CSE 571
Robotics

Recap and Discussion

Goal of this course

- Provide an overview of fundamental problems / techniques in robotics

- Understanding of estimation and decision making in dynamical systems
  - Probabilistic modeling and filtering
  - Deterministic and non-deterministic planning
  - Learning for perception and modeling

- Augment model-based understanding with hands-on experience in deep learning

Bayesian Filtering, Models

ESTIMATION

Bayes Filters

z = observation
u = action
x = state

$$\boxed{Bel(x_t)} = P(x_t \mid u_1, z_1 \ldots, u_t, z_t)$$

Bayes
$$= \eta \; P(z_t \mid x_t, u_1, z_1, \ldots, u_t) \; P(x_t \mid u_1, z_1, \ldots, u_t)$$

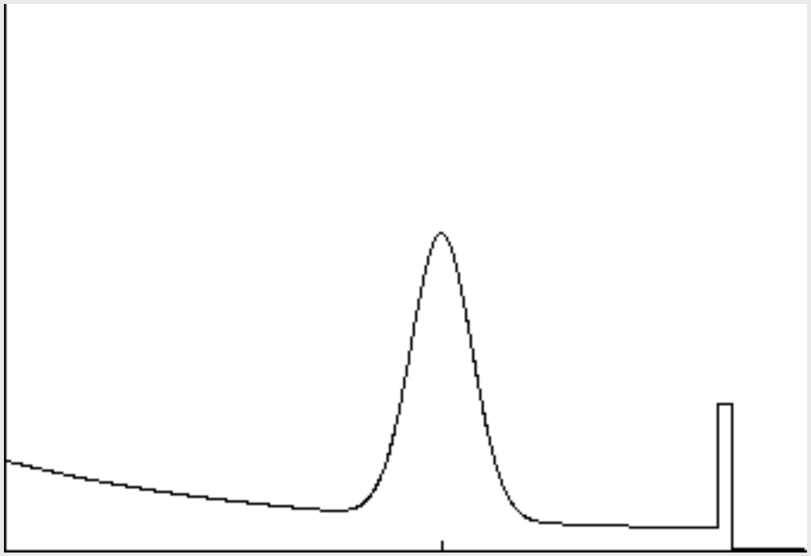
Markov
$$= \eta \; P(z_t \mid x_t) \; P(x_t \mid u_1, z_1, \ldots, u_t)$$

Total prob.
$$= \eta \; P(z_t \mid x_t) \int P(x_t \mid u_1, z_1, \ldots, u_t, x_{t-1}) \; P(x_{t-1} \mid u_1, z_1, \ldots, u_t) \; dx_{t-1}$$

Markov
$$= \eta \; P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) \; P(x_{t-1} \mid u_1, z_1, \ldots, u_t) \; dx_{t-1}$$

$$\boxed{= \eta \; P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) \; Bel(x_{t-1}) \; dx_{t-1}}$$

Parametric Sensor Model



$$P(z \mid x,m) = \begin{pmatrix} \alpha_{\text{hit}} \\ \alpha_{\text{unexp}} \\ \alpha_{\max} \\ \alpha_{\text{rand}} \end{pmatrix}^T \cdot \begin{pmatrix} P_{\text{hit}}(z \mid x,m) \\ P_{\text{unexp}}(z \mid x,m) \\ P_{\max}(z \mid x,m) \\ P_{\text{rand}}(z \mid x,m) \end{pmatrix}$$

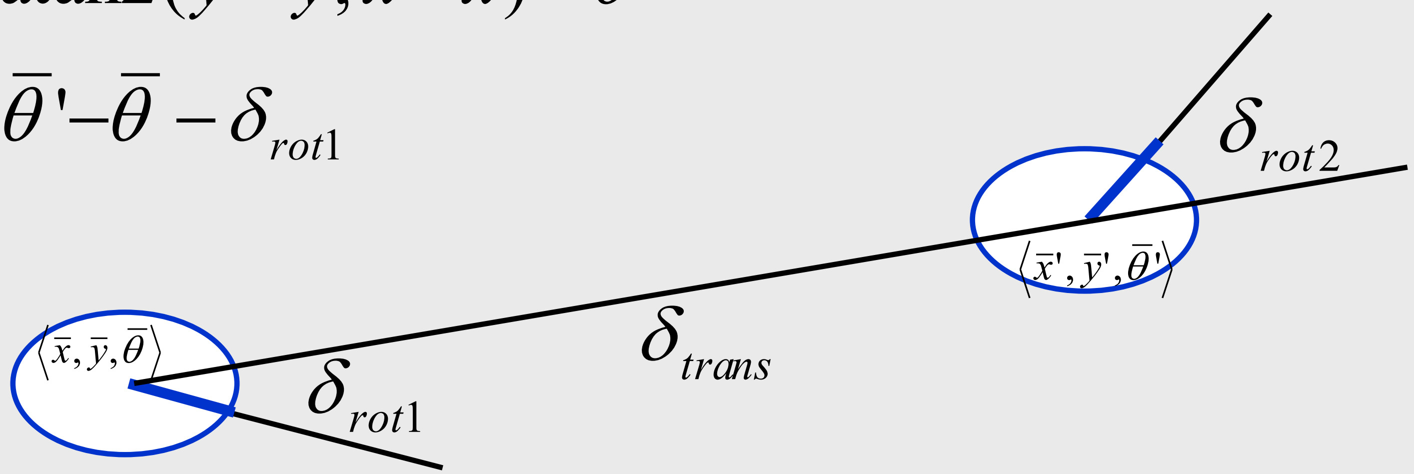
Parametric Kinematics Model

- **Robot moves from** $\langle \bar{x}, \bar{y}, \bar{\theta} \rangle$ **to** $\langle \bar{x}', \bar{y}', \bar{\theta}' \rangle$**.**
- **Odometry information** $u = \langle \delta_{rot1}, \delta_{rot2}, \delta_{trans} \rangle$**.**

$$\delta_{trans} = \sqrt{(\bar{x}' - \bar{x})^2 + (\bar{y}' - \bar{y})^2}$$

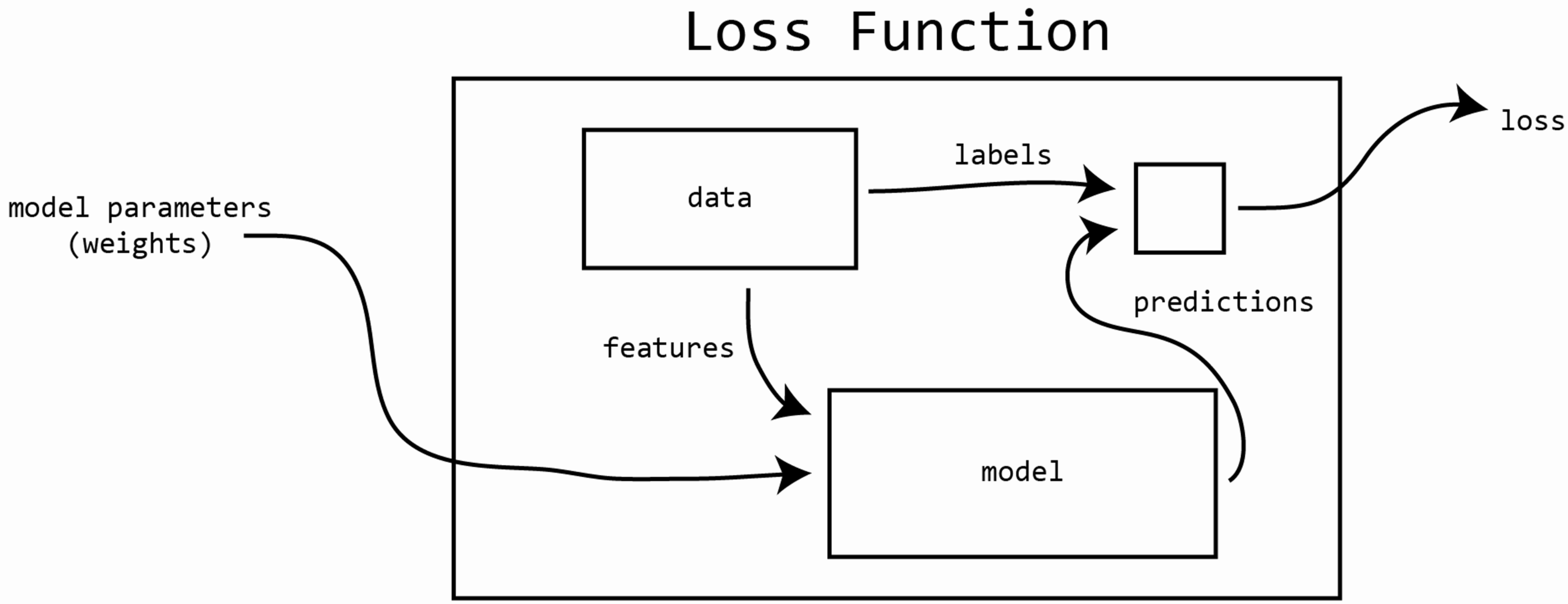
$$\delta_{rot1} = \mathrm{atan2}(\bar{y}' - \bar{y}, \bar{x}' - \bar{x}) - \bar{\theta}$$

$$\delta_{rot2} = \bar{\theta}' - \bar{\theta} - \delta_{rot1}$$



Loss functions are the key!

