

Learning Deep Structured Models

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University of Toronto

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Current Status of your Field?



- ① Part I: Deep learning
- ② Part II: Deep Structured Models

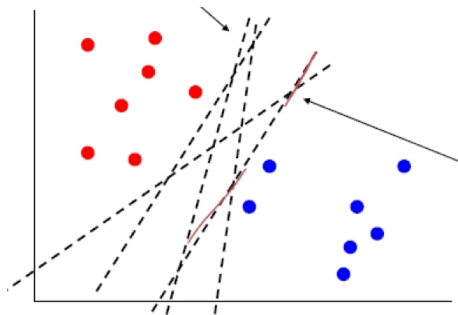
Part I: Deep Learning

- Supervised models
- Unsupervised learning (will not talk about this today)
- Generative models (will not talk about this today)

Binary Classification

- Given inputs \mathbf{x} , and outputs $t \in \{-1, 1\}$
- We want to fit a hyperplane that divides the space into half

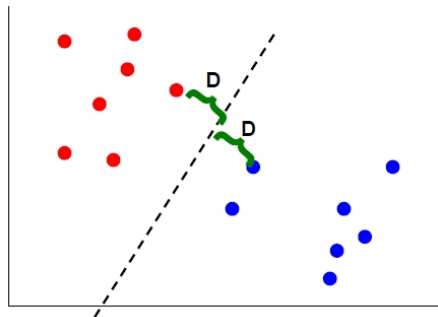
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SVMs try to maximize the margin

Non-linear Predictors

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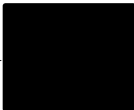
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- **Deep Learning:** Learn parametric non-linear functions

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Supervised Learning: Examples

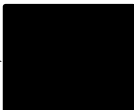
Classification



"dog"

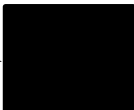
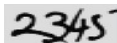
classification

Denosing



regression

OCR



"2 3 4 5"

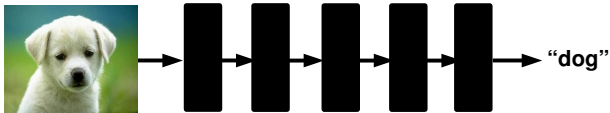
structured prediction

3

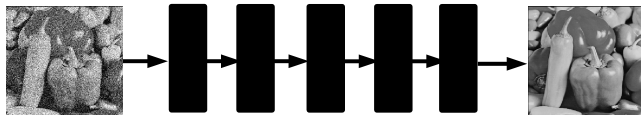
Ranzato 

Supervised Deep Learning

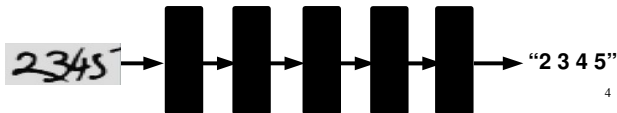
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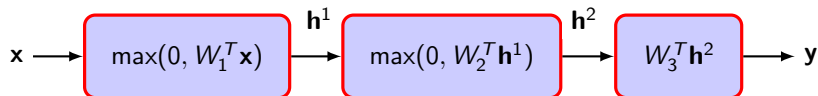
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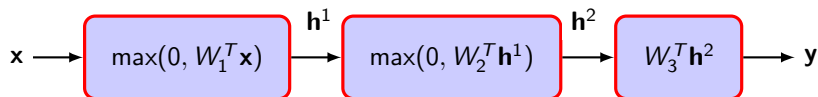
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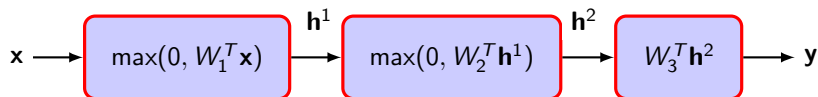
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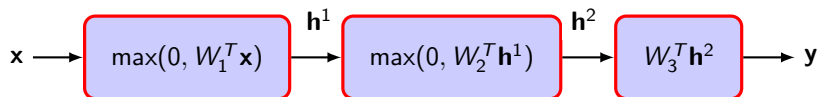
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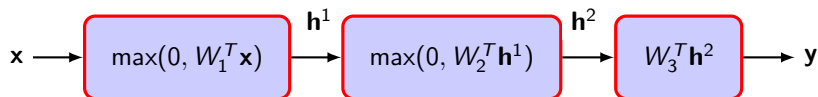
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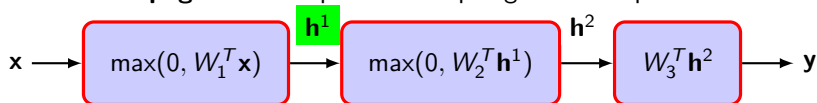
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- h^i is the i -th hidden layer
- W^i are the parameters of the i -th layer

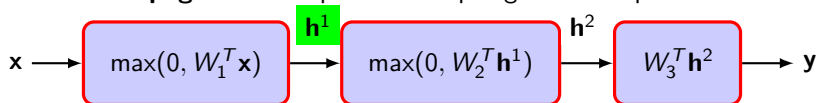
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- **Forward Propagation:** compute the output given the input



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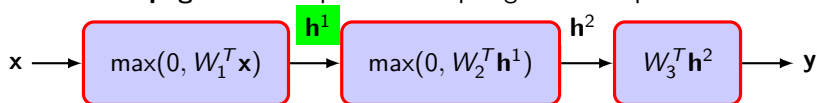
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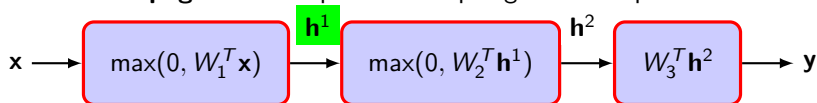
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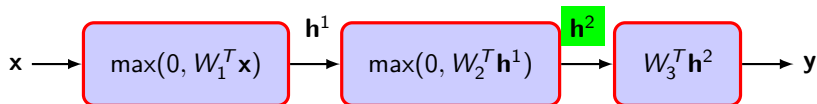


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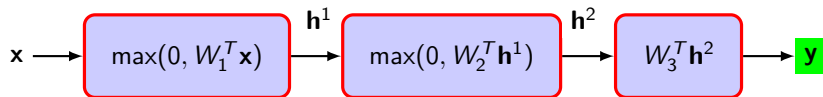
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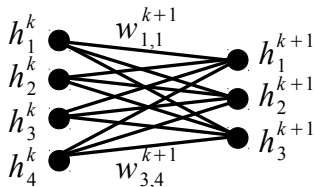
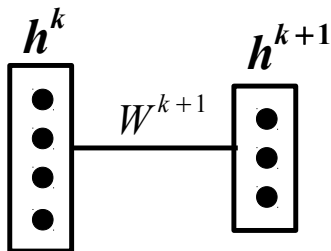
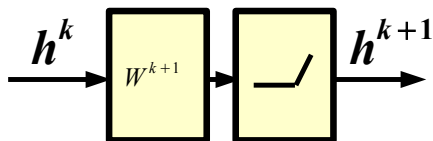
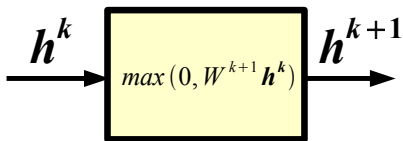
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$$\mathbf{y} = \max(0, W^3 \mathbf{h}^2 + b^3)$$

Alternative Graphical Representation



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Relu Interpretation

- Piece-wise linear tiling: mapping is locally linear.

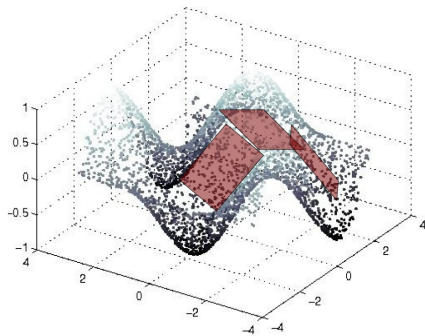


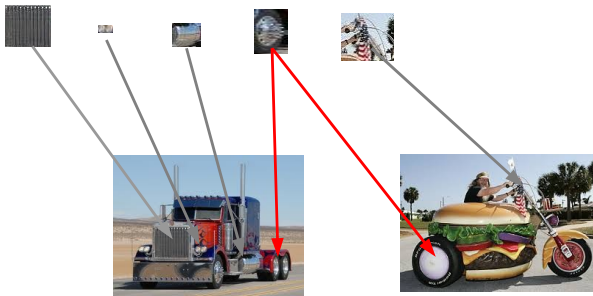
Figure : by M. Ranzato

Why Hierarchical?

Interpretation

[1 1 0 0 0 1 0 **1** 0 0 0 0 1 1 0 1...] motorbike

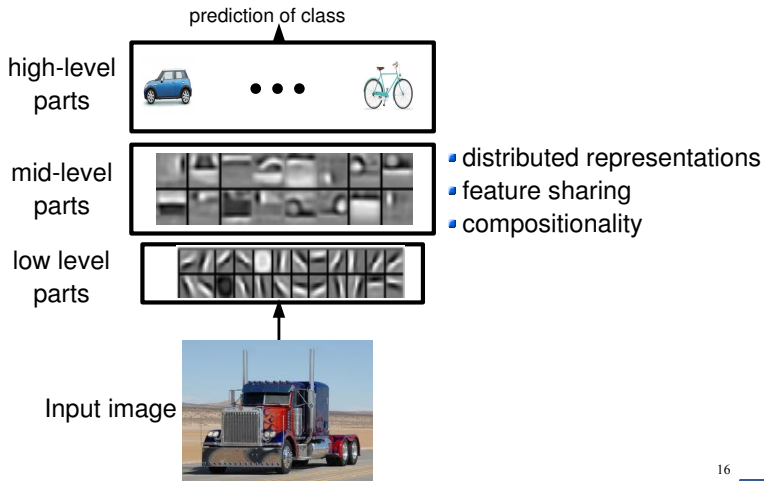
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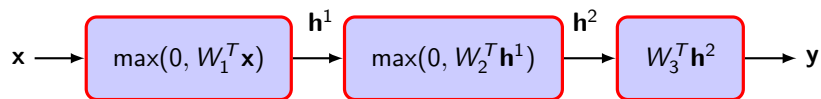


Lee et al. "Convolutional DBN's ..." ICML 2009

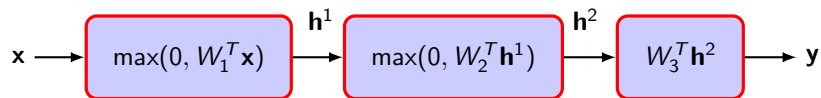
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Learning

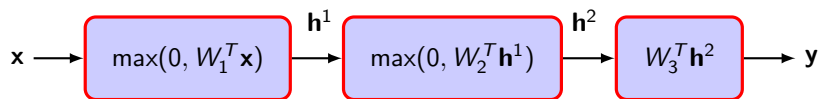


Learning



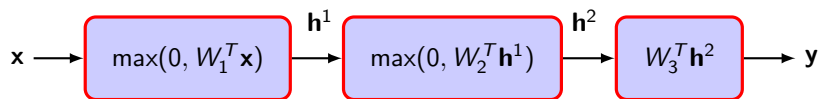
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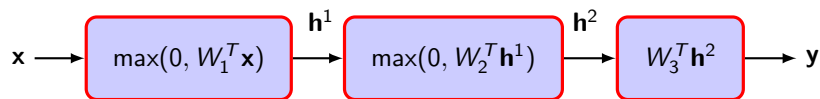


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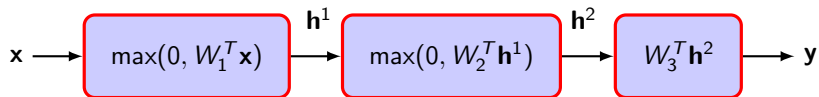
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with N number of examples, \mathcal{R} a regularizer, and \mathbf{w} contains all parameters

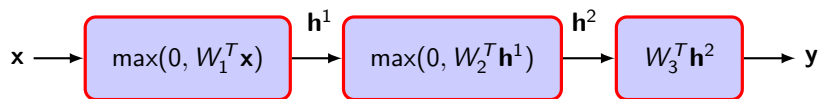


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- The **task loss**: how we are going to evaluate at test time

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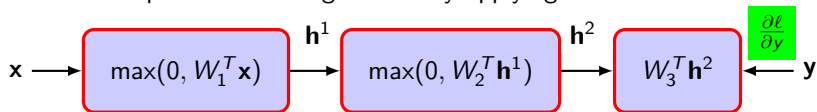
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- Use gradient descent to train the network

$$\min_{\mathbf{w}} \frac{1}{N} \sum_i \ell(\mathbf{w}, \mathbf{x}^{(i)}, t^{(i)}) + \mathcal{R}(\mathbf{w})$$

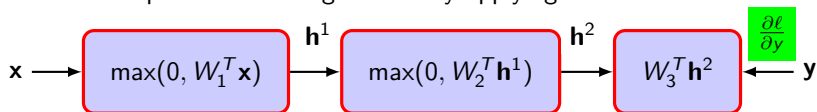
Backpropagation

- Efficient computation of the gradients by applying the chain rule



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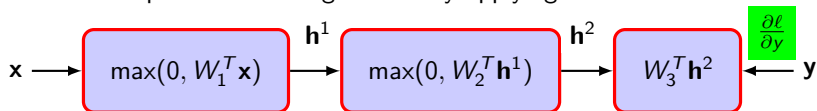
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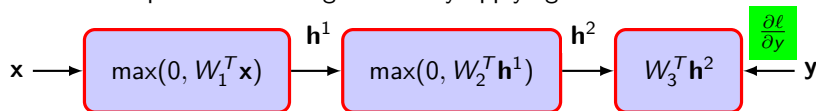


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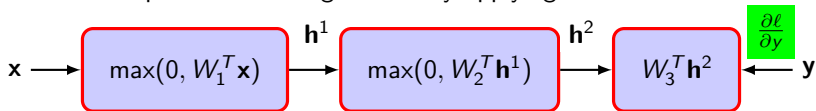
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$$\frac{\partial \ell}{\partial y} = p(c | \mathbf{x}) - t$$

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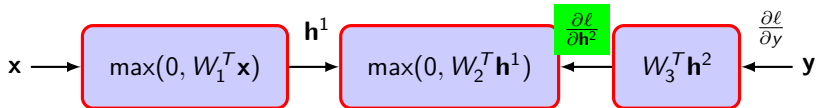
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- Note that the **forward pass** is necessary to compute $\frac{\partial \ell}{\partial y}$

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- Efficient computation of the gradients by applying the chain rule

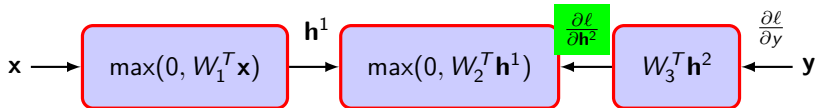


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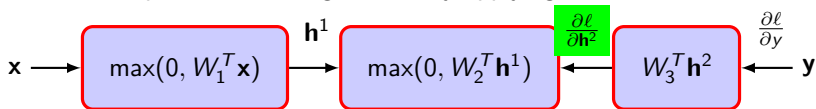
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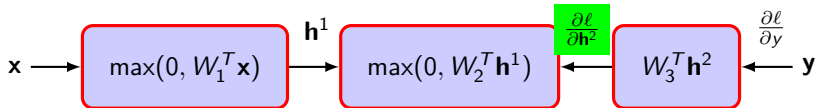
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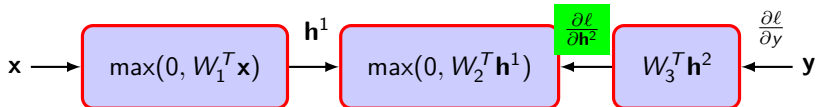
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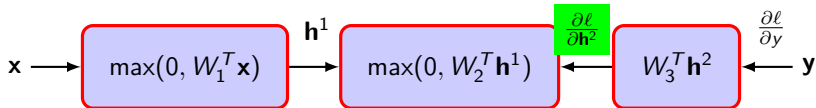
$$\frac{\partial \ell}{\partial \mathbf{y}} = p(c|\mathbf{x}) - t$$

