

Artificial Intelligence Programming
Belief Networks

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18-2: Probability Review

- Probability allows us to represent a belief about a statement, or a likelihood that a statement is true.
 - $P(\text{rain}) = 0.6$ means that we believe it is 60% likely that it is currently raining.
- Axioms:
 - $0 \leq P(a) \leq 1$
 - The probability of $(A \vee B)$ is $P(A) + P(B) - P(A \wedge B)$
 - Tautologies have $P = 1$
 - Contradictions have $P = 0$

18-3: Conditional Probability

- Once we begin to make observations about the value of certain variables, our belief in other variables changes.
 - Once we notice that it's cloudy, $P(Rain)$ goes up.
- this is called *conditional probability*
- Written as: $P(Rain|Cloudy)$
- $P(a|b) = \frac{P(a \wedge b)}{P(b)}$
- or $P(a \wedge b) = P(a|b)P(b)$
 - This is called the *product rule*.

18-4: Conditional Probability

- Example: $P(\textit{Cloudy}) = 0.3$
- $P(\textit{Rain}) = 0.2$
- $P(\textit{cloudy} \wedge \textit{rain}) = 0.15$
- $P(\textit{cloudy} \wedge \neg \textit{Rain}) = 0.1$
- $P(\neg \textit{cloudy} \wedge \textit{Rain}) = 0.1$
- $P(\neg \textit{Cloudy} \wedge \neg \textit{Rain}) = 0.65$
 - Initially, $P(\textit{Rain}) = 0.2$. Once we see that it's cloudy,
$$P(\textit{Rain}|\textit{Cloudy}) = P\frac{(\textit{Rain}\wedge\textit{Cloudy})}{P(\textit{Cloudy})} = \frac{0.15}{0.3} = 0.5$$

18-5: Combinations of events

- The probability of $(A \wedge B)$ is $P(A|B)P(B)$
- What if A and B are independent?
- Then $P(A|B)$ is $P(A)$, and $P(A \wedge B)$ is $P(A)P(B)$.
- Example:
 - What is the probability of “heads” five times in a row?
 - What is the probability of at least one “head”?

18-6: Bayes' Rule

- Often, we want to know how a probability changes as a result of an observation.
- Recall the Product Rule:
 - $P(a \wedge b) = P(a|b)P(b)$
 - $P(a \wedge b) = P(b|a)P(a)$
- We can set these equal to each other
 - $P(a|b)P(b) = P(b|a)P(a)$
- And then divide by $P(a)$
 - $P(b|a) = \frac{P(a|b)P(b)}{P(a)}$
- This equality is known as Bayes' theorem (or rule or law).

18-7: Monty Hall Problem

From the game show “Let’s make a Deal”

- Pick one of three doors. Fabulous prize behind one door, goats behind other 2 doors.
- Monty opens one of the doors you did not pick, shows a goat
- Monty then offers you the chance to switch doors, to the other unopened door
- Should you switch?

18-8: Monty Hall Problem

Problem Clarification:

- Prize location selected randomly
- Monty always opens a door, allows contestants to switch
- When Monty has a choice about which door to open, he chooses randomly.

Variables Prize: $P = p_A, p_B, p_C$
 Choose: $C = c_A, c_B, c_C$
 Monty: $M = m_A, m_B, m_C$

18-9: Monty Hall Problem

Without loss of generality, assume:

- Choose door A
- Monty opens door B

$$P(p_A | c_A, m_B) = ?$$

18-10: Monty Hall Problem

Without loss of generality, assume:

- Choose door A
- Monty opens door B

$$P(p_A | c_A, m_B) = P(m_B | c_A, p_A) \frac{P(p_A | c_A)}{P(m_B | c_A)}$$

18-11: Monty Hall Problem

$$P(p_A|c_A, m_B) = P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)}$$

- $P(m_B|c_A, p_A) = ?$

18-12: Monty Hall Problem

$$P(p_A|c_A, m_B) = P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)}$$

- $P(m_B|c_A, p_A) = 1/2$
- $P(p_A|c_A) = ?$

18-13: Monty Hall Problem

$$P(p_A|c_A, m_B) = P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)}$$

- $P(m_B|c_A, p_A) = 1/2$
- $P(p_A|c_A) = 1/3$
- $P(m_B|c_A) = ?$

18-14: Monty Hall Problem

$$P(p_A|c_A, m_B) = P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)}$$

- $P(m_B|c_A, p_A) = 1/2$
- $P(p_A|c_A) = 1/3$
- $P(m_B|c_A) = P(m_b|c_A, p_A)P(p_A) +$
 $P(m_b|c_A, p_B)P(p_B) +$
 $P(m_b|c_A, p_C)P(p_C)$

