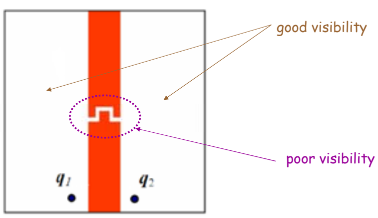
Sampling and Connection Strategies for Probabilistic Roadmaps

Two Types of Strategies

- Where to sample new milestones?
  → Sampling strategy
- Which milestones to connect?
  → Connection strategy
- Goal:
  Minimize roadmap size (~ running time) to correctly answer motion-planning queries

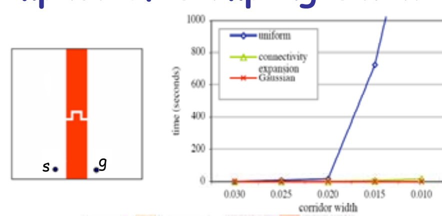
Rationale for Non-Uniform Strategies

Visibility is not uniformly favorable across free space

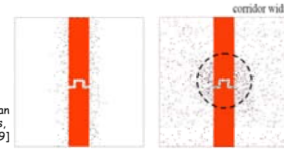


More samples and more connections should be tested in regions with poorer visibility

Impact of Sampling Strategy



Gaussian [Boor, Overmars, van der Stappen, 1999]



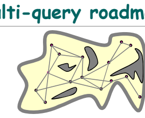
Connectivity expansion [Kavraki, 1994]

How to identify poor visibility regions?

- What is the sources of information?
  - Robot and workspace geometry
  - Current roadmap
- How to exploit it?
  - Workspace-guided strategies
  - Pattern-based filtering strategies
  - Adaptive and diffusive strategies
  - Dilatation/retraction strategies

Multi- vs. Single-Query Roadmaps

Multi-query roadmaps:

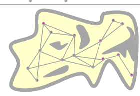


- Precompute + query roadmap

→ The roadmap must cover the feasible space well and capture the connectivity of the feasible space

Multi- vs. Single-Query Roadmaps

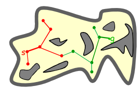
Multi-query roadmaps:



- Precompute + query roadmap

→ The roadmap must cover the feasible space well and capture the connectivity of the feasible space

Single-query roadmaps:



- Compute roadmap from scratch for each query

→ The roadmap should capture just enough of the connectivity of the feasible space to connect the start and goal configurations

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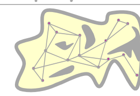
Multi- vs. Single-Query Roadmaps

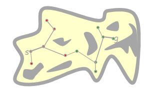
Multi-query roadmaps:



- Precompute + query roadmap

→ The roadmap must cover the feasible space well and capture the connectivity of the feasible space

Single-query roadmaps:



- Compute roadmap from scratch for each query

→ The roadmap should capture just enough of the connectivity of the feasible space to connect the start and goal configurations

Some strategies are more suitable for multi-query roadmaps, others for single query-roadmaps

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- Workspace-guided strategies
  Identify narrow passages in the workspace and map them into the configuration space
- Pattern-based filtering strategies
  Sample many configurations, find interesting patterns, and retain only promising configurations
- Adaptive and diffusive strategies
  Adjust the sampling distribution (π) on the fly
- Dilatation/retraction strategies
  Dilate the feasible space to make it more expansive

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Workspace-Guided Strategies

- Rationale: Most narrow passages in the feasible space are caused by narrow passages in the workspace
- Method:
  - Detect narrow passages in the workspace (e.g., cell decomposition, medial-axis transform)
  - Sample robot configurations that place selected robot points in workspace's narrow passages

- H. Kurniawati and D. Hsu. Workspace importance sampling for probabilistic roadmap planning. In Proc. IEEE/RSJ Int. Conf. on Intelligent Robots & Systems, pp. 1618-1623, 2004.
- J.P. van den Berg and M. H. Overmars. Using Workspace Information as a Guide to Non-Uniform Sampling in Probabilistic Roadmap Planners. IJRR, 24(12):1055-1071, Dec. 2005.

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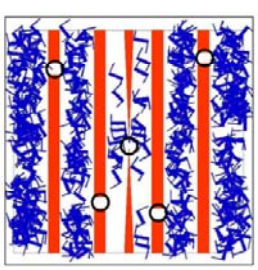
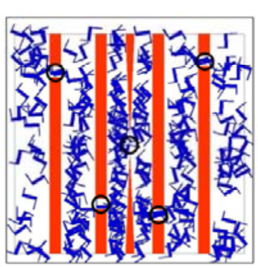
Workspace-Guided Strategies



Uniform sampling



Workspace-guided sampling

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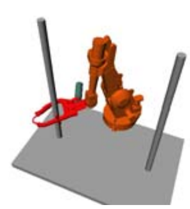
Limitations

- Works well for rigid objects, but not so well for articulated robots, such as manipulator arms Why?
- Not all narrow passages are obvious to detect in workspace



What are the narrow passages?

