

Main approaches to determine posterior distributions in graphical models:

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- Stochastic simulation: random cases are generated according to the probability distributions.
- Variational methods: find the closest tractable distribution to the (posterior) distribution we are interested in.
- Bounding approaches: bound the conditional probabilities above and below and iteratively reduce the bounds.
- ...

- A **factor** is a representation of a function from a tuple of random variables into a number.
- We write factor  $f$  on variables  $X_1, \dots, X_j$  as  $f(X_1, \dots, X_j)$ .

- A **factor** is a representation of a function from a tuple of random variables into a number.
- We write factor  $f$  on variables  $X_1, \dots, X_j$  as  $f(X_1, \dots, X_j)$ .
- We can assign some or all of the variables of a factor:
  - ▶  $f(X_1 = v_1, X_2, \dots, X_j)$ , where  $v_1 \in \text{dom}(X_1)$ , is a factor on  $X_2, \dots, X_j$ .
  - ▶  $f(X_1 = v_1, X_2 = v_2, \dots, X_j = v_j)$  is a number that is the value of  $f$  when each  $X_i$  has value  $v_i$ .

The former is also written as  $f(X_1, X_2, \dots, X_j)_{X_1 = v_1}$ , etc.

# Example factors

$r(X, Y, Z)$ :

| X | Y | Z | val |
|---|---|---|-----|
| t | t | t | 0.1 |
| t | t | f | 0.9 |
| t | f | t | 0.2 |
| t | f | f | 0.8 |
| f | t | t | 0.4 |
| f | t | f | 0.6 |
| f | f | t | 0.3 |
| f | f | f | 0.7 |

$r(X=t, Y, Z)$ :

| Y | Z | val |
|---|---|-----|
| t | t | 0.1 |
| t | f |     |
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| X | Y | Z | val |
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| t | t | t | 0.1 |
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| t | f | f | 0.8 |
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| f | t | f | 0.6 |
| f | f | t | 0.3 |
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| Y | Z | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$r(X=t, Y, Z=f)$ :

| Y | val |
|---|-----|
| t | 0.9 |
| f | 0.8 |

$r(X=t, Y=f, Z=f) = 0.8$

The **product** of factor  $f_1(\overline{X}, \overline{Y})$  and  $f_2(\overline{Y}, \overline{Z})$ , where  $\overline{Y}$  are the variables in common, is the factor  $(f_1 * f_2)(\overline{X}, \overline{Y}, \overline{Z})$  defined by:

$$(f_1 * f_2)(\overline{X}, \overline{Y}, \overline{Z}) = f_1(\overline{X}, \overline{Y})f_2(\overline{Y}, \overline{Z}).$$

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f |      |
| t | f | t |      |
| t | f | f |      |
| f | t | t |      |
| f | t | f |      |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t |      |
| t | f | f |      |
| f | t | t |      |
| f | t | f |      |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f |      |
| f | t | t |      |
| f | t | f |      |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t |      |
| f | t | f |      |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

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| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f |      |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t |      |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

| B | C | val |
|---|---|-----|
| t | t | 0.3 |
| t | f | 0.7 |
| f | t | 0.6 |
| f | f | 0.4 |

$f_1 * f_2$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f |      |

# Multiplying factors example

$f_1$ :

| A | B | val |
|---|---|-----|
| t | t | 0.1 |
| t | f | 0.9 |
| f | t | 0.2 |
| f | f | 0.8 |

$f_2$ :

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|---|---|---|------|
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| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f | 0.32 |

## Summing out variables

We can **sum out** a variable, say  $X_1$  with range  $\{v_1, \dots, v_k\}$ , from factor  $f(X_1, \dots, X_j)$ , resulting in a factor on  $X_2, \dots, X_j$  defined by:

$$\begin{aligned} & \left( \sum_{X_1} f \right) (X_2, \dots, X_j) \\ &= f(X_1 = v_1, \dots, X_j) + \dots + f(X_1 = v_k, \dots, X_j) \end{aligned}$$

# Summing out a variable example

$f_3$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f | 0.32 |

$\sum_B f_3$ :

| A | C | val  |
|---|---|------|
| t | t | 0.57 |
| t | f |      |
| f | t |      |
| f | f |      |

