

# Markov Networks

Or undirected graphical models

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Wilker Aziz

waziz@uva.nl

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<https://probabll.github.io>

# Outline and goals

**Module 2** introduces *Markov networks* (MNs; Chapter 4).

**ILOs** After this module the student

- can map MNs to distributions and vice-versa;
- can reason using an MN;
- recognises the flow of probabilistic influence in MNs;
- recognises independence and separation.

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Textbook for this course: Koller and Friedman [1].

## Overview of Module 2

HC2b: MNs – semantics.

HC3a: MNs – reasoning.

LC3: MNs in code.

HC3b: MNs – influence.

WC3: exercises (semantics, reasoning and influence).

# Table of contents

1. Semantics

2. Reasoning

# Semantics

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## Outline for this section

We will introduce *Markov Networks* (MNs; Chapter 4) via an example from the textbook (the *Misconception* example from Section 4.1).

After presenting the complete example, we will introduce MNs in full generality.

Four students (Alice, Bob, Charles and Debbie) work together in pairs.

Alice and Charles are not on speaking terms, nor are Bob and Debbie.  
Only the following pairs study together:

- Alice and Bob
- Bob and Charles
- Charles and Debbie
- Debbie and Alice

In class, the professor accidentally misspoke, giving rise to a misconception. After class, the students may figure out the problem and share their newfound understanding with their study partners.

The rv  $A$  denotes whether Alice has the misconception  $a^1$  or not  $a^0$ . We use  $B, C, D$  analogously for the other students.

## Conditional Independences

Because Alice and Charles never speak, we have that  $A$  and  $C$  are conditionally independent given  $B$  and  $D$ .

$$A \perp C \mid B, D$$

Similarly,  $B$  and  $D$  are conditionally independent given  $A$  and  $C$ .

$$B \perp D \mid A, C$$

Can we represent these two statements with a BN?

# Conditional Independences

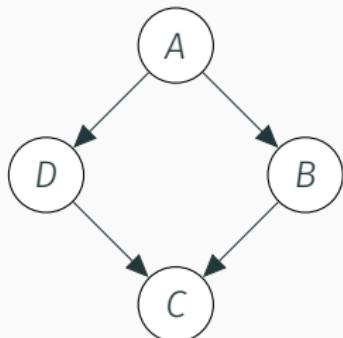
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Can we represent these two statements with a BN?



Attempt 1:

- $A \perp C \mid B, D \checkmark$
- but  $D, B$  are independent given  $A$  alone  $\times$
- and if we are given  $A, C$  then  $D, B$  become dependent  $\times$

# Conditional Independences

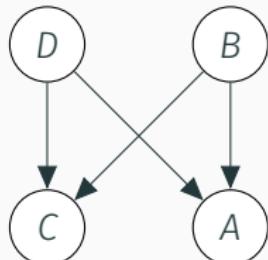
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Attempt 2:

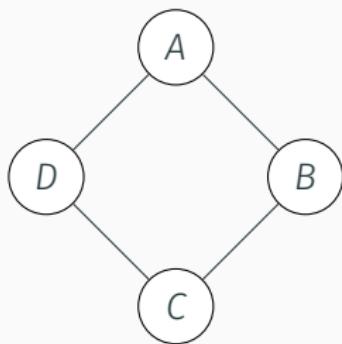
- $A \perp C \mid B, D$  ✓
- but now  $B$  and  $D$  are marginally independent ✗

## Undirected Interaction

We want to represent two conditional independences  $A \perp C | B, D$  and  $B \perp D | A, C$  and no other.

It turns out that no BN structure can do precisely that. Instead,

- we need to represent the interaction between pairs
- and we have no reason to ascribe direction to any interaction



We need an **undirected** representation of the relevant interactions!

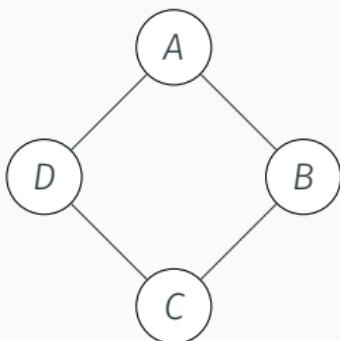
Figure 1: The MN graph for the Misconception example

# Undirected Interaction

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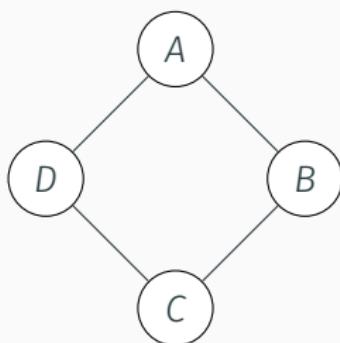


We need an **undirected** representation of the relevant interactions! But how can we parameterise a joint distribution coherent with this view?

Figure 1: The MN graph for the Misconception example

## Factors for the *Misconception* example (Fig 4.1 of textbook)

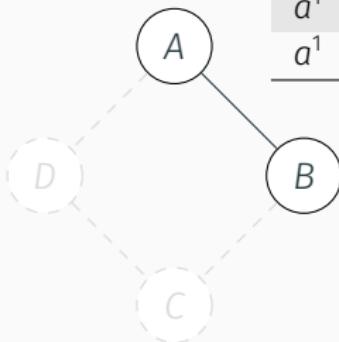
A factor  $\phi$  with scope  $X, Y$  represents the undirected *affinity* between possible outcomes of  $X$  and  $Y$ .



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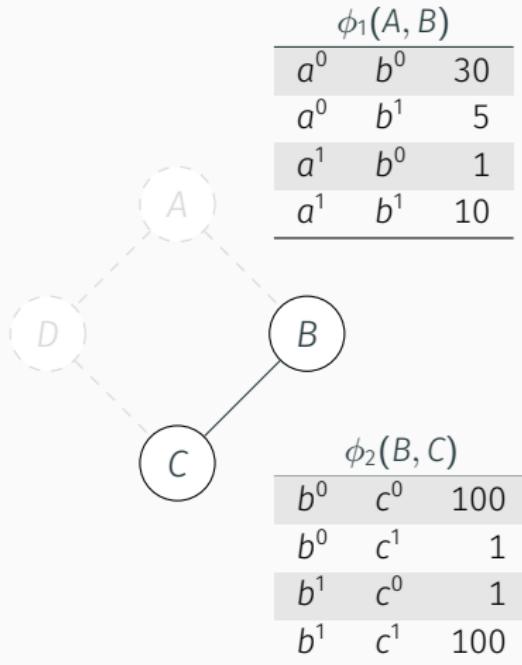
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$\phi_1(A, B)$		
$a^0$	$b^0$	30
$a^0$	$b^1$	5
$a^1$	$b^0$	1
$a^1$	$b^1$	10



