

# CS 5/7320

## Artificial Intelligence

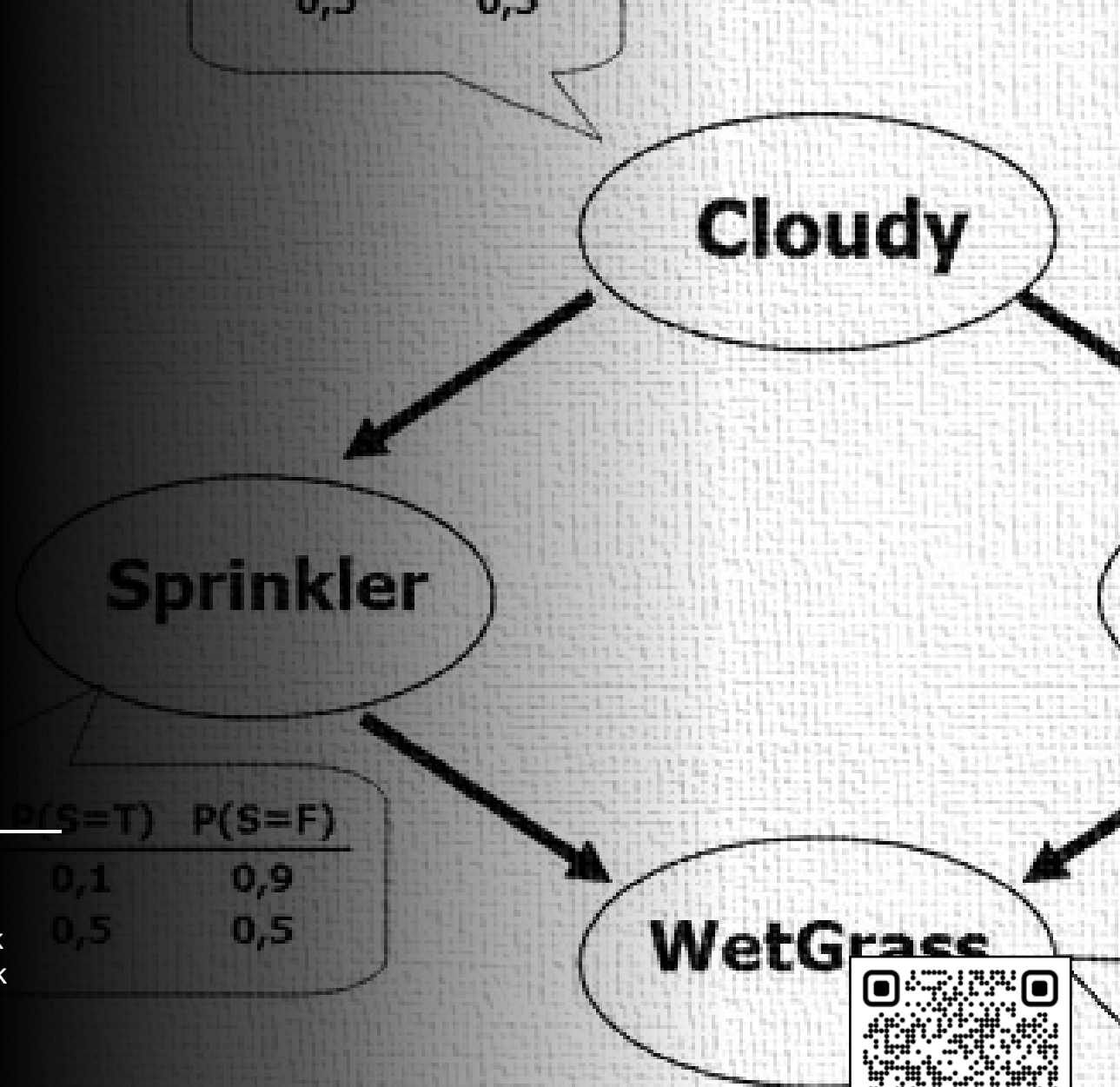
### Probabilistic Reasoning: Bayesian Networks

#### AIMA Chapter 13

Slides by Michael Hahsler  
based on slides by Svetlana Lazepnik  
with figures from the AIMA textbook



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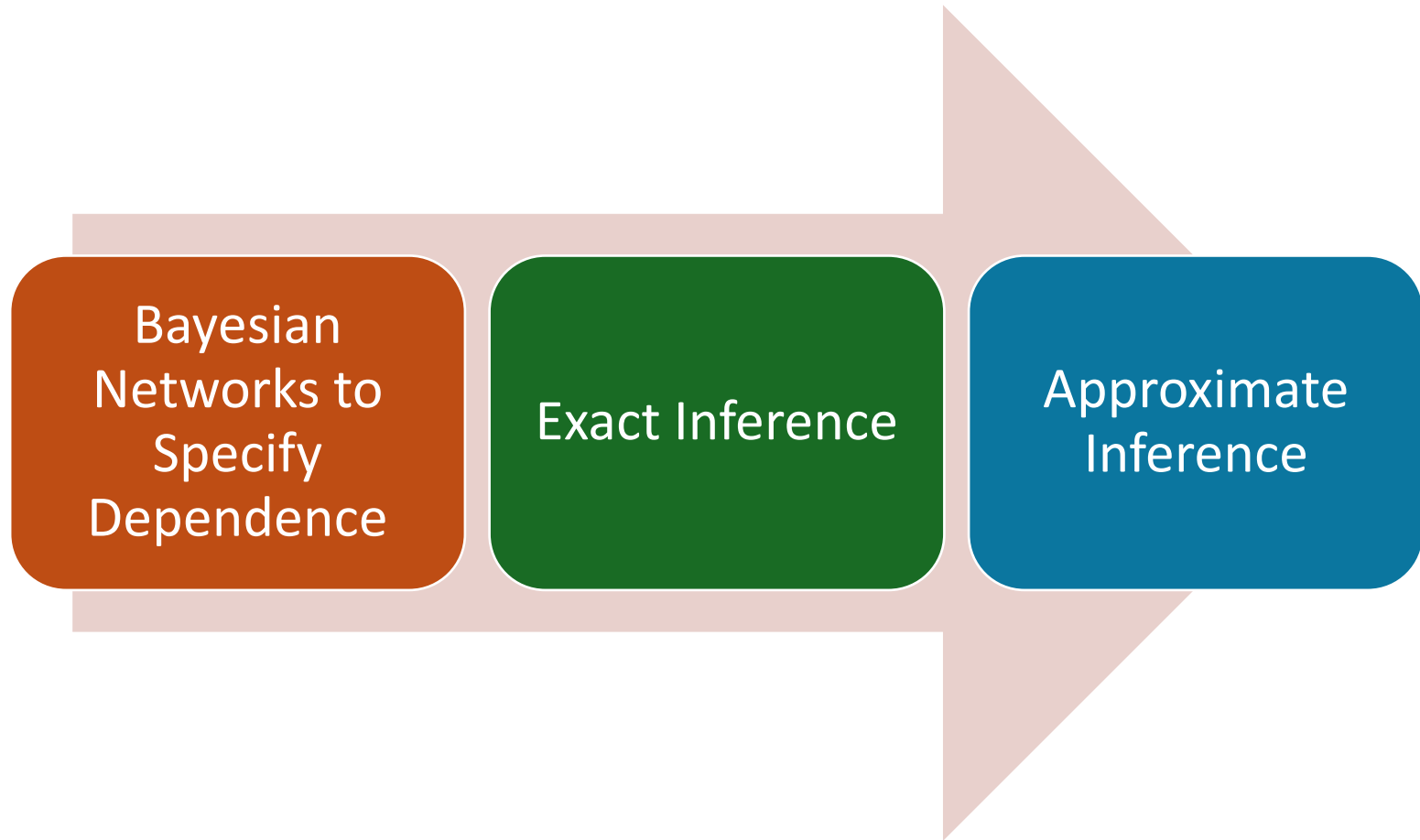


Online Material

# Probability Theory Recap

- Notation: Prob. of an event  $P(X = x) = P(x)$   
Prob. distribution  $\mathbf{P}(X) = \langle P(X = x_1), P(X = x_2), \dots, P(X = x_n) \rangle$
- Product rule  $P(x, y) = P(x|y)P(y)$
- Chain rule  $\mathbf{P}(X_1, X_2, \dots, X_n) = \mathbf{P}(X_1)\mathbf{P}(X_2|X_1)\mathbf{P}(X_3|X_1, X_2) \dots$   
 $= \prod_{i=1}^n \mathbf{P}(X_i|X_1, \dots, X_{i-1})$
- Conditional probability  $P(x|y) = \frac{P(x, y)}{P(y)} = \alpha P(x, y)$
- Marginal distribution given  $\mathbf{P}(X, Y)$   
 $\mathbf{P}(X) = \sum_y \mathbf{P}(X, y)$  (called marginalizing out  $Y$ )
- Independence
  - $X \perp\!\!\!\perp Y$ :  $X, Y$  are independent (written as  $X \perp\!\!\!\perp Y$ ) if and only if:  
 $\forall x, y: P(x, y) = P(x)P(y)$
  - $X \perp\!\!\!\perp Y|Z$ :  $X$  and  $Y$  are conditionally independent given  $Z$  if and only if:  
 $\forall x, y, z: P(x, y|z) = P(x|z)P(y|z)$

# Contents



**Cloudy**

**Sprinkler**

**Rain**

**WetGrass**

# Bayesian Networks

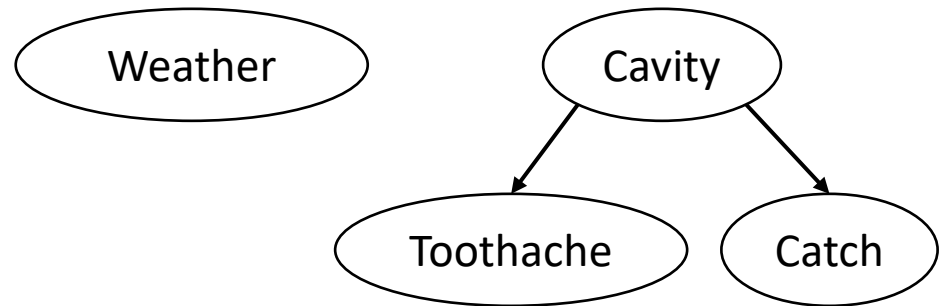
Modeling a Joint Distribution

C	P
T	
F	

C	P(S=T)	P(S=F)
T	0,1	0,9
F	0,5	0,5

S	R	P(W)
T	T	0,9
T	F	0,1
F	T	0,5
F	F	0,5

# Bayesian Networks (aka Belief Networks)



A type of graphical model.



A way to specify dependence between random variables.



A compact specification of a full joint probability distribution.

