Lecture 21 (last one!):

Review

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Koller & Friedman chapters

Chap.	Handout	Title
2	y	Foundations (math review)
3	y	The BN representation (Bayes ball, I-maps)
4	y	Local probabilistic models (CPDs, CSI)
5	y	Undirected GMs (BN $\leftrightarrow$ MN)
6	y	Inference with GMs (overview)
7	y	Variable elimination
8	y	Clique trees
9	y	Particle based approximations
10	n	Inference as optimization (unfinished)
11	n	Inference in hybrid networks
12	y	Learning: introduction
13	y	Parameter estimation (fully obs. BNs)
14	y	Structure learning in BNs
15	y	Partially observed data (EM for BNs)

Jordan chapters

Chap.	Handout	Title
2	n	Cond. Indep and factorization
3	n	The elimination algorithm
4	n	Prob. propagation and factor graphs
5	y	Statistical concepts
6	n	Linear regression and LMS
7	n	Linear classification
8	y	Exponential family and GLIMs
9	y	Completely observed GMs (IPF, etc)
10	y	Mixtures and conditional mixtures
11	y	The EM algorithm
12	y	HMMs
13	y	The multivariate Gaussian
14	y	Factor analysis
15	y	Kalman filtering and smoothing
16	n	Markov properties of graphs

Jordan chapters cont'd

Chap.	Handout	Title
17	n	The junction tree algorithm
18	n	HMM and state space models revisited
19	y	Features, maxent and duality
20	y	Iterative scaling algorithms
21	n	Sampling methods
22	n	Decision graphs
23	n	Bio-informatics

What we covered 1

- 1 node models
  - Coins/dice (Dirichlet priors), Gaussians, exponential family
  - Bayesian vs frequentist (ML/MAP) estimation
  - Bayesian model selection (Occam's razor)
- 2 node BNs
  - Linear regression
  - Linear classification (logistic regression)
  - Generalized linear models (GLIMs)
  - Mixture models: MoG, K-means, EM
  - Latent variable models: PCA, FA
- 3 node BNs
  - Mixtures of FA
  - Mixtures of experts

What we covered 2

- Chains
  - HMMs, forwards-backwards algorithm, EM
  - LDS, Kalman filter, EM
  - EKF, UKF, particle filtering, RB PF
- Trees
  - Belief propagation
  - Structure learning (max spanning tree)

What we covered 3

- General graphs: representation
  - Independence properties (Bayes Ball, I-maps)
  - Directed vs undirected graphs, chordal graphs
- General graphs: exact inference
  - Variable elimination
  - Junction tree
- General graphs: parameter learning
  - Bayesian param. est. for fully observed BNs
  - ML for latent BNs (EM)
  - ML for fully observed UGs (IPF)
  - ML for fully observed CRFs (conjugate gradient)

What we covered 4

- General BNs: structure learning
  - Search and score
  - Partial observability (structural EM, variational Bayes EM)
- General GMs: stochastic approximations
  - Likelihood weighting, Gibbs sampling, Metropolis Hastings
- General GMs: variational approximations
  - Mean field, structured, loopy belief propagation
- Applications
  - SLAM, tracking, image labeling (CRFs), language modeling (HMMs)

Some things we didn't cover

- Swendsen-Wang sampling, perfect sampling, details of MCMC
- Generalized BP, theory of BP, cluster variational methods
- Details of expectation propagation (EP)
- Forwards propagation/ backwards sampling
- Non-parametric Bayes (Dirichlet process, Gaussian process)

- Quickscore/ QMR-DT and other speedup tricks (e.g., lazy Jtree)
- Decision making (influence diagrams, LIMIDS, POMDPs etc)
- First order probabilistic inference (FOPI)

- Causality
- Frequentist hypothesis testing
- Conditional Gaussian models (mixed/ hybrid GMs)
- Applications to error correcting codes, biology, vision, speech

1 node models

- Jordan ch 5, 8, 13; Mackay ch 3, 23, 37
- Coins/dice, Gaussians, exponential family
- Bayesian vs frequentist (ML/MAP) estimation
- Bayesian vs classical hypothesis testing

Coins (Bernoulli Trials)

- We observe M iid coin flips: $\mathcal{D}$=H,H,T,H,...
- Model: $p(H) = \theta \quad p(T) = (1-\theta)$
- We want to estimate θ from D.
- Frequentist (maximum likelihood) approach (point estimate):

$$\hat{\theta}_{ML} = \text{argmax}_\theta \ \ell(\theta; \mathcal{D})$$

where

$$\ell(\theta; D) = \log p(D|\theta) = \sum_m \log p(x^m|\theta)$$

- Bayesian approach

$$p(\theta|\mathcal{D}) = \frac{p(\mathcal{D}|\theta)p(\theta)}{p(\mathcal{D})}$$

or

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{marginal likelihood}}$$

MLE for Bernoulli Trials (L10)

