6.962 Week 6 Tutorial: Approximate Inference Techniques for Graphs with Cycles

Erik Sudderth

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Outline

1. Introduction to Graphical Models

2. Trees and Belief Propagation

3. Mean Field Theory and Variational Methods

4. Understanding Loopy Belief Propagation

5. Generalized Belief Propagation

Bayesian Estimation

- GIVEN: Noisy observations $\mathcal{Y} = \{y_1, y_2, \dots\}$ of some "hidden" random variables $\mathcal{X} = \{x_1, x_2, \dots\}$.

$$\begin{aligned} p(\mathcal{X}) &\quad\Rightarrow\quad \text{prior model} \\ p(\mathcal{Y} \mid \mathcal{X}) &\quad\Rightarrow\quad \text{measurement model} \end{aligned}$$

- Standard estimation problems:

$$\begin{aligned} \widehat{\mathcal{X}}_{\text{MAP}} &= \arg\max_{\mathcal{X}} p(\mathcal{X} \mid \mathcal{Y}) = \arg\max_{\mathcal{X}} p(\mathcal{X})\, p(\mathcal{Y} \mid \mathcal{X}) \\ p(x_i \mid \mathcal{Y}) &= \sum_{\mathcal{X} \setminus x_i} p(\mathcal{X} \mid \mathcal{Y}) = \frac{1}{p(\mathcal{Y})} \sum_{\mathcal{X} \setminus x_i} p(\mathcal{X})\, p(\mathcal{Y} \mid \mathcal{X}) \end{aligned}$$

- Graphical models are a tool for controlling complexity in cases where direct computational costs are prohibitively high:

Discrete N variables drawn from a finite alphabet with M symbols require $\mathcal{O}(M^N)$ computations.

Gaussian N vector Gaussian variables of dimension d require $\mathcal{O}((Nd)^3)$ computations.

Graphical Models

- A graph $\mathcal{G}$ is a collection of nodes $\mathcal{S}$ and edges $\mathcal{E}$.
  - Each node $s_i \in \mathcal{S}$ is associated with a random variable $x_i \in \mathcal{X}$.
  - Each edge $(i, j) \in \mathcal{S}$ connects two nodes s_i and s_j.
- Edges are associated with conditional independencies. There are a variety of formalisms for doing this:

  Undirected Graphs (image processing, statistical physics)

  Directed Graphs (artificial intelligence, systems & control)

  Factor Graphs (error correcting codes)
- Many of the results we will discuss have roots in the statistical physics literature, so we will focus on undirected graphs.
- Equivalent ideas can be developed for directed/factor graphs.

Undirected Graphs and Conditional Independence

- For undirected graphs, we define the *neighborhood* of x_i to be

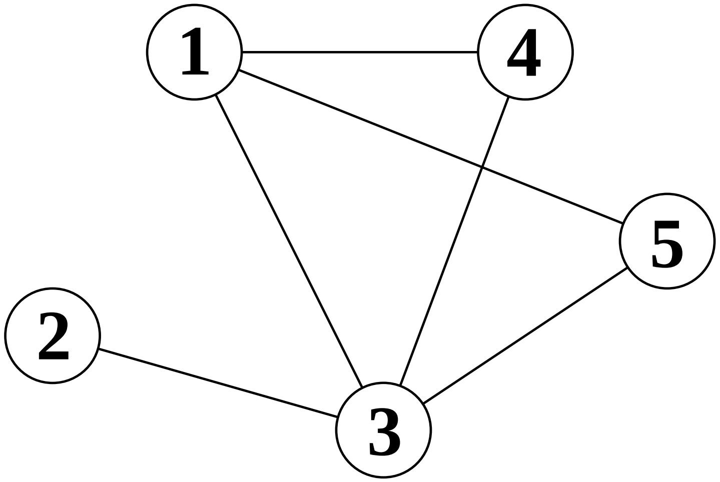
$$\mathcal{N}(x_i) \triangleq \{x_j \in \mathcal{X} \mid (i,j) \in \mathcal{E}\}$$