- Given $\frac{\partial \ell}{\partial \mathbf{y}}$ if we can compute the Jacobian of each module

$$\frac{\partial \ell}{\partial W^3} = \frac{\partial \ell}{\partial \mathbf{y}} \frac{\partial \mathbf{y}}{\partial W^3} = (p(c|\mathbf{x}) - t)(\mathbf{h}^2)^T$$

Backpropagation

- Efficient computation of the gradients by applying the chain rule



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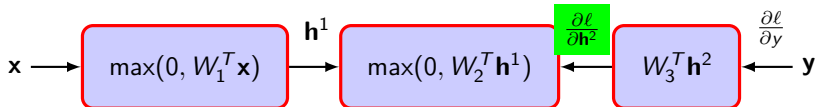
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$$\frac{\partial \ell}{\partial \mathbf{h}^2} =$$

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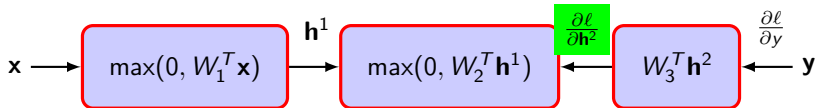
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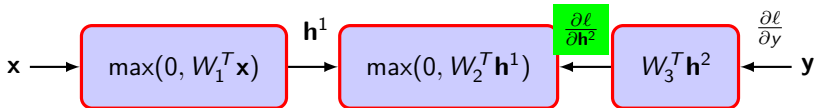
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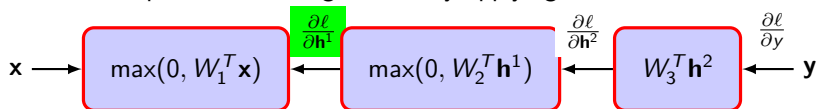
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- Need to compute gradient w.r.t. inputs and parameters in each layer

Backpropagation

- Efficient computation of the gradients by applying the chain rule

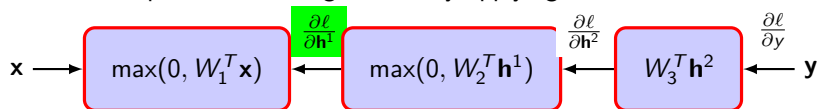


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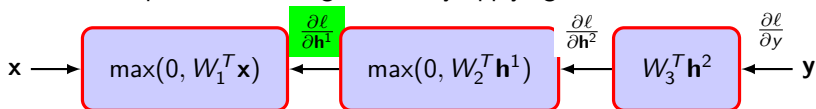
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Backpropagation

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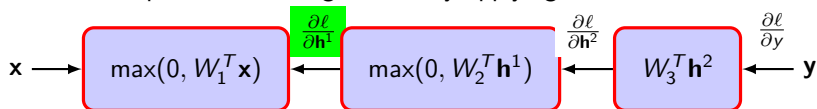
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Backpropagation

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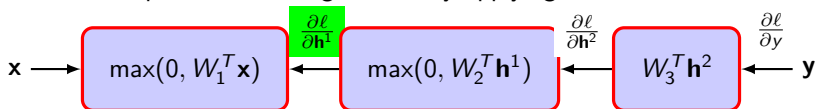
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Backpropagation

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Gradient Descent

- Gradient descent is a first order method, where one takes steps proportional to the negative of the gradient of the function at the current point

$$\mathbf{x}_{n+1} = \mathbf{x}_n - \gamma_n \nabla F(\mathbf{x}_n)$$

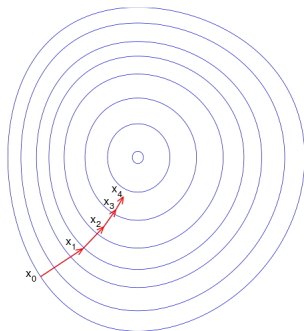
- Example: $f(x) = x^4 - 3x^3 + 2$

```
x_old = 0
x_new = 6 # The algorithm starts at x=6
gamma = 0.01 # step size
precision = 0.00001

def f_derivative(x):
    return 4 * x**3 - 9 * x**2

while abs(x_new - x_old) > precision:
    x_old = x_new
    x_new = x_old - gamma * f_derivative(x_old)

print("Local minimum occurs at", x_new)
```



Learning via Gradient Descent

- Use gradient descent to train the network

$$\min_{\mathbf{w}} \frac{1}{N} \sum_{i=1}^N \ell(\mathbf{w}, \mathbf{x}^{(i)}, t^{(i)}) + \mathcal{R}(\mathbf{w})$$

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- Recall that the backward pass requires the forward pass first

Toy Code (Matlab): Neural Net Trainer

% F-PROP

```
for i = 1 : nr_layers - 1
    [h{i} jac{i}] = nonlinearity(W{i} * h{i-1} + b{i});
end
h{nr_layers-1} = W{nr_layers-1} * h{nr_layers-2} + b{nr_layers-1};
prediction = softmax(h{1-1});
```

% CROSS ENTROPY LOSS

```
loss = - sum(sum(log(prediction) .* target)) / batch_size;
```

% B-PROP

```
dh{1-1} = prediction - target;
for i = nr_layers - 1 : -1 : 1
    Wgrad{i} = dh{i} * h{i-1}';
    bgrad{i} = sum(dh{i}, 2);
    dh{i-1} = (W{i}' * dh{i}) .* jac{i-1};
end
```

% UPDATE

```
for i = 1 : nr_layers - 1
    W{i} = W{i} - (lr / batch_size) * Wgrad{i};
    b{i} = b{i} - (lr / batch_size) * bgrad{i};
end
```

Dealing with Big Data

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- Instead approximate the gradient with a mini-batch (subset of examples)

$$\frac{1}{N} \sum_{i=1}^N \nabla \ell(\mathbf{w}, \mathbf{x}^{(i)}, t^{(i)}) \approx \sum_{i \in \mathcal{S}} \frac{1}{|\mathcal{S}|} \nabla \ell(\mathbf{w}, \mathbf{x}^{(i)}, t^{(i)})$$

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- This is called **stochastic gradient descent**

Stochastic Gradient Descent with Momentum

- Stochastic Gradient Descent update

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- Many other variants exist

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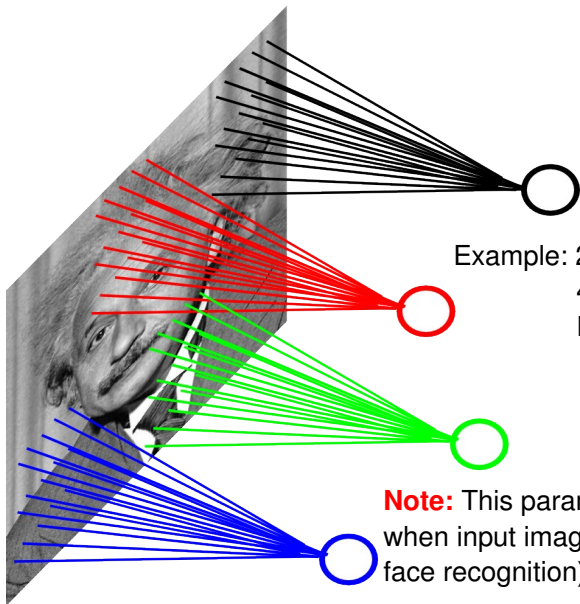
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- We can use a **locally connected layer**
- This is good when the **input is registered**

Locally Connected Layer

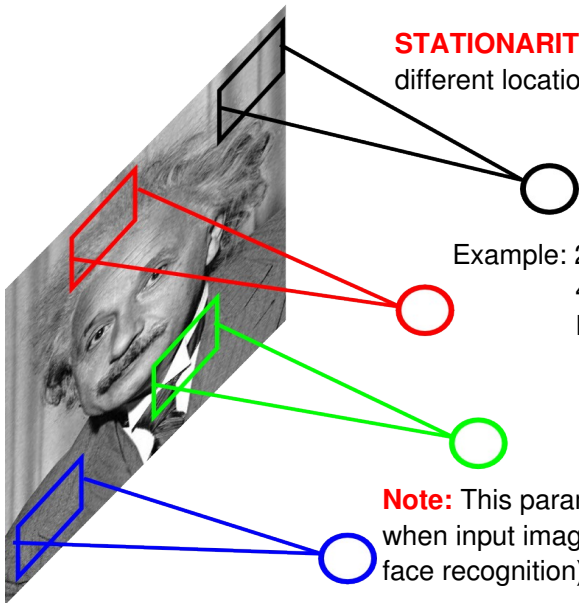


Example: 200x200 image
40K hidden units
Filter size: 10x10
4M parameters

Note: This parameterization is good when input image is registered (e.g., face recognition).³⁴

Locally Connected Layer

STATIONARITY? Statistics is similar at different locations

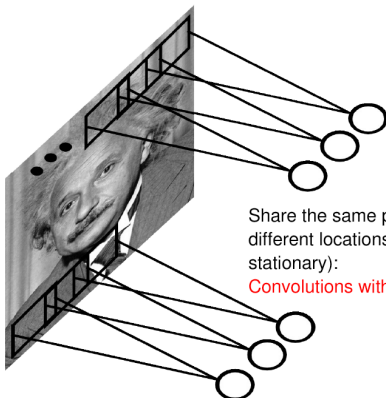


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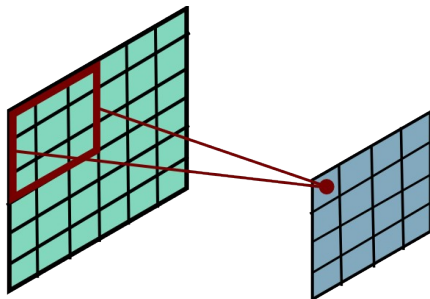
Convolutional Neural Net

- Idea: statistics are similar at different locations (Lecun 1998)
- Connect each hidden unit to a small input patch and share the weight across space
- This is called a **convolution layer** and the network is a **convolutional network**



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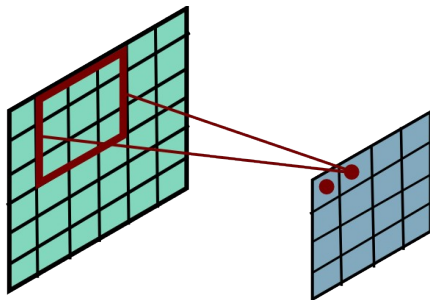
Convolutional Layer



Ranzato 

$$h_j^n = \max(0, \sum_{k=1}^K h_k^{n-1} * w_{jk}^n)$$

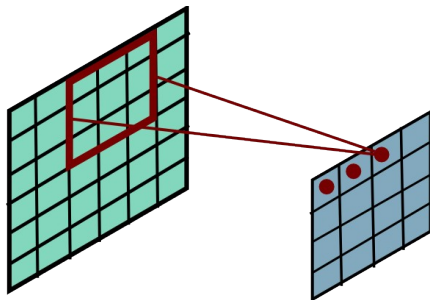
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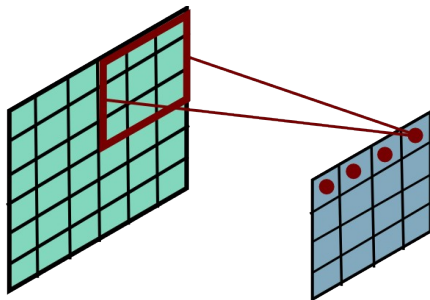
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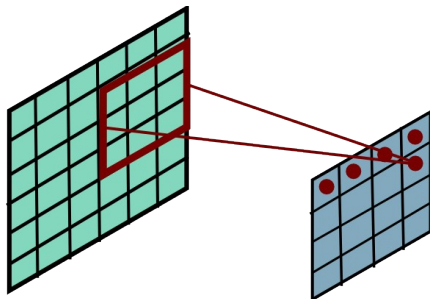
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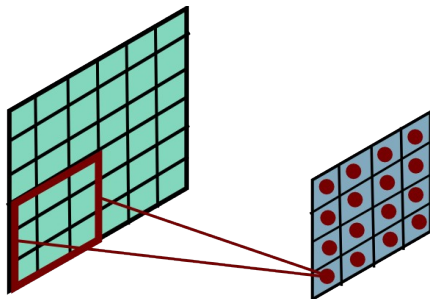
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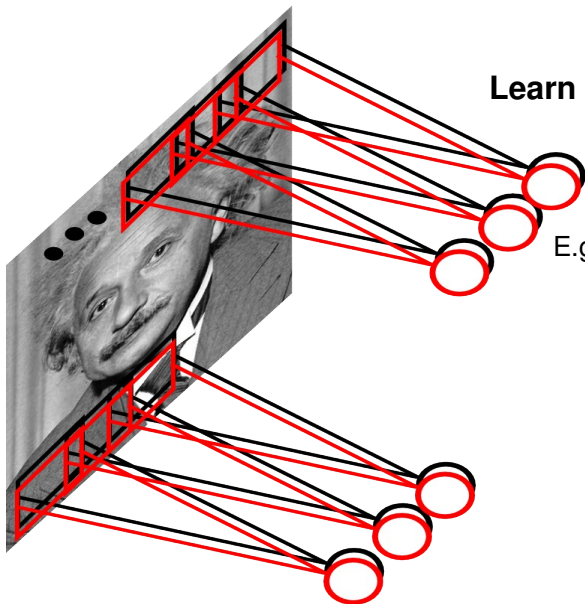
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Convolutional Layer

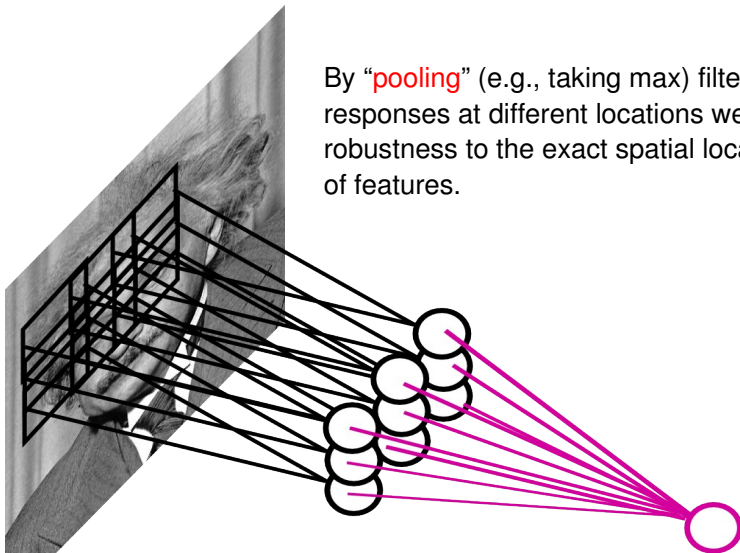


Learn **multiple filters.**

E.g.: 200x200 image
100 Filters
Filter size: 10x10
10K parameters

Pooling Layer

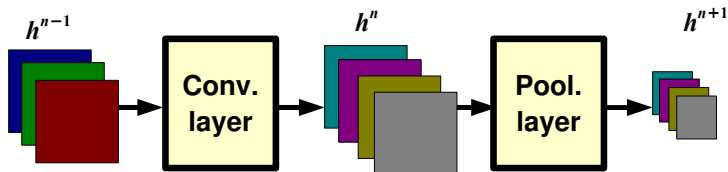
By “pooling” (e.g., taking max) filter responses at different locations we gain robustness to the exact spatial location of features.



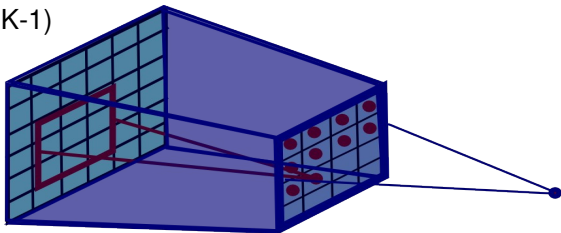
Pooling Options

- **Max Pooling:** return the maximal argument
- **Average Pooling:** return the average of the arguments
- Other types of pooling exist: L_2 pooling

Pooling Layer: Receptive Field Size



If convolutional filters have size $K \times K$ and stride 1, and pooling layer has pools of size $P \times P$, then each unit in the pooling layer depends upon a patch (at the input of the preceding conv. layer) of size: $(P+K-1) \times (P+K-1)$



Now let's make this very deep

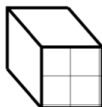
Convolutional Neural Networks (CNN)

- Remember from your image processing / computer vision course about filtering?

