

# Reasoning under Uncertainty

Introduction to Artificial Intelligence

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# Uncertainty

## Toothache (T) and Cavity (C)

Would like to say:

If T then C is likely ( $T \Rightarrow C$ )

There are various ways to model this. Here: [statistical interpretation](#)

“ $T \Rightarrow C$  has probability 0.8.”  
(80% of those with T have C.)

## $\Rightarrow$ Probability Theory

We only need basic discrete Probability Theory (suffices for most AI purposes).

We often abbreviate probability as P.

# Probability Distributions

$P(A)$  is the probability that proposition  $A$  holds, where  $A$  is a Boolean combination ( $\wedge, \vee, \neg$ ) of atomic propositions.

We also allow  $X = n$  as an atomic proposition, where  $X$  is called a **random variable** and  $n$  is taken from a discrete domain.

## Example:

Random variable *weather* with values from the sequence  $\langle \text{sunny, rain, cloudy, snow} \rangle$ .

$$P(\text{weather} = \text{sunny}) = 0.7$$

$$P(\text{weather} = \text{rain}) = 0.2$$

$$P(\text{weather} = \text{cloudy}) = 0.08$$

$$P(\text{weather} = \text{snow}) = 0.02$$

$$P(\text{weather}) = (0.7; 0.2; 0.08; 0.02)$$

stands for the **probability distribution** of the random variable *weather*.

# Probability Theory and Decisions

Let  $A_1$ ,  $A_2$  und  $A_3$  be plans to get to the airport ontime. Let  $P(A_i)$  be the probability that executing  $A_i$  allows us to get to the airport ontime.

$$P(A_1) = 0.9 \quad (\text{Leave 2 hour before departure})$$

$$P(A_2) = 0.96 \quad (\text{Leave 3 hours before departure})$$

$$P(A_3) = 0.9999 \quad (\text{Leave 12 hours before departure})$$

**Note:** The maximum probability need not be optimal. One needs to consider the **utility** of actions as well.

Decision Theory = Probability Theory + Utility Theory.

# The Axioms of Probability Theory

- 1  $P$  is a real number between 0 and 1. ( $0 \leq P(A) \leq 1$ )
- 2  $P(\text{true}) = 1$ ,  $P(\text{false}) = 0$
- 3  $P(A \vee B) = P(A) + P(B) - P(A \wedge B)$

# Why Are These Axioms Reasonable?

de Finetti (1930s) said that someone who believes  $P(A)$  should be willing to bet on  $P(A)$ !

## “Theorem” (de Finetti):

Someone who does not follow the axioms of probability theory will lose his or her bet!

## Example:

Player 1		Player 2	
Proposition	Belief	Bets on	
A	0.4	A	4 to 6
B	0.3	B	3 to 7
$A \vee B$	0.8	$\neg(A \vee B)$	2 to 8

If A happens  
the P2 wins €6  
else P1 wins €4

# Conditional Probabilities (1)

## Rolling dice

$P(\text{roll}=3) = 1/6$ . Let  $E = \text{"Roll is divisible by 3."}$

Then we obtain the **conditional probability**:

$$P(\text{roll}=3 \mid E) = 1/2.$$

$E$  is also called the **evidence**.

$E$  often plays the role of **background knowledge** (similar to a propositional knowledge base).

**Prior:** Probability before evidence.

**Posterior:** Probability after the evidence.

## Conditional Probabilities (2)

$P(C \mid T) = 0.8$  is read as “the prob. to have C when T is given is 0.8.”

### Nonmonotonicity:

$$P(\text{Flies} \mid \text{Bird}) = 0.99$$

$$P(\text{Flies} \mid \text{Bird} \wedge \text{Antarctica}) = 0.4$$

$$P(\text{Flies} \mid \text{Bird} \wedge \text{Antarctica} \wedge \text{Albatross}) = 0.999$$

$$P(A \mid B) = \frac{P(A \wedge B)}{P(B)} \quad \text{or} \quad P(A \wedge B) = P(A \mid B) \cdot P(B)$$

(Product Rule)

$\mathbf{P(X,Y) = P(X \mid Y) \cdot P(Y)}$  stands for a system of equations of the form:

$$P(X=x_i \wedge Y=y_j) = P(X=x_i \mid Y=y_j) \cdot P(Y=y_j)$$

for all  $x_i, y_j$  of the domains of X and Y.