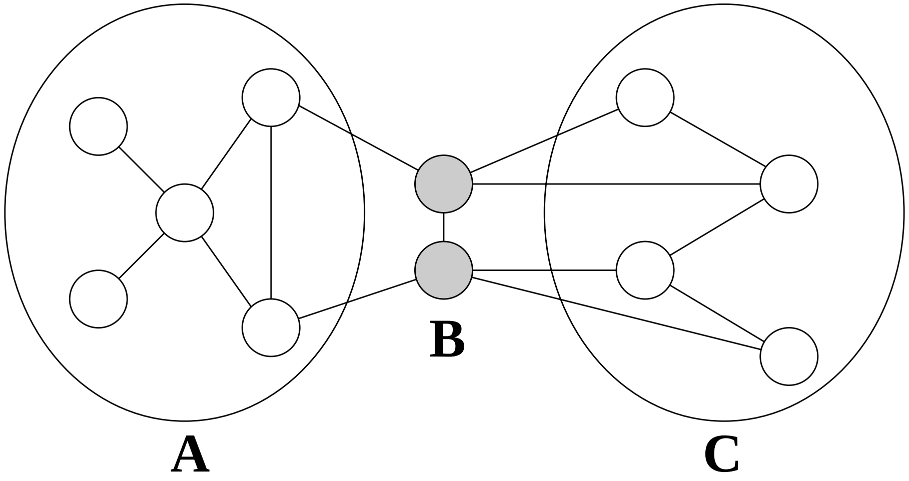
- Conditioned on its immediate neighbors, the probability distribution of a given node is independent of the rest of the graph:

$$p\,(x_i \mid \mathcal{X} \setminus x_i\,) = p\,(x_i \mid \mathcal{N}(x_i)\,)$$

- Alternatively, conditioned on a given set of nodes, the distributions of disjoint subsets of the graph separated by those nodes are independent.

Undirected Graphs

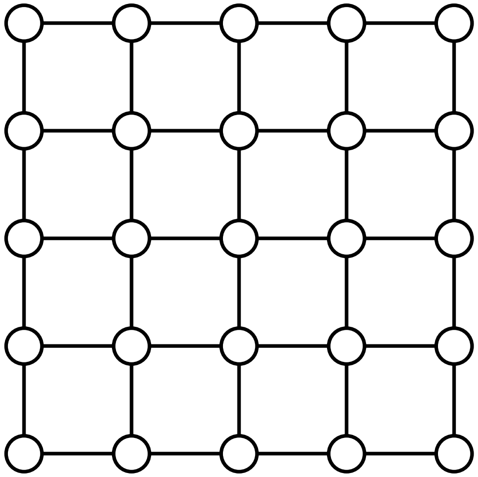




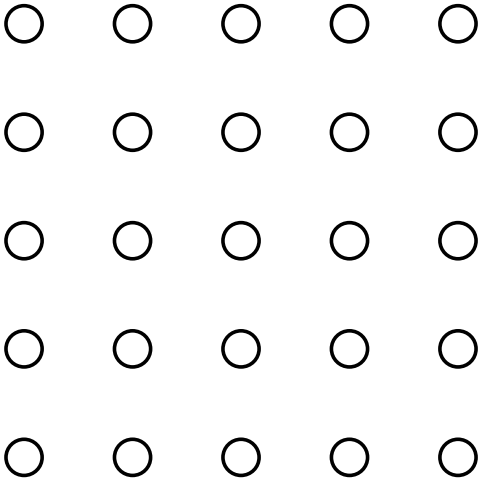
$$\begin{aligned} p\,(x_A \mid x_B, x_C) &= p\,(x_A \mid x_B) \\ p\,(x_A, x_C \mid x_B) &= p\,(x_A \mid x_B)\, p\,(x_C \mid x_B) \end{aligned}$$

$$\begin{aligned} p\,(x_5 \mid x_1, x_2, x_3, x_4) &= p\,(x_5 \mid x_1, x_3) \\ p\,(x_2, x_4, x_5 \mid x_1, x_3) &= p\,(x_2 \mid x_1, x_3)\, p\,(x_4 \mid x_1, x_3)\, p\,(x_5 \mid x_1, x_3) \end{aligned}$$

