

# 732A96/TDDE15 Advanced Machine Learning

## Graphical Models and Hidden Markov Models

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Lecture 1: Causal Models, Bayesian Networks and Markov Networks

# Contents

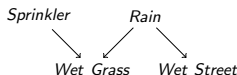
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# Literature

- ▶ Main source
  - ▶ Bishop, C. M. *Pattern Recognition and Machine Learning*. Springer, 2006. Chapter 8.
- ▶ Additional source
  - ▶ Koski, T. J. T. and Noble, J. M. A Review of Bayesian Networks and Structure Learning. *Mathematica Applicanda* 40, 51-103, 2012.

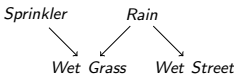
## Causal Models

- ▶ Assume that we want to represent the causal relations between a set of random variables, e.g. the latter may represent the state of the components of a system.
- ▶ A natural and intuitive representation consists of a **graph** where the random variables are the nodes, and the causal relations are the edges. We call the graph a **causal model**.



- ▶ What happens if some random variables are not modeled ?
  - ▶ Nothing if they have at most one modeled effect, e.g. mediators.
  - ▶ Problems otherwise, e.g.  $WG \rightarrow WS$  and  $WG \leftarrow WS$  are both wrong.
- ▶ **Exercise.** Produce a causal model for the domain *Temperature*, *Ice cream sales* and *Soda sales*.
- ▶ **Exercise.** Produce a causal model for Boyle's law, which relates the pressure and volume of a gas as  $Pressure \cdot Volume = constant$  if the temperature and amount of gas remain unchanged within a closed system.

## Bayesian Networks: Definition

DAG	Parameter values for the conditional probability distributions
 <pre> graph TD     Sprinkler --&gt; Wet     Rain --&gt; Grass     Rain --&gt; Street     Wet --&gt; Street     </pre>	$  \begin{aligned}  q(S) &= (0.3, 0.7) \\  q(R) &= (0.5, 0.5) \\  q(WG r_0, s_0) &= (0.1, 0.9) \\  q(WG r_0, s_1) &= (0.7, 0.3) \\  q(WG r_1, s_0) &= (0.8, 0.2) \\  q(WG r_1, s_1) &= (0.9, 0.1) \\  q(WS r_0) &= (0.1, 0.9) \\  q(WS r_1) &= (0.7, 0.3)  \end{aligned}  $ $p(S, R, WG, WS) = q(S)q(R)q(WG S, R)q(WS R)$

- ▶ A **Bayesian network (BN)** over a finite set of **discrete** random variables  $X = X_{1:n} = \{X_1, \dots, X_n\}$  consists of
  - ▶ a DAG  $G$  whose nodes are the elements in  $X$ , and
  - ▶ parameter values  $\theta_G$  specifying conditional probability distributions  $q(X_i|pa_G(X_i))$ .
- ▶ The BN represents a **causal** model of the system.
- ▶ The BN also represents a **probabilistic** model of the system, namely  $p(X) = \prod_i q(X_i|pa_G(X_i))$ .

## Bayesian Networks: Definition

- ▶ We now show that  $p(X) = \prod_i q(X_i|pa_G(X_i))$  is a probability distribution.
- ▶ Clearly,  $0 \leq \prod_i q(X_i|pa_G(X_i)) \leq 1$ .
- ▶ Assume without loss of generality that  $pa_G(X_i) \subseteq X_{1:i-1}$  for all  $i$ . Then

$$\sum_x \prod_i q(x_i|pa_G(X_i)) = \sum_{x_1} [q(x_1) \dots \sum_{x_{n-1}} [q(x_{n-1}|pa_G(X_{n-1})) \sum_{x_n} q(x_n|pa_G(X_n))] \dots] = 1$$

