Bayes Nets for representing and reasoning about uncertainty

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What we'll discuss

- Recall the numerous and dramatic benefits of Joint Distributions for describing uncertain worlds
- Reel with terror at the problem with using Joint Distributions
- Discover how Bayes Net methodology allows us to built Joint Distributions in manageable chunks
- Discover there's still a lurking problem…
- …Start to solve that problem

Why this matters

- In Andrew's opinion, the most important technology in the Machine Learning / AI field to have emerged in the last 10 years.
- A clean, clear, manageable language and methodology for expressing what you're certain and uncertain about
- Already, many practical applications in medicine, factories, helpdesks:
  - P(this problem | these symptoms)
  - anomalousness of this observation
  - choosing next diagnostic test | these observations

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Active Data Collection

Inference

Anomaly Detection

Why Probability?

- There have been attempts to do different methodologies for uncertainty
  - Fuzzy Logic
  - Three-valued logic
  - Dempster-Shafer
  - Non-monotonic reasoning
- But the axioms of probability are the only system with this property:

  If you gamble using them you can't be unfairly exploited by an opponent using some other system [di Finetti 1931]

Definition of Conditional Probability

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

Corollary: The Chain Rule

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

Bayes Rule

P(B|A) = P(A ^ B) / P(A) = P(A|B) P(B) / P(A)

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

This is Bayes Rule

Bayes, Thomas (1763) An essay towards solving a problem in the doctrine of chances. *Philosophical Transactions of the Royal Society of London,* **53:370-418**

More General Forms of Bayes Rule

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

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

More General Forms of Bayes Rule

$$P(A = v_i|B) = \frac{P(B|A = v_i)P(A = v_i)}{\sum_{k=1}^{n_A} P(B|A = v_k)P(A = v_k)}$$

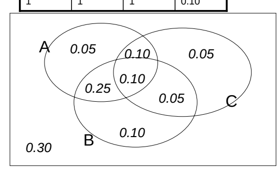
The Joint Distribution

Example: Boolean variables A, B, C

Recipe for making a joint distribution of M variables:

1. Make a truth table listing all combinations of values of your variables (if there are M Boolean variables then the table will have 2^M rows).
2. For each combination of values, say how probable it is.
3. If you subscribe to the axioms of probability, those numbers must sum to 1.

A	B	C	Prob
0	0	0	0.30
0	0	1	0.05
0	1	0	0.10
0	1	1	0.05
1	0	0	0.05
1	0	1	0.10
1	1	0	0.25
1	1	1	0.10



Joint distributions

- Good news

  Once you have a joint distribution, you can ask important questions about stuff that involves a lot of uncertainty

- Bad news

  Impossible to create for more than about ten attributes because there are so many numbers needed when you build the damn thing.

Using fewer numbers

Suppose there are two events:

- M: Manuela teaches the class (otherwise it's Andrew)
- S: It is sunny

The joint p.d.f. for these events contain four entries.

If we want to build the joint p.d.f. we'll have to invent those four numbers. OR WILL WE??

- We don't have to specify with bottom level conjunctive events such as P(~M^S) IF…
- …instead it may sometimes be more convenient for us to specify things like: P(M), P(S).

But just P(M) and P(S) don't derive the joint distribution. So you can't answer all questions.

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But just P(M) … derive the joint distribution. So you can't answer …

What extra assumption can you make?

Independence

"The sunshine levels do not depend on and do not influence who is teaching."

This can be specified very simply:

$P(S \mid M) = P(S)$

This is a powerful statement!

It required extra domain knowledge. A different kind of knowledge than numerical probabilities. It needed an understanding of causation.

