Advanced Machine Learning - HW #2

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Question 2

Show that the tree-width of of a 2D graph of size (m,m) is at most m

Recal tree-width is defined as:

> "The minimum size of the maximum clique [in the induced graph], over all elimination orders, minus one".

Thus, our strategy will be to show an elimination order which has a maximal clique of size m. The minimum over all elimination orders cannot exceed this value so the tree-width of the grid will be at most m (well, $m-1$, but "at most m" holds too). We shall show that eliminating columns of the grid, top to bottom, sequentially results in a maximal clique of size m over the entire elimination.
Denote the variables of column i as $\{x_1^i, .., x_m^i\}$.

Removing the first column:

After removing x_1^1 we end up with:

$$\tau(x_2^1, x_1^2) \prod_{i,j \in E \setminus \{\text{edges involving } x_1^1\}} \phi(x_i, x_j)$$

After removal of x_k^1 for $k < m$:

$$\tau(x_{k+1}^1, x_k^2, ..., x_1^2) \prod_{i,j \in E \setminus \{\text{edges involving } \{x_1^1, .., x_k^1\}\}} \phi(x_i, x_j)$$

Removing x_{m-1}^1, we get a factor of size m, and will thus have a clique of size m. We will show that during the rest of the process no factor larger than m will appear. Continuing:
After removal of x_m^1 we have:

$$\tau(x_m^2, ..., x_1^2) \prod_{i,j \in E \setminus \{\text{edges involving } \{x_1^1, .., x_m^1\}\}} \phi(x_i, x_j) \tag{1}$$

Removing columns 2 to m-1:

second column, removing x_1^2 we arrive at:

$$\tau(x_m^2, ..., x_1^3) \prod_{i,j \in E \setminus \{\text{edges involving } \{x_1^1, .., x_m^1, x_1^2\}\}} \phi(x_i, x_j)$$

Removing x_k^2 for $k < m$:

$$\tau(x_m^2, .., x_{k+1}^2, x_k^3, ., x_1^3) \prod_{i,j \in E \setminus \{\text{edges involving } \{x_1^1, .., x_m^1, x_1^2, ..., x_k^2\}\}} \phi(x_i, x_j)$$

Removing x_m^2 :

$$\tau(x_m^3, .., x_1^3) \prod_{i,j \in E \setminus \{\text{edges involving } \{x_1^1, .., x_m^1, x_1^2, ..., x_k^2\}\}} \phi(x_i, x_j)$$

Note: at this point we arrive at a structure similar to (1). We continue this way, repeating the same steps as in removing the second column untill we arrive at the last column.

Removing the last column:

At this point we have:

$$\tau(x_m^m, .., x_1^m)$$

The last column is removed one by one as the single remaining factor is replaced by one with one variable less at each stage.

In total we have seen a maximal factor of size m. As we know this corresponds with a maximal clique size of size m. Thus, the tree-width cannot exceed m.

Question 3

"Consider the sum-product message update on a tree graph. But, consider the case where all messages are updated simultaneously. Namely:

$$m_{ij}^{t+1}(x_j) = \sum_{x_i} \phi(x_i, x_j) \prod_{k \in N(i) \setminus \{j\}} m_{ki}^t(x_i)$$

Show that this converges to the true marginals at iteration t = n."

Initialization:

$$\forall ij \in E : m_{ij}^0 = \begin{cases} \sum_{x_i} \phi(x_i, x_j) & \text{i is a leaf} \\ 0 & \text{else} \end{cases}$$

Recall our definition for a message between i and j:

$$m_{ij}(x_j) = \sum_{x_i} \phi(x_i, x_j) \prod_{k \in N(i) \setminus \{j\}} m_{ki}(x_i) \tag{2}$$

Claim:

At iteration t: m_{ij}^t holds the correct message value, function (2) we defined above, for all nodes whose longest path to any descendent is at most t. For all other nodes $m_{ij}^t = 0$ (0 as a constant function).

[Note: the notion of "children of a node" is on a per-message basis. For message m_{ij}^t from node i to node j, we "treat" j as the root and the descendents of node i are defined as such.]