- Likelihood:

$$\begin{aligned}\ell(\theta; \mathcal{D}) = \log p(\mathcal{D}|\theta) &= \log \prod_m \theta^{\mathbf{x}^m} (1-\theta)^{1-\mathbf{x}^m} \\ &= \log \theta \sum_m \mathbf{x}^m + \log(1-\theta) \sum_m (1-\mathbf{x}^m) \\ &= \log \theta N_{\mathrm{H}} + \log(1-\theta) N_{\mathrm{T}}\end{aligned}$$

- Take derivatives and set to zero:

$$\frac{\partial \ell}{\partial \theta} = \frac{N_{\mathrm{H}}}{\theta} - \frac{N_{\mathrm{T}}}{1-\theta}$$

$$\Rightarrow \theta^*_{\mathrm{ML}} = \frac{N_{\mathrm{H}}}{N_{\mathrm{H}} + N_{\mathrm{T}}}$$

- The counts $N_H = \sum_m x^m$ and $N_T = \sum_m (1-x^m)$ are sufficient statistics of the data D.

Bayesian estimation for Bernoulli Trials (L11)

- Likelihood
$$P(D|\theta) = \theta^{N_H}(1-\theta)^{N_T}$$
- Conjugate Beta Prior
$$P(\theta|\alpha) = \mathcal{B}(\theta; \alpha_h, \alpha_t) \stackrel{\text{def}}{=} \frac{1}{Z(\alpha_h, \alpha_t)} \theta^{\alpha_h - 1}(1-\theta)^{\alpha_t - 1}$$
- Posterior
$$\begin{aligned} P(\theta|D,\alpha) &= \frac{P(\theta|\alpha)P(D|\theta)}{P(D|\alpha)} \\ &= \frac{1}{Z(\alpha_h, \alpha_t)P(D|\alpha)} \theta^{\alpha_h - 1}\theta^{N_h}(1-\theta)^{\alpha_t - 1}(1-\theta)^{N_t} \\ &= \mathcal{B}(\theta; \alpha_h + N_h, \alpha_t + N_t) \end{aligned}$$
- Posterior mean $E\theta = \frac{\alpha_h}{\alpha_h + \alpha_t}$.

Example of classical hypothesis testing (L15)

- When spun on edge $N = 250$ times, a Belgian one-euro coin came up heads $Y = 140$ times and tails 110.
- We would like to distinguish two models, or hypotheses: H_0 means the coin is unbiased (so $p = 0.5$); H_1 means the coin is biased (has probability of heads $p \neq 0.5$).
- p-value is "less than 7%": $p = P(Y \geq 140) + P(Y \leq 110) = 0.066$:

```
n=250; p = 0.5; y = 140;
p = (1-binocdf(y-1,n,p)) + binocdf(n-y,n,p)
```

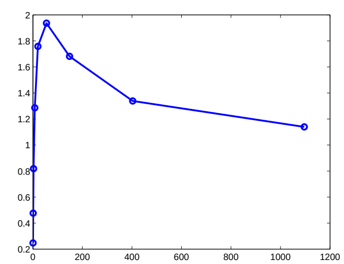
- If $Y = 141$, we get $p = 0.0497$, so we can reject the null hypothesis at significance level 0.05.
- But is the coin really biased?

Bayesian hypothesis testing

- We want to compute the posterior ratio of the 2 hypotheses:
$$\frac{P(H_1|D)}{P(H_0|D)} = \frac{P(D|H_1)P(H_1)}{P(D|H_0)P(H_0)}$$
- Let us assume a uniform prior $P(H_0) = P(H_1) = 0.5$.
- Then we just focus on the ratio of the marginal likelihoods:
$$P(D|H_1) = \int_0^1 d\theta \; P(D|\theta, H_1)P(\theta|H_1)$$
- For H_0, there is no free parameter, so
$$P(D|H_0) = 0.5^N$$
where N is the number of coin tosses in D.

So, is the coin biased or not?

- We plot the Bayes factor vs hyperparameter α:



- For a uniform prior, $\frac{P(H_1|D)}{P(H_0|D)} = 0.48$, (weakly) favoring the fair coin hypothesis H_0!
- At best, for $\alpha = 50$, we can make the biased hypothesis twice as likely.
- Not as dramatic as saying "we reject the null hypothesis (fair coin) with significance 6.6%".

From coins to dice

- Likelihood: binomial → multinomial
$$P(D|\vec{\theta}) = \prod_i \theta_i^{N_i}$$
- Prior: beta → Dirichlet
$$P(\vec{\theta}|\vec{\alpha}) = \frac{1}{Z(\vec{\alpha})} \prod_i \theta_i^{\alpha_i - 1}$$
where
$$Z(\vec{\alpha}) = \frac{\prod_i \Gamma(\alpha_i)}{\Gamma(\sum_i \alpha_i)}$$
- Posterior: beta → Dirichlet
$$P(\vec{\theta}|D) = Dir(\vec{\alpha} + \vec{N})$$
- Evidence (marginal likelihood)
$$P(D|\vec{\alpha}) = \frac{Z(\vec{\alpha} + \vec{N})}{Z(\vec{\alpha})} = \frac{\prod_i \Gamma(\alpha_i + N_i)}{\prod_i \Gamma(\alpha_i)} \frac{\Gamma(\sum_i \alpha_i)}{\Gamma(\sum_i \alpha_i + N_i)}$$

