

Bayesian Networks

Or directed graphical models



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Outline and goals

Module 1 introduces *Bayesian networks* (BNs; Chapter 3).

ILOs After this module the student

- can map BNs to distributions and vice-versa;
- recognises reasoning patterns in BNs;
- recognises the flow of probabilistic influence in BNs;
- recognises independence and directed-separation.

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

Overview of Module 1

HC1: BNs – semantics.

LC1: BNs in code.

HC2: BNs – reasoning and influence.

WC1: exercises (semantics, reasoning and influence).

Table of contents

1. Semantics

2. Reasoning

3. Influence

Semantics

Outline for this section

We will introduce BNs via an example from the textbook (the *Student* example from Section 3.1.3.1).

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

A student scores a passing

Grade (excellent g^1 , good g^2 , or satisfactory g^3)

in a course of a certain

Difficulty level (hard d^1 , or easy d^0)

and obtains a

Letter of recommendation (strong l^1 , or weak l^0)

from the course coordinator.

This kind of information, along with the student's

SAT scores (high s^1 , or low s^0),

is what some company uses to support hiring decisions, with these aspects taken as informative of the candidate's

Intelligence (high i^1 , or low i^0).

- Grade $\text{Val}(G) = \{g^1, g^2, g^3\}$
- Difficulty $\text{Val}(D) = \{d^0, d^1\}$
- Intelligence $\text{Val}(I) = \{i^0, i^1\}$
- SAT $\text{Val}(S) = \{s^0, s^1\}$
- Ref. Letter $\text{Val}(R) = \{l^0, l^1\}$

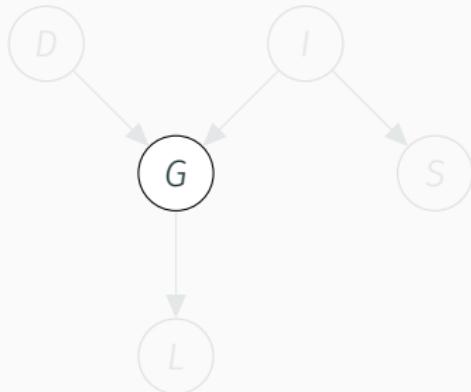


Figure 1: The BN graph for the Student example (Fig 3.3 of textbook).

The BN structure captures our assumptions about the world in terms of: **what variables matter and how they depend on one another.**

The possible outcomes of a random variable X is denoted $\text{Val}(X)$; see section 2.1.3.2 for more.

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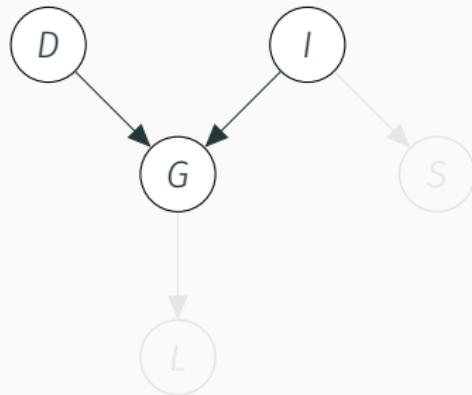


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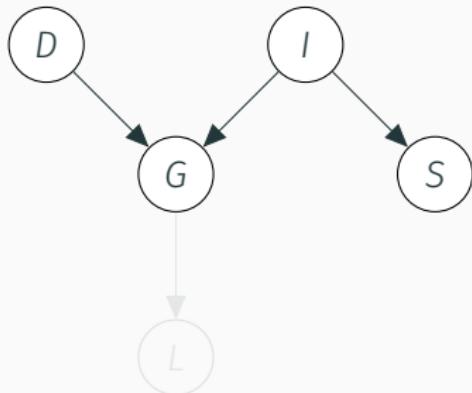


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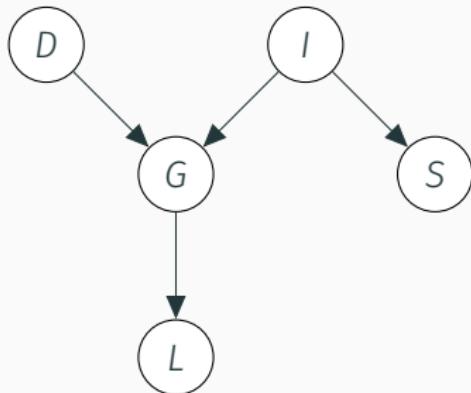


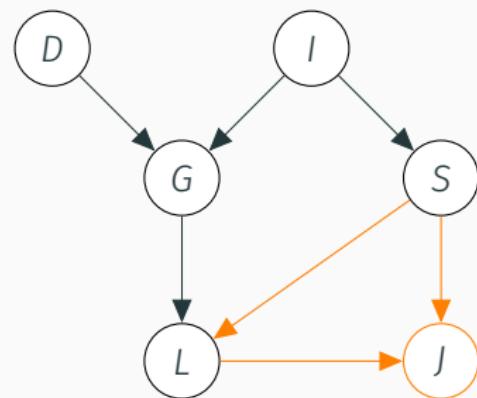
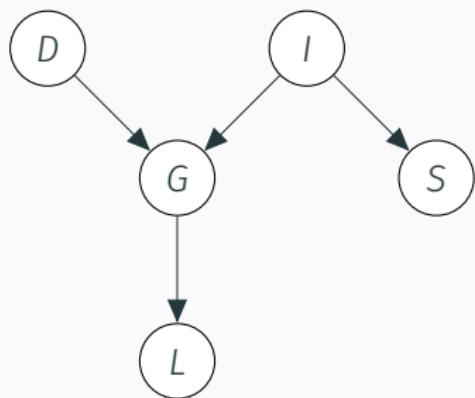
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A model is an assumption about how the world works

We can always motivate different assumptions:



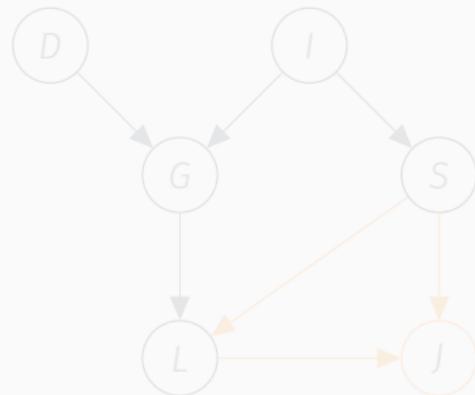
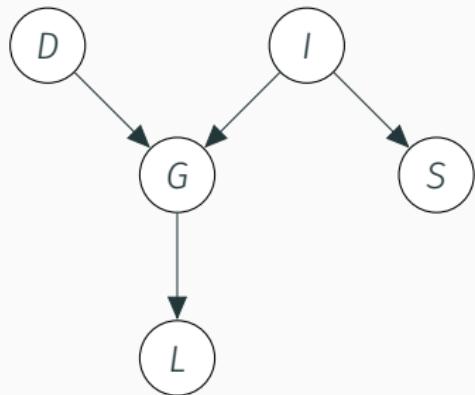
Student example (Fig 3.3 of textbook)

Variant: the Letter is affected by S, and we introduce a new variable (e.g., Job).

We can now prescribe probability models that represent our uncertainty about these rvs, while reflecting interactions in the graph.

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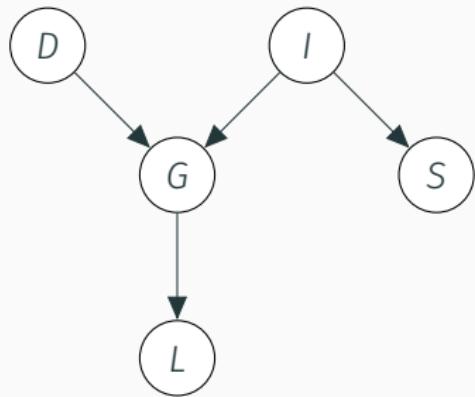
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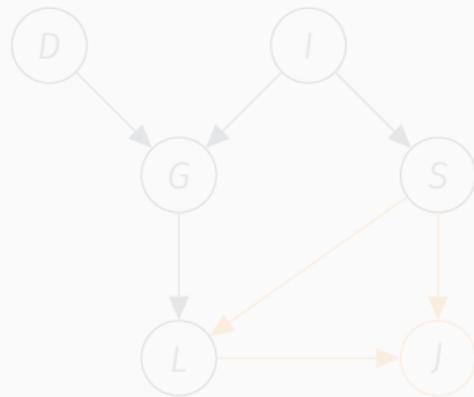
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CPDs for the *Student* example (Fig 3.4 of textbook)

A conditional probability distribution (or CPD) represents our uncertainty about the outcome of a variable in a given context.

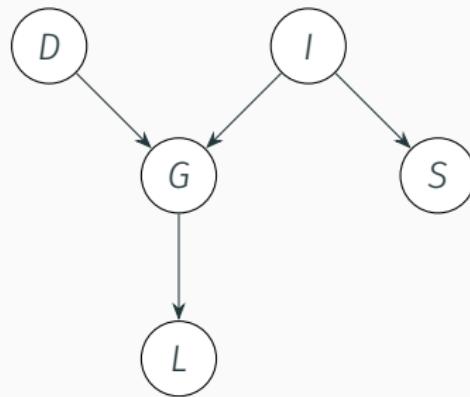


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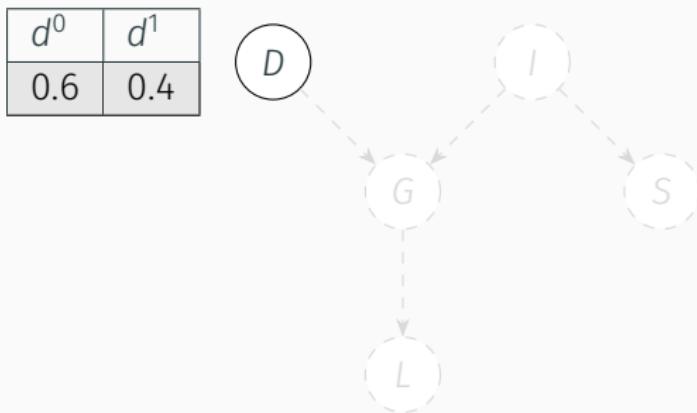


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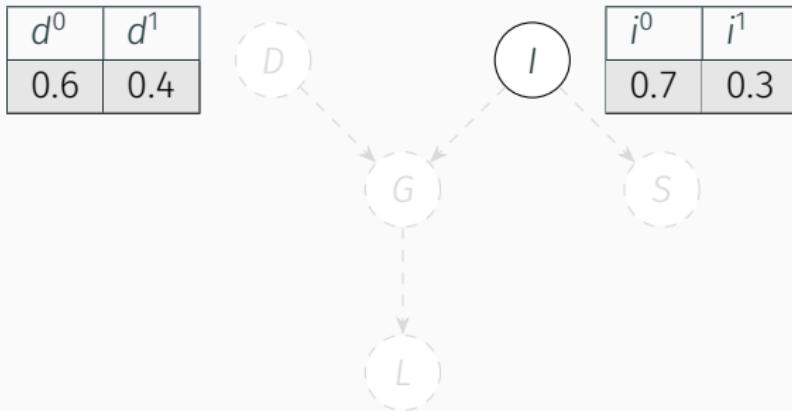


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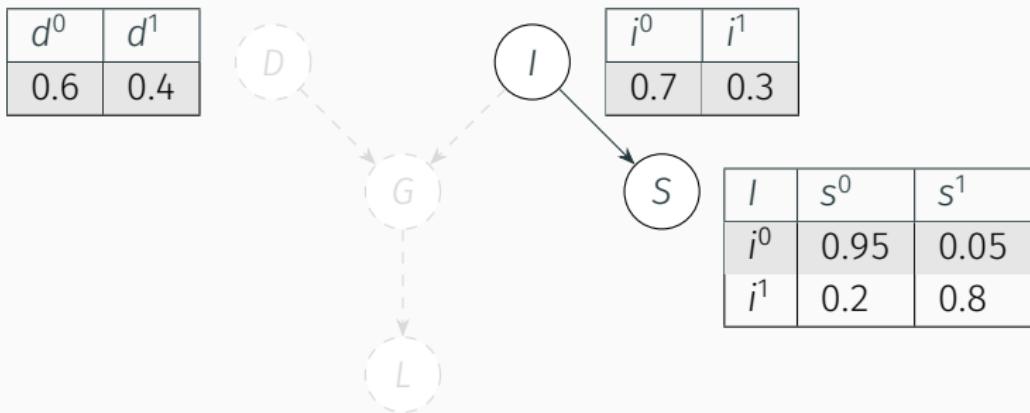


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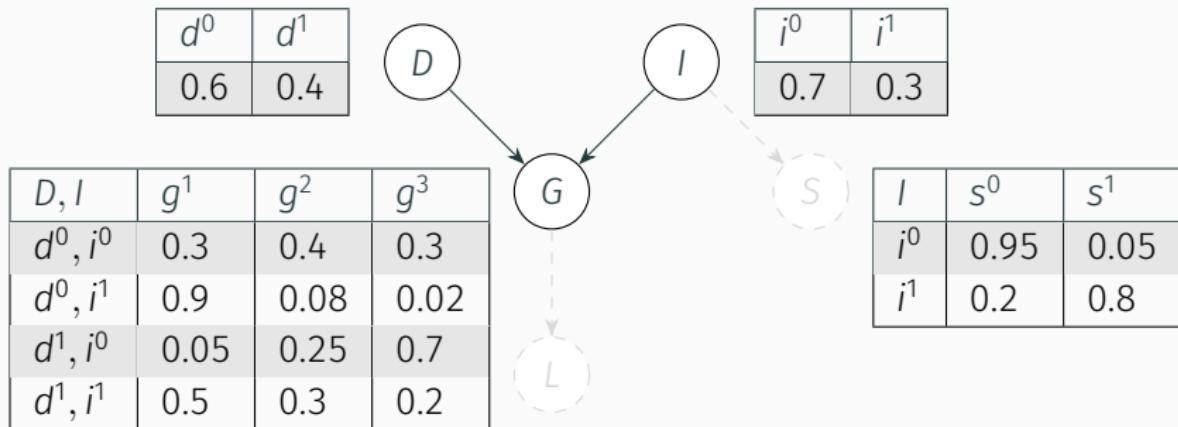


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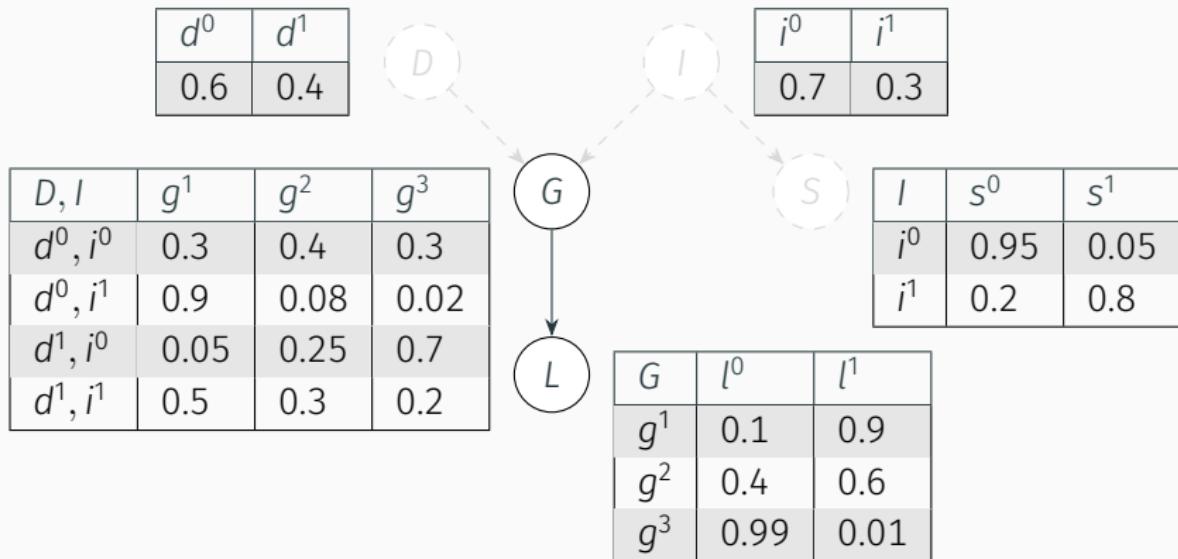