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Non-Uniform Sampling Strategies

- Workspace-guided strategies
- Pattern-based filtering strategies
- Adaptive and diffusive strategies
- Deformation strategies

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Filtering Strategies

Main Idea:

- Sample several configurations in the same small region of configuration space
- If a "pattern" is detected, then retain one of the configurations as a milestone

→ More sampling work, but better distribution of nodes

→ Less time wasted later connecting "non-interesting" milestones

Methods:

- Gaussian sampling
- Bridge Test
- Hybrid

- V. Boor, M. H. Overmars, and A. F. van der Stappen. The Gaussian sampling strategy for probabilistic roadmap planners. In Proc. 1999 IEEE Int. Conf. Robotics and Automation, 1999, pp. 1018–1023.

- Z. Sun, D. Hsu, T. Jiang, H. Kurniawati, and J. Reif . Narrow passage sampling for probabilistic roadmap planners. IEEE Trans. on Robotics, 21(6):1105–1115, 2005.

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Gaussian Sampling

1) Sample a configuration q uniformly at random from configuration space
2) Sample a direction u in configuration space uniformly at random and a distance d with Gaussian distribution $\mathcal{N}_{[0,\sigma]}$. Set q' to the configuration a distance d from q along direction u
3) If only one of q and q' is in feasible space, retain the one in feasible space as a milestone; else retain none

What is the effect?
What is the intuition?

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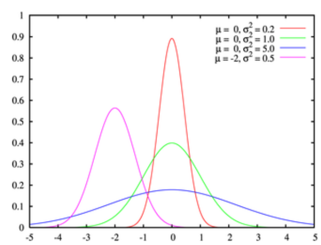
Gaussian Distribution

$$\mathcal{N}_{[\mu,\sigma]}(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$



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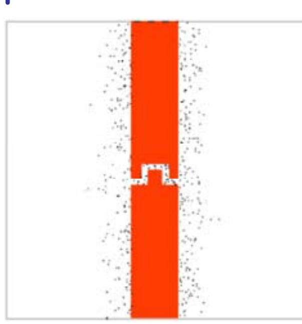
Example of Node Distribution



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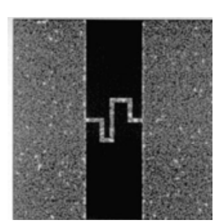
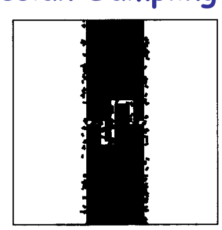
Uniform vs. Gaussian Sampling



Milestones (13,000) created by uniform sampling before the narrow passage was adequately sampled



Milestones (150) created by Gaussian sampling

The gain is not in sampling fewer milestones, but in connecting fewer pairs of milestones

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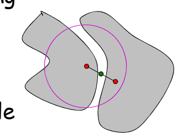
Bridge Test

1) Sample two conformations q and q' using Gaussian sampling technique
2) If none is in feasible space, then

   if $q_m = (q+q')/2$ is in feasible space, then retain q_m as a milestone
3) Else retain none



What is the effect?
What is the intuition?

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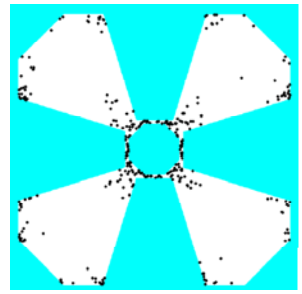
Example of Distribution Generated Using Bridge Test



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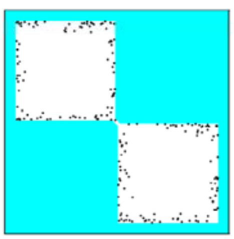
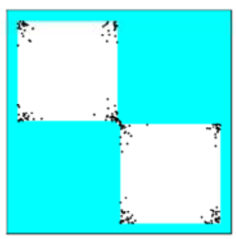
Gaussian vs. Bridge Test



Gaussian



Bridge test

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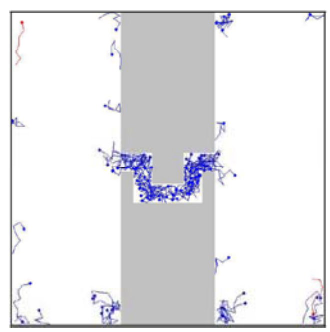
Another Example of Bridge-Test Distribution

8-joint robot
with mobile base



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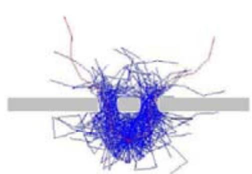
Another Example of Bridge-Test Distribution

7-joint robot
with fixed base



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Drawback of Gaussian and Bridge-Test Sampling

They assume the existence of nasty narrow passages

→ They are slow when there are none!

