Hierarchical task and motion

Planning in the Know

Leslie Pack Kaelbling
Tomas Lozano-Perez
MIT CSAIL

Real robot meets real world: uncertainty

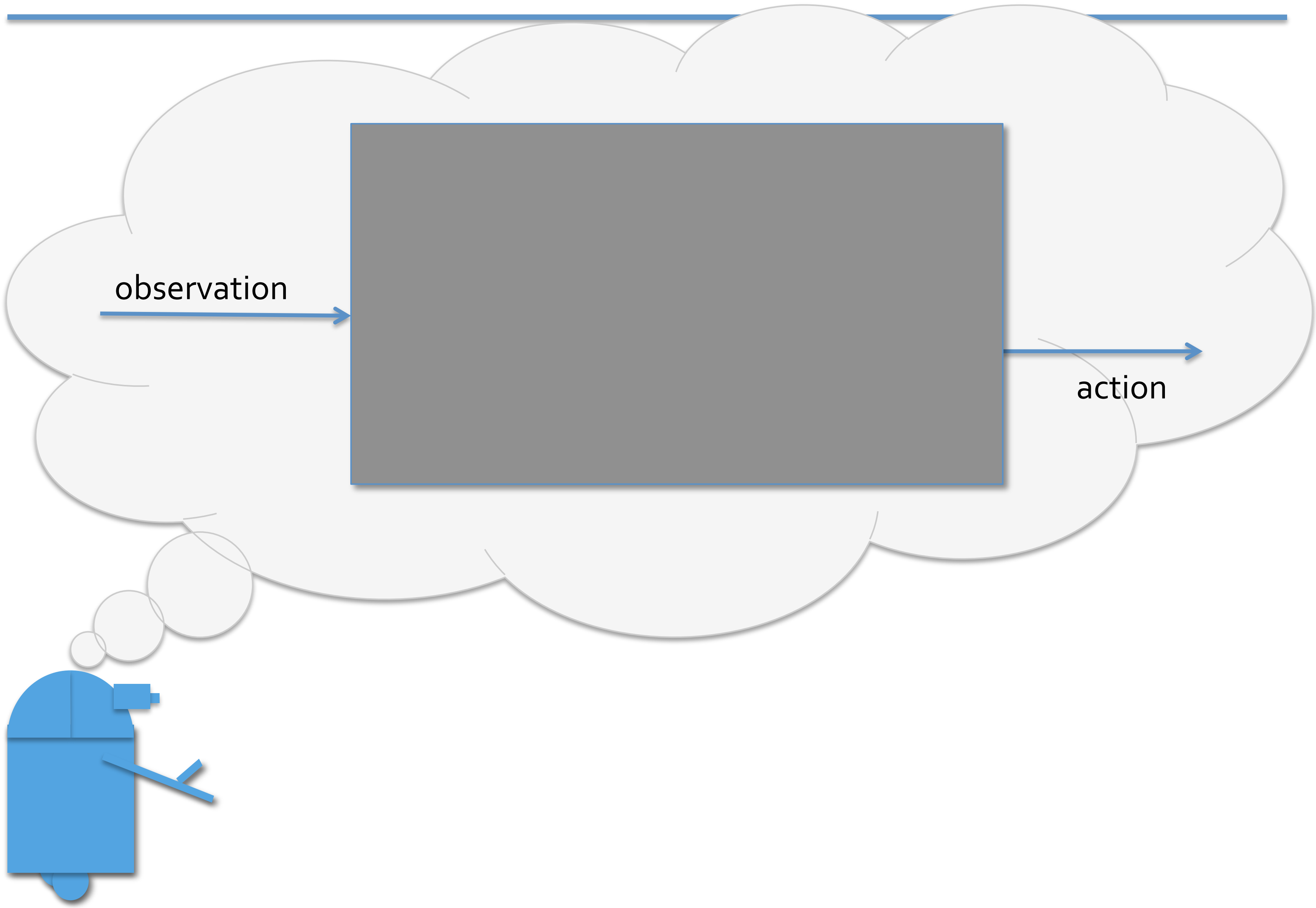
Current-state uncertainty

- What is inside the tupperware?
- Is the dishwasher clean?
- What is the exact pose of the pot?
- What's the friction of a wet dish?

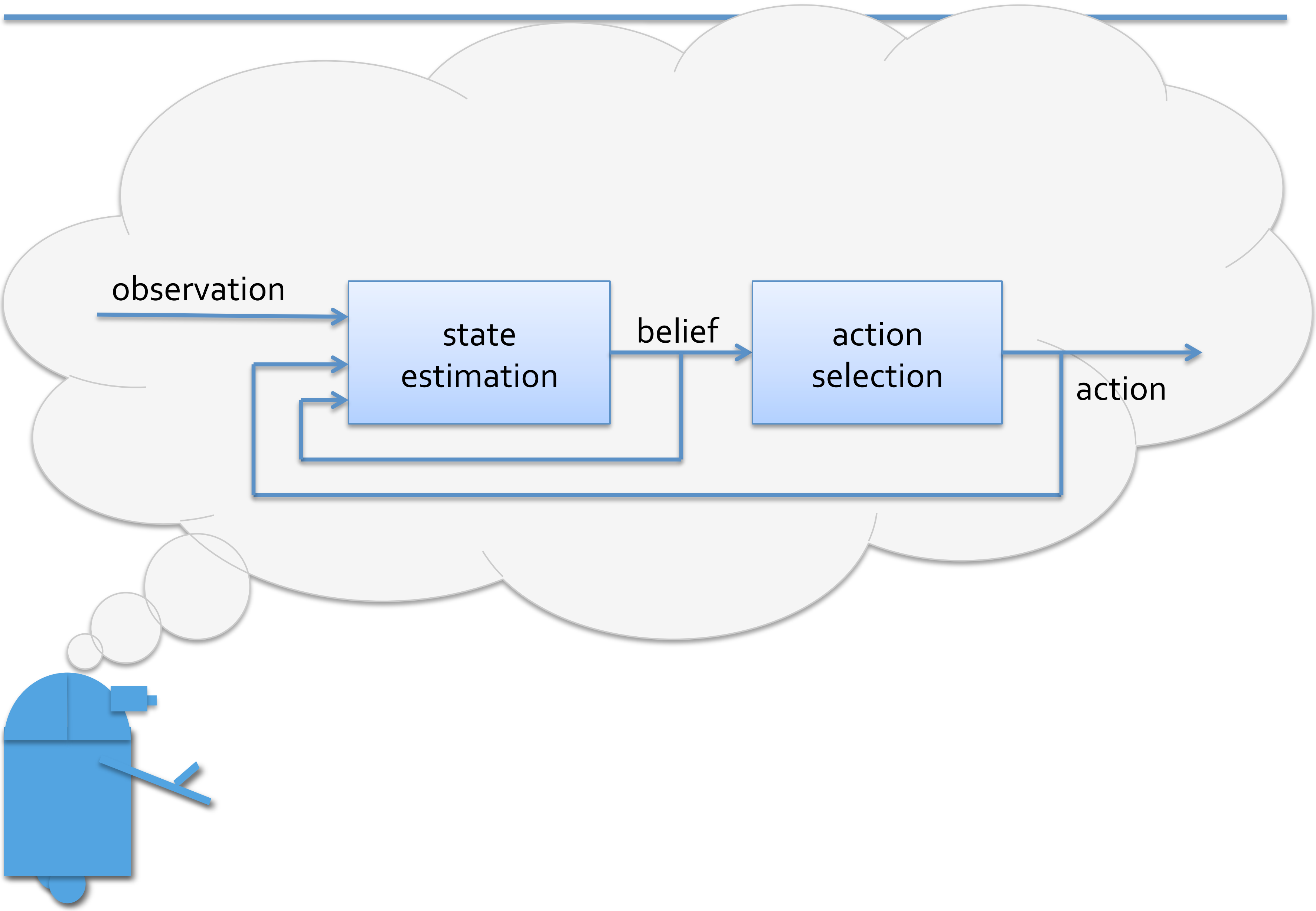
Predictive uncertainty

- What will happen when the robot lifts the cookie sheet?
- What is the error in the motor control?
- When will the inhabitants come home?