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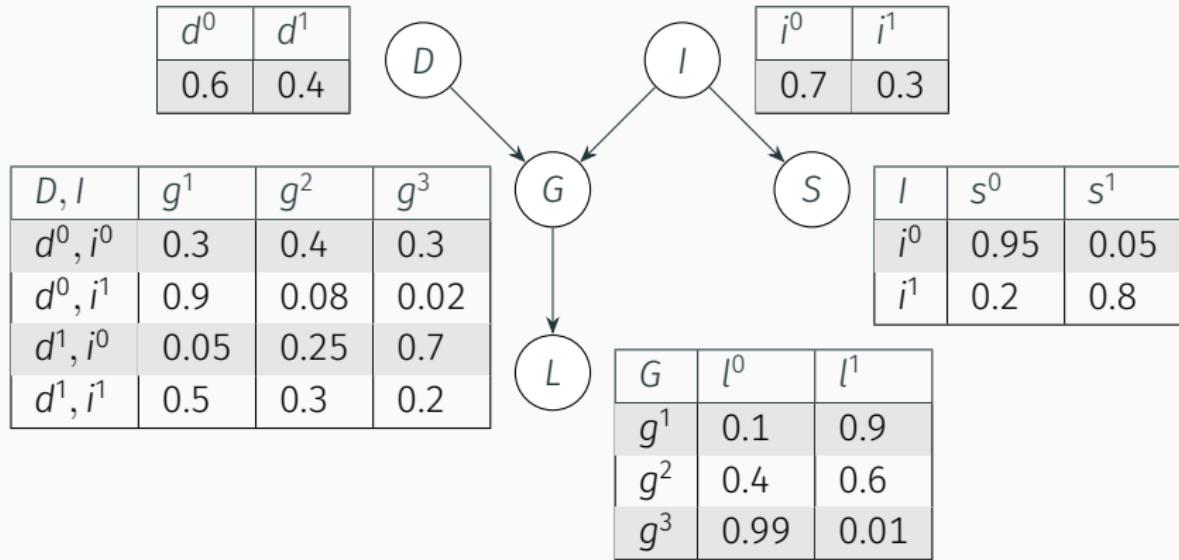
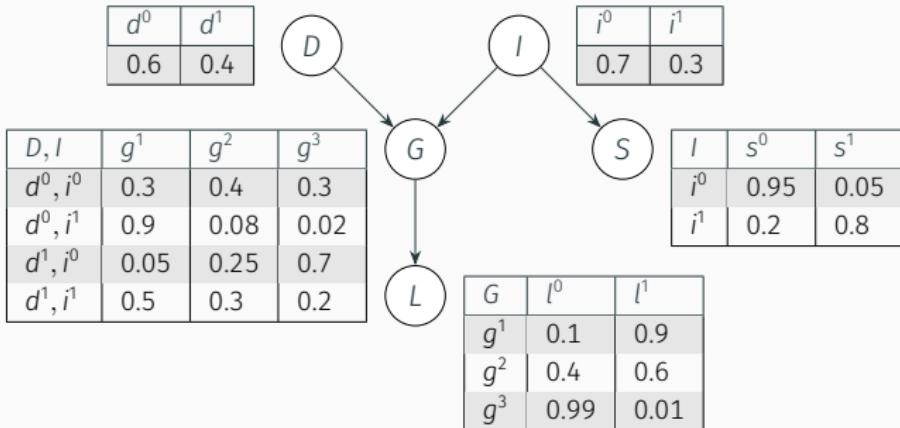


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These are *local prob. models*, prescribed separately for each node.

Can you evaluate these joint probabilities?



CPDs for the *Student* example (Fig 3.4 of textbook)

$$1. P(D = d^1, I = i^1, G = g^2, S = s^1, L = l^1) =$$

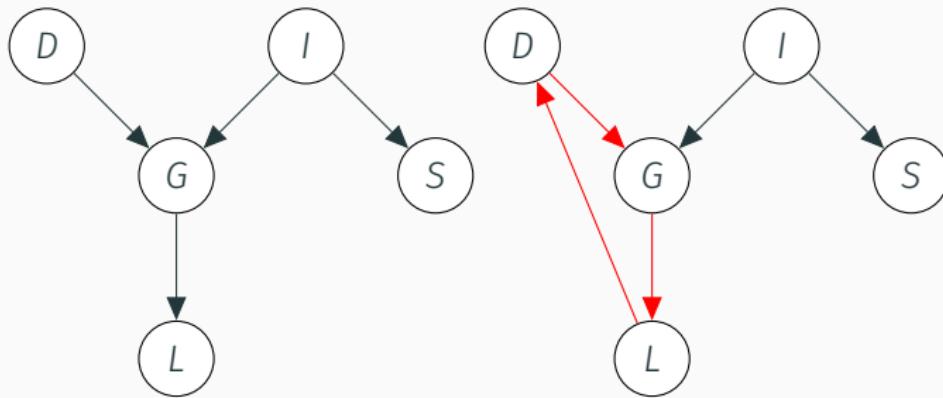
$$2. P(D = d^0, I = i^1, G = g^2, S = s^1, L = l^1) =$$

$$3. P(D = d^0, I = i^1, G = g^3, S = s^1, L = l^1) =$$

BN Structure

A BN is built on a directed acyclic graph (DAG):

- nodes represent random variables (rvs)
- edges represent direct dependence
- there are no **directed cycles**

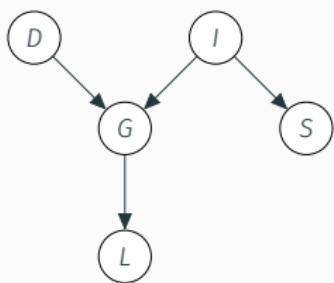


Left: DAG.

Right: Not a DAG.

Semantics of Bayesian networks

A DAG \mathcal{G} represents a collection of *conditional independence* statements. Amongst these, some are readily recognisable from the graph structure: **each rv is conditionally independent of its non-descendants given its parents.**



Student example

| rv | descendants | non-descendants | parents |
|----|-------------|-----------------|---------|
| D | | | |
| I | | | |
| S | | | |
| G | {L} | {D, I, S} | {D, I} |
| L | | | |

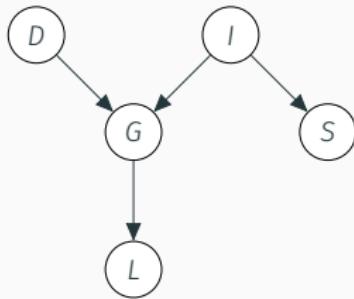
Can you complete the table?

Definition 2.18 of textbook: descendants of X are nodes reachable by paths that begin at X ; non-descendants of X are all nodes except X itself and its descendants; parents of X are non-descendants directly connected to X .

The *local independencies* coded in the BN structure, denoted $\mathcal{I}_l(\mathcal{G})$, is the set of statements of the kind:

For each variable X_i : $X_i \perp \text{NonDesc}_{\mathcal{G}}(X_i) \mid \text{Pa}_{\mathcal{G}}(X_i)$

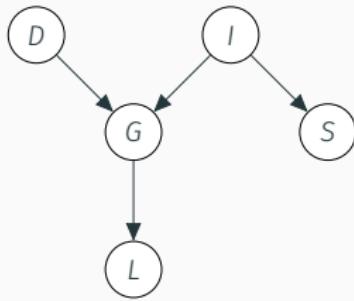
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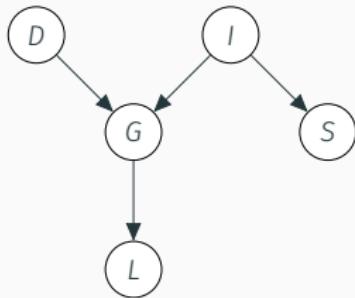


Watch out: it makes little sense to write $G \perp \text{NonDesc}_{\mathcal{G}}(G) \mid \text{Pa}_{\mathcal{G}}(G)$ as G cannot be independent of its parents D, I , the *non-descendants* that we separate (\perp) from G , given the parents, are the non-descendants who are not its parents.

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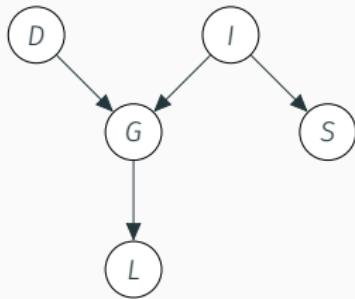
- $D \perp I, S$
- $I \perp D$
- $S \perp D, G, L \mid I$
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Watch out: it makes little sense to write $G \perp \overline{D, I, S} \mid \overline{D, I}$ as G cannot be independent of its parents D, I , the *non-descendants* that we separate (\perp) from G , given the parents, are the non-descendants who are not its parents.

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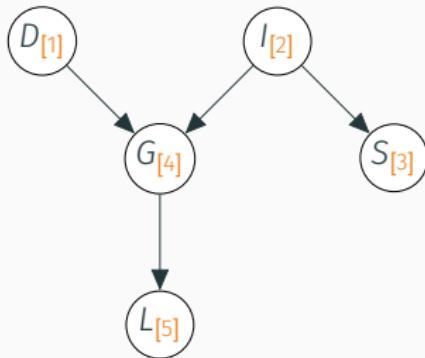
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Now let's try to use this in order to state a joint distribution.

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Topological Ordering (definition 2.19)

Index the nodes such that for any X_i , its parents are in the set $X_{<i} = \{X_j : j < i\}$. By definition then, $X_{<i} \subseteq \text{NonDesc}_{\mathcal{G}}(X_i)$.

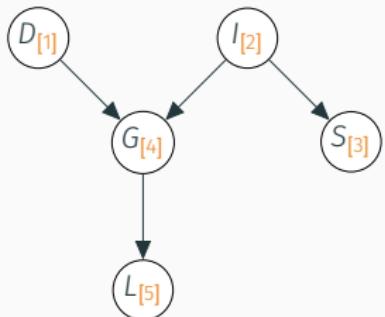


Nodes of the Student example indexed in a topological order

There can be multiple such orders, but all deliver the result $X_{<i} \subseteq \text{NonDesc}_{\mathcal{G}}(X_i)$.
Topological sorting is always possible for DAGs.

Joint probability distribution for the *Student example*

No matter how many rvs and in what order we enumerate them the **chain rule of probability** always holds: $P(X_1, \dots, X_n) = \prod_{i=1}^n P(X_i | X_{<i})$.



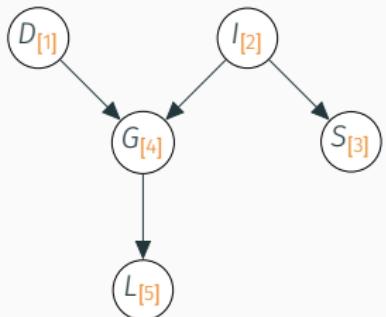
Let's apply chain rule in a topological order:

$$P(D, I, G, S, L) =$$

$$P(D)P(I|D)P(S|D, I)P(G|D, I, S)P(L|D, I, S, G)$$

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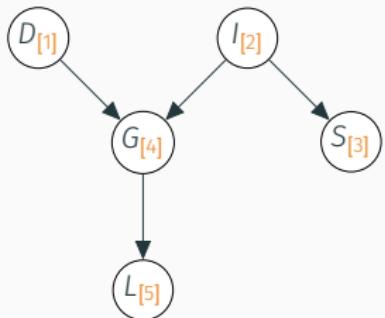
But the BN codes local indep.

$$X_i \perp \text{NonDesc}_{\mathcal{G}}(X_i) \mid \text{Pa}_{\mathcal{G}}(X_i)$$

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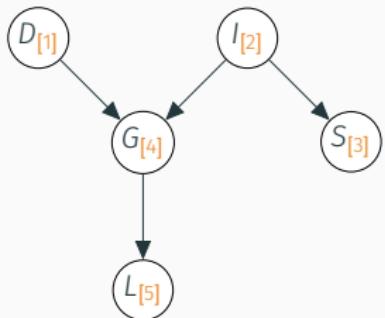
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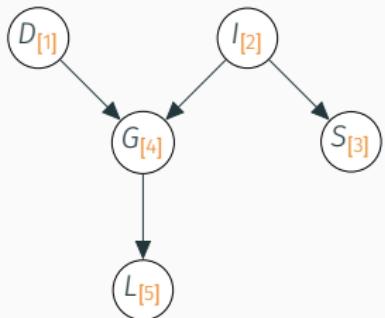
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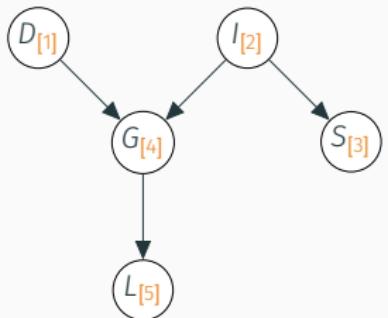
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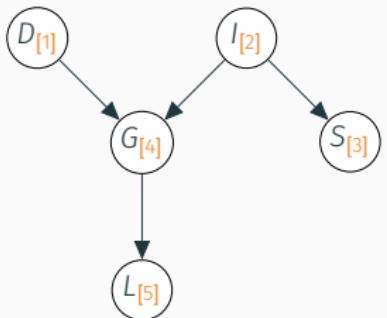
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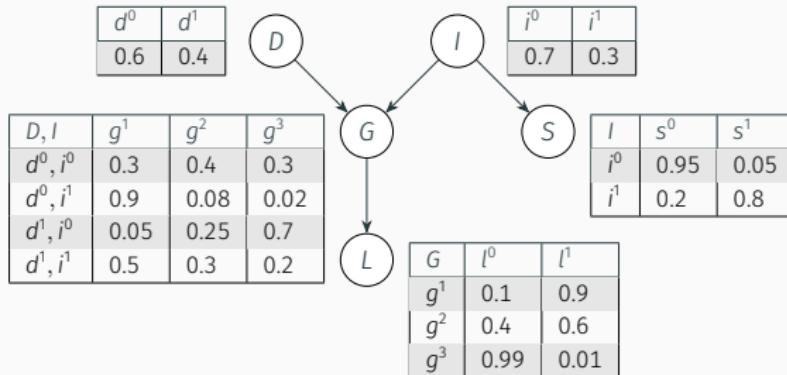
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- $L \perp D, I, S \mid G$ hence $P(L|D, I, S, G) = P(L|G)$

And hence: $P(D, I, G, S, L) \stackrel{\mathcal{G}}{=} P(D)P(I)P(S|I)P(G|D, I)P(L|G)$

A Representation of our Uncertainty over D, I, G, S, L

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



Student example (Fig 3.4 of textbook)

With its DAG and CPDs, a BN identifies one such distribution.