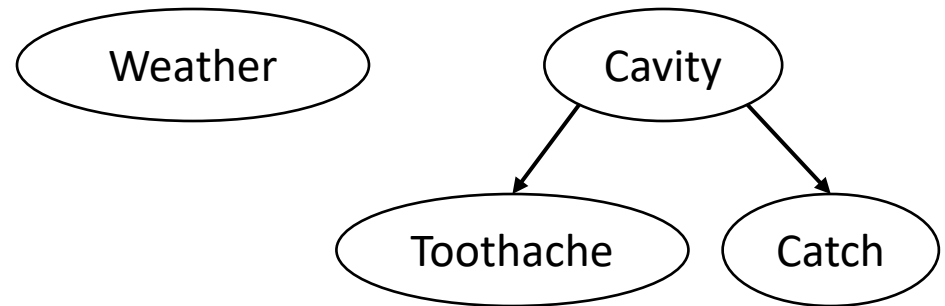


A general and important model to reason with uncertainty in AI.

# Structure of Bayesian Networks

## Nodes: Random variables

- Can be assigned (observed) or unassigned (unobserved)



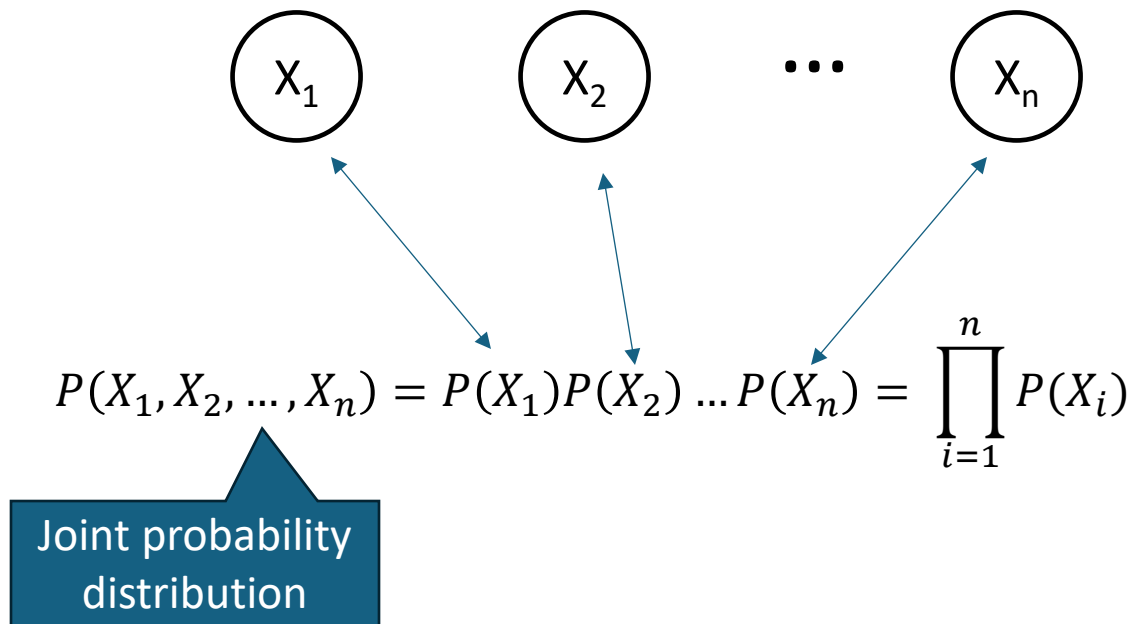
## Edges: Dependencies

- An arrow from one variable to another indicates direct influence.
- Show independence
  - *Weather* is independent of the other variables (no connection).
  - *Toothache* and *Catch* are conditionally independent given *Cavity* (directed arc).
- Must form a directed *acyclic* graph (DAG).

**Relationship to states in AI:** A network can be seen as a factored state representation. If we assign a value to all random variables, then we have a state of the system.

# Example: N independent coin flips

**Complete independence:** no interactions between coin flips

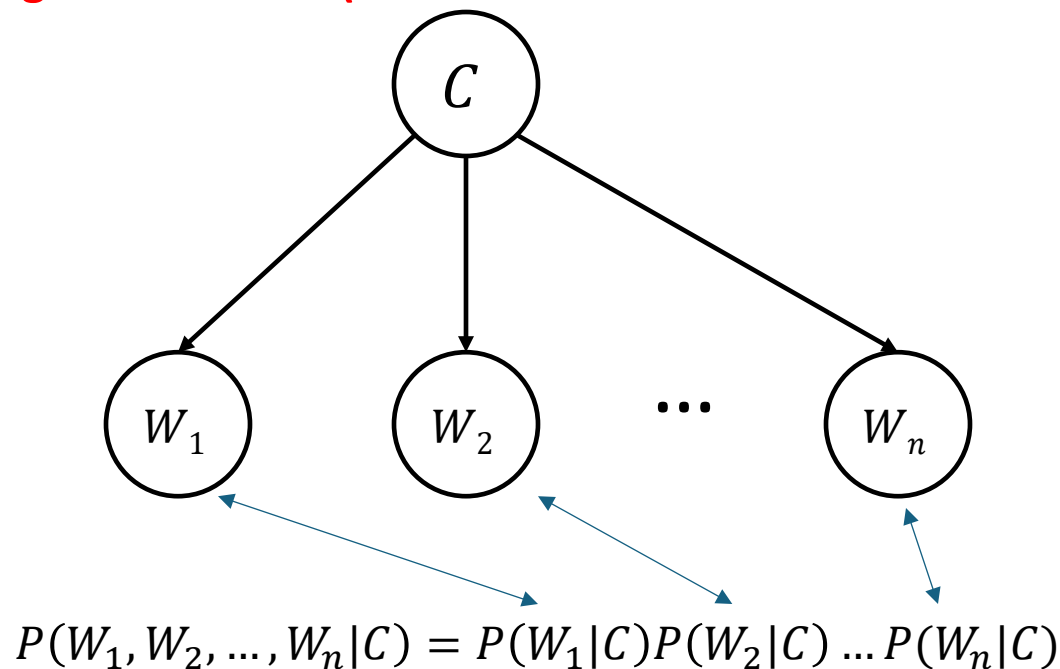


# Example: Naïve Bayes spam filter

Random variables:

- $C$ : message class (spam or not spam)
- $W_1, \dots, W_n$ : presence or absence of words comprising the message

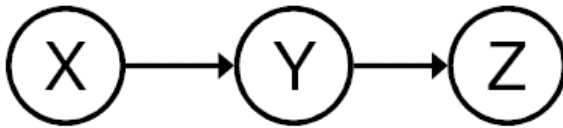
**Words depend on the class, but they are modeled conditional independent of each other given the class (= no direct connection between words).**





# Causal Chains: Dependence

- Example: *causal chain*



X: Low pressure

Y: Rain

Z: Traffic

- Are X and Z independent?

1. Conditioning:  $P(X, Y, Z) = P(X)P(Y|X)P(Z|Y)$

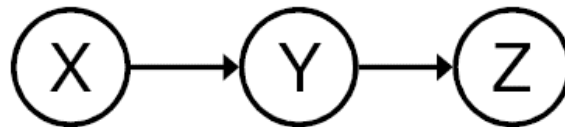
2. Marginalize over  $y$ :  $P(X, Z) = \sum_y P(X)P(y|X)P(Z|y)$   
 $= P(X) \sum_y P(Z|y)P(y|X) \neq P(X)P(Z)$

We are not  
interested in  $y$ .

**X and Z are not  
independent!**

# Causal Chains: Conditional Independence

- Example: *causal chain*



X: Low pressure

Y: Rain

Z: Traffic

- Is Z independent of X given Y?

1. Conditioning: 
$$P(X, Z|Y) = \frac{P(X, Y, Z)}{P(Y)} = \frac{P(X)P(Y|X)P(Z|Y)}{P(Y)}$$

2. Bayes' rule: 
$$= \frac{P(X) \frac{P(X|Y)P(Y)}{P(X)} P(Z|Y)}{P(Y)} = P(X|Y)P(Z|Y)$$

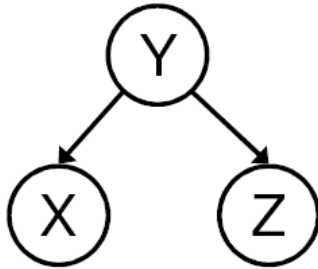
= Definition of  
conditional  
independence



X and Z are conditionally  
independent given Y

# Common Cause vs. Common Effect

- *Common cause*



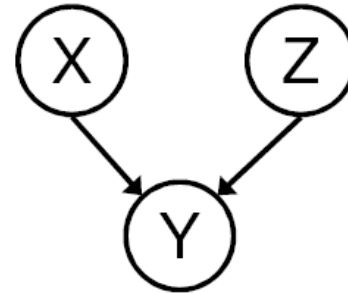
Y: Project due

X: Newsgroup  
busy

Z: Lab full

- Are X and Z independent?
  - No
- Are they conditionally independent given Y?
  - Yes

- *Common effect*



X: Raining

Z: Ballgame

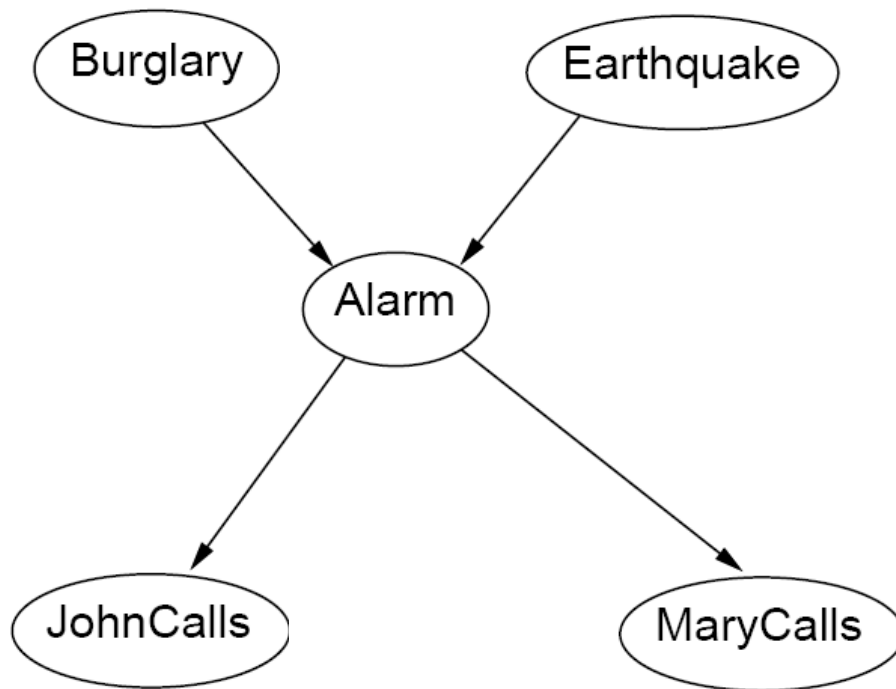
Y: Traffic

- Are X and Z independent?
  - Yes
- Are they conditionally independent given Y?
  - No

# Example: Burglar Alarm

- **Description:** I have a **burglar alarm** that is sometimes set off by minor **earthquakes**. My two neighbors, **John** and **Mary**, promised to call me at work if they hear the alarm.
- Example inference task: Suppose Mary calls, and John doesn't call. What is the probability of a burglary?
- What are the random variables?
  - Burglary, Earthquake, Alarm, JohnCalls, MaryCalls
- What are the direct influence relationships?
  - A burglar can set off the alarm
  - An earthquake can set off the alarm
  - The alarm can cause Mary to call
  - The alarm can cause John to call

# Example: Burglar Alarm as a Network



Direct influence relationships:

- A burglar can set off the alarm
- An earthquake can set off the alarm
- The alarm can cause Mary to call
- The alarm can cause John to call

What are the probabilities?