Input "image"



Filter



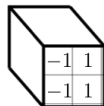
Convolutional Neural Networks (CNN)

- If our filter was $[-1, 1]$, we got a vertical edge detector

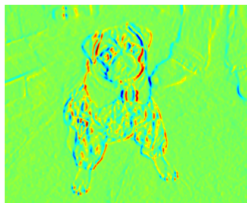
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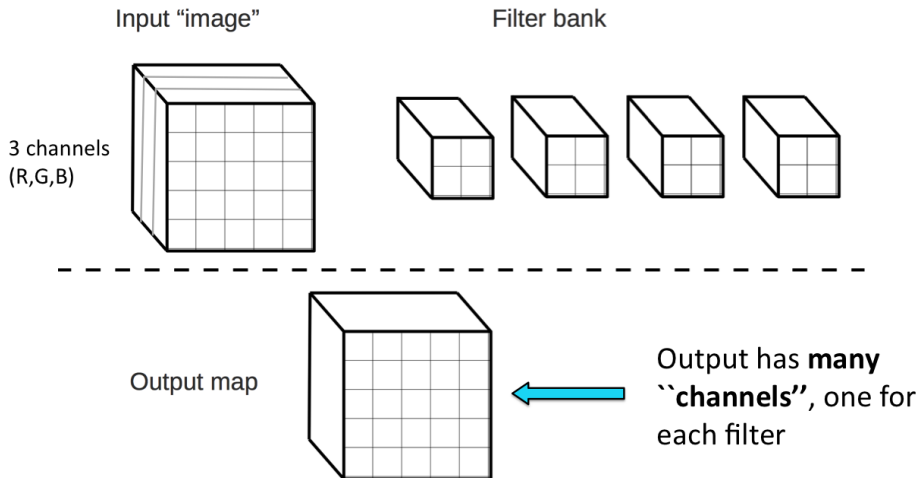


Output map



Convolutional Neural Networks (CNN)

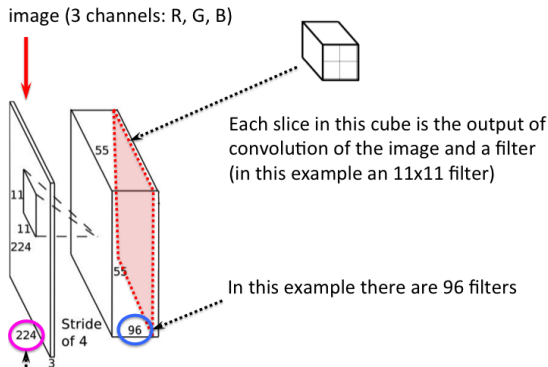
- Now imagine we want to have many filters (e.g., vertical, horizontal, corners, one for dots). We will use a **filterbank**.



[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- So applying a filterbank to an image yields a cube-like output, a 3D matrix in which each slice is an output of convolution with one filter.



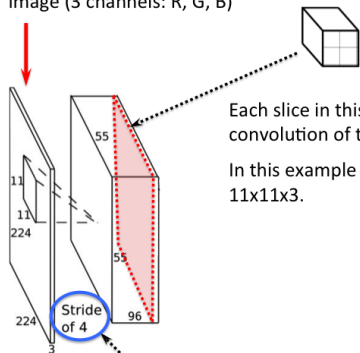
In this example our network will always expect a 224x224x3 image.

[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- So applying a filterbank to an image yields a cube-like output, a 3D matrix in which each slice is an output of convolution with one filter.

image (3 channels: R, G, B)



Each slice in this cube is the output of convolution of the image and a filter.

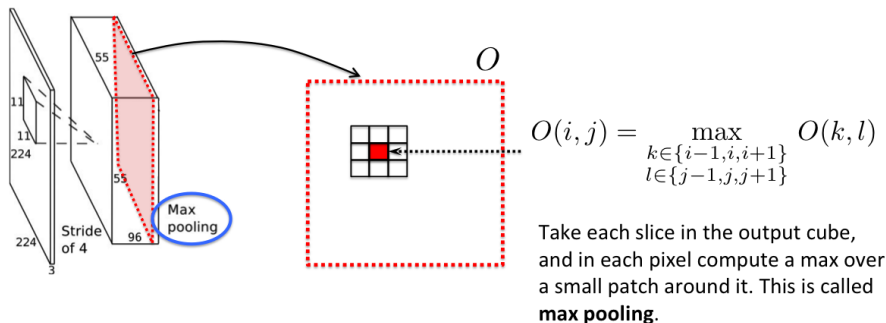
In this example the filter size is $11 \times 11 \times 3$.

We don't do convolution in every pixel, but in every 4th pixel (in x and y direction)

[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

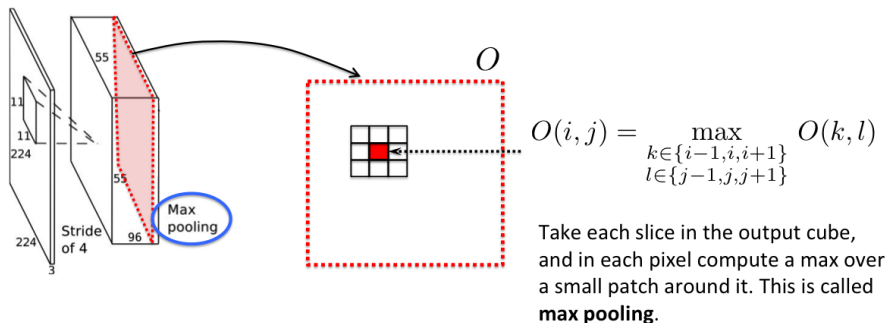
- Do some additional tricks. A popular one is called **max pooling**. Any idea why you would do this?



[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

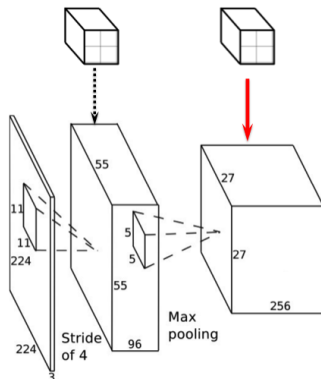
- Do some additional tricks. A popular one is called **max pooling**. Any idea why you would do this? To get **invariance to small shifts in position**.



[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- Now add another “layer” of filters. For each filter again do convolution, but this time with the output cube of the previous layer.



Add one more layer of filters

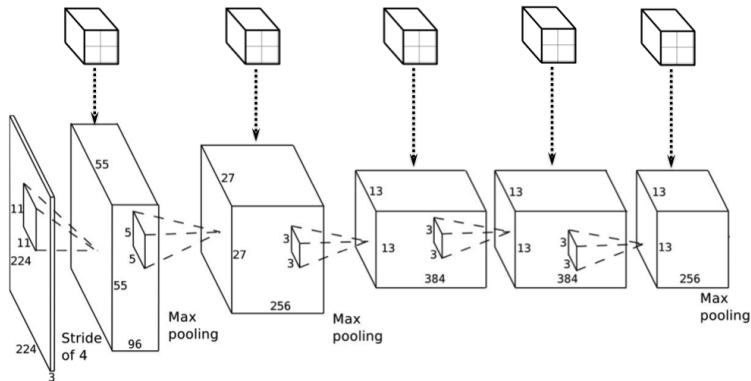
These filters are convolved with the output of the previous layer. The results of each convolution is again a slice in the cube on the right.

What is the dimension of each of these filters?

[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- Keep adding a few layers. Any idea what's the purpose of more layers? Why can't we just have a full bunch of filters in one layer?



Do it recursively
Have multiple "layers"

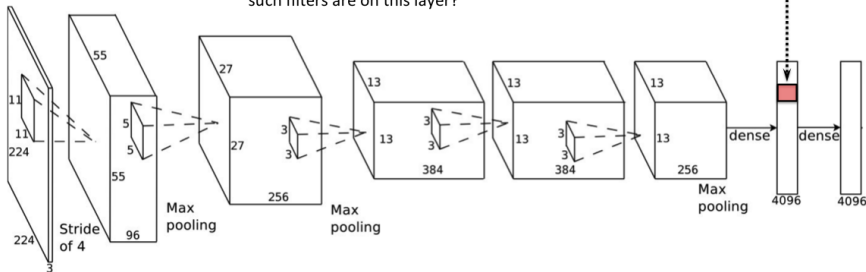
[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- In the end add one or two **fully** (or **densely**) connected layers. In this layer, we don't do convolution we just do a dot-product between the "filter" and the output of the previous layer.

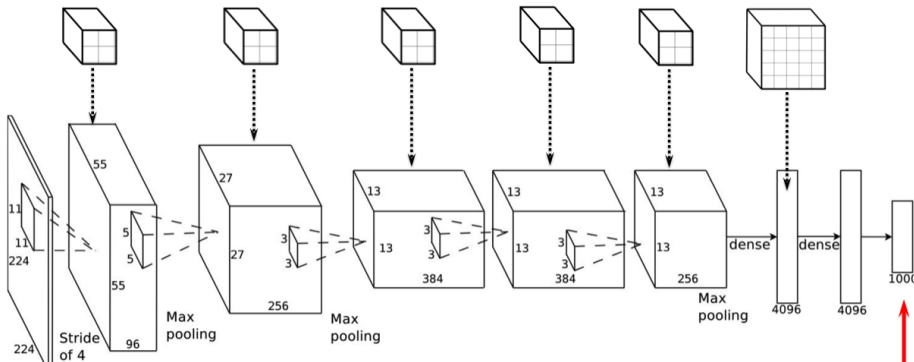
In the top, most networks add a "densely" connected layer. You can think of this as a filter, and the output value is a dot product between the filter and the output cube of the previous layer.

What are the dimensions of this filter in this example? How many such filters are on this layer?



Convolutional Neural Networks (CNN)

- Add one final layer: a **classification** layer. Each dimension of this vector tells us the probability of the input image being of a certain class.



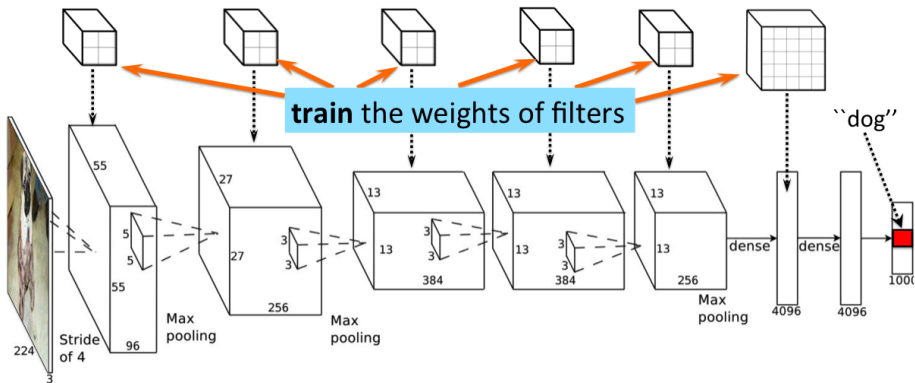
Add a **classification** "layer".

For an input image, the value in a particular dimension of this vector tells you the probability of the corresponding object class.

[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

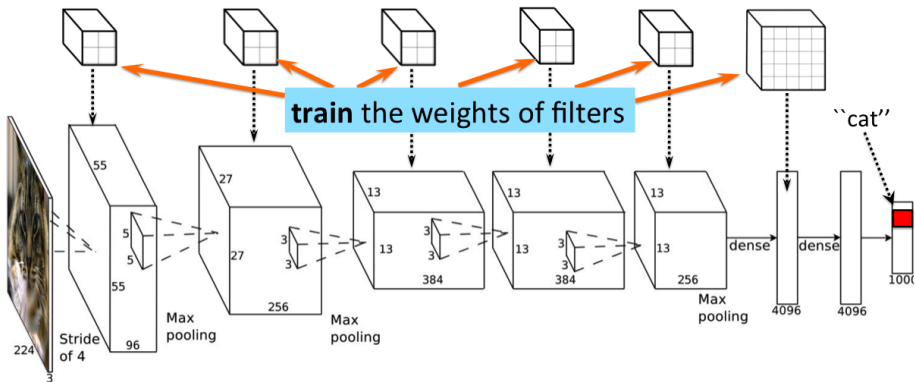
- The trick is to not hand-fix the weights, but to **train** them. Train them such that when the network sees a picture of a dog, the last layer will say "dog".



[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

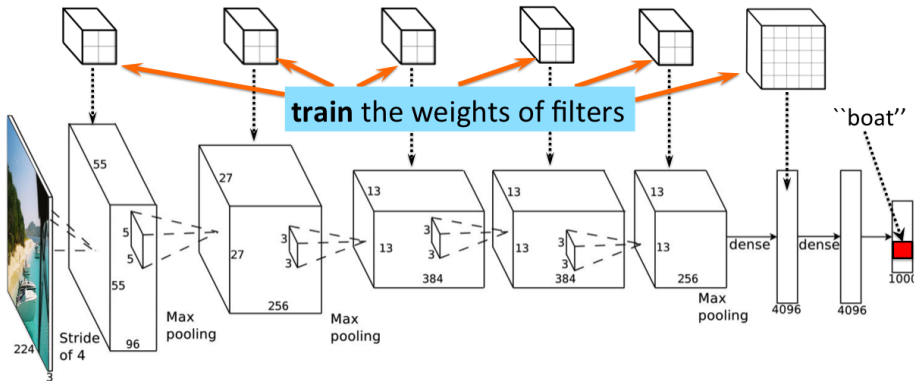
- Or when the network sees a picture of a cat, the last layer will say "cat".



[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Convolutional Neural Networks (CNN)

- Or when the network sees a picture of a boat, the last layer will say “boat”... The more pictures the network sees, the better.



Train on **lots** of examples. Millions. Tens of millions. Wait a week for training to finish.

Share your network (the weights) with others who are not fortunate enough with GPU power.

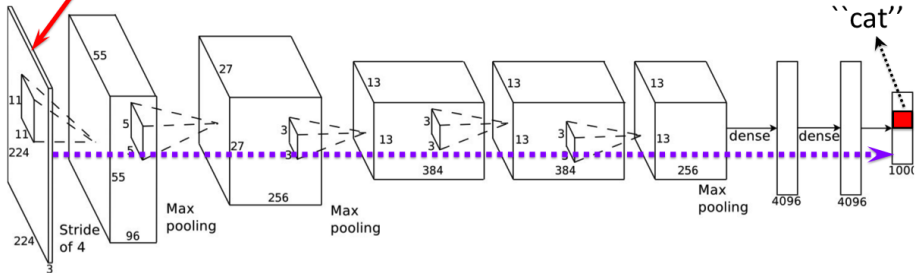
[Slide Credit: Sanja Fidler, Pic adopted from: A. Krizhevsky]

Classification

- Once trained we feed in an image or a crop, run through the network, and read out the class with the highest probability in the last (classif) layer.



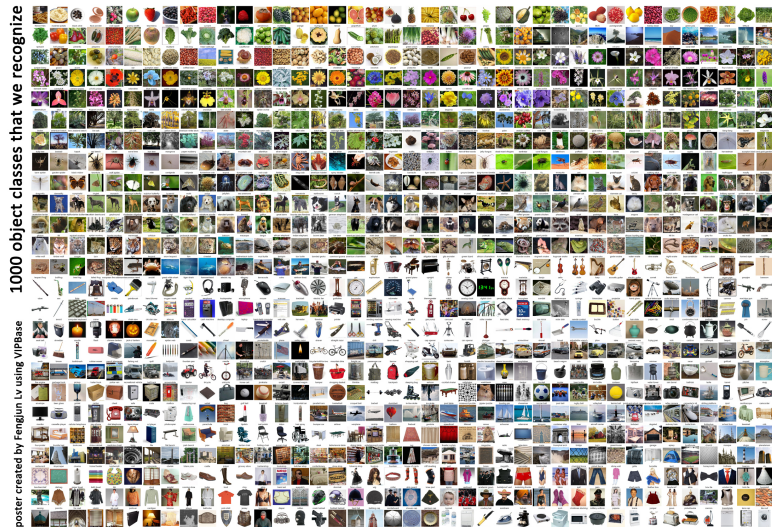
What's the class of this object?