Proof of claim - by induction:

Base case $t = 0$. Leaves are the only nodes "whose longest path to any child is at most 0". Because leaves have only one neighbour - their parent, they do not receive any messages and the value we have computed for leaves upon initialization is the correct value of their message. For all non-leaf nodes, initialization was to 0 and the claim holds.
Assume for $k-1$. We now calculate m_{ij}^k as defined. Let x_i be some node whose longest path to any descendent is at most k, the longest path from any of x_i's children to any of their descendents is at most $k-1$. By the inductive hypothesis their mesasages have been calculated correctly. Thus the update has placed the correct value in m_{ij}^k. For all other nodes, some child of theirs holds 0 and the product will be have a 0 factor for any value of x_i. $\square$

Main proof:

Let $p(x_i)$ be some marginal we wish to compute. From the claim above and the fact that for any tree of size n the distance from root to any of its descendents is at most n, it follows that all messages have been computed correctly. Thus, the process has converged to the true marginals and $p(x_i)$ is given by:

$$p(x_i) = \prod_{k \in N(i)} m_{ki}^n(x_i)$$

$\square$

Question 4

Define:

$$\mu_i(x_i) \propto \prod_{k \in N(i)} m_{ki}(x_i)$$

$$\mu_{ij}(x_i, x_j) \propto \phi(x_i, x_j) \prod_{k \in N(i) \setminus j} m_{ki}(x_i) \prod_{k \in N(j) \setminus j} m_{kj}(x_j)$$

(a)

We should show that $p(x_i, x_j) = \mu_{i,j}(x_i, x_j)$ when G is a tree.
The marginal of $p(x_i, x_j)$ of an edge $(i, j) \in E(G)$ is:

$$p(x_i, x_j) = \sum_{x \setminus \{x_i, x_j\}} p(x) = \frac{\sum_{x \setminus \{x_i, x_j\}} \prod_{(k,l) \in E} \phi_{kl}(X_k, X_l)}{Z}$$

Since G is a tree, if we remove the edge (x_i, x_j) two sub trees will be created with no path between x_i and x_j.
We denote the subtree with $x_i$as G_i and the subtree with x_j as G_j. so the above equation can be written as:

$$\begin{aligned} p(x_i, x_j) = \frac{1}{Z} \sum_{x \setminus \{x_i, x_j\}} \phi_{i,j}(x_i, x_j) \prod_{(k,l) \in E(G_i)} \phi_{k,l}(x_k, x_l) \prod_{(k,l) \in E(G_j)} \phi_{k,l}(x_k, x_l) = \\ = \frac{1}{Z} \times \phi_{i,j}(x_i, x_j) \times \sum_{x \setminus \{x_i, x_j\}} (\prod_{(k,l) \in E(G_i)} \phi_{k,l}(x_k, x_l) \times \prod_{(k,l) \in E(G_j)} \phi_{k,l}(x_k, x_l)) = \\ = \frac{1}{Z} \times \phi_{i,j}(x_i, x_j) \times \sum_{x \setminus \{x_i, x_j\}} \prod_{(k,l) \in E(G_i)} \phi_{k,l}(x_k, x_l) \times \sum_{x \setminus \{x_i, x_j\}} \prod_{(k,l) \in E(G_j)} \phi_{k,l}(x_k, x_l) \end{aligned}$$

Lets divide each subtree G_i and G_j once more to its neighbors sub-trees

$$\begin{aligned} p(x_i, x_j) = \frac{1}{Z} \times \phi_{i,j}(x_i, x_j) \times \prod_{d \in N(i) \setminus \{j\}} \sum_{s \in N(d) \setminus \{i\}} \prod_{(k,l) \in E(G_s)} \phi_{k,l}(x_k, x_l) \\ \times \prod_{d \in N(j) \setminus \{i\}} \sum_{s \in N(d) \setminus \{j\}} \prod_{(k,l) \in E(G_s)} \phi_{k,l}(x_k, x_l) \end{aligned}$$

Since $m_{di}(x_i) = \sum_{s \in N(d) \setminus \{i\}} \prod_{(k,l) \in E(G_s)} \phi_{k,l}(x_k, x_l)$ we get from the definition of $\mu_{i,j}(x_i, x_j)$:
$p(x_i, x_j) = \frac{1}{Z} \phi_{i,j}(x_i, x_j) \times \prod_{d \in N(i) \setminus \{j\}|} m_{di}(x_i) \times \prod_{d \in N(j) \setminus \{i\}|} m_{dj}(x_j) = \mu_{i,j}(x_i, x_j)$

(b)

On Markov net $p(x_{1,\ldots,n}) \propto \prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j)$ so we will show that

$$\prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j) = \prod_i \mu_i(x_i) \times \prod_{(i,j)\in E} \frac{\mu_{i,j}(x_i, x_j)}{\mu_i(x_i)\mu_j(x_j)}$$

