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2. (8 points) This problem concerns predicting the status S of a space probe orbiting Mars. The probe has two states: *collecting data* C or *recharging* R. Each day, it sends a signal back to earth about its status. Due to interference caused by solar flares, the signal is occasionally corrupted, or even lost altogether. Hence, the signal G received by a ground station on earth can be of the following types: *collecting data* c, *recharging* r, and *no signal received* n. Certain conditional probabilities are known and appear below. Let the subscript t denote the discrete time instant. At time instant 0, there is no information about the state and each state is assumed to be equally likely.

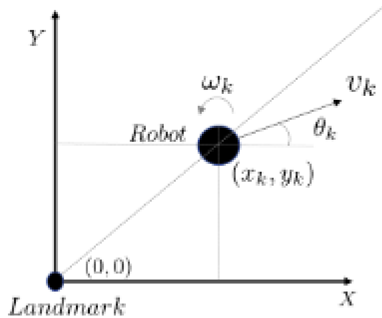
S_t	C	R
$P(S_t \mid S_{t-1} = C)$	$\frac{3}{4}$	$\frac{1}{4}$
$P(S_t \mid S_{t-1} = R)$	$\frac{2}{3}$	$\frac{1}{3}$

G_t	c	r	n
$P(G_t \mid S_t = C)$	$\frac{3}{4}$	0	$\frac{1}{4}$
$P(G_t \mid S_t = R)$	$\frac{1}{6}$	$\frac{1}{2}$	$\frac{1}{3}$

(a) The ground station receives the first observation as $G_0 = r$. What is the likelihood that the probe is collecting data? Please show your work to arrive at the solution.

(b) The ground station receives the second observation as $G_1 = n$. What is the most likely state of the probe after the first and the second observations. Please show your work to arrive at the solution.

3. (10 points) A robot is moving in (x, y) plane and is controlled by providing a linear velocity v_k and an angular velocity ω_k at time k. Let θ_k denote the robot's instantaneous *heading* angle which is the angle between the x-axis and the the robot's heading direction. A landmark is positioned at the origin. At time step k, the robot can measure the *range* r_k (the Euclidean distance to the landmark) and the *bearing* angle ϕ_k (the relative angle to the landmark with respect to the robot's own heading angle).



Assuming a Gaussian noise $\epsilon_\mathbf{k} \sim N(0, \mathbf{Q})$ in the motion and a Gaussian noise $\delta_\mathbf{k} \sim N(0, \mathbf{R})$ in the observations, the robot's motion and observation models can be expressed as follows:

$$\begin{bmatrix} x_k \\ y_k \\ \theta_k \end{bmatrix} = \begin{bmatrix} x_{k-1} \\ y_{k-1} \\ \theta_{k-1} \end{bmatrix} + \begin{bmatrix} cos\theta_{k-1} * \Delta T & 0 \\ sin\theta_{k-1} * \Delta T & 0 \\ 0 & \Delta T \end{bmatrix} \begin{bmatrix} v_k \\ \omega_k \end{bmatrix} + \epsilon_k$$

$$\begin{bmatrix} r_k \\ \phi_k \end{bmatrix} = \begin{bmatrix} \sqrt{{x_k}^2 + {y_k}^2} \\ atan2(-y_k, -x_k) - \theta_k \end{bmatrix} + \delta_k$$

Here, $atan2(y, x)$ returns the arc-tangent value of $(y/x))$ expressed in radians in the range $(-\pi$ to $\pi)$ and ΔT denotes the time step duration.

Your task is to estimate the robot's state (x_k, y_k, θ_k) from observations (r_k, ϕ_k). Please design an estimator for this problem. Please work out the key update equations.

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4. (12 points) An agent is tasked with transporting block-type objects o between a set of discrete locations denoted as l using containers denoted as c. Consider the following symbolic representation and syntax defining the planning domain. Let (at o l) denote the fact that the object o is at the location l. Let (in o c) denote the fact that the object o is present inside (or contained within) the container c. Let unary predicates (container c_i) and (location l_j) denote the types of container and location instances c_i and l_j.

   In addition, this planning model representation supports two addition constructs. First, *conditional effects* where "if p q" implies that q is added or deleted *iff* p is *True* (with no effect if the literal is already present or already deleted from the state). Second, *universal quantification* where the symbol $\forall o$ represents all instances for o in the domain. For example, the syntax (in $\forall o$ c) refers to all the possible object instances o that are contained within the container c. The agent can interact with the environment with actions *Load* and *MoveContainer*. The preconditions and effects (additions and deletions) for these actions as defined below.

   A problem instance is defined over the following set of entities: containers (c_1, c_2), locations (l_1, l_2, l_3) and an object (o_1). The initial and the goal states are also specified below.

Action Name:	*Load* (o, c, l)
Preconditions:	(container c) (location l) (at c l) (at o l)
Effects (*adds*):	(in o c)
Effects (*deletes*):	*none*

Action Name:	*MoveContainer* (c, l, m)
Preconditions:	(container c) (location l) (location m) (at c l)
Effects (*adds*):	(at c m) if (in $\forall o$ c) (at $\forall o$ m)
Effects (*deletes*):	(at c l) if (in $\forall o$ c) (at $\forall o$ l)

Initial state:	(container c_1) (container c_2) (location l_1) (location l_2) (location l_3) (at c_1 l_1) (at c_2 l_1) (at o_1 l_1)
Goal:	(at o_1 l_2) (at o_1 l_3)

   (a) Given the planning domain representation as provided above, is there a *satisficing* plan for the stated problem instance? Please answer as Yes/No. Justify your response. You may include state action transitions in your response.

