

Course Roadmap

Graphical models

Sequential data

Reinforcement learning

Guest lectures

Graphical Models - Part II

CMPT 419/726

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Bishop PRML Ch. 8

Outline

Markov Random Fields

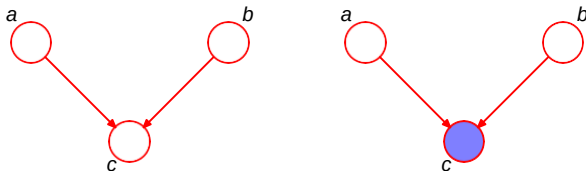
Inference

Outline

Markov Random Fields

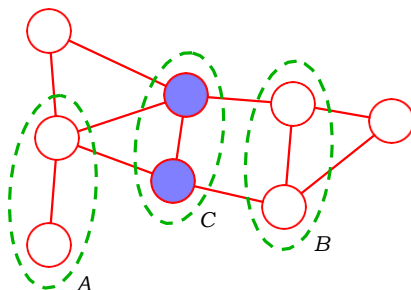
Inference

Conditional Independence in Graphs



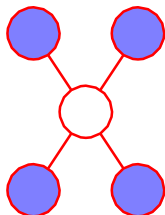
- Recall that for Bayesian Networks, conditional independence was a bit complicated
 - **d-separation** with head-to-head links
- We would like to construct a graphical representation such that conditional independence is straight-forward path checking

Markov Random Fields



- **Markov random fields** (MRFs) contain one node per variable
- Undirected graph over these nodes
- Conditional independence will be given by simple separation, blockage by observing a node on a path
 - e.g. in above graph, $A \perp B | C$

Markov Blanket Markov



- With this simple check for conditional independence, **Markov blanket** is also simple
 - Recall Markov blanket MB of x_i is set of nodes such that x_i conditionally independent from rest of graph given MB
- Markov blanket is neighbours

MRF Factorization

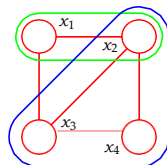
- Remember that graphical models define a factorization of the joint distribution
- What should be the factorization be so that we end up with the simple conditional independence check?
- For x_i and x_j not connected by an edge in graph:

$$x_i \perp\!\!\!\perp x_j | \mathbf{x}_{\setminus \{i,j\}}$$

- So there should not be any factor $\psi(x_i, x_j)$ in the factorized form of the joint

Cliques

- A **clique** in a graph is a subset of nodes such that there is a link between every pair of nodes in the subset
- A **maximal clique** is a clique for which one cannot add another node and have the set remain a clique



MRF Joint Distribution

- Note that nodes in a clique cannot be made conditionally independent from each other
 - So defining factors $\psi(\cdot)$ on nodes in a clique is “safe”
- The joint distribution for a Markov random field is:

$$p(x_1, \dots, x_K) = \frac{1}{Z} \prod_C \psi_C(x_C)$$

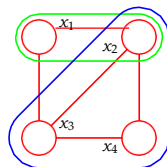
where x_C is the set of nodes in clique C , and the product runs over all maximal cliques

- Each $\psi_C(x_C) \geq 0$
- Z is a normalization constant

MRF Joint Distribution Example

- The joint distribution for a Markov random field is:

$$\begin{aligned} p(x_1, \dots, x_4) &= \frac{1}{Z} \prod_c \psi_c(x_c) \\ &= \frac{1}{Z} \psi_{123}(x_1, x_2, x_3) \psi_{234}(x_2, x_3, x_4) \end{aligned}$$



- Note that maximal cliques subsume smaller ones: $\psi_{123}(x_1, x_2, x_3)$ could include $\psi_{12}(x_1, x_2)$, though sometimes smaller cliques are explicitly used for clarity

MRF Joint - Terminology

- The joint distribution for a Markov random field is:

$$p(x_1, \dots, x_K) = \frac{1}{Z} \prod_c \psi_c(x_c)$$

- Each $\psi_c(x_c)$ is called a **potential function**
- Z , the normalization constant, is called the **partition function**:

$$Z = \sum_x \prod_c \psi_c(x_c)$$

- Z is very costly to compute, since it is a sum/integral over all possible states for all variables in x
- Don't always need to evaluate it though, will cancel for computing conditional probabilities