- ▶ Moreover,  $p(X_j|pa_G(X_j)) = q(X_j|pa_G(X_j))$ . To see it, note that

$$\begin{aligned} p(X_j|pa_G(X_j)) &= \frac{p(X_j, pa_G(X_j))}{p(pa_G(X_j))} = \frac{\sum_{X \setminus \{X_j, pa_G(X_j)\}} \prod_i q(X_i|pa_G(X_i))}{\sum_{X \setminus pa_G(X_j)} \prod_i q(X_i|pa_G(X_i))} \\ &= \frac{\sum_{X_{1:j} \setminus \{X_j, pa_G(X_j)\}} \prod_{i \leq j} q(X_i|pa_G(X_i))}{\sum_{X_{1:j} \setminus pa_G(X_j)} \prod_{i \leq j} q(X_i|pa_G(X_i))} = q(X_j|pa_G(X_j)) \end{aligned}$$

## Bayesian Networks: Separation

- ▶ We now show that many of the independencies in  $p$  can be read off  $G$  without numerical calculations.
- ▶ A path in  $G$  is a sequence of adjacent nodes, i.e. the direction of the edge is irrelevant. A node  $B$  is a descendant of a node  $A$  in  $G$  if there is a path  $A \rightarrow \dots \rightarrow B$ .
- ▶ Let  $\rho$  be a path in  $G$  between the nodes  $\alpha$  and  $\beta$ .
- ▶ A node  $B$  in  $\rho$  is a **collider** when  $A \rightarrow B \leftarrow C$  is a subpath of  $\rho$ .
- ▶ Moreover,  $\rho$  is  $Z$ -open with  $Z \subseteq X \setminus \{\alpha, \beta\}$  when
  - ▶ no non-collider in  $\rho$  is in  $Z$ , and
  - ▶ every collider in  $\rho$  is in  $Z$  or has a descendant in  $Z$ .
- ▶ Let  $U$ ,  $V$  and  $Z$  be three disjoint subsets of  $X$ . Then,  $U$  and  $V$  are **separated** given  $Z$  in  $G$  (i.e.  $U \perp_G V | Z$ ) when there is no  $Z$ -open path in  $G$  between a node in  $U$  and a node in  $V$ .
- ▶ The separation criterion is **sound**, i.e. if  $U \perp_G V | Z$  then  $U \perp_p V | Z$ .
- ▶ For instance,  $S \perp_p R$ ,  $S \not\perp_p R | WG$ ,  $S \not\perp_p WS | WG$ ,  $S \perp_p WS | WG, R$ .



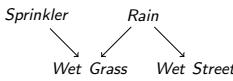

- ▶ Note that we read independencies from  $G$ , never dependencies.

## Bayesian Networks: Separation

- ▶ Moreover, the separation criterion is also **complete**, i.e.  $p$  may be such that  $U \perp_G V|Z$  if and only if  $U \perp_p V|Z$ .
- ▶ Moreover,  $p$  factorizes as  $p(X) = \prod_i q(X_i | pa_G(X_i))$  if and only if it satisfies all the independencies identified by the separation criterion.
- ▶ **Exercise.** Prove that  $A \perp_p B|C$  for the DAGs  $A \rightarrow C \rightarrow B$ ,  $A \leftarrow C \rightarrow B$  and  $A \leftarrow C \leftarrow B$ , i.e. prove that  $p(A, B|C) = p(A|C)p(B|C)$ .
- ▶ **Exercise.** Prove that  $A \perp_p B|\emptyset$  for the DAG  $A \rightarrow C \leftarrow B$ , i.e. prove that  $p(A, B) = p(A)p(B)$ .
- ▶ **Exercise.** Find the minimal set of nodes that separates a given node from the rest. This set is called the Markov blanket of the given node.