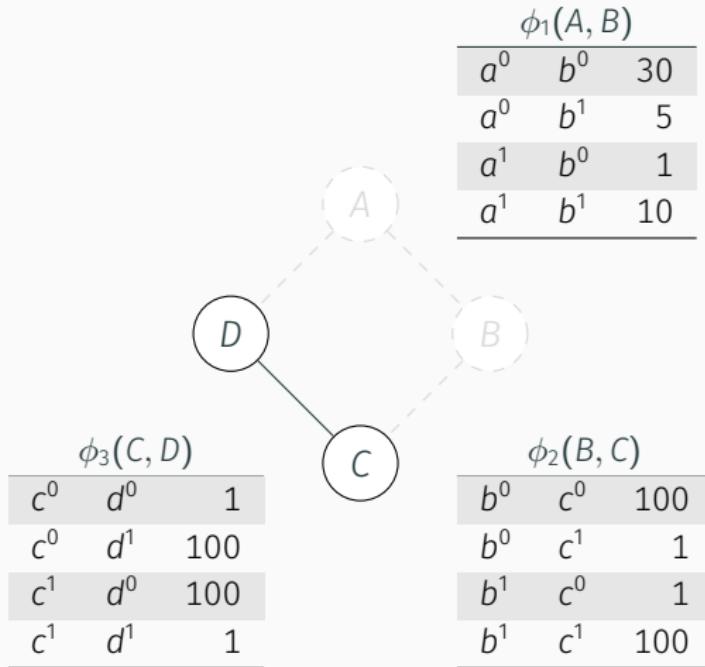
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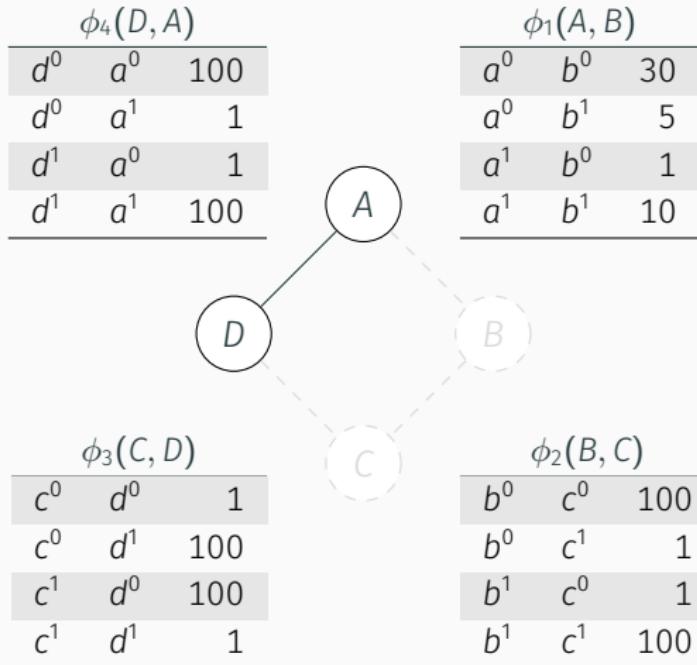
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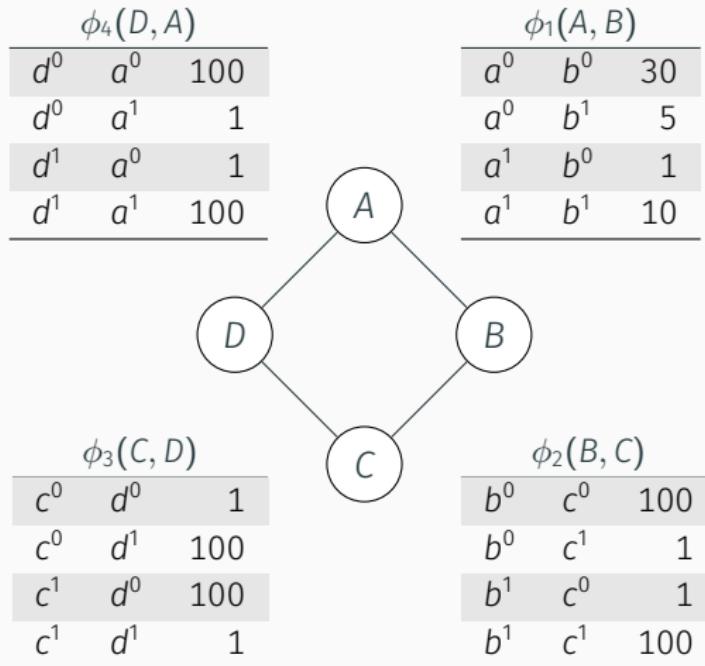


Figure 2: Factors for the *Misconception* example

A factor  $\phi$  is a function from the joint outcome space of a set  $D$  of rvs, which we call the factor's *scope*, to  $\mathbb{R}_{\geq 0}$ . Factors represent affinity amongst interacting variables.

---

Think of a factor  $\phi$  as something like a python function with named arguments, the order of the arguments doesn't matter because they are 'named' with the names of the rvs in  $\text{Scope}[\phi]$ .