Lets develop the right expression:

$$\prod_{(i,j)\in E} \frac{\mu_{i,j}(x_i, x_j)}{\mu_i(x_i)\mu_j(x_j)} = \prod_{(i,j)\in E} \frac{\phi_{i,j}(x_i, x_j) \times \prod_{d\in N(i)\setminus\{j\}} m_{di}(x_i) \times \prod_{d\in N(j)\setminus\{i\}} m_{di}(x_j)}{\mu_i(x_i)\mu_j(x_j)} =$$

$$= \prod_{(i,j)\in E} \frac{\phi_{i,j}(x_i, x_j) \times \prod_{d\in N(i)\setminus\{j\}} m_{di}(x_i) \times \prod_{d\in N(j)\setminus\{i\}} m_{di}(x_j)}{\prod_{d\in N(i)} m_{di}(x_i) \times \prod_{d\in N(j)} m_{dj}(x_j)} =$$

$$= \prod_{(i,j)\in E} \frac{\phi_{i,j}(x_i, x_j)}{m_{ij}(x_j) \times m_{ji}(x_i)} = \frac{\prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j)}{\prod_i \prod_{j\in N(i)} m_{ji}(x_i)} = \frac{\prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j)}{\prod_i \mu_i(x_i)}$$

Place the new form in the first equation to get the result we are looking for:

$$\prod_i \mu_i(x_i) \times \prod_{(i,j)\in E} \frac{\mu_{i,j}(x_i, x_j)}{\mu_i(x_i)\mu_j(x_j)} = \prod_i \mu_i(x_i) \times \frac{\prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j)}{\prod_i \mu_i(x_i)} = \prod_{(i,j)\in E} \phi_{i,j}(x_i, x_j)$$

Therefore $p(x_1 \ldots x_n) \propto \prod_i \mu_i(x_i) \times \prod_{(i,j)\in E} \frac{\mu_{i,j}(x_i,x_j)}{\mu_i(x_i)\mu_j(x_j)}$

(c)

We will prove that at a fixed point of LBP we get

$$\frac{\sum_{x_j} \mu_{i,j}(x_i, x_j)}{\mu_i(x_i)} = 1$$

Lets start with the upper expression, lets say that the normalization factor of $\mu_{ij}$is D_1. so we can rewrite the expression:

$$\sum_{x_j} \mu_{ij}(x_i, x_j) = D_1 \times \sum_{x_j} \phi_{i,j}(x_i, x_j) \times \prod_{d \in N(i) \setminus \{j\}} m_{di}(x_i) \times \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j)$$
$$= D_1 \times \prod_{d \in N(i) \setminus \{j\}} m_{di}(x_i) \times (\sum_{x_j} \phi_{i,j}(x_i, x_j) \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j)$$

On the other hand, lets open the lower expression according to the definition of $\mu_i(x_i)$ and assume the normalization factor is D_2:

$$\mu_i(x_i) \quad = \quad D_2 \quad \times \quad \prod_{d \in N(i)} m_{di}(x_i)$$

Combine it together we get:

$$\frac{\sum_{x_j} \mu_{i,j}(x_i, x_j)}{\mu_i(x_i)} = \frac{D_1 \times \prod_{d \in N(j) \setminus \{i\}} m_{di}(x_i) \times (\sum_{x_j} \phi_{i,j}(x_i, x_j) \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j))}{D_2 \times \prod_{d \in N(i)} m_{di}(x_i)} =$$
$$= \frac{D_1}{D_2} \times \frac{\sum_{x_j} \phi_{i,j}(x_i, x_j) \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j)}{m_{ji}(x_i)}$$

Now lets open the $m_{ji}(x_i)$ expression, and suppose the normalization factor is D_3

$$\frac{\sum_{x_j} \mu_{i,j}(x_i, x_j)}{\mu_i(x_i)} = \frac{D_1}{D_2} \times \frac{\sum_{x_j} \phi_{i,j}(x_i, x_j) \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j)}{D_3 \times \sum_{x_j} \phi_{i,j}(x_i, x_j) \times \prod_{d \in N(j) \setminus \{i\}} m_{dj}(x_j)} = \frac{D_1}{D_2 \times D_3}$$

We've got that the value of this expression depends just on the normalization factors, but the normalization factors sum to 1 over all values. therefore

$$\frac{\sum_{x_j} \mu_{i,j}(x_i, x_j)}{\mu_i(x_i)} \quad = \quad 1 \quad \Rightarrow \quad \sum_{x_j} \mu_{i,j}(x_i, x_j) \quad = \quad \mu_i(x_i)$$

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