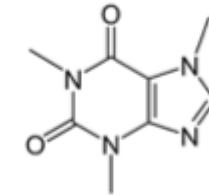


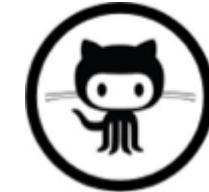
DIY Deep Learning for Vision: a Hands-On Tutorial with Caffe



Maximally accurate	Maximally specific
espresso	2.23192
coffee	2.19914
beverage	1.93214
liquid	1.89367
fluid	1.85519



caffe.berkeleyvision.org



github.com/BVLC/caffe

Look for further
details in the
outline notes



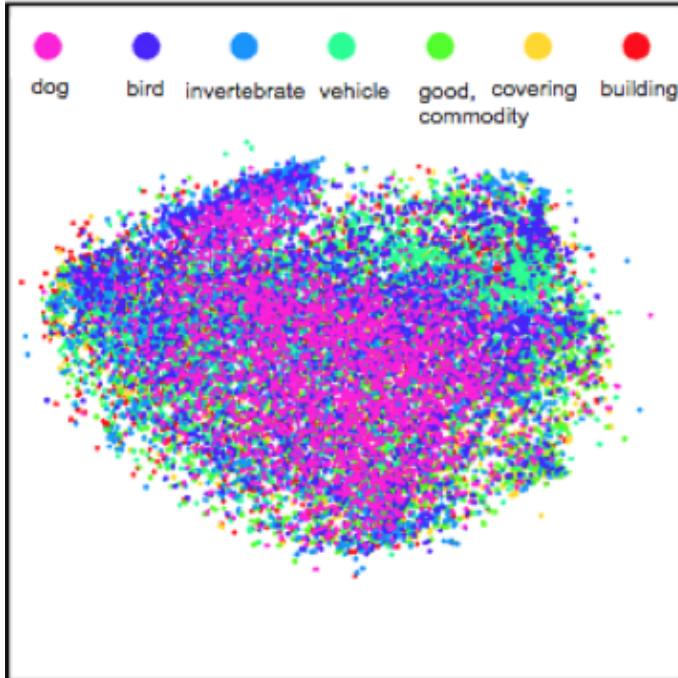
Evan Shelhamer, Jeff Donahue,
Jonathan Long, Yangqing Jia,
Ross Girshick



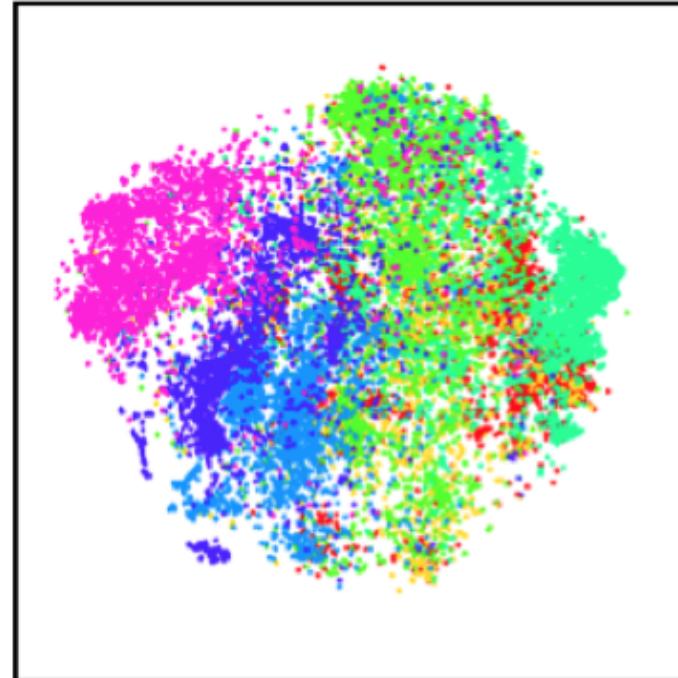
BV
LC

Why Deep Learning?

The Unreasonable Effectiveness of Deep Features



Low-level: Pool₁

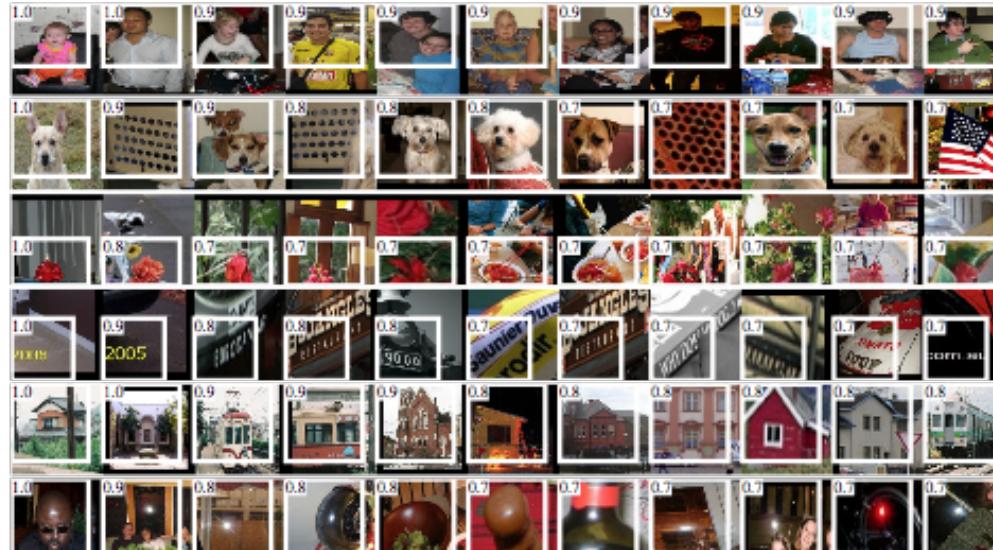


High-level: FC₆

Classes separate in the deep representations and transfer to many tasks.
[DeCAF] [Zeiler-Fergus]

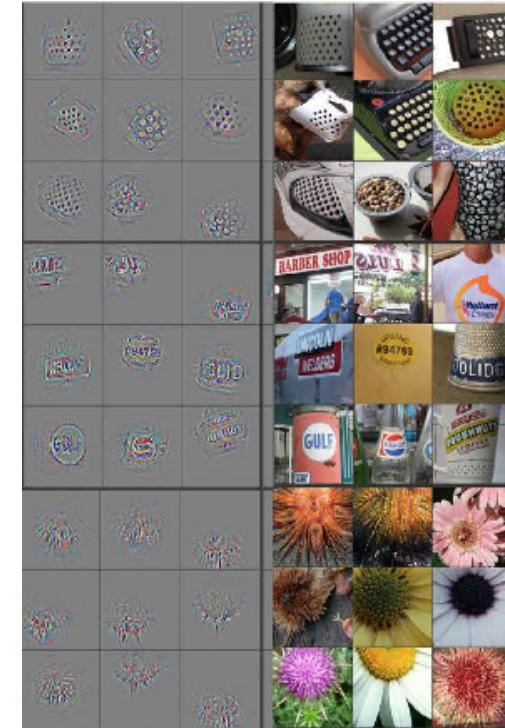
Why Deep Learning?

The Unreasonable Effectiveness of Deep Features



Maximal activations of pool₅ units

[R-CNN]



conv₅ DeConv visualization
[Zeiler-Fergus]

Rich visual structure of features deep in hierarchy.

Why Deep Learning?