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```

graph TD
    A((A)) --> B((B))
    A --> C((C))
    D((D)) --> C
    C --> B
    C --> D
  
```

$\phi_4(D, A)$		
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

$\phi_1(A, B)$		
$a^0$	$b^0$	30
$a^0$	$b^1$	5
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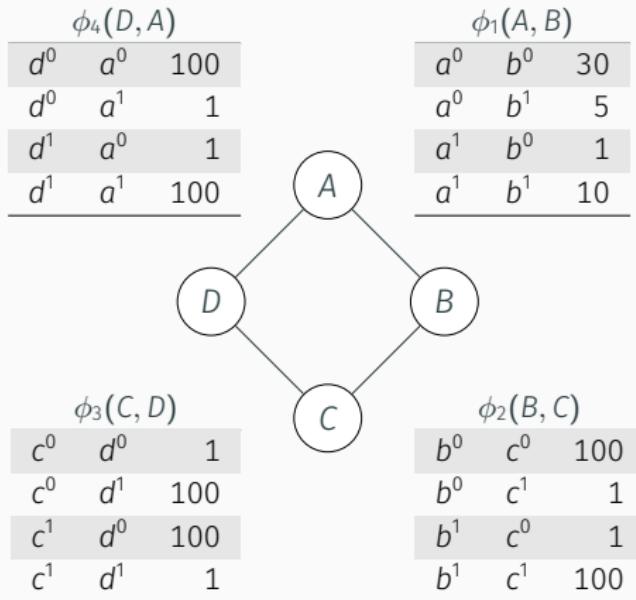
$\phi_3(C, D)$		
$c^0$	$d^0$	1
$c^0$	$d^1$	100
$c^1$	$d^0$	100
$c^1$	$d^1$	1

$\phi_2(B, C)$		
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

- Bob is more strongly inclined to agree with Charles than with Alice.
- Charles and Debbie on the other hand are strongly inclined to disagreement.

Think of a factor  $\phi$  as something like a python function with named arguments, the order of the arguments doesn't matter because they are 'named' with the names of the rvs in  $\text{Scope}[\phi]$ .

# How can we define these joint probabilities?



1.  $P(A = a^0, B = b^0, C = c^0, D = d^0) =$
2.  $P(A = a^1, B = b^0, C = c^0, D = d^1) =$

# A Representation of our Uncertainty over $A, B, C, D$ (section 4.2.1)

A *joint probability distribution* is a means to represent our uncertainty over the possible assignments of the rvs of interest.

The graph shows four nodes: A, B, C, and D. Node A is at the top, connected to both B and D. Nodes B and D are connected to each other, and both are connected to node C at the bottom. This represents the joint distribution  $\phi_4(D, A) \times \phi_1(A, B) \times \phi_3(C, D) \times \phi_2(B, C)$ .

$\phi_4(D, A)$		
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

$\phi_1(A, B)$		
$a^0$	$b^0$	30
$a^0$	$b^1$	5
$a^1$	$b^0$	1
$a^1$	$b^1$	10

$\phi_3(C, D)$		
$c^0$	$d^0$	1
$c^0$	$d^1$	100
$c^1$	$d^0$	100
$c^1$	$d^1$	1

$\phi_2(B, C)$		
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

With its undirected graph and factors, an MN identifies one such distribution.

The probability of any one of the possible outcomes of  $(A, B, C, D)$  in Misconception is proportional to  $\phi_1(A, B) \times \phi_2(B, C) \times \phi_3(C, D) \times \phi_4(D, A)$ .

# Joint Distribution for the Misconception Example

(fig 4.2)

In an MN, we define a distribution by taking the **product of the local factors** and then **normalising it** to define a valid joint distribution:

$A$	$B$	$C$	$D$	Unnormalised product of factors	$P(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000	0.04
$a^0$	$b^0$	$c^0$	$d^1$	300 000	0.04
$a^0$	$b^0$	$c^1$	$d^0$	300 000	0.04
$a^0$	$b^0$	$c^1$	$d^1$	30	$4.1 \times 10^{-6}$
$a^0$	$b^1$	$c^0$	$d^0$	500	$6.9 \times 10^{-5}$
$a^0$	$b^1$	$c^0$	$d^1$	500	$6.9 \times 10^{-5}$
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000	0.69
$a^0$	$b^1$	$c^1$	$d^1$	500	$6.9 \times 10^{-5}$
$a^1$	$b^0$	$c^0$	$d^0$	100	$1.4 \times 10^{-5}$
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000	0.14
$a^1$	$b^0$	$c^1$	$d^0$	100	$1.4 \times 10^{-5}$
$a^1$	$b^0$	$c^1$	$d^1$	100	$1.4 \times 10^{-5}$
$a^1$	$b^1$	$c^0$	$d^0$	10	$1.4 \times 10^{-6}$
$a^1$	$b^1$	$c^0$	$d^1$	100 000	0.014
$a^1$	$b^1$	$c^1$	$d^0$	100 000	0.014
$a^1$	$b^1$	$c^1$	$d^1$	100 000	0.014
Sum				7 201 840	1.0

Table 1: Joint Distribution over  $\text{Val}(A) \times \text{Val}(B) \times \text{Val}(C) \times \text{Val}(D)$

# Compactness

The BN indeed *identifies* the joint distribution, but not by independently representing one probability value per joint outcome.

The probability value of any one of the joint outcomes is expressed via a product of local factors for directly interacting variables.

Bayesian Network structure:

```
graph TD; A((A)) --- B((B)); A --- D((D)); B --- C((C)); D --- C;
```

$\phi_4(D, A)$		
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

$\phi_1(A, B)$		
$a^0$	$b^0$	30
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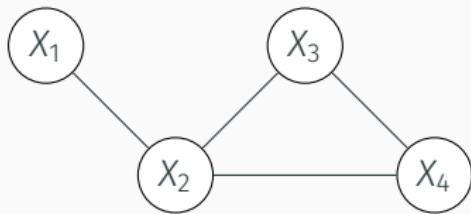
$\phi_3(C, D)$		
$c^0$	$d^0$	1
$c^0$	$d^1$	100
$c^1$	$d^0$	100
$c^1$	$d^1$	1

$\phi_2(B, C)$		
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

If each of  $N$  rvs takes on one of  $K$  values, we infer all  $K^N$  joint probabilities from the affinities of  $N$   $K$ -by- $K$ -dimensional factors.

While in this example ( $K=2, N=4$ ),  $K^N$  happens to be equal to  $NK^2$ , for larger  $K$  and  $N$  the MN is very compact.

The notion of *directly interacting variables* corresponds to what is known as **complete subgraphs**. The factors in the MN, by definition, have complete subgraphs as their scope.

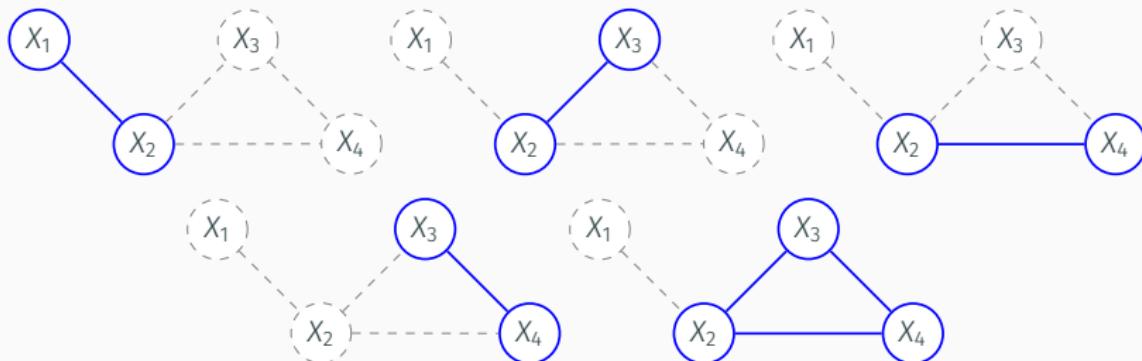


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Some PGM jargon: we say that a factor ‘covers’ the rvs in its scope, and we also say that a factor ‘covers’ the edges that connect any two rvs in its scope.

**Definition 2.13.** In a complete subgraph, also known as *clique*, every two nodes are connected by some edge.

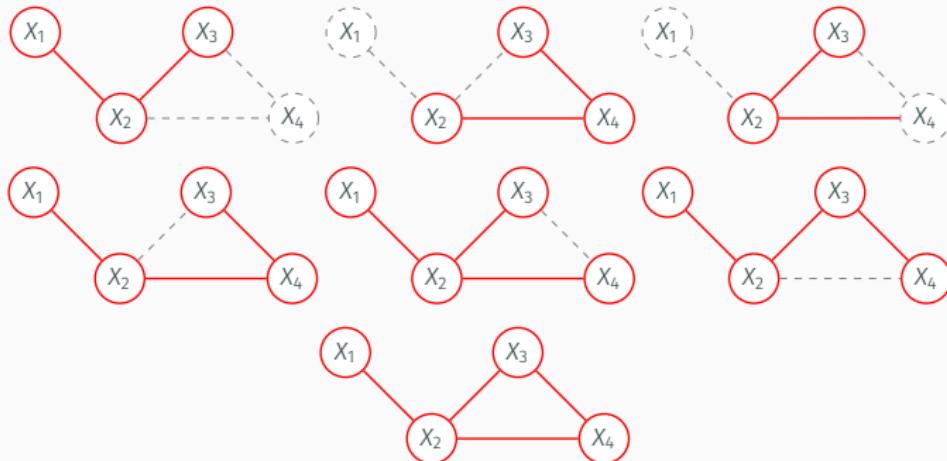
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Some PGM jargon: we say that a factor ‘covers’ the rvs in its scope, and we also say that a factor ‘covers’ the edges that connect any two rvs in its scope.

**Definition 2.13.** In a complete subgraph, also known as *clique*, every two nodes are connected by some edge.

An MN is a graph  $\mathcal{H}$  and a collection  $\Phi$  of factors such that:

- $\mathcal{H}$  is an undirected graph;
- nodes in  $\mathcal{H}$  represent the rvs  $X_1, \dots, X_n$ ;
- the edges in  $\mathcal{H}$  indicate direct interaction between rvs;
- the scope  $D_i$  of a factor  $\phi_i \in \Phi$  is a complete subgraph of  $\mathcal{H}$ ;
- $\Phi$  covers all nodes and all edges in the graph.

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$Z$  is also known as the *partition function* (a term that comes from statistical physics).

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- the scope  $D_i$  of a factor  $\phi_i \in \Phi$  is a complete subgraph of  $\mathcal{H}$ ;
- $\Phi$  covers all nodes and all edges in the graph.

The MN represents a joint distribution by **normalisation** of the **product of factors**  $\Phi$ :

$$P_\Phi(X_1, \dots, X_n) = \frac{1}{Z} \prod_{\phi_i \in \Phi} \phi_i(D_i) \quad (1)$$

where  $\tilde{P}_\Phi(X_1, \dots, X_n) = \prod_{\phi_i \in \Phi} \phi_i(D_i)$  is an unnormalised measure, and  $Z = \sum_{X_1, \dots, X_n} \tilde{P}_\Phi(X_1, \dots, X_n)$  is the constant that normalises it.

---

$Z$  is also known as the *partition function* (a term that comes from statistical physics).

# Graphs and Distributions (1/4)

With its undirected graph  $\mathcal{H}$  and a collection of factors  $\Phi$ , an MN identifies a factorised distribution  $P_\Phi$ .

In the *Misconception* example:

The graph  $\mathcal{H}$  consists of four nodes: A (top), B (right), C (bottom), and D (left). Node A is connected to nodes B and C. Node D is connected to nodes A and C.

$\phi_4(D, A)$		
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

$\phi_1(A, B)$		
$a^0$	$b^0$	30
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$\phi_3(C, D)$		
$c^0$	$d^0$	1
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$\phi_2(B, C)$		
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

$\Phi$	$D_i = \text{Scope}[\phi_i]$
$\phi_1$	$\{A, B\}$
$\phi_2$	$\{B, C\}$
$\phi_3$	$\{C, D\}$
$\phi_4$	$\{D, A\}$

Factors and their scope

$$P_\Phi(A, B, C, D) = \frac{1}{Z} \prod_{\phi_i \in \Phi} \phi_i(D_i) = \frac{1}{Z} \phi_1(A, B) \phi_2(B, C) \phi_3(C, D) \phi_4(D, A)$$

This is similar for BNs, whose DAG and CPDs identify a factorised distribution.

## Graphs and Distributions (2/4)

Since we defined factors as functions whose scopes are complete subgraphs (any two rvs in the scope must be connected by an edge), a collection of factors  $\Phi$  identifies a graph  $\mathcal{H}$  uniquely.

Can you identify the graph in each case?

Misconception	
$\Phi$	$D_i = \text{Scope}[\phi_i]$
$\phi_1$	$\{A, B\}$
$\phi_2$	$\{B, C\}$
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$\phi_4$	$\{D, A\}$

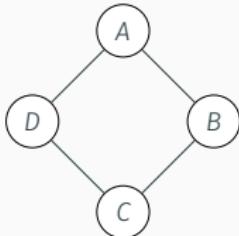
Common Friend	
$\Phi$	$D_i = \text{Scope}[\phi_i]$
$\phi_1$	$\{A, B\}$
$\phi_2$	$\{A, C\}$
$\phi_3$	$\{B, C\}$
$\phi_4$	$\{C, D, E\}$

## Graphs and Distributions (2/4)

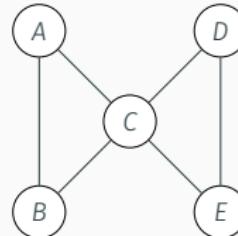
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$\phi_3$	$\{C, D\}$
$\phi_4$	$\{D, A\}$



Common Friend	
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$\phi_1$	$\{A, B\}$
$\phi_2$	$\{A, C\}$
$\phi_3$	$\{B, C\}$
$\phi_4$	$\{C, D, E\}$



## Graphs and Distributions (3/4)

But if we only know the graph  $\mathcal{H}$ , then the factorisation is **not unique**!

Can you tell why?

(Hint: by definition, the scope of factor is a complete subgraph)

