Assignment3 – Decisions and Markov Models

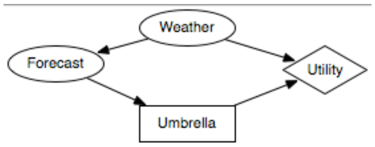
Given: May 16   Due: May 23

Problem 3.1 (Decision Network)

You try to decide on whether to take an umbrella (boolean variable M) to Uni. Obviously, it is useful (numeric variable U for the utility) to do so if it rains (boolean variable W) when you go back home, but it is annoying to carry around if it does not even rain. You decide based on whether the weather forecast predicts rain (boolean variable F).

1. Draw the decision network for bringing/leaving an umbrella depending on the weather forecast and the actual weather. Explain the four variables M, U, W, and F and what to store in their probability tables.

Solution:



We use four random variables:

- Boolean F for the weather forecast (true if rainy).
- Boolean W for the weather (true if rainy).
- Number U for the utility. U is a utility node and as such is a deterministic variable. Instead of a probability table $P(U = u \mid W = w, M = m)$, we store the function $U(w, m)$ that yields the utility u of (not) having an umbrella if it is (not) rainy.
- Boolean M for whether we took an umbrella. As a Bayesian network variable, M is influenced by F. But because it is a decision variable, there is no probability table $P(M \mid F)$ for it. Instead, the value of M is a decision that we make based on the value of F.

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2. Explain formally how to compute whether or not to take an umbrella, assuming you know the probability that the forecast is correct.

Solution: The probability of the forecast being correct gives us $P(W = b \mid F = b)$ for booleans b. Now given evidence $F = b$, we plug in each possible value for the decision variable M and compute the value of the utility variable.

- $M = true$

$$P(W = true \mid F = b)U(W = true, M = true) +$$

$$P(W = false \mid F = b)U(W = false, M = true)$$

- $M = false$

$$P(W = true \mid F = b)U(W = true, M = false) +$$

$$P(W = false \mid F = b)U(W = false, M = false)$$

We choose the decision that yields higher utility. Note that we may arrive at different decisions for different values of b.

Problem 3.2 (The Value of Information)

Chef Giordana runs a kitchen that provides food for a large organisation. A salad is sold for €6 and costs €4 to prepare. So a sold salad is profit of €2, and an unsold salad a loss of €4. Actual demand will be 40 (with probability 0.5) or 60 (also with probability 0.5) each day.

Each day, Giordana must decide in advance between two options: prepare 40 or 60 salads.

1. In the absence of additional information, compute the expected utility of each decision option, and choose the best option.
2. She is considering a new ordering system, where she knows the demand perfectly in advance. So she can always choose the better of the two options. State the formula for computing the value of this perfect information, explain the components in Giordana's case, and compute the value.

Solution: Giordana's payoff table looks as follows:

Demand	Probability	40 salads	60 salads
40	0.5	€80	€0
60	0.5	€80	€120

1. Thus, the expected utility for making 40 salads is 80 and the expected utility for making 60 salads is 60. Based on these expected values without additional information, Giordana would choose to make 40 salads per day with an *expected utility* of €80 per day.
2. The value of information is equal to the expected value of best action given the information minus expected value of best action without information. Consider a random variable X with possible values $x_1, \dots, x_n$. Let A_k be the optimal action to take if $X = x_k$, and let B be the optimal action to take in the absence of information on X. The general formula for the value of perfect information on variable X given evidence E is

$$VPI_E(X) = \sum_k P(X = x_k \mid E) \cdot \mathrm{EU}(A_k | E, X = x_k) - \mathrm{EU}(B|E)$$

In Giordana's case, X is the demand, i.e., $x_1 = 40$ and $x_2 = 60$, and E is all background information already known. B is to prepare 40 salads, and

EU($B|E$) = 80. A_1 and A_2 are to prepare 40 and 60 salads, respectively, and

$$\sum_k P(X = x_k \mid E) \cdot \mathrm{EU}(A_k|E, X = x_k) = 0.5 \cdot 80 + 0.5 \cdot 120 = 100$$

So $VPI_E(X) = 100 - 80 = 20$. So Giordana should pay at most €20 for the perfect information.

Problem 3.3 (Markov Mood Detection)

On any given day d, your roommate Moody is either happy or sad, so $M_d \in \{h, s\}$. Usually when he is sad, he stays sad for a while, and $P(M_{d+1} = s \mid M_d = s) = 0.7$. But aside from that he is a cheery guy, and $P(M_{d+1} = h \mid M_d = h) = 0.85$.

He either listens to jazz or metal music, so $L_d \in \{j, m\}$. On a happy day he usually listens to Jazz, and $P(L_d = j \mid M_d = h) = 0.7$. On a sad day, he slightly prefers metal, and $P(L_d = m \mid M_d = s) = 0.6$.

1. Model this situation as a Markov process. Explain what the state and evidence variables are. What order does the process have? Is the transition model stationary? Is the sensor model stationary? Does the transition model have the Markov property? Does the sensor model have the sensor Markov property? Explain all answers in one short sentence each.