MLE for Univariate Normal (L10)

- We observe M iid real samples: $\mathcal{D}$=1.18,-.25,.78,...
- Model: $p(x) = (2\pi\sigma^2)^{-1/2} \exp\{-(x-\mu)^2/2\sigma^2\}$
- Log likelihood:
$$\begin{aligned}\ell(\theta; \mathcal{D}) &= \log p(\mathcal{D}|\theta) \\ &= -\frac{M}{2} \log(2\pi\sigma^2) - \frac{1}{2} \sum_m \frac{(x^m - \mu)^2}{\sigma^2}\end{aligned}$$
- Take derivatives and set to zero:
$$\begin{aligned}\frac{\partial \ell}{\partial \mu} &= (1/\sigma^2) \textstyle\sum_m (x_m - \mu) \\ \frac{\partial \ell}{\partial \sigma^2} &= -\frac{M}{2\sigma^2} + \frac{1}{2\sigma^4} \textstyle\sum_m (x_m - \mu)^2 \\ \Rightarrow \mu_{\text{ML}} &= (1/M) \textstyle\sum_m x_m \\ \sigma^2_{\text{ML}} &= (1/M) \textstyle\sum_m (x_m - \mu_{\text{ML}})^2\end{aligned}$$

Fun with Gaussians

- Bayesian estimation of 1D Gaussian (homework 5)
- MLE for multivariate Gaussian (Jordan ch 13)
- Bayesian estimation for multivariate Gaussian (Minka TR)
- Inference with multivariate Gaussians (Jordan ch 13)
- Moment vs canonical parameters (Jordan ch 13)

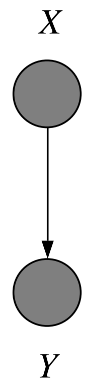
Exponential Family (L4, L10)

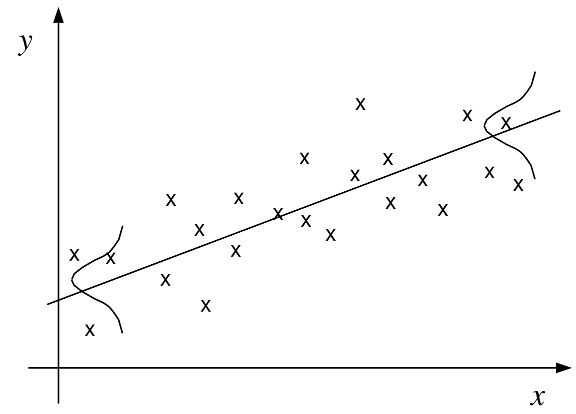
- For a numeric random variable $\mathbf{x}$
$$\begin{aligned}p(\mathbf{x}|\eta) &= h(\mathbf{x}) \exp\{\eta^\top T(\mathbf{x}) - A(\eta)\} \\ &= \frac{1}{Z(\eta)} h(\mathbf{x}) \exp\{\eta^\top T(\mathbf{x})\}\end{aligned}$$
is an exponential family distribution with *natural (canonical) parameter* η.
- Function $T(\mathbf{x})$ is a *sufficient statistic*.
- Function $A(\eta) = \log Z(\eta)$ is the log normalizer.
- Examples: Bernoulli, multinomial, Gaussian, Poisson, gamma,...
- A distribution $p(x)$ has finite sufficient statistics (independent of number of data cases) iff it is in the exponential family.
- See Jordan ch 8

2 node Bayes nets

- Linear regression (Jordan ch 6)
- Linear classification (logistic regression; Jordan ch 7)
- Generalized linear models (GLIMs; Jordan ch 8)
- Mixture models: MoG, K-means, EM (Jordan ch 10)
- Latent variable models: PCA, FA (Jordan ch 14)

Linear Regression (L11)

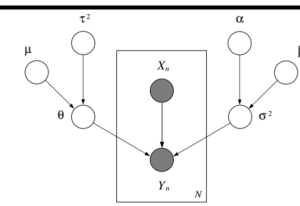




MLE for Linear Regression

- For vector outputs,
$$A = S_{YX'} S_{XX'}^{-1}$$
where $S_{YX'} = \sum_m y_m x_m^T$ and $S_{XX'} = \sum_m x_m x_m^T$.
- In the special case of scalar outputs, let $A = \theta^T$, and the design matrix $X = [x_m^T]$ stacked as rows and $Y = [y_m]$ a column vector. Then we get the normal equations
$$\theta = (X^T X)^{-1} X^T Y$$