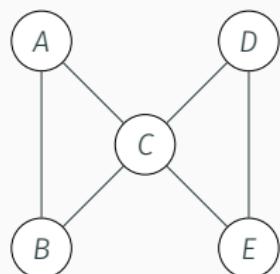
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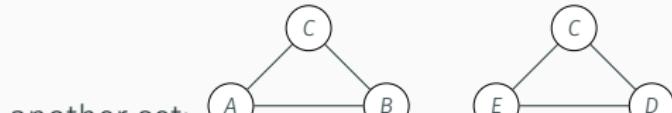
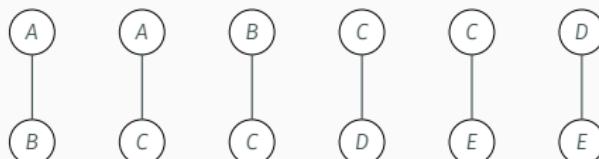
Can you tell why?

(Hint: by definition, the scope of factor is a complete subgraph)

Consider this graph



One set of complete subgraphs for  $A, B, C, D$ :



another set:  
and combinations of these, and others...

There are many sets of complete subgraphs (cliques) that cover all nodes and edges in  $\mathcal{H}$ . Each set corresponds to a factorisation.

## Graphs and Distributions (4/4)

There are differently-factorised distributions that are consistent with  $\mathcal{H}$ .

This is different in BNs, whose DAG implies a unique factorisation.

Then the question to ask is: if  $\mathcal{H}$  does not imply a factorisation, what then do all distributions that are ‘compatible’ with  $\mathcal{H}$  have in common?

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Then the question to ask is: if  $\mathcal{H}$  does not imply a factorisation, what then do all distributions that are ‘compatible’ with  $\mathcal{H}$  have in common?

$\mathcal{H}$  implies a set of conditional independence statements and that is what all distributions that factorise over  $\mathcal{H}$  have in common.

## Summary

- An MN uses an undirected graph  $\mathcal{H}$  to encode statements of (conditional) independence without ascribing directionality to interactions amongst rvs.
- To parameterise the MN, we specify a collection of factors (such as tabular factors) whose scopes are complete subgraphs.
- Unlike we did for BNs, we cannot read a unique factorisation readily from the MN structure.
- But, having a collection of factors, we can identify the graph. With the graph and its factors  $\Phi$ , an MN is a complete representation of a joint distribution  $P_\Phi$ .

## What's Next?

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LC3: MNs in code.

HC3ab: MNs – reasoning and influence.

WC3: exercises (semantics, reasoning and influence).

# Reasoning

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## Outline for this section

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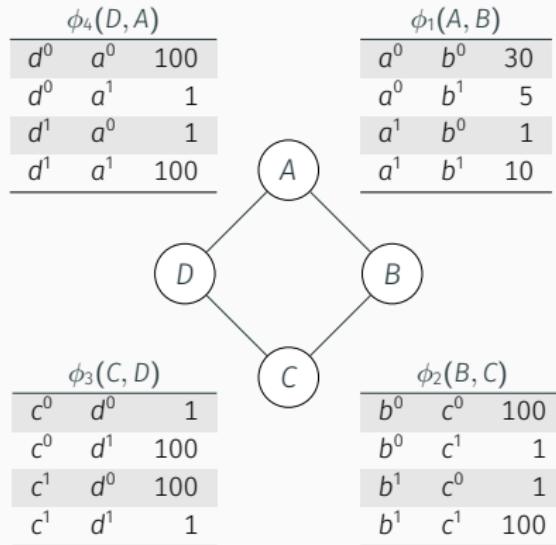
We begin by restating fundamental results of probability theory using general *factors* (as opposed to CPDs).

We then exploit those results and the MN representation to respond to queries about subsets of random variables and sets of observations.

We will start to see a connection between probabilistic inference and manipulation of the MN structure. This connection will be exploited more fully later in the course.

# A Representation of our Uncertainty over $A, B, C, D$

With its undirected graph and factors, an MN identifies a *joint probability distribution* over the rvs of interest.



The probability of any one of the possible outcomes of  $(A, B, C, D)$  in *Misconception is proportional to*  $\phi_1(A, B) \times \phi_2(B, C) \times \phi_3(C, D) \times \phi_4(D, A)$ .

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B)$$

---

These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B) = \sum_B \frac{1}{Z} \tilde{P}(A, B)$$

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These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B) = \sum_B \frac{1}{Z} \tilde{P}(A, B) = \frac{1}{Z} \underbrace{\sum_B \tilde{P}(A, B)}_{\tilde{P}(A)} \quad (2)$$

---

These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B) = \sum_B \frac{1}{Z} \tilde{P}(A, B) = \frac{1}{Z} \underbrace{\sum_B \tilde{P}(A, B)}_{\tilde{P}(A)} \quad (2)$$

## Conditioning

$$P(B|A) = \frac{P(A, B)}{P(A)}$$

---

These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B) = \sum_B \frac{1}{\bar{Z}} \tilde{P}(A, B) = \frac{1}{\bar{Z}} \underbrace{\sum_B \tilde{P}(A, B)}_{\tilde{P}(A)} \quad (2)$$

## Conditioning

$$P(B|A) = \frac{P(A, B)}{P(A)} = \frac{\frac{1}{\bar{Z}} \tilde{P}(A, B)}{\frac{1}{\bar{Z}} \tilde{P}(A)}$$

---

These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

# Probability Calculus

## Marginalisation

$$P(A) = \sum_B P(A, B) = \sum_B \frac{1}{\bar{Z}} \tilde{P}(A, B) = \frac{1}{\bar{Z}} \underbrace{\sum_B \tilde{P}(A, B)}_{\tilde{P}(A)} \quad (2)$$

## Conditioning

$$P(B|A) = \frac{P(A, B)}{P(A)} = \frac{\frac{1}{\bar{Z}} \tilde{P}(A, B)}{\frac{1}{\bar{Z}} \tilde{P}(A)} = \frac{\tilde{P}(A, B)}{\tilde{P}(A)} \quad (3)$$

---

These results extend to the cases where  $A$  and/or  $B$  are sets of rvs.

## Let's compute some marginals for the *Misconception* example

A	B	C	D	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

1.  $P(A = a^0) =$
2.  $P(A = a^0, B = b^0) =$

## Let's compute some marginals for the *Misconception* example

A	B	C	D	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

$$1. P(A = a^0) = \frac{\text{yellow}}{\text{blue}} = \frac{5901530}{7201840} \approx 0.8194$$

$$2. P(A = a^0, B = b^0) =$$

## Let's compute some marginals for the *Misconception* example

A	B	C	D	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

