

These lecture notes are heavily based on notes originally written by Nikhil Sharma.

Last updated: April 27, 2023 (re-numbered Notes 19-26 to align with lectures)

## Particle Filtering

Recall that with Bayes' nets, when running exact inference was too computationally expensive, using one of the sampling techniques we discussed was a viable alternative to efficiently approximate the desired probability distribution(s) we wanted. Hidden Markov Models have the same drawback - the time it takes to run exact inference with the forward algorithm scales with the number of values in the domains of the random variables. This was acceptable in our current weather problem formulation where the weather can only take on 2 values,  $W_i \in \{sun, rain\}$ , but say instead we wanted to run inference to compute the distribution of the actual temperature on a given day to the nearest tenth of a degree.

The Hidden Markov Model analog to Bayes' net sampling is called **particle filtering**, and involves simulating the motion of a set of particles through a state graph to approximate the probability (belief) distribution of the random variable in question. This solves the same question as the Forward Algorithm: it gives us an approximation of  $P(X_N | e_{1:N})$ .

Instead of storing a full probability table mapping each state to its belief probability, we'll instead store a list of  $n$  **particles**, where each particle is in one of the  $d$  possible states in the domain of our time-dependent random variable. Typically,  $n$  is significantly smaller than  $d$  (denoted symbolically as  $n \ll d$ ) but still large enough to yield meaningful approximations; otherwise the performance advantage of particle filtering becomes negligible. Particles are just the name for samples in this algorithm.

Our belief that a particle is in any given state at any given timestep is dependent entirely on the number of particles in that state at that timestep in our simulation. For example, say we indeed wanted to simulate the belief distribution of the temperature  $T$  on some day  $i$  and assume for simplicity that this temperature can only take on integer values in the range  $[10, 20]$  ( $d = 11$  possible states). Assume further that we have  $n = 10$  particles, which take on the following values at timestep  $i$  of our simulation:

[15, 12, 12, 10, 18, 14, 12, 11, 11, 10]

By taking counts of each temperature that appears in our particle list and dividing by the total number of particles, we can generate our desired empirical distribution for the temperature at time  $i$ :

$T_i$	10	11	12	13	14	15	16	17	18	19	20
$B(T_i)$	0.2	0.2	0.3	0	0.1	0.1	0	0	0.1	0	0

Now that we've seen how to recover a belief distribution from a particle list, all that remains to be discussed is how to generate such a list for a timestep of our choosing.

# Particle Filtering Simulation

Particle filtering simulation begins with particle initialization, which can be done quite flexibly - we can sample particles randomly, uniformly, or from some initial distribution. Once we've sampled an initial list of particles, the simulation takes on a similar form to the forward algorithm, with a time elapse update followed by an observation update at each timestep:

- *Time Elapse Update* - Update the value of each particle according to the transition model. For a particle in state  $t_i$ , sample the updated value from the probability distribution given by  $P(T_{i+1}|t_i)$ . Note the similarity of the time elapse update to prior sampling with Bayes' nets, since the frequency of particles in any given state reflects the transition probabilities.
- *Observation Update* - During the observation update for particle filtering, we use the sensor model  $P(F_i|T_i)$  to weight each particle according to the probability dictated by the observed evidence and the particle's state. Specifically, for a particle in state  $t_i$  with sensor reading  $f_i$ , assign a weight of  $P(f_i|t_i)$ . The algorithm for the observation update is as follows:
  1. Calculate the weights of all particles as described above.
  2. Calculate the total weight for each state.
  3. If the sum of all weights across all states is 0, reinitialize all particles.
  4. Else, normalize the distribution of total weights over states and resample your list of particles from this distribution.

Note the similarity of the observation update to likelihood weighting, where we again downweight samples based on our evidence.

Let's see if we can understand this process slightly better by example. Define a transition model for our weather scenario using temperature as the time-dependent random variable as follows: for a particular temperature state, you can either stay in the same state or transition to a state one degree away, within the range  $[10, 20]$ . Out of the possible resultant states, the probability of transitioning to the one closest to 15 is 80% and the remaining resultant states uniformly split the remaining 20% probability amongst themselves.

