Motion Planning:

A Journey of Robots, Digital Actors, Molecules and Other Artifacts

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My Research Interests

- Autonomous agents that sense, plan, and act in real and/or virtual worlds
- Algorithms and systems for representing, capturing, planning, controlling, and rendering motions of physical objects
- Applications:
  - Manufacturing
  - Mobile robots
  - Computational biology
  - Computer-assisted surgery
  - Digital actors

Goal of Motion Planning

- Compute motion strategies, e.g.:
  - geometric paths
  - time-parameterized trajectories
  - sequence of sensor-based motion commands
- To achieve high-level goals, e.g.:
  - go to A without colliding with obstacles
  - assemble product P
  - build map of environment E
  - find object O

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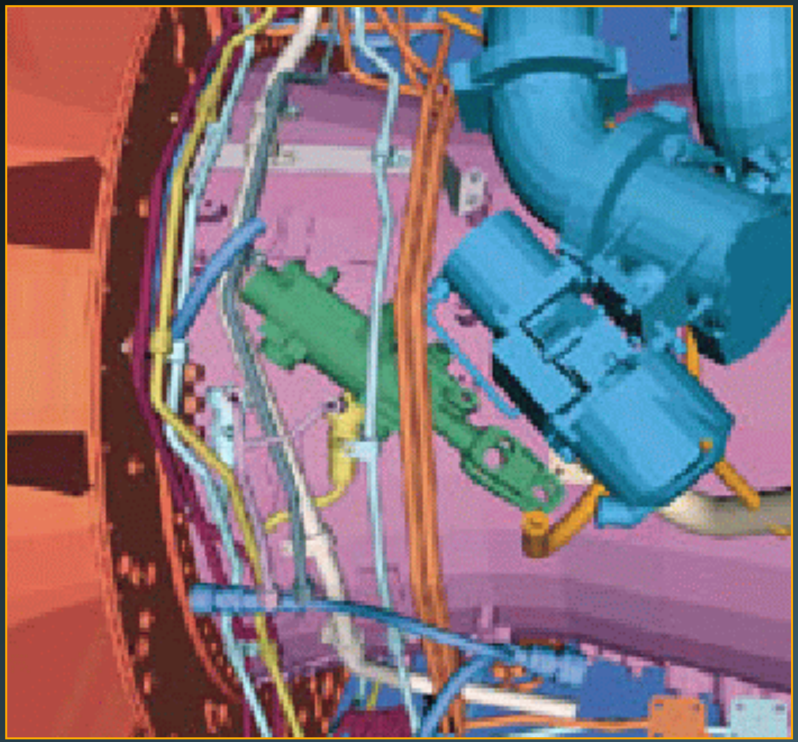
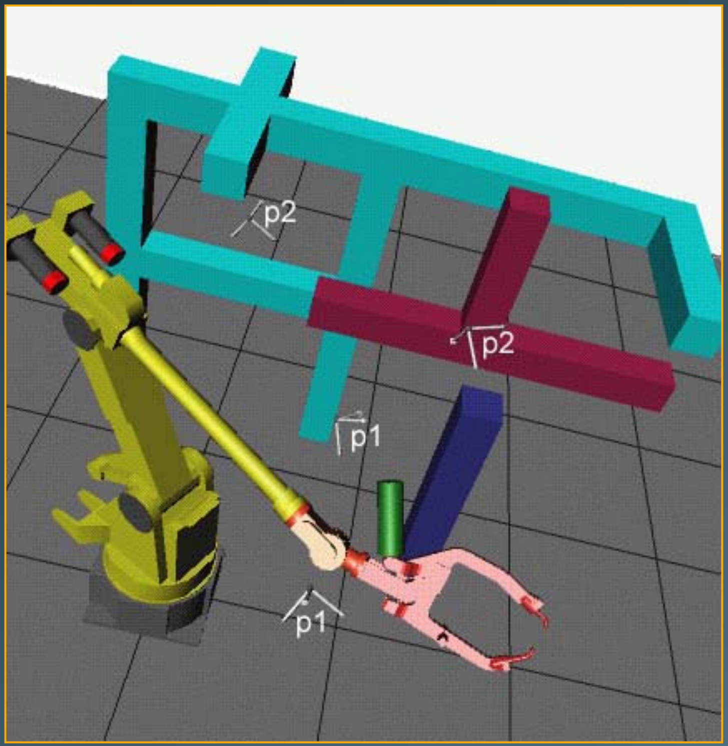
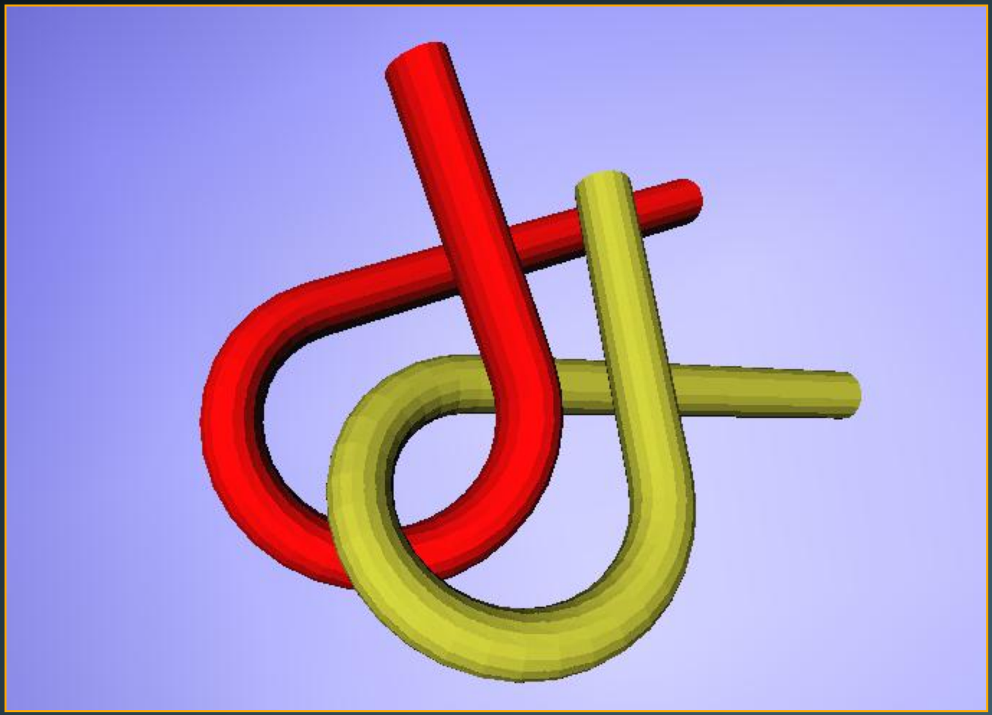
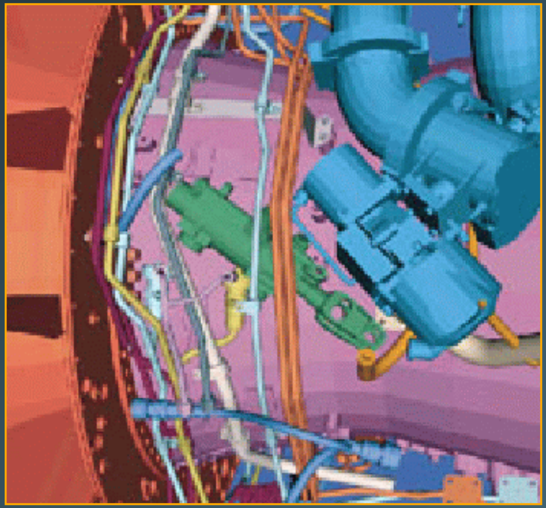
Examples

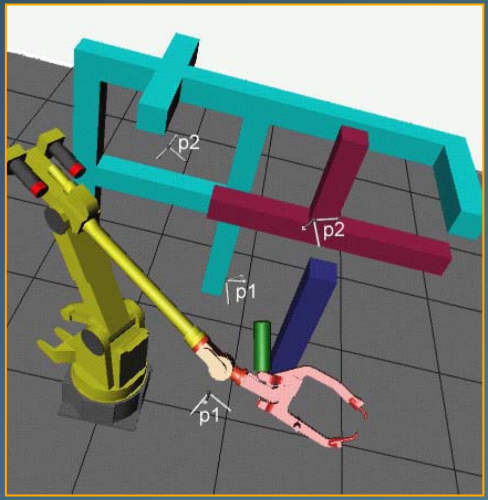




Is It Easy?



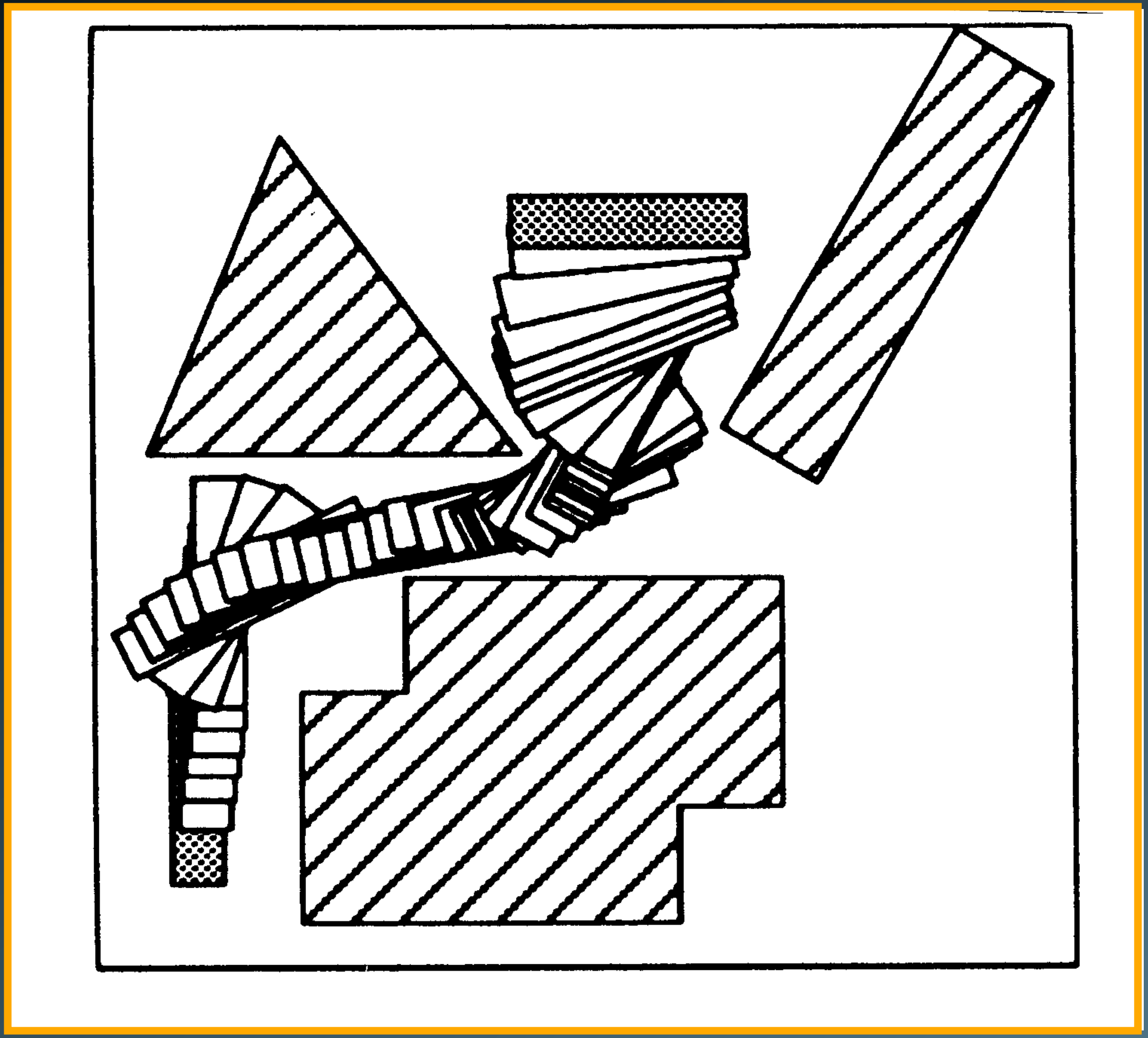




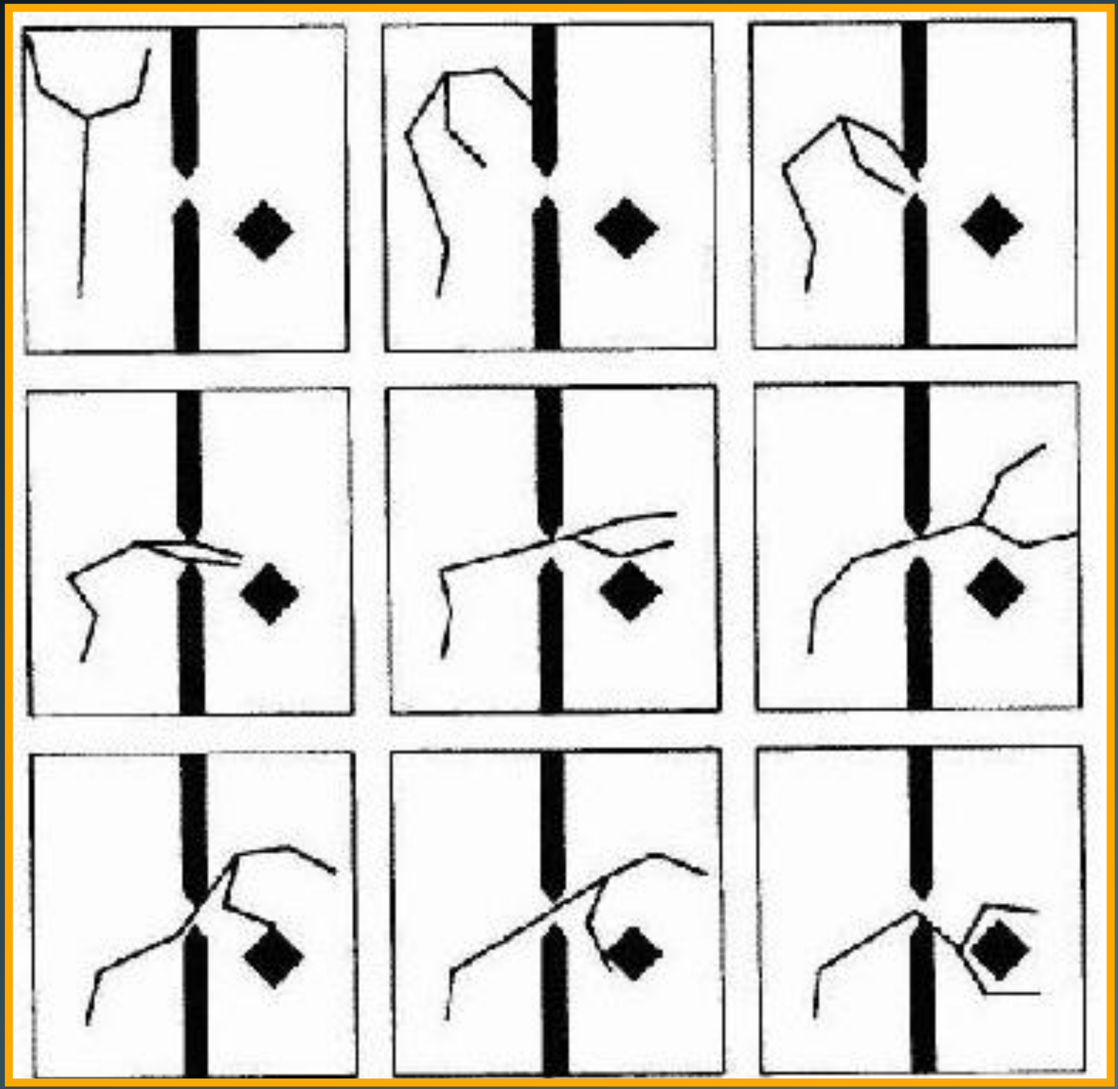
Basic Problem

- Statement:
  Compute a collision-free path for a rigid or articulated object (the robot) among static obstacles
- Inputs:
  - Geometry of robot and obstacles
  - Kinematics of robot (degrees of freedom)
  - Initial and goal robot configurations (placements)
- Outputs:
  - Continuous sequence of collision-free robot configurations connecting the initial and goal configurations