# Joint Distributions

Let  $X_1, X_2, \dots, X_n$  be random variables. An **atomic event** is an assignment of values to all variables  $X_i$ .

The joint distribution  $\mathbf{P}(X_1, X_2, \dots, X_n)$  assigns a probability to all atomic events.

## Toothache-Cavity Example:

	T	$\neg T$
C	0.04	0.06
$\neg C$	0.01	0.89

- Atomic events exclude one another.
- $\sum_{x_1, \dots, x_n} \mathbf{P}(X_1 = x_1, \dots, X_n = x_n) = 1$
- From the table one can read off all probabilities.
- **Problem:** Table grows exponentially in the number of variables. Thus probability-based systems work directly with conditional probs.

# Bayes Rule

$$P(A \wedge B) = P(A | B) \cdot P(B)$$

$$P(A \wedge B) = P(B | A) \cdot P(A)$$

Thus we have:

$$P(A | B) \cdot P(B) = P(B | A) \cdot P(A),$$

from which we obtain:

Bayes Rule:

*for diagnostic reasoning*

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

*causal relationship*

*A: symptom / effect*

*B: cause / disease*

For variables X and Y we write

$$P(Y | X) = \frac{P(X | Y) \cdot P(Y)}{P(X)},$$

which again corresponds to a system of equations.

Often there is additional evidence E:

$$P(Y | X, E) = \frac{P(X | Y, E) \cdot P(Y | E)}{P(X | E)}$$

# Normalisation

For

$$\mathbf{P(Y \mid X)} = \frac{\mathbf{P(X \mid Y) \cdot P(Y)}}{\mathbf{P(X)}},$$

$1/\mathbf{P(X)}$  only plays the role of a normalising constant so that the right-hand side sums to 1 over all values of  $Y$ .

In the literature one therefore often finds the following form:

$$\mathbf{P(Y \mid X)} = \alpha \cdot \mathbf{P(X \mid Y) \cdot P(Y)}.$$

In practice one usually calculates the unnormalised case first, and then looks for an appropriate  $\alpha$ .

# Combining Evidence

How does one combine evidence consisting of several variables??

Example: ( $A = \text{"Catch"}$ )

How do we get from  $P(C \mid T)$  to  $P(C \mid T \wedge A)$ , that is, how does the probability of cavity change if one also finds out that there is a catch.

According to Bayes we have:

$$P(C \mid T \wedge A) = \frac{P(T \wedge A \mid C) \cdot P(C)}{P(T \wedge A)}.$$

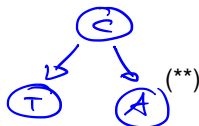
The term  $P(T \wedge A \mid C)$  is problematic. For  $n$  variables we would need to compute  $2^n$  combinations. If there are many variables as evidence, we have exponential growth!

# Bayesian Update

An elegant and efficient solution is possible when certain **conditional independence assumptions** can be made:

$$P(A \mid C \wedge T) = P(A \mid C)$$

*$P(T \mid C \wedge A) = P(T \mid C)$*



“If C is given, then T and A are independent of each other.”

In that case, the evidence can be added one by one using a simple iterative method. According to Bayes (slightly reformulated):

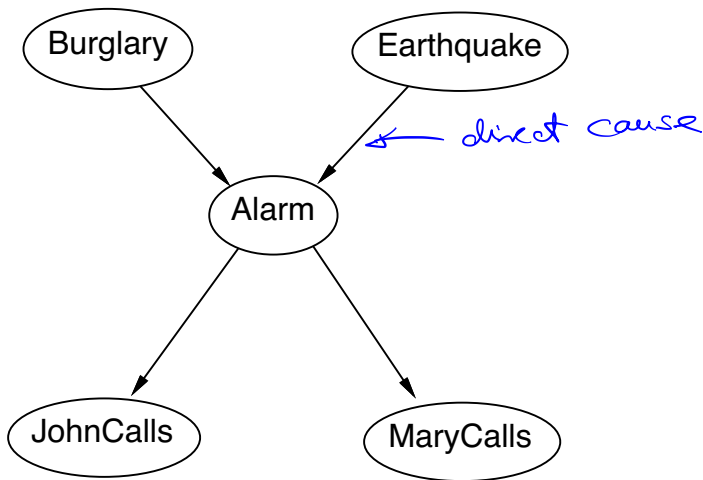
$$P(C \mid T \wedge A) = P(C) \cdot \frac{P(T \mid C)}{P(T)} \cdot \frac{P(A \mid T \wedge C)}{P(A \mid T)}$$