The probability of any one of the possible outcomes of (D, I, G, S, L) is given by $P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$.

| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
| d^0 | i^0 | g^1 | s^0 | l^0 | 0.01197 |
| d^0 | i^0 | g^1 | s^0 | l^1 | 0.10773 |
| d^0 | i^0 | g^1 | s^1 | l^0 | 0.00063 |
| d^0 | i^0 | g^1 | s^1 | l^1 | 0.00567 |
| d^0 | i^0 | g^2 | s^0 | l^0 | 0.06384 |
| d^0 | i^0 | g^2 | s^0 | l^1 | 0.09576 |
| d^0 | i^0 | g^2 | s^1 | l^0 | 0.00336 |
| d^0 | i^0 | g^2 | s^1 | l^1 | 0.00504 |
| d^0 | i^0 | g^3 | s^0 | l^0 | 0.11850 |
| d^0 | i^0 | g^3 | s^0 | l^1 | 0.00120 |
| d^0 | i^0 | g^3 | s^1 | l^0 | 0.00624 |
| d^0 | i^0 | g^3 | s^1 | l^1 | 0.00006 |
| d^0 | i^1 | g^1 | s^0 | l^0 | 0.00324 |
| d^0 | i^1 | g^1 | s^0 | l^1 | 0.02916 |
| d^0 | i^1 | g^1 | s^1 | l^0 | 0.01296 |
| d^0 | i^1 | g^1 | s^1 | l^1 | 0.11664 |
| d^0 | i^1 | g^2 | s^0 | l^0 | 0.00115 |
| d^0 | i^1 | g^2 | s^0 | l^1 | 0.00173 |
| d^0 | i^1 | g^2 | s^1 | l^0 | 0.00461 |
| d^0 | i^1 | g^2 | s^1 | l^1 | 0.00691 |
| d^0 | i^1 | g^3 | s^0 | l^0 | 0.00071 |
| d^0 | i^1 | g^3 | s^0 | l^1 | 0.00001 |
| d^0 | i^1 | g^3 | s^1 | l^0 | 0.00285 |
| d^0 | i^1 | g^3 | s^1 | l^1 | 0.00003 |

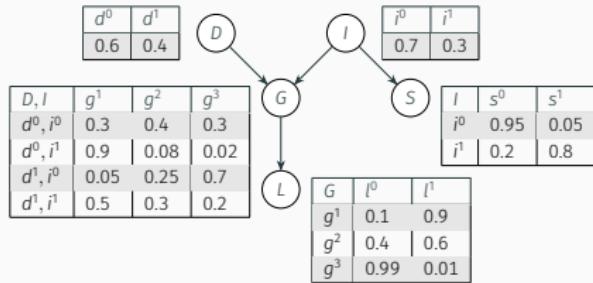
| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
| d^1 | i^0 | g^1 | s^0 | l^0 | 0.00133 |
| d^1 | i^0 | g^1 | s^0 | l^1 | 0.01197 |
| d^1 | i^0 | g^1 | s^1 | l^0 | 0.00007 |
| d^1 | i^0 | g^1 | s^1 | l^1 | 0.00063 |
| d^1 | i^0 | g^2 | s^0 | l^0 | 0.02660 |
| d^1 | i^0 | g^2 | s^0 | l^1 | 0.03990 |
| d^1 | i^0 | g^2 | s^1 | l^0 | 0.00140 |
| d^1 | i^0 | g^2 | s^1 | l^1 | 0.00210 |
| d^1 | i^0 | g^3 | s^0 | l^0 | 0.18434 |
| d^1 | i^0 | g^3 | s^0 | l^1 | 0.00186 |
| d^1 | i^0 | g^3 | s^1 | l^0 | 0.00970 |
| d^1 | i^0 | g^3 | s^1 | l^1 | 0.00010 |
| d^1 | i^1 | g^1 | s^0 | l^0 | 0.00120 |
| d^1 | i^1 | g^1 | s^0 | l^1 | 0.01080 |
| d^1 | i^1 | g^1 | s^1 | l^0 | 0.00480 |
| d^1 | i^1 | g^1 | s^1 | l^1 | 0.04320 |
| d^1 | i^1 | g^2 | s^0 | l^0 | 0.00288 |
| d^1 | i^1 | g^2 | s^0 | l^1 | 0.00432 |
| d^1 | i^1 | g^2 | s^1 | l^0 | 0.01152 |
| d^1 | i^1 | g^2 | s^1 | l^1 | 0.01728 |
| d^1 | i^1 | g^3 | s^0 | l^0 | 0.00475 |
| d^1 | i^1 | g^3 | s^0 | l^1 | 0.00005 |
| d^1 | i^1 | g^3 | s^1 | l^0 | 0.01901 |
| d^1 | i^1 | g^3 | s^1 | l^1 | 0.00019 |

Table 1: Joint distribution over $\text{Val}(D) \times \text{Val}(I) \times \text{Val}(G) \times \text{Val}(S) \times \text{Val}(L)$.

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 probabilities assigned by *local probability models* to subsets of directly interacting variables.



We infer all 48 joint probabilities from the probabilities in the CPDs $P(D), P(I), P(S|I), P(G|D, I), P(L|G)$. Their tabular representations require $2 + 2 + 2 \times 2 + 4 \times 3 + 3 \times 2 = 26$ parameters, rather than 48.

A BN model is a graph \mathcal{G} and a collection \mathcal{C} of CPDs such that:

- \mathcal{G} is a directed acyclic graph (DAG);
- the nodes in \mathcal{G} represent the random variables X_1, \dots, X_n ;
- the edges in \mathcal{G} indicate *direct* conditional dependence of a random variable X_i on its parents $\text{Pa}_{\mathcal{G}}(X_i)$;
- for each node X_i , \mathcal{C} contains a CPD $P(X_i|\text{Pa}_{\mathcal{G}}(X_i))$ specifying the probabilities of the outcomes of X_i given outcomes of $\text{Pa}_{\mathcal{G}}(X_i)$.

The BN represents a joint distribution via the *chain rule of probabilities for Bayesian networks*:

$$P(X_1, \dots, X_n) \stackrel{\mathcal{G}}{=} \prod_{i=1}^n P(X_i|\text{Pa}_{\mathcal{G}}(X_i)) \quad (1)$$

Graphs and Distributions

We say that a joint distribution P **factorises** according to \mathcal{G} if

$$P(X_1, \dots, X_n) = \prod_{i=1}^n P(X_i | \text{Pa}_{\mathcal{G}}(X_i))$$

The BN structure and the factorisation imply one another.

To fully identify a distribution, the BN associates the factors $P(X_i | \text{Pa}_{\mathcal{G}}(X_i))$ with local probability models such as tabular CPDs.

The word *factorisation* means decomposition into a product of factors.

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To fully identify a distribution, the BN associates the factors $P(X_i | \text{Pa}_{\mathcal{G}}(X_i))$ with local probability models such as tabular CPDs.

Once one such joint distribution is in place, we can manipulate it via probability calculus to infer the result of *any* probability query about marginals and conditionals of P .

The word *factorisation* means decomposition into a product of factors.

Summary

- A BN uses a DAG \mathcal{G} to encode statements of (conditional) independence, and these must hold in any distribution P that factorises over \mathcal{G} .
- We can read the factorisation readily from the BN structure: a node is independent of its non-descendants given its parents.
- To each node, a BN associates a local probability model (such as a tabular CPD).
- With a CPD attached to each node, a BN is a complete representation of a joint distribution P .

What's Next?

LC1: BN in code.

HC1b: BN – reasoning and influence.

WC1: exercises (semantics, reasoning and influence).

Reasoning

Outline for this section

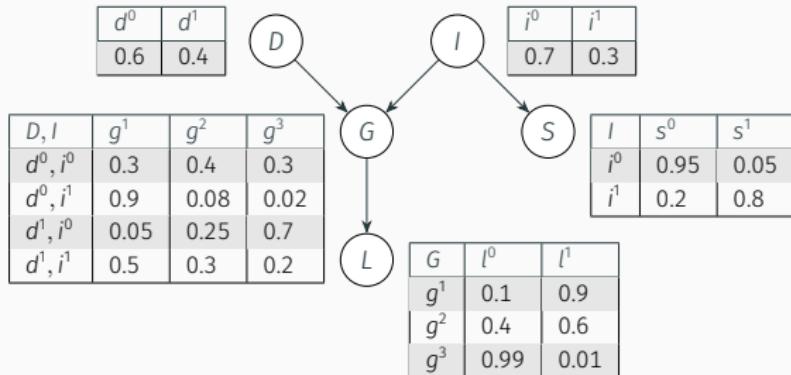
We begin by restating three of the most fundamental results of probability theory.

We then exploit those results and the BN 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 BN structure. This connection will be exploited more fully later in the course.

Beliefs

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



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

With its DAG and CPDs, a BN identifies one such distribution.

Having a joint distribution, we can reason about subsets of variables and given observed data.

Chain rule

$$P(A, B) = P(A)P(B|A) = P(B)P(A|B) \quad (2)$$

Marginalisation

$$P(A) = \sum_B P(A, B) \quad (3)$$

Conditioning

$$P(B|A) = \frac{P(A, B)}{P(A)} \quad (4)$$

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

Marginal Queries

If we have a *joint distribution*, such as we see in Table 1, we can easily reason about subsets of rvs via *marginalisation*: **we need only sum the probabilities of the relevant joint assignments.**

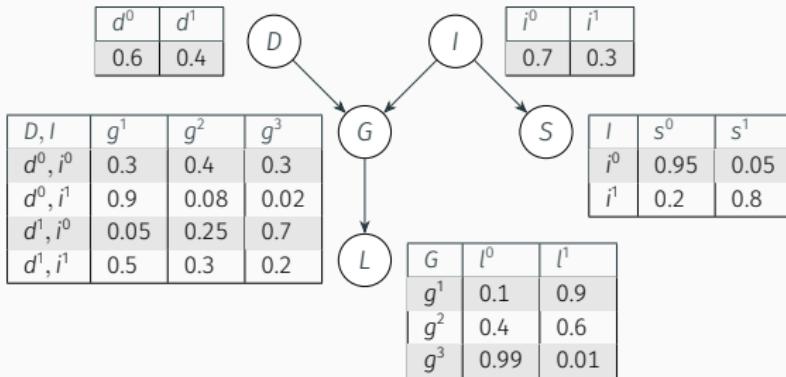
| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
| d^0 | i^0 | g^1 | s^0 | l^0 | 0.01197 |
| d^0 | i^0 | g^1 | s^0 | l^1 | 0.10773 |
| d^0 | i^0 | g^1 | s^1 | l^0 | 0.00063 |
| d^0 | i^0 | g^1 | s^1 | l^1 | 0.00567 |
| d^0 | i^0 | g^2 | s^0 | l^0 | 0.06384 |
| d^0 | i^0 | g^2 | s^0 | l^1 | 0.09576 |
| d^0 | i^0 | g^2 | s^1 | l^0 | 0.00336 |
| d^0 | i^0 | g^2 | s^1 | l^1 | 0.00504 |
| d^0 | i^0 | g^3 | s^0 | l^0 | 0.11850 |
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| d^0 | i^1 | g^1 | s^0 | l^0 | 0.00324 |
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| d^0 | i^1 | g^3 | s^0 | l^0 | 0.00071 |
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| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
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| d^1 | i^0 | g^1 | s^1 | l^0 | 0.00007 |
| d^1 | i^0 | g^1 | s^1 | l^1 | 0.00063 |
| d^1 | i^0 | g^2 | s^0 | l^0 | 0.02660 |
| d^1 | i^0 | g^2 | s^0 | l^1 | 0.03990 |
| d^1 | i^0 | g^2 | s^1 | l^0 | 0.00140 |
| d^1 | i^0 | g^2 | s^1 | l^1 | 0.00210 |
| d^1 | i^0 | g^3 | s^0 | l^0 | 0.18434 |
| d^1 | i^0 | g^3 | s^0 | l^1 | 0.00186 |
| d^1 | i^0 | g^3 | s^1 | l^0 | 0.00970 |
| d^1 | i^0 | g^3 | s^1 | l^1 | 0.00010 |
| d^1 | i^1 | g^1 | s^0 | l^0 | 0.00120 |
| d^1 | i^1 | g^1 | s^0 | l^1 | 0.01080 |
| d^1 | i^1 | g^1 | s^1 | l^0 | 0.00480 |
| d^1 | i^1 | g^1 | s^1 | l^1 | 0.04320 |
| d^1 | i^1 | g^2 | s^0 | l^0 | 0.00288 |
| d^1 | i^1 | g^2 | s^0 | l^1 | 0.00432 |
| d^1 | i^1 | g^2 | s^1 | l^0 | 0.01152 |
| d^1 | i^1 | g^2 | s^1 | l^1 | 0.01728 |
| d^1 | i^1 | g^3 | s^0 | l^0 | 0.00475 |
| d^1 | i^1 | g^3 | s^0 | l^1 | 0.00005 |
| d^1 | i^1 | g^3 | s^1 | l^0 | 0.01901 |
| d^1 | i^1 | g^3 | s^1 | l^1 | 0.00019 |

Table 2: In yellow we show all assignments where $S = s^1$, the marginal probability of $S = s^1$ is then $P(S = s^1) = \sum_{D, I, G, L} P(D, I, G, S = s^1, L) = \text{sum of yellow cells.}$

Marginal Queries for BNs

A BN represents a joint distribution, but the representation is not tabular like in Table 1. Still, we can reason about subsets of rvs.

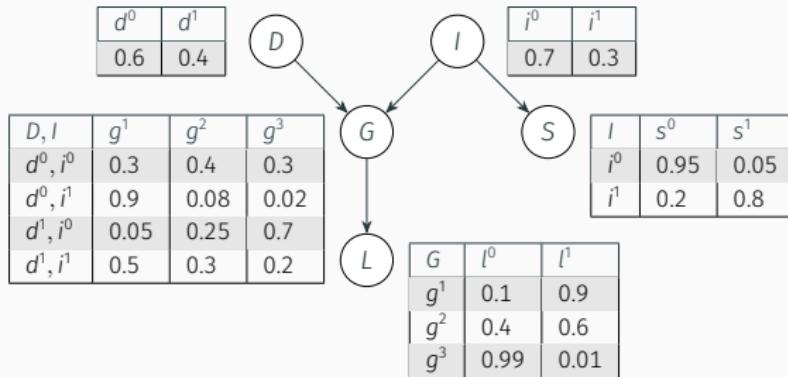


$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(S = s^1)$

Marginal Queries for BNs

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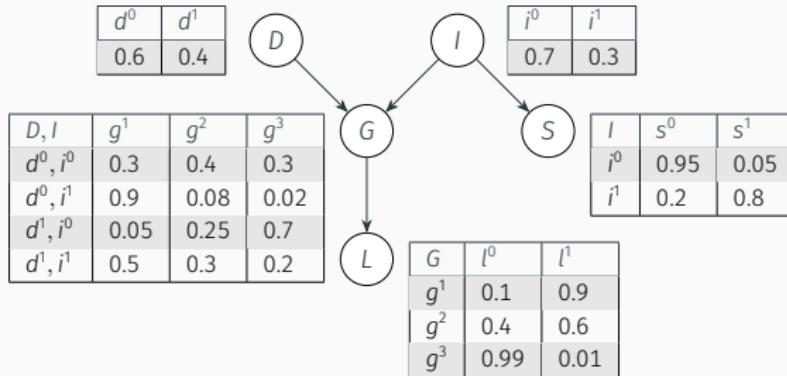
$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$\text{Evaluate } P(S = s^1) = 0.275$$

$$\text{Evaluate } P(G = g^1)$$

Marginal Queries for BNs

A BN represents a joint distribution, but the representation is not tabular like in Table 1. Still, we can reason about subsets of rvs.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

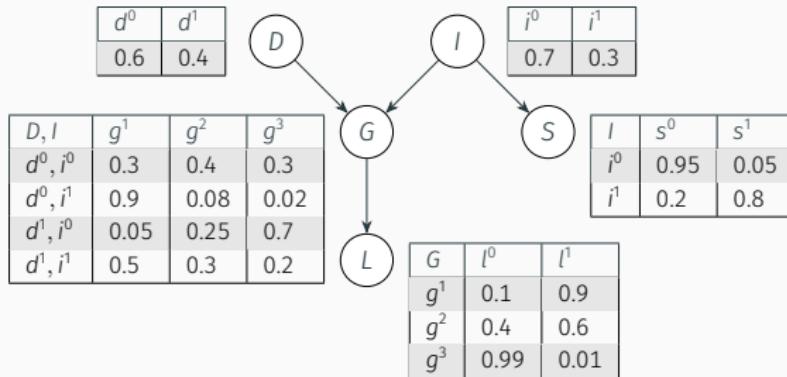
Evaluate $P(S = s^1) = 0.275$

Evaluate $P(G = g^1) = 0.3620$

Evaluate $P(L = l^1)$

Marginal Queries for BNs

A BN represents a joint distribution, but the representation is not tabular like in Table 1. Still, we can reason about subsets of rvs.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(S = s^1) = 0.275$