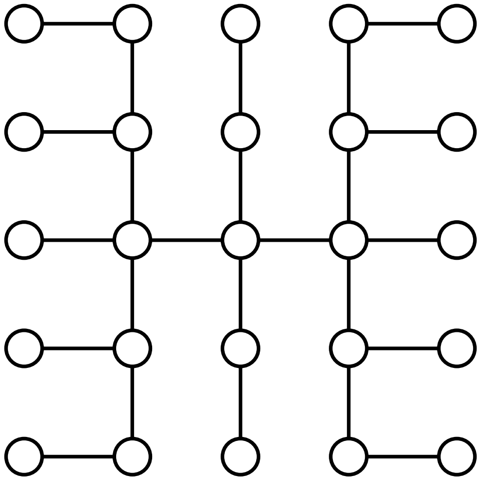
Markov Random Fields



Nearest–Neighbor Grid



Mean Field Approximation



Structured Mean Field

Cliques

- *QUESTION:* How do we determine if a distribution $p(\mathcal{X})$ satisfies the conditional independencies implied by a given graph $\mathcal{G}$?
- To provide an answer, the following definitions will be useful:

Clique A set of nodes in which every node is *directly* connected to every other node in the clique

Maximal Clique A clique which is not a proper subset of any other clique

Hammersley-Clifford Theorem (1971)

$$\begin{aligned}
\mathcal{G} \quad &\Rightarrow \quad \text{Undirected graph defined on a set of random variables } \mathcal{X} \\
\mathcal{C} \quad &\Rightarrow \quad \text{Set of all maximal cliques of } \mathcal{G} \\
\psi_C(x_C) \quad &\Rightarrow \quad \text{Arbitrary positive “clique potential” function}
\end{aligned}$$

- A positive distribution $p(\mathcal{X})$ satisfies the conditional independencies implied by $\mathcal{G}$ if and only if it can be written in the factorized form

$$\begin{aligned}
p(\mathcal{X}) &= \frac{1}{Z} \prod_{C \in \mathcal{C}} \psi_C(x_C) \\
Z &= \sum_{\mathcal{X}} \prod_{C \in \mathcal{C}} \psi_C(x_C)
\end{aligned}$$

- We may equivalently define $\phi_C(x_C) \triangleq -\log \psi_C(x_C)$ and write

$$p(\mathcal{X}) = \frac{1}{Z} \exp\left\{ -\sum_{C \in \mathcal{C}} \phi_C(x_C) \right\}$$

Inference on Undirected Graphs

- For convenience, we will assume that all cliques involve at most two nodes, allowing the graph–structured prior $p\left(\mathcal{X}\right)$ to be written as

$$p\left(\mathcal{X}\right) = \frac{1}{Z} \prod_{(i,j) \in \mathcal{E}} \psi_{i,j}\left(x_i, x_j\right) \prod_{s_i \in \mathcal{S}} \psi_i\left(x_i\right)$$

- If we associate a single measurement with each hidden node, $p\left(\mathcal{X} \mid \mathcal{Y}\right)$ has the same graphical structure as the prior $p\left(\mathcal{X}\right)$

$$p\left(\mathcal{X} \mid \mathcal{Y}\right) = \frac{1}{Z(\mathcal{Y})} \prod_{(i,j) \in \mathcal{E}} \psi_{i,j}\left(x_i, x_j\right) \prod_{s_i \in \mathcal{S}} \psi_i\left(x_i\right) p\left(y_i \mid x_i\right)$$

- Computing marginals $p\left(x_i\right)$ and conditional marginals $p\left(x_i \mid \mathcal{Y}\right)$ are therefore equivalent problems.

$$p\left(x_i \mid \mathcal{Y}\right) = \frac{1}{Z(\mathcal{Y})} \sum_{\mathcal{X} \setminus x_i} \prod_{(i,j) \in \mathcal{E}} \psi_{i,j}\left(x_i, x_j\right) \prod_{s_i \in \mathcal{S}} \psi_i\left(x_i\right) p\left(y_i \mid x_i\right)$$

Tree–Structured Graphs

- Any tree–structured prior distribution may be factorized as

$$p\left(\mathcal{X}\right) = \prod_{(i,j)\in\mathcal{E}} \frac{p\left(x_i, x_j\right)}{p\left(x_i\right) p\left(x_j\right)} \prod_{s_i\in\mathcal{S}} p\left(x_i\right)$$