Example with Rigid Object



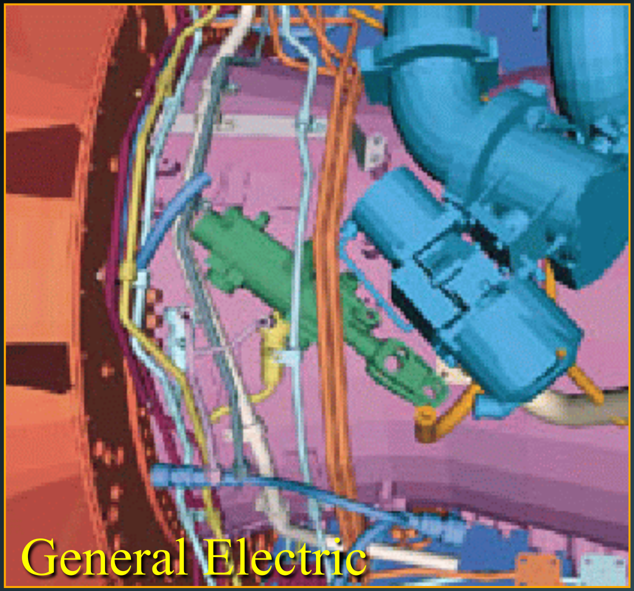
Example with Articulated Object

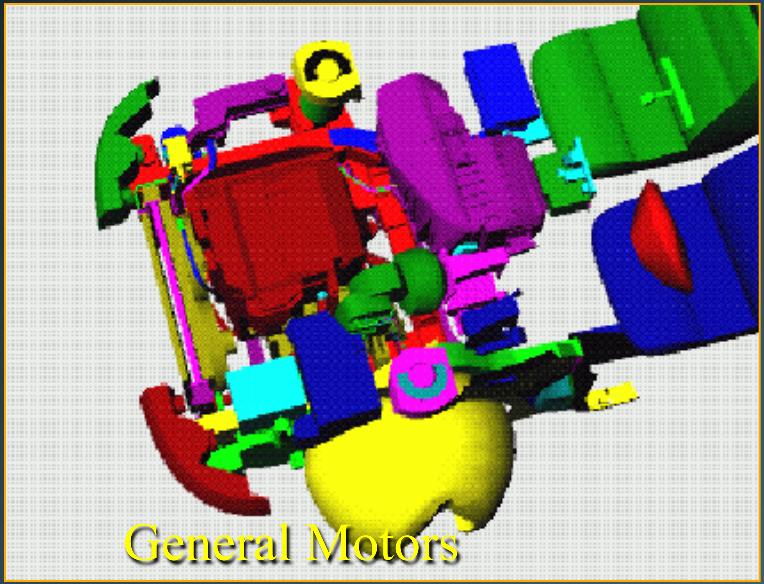


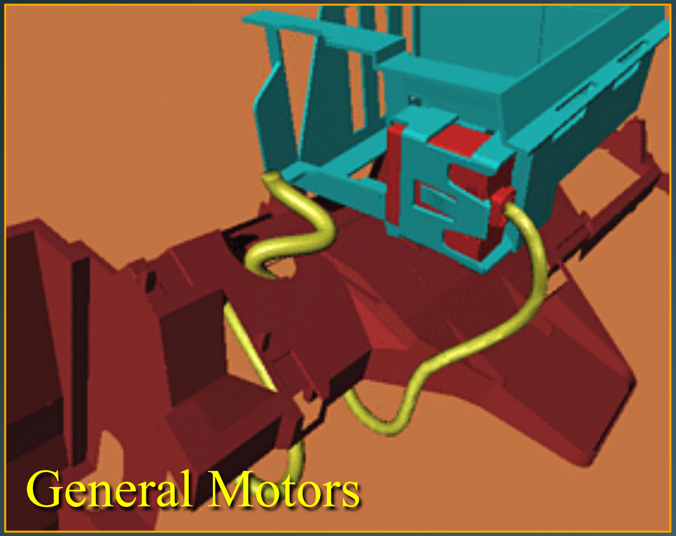
Extensions to the Basic Problem

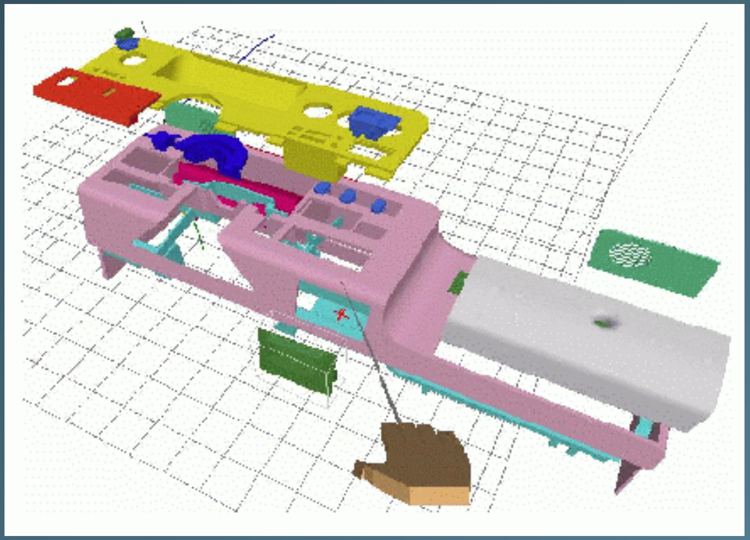
- Moving obstacles
- Multiple robots
- Movable objects
- Deformable objects
- Goal is to gather data by sensing
- Nonholonomic constraints
- Dynamic constraints
- Optimal planning
- Uncertainty in control and sensing

Application: Design for Manufacturing

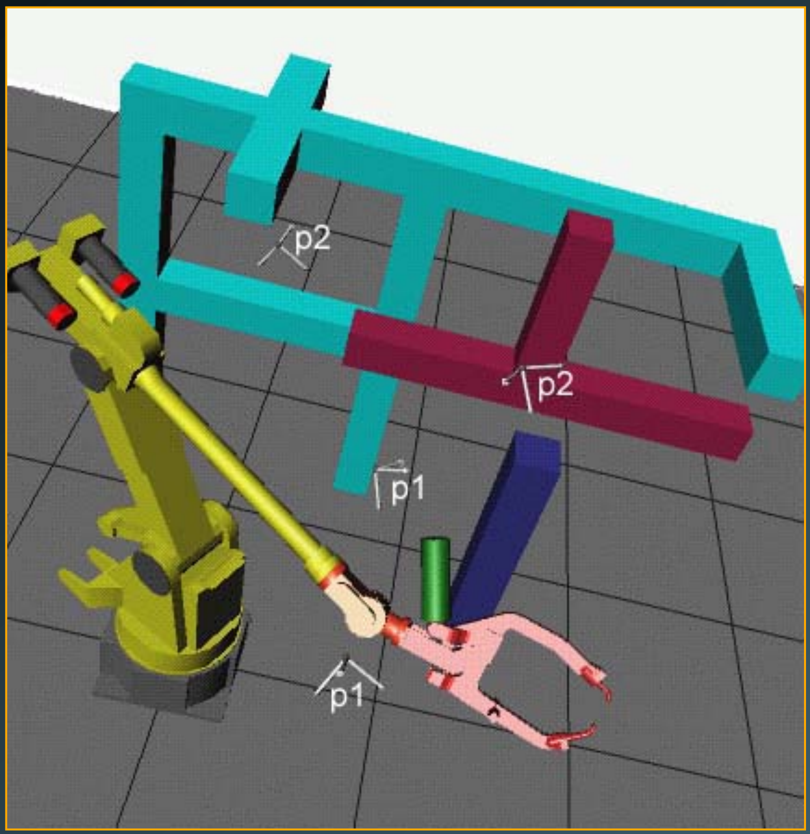


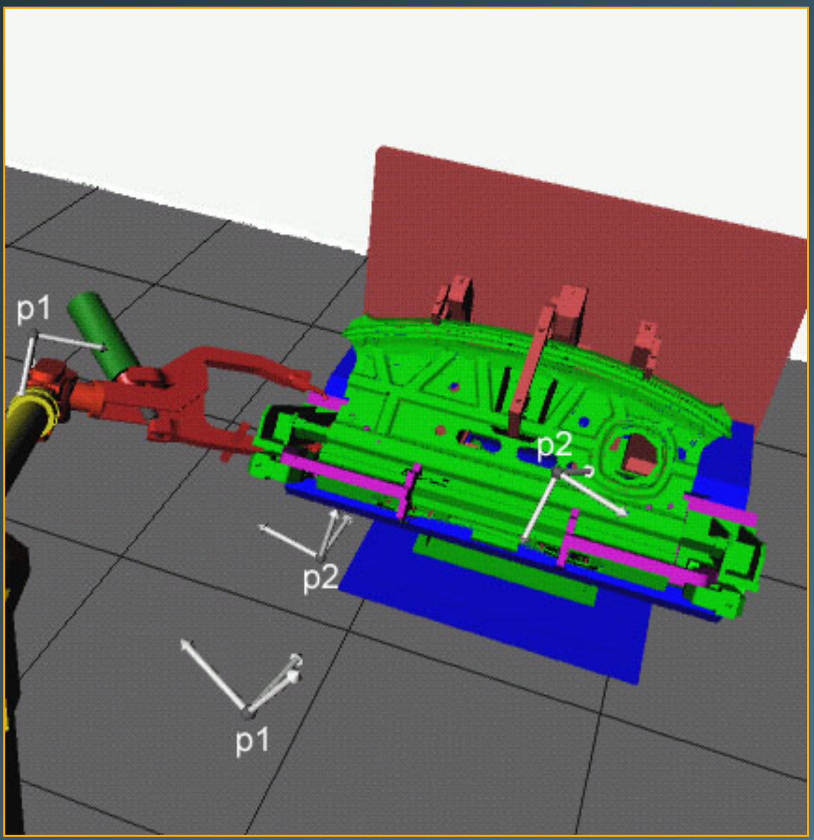






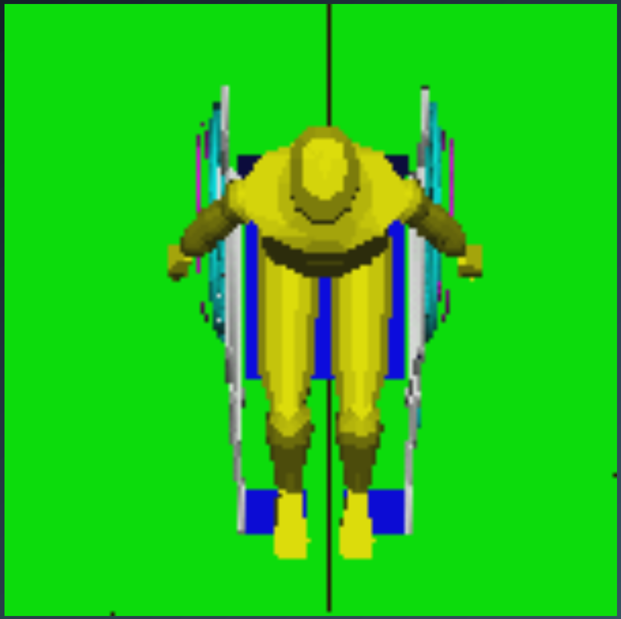
Application: Robot Programming and Placement

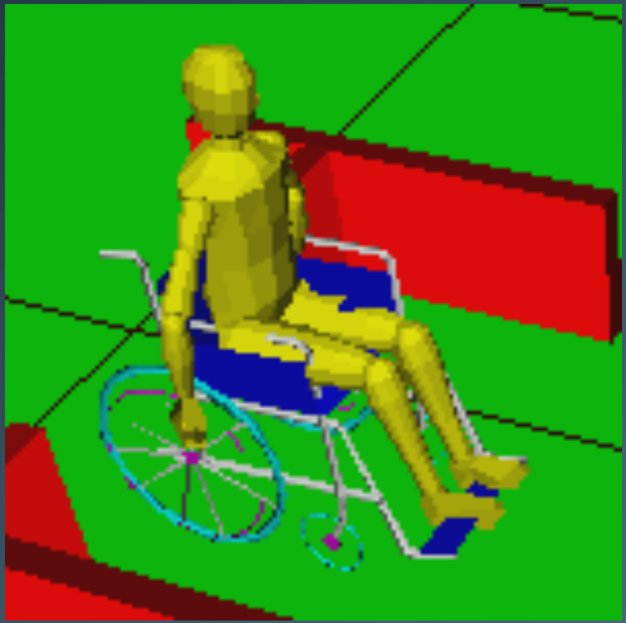




David Hsu’s PhD

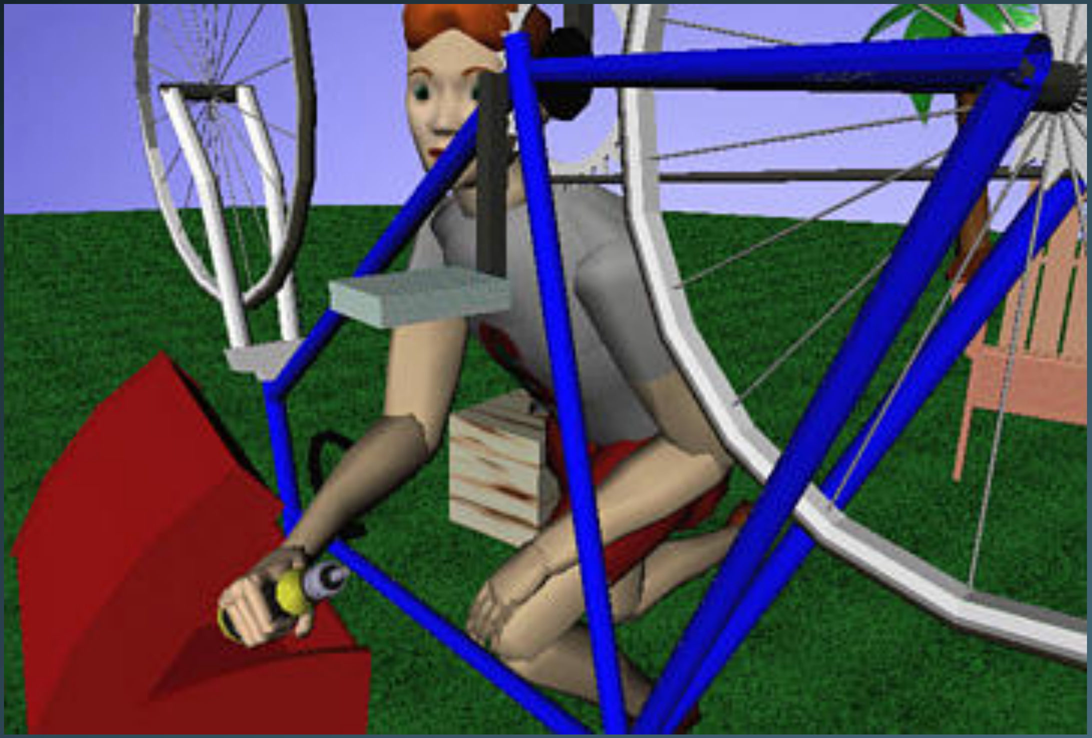
Application: Checking Building Code



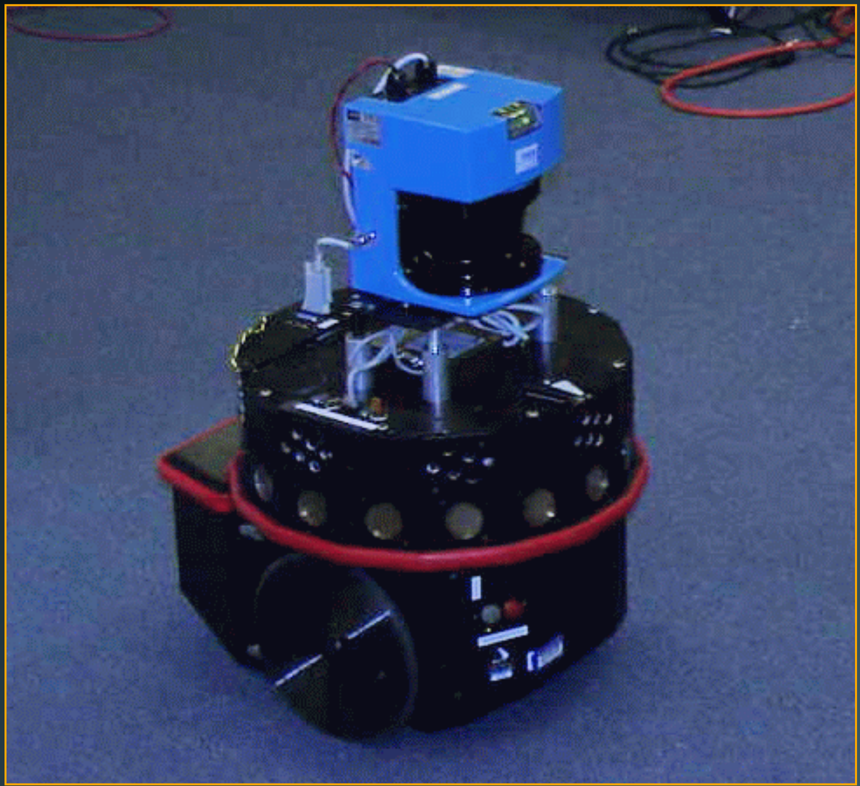


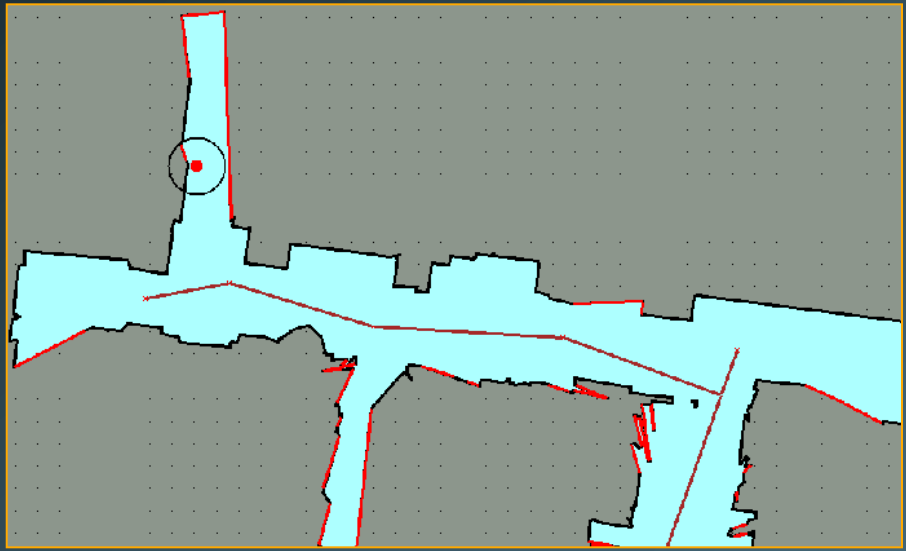
Charles Han's PhD

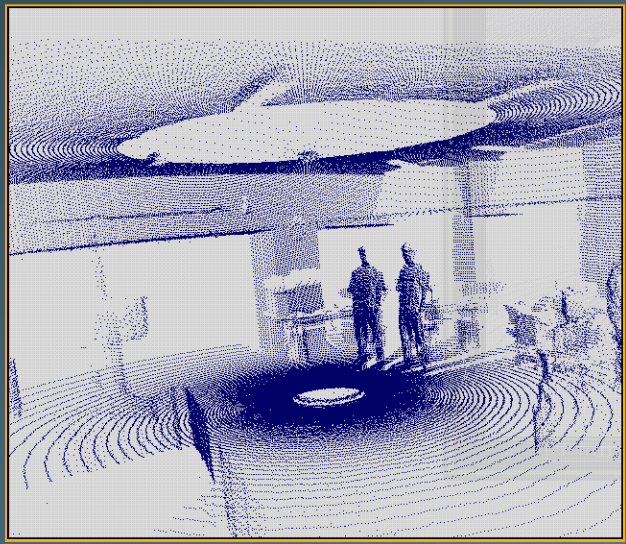
Application: Generation of Instruction Sheets