Hammersley-Clifford

- The definition of the joint:

$$p(x_1, \dots, x_K) = \frac{1}{Z} \prod_c \psi_c(\mathbf{x}_c)$$

- Note that we started with particular conditional independences
- We then formulated the factorization based on clique potentials
 - This formulation resulted in the right conditional independences
- **Hammersley-Clifford** theorem: The following sets of distributions are equivalent.
 - the set of distributions consistent with conditional independences implied by the graph
 - any distribution in the above form, $\frac{1}{Z} \prod_c \psi_c(\mathbf{x}_c)$

Energy Functions

- Often use exponential, which is non-negative, to define potential functions:

$$\psi_C(\mathbf{x}_C) = \exp\{-E_C(\mathbf{x}_C)\}$$

- Minus sign – by convention
- $E_C(\mathbf{x}_C)$ is called an **energy function**
 - From physics, low energy = high probability
- This exponential representation is known as the **Boltzmann distribution**

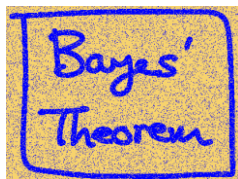
Energy Functions - Intuition

- Joint distribution nicely rearranges as

$$\begin{aligned} p(x_1, \dots, x_K) &= \frac{1}{Z} \prod \psi_c(\mathbf{x}_c) \\ &= \frac{1}{Z} \exp \left\{ - \sum_c E_c(\mathbf{x}_c) \right\} \end{aligned}$$

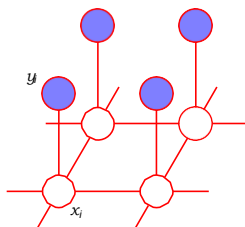
- Intuition about potential functions: ψ_c are describing good (low energy) sets of states for adjacent nodes
- An example of this is next

Image Denoising



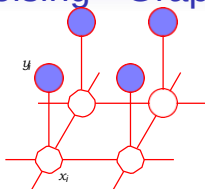
- Consider the problem of trying to correct (denoise) an image that has been corrupted
- Assume image is binary
- Observed (noisy) pixel values $y_i \in \{-1, +1\}$
- Unobserved true pixel values $x_i \in \{-1, +1\}$

Image Denoising - Graphical Model



- Cliques containing each true pixel value $x_i \in \{-1, +1\}$ and observed value $y_i \in \{-1, +1\}$
 - Observed pixel value is usually same as true pixel value
 - Energy function $-\eta x_i y_i, \eta > 0$, lower energy (better) if $x_i = y_i$
- Cliques containing adjacent true pixel values x_i, x_j
 - Nearby pixel values are usually the same
 - Energy function $-\beta x_i x_j, \beta > 0$, lower energy (better) if $x_i = x_j$

Image Denoising - Graphical Model



- Complete energy function:

$$E(\mathbf{x}, \mathbf{y}) = -\beta \sum_{\{i,j\}} x_i x_j - \eta \sum_i x_i y_i$$

- Joint distribution:

$$p(\mathbf{x}, \mathbf{y}) = \frac{1}{Z} \exp\{-E(\mathbf{x}, \mathbf{y})\}$$

- Or, as potential functions $\psi_n(x_i, x_j) = \exp(\beta x_i x_j)$, $\psi_p(x_i, y_i) = \exp(\eta x_i y_i)$:

$$p(\mathbf{x}, \mathbf{y}) = \frac{1}{Z} \prod_{i,j} \psi_n(x_i, x_j) \prod_i \psi_p(x_i, y_i)$$

Image Denoising - Inference



- The denoising query is $\arg \max_x p(\mathbf{x}|\mathbf{y})$
- Two approaches:
 - **Iterated conditional modes** (ICM): hill climbing in $\mathbf{x}$, one variable x_i at a time
 - Simple to compute, Markov blanket is just observation plus neighbouring pixels
 - **Graph cuts**: formulate as max-flow/min-cut problem, exact inference (for this graph)

Converting Directed Graphs into Undirected Graphs



- Consider a simple directed chain graph:

$$p(x) = p(x_1)p(x_2|x_1)p(x_3|x_2) \dots p(x_N|x_{N-1})$$

- Can convert to undirected graph

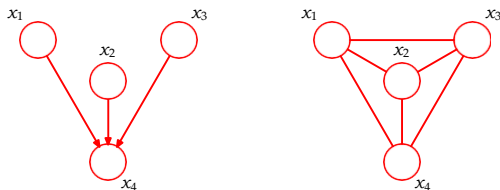
$$p(x) = \frac{1}{Z} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \dots \psi_{N-1,N}(x_{N-1}, x_N)$$

