

# Probabilistic Graphical Models

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# Chapter 1

## Representation

### 1.1 Introduction

Model

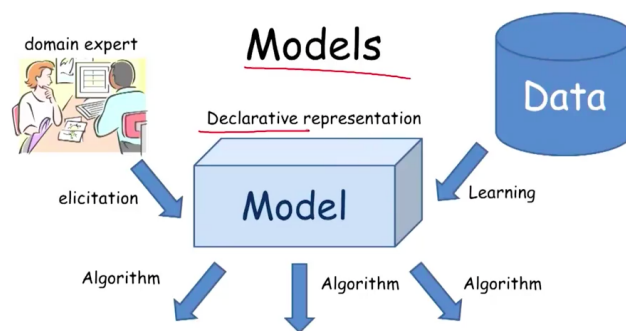


Figure 1.1: Model is a declarative representation of our understanding of the world

It is important because the same representation, that same model can be used in the the context of one algorithms that might answer different kind of questions. Or the same question in more efficient way.

We can construct methodologies the elicit these models from a human expert, or learn from data or combination.

Uncertainty

- Partial knowledges of state of the world
- Noisy observations
- Phenomena not covered by our model
- Inherent stochasticity

Probability Theory

- Declarative representation with clear semantics
- Powerful reasoning patterns: conditioning decision making

- Established learning methods
- Complex Systems
- Graphical Models: Bayesian Networks, Markov Networks (directed or undirected graphs)
- Graphical Representation
  - Intuitive and compact data structure
  - Efficient reasoning using general purpose algorithms
  - Sparse parameterization
  - feasible elicitation : by hand
  - learning from data automatically

### 1.1.1 Distribution:Marginalization,Conditioning

Joint Distribution:  $P(I,D,G)$

Conditioning: observation 1 value of variable  $\rightarrow$  Reduction  $\rightarrow$  Renormalization  $P(I,D,g^1) \rightarrow P(I,D|g^1)$

Marginalization:  $\sum_I P(I,D) = P(D)$  . Example: you have thrown two 6-sided dice,  $D_1$  and  $D_2$ .  $P(D_1,D_2)$  is a joint probability distribution. The probability that  $D_2 = 1$  is equals to  $\sum_{i=1}^6 P(D_1 = i, D_2 = 1)$ .

### 1.1.2 Factors

A factor is a function or table  $\phi(X_1, \dots, X_k)$

$\phi : Val(X_1, \dots, X_k) \rightarrow R$

Scope =  $X_1, \dots, X_k$

Joint distribution is a factor

Unnormalized measure is a factor

Conditional Probability Distribution (CPD) is a factor  $P(G|I,D)$ :  $G$  in columns while  $I,D$  in rows.

Why factors?

- Fundamental building block for defining distributions in high-dimensional spaces
- Set of basic operations for manipulating these probability distributions

## 1.2 Bayesian Network (Directed Models)

### 1.2.1 Semantics and Factorization

What does random variable depend on?

Draw nodes, edges, each node with a factor is CPD (conditional probability distribution)

A bayesian network is:

- A directed acyclic graph (DAG)  $G$  whose nodes represent the random variables
- For each node  $X_i$  a CPD  $P(X_i|Par_G(X_i))$

The BN represent a joint distribution via the chain rule for Bayesian Networks

$$P(X_1, \dots, X_n) = \prod_i P(X_i | \text{Par}_G(X_i))$$

BN is a Legal distribution :  $\sum P = 1$  and  $P > 0$

### 1.2.2 Reasoning Pattern

Causal Reasoning: reasoning going down

Evidential Reasoning: reasoning going up

Inter-causal Reasoning: The probability of class is hard, if we observe the "C" grade and change the posterior probability of high intelligence is goes up

### 1.2.3 Flow of Probabilistic Influence: active trail

When can X influence Y?

$$X \rightarrow Y$$

$$X \leftarrow Y$$

Active Trails:

A trail  $X_1 - \dots - X_k$  is active if: it has no v-structures  $X_{i-1} \rightarrow X_i \leftarrow X_{i+1}$

When can X influence Y given evidence about Z?