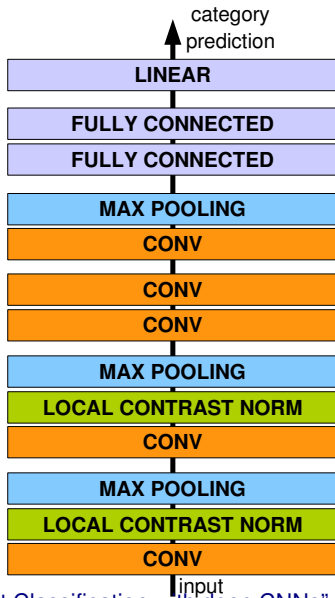
[Slide Credit: Sanja Fidler]

Classification Performance

- Imagenet, main challenge for object classification: <http://image-net.org/>
- 1000 classes, 1.2M training images, 150K for test



Architecture for Classification



Krizhevsky et al. "ImageNet Classification with deep CNNs" NIPS 2012

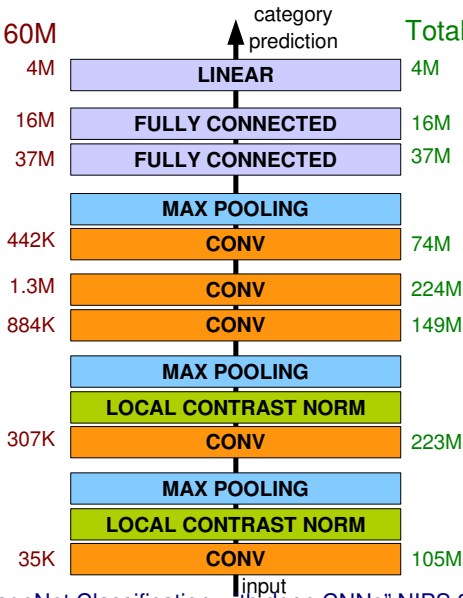
95

Ranzato  

Architecture for Classification

Total nr. params: 60M

Total nr. flops: 832M



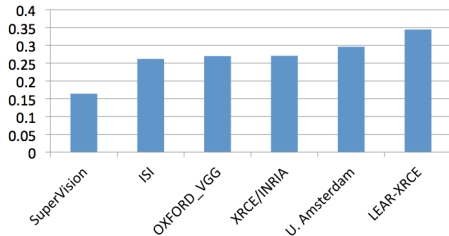
Krizhevsky et al. "ImageNet Classification with deep CNNs" NIPS 2012

96 Ranzato  

The 2012 Computer Vision Crisis

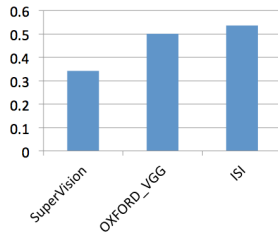


Error (5 predictions)



(Classification)

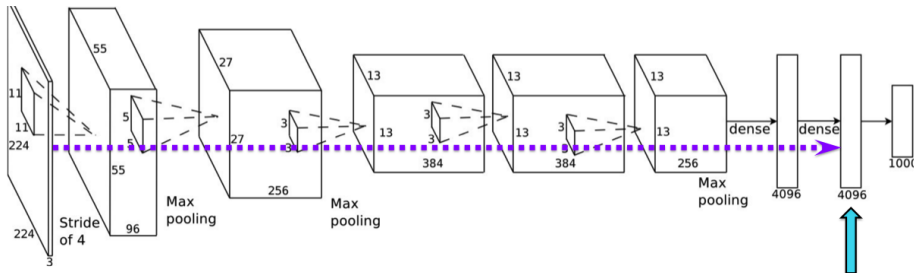
Error (5 predictions)



(Detection)

Neural Networks as Descriptors

- What vision people like to do is take the already trained network (avoid one week of training), and remove the last classification layer. Then take the top remaining layer (the 4096 dimensional vector here) and use it as a descriptor (feature vector).

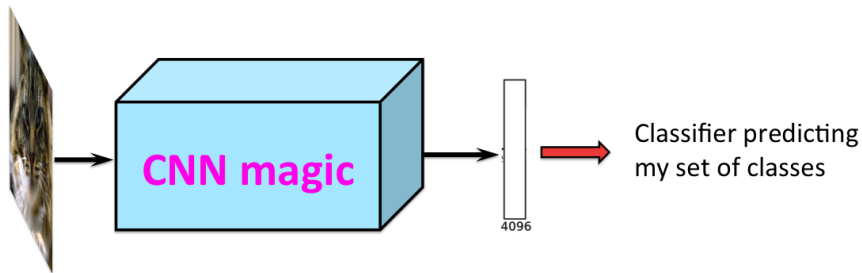


Vision people are mainly interested in this vector. **You can use it as a descriptor.** A much better descriptor than SIFT, etc.

Train your own classifier on top for your choice of classes.

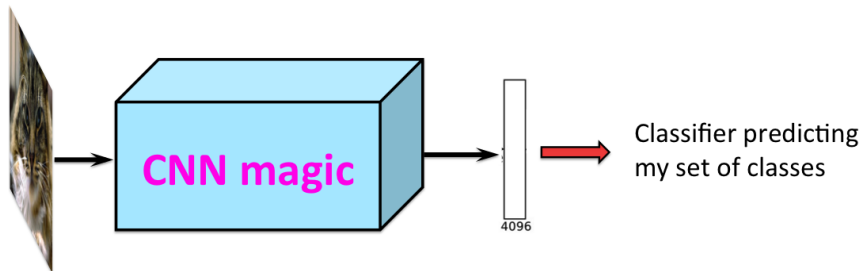
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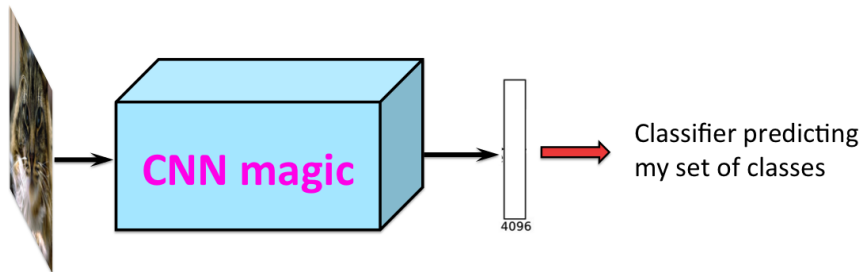
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- This is quite hacky, but works miraculously well.

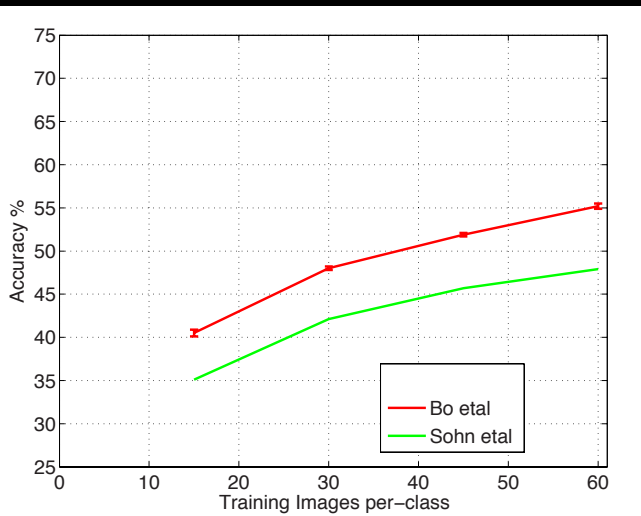


Neural Networks as Descriptors

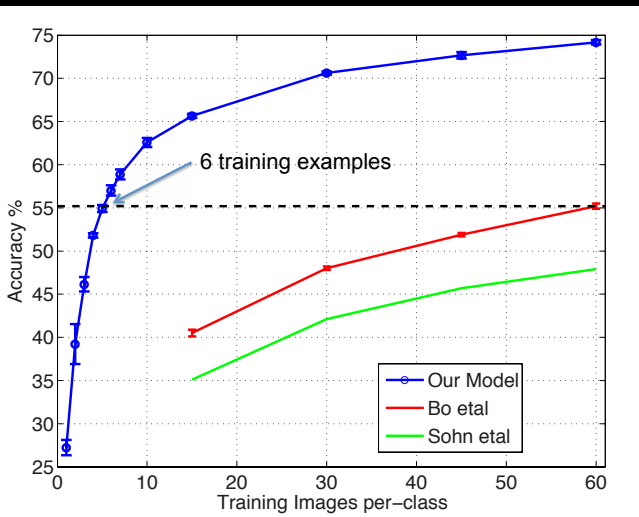
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- Now train your own classifier on top of these features for arbitrary classes.
- This is quite hacky, but works miraculously well.
- Everywhere where we were using SIFT (or anything else), you can use NNs.



Zeiler & Fergus, *Visualizing and Understanding Convolutional Networks*, arXiv 1311.2901, 2013

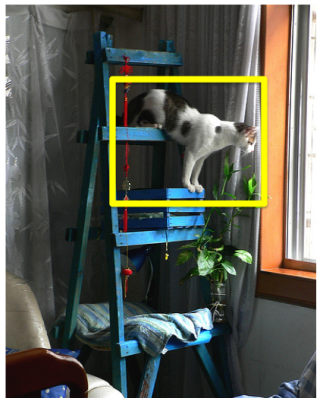


Zeiler & Fergus, *Visualizing and Understanding Convolutional Networks*, arXiv 1311.2901, 2013



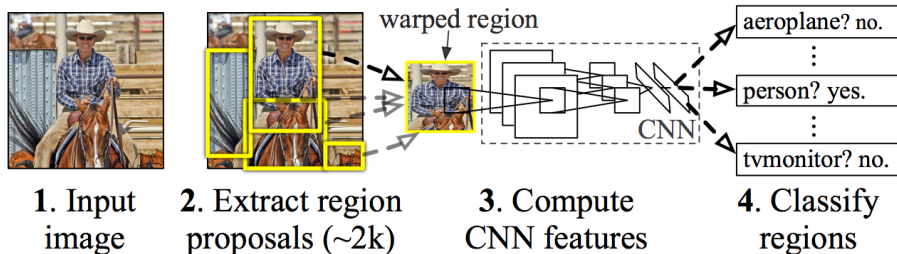
And Detection?

- For classification we feed in the full image to the network. But how can we perform detection?



Find all objects of interest in this image!

R-CNN: *Regions with CNN features*



- Extract object proposals with bottom up grouping
- and then classify them using your big net

Detection Performance

- **PASCAL VOC challenge:** <http://pascallin.ecs.soton.ac.uk/challenges/VOC/>.



Figure : PASCAL has 20 object classes, 10K images for training, 10K for test

Detection Performance a Year Ago: 40.4%

A year ago, no networks:

- Results on the main recognition benchmark, the **PASCAL VOC challenge**.

| | mean | aero plane | bicycle | bird | boat | bottle | bus | car | cat | chair | cow | dining table | dog | horse | motor bike | person | potted plant | sheep | sofa | train | tv/ monitor | submission date |
|--|------|------------|---------|------|------|--------|------|------|------|-------|------|--------------|------|-------|------------|--------|--------------|-------|------|-------|-------------|-----------------|
| segDPM [7] | 40.4 | 61.4 | 53.4 | 25.6 | 25.2 | 35.5 | 51.7 | 50.6 | 50.8 | 19.3 | 33.8 | 26.8 | 40.4 | 48.3 | 54.4 | 47.1 | 14.8 | 38.7 | 35.0 | 52.8 | 43.1 | 24-Feb-2014 |
| Boosted HOG-LBP and multi-context (LC, EGC, HLC) [7] | 36.8 | 53.3 | 55.3 | 19.2 | 21.0 | 30.0 | 54.5 | 46.7 | 41.2 | 20.0 | 31.5 | 20.8 | 30.3 | 48.6 | 55.3 | 46.5 | 10.2 | 34.4 | 26.6 | 50.3 | 40.3 | 29-Aug-2010 |
| MITUCLA_Hierarchy [7] | 36.0 | 54.3 | 48.5 | 15.7 | 19.2 | 29.2 | 55.6 | 43.5 | 41.7 | 16.9 | 28.5 | 26.7 | 30.9 | 48.3 | 55.0 | 41.7 | 9.7 | 35.8 | 30.8 | 47.2 | 40.8 | 30-Aug-2010 |
| HOGLBP_context_classification_rescore_v2 [7] | 34.2 | 49.1 | 52.4 | 17.8 | 12.0 | 30.6 | 53.5 | 32.8 | 37.3 | 17.7 | 30.6 | 27.7 | 29.5 | 51.9 | 56.3 | 44.2 | 9.6 | 14.8 | 27.9 | 49.5 | 38.4 | 30-Aug-2010 |
| LSVM-MDPM [7] | 33.7 | 52.4 | 54.3 | 13.0 | 15.6 | 35.1 | 54.2 | 49.1 | 31.8 | 15.5 | 26.2 | 13.5 | 21.5 | 45.4 | 51.6 | 47.5 | 9.1 | 35.1 | 19.4 | 46.6 | 38.0 | 26-Aug-2010 |
| UOCTTL_LSVM_MDPM [7] | 33.4 | 49.2 | 53.8 | 13.1 | 15.3 | 35.5 | 53.4 | 49.7 | 27.0 | 17.2 | 28.8 | 14.7 | 17.8 | 46.4 | 51.2 | 47.7 | 10.8 | 34.2 | 20.7 | 43.8 | 38.3 | 21-May-2012 |
| Detection Monkey [7] | 32.9 | 56.7 | 39.8 | 16.8 | 12.2 | 13.8 | 44.9 | 36.9 | 47.7 | 12.1 | 26.9 | 26.5 | 37.2 | 42.1 | 51.9 | 25.7 | 12.1 | 37.8 | 33.0 | 41.5 | 41.7 | 30-Aug-2010 |
| RM^2C [7] | 32.8 | 49.8 | 50.6 | 15.1 | 15.5 | 28.5 | 51.1 | 42.2 | 30.5 | 17.3 | 28.3 | 12.4 | 26.0 | 45.6 | 51.8 | 41.4 | 12.6 | 30.4 | 26.1 | 44.0 | 37.6 | 29-Oct-2013 |
| UOCTTL_LSVM_MDPM [7] | 32.2 | 48.2 | 52.2 | 14.8 | 13.8 | 28.7 | 53.2 | 44.9 | 26.0 | 18.4 | 24.4 | 13.7 | 23.1 | 45.8 | 50.5 | 43.7 | 9.8 | 31.1 | 21.5 | 44.4 | 35.7 | 11-May-2012 |
| GroupLoc [7] | 31.9 | 58.4 | 39.6 | 18.0 | 13.3 | 11.1 | 46.4 | 37.8 | 43.9 | 10.3 | 27.5 | 20.8 | 36.0 | 39.4 | 48.5 | 22.9 | 13.0 | 36.9 | 30.5 | 41.2 | 41.9 | 30-Aug-2010 |
| UOCTTL_LSVM_MDPM [7] | 29.6 | 45.6 | 49.0 | 11.0 | 11.6 | 27.2 | 50.5 | 43.1 | 23.6 | 17.2 | 23.2 | 10.7 | 20.5 | 42.5 | 44.5 | 41.3 | 8.7 | 29.0 | 18.7 | 40.0 | 34.5 | 21-May-2012 |
| Bonn_FGT_Segm [7] | 26.1 | 52.7 | 33.7 | 13.2 | 11.0 | 14.2 | 43.2 | 31.9 | 35.6 | 5.8 | 25.4 | 14.4 | 20.6 | 38.1 | 41.7 | 25.0 | 5.8 | 26.3 | 18.1 | 37.6 | 28.1 | 30-Aug-2010 |
| HOG-LBP + DHOOG bag of words, SVM [7] | 23.5 | 40.4 | 34.7 | 2.7 | 8.4 | 26.0 | 43.1 | 33.8 | 17.2 | 11.2 | 14.3 | 14.5 | 14.9 | 31.8 | 37.3 | 30.0 | 6.4 | 25.2 | 11.6 | 30.0 | 35.7 | 30-Aug-2010 |
| Svr-Segm [7] | 23.4 | 50.5 | 24.5 | 17.1 | 13.3 | 10.9 | 39.5 | 32.9 | 36.5 | 5.6 | 16.0 | 6.6 | 22.3 | 24.9 | 29.0 | 29.8 | 6.7 | 28.4 | 13.3 | 32.1 | 27.2 | 30-Aug-2010 |
| HOG-LBP Linear SVM [7] | 22.1 | 37.9 | 33.7 | 2.7 | 6.5 | 25.3 | 37.5 | 33.1 | 15.5 | 10.9 | 12.3 | 12.5 | 13.7 | 29.7 | 34.5 | 33.8 | 7.2 | 22.9 | 9.9 | 28.9 | 34.1 | 29-Aug-2010 |
| HOG+LBP+LTP+PLS2ROOTS [7] | 17.5 | 32.7 | 29.7 | 0.8 | 1.1 | 19.9 | 39.4 | 27.5 | 8.6 | 4.5 | 8.1 | 6.3 | 11.0 | 22.9 | 34.1 | 24.6 | 3.1 | 24.0 | 2.0 | 23.5 | 27.0 | 31-Aug-2010 |
| RandomParts [7] | 14.2 | 23.8 | 31.7 | 1.2 | 3.4 | 11.1 | 29.7 | 19.5 | 14.2 | 0.8 | 11.1 | 7.0 | 4.7 | 16.4 | 31.5 | 16.0 | 1.1 | 15.6 | 10.2 | 14.7 | 21.0 | 25-Aug-2010 |
| SIFT-GMM-MKL2 [7] | 8.3 | 20.0 | 14.5 | 3.8 | 1.2 | 0.5 | 17.6 | 8.1 | 28.5 | 0.1 | 2.9 | 3.1 | 17.5 | 7.2 | 18.8 | 3.3 | 0.8 | 2.9 | 6.3 | 7.6 | 1.1 | 30-Aug-2010 |
| UC3M_Generative_Discriminative [7] | 6.3 | 15.8 | 5.5 | 5.6 | 2.3 | 0.3 | 10.2 | 5.4 | 12.6 | 0.5 | 5.6 | 4.5 | 7.7 | 11.3 | 12.6 | 5.3 | 1.5 | 2.0 | 5.9 | 9.1 | 3.2 | 30-Aug-2010 |
| SIFT-GMM-MKL [7] | 2.3 | 10.6 | 1.6 | 1.2 | 0.9 | 0.1 | 2.8 | 1.6 | 6.7 | 0.1 | 2.0 | 0.4 | 3.0 | 2.0 | 4.4 | 2.0 | 0.3 | 1.1 | 1.2 | 2.1 | 1.9 | 30-Aug-2010 |

Figure : Leading method segDPM (ours). Those were the good times...