Bayesian 1D Linear Regression

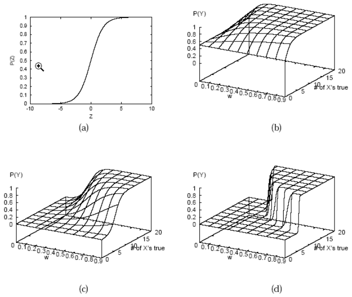


- For scalar (1D) output
$$p(y_n|x_n, \theta, \sigma^2) p(\theta|\mu, \tau^2) p(\sigma^2|\alpha, \beta)$$
Gaussian × Gaussian × Gamma
- For vector output
$$p(y_n|x_n, A, \Sigma) p(A|\mu, \tau^2) p(\Sigma|\alpha, \beta)$$
Gaussian × matrix-Gaussian × Wishart
- See Tom Minka tutorial

Logistic regression (L4)

$$P(Y=1|X_1,\ldots,X_n) = \sigma(w_0 + \sum_{i=1}^{n} w_i X_i)$$

$P(Y=1)$ vs number of X's that are on vs w



- a: 1D sigmoid
- b: $w_0 = 0$
- c: $w_0 = -5$
- d: w and w_0 are multiplied by 10

Generalized Linear Models

Canonical CPDs for $X \to Y$ (L4)

X	Y	$p(Y\|X)$
$\mathbb{R}^n$	$\mathbb{R}^m$	Gauss$(Y; WX+\mu, \Sigma)$
$\mathbb{R}^n$	$\{0,1\}$	Bernoulli$(Y; p = \frac{1}{1+e^{-\theta^T x}})$
$\{0,1\}^n$	$\{0,1\}$	Bernoulli$(Y; p = \frac{1}{1+e^{-\theta^T x}})$
$\mathbb{R}^n$	$\{1,\ldots,K\}$	Multinomial$(Y; p_i = \text{softmax}(x,\theta))$

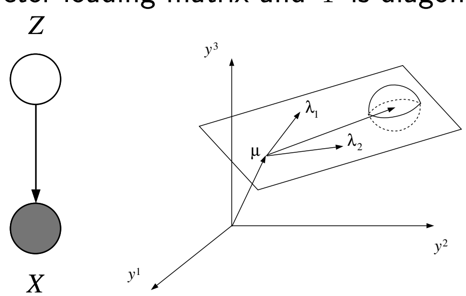
Learn using IRLS or conjugate gradient (L11)

Factor analysis (L17)

- Unsupervised linear regression is called factor analysis.

$$p(x) = \mathcal{N}(x; 0, I)$$
$$p(y|x) = \mathcal{N}(y; \mu + \Lambda x, \Psi)$$

where Λ is the factor loading matrix and Ψ is diagonal.



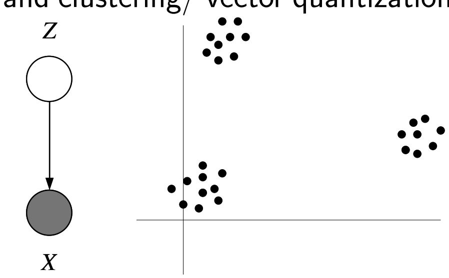
- To generate data, first generate a point within the manifold then add noise. Coordinates of point are components of latent variable.
- PCA (Karhunen-Loeve Transform) is zero noise limit of FA.

Mixtures of Gaussians (L12)

- Mixture of Gaussians:

$$P(Z=i) = \theta_i$$
$$p(X=x|Z=i) = \mathcal{N}(x; \mu_i, \Sigma_i)$$

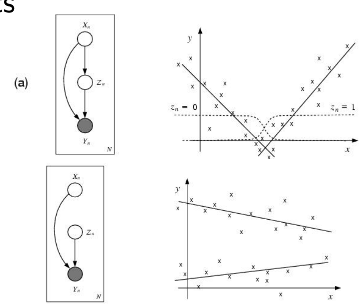
- This can be used for classification (supervised) and clustering/ vector quantization (unsupervised).



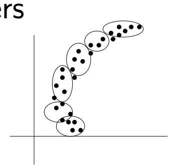
- We can find MLE/MAP estimates of the parameters using EM.
- K-means is a deterministic approximation (vector quantization).

3 node Bayes nets (L12)

- Mixtures of experts



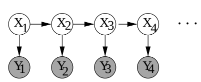
- Mixtures of factor analysers

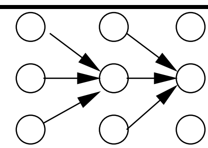


Chains

- HMMs (Jordan ch 12, Rabiner tutorial)
- LDS (Jordan ch 15, handouts on web)
- Nonlinear state space models (my DBN tutorial)