Together with (\*\*) we then obtain

$$P(C \mid T \wedge A) = P(C \mid T) \cdot \frac{P(A \mid C)}{P(A \mid T)}$$

In general, for multi-valued X, Y, Z:

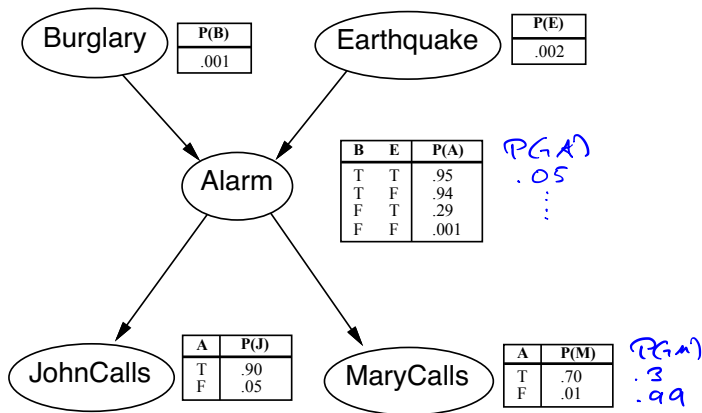
$$\mathbf{P(X \mid Y, Z)} = \alpha \cdot \mathbf{P(X)} \cdot \mathbf{P(Y \mid X)} \cdot \mathbf{P(Z \mid X)}$$



**Idea:** Only represent **causal** connections. Surprisingly simple in many applications!

## Belief Networks (2)

Same Example with labelled nodes  $P(X \mid \text{Parents}(X))$ :



# Belief Networks in General

A belief network is an **acyclic graph** where

- the nodes represent random variables;
- each node  $X$  is labelled with the conditional probabilities

$$\mathbf{P}(X \mid \text{Parents}(X)),$$

where  $Y$  is in  $\text{Parents}(X)$  if there is an edge from  $Y$  to  $X$ .  
(The label is called a Conditional Probability Table (CPT).)

The topology of the network should be chosen in such a way that for each edge from  $Y$  to  $X$ , the parent node  $Y$  has **direct causal influence on  $X$** .



# Belief Networks and Joint Distributions

Let  $X_1, \dots, X_n$  be random variables. We abbreviate  $P(X_1 = x_1 \wedge \dots \wedge X_n = x_n)$  as  $P(x_1, \dots, x_n)$ .

We can rewrite the joint distribution in the following way:

$$P(x_1, \dots, x_n) = P(x_n | x_{n-1}, \dots, x_1) \times P(x_{n-1}, \dots, x_1)$$

Applying this rewriting recursively we get

$$P(x_1, \dots, x_n) = \prod_{i=1}^n P(x_i | \cancel{x_{i-1}, \dots, x_1})$$

*Parents( $x_i$ )*

A Belief network is a **correct representation of a joint distribution** if

$$P(X_i | X_{i-1}, \dots, X_1) = P(X_i | \text{Parents}(X_i)) \text{ and } \text{Parents}(X_i) \subseteq \{X_{i-1}, \dots, X_1\}.$$

In other words, each node must be **conditionally independent of its predecessors given its parents**.