Independence

From $P(S \mid M) = P(S)$, the rules of probability imply: (*can you prove these?*)

- $P(\sim S \mid M) = P(\sim S)$
- $P(M \mid S) = P(M)$
- $P(M \wedge S) = P(M)\, P(S)$
- $P(\sim M \wedge S) = P(\sim M)\, P(S)$, $(PM \wedge \sim S) = P(M)P(\sim S)$, $P(\sim M \wedge \sim S) = P(\sim M)P(\sim S)$

Independence

From $P(S \mid M) = P(S)$, the rules of probability imply: (*can you prove these?*)

- P(~S
- P(M
- P(M
- P(~M … $P(\sim M \wedge \sim S) = P(\sim M)P(\sim S)$

And in general:

$P(M=u \wedge S=v) = P(M=u)\, P(S=v)$

for each of the four combinations of

u=True/False

v=True/False

Independence

We've stated:

$P(M) = 0.6$

$P(S) = 0.3$

$P(S \mid M) = P(S)$

From these statements, we can derive the full joint pdf.

M	S	Prob
T	T	
T	F	
F	T	
F	F	

And since we now have the joint pdf, we can make any queries we like.

A more interesting case

- M : Manuela teaches the class
- S : It is sunny
- L : The lecturer arrives slightly late.

Assume both lecturers are sometimes delayed by bad weather. Andrew is more likely to arrive late than Manuela.

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Let's begin with writing down knowledge we're happy about:

P(S | M) = P(S), P(S) = 0.3, P(M) = 0.6
Lateness is not independent of the weather and is not independent of the lecturer.

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We already know the Joint of S and M, so all we need now is

P(L | S=u, M=v)

in the 4 cases of u/v = True/False.

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P(S | M) = P(S)
P(S) = 0.3
P(M) = 0.6

P(L | M ^ S) = 0.05
P(L | M ^ ~S) = 0.1
P(L | ~M ^ S) = 0.1
P(L | ~M ^ ~S) = 0.2

Now we can derive a full joint p.d.f. with a "mere" six numbers instead of seven*

**Savings are larger for larger numbers of variables.*

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Question: Express

P(L=x ^ M=y ^ S=z)

in terms that only need the above expressions, where *x,y* and *z* may each be True or False.

A bit of notation

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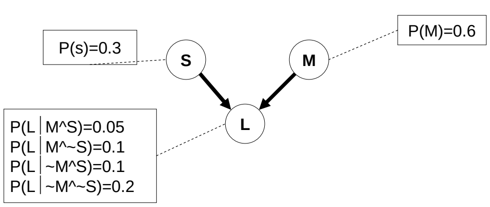

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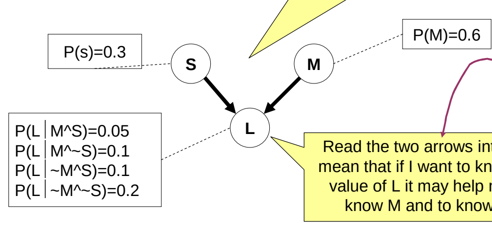
Read the absence of an arrow between S and M to mean "it would not help me predict M if I knew the value of S"

This kind of stuff will be thoroughly formalized later



Read the two arrows into L to mean that if I want to know the value of L it may help me to know M and to know S.

An even cuter trick

Suppose we have these three events:

- M : Lecture taught by Manuela
- L : Lecturer arrives late
- R : Lecture concerns robots

Suppose:

- Andrew has a higher chance of being late than Manuela.
- Andrew has a higher chance of giving robotics lectures.

What kind of independence can we find?

How about:

- P(L | M) = P(L) ?
- P(R | M) = P(R) ?
- P(L | R) = P(L) ?

Conditional independence

Once you know who the lecturer is, then whether they arrive late doesn't affect whether the lecture concerns robots.

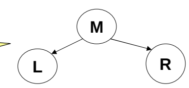
P(R | M,L) = P(R | M) and

P(R | ~M,L) = P(R | ~M)

We express this in the following way:

"R and L are conditionally independent given M"

..which is also notated by the following diagram.



Given knowledge of M, knowing anything else in the diagram won't help us with L, etc.

Conditional Independence formalized

R and L are conditionally independent given M if

for all x,y,z in {T,F}:

P(R=x | M=y ^ L=z) = P(R=x | M=y)

More generally:

Let S1 and S2 and S3 be sets of variables.

