

Computer Vision

Lecture 7 – Learning in Graphical Models

Prof. Dr.-Ing. Andreas Geiger

Autonomous Vision Group

University of Tübingen / MPI-IS

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN



e l l i s
European Laboratory for Learning and Intelligent Systems

Agenda

7.1 Conditional Random Fields

7.2 Parameter Estimation

7.3 Deep Structured Models

7.1

Conditional Random Fields

Inference vs. Learning

Markov Random Field:

$$p(x_1, \dots, x_{100}) = \frac{1}{Z} \exp \left\{ \sum_i \psi_i(x_i) + \lambda \sum_{i \sim j} \psi_{ij}(x_i, x_j) \right\}$$

► So far: **Inference**

- Marginal distributions: $p(x_i) = \sum_{x_{\setminus x_i}} p(x_1, \dots, x_{100})$
- MAP solution: $x_1^*, \dots, x_{100}^* = \operatorname{argmax}_{x_1, \dots, x_{100}} p(x_1, \dots, x_{100})$

► Now: **Learning**

- Estimate parameters (here regularization strength λ) from dataset
- Remark: In the literature, potentials are sometimes defined as the negative log factors, but here we will consider them as generic features and omit the sign

Conditional Random Fields

Markov Random Field:

$$p(\mathcal{X}) = \frac{1}{Z} \exp \left\{ \sum_i \psi_i(x_i) + \lambda \sum_{i \sim j} \psi_{ij}(x_i, x_j) \right\}$$

- ▶ Reason about output variables $\mathcal{X} \in \mathbb{X}$ given one particular model instantiation

Structured Output Learning:

$$f_{\mathbf{w}} : \mathbb{X} \rightarrow \mathbb{Y}$$

- ▶ Inputs $\mathcal{X} \in \mathbb{X}$ can be any kind of objects
- ▶ Outputs $\mathcal{Y} \in \mathbb{Y}$ are complex (structured) objects
 - ▶ images, text, parse trees, folds of a protein, computer programs, ...

Conditional Random Fields

Markov Random Field:

$$p(\mathcal{X}) = \frac{1}{Z} \exp \left\{ \sum_i \psi_i(x_i) + \lambda \sum_{i \sim j} \psi_{ij}(x_i, x_j) \right\}$$

- Reason about output variables $\mathcal{X} \in \mathbb{X}$ given one particular model instantiation

Conditional Random Field:

$$p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) = \frac{1}{Z} \exp \left\{ \sum_i \psi_i(\mathcal{X}, y_i) + \lambda \sum_{i \sim j} \psi_{ij}(\mathcal{X}, y_i, y_j) \right\}$$

- Make conditioning of output \mathcal{Y} on input \mathcal{X} and parameters \mathbf{w} explicit (here $\mathbf{w} = \lambda$)
- MRF notation: outputs $\mathcal{X} \in \mathbb{X} \Rightarrow$ CRF notation: inputs $\mathcal{X} \in \mathbb{X}$, outputs $\mathcal{Y} \in \mathbb{Y}$
- Learning: Estimate \mathbf{w} from dataset $\mathcal{D} = \{(\mathcal{X}^1, \mathcal{Y}^1), \dots, (\mathcal{X}^N, \mathcal{Y}^N)\}$

Conditional Random Fields

Conditional Random Field – General Form:

$$p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) = \frac{1}{Z(\mathcal{X}, \mathbf{w})} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}, \mathcal{Y}) \rangle \}$$

- **Feature function:** $\psi(\mathcal{X}, \mathcal{Y}) : \mathbb{X} \times \mathbb{R}^M \rightarrow \mathbb{R}^D$ (concatenates potentials/features)

Graphical model specifies decomposition of ψ into potentials (=log factors) ψ_k :

$$\psi(\mathcal{X}, \mathcal{Y}) = (\psi_1(\mathcal{X}, \mathcal{Y}_1), \dots, \psi_K(\mathcal{X}, \mathcal{Y}_K))$$

- **Parameter vector:** $\mathbf{w} \in \mathbb{R}^D$ (M : num. output nodes, D : dim. of feature space)

Note that this model is much more flexible than a model with a single λ

- **Partition function:** $Z(\mathcal{X}, \mathbf{w}) = \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}, \mathcal{Y}) \rangle \}$

- **Learning:** Estimate \mathbf{w} from dataset $\mathcal{D} = \{(\mathcal{X}^1, \mathcal{Y}^1), \dots, (\mathcal{X}^N, \mathcal{Y}^N)\}$

Parameter Estimation

Goal: Maximize likelihood of outputs \mathcal{Y} conditioned on inputs \mathcal{X} wrt. \mathbf{w} , assuming independent and identically distributed (IID) data (likelihood factorizes):

$$\hat{\mathbf{w}}_{ML} = \operatorname{argmax}_{\mathbf{w} \in \mathbb{R}^D} p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) \quad \text{with} \quad p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) = \prod_{n=1}^N p(\mathcal{Y}^n|\mathcal{X}^n, \mathbf{w})$$

In other words, find parameter vector $\hat{\mathbf{w}}_{ML}$ such that $p_{model}(\mathcal{Y}|\mathcal{X}, \hat{\mathbf{w}}_{ML}) \approx p_{data}(\mathcal{Y}|\mathcal{X})$.