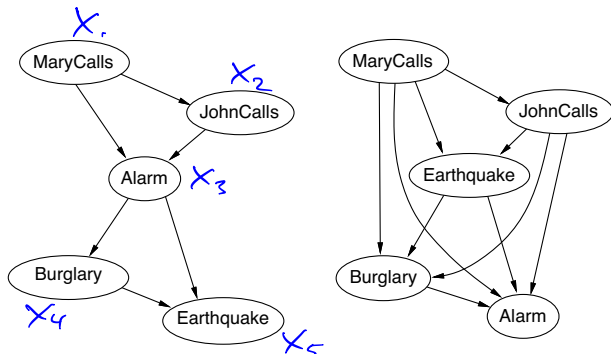
# Constructing a Belief Network

- 1 Choose the relevant random variables that describe your application.
- 2 Choose an ordering  $X_1, X_2, \dots, X_n$  for those variables.
- 3 **While** there are still variables to consider **do**
  - Choose the least  $X_i$  and create a node in the network
  - $\text{Parents}(X_i) :=$  minimal set so that the following holds:

$$\mathbf{P}(X_i \mid X_{i-1}, \dots, X_1) = \mathbf{P}(X_i \mid \text{Parents}(X_i))$$

- Create a CPT for  $X_i$

# The Ordering of Nodes Matters



A bad choice in the ordering of the variables leads to large networks.

Orderings in the examples:

**Left:** MaryCalls, JohnCalls, Alarm, Burglary, Earthquake.

**Right:** MaryCalls, JohnCalls, Earthquake, Burglary, Alarm.

## d-Separation (1)

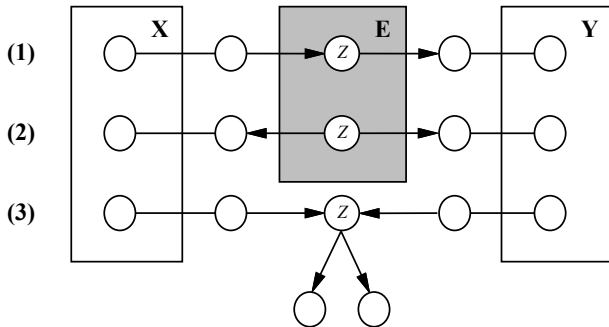
direction - dependent  
separation

A set of nodes  $\mathbf{E}$  is said to **d-separate** the sets of nodes  $\mathbf{X}$  and  $\mathbf{Y}$  iff **every undirected path** from a node in  $\mathbf{X}$  to a node in  $\mathbf{Y}$  is **blocked** by  $\mathbf{E}$ . Blocking means that there is a node  $Z$  on this path such that one of the following conditions hold:

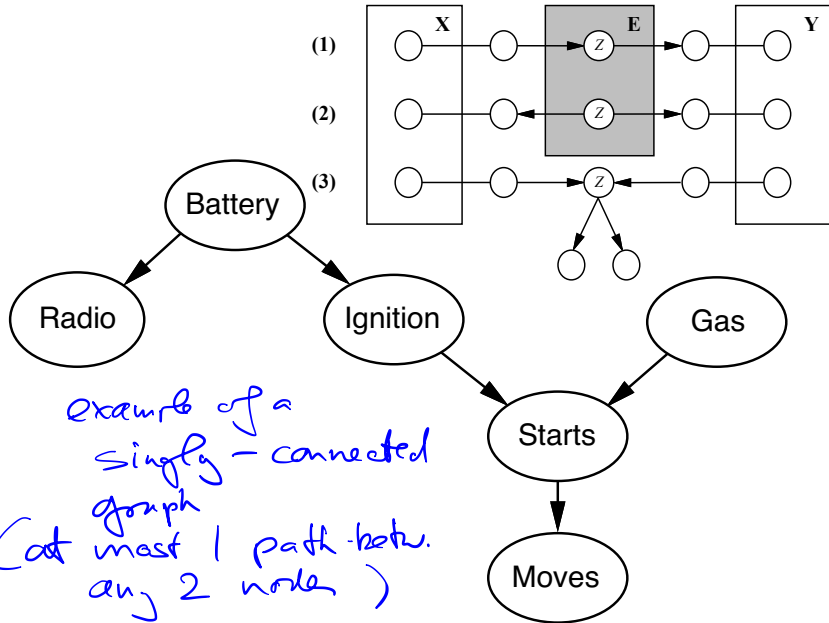
- 1  $Z \in \mathbf{E}$  and one directed edge on the path leads into  $Z$  and another points away from  $Z$ .
- 2  $Z \in \mathbf{E}$  and both edges point away from  $Z$ .
- 3 Neither  $Z$  nor any of its successors are in  $\mathbf{E}$  and both edges connected to  $Z$  on the path lead into  $Z$ .