S. Fidler, R. Mottaghi, A. Yuille, R. Urtasun, Bottom-up Segmentation for Top-down Detection, CVPR'13

The Era Post-Alex Net: PASCAL VOC detection

| | | |
|---|------------------------------|------|
| ▷ | R-CNN [?] | 50.2 |
| ▷ | BERKELEY POSELETS [?] | - |
| ▷ | poselets [?] | - |
| ▷ | ** UCI_L SVM-MDPM-10X ** [?] | - |
| ▷ | Head-Detect-Segment [?] | - |

So Neural Networks are Great

- So networks turn out to be great.
- Everything is deep, even if it's shallow!
- Companies leading the competitions: ImageNet, KITTI, but not yet PASCAL
- At this point Google, Facebook, Microsoft, Baidu “steal” most neural network professors from academia.
- ... and a lot of our good students :(

So Neural Networks are Great

- But to train the networks you need quite a bit of computational power. So what do you do?



So Neural Networks are Great

- Buy even more.



So Neural Networks are Great

- And train **more layers**. 16 instead of 7 before. 144 million parameters.

add more layers

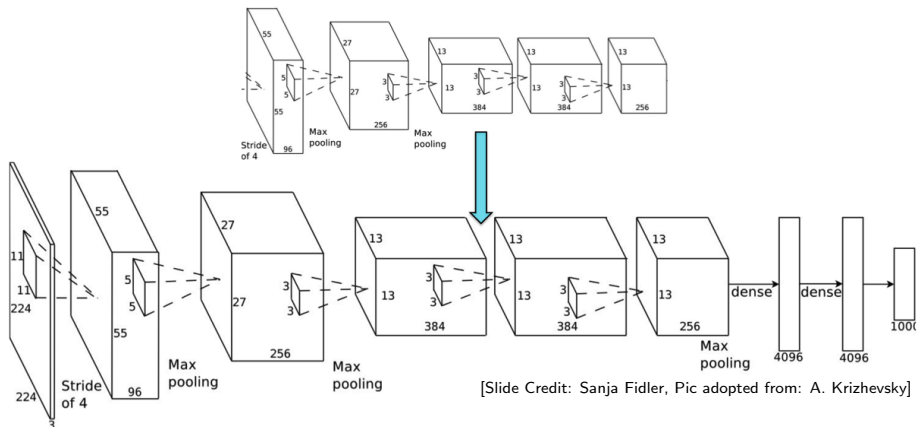
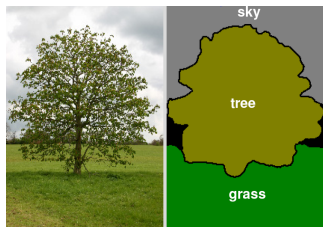


Figure : K. Simonyan, A. Zisserman, Very Deep Convolutional Networks for Large-Scale Image Recognition. arXiv 2014

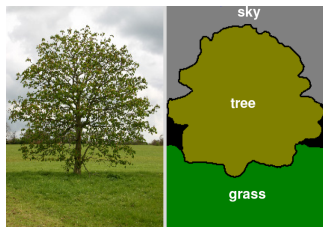
The Era Post-Alex Net: PASCAL VOC detection

| | | |
|---|---------------------------------|------|
| ▶ | Fast R-CNN + YOLO [?] | 70.8 |
| ▷ | Fast R-CNN VGG16 extra data [?] | 68.8 |
| ▷ | segDeepM [?] | 67.2 |
| ▷ | BabyLearning [?] | 63.8 |
| ▷ | R-CNN (bbox reg) [?] | 62.9 |
| ▷ | R-CNN [?] | 59.8 |
| ▷ | Feature Edit [?] | 56.4 |
| ▷ | YOLO [?] | 55.3 |
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| ▷ | R-CNN [?] | 50.2 |
| ▷ | poselets [?] | - |
| ▷ | Head-Detect-Segment [?] | - |
| ▷ | BERKELEY POSELETS [?] | - |
| ▷ | ** UCI_LSVM-MDPM-10X ** [?] | - |

What if we Want Semantic Segmentation?

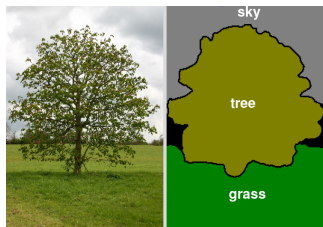


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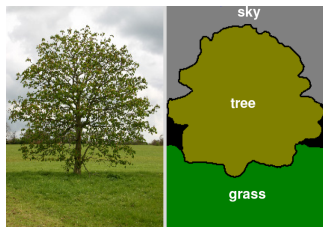
- Every layer, even fully connected can be treated as a convolutional layer, and then we can deal with arbitrary dimensions of the input

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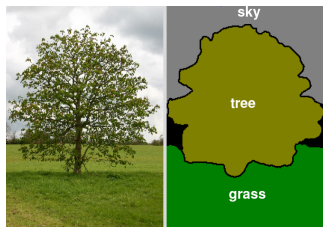
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- The network can work on super pixels, or can directly operate in pixels

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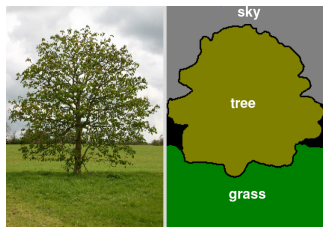
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- More to come in Part II

Practical Tips

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- **Hyperparameters:** architecture, learning rate, num layers, num features, etc

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 - 4 Bayesian optimization [Whetlab Toronto]

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(good)



(bad)

Figure : from M. Ranzato

Good to Know

- ALWAYS check gradients numerically by finite differences!
- Measure error on both training and validation set, NEVER TEST
- Test on a small subset of the data and check that you can over fit (i.e., error $\rightarrow 0$)
- Visualize features (feature maps need to be uncorrelated) and have high variance.
- Visualize parameters

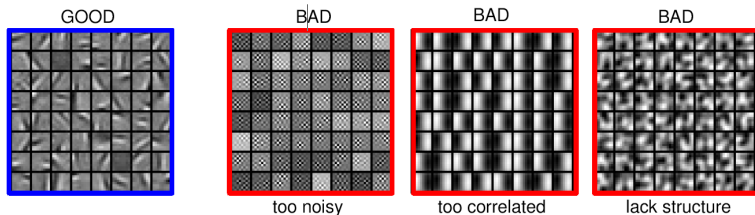


Figure : from M. Ranzato

What if it doesn't work?

- Training diverges

What if it doesn't work?

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 - Decrease learning rate

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What if it doesn't work?

- Training diverges
 - Decrease learning rate
 - Check gradients
- Parameters collapse / loss is minimized but accuracy is low
 - Appropriate loss function?

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[Slide credit: M. Ranzato]

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- Multi-task learning

[Slide credit: M. Ranzato]

- Torch7: learning library that supports neural net training
<http://www.torch.ch>
<http://code.cogbits.com/wiki/doku.php> (tutorial with demos by C. Farabet)
<https://github.com/sermanet/OverFeat>
- Python-based learning library (U. Montreal)
<http://deeplearning.net/software/theano/> (does automatic differentiation)
- Efficient CUDA kernels for ConvNets (Krizhevsky)
code.google.com/p/cuda-convnet
- Caffe (Yangqing Jia)
<http://caffe.berkeleyvision.org>
- Deep Structured Models
<http://www.alexander-schwing.de/> (soon available)

[Slide Credit: M. Ranzato]

Part II: Deep Structured Learning

Your current Status?



What's next?



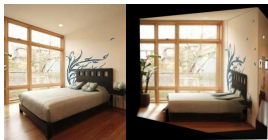
What's next?

- 1 Theoretical Understanding
- 2 Unsupervised Learning
- 3 Structured models

Structure!

- Many Vision Problems are complex and involve predicting many random variables that are statistically related

Scene understanding



$x = \text{image}$

$y : \text{room layout}$

Tag prediction



$x = \text{image}$

$y : \text{tag "combo"}$

Segmentation



$x = \text{image}$

$y : \text{segmentation}$

- Complex mapping $F(\mathbf{x}, y, \mathbf{w})$ to predict output y given input \mathbf{x} through a series of matrix multiplications, non-linearities and pooling operations

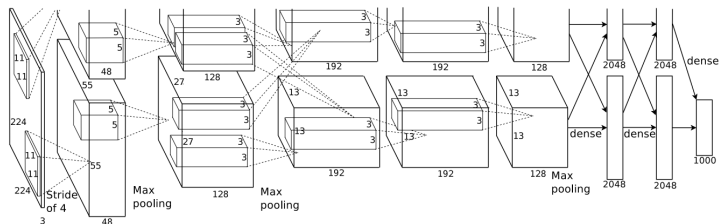


Figure : Imagenet CNN [Krizhevsky et al. 13]

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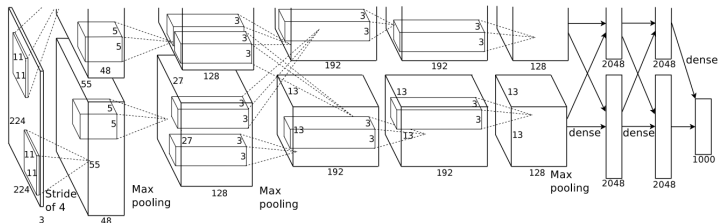


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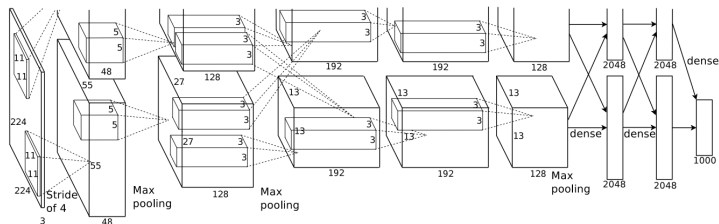


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- We typically train the network to predict one random variable (e.g., ImageNet) by minimizing cross-entropy
- Multi-task extensions: sum the loss of each task, and share part of the features (e.g., segmentation)
- Use an MRF as a post processing step

PROBLEM: *How can we take into account complex dependencies when predicting multiple variables?*

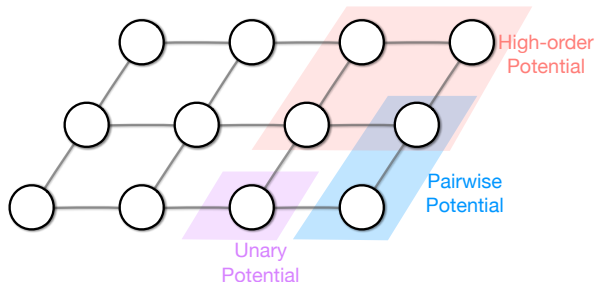
PROBLEM: *How can we take into account complex dependencies when predicting multiple variables?*

SOLUTION: *Graphical models*

Graphical Models

- Convenient tool to illustrate dependencies among random variables

$$E(\mathbf{y}) = - \underbrace{\sum_i f_i(y_i)}_{\text{unaries}} - \underbrace{\sum_{i,j \in \mathcal{E}} f(y_i, y_j)}_{\text{pairwise}} - \underbrace{\sum_{\alpha} f_{\alpha}(\mathbf{y}_{\alpha})}_{\text{high-order}}$$



- Widespread usage among different fields: vision, NLP, comp. bio, ...

Compact Notation

- In Computer Vision we usually express

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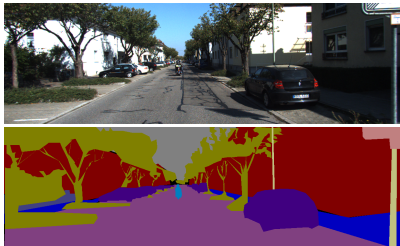
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- The functions f_r are a function of parameters \mathbf{w}

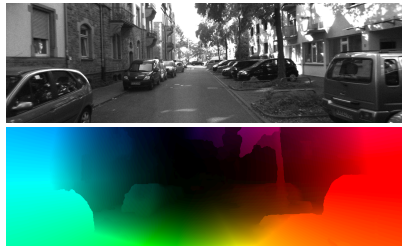
Continuous vs Discrete MRFs

$$E(\mathbf{y}, \mathbf{w}) = - \sum_{r \in \mathcal{R}} f_r(\mathbf{y}_r, \mathbf{w})$$

- Discrete MRFs:
 $y_i \in \{1, \dots, C_i\}$



- Continuous MRFs:
 $y_i \in \mathcal{Y} \subseteq \mathbb{R}$

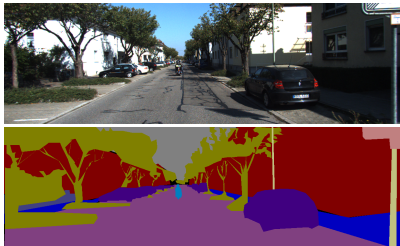


- Hybrid MRFs with continuous and discrete variables

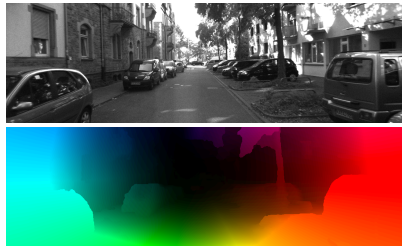
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- Hybrid MRFs with continuous and discrete variables
- Today's talk: only discrete MRFs

Probabilistic Interpretation

- The energy is defined as

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- CRFs vs MRFs

$$p(\mathbf{y}|\mathbf{x}; \mathbf{w}) = \frac{1}{Z(\mathbf{x})} \exp \left(\sum_{r \in \mathcal{R}} f_r(\mathbf{x}, \mathbf{y}_r, \mathbf{w}) \right)$$

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Very difficult tasks in general (i.e., NP-hard). Some exceptions, e.g., low-tree width models and binary MRFs with sub-modular energies

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- Given a training set of N pairs $(\mathbf{x}, \mathbf{y}) \in \mathcal{D}$, we want to estimate the functions $f_r(\mathbf{x}, \mathbf{y}_r, \mathbf{w})$
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- Very difficult, instead we minimize the sum of a surrogate (typically convex) loss and a regularizer

$$\min_{\mathbf{w}} R(\mathbf{w}) + \frac{C}{N} \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} \bar{\ell}(\mathbf{x}, \mathbf{y}, \mathbf{w})$$