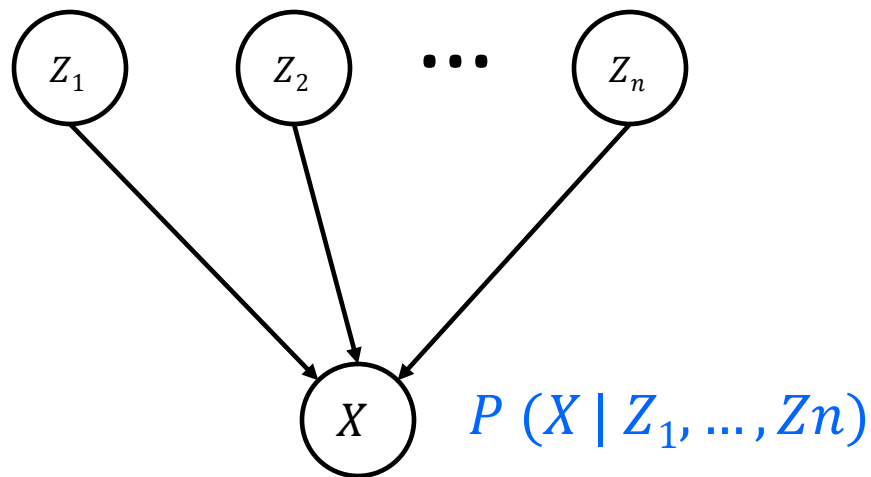
# Parameters: Conditional probability tables

The full joint distribution, can be broken down into *conditional* distribution for each node given its parents:

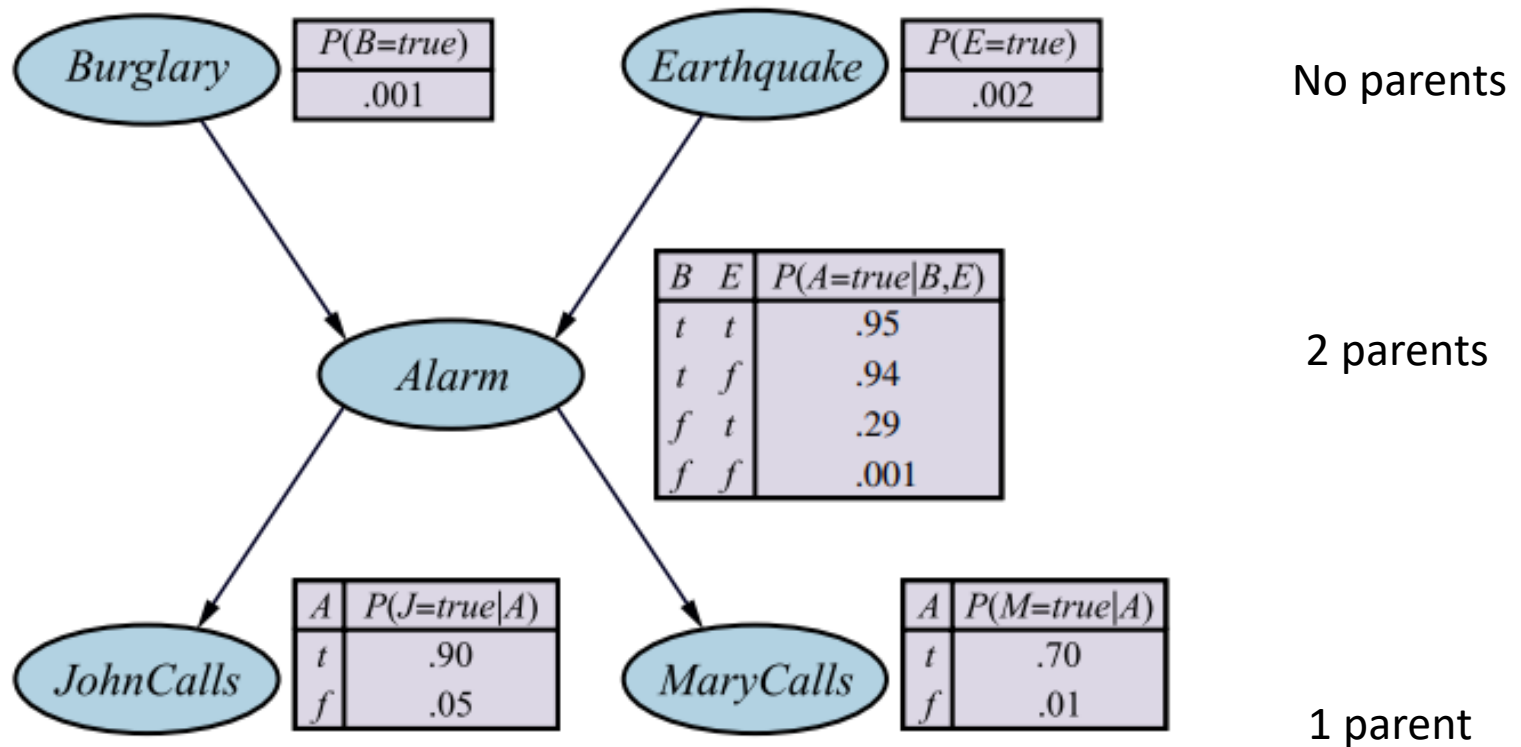
$$P(X | \text{Parents}(X))$$

These distributions are stored in conditional probability tables (CPTs)

Example:



# Example: Burglar Alarm with CPTs

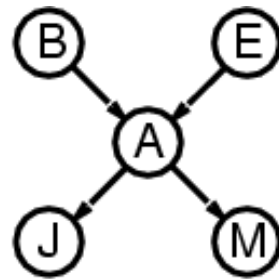


# Extracting the Joint Probability Distribution

- For each node  $X_i$ , we know  $P(X_i \mid \text{Parents}(X_i))$
- How do we get the full joint distribution  $P(X_1, \dots, X_n)$ ?
- Using chain rule, but only depends on parents:

$$P(X_1, \dots, X_n) = \prod_{i=1}^n P(X_i \mid \text{Parents}(X_i))$$

- Example:

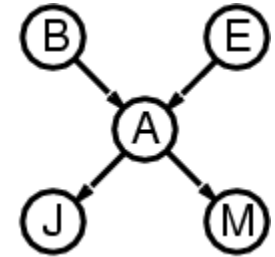


Construct  
following  
arrows

$$P(J, M, A, B, E) = P(B) P(E) P(A \mid B, E) P(J \mid A) P(M \mid A)$$



# Compactness

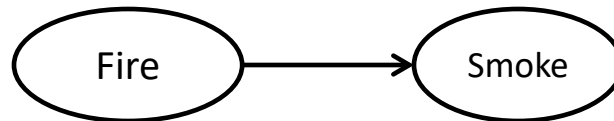


- For a network with  $n$  Boolean variables, the full joint distribution requires  $O(2^n)$  probabilities.  
Example: Burglary network  
Complete joint probability specification  $2^5 - 1 = \mathbf{31}$  probabilities
- If each variable  $X_i$  has at most  $k$  Boolean parents, then each conditional probability table (CPT) has at most  $2^k$  rows.
- The CPTs for all  $n$  nodes contain then at most  $O(n \times 2^k)$  probabilities.
- This reduces the complexity from exponential to linear in  $n$  and makes it very compact!
- Example: Burglary network  
Using CPTs:  $1 + 1 + 4 + 2 + 2 = \mathbf{10}$  probabilities
- **Note:** The Bayesian network stores all information needed for the complete joint probability. It let's us make optimal Bayesian decisions.

# Constructing Bayesian Networks

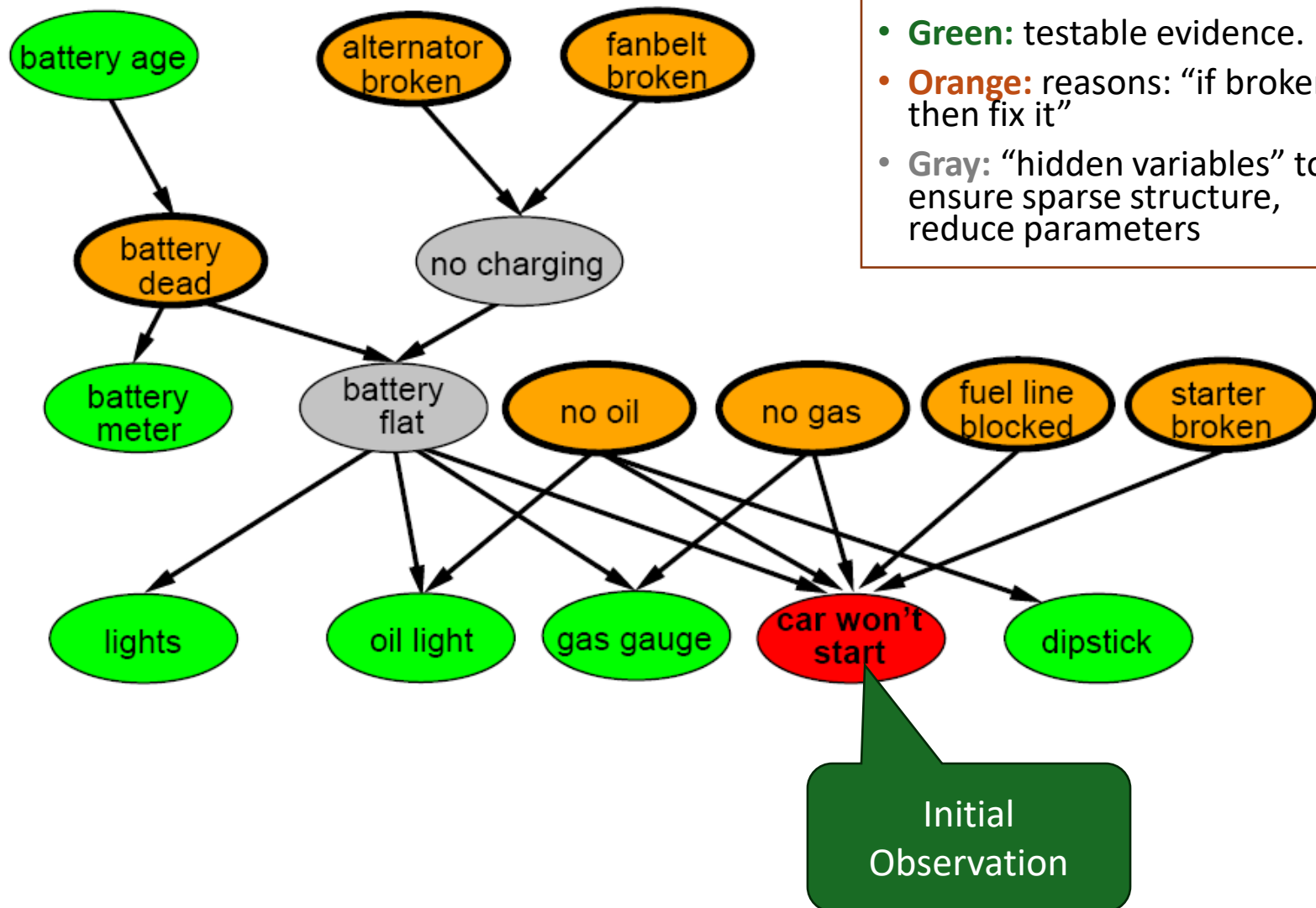
1. Choose an ordering of variables  $X_1, \dots, X_n$
2. For  $i = 1$  to  $n$ 
  - add  $X_i$  to the network
  - select parents from  $X_1, \dots, X_{i-1}$  such that
$$P(X_i \mid \text{Parents}(X_i)) = P(X_i \mid X_1, \dots, X_{i-1})$$
that is, add a connection only from nodes it directly depends on.