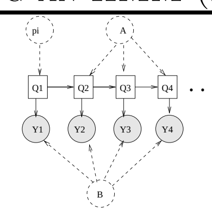
Forwards-backwards algorithm (L8)





$$\alpha_t(j) = \sum_i \alpha_{t-1}(i) A(i,j) B_t(j)$$
$$\alpha_t = (A^T \alpha_{t-1}) .* B_t$$
$$\beta_t(i) = \sum_j \beta_{t+1}(j) A(i,j) B_{t+1}(j)$$
$$\beta_t = A(\beta_{t+1} .* B_{t+1})$$
$$\xi_t(i,j) = \alpha_t(i) \beta_{t+1}(j) A(i,j) B_{t+1}(j)$$
$$\xi_t = \left(\alpha_t (\beta_{t+1} .* B_{t+1})^T \right) .* A$$
$$\gamma_t(i) \propto \alpha_t(i) \beta_t(j)$$
$$\gamma_t \propto \alpha_t .* \beta_t$$

Learning an HMM (L10, L12)



- Consider a time-invariant hidden Markov model (HMM)
  - State transition matrix $A(i,j) \stackrel{\text{def}}{=} P(X_t = j | X_{t-1} = i)$,
  - Discrete observation matrix $B(i,j) \stackrel{\text{def}}{=} P(Y_t = j | X_t = i)$
  - State prior $\pi(i) \stackrel{\text{def}}{=} P(X_1 = i)$.
- If all nodes are observed, we can find the globally optimal MLE.
- Otherwise using EM (aka Baum Welch).

Kalman filter (L17, L18)

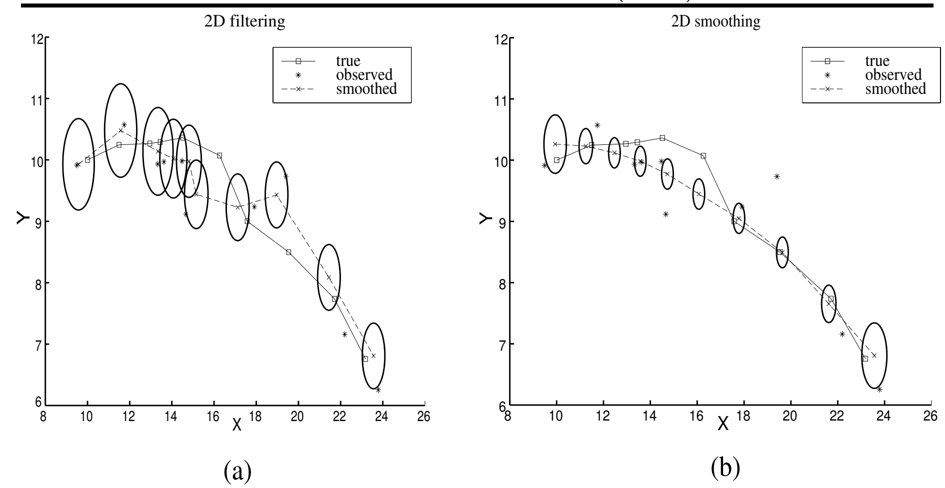
- LDS model: $x_t = Ax_{t-1} + v_t, \;\; y_t = Cx_t + w_t$
- Time update (prediction step):

$$x_{t|t-1} = Ax_{t-1|t-1}, \;\; P_{t|t-1} = AP_{t-1|t-1}A^T + Q, \;\; y_{t|t-1} = Cx_{t|t-1}$$

- Measurement update (correction step):

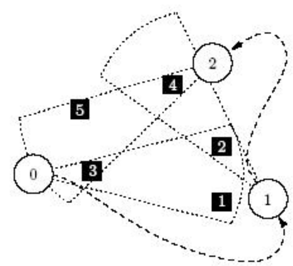
$$\begin{aligned}
\tilde{y}_t &= y_t - \hat{y}_{t|t-1} \text{ (error/ innovation)} \\
P_{\tilde{y}_t} &= CP_{t|t-1}C^T + R \text{ (covariance of error)} \\
P_{x_t y_t} &= P_{t|t-1}C^T \text{ (cross covariance)} \\
K_t &= P_{x_t y_t} P_{\tilde{y}_t}^{-1} \text{ (Kalman gain matrix)} \\
x_{t|t} &= x_{t|t-1} + K_t(y_t - y_{t|t-1}) \\
P_{t|t} &= P_{t|t-1} - K_t P_{x_t y_t}^T
\end{aligned}$$

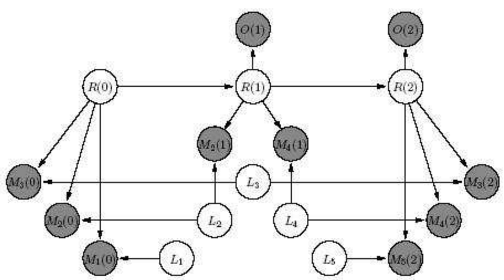
KF for 2D tracking (L17)



KF for SLAM (L18)

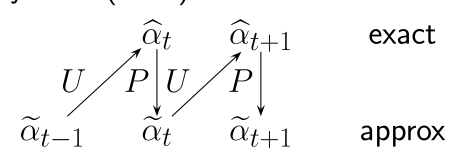
- State is location of robot and landmarks $X_t = (R_t, L_t^{1:N})$
- Measure location of subset of landmarks at each time step.
- Assume everything is linear Gaussian.
- Use Kalman filter to solve optimally.