- This allows the conditional distribution to be factorized as

$$\begin{aligned} p\left(\mathcal{X} \mid \mathcal{Y}\right) &= \frac{1}{p\left(\mathcal{Y}\right)} \prod_{(i,j)\in\mathcal{E}} \frac{p\left(x_i, x_j\right)}{p\left(x_i\right) p\left(x_j\right)} \prod_{s_i\in\mathcal{S}} p\left(x_i\right) p\left(y_i \mid x_i\right) \\ &\triangleq \frac{1}{p\left(\mathcal{Y}\right)} \prod_{(i,j)\in\mathcal{E}} \psi_{i,j}\left(x_i, x_j\right) \prod_{s_i\in\mathcal{S}} \psi_i\left(x_i\right) \end{aligned}$$

- Using Bayes' rule and the Markov properties of $\mathcal{G}$, we have

$$\begin{aligned} p\left(x_i \mid \mathcal{Y}\right) &= \frac{p\left(x_i\right) p\left(\mathcal{Y} \mid x_i\right)}{p\left(\mathcal{Y}\right)} = \frac{p\left(x_i\right) p\left(y_i \mid x_i\right)}{p\left(\mathcal{Y}\right)} \prod_{s_j\in\mathcal{N}(s_i)} p\left(\mathcal{Y}_{j\setminus i} \mid x_i\right) \\ &= \alpha\psi_i\left(x_i\right) \prod_{s_j\in\mathcal{N}(s_i)} p\left(\mathcal{Y}_{j\setminus i} \mid x_i\right) \end{aligned}$$

Belief Propagation on Tree–Structured Graphs

- Suppose we associate the conditional likelihoods $p\left(\mathcal{Y}_{j\backslash i} \mid x_i\right)$ with a "message" $m_{j\rightarrow i}\left(x_i\right)$ that s_j sends to s_i
- Each message $m_{j\rightarrow i}\left(x_i\right)$ is an M–dimensional vector of real numbers giving the likelihood of each possible value of x_j conditioned on the observations in the subtree rooted at x_i
- Belief Propagation (BP) operates through an iterative "message–passing" procedure:

$$\begin{aligned} p\left(x_i \mid \mathcal{Y}\right) &= \alpha\psi_i\left(x_i\right) \prod_{s_j \in \mathcal{N}(s_i)} m_{j\rightarrow i}\left(x_i\right) \\ m_{j\rightarrow i}\left(x_i\right) &= \sum_{x_j} \psi_{i,j}\left(x_i, x_j\right) \psi_j\left(x_j\right) \prod_{s_k \in \mathcal{N}(s_j)\backslash s_i} m_{k\rightarrow j}\left(x_j\right) \end{aligned}$$

- On trees, BP converges to the *exact* $p\left(x_i \mid \mathcal{Y}\right)$ once messages have been allowed to propagate across the entire diameter of the graph
- BIG computational savings $\Rightarrow$ $\mathcal{O}(M^2 N)$ versus $\mathcal{O}(M^N)$ operations

Belief Propagation on Graphs with Cycles

- When $\mathcal{G}$ has cycles, the conditional independencies used to derive the BP algorithm no longer hold

Junction Tree Algorithm Cluster nodes until you have a tree–structured "super–graph" and then run the BP algorithm

- Gives exact answers, but creates intractably large clusters for most interesting architectures

Loopy Belief Propagation Use the BP message passing as an iterative procedure and hope for convergence

- Messages lose their strict probabilistic interpretation, so the standard BP derivation provides no justification for this procedure
- If cycles are long, we expect conditional independencies to "approximately" hold, so loopy BP may give decent approximations
- Excellent empirical performance for *some* problems motivates further investigation

Approximating Distributions

- If $p\,(\mathcal{X} \mid \mathcal{Y}\,)$ is intractable, we could consider approximating it by a tractable distribution $q\,(\mathcal{X} \mid \mathcal{Y}, \lambda\,)$

$$\lambda \Rightarrow \text{parameterizes a class of tractable distributions}$$

- We would like the "best" $q\,(\mathcal{X} \mid \mathcal{Y}, \lambda\,)$. One reasonable metric is

$$\begin{aligned} \lambda^* &= \arg\min_{\lambda} D\,(p\,(\mathcal{X} \mid \mathcal{Y}\,) \,||\, q\,(\mathcal{X} \mid \mathcal{Y}, \lambda\,)\,) \\ &= \arg\min_{\lambda} \sum_{\mathcal{X}} p\,(\mathcal{X} \mid \mathcal{Y}\,) \log \frac{p\,(\mathcal{X} \mid \mathcal{Y}\,)}{q\,(\mathcal{X} \mid \mathcal{Y}, \lambda\,)} \end{aligned}$$