**Note:** There are many ways to order the variables. Networks are typically constructed by domain experts with causality in mind. E.g., Fire causes Smoke:



The network resulting from causal ordering is typically sparse and conditional probabilities are easier to judge because they represent causal relationships.

# A Larger Bayes Network: Car diagnosis

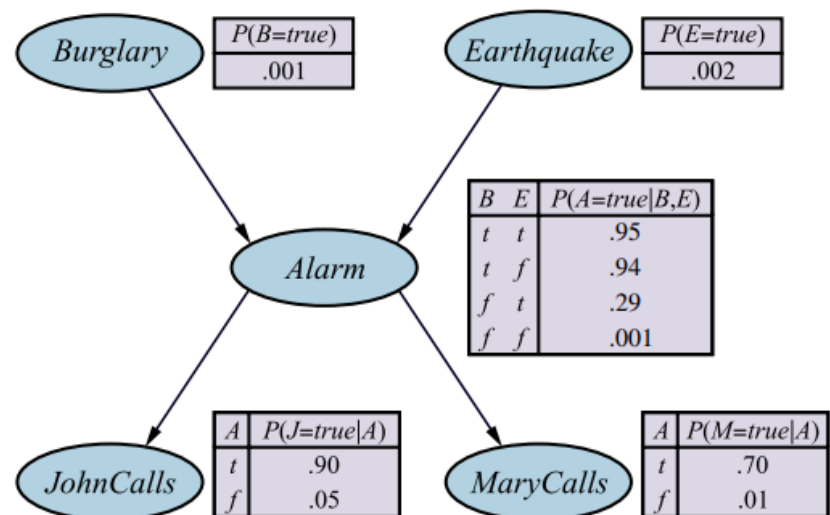


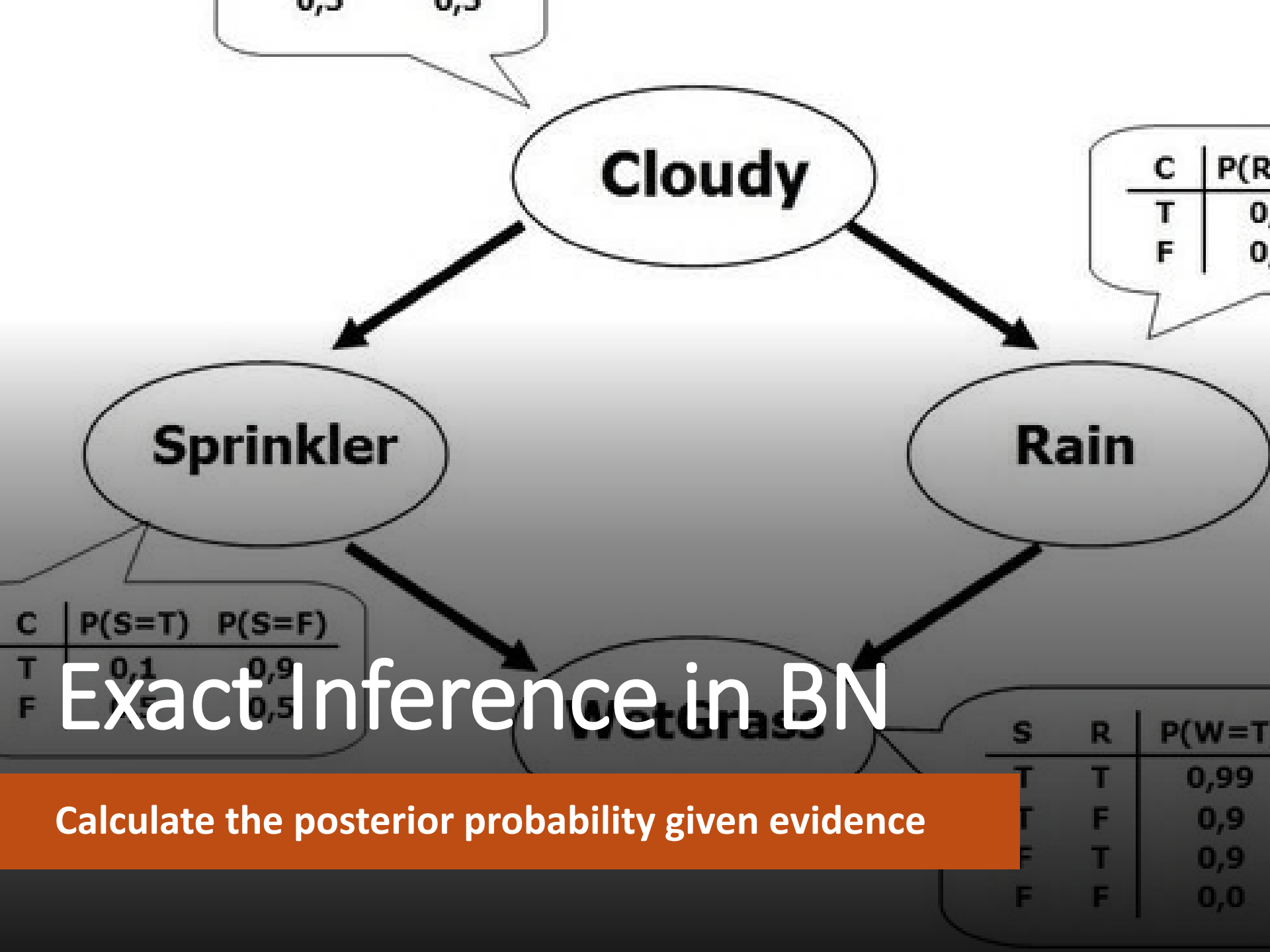
- **Initial observation:** car won't start.
- **Green:** testable evidence.
- **Orange:** reasons: "if broken, then fix it"
- **Gray:** "hidden variables" to ensure sparse structure, reduce parameters

# Summary

- Bayesian networks provide a **natural representation for joint probabilities** used to calculate conditional probabilities needed for inference (prediction).
- **Independence** and **conditional independence** (induced by causality) reduce the number of needed parameters and create a compact network.
- Bayesian networks still let us make optimal decisions as long as independence assumptions hold.
- Representation
  - Topology (nodes and edges)
  - Conditional probability tables
  - Typically easy for domain experts to construct

$P(B, E, A, J, M)$  is defined by





# Exact Inference in BN

Calculate the posterior probability given evidence

# Exact Inference

## Goal

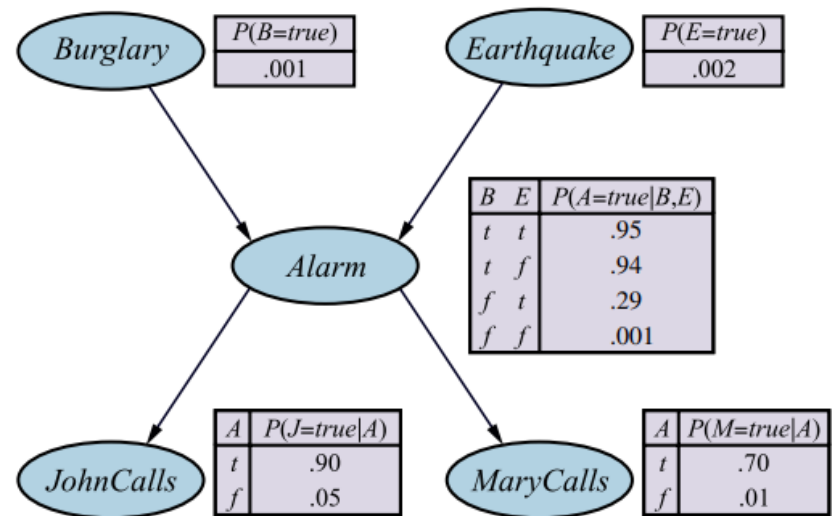
- Query variables:  $X$
- Evidence (observed) variables:  $E = e$
- Set of unobserved variables:  $Y$
- Calculate the probability of  $X$  given  $e$ .

If we know the full joint distribution  $P(X, E, Y)$ , we can infer  $X$  by:

$$P(X|E = e) = \frac{P(X, e)}{P(e)} = \frac{\sum_y P(X, e, y)}{P(e)} \propto \sum_y P(X, e, y)$$

Sum over values of unobservable variables = marginalizing them out.

# Exact inference: Example – Calculation



Assume we can observe being called and the two variables have the values  $j$  and  $m$ .  
We want to know the probability of a burglary.