## d-Separation (2)

3 ways of blocking paths from X to Y:



# Examples for d-Separation



# Why d-Separation is Important

## Theorem (Judea Pearl):

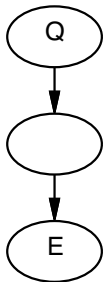
If  $\mathbf{E}$  d-separates  $\mathbf{X}$  from  $\mathbf{Y}$ , then  $\mathbf{X}$  is independent of  $\mathbf{Y}$  given  $\mathbf{E}$ .

**Note:** d-separation

- can be computed in **polynomial time**;
- is **incomplete**, that is, not every conditional independence is detected;
- is nevertheless sufficient for a number of inference algorithms.

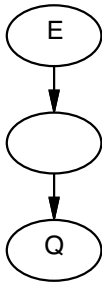
# Kinds of Inferences in Belief Networks

$$P(Q|E)$$



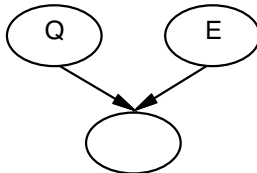
**Diagnostic**

$$P(B|J) = .016$$
$$P(B|A) = .376$$



**Causal**

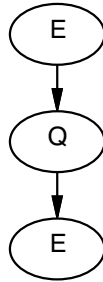
$$P(J|B) = .86$$



**(Explaining Away)**

**Intercausal**

$$P(B|A, E) = .003$$



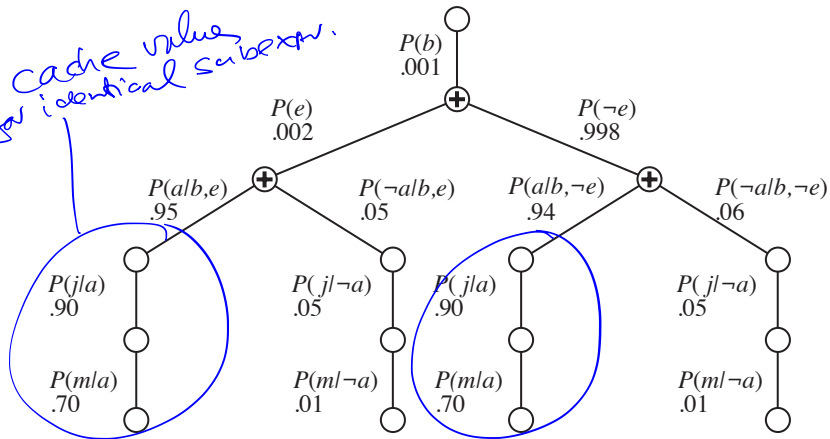
**Mixed**

$$P(A|J, \neg E) = .03$$



# Example Computation

cache values  
for identical subexp.



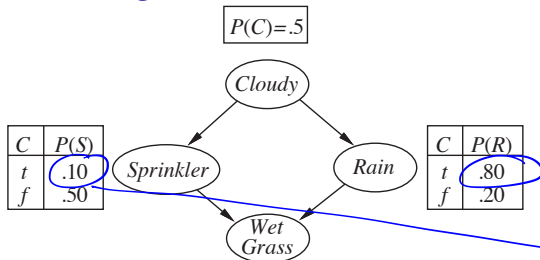
# Computational Complexity

The problem is **NP-hard** for multiply connected networks.

(Actually, the problem is at least as hard as enumerating all satisfying assignments of a propositional formula (**#P-hard**), which is strictly harder than NP-completeness.)

It is **linear** in the case of singly connected networks.

# Clustering

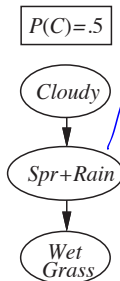


CPT  
may grow  
exponentially  
in # merged  
nodes

.8 x .1

S	R	P(W)
t	t	.99
t	f	.90
f	t	.90
f	f	.00

S+R	P(W)
t t	.99
t f	.90
f t	.90
f f	.00



C	P(S+R=x)			
	tt	tf	ft	ff
t	.08	.02	.72	.18
f	.10	.40	.10	.40