Just a function! Want to find $\text{argmin}_{\text{weights}}$(Loss Function)



Stochastic gradient descent (SGD)

Estimate $\nabla L(\mathbf{w})$ with only some of the data

Before:

$$\mathbf{w}_{t+1} = \mathbf{w}_t - \eta \, \Sigma_i \nabla L_i(\mathbf{w}), \text{ for all i in |data|}$$

Now:

$$\mathbf{w}_{t+1} = \mathbf{w}_t - \eta \, \Sigma_j \nabla L_j(\mathbf{w}), \text{ for some subset j}$$

Maybe even:

$$\mathbf{w}_{t+1} = \mathbf{w}_t - \eta \, \nabla L_k(\mathbf{w}), \text{ for some random k}$$

# of points used for update is called *batch size*

The Prediction-Correction-Cycle of Kalman Filters

Prediction

$$bel(x_t) = \begin{cases} \mu_t = \bar{\mu}_t + K_t(z_t - \bar{\mu}_t) \\ \sigma_t^2 = (1 - K_t)\bar{\sigma}_t^2 \end{cases}, K_t = \frac{\bar{\sigma}_t^2}{\bar{\sigma}_t^2 + \bar{\sigma}_{obs,t}^2}$$

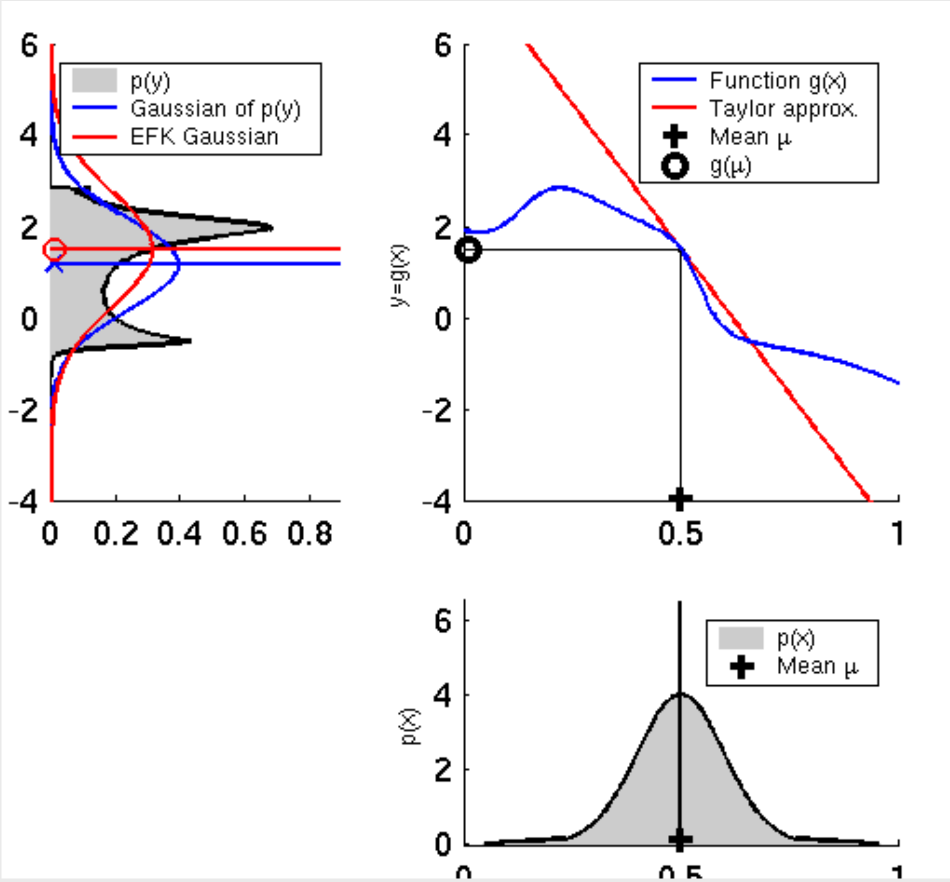
$$bel(x_t) = \begin{cases} \mu_t = \bar{\mu}_t + K_t(z_t - C_t\bar{\mu}_t) \\ \Sigma_t = (I - K_t C_t)\bar{\Sigma}_t \end{cases}, K_t = \bar{\Sigma}_t C_t^T (C_t \bar{\Sigma}_t C_t^T + Q_t)^{-1}$$

$$\overline{bel}(x_t) = \begin{cases} \bar{\mu}_t = a_t \mu_{t-1} + b_t u_t \\ \bar{\sigma}_t^2 = a_t^2 \sigma_t^2 + \sigma_{act,t}^2 \end{cases}$$

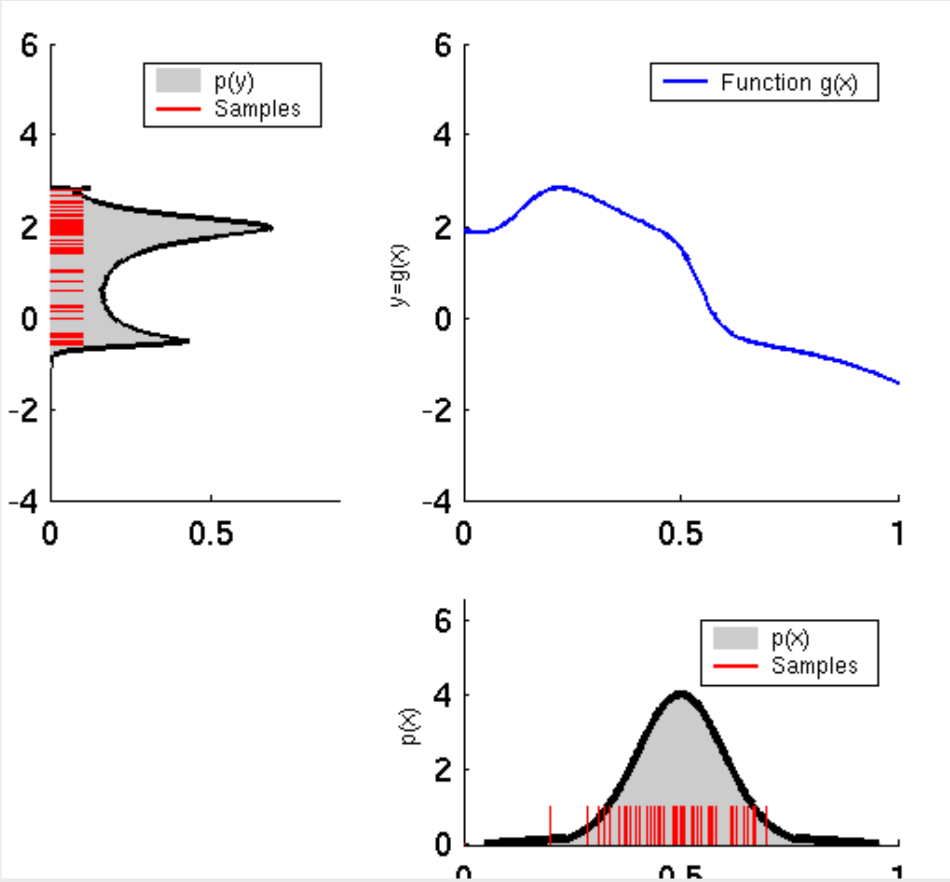
$$\overline{bel}(x_t) = \begin{cases} \bar{\mu}_t = A_t \mu_{t-1} + B_t u_t \\ \bar{\Sigma}_t = A_t \Sigma_{t-1} A_t^T + R_t \end{cases}$$

Correction

EKF Linearization



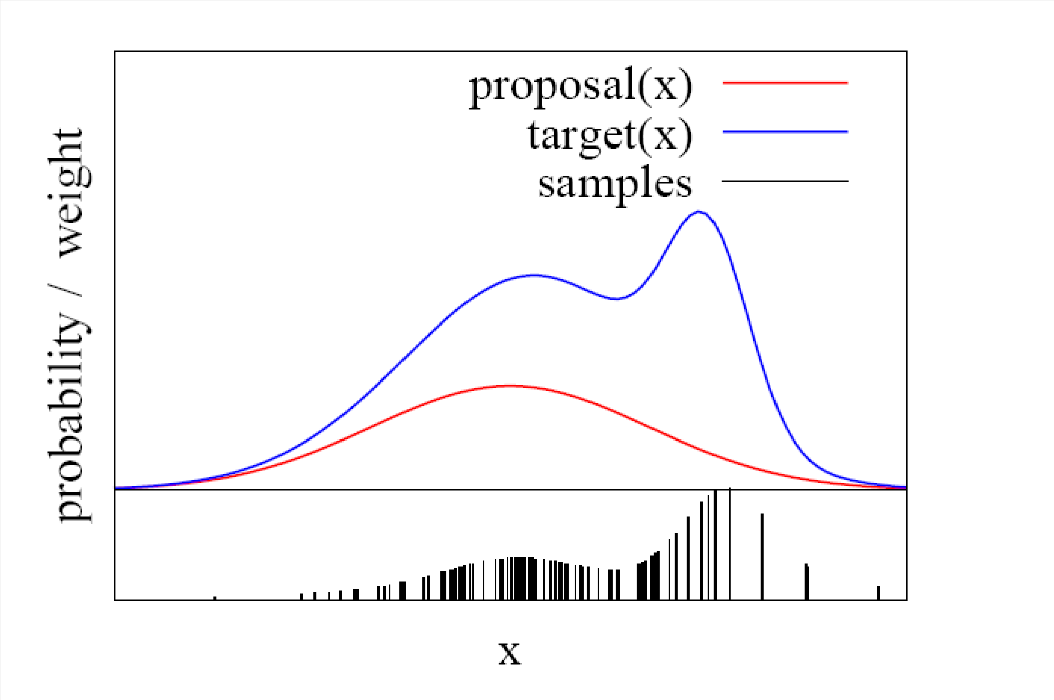
Particle Filter Projection



Importance Sampling Principle

- We can use a different distribution g to generate samples from f
- By introducing an importance weight w, we can account for the "differences between g and f"

$$\boldsymbol{w = f / g}$$

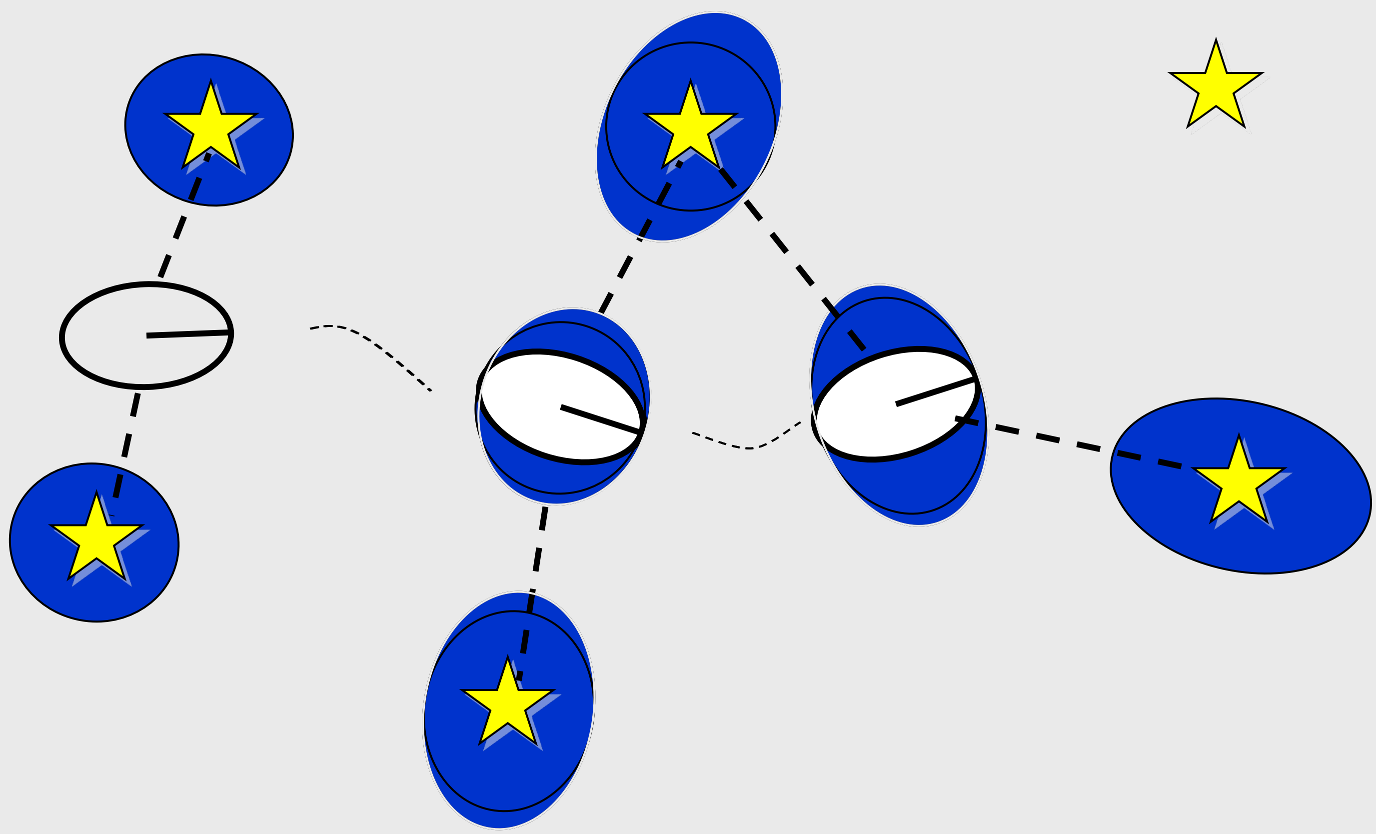


SLAM

ESTIMATION

Why is SLAM a hard problem?