This is equivalent to minimizing the **negative conditional log-likelihood**:

$$\hat{\mathbf{w}}_{ML} = \operatorname{argmin}_{\mathbf{w} \in \mathbb{R}^D} \mathcal{L}(\mathbf{w}) \quad \text{with} \quad \mathcal{L}(\mathbf{w}) = - \sum_{n=1}^N \log p(\mathcal{Y}^n|\mathcal{X}^n, \mathbf{w})$$

Parameter Estimation

Goal: Minimize negative conditional log-likelihood $\mathcal{L}(\mathbf{w})$

$$\hat{\mathbf{w}}_{ML} = \operatorname{argmin}_{\mathbf{w} \in \mathbb{R}^D} \mathcal{L}(\mathbf{w})$$

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= - \sum_{n=1}^N \log p(\mathcal{Y}^n | \mathcal{X}^n, \mathbf{w}) \\ &= - \sum_{n=1}^N \left[\log \frac{1}{Z(\mathcal{X}^n, \mathbf{w})} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle \} \right] \\ &= - \sum_{n=1}^N [-\log Z(\mathcal{X}^n, \mathbf{w}) + \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle] \\ &= - \sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y} \in \mathbb{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right]\end{aligned}$$

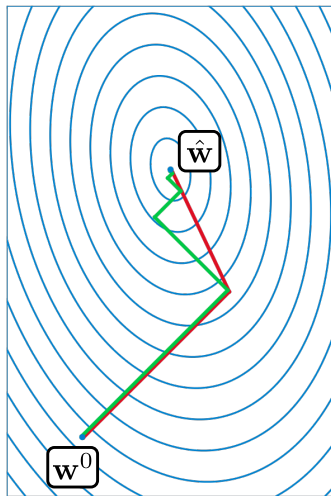
Optimization

Gradient Descent:

- ▶ Pick step size η and tolerance ϵ
- ▶ Initialize \mathbf{w}^0
- ▶ Repeat until $\|\mathbf{v}\| < \epsilon$
 - ▶ $\mathbf{v} = \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) = \sum_{i=1}^N \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w})$
 - ▶ $\mathbf{w}^{t+1} = \mathbf{w}^t - \eta \mathbf{v}$

Variants:

- ▶ Line search (green)
- ▶ Conjugate gradients (red)
- ▶ All require gradients, some (e.g., line search) require function evaluation



Gradient of Negative Conditional Log-Likelihood

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \frac{\sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \psi(\mathcal{X}^n, \mathcal{Y})}{\sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \}} \right] \\ &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y}} \frac{\exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \}}{\sum_{\mathcal{Y}'} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}') \rangle \}} \psi(\mathcal{X}^n, \mathcal{Y}) \right] \\ &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right] \\ &= -\sum_{n=1}^N [\psi(\mathcal{X}^n, \mathcal{Y}^n) - \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w})} \psi(\mathcal{X}^n, \mathcal{Y})]\end{aligned}$$

Gradient of Negative Conditional Log-Likelihood

$$\nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) = - \sum_{n=1}^N [\psi(\mathcal{X}^n, \mathcal{Y}^n) - \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi(\mathcal{X}^n, \mathcal{Y})]$$

When is $\mathcal{L}(\mathbf{w})$ minimal?

$$\mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi(\mathcal{X}^n, \mathcal{Y}) = \psi(\mathcal{X}^n, \mathcal{Y}^n) \Rightarrow \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) = 0$$

- Interpretation: we aim at **expectation matching**: $\mathbb{E}_{\mathcal{Y} \sim p(\cdot)} \psi(\mathcal{X}, \mathcal{Y}) = \psi(\mathcal{X}, \mathcal{Y}^{\text{obs}})$, but discriminatively: only for $\mathcal{X} \in \{\mathcal{X}^1, \dots, \mathcal{X}^N\}$

Note:

- $\mathcal{L}(\mathbf{w})$ convex (Hessian positive semi-definite) $\Rightarrow \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) = 0 \Rightarrow$ **global optimum**
- Only true as $p(\mathcal{Y}|\mathcal{X}, \mathbf{w})$ is log-linear in $\mathbf{w} \in \mathbb{R}^D$ (we will also see non-linear models)

LOG LINEAR! !