**Query:**  $P(B | j, m)$  with unobservable variables: Earthquake  $E$ , Alarm  $A$

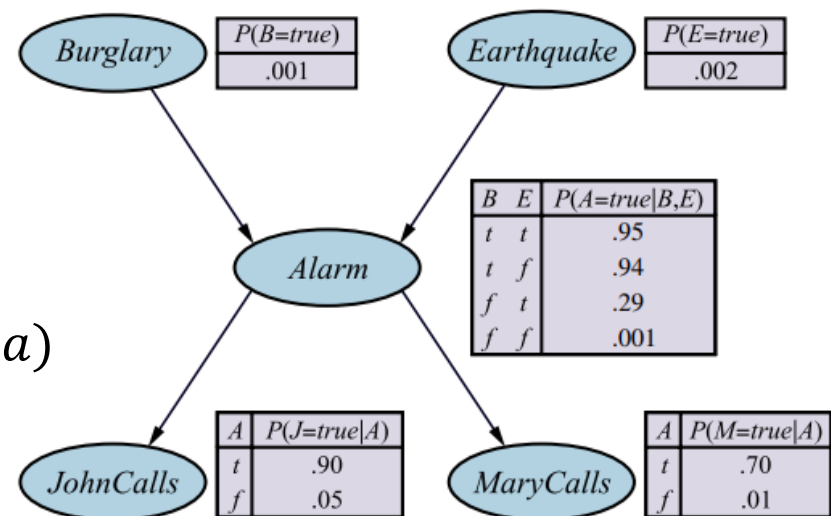
$$\begin{aligned}
 P(b|j, m) &= \frac{P(b, j, m)}{P(j, m)} \propto \sum_e \sum_a P(b, e, a, j, m) \\
 &= \sum_e \sum_a P(b)P(e)P(a|b, e)P(j|a)P(m|a) \\
 &= P(b) \sum_e P(e) \sum_a P(a|b, e) P(j|a)P(m|a)
 \end{aligned}$$

Full joint  
probability and  
marginalize over  
E and A

# Exact inference: Example – Evaluation Tree

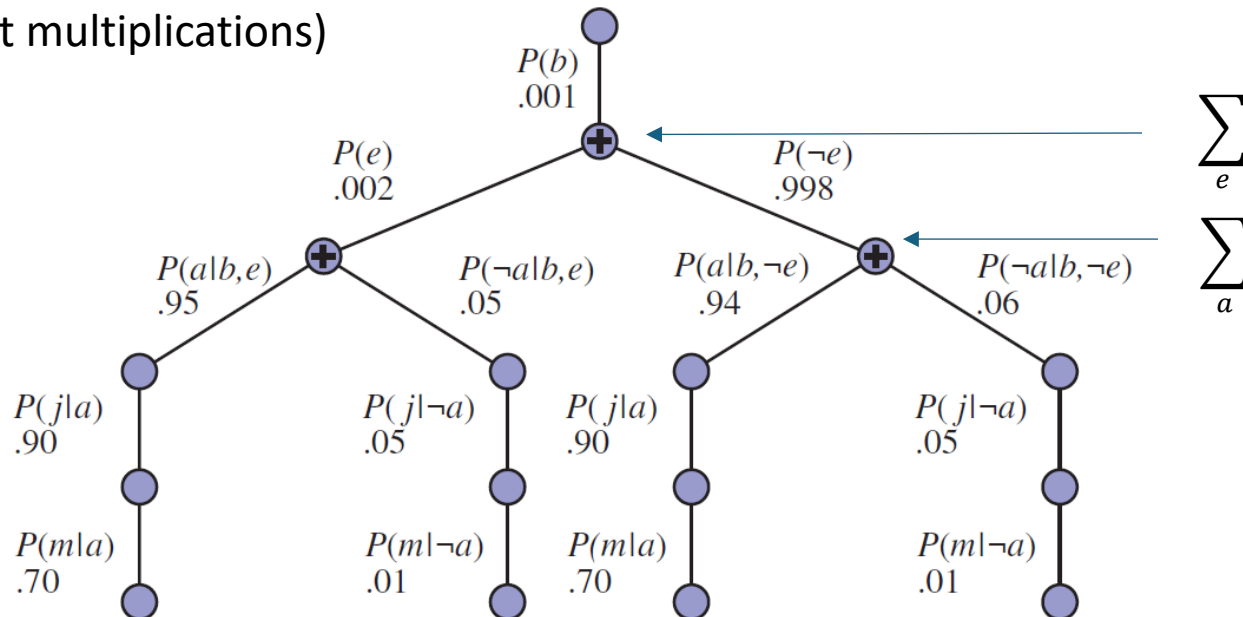
$$P(b|j, m)$$

$$\propto P(b) \sum_e P(e) \sum_a P(a|b, e) P(j|a) P(m|a)$$



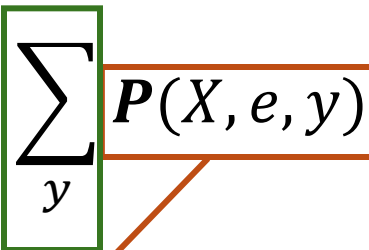
## Implementation using an evaluation tree and CPTs

(lines represent multiplications)





# Issues with Exact Inference in AI

$$P(X|E = e) = \frac{P(X, e)}{P(e)} \propto \sum_y P(X, e, y)$$


## Problems

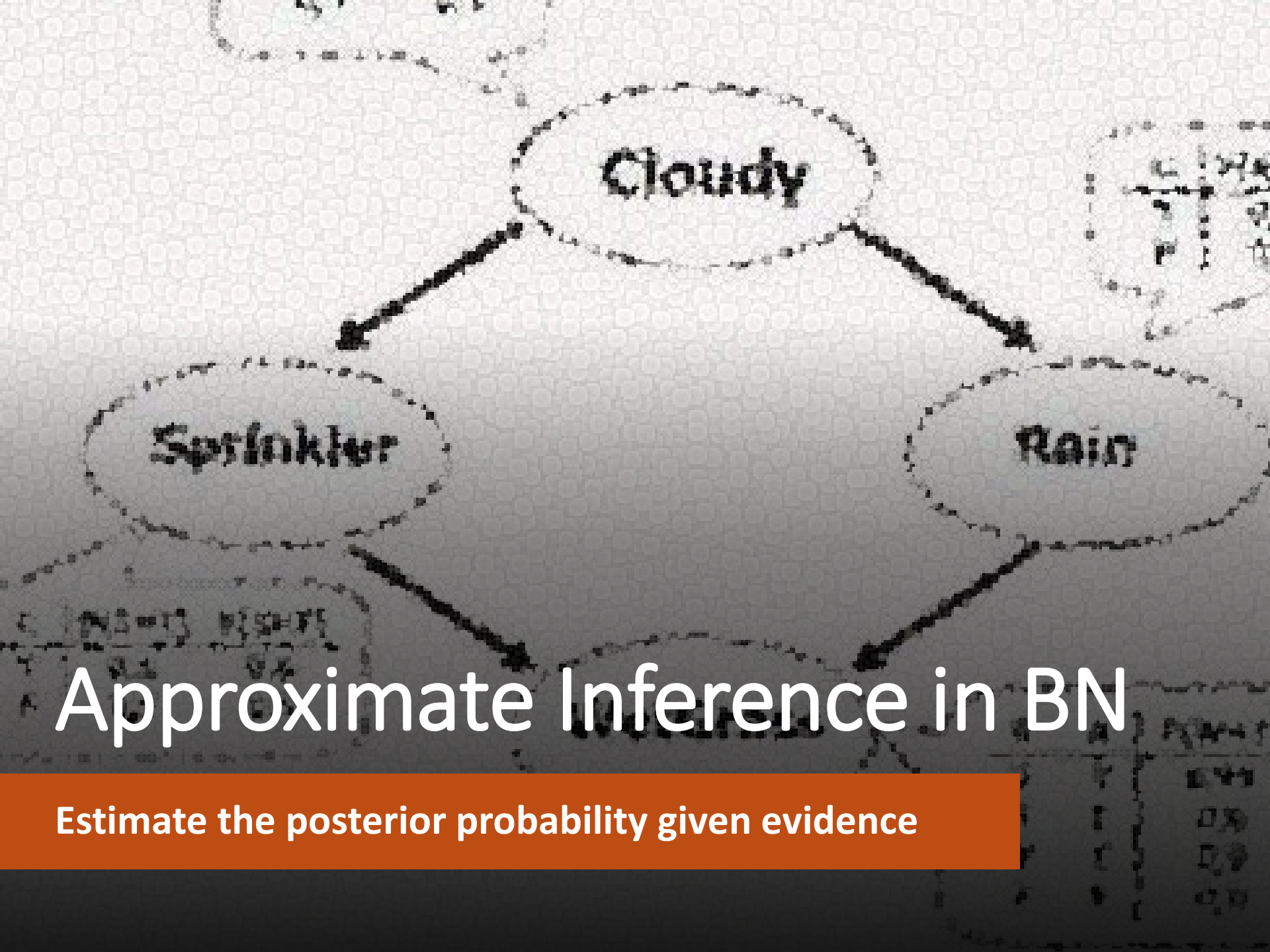
1. **Full joint distribution is too large** to store.

Bayes nets provide significant savings for representing the conditional probability structure using CPTs.

2. Marginalizing out many unobservable variables  $Y$  may involve **too many summation terms**.

This summation is called **exact inference by enumeration**. Unfortunately, it does not scale well (#p-hard).

In praxis, **approximate inference by sampling** is used.



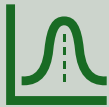
# Approximate Inference in BN

Estimate the posterior probability given evidence

# Bayesian Networks as a Generative Models



Bayesian networks can be used as ***generative models***.



Generative models allow us to efficiently **generate samples** from the joint distribution.

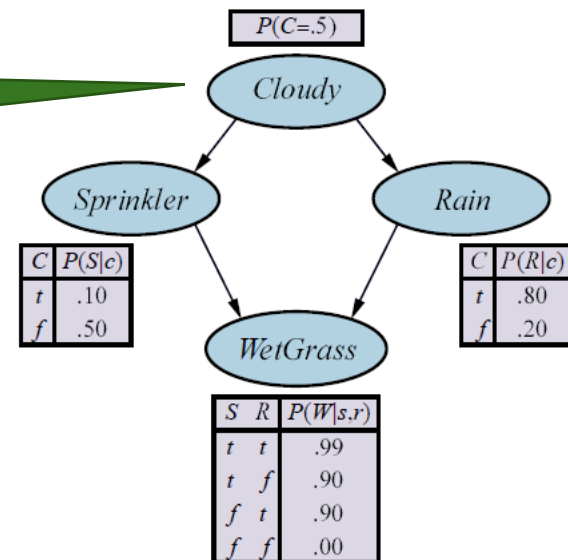


**Idea:** Generate samples from the network to estimate joint and conditional probability distributions using **Monte Carlo** methods.