   (b) Is there a flaw in the domain representation? Please answer as Yes/No and briefly justify for your response.

   (c) If the answer to part (b) is Yes, then please provide a simple fix for a flaw (if it exists) by correcting the action/state representations without introducing any additional entities. You may assume that the agent can additionally peform an *Unload* action if that is helpful for your solution.

5. (5 points) Please write the correct option(s) for the questions below. Note that more than one option may be correct. A correct answer will receive 1 point each and no points otherwise. No negative marks.

(a) Which of the following statements are true about RRTs?

- ◯ Cannot account for C-space obstacles
- ◯ Sampling is biased towards the smallest Voronoi region
- ◯ Is an asymptotically-optimal planning algorithm
- ◯ Is a probabilistically-complete planning algorithm

(b) The Kalman Filter's ability to update the belief over the full state despite partial observations is attributed to

- ◯ Ability to incorporate a prior over the state variables
- ◯ Maintenance of correlations between the state variables in the covariance matrix
- ◯ Ability to perform measurement updates in constant time
- ◯ Ability to perform motion model updates in constant time

(c) The ratio between the volume swept by a unidirectional RRT search and a bi-directional RRT search in a configuration space of dimension d:

- ◯ Increases as d increases
- ◯ Decreases as d increases
- ◯ Stays constant as d increases
- ◯ Is independent of d

(d) Consider Backward Search for a symbolic planning problem. Given a ground goal g and a ground action a, the regression from g with a returns a state g' as which of the following expressions?

- ◯ $g' = (g - \text{Add}(a)) \cup \text{Preconditions}(a)$
- ◯ $g' = (g + \text{Add}(a)) \cup \text{Preconditions}(a)$
- ◯ $g' = (g - \text{Add}(a)) \cup \text{Effects}(a)$
- ◯ $g' = (g + \text{Add}(a)) \cup \text{Effects}(a)$

(e) Which of the following are true for a particle filter?

- ◯ It represents the exact belief distribution at any time step
- ◯ Multiple copies of a particle can be propagated to the next time step
- ◯ Observation likelihood is only incorporated at the final time step
- ◯ Does not extend to continuous domains

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6. (5 points) Please write if the following statements are True or False. A correct answer will receive (+0.5) point each. An incorrect answer will receive a negative (−0.25) point. No points are awarded for leaving blank.

(a) In *episodic* decision-making, future actions are correlated with the last two actions performed by a robot.

◯ True

◯ False

(b) In a hidden Markov model, an evidence/observation variable, E_i, is independent of all other evidence variables given its associated hidden state, X_i.

◯ True

◯ False

(c) The performance of an Extended Kalman Filter degrades if the variance in the current belief is high relative to the region of linearization.

◯ True

◯ False

(d) Motion planning with potential fields has the advantage of always finding the globally optimal solution.

◯ True

◯ False

(e) An intertial measurement unit (IMU) sensor provides direct measurements of linear and angular velocities.

◯ True

◯ False

(f) *Epistemic* uncertainty is concerned with the uncertainty in the action outcomes.

◯ True

◯ False

(g) In a fully constructed planning graph, the set of action mutexes represent all possible negative interactions between actions.

◯ True

◯ False

(h) The Backward Search often shows a lower branching factor compared to Forward Search in symbolic planning.

◯ True

◯ False

(i) In a scheduling problem the agent must decide *which* tasks are to be performed and in *what* order.

◯ True

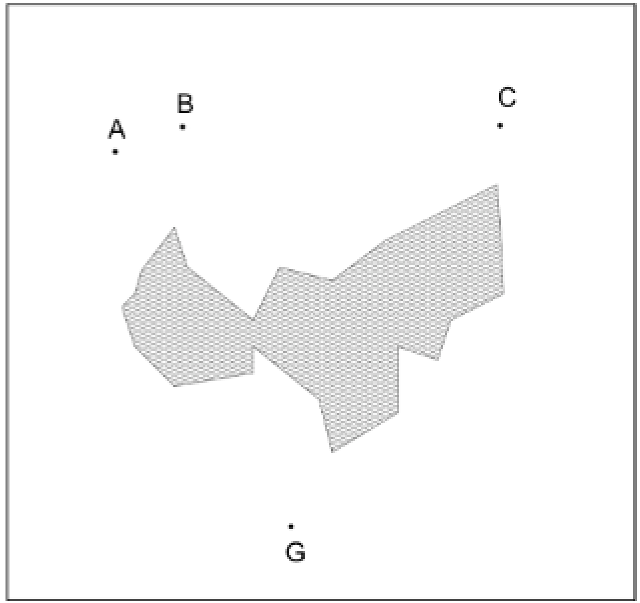
◯ False

(j) A* search will be *complete* even if an *inadmissible* heuristic is used.

◯ True

◯ False

1. (5 points) A point robot is moving in the configuration space shown in the figure below. The obstacle is shown as a textured polygon. Let d_o denote the distance from the robot to the closest point on the obstacle. Let d_g denote the distance from the robot to the goal position denoted as G.



Suppose the robot uses the potential field method of path planning, with the field value defined as $d_g + 1/d_o$. Draw the approximate paths the robot would take starting from points A, B and C for this scenario. The path can be approximate but should capture the essential behaviour that is expected. Briefly justify your answer in each case and indicate if the solution is global optimum or local optimum in each case.