Solution: Hybrid adaptive strategy
(a combination of strategies)

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One Possible Hybrid Sampling Strategy

At each sampling operation do the following:

1) With probability π_1 sample a milestone using Bridge-Test sampling and exit
2) With probability π_2 sample a milestone using Gaussian sampling and exit
3) Sample a milestone uniformly at random

Start with $\pi_1 = 0$ and $\pi_2 = 0$.

After N_1 milestones have been generated,
increase π_2 slowly after each sampling operation.

After $N_2 > N_1$ milestones have been generated,
increase π_1 slowly (but at a slightly faster rate than π_2).

What is the intuition?

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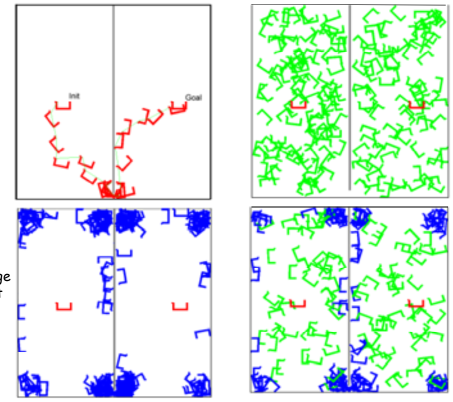

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Non-Uniform Sampling Strategies

- Workspace-guided strategies
- Pattern-based filtering strategies
- Adaptive and diffusive strategies
- Dilatation/retraction strategies

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Adaptive/Diffusive Strategies

Main idea:

Use information gathered during roadmap construction to adjust the sampling probability measure
→ Time-varying sampling measure

Methods:

- Identification of "difficult" regions
- Diffusion
- Adaptive steps
- $\pi = \alpha_1\pi_1 + \alpha_2\pi_2 + \ldots + \alpha_n\pi_n$, where the π_i are constant and the π_i are adjusted, e.g., using machine learning techniques

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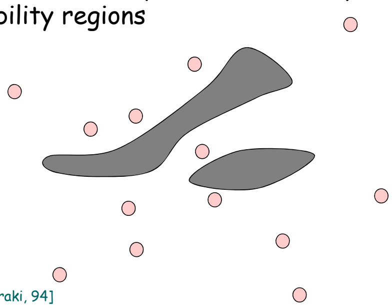
Connectivity Expansion

Use work already done to detect poor-visibility regions



[Kavraki, 94]

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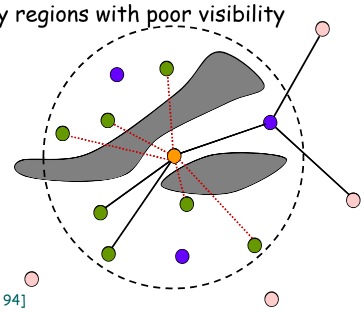
Detection of "Difficult" Regions

Idea: Use failures to connect milestones to identify regions with poor visibility



[Kavraki, 94]

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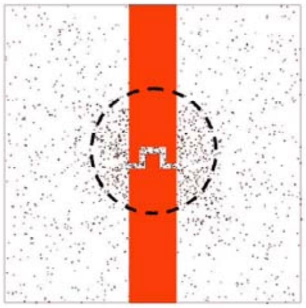
Example of Distribution



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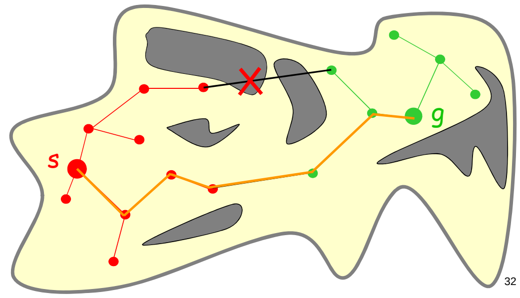
Diffusion Strategy

Idea: Grow distributions from "seed" configurations (e.g., the start and the goal configurations)



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Diffusion Strategy

Idea: Grow distributions from "seed" configurations (e.g., the start and the goal configurations)

Two main techniques:

- Pick a milestone q with probability proportional to the inverse of the local sampling density.
  Sample a new configuration q' at random around q
- Pick a conformation q_r at random in configuration space.
  Identify the closest milestone q from q_r.
  Sample a new configuration q' at random around q, possibly in the direction of q_r (RRT)

Intuition?