$$1. P(A = a^0) = \frac{\text{yellow}}{\text{blue}} = \frac{5901530}{7201840} \approx 0.8194$$

$$2. P(A = a^0, B = b^0) =$$

# Let's compute some marginals for the *Misconception* example

$A$	$B$	$C$	$D$	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

$$1. P(A = a^0) = \frac{\text{yellow}}{\text{blue}} = \frac{5901530}{7201840} \approx 0.8194$$

$$2. P(A = a^0, B = b^0) = \frac{\text{dark yellow}}{\text{blue}} = \frac{900030}{7201840} \approx 0.1249$$

## Let's compute some conditionals for the *Misconception* example

A	B	C	D	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

$$1. P(B = b^0 | A = a^0) =$$

$$2. P(B = b^1 | A = a^0) =$$

# Let's compute some conditionals for the *Misconception* example

$A$	$B$	$C$	$D$	$\tilde{P}(A, B, C, D)$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
	$b^0$	$c^0$	$d^1$	300 000
	$b^0$	$c^1$	$d^0$	300 000
	$b^0$	$c^1$	$d^1$	30
	$b^1$	$c^0$	$d^0$	500
	$b^1$	$c^0$	$d^1$	500
	$b^1$	$c^1$	$d^0$	5 000 000
	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
	$b^0$	$c^0$	$d^1$	1 000 000
	$b^0$	$c^1$	$d^0$	100
	$b^0$	$c^1$	$d^1$	100
	$b^1$	$c^0$	$d^0$	10
	$b^1$	$c^0$	$d^1$	100 000
	$b^1$	$c^1$	$d^0$	100 000
	$b^1$	$c^1$	$d^1$	100 000
Sum				7 201 840

$$1. P(B = b^0 | A = a^0) = \frac{\text{dark yellow}}{\text{light/dark yellow}} = \frac{900030}{5901530} \approx 0.1525$$

$$2. P(B = b^1 | A = a^0) = \frac{\text{light yellow}}{\text{light/dark yellow}} = \frac{900030}{5901530} \approx 0.8475$$

# Factor Operations

We can also reason using the MN representation, as opposed to the tabular view of the distribution.

For that, we need to learn more about how to manipulate factors:

- factor product
- factor normalisation
- factor reduction
- factor marginalisation

(Chapter 9)

Let  $\phi_1(X, Y)$  and  $\phi_2(Y, Z)$  be two factors.

The **factor product**  $\phi_1(X, Y) \times \phi_2(Y, Z)$  is the factor  $\psi$  defines as:

$$\psi(X, Y, Z) = \phi_1(X, Y) \times \phi_2(Y, Z) \quad (4)$$

The scope of the new factor is

$$\text{Scope}[\psi] = \text{Scope}[\phi_1] \cup \text{Scope}[\phi_2] = \{X, Y, Z\}.$$

This definition extends naturally to the case where  $X, Y, Z$  are replaced by disjoint sets of rvs.

## Factor Product - Example 1/3

A	<u>B</u>	$\phi_1$
$a^0$	$b^0$	30
$a^0$	$b^1$	5
$a^1$	$b^0$	1
$a^1$	$b^1$	10

$\times$

<u>B</u>	C	$\phi_2$
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

---

Dark green ( $b^1$ ), light green ( $b^0$ ).

## Factor Product - Example 1/3

<u>A</u>	<u>B</u>	$\phi_1$
$a^0$	$b^0$	30
$a^0$	$b^1$	5
$a^1$	$b^0$	1
$a^1$	$b^1$	10

<u>B</u>	<u>C</u>	$\phi_2$
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

$\times$

<u>A</u>	<u>B</u>	<u>C</u>	$\psi_{A,B,C}$
$a^0$	$b^0$	$c^0$	3000
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^0$	5
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^0$	100
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^0$	10
$a^1$	$b^1$	$c^1$	1000

---

Dark green ( $b^1$ ), light green ( $b^0$ ).

## Factor Product - Example 2/3

$C$	$D$	$\phi_3$
$c^0$	$d^0$	1
$c^0$	$d^1$	100
$c^1$	$d^0$	100
$c^1$	$d^1$	1

$\times$

$D$	$A$	$\phi_4$
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

---

Dark red ( $d^1$ ), light red ( $d^0$ ).

## Factor Product - Example 2/3

<u>C</u>	<u>D</u>	$\phi_3$
$c^0$	$d^0$	1
$c^0$	$d^1$	100
$c^1$	$d^0$	100
$c^1$	$d^1$	1

<u>D</u>	A	$\phi_4$
$d^0$	$a^0$	100
$d^0$	$a^1$	1
$d^1$	$a^0$	1
$d^1$	$a^1$	100

$\times$

<u>C</u>	<u>D</u>	A	$\psi_{C,D,A}$
$c^0$	$d^0$	$a^0$	100
$c^0$	$d^0$	$a^1$	1
$c^0$	$d^1$	$a^0$	100
$c^0$	$d^1$	$a^1$	10000
$c^1$	$d^0$	$a^0$	10000
$c^1$	$d^0$	$a^1$	100
$c^1$	$d^1$	$a^0$	1
$c^1$	$d^1$	$a^1$	100

Dark red ( $d^1$ ), light red ( $d^0$ ).

# Factor Product - Example 3/3

<u>A</u>	B	<u>C</u>	$\psi_{A,B,C}$
$a^0$	$b^0$	$c^0$	3000
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^0$	5
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^0$	100
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^0$	10
$a^1$	$b^1$	$c^1$	1000

×

<u>C</u>	D	<u>A</u>	$\psi_{C,D,A}$
$c^0$	$d^0$	$a^0$	100
$c^0$	$d^0$	$a^1$	1
$c^0$	$d^1$	$a^0$	100
$c^0$	$d^1$	$a^1$	10000
$c^1$	$d^0$	$a^0$	10000
$c^1$	$d^0$	$a^1$	100
$c^1$	$d^1$	$a^0$	1
$c^1$	$d^1$	$a^1$	100

Light yellow ( $a^0, c^0$ ), dark yellow ( $a^0, c^1$ ), light blue ( $a^1, c^0$ ), dark blue ( $a^1, c^1$ ).

# Factor Product - Example 3/3

<u>A</u>	B	<u>C</u>	$\psi_{A,B,C}$
$a^0$	$b^0$	$c^0$	3000
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^0$	5
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^0$	100
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^0$	10
$a^1$	$b^1$	$c^1$	1000

×

<u>C</u>	D	<u>A</u>	$\psi_{C,D,A}$
$c^0$	$d^0$	$a^0$	100
$c^0$	$d^0$	$a^1$	1
$c^0$	$d^1$	$a^0$	100
$c^0$	$d^1$	$a^1$	10000
$c^1$	$d^0$	$a^0$	10000
$c^1$	$d^0$	$a^1$	100
$c^1$	$d^1$	$a^0$	1
$c^1$	$d^1$	$a^1$	100

=

<u>A</u>	B	<u>C</u>	D	$\psi_{A,B,C,D}$
$a^0$	$b^0$	$c^0$	$d^0$	300 000
$a^0$	$b^0$	$c^0$	$d^1$	300 000
$a^0$	$b^0$	$c^1$	$d^0$	300 000
$a^0$	$b^0$	$c^1$	$d^1$	30
$a^0$	$b^1$	$c^0$	$d^0$	500
$a^0$	$b^1$	$c^0$	$d^1$	500
$a^0$	$b^1$	$c^1$	$d^0$	$5 \times 10^6$
$a^0$	$b^1$	$c^1$	$d^1$	500
