

# 732A96/TDDE15 Advanced Machine Learning

## Graphical Models and Hidden Markov Models

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Lecture 2: Probabilistic Reasoning

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- ▶ Main source
  - ▶ Lauritzen, S. L. and Spiegelhalter, D. J. Local Computations with Probabilities on Graphical Structures and Their Application to Expert Systems. *Journal of the Royal Statistical Society B* 50, 157-224, 1988.
- ▶ Additional source
  - ▶ Bishop, C. M. *Pattern Recognition and Machine Learning*. Springer, 2006. Chapter 8.

# Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

Original	Moralization	Triangulation	Triangulation
		<p>Ordering: <math>E, D, A, B, C</math></p>	<p>Ordering: <math>E, B, A, C, D</math></p>

## Moralization

Repeat for every node in  $G$

Make its parents pairwise adjacent

Replace all the directed edges in  $G$  with undirected edges

- An UG is **triangulated** if every cycle in it contains a chord, i.e. an edge between two non-consecutive nodes in the cycle.

## Triangulation

Repeat until all the nodes in  $G$  are marked

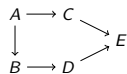
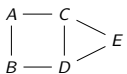
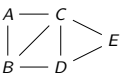
If there is an unmarked node whose unmarked neighbours are a complete set then

Mark it

Else

Mark any unmarked node and make its unmarked neighbours a complete set

## Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

Original	Moralization	Triangulation
		 <p>Ordering: <math>E, D, A, B, C</math>  Candidate cliques: <math>\{C, D, E\}, \{B, C, D\}, \{A, B, C\}, \{B, C\}, \{C\}</math>  Cliques: <math>\{C, D, E\}, \{A, B, C\}, \{B, C, D\}</math>  RIP: <math>C_1 = \{A, B, C\}, C_2 = \{B, C, D\}, C_3 = \{C, D, E\}</math></p>

- ▶ A clique is a maximal complete set of nodes. The cliques of a triangulated graph can be ordered as  $C_{1:k}$  to have the **running intersection property (RIP)**, i.e.  $C_j \cap C_{1:j-1} \subset C_i$  with  $i < j$ .

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RIP

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Repeat until all the nodes in  $G$  are marked

Mark an unmarked node whose unmarked neighbours are a complete set

Record the union of the node and its unmarked neighbours as a candidate clique

Remove any candidate clique that is included in any other

Label every clique with the number of the first iteration that marked one of its nodes

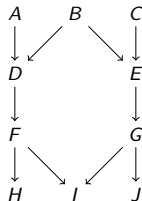
Sort the cliques in descending order of their labels

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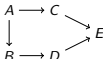
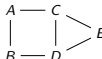
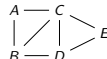
- ▶ Let  $S_j = C_j \cap C_{1:j-1}$  and  $R_j = C_j \setminus S_j$ .
- ▶ **Note that**  $R_j \perp_G C_{1:j-1} \setminus S_j | S_j$ .

## Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

- **Exercise.** Moralize, triangulate and order the resulting cliques of the following DAG so as to satisfy the RIP.



# Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

Original	Moralization	Triangulation
 $p(A, B, C, D, E) = q(A)q(B A)q(C A)q(D B)q(E C, D)$		 <p>RIP: <math>C_1 = \{A, B, C\}</math>, <math>C_2 = \{B, C, D\}</math>, <math>C_3 = \{C, D, E\}</math></p>

- ▶ Let  $\varphi(C_1) := q(A)q(B|A)q(C|A)$ ,  $\varphi(C_2) := q(D|B)$ ,  $\varphi(C_3) := q(E|C, D)$ .
- ▶ Then

$$p(R_3|S_3) = p(E|C, D) := \varphi(C_3) / \sum_{R_3} \varphi(C_3) = q(E|C, D) / \sum_E q(E|C, D) = q(E|C, D)$$

- ▶ Since  $S_3 \subset C_2$  by RIP, let

$$\varphi(C_2) := \varphi(C_2) \sum_{R_3} \varphi(C_3) = q(D|B) \sum_E q(E|C, D) = q(D|B)$$