The Unreasonable Effectiveness of Deep Features

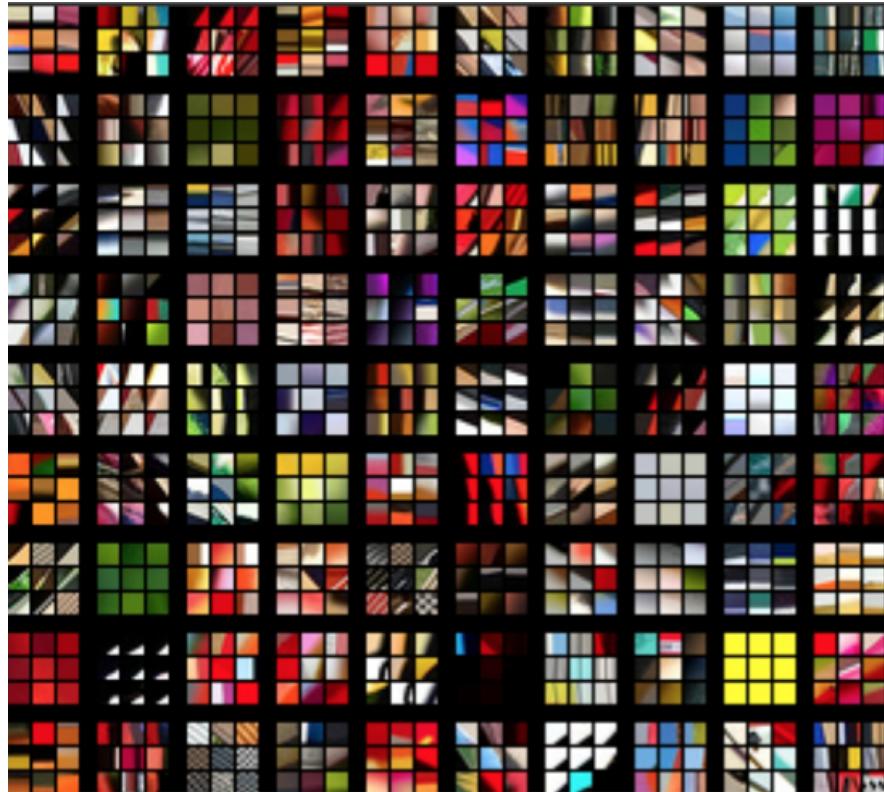
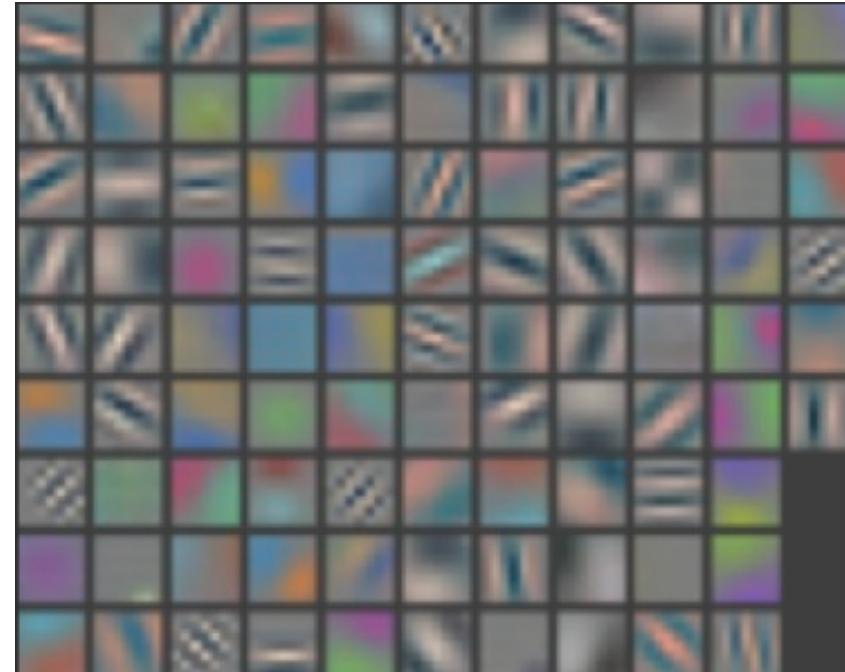


image patches that strongly activate 1st layer filters



1st layer filters

[Zeiler-Fergus]

What is Deep Learning?

Compositional Models
Learned End-to-End

What is Deep Learning?

Compositional Models

Learned End-to-End

Hierarchy of Representations

- vision: pixel, motif, part, object
- text: character, word, clause, sentence
- speech: audio, band, phone, word

concrete  abstract
 learning

What is Deep Learning?

Compositional Models

Learned End-to-End

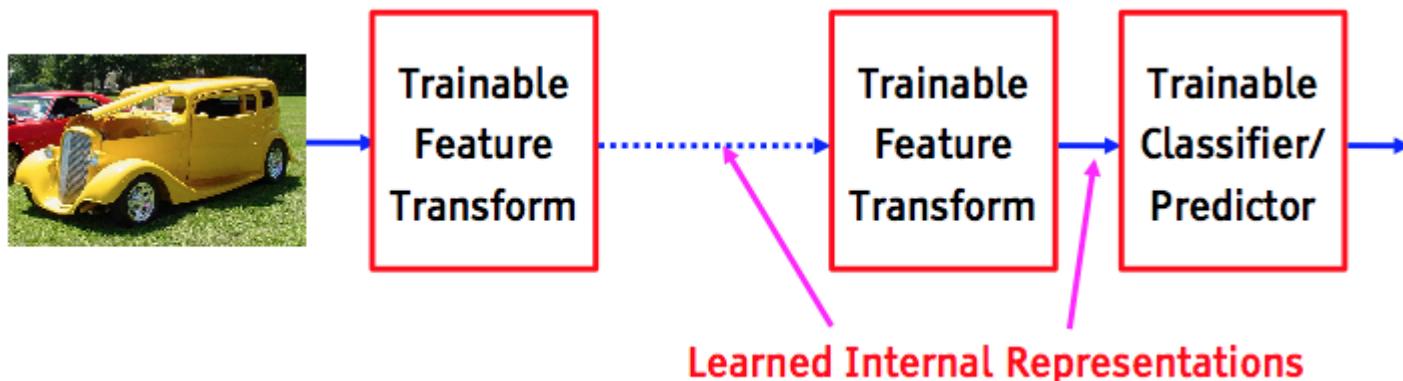


figure credit Yann LeCun, ICML '13 tutorial

What is Deep Learning?

Compositional Models
Learned End-to-End

Back-propagation: take the gradient of the model layer-by-layer by the chain rule to yield the gradient of all the parameters.

