

Informatics 2D – Reasoning and Agents

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Lecture 22 – Probabilities and Bayes' Rule
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adapted from slides by Michael Rovatsos

Where are we?

Last time ...

- ▶ Introduced basics of decision theory (probability theory + utility)
- ▶ Talked about random variables, probability distributions
- ▶ Introduced basic probability notation and axioms

Today ...

- ▶ **Probabilities and Bayes' Rule**

Inference with joint probability distributions

- ▶ Last time we talked about joint probability distributions (JPDs) but didn't present a method for **probabilistic inference** using them
- ▶ Problem: Given some observed evidence and a query proposition, how can we compute the **posterior probability** of that proposition?
- ▶ We will first discuss a simple method using a JPD as "knowledge base"
- ▶ Although not very useful in practice, it helps us to discuss interesting issues along the way

Example

- ▶ Domain consisting only of Boolean variables *Toothache*, *Cavity* and *Catch* (steel probe catches in tooth)
- ▶ Consider the following JPD:

	<i>toothache</i>		\neg <i>toothache</i>	
	<i>catch</i>	\neg <i>catch</i>	<i>catch</i>	\neg <i>catch</i>
<i>cavity</i>	0.108	0.012	0.072	0.008
\neg <i>cavity</i>	0.016	0.064	0.144	0.576

- ▶ Probabilities (table entries) sum to 1
- ▶ We can compute probability of any proposition, e.g.
 $P(\text{catch} \vee \text{cavity}) =$
 $0.108 + 0.016 + 0.072 + 0.144 + 0.012 + 0.008 = 0.36$

Marginalisation, conditioning & normalisation

- ▶ Extracting distribution of subset of variables is called

marginalisation: $P(\mathbf{Y}) = \sum_{\mathbf{z}} P(\mathbf{Y}, \mathbf{z})$

- ▶ Example:

$$\begin{aligned} P(\text{cavity}) &= P(\text{cavity}, \text{toothache}, \text{catch}) + P(\text{cavity}, \text{toothache}, \neg\text{catch}) \\ &\quad + P(\text{cavity}, \neg\text{toothache}, \text{catch}) + P(\text{cavity}, \neg\text{toothache}, \neg\text{catch}) \\ &= 0.108 + 0.012 + 0.072 + 0.008 = 0.2 \end{aligned}$$

- ▶ **Conditioning** – variant using the product rule:

$$P(\mathbf{Y}) = \sum_{\mathbf{z}} P(\mathbf{Y}|\mathbf{z})P(\mathbf{z})$$

Marginalisation, conditioning & normalisation

- ▶ Computing conditional probabilities:

$$\begin{aligned} P(\text{cavity}|\text{toothache}) &= \frac{P(\text{cavity} \wedge \text{toothache})}{P(\text{toothache})} \\ &= \frac{0.108 + 0.012}{0.108 + 0.012 + 0.016 + 0.064} = 0.6 \end{aligned}$$

- ▶ **Normalisation** ensures probabilities sum to 1, normalisation constants often denoted by α

- ▶ Example:

$$\begin{aligned} P(\text{Cavity}|\text{toothache}) &= \alpha P(\text{Cavity}, \text{toothache}) \\ &= \alpha [P(\text{Cavity}, \text{toothache}, \text{catch}) + P(\text{Cavity}, \text{toothache}, \neg\text{catch})] \\ &= \alpha [(0.108, 0.016) + (0.012, 0.064)] = \alpha (0.12, 0.08) = (0.6, 0.4) \end{aligned}$$

A general inference procedure

- ▶ Let X be a query variable (e.g. *Cavity*), \mathbf{E} set of evidence variables (e.g. $\{\textit{Toothache}\}$) and \mathbf{e} their observed values, \mathbf{Y} remaining unobserved variables
- ▶ Query evaluation: $P(X|\mathbf{e}) = \alpha P(X, \mathbf{e}) = \alpha \sum_{\mathbf{y}} P(X, \mathbf{e}, \mathbf{y})$
- ▶ Note that X , \mathbf{E} , and \mathbf{Y} constitute complete set of variables, i.e. $P(x, \mathbf{e}, \mathbf{y})$ simply a subset of probabilities from the JPD
- ▶ For every value x_i of X , sum over all values of every variable in \mathbf{Y} and normalise the resulting probability vector
- ▶ Only theoretically relevant, it requires $O(2^n)$ steps (and entries) for n Boolean variables (and we don't have these values)
- ▶ Basically, all methods we will talk about deal with tackling this problem!