Observations to actions



Observations to actions



Perception as action

Perception is never free

- Select perception actions as needed for task
- Information requirements for tasks must be explicitly stated

Actions generate information

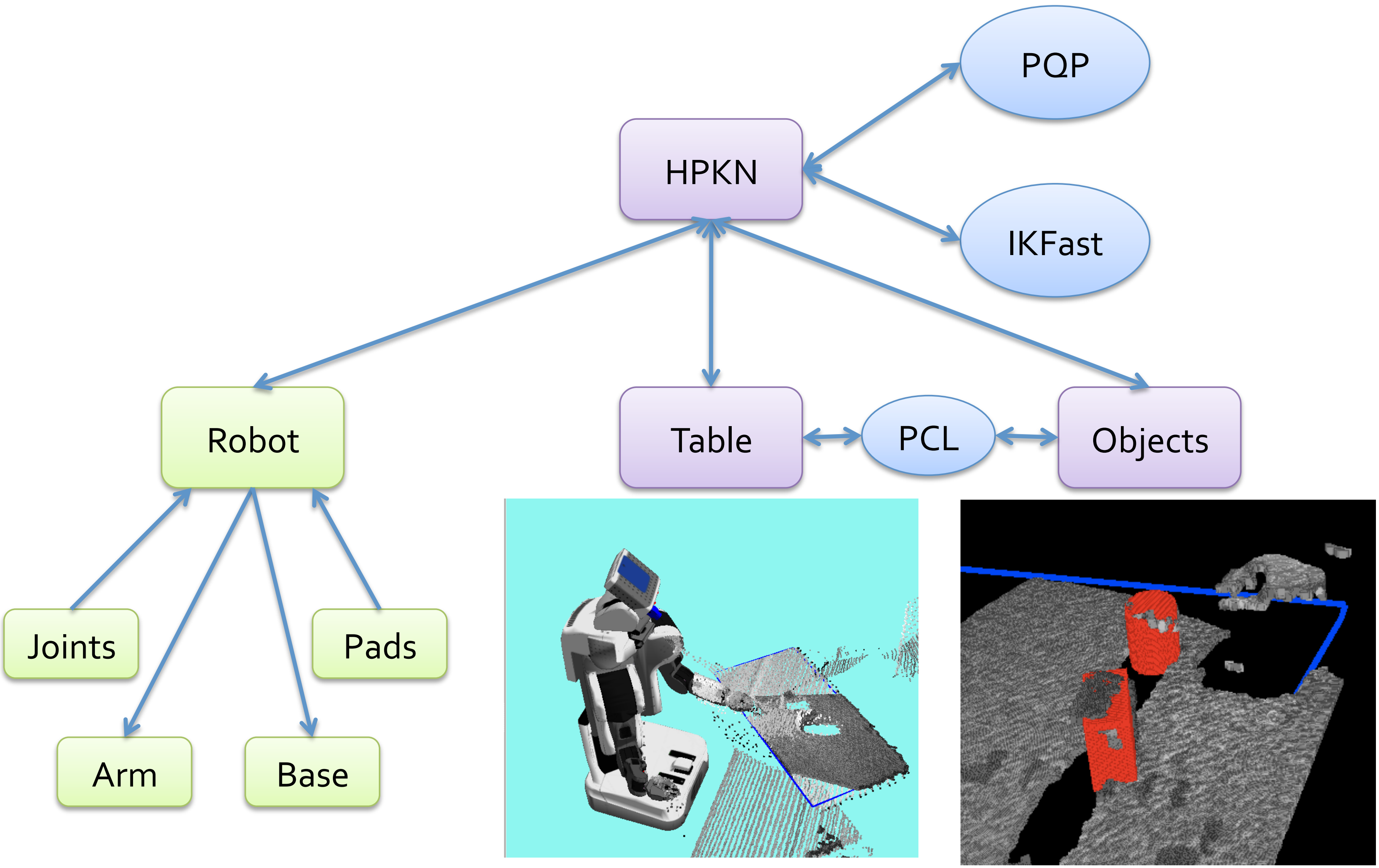
Our approach

- Plan explicitly in belief space
- Use symbolic / geometric planning operators to characterize preimages of **belief goals** in belief space

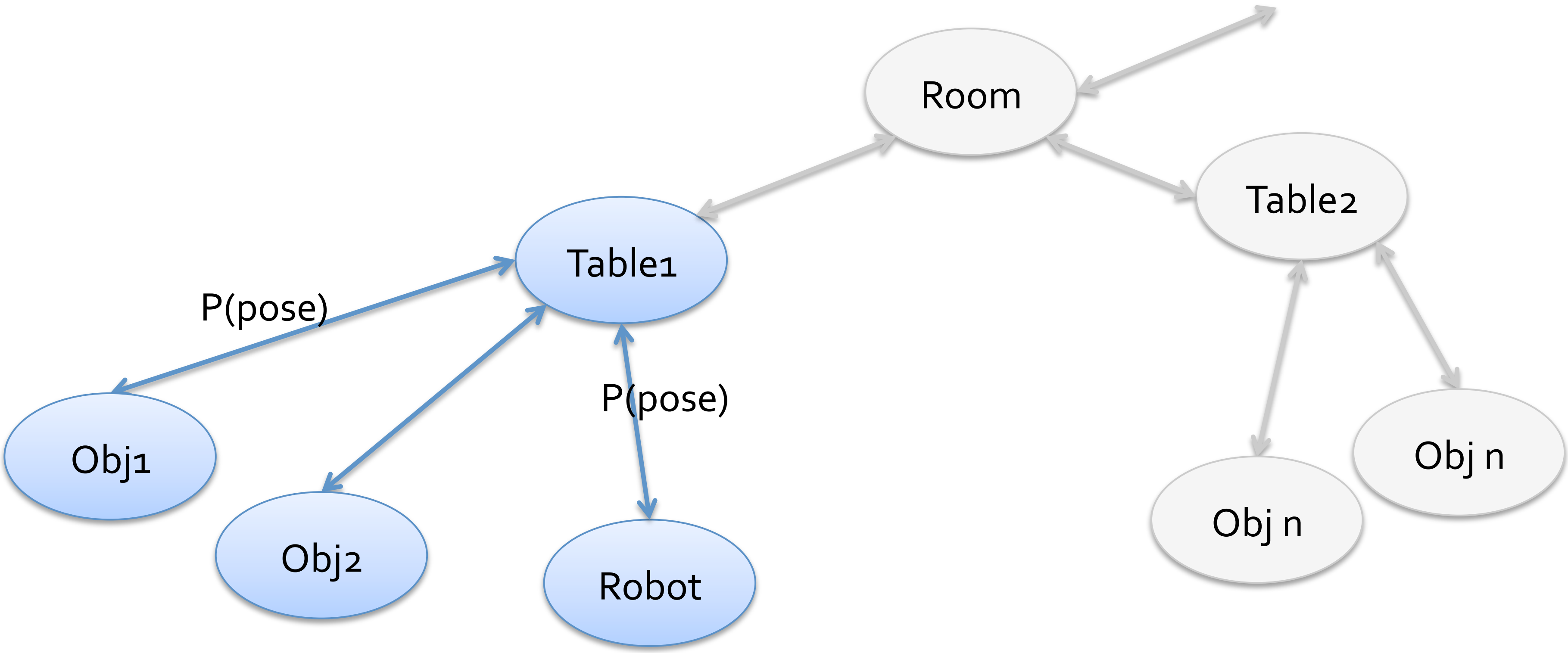
Noisy perception of robot and object poses