- *GOOD NEWS:* If we choose $q\,(\mathcal{X} \mid \mathcal{Y}, \lambda\,) = \prod_i q_i(x_i|\lambda_i)$ to be the class of fully factorized distributions, minimizing $D\,(p \,||\, q\,)$ recovers the *exact* marginals $q_i(x_i|\lambda_i) = p\,(x_i \mid \mathcal{Y}\,)$
- *BAD NEWS:* $D\,(p \,||\, q\,)$ involves averages with respect to the intractable distribution $p\,(\mathcal{X} \mid \mathcal{Y}\,)$, and is as hard to deal with as the original problem

A Tractable Approximation

$$\lambda^* = \arg\min_\lambda D\left(q \,||\, p\,\right) = \arg\min_\lambda \sum_{\mathcal{X}} q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right) \log \frac{q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right)}{p\left(\mathcal{X} \mid \mathcal{Y}\right)}$$

- *GOOD NEWS:* $D\left(q \,||\, p\,\right)$ takes expectations with respect to the *tractable* distribution $q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right)$, so this minimization is possible for certain approximating classes
- *BAD NEWS:* Since it weights distance by the approximating distribution, it is not clear if $D\left(q \,||\, p\,\right)$ will give good approximations. One justification:

$$\begin{aligned}
\log p\left(\mathcal{Y}\right) &= \log \sum_{\mathcal{X}} p\left(\mathcal{X}, \mathcal{Y}\right) \\
&= \log \sum_{\mathcal{X}} q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right) \frac{p\left(\mathcal{X}, \mathcal{Y}\right)}{q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right)} \\
&\geq \sum_{\mathcal{X}} q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right) \log \left[\frac{p\left(\mathcal{X}, \mathcal{Y}\right)}{q\left(\mathcal{X} \mid \mathcal{Y}, \lambda\right)}\right]
\end{aligned}$$

Classical Mean Field Theory

$$p\left(\mathcal{X}\right) = \frac{1}{Z} \exp \left\{ - \sum_{(i,j) \in \mathcal{E}} \phi_{i,j}\left(x_i, x_j\right) - \sum_{s_i \in \mathcal{S}} \phi_i\left(x_i\right) \right\}$$

- The mean field approximation chooses the simplest possible approximating distribution by removing *all* of the edges

$$\begin{aligned} q\left(\mathcal{X}\right) &= \prod_i q_i\left(x_i\right) \\ D\left(q \,\|\, p\,\right) &= \sum_{(i,j) \in \mathcal{E}} \sum_{x_i, x_j} q_i\left(x_i\right) q_j\left(x_j\right) \phi_{i,j}\left(x_i, x_j\right) + \sum_{s_i \in \mathcal{S}} \sum_{x_i} q_i\left(x_i\right) \phi_i\left(x_i\right) \\ &\quad + \sum_{s_i \in \mathcal{S}} \sum_{x_i} q_i\left(x_i\right) \log q_i\left(x_i\right) \end{aligned}$$

- Notice that the $\phi_{i,j}\left(x_i, x_j\right)$ terms cause the optimization of the $q_i\left(x_i\right)$ distributions at different nodes to become coupled

Minimizing the Mean Field Equations

- The mean field approximation removes intractable dependencies in the original graph by adding a set of extra parameters which must then be optimized
- Although the final model $q\left(\mathcal{X}\right)$ fully decouples the nodes, the optimization process allows the edges in $p\left(\mathcal{X}\right)$ to be (approximately) accounted for
- For nonhomogeneous MRFs, we use Lagrange multipliers to enforce the normalization constraint $\sum_{x_i} q_i\left(x_i\right) = 1$. Taking derivates gives

$$q_i\left(x_i\right) = \alpha \psi_i\left(x_i\right) \prod_{s_j \in \mathcal{N}\left(s_i\right)} \prod_{x_j} \psi_{i,j}\left(x_i, x_j\right)^{q_j\left(x_j\right)}$$

- We can attempt to solve these equations by iteratively passing $q_i\left(x_i\right)$ terms between nodes (reminiscent of BP messages)
- Unfortunately, there are no guarantees of convergence to a global optimum.