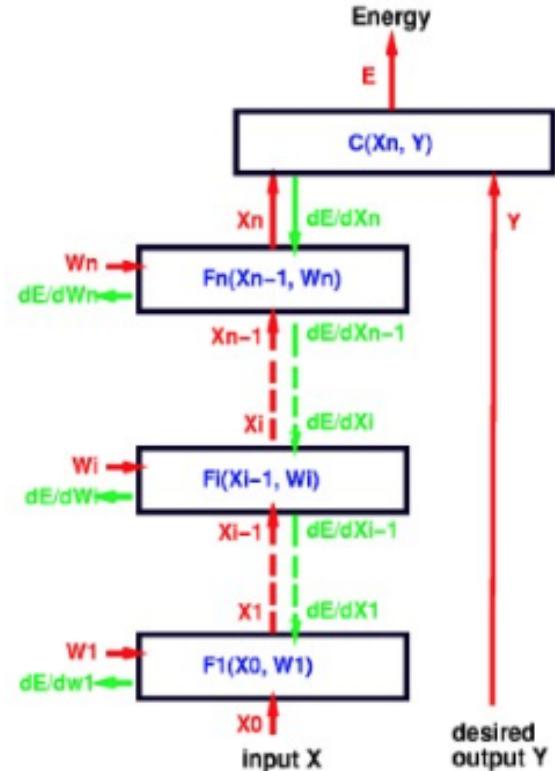
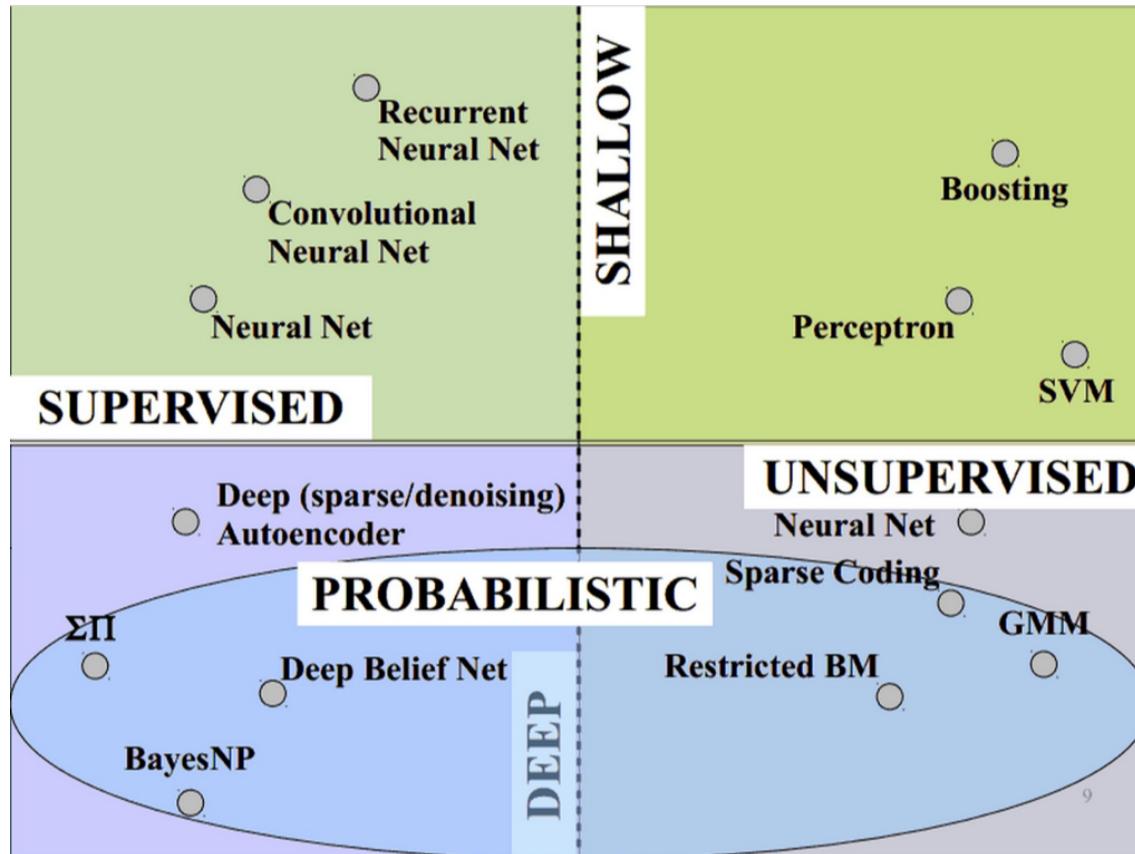


figure credit Yann LeCun, ICML '13 tutorial

What is Deep Learning?



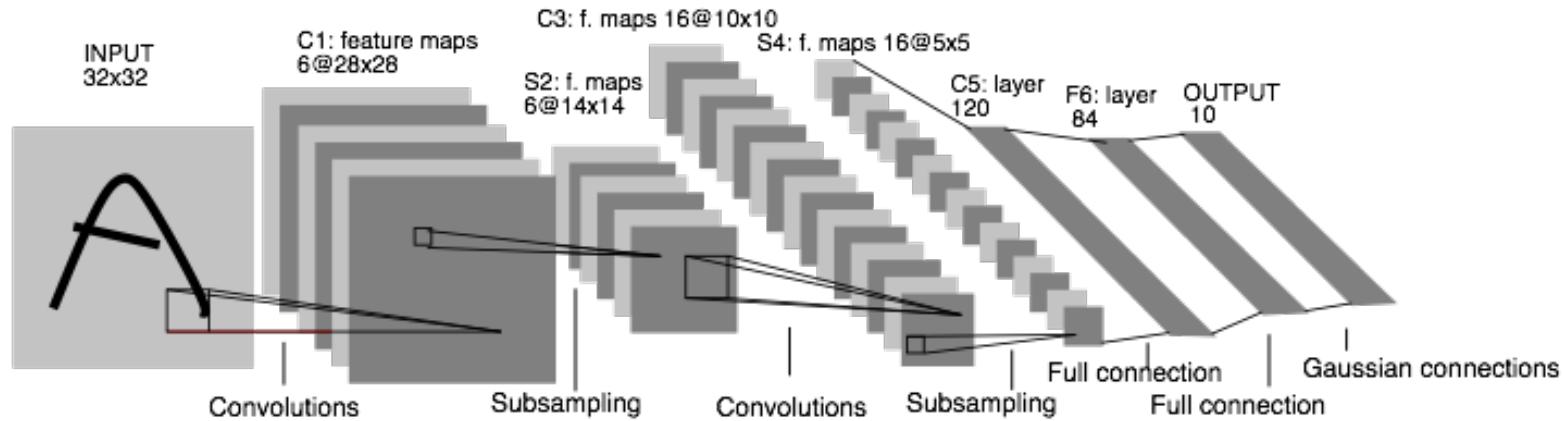
Vast space of models!

Caffe models are loss-driven:

- supervised
- unsupervised

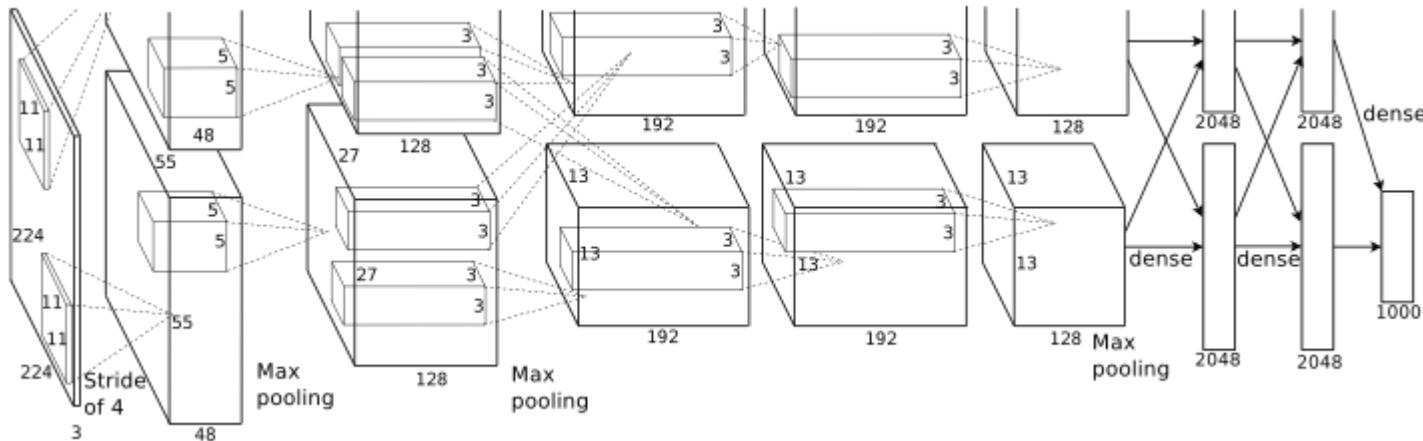
slide credit Marc'aurelio Ranzato,
CVPR '14 tutorial.