- ▶ Then

$$p(R_2|S_2) = p(D|B, C) := \varphi(C_2) / \sum_{R_2} \varphi(C_2) = q(D|B) / \sum_D q(D|B) = q(D|B)$$

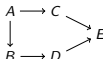
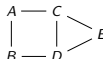
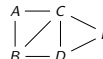
- ▶ Since  $S_2 \subset C_1$  by RIP, let

$$\varphi(C_1) := \varphi(C_1) \sum_{R_2} \varphi(C_2) = q(A)q(B|A)q(C|A) \sum_D q(D|B) = q(A)q(B|A)q(C|A)$$

- ▶ Then,  $p(R_1|S_1) = p(A, B, C) := \varphi(C_1) / \sum_{R_1} \varphi(C_1)$

$$= q(A)q(B|A)q(C|A) / \sum_{A, B, C} q(A)q(B|A)q(C|A) = q(A)q(B|A)q(C|A)$$

# Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

Original	Moralization	Triangulation
 <p> <math>p(A, B, C, D, E) = q(A)q(B A)q(C A)q(D B)q(E C, D)</math> </p>		 <p>             RIP: <math>C_1 = \{A, B, C\}</math>, <math>C_2 = \{B, C, D\}</math>, <math>C_3 = \{C, D, E\}</math> </p>

- ▶ Note that  $S_1 = \emptyset$  and, thus,  $p(C_1) = p(R_1|S_1)$ .

- ▶ Since  $S_2 \subset C_1$  by RIP

$$p(S_2) = \sum_{C_1 \setminus S_2} p(C_1)$$

- ▶ Then

$$p(C_2) := p(R_2|S_2)p(S_2)$$

- ▶ Since  $S_3 \subset C_2$  by RIP

$$p(S_3) = \sum_{C_2 \setminus S_3} p(C_2)$$

- ▶ Then

$$p(C_3) := p(R_3|S_3)p(S_3)$$

- ▶ **Output:**  $p(C_1)$ ,  $p(C_2)$  and  $p(C_3)$ .



## Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

- ▶ In general, rewrite

$$p(X) = \prod_{i=1}^n q(X_i | pa_G(X_i)) = \prod_{i=1}^k \varphi(C_i)$$

- ▶ Note that

$$p(X) = f(C_{1:k-1} \setminus S_k, S_k) g(S_k, R_k)$$

and thus

$$R_k \perp_p C_{1:k-1} \setminus S_k | S_k$$

- ▶ Then

$$p(X) = p(C_{1:k-1}) p(R_k | C_{1:k-1}) = p(C_{1:k-1}) p(R_k | S_k)$$

- ▶ Note that

$$p(C_{1:k-1}) = \sum_{R_k} p(X) = \left[ \prod_{i=1}^{k-1} \varphi(C_i) \right] \sum_{R_k} \varphi(C_k)$$

and thus

$$p(R_k | S_k) = \varphi(C_k) / \sum_{R_k} \varphi(C_k)$$

- ▶ Let  $S_k \subset C_j$  by RIP. Then, replace  $\varphi(C_j)$  with  $\varphi(C_j) \sum_{R_k} \varphi(C_k)$ .
- ▶ Then,  $p(C_{1:k-1}) = \prod_{i=1}^{k-1} \varphi(C_i)$
- ▶ Repeat the above for  $p(C_{1:k-1})$ . **Output:**  $p(R_i | S_i)$  for all  $i$ .

## Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

- ▶ Note that  $S_1 = \emptyset$  and, thus,  $p(C_1) = p(R_1|S_1)$ .
- ▶ Since  $S_2 \subset C_1$  by RIP

$$p(S_2) = \sum_{C_1 \setminus S_2} p(C_1)$$

- ▶ Then

$$p(C_2) = p(R_2|S_2)p(S_2)$$

- ▶ Repeat the above for  $C_{3:k}$ . **Output:**  $p(C_i)$  for all  $i$ .