4x + Long, tedious gaps elided

HPKN / MandM Software Architecture



State estimator: relative pose distribution tree



- Pose estimates updated based on observations
- Accuracy is number of observations
- Robot pose estimate reset on move
- Object pose estimate reset on place

Planning operator: Pick

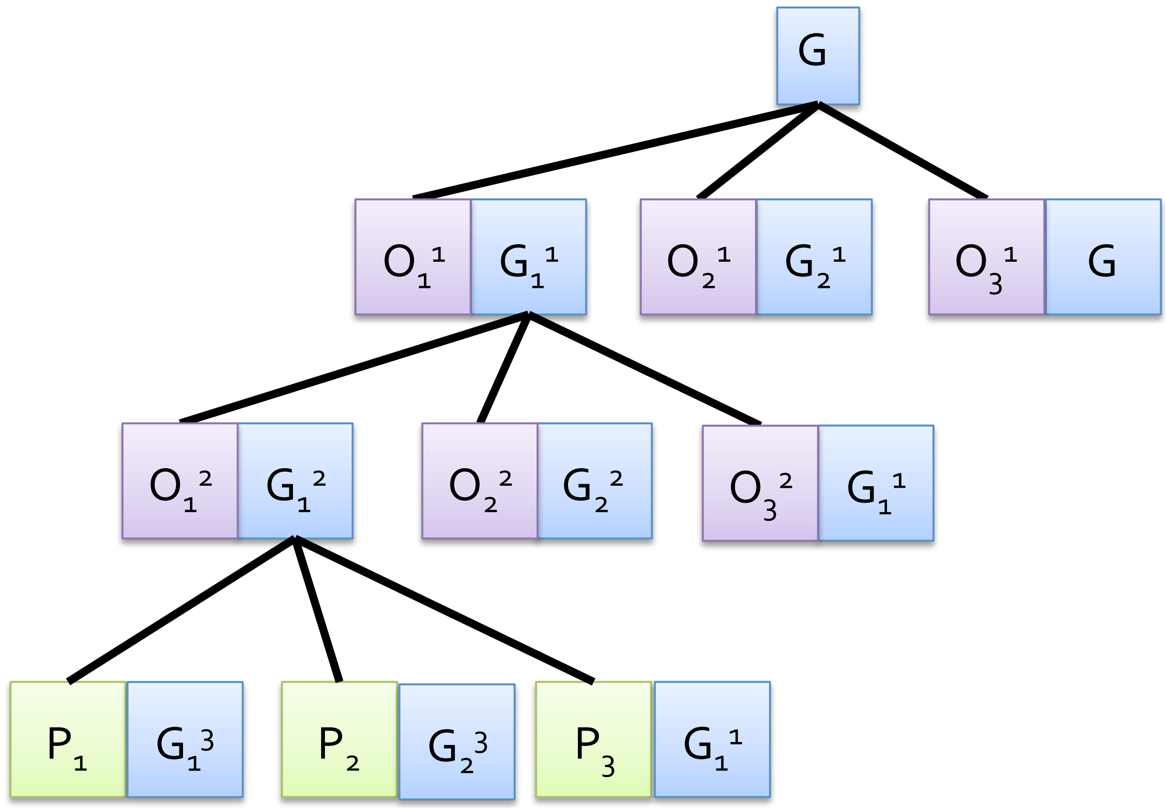
```
Pick(O):
  exists: ObjLoc ∈ {modeCurrLoc} U generateParking(O)
  exists: P ∈ generatePickPaths(ObjLoc)

   pre: ClearX(sweptVol(P), O)
        Holding(None)

        KVObjLoc(O, ObjLoc)
        KVRobotLoc(basePose(P))

   result: Holding(O)
   prim: PickPrim(O, Objloc)
```

Planning operator: LookObj

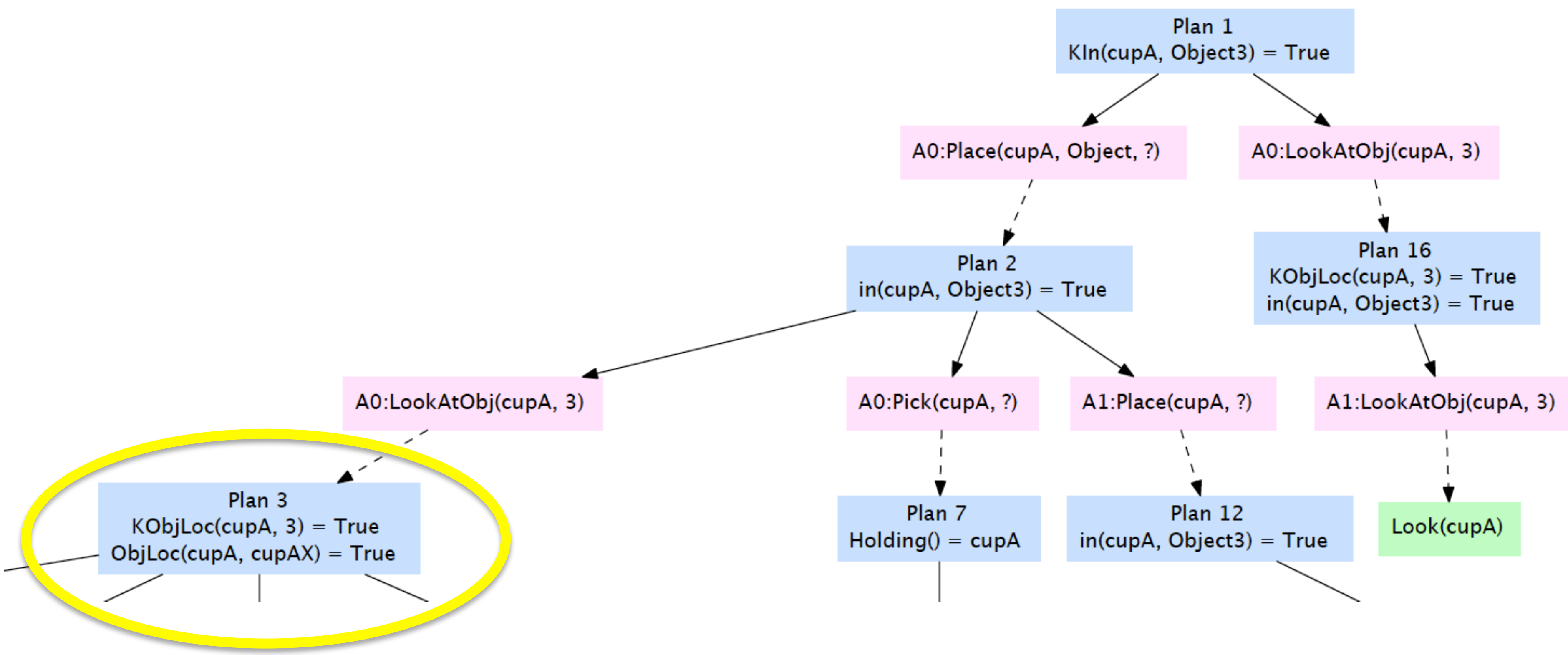
```
LookObj(O, N):
   exists: ObjLoc = modeCurrLoc(O)
   exists: P ∈ generateLookPaths(ObjLoc)

  pre: ClearX(sweptVol(P), O)

       KVRobotLoc(basePose(P))
       KObjLoc(O, N-1)

  result: KObjLoc(O, N)

  prim: LookPrim(ObjLoc)
```