Computational Complexity

Task: For gradient descent with line search we must evaluate $\mathcal{L}(\mathbf{w})$ and $\nabla_{\mathbf{w}}\mathcal{L}(\mathbf{w})$:

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y} \in \mathbb{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y} \in \mathbb{Y}} p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

Problem: \mathbb{Y} is typically very (exponentially) large!

- ▶ Binary image segmentation: $|\mathbb{Y}| = 2^{640 \times 480} \approx 10^{92475}$
- ▶ We must use the structure in \mathbb{Y} , or we are lost!

Computational Complexity

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y} \in \mathbb{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y} \in \mathbb{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

Computational complexity: $O(NC^M D)$

- ▶ N : number of samples in dataset (≈ 100 to $1,000,000$)
- ▶ M : number of output nodes (≈ 100 to $1,000,000$)
- ▶ C : maximal number of labels per output node (≈ 2 to 100)
- ▶ D : dimensionality of feature space ψ

Computational Complexity

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y} \in \mathbb{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y} \in \mathbb{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

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- ▶ D : dimensionality of feature space

Probabilistic Inference to the Rescue

Remember: in a graphical model, **features and weights decompose** as follows

$$\psi(\mathcal{X}, \mathcal{Y}) = (\psi_1(\mathcal{X}, \mathcal{Y}_1), \dots, \psi_K(\mathcal{X}, \mathcal{Y}_K)) \quad \mathbf{w} = (\mathbf{w}_1, \dots, \mathbf{w}_K)$$

Thus, the **partition function simplifies** as:

$$\begin{aligned} \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} &= \sum_{\mathcal{Y}} \exp \left\{ \sum_k \langle \mathbf{w}_k, \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \rangle \right\} \\ &= \sum_{\mathcal{Y}} \prod_k \underbrace{\exp \{ \langle \mathbf{w}_k, \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \rangle \}}_{k\text{'th factor}} \end{aligned}$$

我的理解：把一张大图Y做了分割， y_k 对应每个小部分，再与不同特征函数进行处理 这样去简化对整个图片的计算

- Can be efficiently calculated/approximated using **message passing** (run sum-product belief propagation, sum over any of the unnorm. marginals)

Probabilistic Inference to the Rescue

Similarly, the **feature expectation simplifies** as:

$$\begin{aligned}\sum_{\mathcal{Y}} p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) &= \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi(\mathcal{X}^n, \mathcal{Y}) \\ &= \left(\mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \right)_{k \in 1, \dots, K} \\ &= \left(\mathbb{E}_{\mathcal{Y}_k \sim p(\mathcal{Y}_k|\mathcal{X}^n, \mathbf{w})} \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \right)_{k \in 1, \dots, K} \\ &= \left(\sum_{\mathcal{Y}_k} p(\mathcal{Y}_k|\mathcal{X}^n, \mathbf{w}) \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \right)_{k \in 1, \dots, K}\end{aligned}$$

- ▶ Now only C^F terms in sum over \mathcal{Y}_k (C : max. number of labels, F : largest order)
- ▶ Marginals $p(\mathcal{Y}_k|\mathcal{X}^n, \mathbf{w})$ can be calculated efficiently (e.g., with BP)

Probabilistic Inference to the Rescue

Similarly, the **feature expectation simplifies** as:



$$\begin{aligned} \sum_{\mathcal{Y}} p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) &= \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \sum_k \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \\ &= \sum_k \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \\ &= \sum_k \mathbb{E}_{\mathcal{Y}_k \sim p(\mathcal{Y}_k|\mathcal{X}^n, \mathbf{w})} \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \\ &= \underbrace{\sum_k}_{K} \underbrace{\sum_{\mathcal{Y}_k}}_{C^F} \underbrace{p(\mathcal{Y}_k|\mathcal{X}^n, \mathbf{w})}_{\text{marginal}} \psi_k(\mathcal{X}^n, \mathcal{Y}_k) \end{aligned}$$

- K : number of potentials, C : max. number of labels, F : largest order
- Marginals can be calculated efficiently in polynomial time (e.g., with BP)

Computational Complexity

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

Computational complexity: $\mathcal{O}(N \cancel{C^M} D) \rightarrow \mathcal{O}(N K C^F D)$

- ▶ N : number of samples in dataset (≈ 100 to $1,000,000$)
- ▶ M : number of output nodes (≈ 100 to $1,000,000$)
- ▶ C : maximal number of labels per output node (≈ 2 to 100)
- ▶ D : dim. of feature space, K : number of factors, F : order of largest factor (≈ 2 -3)