18-15: Monty Hall Problem

$$P(p_A|c_A, m_B) = P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)}$$

- $P(m_B|c_A, p_A) = 1/2$
- $P(p_A|c_A) = 1/3$
- $P(m_B|c_A) = P(m_b|c_A, p_A)P(p_A) +$
 $P(m_b|c_A, p_B)P(p_B) +$
 $P(m_b|c_A, p_C)P(p_C)$
 - $P(p_A) = P(p_B) = P(p_C) = 1/3$
 - $P(m_b|c_A, p_A) = 1/2$
 - $P(m_b|c_A, p_B) = 0$ Won't open prize door
 - $P(m_b|c_A, p_C) = 1$ Monty has no choice

18-16: Monty Hall Problem

$$\begin{aligned}P(p_A|c_A, m_B) &= P(m_B|c_A, p_A) \frac{P(p_A|c_A)}{P(m_B|c_A)} \\ &= 1/3\end{aligned}$$

- $P(m_B|c_A, p_A) = 1/2$
- $P(p_A|c_A) = 1/3$
- $P(m_B|c_A) = P(m_b|c_A, p_A)P(p_A) +$
 $P(m_b|c_A, p_B)P(p_B) +$
 $P(m_b|c_A, p_C)P(p_C) = 1/2$
 - $P(p_A) = P(p_B) = P(p_C) = 1/3$
 - $P(m_b|c_A, p_A) = 1/2$
 - $P(m_b|c_A, p_B) = 0$ Won't open prize door
 - $P(m_b|c_A, p_C) = 1$ Monty has no choice

18-17: Monty Hall Problem

$$\begin{aligned}P(p_C|c_A, m_B) &= P(m_B|c_A, p_C) \frac{P(p_C|c_A)}{P(m_B|c_A)} \\ &= 2/3\end{aligned}$$

- $P(m_B|c_A, p_C) = 1$
- $P(p_C|c_A) = 1/3$
- $P(m_B|c_A) = P(m_b|c_A, p_A)P(p_A) +$
 $P(m_b|c_A, p_B)P(p_B) +$
 $P(m_b|c_A, p_C)P(p_C) = 1/2$
 - $P(p_A) = P(p_B) = P(p_C) = 1/3$
 - $P(m_b|c_A, p_A) = 1/2$
 - $P(m_b|c_A, p_B) = 0$ Won't open prize door
 - $P(m_b|c_A, p_C) = 1$ Monty has no choice

18-18: Inference with the Joint Probability Distribution

- Remember that we can list all combinations of events and use this to do inference. This is the joint distribution.

	Hum = High Sky = Overcast	Hum = High Sky = Sunny	Hum = Normal Sky = Overcast	Hum = Normal Sky = Sunny
Rain	0.1	0.05	0.15	0.05
\neg Rain	0.2	0.15	0.1	0.2

- $$P(\text{Rain}) = P(\text{Rain} \wedge \text{Hum} = \text{High} \wedge \text{Sky} = \text{Overcast}) \vee P(\text{Rain} \wedge \text{Hum} = \text{Normal} \wedge \text{Sky} = \text{Overcast}) \vee P(\text{Rain} \wedge \text{Hum} = \text{High} \wedge \text{Sky} = \text{Sunny}) \vee P(\text{Rain} \wedge \text{Hum} = \text{Normal} \wedge \text{Sky} = \text{Sunny})$$
- $$P(\text{Rain}) = 0.1 + 0.05 + 0.15 + 0.05 = 0.35$$