A trail  $X_1 - \dots - X_k$  is active given Z if:

— for any v-structure  $X_{i-1} \rightarrow X_i \leftarrow X_{i+1}$  we have that  $X_i$  or one of its descendants  $\in Z$

— no other  $X_i$  is in Z

Assignment

1. How many parameter to present a CPD. If X have m possibilities the  $P(X)$  needs m-1 independent parameters

If Y have k possibilities, Z have l possibilities then  $P(X \rightarrow Y, Z)$  has (m-1)\*k\*l independent parameters.

2. Inter-causal reasoning

To calculate the required values, we can apply Bayes' rule. For instance,

$$\begin{aligned} \frac{P(A=1|T=1, P=1)}{P(T=1, P=1)} &= \frac{P(A=1, T=1, P=1)}{P(A=0, T=1, P=1) + P(A=1, T=1, P=1)} \\ &= \frac{P(A=1, T=1, P=1)}{P(A=0, T=1, P=1) + P(A=1, T=1, P=1)} \end{aligned}$$

We can then use the chain rule of Bayesian networks to substitute the correct values in, e.g.,

$$P(A=1, T=1, P=1) = P(P=1) * P(A=1) * P(T=1|P=1, A=1)$$

This example of inter-causal reasoning meshes well with common sense: if we see a traffic jam, the probability that there was a car accident is relatively high. However, if we also see that the president is visiting town, we can reason that the president's visit is the cause of the traffic jam; the probability that there was a car accident therefore drops correspondingly.

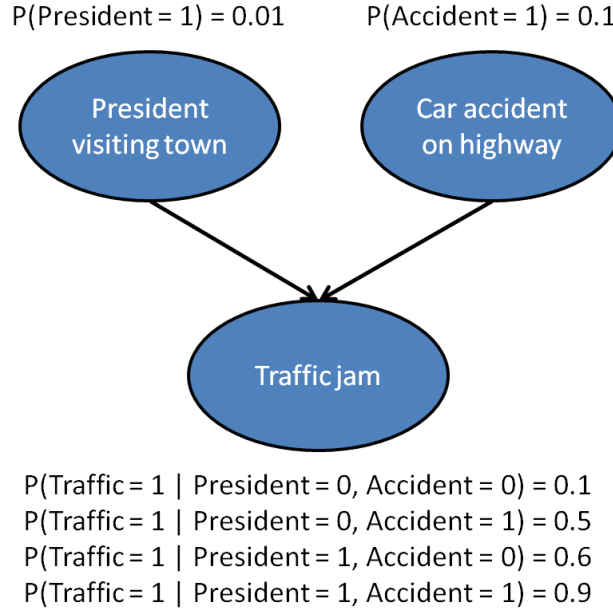


Figure 1.2:

## 1.3 Bayesian Networks: In-dependencies

### 1.3.1 Conditional Independence

Independence

For events  $\alpha, \beta$ ,  $P$  satisfy independence if:

- $P(\alpha, \beta) = P(\alpha) * P(\beta)$
- $P(\alpha|\beta) = P(\alpha)$
- $P(\beta|\alpha) = P(\beta)$

Conditional Independence

For random variables  $X, Y, Z$ ;  $P$  satisfy ( $X$  independence  $Y \mid Z$ ) if

- $P(X, Y|Z) = P(X|Z) * P(Y|Z)$
- $P(X|Y, Z) = P(X|Z)$
- $P(Y|X, Z) = P(Y|Z)$
- $P(X, Y, Z) \propto \phi_1(X, Z) * \phi_2(Y, Z)$

We need to check for all cases

$S$  and  $G$  are dependent but conditionally independent given  $I$ .  $I$  and  $D$  are independent but conditionally dependent given  $G$ , which active the V-structure here



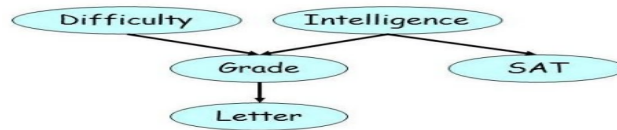


Figure 1.3: Example of student: independence

### 1.3.2 Independence in Bayesian Networks: d-separate, I-map

Flow of influence and d-separation

X and Y are d-separated in G given Z if there is no active trail in G between X and Y given Z.  $d-sep_G(X, Y|Z)$

**Factorization to Independences: BNs**

Theorem If P factorizes over G, and  $d-sep_G(X, Y|Z)$  then P satisfies  $(X \perp Y|Z)$ .