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LS algorithm

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Moralize  $G$

Triangulate  $G$

Order the cliques of  $G$  so as to satisfy the RIP

For  $i = k, \dots, 1$  do

    Let  $S_i \subset C_i$  by RIP

$p(R_i|S_i) := \varphi(C_i) / \sum_{R_i} \varphi(C_i)$

$\varphi(C_j) := \varphi(C_j) \sum_{R_i} \varphi(C_i)$

For  $i = 1, \dots, k$  do

    Let  $S_i \subset C_i$  by RIP

$p(S_i) := \sum_{C_j \setminus S_i} p(C_j)$

$p(C_i) := p(R_i|S_i)p(S_i)$

Return  $p(C_1), \dots, p(C_k)$

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## Probabilistic Reasoning for BNs: Lauritzen-Spiegelhalter Algorithm

- ▶ Then, we know  $p(Y)$  for all  $Y \subseteq C_i$ .
- ▶ What if we want  $p(Y|o)$  with  $O \subseteq X \setminus Y$  ?
  - ▶ Let  $U = X \setminus O$ . Note that  $p(U|o)$  is a normalized version of  $p(U, o)$ , i.e.  $p(U|o) = p(U, o) / \sum_U p(U, o)$ . Moreover,  $p(U, o)$  can be expressed as  $P(U, o) = P(X) \prod_i 1_{O_i=o_i}$ .
  - ▶ Then, just add the factors  $1_{O_i=o_i}$  to the appropriate cliques, perform inference as before to obtain  $p(Y, o)$ , and finally normalize.
- ▶ What if  $Y \not\subseteq C_i$  for all  $i$  ?
  - ▶ For any  $A \in X$ , compute  $p(A, o')$  for all  $y$ , where  $o' = \{y, o\}$ .
  - ▶ Then,  $p(o') = \sum_A p(A, o')$  for all  $y$ . This produces  $p(Y, o)$ .
  - ▶ Finally, normalize  $p(Y, o)$ .
- ▶ **Exercise.** Apply the LS algorithm to compute  $p(J|a)$  in the previous exercise.

## Probabilistic Reasoning for BNs: Most Probable Configuration

- Note that

$$\max_X p(X) = \max_{R_1, \dots, R_k} \varphi(C_1) \dots \varphi(C_k) = \max_{R_1, \dots, R_{k-1}} [\varphi(C_1) \dots \varphi(C_{k-1}) \max_{R_k} \varphi(C_k)]$$

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Probability of the most probable configuration

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For  $i = k, \dots, 1$  do

Let  $S_i \subset C_j$  by RIP

$\phi(S_i) := \max_{R_i} \varphi(C_i)$

$\varphi(C_j) := \varphi(C_j)\phi(S_i)$

$\psi(S_i) := \arg \max_{R_i} \varphi(C_i)$

Return  $\psi(S_1), \dots, \psi(S_k)$

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Most probable configuration

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For  $i = 1, \dots, k$  do

$R_i^{max} := \psi(S_i^{max})$

Return  $R_1^{max}, \dots, R_k^{max}$

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- 
- After running the first algorithm and since  $S_1 = S_1^{max} = \emptyset$ , we have that

$$R_1^{max} = \arg \max_{R_1} [\max_{R_2, \dots, R_k} p(X)] = \arg \max_{R_1} \varphi(C_1) = \psi(S_1^{max})$$

- Note that

$$\arg \max_{R_1, R_2} [\max_{R_3, \dots, R_k} p(X)] = \arg \max_{R_1, R_2} \varphi(C_1)\varphi(C_2)$$

and since it has to be consistent with  $R_1^{max}$ , then

$$R_2^{max} = \arg \max_{R_2} \varphi(S_1^{max}, R_1^{max})\varphi(S_2^{max}, R_2) = \psi(S_2^{max})$$

- And so on.

# Probabilistic Reasoning for MNs

- ▶ The same as for BNs. Just skip the moralization step.
- ▶ No need to include  $Z$ . After inference, just normalize any  $p(C_i)$  to obtain  $Z$  and use it to normalize the rest of the output.

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Thank you