Application: Model Construction by Mobile Robot





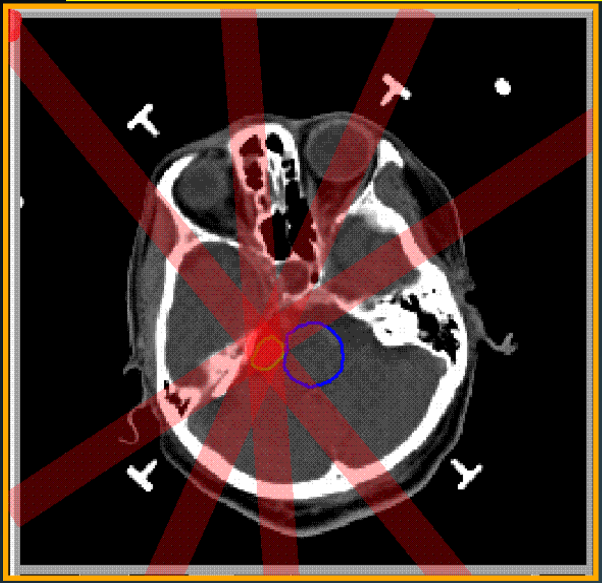


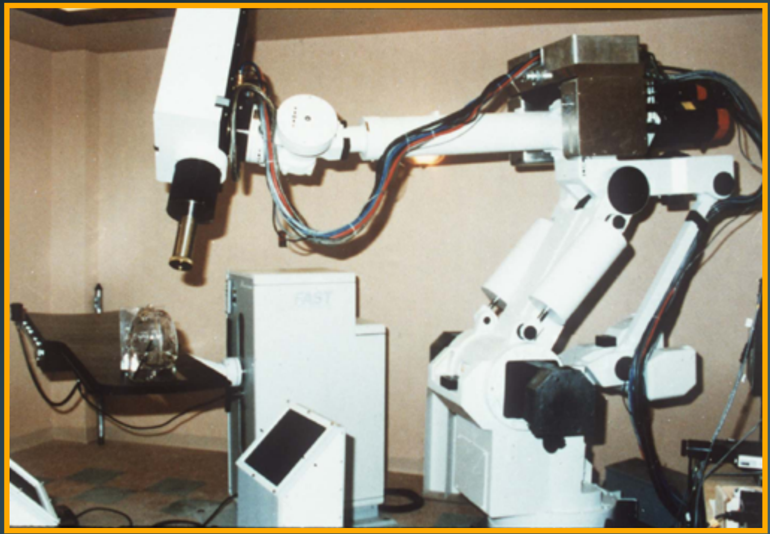
Hector Gonzalez's PhD

Application: Graphic Animation of Digital Actors

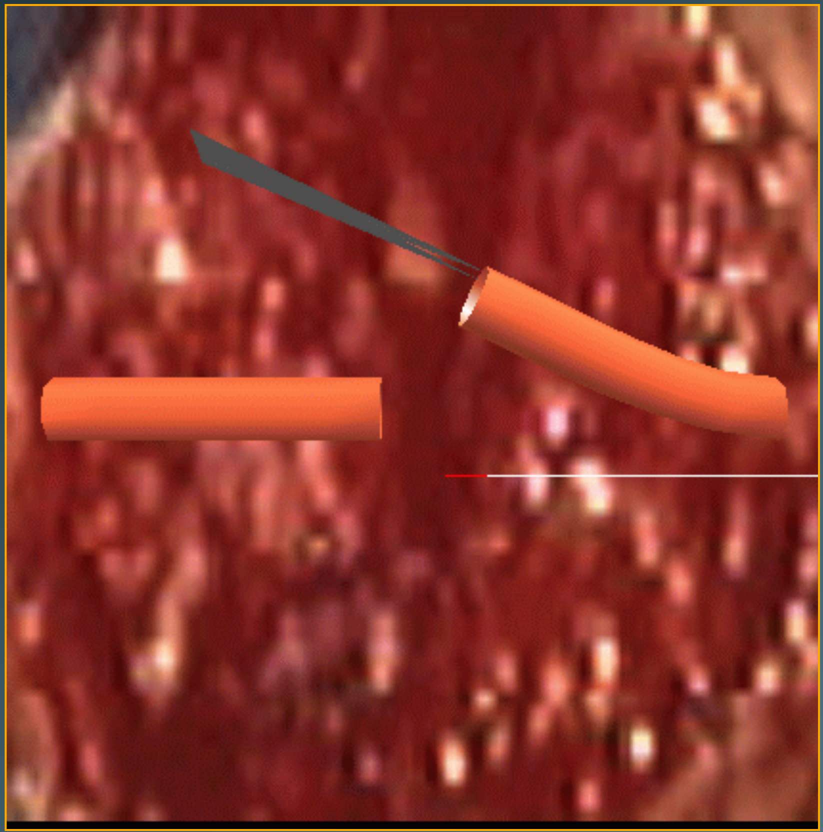
James Kuffner's PhD

Application: Computer-Assisted Surgical Planning



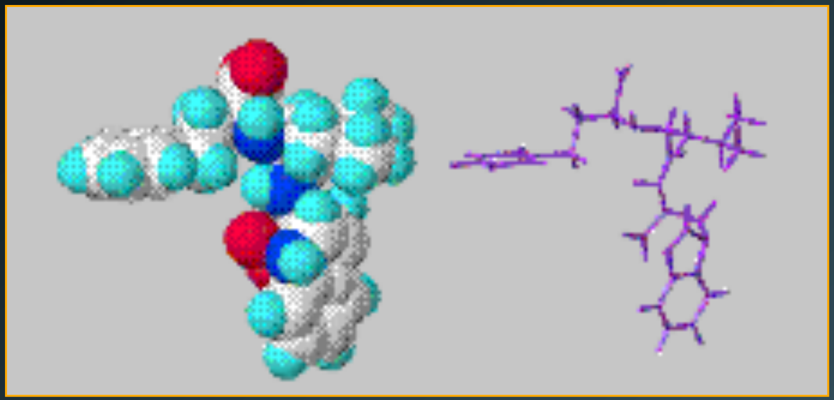


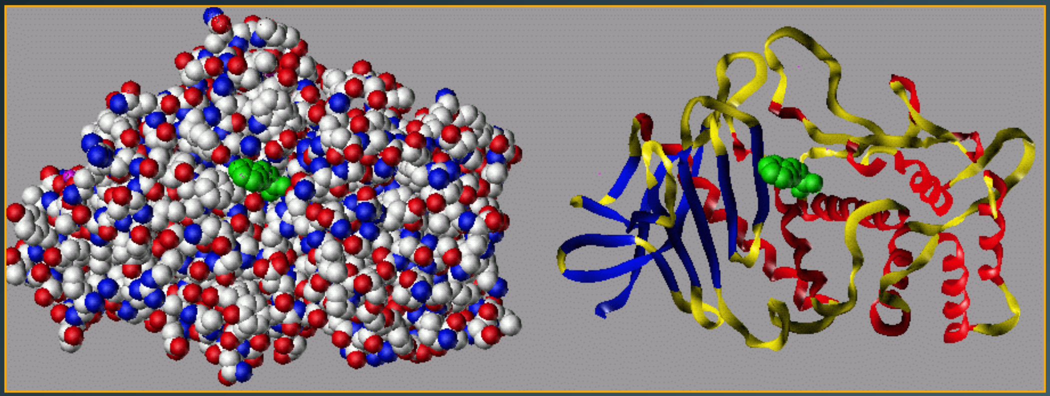
Rhea Tombropoulos's PhD

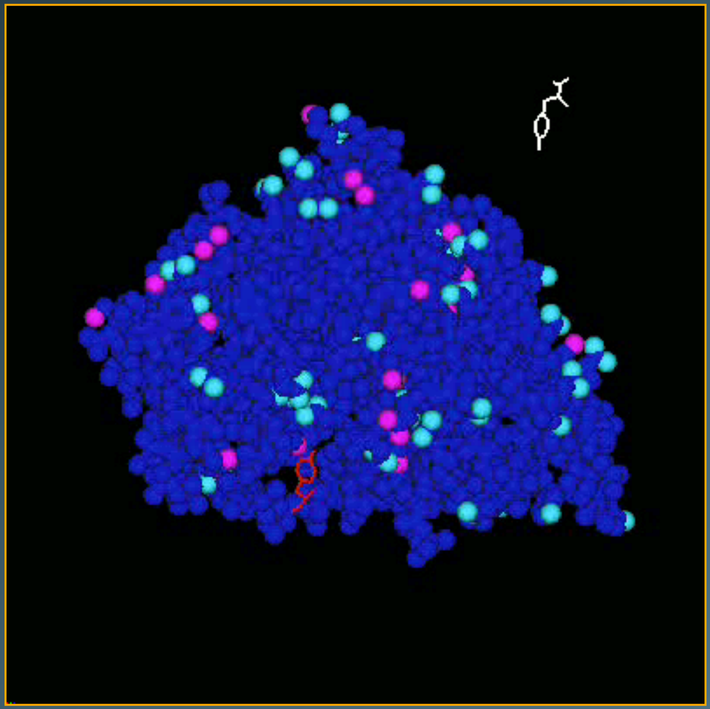


Joel Brown's PhD

Application: Prediction of Molecular Motions

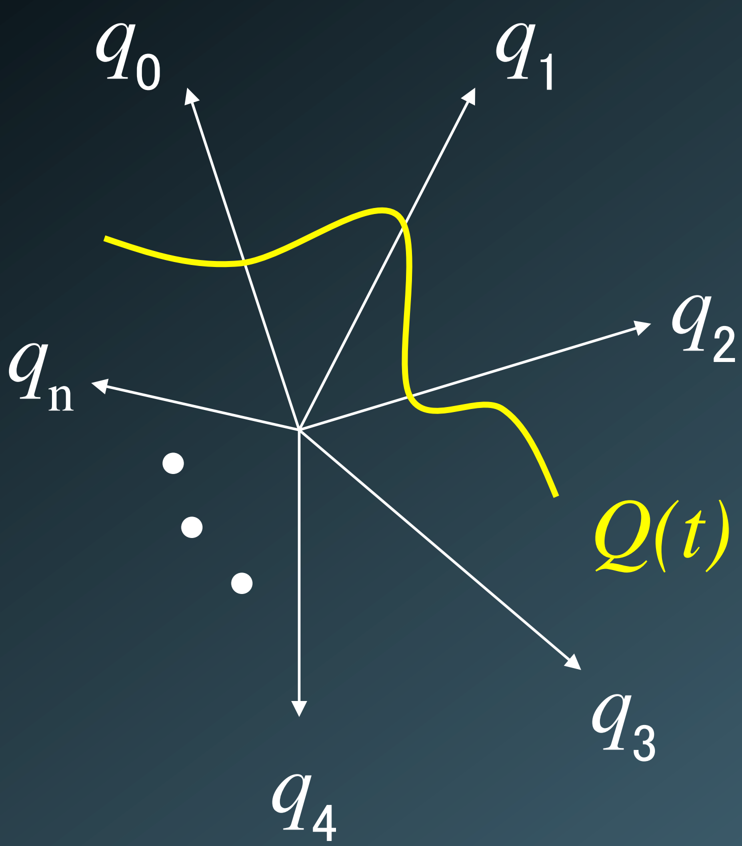






Amit Singh's PhD

Motion in Configuration Space

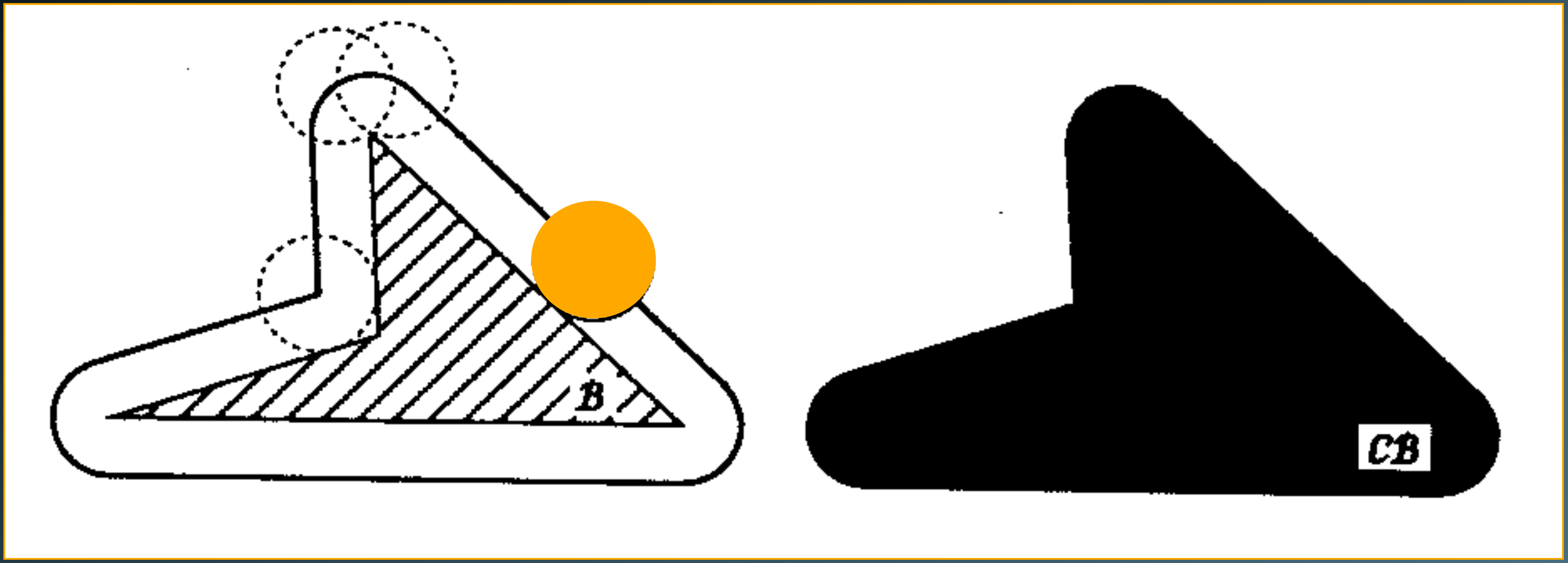


$$Q(t) = \begin{bmatrix} q_0(t) \\ \vdots \\ q_n(t) \end{bmatrix}$$

$$t \in [0, T]$$

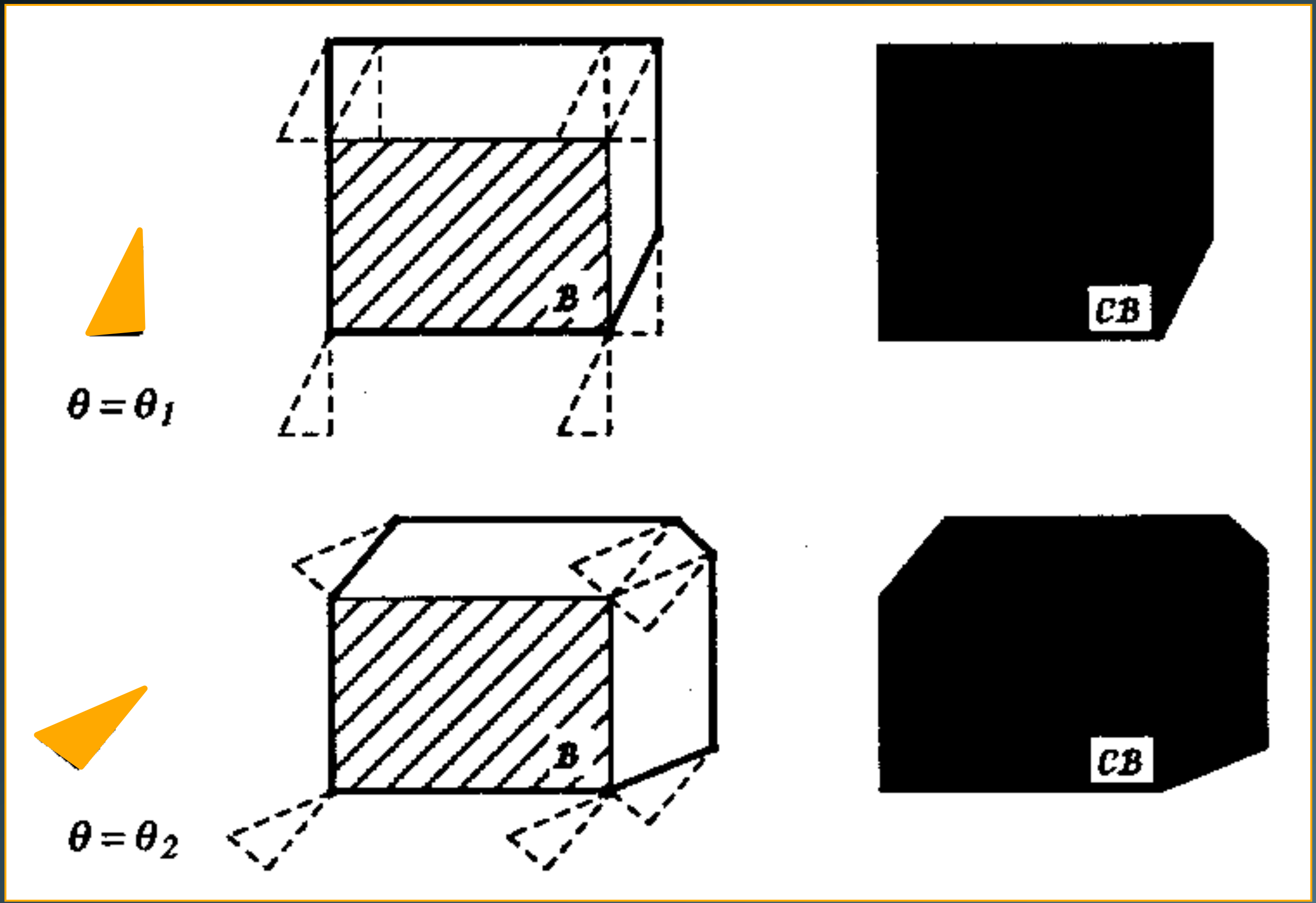
	Parts	DOF
L	19	68
H	51	118

Disc Robot in 2-D Workspace

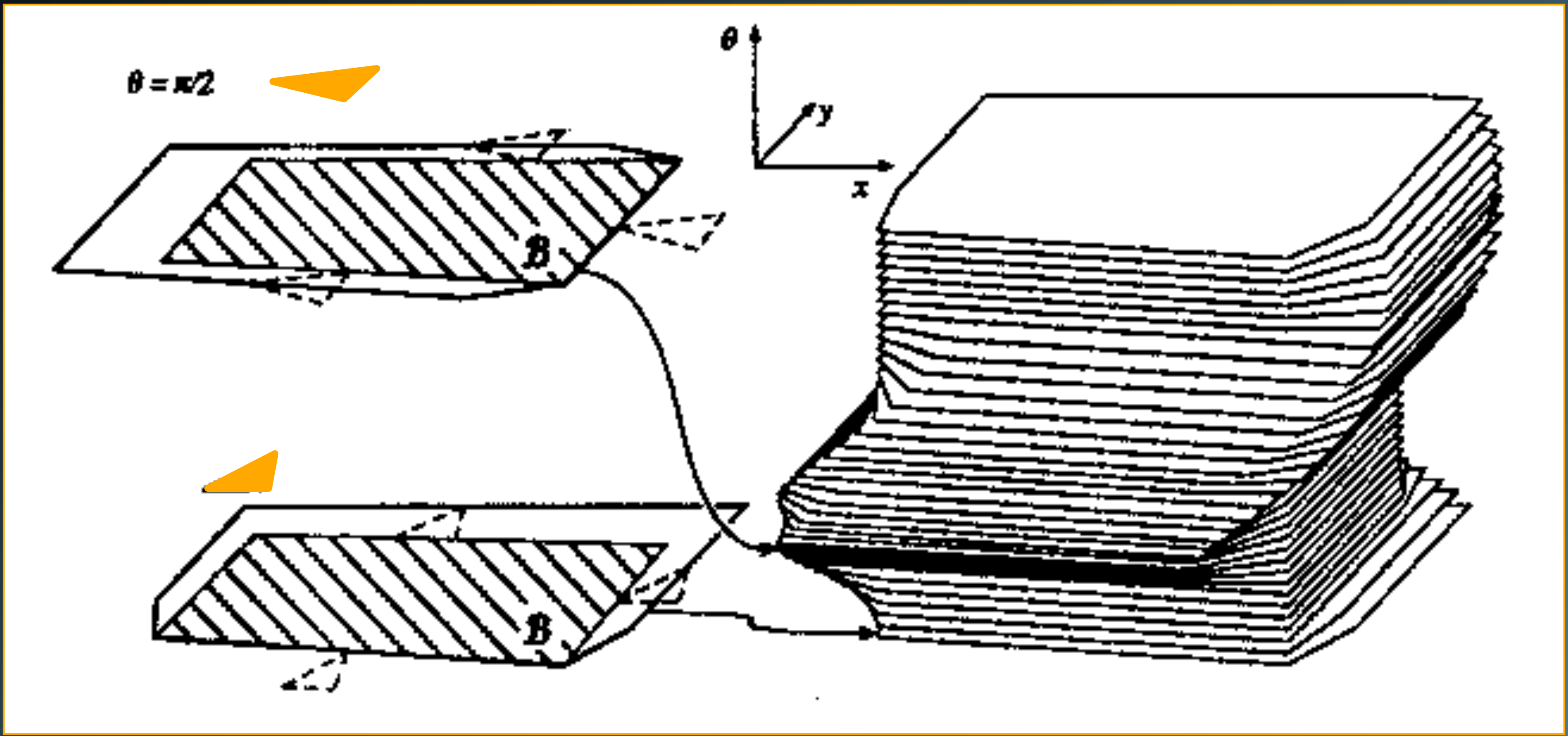


Rigid Robot Translating in 2-D

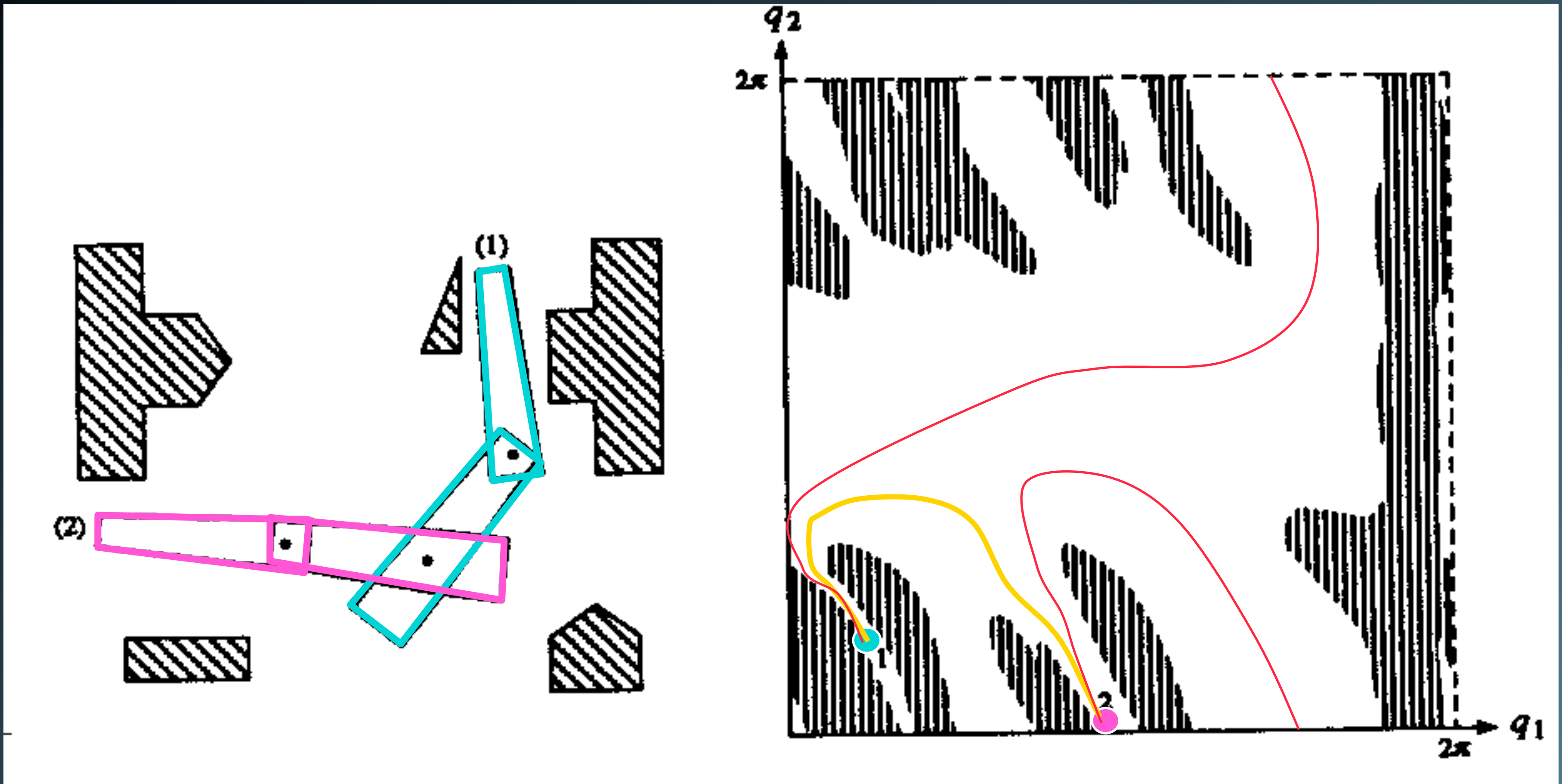
CB = B⊖A = {b - a | a in A, b in B}



Rigid Robot Translating and Rotating in 2-D



C-Obstacle for Articulated Robot



Other Representation Concepts

- State space (configuration x velocity)
- Configuration/state x time space