Our temperature particle list was as follows:

[15, 12, 12, 10, 18, 14, 12, 11, 11, 10]

To perform a time elapse update for the first particle in this particle list, which is in state  $T_i = 15$ , we need the corresponding transition model:

$T_{i+1}$	14	15	16
$P(T_{i+1} T_i = 15)$	0.1	0.8	0.1

In practice, we allocate a different range of values for each value in the domain of  $T_{i+1}$  such that together the ranges entirely span the interval  $[0, 1)$  without overlap. For the above transition model, the ranges are as follows:

1. The range for  $T_{i+1} = 14$  is  $0 \leq r < 0.1$ .
2. The range for  $T_{i+1} = 15$  is  $0.1 \leq r < 0.9$ .

3. The range for  $T_{i+1} = 16$  is  $0.9 \leq r < 1$ .

In order to resample our particle in state  $T_i = 15$ , we simply generate a random number in the range  $[0, 1)$  and see which range it falls in. Hence if our random number is  $r = 0.467$ , then the particle at  $T_i = 15$  remains in  $T_{i+1} = 15$  since  $0.1 \leq r < 0.9$ . Now consider the following list of 10 random numbers in the interval  $[0, 1)$ :

[0.467, 0.452, 0.583, 0.604, 0.748, 0.932, 0.609, 0.372, 0.402, 0.026]

If we use these 10 values as the random value for resampling our 10 particles, our new particle list after the full time elapse update should look like this:

[15, 13, 13, 11, 17, 15, 13, 12, 12, 10]

Verify this for yourself! The updated particle list gives rise to the corresponding updated belief distribution  $B(T_{i+1})$ :

$T_i$	10	11	12	13	14	15	16	17	18	19	20
$B(T_{i+1})$	0.1	0.1	0.2	0.3	0	0.2	0	0.1	0	0	0

Comparing our updated belief distribution  $B(T_{i+1})$  to our initial belief distribution  $B(T_i)$ , we can see that as a general trend the particles tend to converge towards a temperature of  $T = 15$ .

Next, let's perform the observation update, assuming that our sensor model  $P(F_i|T_i)$  states that the probability of a correct forecast  $f_i = t_i$  is 80%, with a uniform 2% chance of the forecast predicting any of the other 10 states. Assuming a forecast of  $F_{i+1} = 13$ , the weights of our 10 particles are as follows:

<b>Particle</b>	$p_1$	$p_2$	$p_3$	$p_4$	$p_5$	$p_6$	$p_7$	$p_8$	$p_9$	$p_{10}$
<b>State</b>	15	13	13	11	17	15	13	12	12	10
<b>Weight</b>	0.02	0.8	0.8	0.02	0.02	0.02	0.8	0.02	0.02	0.02

Then we aggregate weights by state:

<b>State</b>	10	11	12	13	15	17
<b>Weight</b>	0.02	0.02	0.04	2.4	0.04	0.02

Summing the values of all weights yields a sum of 2.54, and we can normalize our table of weights to generate a probability distribution by dividing each entry by this sum:

<b>State</b>	10	11	12	13	15	17
<b>Weight</b>	0.02	0.02	0.04	2.4	0.04	0.02
<b>Normalized Weight</b>	0.0079	0.0079	0.0157	0.9449	0.0157	0.0079

The final step is to resample from this probability distribution, using the same technique we used to resample during the time elapse update. Let's say we generate 10 random numbers in the range  $[0, 1)$  with the following values:

[0.315, 0.829, 0.304, 0.368, 0.459, 0.891, 0.282, 0.980, 0.898, 0.341]

This yields a resampled particle list as follows:

[13, 13, 13, 13, 13, 13, 13, 15, 13, 13]

With the corresponding final new belief distribution:

$T_i$	10	11	12	13	14	15	16	17	18	19	20
$B(T_{i+1})$	0	0	0	0.9	0	0.1	0	0	0	0	0

Observe that our sensor model encodes that our weather prediction is very accurate with probability 80%, and that our new particles list is consistent with this since most particles are resampled to be  $T_{i+1} = 13$ .

## Summary

In this note, we covered two new types of models:

- *Markov models*, which encode time-dependent random variables that possess the Markov property. We can compute a belief distribution at any timestep of our choice for a Markov model using probabilistic inference with the mini-forward algorithm.
- *Hidden Markov Models*, which are Markov models with the additional property that new evidence which can affect our belief distribution can be observed at each timestep. To compute the belief distribution at any given timestep with Hidden Markov Models, we use the forward algorithm.

Sometimes, running exact inference on these models can be too computationally expensive, in which case we can use particle filtering as a method of approximate inference.