# Summing out a variable example

$f_3$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f | 0.32 |

$\sum_B f_3$ :

| A | C | val  |
|---|---|------|
| t | t | 0.57 |
| t | f | 0.43 |
| f | t |      |
| f | f |      |

# Summing out a variable example

$f_3$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f | 0.32 |

$\sum_B f_3$ :

| A | C | val  |
|---|---|------|
| t | t | 0.57 |
| t | f | 0.43 |
| f | t | 0.54 |
| f | f |      |

# Summing out a variable example

$f_3$ :

| A | B | C | val  |
|---|---|---|------|
| t | t | t | 0.03 |
| t | t | f | 0.07 |
| t | f | t | 0.54 |
| t | f | f | 0.36 |
| f | t | t | 0.06 |
| f | t | f | 0.14 |
| f | f | t | 0.48 |
| f | f | f | 0.32 |

$\sum_B f_3$ :

| A | C | val  |
|---|---|------|
| t | t | 0.57 |
| t | f | 0.43 |
| f | t | 0.54 |
| f | f | 0.46 |

# Exercise

Given factors:

s:

| A | val  |
|---|------|
| t | 0.75 |
| f | 0.25 |

t:

| A | B | val |
|---|---|-----|
| t | t | 0.6 |
| t | f | 0.4 |
| f | t | 0.2 |
| f | f | 0.8 |

o:

| A | val |
|---|-----|
| t | 0.3 |
| f | 0.1 |

What are the following factors over?

- (a)  $s * t$
- (b)  $\sum_A s * t$
- (c)  $\sum_B s * t$
- (d)  $\sum_A \sum_B s * t$
- (e)  $s * t * o$
- (f)  $\sum_B s * t * o$

- If we want to compute the posterior probability of  $Z$  given evidence  $Y_1 = v_1 \wedge \dots \wedge Y_j = v_j$ :

$$P(Z | Y_1 = v_1, \dots, Y_j = v_j)$$

=

- If we want to compute the posterior probability of  $Z$  given evidence  $Y_1 = v_1 \wedge \dots \wedge Y_j = v_j$ :

$$\begin{aligned} &P(Z|Y_1 = v_1, \dots, Y_j = v_j) \\ &= \frac{P(Z, Y_1 = v_1, \dots, Y_j = v_j)}{P(Y_1 = v_1, \dots, Y_j = v_j)} \\ &= \end{aligned}$$

- If we want to compute the posterior probability of  $Z$  given evidence  $Y_1 = v_1 \wedge \dots \wedge Y_j = v_j$ :

$$\begin{aligned} P(Z|Y_1 = v_1, \dots, Y_j = v_j) \\ &= \frac{P(Z, Y_1 = v_1, \dots, Y_j = v_j)}{P(Y_1 = v_1, \dots, Y_j = v_j)} \\ &= \frac{P(Z, Y_1 = v_1, \dots, Y_j = v_j)}{\sum_Z P(Z, Y_1 = v_1, \dots, Y_j = v_j)}. \end{aligned}$$

- So the computation reduces to the probability of  $P(Z, Y_1 = v_1, \dots, Y_j = v_j)$ .
- Normalize at the end, by summing out  $Z$  and dividing.

# Probability of a conjunction

Suppose the variables of the belief network are  $X_1, \dots, X_n$ .  
To compute  $P(Z, Y_1 = v_1, \dots, Y_j = v_j)$ , we sum out the other variables,  $Z_1, \dots, Z_k = \{X_1, \dots, X_n\} - \{Z\} - \{Y_1, \dots, Y_j\}$ .  
We order the  $Z_i$  into an **elimination ordering**.

$$P(Z, Y_1 = v_1, \dots, Y_j = v_j)$$

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We order the  $Z_i$  into an **elimination ordering**.

$$\begin{aligned} & P(Z, Y_1 = v_1, \dots, Y_j = v_j) \\ &= \sum_{Z_k} \cdots \sum_{Z_1} P(X_1, \dots, X_n)_{Y_1 = v_1, \dots, Y_j = v_j} \\ &= \end{aligned}$$