- Composite configuration/state spaces
- Stability regions in configuration/state spaces
- Visibility regions in configuration/state spaces
- Etc …

Motion Planning as a Computational Problem

- Goal:
  Compute the connectivity of a space (e.g., the collision-free subset of configuration space)
- High computational complexity:
  Typically requires time exponential in an input parameter, e.g., the number of degrees of freedom, the number of moving obstacles, …
- Two main algorithmic approaches:
  - Planning by random sampling
  - Planning by computing criticalities

Motion Planning as a Computational Problem

- Goal: Characterize the connectivity of a space (e.g., the collision-free subset of configuration space)
- High computational complexity: Requires time exponential in number of degrees of freedom, or number of moving obstacles, or etc…
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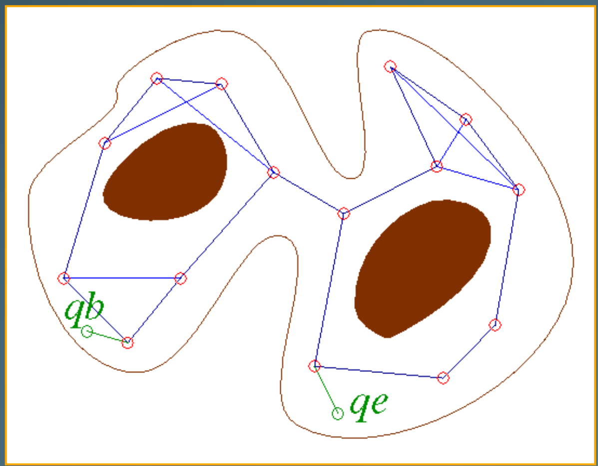

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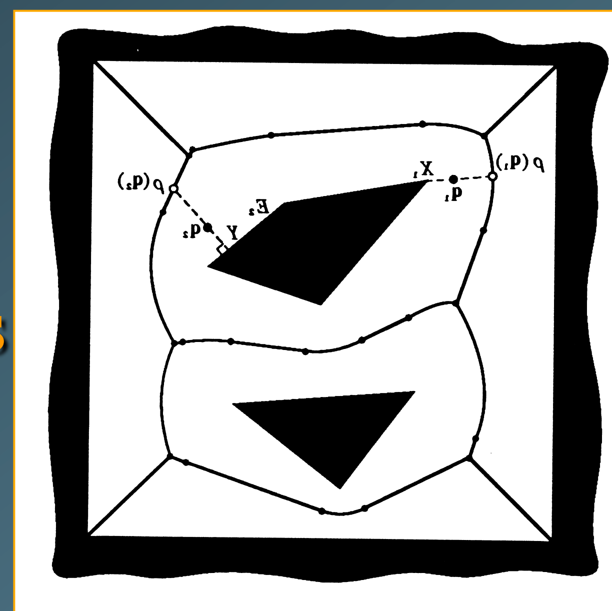
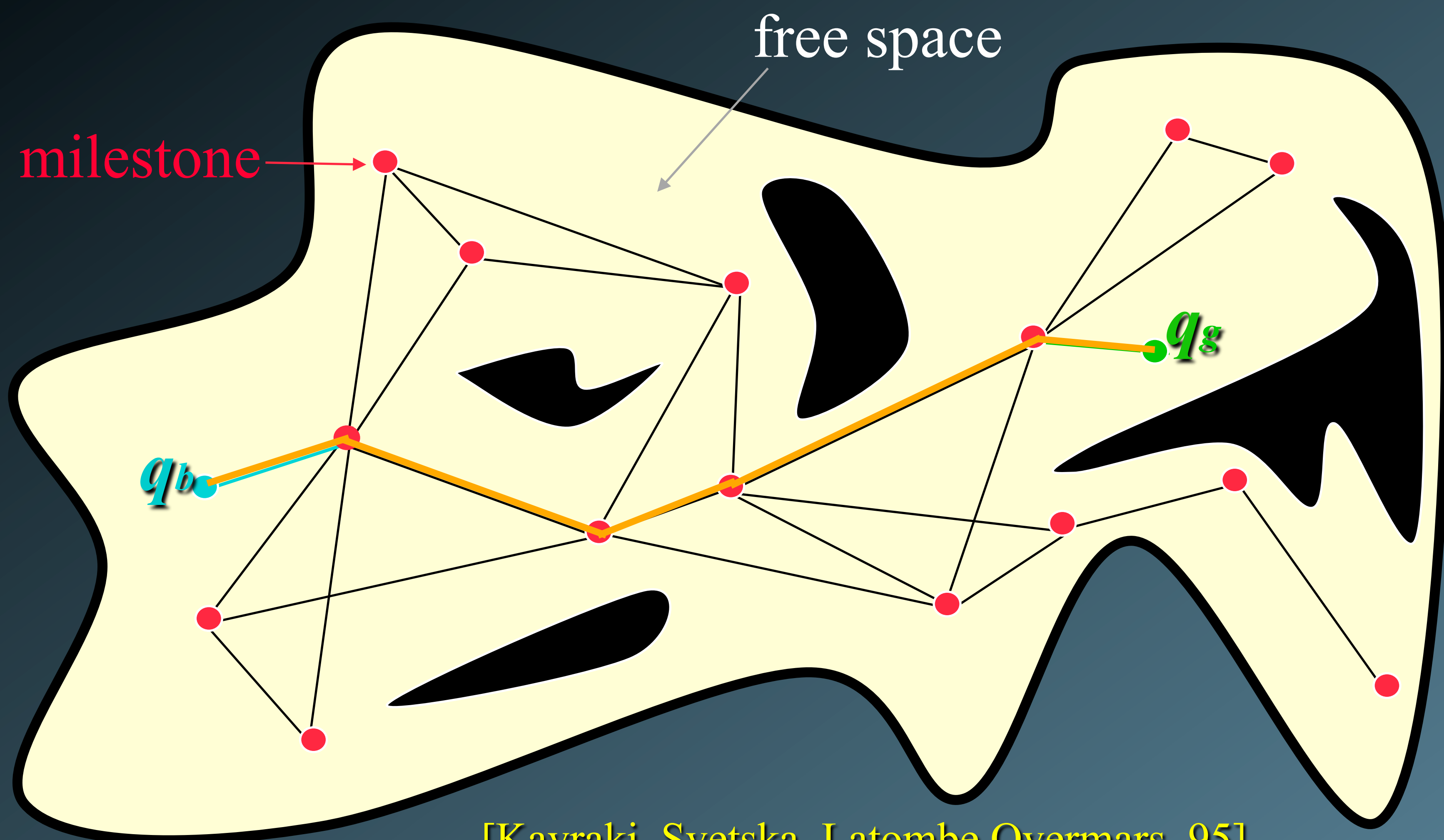


Principle of Randomized Planning

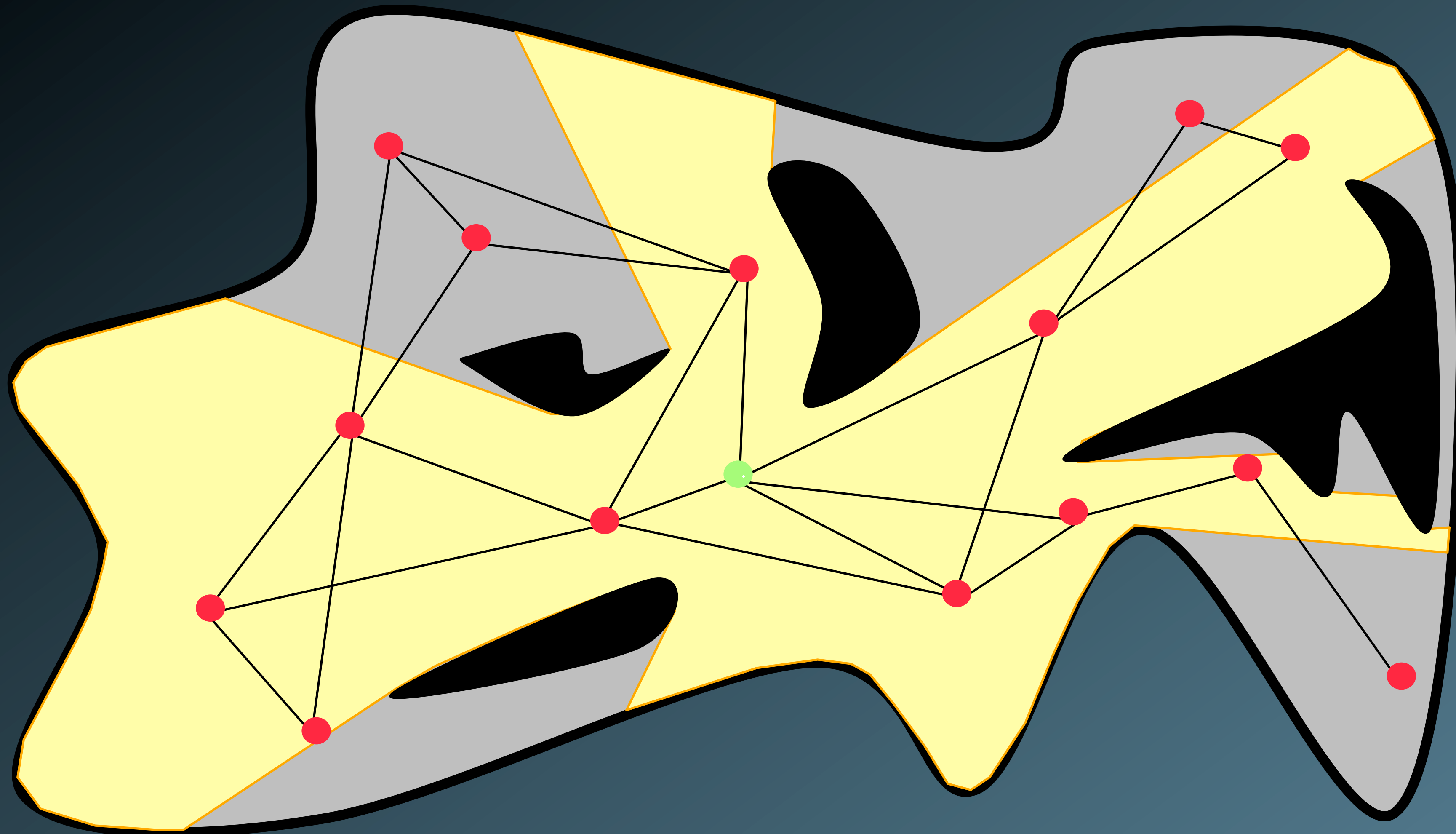
(Probabilistic Roadmap)



[Kavraki, Svetska, Latombe,Overmars, 95]

Why Does it Work?