- SLAM: robot path and map are both unknown



- Robot path error correlates errors in the map

EKF-SLAM

- Map with N landmarks:(3+2N)-dimensional Gaussian

$$Bel(x_t, m_t) = \left\langle \begin{pmatrix} x \\ y \\ \theta \\ l_1 \\ l_2 \\ \vdots \\ l_N \end{pmatrix}, \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{x\theta} & \sigma_{xl_1} & \sigma_{xl_2} & \cdots & \sigma_{xl_N} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{y\theta} & \sigma_{yl_1} & \sigma_{yl_2} & \cdots & \sigma_{yl_N} \\ \sigma_{x\theta} & \sigma_{y\theta} & \sigma_\theta^2 & \sigma_{\theta l_1} & \sigma_{\theta l_2} & \cdots & \sigma_{\theta l_N} \\ \sigma_{xl_1} & \sigma_{yl_1} & \sigma_{\theta l_1} & \sigma_{l_1}^2 & \sigma_{l_1 l_2} & \cdots & \sigma_{l_1 l_N} \\ \sigma_{xl_2} & \sigma_{yl_2} & \sigma_{\theta l_2} & \sigma_{l_1 l_2} & \sigma_{l_2}^2 & \cdots & \sigma_{l_2 l_N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \sigma_{xl_N} & \sigma_{yl_N} & \sigma_{\theta l_N} & \sigma_{l_1 l_N} & \sigma_{l_2 l_N} & \cdots & \sigma_{l_N}^2 \end{pmatrix} \right\rangle$$

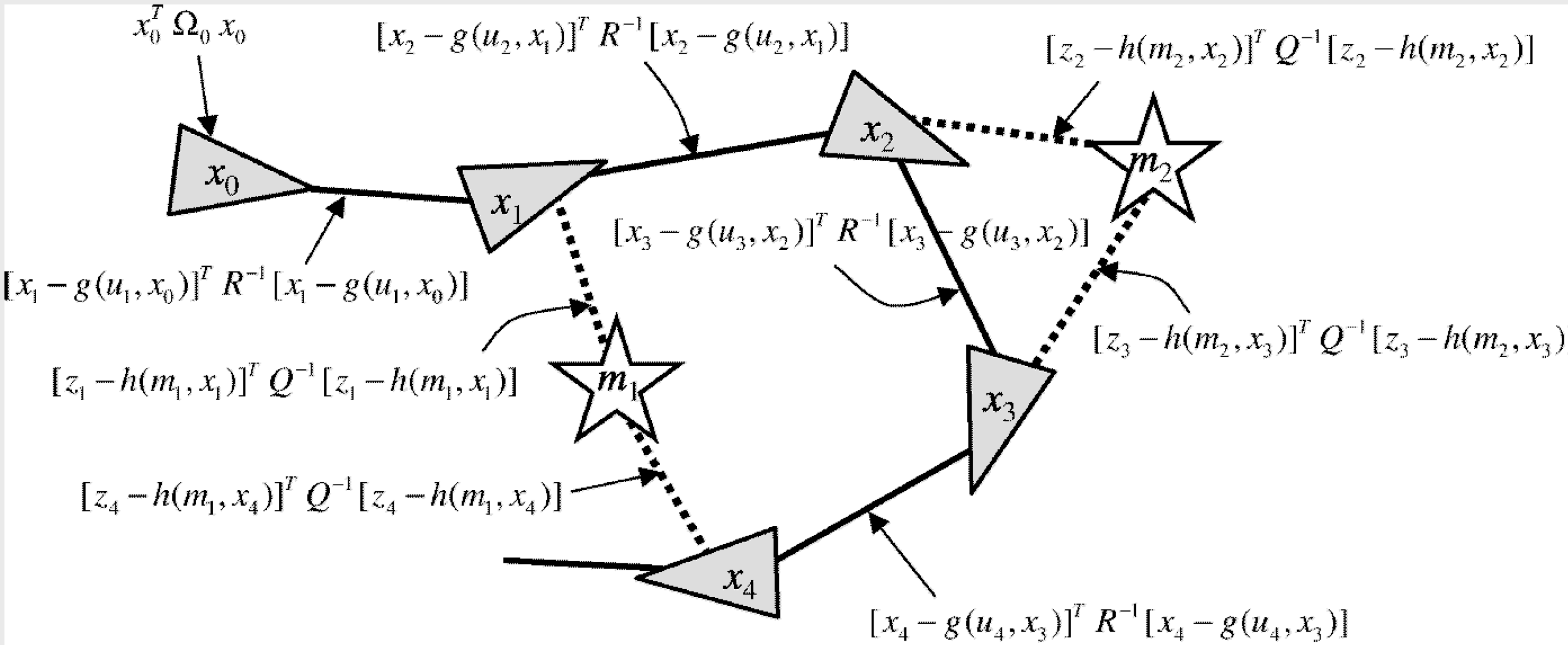
- Can handle hundreds of dimensions

FastSLAM

	Robot Pose	2 x 2 Kalman Filters			
Particle #1	x, y, z	Landmark 1	Landmark 2	…	Landmark N
Particle #2	x, y, z	Landmark 1	Landmark 2	…	Landmark N
Particle #3	x, y, z	Landmark 1	Landmark 2	…	Landmark N
⋮					
Particle M	x, y, z	Landmark 1	Landmark 2	…	Landmark N

[Courtesy of Mike Montemerlo]

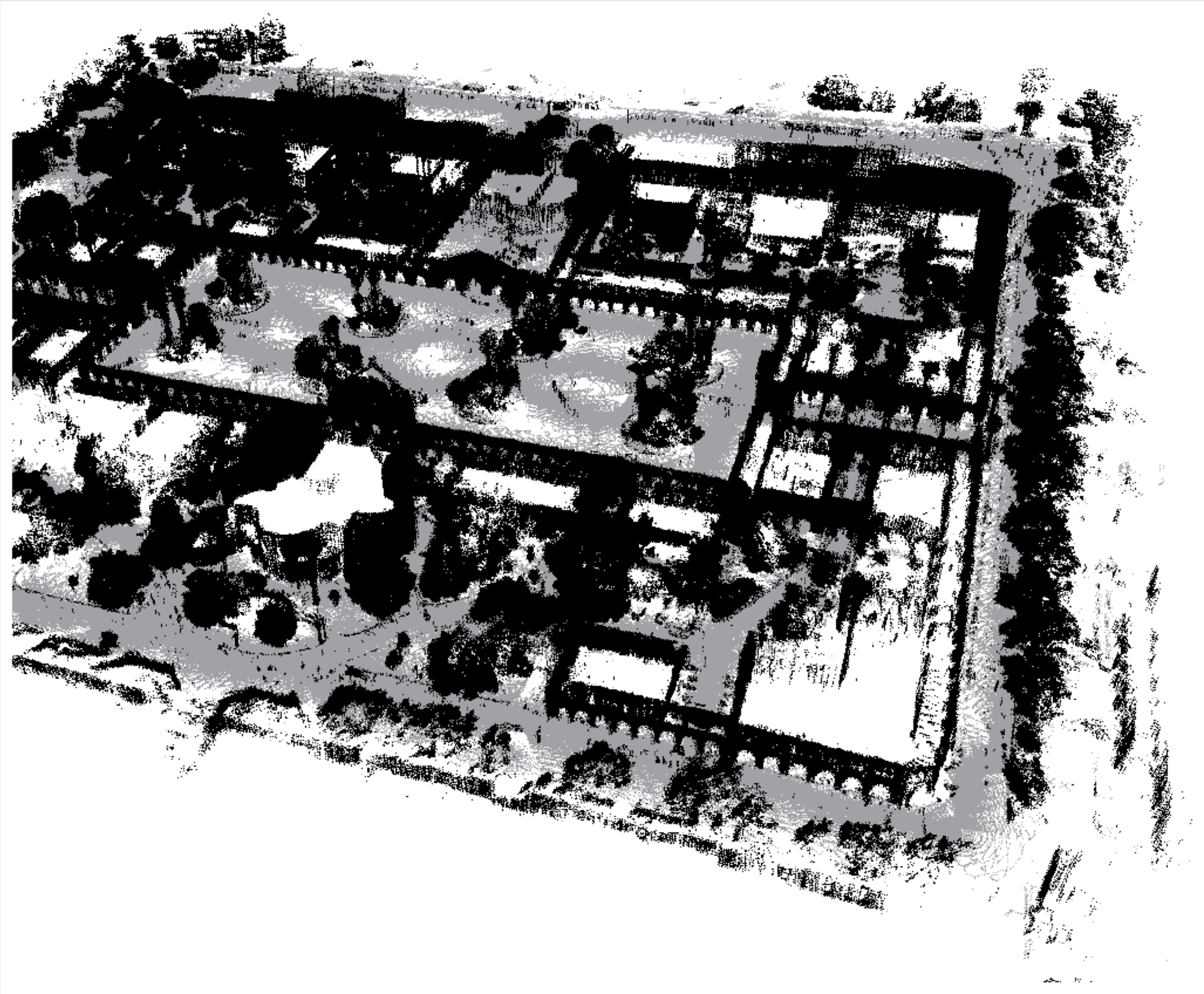
Graph-SLAM Idea



<u>Sum of all constraints:</u>

$$J_{\text{GraphSLAM}} = x_0^T \Omega_0 x_0 + \sum_t [x_t - g(u_t, x_{t-1})]^T R^{-1} [x_t - g(u_t, x_{t-1})] + \sum_t [z_t - h(m_{c_t}, x_t)]^T Q^{-1} [z_t - h(m_{c_t}, x_t)]$$