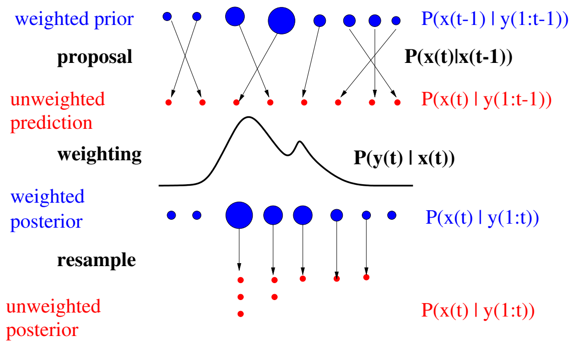
Approximate determinsitic filtering (L18)

- Extended Kalman filter (EKF)
- Unscented Kalman filter (UKF)
- Assumed density filter (ADF)



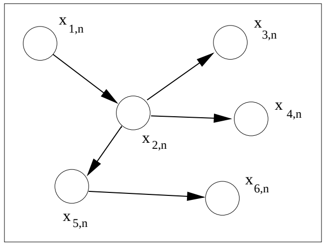
Particle filtering (sequential Monte Carlo) (L19)

- PF is sequential importance sampling with resampling (SISR).
- Goal is to estimate $P(x_{1:t}|y_{1:t})$ recursively (online) for a state-space model for which Kalman filter/ HMM filter is inapplicable.



Trees

- Inference (belief propagation): L9, Yedidia tutorial
- Structure learning (max weight spanning tree): L16
- Application: KF trees for multiscale image analysis (skipped)

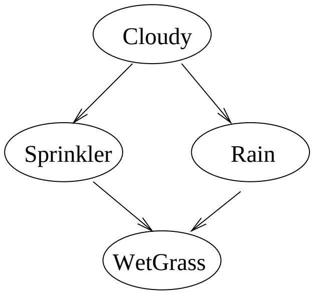


General graphs

- Representation: Markov properties, CPDs, log linear models
- Exact inference: var elim, Jtree
- Fully observed param learning
- Fully observed structure learning
- Partially observed param learning
- Approximate inference

Example BN: Water sprinkler (L1)

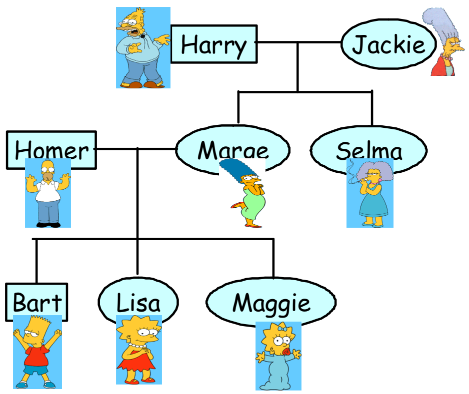
$$P(X_{1:N}) = \prod_{i=1}^{N} P(X_i|\mathsf{Pa}(X_i))$$



$$P(C,S,R,W) = P(C)P(S|C)P(R|C)P(W|S,R)$$

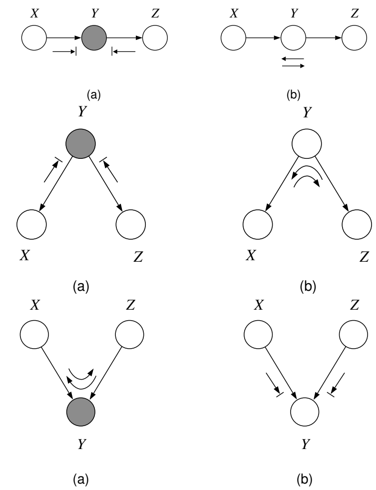
Bayes net for genetic pedigree analysis (L1)

- $G_i \in \{a, b, o\} \times \{a, b, o\}$ = genotype (allele) of person i
- $B_i \in \{a, b, o, ab\}$ = phenotype (blood type) of person i



Global Markov properties for DGs: Bayes-Ball (L2)

A is d-separated from B given C if we cannot send a ball from any node in A to any node in B according to the rules below, where shaded nodes are in C.



Markov properties for UGs (L3)

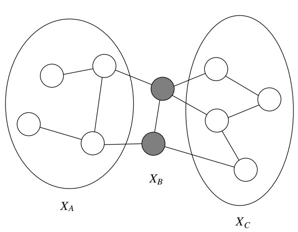
- Defn: the **global Markov properties** of a UG H are

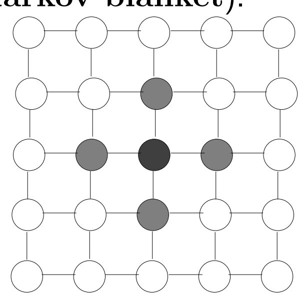
$$I(H) = \{(X \perp Y|Z) : sep_H(X; Y|Z)\}$$

- Defn: The **local markov independencies** are

$$I_l(H) = \{(X \perp V \setminus \{X\} \setminus N_H(X)|N_H(X)) : X \in V\}$$

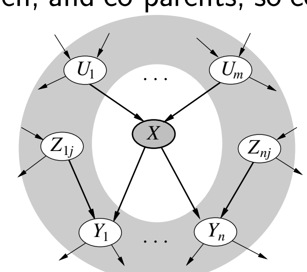
where $N_H(X)$ are the neighbors (**Markov blanket**).