$P(S) = \sum_I P(I)P(S|I)$  (standard marginalization operation) because  $P(S, I) = P(I) * P(S|I)$

If P factorizes over G, then in P, any variable is independent of its non-descendants given its parents

**I-maps**

d-separation in G  $\rightarrow$  P satisfies corresponding independence statement

$I(G) = (X \perp Y|Z) : d-sep_G(X, Y|Z)$

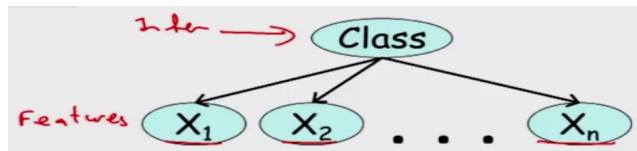
Definition: If P satisfies  $I(G)$ , we say that G is an I-map (in-dependency map) of P

**Theorem:** If P factorizes over G, then G is an I-map for P

**Theorem:** If G is an I-map for P, then P factorizes over G

### 1.3.3 Naive Bayes Model

Assumption: Given the class variable, each observed variable is independent of the other observed variables.

Figure 1.4: Naive Bayes:  $(X_i \perp X_j|C)$  for all  $X_i, X_j$ 

Naive Bayes Classifier

Bernoulli Naive Bayes: each observed variable is binary: 1 if appear and 0 otherwise

Multinomial Naive Bayes for Text: values of each random variable is the actual word in each document

### 1.3.4 Assignment

If there is no active trails between A and D, then they are independent

I-maps: if G is an I-map of P, all in-dependencies in G also in P. However, this does not mean that all in-dependencies in P also in G

I-maps can also be defined directly on graphs as follow: Let  $I(G)$  be the set of in-dependencies encoded by a graph G. Then  $G_1$  is an I-map for  $G_2$  if  $I(G_1) \subseteq I(G_2)$

I-map is not a function

## 1.4 Bayesian Networks: Knowledge Engineering

### 1.4.1 Medical Diagnosis

### 1.4.2 Knowledge Engineering: Example SAMIAM

### 1.4.3 Programming Assignment 1

Compute  $P(A, B | C = C_i)$  means that observes the specific value of C and  $P(C_i) = 1$  otherwise is 0

- Compute  $P(A, B, C)$
- if  $C_j \neq C_i$  then  $P(A, B, C_j) = 0$
- $M = \sum_k P(A, B, C_k)$
- Normalize M

## 1.5 Template Models

Same model that can resolve multiple problems

Sharing between models + within models  $\rightarrow$  reuse parameters

Template variable  $X(U_1, \dots, U_k)$  is instantiated (duplicated) multiple times

Template Models:

— Languages that specify how variables inherit dependency model from template

— Dynamic Bayesian Networks: temporal

— Object-relational models: Directed and Undirected models

## 1.6 Temporal Models - DBNs

Distributions over Trajectories

- Pick time granularity  $\Delta$

- $X^{(t)}$  - variable  $X$  at time  $t \Delta$
- $X^{t:t'} = X^{(t)}, \dots, X^{(t')}(t \leq t')$
- Want to represent  $P(X^{(t:t')})$  for any  $t, t'$

**Markov Assumption:** time flows forward

$$P(X^{(0:T)}) = P(X^{(0)}) * \prod_{t=0}^{T-1} P(X^{(t+1)} | X^{(0:t)})$$

Assumption:  $(X^{(t+1)} \perp X^{(0:t-1)} | X^{(t)})$  : next step independent to the past

if observed current state

$$\text{Go back chain rules: } P(X^{(0:T)}) = P(X^{(0)}) * \prod_{t=0}^{T-1} P(X^{(t+1)} | X^{(t)})$$