Convolutional Neural Nets (CNNs): 1989



LeNet: a layered model composed of convolution and subsampling operations followed by a holistic representation and ultimately a classifier for handwritten digits. [LeNet]

Convolutional Nets: 2012



AlexNet: a layered model composed of convolution, subsampling, and further operations followed by a holistic representation and all-in-all a landmark classifier on ILSVRC12. [AlexNet]

- + data
- + gpu
- + non-saturating nonlinearity
- + regularization

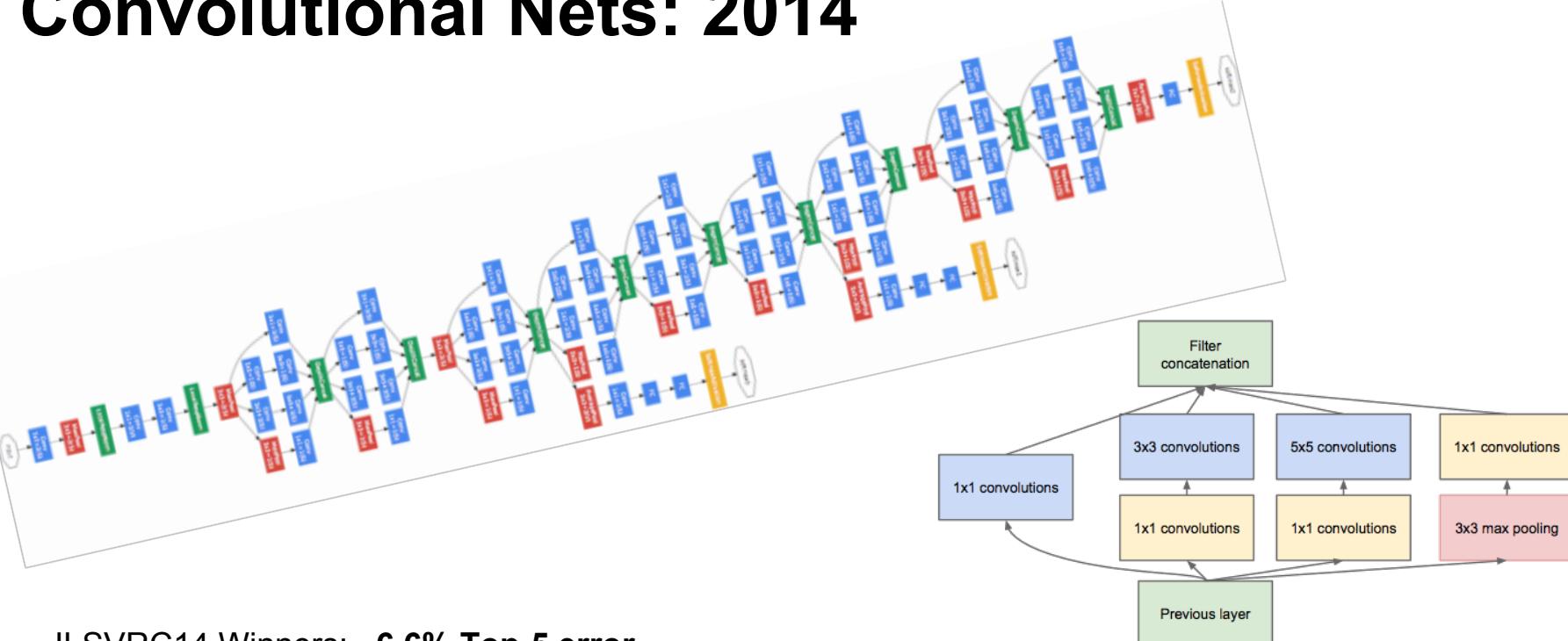
Convolutional Nets: 2012

parameters		FLOPs
4M	FULL CONNECT	4Mflop
16M	FULL 4096/ReLU	16M
37M	FULL 4096/ReLU	37M
	MAX POOLING	
442K	CONV 3x3/ReLU 256fm	74M
1.3M	CONV 3x3ReLU 384fm	224M
884K	CONV 3x3/ReLU 384fm	149M
	MAX POOLING 2x2sub	
	LOCAL CONTRAST NORM	
307K	CONV 11x11/ReLU 256fm	223M
	MAX POOL 2x2sub	
	LOCAL CONTRAST NORM	
35K	CONV 11x11/ReLU 96fm	105M

AlexNet: a layered model composed of convolution, pooling, and further operations followed by a holistic representation and all-in-all a landmark classifier on ILSVRC12. [AlexNet]

The fully-connected “FULL” layers are linear classifiers / matrix multiplications. ReLU are rectified-linear non-linearities on the output of layers.

Convolutional Nets: 2014



ILSVRC14 Winners: ~6.6% Top-5 error

- GoogLeNet: composition of multi-scale dimension-reduced modules (pictured)
 - VGG: 16 layers of 3x3 convolution interleaved with max pooling + 3 fully-connected layers
- + depth
+ data
+ dimensionality reduction

Learning about Deep Learning

Refer to the [Tutorial on Deep Learning for Vision](#) from CVPR '14.

- Fundamentals on supervised and unsupervised deep learning by Marc'Aurelio Ranzato
- List of references to explore
- Advanced ideas and current research directions

Pairs well with this tutorial!

Deep Learning, as it is executed...

What should a framework handle?

Compositional Models

Decompose the problem and code!

End-to-End Learning

Solve and check!

Vast Space of Architectures and Tasks

Define, experiment, and extend!

Frameworks

- Torch7
 - NYU
 - scientific computing framework in Lua
 - supported by Facebook
- Theano/Pylearn2
 - U. Montreal
 - scientific computing framework in Python
 - symbolic computation and automatic differentiation
- Cuda-Convnet2
 - Alex Krizhevsky
 - Very fast on state-of-the-art GPUs with Multi-GPU parallelism
 - C++ / CUDA library

Framework Comparison

- More alike than different
 - All express deep models
 - All are nicely open-source
 - All include scripting for hacking and prototyping
- No strict winners – experiment and choose the framework that best fits your work
- We like to brew our deep networks with **Caffe**

Why Caffe? In one sip...

- **Expression:** models + optimizations are plaintext schemas, not code.
- **Speed:** for state-of-the-art models and massive data.
- **Modularity:** to extend to new tasks and settings.
- **Openness:** common code and reference models for reproducibility.
- **Community:** joint discussion and development through BSD-2 licensing.

So what is Caffe?

- Pure C++ / CUDA architecture for deep learning
 - command line, Python, MATLAB interfaces
- Fast, well-tested code
- Tools, reference models, demos, and recipes
- Seamless switch between CPU and GPU
 - `Caffe::set_mode(Caffe::GPU);`



Prototype



Training



Deployment

All with essentially the same code!

Caffe is a Community

[project pulse](#)



[Unwatch](#) 631

[Unstar](#) 3,492

[Fork](#) 2,043

April 12, 2015 – May 12, 2015

Period: 1 month ▾

Overview



35 Active Pull Requests



218 Active Issues



10
Merged Pull Requests



25
Proposed Pull Requests



196
Closed Issues



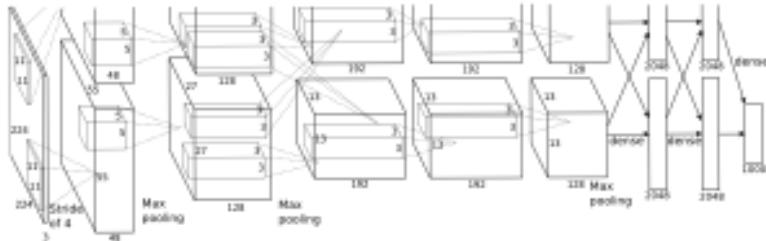
22
New Issues

Excluding merges, **27 authors** have pushed **15 commits** to master and **86 commits** to all branches. On master, **21 files** have changed and there have been **134 additions** and **101 deletions**.

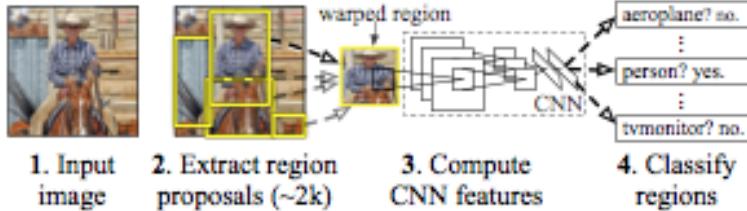


Reference Models

AlexNet: ImageNet Classification



R-CNN: Regions with CNN features



Caffe offers the

- model definitions
- optimization settings
- pre-trained weights

so you can start right away.

The BVLC models are licensed for unrestricted use.