# Bayesian Networks: Causal Reasoning

Original	After $do(r_1)$
 <p> <math>q(S) = (0.3, 0.7)</math>  <math>q(R) = (0.5, 0.5)</math>  <math>q(WG r_0, s_0) = (0.1, 0.9)</math>  <math>q(WG r_0, s_1) = (0.7, 0.3)</math>  <math>q(WG r_1, s_0) = (0.8, 0.2)</math>  <math>q(WG r_1, s_1) = (0.9, 0.1)</math>  <math>q(WS r_0) = (0.1, 0.9)</math>  <math>q(WS r_1) = (0.7, 0.3)</math> </p> <p> <math>p(S, R, WG, WS) = q(S)q(R)q(WG S, R)q(WS R)</math> </p>	 <p> <math>q(S) = (0.3, 0.7)</math>  <math>q(WG s_0) = (0.8, 0.2)</math>  <math>q(WG s_1) = (0.9, 0.1)</math>  <math>q(WS) = (0.7, 0.3)</math> </p> <p> <math>p(S, WG, WS) = q(S)q(WG S)q(WS)</math> </p>

- What would be the state of the system if a random variable  $X_j$  is **forced** to take the state  $x_j$ , i.e.  $p(X \setminus X_j | do(x_j))$  ?
  - Remove  $X_j$  and all the edges from and to  $X_j$  from  $G$ .
  - Remove  $q(X_j | pa_G(X_j))$ .
  - If  $X_j \in pa_G(X_i)$ , then replace  $q(X_i | pa_G(X_i))$  with  $q(X_i | pa_G(X_i) \setminus X_j, x_j)$
  - Set  $p(X \setminus X_j | do(x_j)) = \prod_i q(X_i | pa_G(X_i))$ .
- So, the result of  $do(x)$  on a BN is a **BN**.

## Bayesian Networks: Probabilistic Reasoning

- What is the state of the system if a random variable  $X_i$  is **observed** to be in the state  $x_i$ , i.e.  $p(X \setminus X_i | x_i)$  ?

- $$p(X \setminus X_i | x_i) = \frac{p(X \setminus X_i, x_i)}{p(x_i)} = \frac{p(X \setminus X_i, x_i)}{\sum_{X \setminus X_i} p(X \setminus X_i, x_i)}$$
- $$p(R, WG, WS | s) = \frac{q(s)q(R)q(WG|s,R)q(WS|R)}{\sum_{r, wg, ws} q(s)q(r)q(wg|s,r)q(ws|r)}$$
$$= \frac{q(s)q(R)q(WG|s,R)q(WS|R)}{q(s) \sum_r [q(r) \sum_{wg} [q(wg|s,r) \sum_{ws} q(ws|r)]]}$$


- What is the state of a random variable  $Y$  if a random variable  $X_i$  is **observed** to be in the state  $x_i$ , i.e.  $p(Y | x_i)$  ?

- $$p(Y | x_i) = \frac{p(Y, x_i)}{p(x_i)} = \frac{\sum_{X \setminus \{X_i, Y\}} p(X \setminus X_i, x_i)}{\sum_{X \setminus X_i} p(X \setminus X_i, x_i)}$$
- $$p(WS | s) = \frac{\sum_{r, wg} q(s)q(r)q(wg|s,r)q(WS|r)}{\sum_{r, wg, ws} q(s)q(r)q(wg|s,r)q(ws|r)}$$
$$= \frac{q(s) \sum_r [q(r)q(WS|r) \sum_{wg} q(wg|s,r)]}{q(s) \sum_r [q(r) \sum_{wg} [q(wg|s,r) \sum_{ws} q(ws|r)]]}$$

- What is the state of a random variable  $Y$  if a random variable  $X_i$  is **observed** to be in the state  $x_i$ , after **forcing** a random variable  $X_j$  to take the state  $x_j$ , i.e.  $p(Y | x_i, do(x_j))$  ?
- Answering questions like the one above can be computationally hard.
- A BN is an efficient formalism to compute a posterior probability distribution from a prior probability distribution in the light of observations, hence the name.

## Markov Networks: Definition

- ▶ A BN represents asymmetric (causal) relations, whereas a Markov network represents **symmetric** relations, e.g. physical laws.