Hierarchical planning in the now

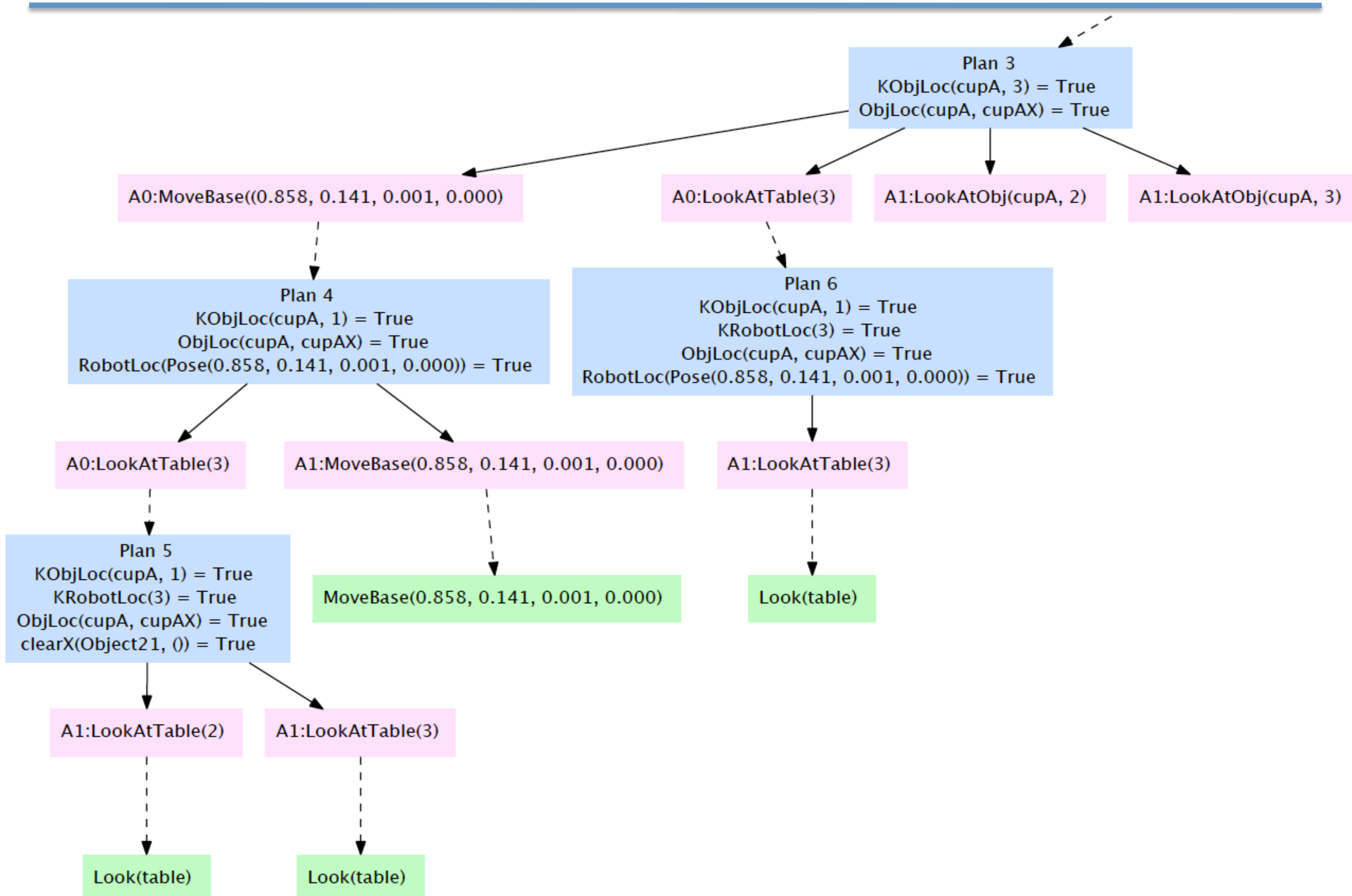
- maintain left expansion of plan tree
- each level uses a higher-fidelity model
- keep track of pre-image for each operation
- recursively plan to achieve those preconditions
- execute primitives



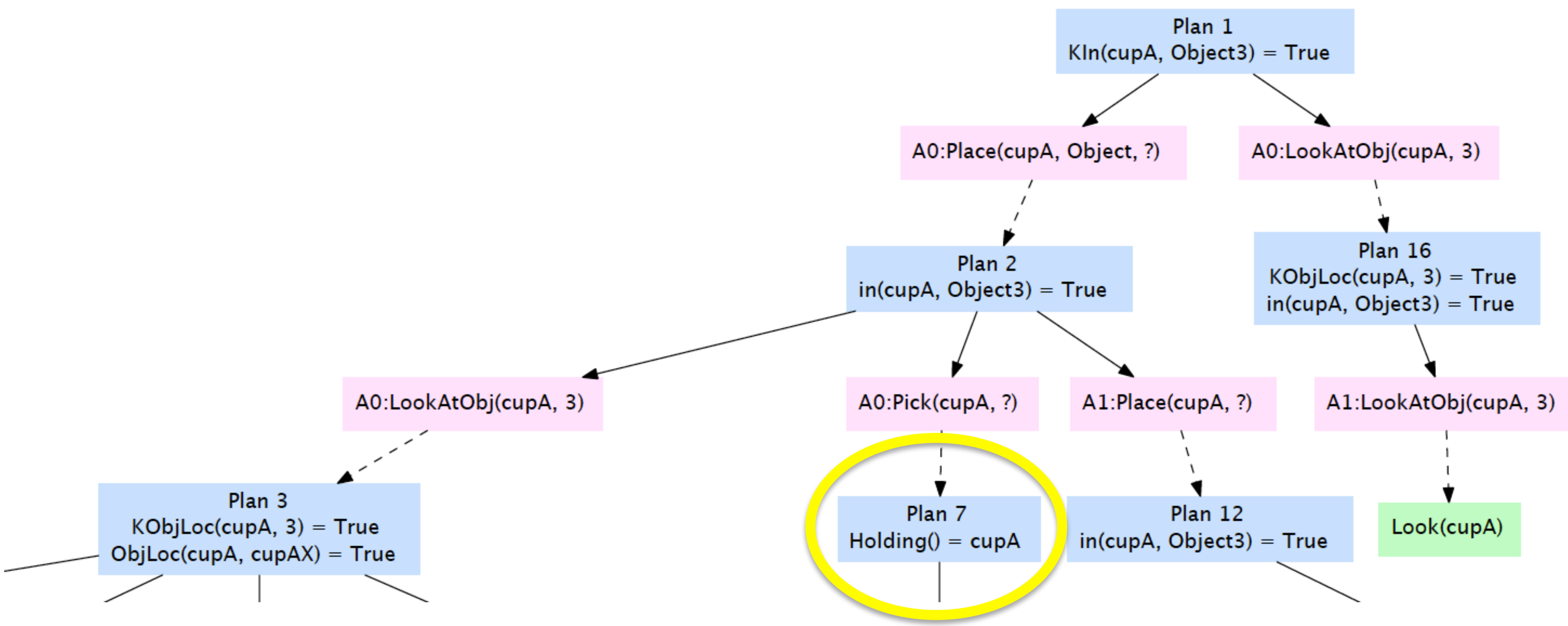
Simple pick and place: KIn(cupA, target)