Open Model Collection

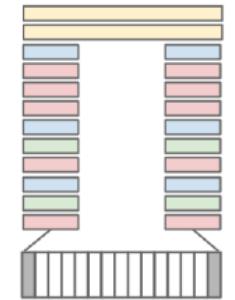
The Caffe [Model Zoo](#)

- open collection of deep models to share innovation
 - VGG ILSVRC14 + Devil models **in the zoo**
 - Network-in-Network / CCCP model **in the zoo**
 - MIT Places scene recognition model **in the zoo**
- help disseminate and reproduce research
- bundled tools for loading and publishing models

Share Your Models! with your citation + license of course

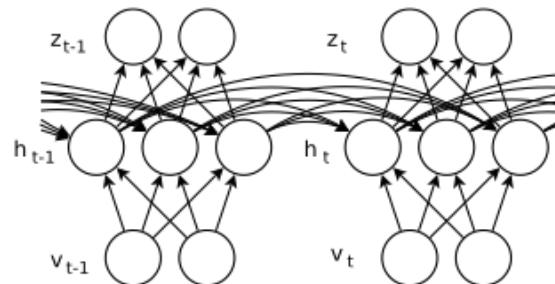
Architectures

DAGs
multi-input
multi-task



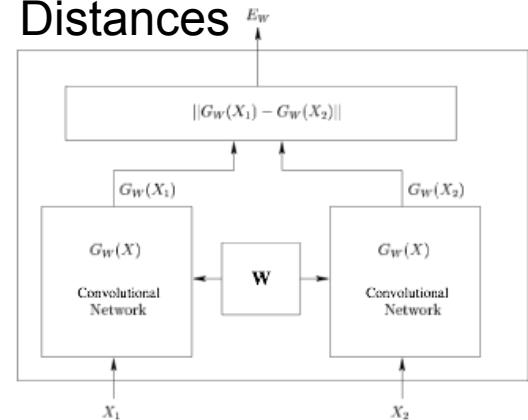
[Karpathy14]

Weight Sharing
Recurrent (RNNs)
Sequences



[Sutskever13]

Siamese Nets
Distances



[Chopra05]

Define your own model from our catalogue
of layers types and start learning.

Brewing by the Numbers...

- Speed with Krizhevsky's 2012 model:
 - 2 ms / image on K40 GPU
 - ~1 ms inference with Caffe + cuDNN
 - 60 million images / day
 - 8-core CPU: ~20 ms/image
- 9k lines of C++ code (20k with tests)

● C++ 84.2%

● Python 10.5%

● Cuda 3.9%

● Other 1.4%

CAFFE INTRO

Net

- A network is a set of layers connected as a DAG:

```
name : "dummy-net"
```

```
layers { name: "data" ... }
```

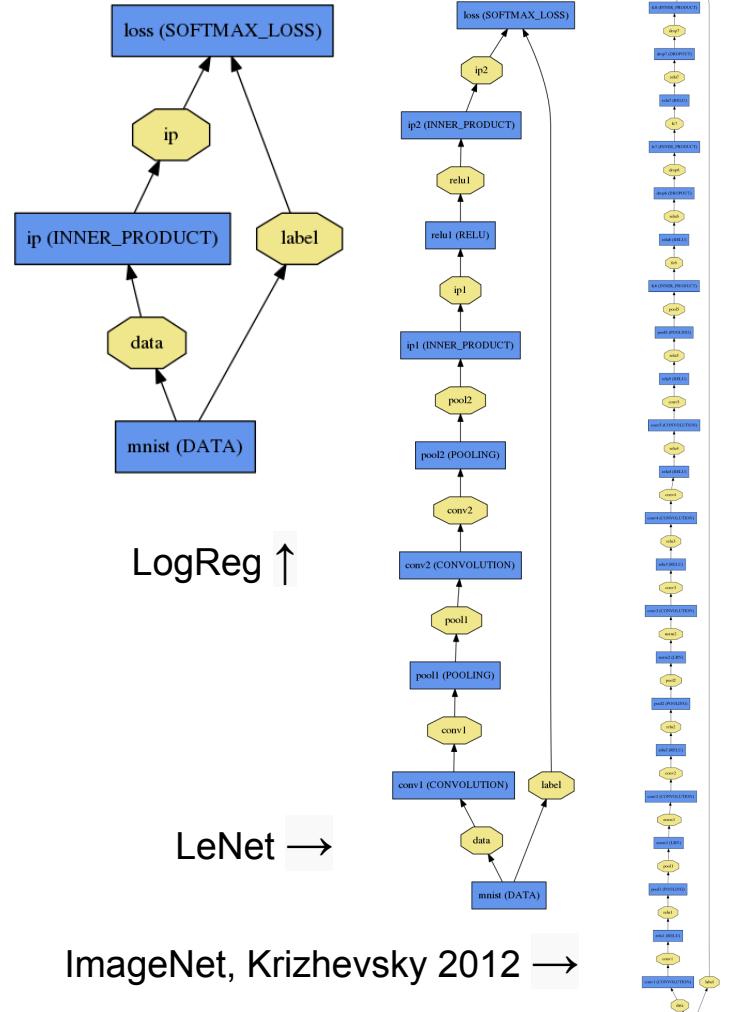
```
layers { name: "conv" ... }
```

```
layers { name: "pool" ... }
```

... more layers ...

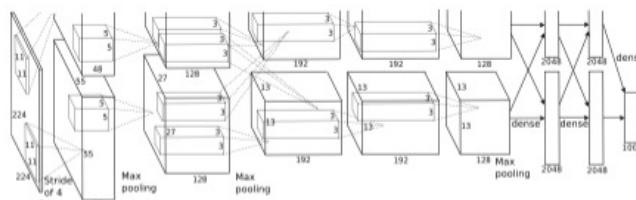
```
layers { name: "loss" ... }
```

- Caffe creates and checks the net from the definition.
- Data and derivatives flow through the net as *blobs* – a an array interface



Forward / Backward the essential Net computations

Forward:
inference $f_W(x)$



“espresso”
+ loss

$\nabla f_W(x)$ Backward:
learning

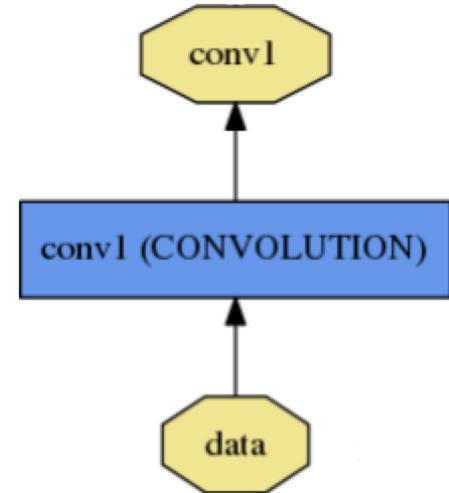
Caffe models are complete machine learning systems for inference and learning.
The computation follows from the model definition. Define the model and run.

Layer

```
name: "conv1"
type: CONVOLUTION
bottom: "data"
top: "conv1"
convolution_param {
    num_output: 20
    kernel_size: 5
    stride: 1
    weight_filler {
        type: "xavier"
    }
}
```

} name, type, and the connection structure (input blobs and output blobs)

} layer-specific parameters



- Every layer type defines

- **Setup**
- **Forward**
- **Backward**

* Nets + Layers are defined by [protobuf](#) schema

Protobuf

```
name: "conv1"
type: "Convolution"
bottom: "data"
top: "conv1"
convolution_param {
    num_output: 20
    kernel_size: 5
    stride: 1
    weight_filler {
        type: "xavier"
    }
}
```

- Nets + Layers are defined by [protobuf](#) schema
- Net / Layer / Solver schema is defined by **caffe.proto**
- Consult this definition for all the configuration options (inline comments explain it)

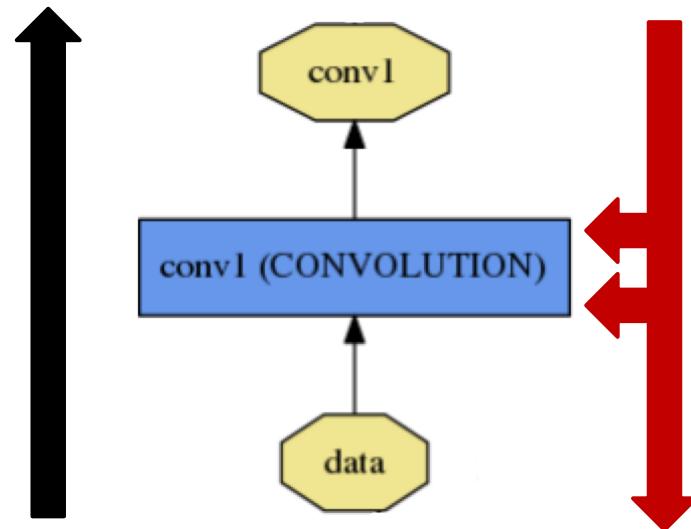
Layer Protocol

Setup: run once for initialization.