Computational Complexity

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= - \sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= - \sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

Computational complexity: $O(NKC^FD)$

- ▶ N : number of samples in dataset (≈ 100 to $1,000,000$)
- ▶ M : number of output nodes (≈ 100 to $1,000,000$)
- ▶ C : maximal number of labels per output node (≈ 2 to 100)
- ▶ D : dim. of feature space, K : number of factors, F : order of largest factor

Computational Complexity

Learning on large datasets:

- ▶ Processing all N training samples for one gradient update is slow
- ▶ Furthermore, often not all data fits into memory (as in deep learning)

How can we estimate parameters in this setting?

- ▶ Simplify model to make gradient updates faster \Rightarrow results get worse
- ▶ Train model on subsampled dataset \Rightarrow ignores information
- ▶ Parallelize across CPUs/GPUs \Rightarrow bottlenecks, doesn't save computation
- ▶ Stochastic gradient descent

Stochastic Gradient Descent (SGD)

Stochastic Gradient Descent:

- ▶ In each gradient step:
 - ▶ Create random subset $\mathcal{D}' \subset \mathcal{D}$ (typically $|\mathcal{D}'| \leq 256$)
 - ▶ Follow approximate gradient:

$$\nabla_{\mathbf{w}} \approx - \sum_{(\mathcal{X}^n, \mathcal{Y}^n) \in \mathcal{D}'} [\psi(\mathcal{X}^n, \mathcal{Y}^n) - \mathbb{E}_{\mathcal{Y} \sim p(\mathcal{Y}|\mathcal{X}^n, \mathbf{w})} \psi(\mathcal{X}^n, \mathcal{Y})]$$

Comments:

- ▶ Line search no longer possible \Rightarrow extra step-size hyper-parameter η
- ▶ SGD converges to $\operatorname{argmin}_{\mathbf{w}} \mathcal{L}(\mathbf{w})$! (if η chosen right)
- ▶ SGD needs more iterations, but each one is faster
- ▶ See also: Bottou & Bousquet: The Tradeoffs of Large Scale Learning, NIPS 2007

Computational Complexity

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \psi(\mathcal{X}^n, \mathcal{Y}) \right]\end{aligned}$$

Computational complexity: $O(NKC^F D)$

- ▶ N : number of samples in dataset (≈ 100 to $1,000,000$)
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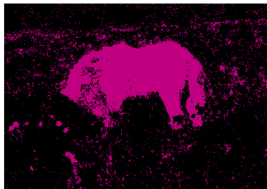
Applications / Feature Functions

Semantic Segmentation:

- ▶ $\psi_i(\mathcal{X}, y_i) \in \mathbb{R}^{\approx 1000}$: local image features (e.g., bag of words, deep features)
→ $\langle \mathbf{w}_i, \psi_i(\mathcal{X}, y_i) \rangle$: local classifier (like logistic regression)
- ▶ $\psi_{ij}(y_i, y_j) = [y_i = y_j] \in \mathbb{R}^1$: test for same label
→ $\langle w_{ij}, \psi_{ij}(y_i, y_j) \rangle$: penalizer for label changes (if $w_{ij} > 0$)
- ▶ combined: $\operatorname{argmax}_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}, \mathbf{w})$ is smoothed version of local cues



original



local classification

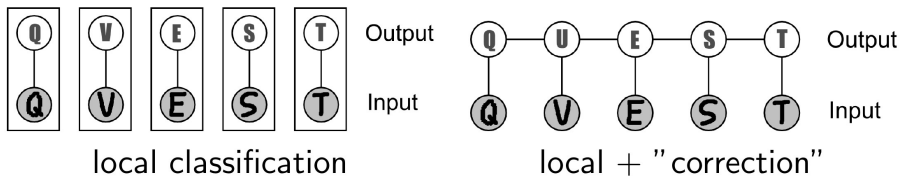


local + smoothness

Applications / Feature Functions

Handwriting Recognition:

- ▶ $\psi_i(\mathcal{X}, y_i) \in \mathbb{R}^{\approx 1000}$: image representation (e.g., pixels, gradients)
→ $\langle \mathbf{w}_i, \psi_i(\mathcal{X}, y_i) \rangle$: local classifier for letters
- ▶ $\psi_{ij}(y_i, y_j) = \mathbf{e}_{y_i} \mathbf{e}_{y_j}^\top \in \mathbb{R}^{26 \times 26}$: letter/letter indicator (matrix with one element = 1)
→ $\langle \mathbf{w}_{ij}, \psi_{ij}(y_i, y_j) \rangle$: encourage/suppress letter combinations
- ▶ Combined: $\operatorname{argmax}_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}, \mathbf{w})$ is “corrected” version of local cues