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To compute  $P(Z, Y_1 = v_1, \dots, Y_j = v_j)$ , we sum out the other variables,  $Z_1, \dots, Z_k = \{X_1, \dots, X_n\} - \{Z\} - \{Y_1, \dots, Y_j\}$ .  
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$$\begin{aligned} &P(Z, Y_1 = v_1, \dots, Y_j = v_j) \\ &= \sum_{Z_k} \cdots \sum_{Z_1} P(X_1, \dots, X_n)_{Y_1 = v_1, \dots, Y_j = v_j} \\ &= \sum_{Z_k} \cdots \sum_{Z_1} \prod_{i=1}^n P(X_i | \text{parents}(X_i))_{Y_1 = v_1, \dots, Y_j = v_j} \end{aligned}$$

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- How can we compute  $ab + ac$  efficiently?

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Computation in belief networks reduces to computing the sums of products.

- How can we compute  $ab + ac$  efficiently?
- Distribute out the  $a$  giving  $a(b + c)$
- How can we compute  $\sum_{Z_1} \prod_{i=1}^n P(X_i | \text{parents}(X_i))$  efficiently?
- Distribute out those factors that don't involve  $Z_1$ .

# Variable elimination algorithm

To compute  $P(Z|Y_1 = v_1 \wedge \dots \wedge Y_j = v_j)$ :

- Construct a factor for each conditional probability.
- Set the observed variables to their observed values.
- Sum out each of the other variables (the  $\{Z_1, \dots, Z_k\}$ ) according to some elimination ordering.
- Multiply the remaining factors. Normalize by dividing the resulting factor  $f(Z)$  by  $\sum_Z f(Z)$ .

# Summing out a variable

To sum out a variable  $Z_j$  from a product  $f_1, \dots, f_k$  of factors:

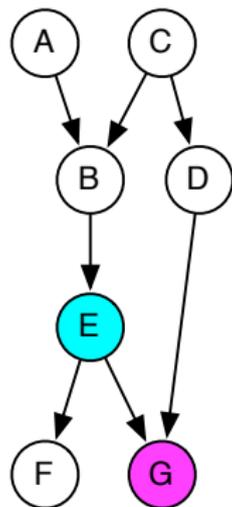
- Partition the factors into
  - ▶ those that don't contain  $Z_j$ , say  $f_1, \dots, f_i$ ,
  - ▶ those that contain  $Z_j$ , say  $f_{i+1}, \dots, f_k$

We know:

$$\sum_{Z_j} f_1 * \dots * f_k = f_1 * \dots * f_i * \left( \sum_{Z_j} f_{i+1} * \dots * f_k \right).$$

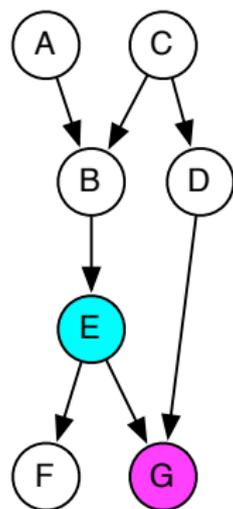
- Explicitly construct a representation of the rightmost factor. Replace the factors  $f_{i+1}, \dots, f_k$  by the new factor.

# Example



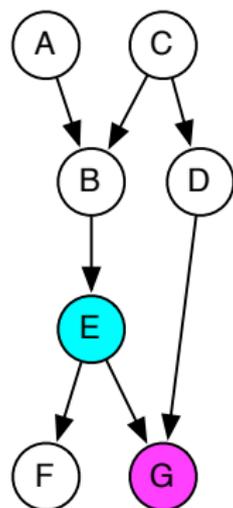
$$P(E \mid g) =$$

# Example



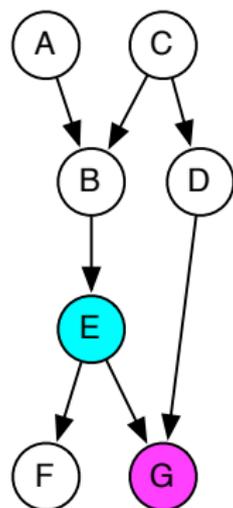
$$P(E | g) = \frac{P(E \wedge g)}{\sum_E P(E \wedge g)}$$