Variational Methods

- Our justification for the use of $D\,(q \mid\mid p\,)$ in terms of maximizing a lower bound on $p\,(\mathcal{Y})$ is a simple example of a *variational method.*
- More generally, we choose a family of tractable functions $g(x;\lambda)$ which each approximate $f(x)$, and then attempt to find λ^* such that $g(x;\lambda^*)$ "best" approximates $f(x)$.
- The notion of "best approximation" is often made precise by choosing $g(x;\lambda)$ which bound $f(x)$, and then optimizing that bound.
- Structured Mean Field methods notice that we do not have to remove *all* of a graph's edges to make calculations tractable.
  - Alternate between calculating the variational parameters λ^* of the best subgraph and running a tractable exact algorithm on the resulting subgraph (Markov chain, tree, etc.)
- No general methods for picking tractable variational classes which are also good approximations (often must exploit specific graphical structures, functional forms of clique potentials, etc.)

Gibbs Free Energy

$$G \triangleq \sum_{\mathcal{X}} p\left(\mathcal{X}\right) \left[\sum_{(i,j)\in\mathcal{E}} \phi_{i,j}\left(x_i, x_j\right) + \sum_{s_i \in \mathcal{S}} \phi_i\left(x_i\right) \right] - \left[-\sum_{\mathcal{X}} p\left(\mathcal{X}\right) \log p\left(\mathcal{X}\right) \right]$$

- Exactly minimizing G with respect to $p\left(\mathcal{X}\right)$ recovers

$$p\left(\mathcal{X}\right) = \frac{1}{Z} \exp\left\{ -\sum_{(i,j)\in\mathcal{E}} \phi_{i,j}\left(x_i, x_j\right) - \sum_{s_i \in \mathcal{S}} \phi_i\left(x_i\right) \right\}$$

- For complex MRFs, this minimization is intractable. Physicists often minimize an approximate free energy to produce $q\left(\mathcal{X}\right) \approx p\left(\mathcal{X}\right)$
- If we assume $q\left(\mathcal{X}\right) = \prod_i q_i\left(x_i\right)$, we get the mean field free energy

$$\begin{aligned} G_{\mathrm{MF}} &= \sum_{\mathcal{X}} \prod_i q_i\left(x_i\right) \left[\sum_{(j,k)\in\mathcal{E}} \phi_{j,k}\left(x_j, x_k\right) + \sum_{s_k \in \mathcal{S}} \phi_k\left(x_k\right) \right] \\ &\quad + \sum_{\mathcal{X}} \prod_i q_i\left(x_i\right) \log \prod_i q_i\left(x_i\right) \end{aligned}$$

Bethe Free Energy

- For tree–structured graphs, the exact free energy is given by

$$\begin{aligned} p(\mathcal{X}) &= \prod_{(i,j)\in\mathcal{E}} \frac{p(x_i,x_j)}{p(x_i)\,p(x_j)} \prod_{s_i\in\mathcal{S}} p(x_i) \\ G_{\mathrm{B}} &= \sum_{(i,j)\in\mathcal{E}} \sum_{x_i,x_j} q_{i,j}(x_i,x_j)\left[\log \frac{q_{i,j}(x_i,x_j)}{q_i(x_i)\,q_j(x_j)} + \phi_{i,j}(x_i,x_j)\right] \\ &\quad + \sum_{s_i\in\mathcal{S}} \sum_{x_i} q_i(x_i)\left[\log q_i(x_i) + \phi_i(x_i)\right] \end{aligned}$$

- We cannot write the free energy for graphs with cycles solely in terms of $q_i(x_i)$ and $q_{i,j}(x_i,x_j)$ because of the partition function Z
- Bethe Approximation ⇒ Use the tree–structured free energy G_{B} even though $\mathcal{G}$ is *not* tree–structured.