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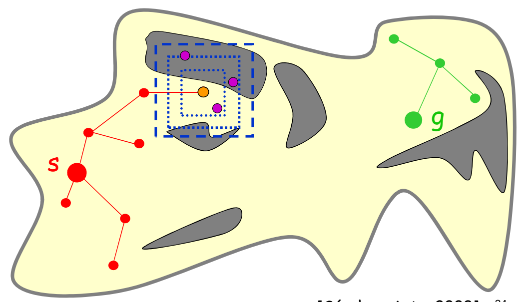
Adaptive-Step Sampling



[Sánchez-Ante, 2003]

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Non-Uniform Sampling Strategies

- Workspace-guided strategies
- Pattern-based filtering strategies
- Adaptive and diffusive strategies
- Dilatation/retraction strategies

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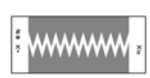
Dilatation/Retraction Strategies

Main idea:

Dilate the feasible space to make it more expansive

Motivation:



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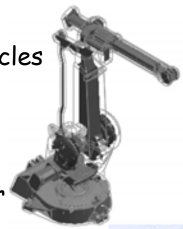
Feasible Space Dilatation

1. Pre-computation:
   Slim the robot / obstacles
2. Planning:
   - Compute a path for slimmed robot
   - Deform this path for original robot



-M. Saha, J.C. Latombe, Y.-C. Chang, F. Prinz. Finding Narrow Passages with Probabilistic Roadmaps: The Small-Step Retraction Method. Autonomous Robots, 19(3):301-319, Dec. 2005.

-H.-L. Cheng, D. Hsu, J.-C. Latombe, and G. Sánchez-Ante . Multi-level free-space dilation for sampling narrow passages in PRM planning. Proc. IEEE Int. Conf. on Robotics & Automation, 2006.

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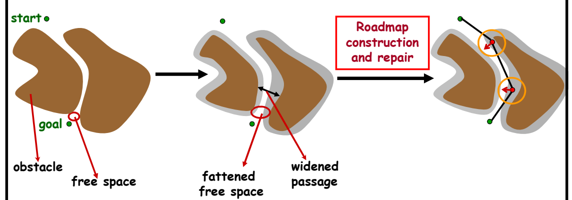
Free Space Dilatation



→ ~ up to 2 orders of magnitude speedup

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Connection Strategies

- Limit number of connections:
  - Nearest-neighbor strategy
  - Connected component strategy
- Increase expansiveness:
  - Library of local path shapes [Amato 98]
  - Local search strategy [Isto 04]
- Delay costly computation:
  - Lazy collision checking [Sanchez-Ante, 02]

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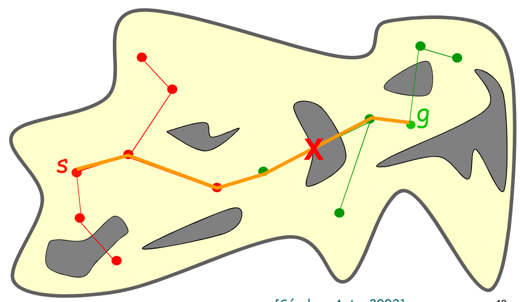
Lazy Collision Checking



[Sánchez-Ante, 2002]

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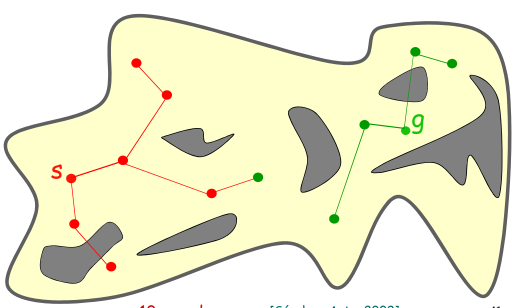
Lazy Collision Checking



x10 speedup

[Sánchez-Ante, 2002]

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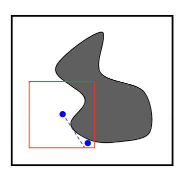
Rationale of Lazy Collision Checking



- Connections between close milestones have high probability of being free of collision
- Most of the time spent in collision checking is done to test connections
- Most collision-free connections will not be part of the final path
- Testing connections is more expensive for collision-free connections
- **Hence: Postpone the tests of connections until they are absolutely needed**

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Example of Integration

SBL (http://ai.stanford.edu/~mitul/mpk/):

- Single-query planner
- Grows two trees from start and goal configurations
- Uses:
  - density-based diffusive strategy
  - adaptive-step strategy
  - dilatation-retraction strategy
  - lazy collision-checking connection strategy

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