# Example



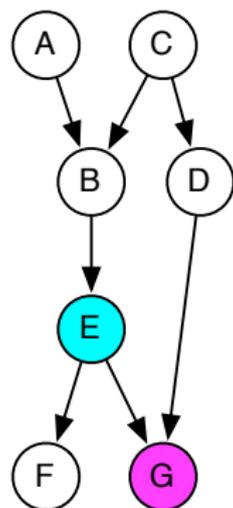
$$\begin{aligned} P(E | g) &= \frac{P(E \wedge g)}{\sum_E P(E \wedge g)} \\ &= \sum_F \sum_B \sum_C \sum_A \sum_D \end{aligned}$$

# Example



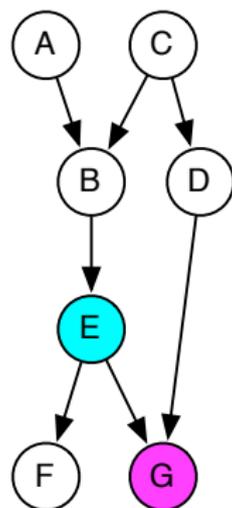
$$\begin{aligned} P(E | g) &= \frac{P(E \wedge g)}{\sum_E P(E \wedge g)} \\ &= \sum_F \sum_B \sum_C \sum_A \sum_D P(A)P(B | AC) \\ &\quad P(C)P(D | C)P(E | B)P(F | E)P(g | ED) \end{aligned}$$

# Example



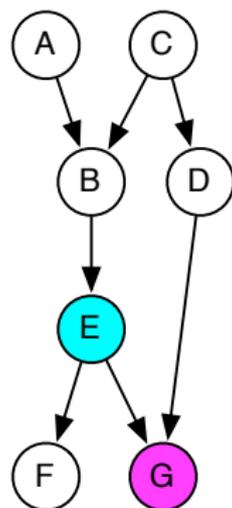
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# Example



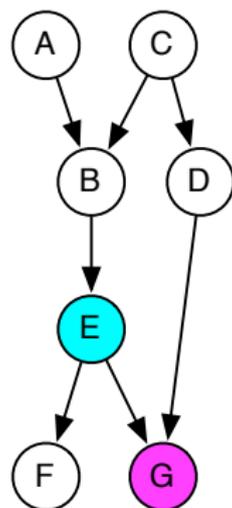
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# Example



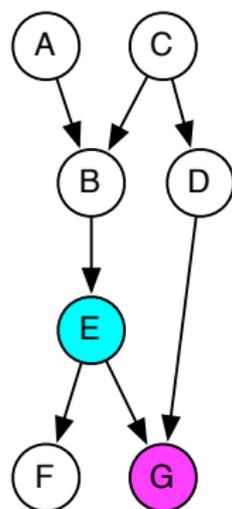
$$\begin{aligned} P(E | g) &= \frac{P(E \wedge g)}{\sum_E P(E \wedge g)} \\ &= \sum_F \sum_B \sum_C \sum_A \sum_D P(A)P(B | AC) \\ &\quad P(C)P(D | C)P(E | B)P(F | E)P(g | ED) \end{aligned}$$

# Example



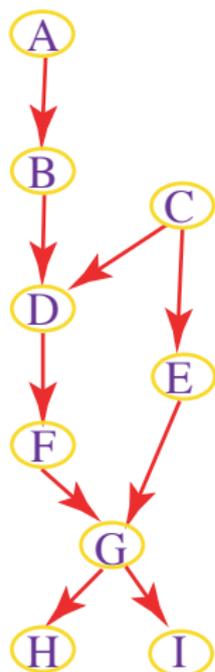
$$\begin{aligned} P(E | g) &= \frac{P(E \wedge g)}{\sum_E P(E \wedge g)} \\ &= \sum_F \sum_B \sum_C \sum_A \sum_D P(A)P(B | AC) \\ &\quad P(C)P(D | C)P(E | B)P(F | E)P(g | ED) \end{aligned}$$

# Example



$$\begin{aligned} P(E | g) &= \frac{P(E \wedge g)}{\sum_E P(E \wedge g)} \\ &= \sum_F \sum_B \sum_C \sum_A \sum_D P(A)P(B | AC) \\ &\quad P(C)P(D | C)P(E | B)P(F | E)P(g | ED) \end{aligned}$$

