1 Human (PO)MDP

This is a MDP that the human runs in their mind. It can be formalized as a POMDP, but right now we have a weak POMDP with a a belief distribution over the robot's distribution of objects.

1. $S = \langle \iota, \mathcal{I}, d, H \rangle$
   (a) Here $\mathcal{I}$ is the set of items the robot can pass.
   (b) Item ι is the object the human wants, and this is hidden information for the robot.
   (c) d is the dialogue state - what question was asked previously by the robot.
   (d) Here $B(i \in \mathcal{I} == \iota)$ is the belief distribution of the robot over the items in $\mathcal{I}$. In the POMDP formulation B would be part of the state that is hidden from the human. Instead we model a distribution that tracks B allowing the human to solve an MDP instead of nested POMDPs. We will go back to the nested POMDP model repeatedly to make sure our MDP model is equivalent.
   (e) Human's hunch of the robot's belief $H = P(\widehat{B}|\eta)$, where $\widehat{B}$ is an estimate of the distribution of B, it is over the set of items $\mathcal{I}$. η is a set of priors that defines the distribution $\widehat{B}$, hence H is over the space of all possible priors values. We propose to use the Dirichlet distribution to model H.
2. $A_h = \langle l, g \rangle$, where A_h is the human action set and l and g are language and gesture actions respectively.
3. If this were a POMDP we would need observation functions and a observation set.
   (a) $\Omega_h = \langle A_r \rangle$, where A_r is the set of robot actions and Ω_h is the set of human observations.
   (b) $O = P(A_r|\iota, \mathcal{I}, d, H, B)$ is the observation function and it is hand coded by us so we know it, since we know the robots response to all the belief states.
   (c) $T = P(\iota', \mathcal{I}', d', H', B'|\iota, \mathcal{I}, d, H, B, a_h, a_r) = P(\iota', \mathcal{I}', d'|\iota, \mathcal{I}, d, H, B, a_h, a_r) \times P(H'|\iota, \mathcal{I}, d, H, B, a_h, a_r) \times P(B'|\iota, \mathcal{I}, d, H, B, a_h, a_r)$
4. MDP formulation of this problem would not need the observation set or the observation functions, instead H would get updated based on A_r and A_h. This just has a transition function now defined as
   $T = P(\iota', \mathcal{I}', d', H'|\iota, \mathcal{I}, d, H, a_h, a_r) = P(\iota', \mathcal{I}', d'|\iota, \mathcal{I}, d, H, a_h, a_r) \times P(H'|\iota, \mathcal{I}, d, H, B, a_h, a_r)$
   The conditional independence of the human's hunch H from the distribution over the required item, or set of items left over or the last question asked comes from visible robot actions. $P(H'|\iota, \mathcal{I}, d, H, B, a_h, a_r)$ is being

designed by us as an approximation and we need to think of data intensive methods of measuring this transition. $P(\iota', \mathcal{I}', d' | \iota, \mathcal{I}, d, H, a_h, a_r) =$

$\{$ `wait`, `pick(object)`, `ask(property)` $\}$

5. $T = p(\omega', \mathcal{O}', ds' | \omega, \mathcal{O}, ds, a)$

   If a is a pick action and $a.object == \omega$:

$$p(\omega', \mathcal{O}', ds' | \omega, \mathcal{O}, ds, a) = \begin{cases} 1/|\mathcal{O} \setminus \omega| & \text{if } \omega' != \omega, ds = None, \mathcal{O}' = \mathcal{O} \setminus \omega \\ 0 & \text{otherwise} \end{cases}$$

   If a is a pick action and $a.object != \omega$, we transition to the state where $s' = \langle \omega', \mathcal{O}', ds' \rangle = \langle \omega, \mathcal{O} \setminus a.object, ds \rangle$.

6.

$$R(\omega, \mathcal{O}, ds, a) = \begin{cases} 10 & \text{if a} == \texttt{pick} \text{ and a.object} == \omega \\ -80 & \text{if a} == \texttt{pick} \text{ and a.object} \mathrel{!=} \omega \\ -1 & \text{if a} == \texttt{wait} \\ -3 & \text{if a} == \texttt{ask} \end{cases}$$

7. $\Omega = \langle l, g \rangle$

8. $O = p(l, g | \omega, \mathcal{O}, ds, a) = p(l | \omega, \mathcal{O}, ds, a) p(g | \omega, \mathcal{O}, ds, a)$

$$p(l | \mathcal{O}, \omega, a) = p(c | \omega^{t+1}, a^t) \prod_{w \in l} p(w | \omega, a) \tag{1}$$

$$p(c | a^t) = \begin{cases} 0.8 & \text{if } a^t \text{ is a question} \\ 0.2 & \text{otherwise} \end{cases} \tag{2}$$

$$p(w | \omega, a) = \frac{\text{Number of times } w \text{ is used to describe } \omega}{\text{Total counts for words describing } \omega}$$