$a^1$	$b^0$	$c^0$	$d^0$	100
$a^1$	$b^0$	$c^0$	$d^1$	$1 \times 10^6$
$a^1$	$b^0$	$c^1$	$d^0$	100
$a^1$	$b^0$	$c^1$	$d^1$	100
$a^1$	$b^1$	$c^0$	$d^0$	10
$a^1$	$b^1$	$c^0$	$d^1$	100 000
$a^1$	$b^1$	$c^1$	$d^0$	100 000
$a^1$	$b^1$	$c^1$	$d^1$	100 000

Light yellow ( $a^0, c^0$ ), dark yellow ( $a^0, c^1$ ), light blue ( $a^1, c^0$ ), dark blue ( $a^1, c^1$ ).

## Factor Normalisation

Let  $\phi$  be a factor with scope  $X$  and  $Z_\phi = \sum_X \phi(X)$ .

If  $Z_\phi \in \mathbb{R}_{>0}$ , we can obtain the normalised factor  $\eta$ :

$$\eta(X) = \frac{1}{Z_\phi} \phi(X) \tag{5}$$

A normalised factor may parameterise a joint probability distribution over  $X$ .

# Factor Normalisation - Misconception Example

$A$	$B$	$C$	$D$	$\psi_{A,B,C,D} = \tilde{P}_\Phi$	$\eta_{A,B,C,D} = P_\Phi$
$a^0$	$b^0$	$c^0$	$d^0$	300 000	0.04
$a^0$	$b^0$	$c^0$	$d^1$	300 000	0.04
$a^0$	$b^0$	$c^1$	$d^0$	300 000	0.04
$a^0$	$b^0$	$c^1$	$d^1$	30	$4.1 \times 10^{-6}$
$a^0$	$b^1$	$c^0$	$d^0$	500	$6.9 \times 10^{-5}$
$a^0$	$b^1$	$c^0$	$d^1$	500	$6.9 \times 10^{-5}$
$a^0$	$b^1$	$c^1$	$d^0$	5 000 000	0.69
$a^0$	$b^1$	$c^1$	$d^1$	500	$6.9 \times 10^{-5}$
$a^1$	$b^0$	$c^0$	$d^0$	100	$1.4 \times 10^{-5}$
$a^1$	$b^0$	$c^0$	$d^1$	1 000 000	0.14
$a^1$	$b^0$	$c^1$	$d^0$	100	$1.4 \times 10^{-5}$
$a^1$	$b^0$	$c^1$	$d^1$	100	$1.4 \times 10^{-5}$
$a^1$	$b^1$	$c^0$	$d^0$	10	$1.4 \times 10^{-6}$
$a^1$	$b^1$	$c^0$	$d^1$	100 000	0.014
$a^1$	$b^1$	$c^1$	$d^0$	100 000	0.014
$a^1$	$b^1$	$c^1$	$d^1$	100 000	0.014
Sum			7 201 840	1.0	

# Factor Normalisation - Warning

While a normalised factor has the *form* of a joint distribution, not every normalised factor is coherent with a given Markov network!

For example, if we normalise  $\psi_{A,B,C}$  the result ‘looks’ like a distribution over  $A, B, C$ :

A	B	C	$\psi_{A,B,C}$	$\eta_{A,B,C}$
$a^0$	$b^0$	$c^0$	3000	0.6458
$a^0$	$b^0$	$c^1$	30	0.0065
$a^0$	$b^1$	$c^0$	5	0.0011
$a^0$	$b^1$	$c^1$	500	0.1076
$a^1$	$b^0$	$c^0$	100	0.0215
$a^1$	$b^0$	$c^1$	1	0.0002
$a^1$	$b^1$	$c^0$	10	0.0021
$a^1$	$b^1$	$c^1$	1000	0.2152
Sum			4646	1.0

While  $\eta_{A,B,C}$  can parameterise some distribution over  $A$  and  $C$ , it is not the marginal distribution  $P_\Phi(A, C)$  of the Misconception example. Can you tell why?

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While  $\eta_{A,B,C}$  can parameterise some distribution over  $A$  and  $C$ , it **is not** the marginal distribution  $P_\Phi(A, C)$  of the Misconception example.  
Can you tell why?

In the Misconception MN,  $A$  and  $C$  depend on variables ( $D$ ) and factors ( $\phi_3$  and  $\phi_4$ ) not yet accounted for in  $\psi_{A,B,C}$ .

Let  $\phi(X, Y)$  be a factor, and  $Y = y$  an assignment for  $Y \in \text{Scope}[\phi]$ . We define **the reduction of the factor  $\phi$  to the context  $Y = y$** , denoted  $\phi[Y = y]$  and abbreviated to  $\phi[y]$  when unambiguous, to be the factor:

$$\phi[y](x) = \phi(x, y)$$

The scope of the new factor is  $\text{Scope}[\phi] \setminus \{Y\} = \{X\}$ .

This definition extends naturally to the case where  $X$  and or  $Y$  are replaced by disjoint sets of variables.

## Factor Reduction - Example 1/2

B	C	$\phi_2$
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

$c=c^1$

---

Dark pink ( $c^1$ ), light pink ( $c^0$ ).

## Factor Reduction - Example 1/2

B	C	$\phi_2$
$b^0$	$c^0$	100
$b^0$	$c^1$	1
$b^1$	$c^0$	1
$b^1$	$c^1$	100

$\xrightarrow{C=c^1}$

B	C	$\phi_2[c^1]$
$b^0$	$c^1$	1
$b^1$	$c^1$	100

---

Dark pink ( $c^1$ ), light pink ( $c^0$ ).

## Factor Reduction - Example 2/2

Reduced factors are factors, they can take part in factor products:

$$\begin{array}{c} \begin{array}{ccc} A & \underline{B} & \phi_1 \\ \hline a^0 & b^0 & 30 \\ a^0 & b^1 & 5 \\ a^1 & b^0 & 1 \\ a^1 & b^1 & 10 \end{array} & \times & \begin{array}{ccc} \underline{B} & C & \phi_2[c^1] \\ \hline b^0 & c^1 & 1 \\ b^1 & c^1 & 100 \end{array} \end{array}$$

---

Dark green ( $b^1$ ), light green ( $b^0$ ).

## Factor Reduction - Example 2/2

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A	B	$\phi_1$	
$a^0$	$b^0$	30	
$a^0$	$b^1$	5	
$a^1$	$b^0$	1	
$a^1$	$b^1$	10	

$\times$

B	C	$\phi_2[c^1]$	
$b^0$	$c^1$	1	
$b^1$	$c^1$	100	

=

A	B	C	$\psi_{A,B,C}[c^1]$
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^1$	1000

Dark green ( $b^1$ ), light green ( $b^0$ ).

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A	B	$\phi_1$	
$a^0$	$b^0$	30	
$a^0$	$b^1$	5	
$a^1$	$b^0$	1	
$a^1$	$b^1$	10	

$\times$

B	C	$\phi_2[c^1]$	
$b^0$	$c^1$	1	
$b^1$	$c^1$	100	

=

A	B	C	$\psi_{A,B,C}[c^1]$
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^1$	1000

Do you think this is true?

$$(\phi_1(A, B) \times \phi_2(B, C))[c^1] = \phi_1(A, B) \times \phi_2[c^1](B)$$

---

Dark green ( $b^1$ ), light green ( $b^0$ ).

## Factor Reduction - Example 2/2

Reduced factors are factors, they can take part in factor products:

A	B	$\phi_1$	
$a^0$	$b^0$	30	
$a^0$	$b^1$	5	
$a^1$	$b^0$	1	
$a^1$	$b^1$	10	

$\times$

B	C	$\phi_2[c^1]$	
$b^0$	$c^1$	1	
$b^1$	$c^1$	100	

=

A	B	C	$\psi_{A,B,C}[c^1]$
$a^0$	$b^0$	$c^1$	30