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$$\bar{\ell}_{\text{hinge}}(\mathbf{x}, \mathbf{y}, \mathbf{w}) = \max_{\hat{\mathbf{y}} \in \mathcal{Y}} \{ \ell(\mathbf{y}, \hat{\mathbf{y}}) - \mathbf{w}^\top \Phi(\mathbf{x}, \hat{\mathbf{y}}) + \mathbf{w}^\top \Phi(\mathbf{x}, \mathbf{y}) \}$$

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- The assumption is that the model is **log-linear**

$$E(\mathbf{x}, \mathbf{y}, \mathbf{w}) = -F(\mathbf{x}, \mathbf{y}, \mathbf{w}) = -\mathbf{w}^\top \phi(\mathbf{x}, \mathbf{y})$$

and the features decompose in a graph

$$\mathbf{w}^\top \phi(\mathbf{x}, \mathbf{y}) = \sum_{r \in \mathcal{R}} \mathbf{w}_r^\top \phi_r(\mathbf{x}, \mathbf{y})$$

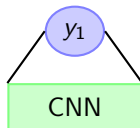
PROBLEM: *How can we remove the log-linear restriction?*

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SOLUTION: *Deep Structured Models*

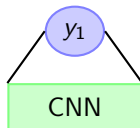
With Pictures ;)

- Standard CNN

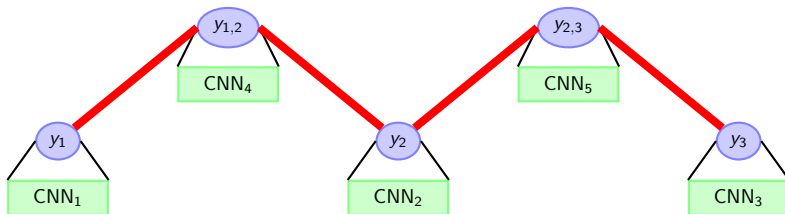


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Probability of a configuration \mathbf{y} :

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Maximize the likelihood of training data via

$$\begin{aligned} \mathbf{w}^* &= \arg \max_{\mathbf{w}} \prod_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} p(\mathbf{y} \mid \mathbf{x}; \mathbf{w}) \\ &= \arg \max_{\mathbf{w}} \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} \left(F(\mathbf{x}, \mathbf{y}, \mathbf{w}) - \ln \sum_{\hat{\mathbf{y}} \in \mathcal{Y}} \exp F(\mathbf{x}, \hat{\mathbf{y}}, \mathbf{w}) \right) \end{aligned}$$

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Maximum likelihood is equivalent to maximizing cross-entropy when the target distribution $p_{(\mathbf{x}, \mathbf{y}), \text{tg}}(\hat{\mathbf{y}}) = \delta(\hat{\mathbf{y}} = \mathbf{y})$

Gradient Ascent on Cross Entropy

Program of interest:

$$\max_{\mathbf{w}} \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}, \hat{\mathbf{y}}} p_{(\mathbf{x}, \mathbf{y}), \text{tg}}(\hat{\mathbf{y}}) \ln p(\hat{\mathbf{y}} | \mathbf{x}; \mathbf{w})$$

Optimize via gradient ascent

$$\begin{aligned} \frac{\partial}{\partial \mathbf{w}} & \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}, \hat{\mathbf{y}}} p_{(\mathbf{x}, \mathbf{y}), \text{tg}}(\hat{\mathbf{y}}) \ln p(\hat{\mathbf{y}} | \mathbf{x}; \mathbf{w}) \\ &= \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}, \hat{\mathbf{y}}} (p_{(\mathbf{x}, \mathbf{y}), \text{tg}}(\hat{\mathbf{y}}) - p(\hat{\mathbf{y}} | \mathbf{x}; \mathbf{w})) \frac{\partial}{\partial \mathbf{w}} F(\hat{\mathbf{y}}, \mathbf{x}, \mathbf{w}) \\ &= \underbrace{\sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} \left(\mathbb{E}_{p_{(\mathbf{x}, \mathbf{y}), \text{tg}}} \left[\frac{\partial}{\partial \mathbf{w}} F(\hat{\mathbf{y}}, \mathbf{x}, \mathbf{w}) \right] - \mathbb{E}_{p_{(\mathbf{x}, \mathbf{y})}} \left[\frac{\partial}{\partial \mathbf{w}} F(\hat{\mathbf{y}}, \mathbf{x}, \mathbf{w}) \right] \right)}_{\text{moment matching}} \end{aligned}$$

- Compute predicted distribution $p(\hat{\mathbf{y}} | \mathbf{x}; \mathbf{w})$
- Use chain rule to pass back difference between prediction and observation

Repeat until stopping criteria

- 1 Forward pass to compute $F(\mathbf{y}, \mathbf{x}, \mathbf{w})$
- 2 Compute $p(\mathbf{y} | \mathbf{x}, \mathbf{w})$
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What is the PROBLEM?

- How do we even represent $F(\mathbf{y}, \mathbf{x}, \mathbf{w})$ if \mathcal{Y} is large?
- How do we compute $p(\mathbf{y} | \mathbf{x}, \mathbf{w})$?

Use the Graphical Model Structure

- 1 Use the graphical model $F(\mathbf{y}, \mathbf{x}, \mathbf{w}) = \sum_r f_r(\mathbf{y}_r, \mathbf{x}, \mathbf{w})$

$$\begin{aligned} \frac{\partial}{\partial \mathbf{w}} & \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}, \hat{\mathbf{y}}} p_{(\mathbf{x}, \mathbf{y}), \text{tg}}(\hat{\mathbf{y}}) \ln p(\hat{\mathbf{y}} \mid \mathbf{x}; \mathbf{w}) \\ &= \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}, r} \left(\mathbb{E}_{p_{(\mathbf{x}, \mathbf{y}), r, \text{tg}}} \left[\frac{\partial}{\partial \mathbf{w}} f_r(\hat{\mathbf{y}}_r, \mathbf{x}, \mathbf{w}) \right] - \mathbb{E}_{p_{(\mathbf{x}, \mathbf{y}), r}} \left[\frac{\partial}{\partial \mathbf{w}} f_r(\hat{\mathbf{y}}_r, \mathbf{x}, \mathbf{w}) \right] \right) \end{aligned}$$

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- ② Approximate marginals $p_r(\hat{\mathbf{y}}_r | \mathbf{x}, \mathbf{w})$ via beliefs $b_r(\hat{\mathbf{y}}_r | \mathbf{x}, \mathbf{w})$ computed by:
- Sampling methods
 - Variational methods

Repeat until stopping criteria

- 1 Forward pass to compute the $f_r(\mathbf{y}_r, \mathbf{x}, \mathbf{w})$
- 2 Compute the $b_r(\mathbf{y}_r | \mathbf{x}, \mathbf{w})$ by running approximated inference
- 3 Backward pass via chain rule to obtain gradient
- 4 Update parameters \mathbf{w}

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PROBLEM: We have to run inference in the graphical model every time we want to update the weights

How to deal with Big Data

Dealing with large number $|\mathcal{D}|$ of training examples:

- Parallelized across samples (any number of machines and GPUs)
- Usage of mini batches

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Dealing with large output spaces \mathcal{Y} :

- Variational approximations
- Blending of learning and inference

Sample parallel implementation:

Partition data \mathcal{D} onto compute nodes

Repeat until stopping criteria

- 1 Each compute node uses GPU for CNN Forward pass to compute $f_r(\mathbf{y}_r, \mathbf{x}, \mathbf{w})$
- 2 Each compute node estimates beliefs $b_r(\mathbf{y}_r | \mathbf{x}, \mathbf{w})$ for assigned samples
- 3 Backpropagation of difference using GPU to obtain **machine local** gradient
- 4 Synchronize gradient across all machines using MPI
- 5 Update parameters \mathbf{w}

Better Option: Interleaving Learning and Inference

- Use LP relaxation instead

$$\min_{\mathbf{w}} \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} \left(\max_{b_{(x,y)} \in \mathcal{C}_{(x,y)}} \left\{ \sum_{r, \hat{\mathbf{y}}_r} b_{(x,y),r}(\hat{\mathbf{y}}_r) f_r(\mathbf{x}, \hat{\mathbf{y}}_r; \mathbf{w}) + \sum_r \epsilon c_r H(b_{(x,y),r}) \right\} - F(\mathbf{x}, \mathbf{y}; \mathbf{w}) \right)$$

Better Option: Interleaving Learning and Inference

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- More efficient algorithm by blending min. w.r.t. \mathbf{w} and max. of the beliefs b
- After introducing Lagrange multipliers λ , the dual becomes

$$\min_{\mathbf{w}, \lambda} \sum_{(\mathbf{x}, \mathbf{y}), r} \epsilon_{C_r} \ln \sum_{\hat{\mathbf{y}}_r} \exp \frac{f_r(\mathbf{x}, \hat{\mathbf{y}}_r; \mathbf{w}) + \sum_{c \in C(r)} \lambda_{(\mathbf{x}, \mathbf{y}), c \rightarrow r}(\hat{\mathbf{y}}_c) - \sum_{p \in P(r)} \lambda_{(\mathbf{x}, \mathbf{y}), r \rightarrow p}(\hat{\mathbf{y}}_r)}{\epsilon_{C_r}} - \bar{F}(\mathbf{w}).$$

with $\bar{F}(\mathbf{w}) = \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} F(\mathbf{x}, \mathbf{y}; \mathbf{w})$ the sum of empirical function observations

Better Option: Interleaving Learning and Inference

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$$\min_{\mathbf{w}} \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} \left(\max_{b_{(\mathbf{x}, \mathbf{y})} \in \mathcal{C}_{(\mathbf{x}, \mathbf{y})}} \left\{ \sum_{r, \hat{\mathbf{y}}_r} b_{(\mathbf{x}, \mathbf{y}), r}(\hat{\mathbf{y}}_r) f_r(\mathbf{x}, \hat{\mathbf{y}}_r; \mathbf{w}) + \sum_r \epsilon_{C_r} H(b_{(\mathbf{x}, \mathbf{y}), r}) \right\} - F(\mathbf{x}, \mathbf{y}; \mathbf{w}) \right)$$

- More efficient algorithm by blending min. w.r.t. \mathbf{w} and max. of the beliefs b
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with $\bar{F}(\mathbf{w}) = \sum_{(\mathbf{x}, \mathbf{y}) \in \mathcal{D}} F(\mathbf{x}, \mathbf{y}; \mathbf{w})$ the sum of empirical function observations

- We can then do block coordinate descent to solve the minimization problem, and we get the following algorithm ...

Repeat until stopping criteria

- 1 Forward pass to compute the $f_r(\mathbf{y}_r, \mathbf{x}, \mathbf{w})$
- 2 Update (some) messages λ
- 3 Backward pass via chain rule to obtain gradient
- 4 Update parameters \mathbf{w}

Sample parallel implementation:

Partition data \mathcal{D} onto compute nodes

Repeat until stopping criteria

- 1 Each compute node uses GPU for CNN Forward pass to compute $f_r(\mathbf{y}_r, \mathbf{x}, \mathbf{w})$
- 2 Each compute node updates (some) messages λ
- 3 Backpropagation of difference using GPU to obtain **machine local** gradient
- 4 Synchronize gradient across all machines using MPI
- 5 Update parameters \mathbf{w}



Wake Up
Call!

Application 1: Character Recognition

- **Task:** Word Recognition from a fixed vocabulary of 50 words, 28×28 sized image patches
- Characters have complex backgrounds and suffer many different distortions
- Training, validation and test set sizes are 10k, 2k and 2k variations of words



banal



julep



resty



drein



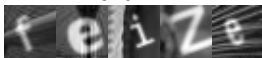
yojan



mothy



snack



feize



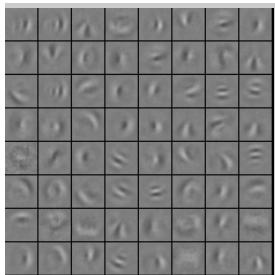
porer

Results

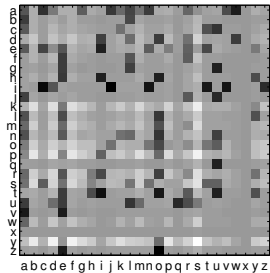
- Graphical model has 5 nodes, MLP for each unary and non-parametric pairwise potentials
- Joint** training, **structured**, **deep** and more **capacity** helps

| Grap | MLP | Method | $H_1 = 128$ | $H_1 = 256$ | $H_1 = 512$ | $H_1 = 768$ | $H_1 = 1024$ |
|------|------|---------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1st | 1lay | Unary only | 8.60 / 61.32 | 10.80 / 64.41 | 12.50 / 65.69 | 12.95 / 66.66 | 13.40 / 67.02 |
| | | JointTrain | 16.80 / 65.28 | 25.20 / 70.75 | 31.80 / 74.90 | 33.05 / 76.42 | 34.30 / 77.02 |
| | | PwTrain | 12.70 / 64.35 | 18.00 / 68.27 | 22.80 / 71.29 | 23.25 / 72.62 | 26.30 / 73.96 |
| | | PreTrainJoint | 20.65 / 67.42 | 25.70 / 71.65 | 31.70 / 75.56 | 34.50 / 77.14 | 35.85 / 78.05 |
| 2nd | 1lay | JointTrain | 25.50 / 67.13 | 34.60 / 73.19 | 45.55 / 79.60 | 51.55 / 82.37 | 54.05 / 83.57 |
| | | PwTrain | 10.05 / 58.90 | 14.10 / 63.44 | 18.10 / 67.31 | 20.40 / 70.14 | 22.20 / 71.25 |
| | | PreTrainJoint | 28.15 / 69.07 | 36.85 / 75.21 | 45.75 / 80.09 | 50.10 / 82.30 | 52.25 / 83.39 |
| 1st | 2lay | $H_1 = 512$ | $H_2 = 32$ | $H_2 = 64$ | $H_2 = 128$ | $H_2 = 256$ | $H_2 = 512$ |
| | | Unary only | 15.25 / 69.04 | 18.15 / 70.66 | 19.00 / 71.43 | 19.20 / 72.06 | 20.40 / 72.51 |
| | | JointTrain | 35.95 / 76.92 | 43.80 / 81.64 | 44.75 / 82.22 | 46.00 / 82.96 | 47.70 / 83.64 |
| | | PwTrain | 34.85 / 79.11 | 38.95 / 80.93 | 42.75 / 82.38 | 45.10 / 83.67 | 45.75 / 83.88 |
| | | PreTrainJoint | 42.25 / 81.10 | 44.85 / 82.96 | 46.85 / 83.50 | 47.95 / 84.21 | 47.05 / 84.08 |
| 2nd | 2lay | JointTrain | 54.65 / 83.98 | 61.80 / 87.30 | 66.15 / 89.09 | 64.85 / 88.93 | 68.00 / 89.96 |
| | | PwTrain | 39.95 / 81.14 | 48.25 / 84.45 | 52.65 / 86.24 | 57.10 / 87.61 | 62.90 / 89.49 |
| | | PreTrainJoint | 62.60 / 88.03 | 65.80 / 89.32 | 68.75 / 90.47 | 68.60 / 90.42 | 69.35 / 90.75 |

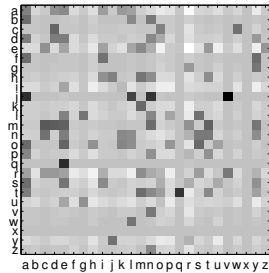
Learned Weights



Unary weights



distance-1 edges



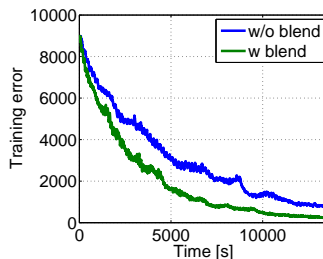
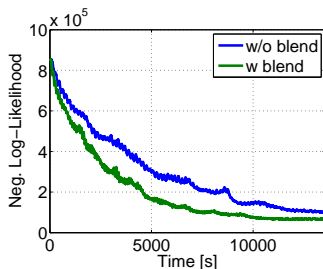
distance-2 edges

Example 2: Image Tagging

[Chen & Schwing & Yuille & Urtasun ICML'15]

- Flickr dataset: 38 possible tags, $|\mathcal{Y}| = 2^{38}$
- 10k training, 10k test examples

| Training method | Prediction error [%] |
|---------------------------|----------------------|
| Unary only | 9.36 |
| Piecewise | 7.70 |
| Joint (with pre-training) | 7.25 |