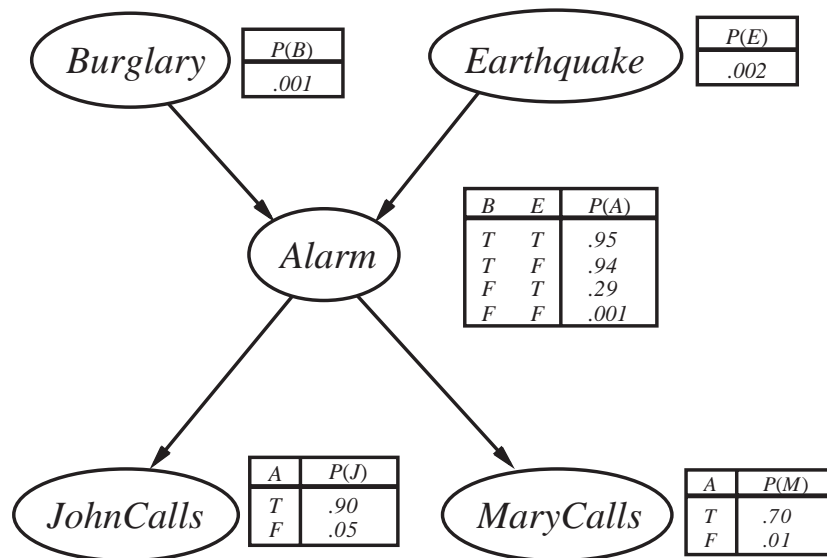
18-19: Probabilistic Inference

- Problems in working with the joint probability distribution:
 - Exponentially large table.
- We need a data structure that captures the fact that many variables do not influence each other.
 - For example, the color of Bart's hat does not influence whether Homer is hungry.
- We call this structure a *Bayesian network* (or a *belief network*)

18-20: Bayesian Network

- A Bayesian network is a directed graph in which each node is annotated with probability information. A network has:
 - A set of random variables that correspond to the nodes in the network.
 - A set of directed edges or arrows connecting nodes. These represent influence. In there is an arrow from X to Y , then X is the parent of Y .
 - Each node keeps a conditional probability distribution indicating the probability of each value it can take, conditional on its parents values.
 - No cycles. (it is a directed acyclic graph)
- The topology of the network specifies what variables directly influence other variables. (conditional independence relationships).

18-21: Burglary example



- Two neighbors will call when they hear your alarm.
 - John sometimes overreacts
 - Mary sometimes misses the alarm.
- Two things can set off the alarm
 - Earthquake
 - Burglary
- Given who has called, what's the probability of a burglary?

18-22: Network structure

- Each node has a conditional probability table.
- This gives the probability of each value of that node, given its parents' values.
- These sum to 1.
- Nodes with no parents just contain priors.

18-23: Summarizing uncertainty

- Notice that we don't need to have nodes for all the reasons why Mary might not call.
 - A probabilistic approach lets us summarize this information in $\neg M$
- This allows a small agent to deal with large worlds that have a large number of possibly uncertain outcomes.
- How would we handle this with logic?

18-24: Implicitly representing the full joint distribution

- Recall that the full joint distribution allows us to calculate the probability of any variable, given all the others.
- Independent events can be separated into separate tables.
- These are the CPTs seen in the Bayesian network.
- Therefore, we can use this info to perform computations.
- $P(x_1, x_2, \dots, x_n) = \prod P(x_i | \text{parents}(x_i))$
- $P(A \wedge \neg E \wedge \neg B \wedge J \wedge M) = P(J|A)P(M|A)P(A|\neg B \wedge \neg E)P(\neg B)P(\neg E) = 0.90 * 0.70 * 0.001 * 0.999 * 0.998 = 0.00062$

18-25: Some examples

- What is the probability that Both Mary and John call, given that the alarm sounded?
 - $P(M|A) * P(J|A) = .90 * .70 = 0.63$
- What is the probability of a breakin, given that we hear an alarm?
 - $P(B|A) = 0.95 + 0.001$
- What is the probability of a breakin given that both John and Mary called?
 - $P(B|J, M) = P(B \wedge J \wedge M \wedge A \wedge \neg E) \vee P(B \wedge J \wedge M \wedge A \wedge E) \vee P(B \wedge J \wedge M \wedge \neg A \wedge \neg E)P(B \wedge J \wedge M \wedge \neg A \wedge E)$
- This last example shows a form of *inference*.