Forward: make output given input.

Backward: make gradient of output

- w.r.t. bottom
- w.r.t. parameters (if needed)



Compositional Modeling

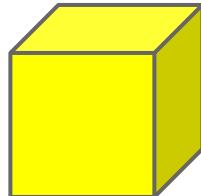
The Net's forward and backward passes
are composed of the layers' steps.

[Layer Development Checklist](#)

Blob

Blobs are 4-D arrays for storing and communicating information.

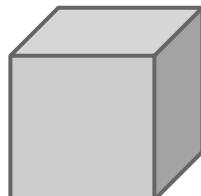
- hold data, derivatives, and parameters
- lazily allocate memory
- shuttle between CPU and GPU



Data

Number x K Channel x Height x Width

256 x 3 x 227 x 227 for ImageNet train input



Parameter: Convolution Weight

N Output x K Input x Height x Width

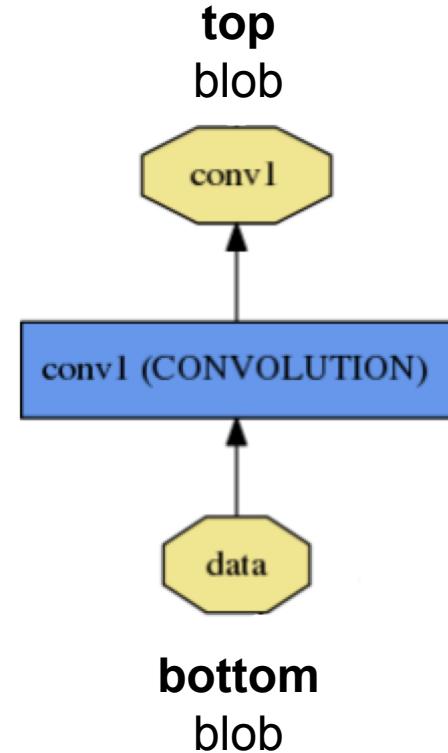
96 x 3 x 11 x 11 for CaffeNet conv1



Parameter: Convolution Bias

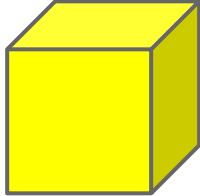
96 x 1 x 1 x 1 for CaffeNet conv1

```
name: "conv1"
type: CONVOLUTION
bottom: "data"
top: "conv1"
... definition ...
```



Blob

Blobs provide a unified memory interface.



Reshape(num, channel, height, width)

- declare dimensions
- make *SyncedMem* -- but only lazily allocate

cpu_data(), mutable_cpu_data()

- host memory for CPU mode

gpu_data(), mutable_gpu_data()

- device memory for GPU mode

{cpu,gpu}_diff(), mutable_{cpu,gpu}_diff()

- derivative counterparts to data methods
- easy access to data + diff in forward / backward



SyncedMem
allocation + communication



Solving: Training a Net

Optimization like model definition is configuration.

`train_net`: "lenet_train.prototxt"

`base_lr`: 0.01

`momentum`: 0.9

`weight_decay`: 0.0005

`max_iter`: 10000

`snapshot_prefix`: "lenet_snapshot"

All you need to run things
on the GPU.

```
> caffe train -solver lenet_solver.prototxt -gpu 0
```

Stochastic Gradient Descent (SGD) + momentum ·

Adaptive Gradient (ADAGRAD) · Nesterov's Accelerated Gradient (NAG)

Recipe for Brewing

- Convert the data to Caffe-format
 - Imdb, leveldb, hdf5 / .mat, list of images, etc.
- Define the Net
- Configure the Solver
- `caffe train -solver solver.prototxt -gpu 0`
- Examples are your friends
 - `caffe/examples/mnist`, `cifar10`, `imagenet`
 - `caffe/examples/*.ipynb`
 - `caffe/models/*`

(Examples)

Logistic Regression

Learn LeNet on MNIST

Help Brewing

Documentation

- [tutorial documentation](#)
- [worked examples](#)

Modeling, Usage, and Installation

- [caffe-users group](#)
- [gitter.im chat](#)

EXAMPLES + APPLICATIONS

Share a Sip of Brewed Models

demo.caffe.berkeleyvision.org

demo code open-source and bundled



Maximally accurate	Maximally specific
cat	1.80727
domestic cat	1.74727
feline	1.72787
tabby	0.99133
domestic animal	0.78542

Scene Recognition

<http://places.csail.mit.edu/>



Predictions:

- **Type of environment:** outdoor
- **Semantic categories:** skyscraper:0.69, tower:0.16, office_building:0.11,
- **SUN scene attributes:** man-made, vertical components, natural light, open area, nohorizon, glossy, metal, wire, clouds, far-away horizon

Object Detection

R-CNN: Regions with Convolutional Neural Networks

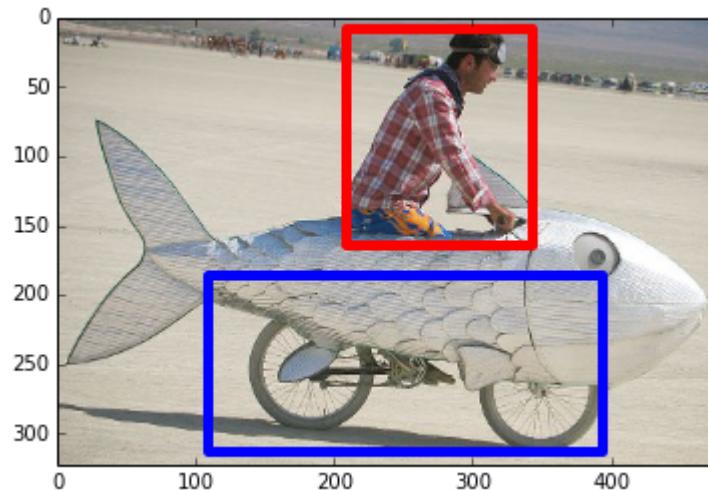
<http://nbviewer.ipython.org/github/BVLC/caffe/blob/master/examples/detection.ipynb>

Full R-CNN scripts available at

<https://github.com/rbgirshick/rcnn>

Ross Girshick et al.

*Rich feature hierarchies for accurate
object detection and semantic
segmentation.* CVPR14.



Visual Style Recognition

Karayev et al. *Recognizing Image Style*. BMVC14. Caffe fine-tuning example.

Demo online at <http://demo.vislab.berkeleyvision.org/> (see Results Explorer).

Ethereal



HDR



Melancholy



Minimal



Other Styles:

[Vintage](#)

[Long Exposure](#)

[Noir](#)

[Pastel](#)

[Macro](#)

... and so on.

Embedded Caffe

Caffe on the NVIDIA Jetson TK1 mobile board



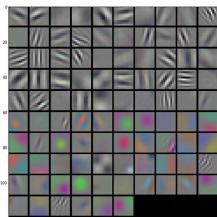
- 10 watts of power
- inference at 35 ms per image
- how-to guide
courtesy of Pete Warden
- cuDNN for TK1 recently released!