Evaluate $P(G = g^1) = 0.3620$

Evaluate $P(L = l^1) \approx 0.5023$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

Marginal $P(S) =$

$$\begin{aligned} & \sum_{D,I,G,L} P(D, I, G, S, L) \\ &= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G) \end{aligned}$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D) \sum_G P(G|D, I)$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D) \sum_G P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D)$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D) \sum_G P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D)$$

$$= \sum_I P(S|I)P(I) \sum_D P(D)$$

Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

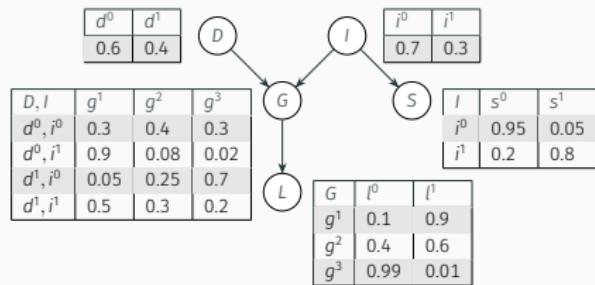
$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D) \sum_G P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D)$$

$$= \sum_I P(S|I)P(I) \sum_D P(D)$$

$$= \sum_I P(S|I)P(I)$$



Marginal $P(S) =$

$$\sum_{D,I,G,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,L} P(S|I)P(I)P(D)P(G|D, I)P(L|G)$$

$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I) \sum_L P(L|G)$$

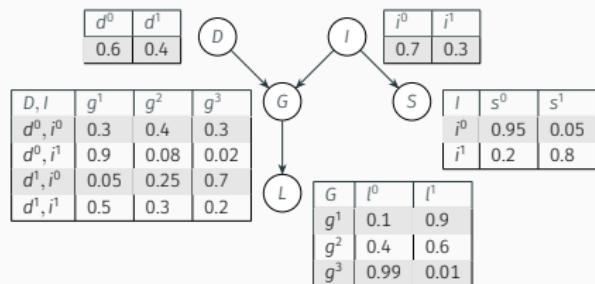
$$= \sum_{D,I,G} P(S|I)P(I)P(D)P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D) \sum_G P(G|D, I)$$

$$= \sum_{D,I} P(S|I)P(I)P(D)$$

$$= \sum_I P(S|I)P(I) \sum_D P(D)$$

$$= \sum_I P(S|I)P(I)$$



| S | $\sum_I P(S I)P(I)$ | $P(S)$ |
|-------|------------------------------------|--------|
| s^0 | $0.95 \times 0.7 + 0.2 \times 0.3$ | 0.725 |
| s^1 | $0.05 \times 0.7 + 0.8 \times 0.3$ | 0.275 |

Marginal $P(G) =$

$$\sum_{D,I,S,L} P(D, I, G, S, L)$$

Marginal $P(G) =$

$$\begin{aligned} & \sum_{D,I,S,L} P(D, I, G, S, L) \\ &= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G) \end{aligned}$$

Marginal $P(G) =$

$$\sum_{D,I,S,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G)$$

$$= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I) \sum_L P(L|G)$$

Marginal $P(G) =$

$$\begin{aligned} & \sum_{D,I,S,L} P(D, I, G, S, L) \\ &= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G) \\ &= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I) \sum_L P(L|G) \\ &= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I) \end{aligned}$$

Marginal $P(G) =$

$$\sum_{D,I,S,L} P(D, I, G, S, L)$$

$$= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G)$$

$$= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I) \sum_L P(L|G)$$

$$= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I)$$

$$= \sum_{D,I} P(G|D, I)P(D)P(I) \sum_S P(S|I)$$

Marginal $P(G) =$

$$\sum_{D,I,S,L} P(D, I, G, S, L)$$

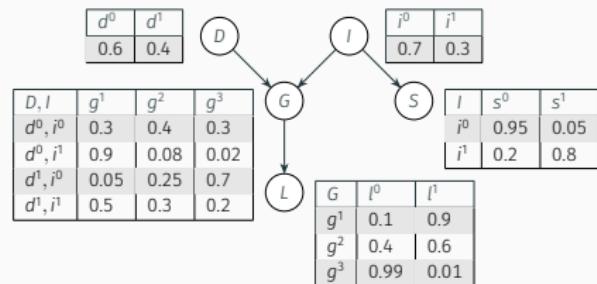
$$= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G)$$

$$= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I) \sum_L P(L|G)$$

$$= \sum_{D,I,S} P(G|D, I)P(D)P(I)P(S|I)$$

$$= \sum_{D,I} P(G|D, I)P(D)P(I) \sum_S P(S|I)$$

$$= \sum_{D,I} P(G|D, I)P(D)P(I)$$



Marginal $P(G) =$

$$\sum_{D,I,S,L} P(D, I, G, S, L)$$

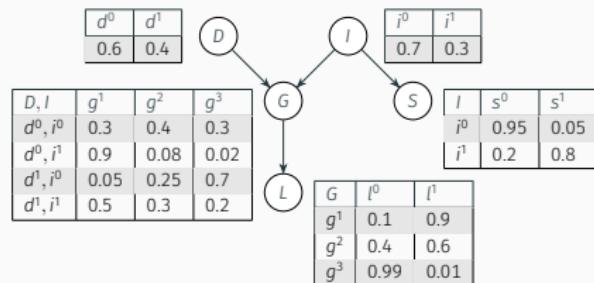
$$= \sum_{D,I,S,L} P(G|D, I)P(D)P(I)P(S|I)P(L|G)$$

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$$= \sum_{D,I} P(G|D, I)P(D)P(I) \sum_S P(S|I)$$

$$= \sum_{D,I} P(G|D, I)P(D)P(I)$$



| G | $\sum_{D,I} P(G D, I)P(D)P(I)$ | $P(G)$ |
|-------|---|--------|
| g^1 | $0.3 \times 0.6 \times 0.7 + 0.90 \times 0.6 \times 0.3 + 0.05 \times 0.4 \times 0.7 + 0.5 \times 0.4 \times 0.3$ | 0.3620 |
| g^2 | $0.4 \times 0.6 \times 0.7 + 0.08 \times 0.6 \times 0.3 + 0.25 \times 0.4 \times 0.7 + 0.3 \times 0.4 \times 0.3$ | 0.2884 |
| g^3 | $0.3 \times 0.6 \times 0.7 + 0.02 \times 0.6 \times 0.3 + 0.70 \times 0.4 \times 0.7 + 0.2 \times 0.4 \times 0.3$ | 0.3496 |

Marginal $P(L) =$

$$\sum_{D,I,G,S} P(D, I, G, S, L)$$

Marginal $P(L) =$

$$\begin{aligned} & \sum_{D,I,G,S} P(D, I, G, S, L) \\ &= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I) \end{aligned}$$

Marginal $P(L) =$

$$\begin{aligned} & \sum_{D,I,G,S} P(D, I, G, S, L) \\ &= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I) \\ &= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \sum_S P(S|I) \end{aligned}$$

Marginal $P(L) =$

$$\begin{aligned} & \sum_{D,I,G,S} P(D, I, G, S, L) \\ &= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I) \\ &= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \sum_S P(S|I) \\ &= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \end{aligned}$$

Marginal $P(L) =$

$$\sum_{D,I,G,S} P(D, I, G, S, L)$$

$$= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I)$$

$$= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \sum_S P(S|I)$$

$$= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I)$$

$$= \sum_G P(L|G) \sum_{D,I} P(D)P(I)P(G|D, I)$$

Marginal $P(L) =$

$$\sum_{D,I,G,S} P(D, I, G, S, L)$$

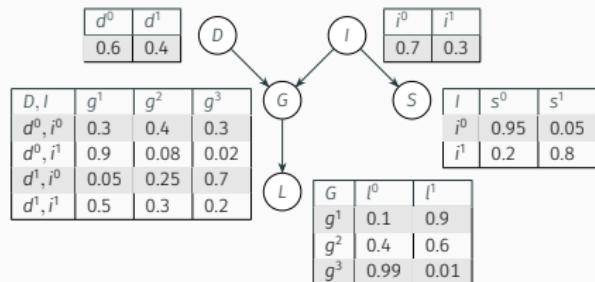
$$= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I)$$

$$= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \sum_S P(S|I)$$

$$= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I)$$

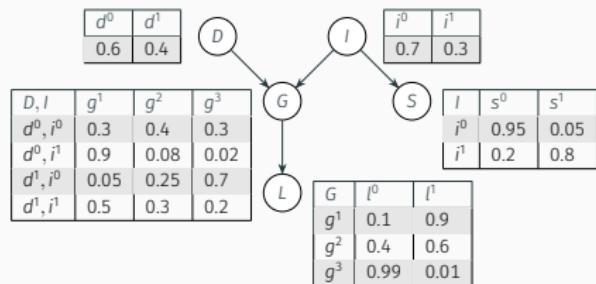
$$= \sum_G P(L|G) \sum_{D,I} P(D)P(I)P(G|D, I)$$

$$= \sum_G P(L|G)P(G)$$



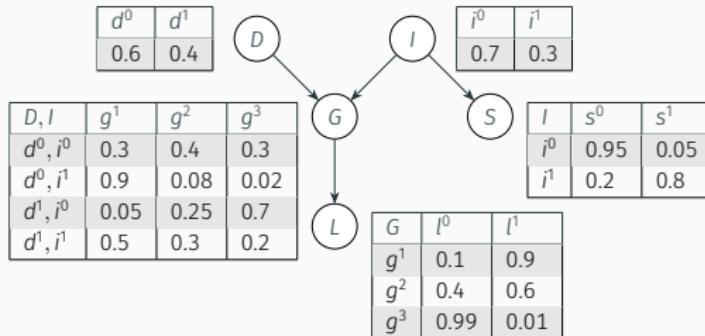
Marginal $P(L) =$

$$\begin{aligned}
 & \sum_{D,I,G,S} P(D, I, G, S, L) \\
 &= \sum_{D,I,G,S} P(L|G)P(D)P(I)P(G|D, I)P(S|I) \\
 &= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \sum_S P(S|I) \\
 &= \sum_{D,I,G} P(L|G)P(D)P(I)P(G|D, I) \\
 &= \sum_G P(L|G) \sum_{D,I} P(D)P(I)P(G|D, I) \\
 &= \sum_G P(L|G)P(G)
 \end{aligned}$$



| L | $\sum_G P(L G)P(G)$ | $P(L)$ |
|-------|--|--------|
| l^0 | $0.1 \times 0.3630 + 0.4 \times 0.2884 + 0.99 \times 0.3496$ | 0.4977 |
| l^1 | $0.9 \times 0.3630 + 0.6 \times 0.2884 + 0.01 \times 0.3496$ | 0.5023 |

Single-Variable Marginals



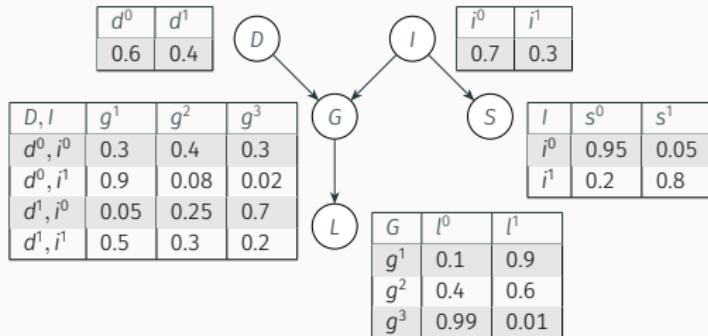
$P(D)$ and $P(I)$ are given CPDs

The other single-variable marginals are CPDs which we inferred via

- $P(S) = \sum_I P(I)P(S|I)$
- $P(G) = \sum_{D,I} P(D)P(I)P(G|D, I)$
- $P(L) = \sum_G P(L|G)P(G)$

as $P(S|I)$, $P(G|D, I)$, and $P(L|G)$ are also given CPDs.

Other Marginals



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

We can similarly express any other marginal, involving any subset of rvs, in terms of CPDs that are given:

- $P(D, I)$
- $P(D, G)$
- $P(D, L)$
- $P(I, G, S)$
- $P(S, G, L)$
- ...

Evaluate $P(S = s^1, I = i^1)$, $P(G = g^1, I = i^1)$, $P(L = l^1, I = i^1)$

Marginal $P(D, G) =$

$$\sum_{I, S, L} P(D, I, G, S, L)$$

Marginal $P(D, G) =$

$$\sum_{I,S,L} P(D, I, G, S, L)$$

$$= \sum_{I,S,L} P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Marginal $P(D, G) =$

$$\sum_{I,S,L} P(D, I, G, S, L)$$

$$= \sum_{I,S,L} P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$= \sum_{I,S} P(D)P(I)P(G|D, I)P(S|I) \sum_L P(L|G)$$

Marginal $P(D, G) =$

$$\sum_{I,S,L} P(D, I, G, S, L)$$

$$= \sum_{I,S,L} P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$= \sum_{I,S} P(D)P(I)P(G|D, I)P(S|I) \sum_L P(L|G)$$

$$= \sum_I P(D)P(I)P(G|D, I) \sum_S P(S|I)$$

Marginal $P(D, G) =$

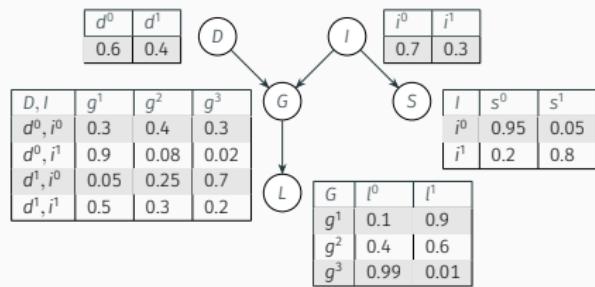
$$\sum_{I,S,L} P(D, I, G, S, L)$$

$$= \sum_{I,S,L} P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$= \sum_{I,S} P(D)P(I)P(G|D, I)P(S|I) \sum_L P(L|G)$$

$$= \sum_I P(D)P(I)P(G|D, I) \sum_S P(S|I)$$

$$= P(D) \sum_I P(I)P(G|D, I)$$



Marginal $P(D, G) =$

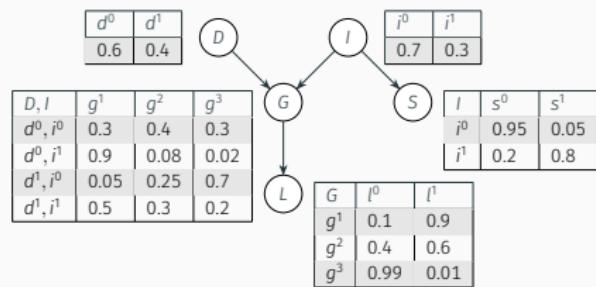
$$\sum_{I,S,L} P(D, I, G, S, L)$$

$$= \sum_{I,S,L} P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$= \sum_{I,S} P(D)P(I)P(G|D, I)P(S|I) \sum_L P(L|G)$$

$$= \sum_I P(D)P(I)P(G|D, I) \sum_S P(S|I)$$

$$= P(D) \sum_I P(I)P(G|D, I)$$

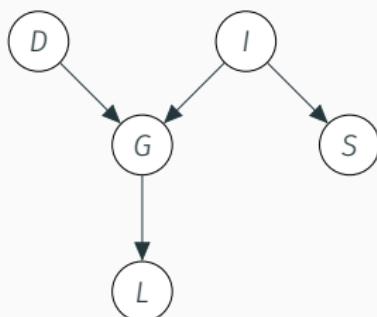


| D, G | Marginalisation | $P(D, G)$ |
|------------|--|-----------|
| d^0, g^1 | $0.6 \times (0.7 \times 0.30 + 0.3 \times 0.90)$ | 0.288 |
| d^0, g^2 | $0.6 \times (0.7 \times 0.40 + 0.3 \times 0.08)$ | 0.1824 |
| d^0, g^3 | $0.6 \times (0.7 \times 0.30 + 0.3 \times 0.02)$ | 0.1296 |
| d^1, g^1 | $0.4 \times (0.7 \times 0.05 + 0.3 \times 0.50)$ | 0.0740 |
| d^1, g^2 | $0.4 \times (0.7 \times 0.25 + 0.3 \times 0.30)$ | 0.1060 |
| d^1, g^3 | $0.4 \times (0.7 \times 0.70 + 0.3 \times 0.20)$ | 0.220 |

Ancestors (definition 2.18)

So far, we used probability calculus, the DAG \mathcal{G} only provided us with $\mathcal{I}_l(\mathcal{G})$. Let's try to use more of the graph structure.