[Kavraki, Latombe, Motwani, Raghavan, 95]



In Theory, a PRM Planner …

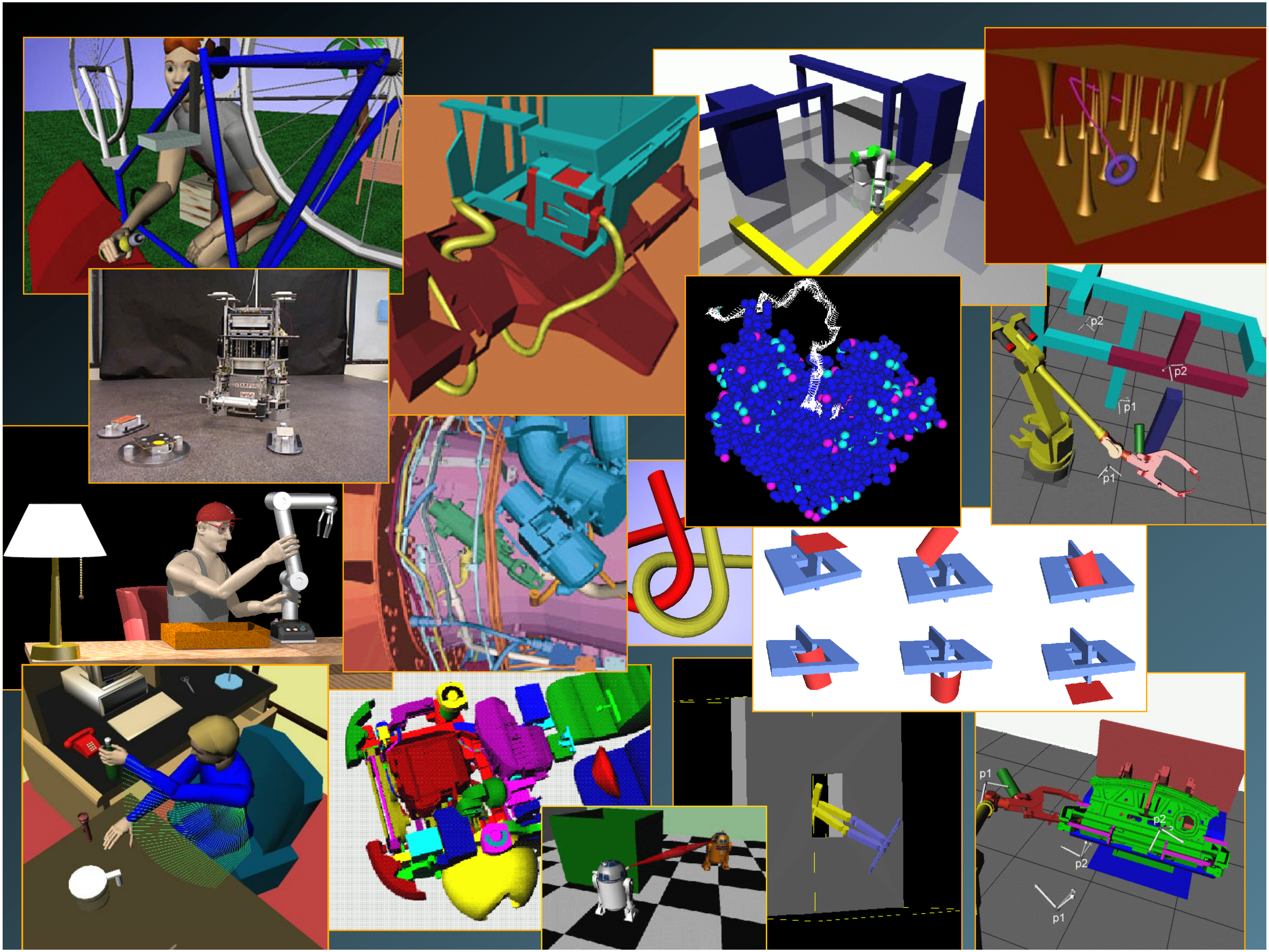
- Is probabilistically complete, i.e., whenever a solution exists, the probability that it finds one tends toward 1 as the number N of milestones increases

- Under rather general hypotheses, the rate of convergence is exponential in the number N of milestones, i.e.:

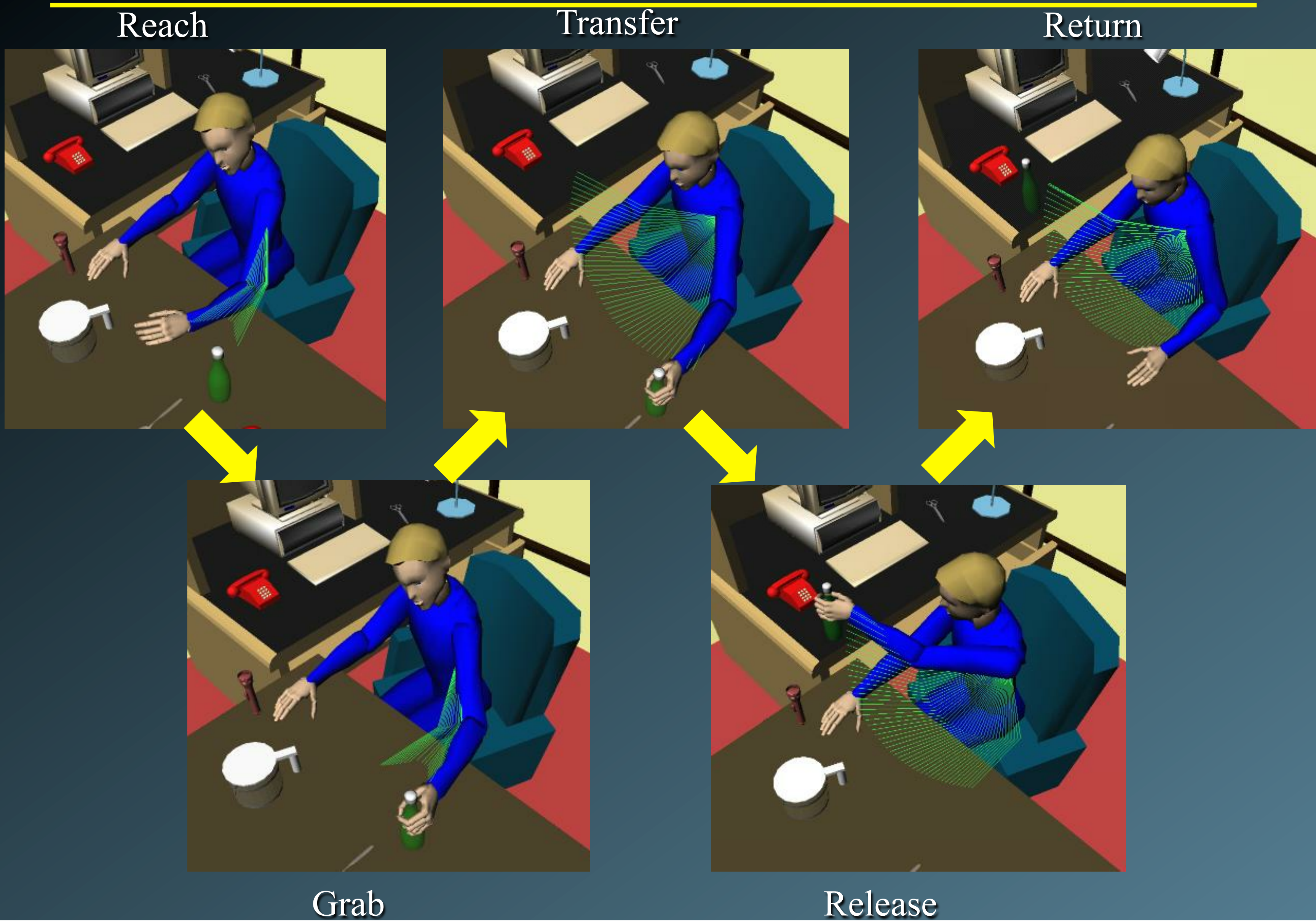
$$\text{Prob[failure]} \sim \exp(-N)$$

In practice, PRM Planners …

- Are fast
- Deal effectively with many-dof robots
- Are easy to implement
- Have solved complex problems

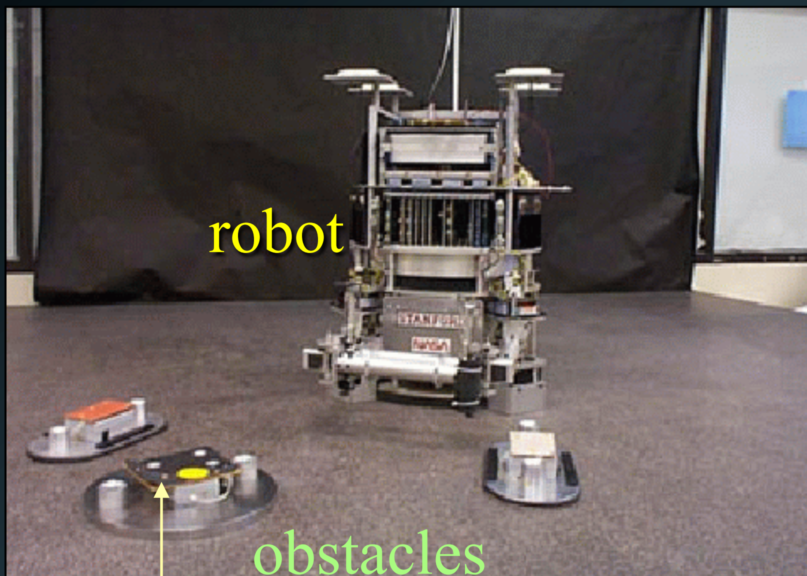

p2
p2
p1
p1
p1
p2
p2
p1

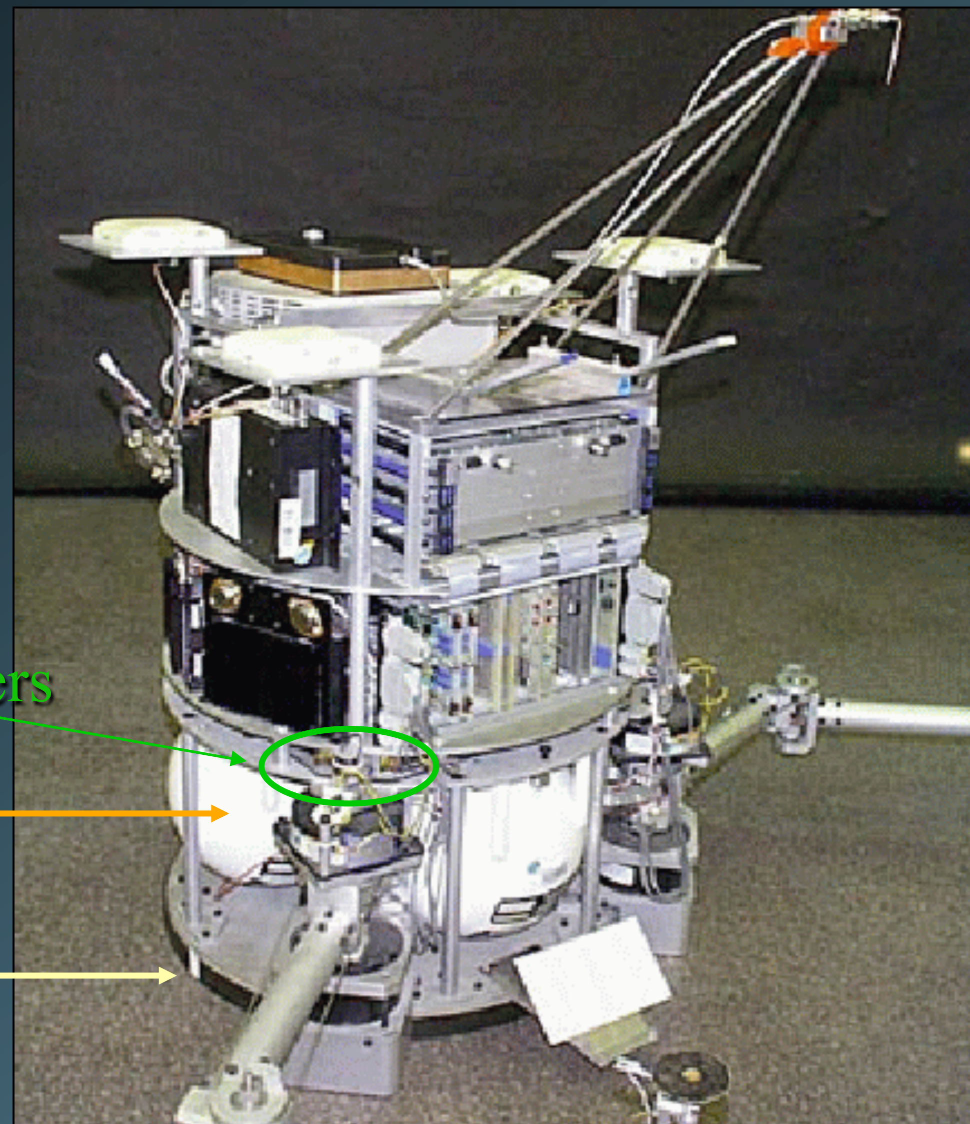
Example 1: Planning of Manipulation Motions



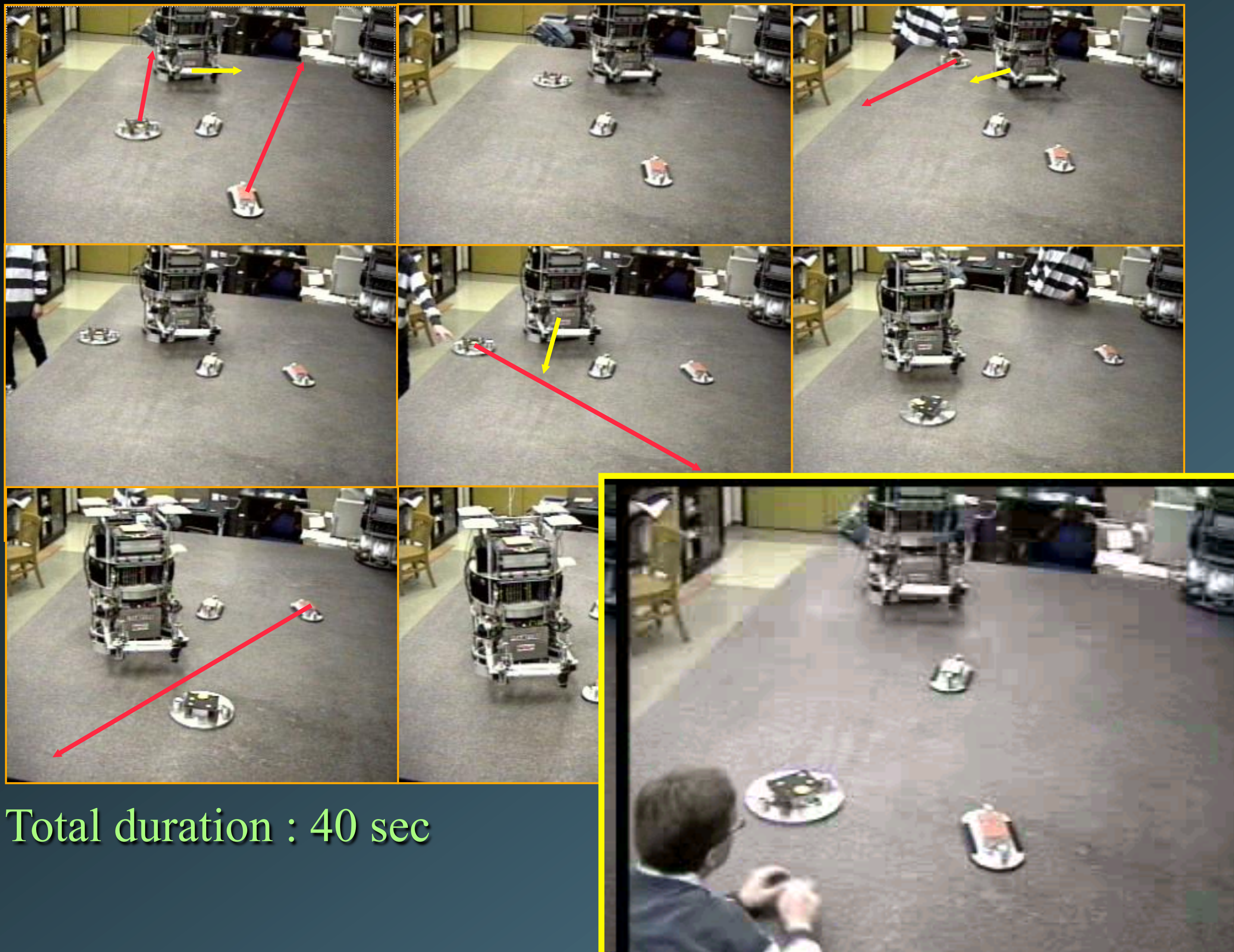
Example 1: Planning of Manipulation Motions

Example 2: Air-Cushioned Robot



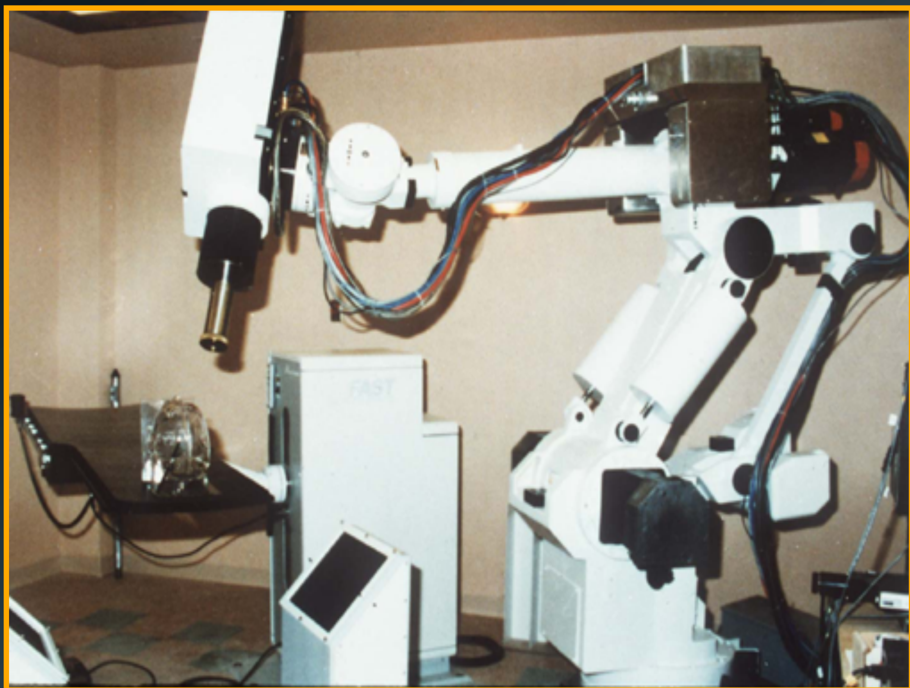


(Aerospace Robotics Lab)