Feature Extraction + Visualization



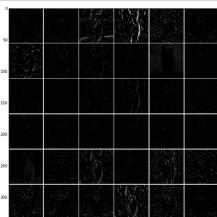
The first layer filters, conv1

```
In [8]: # the parameters are a list of [weights, biases]
filters = net.params['conv1'][0].data
vis_square(filters.transpose(0, 2, 3, 1))
```

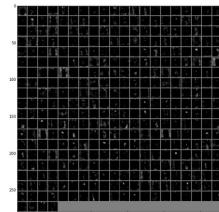


The first layer output, conv1 (rectified responses of the filters above, first 36 only)

```
In [9]: feat = net.blobs['conv1'].data[4, :36]
vis_square(feat, padval=1)
```

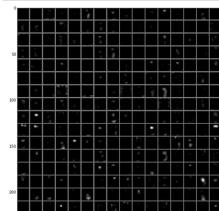


```
In [13]: feat = net.blobs['conv4'].data[4]
vis_square(feat, padval=0.5)
```



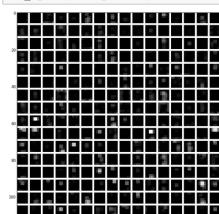
The fifth layer output, conv4 (rectified, all 256 channels)

```
In [14]: feat = net.blobs['conv5'].data[4]
vis_square(feat, padval=0.5)
```

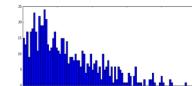
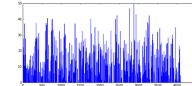


The fifth layer after pooling, pool5

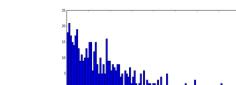
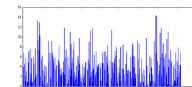
```
In [15]: feat = net.blobs['pool5'].data[4]
vis_square(feat, padval=1)
```



```
In [16]: feat = net.blobs['fc6'].data[4]
plt.subplot(2, 1, 1)
plt.plot(feat.flat)
plt.subplot(2, 1, 2)
_= plt.hist(feat.flat[feat.flat > 0], bins=100)
```

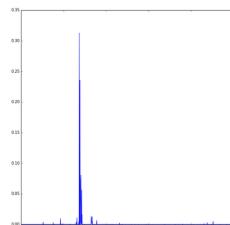


```
In [17]: feat = net.blobs['fc7'].data[4]
plt.subplot(2, 1, 1)
plt.plot(feat.flat)
plt.subplot(2, 1, 2)
_= plt.hist(feat.flat[feat.flat > 0], bins=100)
```

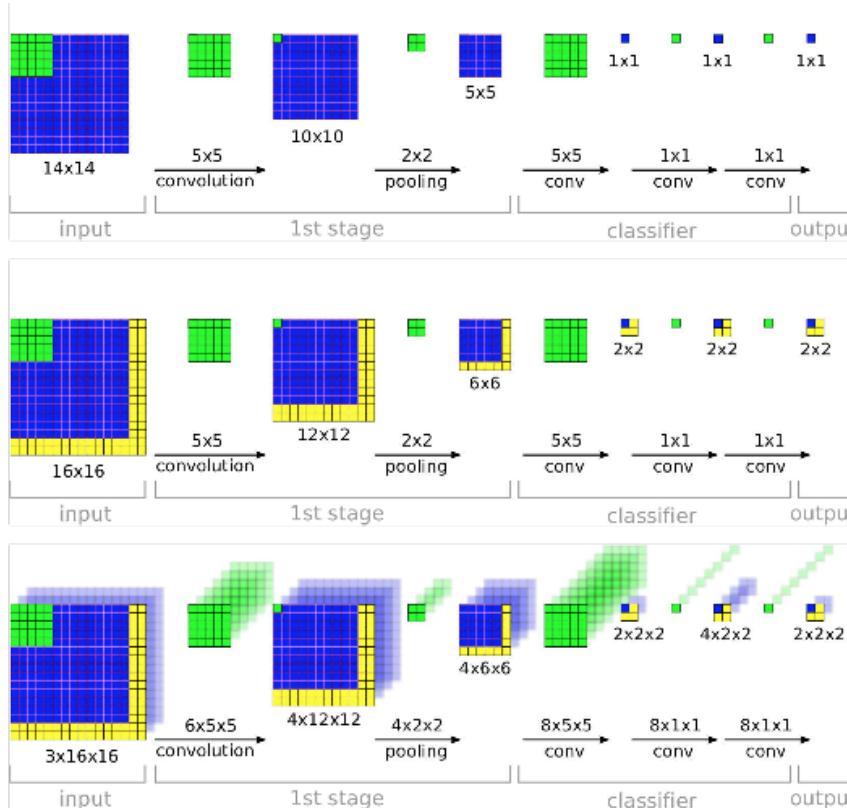


```
In [18]: feat = net.blobs['prob'].data[4]
plt.plot(feat.flat)
```

```
Out[18]: [matplotlib.lines.Line2D at 0x12b260710>]
```



Editing Model Parameters



Transform fixed-input models into any-size models by translating inner products to convolutions.

The computation exploits a natural efficiency of convolutional neural network (CNN) structure by dynamic programming in the forward pass from shallow to deep layers and analogously in backward.

Net surgery in Caffe

how to transform models:

- make fully convolutional
- transplant parameters

FINE-TUNING

Fine-tuning

Transferring learned weights to kick-start models

- Take a pre-trained model and fine-tune to new tasks
[DeCAF] [Zeiler-Fergus] [OverFeat]



dog bird invertebrate vehicle good, covering commodity building



Your Task



**Style
Recognition**



© kaggle.com

**Dogs vs.
Cats**
top 10 in
10 minutes

From ImageNet to Style

Simply change a few lines in the layer definition

```
layers {
  name: "data"
  type: DATA
  data_param {
    source: "ilsvrc12 train leveldb" ⇢
    mean_file: "../../data/ilsvrc12"
    ...
  }
  ...
}

layers {
  name: "fc8"
  type: INNER_PRODUCT
  blobs_lr: 1
  blobs_lr: 2
  weight_decay: 1
  weight_decay: 0
  inner_product_param {
    num_output: 1000
    ...
  }
}

layers {
  name: "data"
  type: DATA
  data_param {
    source: "style leveldb"
    mean_file: "../../data/ilsvrc12"
    ...
  }
  ...
}

layers {
  name: "fc8-style" new name = new params
  type: INNER_PRODUCT
  blobs_lr: 1
  blobs_lr: 2
  weight_decay: 1
  weight_decay: 0
  inner_product_param {
    num_output: 20
    ...
  }
}
```

Input:
A different source

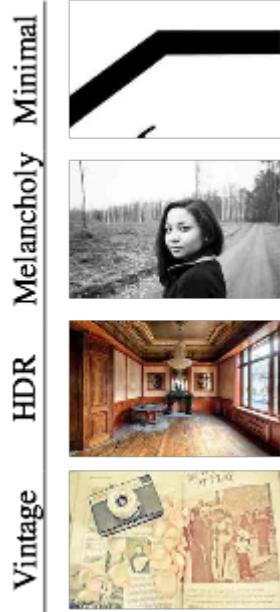
Last Layer:
A different classifier

From ImageNet to Style

```
> caffe train -solver models/finetune_flickr_style/solver.prototxt  
      -weights bvlc_reference_caffenet.caffemodel
```

Step-by-step in pycaffe:

```
pretrained_net = caffe.Net(  
    "net.prototxt", "net.caffemodel")  
  
solver = caffe.SGDSolver("solver.prototxt")  
solver.net.copy_from(pretrained_net)  
solver.solve()
```



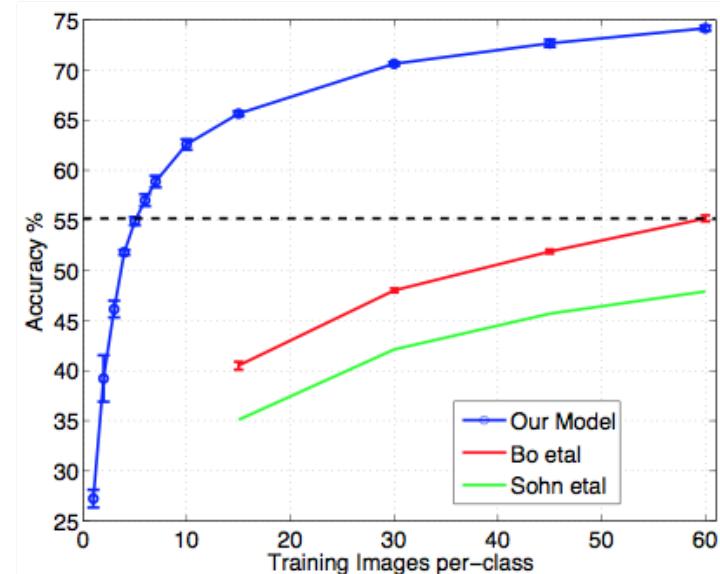
When to Fine-tune?