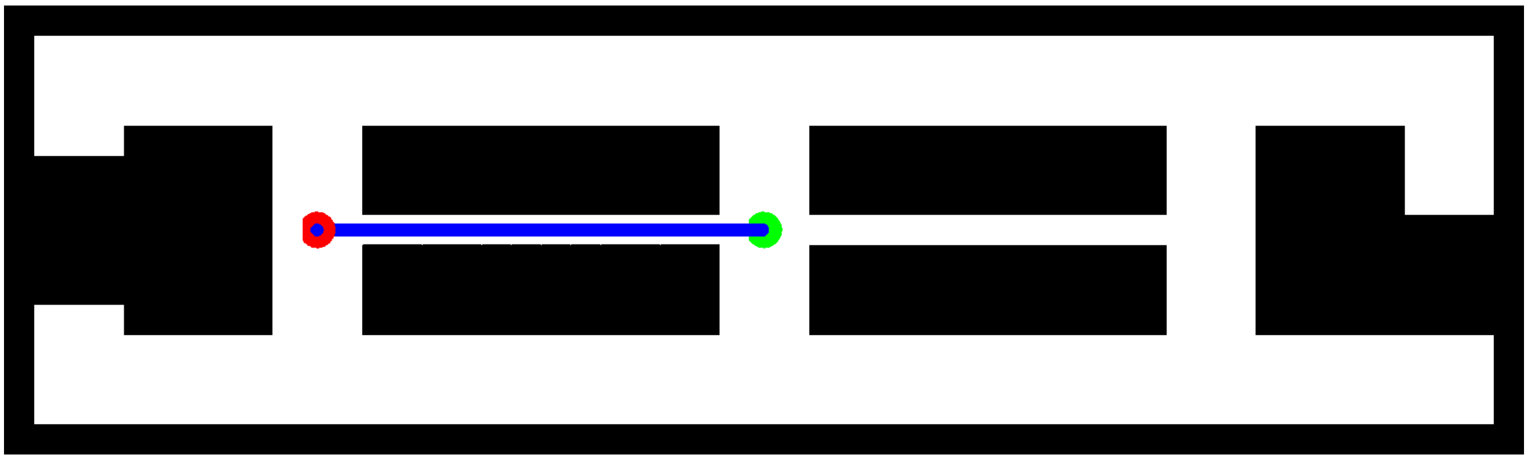
3D Outdoor Mapping



10^8 features, 10^5 poses, only few secs using cg.

PLANNING / CONTROL

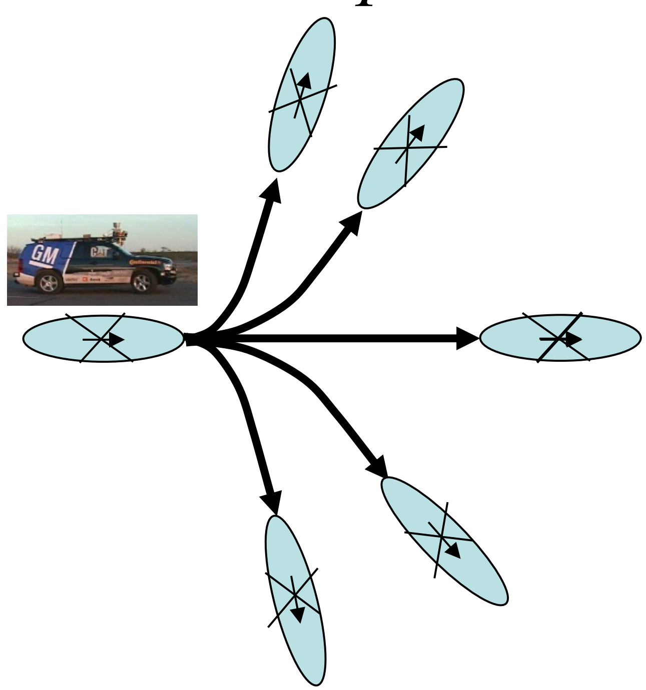
Deterministic, fully observable



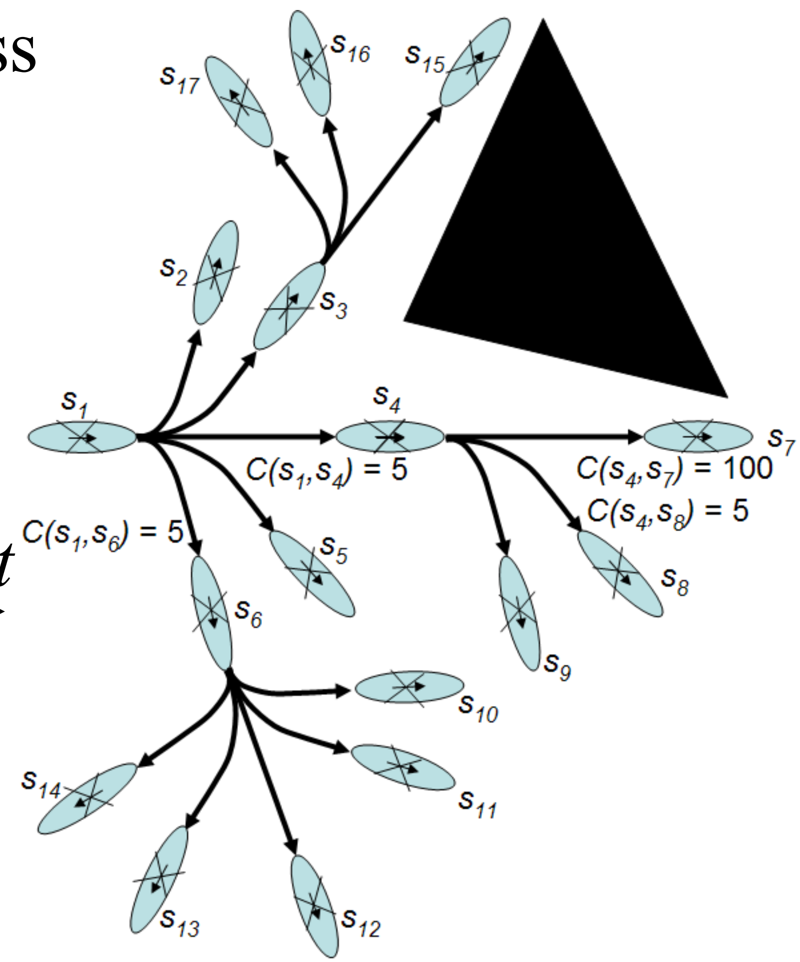
Planning via Cell Decomposition

- Graph construction:
  - lattice graph
  - pros: sparse graph, feasible paths
  - cons: possible incompleteness