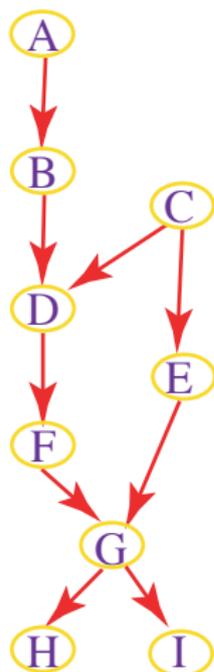
# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A}$$
$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\}$$
$$P(F|D)$$
$$P(G|FE)$$
$$P(H|G) \}$$
$$P(I|G) \}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

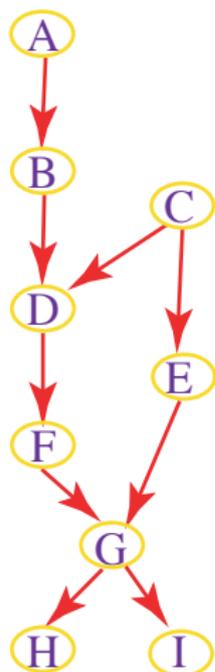
# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$
$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\}$$
$$P(F|D)$$
$$P(G|FE)$$
$$P(H|G) \}$$
$$P(I|G) \}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C}$$

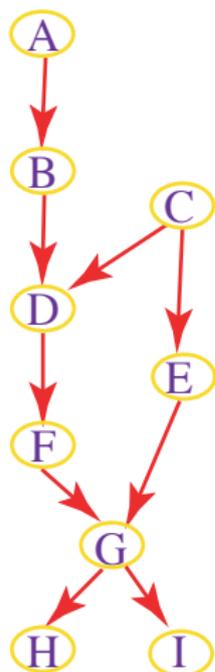
$$P(F|D)$$

$$P(G|FE)$$

$$\left. \begin{array}{l} P(H|G) \\ P(I|G) \end{array} \right\}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C} f_2(BDE)$$

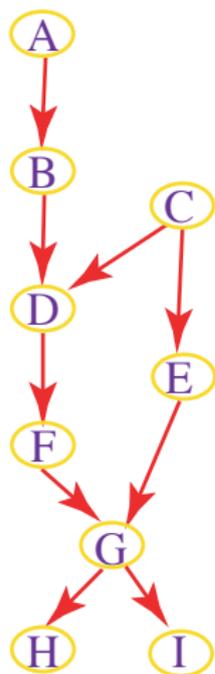
$$P(F|D)$$

$$P(G|FE)$$

$$\left. \begin{array}{l} P(H|G) \\ P(I|G) \end{array} \right\}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C} f_2(BDE)$$

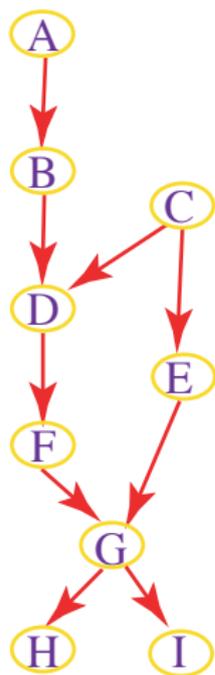
$$P(F|D)$$
$$P(G|FE)$$

$$P(H|G) \} \xrightarrow{\text{obs } H}$$

$$P(I|G) \}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C} f_2(BDE)$$

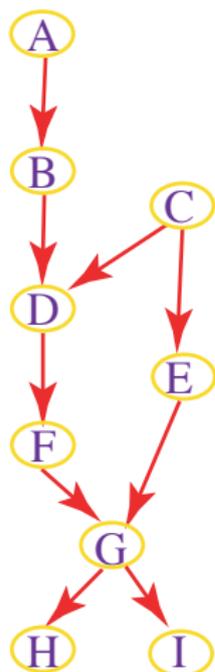
$$\begin{array}{l} P(F|D) \\ P(G|FE) \end{array}$$