- Where $\psi_{12} = p(x_1)p(x_2|x_1)$, $\psi_{k-1,k} = p(x_k|x_{k-1})$, $Z = 1$

Converting Directed Graphs into Undirected Graphs

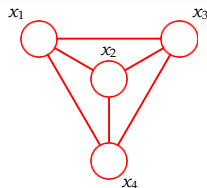
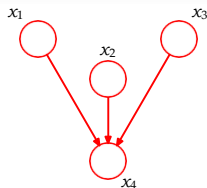
- The chain was straight-forward because for each conditional $p(x_i | pa_i)$, nodes $x_i \cup pa_i$ were contained in one clique
 - Hence we could define that clique potential to include that conditional
- For a general undirected graph we can force this to occur by “marrying” the parents
 - Add links between all parents in pa_i
 - This process known as **moralization**, creating a **moral graph**

Strong Morals



- Start with directed graph on left
- Add undirected edges between all parents of each node
- Remove directionality from original edges

Constructing Potential Functions

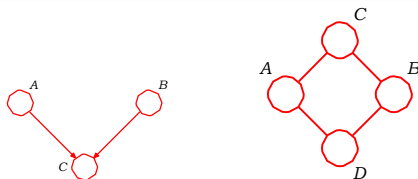


- Initialize all potential functions to be 1
- With moral graph, for each $p(x_i|pa_i)$, there is at least one clique which contains all of $x_i \cup pa_i$
 - Multiply $p(x_i|pa_i)$ into potential function for one of these cliques
- $Z = 1$ again since

$$p(\mathbf{x}) = \prod_c \psi_c(\mathbf{x}_c) = \prod_i p(x_i|pa_i)$$

which is already normalized

Equivalence Between Graph Types



- Note that the moralized undirected graph loses some of the conditional independence statements of the directed graph
- Further, there are certain conditional independence assumptions which can be represented by directed graphs which **cannot** be represented by undirected graphs, **and vice versa**
- Directed graph: $A \perp\!\!\!\perp B | \emptyset, A \not\perp\!\!\!\perp B | C$, cannot be represented using undirected graph
- Undirected graph: $A \not\perp\!\!\!\perp B | \emptyset, A \perp\!\!\!\perp B | C \cup D, C \perp\!\!\!\perp D | A \cup B$ cannot be represented using directed graph

Outline

Markov Random Fields

Inference

Inference

- **Inference** is the process of answering queries such as

$$p(x_n | \mathbf{x}_e = \mathbf{e})$$

- We will focus on computing **marginal posterior distributions** over single variables x_n using

$$p(x_n | \mathbf{x}_e = \mathbf{e}) \propto p(x_n, \mathbf{x}_e = \mathbf{e})$$

- The proportionality constant can be obtained by enforcing

$$\sum_{x_n} p(x_n | \mathbf{x}_e = \mathbf{e}) = 1$$

Inference on a Chain



- Consider a simple undirected chain
- For inference, we want to compute $p(x_n, \mathbf{x}_e = \mathbf{e})$
- First, we'll show how to compute $p(x_n)$
 - $p(x_n, \mathbf{x}_e = \mathbf{e})$ will be a simple modification of this

Inference on a Chain



- The naive method of computing the marginal $p(x_n)$ is to write down the factored form of the joint, and marginalize (sum out) all other variables:

$$\begin{aligned}
 p(x_n) &= \sum_{x_1} \dots \sum_{x_{n-1}} \sum_{x_{n+1}} \dots \sum_{x_N} p(\mathbf{x}) \\
 &= \sum_{x_1} \dots \sum_{x_{n-1}} \sum_{x_{n+1}} \dots \sum_{x_N} \frac{1}{Z} \prod_C \psi_C(\mathbf{x}_C)
 \end{aligned}$$

- This would be slow: $O(K^N)$ work if each variable could take K values

Inference on a Chain



- However, due to the factorization terms in this summation can be rearranged nicely
- This will lead to efficient algorithms

A Simple Chain



- First consider a chain with 3 nodes, and computing $p(x_3)$:

$$\begin{aligned} p(x_3) &= \sum_{x_1} \sum_{x_2} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \\ &= \sum_{x_2} \psi_{23}(x_2, x_3) \sum_{x_1} \psi_{12}(x_1, x_2) \end{aligned}$$