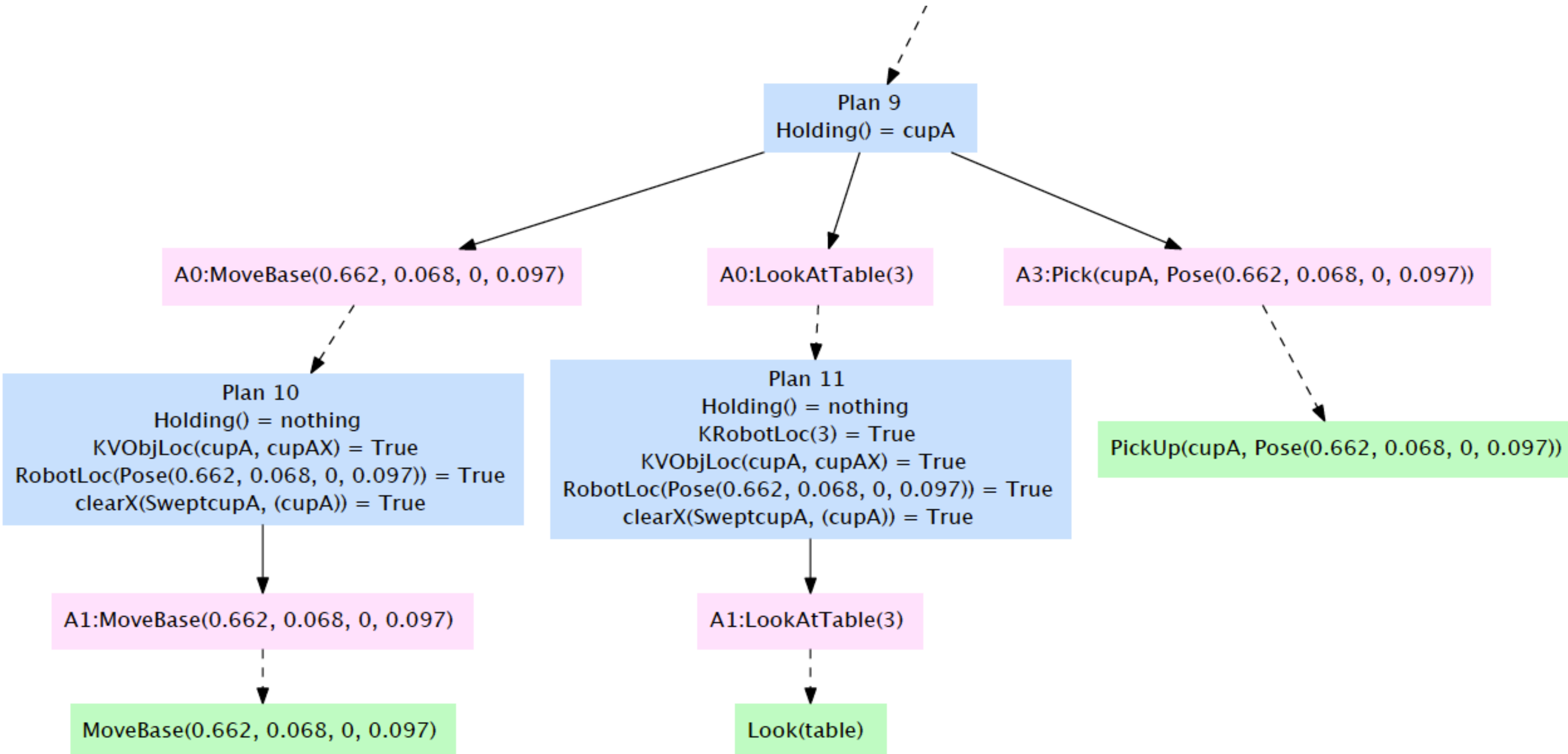
Finding cupA



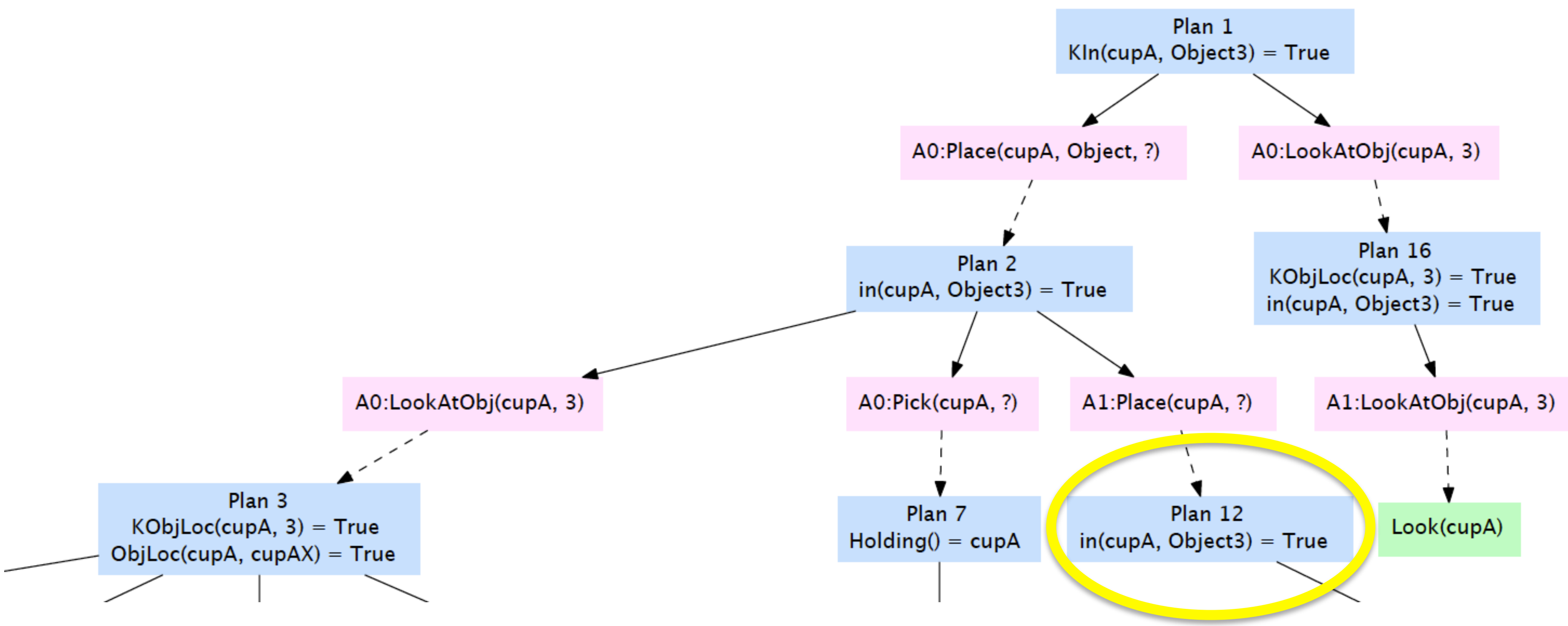
Simple pick and place



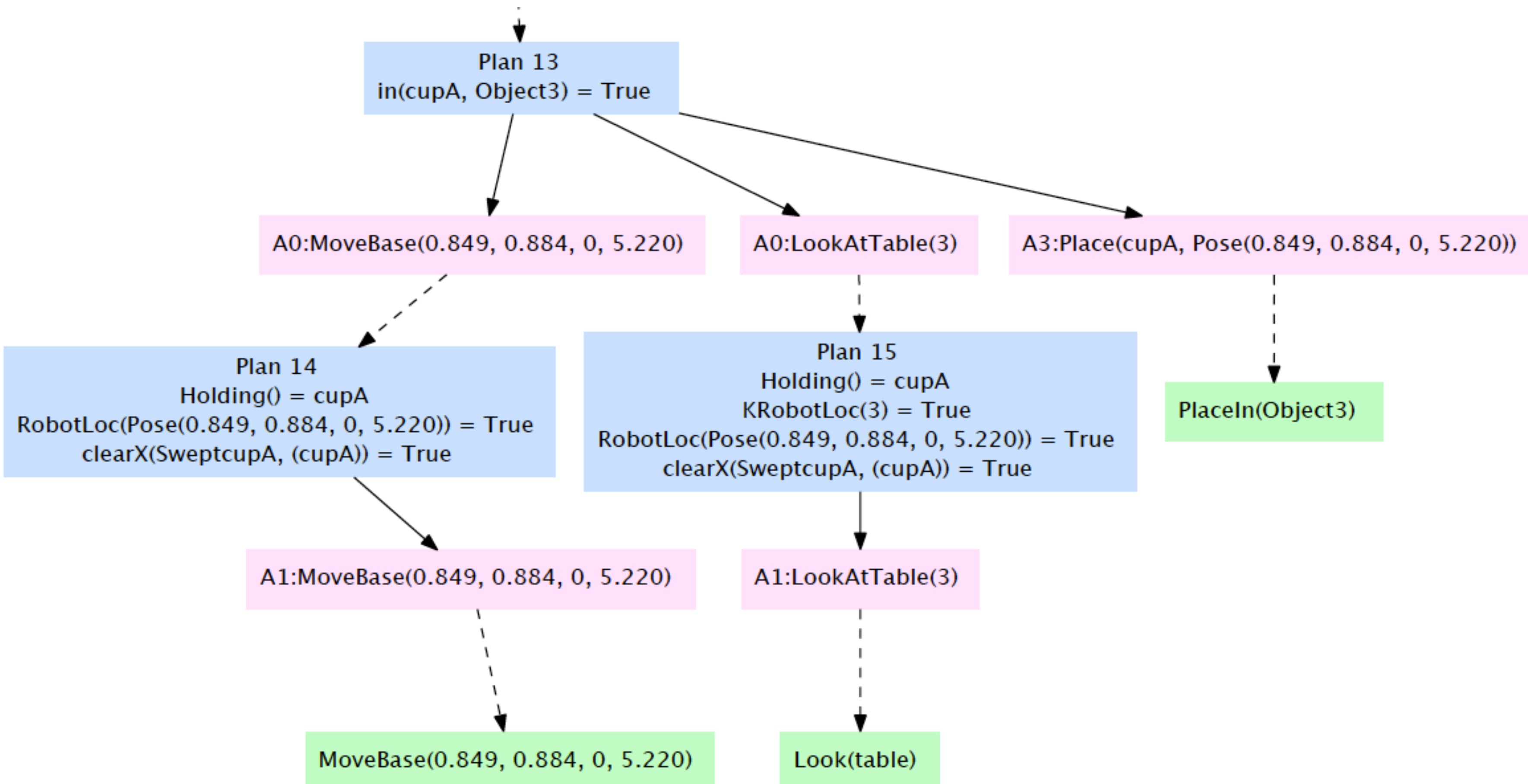
Picking cup A



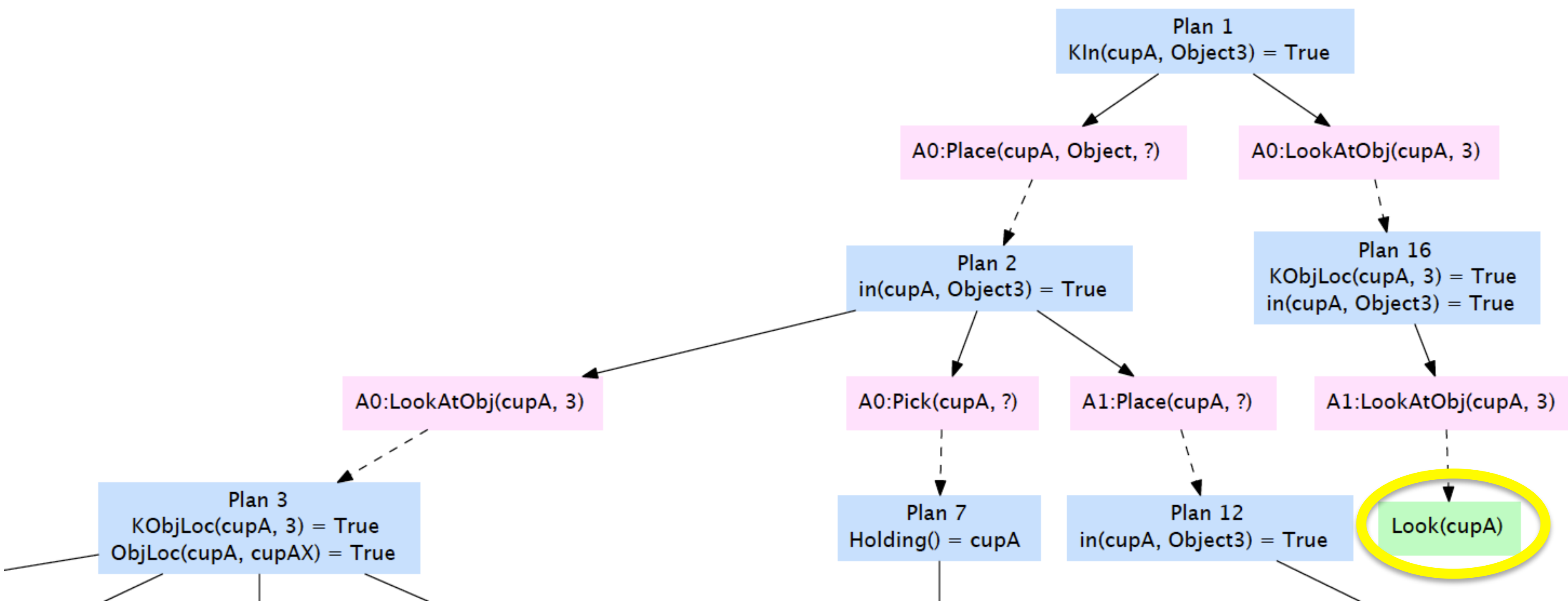
Simple pick and place



Placing cup A



Verifying cup A is in the right location



Handling stochastic actions

- In belief space, next state depends on observation
- Observations are stochastic
- Make plan assuming most likely observations
- Monitor plan during execution
- Replan if conditions are violated