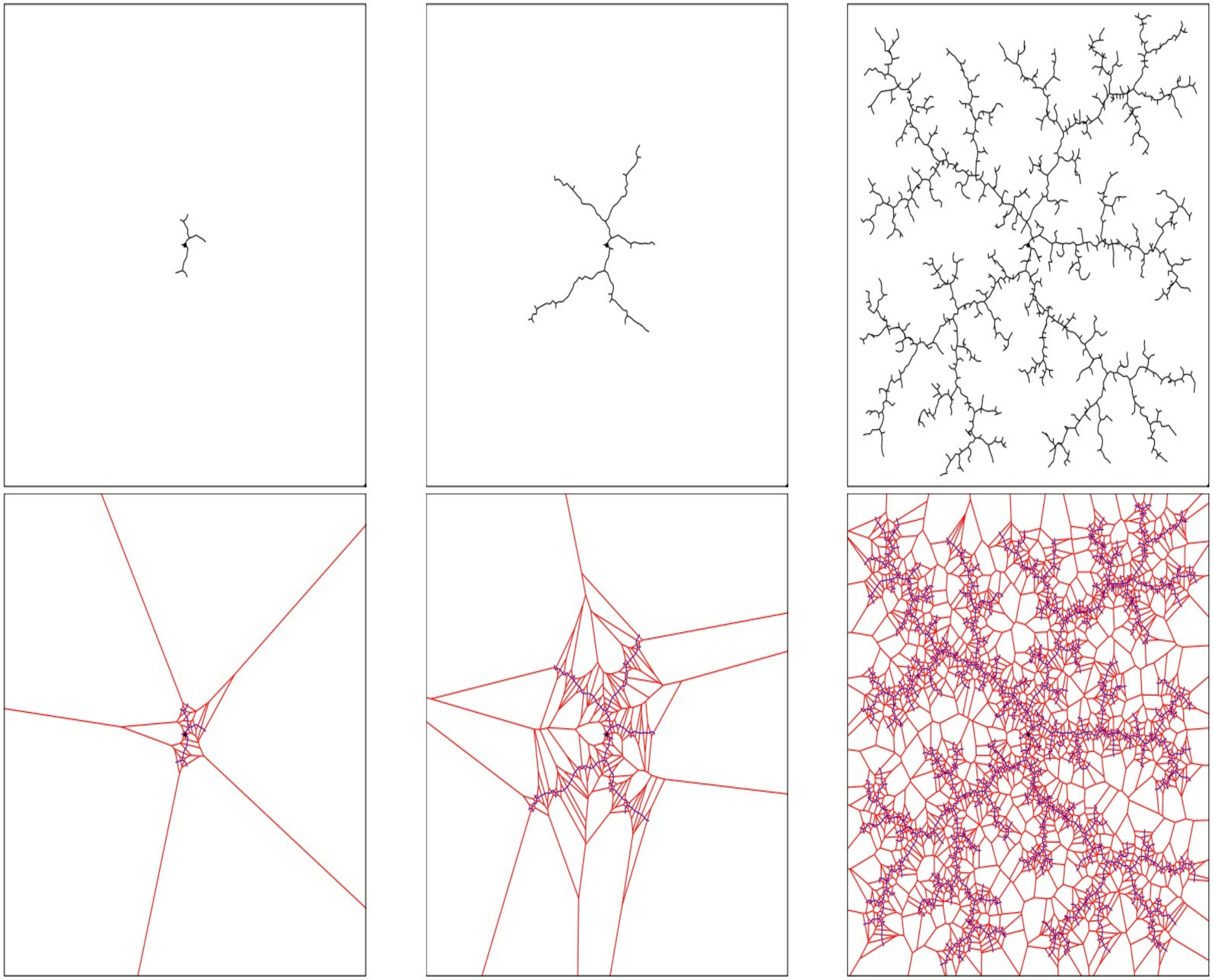
action template



replicate it online

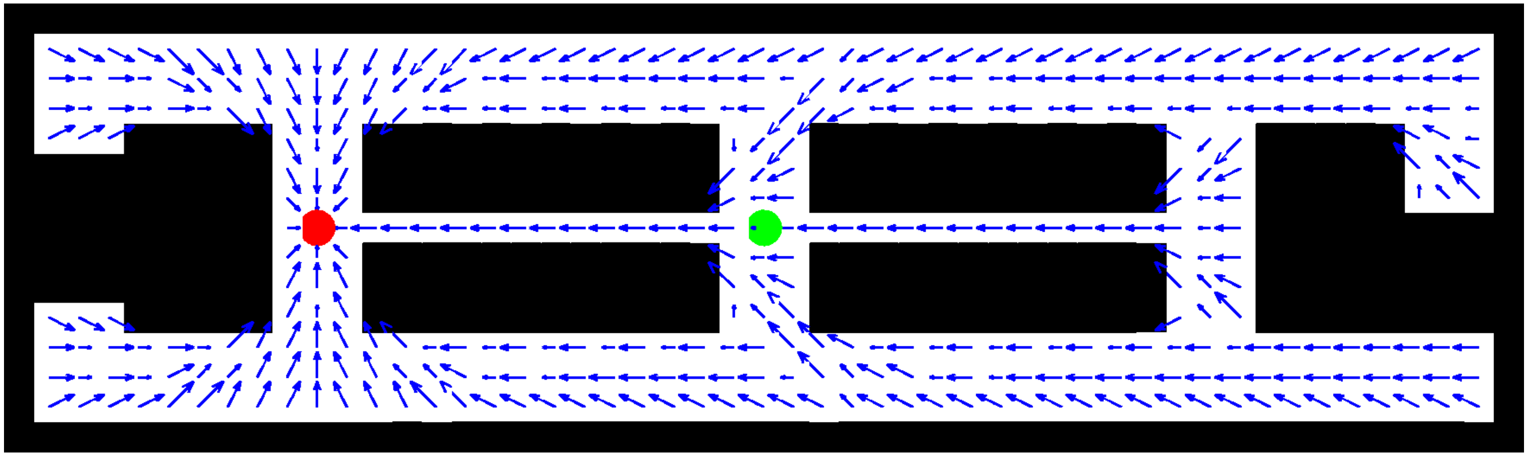


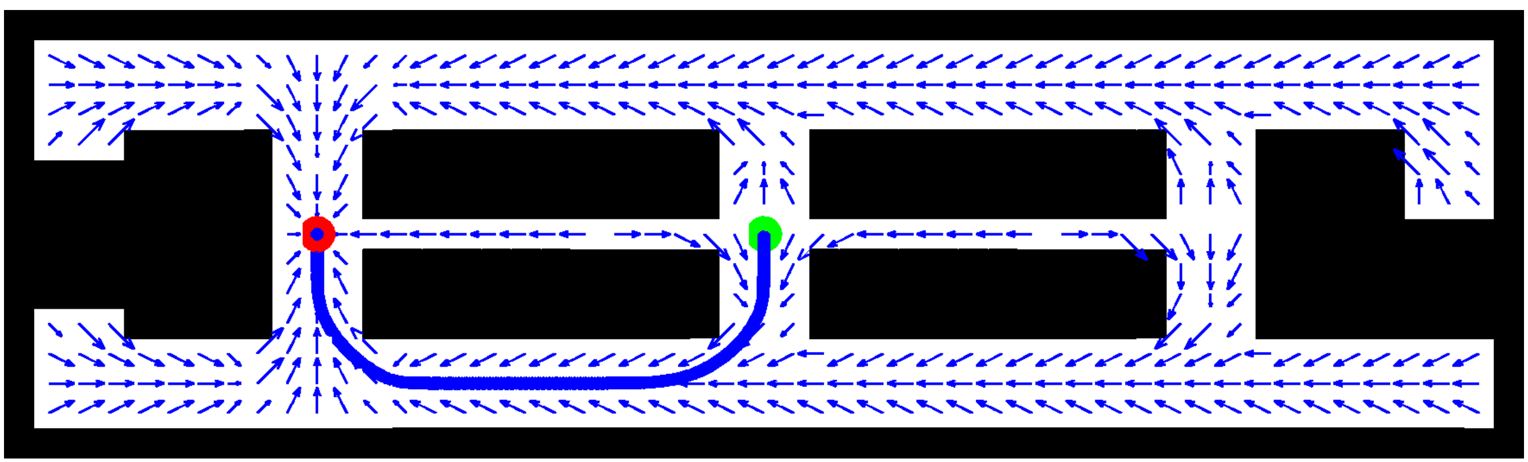
Rapidly exploring Random Tree (RRT)