Independence

- ▶ Suppose we extend our example with the variable *Weather*
- ▶ What is the relationship between old and new JPD?
- ▶ Can compute $P(\textit{toothache}, \textit{catch}, \textit{cavity}, \textit{Weather} = \textit{cloudy})$ as:

$$P(\textit{Weather} = \textit{cloudy}|\textit{toothache}, \textit{catch}, \textit{cavity})P(\textit{toothache}, \textit{catch}, \textit{cavity})$$

- ▶ And since the weather does not depend on dental stuff, we expect that

$$P(\textit{Weather} = \textit{cloudy}|\textit{toothache}, \textit{catch}, \textit{cavity}) = P(\textit{Weather} = \textit{cloudy})$$

- ▶ So

$$\begin{aligned} P(\textit{toothache}, \textit{catch}, \textit{cavity}, \textit{Weather} = \textit{cloudy}) &= \\ P(\textit{Weather} = \textit{cloudy})P(\textit{toothache}, \textit{catch}, \textit{cavity}) & \end{aligned}$$

- ▶ One 8-element and one 4-element table rather than a 32-table

Independence

- This is called **independence**, usually written as $P(X|Y) = P(X)$ or $P(Y|X) = P(Y)$ or $P(X, Y) = P(X)P(Y)$

- Depends on domain knowledge; can factor distributions



- Such independence assumptions can help to dramatically reduce complexity
- Independence assumptions are sometimes *necessary* even when not entirely justified, so as to make probabilistic reasoning in the domain practical (more later).

Bayes' rule

- Bayes' rule** is derived by writing the product rule in two forms and equating them:

$$\frac{P(a \wedge b) = P(a|b)P(b)}{P(a \wedge b) = P(b|a)P(a)} \Rightarrow P(b|a) = \frac{P(a|b)P(b)}{P(a)}$$

- General case for multivaried variables using background evidence e :

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

- Useful because often we have good estimates for three terms on the right and are interested in the fourth

Applying Bayes' rule

- Example: meningitis causes stiff neck with 50%, probability of meningitis (m) 1/50000, probability of stiff neck (s) 1/20

$$P(m|s) = \frac{P(s|m)P(m)}{P(s)} = \frac{\frac{1}{2} \times \frac{1}{50000}}{\frac{1}{20}} = \frac{1}{5000}$$

- Previously, we were able to avoid calculating probability of evidence ($P(s)$) by using normalisation
- With Bayes' rule: $P(M|s) = \alpha(P(s|m)P(m), P(s|\neg m)P(\neg m))$
- Usefulness of this depends on whether $P(s|\neg m)$ is easier to calculate than $P(s)$
- Obvious question: why would conditional probability be available in one direction and not in the other?
- Diagnostic knowledge (from symptoms to causes) is often fragile (e.g. $P(m|s)$ will go up if $P(m)$ goes up due to epidemic)

Combining evidence

- Attempting to use additional evidence is easy in the JPD model

$$P(\text{Cavity}|\text{toothache} \wedge \text{catch}) = \alpha(0.108, 0.016) \approx (0.871, 0.129)$$

but requires additional knowledge in Bayesian model:

$$P(\text{Cavity}|\text{toothache} \wedge \text{catch}) = \alpha P(\text{toothache} \wedge \text{catch}|\text{Cavity})P(\text{Cavity})$$

- This is basically almost as hard as JPD calculation
- Refining idea of independence: *Toothache* and *Catch* are independent given presence/absence of *Cavity* (both caused by cavity, no effect on each other)

$$P(\text{toothache} \wedge \text{catch}|\text{Cavity}) = P(\text{toothache}|\text{Cavity})P(\text{catch}|\text{Cavity})$$

Conditional independence

- ▶ Two variables X and Y are conditionally independent given Z if $\mathbf{P}(X, Y|Z) = \mathbf{P}(X|Z)\mathbf{P}(Y|Z)$
- ▶ Equivalent forms $\mathbf{P}(X|Y, Z) = \mathbf{P}(X|Z)$,
 $\mathbf{P}(Y|X, Z) = \mathbf{P}(Y|Z)$
- ▶ So in our example:

$$\mathbf{P}(\text{Cavity}|\text{toothache} \wedge \text{catch}) = \alpha \mathbf{P}(\text{toothache}|\text{Cavity})\mathbf{P}(\text{catch}|\text{Cavity})\mathbf{P}(\text{Cavity})$$

- ▶ As before, this allows us to decompose large JPD tables into smaller ones, grows as $O(n)$ instead of $O(2^n)$
- ▶ This is what makes probabilistic reasoning methods scalable at all!

Conditional independence

- ▶ Conditional independence assumptions much more often reasonable than absolute independence assumptions
- ▶ **Naive Bayes model:**

$$\mathbf{P}(\text{Cause}, \text{Effect}_1, \dots, \text{Effect}_n) = \mathbf{P}(\text{Cause}) \prod_i \mathbf{P}(\text{Effect}_i|\text{Cause})$$

- ▶ Based on the idea that all effects are conditionally independent given the cause variable
- ▶ Also called **Bayesian classifier** or (by some) even “**idiot Bayes model**”
- ▶ Works surprisingly well in many domains despite its simplicity!

Summary

- ▶ Probabilistic inference with full JPDs
- ▶ Independence and conditional independence
- ▶ Bayes' rule and its applications problems with fairly simple techniques
- ▶ Next time: **Probabilistic Reasoning with Bayesian Networks**