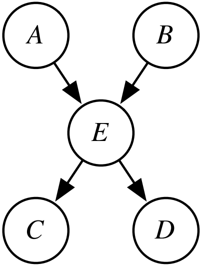
Learning a Belief Network

- If you
  - know the structure
  - have observed all of the variables
  - have no missing data
- you can learn each conditional probability separately.

Learning belief network example

Model Data $\longrightarrow$ Probabilities



A	B	C	D	E
t	f	t	t	f
f	t	t	t	t
t	t	f	t	f
		$\dots$		

$P(A)$
$P(B)$
$P(E \mid A, B)$
$P(C \mid E)$
$P(D \mid E)$

Learning conditional probabilities

- Each conditional probability distribution can be learned separately:
- For example:

$$P(E = t \mid A = t \wedge B = f) = \frac{(\#\text{examples: } E = t \wedge A = t \wedge B = f) + c_1}{(\#\text{examples: } A = t \wedge B = f) + c}$$

  where c_1 and c reflect prior (expert) knowledge ($c_1 \leq c$).
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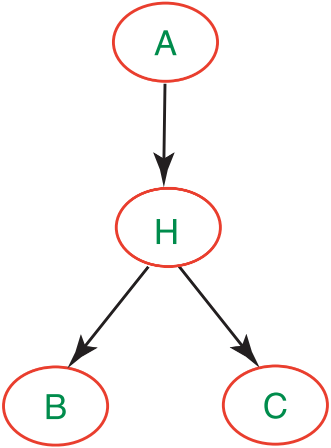
  where c_1 and c reflect prior (expert) knowledge ($c_1 \leq c$).
- When there are many parents to a node, there can little or no data for each probability estimate: use supervised learning to learn a decision tree, linear classifier, a neural network or other representation of the conditional probability.
- A conditional probability doesn't need to be represented as a table!

Unobserved Variables



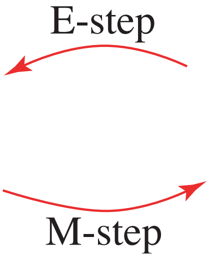
- What if we had only observed values for A, B, C?

A	B	C
t	f	t
f	t	t
t	t	f
	...	

EM Algorithm

Augmented Data

A	B	C	H	$Count$
t	f	t	t	0.7
t	f	t	f	0.3
f	t	t	f	0.9
f	t	t	t	0.1
	$\dots$			$\dots$



Probabilities

$P(A)$
$P(H \mid A)$
$P(B \mid H)$
$P(C \mid H)$

EM Algorithm

- Repeat the following two steps:
  - E-step give the expected number of data points for the unobserved variables based on the given probability distribution. Requires probabilistic inference.
  - M-step infer the (maximum likelihood) probabilities from the data. This is the same as the full observable case.
- Start either with made-up data or made-up probabilities.
- EM will converge to a local maxima.

Belief network structure learning (I)

Given examples $\mathbf{e}$, and model m:

$$P(m \mid \mathbf{e}) = \frac{P(\mathbf{e} \mid m) \times P(m)}{P(\mathbf{e})}.$$

- A model here is a belief network.
- A bigger network can always fit the data better.
- $P(m)$ lets us encode a preference for simpler models (e.g, smaller networks)

$\longrightarrow$ search over network structure looking for the most likely model.

A belief network structure learning algorithm

- Search over total orderings of variables.
- For each total ordering $X_1, \ldots, X_n$ use supervised learning to learn $P(X_i \mid X_1 \ldots X_{i-1})$.
- Return the network model found with minimum:
  $-\log P(\mathbf{e} \mid m) - \log P(m)$
  - $P(\mathbf{e} \mid m)$ can be obtained by inference.
  - How to determine $-\log P(m)$?

Bayesian Information Criterion (BIC) Score

$$P(m \mid \mathbf{e}) = \frac{P(\mathbf{e} \mid m) \times P(m)}{P(\mathbf{e})}$$

$$-\log P(m \mid \mathbf{e}) \propto -\log P(\mathbf{e} \mid m) - \log P(m)$$

- $-\log P(\mathbf{e} \mid m)$ is the negative log likelihood of model m: number of bits to describe the data in terms of the model.
- If $|\mathbf{e}|$ is the number of examples,
  there are   different probabilities to distinguish.
  Each one can be described in   bits.
- If there are $||m||$ independent parameters ($||m||$ is the dimensionality of the model):

$$-\log P(m \mid \mathbf{e}) \propto$$

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- $-\log P(\mathbf{e} \mid m)$ is the negative log likelihood of model m: number of bits to describe the data in terms of the model.
- If $|\mathbf{e}|$ is the number of examples, there are $|\mathbf{e}| + 1$ different probabilities to distinguish. Each one can be described in $\log(|\mathbf{e}| + 1)$ bits.
- If there are $||m||$ independent parameters ($||m||$ is the dimensionality of the model):

$$-\log P(m \mid \mathbf{e}) \propto -\log P(\mathbf{e} \mid m) + ||m|| \log(|\mathbf{e}| + 1)$$

This is (approximately) the BIC score.

Belief network structure learning (II)

- Given a total ordering, to determine $parents(X_i)$ do independence tests to determine which features should be the parents
- XOR problem: just because features do not give information individually, does not mean they will not give information in combination
- Search over total orderings of variables

Missing Data

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- For example: data in a clinical trial to test a drug may be missing because:
  - the patient dies
  - the patient had severe side effects
  - the patient was cured
  - the patient had to visit a sick relative.

  — ignoring some of these may make the drug look better or worse than it is.
- In general you need to model why data is missing.

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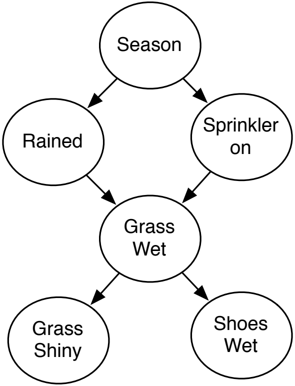
- A causal model is a model which predicts the effects of interventions.
- The parents of a node are its direct causes.
- We would expect that a causal model to obey the independence assumption of a belief network.
  - All causal networks are belief networks.
  - Not all belief networks are causal networks.

Sprinkler Example



- Which probabilities change if we observe sprinkler on?

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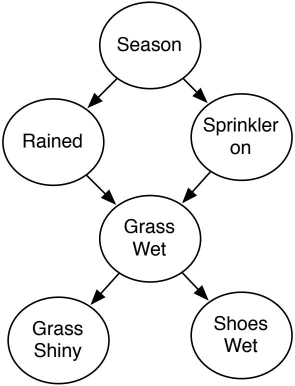

- Which probabilities change if we observe sprinkler on?
- Which probabilities change if we turn the sprinkler on?

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- An intervention has a different effect than an observation.
- Intervening on a variable only affects its descendants.
- Can be modelled by each variable X having a new parent, "Force X", where X is
  true if "Force X" is true and
  X depends on its other parents if "Force X" is false.

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- We can't learn causal models from observational data unless we are prepared to make modeling assumptions.
- Causal models can be learned from randomized experiments.
- Conjecture: causal belief networks are more natural and more concise than non-causal networks.
- Conjecture: causal model are more stable to changing circumstances (transportability)

General Learning of Belief Networks

- We have a mixture of observational data and data from randomized studies.
- We are not given the structure.
- We don't know whether there are hidden variables or not. We don't know the domain size of hidden variables.
- There is missing data.

. . . this is too difficult for current techniques!