Visual results



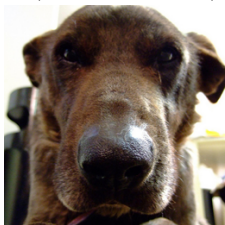
female/indoor/portrait
female/indoor/portrait



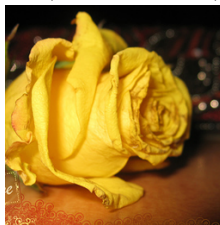
sky/plant life/tree
sky/plant life/tree



water/animals/sea
water/animals/sky



animals/dog/indoor
animals/dog



indoor/flower/plant life
∅

Learned class correlations

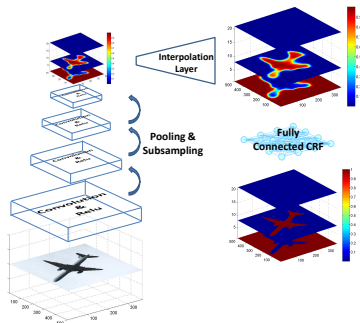
| | | | | | | | | | |
|------------|-------------|-------------|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| female | 0.00 | 0.68 | 0.04 | 0.24 | -0.01 | -0.05 | 0.07 | -0.01 | 0.01 |
| people | 0.68 | 0.00 | 0.06 | 0.36 | -0.05 | -0.12 | 0.74 | -0.04 | -0.03 |
| indoor | 0.04 | 0.06 | 0.00 | 0.07 | -0.35 | -0.34 | 0.02 | -0.15 | -0.21 |
| portrait | 0.24 | 0.36 | 0.07 | 0.00 | -0.02 | -0.01 | 0.12 | 0.02 | 0.05 |
| sky | -0.01 | -0.05 | -0.35 | -0.02 | 0.00 | 0.24 | -0.00 | 0.44 | 0.30 |
| plant life | -0.05 | -0.12 | -0.34 | -0.01 | 0.24 | 0.00 | -0.07 | 0.09 | 0.68 |
| male | 0.07 | 0.74 | 0.02 | 0.12 | -0.00 | -0.07 | 0.00 | 0.00 | -0.02 |
| clouds | -0.01 | -0.04 | -0.15 | 0.02 | 0.44 | 0.09 | 0.00 | 0.00 | 0.11 |
| tree | 0.01 | -0.03 | -0.21 | 0.05 | 0.30 | 0.68 | -0.02 | 0.11 | 0.00 |

Only part of the correlations are shown for clarity

Example 3: Semantic Segmentation

[Chen et al. ICLR'15; Krähenbühl & Koltun NIPS'11, ICML'13; Zhen et al. Arxiv'15; Schwing & Urtasun Arxiv'15]

- $|\mathcal{Y}| = 21^{350 \cdot 500}$, $\approx 10k$ training, ≈ 1500 test examples
- Oxford-net pre trained on PASCAL, predicts 40×40 + upsampling
- The graphical model is a fully connected CRF with Gaussian potentials
- Inference using (algo2), with mean-field as approx. inference



Pascal VOC 2012 dataset

[Chen et al. ICLR'15; Krähenbühl & Koltun NIPS'11, ICML'13; Zhen et al. Arxiv'15; Schwing & Urtasun Arxiv'15]

- $|\mathcal{Y}| = 21^{350 \cdot 500}$, $\approx 10k$ training, ≈ 1500 test examples
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| Training method | Mean IoU [%] |
|-----------------|---------------|
| Unary only | 61.476 |
| Joint | 64.060 |

Pascal VOC 2012 dataset

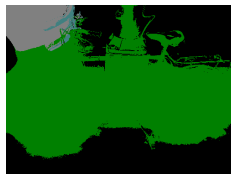
[Chen et al. ICLR'15; Krähenbühl & Koltun NIPS'11, ICML'13; Zhen et al. Arxiv'15; Schwing & Urtasun Arxiv'15]

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- **Disclaimer:** Much better results now with a few tricks. Zheng et al. 15 is now at 74.7%!

Visual results



Example 4: 3D Object Proposals for Detection

- Use structured prediction to learn to propose object candidates (i.e., grouping)



- Use deep learning to do final detection: OxfordNet



- Only 1.2s to generate proposals

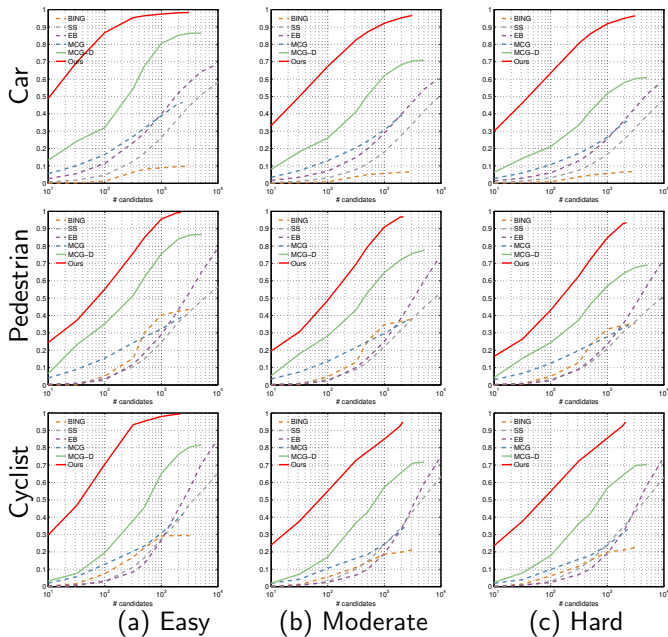
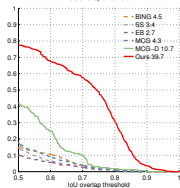
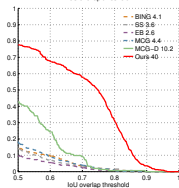
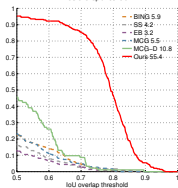
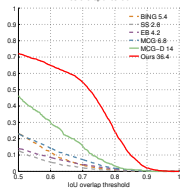
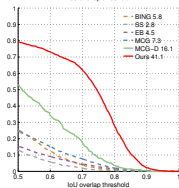
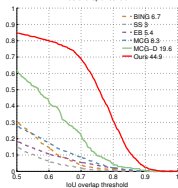
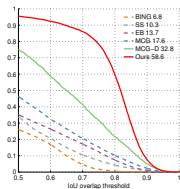
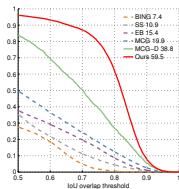
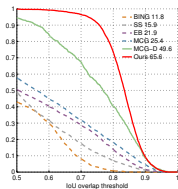


Figure : **Proposal recall:** 0.7 overlap threshold for *Car*, and 0.5 for rest.



(a) Easy

(b) Moderate

(c) Hard

Figure : Recall vs IoU for 500 proposals. (Top) Cars, (Middle) Pedestrians, (Bottom) Cyclists.

KITTI Detection Results

[X. Chen, K. Kundu and S. Fidler and R. Urtasun, On Arxiv soon]

| | Cars | | | Pedestrians | | | Cyclists | | |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| | Easy | Moderate | Hard | Easy | Moderate | Hard | Easy | Moderate | Hard |
| LSVM-MDPM-sv | 68.02 | 56.48 | 44.18 | 47.74 | 39.36 | 35.95 | 35.04 | 27.50 | 26.21 |
| SquaresICF | - | - | - | 57.33 | 44.42 | 40.08 | - | - | - |
| DPM-C8B1 | 74.33 | 60.99 | 47.16 | 38.96 | 29.03 | 25.61 | 43.49 | 29.04 | 26.20 |
| MDPM-un-BB | 71.19 | 62.16 | 48.43 | - | - | - | - | - | - |
| DPM-VOC+VP | 74.95 | 64.71 | 48.76 | 59.48 | 44.86 | 40.37 | 42.43 | 31.08 | 28.23 |
| OC-DPM | 74.94 | 65.95 | 53.86 | - | - | - | - | - | - |
| AOG | 84.36 | 71.88 | 59.27 | - | - | - | - | - | - |
| SubCat | 84.14 | 75.46 | 59.71 | 54.67 | 42.34 | 37.95 | - | - | - |
| DA-DPM | - | - | - | 56.36 | 45.51 | 41.08 | - | - | - |
| Fusion-DPM | - | - | - | 59.51 | 46.67 | 42.05 | - | - | - |
| R-CNN | - | - | - | 61.61 | 50.13 | 44.79 | - | - | - |
| FilteredICF | - | - | - | 61.14 | 53.98 | 49.29 | - | - | - |
| pAUCEnST | - | - | - | 65.26 | 54.49 | 48.60 | 51.62 | 38.03 | 33.38 |
| MV-RGBD-RF | - | - | - | 70.21 | 54.56 | 51.25 | 54.02 | 39.72 | 34.82 |
| 3DVP | 87.46 | 75.77 | 65.38 | - | - | - | - | - | - |
| Regionlets | 84.75 | 76.45 | 59.70 | 73.14 | 61.15 | 55.21 | 70.41 | 58.72 | 51.83 |
| Ours | 88.33 | 87.14 | 76.11 | 70.16 | 59.35 | 52.76 | 77.94 | 67.35 | 59.49 |

Table : Average Precision (AP) (in %) on the test set of the KITTI Object Detection Benchmark.

KITTI Detection Results

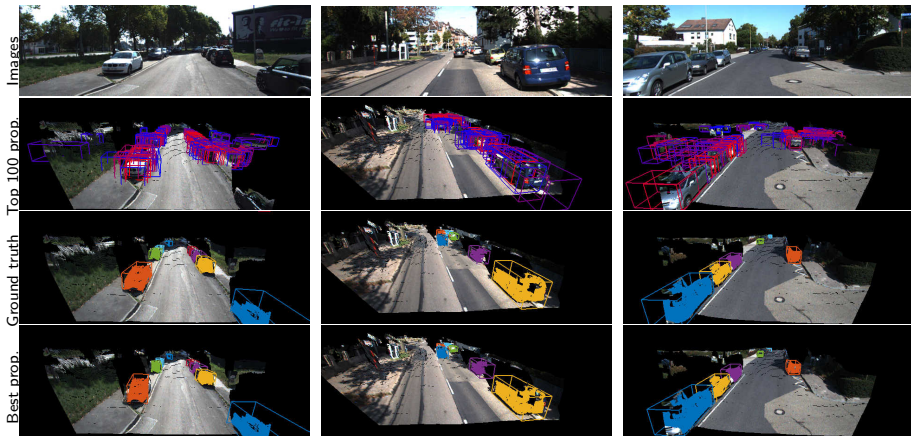
[X. Chen, K. Kundu and S. Fidler and R. Urtasun, On Arxiv soon]

| | Cars | | | Pedestrians | | | Cyclists | | |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| | Easy | Mod. | Hard | Easy | Mod. | Hard | Easy | Mod. | Hard |
| AOG | 43.81 | 38.21 | 31.53 | - | - | - | - | - | - |
| DPM-C8B1 | 59.51 | 50.32 | 39.22 | 31.08 | 23.37 | 20.72 | 27.25 | 19.25 | 17.95 |
| LSVM-MDPM-sv | 67.27 | 55.77 | 43.59 | 43.58 | 35.49 | 32.42 | 27.54 | 22.07 | 21.45 |
| DPM-VOC+VP | 72.28 | 61.84 | 46.54 | 53.55 | 39.83 | 35.73 / | 30.52 | 23.17 | 21.58 |
| OC-DPM | 73.50 | 64.42 | 52.40 | - | - | - | - | - | - |
| SubCat | 83.41 | 74.42 | 58.83 | 44.32 | 34.18 | 30.76 | - | - | - |
| 3DVP | 86.92 | 74.59 | 64.11 | - | - | - | - | - | - |
| Ours | 83.03 | 80.21 | 69.60 | 48.58 | 40.56 | 36.08 | 57.72 | 48.21 | 42.72 |

Table : AOS scores on the KITTI Object Detection and Orientation Benchmark (test set).

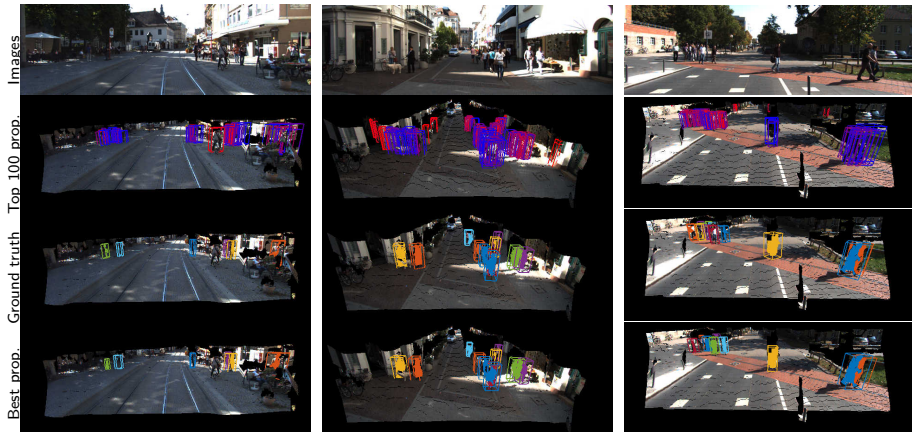
Car Results

[X. Chen, K. Kundu, Y. Zhu, S. Fidler and R. Urtasun, On Arxiv soon]



Pedestrian Results

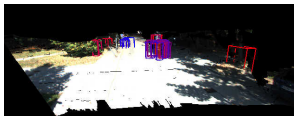
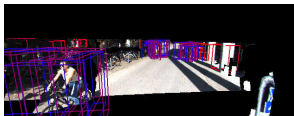
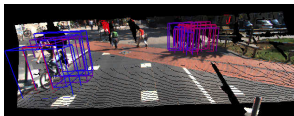
[X. Chen, K. Kundu, Y. Zhu, S. Fidler and R. Urtasun, On Arxiv soon]



Cyclist Results

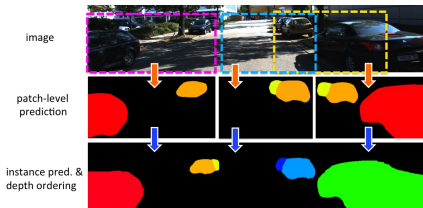
[X. Chen, K. Kundu, Y. Zhu, S. Fidler and R. Urtasun, On Arxiv soon]

Best proposals
Ground truth
Top 100 Prop.
2D images



Example 5: More Precise Grouping

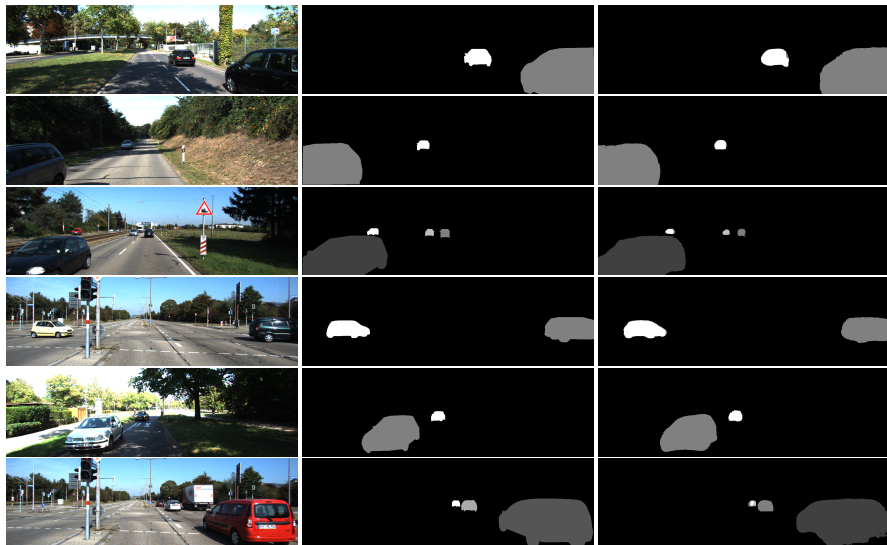
- Given a single image, we want to infer **Instance-level Segmentation** and **Depth Ordering**



- Use deep convolutional nets to do both tasks simultaneously
- Trick: Encode both tasks with a single parameterization
- Run the conv. net at multiple resolutions
- Use MRF to form a single coherent explanation across all the image combining the conv nets at multiple resolutions
- Important:** we do not use a single pixel-wise training example!