Performing the sums

$$p(x_3) = \sum_{x_2} \psi_{23}(x_2, x_3) \sum_{x_1} \psi_{12}(x_1, x_2)$$

- For example, if x_i are binary:

$$\psi_{12}(x_1, x_2) = \begin{matrix} x_1 \uparrow \\ \begin{bmatrix} a & b \\ c & d \end{bmatrix} \\ \rightarrow x_2 \end{matrix} \quad \psi_{23}(x_2, x_3) = \begin{matrix} x_2 \uparrow \\ \begin{bmatrix} s & t \\ u & v \end{bmatrix} \\ \rightarrow x_3 \end{matrix}$$

$$\sum_{x_1} \psi_{12}(x_1, x_2) = \begin{matrix} \rightarrow x_2 \\ [a+c \quad b+d] \equiv \mu_{12}(x_2) \end{matrix}$$

$$\psi_{23}(x_2, x_3) \times \mu_{12}(x_2) = \begin{matrix} x_2 \uparrow \\ \begin{bmatrix} s(a+c) & t(a+c) \\ u(b+d) & v(b+d) \end{bmatrix} \\ \rightarrow x_3 \end{matrix}$$

$$p(x_3) = \begin{matrix} \rightarrow x_3 \\ [s(a+c) + u(b+d) \quad t(a+c) + v(b+d)] \end{matrix}$$

Complexity of Inference

- There were two types of operations

- Summation

$$\sum_{x_1} \psi_{12}(x_1, x_2)$$

$K \times K$ numbers in ψ_{12} , takes $O(K^2)$ time

- Multiplication

$$\psi_{23}(x_2, x_3) \times \mu_{12}(x_2)$$

Again $O(K^2)$ work

- For a chain of length N , we repeat these operations $N - 1$ times each
 - $O(NK^2)$ work, versus $O(K^N)$ for naive evaluation

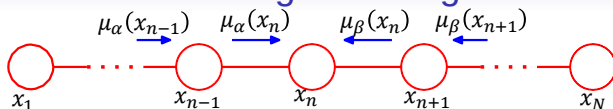
More complicated chain

- Now consider a 5 node chain, again asking for $p(x_3)$

$$\begin{aligned} p(x_3) &= \sum_{x_1} \sum_{x_2} \sum_{x_4} \sum_{x_5} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5) \\ &= \sum_{x_2} \sum_{x_1} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \sum_{x_4} \sum_{x_5} \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5) \\ &= \left[\sum_{x_2} \sum_{x_1} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \right] \left[\sum_{x_4} \sum_{x_5} \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5) \right] \end{aligned}$$

- Each of these factors resembles the previous, and can be computed efficiently
 - Again $O(NK^2)$ work

Message Passing



- The factors can be thought of as **messages** being passed between nodes in the graph

$$\mu_{12}(x_2) \equiv \sum_{x_1} \psi_{12}(x_1, x_2)$$

is a message passed from node x_1 to node x_2 containing all information in node x_1

- In general,

$$\mu_{k-1,k}(x_k) \equiv \sum_{x_{k-1}} \psi_{k-1,k}(x_{k-1}, x_k) \mu_{k-2,k-1}(x_{k-1})$$

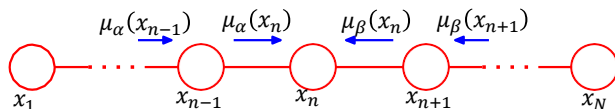
- Possible to do so because of conditional independence

More complicated chain

- Now consider a 5 node chain, again asking for $p(x_3)$

$$\begin{aligned}
 p(x_3) &= \sum_{x_1} \sum_{x_2} \sum_{x_4} \sum_{x_5} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5) \\
 &= \sum_{x_2} \sum_{x_1} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \sum_{x_4} \sum_{x_5} \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5) \\
 &= \left[\sum_{x_2} \psi_{23}(x_2, x_3) \sum_{x_1} \psi_{12}(x_1, x_2) \right] \left[\sum_{x_4} \psi_{34}(x_3, x_4) \sum_{x_5} \psi_{45}(x_4, x_5) \right] \\
 &= \left[\sum_{x_2} \psi_{23}(x_2, x_3) \mu_{12}(x_2) \right] \left[\sum_{x_4} \psi_{34}(x_3, x_4) \mu_{54}(x_4) \right] \\
 &= \mu_{23}(x_3) \mu_{43}(x_3)
 \end{aligned}$$