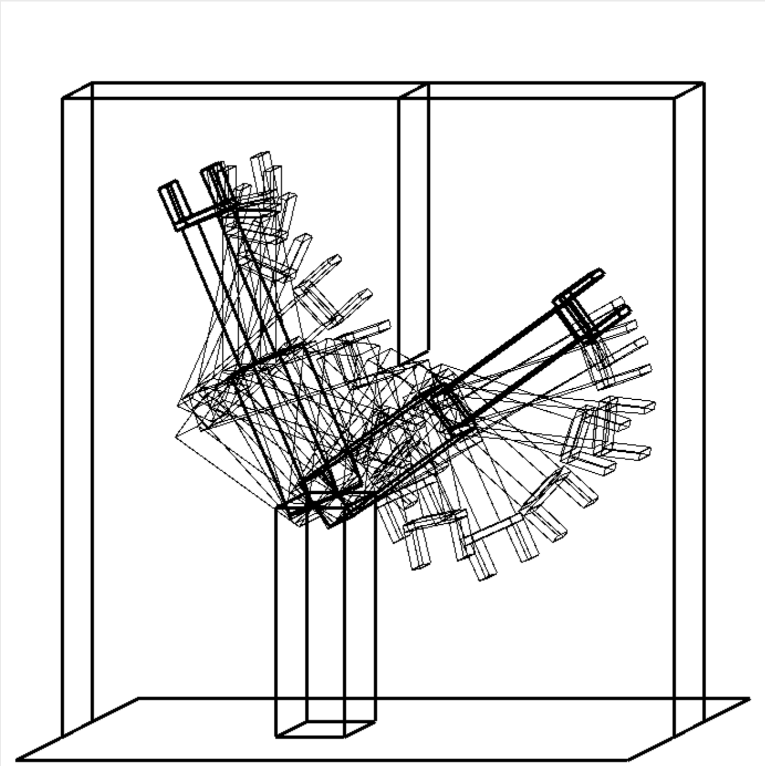
Source: LaValle and Kuffner 01

Stochastic, Fully Observable

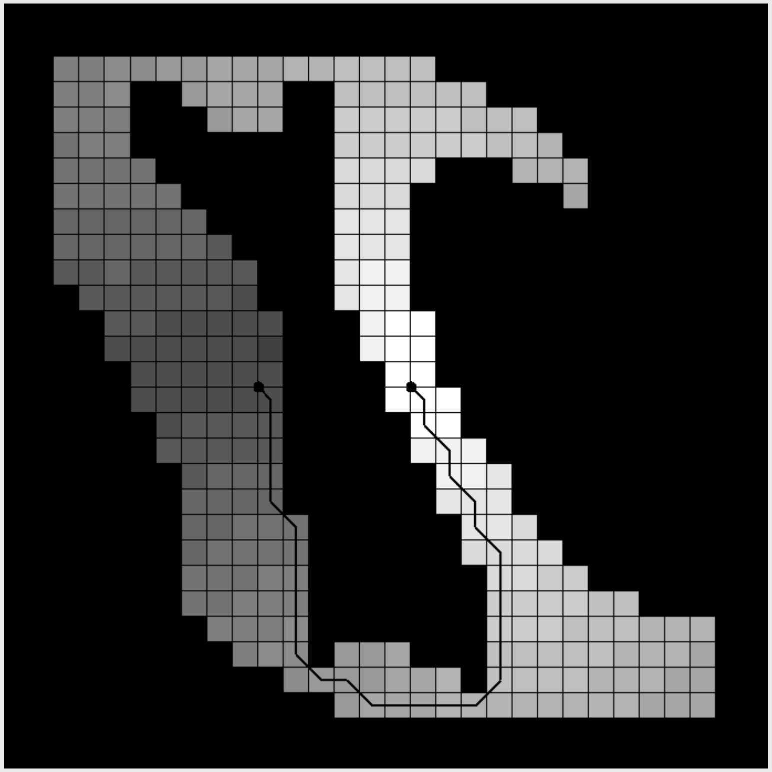




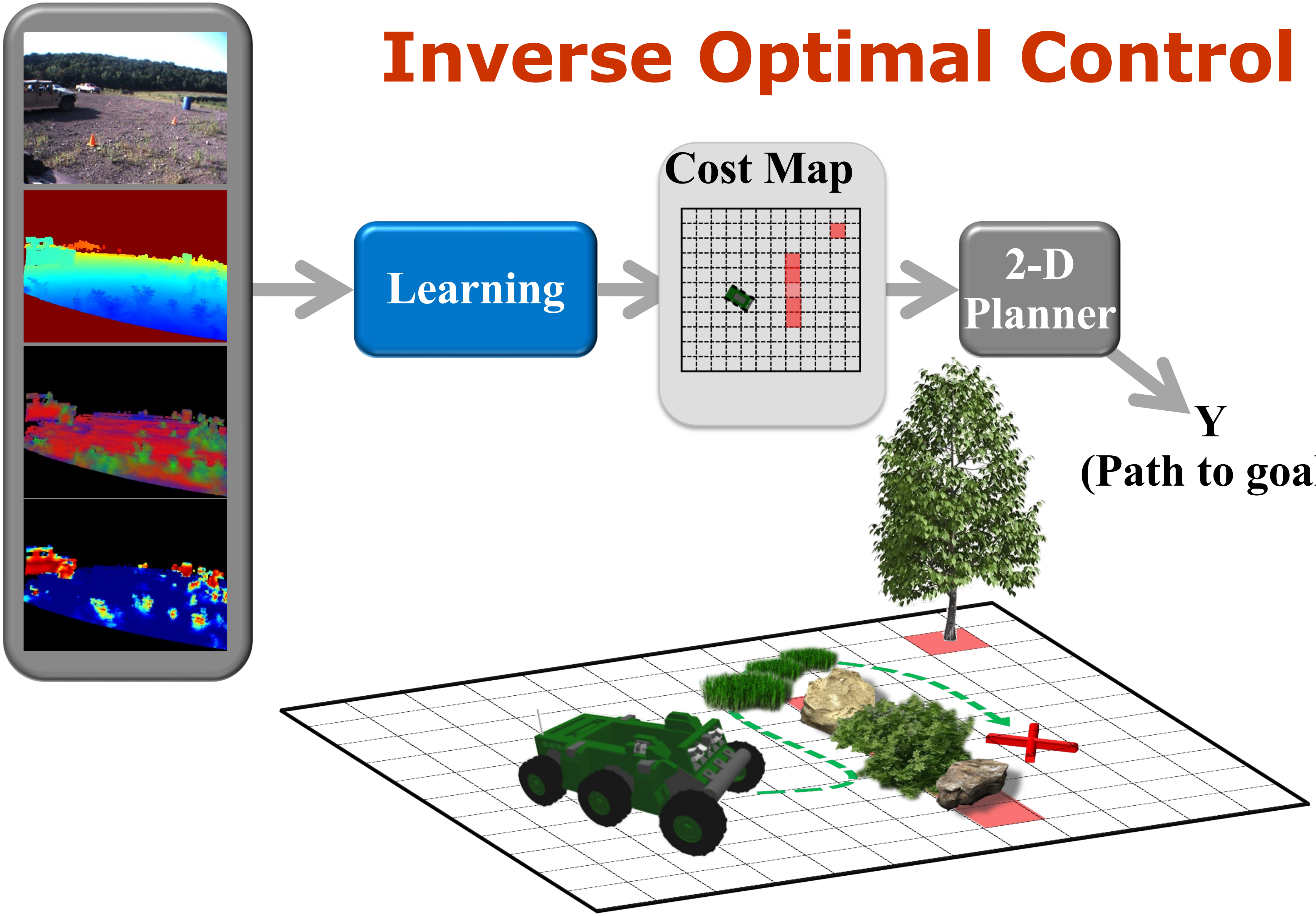
Manipulator Control Path



State space



Configuration space

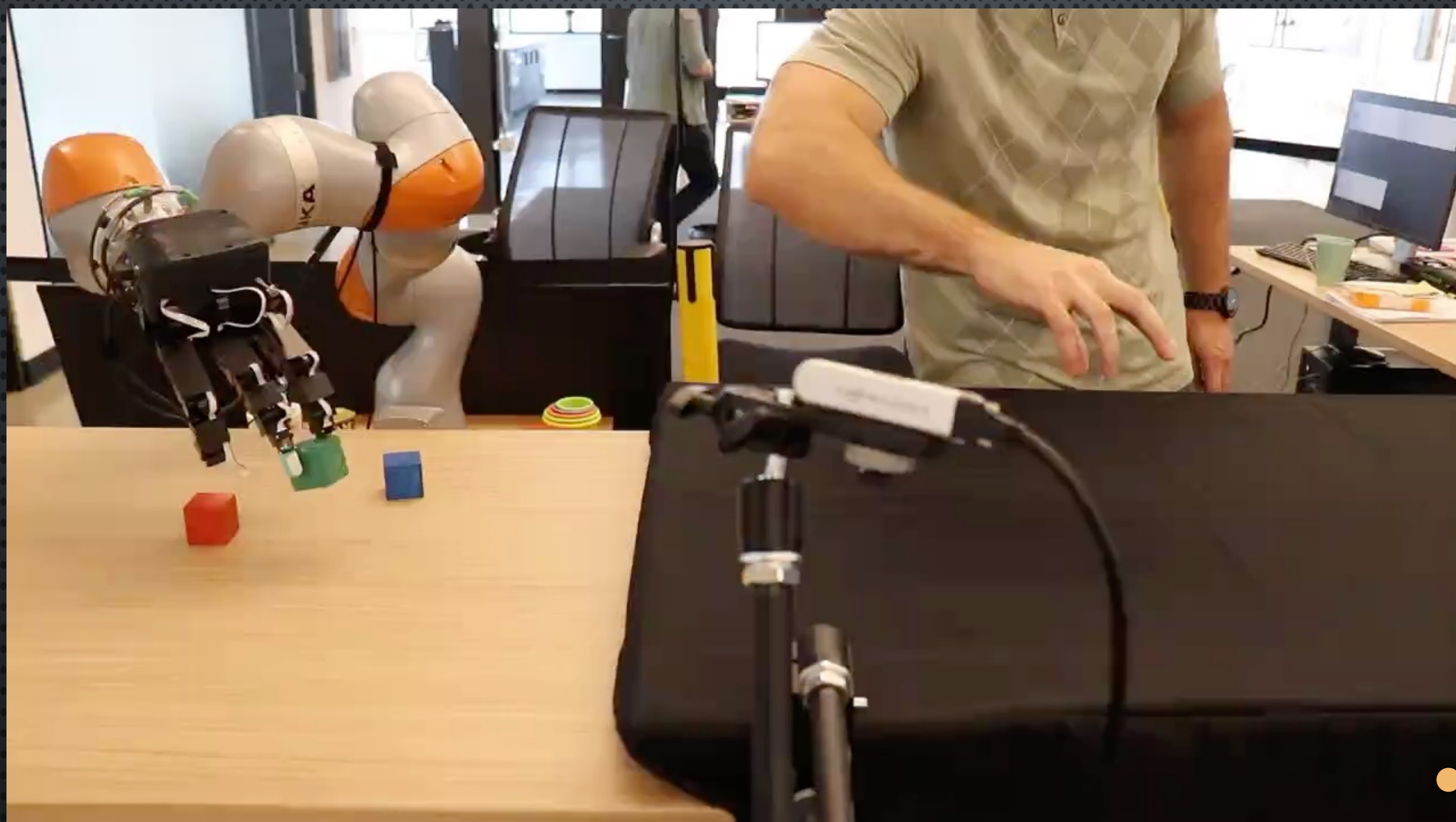

Inverse Optimal Control
Learning
Cost Map
2-D
Planner
Y
(Path to goal)

COOKING WITH JULIA

GRAVITY AND ONIONS

[Handa-VanWyk-Yang-Liang-Chao-Wan-Birchfield-F: ICRA-19

TELEOPERATION OF DEXTEROUS MANIPULATION



- 6x

Intuitive Physics

- People have intuitive understanding of how things evolve over time, and how to achieve desired change
- Qualitatively related to physics underlying a scene: gravity, forces, friction, mass, size, persistence, rigid and non-rigid motion, …
- Good enough for control since tightly coupled to perception --> closed loop control

- Physics based models in robotics generalize well but are not tightly coupled to perception

- Can we learn intuitive physics models for robots?
  - Ideally suited for closed-loop control since fully grounded in perceptual experience
  - Applicable across a wide range of tasks

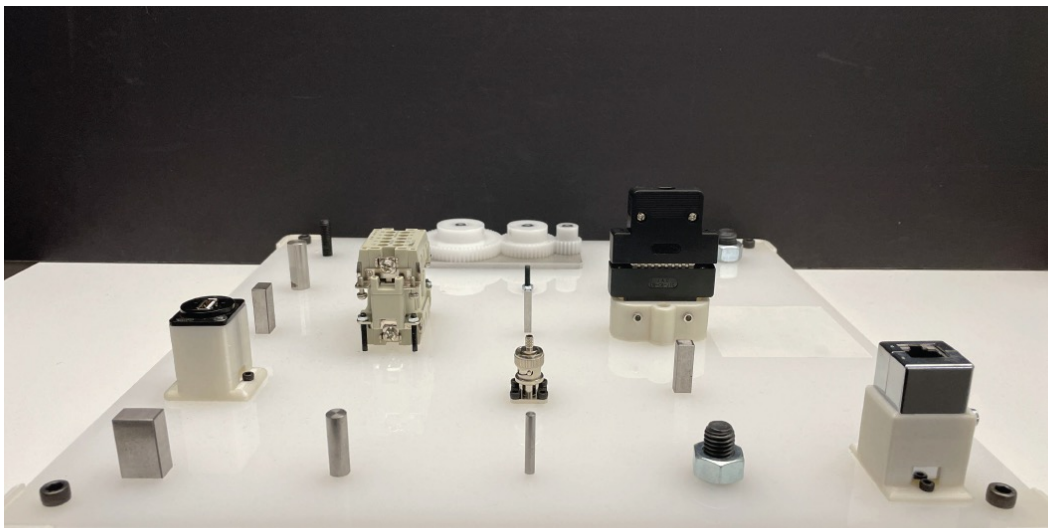
Deep Learning for Robotics

- Extremely flexible and expressive framework for learning from raw data
  - Will dominate many recognition / control tasks, especially well suited for closed-loop control with complex perception and state spaces
  - In robotics, future data provides supervisory signals
- Challenges
  - How to get training data (scalabiltiy, safety, overfitting, simulation)?
  - How to best combine models and deep learning?
  - How to extract / model uncertainty and Guarantees?
  - Understanding of network structures, training regimes, generalization capabilities
- Risks
  - Students degraded to network and data engineers
  - Company or lab with most GPU's wins
- A toolbox to try new things and revisit tasks from new perspectives

[Narang, Storey, Akinola, Macklin, Reist, Wawryzniak, Guo, State, Moravanszky, Lu, Handa, Fox: RSS 2022]

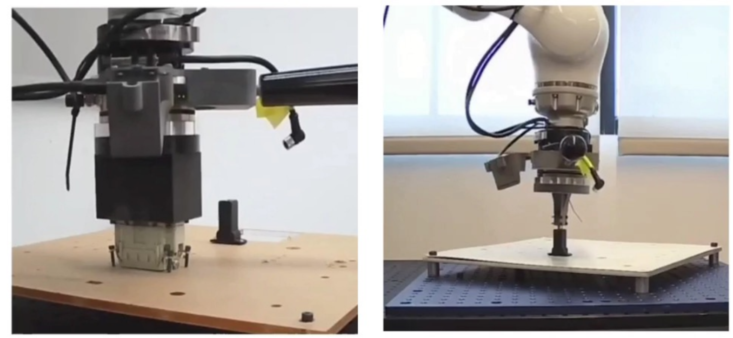
CONTACT-RICH TASKS: NIST BENCHMARK ENVIRONMENT

High Relevance to Applications in Industrial Assembly



Established real-world benchmark:

Round and rect. pegs/holes
Nuts/bolts
Gear assembly
Electrical connectors



Recent advances in real world RL

[Lian, Kelch, Holz, Norton, Schaal, 2021]
[Luo, Sushkov, Pevceviciute, Lian, Su, Vecerik, Ye, Schaal, Scholz, 2021]

CONTACT-RICH SIMULATION

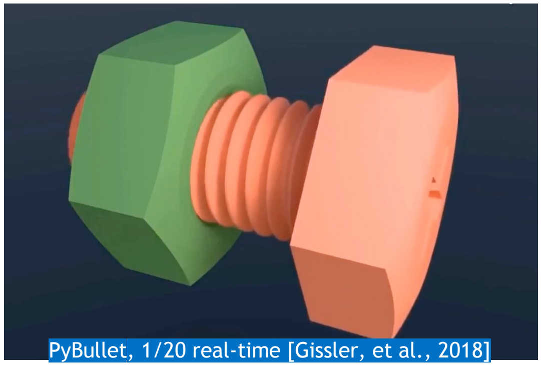
Simulation has accelerated robotics, but contact-rich simulation is a grand challenge.