# Prior-Sample Algorithm

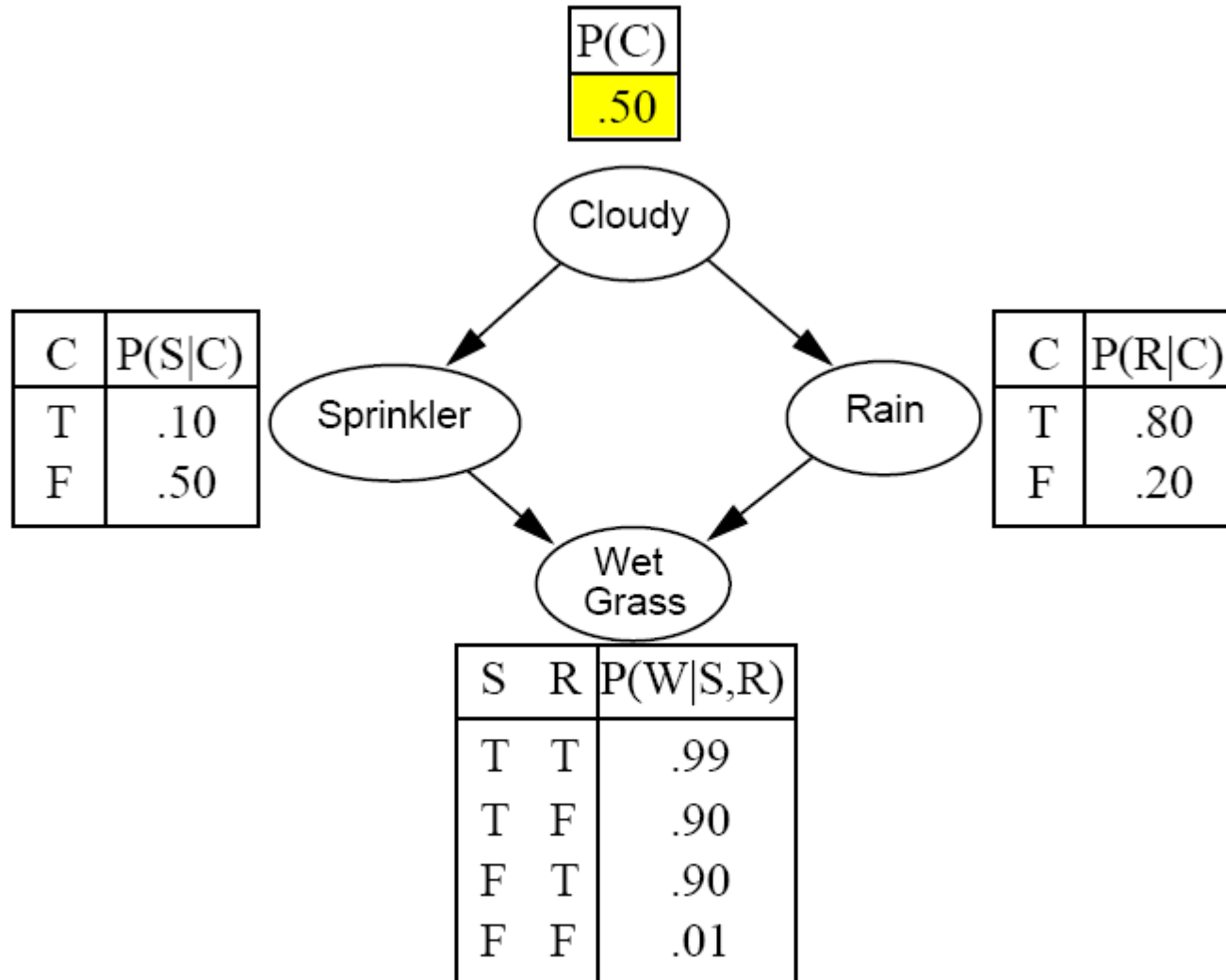
```
function PRIOR-SAMPLE( $bn$ ) returns an event sampled from the prior specified by  $bn$   
inputs:  $bn$ , a Bayesian network specifying joint distribution  $\mathbf{P}(X_1, \dots, X_n)$   
  
 $\mathbf{x} \leftarrow$  an event with  $n$  elements  
for each variable  $X_i$  in  $X_1, \dots, X_n$  do  
     $\mathbf{x}[i] \leftarrow$  a random sample from  $\mathbf{P}(X_i \mid \text{parents}(X_i))$   
return  $\mathbf{x}$ 
```

Order is important! We need to start with the random variables that have no parents.



Variable Order

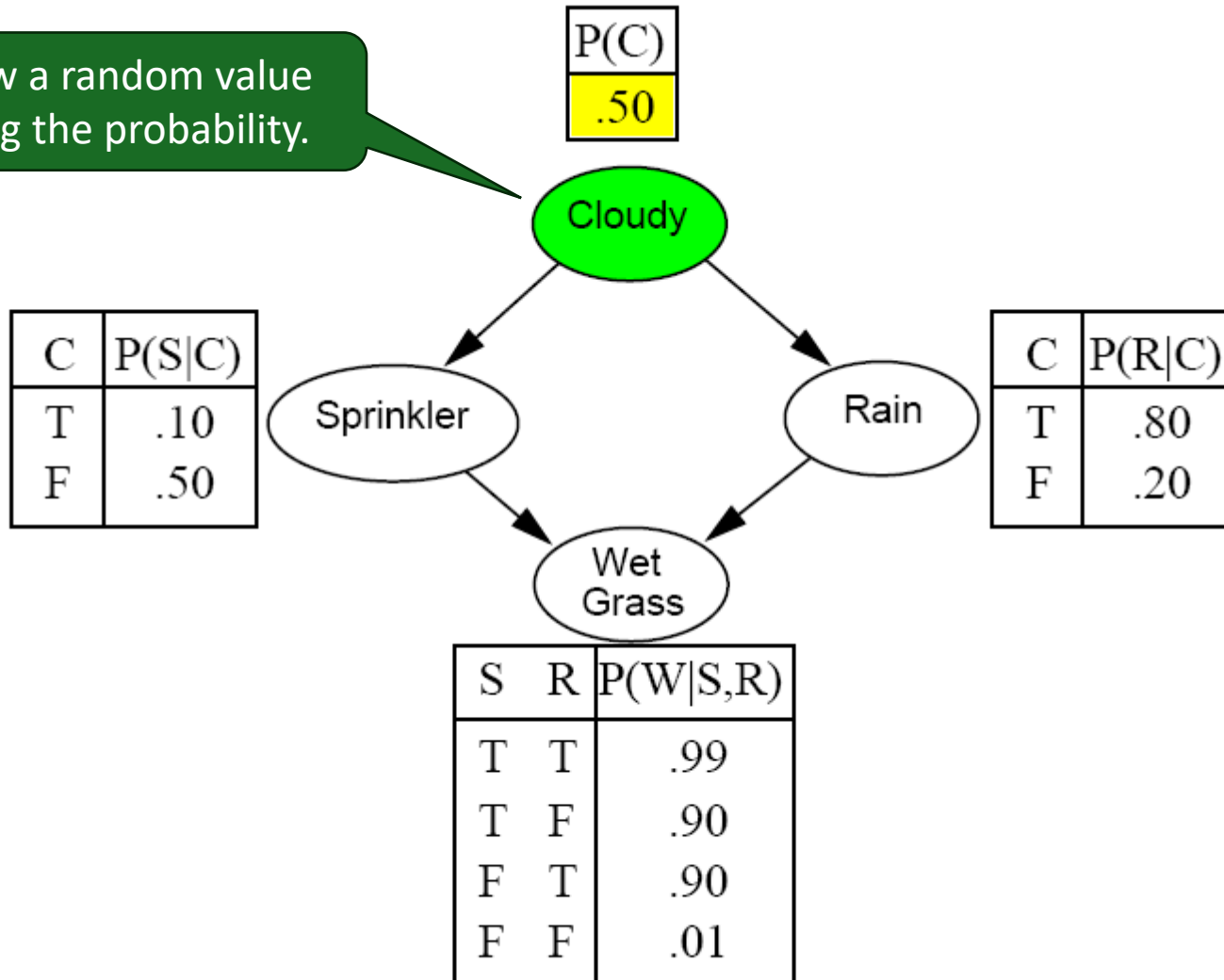
# Example: Sampling from a Bayesian Network