$a^0$	$b^1$	$c^1$	500
$a^1$	$b^0$	$c^1$	1
$a^1$	$b^1$	$c^1$	1000

Do you think this is true?

$$(\phi_1(A, B) \times \phi_2(B, C))[c^1] = \phi_1(A, B) \times \phi_2[c^1](B)$$

Yes! And, if we are working with tabular factors, the second option is more efficient since we do not have to create the large table  $\psi_{A,B,C}$ .

---

Dark green ( $b^1$ ), light green ( $b^0$ ).

## Factor Reduction and Conditioning

If we find that Debbie and Bob have the misconception, that is,  $(D = d^1, B = b^1)$ , then we can obtain a factor that is proportional to  $P_\Phi(A, C|B = b^1, D = d^1)$  via:

$$(\phi_1(A, B) \times \phi_2(B, C) \times \phi_3(C, D) \times \phi_4(D, A))[b^1, d^1]$$

which is  $\tilde{P}_\Phi(A, B = b^1, C, D = d^1)$ .

And, of course,  $P_\Phi(A, C|B = b^1, D = d^1) \propto \tilde{P}_\Phi(A, B = b^1, C, D = d^1)$

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If we find that Debbie and Bob have the misconception, that is,  $(D = d^1, B = b^1)$ , then we can obtain a factor that is proportional to  $P_\Phi(A, C|B = b^1, D = d^1)$  via:

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which is  $\tilde{P}_\Phi(A, B = b^1, C, D = d^1)$ .

And, of course,  $P_\Phi(A, C|B = b^1, D = d^1) \propto \tilde{P}_\Phi(A, B = b^1, C, D = d^1)$

Alternatively, we can reduce the factors first:

$$\psi_{b1d1}(A, C) = \phi_1[b^1](A) \times \phi_2[b^1](C) \times \phi_3[d^1](C) \times \phi_4[d^1](A)$$

Then, to obtain the distribution, we simply normalise  $\psi_{b1d1}$ .

## Exercise

Express  $P_{\Phi}(A, C|B = b^1, D = d^1)$  for the Misconception MN.

## Exercise

Express  $P_{\Phi}(A, C|B = b^1, D = d^1)$  for the Misconception MN.

$$\begin{array}{c}
 \begin{array}{c}
 \begin{array}{ccc}
 \hline A & B & \phi_1[b_1] \\
 \hline a^0 & b^1 & 5 \\
 a^1 & b^1 & 10
 \end{array} & \times & \begin{array}{ccc}
 \hline B & C & \phi_2[b^1] \\
 \hline b^1 & c^0 & 1 \\
 b^1 & c^1 & 100
 \end{array} & \times & \begin{array}{ccc}
 \hline C & D & \phi_3[d^1] \\
 \hline c^0 & d^1 & 100 \\
 c^1 & d^1 & 1
 \end{array} & \times & \begin{array}{ccc}
 \hline D & A & \phi_4[d^1] \\
 \hline d^1 & a^0 & 1 \\
 d^1 & a^1 & 100
 \end{array}
 \end{array} \\
 \hline
 \begin{array}{ccccc}
 A & C & \tilde{P}_{\Phi}[b^1, d^1] & P_{\Phi}(A, C|B = b^1, D = d^1) \\
 \hline
 a^0 & c^0 & & \\
 a^0 & c^1 & & \\
 a^1 & c^0 & & \\
 a^1 & c^1 & &
 \end{array}
 \end{array}$$

Sum

## Exercise

Express  $P_{\Phi}(A, C|B = b^1, D = d^1)$  for the Misconception MN.

$A$	$B$	$\phi_1[b_1]$	$\times$	$B$	$C$	$\phi_2[b^1]$	$\times$	$C$	$D$	$\phi_3[d^1]$	$\times$	$D$	$A$	$\phi_4[d^1]$
$a^0$	$b^1$	5	$\times$	$b^1$	$c^0$	1	$\times$	$c^0$	$d^1$	100	$\times$	$d^1$	$a^0$	1
$a^1$	$b^1$	10	$\times$	$b^1$	$c^1$	100	$\times$	$c^1$	$d^1$	1	$\times$	$d^1$	$a^1$	100

$A$	$C$	$\tilde{P}_{\Phi}[b^1, d^1]$	$P_{\Phi}(A, C B = b^1, D = d^1)$
$a^0$	$c^0$	500	0.0025
$a^0$	$c^1$	500	0.0025
$a^1$	$c^0$	100000	0.4975
$a^1$	$c^1$	100000	0.4975
Sum		201000	1.0

## Exercise

Express  $P_{\Phi}(A, C|B = b^1, D = d^1)$  for the Misconception MN.

$A$	$B$	$\phi_1[b_1]$	$\times$	$B$	$C$	$\phi_2[b^1]$	$\times$	$C$	$D$	$\phi_3[d^1]$	$\times$	$D$	$A$	$\phi_4[d^1]$
$a^0$	$b^1$	5	$\times$	$b^1$	$c^0$	1	$\times$	$c^0$	$d^1$	100	$\times$	$d^1$	$a^0$	1
$a^1$	$b^1$	10	$\times$	$b^1$	$c^1$	100	$\times$	$c^1$	$d^1$	1	$\times$	$d^1$	$a^1$	100

$A$	$C$	$\tilde{P}_{\Phi}[b^1, d^1]$	$P_{\Phi}(A, C B = b^1, D = d^1)$
$a^0$	$c^0$	500	0.0025
$a^0$	$c^1$	500	0.0025
$a^1$	$c^0$	100000	0.4975
$a^1$	$c^1$	100000	0.4975
Sum		201000	1.0

Can you now assess the marginal probability  $P(B = b^1, D = d^1)$ ?

## Exercise

Express  $P_\Phi(A, C|B = b^1, D = d^1)$  for the Misconception MN.

$A$	$B$	$\phi_1[b_1]$	$\times$	$B$	$C$	$\phi_2[b^1]$	$\times$	$C$	$D$	$\phi_3[d^1]$	$\times$	$D$	$A$	$\phi_4[d^1]$
$a^0$	$b^1$	5	$\times$	$b^1$	$c^0$	1	$\times$	$c^0$	$d^1$	100	$\times$	$d^1$	$a^0$	1
$a^1$	$b^1$	10	$\times$	$b^1$	$c^1$	100	$\times$	$c^1$	$d^1$	1	$\times$	$d^1$	$a^1$	100

$A$	$C$	$\tilde{P}_\Phi[b^1, d^1]$	$P_\Phi(A, C B = b^1, D = d^1)$
$a^0$	$c^0$	500	0.0025
$a^0$	$c^1$	500	0.0025
$a^1$	$c^0$	100000	0.4975
$a^1$	$c^1$	100000	0.4975
Sum		201000	1.0

Can you now assess the marginal probability  $P(B = b^1, D = d^1)$ ? It is  $\frac{201000}{Z}$ , we still need the normaliser  $Z$  of the the complete  $\tilde{P}_\Phi$ .

## Summary

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- An MN identifies a joint distribution, hence it is possible to reason marginally or conditionally.
- We can perform marginalisation and conditioning using the unnormalised measure.
- We can use factor product, reduction and normalisation to condition more efficiently.
- Later in the course we will develop a general graph-based algorithm that can lead to more efficient inference (both conditioning and marginalisation).

# What Next?

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We will turn to influence and independence.

## References

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- [1] Daphne Koller and Nir Friedman. *Probabilistic graphical models: principles and techniques*. MIT press, 2009.