Simulation in robotics

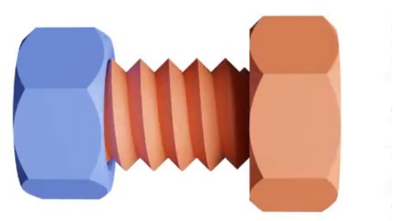
MuJoCo-based training [Akkaya, et al., 2019]

Isaac Gym-based training [Rudin, et al., 2021]

Contact-rich simulation



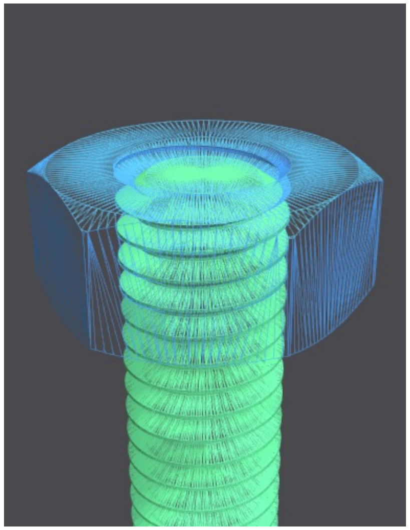
PyBullet, 1/20 real-time [Gissler, et al., 2018]



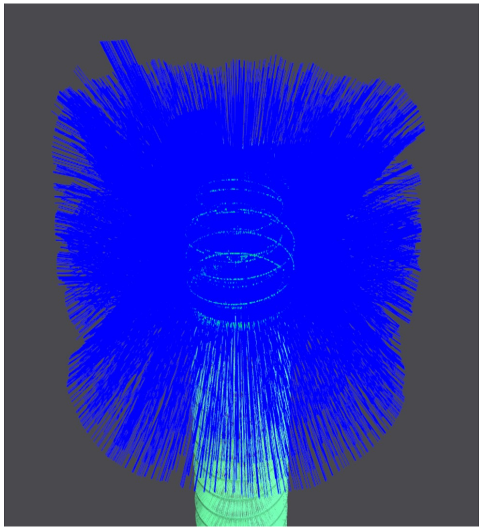
1/350 real-time [Ferguson, et al., 2020]

Based on [Macklin, Erleben, Mueller, Chentanez, Jeschke, Corse: ACM Comput. Graph. Interact. Tech. 2020]
[Moravanszky, Terdiman: Game Programming Gems, 2004]

SDF-BASED COLLISIONS AND CONTACT REDUCTION

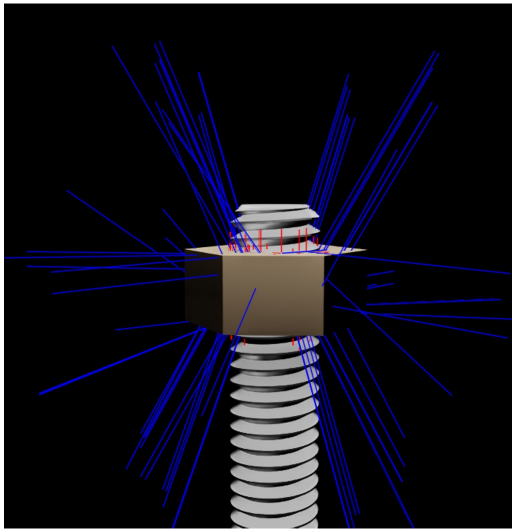


Bolt: SDF values stored as 3D texture
Nut: Mesh



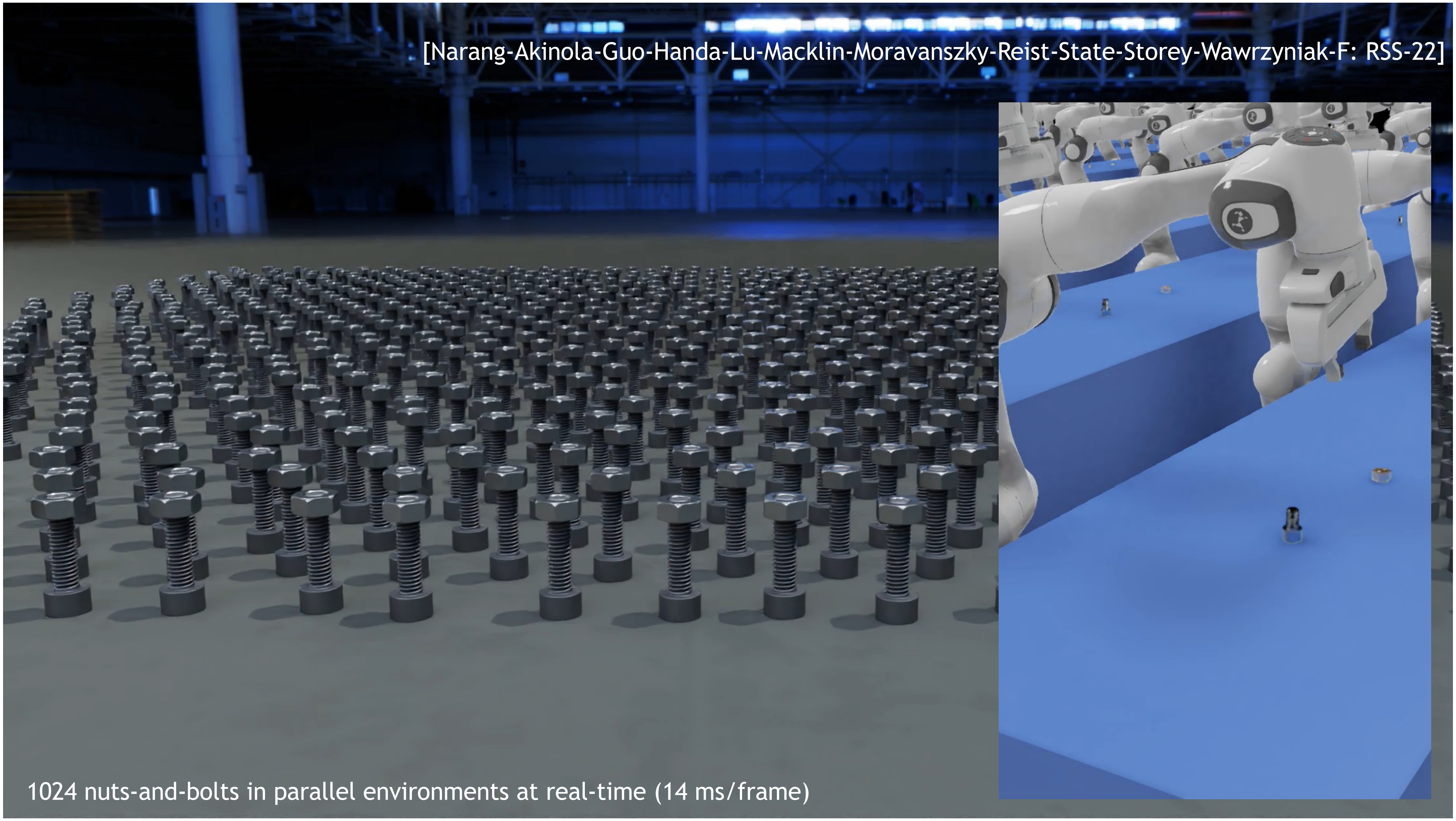
16k contacts generated in <1 ms

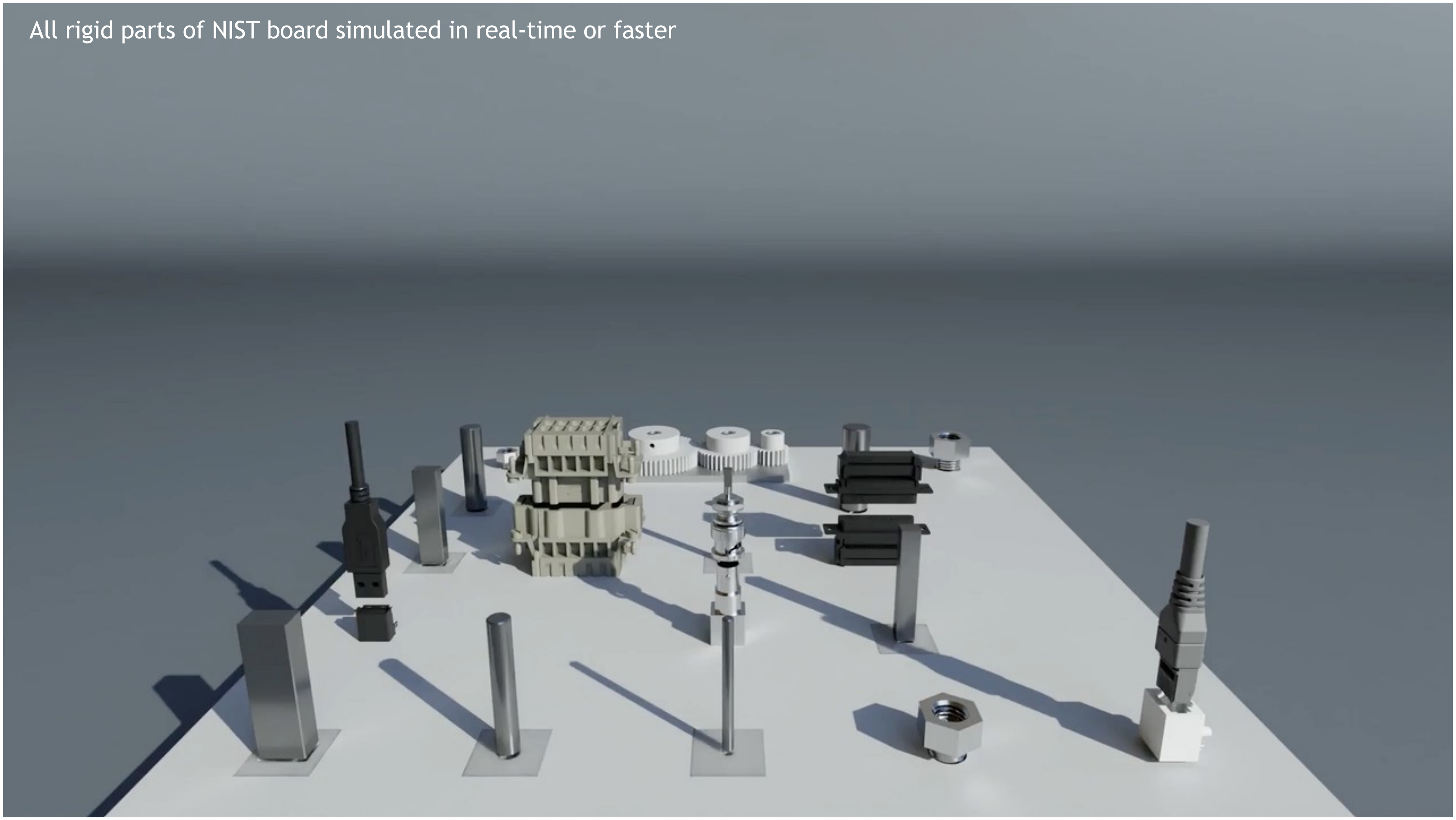
With Jacobi solver (inherently parallel), max 20 nuts/bolts.