Computing All Marginals



- Computing one marginal $p(x_n)$ takes $O(NK^2)$ time
- Naively running same algorithms for all nodes in a chain would take $O(N^2K^2)$ time
- But this isn't necessary, same messages can be reused at all nodes in the chain
- Pass all messages from one end of the chain to the other, pass all messages in the other direction too
- Can compute marginal at any node by multiplying the two messages delivered to the node
 - $2(N - 1)K^2$ work, twice as much as for just one node

Including Evidence

- If a node $x_{k-1} = e$ is observed, simply clamp to observed value rather than summing:

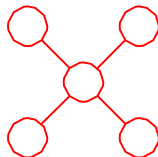
$$\mu_{k-1,k}(x_k) = \sum_{x_{k-1}} \psi_{k-1,k}(x_{k-1}, x_k) \mu_{k-2,k-1}(x_{k-1})$$

becomes

$$\mu_{k-1,k}(x_k) = \psi_{k-1,k}(x_{k-1} = e, x_k) \mu_{k-2,k-1}(x_{k-1} = e)$$

Trees

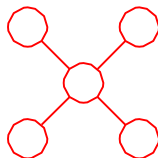
- The algorithm for a tree-structured graph is very similar to that for chains
- Formulation in PRML uses **factor graphs**, we'll just give the intuition here
- Consider calculating the marginal $p(x_n)$ for the center node of the graph at right
- Treat x_n as root of tree, pass messages from leaf nodes up to root



Trees

- Message passing similar to that in chains, but possibly multiple messages reaching a node
- With multiple messages, multiply them together
- As before, sum out variables

$$\mu_{k-1,k}(x_k) = \sum_{x_{k-1}} \psi_{k-1,k}(x_{k-1}, x_k) \mu_{k-2,k-1}(x_{k-1})$$



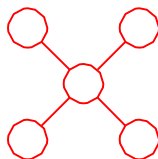
- Known as **sum-product algorithm**
- Complexity still $O(NK^2)$

Most Likely Configuration

- A similar algorithm exists for finding

$$\arg \max_{x_1, \dots, x_N} p(x_1, \dots, x_N)$$

- Replace summation operations with **maximize** operations
- Maximum of products at each node
- Known as **max-sum**, since often take log-probability to avoid underflow errors



5 node chain

- Consider a 5 node chain, asking for $\arg \max_{x_1, \dots, x_5} p(x_1, \dots, x_5)$

$$\max_{x_1, \dots, x_5} p(x_1, \dots, x_N) = \max_{x_1, \dots, x_5} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \psi_{34}(x_3, x_4) \psi_{45}(x_4, x_5)$$

$$= \max_{x_1, \dots, x_4} \psi_{12}(x_1, x_2) \psi_{23}(x_2, x_3) \psi_{34}(x_3, x_4) \underbrace{\max_{x_5} \psi_{45}(x_4, x_5)}_{v(x_4)}$$

$$= \max_{x_2} \left(\psi_{23}(x_2, x_3) \underbrace{\max_{x_1} \psi_{12}(x_1, x_2)}_{v_{12}(x_2)} \right) \max_{x_4} \left(\psi_{34}(x_3, x_4) \underbrace{\max_{x_5} \psi_{45}(x_4, x_5)}_{v_{54}(x_4)} \right)$$

General Graphs

- **Junction tree algorithm** is an exact inference method for arbitrary graphs
 - A particular tree structure defined over cliques of variables
 - Inference ends up being exponential in maximum clique size
 - Therefore slow in many cases
- Approximate inference techniques
 - **Loopy belief propagation**: run message passing scheme (sum-product) for a while
 - Sometimes works
 - Not guaranteed to converge
 - **Variational methods**: approximate desired distribution using analytically simple forms, find parameters to make these forms similar to actual desired distribution (Ch. 10)
 - **Sampling methods**: represent desired distribution with a set of samples, as more samples are used, obtain more accurate representation (Ch. 11)

Conclusion

- Readings: Ch. 8
- Graphical models depict conditional independence assumptions
- Directed graphs (Bayesian networks)
 - Factorization of joint distribution as conditional on node given parents
- Undirected graphs (Markov random fields)
 - Factorization of joint distribution as clique potential functions
- Inference algorithm sum-product, based on local message passing
 - Works for tree-structured graphs
 - Non-tree-structured graphs, either slow exact or approximate inference