A is **an ancestor of** B in the DAG, if the DAG contains at least one directed path from A to B.



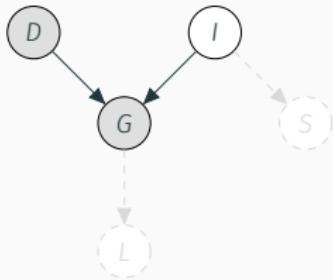
| node | ancestors |
|------|-------------|
| D | \emptyset |
| I | \emptyset |
| S | {I} |
| G | |
| L | |

Can you list the ancestors?

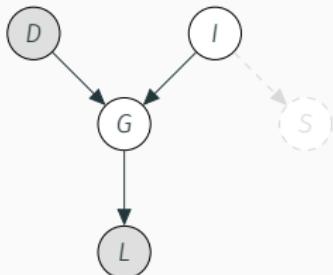
Marginalisation

To obtain marginal probabilities for a subset of nodes (shaded gray)

1. ignore their non-ancestral nodes (faded out);
2. and marginalise out the unassigned ancestors (unshaded).



To express $P(D, G)$, we can act as if L and S were not in the BN, then sum $P(D, G, I)$ over the outcome space of I : $\{i^0, i^1\}$.



To express $P(D, L)$, we can act as if S were not in the BN, then sum $P(D, L, G, I)$ over the Cartesian product of the outcome spaces of G and I : $\{g^1, g^2, g^3\} \times \{i^0, i^1\}$

Conditional Queries

If we have a *joint distribution*, such as we see in Table 1, we can easily reason about any subset \mathbf{Y} of rvs given any subset \mathbf{X} of other rvs via *conditional probability* $P(\mathbf{Y}|\mathbf{X}) = \frac{P(\mathbf{X},\mathbf{Y})}{P(\mathbf{X})}$.

We need only sum the probabilities of the relevant joint assignments featuring in the numerator, sum those featuring in the denominator, and divide one by the other.

| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
| d^0 | i^0 | g^1 | s^0 | l^0 | 0.01197 |
| d^0 | i^0 | g^1 | s^0 | l^1 | 0.10773 |
| d^0 | i^0 | g^1 | s^1 | l^0 | 0.00063 |
| d^0 | i^0 | g^1 | s^1 | l^1 | 0.00567 |
| d^0 | i^0 | g^2 | s^0 | l^0 | 0.06384 |
| d^0 | i^0 | g^2 | s^0 | l^1 | 0.09576 |
| d^0 | i^0 | g^2 | s^1 | l^0 | 0.00336 |
| d^0 | i^0 | g^2 | s^1 | l^1 | 0.00504 |
| d^0 | i^0 | g^3 | s^0 | l^0 | 0.11850 |
| d^0 | i^0 | g^3 | s^0 | l^1 | 0.00120 |
| d^0 | i^0 | g^3 | s^1 | l^0 | 0.00624 |
| d^0 | i^0 | g^3 | s^1 | l^1 | 0.00006 |
| d^0 | i^1 | g^1 | s^0 | l^0 | 0.00324 |
| d^0 | i^1 | g^1 | s^0 | l^1 | 0.02916 |
| d^0 | i^1 | g^1 | s^1 | l^0 | 0.01296 |
| d^0 | i^1 | g^1 | s^1 | l^1 | 0.11664 |
| d^0 | i^1 | g^2 | s^0 | l^0 | 0.00115 |
| d^0 | i^1 | g^2 | s^0 | l^1 | 0.00173 |
| d^0 | i^1 | g^2 | s^1 | l^0 | 0.00461 |
| d^0 | i^1 | g^2 | s^1 | l^1 | 0.00691 |
| d^0 | i^1 | g^3 | s^0 | l^0 | 0.00071 |
| d^0 | i^1 | g^3 | s^0 | l^1 | 0.00001 |
| d^0 | i^1 | g^3 | s^1 | l^0 | 0.00285 |
| d^0 | i^1 | g^3 | s^1 | l^1 | 0.00003 |

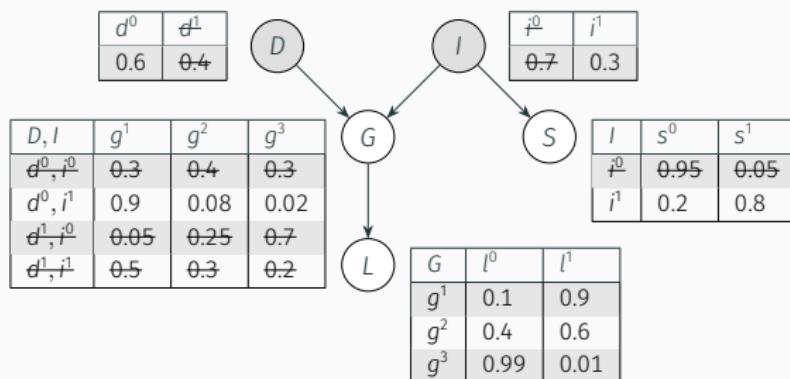
| D | I | G | S | L | $P(D, I, G, S, L)$ |
|-------|-------|-------|-------|-------|--------------------|
| d^1 | i^0 | g^1 | s^0 | l^0 | 0.00133 |
| d^1 | i^0 | g^1 | s^0 | l^1 | 0.01197 |
| d^1 | i^0 | g^1 | s^1 | l^0 | 0.00007 |
| d^1 | i^0 | g^1 | s^1 | l^1 | 0.00063 |
| d^1 | i^0 | g^2 | s^0 | l^0 | 0.02660 |
| d^1 | i^0 | g^2 | s^0 | l^1 | 0.03990 |
| d^1 | i^0 | g^2 | s^1 | l^0 | 0.00140 |
| d^1 | i^0 | g^2 | s^1 | l^1 | 0.00210 |
| d^1 | i^0 | g^3 | s^0 | l^0 | 0.18434 |
| d^1 | i^0 | g^3 | s^0 | l^1 | 0.00186 |
| d^1 | i^0 | g^3 | s^1 | l^0 | 0.00970 |
| d^1 | i^0 | g^3 | s^1 | l^1 | 0.00010 |
| d^1 | i^1 | g^1 | s^0 | l^0 | 0.00120 |
| d^1 | i^1 | g^1 | s^0 | l^1 | 0.01080 |
| d^1 | i^1 | g^1 | s^1 | l^0 | 0.00480 |
| d^1 | i^1 | g^1 | s^1 | l^1 | 0.04320 |
| d^1 | i^1 | g^2 | s^0 | l^0 | 0.00288 |
| d^1 | i^1 | g^2 | s^0 | l^1 | 0.00432 |
| d^1 | i^1 | g^2 | s^1 | l^0 | 0.01152 |
| d^1 | i^1 | g^2 | s^1 | l^1 | 0.01728 |
| d^1 | i^1 | g^3 | s^0 | l^0 | 0.00475 |
| d^1 | i^1 | g^3 | s^0 | l^1 | 0.00005 |
| d^1 | i^1 | g^3 | s^1 | l^0 | 0.01901 |
| d^1 | i^1 | g^3 | s^1 | l^1 | 0.00019 |

Table 3: In dark yellow we show assignments with ($G = g^1, I = i^1$). In yellow (dark or light) we show $I = i^1$. Then $P(G = g^1 | I = i^1) = \frac{P(G=g^1, I=i^1)}{P(I=i^1)} = \frac{\text{sum dark yellow}}{\text{sum dark/light yellow}}$.

Conditional Queries for BNs

A BN represents a joint distribution, but the representation is not tabular like in Table 1. Still, we can reason by *conditioning* one set of rvs on another.

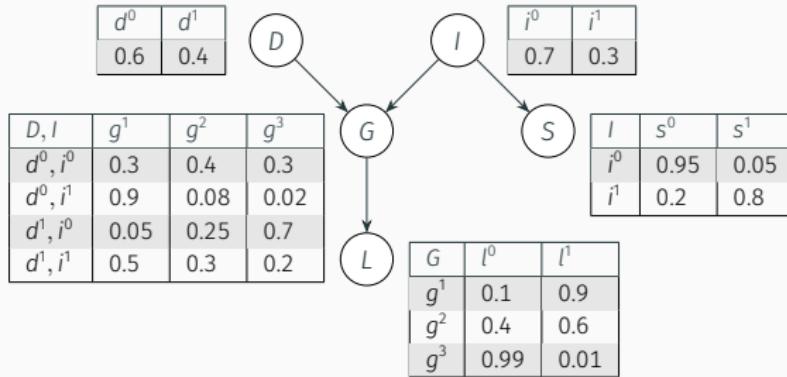
For example, we may observe $D = d^0$ and $I = i^1$ and ask ourselves what happens to $P(G|D = d^0, I = i^1)$, or $P(S|D = d^0, I = i^1)$, etc.



Shading a node indicates that it has been observed.

Conditional Queries – Causal Reasoning

When we condition on an *ancestor* of the variable of interest, we say we are reasoning '**causally**'.



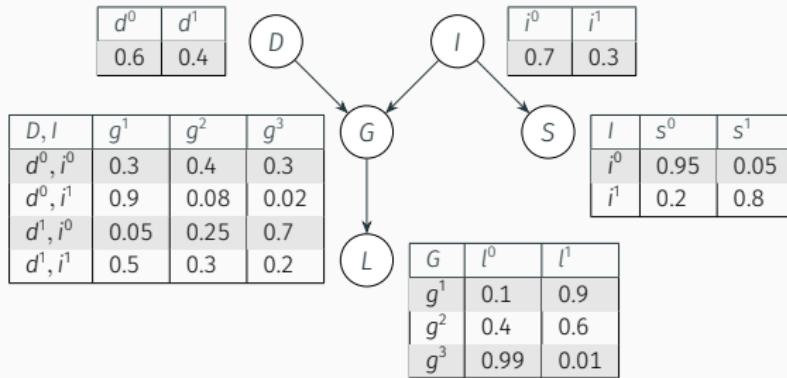
$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(S = s^1 | I = i^1)$

For comparison: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Causal Reasoning

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$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

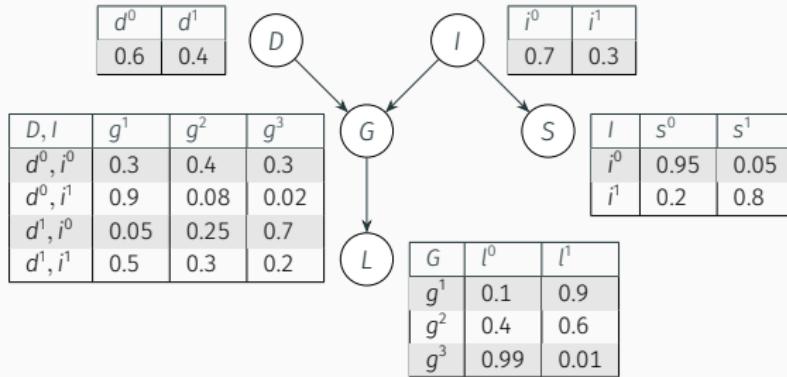
$$\text{Evaluate } P(S = s^1 | I = i^1) = 0.8$$

$$\text{Evaluate } P(G = g^1 | I = i^1)$$

For comparison: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Causal Reasoning

When we condition on an *ancestor* of the variable of interest, we say we are reasoning '**causally**'.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$\text{Evaluate } P(S = s^1 | I = i^1) = 0.8$$

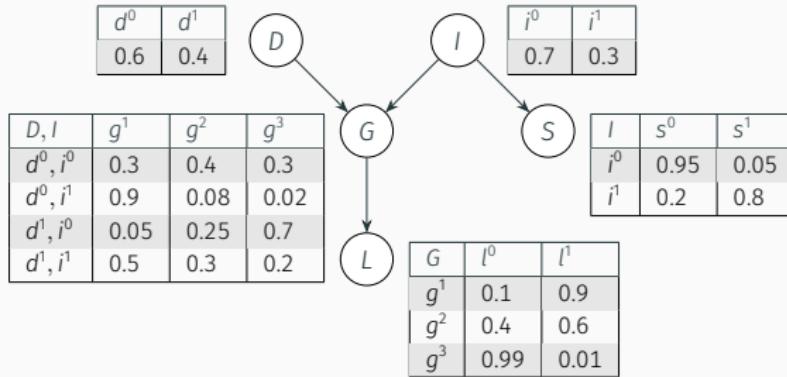
$$\text{Evaluate } P(G = g^1 | I = i^1) = 0.74$$

$$\text{Evaluate } P(L = l^1 | I = i^1)$$

For comparison: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Causal Reasoning

When we condition on an *ancestor* of the variable of interest, we say we are reasoning '**causally**'.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$\text{Evaluate } P(S = s^1 | I = i^1) = 0.8$$

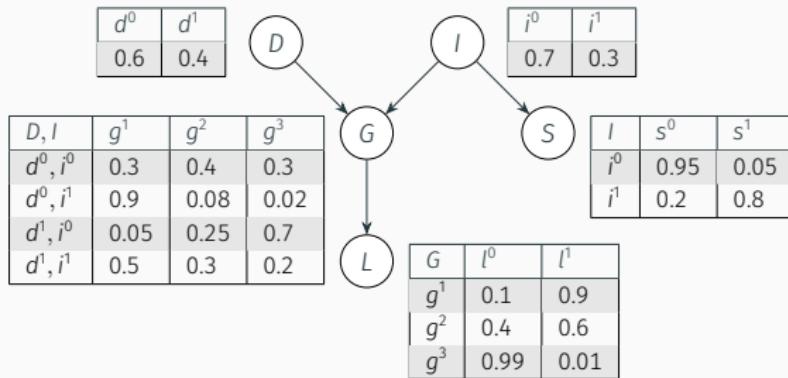
$$\text{Evaluate } P(G = g^1 | I = i^1) = 0.74$$

$$\text{Evaluate } P(L = l^1 | I = i^1) \approx 0.7677$$

For comparison: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Evidential Reasoning

When we condition on a *descendant* of the variable of interest, we say we are reasoning '**evidentially**'.