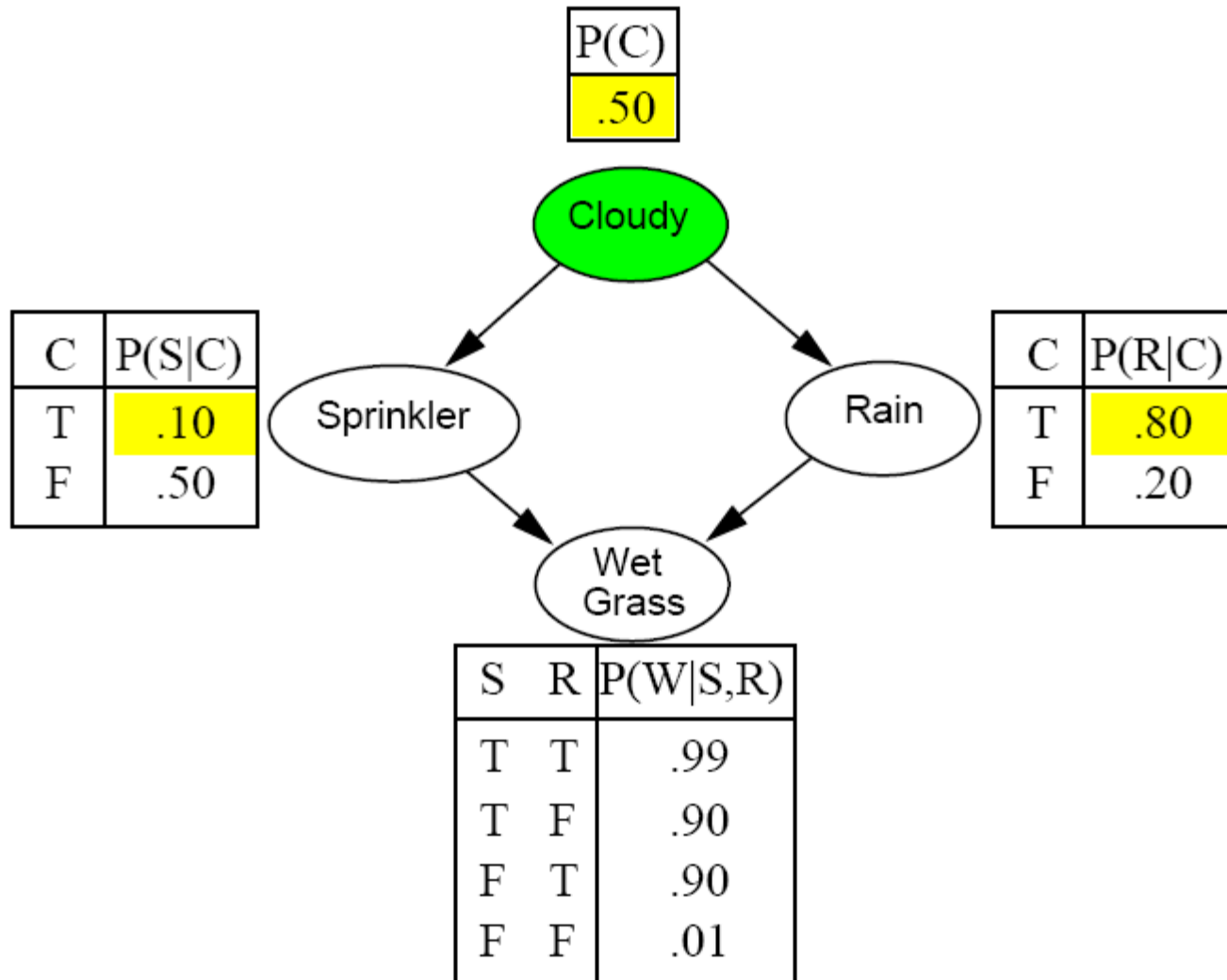
Variable order

# Example: Sampling from a Bayesian Network

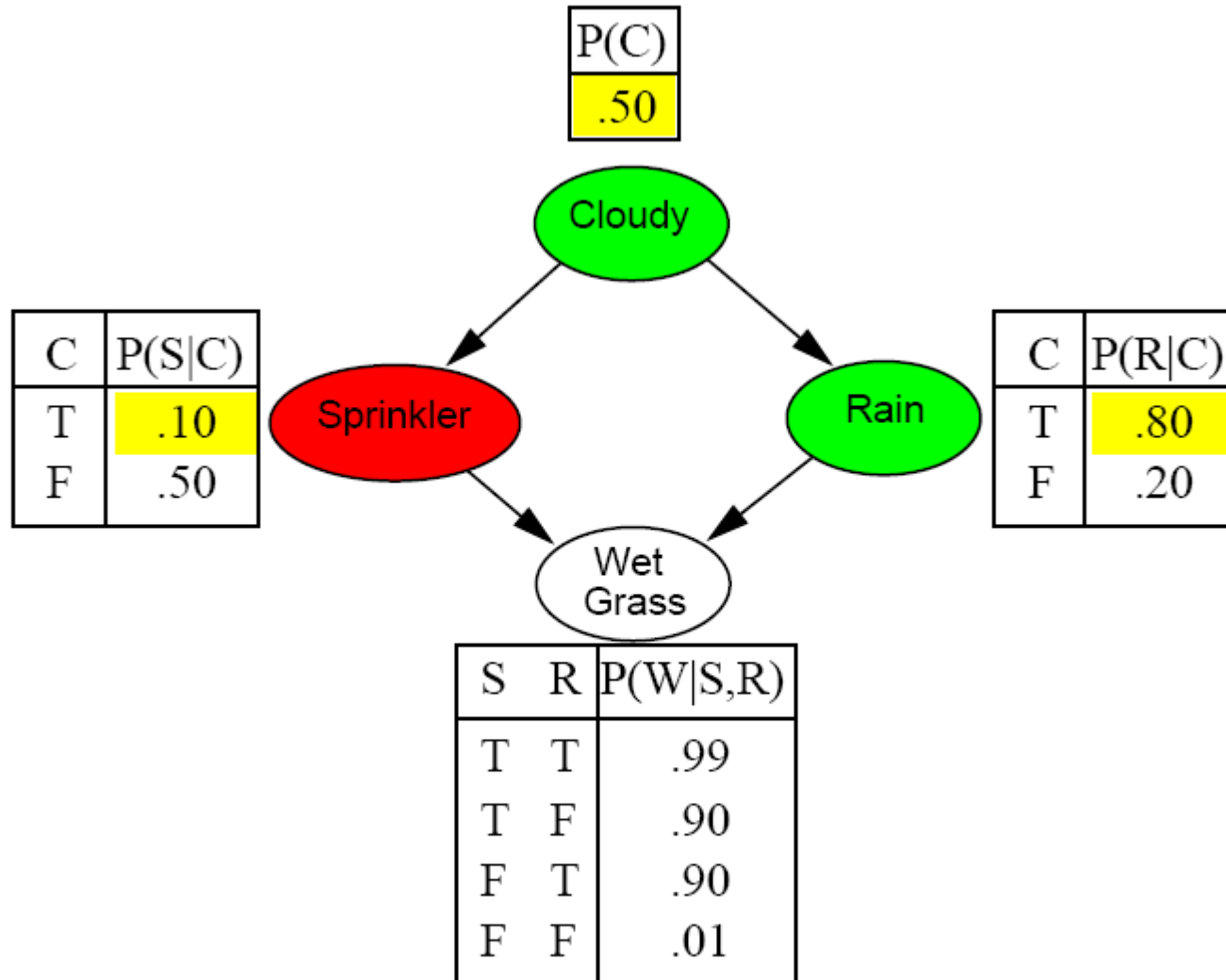
Draw a random value using the probability.



# Example: Sampling from a Bayesian Network

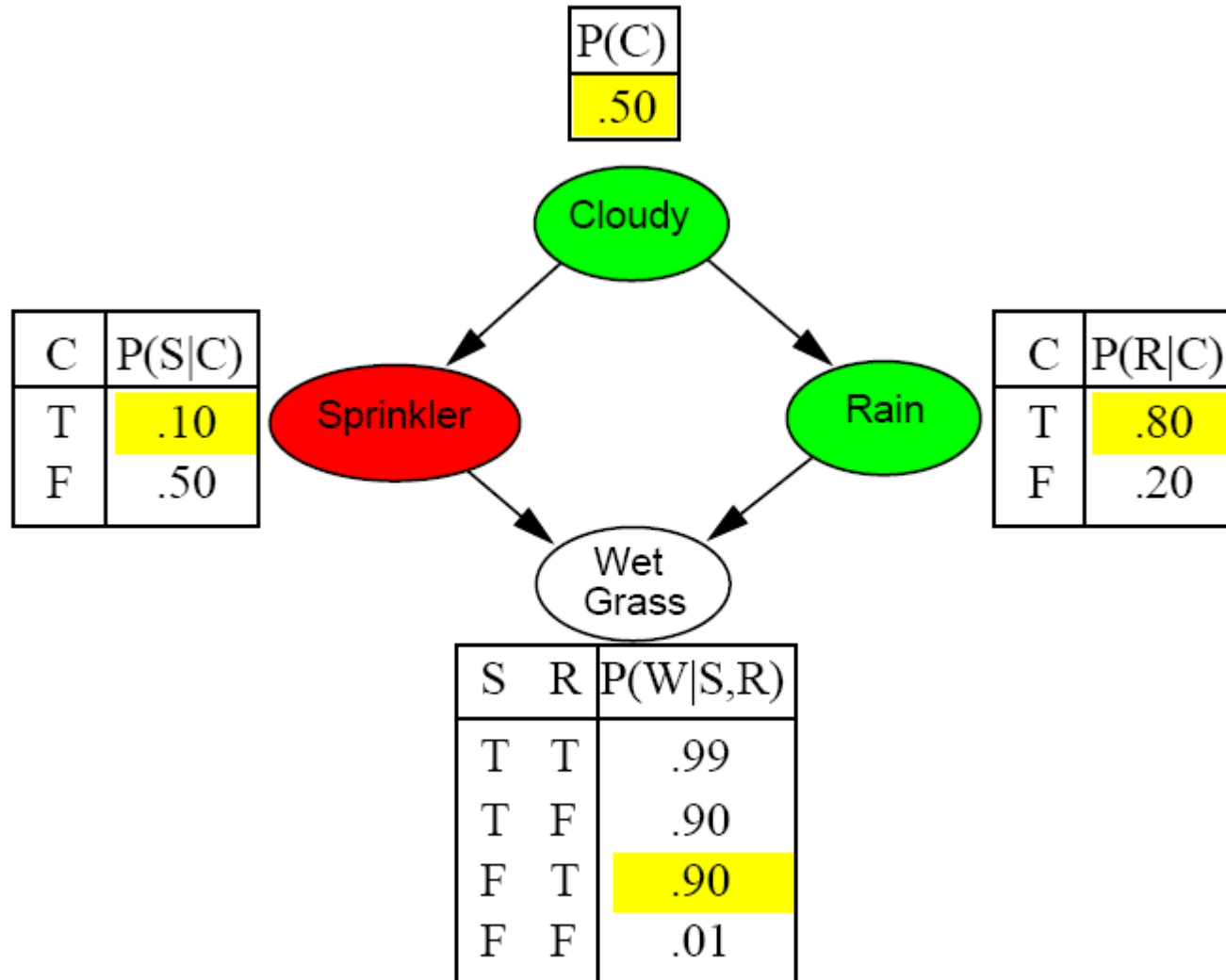


# Example: Sampling from a Bayesian Network

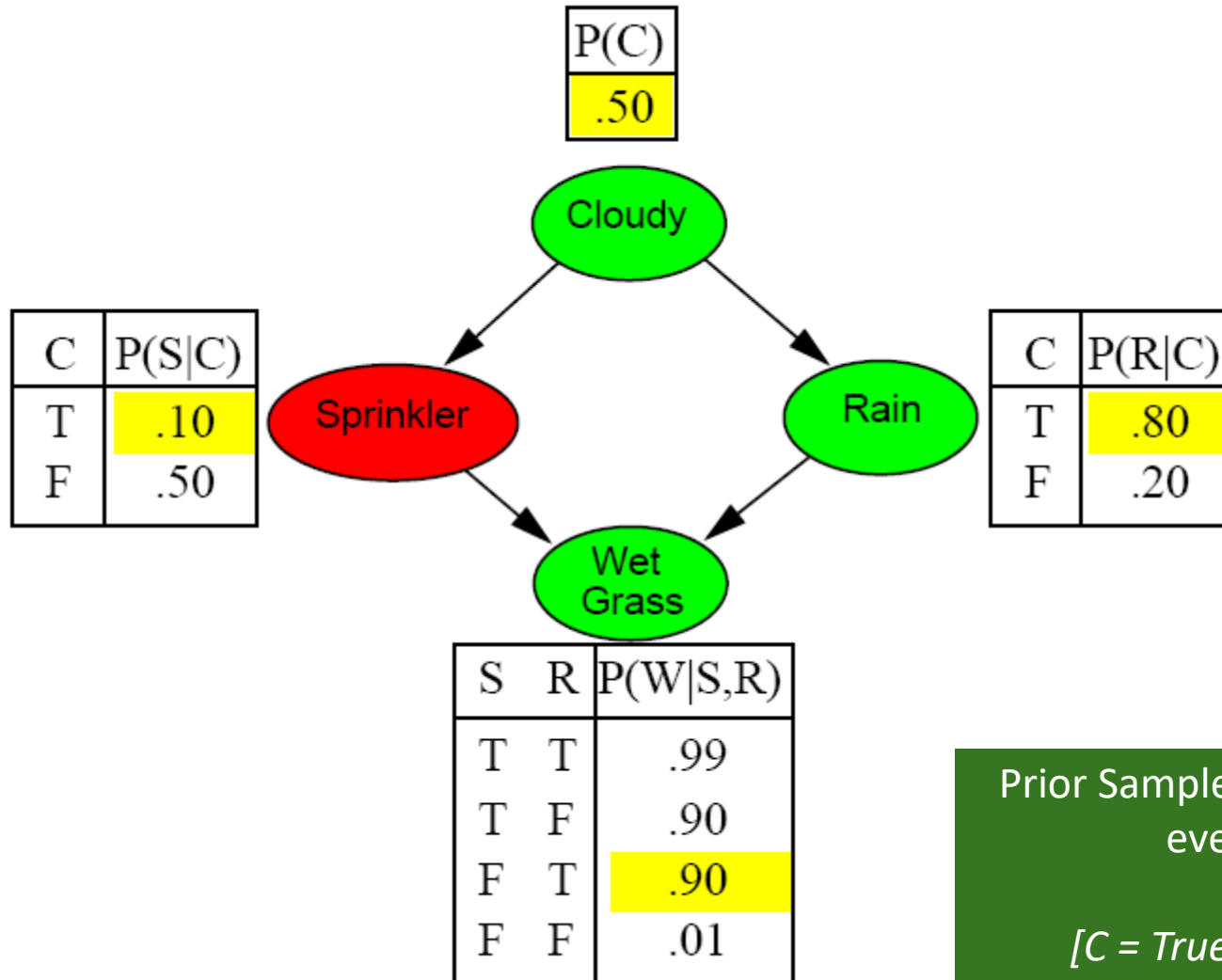




# Example: Sampling from a Bayesian Network



# Example: Sampling from a Bayesian Network



Prior Sample returns the event:

*[C = True, S = False,  
R = True, W = True]*

# Estimating the Joint Probability Distribution from Individual Samples

Sample  $N$  times and determine  $N_{PS}(x_1, x_2, \dots, x_n)$ , the count of how many times Prior-Sample produces event  $(x_1, x_2, \dots, x_n)$ .

$$\hat{P}(x_1, x_2, \dots, x_n) = \frac{N_{PS}(x_1, x_2, \dots, x_n)}{N}$$


The marginal probability of partially specified event (some  $x$  values are known) can also be calculated using the same samples. E.g.,

$$\hat{P}(x_1) = \frac{N_{PS}(x_1)}{N}$$

# Estimating Conditional Probabilities: Rejection Sampling

Sample  $N$  times and **ignore the samples that are not consistent with the evidence  $e$ .**

$$\hat{P}(X|e) = \frac{N_{PS}(X, e)}{N_{PS}(e)} = \alpha N_{PS}(X, e)$$



Normalization  
trick

**Issue:** What if  $e$  is a rare event?

- Example: burglary  $\wedge$  earthquake
- Rejection sampling ends up throwing away most of the samples. This is very inefficient!

# Estimating Conditional Probabilities: Rejection Sampling

**function** REJECTION-SAMPLING( $X, \mathbf{e}, bn, N$ ) **returns** an estimate of  $\mathbf{P}(X \mid \mathbf{e})$   
**inputs:**  $X$ , the query variable  
           $\mathbf{e}$ , observed values for variables  $\mathbf{E}$   
           $bn$ , a Bayesian network  
           $N$ , the total number of samples to be generated  
**local variables:**  $\mathbf{C}$ , a vector of counts for each value of  $X$ , initially zero  
**for**  $j = 1$  **to**  $N$  **do**  
     $\mathbf{x} \leftarrow \text{PRIOR-SAMPLE}(bn)$   
    **if**  $\mathbf{x}$  is consistent with  $\mathbf{e}$  **then**  
         $\mathbf{C}[j] \leftarrow \mathbf{C}[j] + 1$  where  $x_j$  is the value of  $X$  in  $\mathbf{x}$   
**return** NORMALIZE( $\mathbf{C}$ )

We throw away many samples  
if  $\mathbf{e}$  is rare!

# Estimating Conditional Probabilities: Importance Sampling (likelihood weighting)

**Goal:** Avoid throwing out samples like in rejection sampling.

**1. Fix the evidence  $E = e$**  for sampling and estimate the probability for the non-evidence variables using prior-sampling. We call this probability  $Q_{WS}(x)$

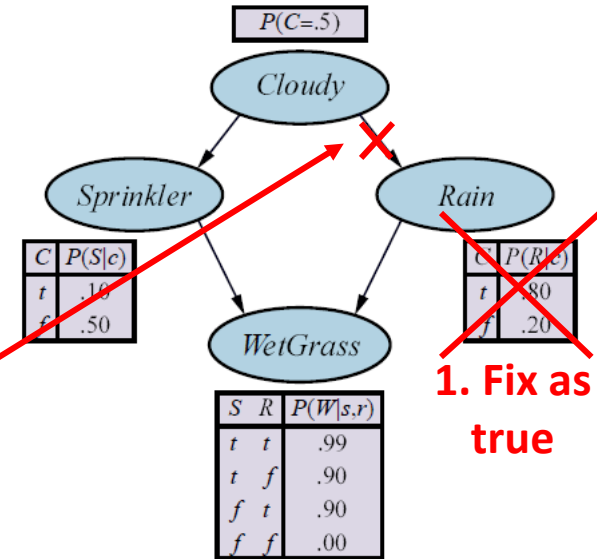
Note: Fixing the evidence breaks the dependence between the evidence variable and the evidence parents!

**2. Correct the probabilities** using weights  $P(x|e) = w(x)Q_{WS}(x)$

The right weight to fix the broken dependence is the chance that we see the evidence given its parent.

$$w(x) = \frac{1}{P(e)} \prod_{i=1}^m P(e_i | \text{parents}(E_i))$$

Example: Evidence = it rains



# Estimating Conditional Probabilities: Markov Chain Monte Carlo Sampling (MCMC)

- **Idea:** Instead of creating each sample individually from scratch, **generates a sequence of samples**.
- Create the next state (= sample) by making random changes to the current state (= modify non-evidence variables). The sequence of states forms a random process called a **Markov Chain** (MC).
- The MC is constructed such that its stationary distribution is the posterior distribution of the non-evidence variables.
- The stationary distribution of a MC can be estimated using **Monte Carlo** simulation by counting how often each state is reached in a random walk and normalizing to obtain probability estimates.
- Algorithms:
  1. Gibbs sampling works well for BNs since it needs conditional probabilities and we have CPTs.
  2. Metropolis-Hastings sampling is more general.

*Note:* Simulated annealing local search also belongs to the family of MCMC algorithms.

# Gibbs Sampling in Bayes Networks

**function** GIBBS-ASK( $X, \mathbf{e}, bn, N$ ) **returns** an estimate of  $\mathbf{P}(X | \mathbf{e})$

**local variables:**  $\mathbf{C}$ , a vector of counts for each value of  $X$ , initially zero

$\mathbf{Z}$ , the nonevidence variables in  $bn$

$\mathbf{x}$ , the current state of the network, initialized from  $\mathbf{e}$

initialize  $\mathbf{x}$  with random values for the variables in  $\mathbf{Z}$

**for**  $k = 1$  **to**  $N$  **do**

**choose** any variable  $Z_i$  from  $\mathbf{Z}$  according to any distribution  $\rho(i)$

set the value of  $Z_i$  in  $\mathbf{x}$  by sampling from  $\mathbf{P}(Z_i | mb(Z_i))$

$\mathbf{C}[j] \leftarrow \mathbf{C}[j] + 1$  where  $x_j$  is the value of  $X$  in  $\mathbf{x}$

**return** NORMALIZE( $\mathbf{C}$ )

Start with a random state

Change one non-evidence variable at a time

Count

Convert to probabilities

- $mb(Z_i)$  is the Markov blanket of random variable  $Z_i$ . It makes sure that the new value is consistent with the other values. The Markov blanket of a variable consists of all variables it can be dependent of (parents, children, and parents of children). This ensures that the MC's stationary distribution gives the desired probability.

$$P(z_i | mb(Z_i)) = \alpha P(z_i | \text{parents}(Z_i)) \prod_{Y_j \in \text{children}(Z_i)} P(y_j | \text{parents}(Y_j))$$



# Gibbs Sampling: Example

Find

$$P(\text{Rain} \mid \text{Sprinkler} = \text{true}, \text{WetGrass} = \text{true}).$$

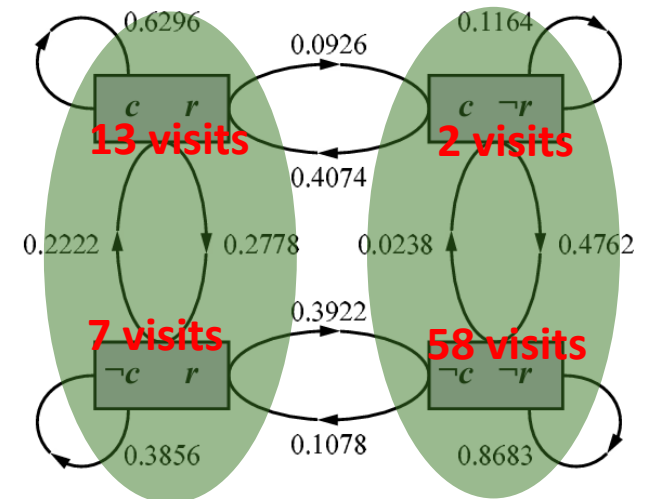
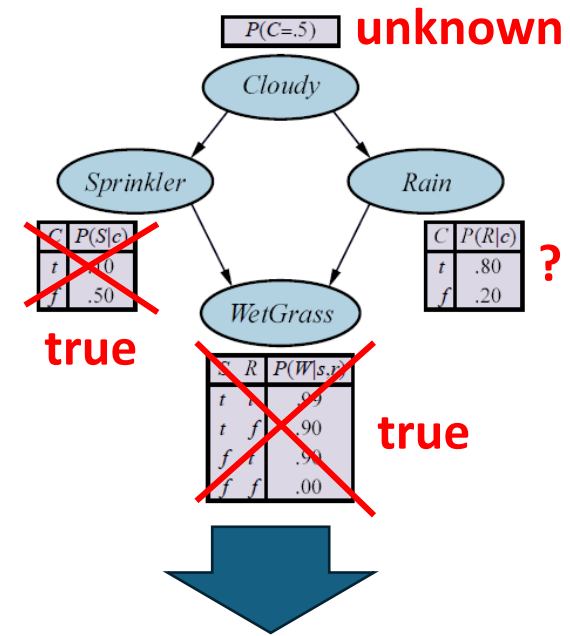
Determine states and calculate transition probabilities of the Markov chain for changing one variable using  $P(z_i \mid mb(Z_i))$ . This will repair all dependencies broken by fixing the evidence.

The algorithm randomly wanders around in this graph using the stated transition probabilities. This will produce the stationary distribution.

Assume that we observe 20 states with  $\text{Rain} = \text{true}$  and 60 with  $\text{rain} = \text{false}$ :

$$\text{NORMALIZE}(\langle 13 + 7, 2 + 58 \rangle) = \langle 0.25, 0.75 \rangle$$

$$P(\text{Rain} \mid \text{Sprinkler} = \text{true}, \text{WetGrass} = \text{true}) \approx 0.25$$



Note the self-loops: the state stays the same when the resampled value is same it already has.



## Conclusion

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- Bayesian networks provide an efficient way to store a complete probabilistic model by exploiting (conditional) independence between variables.
- Inference means querying the model for a conditional probability given some evidence.
- Exact inference is difficult, for all but tiny models.
- State of the art is to use approximate inference by sampling from the model.
- Software libraries provide general inference engines.