18-26: Constructing a Bayesian network

- There are often several ways to construct a Bayesian network.
- The knowledge engineer needs to discover *conditional independence* relationships.
- Parents of a node should be those variables that directly influence its value.
 - JohnCalls is influenced by Earthquake, but not directly.
 - John and Mary calling don't influence each other.
- Formally, we believe that:
- $P(MaryCalls|JohnCalls, Alarm, Earthquake, Burglary) = P(MaryCalls|Alarm)$

18-27: Compactness and Node Ordering

- Bayesian networks allow for a more compact representation of the domain
 - Redundant information is removed.
- Example: Say we have 30 nodes, each with 5 parents.
- Each CPT will contain $2^5 = 32$ numbers Total: 960.
- Joint: 2^{30} entries, nearly all redundant.

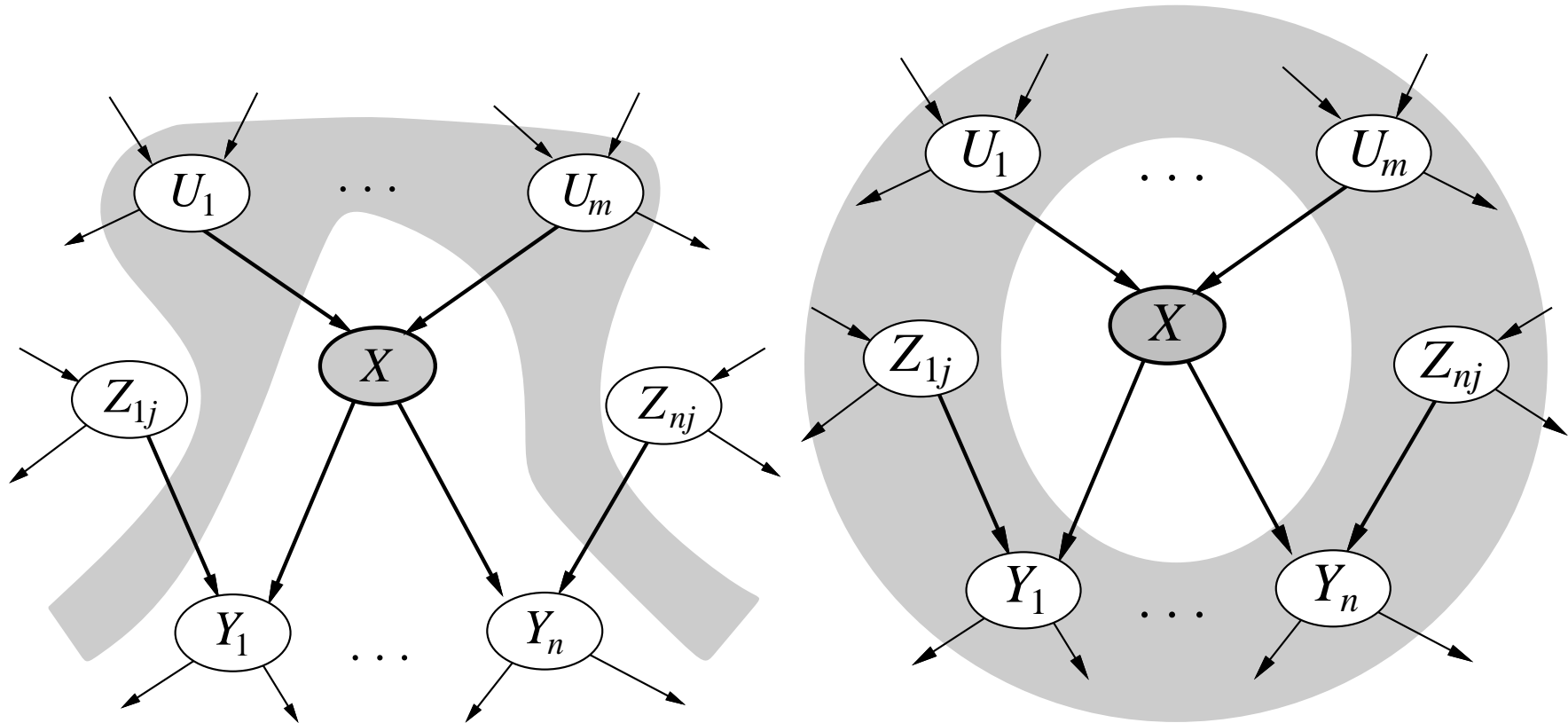
18-28: Building a network

- Begin with root causes
- Then add the variables they directly influence.
- Then add their direct children.
- This is called a *causal model*
 - Reasoning in terms of cause and effect
- Estimates are much easier to come up with this way.
- We could try to build from effect to cause, but the network would be more complex, and the CPTs hard to estimate. $P(E|B) = ?$