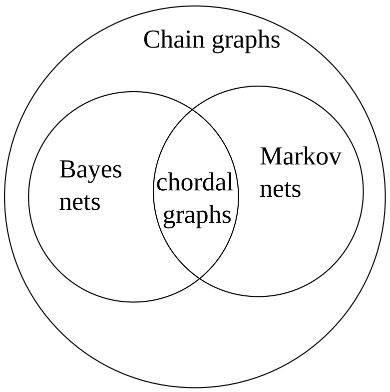
Converting Bayes nets to Markov nets (L3)

- Defn: A Markov net H is an I-map for a Bayes net G if $I(H) \subseteq I(G)$.
- We can construct a minimal I-map for a BN by finding the minimal Markov blanket for each node.
- We need to block all active paths coming into node X, from parents, children, and co-parents; so connect them all to X.

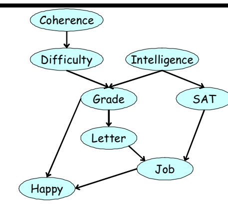


Chordal graphs (L4)

- Chordal graphs encode independencies that can be exactly represented by either directed or undirected graphs.
- Chain graphs combine directed and undirected graphs and represent a larger set of distributions.



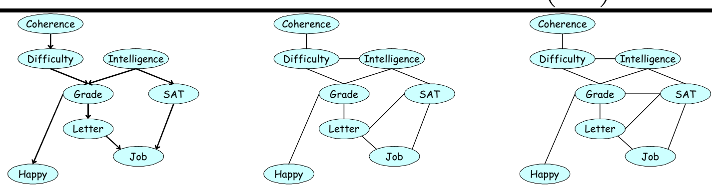
Variable elimination algorithm (L7)



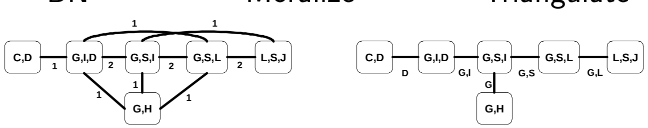
- Key idea 1: push sum inside products.
- Key idea 2: use (non-serial) dynamic programming to cache shared subexpressions.

$$
\begin{aligned}
P(J) &= \sum_L \sum_S \sum_G \sum_H \sum_I \sum_D \sum_C P(C,D,I,G,S,L,J,H) \\
&= \sum_L \sum_S \sum_G \sum_H \sum_I \sum_D \sum_C P(C)P(D|C)P(I)P(G|I,D)P(S|I)P(L|G)P(J|L,S)P(H|G,J) \\
&= \sum_L \sum_S \sum_G \sum_H \sum_I \sum_D \sum_C \phi_C(C)\phi_D(D,C)\phi_I(I)\phi_G(G,I,D)\phi_S(S,I)\phi_L(L,G)\phi_J(J,L,S)\phi_H(H,G,J) \\
&= \sum_L \sum_S \phi_J(J,L,S) \sum_G \phi_L(L,G) \sum_H \phi_H(H,G,J) \sum_I \phi_S(S,I)\phi_I(I) \sum_D \phi(G,I,D) \sum_C \phi_C(C)\phi_D(D,C)
\end{aligned}
$$

From Bayes net to jtree (L8)



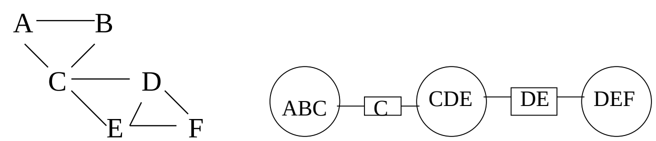
BN Moralize Triangulate



Jgraph Jtree

Message passing on jtrees (L8, L9)

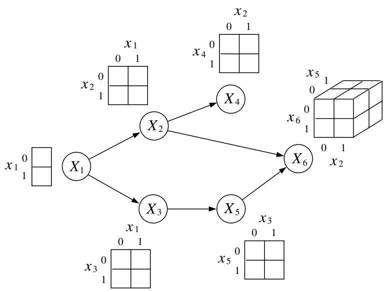
- Hugin vs Shafer Shenoy



MLE for fully observed BNs (L10)

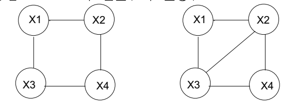
- If we assume the parameters for each CPD are globally independent, then the log-likelihood function decomposes into a sum of local terms, one per node:

$$\log p(\mathcal{D}|\theta) = \log \prod_m \prod_i p(\mathbf{x}_i^m | x_{\pi_i}, \theta_i) = \sum_i \sum_m \log p(\mathbf{x}_i^m | x_{\pi_i}, \theta_i)$$



MLE for fully observed UGM (L13)

- Is the graph *decomposable* (triangulated)?
- Are all the clique potentials defined on maximal cliques (not sub-cliques)? e.g., ψ_{123}, ψ_{234} not $\psi_{12}, \psi_{23}, \ldots$.