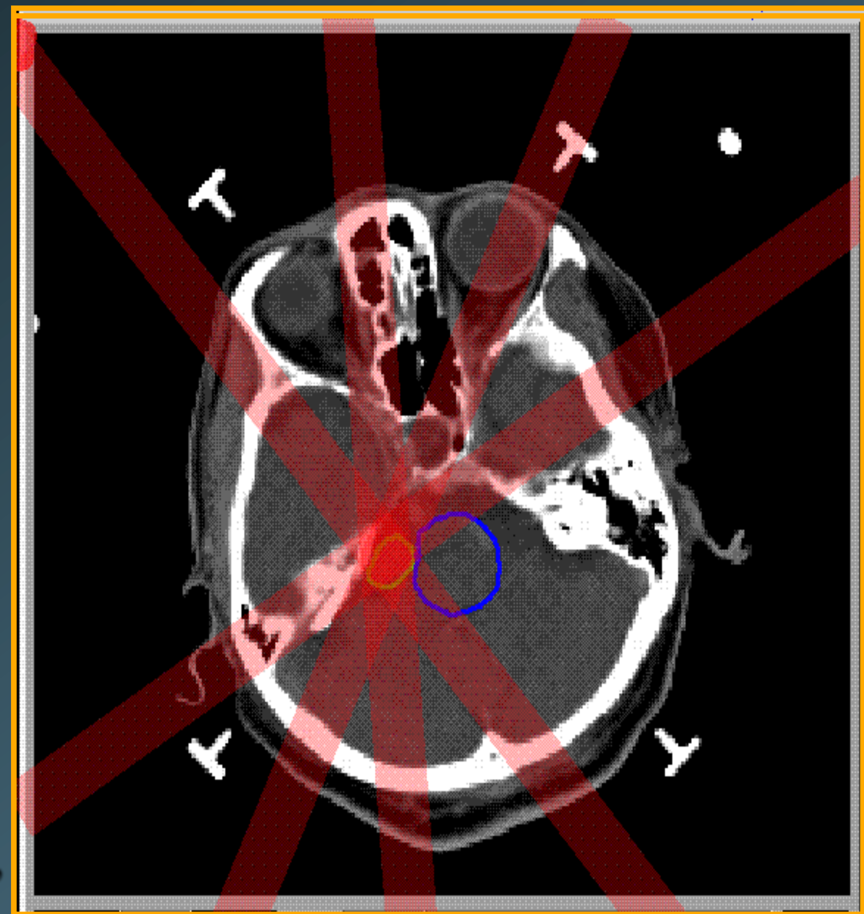


Total duration : 40 sec

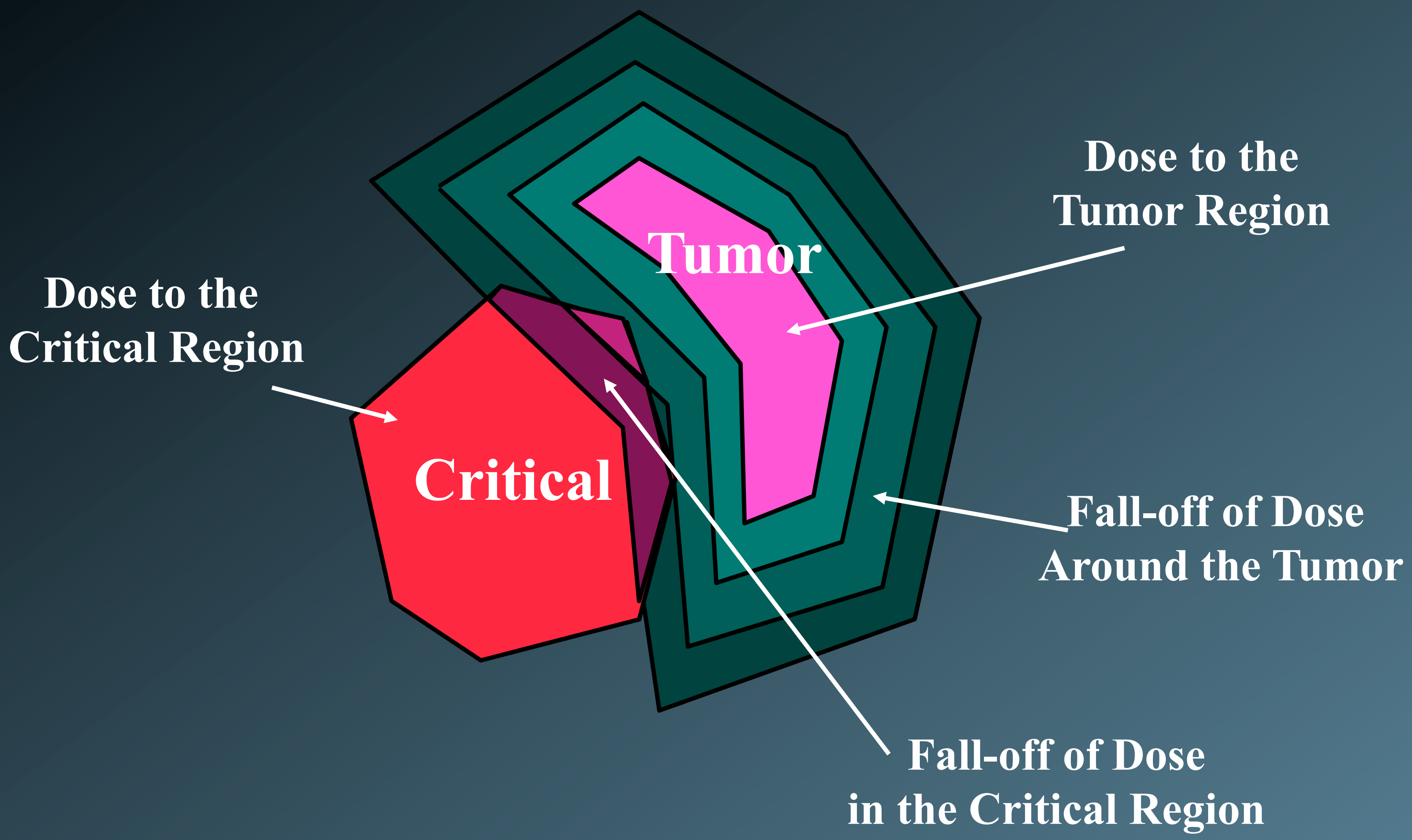
Example 3: Radiosurgical Planning



Cyberknife (Neurosurgery Dept., Stanford, Accuray)

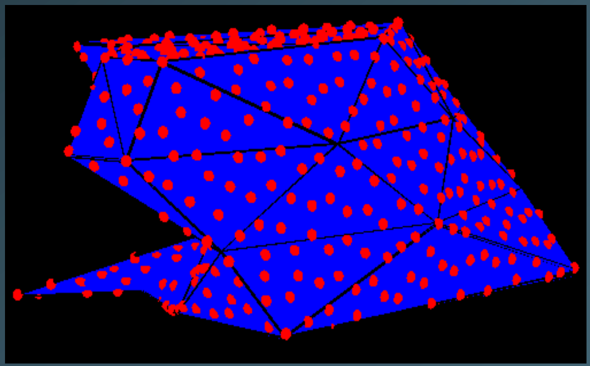


Surgeon Specifies Dose Constraints



Beam Selection Algorithm

- Place points uniformly at random on the surface of the tumor
- Pick beam orientations at random at these points



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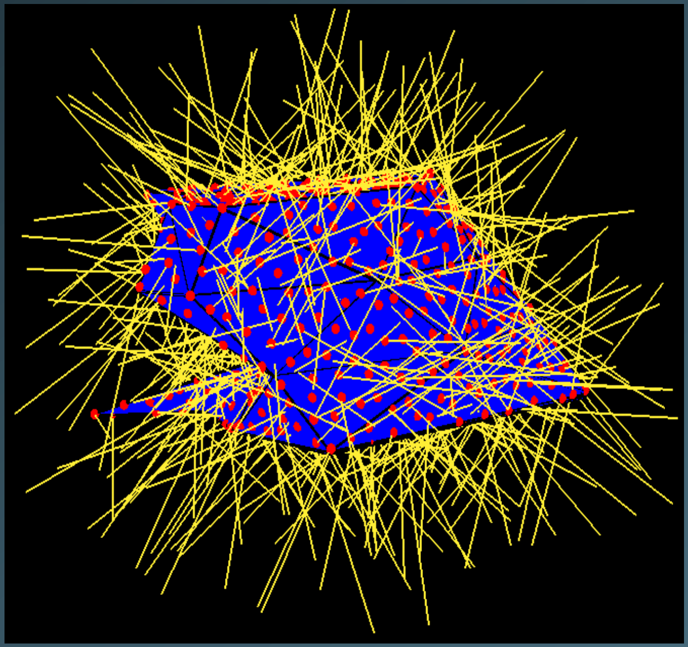
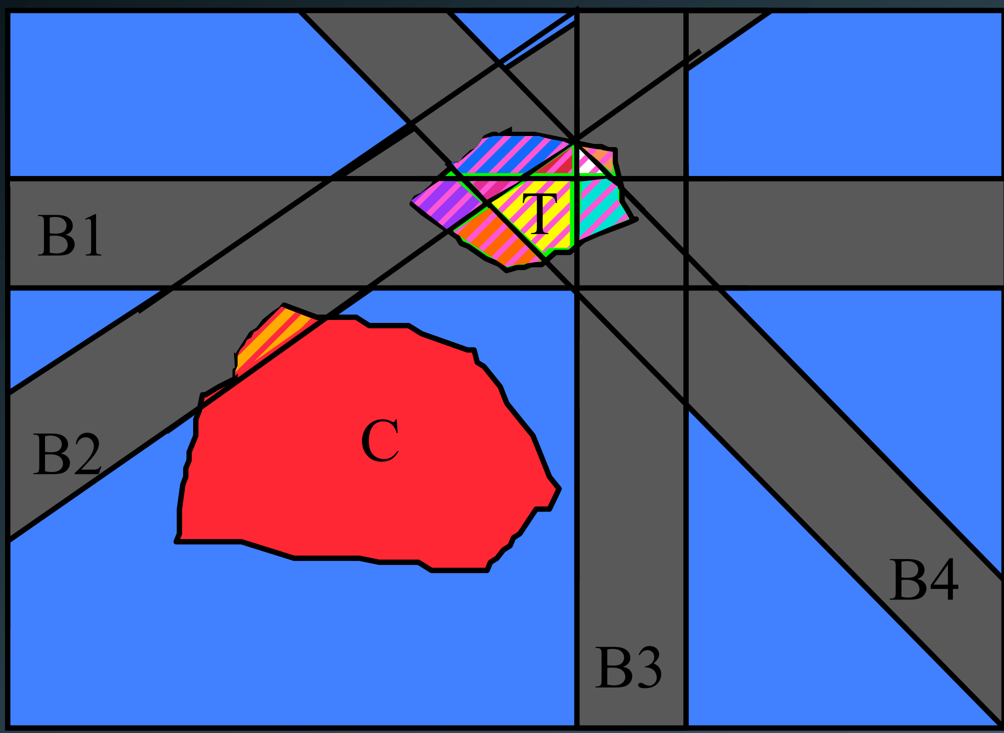
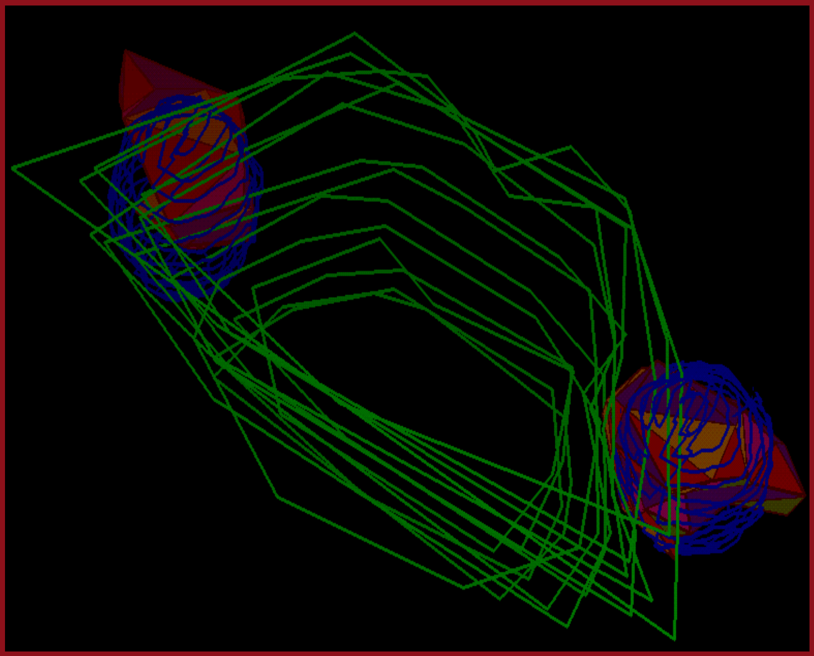


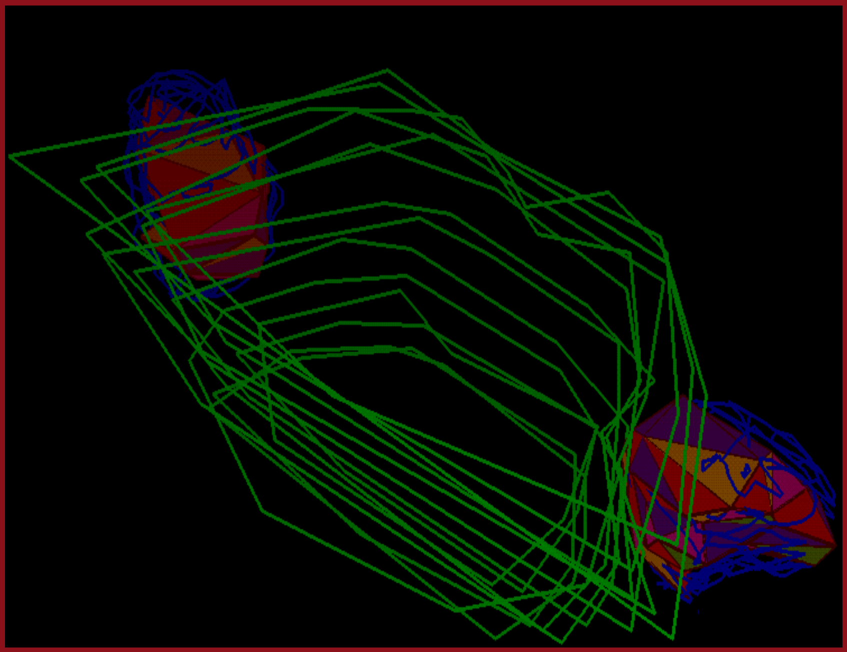
Compute Beam Weights



- 2000 < Tumor < 2200
  - 2000 < B2 + B4 < 2200
  - 2000 < B4 < 2200
  - 2000 < B3 + B4 < 2200
  - 2000 < B3 < 2200
  - 2000 < B1 + B3 + B4 < 2200
  - 2000 < B1 + B4 < 2200
  - 2000 < B1 + B2 + B4 < 2200
  - 2000 < B1 < 2200
  - 2000 < B1 + B2 < 2200
- 0 < Critical < 500
  - 0 < B2 < 500