Applications / Feature Functions

Pose Estimation:

- ▶ $\psi_i(\mathcal{X}, y_i) \in \mathbb{R}^{\approx 1000}$: image representation (e.g., HoG, deep features)
→ $\langle \mathbf{w}_i, \psi_i(\mathcal{X}, y_i) \rangle$: local confidence map
- ▶ $\psi_{ij}(y_i, y_j) = \text{fit}(y_i, y_j) \in \mathbb{R}^1$: test for geometric fit / pose prior
→ $\langle w_{ij}, \psi_{ij}(y_i, y_j) \rangle$: penalizer for unrealistic poses
- ▶ Combined: $\text{argmax}_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}, \mathbf{w})$ is sanitized version of local cues



original



local classification



local + geometry

Applications / Feature Functions

Typical feature functions for CRFs in computer vision:

- ▶ Unary terms $\psi_i(\mathcal{X}, y_i)$: local representation, high-dimensional
→ $\langle \mathbf{w}_i, \psi_i(\mathcal{X}, y_i) \rangle$: local classifier
- ▶ Pairwise terms $\psi_{ij}(y_i, y_j)$: prior knowledge, typically low-dimensional
→ $\langle w_{ij}, \psi_{ij}(y_i, y_j) \rangle$: penalize inconsistencies
- ▶ Pairwise terms sometimes also depend on \mathcal{X} : $\psi_{ij}(\mathcal{X}, y_i, y_j)$

Learning adjusts parameters:

- ▶ Unary weights \mathbf{w}_i : learn local linear classifiers
- ▶ Pairwise weights w_{ij} : learn importance of smoothing/penalization
- ▶ $\operatorname{argmax}_{\mathbf{y}} p(\mathcal{Y}|\mathcal{X}, \mathbf{w})$ is cleaned up version of local prediction

Piece-wise Training

Sometimes, training the entire model at once is not easy:

- ▶ If terms actually depend on parameters in non-linear fashion
- ▶ If features are high-dimensional, learning can be very slow

Alternative: **Piece-wise Training**

- ▶ Pre-train classifiers $p(y_i|\mathcal{X})$; set $\psi_i(\mathcal{X}, y_i) = \log p(y_i|\mathcal{X}) \in \mathbb{R}$
- ▶ Learn one-dimensional weight per classifier: $\langle w_i, \psi_i(\mathcal{X}, y_i) \rangle$

Advantage:

- ▶ Lower dimensional feature vector during training/inference \rightarrow faster
- ▶ $\log p(y_i|\mathcal{X})$ can be stronger classifiers, e.g., non-linear SVMs, CNNs, ..

Disadvantage

- ▶ If local classifiers are bad, CRF training cannot fix this

Summary

Given:

- ▶ Training set $\mathcal{D} = \{(\mathcal{X}^1, \mathcal{Y}^1), \dots, (\mathcal{X}^N, \mathcal{Y}^N)\}$ with $(\mathcal{X}^n, \mathcal{Y}^n) \stackrel{\text{i.i.d.}}{\sim} p_{\text{data}}(\mathcal{X}, \mathcal{Y})$
- ▶ Feature function: $\psi(\mathcal{X}, \mathcal{Y}) : \mathbb{X} \times \mathbb{R}^M \rightarrow \mathbb{R}^D$

Task:

- ▶ Find parameter vector $\hat{\mathbf{w}}_{ML}$ such that

$$p_{\text{model}}(\mathcal{Y}|\mathcal{X}, \hat{\mathbf{w}}_{ML}) = \frac{1}{Z(\mathcal{X}, \hat{\mathbf{w}}_{ML})} \exp \{ \langle \hat{\mathbf{w}}_{ML}, \psi(\mathcal{X}, \mathcal{Y}) \rangle \} \approx p_{\text{data}}(\mathcal{Y}|\mathcal{X})$$

Minimize negative conditional log-likelihood:

$$\mathcal{L}(\mathbf{w}) = - \sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right]$$

- ▶ Convex optimization problem \rightarrow gradient descent leads to global optimum
- ▶ Training needs repeated runs of probabilistic inference \Rightarrow must be fast

Summary

Gradient of negative conditional log-likelihood:

$$\mathcal{L}(\mathbf{w}) = - \sum_{n=1}^N \left[\langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}^n) \rangle - \log \sum_{\mathcal{Y} \in \mathbb{Y}} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}^n, \mathcal{Y}) \rangle \} \right]$$