Minimization of Bethe Free Energy

- In order to minimize G_{B}, we add Lagrange multipliers to enforce the various marginalization constraints

$$
\begin{aligned}
\lambda_{i,j}(x_j) &\iff \sum_{x_i} q_{i,j}(x_i, x_j) = q_j(x_j) \\
\lambda_{j,i}(x_i) &\iff \sum_{x_j} q_{i,j}(x_i, x_j) = q_i(x_i) \\
\gamma_i &\iff \sum_{x_i} q_i(x_i) = 1 \\
\gamma_{ij} &\iff \sum_{x_i, x_j} q_{i,j}(x_i, x_j) = 1
\end{aligned}
$$

Bethe Free Energy & Belief Propagation

- Taking the derivative of the resulting Lagrangian and manipulating

$$\begin{aligned}
q_i\left(x_i\right) &= \alpha \exp\left\{\phi_i\left(x_i\right) + \frac{1}{|\mathcal{N}(s_i)|-1}\sum_{s_j\in\mathcal{N}(s_i)}\lambda_{j,i}\left(x_i\right)\right\} \\
q_{i,j}\left(x_i,x_j\right) &= \alpha \exp\left\{\phi_{i,j}\left(x_i,x_j\right) + \phi_i\left(x_i\right) + \phi_j\left(x_j\right) + \lambda_{i,j}\left(x_j\right) + \lambda_{j,i}\left(x_i\right)\right\}
\end{aligned}$$

- Recall that the BP update equations are given by

$$\begin{aligned}
p\left(x_i \mid \mathcal{Y}\right) &= \alpha\psi_i\left(x_i\right)\prod_{s_j\in\mathcal{N}(s_i)} m_{j\to i}\left(x_i\right) \\
m_{j\to i}\left(x_i\right) &= \sum_{x_j}\psi_{i,j}\left(x_i,x_j\right)\psi_j\left(x_j\right)\prod_{s_k\in\mathcal{N}(s_j)\backslash s_i} m_{k\to j}\left(x_j\right)
\end{aligned}$$

- These equations are *exactly* equivalent if we make the following association between Lagrange multipliers and messages:

$$\lambda_{i,j}\left(x_j\right) = \sum_{s_k\in\mathcal{N}(s_j)\backslash s_i}\log m_{k\to j}\left(x_j\right)$$

Duality of KL and Free Energy

- The mean field approximation can be derived by minimizing either an approximate free energy G_{MF} or the KL divergence $D\left(q \,||\, p\right)$ between the fully factorized and true distributions.
- QUESTION: Is there a KL interpretation of the Bethe tree approximation?
- Minimizing G_{B} is equivalent to minimizing an approximate $D\left(q \,||\, p\right)$, where the approximation arises from

$$\log q\left(\mathcal{X}\right) \approx \sum_{(i,j)\in\mathcal{E}} \log \frac{q_{i,j}\left(x_i, x_j\right)}{q_i\left(x_i\right) q_j\left(x_j\right)} + \sum_{s_i\in\mathcal{S}} \log q_i\left(x_i\right)$$

  (derived from the Möbius inversion formula)

- These are a few examples of a much deeper duality between free energy and relative entropy.

Generalized Belief Propagation

- We have interpreted BP messages as exponentiated Lagrange multipliers which enforce a set of local consistency constraints.
- BP only considers pairwise consistency. This ensures that the beliefs at all pairs of nodes will be consistent, but does *not* guarantee that the beliefs at larger clusters of nodes will be consistent.
- Yedidia, Freeman, and Weiss (NIPS 2000) have introduced a new class of generalized belief propagation (GBP) algorithms which enforce the consistency of larger clusters by passing more messages
  - Clustering can produce good estimates for problems where BP gives poor results or fails to converge
  - Changing cluster sizes allows computational complexity and solution accuracy to be balanced
- GBP algorithms correspond to a class of higher–order free energy approximations known as Kikuchi approximation

Double Loop Algorithms

- Yuille has recently introduced a “double–loop” algorithm which is guaranteed to converge to a local minimum of the Bethe free energy.
- Functions by iterating between an “inner” and an “outer” loop:
  - Inner loop determines a set of Lagrange multipliers
  - Outer loop updates beliefs based on Lagrange multipliers
- Derivation depends on decomposition of free energy into a sum of convex and concave parts
- Loopy BP can be viewed as an approximation to double–loop in which the two loops are collapsed together
- GBP–style generalizations of double–loop are also proposed

Summary

- For tree–structured graphs, BP messages have a direct probabilistic interpretation as likelihoods
- For graphs with cycles, BP messages can be interpreted as Lagrange multipliers which attempt to enforce local consistency constraints
- Variational methods, including the mean field approximation, are closely related to BP, and may offer attractive alternatives in certain situations
- KL divergence and Gibbs free energy are connected in a number of very fundamental ways