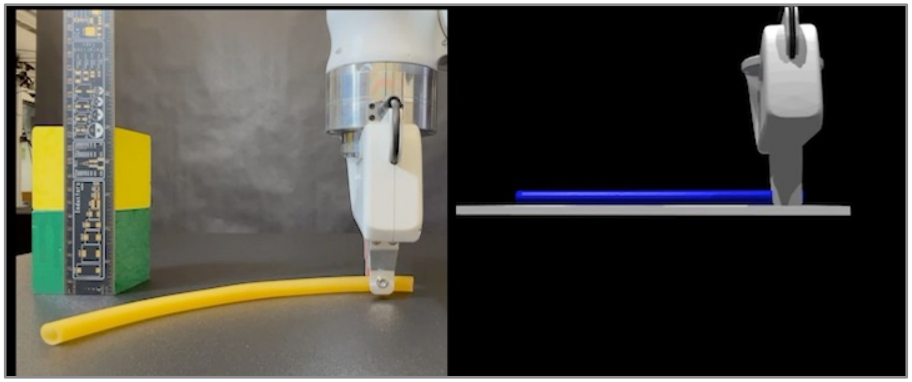


Clustering algorithm based on similarity-of-normals and depth-of-contact: 300 contacts (1.9%).

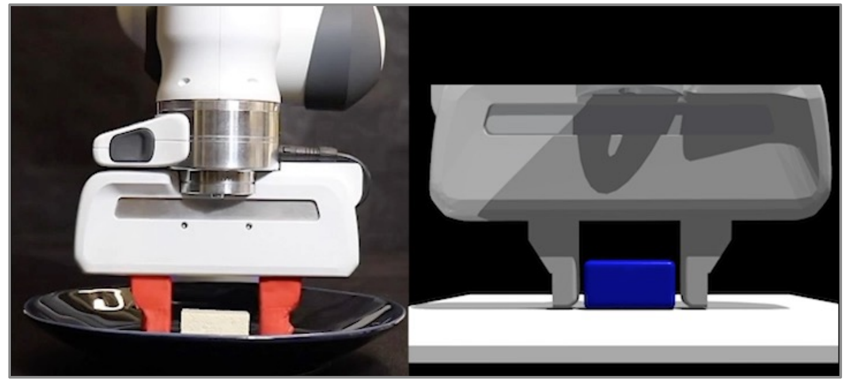
With Gauss-Seidel solver (fast convergence), max 35k nuts/bolts.


[Narang-Akinola-Guo-Handa-Lu-Macklin-Moravanszky-Reist-State-Storey-Wawrzyniak-F: RSS-22]
1024 nuts-and-bolts in parallel environments at real-time (14 ms/frame)


All rigid parts of NIST board simulated in real-time or faster



Tube deformation



Grasping and squeezing tofu

Deformable objects and granular media

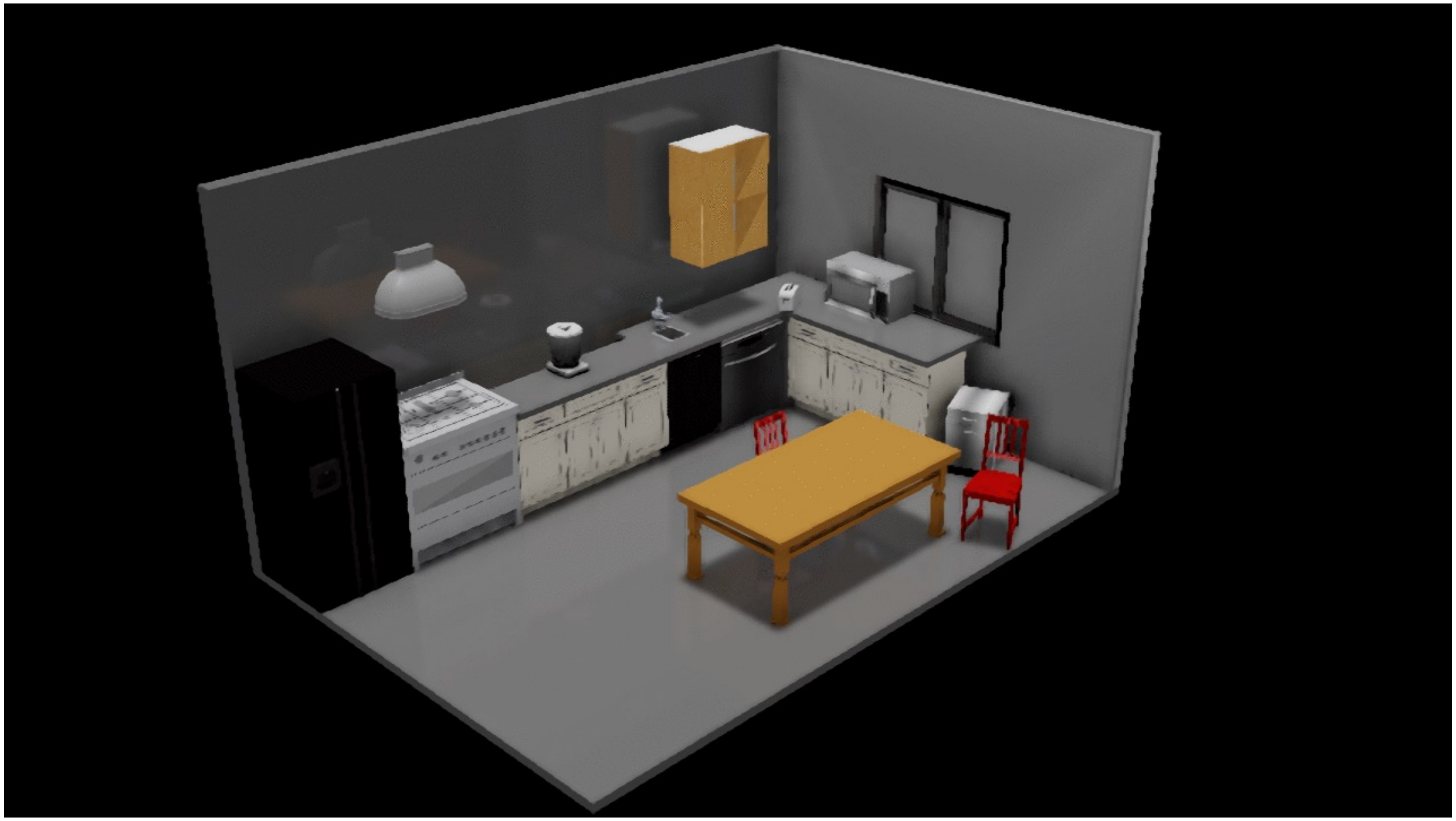
- DefGraspSim: dataset on 34 deformable objects along with deformations, stress fields, grasp successes
- Simulation matches real world behavior very well (w/ off the shelf material parameters)
- Sim parameters can be adjusted to real world data

[Huang-Narang-Eppner-Sundaralingam-Macklin-Hermans-F: RA-L-22]
[Matl-Narang-Ramos-F: ICRA-20]
[Ramos-Posas-F: RSS-19]

Pouring granular media

GENERATING SCENES FOR ROBOT MANIPULATION TASKS

ShapeNet, PartNet Mobility, ModelNet, Google Scanned Objects

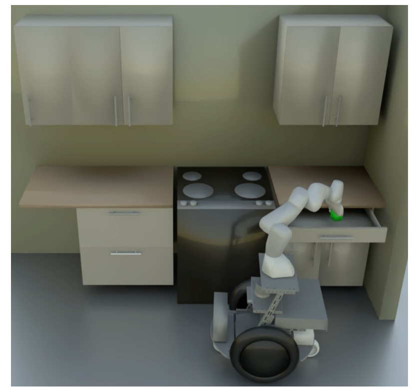


TASK GENERATION

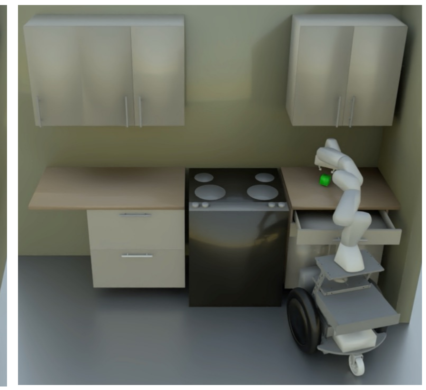
Diversity in Initial States, Manipulation Skills, and Goal Conditions

- **Logical goal conditions** describe sets of scene states
  - **On**(*A*, *B*) := *A* at a pose that is supported by surface *B*
- Use planner to generate **reachable** state/goal pairs
- Scale **task complexity**
  - Obstacles and clutter
  - Diverse manipulation skills
  - Compound goals
  - Long time horizons

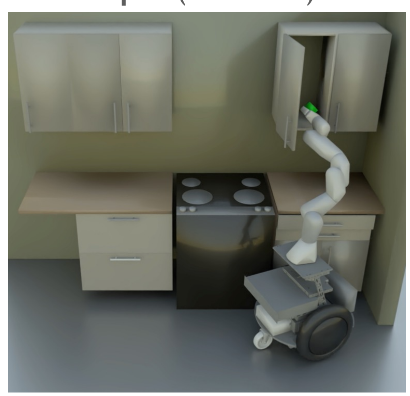
Open(*drawer1*)



Holding(*robot*, *green_block*)

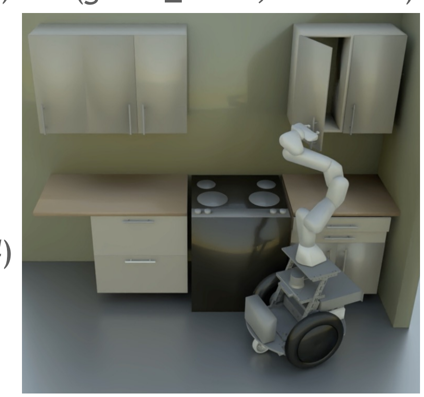


On(*green_block*, *counter2*)



In(*green_block*, *cabinet4*)

Closed(*cabinet4*)



[Garrett-Paxton-Lozano-Perez-Kaelbling-Fox: ICRA-20]

SOLUTION GENERATION

TAMP to Generate Motion Data for Completing Complex Tasks