Problem	Solution	Method
$ \mathbb{Y} $ too large	exploit structure	belief propagation
N too large	mini-batches	stochastic gradient descent
D too large	trained ψ	piece-wise training

7.3

Deep Structured Models

Motivation

Log-Linear Models:

$$p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) = \frac{1}{Z(\mathcal{X}, \mathbf{w})} \exp \{ \langle \mathbf{w}, \psi(\mathcal{X}, \mathcal{Y}) \rangle \}$$

- ▶ Log-linear in the parameters $\mathbf{w} \Rightarrow$ features must do all the heavy lifting
- ▶ Only linear combination of features is learned

Deep Structured Models:

$$p(\mathcal{Y}|\mathcal{X}, \mathbf{w}) = \frac{1}{Z(\mathcal{X}, \mathbf{w})} \exp \{ \psi(\mathcal{X}, \mathcal{Y}, \mathbf{w}) \}$$

- ▶ Potential functions directly parametrized via \mathbf{w}
- ▶ Results in a much more flexible model (ψ can represent, e.g., a neural network)

Deep Structured Models

Negative Log-Likelihood and its Gradient:

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n, \mathbf{w}) - \log \sum_{\mathcal{Y}} \exp \{ \psi(\mathcal{X}^n, \mathcal{Y}, \mathbf{w}) \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\nabla_{\mathbf{w}} \psi(\mathcal{X}^n, \mathcal{Y}^n, \mathbf{w}) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \nabla_{\mathbf{w}} \psi(\mathcal{X}^n, \mathcal{Y}, \mathbf{w}) \right]\end{aligned}$$

- ▶ Similar form as for log-linear models
- ▶ Differences to log-linear model highlighted in red

Deep Structured Models

Negative Log-Likelihood and its Gradient:

$$\begin{aligned}\mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\psi(\mathcal{X}^n, \mathcal{Y}^n, \mathbf{w}) - \log \sum_{\mathcal{Y}} \exp \{ \psi(\mathcal{X}^n, \mathcal{Y}, \mathbf{w}) \} \right] \\ \nabla_{\mathbf{w}} \mathcal{L}(\mathbf{w}) &= -\sum_{n=1}^N \left[\nabla_{\mathbf{w}} \psi(\mathcal{X}^n, \mathcal{Y}^n, \mathbf{w}) - \sum_{\mathcal{Y}} p(\mathcal{Y} | \mathcal{X}^n, \mathbf{w}) \nabla_{\mathbf{w}} \psi(\mathcal{X}^n, \mathcal{Y}, \mathbf{w}) \right]\end{aligned}$$

- Again, sums can be efficiently computed as features decompose

$$\psi(\mathcal{X}, \mathcal{Y}, \mathbf{w}) = (\psi_1(\mathcal{X}, \mathcal{Y}_1, \mathbf{w}), \dots, \psi_K(\mathcal{X}, \mathcal{Y}_K, \mathbf{w}))$$

Deep Structured Models

Algorithm:

- ▶ Forward pass to compute $\psi_k(\mathcal{X}, \mathcal{Y}_k, \mathbf{w})$
- ▶ Backward pass to obtain gradients $\nabla_{\mathbf{w}}\psi(\mathcal{X}^n, \mathcal{Y}, \mathbf{w})$
- ▶ Compute marginals using message passing
- ▶ Update parameters \mathbf{w}

What is the problem with this approach?

- ▶ Very slow as forward and backward pass are required to calculate features and gradients for GM inference in every gradient update step

Alternatives:

- ▶ Interleave learning and inference [Chen et al., ICML 2015], but still slow
- ▶ Unrolled inference (simple, but we loose probabilistic interpretation)

Inference Unrolling

Inference Unrolling

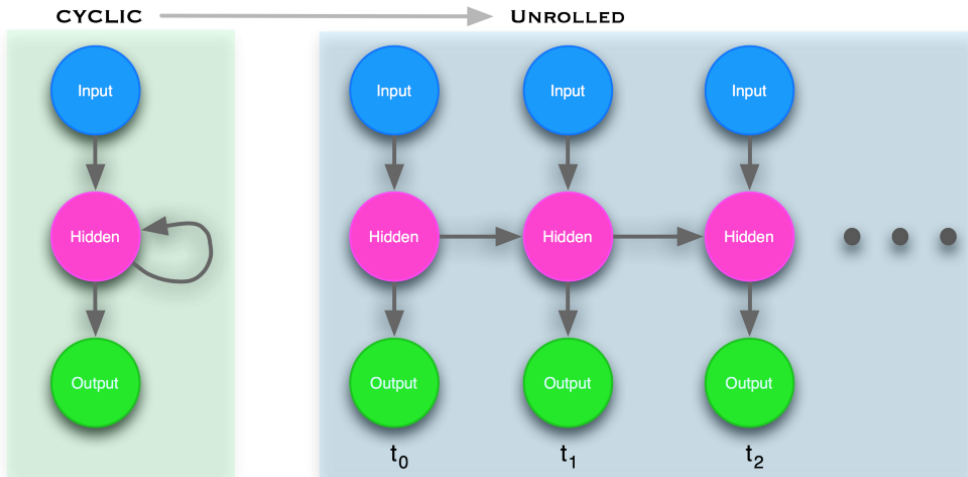
Idea:

- ▶ Consider inference as sequence of small computations
- ▶ “Unroll” a **fixed** number of inference iterations similar to RNN
- ▶ Compute gradients using automatic differentiation

Remarks:

- ▶ Now: empirical risk minimization
- ▶ Thus purely deterministic approach, giving up probabilistic viewpoint
- ▶ But often fast enough for efficient training in deep models
- ▶ Effectively integrates structure of the problem into architecture of the network
- ▶ Can be thought of as a form of regularization (hard constraint)

Inference Unrolling



Automatic Differentiation

Automatic Differentiation:

- Rewrite complicated function as **composition** of simple functions:

$$f = f_0 \circ f_1 \circ \dots \circ f_n$$

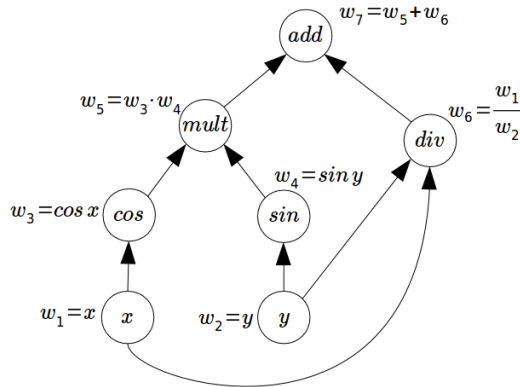
- Each simple function f_k has a simple derivative

- Use chain rule: $\frac{\partial f_0}{\partial f_1} \frac{\partial f_1}{\partial f_2} \dots \frac{\partial f_n}{\partial x}$

- **Example:**

$$f(x, y) = \cos(x) \sin(y) + \frac{x}{y}$$

Computation Graph:

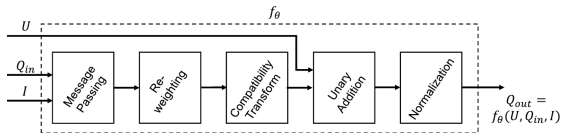


Examples

Conditional Random Fields as Recurrent Neural Networks

$$E(\mathbf{x}) = \sum_i \psi_u(x_i) + \sum_{i < j} \psi_p(x_i, x_j), \quad (1)$$

$$\psi_p(x_i, x_j) = \mu(x_i, x_j) \sum_{m=1}^M w^{(m)} k_G^{(m)}(\mathbf{f}_i, \mathbf{f}_j), \quad (2)$$



Algorithm 1 Mean-field in dense CRFs [29], broken down to common CNN operations.

$Q_i(l) \leftarrow \frac{1}{Z_i} \exp(U_i(l))$ for all i ▷ Initialization

while not converged **do**

$\tilde{Q}_i^{(m)}(l) \leftarrow \sum_{j \neq i} k^{(m)}(\mathbf{f}_i, \mathbf{f}_j) Q_j(l)$ for all m ▷ Message Passing

$\check{Q}_i(l) \leftarrow \sum_m w^{(m)} \tilde{Q}_i^{(m)}(l)$ ▷ Weighting Filter Outputs

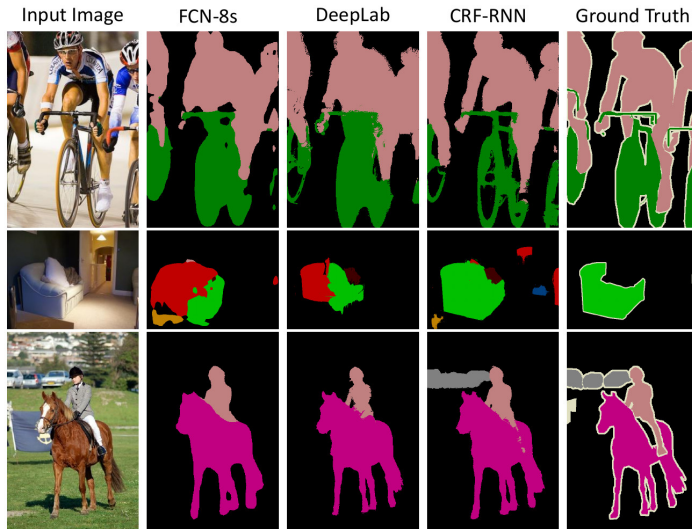
$\hat{Q}_i(l) \leftarrow \sum_{l' \in \mathcal{L}} \mu(l, l') \check{Q}_i(l')$ ▷ Compatibility Transform