$$P(H|G) \} \xrightarrow{\text{obs } H} f_3(G)$$

$$P(I|G) \}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C} f_2(BDE)$$

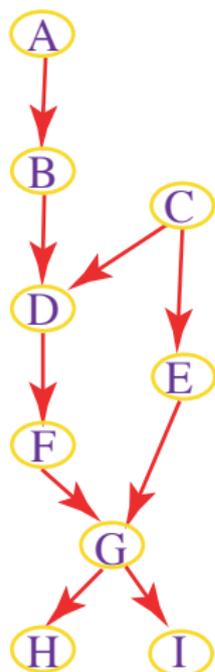
$$P(F|D) \\ P(G|FE)$$

$$P(H|G) \left. \right\} \xrightarrow{\text{obs } H} f_3(G)$$

$$P(I|G) \left. \right\} \xrightarrow{\text{elim } I}$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

# Variable elimination example



$$\left. \begin{array}{l} P(A) \\ P(B|A) \end{array} \right\} \xrightarrow{\text{elim } A} f_1(B)$$

$$\left. \begin{array}{l} P(C) \\ P(D|BC) \\ P(E|C) \end{array} \right\} \xrightarrow{\text{elim } C} f_2(BDE)$$

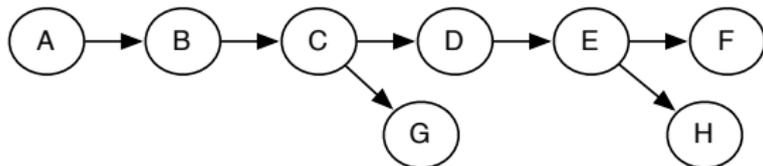
$$\begin{array}{l} P(F|D) \\ P(G|FE) \end{array}$$

$$P(H|G) \} \xrightarrow{\text{obs } H} f_3(G)$$

$$P(I|G) \} \xrightarrow{\text{elim } I} f_4(G)$$

$$P(D, h) = \dots (\sum_A P(A)P(B|A)) (\sum_I P(I|G))$$

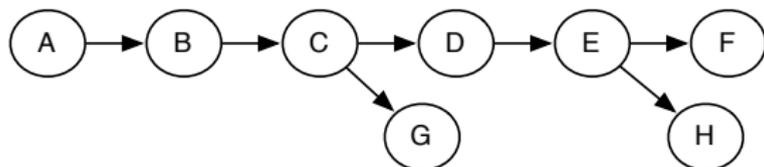
# Variable Elimination example



Query:  $P(G|f)$ ; elimination ordering:  $A, H, E, D, B, C$

$$P(G|f) \propto$$

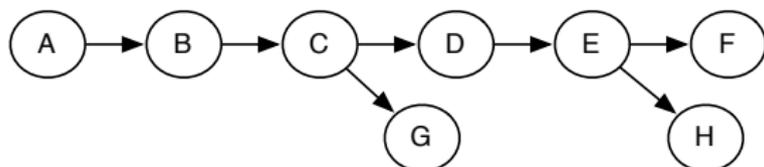
# Variable Elimination example



Query:  $P(G|f)$ ; elimination ordering:  $A, H, E, D, B, C$

$$P(G|f) \propto \sum_C \sum_B \sum_D \sum_E \sum_H \sum_A P(A)P(B|A)P(C|B) \\ P(D|C)P(E|D)P(f|E)P(G|C)P(H|E)$$

# Variable Elimination example



Query:  $P(G|f)$ ; elimination ordering:  $A, H, E, D, B, C$

$$P(G|f) \propto \sum_C \sum_B \sum_D \sum_E \sum_H \sum_A P(A)P(B|A)P(C|B) \\ P(D|C)P(E|D)P(f|E)P(G|C)P(H|E)$$

$$= \sum_C \left( \sum_B \left( \sum_A P(A)P(B|A) \right) P(C|B) \right) P(G|C) \\ \left( \sum_D P(D|C) \left( \sum_E P(E|D)P(f|E) \sum_H P(H|E) \right) \right)$$

# Pruning Irrelevant Variables (Belief networks)

Suppose you want to compute  $P(X \mid e_1 \dots e_k)$ :

- Prune any variables that have no observed or queried descendants.
- Connect the parents of any observed variable.
- Remove arc directions.
- Remove observed variables.
- Remove any variables not connected to  $X$  in the resulting (undirected) graph.