Set-of-variables S1 and set-of-variables S2 are conditionally independent given S3 if for all assignments of values to the variables in the sets,

P(S_1's assignments | S_2's assignments & S_3's assignments)=

P(S1's assignments | S3's assignments)

Example:

"Shoe-size is conditionally independent of Glove-size given height weight and age"

means

forall s,g,h,w,a

P(ShoeSize=s|Height=h,Weight=w,Age=a)

=

P(ShoeSize=s|Height=h,Weight=w,Age=a,GloveSize=g)

R and L are

for all x,y,z

P(R=

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does not mean

forall s,g,h

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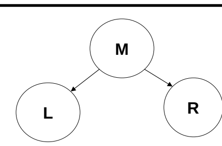
Conditional independence



We can write down P(M). And then, since we know L is only directly influenced by M, we can write down the values of P(L|M) and P(L|~M) and know we've fully specified L's behavior. Ditto for R.

P(M) = 0.6

P(L | M) = 0.085

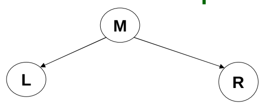
P(L | ~M) = 0.17

P(R | M) = 0.3

P(R | ~M) = 0.6

'R and L conditionally independent given M'

Conditional independence



P(M) = 0.6

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P(R | M) = 0.3

P(R | ~M) = 0.6

Conditional Independence:

P(R | M,L) = P(R | M),

P(R | ~M,L) = P(R | ~M)

Again, we can obtain any member of the Joint prob dist that we desire:

P(L=x ^ R=y ^ M=z) =

Assume five variables

T: The lecture started by 10:35

L: The lecturer arrives late

R: The lecture concerns robots

M: The lecturer is Manuela

S: It is sunny

- T only directly influenced by L (i.e. T is conditionally independent of R,M,S given L)
- L only directly influenced by M and S (i.e. L is conditionally independent of R given M & S)
- R only directly influenced by M (i.e. R is conditionally independent of L,S, given M)
- M and S are independent

Making a Bayes net

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L: The lecturer arrives late
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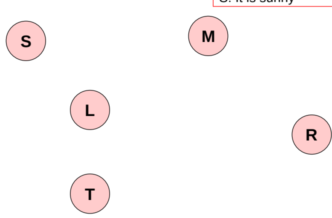

Step One: add variables.

- Just choose the variables you'd like to be included in the net.

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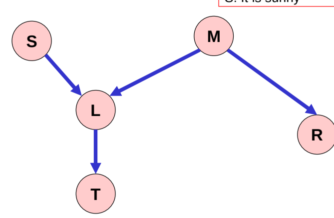

Step Two: add links.

- The link structure must be acyclic.
- If node X is given parents $Q_1,Q_2,..Q_n$ you are promising that any variable that's a non-descendent of X is conditionally independent of X given $\{Q_1,Q_2,..Q_n\}$

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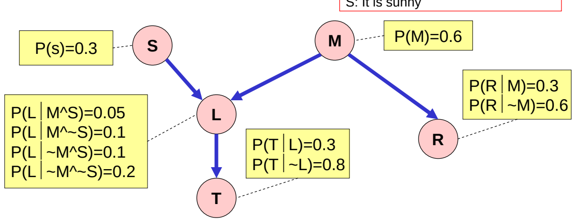

Step Three: add a probability table for each node.

- The table for node X must list P(X|Parent Values) for each possible combination of parent values

Making a Bayes net

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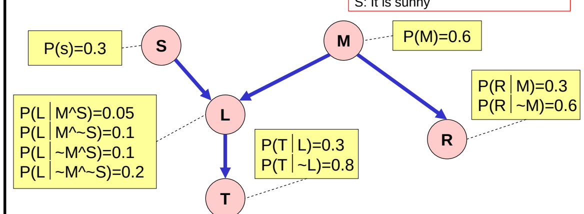


- Two unconnected variables may still be correlated
- Each node is conditionally independent of all non-descendants in the tree, given its parents.
- You can deduce many other conditional independence relations from a Bayes net. See the next lecture.

Bayes Nets Formalized

A Bayes net (also called a belief network) is an augmented directed acyclic graph, represented by the pair V , E where:

- V is a set of vertices.
- E is a set of directed edges joining vertices. No loops of any length are allowed.