18-29: Conditional Independence in Bayesian networks

- Recall that conditional independence means that two variables are independent of each other, given the observation of a third variable.
- $P(a \wedge b|c) = P(a|c)P(b|c)$
- A node is conditionally independent of its nondescendants, given its parents.
 - Given Alarm, JohnCalls is independent of Burglary and Earthquake.
- A node is conditionally independent of all other nodes, given its parents, children, and siblings (the children's other parents).
 - Burglary is independent of JohnCalls given Alarm and Earthquake.

18-30: Conditional Independence in Bayesian networks



18-31: Conditional Independence in Bayesian networks

- General rules:
 - Two nodes are conditionally independent, given their parents. (JohnCalls and MaryCalls, given Alarm)
 - A node is conditionally independent of non-descendants, given its parents. (JohnCalls is conditionally independent of Burglary given Alarm).
 - A node is conditionally independent of all other nodes, given its parents, children, and its children's other parents.

18-32: Inference in Bayesian networks

- In most cases, we'll want to use a Bayesian network to tell us posterior probabilities.
- We observe a variable - how do other variables change?
- We can distinguish between *query variables* (things we want to know about) and *evidence variables* (things we can observe).
- There are also *hidden variables*, which influence query variables but are not directly observable.
- JohnCalls and MaryCalls are evidence, Earthquake and Burglary are queries, and Alarm is hidden.
- Updating in Bayesian networks can be quite complex - we'll skip over this.
 - For more information, see R & N

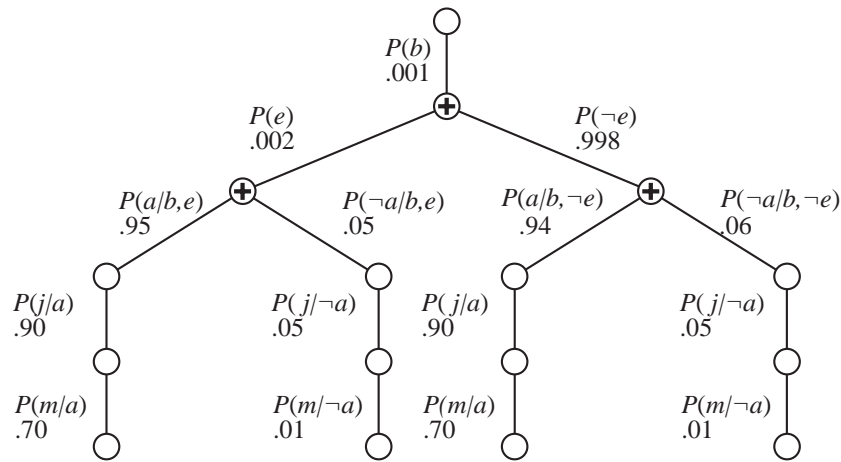
18-33: Enumeration

- In some cases, reasoning in a Bayesian network is still very expensive.
- For example, we can rewrite the probability $P(X|e) = \alpha P(X, e) = \alpha \sum P(X, e, y)$ where y are hidden variables.
- This is equivalent to summing within the joint probability distribution.
- Consider $P(\text{Burglary} | \text{JohnCalls}, \text{MaryCalls}) = \alpha P(\text{Burglary} \wedge \text{JohnCalls} \wedge \text{MaryCalls})$
- This is $\alpha \sum_E \sum_A P(B, E, A, J, M)$ For $B = \text{true}$, we must calculate:
$$P(B|J, M) = \alpha \sum_E \sum_A P(B)P(E)P(A|B, E)P(J|A)P(M|A)$$

18-34: Enumeration

- Problem- a network with n nodes will require $O(n2^n)$ computations.
- We can simplify by bringing the priors outside the summation.
- $\alpha P(B) \sum_E P(E) \sum_A P(A|B, E) P(J|A) P(M|A)$
- Still requires $O(2^n)$ calculations

18-35: Enumeration



- This tree shows the computations needed to determine $P(B|J, M)$
- Notice that there are lots of repeated computations in here.
- By eliminating repeated computations, we can speed things up.