UG	Potentials assuming binary random variables
 <pre> graph LR     A --- B     A --- C     B --- D     C --- D         </pre>	$\varphi(A, B, C) = (0, 0, 0, 0, 1, 1, 1, 1)$ $\varphi(B, C, D) = (1, 2, 3, 4, 5, 6, 7, 8)$  $p(A, B, C, D) = \varphi(A, B, C)\varphi(B, C, D)/Z$ with $Z = \sum_{a,b,c,d} \varphi(a, b, c)\varphi(b, c, d)$

- ▶ A **Markov network (MN)** over  $X$  consists of
  - ▶ an undirected graph (UG)  $G$  whose nodes are the elements in  $X$ , and
  - ▶ a set of non-negative functions  $\varphi(K)$  over the cliques  $Cl(G)$  of  $G$ .
- ▶ A clique is a maximal complete set of nodes. The functions are called potentials. They represent **compatibility** relations between the random variables in the cliques.
- ▶ The MN represents a **probabilistic** model of the system, namely

$$p(X) = \frac{1}{Z} \prod_{K \in Cl(G)} \varphi(K)$$

where  $Z$  is a normalization constant, i.e.

$$Z = \sum_x \prod_{K \in Cl(G)} \varphi(k)$$

- ▶ Clearly,  $p(X)$  is a probability distribution.

## Markov Networks: Separation

- ▶ We now show that many of the independencies in  $p$  can be read off  $G$  without numerical calculations.
- ▶ A path  $\rho$  in  $G$  between two nodes  $\alpha$  and  $\beta$  is  $Z$ -open with  $Z \subseteq X \setminus \{\alpha, \beta\}$  when no node in  $\rho$  is in  $Z$ .
- ▶ Let  $U$ ,  $V$  and  $Z$  be three disjoint subsets of  $X$ . Then,  $U$  and  $V$  are **separated** given  $Z$  in  $G$  (i.e.  $U \perp_G V | Z$ ) when there is no  $Z$ -open path in  $G$  between a node in  $U$  and a node in  $V$ .
- ▶ The separation criterion is **sound**, i.e. if  $U \perp_G V | Z$  then  $U \perp_p V | Z$ .
- ▶ Moreover, it is also **complete**, i.e.  $p$  may be such that  $U \perp_G V | Z$  if and only if  $U \perp_p V | Z$ .
- ▶ Moreover,  $p$  factorizes as  $p(X) = \frac{1}{Z} \prod_{K \in Cl(G)} \varphi(K)$  if and only if it satisfies all the independencies identified by the separation criterion.

## Markov Networks: Separation

- ▶ **Exercise.** Prove that  $A \perp_p B | C$  for the UG  $A - C - B$ , i.e. prove that  $p(A, B | C) = f(A, C)g(B, C)$  for some functions  $f$  and  $g$ .
- ▶ **Exercise.** Find the minimal set of nodes that separates a given node from the rest. This set is called the Markov blanket of the given node.

# Markov Networks: Probabilistic Reasoning

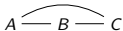
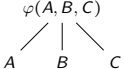
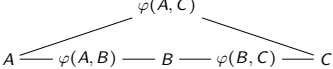
- ▶ What is the state of a random variable  $A$  if a random variable  $B$  is **observed** to be in the state  $b$  ?

$$p(A|b) = \frac{\sum_{c,d} \varphi(A, b, c) \varphi(b, c, d) / Z}{\sum_{a,c,d} \varphi(a, b, c) \varphi(b, c, d) / Z} = \frac{\sum_c [\varphi(A, b, c) \sum_d \varphi(b, c, d)]}{\sum_{a,c} [\varphi(a, b, c) \sum_d \varphi(b, c, d)]}$$

- ▶ Answering questions like the one above can be computationally hard.
- ▶ A MN is an efficient formalism to answer such questions.

## Markov Networks: Factor Graphs

- What if  $\varphi(A, B, C) = \varphi(A, B)\varphi(B, C)\varphi(A, C)$  ? I.e.  $\varphi(C_i) = \prod_j \varphi(C_i^j)$  with  $C_i^j \subset C_i$ .
- A MN may obscure the structure of the potentials. Solution: Factor graphs.
- A **factor graph** over  $X$  consists of an UG  $G$  with two types of nodes: The elements in  $X$  and a set of potentials  $\varphi(K)$  over subsets of  $X$ . All the edges in  $G$  are between a potential and the elements of  $X$  that are in the potential's domain.