Each vertex in V contains the following information:

- The name of a random variable
- A probability distribution table indicating how the probability of this variable's values depends on all possible combinations of parental values.

Building a Bayes Net

1. Choose a set of relevant variables.
2. Choose an ordering for them
3. Assume they're called X_1 .. X_m (where X_1 is the first in the ordering, X_1 is the second, etc)
4. For *i = 1 to m*:
   1. Add the X_i node to the network
   2. Set *Parents*(X_i) to be a minimal subset of {X_1…X_{i-1}} such that we have conditional independence of X_i and all other members of {X_1…X_{i-1}} given *Parents*(X_i)
   3. Define the probability table of P(X_i =*k* | Assignments of *Parents*(X_i)).

Example Bayes Net Building

Suppose we're building a nuclear power station. There are the following random variables:

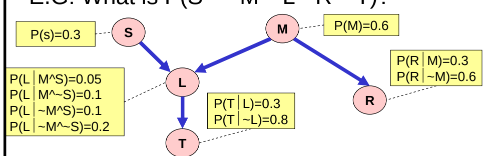
GRL : Gauge Reads Low.
CTL : Core temperature is low.
FG : Gauge is faulty.
FA : Alarm is faulty
AS : Alarm sounds

- If alarm working properly, the alarm is meant to sound if the gauge stops reading a low temp.
- If gauge working properly, the gauge is meant to read the temp of the core.

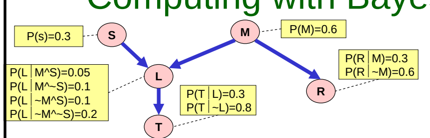
Computing a Joint Entry

How to compute an entry in a joint distribution?

E.G: What is P(S ^ ~M ^ L ~R ^ T)?



Computing with Bayes Net



P(T ^ ~R ^ L ^ ~M ^ S) =
P(T | ~R ^ L ^ ~M ^ S) * P(~R ^ L ^ ~M ^ S) =
P(T | L) * P(~R ^ L ^ ~M ^ S) =
P(T | L) * P(~R | L ^ ~M ^ S) * P(L^~M^S) =
P(T | L) * P(~R | ~M) * P(L^~M^S) =
P(T | L) * P(~R | ~M) * P(L|~M^S)*P(~M^S) =
P(T | L) * P(~R | ~M) * P(L|~M^S)*P(~M | S)*P(S) =
P(T | L) * P(~R | ~M) * P(L|~M^S)*P(~M)*P(S).

The general case

$P(X_1=x_1 \wedge X_2=x_2 \wedge \ldots X_{n-1}=x_{n-1} \wedge X_n=x_n) =$
$P(X_n=x_n \wedge X_{n-1}=x_{n-1} \wedge \ldots X_2=x_2 \wedge X_1=x_1) =$
$P(X_n=x_n \mid X_{n-1}=x_{n-1} \wedge \ldots X_2=x_2 \wedge X_1=x_1) * P(X_{n-1}=x_{n-1} \wedge \ldots X_2=x_2 \wedge X_1=x_1) =$
$P(X_n=x_n \mid X_{n-1}=x_{n-1} \wedge \ldots X_2=x_2 \wedge X_1=x_1) * P(X_{n-1}=x_{n-1} \mid \ldots X_2=x_2 \wedge X_1=x_1) *$
$P(X_{n-2}=x_{n-2} \wedge \ldots X_2=x_2 \wedge X_1=x_1) =$
:
:

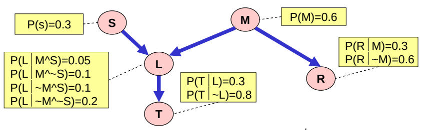
$$= \prod_{i=1}^{n} P\left((X_i = x_i) \mid ((X_{i-1} = x_{i-1}) \wedge \ldots (X_1 = x_1))\right)$$

$$= \prod_{i=1}^{n} P\left((X_i = x_i) \mid \text{Assignments of Parents}(X_i)\right)$$

So any entry in joint pdf table can be computed. And so **any conditional probability** can be computed.

Where are we now?