18-36: Variable Elimination

- We can reduce the number of calculations by caching results and reusing them.
- Evaluate the expression from right-to-left.
- Summations are done only for nodes influenced by the variable being summed.

- Consider

$$P(B|j, m) = \alpha \underbrace{P(B)}_B \sum_e \underbrace{P(e)}_E \sum_a \underbrace{P(a|B, e)}_A \underbrace{P(j|a)}_J \underbrace{P(m|a)}_M$$

- The equation has been separated into factors.
- Once we compute $P(M|a)$ and $P(M|\neg a)$, we cache those results in a matrix f_M .
- Similarly for $P(J|a)$ and $P(J|\neg a)$ stored in f_J

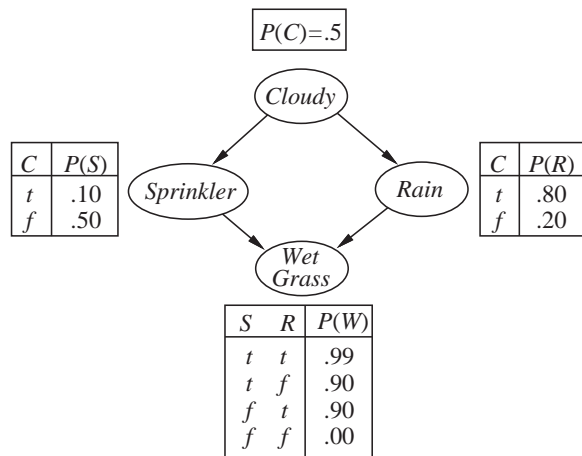
18-37: Variable Elimination

- $P(A|B, E)$ will result in a $2 \times 2 \times 2$ matrix, stored in F_A .
- We then need to compute the sum over the different possible values of A
- This sum is $\sum_a f_A(A, B, E) f_J(A) f_M(A)$
- We can process E the same way.
- In essence, we're doing dynamic programming here, and exploiting the same memoization process.
- Complexity
 - Polytrees: (one undirected path between any two nodes) - linear in the number of nodes.
 - Multiply-connected nodes: Exponential.

18-38: Scaling Up

- Many techniques have been developed to allow Bayesian networks to scale to hundreds of nodes.
- Clustering
 - Nodes are joined together to make the network into a polytree.
 - CPT within the node grows, but network structure is simplified.
- Approximating inference
 - Monte Carlo sampling is used to estimate conditional probabilities.

18-39: Monte Carlo sampling example



- Start at the top of the network and select a random sample. (say it's *true*).
- Draw a random sample from its children. conditioned on *true*.
 - $P(\textit{Sprinkler} | \textit{Cloudy} = \textit{true}) = \langle 0.1, 0.9 \rangle$. Say we select *False*
 - $P(\textit{Rain} | \textit{Cloudy} = \textit{true}) = \langle 0.8, 0.2 \rangle$. Say we select *True*
 - $P(\textit{WetGrass} | \textit{Sprinkler} = \textit{false}, \textit{Rain} = \textit{true}) = \langle 0.9, 0.1 \rangle$. Say we select *true*.
- This gives us a sample for $\langle \textit{cloudy}, \neg \textit{Sprinkler}, \textit{Rain}, \textit{WetGrass} \rangle$
- As we increase the number of samples, this provides an estimate of $P(\textit{cloudy}, \neg \textit{Sprinkler}, \textit{Rain}, \textit{WetGrass})$.
- In this way, we choose the query we are interested in and then sample the network “enough” times to determine the probability of that event occurring,

18-40: Applications of Bayesian Networks

- Diagnosis (widely used in Microsoft's products)
- Medical diagnosis
- Spam filtering
- Expert systems applications (plant control, monitoring)
- Robotic control