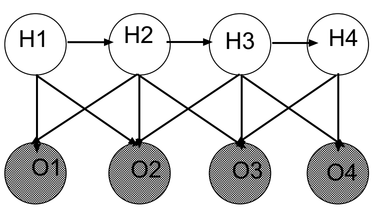


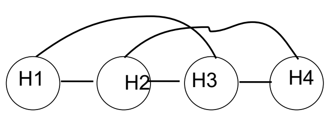
- Are the clique potentials full tables (or Gaussians), or parameterized more compactly, e.g., $\psi_c(x_c) = exp(\sum_k w_k f_k(x_c))$?

Decomposable?	Max. Cliques	Tabular	Method
Yes	Yes	Yes	Direct
-	-	Yes	IPF
-	-	-	Gradient ascent
-	-	-	Iterative scaling

Learning CRFs (L14)

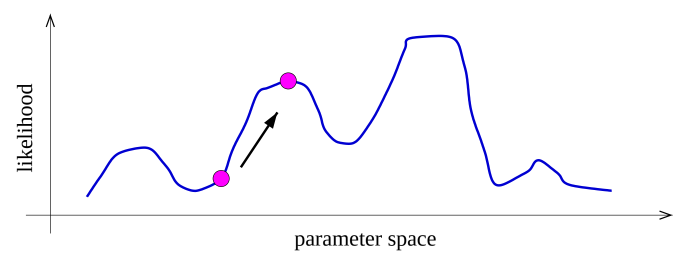
- Conditional random fields are discriminative models.
- Assuming fully observed training data, learning can be done using conjugate gradient descent, just as in a regular MRF with non-maximal cliques.
- Gradient requires computing the partition function, which is (in general) only tractable for low treewidth models (eg chains).





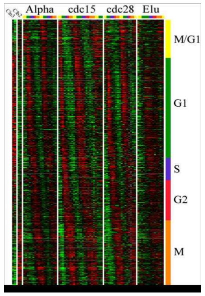
MLE for partially observed BNs (L12)

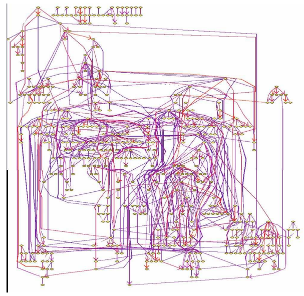
- Use (conjugate) gradient or EM
- M-step is what we did for the 1 node/2 node BNs



Learning structure of fully observed BNs (L15, L16)

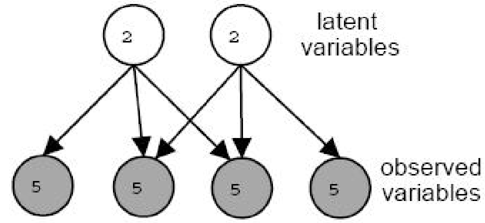
- Search + score (local search + Occam's razor)

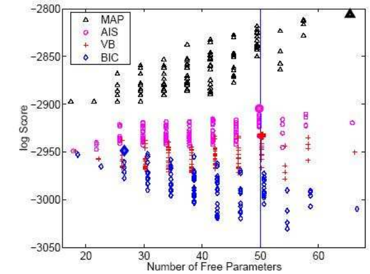




Learning structure of partially observed BNs (L16)

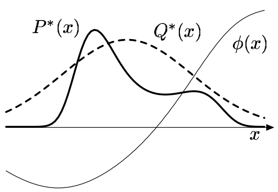
- Search = local search
- Score = expected BIC (structural EM)
- Score = variational Bayes (VB-EM)

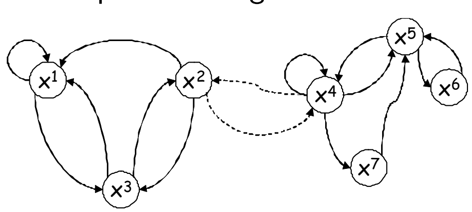




Monte Carlo methods (L19)

- Importance sampling
- Particle filtering
- RBPF
- MCMC: Gibbs sampling and Metropolis Hastings

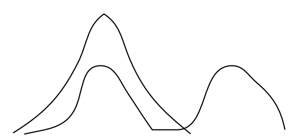




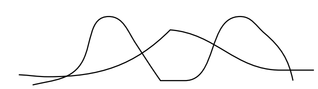
Variational methods (L20)

- Iterative Conditional Modes (ICM)
- Mean field
- Structured variational methods
- Loopy belief propagation

D(q, p)



D(p, q)



A Generative Model for Generative Models