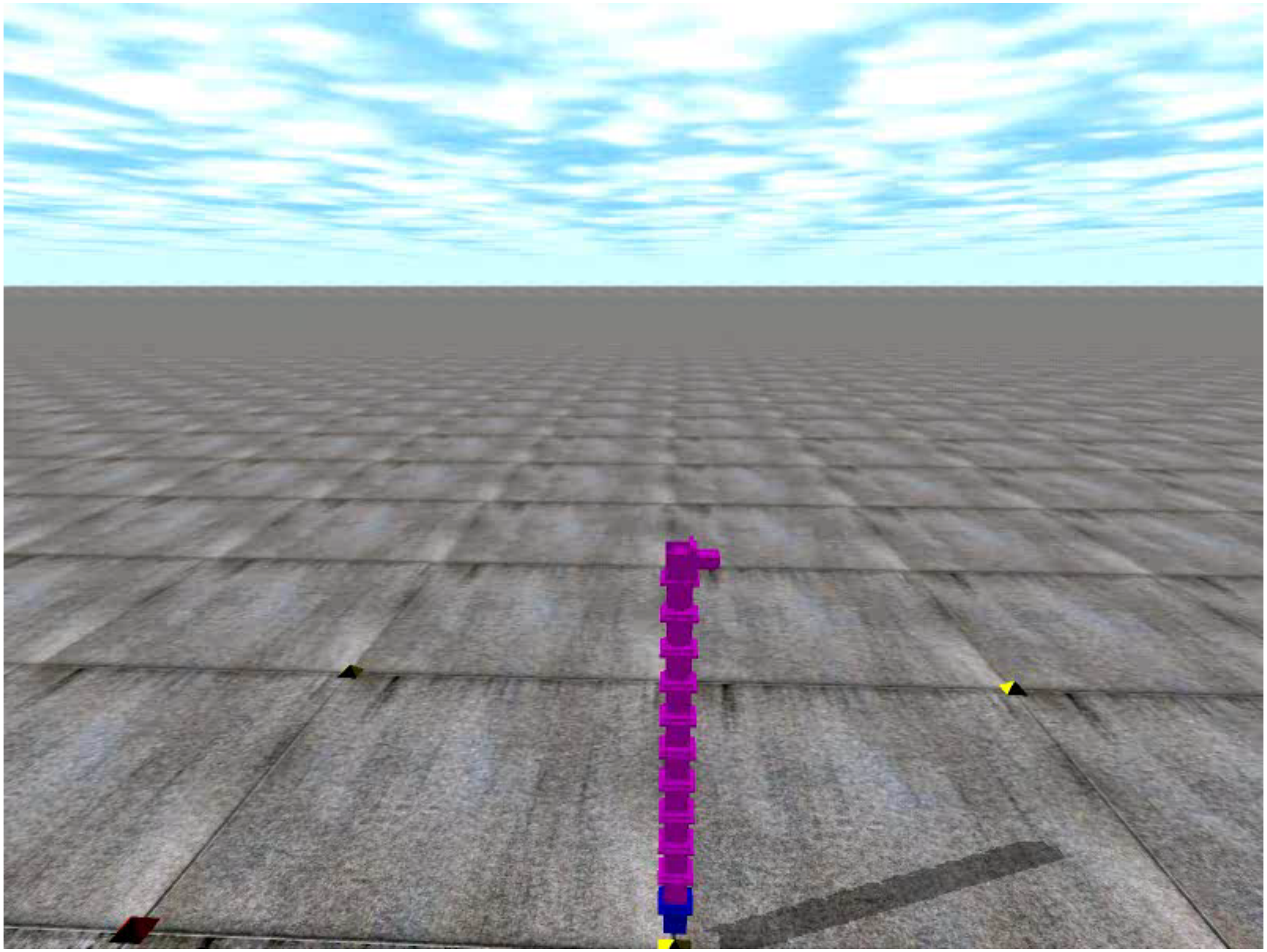
DSLX

Combining discrete search with continuous exploration

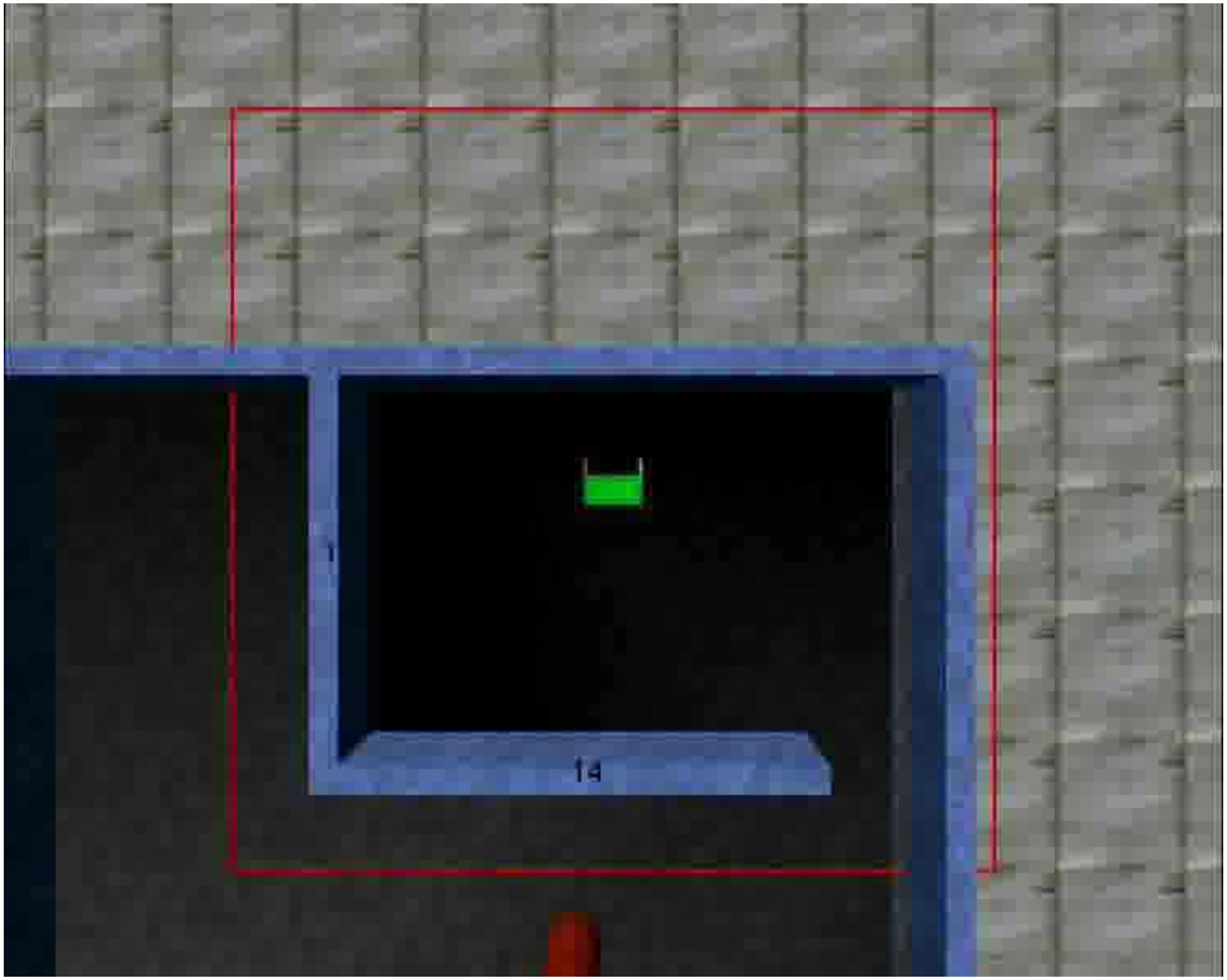


KPIECE

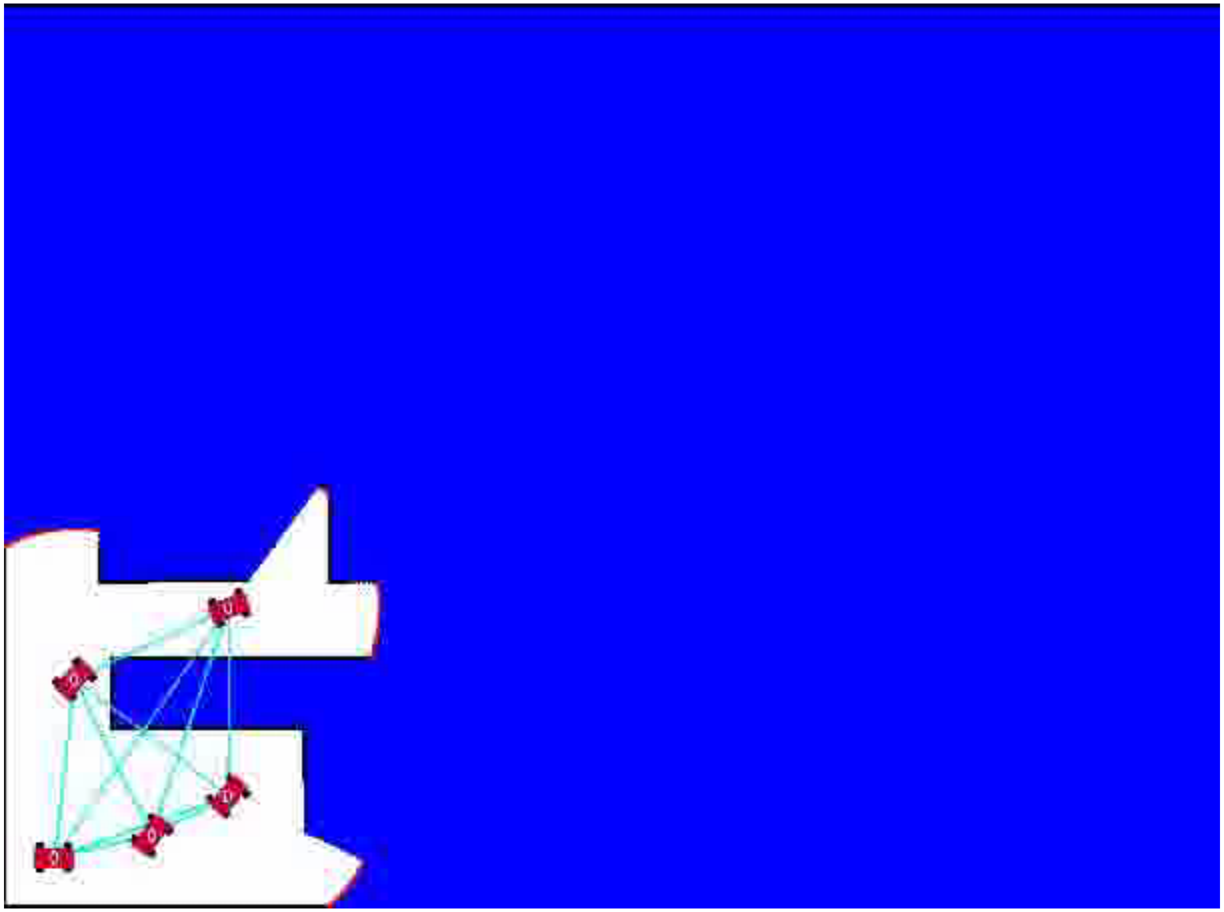
Planning in high dimensional state and control spaces



Planning in partially known environments within moving obstacles



Multirobot coordinated exploration



Some facts about sampling-based planners

- General and applicable to many different systems
- Very efficient on average, yielding solutions to many previously intractable problems
- Relatively simple to describe and implement
- Subject to problem specific optimizations

- At best only probabilistically complete
- Face difficulties in dealing with narrow passages

And some more facts…

- Sampling-based planners contain many standardized building blocks
- As planners get more complicated it is useful to not have to code the basic components again and again
- There is not common benchmarking platform and planning problems
- Performance comparisons are not always fair
- Speedups may be misleading due to non-uniform implementation details

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Where OOPSMP comes in

- Different planners can be tested on the exact same planning scenario
- All planners use common data structures and utilities
- "Quick and dirty" testing is possible due to many already existing planners and modules
- The focus can be on algorithmic aspects rather than implementation details
- Can be integrated with different visualization software and physics simulators for nicer looking and more realistic results
- OOPSMP is currently unique at providing a large variety of sampling-based motion planners, data structures and building blocks that are tuned for motion planning applications

Thank you!