HPN in belief space

g_0^2 | a_1^2 g_1^2 | a_2^2 g_2^2 | a_3^2 g_1^1

$\text{BHPN}(\mathit{belief}, \mathit{goal}, \mathit{abs}, \mathit{world})$:

  p = $\text{PLAN}(\mathit{belief}, \mathit{goal}, \mathit{abs})$

  for (a_i, g_i) **in** p

    while $\mathit{belief} \in g_{i\text{-}1}$ **and not** $\mathit{belief} \in g_i$

      if $\text{ISPRIM}(a_i)$

        $\mathit{obs} = \mathit{world}.\text{EXECUTE}(a_i)$

        $\mathit{belief}.\text{UPDATE}(a_i, \mathit{obs})$

      else

        $\text{BHPN}(\mathit{belief}, g_i, \text{NEXTLEVEL}(\mathit{abs}, a_i), \mathit{world})$

    if not $\mathit{belief} \in g_i$ **return**

Preconditions hold

Result does not hold

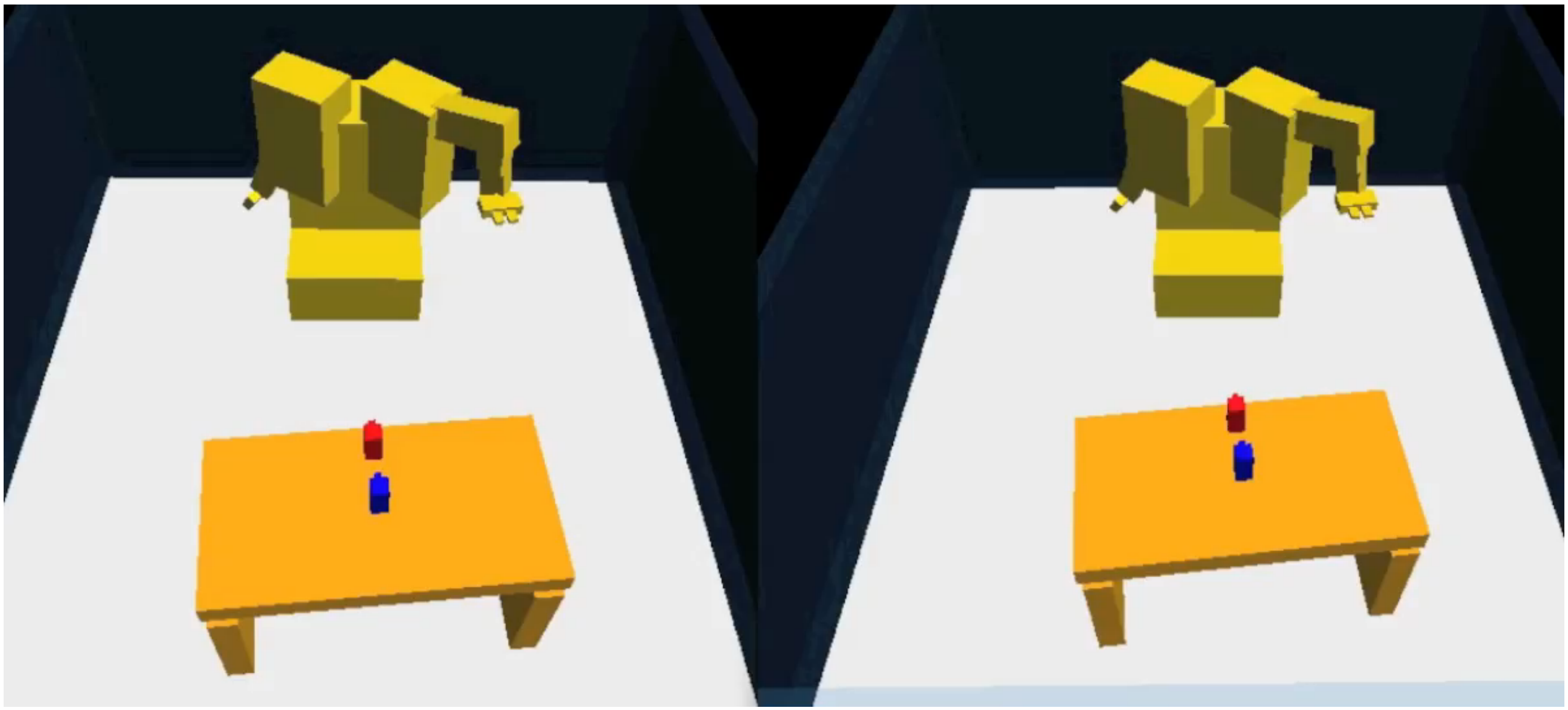
State estimation

Preconditions failed

Example with errors: 5 cm perception stdev

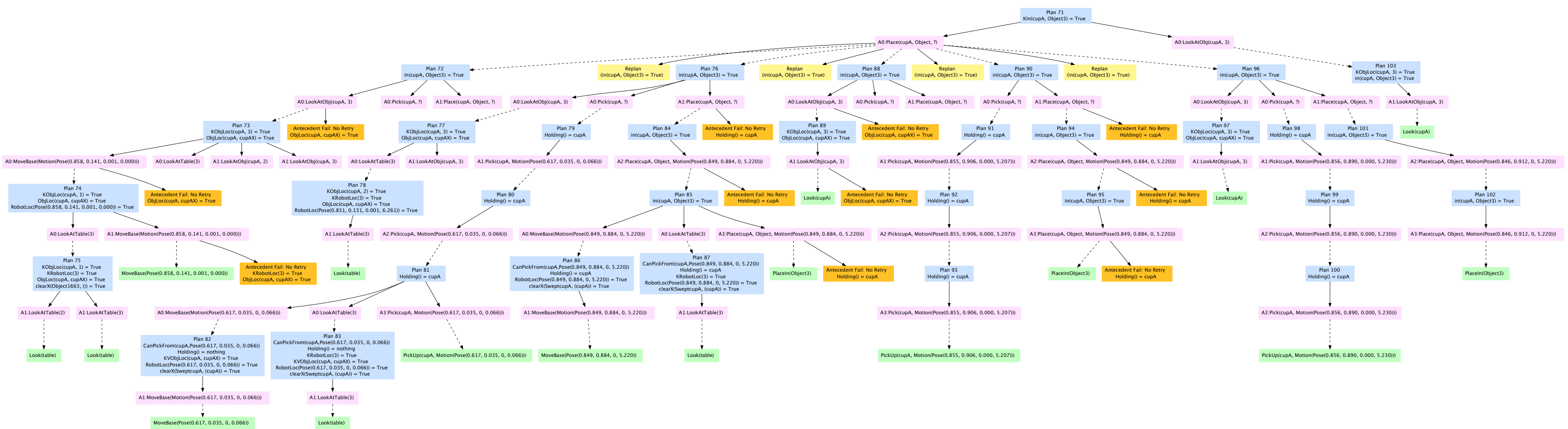
“Real” world

Max likelihood belief



Example with errors

Orange: precondition failure
Yellow: replan



Characterizing certainty

Characterize concentration of distribution with PNM: amount of probability mass within delta of the mode of the dist'n

For Gaussian:

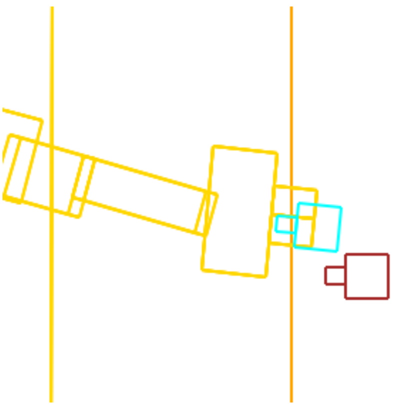
$$PNM(X,\delta) = \Phi(\mu+\delta) - \Phi(\mu-\delta) = \operatorname{erf}\left(\frac{\delta}{\sqrt{2}\sigma}\right)$$