Sample Case

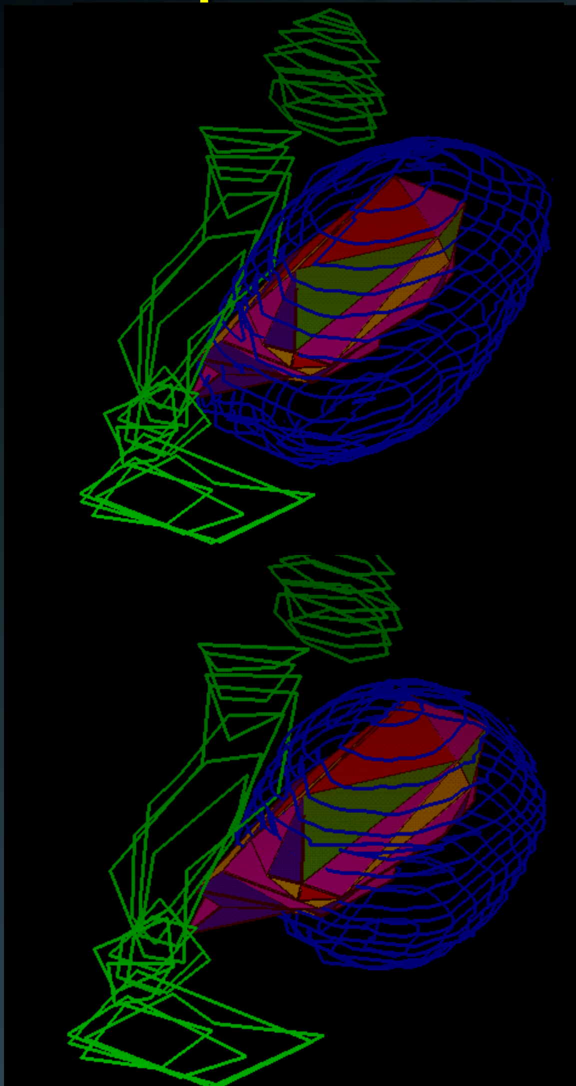




Linac plan
80% Isodose surface

CARABEAMER's plan
80% Isodose surface

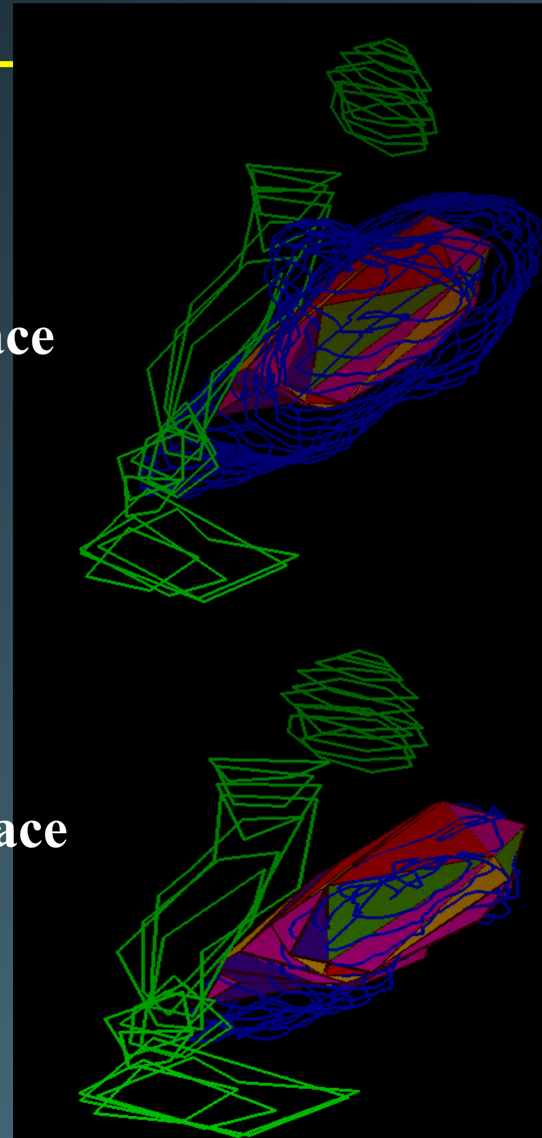
Sample Case



Linac plan

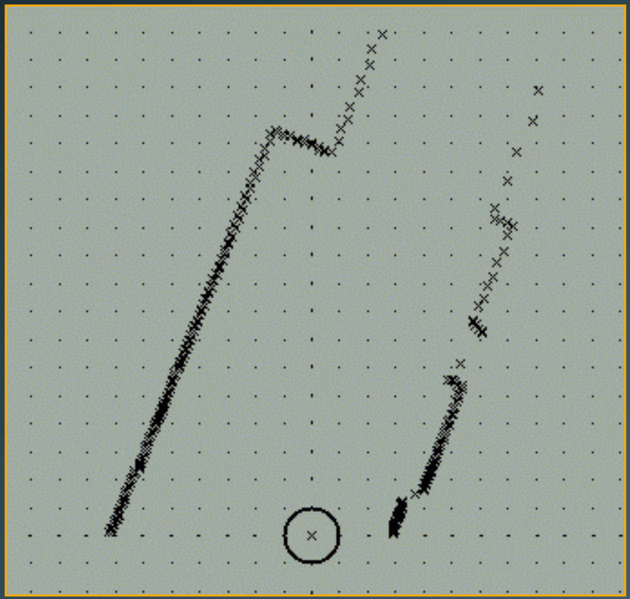
50% Isodose Surface

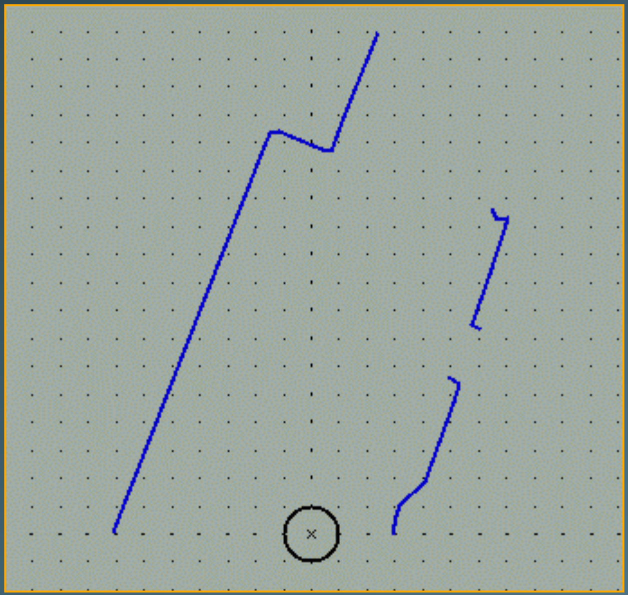
80% Isodose Surface



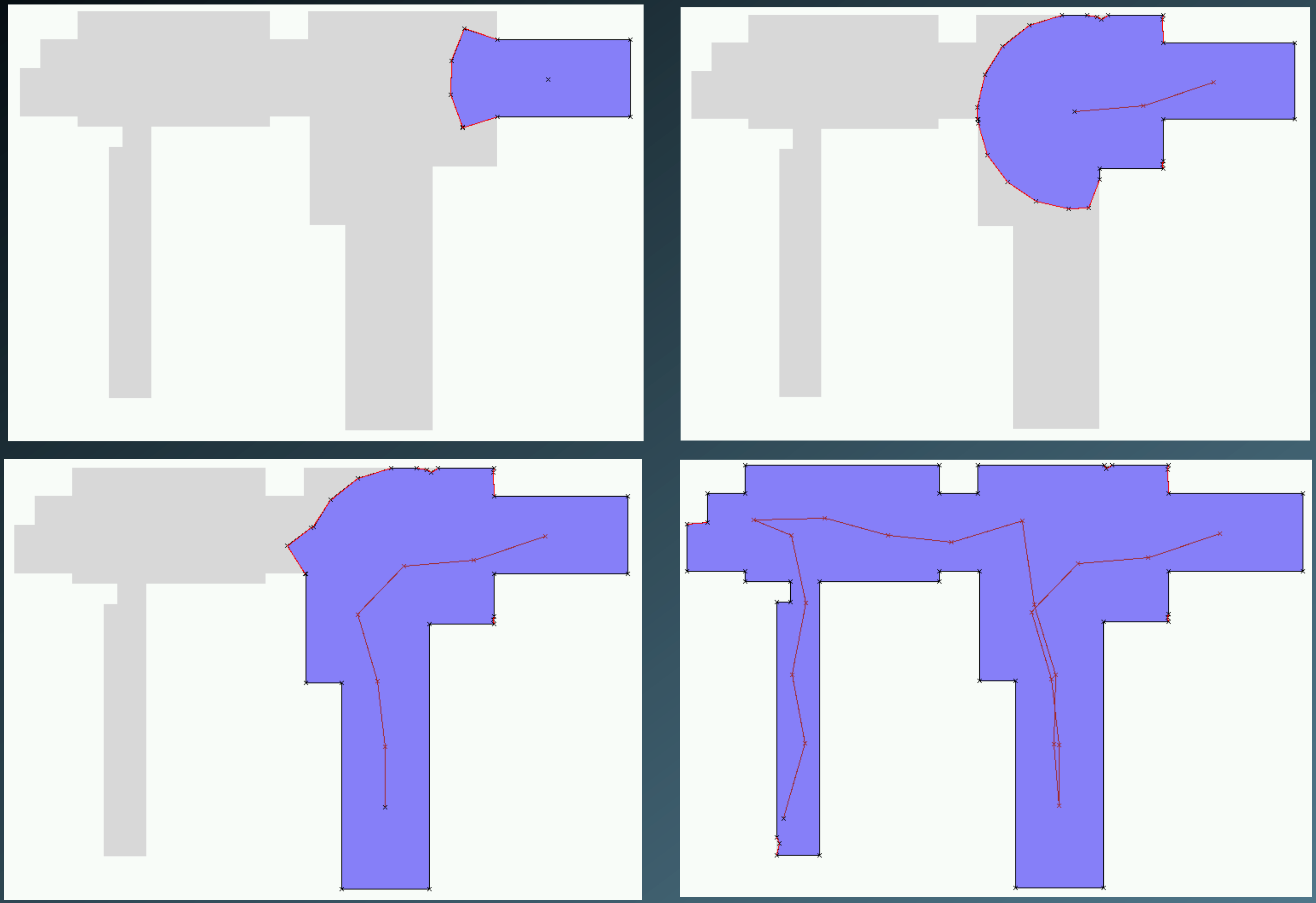
CARABEAMER's plan

Example 4: Indoor Map Building by Robot



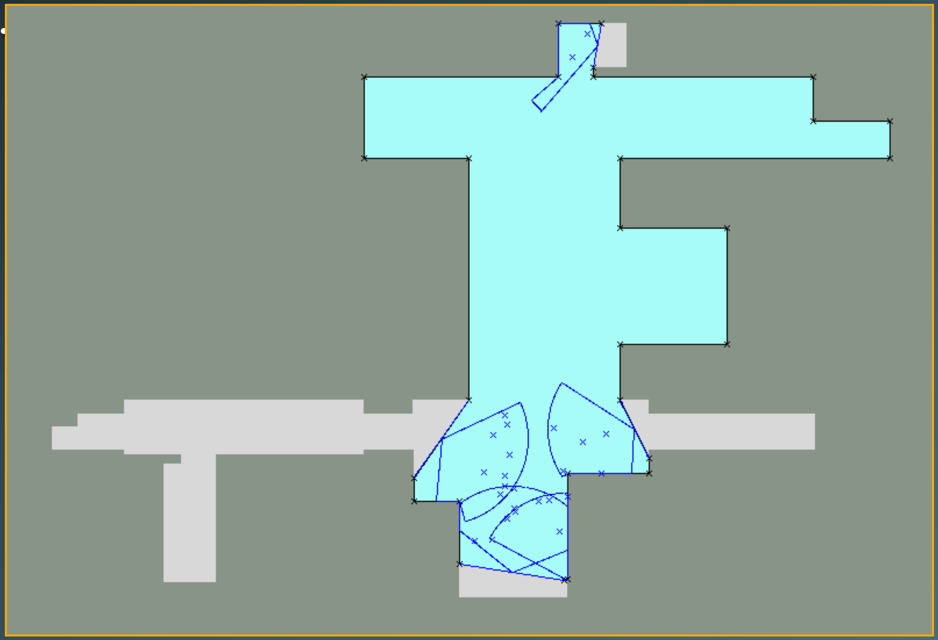


Next-Best View Strategy



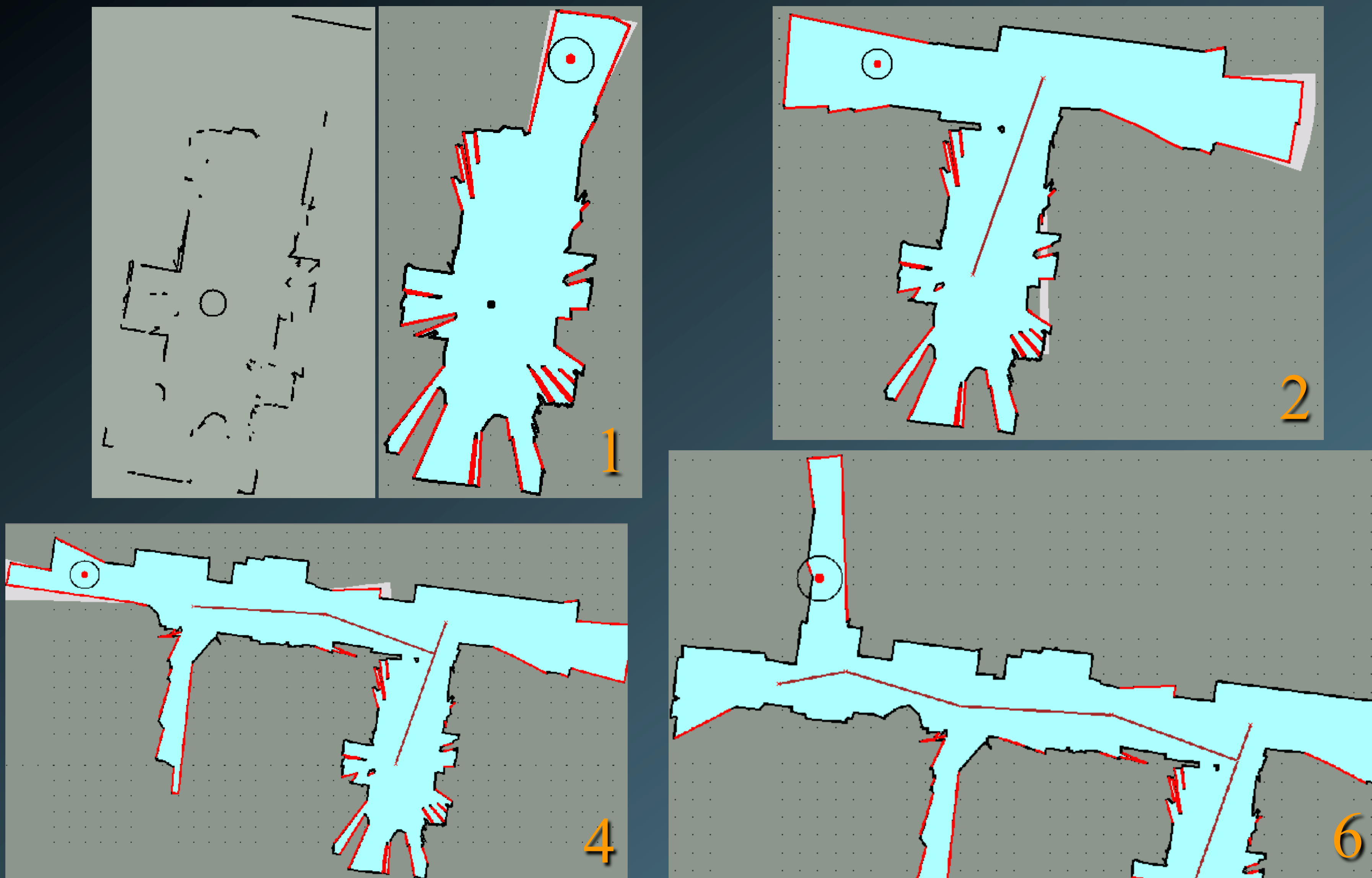
Computing Next Sensing Position

- Sample the free edges of the visited region at random. For each sample point, compute the subset of visited region from which this point is visible and sample this subset at random.
  >> Set of candidate positions *q*

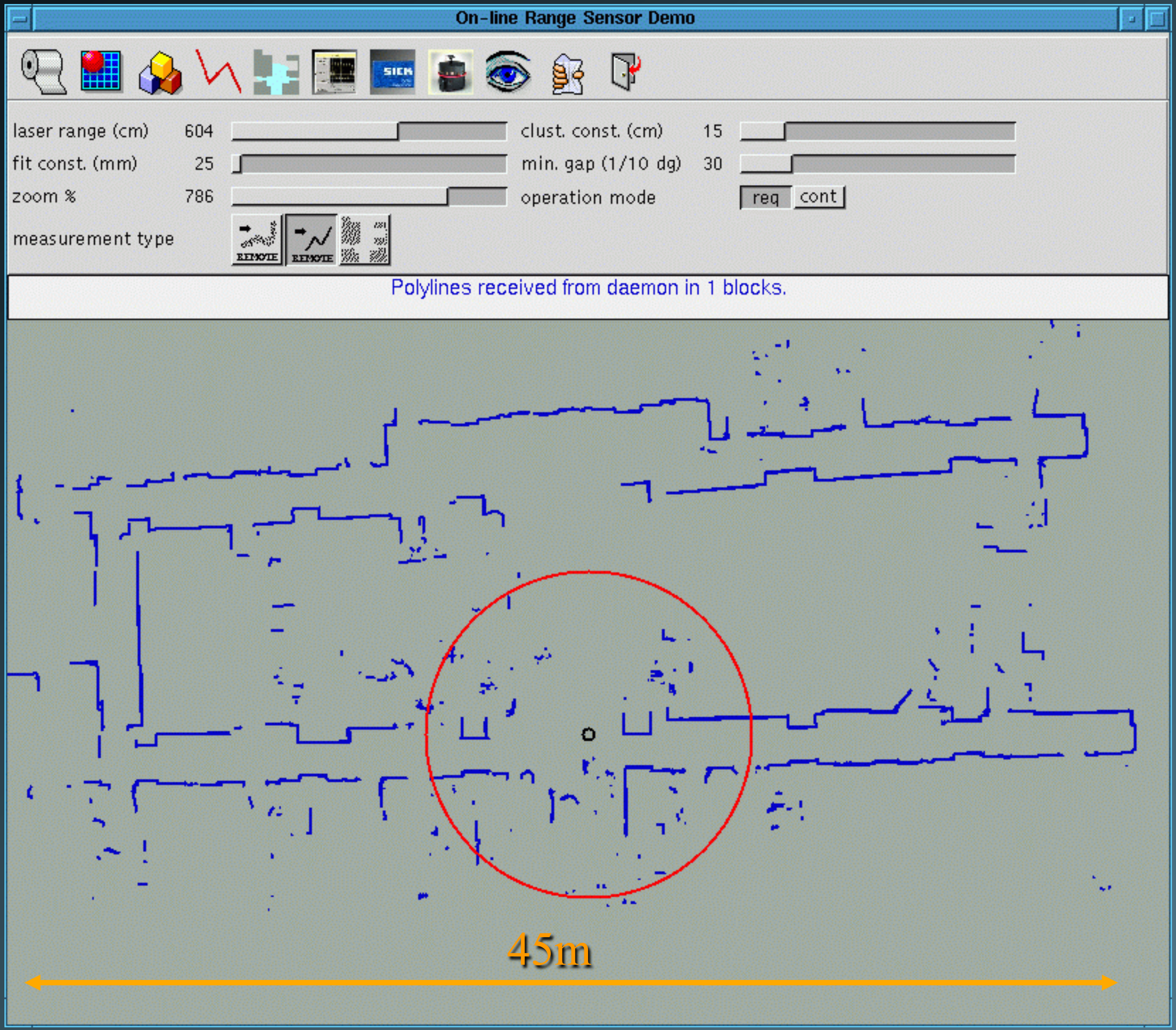


- Select "best" candidate *q* based on following criteria:
  – overlap of visible environment edges (to ensure reliable alignment)
  – amount of potential new space visible from *q*
  – length of path to go to *q*