- We have a methodology for building Bayes nets.
- We don't require exponential storage to hold our probability table. Only exponential in the maximum number of parents of any node.
- We can compute probabilities of any given assignment of truth values to the variables. And we can do it in time linear with the number of nodes.
- So we can also compute answers to any questions.



E.G. What could we do to compute P(R | T,~S)?

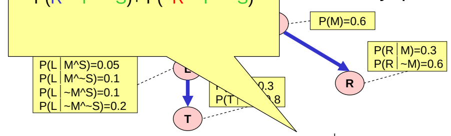
Where are we now?

Step 1: Compute P(R ^ T ^ ~S)

Step 2: Compute P(~R ^ T ^ ~S)

Step 3: Return

$$\frac{P(R \wedge T \wedge \sim S)}{P(R \wedge T \wedge \sim S) + P(\sim R \wedge T \wedge \sim S)}$$



E.G. What could we do to compute P(R | T,~S)?

Where are we now?

Step 1: Compute P(R ^ T ^ ~S) — Sum of all the rows in the Joint that match R ^ T ^ ~S

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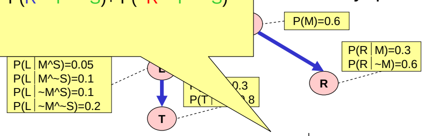


E.G. What could we do to compute P(R | T,~S)?

Where are we now?

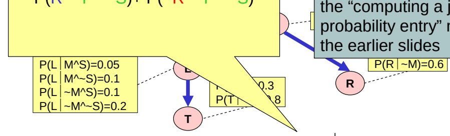
Step 1: Compute P(R ^ T ^ ~S) — Sum of all the rows in the Joint that match R ^ T ^ ~S (4 joint computes)

Step 2: Compute P(~R ^ T ^ ~S) — Sum of all the rows in the Joint that match ~R ^ T ^ ~S (4 joint computes)

Each of these obtained by the "computing a joint probability entry" method of the earlier slides

Step 3: Return

$$\frac{P(R \wedge T \wedge \sim S)}{P(R \wedge T \wedge \sim S) + P(\sim R \wedge T \wedge \sim S)}$$



E.G. What could we do to compute P(R | T,~S)?

The good news

We can do inference. We can compute any conditional probability:

P(Some variable | Some other variable values)

$$P(E_1 | E_2) = \frac{P(E_1 \wedge E_2)}{P(E_2)} = \frac{\sum_{\text{joint entries matching } E_1 \text{ and } E_2} P(\text{joint entry})}{\sum_{\text{joint entries matching } E_2} P(\text{joint entry})}$$

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Suppose you have *m* binary-valued variables in your Bayes Net and expression E_2 mentions *k* variables.

How much work is the above computation?

The sad, bad news

Conditional probabilities by enumerating all matching entries in the joint are expensive:

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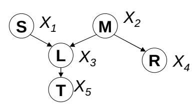
Sadder and worse news:

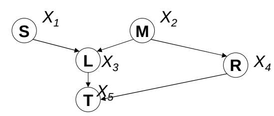
General querying of Bayes nets is NP-complete.

Bayes nets inference algorithms

A poly-tree is a directed acyclic graph in which no two nodes have more than one path between them.



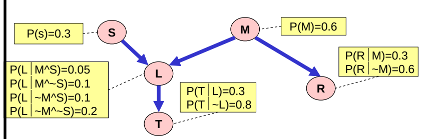
A poly tree



Not a poly tree
(but still a legal Bayes net)

- If net is a poly-tree, there is a linear-time algorithm (see a later Andrew lecture).
- The best general-case algorithms convert a general net to a poly-tree (often at huge expense) and calls the poly-tree algorithm.
- Another popular, practical approach (doesn't assume poly-tree): Stochastic Simulation.

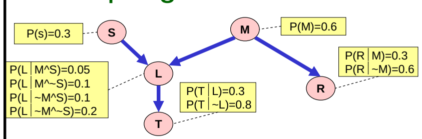
Sampling from the Joint Distribution



It's pretty easy to generate a set of variable-assignments at random with the same probability as the underlying joint distribution.