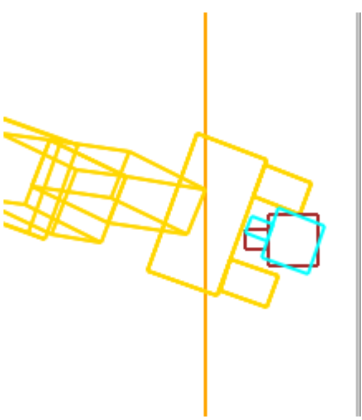
Regression condition:

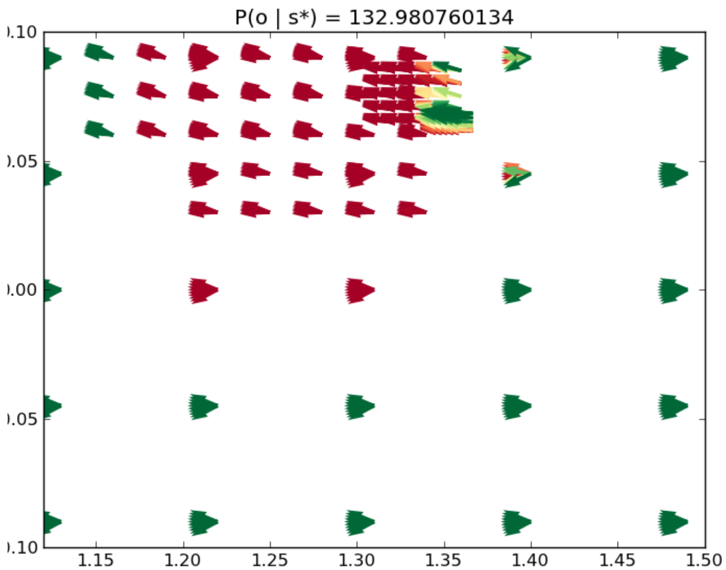
$$\theta_t = PNMregress(\theta_{t+1}, \delta, \sigma_o^2) = \operatorname{erf}\left(\sqrt{\operatorname{erf}^{-1}(\theta_{t+1})^2 - \frac{\delta^2}{2\sigma_o^2}}\right)$$

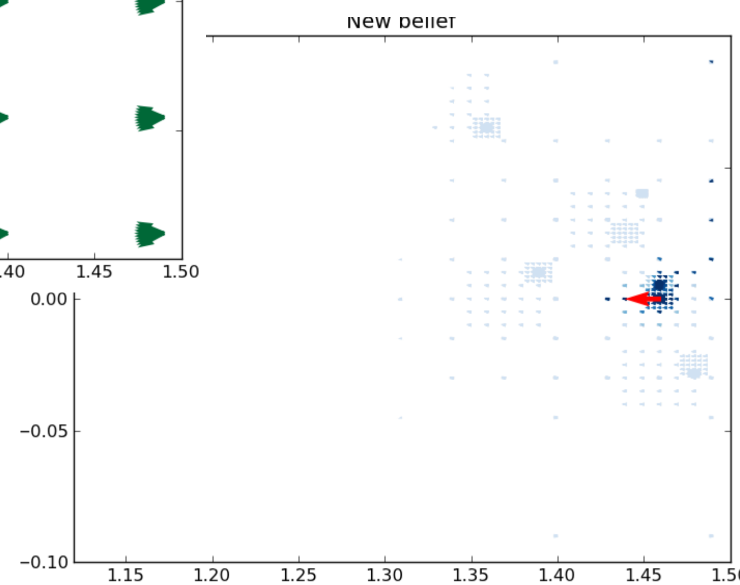
Application to tactile sensing

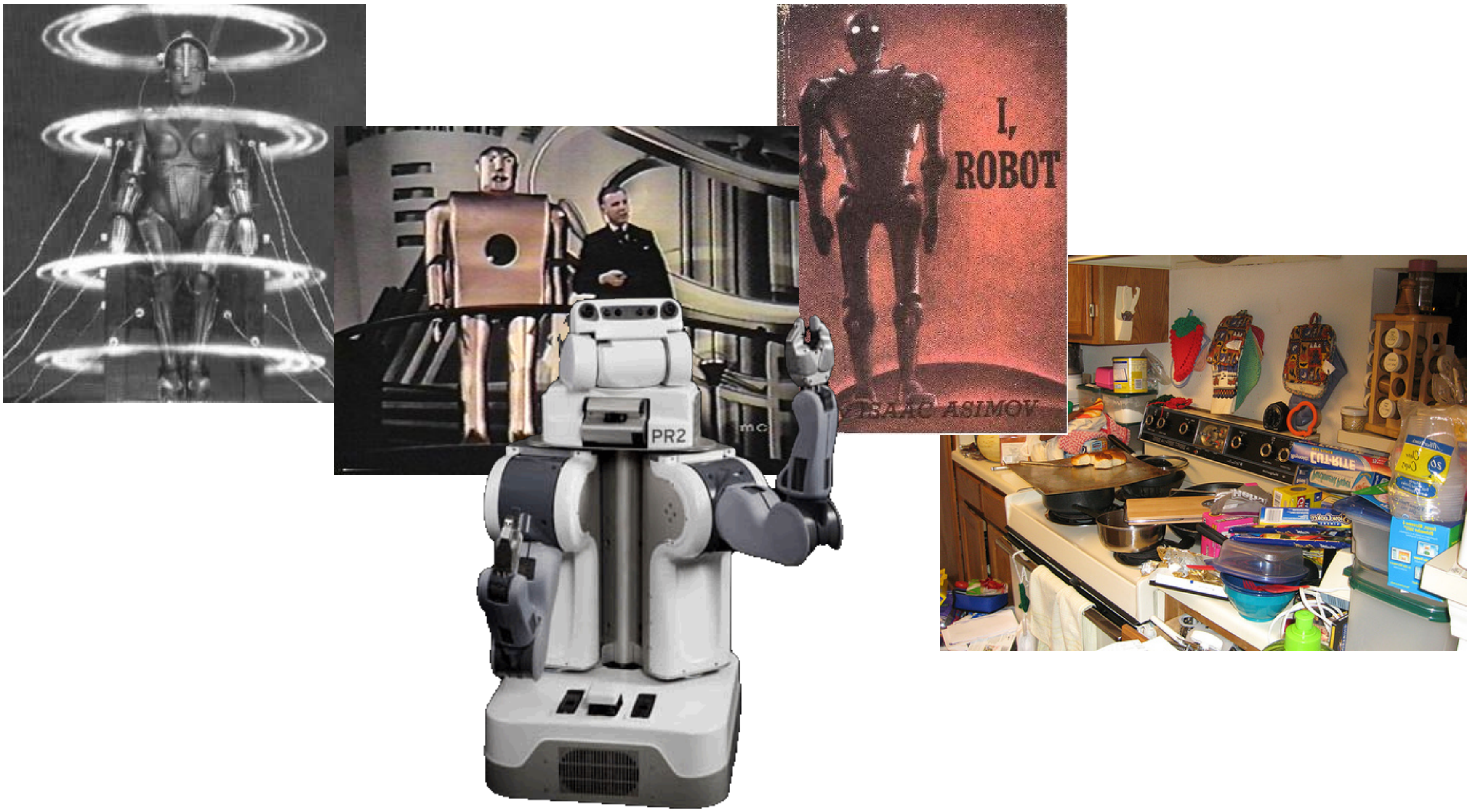
Integrating tactile observations for pose estimation







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ROBOT
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