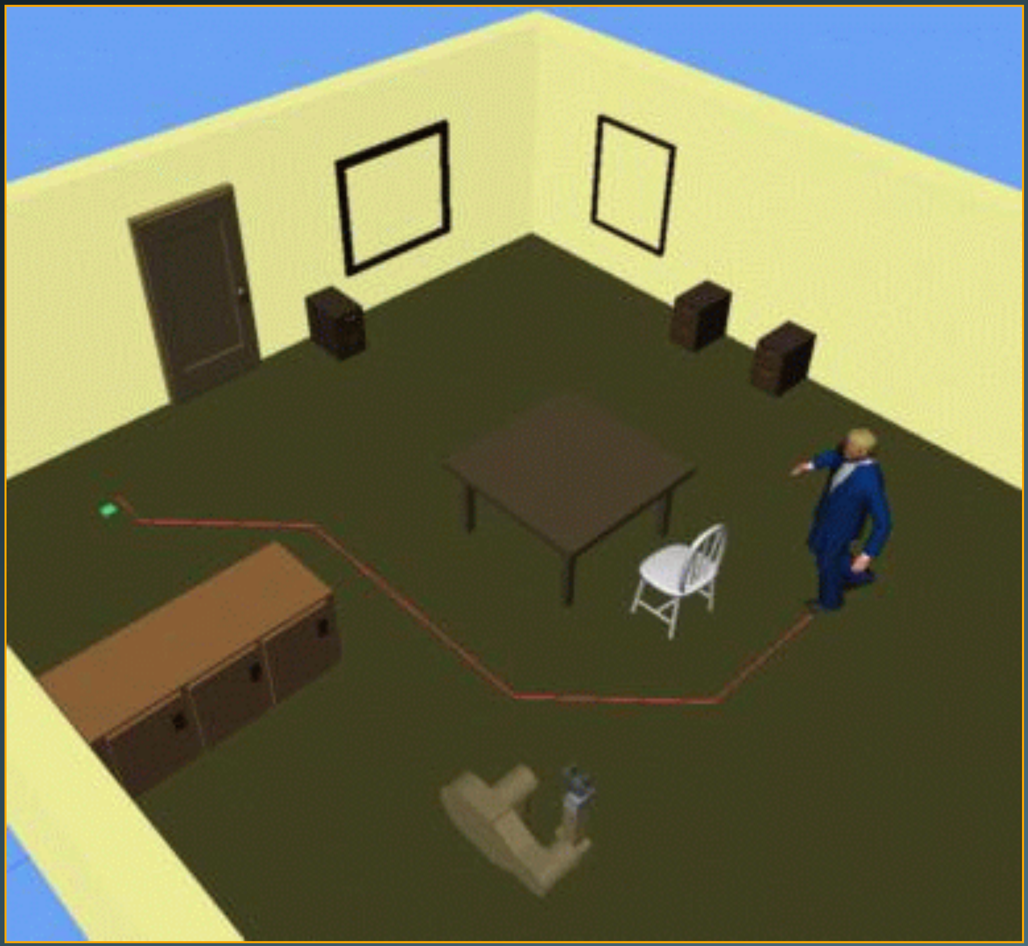
Map Construction Example



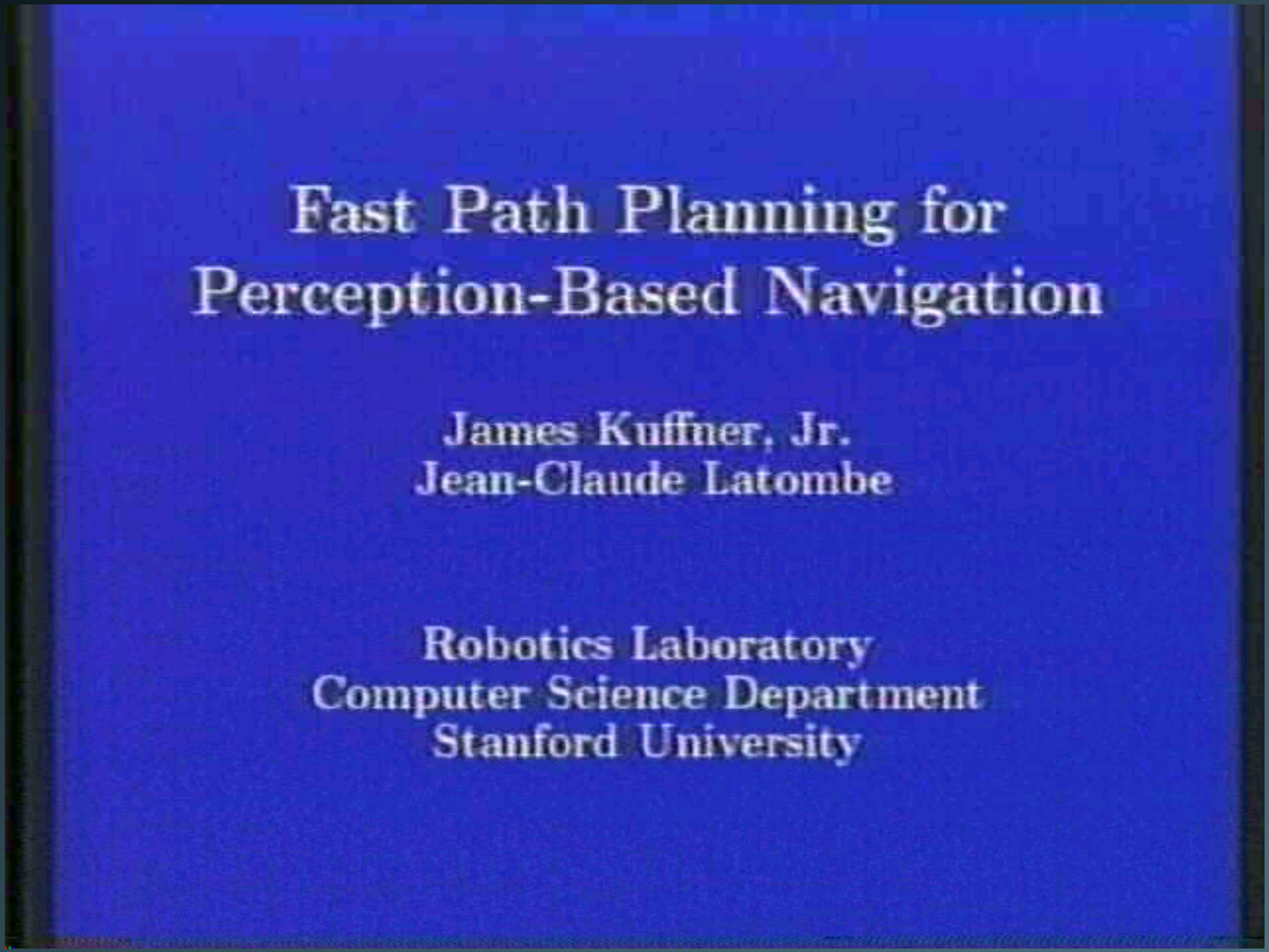
Robotics Lab Map



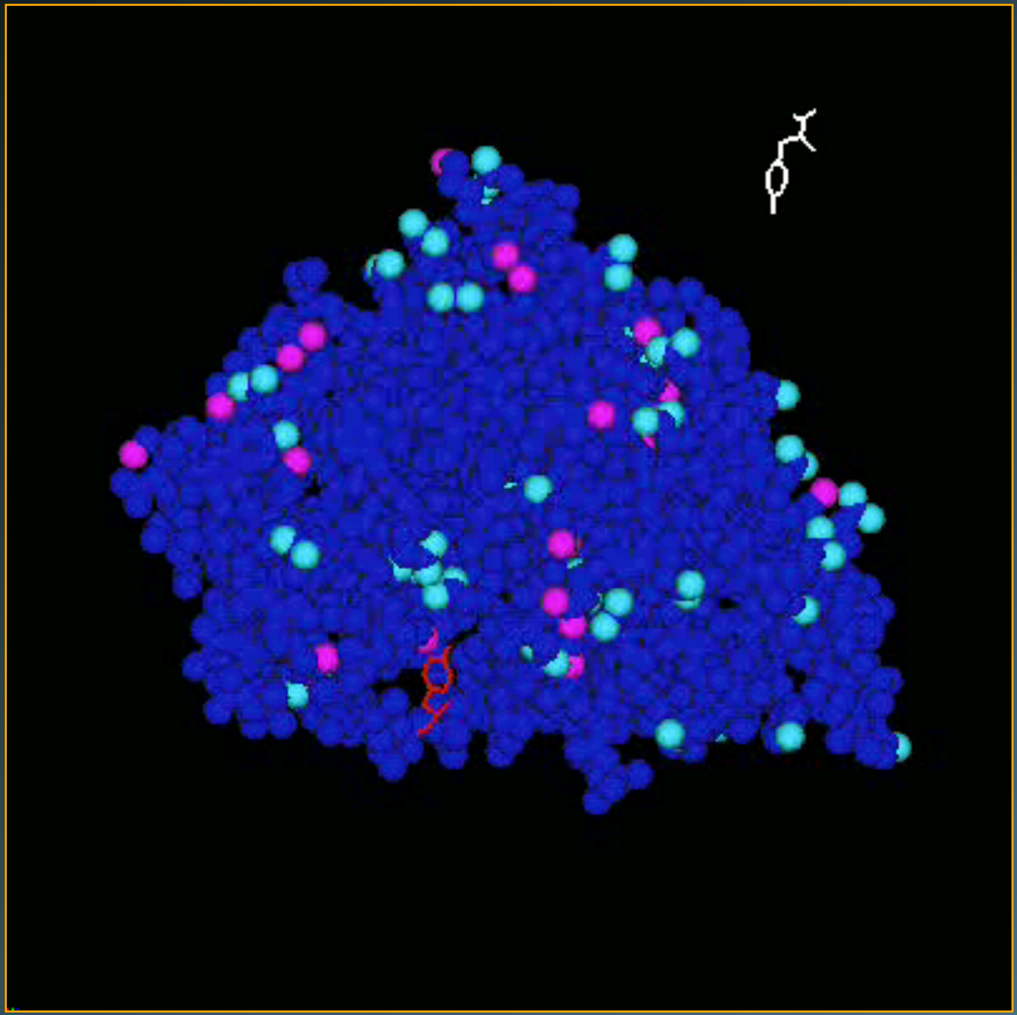
Example 5: Digital Actor with Vision Sensing



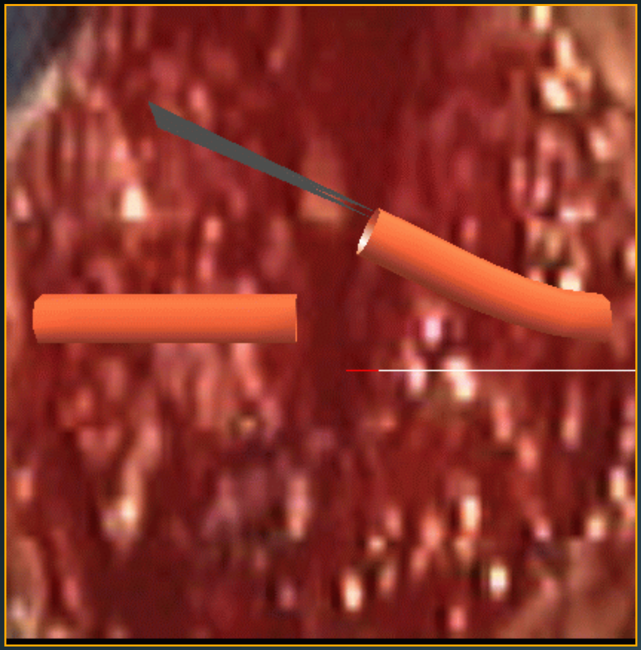
Example 5: Digital Actor with Vision Sensing

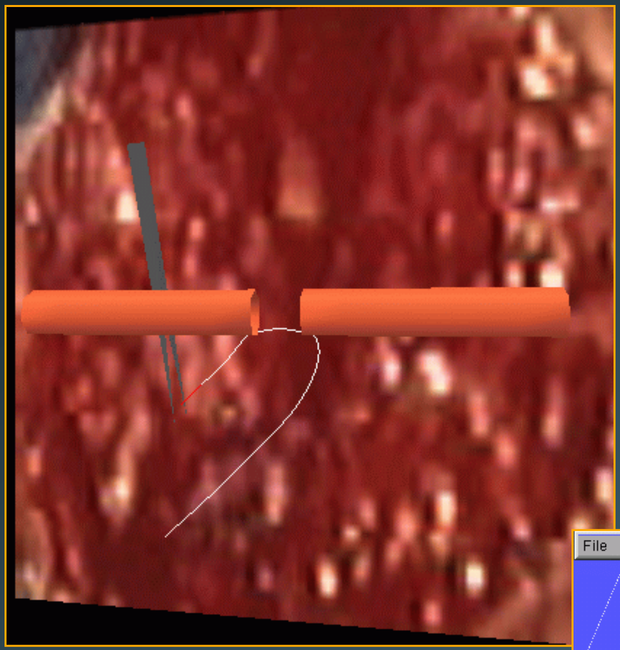


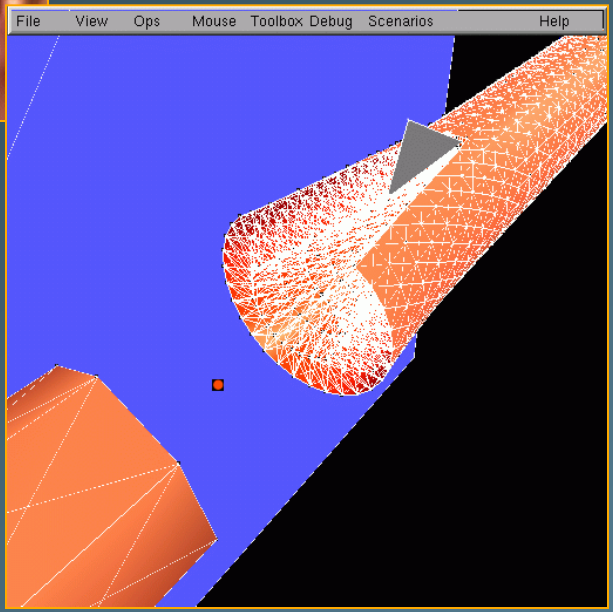
Example 6: Predicting Molecule Docking Motions



Future Work: Minimally Invasive Surgey Amidst Soft Tissue Structures

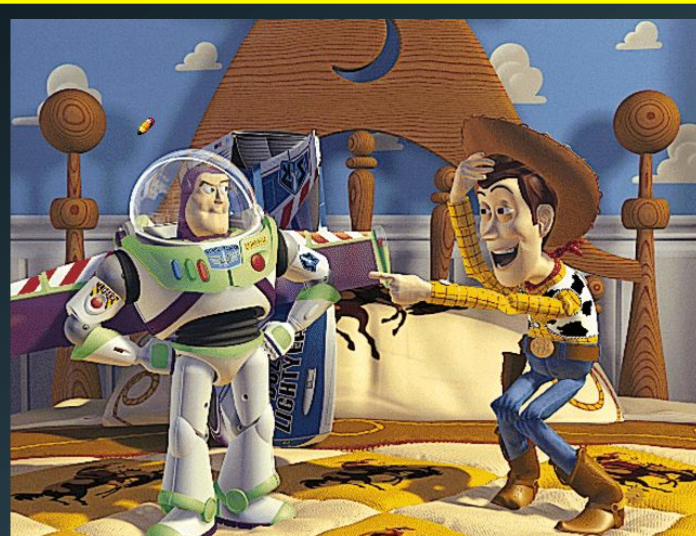






Future Work: Autonomous Interactive Characters

A Bug's Life (Pixar/Disney)



Toy Story (Pixar/Disney)

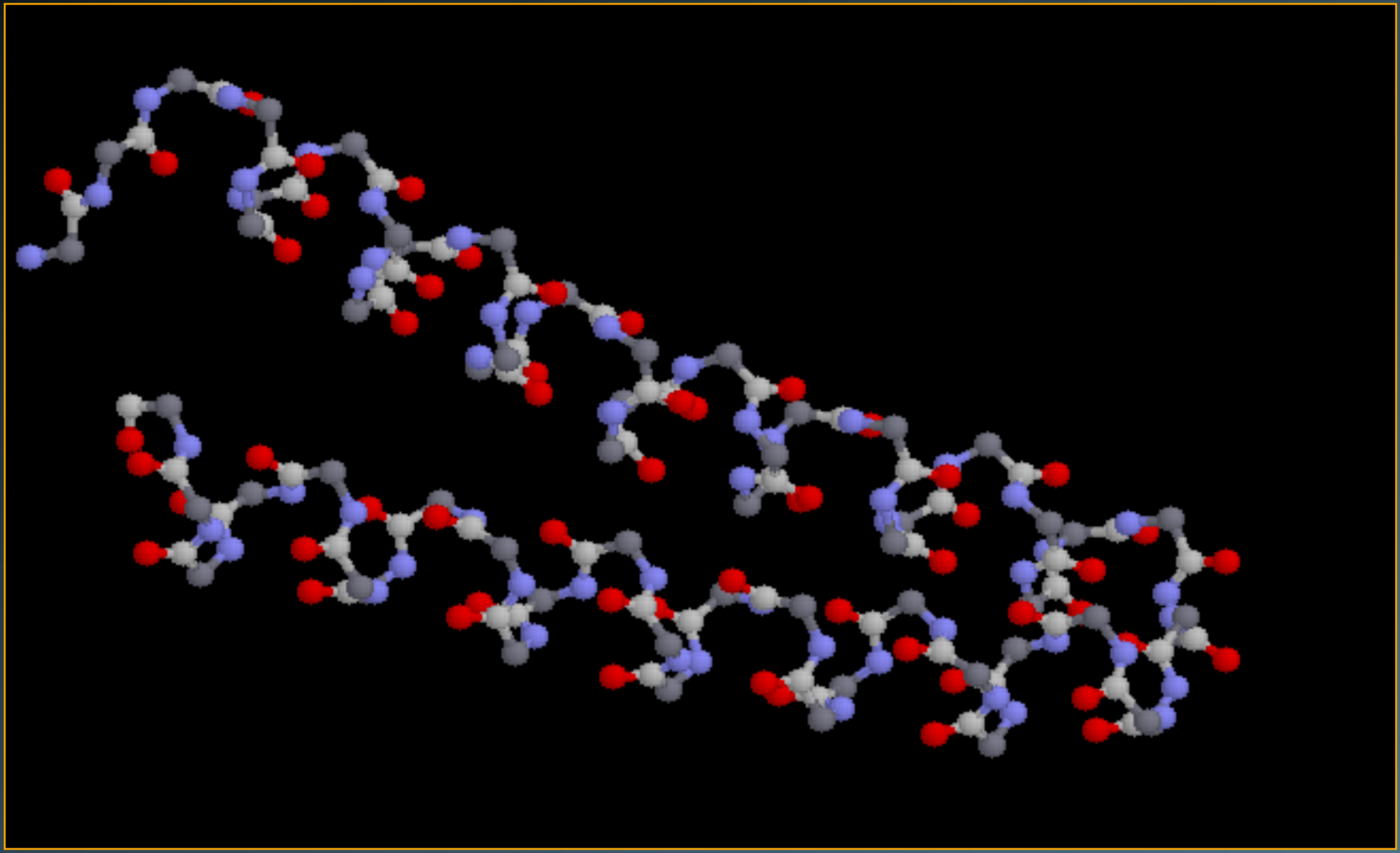
Antz (Dreamworks)

Tomb Raider 3 (Eidos Interactive)

The Legend of Zelda (Nintendo)

Final Fantasy VIII (SquareOne)

Future Work: Protein Folding



Summary/Conclusion

- Over the last decade there has been considerable progress in motion planning techniques and their application
- While motion planning originated in robotics, the areas of application are now very diverse: product design, manufacturing, graphic animation, video games, biology, etc…
- There are orders of magnitude more processors embedded in physical devices (cars, planes, surgical instruments, etc) than desktop computers, and the gap is still growing. The interest in modeling and computing the motion of physical objects will continue to grow.