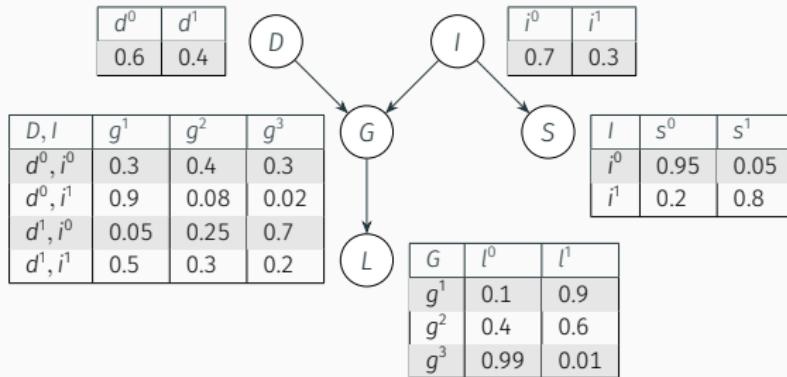
$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(I = i^1 | S = s^1)$

Useful marginals: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Evidential Reasoning

When we condition on a *descendant* of the variable of interest, we say we are reasoning '**evidentially**'.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

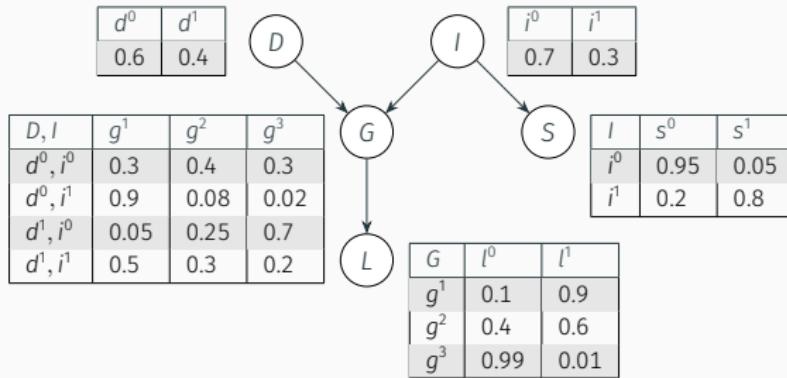
$$\text{Evaluate } P(I = i^1 | S = s^1) = 0.8727$$

$$\text{Evaluate } P(I = i^1 | G = g^1)$$

Useful marginals: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Evidential Reasoning

When we condition on a *descendant* of the variable of interest, we say we are reasoning '**evidentially**'.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(I = i^1 | S = s^1) = 0.8727$

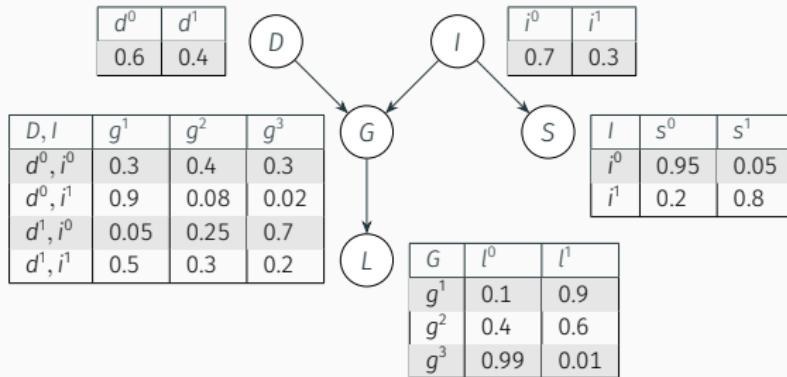
Evaluate $P(I = i^1 | G = g^1) \approx 0.6133$

Evaluate $P(I = i^1 | L = l^1)$

Useful marginals: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Evidential Reasoning

When we condition on a *descendant* of the variable of interest, we say we are reasoning '**evidentially**'.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$\text{Evaluate } P(I = i^1 | S = s^1) = 0.8727$$

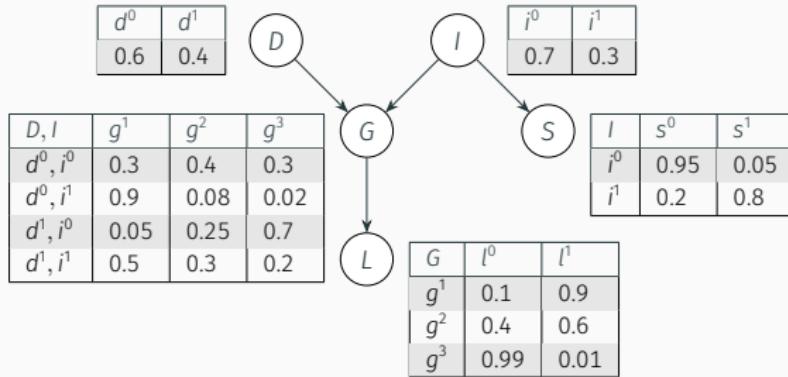
$$\text{Evaluate } P(I = i^1 | G = g^1) \approx 0.6133$$

$$\text{Evaluate } P(I = i^1 | L = l^1) \approx 0.4585$$

Useful marginals: $P(S = s^1) = 0.275$, $P(G = g^1) = 0.3620$ and $P(L = l^1) = 0.502336$

Conditional Queries – Intercausal Reasoning

Here D and I (the ‘causes’ of G) are independent of one another, but upon observing their ‘effect’ G , they can influence each other.



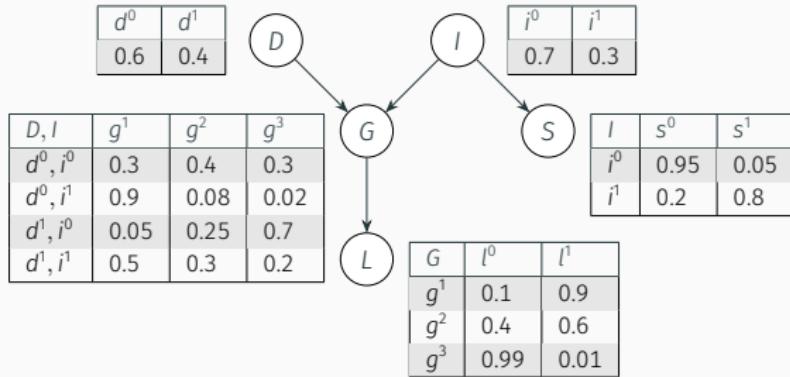
$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

Evaluate $P(I = i^1 | D = d^0)$

Useful marginals: $P(G = g^1) = 0.3620$ and $P(G = g^1, D = d^0) = 0.288$

Conditional Queries – Intercausal Reasoning

Here D and I (the ‘causes’ of G) are independent of one another, but upon observing their ‘effect’ G , they can influence each other.



$$P(D, I, G, S, L) = P(D)P(I)P(G|D, I)P(S|I)P(L|G)$$

$$\text{Evaluate } P(I = i^1 | D = d^0) = 0.3$$

$I \perp D$ in the BN

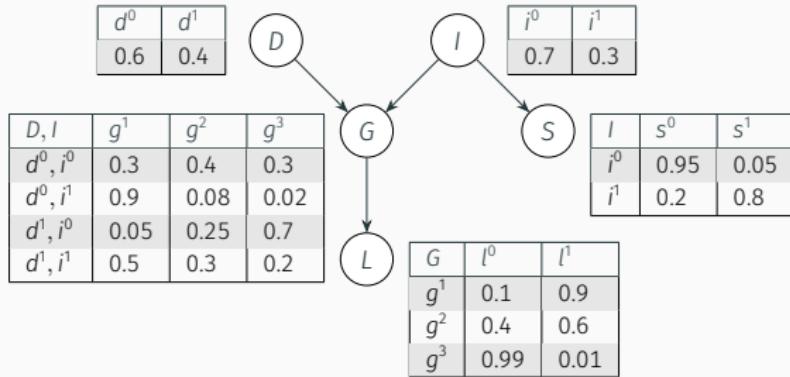
$$\text{Evaluate } P(I = i^1 | G = g^1) \approx 0.6133$$

evidential reasoning

Useful marginals: $P(G = g^1) = 0.3620$ and $P(G = g^1, D = d^0) = 0.288$

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Evaluate $P(I = i^1 | D = d^0) = 0.3$

$I \perp D$ in the BN

Evaluate $P(I = i^1 | G = g^1) \approx 0.6133$

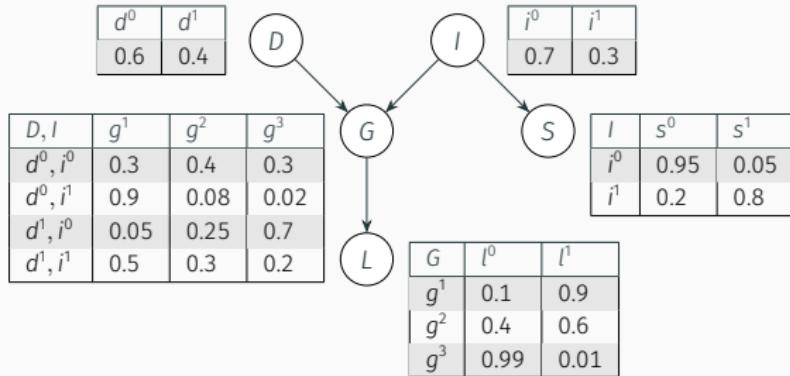
evidential reasoning

Evaluate $P(I = i^1 | G = g^1, D = d^0)$

Useful marginals: $P(G = g^1) = 0.3620$ and $P(G = g^1, D = d^0) = 0.288$

Conditional Queries – Intercausal Reasoning

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Evaluate $P(I = i^1 | D = d^0) = 0.3$

$I \perp D$ in the BN

Evaluate $P(I = i^1 | G = g^1) \approx 0.6133$

evidential reasoning

Evaluate $P(I = i^1 | G = g^1, D = d^0) = 0.5625$

intercausal

Useful marginals: $P(G = g^1) = 0.3620$ and $P(G = g^1, D = d^0) = 0.288$

Summary

- Having a BN representation of P (that is, factorisation and CPDs), we can reason about its marginals and conditionals using probability calculus.
- Observing an ancestor or a descendant triggers different reasoning patterns (causal or evidential).
- These patterns show us that the influence of an observation ‘flows’ through the BN affecting beliefs about other rvs (e.g., a strong letter affects the company’s beliefs on high intelligence).

What's Next?

So far the DAG mostly only provided us with statements of local independence (i.e., a factorisation), and we used probability calculus for reasoning.

Next, we develop tools to characterise how influence ‘flows’ through BNs, enabling some forms of reasoning by analysis of the BN structure alone.

Influence

Outline for this section

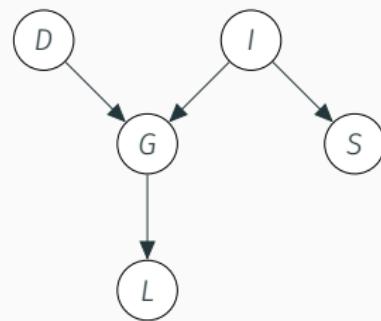
We start by discussing influence in the absence of observations, both direct and indirect influence.

We then introduce observations and review their effects on indirect influence.

We recap the notion of independence, and show how influence allows us to ascertain independence even when we do not have a complete representation of a distribution (e.g., we know its factorisation, but not its factors).

When can X influence Y ?

Can knowledge about X influence our beliefs about Y ?

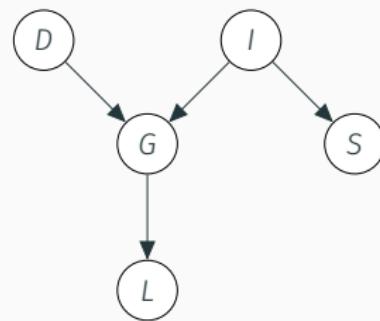


When can X influence Y ?

Can knowledge about X influence our beliefs about Y ?

Direct influence:

- $X \rightarrow Y$ e.g., $D \rightarrow G$

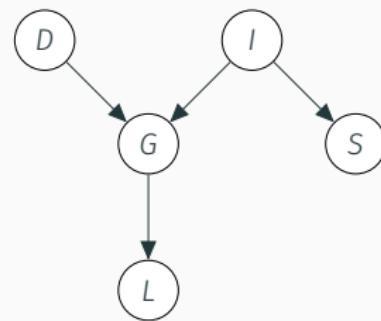


When can X influence Y ?

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Direct influence:

- $X \rightarrow Y$ e.g., $D \rightarrow G$ ✓ causal effect

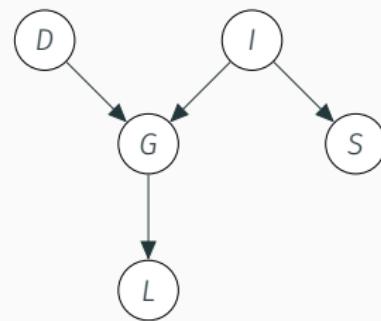


When can X influence Y ?

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Direct influence:

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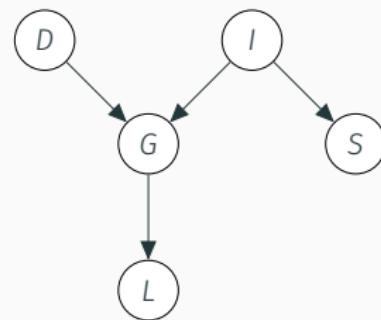


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When can X influence Y ?

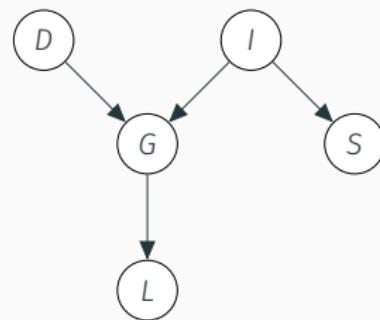
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- $X \leftarrow Y$ e.g., $G \leftarrow D$ ✓ evidential effect

Indirect influence:

- $X \rightarrow W \rightarrow Y$ e.g., $D \rightarrow G \rightarrow L$



When can X influence Y ?

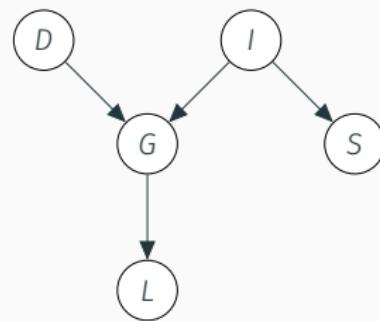
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indirect causal effect



When can X influence Y ?

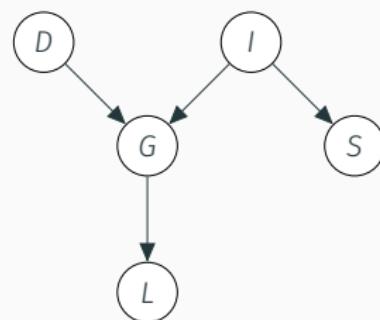
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Indirect influence:

- $X \rightarrow W \rightarrow Y$ e.g., $D \rightarrow G \rightarrow L$ ✓
indirect causal effect
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When can X influence Y ?

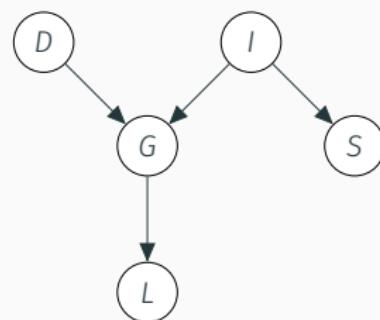
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- $X \leftarrow W \leftarrow Y$ e.g., $L \leftarrow G \leftarrow D$ ✓
indirect evidential effect



When can X influence Y ?

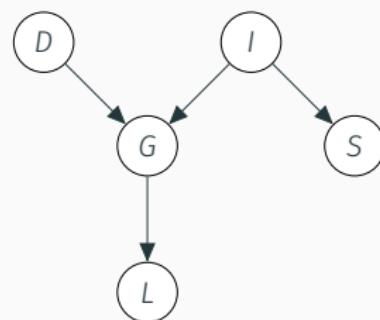
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- $X \leftarrow W \rightarrow Y$ e.g., $G \leftarrow I \rightarrow S$



When can X influence Y ?

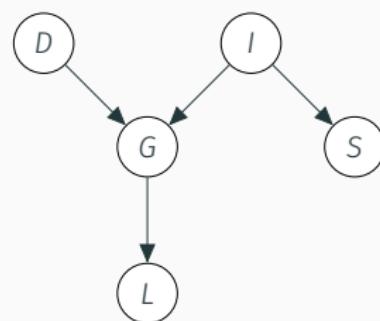
Can knowledge about X influence our beliefs about Y ?