Solution: The state variables are the M_d. The evidence variables are the L_d. The process is first-order: $P(M_d \mid M_{0:d-1}) = P(M_d \mid M_{d-1})$ and thus has the Markov property (and thus is a Markov process). The transition model is stationary: $P(M_d \mid M_{d-1})$ does not depend on d. The sensor Markov property holds: $P(L_d \mid M_{0:d-1}, L_{1:d-1}) = P(L_d \mid M_d)$. The sensor model is stationary: $P(L_d \mid M_d)$ does not depend on d.

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2. State the formula for the full joint probability distribution. You know that he was happy at day d_0. What is the probability that he is happy and plays Jazz for the next two days?

Solution: The distribution is

$$P(M_{0:n}, L_{1:n}) = P(M_0) \cdot \prod_{i=1}^{n} P(M_i \mid M_{i-1}) \cdot P(L_i \mid M_i)$$

In our case, $n = 2$, $P(M_0 = h) = 1$, $P(M_i = h \mid M_{i-1} = h) = 0.85$ and $P(L_i = j \mid M_i = h) = 0.7$. So $P(M_0 = h, M_1 = h, M_2 = h, L_1 = j, L_2 = j) = 0.85^2 * 0.7^2$.

Problem 3.4 (Moody HMM)

Consider the Markov process from before about the roommate Moody (which in particular gives the concrete probabilities needed below). We have already modeled it as an HMM with state variables M_d and evidence variables L_d.

Because the transition model is first-order and stationary, we can collect the conditional probabilities for the state transitions into a matrix $T_{ij} = P(M_d = x_j \mid M_{d-1} = x_i)$ where x_i, x_j are two states (i.e., two possible values of the state variable). We use S for the number of states, and T is an $S \times S$ matrix.

Because the sensor model is stationary and has the sensor Markov property, we can collect the conditional probabilities for the observations into a matrix $O_{ij} = P(L_d = y_i \mid M_d = x_j)$ where x_j is a state and the y_i are the possible observations. If there are N possible observations, this is an $N \times S$ matrix. For a fixed observation e, the diagonal $S \times S$ matrices O_e from the lecture notes are obtained from the rows of this matrix.

1. Clarify the modeling as an HMM. Concretely:
   2. What is S? Give the transition matrix T.

      Solution: $S = 2$ and we use the ordering $[h, s]$ for the states. Then $T = \begin{pmatrix} 0.85 & 0.15 \\ 0.3 & 0.7 \end{pmatrix}$. For example, $T_{12} = T_{hs} = P(M_d = s \mid M_{d-1} = h) = 0.15$.

   3. What is N? Give the sensor matrix O.

      Solution: $N = 2$ and we use the ordering $[j, m]$. Then $O = \begin{pmatrix} 0.7 & 0.4 \\ 0.3 & 0.6 \end{pmatrix}$.

      For example, $O_{12} = O_{js} = P(L_d = j \mid M_d = s) = 0.3$.

   Note that you need to choose and state orderings for the states and observations so that it is clear which state/observation corresponds to which row/-column of T and O.
4. Now consider a fixed sequence $L_1 = e_1, L_2 = e_2$ of observations that we have made for two days. Concretely, you heard Moody play metal on day $d = 1$ and jazz on day $d = 2$.
   5. Give the diagonal sensor matrices O_1 and O_2 corresponding to the observation at $d = 1$ and $d = 2$.

      Solution: We have $e_1 = m$ and $e_2 = j$.

      We have $O_1 = O_m = \begin{pmatrix} O_{mh} & 0 \\ 0 & O_{ms} \end{pmatrix} = \begin{pmatrix} 0.3 & 0 \\ 0 & 0.6 \end{pmatrix}$ and $O_2 = O_j = \begin{pmatrix} O_{jh} & 0 \\ 0 & O_{js} \end{pmatrix} = \begin{pmatrix} 0.7 & 0 \\ 0 & 0.4 \end{pmatrix}$.

6. You are not sure what kind of mood your flatmate was in on day $d = 0$, but it was either good or bad with equal probability. The HMM algorithm for filtering and smoothing uses compact matrix/vector equation to compute f and b. Use those equation to determine the probability distribution of Moody's mood on day $d = 1$.
   Note that T^t in the filtering equation in the lecture notes denotes the transpose of T.
   Grading will focus on writing out the matrices with the correct probabilities in them and on formally stating the computations that need to applied to those matrices. You should also actually do those computations, but that is secondary.

Solution: We need to apply smoothing at $k = 1$. The general equation for smoothing is $P(M_1 \mid L_{1:2} = e_{1:2}) = \alpha \cdot (f_{1:1} \cdot b_{2:2})$. And the HMM matrix equation for f give us $f_{1:1} = \alpha \cdot (O_1 T^t f_{1:0})$ We have the prior probabilities $P(M_0) = \begin{pmatrix} 0.5 \\ 0.5 \end{pmatrix}$, and we use that for the starting value $f_{1:0}$ of the forward iteration. The HMM matrix equation for b gives us $b_{2:2} = T O_2 b_{3:2}$. As the starting value $b_{3:2}$ of the backward iteration, we use the vector containing all 1s, i.e., $b_{3:2} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$.
Note that, for simplicity, this example is chosen such that only one iteration step each is needed for f and b — for the general case we would need to apply the matrix equations multiple times to iterate towards the needed value.
We omit the concrete calculation.