How?

Sampling from the Joint Distribution



1. Randomly choose S. S = True with prob 0.3
2. Randomly choose M. M = True with prob 0.6
3. Randomly choose L. The probability that L is true depends on the assignments of S and M. E.G. if steps 1 and 2 had produced S=True, M=False, then probability that L is true is 0.1
4. Randomly choose R. Probability depends on M.
5. Randomly choose T. Probability depends on L

A general sampling algorithm

Let's generalize the example on the previous slide to a general Bayes Net.

As in Slides 16-17 , call the variables $X_1 .. X_n$, where $Parents(X_i)$ must be a subset of $\{X_1 .. X_{i-1}\}$.

For $i=1$ to n:

1. Find parents, if any, of X_i. Assume $n(i)$ parents. Call them $X_{p(i,1)}$, $X_{p(i,2)}$, $\ldots X_{p(i,n(i))}$.
2. Recall the values that those parents were randomly given: $x_{p(i,1)}$, $x_{p(i,2)}$, $\ldots x_{p(i,n(i))}$.
3. Look up in the lookup-table for: $P(X_i=True \mid X_{p(i,1)}=x_{p(i,1)}, X_{p(i,2)}=x_{p(i,2)} \ldots X_{p(i,n(i))}=x_{p(i,n(i))})$
4. Randomly set $x_i=True$ according to this probability

$x_1, x_2, \ldots x_n$ are now a sample from the joint distribution of $X_1, X_2, \ldots X_n$.

Stochastic Simulation Example

Someone wants to know P(R = True | T = True ^ S = False)

We'll do lots of random samplings and count the number of occurrences of the following:

- N_c : Num. samples in which T=True and S=False.
- N_s : Num. samples in which R=True, T=True and S=False.
- N : Number of random samplings

Now if N is big enough:

N_c /N is a good estimate of *P(T=True and S=False)*.

N_s /N is a good estimate of *P(R=True ,T=True , S=False)*.

P(R|T^~S) = P(R^T^~S)/P(T^~S), so N_s / N_c can be a good estimate of P(R|T^~S).

General Stochastic Simulation

Someone wants to know P(E_1 | E_2)

We'll do lots of random samplings and count the number of occurrences of the following:

- N_c : Num. samples in which E_2
- N_s : Num. samples in which E_1 and E_2
- N : Number of random samplings

Now if N is big enough:

N_c /N is a good estimate of $P(E_2)$.

N_s /N is a good estimate of $P(E_1 , E_2)$.

P(E_1 | E_2) = P(E_1^ E_2)/P(E_2), so N_s / N_c can be a good estimate of P(E_1| E_2).

Likelihood weighting

Problem with Stochastic Sampling:

With lots of constraints in E, or unlikely events in E, then most of the simulations will be thrown away, (they'll have no effect on Nc, or Ns).

Imagine we're part way through our simulation.

In E2 we have the constraint Xi = v

We're just about to generate a value for Xi at random. Given the values assigned to the parents, we see that P(Xi = v | parents) = p .

Now we know that with stochastic sampling:

- we'll generate "Xi = v" proportion p of the time, and proceed.
- And we'll generate a different value proportion 1-p of the time, and the simulation will be wasted.

Instead, always generate Xi = v, but weight the answer by weight "p" to compensate.

Likelihood weighting

Set N_c :=0, N_s :=0

1. Generate a random assignment of all variables that matches E_2. This process returns a weight w.
2. Define w to be the probability that this assignment would have been generated instead of an unmatching assignment during its generation in the original algorithm.Fact: w is a product of all likelihood factors involved in the generation.
3. $N_c := N_c + w$
4. If our sample matches E_1 then $N_s := N_s + w$
5. Go to 1

Again, N_s / N_c estimates P(E_1 | E_2)

What you should know

- The meanings and importance of independence and conditional independence.
- The definition of a Bayes net.
- Computing probabilities of assignments of variables (i.e. members of the joint p.d.f.) with a Bayes net.
- The slow (exponential) method for computing arbitrary, conditional probabilities.
- The stochastic simulation method and likelihood weighting.