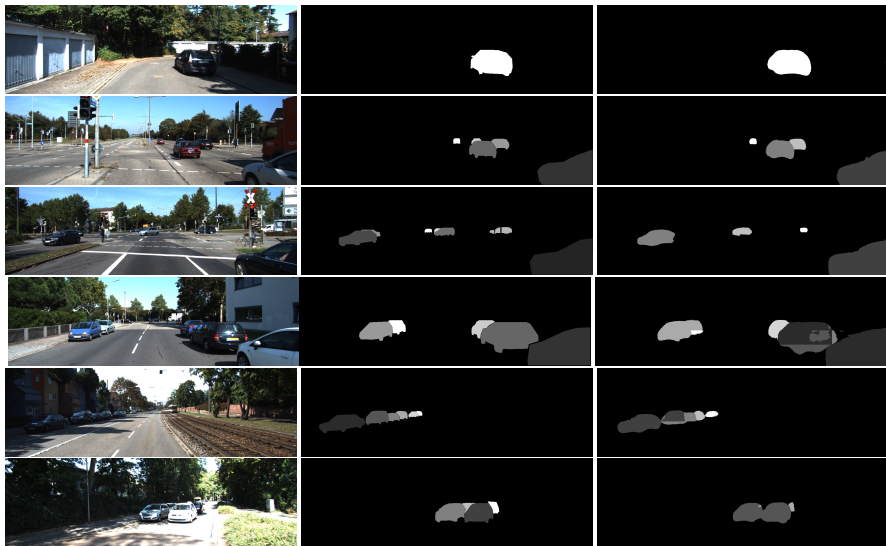
Results on KITTI

[Z. Zhang, A. Schwing, S. Fidler and R. Urtasun, ICCV '15]



More Results (including failures/difficulties)

[Z. Zhang, A. Schwing, S. Fidler and R. Urtasun, ICCV '15]

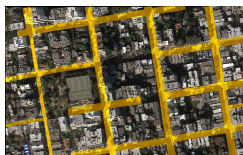


Example 6: Enhancing freely-available maps

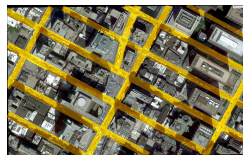
[G. Matthyus, S. Wang, S. Fidler and R. Urtasun, ICCV '15]



Toronto: Airport



San Francisco: Russian Hill



NYC: Times square



Kyoto: Kinkakuji



Sydney: At Harbour bridge



Monte Carlo: Casino

- Enhancing OpenStreetMaps
- Can be trained on a single image and test on the whole world
- Trick: Not to reason at the pixel level
- Very efficient: 0.1s/km of road
- Preserves topology and is state-of-the-art

Example 7: Fashion

[E. Simo-Serra, S. Fidler, F. Moreno, R. Urtasun, CVPR15]



LOS ANGELES, CA

466 FANS

288 VOTES

62 FAVOURITES

TAGS

CHIC

EVERDAY

FALL

COLOURS

WHITE-BOOTS

NOVEMBER 10, 2014

GARMENTS

White Cheap Monday Boots

Chilli Beans Sunglasses

Missguided Romper

Daniel Wellington Watch

COMMENTS

Nice!!

Love the top!

cute

...

Figure : An example of a post on <http://www.chictopia.com>. We crawled the site for 180K posts.

How Fashionable Are You?

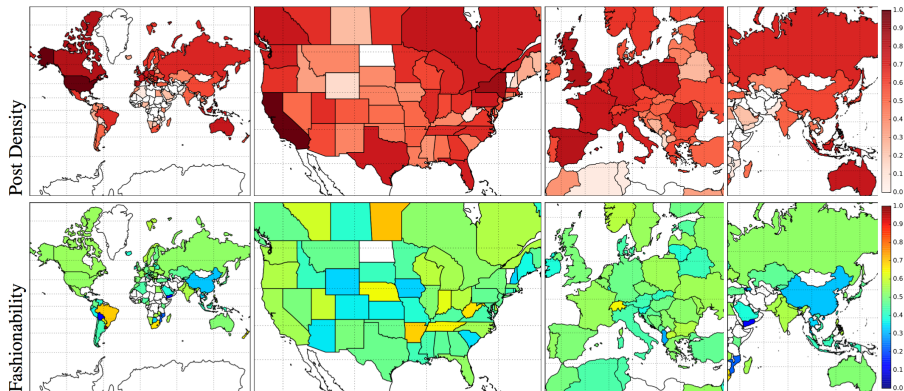


Figure 3: Visualization of the density of posts and fashionability by country.

How Fashionable Are You?

| City Name | Posts | Fashionability |
|---------------|-------|----------------|
| Manila | 4269 | 6.627 |
| Los Angeles | 8275 | 6.265 |
| Melbourne | 1092 | 6.176 |
| Montreal | 1129 | 6.144 |
| Paris | 2118 | 6.070 |
| Amsterdam | 1111 | 6.059 |
| Barcelona | 1292 | 5.845 |
| Toronto | 1471 | 5.765 |
| Bucharest | 1385 | 5.667 |
| New York | 4984 | 5.514 |
| London | 3655 | 5.444 |
| San Francisco | 2880 | 5.392 |
| Madrid | 1747 | 5.371 |
| Vancouver | 1468 | 5.266 |
| Jakarta | 1156 | 4.398 |

Table 2: Fashionability of cities with at least 1000 posts.

How Fashionable Are You?

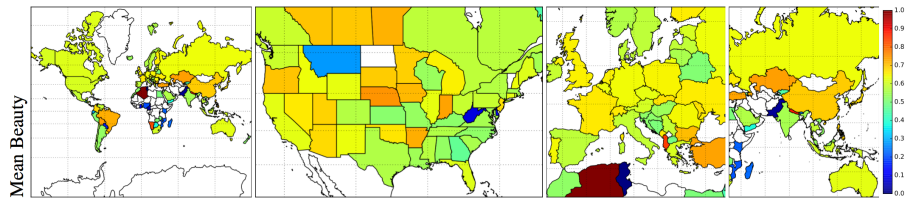
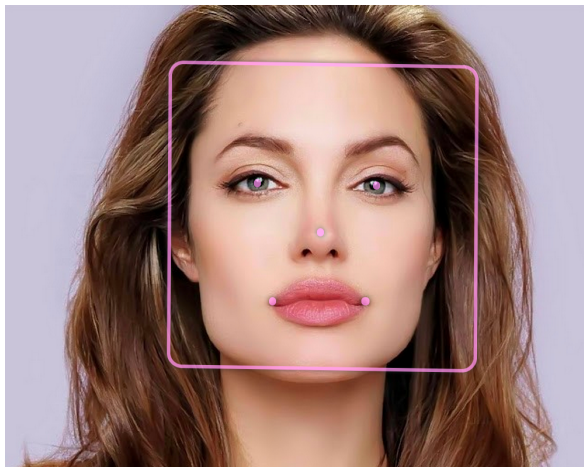


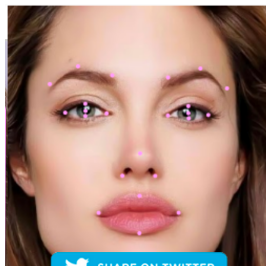
Figure : We ran a face detector that predicts also beauty of the face, age, ethnicity, mood.

How Fashionable Are You?

- Face detector + attributes



<http://www.rekognition.com>

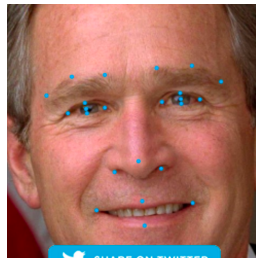
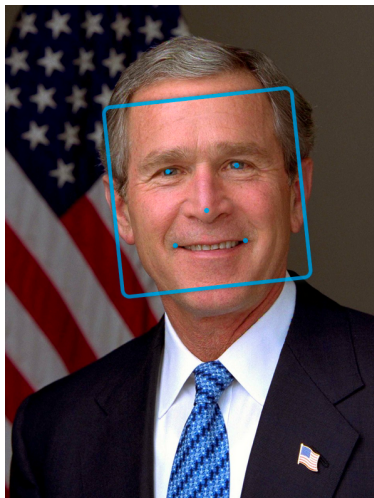


SHARE ON TWITTER

```
confidence : true ( value : 1 )
pose : roll(0.9) ,yaw(3.59) ,pitch(8.63)
race : white(0.28)
emotionin : calm:68%,happy:28%
age : 29.52 ( value : 29.52 )
smile : true ( value : 0.65 )
glasses : no glass ( value : 0 )
sunglasses : false ( value : 0 )
eye_closed : open ( value : 0 )
mouth_open_wide : 3% ( value : 0.03 )
beauty : 99.42 ( value : 0.99422 )
gender : female ( value : 0 )
```


How Fashionable Are You?

- Face detector + attributes

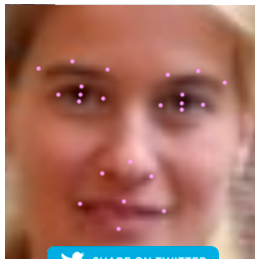
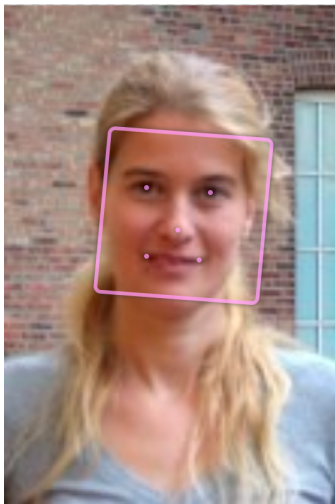


confidence : true (value : 1)
pose : roll(-6.26) ,yaw(-6.81) ,pitch(1.66)
race : white(0.99)
emotion : happy:92%,confused:1%
age : 60.9 (value : 60.9)
smile : true (value : 0.87)
glasses : no glass (value : 0.01)
sunglasses : false (value : 0)
eye_closed : open (value : 0)
mouth_open_wide : 3% (value : 0.03)
beauty : 78.62 (value : 0.78628)
gender : male (value : 1)

<http://www.rekognition.com>

How Fashionable Are You?

- Face detector + attributes



 SHARE ON TWITTER

```
confidence : true ( value : 1 )  
pose : roll(4.3) , yaw(10.36) , pitch(-5.4)  
race : white(0.73)  
emotion : happy:99% , calm:3%  
age : 29.12 ( value : 29.12 )  
smile : true ( value : 0.86 )  
glasses : no glass ( value : 0 )  
sunglasses : false ( value : 0 )  
eye_closed : open ( value : 0 )  
mouth_open_wide : 0% ( value : 0 )  
beauty : 53.67 ( value : 0.53674 )  
gender : female ( value : 0.03 )
```

<http://www.rekognition.com>

How Fashionable Are You?

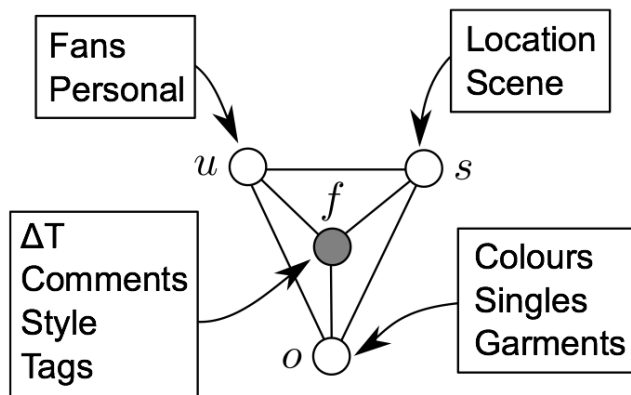


Figure : Our model is a Conditional Random Field that uses many visual and textual features, as well as meta-data features such as where the user is from.

How Fashionable Are You?



Figure : We predict fashionability of users.



Figure : We predict what kind of outfit the person wears.

How Fashionable Can You Become?



Current Outfit:
Pink Outfit (3)

Recommendations:
Heels (8)
Pastel Shirts/Skirts (8)
Black/Gray Tights/Sweater (5)



Current Outfit:
Pink/Blue Shoes/Dress Shorts (3)

Recommendations:
Black/Gray Tights/Sweater (5)
Black Casual (5)
Black Boots/Tights (5)



Current Outfit:
Pink/Black Misc. (5)

Recommendations:
Pastel Dress (8)
Black/Blue Going out (8)
Black Casual (8)



Current Outfit:
Blue with Scarf (3)

Recommendations:
Heels (8)
Pastel Shirts/Skirts (8)
Black Casual (8)



Current Outfit:
Pink/Blue Shoes/Dress Shorts (3)

Recommendations:
Black Casual (7)
Black Heavy (3)
Navy and Bags (3)



Current Outfit:
Formal Blue/Brown (5)



















Recommendations:
Pastel Shirts/Skirts (9)
Black/Blue Going out (8)
Black Boots/Tights (8)

Figure : Examples of recommendations provided by our model. The parenthesis we show the fashionability scores.

Not a big deal... but

- Appear all over the Tech and News

News and Tech websites

| | | | | |
|---|--|--|---|---|
|  New Scientist |  Quartz |  Tech Times |  Wired, UK |  Mashable |
|  AOL News (video) |  Huffington Post, UK (video) |  Huffington Post, Canada |  MSN, Canada |  Protein |
|  Yahoo, Canada |  Science Daily |  Daily Mail, UK |  PSFK |  Toronto Star |
|  Gizmag |  TheRecord.com |  iDigitalTimes | | |

Not a big deal... but

- Appear all over the Tech and News
- All over the Fashion press

Fashion Magazines (Online)

BAZAAR
Harper's Bazaar

marieclaire
Marie Claire

E L L E
Elle

Red
Red Magazine
(UK)

GLAMOUR
Glamour

YAHOO!
STYLE
Yahoo Style

COSMOPOLITAN
Cosmopolitan

FASHION
Fashion
Magazine

The Pool
The Pool (UK)

FashionNotes
FASHION + TECHNOLOGY
FashionNotes

Not a big deal... but

- Appear all over the Tech and News
- All over the Fashion press
- International News and TV (Fox, BBC, SkypeNews, RTVE, etc)

International News

VOGUE
Vogue (ES)

WIRED
Wired (DE)

jetzt.de
Süddeutsche Zeitung
Jetzt (DE)

SinEmbargo.mx
SinEmbargo
(MX)

pop Nauka w Polsce
Nauka (PL)

STYLEBOOK
Stylebook (DE)

marieclaire
Marie Claire
(FR)

FASHION POLICE.ng
Fashion Police
(NG)

FASHION
Amsterdam
Fashion (NL)

ANSA.it
Ansa (IT)

Pluska
Pluska (SK)

ELLE
Elle (NL)

IT NEWS
IT News (SK)

POPSUGAR
PopSugar (AU)

CenárioMT.com.br
CenárioMT (BR)

pressetext
Presstext (AT)

La Gazzetta dello Sport
Tutto il mondo della sport
La Gazzetta
dello Sport (IT)

woman
Woman (ES)

CSIC
CSIC (ES)

EFE ESTILO
EFE (ES)

Cosmopolitan (UK): *The technology scores your facial attributes (this just keeps getting better, doesn't it) from your looks, to your age, and the emotion you're showing, before combining all the information using an equation SO complex we won't begin to go into it.*

But the Most Important Impact



Previous Work

- Use the hinge loss to optimize the unaries only which are neural nets (Li and Zemel 14). Correlations between variables are not used for learning

Previous Work

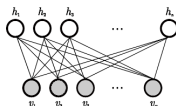
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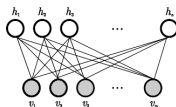
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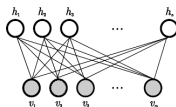
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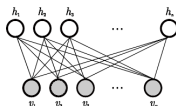
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- (Domke 13) treat the problem as learning a set of logistic regressors
- Fields of experts (Roth et al. 05), not deep, use CD training
- Many ideas go back to (Boutou 91)

Conclusions and Future Work

Conclusions:

- Modeling of correlations between variables
- Non-linear dependence on parameters
- Joint training of many convolutional neural networks
- Parallel implementation
- Wide range of applications: Word recognition, Tagging, Segmentation

Future work:

- Latent Variables
- More applications

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- Liang Chieh Chen (student)
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- Allan Yuille
- Ziyu Zhang (student)
- Yukun Zhu (student)

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