Direct influence:

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- $X \leftarrow Y$ e.g., $G \leftarrow D$ ✓ evidential effect

Indirect influence:

- $X \rightarrow W \rightarrow Y$ e.g., $D \rightarrow G \rightarrow L$ ✓
indirect causal effect
- $X \leftarrow W \leftarrow Y$ e.g., $L \leftarrow G \leftarrow D$ ✓
indirect evidential effect
- $X \leftarrow W \rightarrow Y$ e.g., $G \leftarrow I \rightarrow S$ ✓
 X and Y are joint effects of a common cause W



When can X influence Y ?

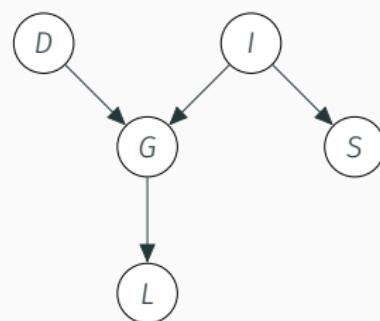
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- $X \leftarrow W \rightarrow Y$ e.g., $G \leftarrow I \rightarrow S$ ✓
 X and Y are joint effects of a common cause W
- $X \rightarrow W \leftarrow Y$ e.g., $D \rightarrow G \leftarrow I$



When can X influence Y ?

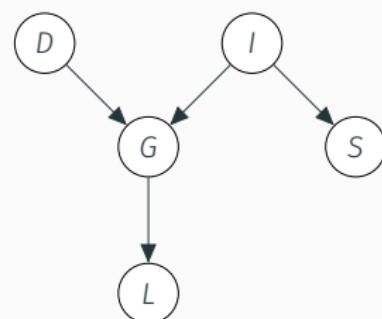
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Indirect influence:

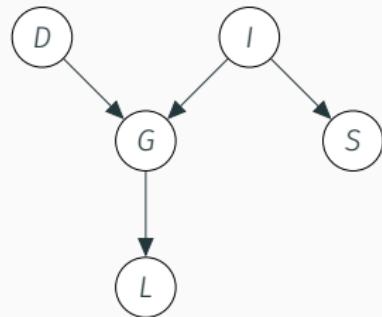
- $X \rightarrow W \rightarrow Y$ e.g., $D \rightarrow G \rightarrow L$ ✓
indirect causal effect
- $X \leftarrow W \leftarrow Y$ e.g., $L \leftarrow G \leftarrow D$ ✓
indirect evidential effect
- $X \leftarrow W \rightarrow Y$ e.g., $G \leftarrow I \rightarrow S$ ✓
 X and Y are joint effects of a common cause W
- $X \rightarrow W \leftarrow Y$ e.g., $D \rightarrow G \leftarrow I$ ✗
 X and Y are joint causes of a common effect W



v-structure

Can X influence Y given evidence about Z ?

Let us see if anything changes when we also have knowledge about an additional set of variables Z .

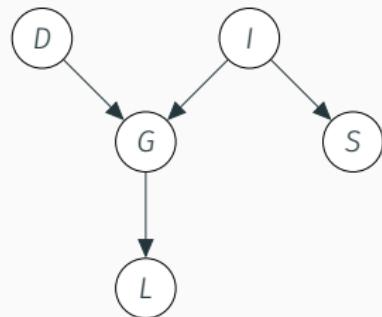


Can X influence Y given evidence about Z ?

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Direct influence: unaffected by other evidence

- $X \rightarrow Y$ e.g., $D \rightarrow G$ ✓
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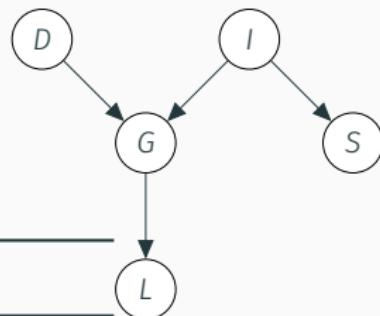


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- $X \leftarrow Y$ e.g., $G \leftarrow D$ ✓



Indirect influence: depends on W and Z

| pattern | example | $W \in Z$ | $W \notin Z$ |
|---------|---------|-----------|--------------|
|---------|---------|-----------|--------------|

$X \rightarrow W \rightarrow Y$ $D \rightarrow G \rightarrow L$

$X \leftarrow W \leftarrow Y$ $L \leftarrow G \leftarrow D$

$X \leftarrow W \rightarrow Y$ $G \leftarrow I \rightarrow S$

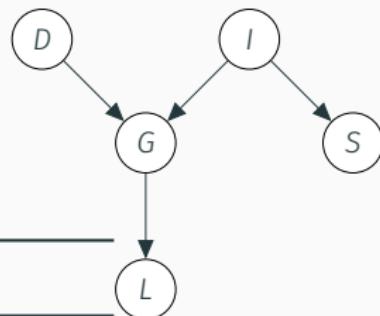
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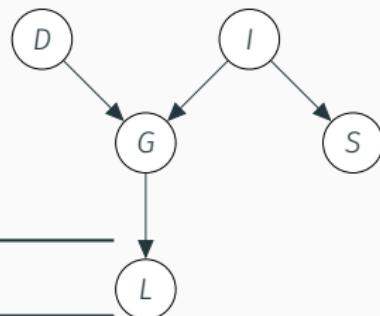
| pattern | example | $W \in Z$ | $W \notin Z$ |
|---------------------------------|---------------------------------|-----------|--------------|
| $X \rightarrow W \rightarrow Y$ | $D \rightarrow G \rightarrow L$ | ✗ | ✓ |
| $X \leftarrow W \leftarrow Y$ | $L \leftarrow G \leftarrow D$ | | |
| $X \leftarrow W \rightarrow Y$ | $G \leftarrow I \rightarrow S$ | | |
| $X \rightarrow W \leftarrow Y$ | $D \rightarrow G \leftarrow I$ | | |

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Indirect influence: depends on W and Z

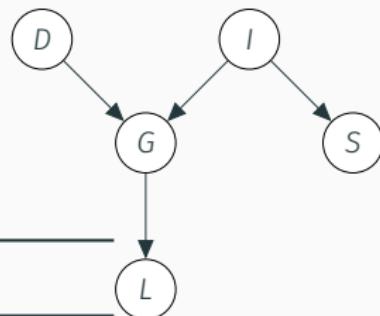
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| $X \rightarrow W \leftarrow Y$ | $D \rightarrow G \leftarrow I$ | | |

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- $X \leftarrow Y$ e.g., $G \leftarrow D$ ✓



Indirect influence: depends on W and Z

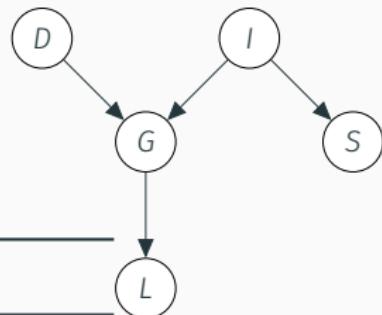
| pattern | example | $W \in Z$ | $W \notin Z$ |
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| $X \rightarrow W \rightarrow Y$ | $D \rightarrow G \rightarrow L$ | ✗ | ✓ |
| $X \leftarrow W \leftarrow Y$ | $L \leftarrow G \leftarrow D$ | ✗ | ✓ |
| $X \leftarrow W \rightarrow Y$ | $G \leftarrow I \rightarrow S$ | ✗ | ✓ |
| $X \rightarrow W \leftarrow Y$ | $D \rightarrow G \leftarrow I$ | | |

Can X influence Y given evidence about Z ?

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| pattern | example | $W \in Z$ | $W \notin Z$ |
|---------------------------------|---------------------------------|-----------|--|
| $X \rightarrow W \rightarrow Y$ | $D \rightarrow G \rightarrow L$ | ✗ | ✓ |
| $X \leftarrow W \leftarrow Y$ | $L \leftarrow G \leftarrow D$ | ✗ | ✓ |
| $X \leftarrow W \rightarrow Y$ | $G \leftarrow I \rightarrow S$ | ✗ | ✓ |
| $X \rightarrow W \leftarrow Y$ | $D \rightarrow G \leftarrow I$ | ✓ | ✗ e.g., with $Z = \{S\}$ ✓ e.g., with $Z = \{L\}$ |

The v-structure enables indirect influence of X on Y through W when Z contains W or any of its descendants.

Colliders

C is a **collider** in the v-structure (left) and a **non-collider** in the rest.



When C is a collider, observing it or any of its descendants **activates** the flow of influence between A and B.

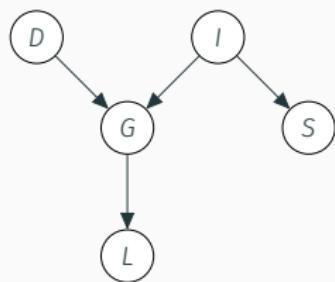
When C is a non-collider, observing it **blocks** the flow of influence between A and B.



In some textbooks, these patterns of junction are called collider (first), fork (second) and chain (third and fourth).

Trails

A **trail** (definition 2.16) is a sequence of nodes X_1, \dots, X_k connected by edges, ignoring the direction of the edges.



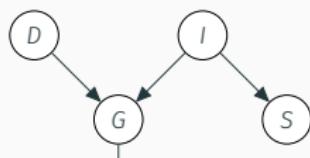
Examples

- (I, G, L)
- (D, G, L)
- (D, G, I)
- (D, G, I, S)

Active Trails (definition 3.6)

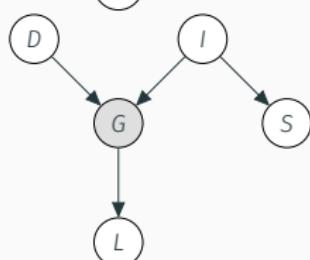
A trail is **active** if

- for any v-structure, the collider or any of its descendants is observed
- no other node along the trail is observed
(which implies that non-colliders are not observed)



Examples

- (I, G, L) ✓
- (D, G, L) ✓
- (D, G, I) ✗
- (D, G, I, S) ✗



Examples

- (I, G, L) ✗
- (D, G, L) ✗
- (D, G, I) ✓
- (D, G, I, S) ✓

Independence

A joint distribution P satisfies independence between the random variables X and Y , which we denote by $P \models A \perp B$, if:

- $P(X, Y) = P(X)P(Y)$
- $P(X|Y) = P(X)$
- $P(Y|X) = P(Y)$

Independence

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- $P(X, Y) = P(X)P(Y)$
- $P(X|Y) = P(X)$
- $P(Y|X) = P(Y)$

A joint distribution P satisfies independence of the rvs X and Y given Z , which we denote by $P \models (X \perp Y | Z)$, if:

- $P(X, Y|Z) = P(X|Z)P(Y|Z)$
- $P(X|Y, Z) = P(X|Z)$
- $P(Y|X, Z) = P(Y|Z)$

These definitions are equivalent, if one is met they are all met.

Testing independence when we know all relevant factors

| I | D | $P(D I)$ |
|-------|-------|----------|
| i^0 | d^0 | 0.6 |
| i^0 | d^1 | 0.4 |
| i^1 | d^0 | 0.6 |
| i^1 | d^1 | 0.4 |

Does $P \models D \perp I$ hold?

Testing independence when we know all relevant factors

| I | D | $P(D I)$ |
|-------|-------|----------|
| i^0 | d^0 | 0.6 |
| i^0 | d^1 | 0.4 |
| i^1 | d^0 | 0.6 |
| i^1 | d^1 | 0.4 |

Does $P \models D \perp I$ hold?

| G | I | D | $P(D I, G)$ |
|-------|-------|-------|-------------|
| g^1 | i^0 | d^0 | 0.9 |
| g^1 | i^0 | d^1 | 0.1 |
| g^1 | i^1 | d^0 | 0.7297 |
| g^1 | i^1 | d^1 | 0.2703 |
| g^2 | i^0 | d^0 | 0.7059 |
| g^2 | i^0 | d^1 | 0.2941 |
| g^2 | i^1 | d^0 | 0.2857 |
| g^2 | i^1 | d^1 | 0.7143 |
| g^3 | i^0 | d^0 | 0.3913 |
| g^3 | i^0 | d^1 | 0.6087 |
| g^3 | i^1 | d^0 | 0.1304 |
| g^3 | i^1 | d^1 | 0.8696 |

Does $P \models (D \perp I | G)$ hold?

Testing independence when we know all relevant factors

| I | D | $P(D I)$ |
|-------|-------|----------|
| i^0 | d^0 | 0.6 |
| i^0 | d^1 | 0.4 |
| i^1 | d^0 | 0.6 |
| i^1 | d^1 | 0.4 |

Does $P \models D \perp I$ hold?

What if we do not know these factors in tabular form, but we have a tabular view of the joint distribution $P(D, I, G, S, L)$, as shown in Table ???

| G | I | D | $P(D I, G)$ |
|-------|-------|-------|-------------|
| g^1 | i^0 | d^0 | 0.9 |
| g^1 | i^0 | d^1 | 0.1 |
| g^1 | i^1 | d^0 | 0.7297 |
| g^1 | i^1 | d^1 | 0.2703 |
| g^2 | i^0 | d^0 | 0.7059 |
| g^2 | i^0 | d^1 | 0.2941 |
| g^2 | i^1 | d^0 | 0.2857 |
| g^2 | i^1 | d^1 | 0.7143 |
| g^3 | i^0 | d^0 | 0.3913 |
| g^3 | i^0 | d^1 | 0.6087 |
| g^3 | i^1 | d^0 | 0.1304 |
| g^3 | i^1 | d^1 | 0.8696 |

Does $P \models (D \perp I | G)$ hold?

Watch Out!

Whichever definition we pick, it's necessary to **test all relevant assignments**. Example:

| A | B | $P(B A)$ |
|-------|-------|----------|
| a^1 | b^0 | 0.7 |
| a^1 | b^1 | 0.3 |
| a^2 | b^0 | 0.7 |
| a^2 | b^1 | 0.3 |
| a^3 | b^0 | 0.4 |
| a^3 | b^1 | 0.6 |

Does $P \models B \perp A$ hold?

Watch Out!

Whichever definition we pick, it's necessary to **test all relevant assignments**. Example:

| A | B | $P(B A)$ |
|-------|-------|----------|
| a^1 | b^0 | 0.7 |
| a^1 | b^1 | 0.3 |
| a^2 | b^0 | 0.7 |
| a^2 | b^1 | 0.3 |
| a^3 | b^0 | 0.4 |
| a^3 | b^1 | 0.6 |

Does $P \models B \perp A$ hold?

Finding that $P_{B|A=a^1}$ and $P_{B|A=a^2}$ are the same is not enough to ascertain independence.

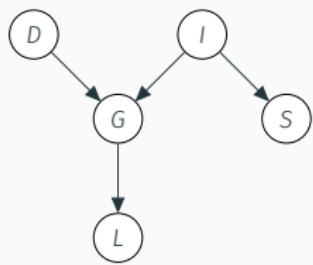
The same applies when testing *conditional* independence.

BNs and Independence

A BN structure \mathcal{G} encodes a set of (conditional) independences.

The more elementary ones are readily recognisable from the graph structure, they are called the *local independencies* of \mathcal{G} , denoted $\mathcal{I}_l(\mathcal{G})$.

$\mathcal{I}_l(\mathcal{G})$ is the set of statements of the kind $X_i \perp \text{NonDesc}_{\mathcal{G}}(X_i) \mid \text{Pa}_{\mathcal{G}}(X_i)$



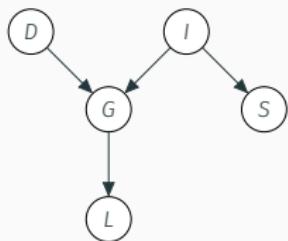
For the Student BN, $\mathcal{I}_l(\mathcal{G}) =$

- $D \perp I, S$
- $I \perp D$
- $S \perp D, G, L \mid I$
- $G \perp S \mid D, I$
- $L \perp D, I, S \mid G$

But how can we ascertain all conditional independences implied by \mathcal{G} ? For example, if P factorises over \mathcal{G} , does that imply that $P \models (D \perp S \mid L)$?