$\check{\check{Q}}_i(l) \leftarrow U_i(l) - \hat{Q}_i(l)$ ▷ Adding Unary Potentials

$Q_i \leftarrow \frac{1}{Z_i} \exp(\check{\check{Q}}_i(l))$ ▷ Normalizing

end while

Conditional Random Fields as Recurrent Neural Networks



RayNet: Learning Volumetric 3D Reconstruction

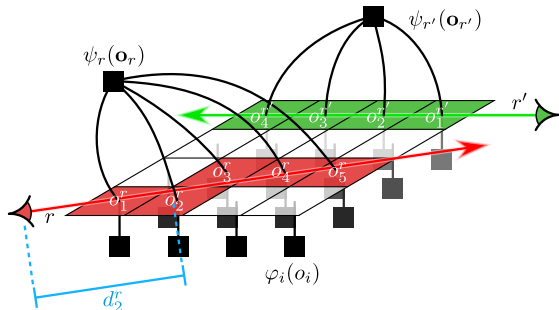
Distribution over voxel occupancies:

$$p(\mathbf{o}) = \frac{1}{Z} \prod_{i \in \mathcal{X}} \underbrace{\varphi_i(o_i)}_{\text{unary}} \prod_{r \in \mathcal{R}} \underbrace{\psi_r(\mathbf{o}_r)}_{\text{ray}}$$

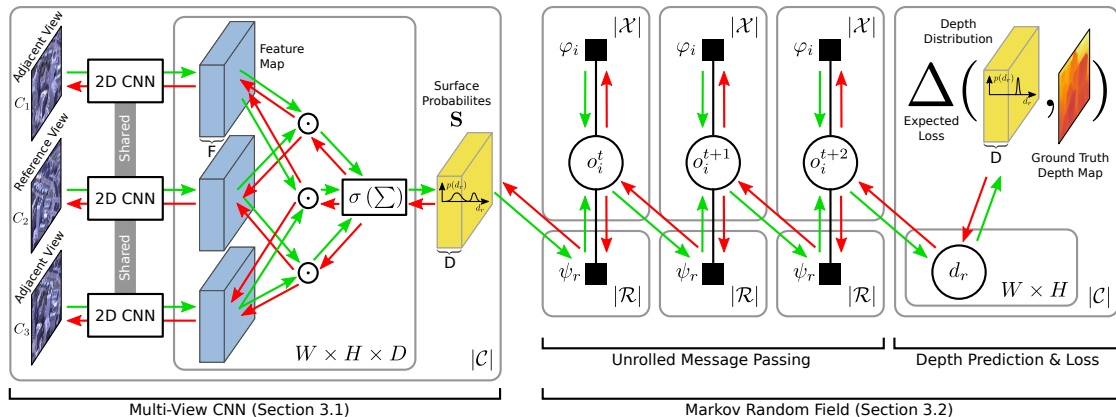
$$\varphi_i(o_i) = \gamma^{o_i} (1 - \gamma)^{1-o_i}$$

$$\psi_r(\mathbf{o}_r) = \sum_{i=1}^{N_r} o_i^r \prod_{j < i} (1 - o_j^r) s_i^r$$

Corresponding factor graph:



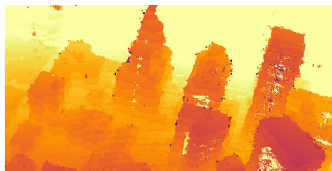
RayNet: Learning Volumetric 3D Reconstruction



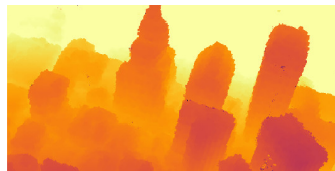
RayNet: Learning Volumetric 3D Reconstruction



(a) Image



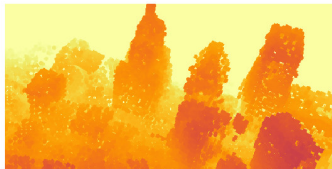
(b) Ours (CNN)



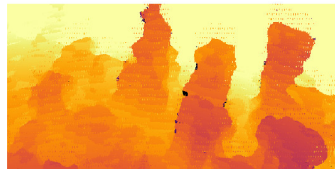
(c) Ours (CNN+MRF)



(d) ZNCC



(e) Ulusoy et al. [35]



(f) Hartmann et al. [14]