**Time Invariance**

— Template probability model  $P(X' | X)$

— For all  $t$ :

—  $P(X^{(t+1)} | X^{(t)}) = P(X' | X)$  : for example: traffic time of day, week

**Template Transition Model**

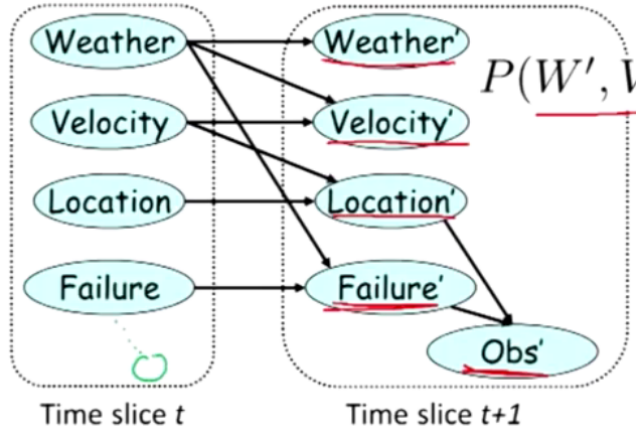


Figure 1.5: Template Transition Model

Based on network fragment, we need to compute the condition

$$P = P(W', V', L', F', O' | W, V, L, F)$$

We have CPD:  $P = P(W' | W) * P(V' | V, W) * P(L' | L, V) * P(F' | F, W) * P(O' | F', L')$

We have dependence within (intra-time slice) and between (inter time slice).

**Initial State Distribution:** use chain rule

**Ground Bayesian Network:** copy the present of time 0 to time 1

**2 time-slice Bayesian Network**

— A transition model (2TBN) over  $X_1, \dots, X_n$  is specified as as BN fragment such that:

- The nodes includes  $X'_1, \dots, X'_n$  and a subset  $X_1, \dots, X_n$
- Only the nodes  $X'_1, \dots, X'_n$  have parents and a CPD
- The 2 TBN defines a conditional distribution
- $P(X' | X) = \prod_{i=1}^n P(X'_i | Pa_{X'_i})$

**Dynamic Bayesian Network**

- A dynamic Bayesian network (DBN) over  $X_1, \dots, X_n$  is defined by a
  - 2TBN  $BN_{\rightarrow}$  over  $X_1, \dots, X_n$
  - a Bayesian network  $BN^{(0)}$  over  $X_1^{(0)}, \dots, X_n^{(0)}$

**Ground Network**

- For a trajectory over  $0, \dots, T$ , ground (unrolled network)
  - The dependency model for  $X_1^{(0)}, \dots, X_n^{(0)}$  is copied from  $BN^{(0)}$
  - The dependency model for  $X_1^{(t)}, \dots, X_n^{(t)}$  for all  $t > 0$  is copied from  $BN_{\rightarrow}$

## 1.7 Temporal Models - HMMs

Hidden Markov Models

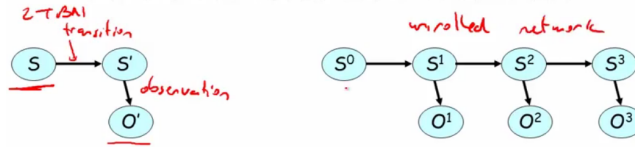


Figure 1.6: Unrolled network

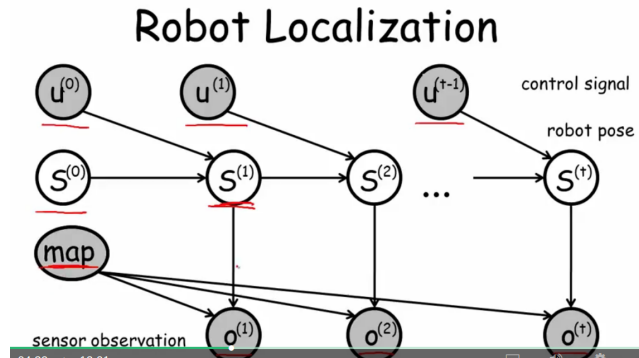


Figure 1.7:

HMM: self-transition (different with Bayesian Network): subclass of DBNs

## 1.8 Plate Models

Objects of the same type

### 1.8.1 Modeling Repetition

Box is put around Outcome variable: plate

Parameters outside of the plate (CPD)

For example: model of university with multiple students

**Nested Plates**

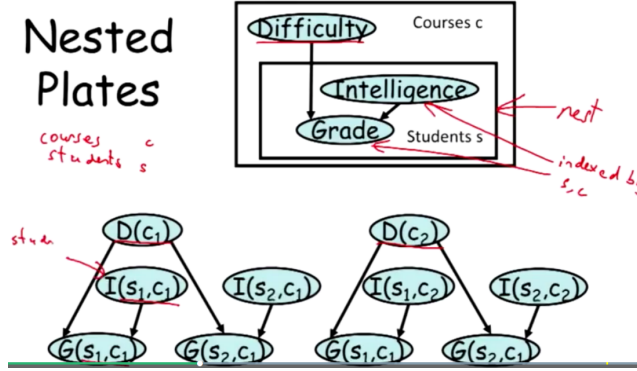


Figure 1.8: Nested Plates

**Overlapping Plates**

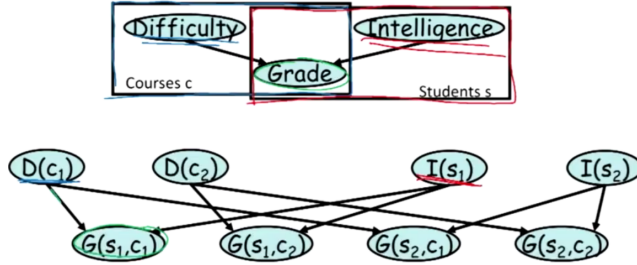


Figure 1.9: Overlapping Model

## 1.9 Plate Dependency Model

For a template variable  $A(U_1, \dots, U_k)$ :

— Template parents  $B_i(U_1), \dots, B_m(U_m)$

— CPD  $P(A|B_1, \dots, B_m)$

**Ground Network**

**Plate Dependency Model**

Template for an infinite set of BNs, each induced by a difference set of domain objects

Parameters and structures are reused within a BN and across different BNs

Models encode correlation across multiple objects, allowing collective inference

## 1.10 Structured CPDs

General CPD

- CPD  $P(X|Y_1, \dots, Y_k)$  specifies distribution over  $X$  for each assignment  $y_1, \dots, y_k$
- can use any function to specify a factor  $\phi(X, Y_1, \dots, Y_k)$  such that
- $\sum_X \phi(x, y_1, \dots, y_k) = 1$  for all  $y_1, \dots, y_k$

### Context-Specific Independence

$P \models (X \perp_C Y|Z, c)$  assignment to  $c$

- $P(X, Y|Z, c) = P(X|Z, c)P(Y|Z, c)$
- $P(X|Y, Z, c) = P(X|Z, c)$
- $P(Y|X, Z, c) = P(Y|Z, c)$

## 1.11 Deterministic CPDs

non-tabular CPD arises when a variable  $X$  is deterministic function of its parents  $Pa_X$ . There is a function  $f: Val(Pa_X) \rightarrow Val(X)$  such that

$P(x|pa_X) = 1$  only  $x = f(pa_X)$ , otherwise is 0

For example, the the case of binary-valued variables,  $X$  might be the "or" of its parents. In a continuous domain, we might want to assert in  $P(X|Y, Z)$  that  $X$  is equal  $Y+Z$