BNs and Independence

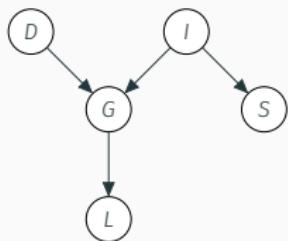
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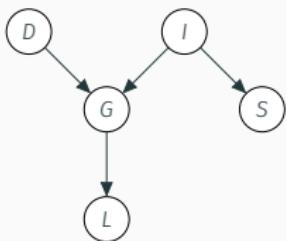


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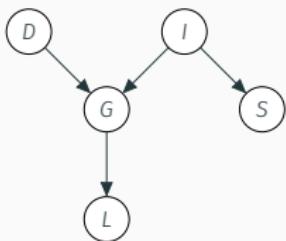
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First idea. Use prob. calculus and test by checking the relevant distributions against any of the definitions of independence.

Second idea. Use *flow of influence* (namely, active trails) to test for independence by analysis of the BN structure alone. In the example, observing L activates the v-structure so $P \not\models (D \perp S | L)$.

Modifying the Student Example with Additional Variables

We further assume that the student gets a Job (yes j^1 , or no j^0) depending on S and G , and we regard the student's own Happiness (happy h^1 , or unhappy h^0) as dependant on G and J .

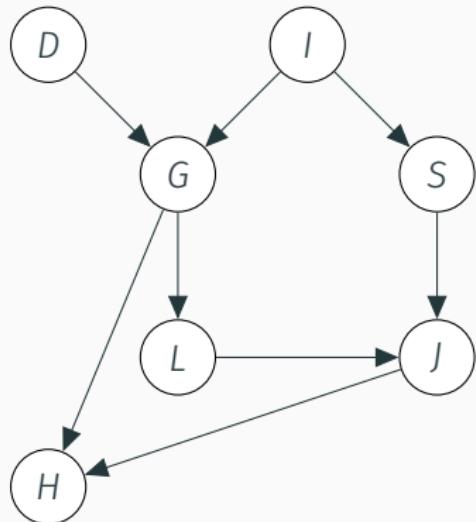
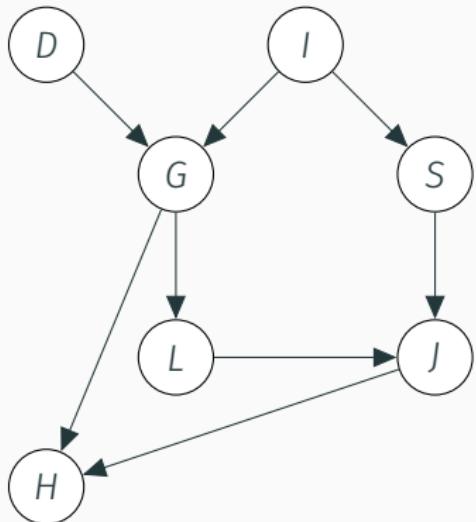


Figure 3: The Extended Student Example

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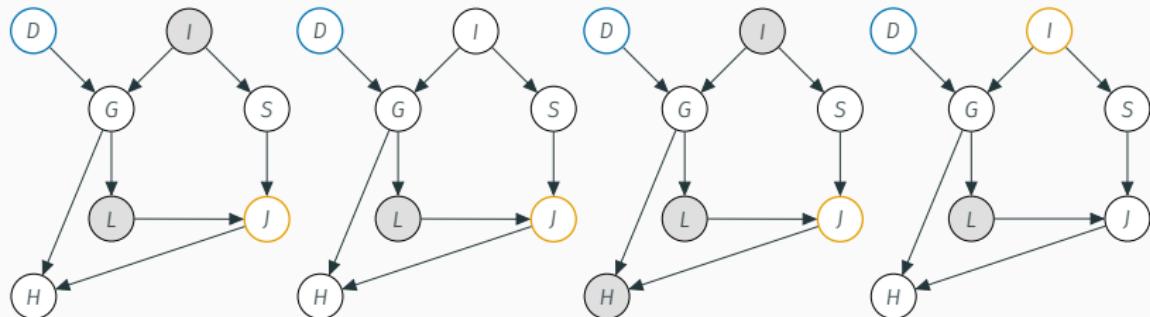
At this point, we do not have CPDs for this DAG. Yet, we can reason about independencies.

Figure 3: The Extended Student Example

Directed Separation (section 3.3.1, definition 3.7)

We say that X and Y are d-separated given Z , denoted $d\text{-sep}_G(X; Y|Z)$, if there is no active trail between any node $X \in X$ and $Y \in Y$ given Z .

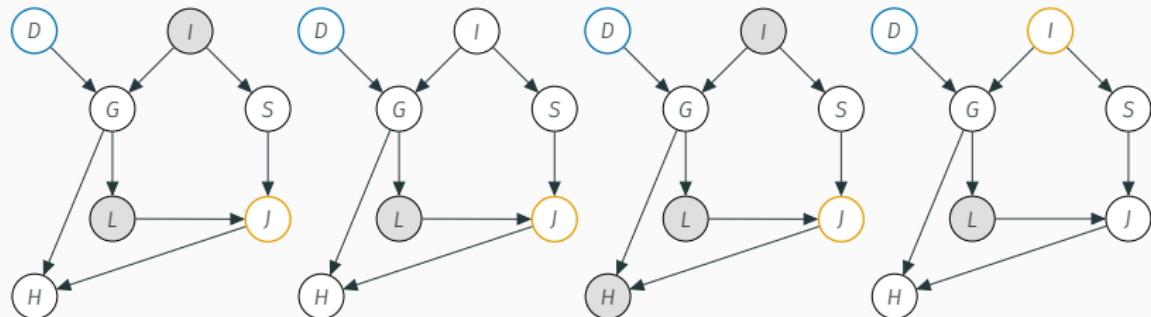
Examples:



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Examples:



$d\text{-sep}(D; J|L, I)$ ✓

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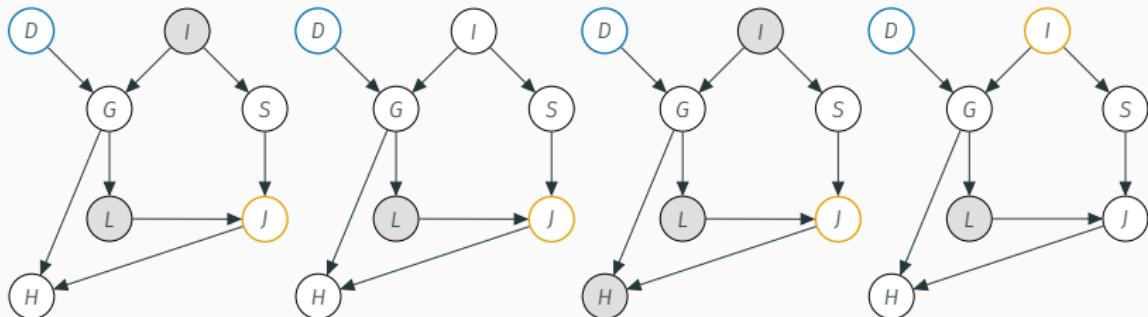
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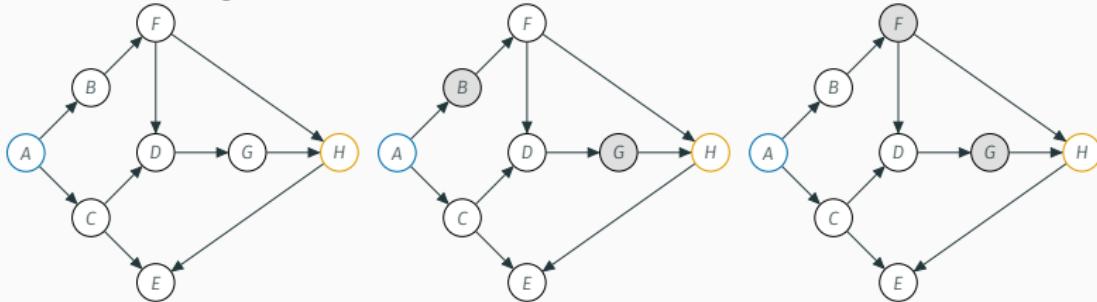
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D-separation in \mathcal{G} implies conditional independence in any P that factorises over \mathcal{G} .

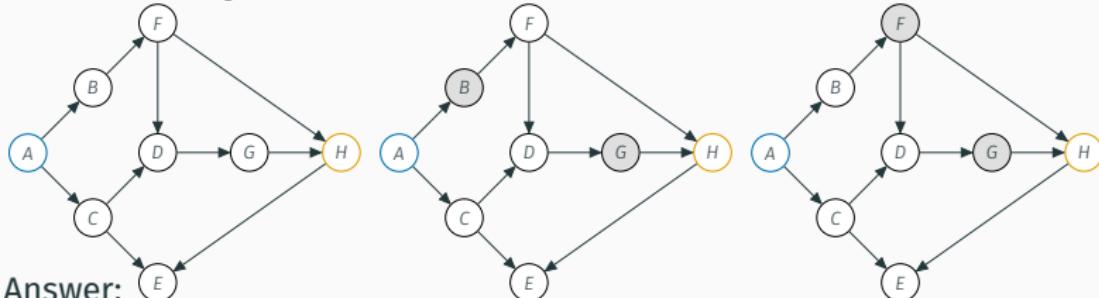
Exercises

1) Assess $d\text{-sep}_G(\text{X}; \text{Y} | \text{Z})$ in each case:



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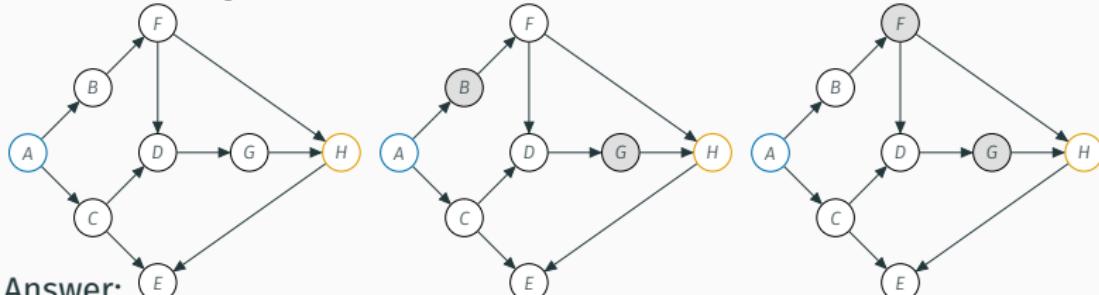


Answer:

- $d\text{-sep}(A; H)$ ✗ at least A B F H is active
- $d\text{-sep}(A; H|B, G)$ ✗ at least ACDFH is active (observed G activates the v-structure at D)
- $d\text{-sep}(A; H|F, G)$ ✓ F is an observed non-collider in all trails, same for G, and E is an inactive collider.

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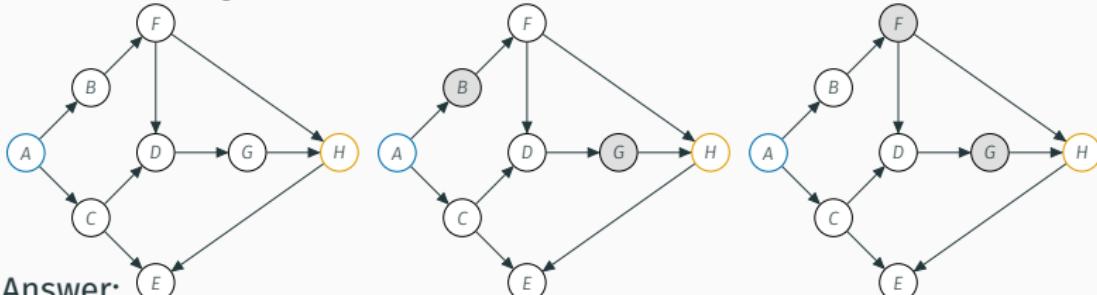
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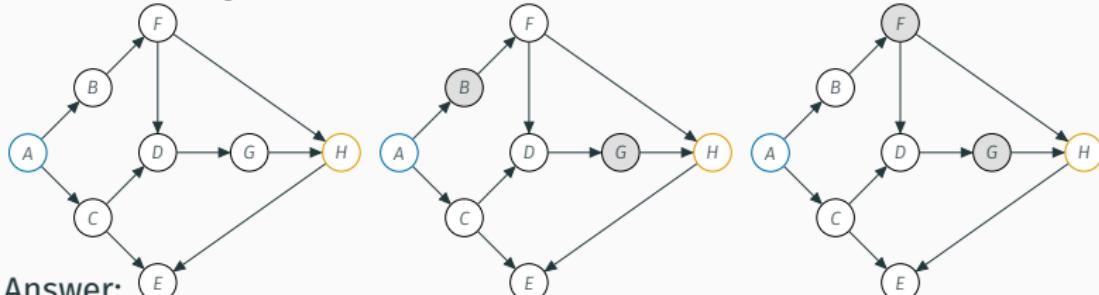
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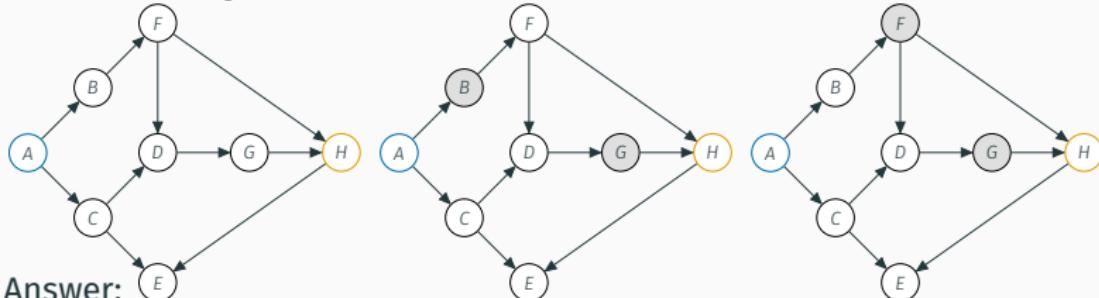
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Answer: (B, C) or (C, F) or (D, F) or (F, G).

I know how to test independence, why learn about d-sep?

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D-separation in \mathcal{G} gives us a complete view of all the independencies that hold for *any* distribution that factorises over \mathcal{G} .

This has impacts on

- inference, e.g. telling us what computations we need to perform or may safely skip when we need marginals and conditionals
- learning, e.g. telling us what parameters are necessary or superfluous

Probability Calculus or D-Separation?

Both are provably correct, so you can decide based on convenience.

- Probability calculus can be tedious and we may need access to the actual probability factors.
- D-separation uses the graph structure alone, the actual probability factors are not needed.
- Enumerating trails and testing for activation can be tedious, but graph algorithms are systematic and can be rather efficient.

Local and Global Independencies

The local independencies implied by the BN structure \mathcal{G} is the set

$$\mathcal{I}_l(\mathcal{G}) = \{X_i \perp \text{NonDesc}_{\mathcal{G}}(X_i) \mid \text{Pa}_{\mathcal{G}}(X_i) : \text{for all } X_i\}$$

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In a BN, local independencies *imply* the global ones and vice-versa.

- If a distribution P factorises over \mathcal{G} , then it complies with the statements in $\mathcal{I}_l(\mathcal{G})$.
- Any distribution P that complies with $\mathcal{I}_l(\mathcal{G})$ also complies with the statements in $\mathcal{I}(\mathcal{G})$.

Summary

- Influence may flow through trails regardless of directionality, but it is blocked by the v-structure, unless the collider or any of its descendants is observed, and it is blocked by observation of a non-collider.
- With an explicit representation of P , we can ascertain any independence via probability calculus (i.e., we infer the relevant factors from the joint distribution and test independence).
- Without requiring an explicit representation of P , and simply knowing that it factorises over the BN structure \mathcal{G} , we can ascertain any independence via d-separation.

What's Next?

WC2: exercises (reasoning and influence).

Friday: P2 deadline.

Module 2: Markov Networks.

References

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