MN	Factor graph	Factor graph
		

- The factor graph represents a **probabilistic** model of the system, namely

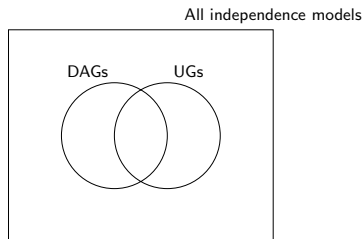
$$p(X) = \frac{1}{Z} \prod_K \varphi(K)$$

where  $Z$  is a normalization constant, i.e.

$$Z = \sum_x \prod_K \varphi(k)$$

- Factor graphs: Finer-grained parameterization of MNs.

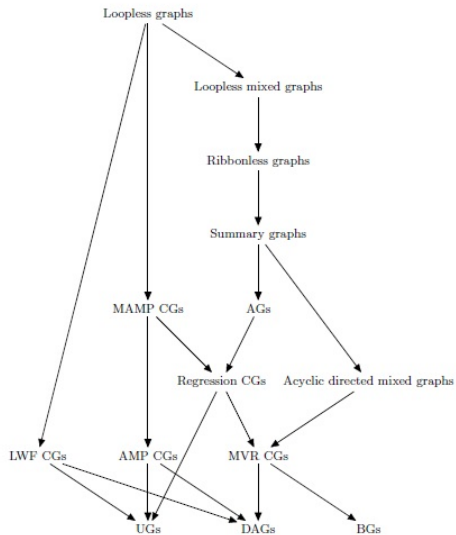
# Intersection of Bayesian and Markov Networks




- ▶ An **unshielded collider** in a DAG is a subgraph of the form  $A \rightarrow C \leftarrow B$  such that  $A$  and  $B$  are not adjacent in the DAG.
- ▶ An UG is **triangulated** if every cycle in it contains a chord, i.e. an edge between two non-consecutive nodes in the cycle.
- ▶ Given a DAG  $G$ , there is an UG  $H$  such that  $\perp_G \equiv \perp_H$  if and only if  $G$  has no unshielded colliders.
- ▶ Given an UG  $G$ , there is a DAG  $H$  such that  $\perp_G \equiv \perp_H$  if and only if  $G$  is triangulated.




# Families of Graphical Models




# Relevance of Graphical Models




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**BIRTH:**  
September 4, 1936, Tel Aviv.


**EDUCATION:**  
B.S., Electrical Engineering (Technion, 1960); M.S., Electronics (Newark College of Engineering, 1961); M.S., Physics (Rutgers University, 1965); Ph.D., Electrical Engineering (Polytechnic Institute of Brooklyn, 1965).


**EXPERIENCE:**


## JUDEA PEARL


United States – 2011


**CITATION**  
For fundamental contributions to artificial intelligence through the development of a calculus for probabilistic and causal reasoning.

 SHORT ANNOTATED BIBLIOGRAPHY

 ACM DL AUTHOR PROFILE

 ACM TURING AWARD LECTURE VIDEO

 RESEARCH SUBJECTS

 ADDITIONAL MATERIALS

Judea Pearl created the representational and computational foundation for the processing of information under uncertainty.

He is credited with the invention of *Bayesian networks*, a mathematical formalism for defining complex probability models, as well as the principal algorithms used for inference in these models. This work not only revolutionized the field of artificial intelligence but also became an important tool for many other branches of engineering and the natural sciences. He later created a mathematical framework for *causal inference* that has had significant impact in the social sciences.

Judea Pearl was born on September 4, 1936, in Tel Aviv, which was at that time administered under the British Mandate for Palestine. He grew up in *Bnei Brak*, a Biblical town his grandfather went to reestablish in 1924. In 1956, after serving in the Israeli army and joining a Kibbutz, Judea decided to study engineering. He attended the Technion, where he met his wife, Ruth, and received a B.S. degree in Electrical Engineering in 1960. Recalling the Technion faculty members in a 2012 interview in the *Technion Magazine*, he emphasized the thrill of discovery:

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Thank you