## 1.12 Tree- structured CPDs

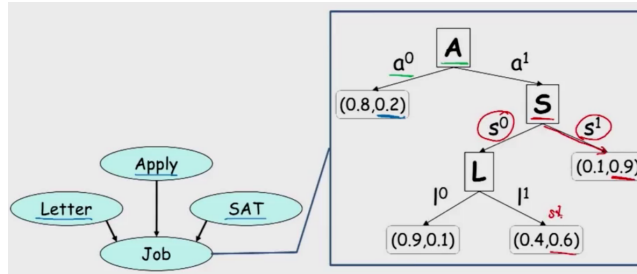


Figure 1.10: Tree-structured CPD

context-specific in-dependencies

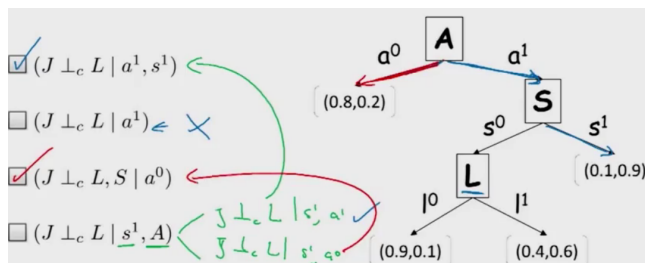


Figure 1.11: context-specific in-dependencies

## 1.13 Independence of Causal Influence

### Noisy OR CPD

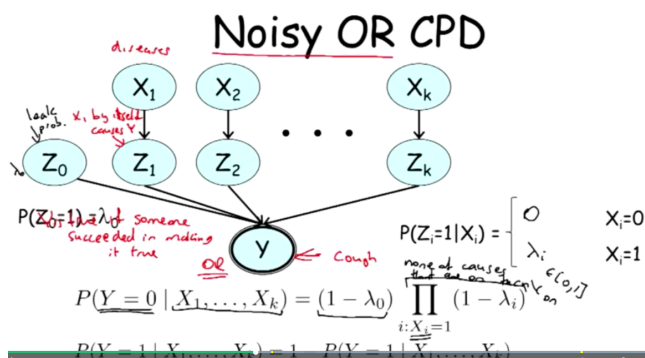


Figure 1.12: Noisy OR CPD

### 1.13.1 Independence of Causal Influence

### 1.13.2 Sigmoid CPD

## 1.14 Continue Variables

Use Gaussian model

## 1.15 Exercise: Tree CPD - context specific In-dependencies

Base on Fig 1.14:  $(E \perp_c D | b^1)$  and  $(E \perp_c D, B | a^1)$

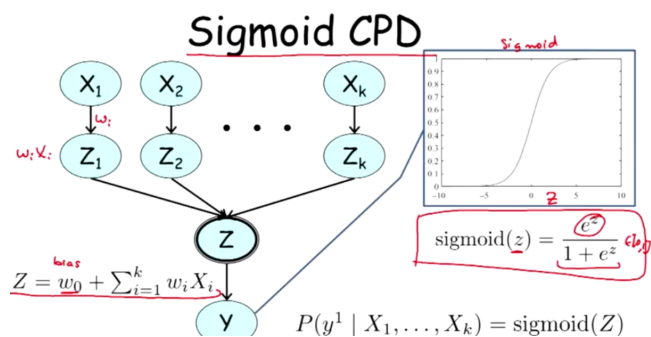


Figure 1.13: Sigmoid CPD

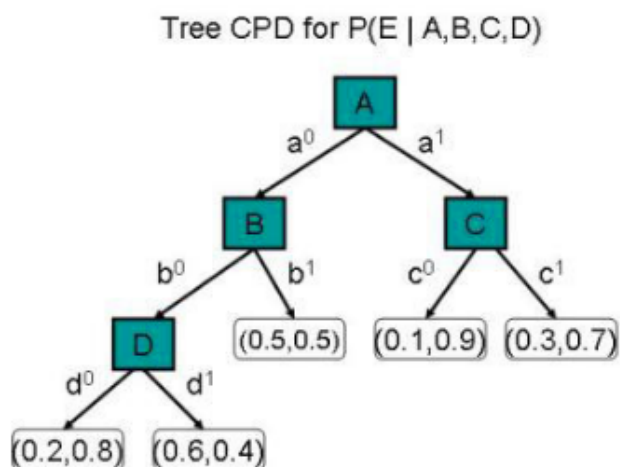


Figure 1.14: Which are context-specific independences?

## 1.16 Markov Networks: Undirected Models