A good first step

- More robust optimization – good initialization helps
- Needs less data
- Faster learning

State-of-the-art results in

- recognition
- detection
- segmentation



Fine-tuning Tricks

Learn the last layer first

- Caffe layers have local learning rates: `param { lr_mult: 1 }`
- Freeze all but the last layer for fast optimization and avoiding early divergence.
- Stop if good enough, or keep fine-tuning

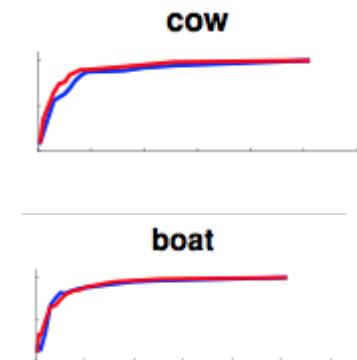
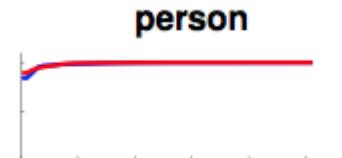
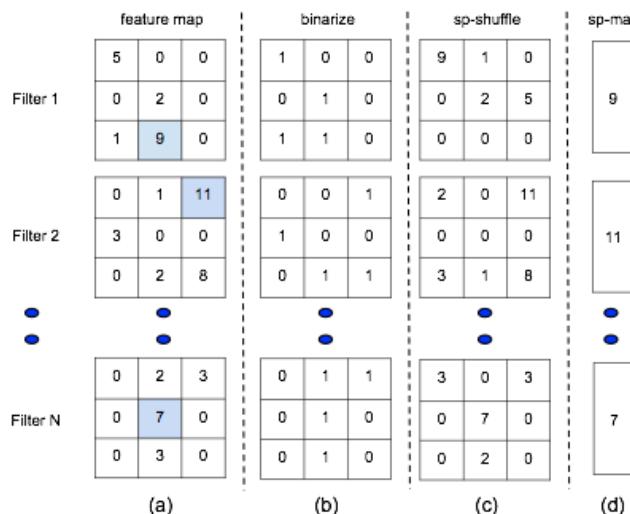
Reduce the learning rate

- Drop the solver learning rate by 10x, 100x
- Preserve the initialization from pre-training and avoid thrashing

Do net surgery

Training & Fine-tuning Analysis

- Supervised pre-training does not overfit
- Representation is (mostly) distributed
- Sparsity comes “for free” in deep representation



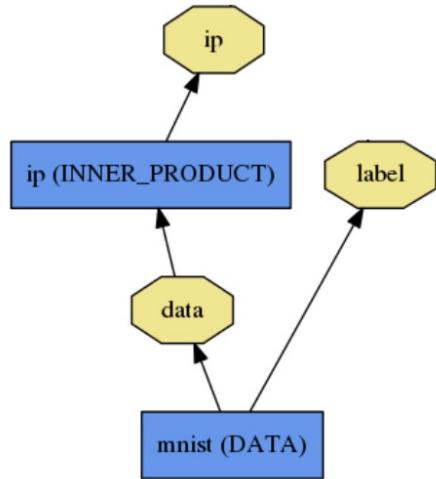
(Example)

Fine-tuning from ImageNet to Style

LOSS

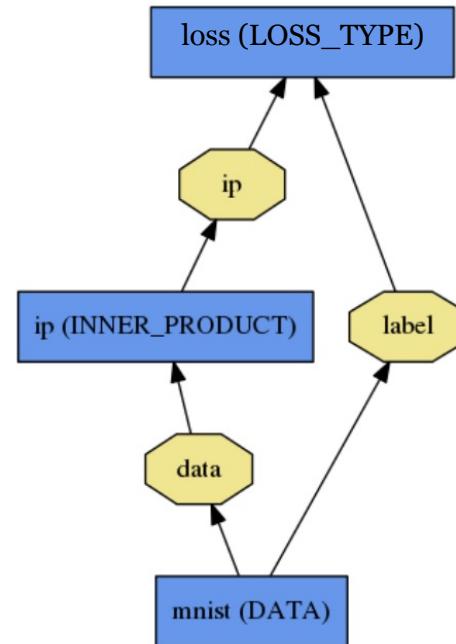
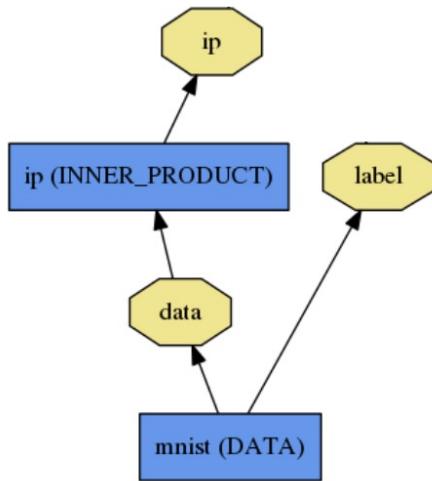
Loss

What kind of model is this?



Loss

What kind of model is this?



Who knows! Need a **loss function**.

Classification
SOFTMAX_LOSS
HINGE_LOSS

Linear Regression
EUCLIDEAN_LOSS

Attributes / Multiclassification
SIGMOID_CROSS_ENTROPY_LOSS

Others...

New Task
NEW_LOSS

Loss

- **Loss function** determines the learning task.
- Given data D, a Net typically minimizes:

$$L(W) = \frac{1}{|D|} \sum_i^{|D|} f_W(X^{(i)}) + \lambda r(W)$$

Data term: error averaged
over instances

Regularization
term: penalize
large weights to
improve
generalization

Loss

- The data error term $f_W(X^{(i)})$ is computed by Net::Forward
- Loss is computed as the output of Layers
- Pick the loss to suit the task – many different losses for different needs

Softmax Loss Layer

- Multinomial logistic regression: used for predicting a single class of K mutually exclusive classes

```
layers {
    name: "loss"
    type: SOFTMAX_LOSS
    bottom: "pred"
    bottom: "label"
    top: "loss"
}
```

$$\hat{p}_{nk} = \exp(x_{nk}) / [\sum_{k'} \exp(x_{nk'})]$$

$$E = \frac{-1}{N} \sum_{n=1}^N \log(\hat{p}_{n,l_n}),$$

Sigmoid Cross-Entropy Loss

- Binary logistic regression: used for predicting K independent probability values in $[0, 1]$

```
layers {
    name: "loss"
    type: SIGMOID_CROSS_ENTROPY_LOSS
    bottom: "pred"
    bottom: "label"
    top: "loss"
}
```

$$y = (1 + \exp(-x))^{-1}$$

$$E = \frac{-1}{n} \sum_{n=1}^N [p_n \log \hat{p}_n + (1 - p_n) \log(1 - \hat{p}_n)]$$

Euclidean Loss

- A loss for regressing to real-valued labels [-inf, inf]

```
layers {
    name: "loss"
    type: EUCLIDEAN_LOSS
    bottom: "pred"
    bottom: "label"
    top: "loss"
}
```

$$E = \frac{1}{2N} \sum_{n=1}^N \|\hat{y}_n - y_n\|_2^2$$

Multiple loss layers

- Your network can contain as many loss functions as you want
- Reconstruction and Classification:

$$E = \frac{1}{2N} \sum_{n=1}^N \|\hat{y}_n - y_n\|_2^2 + \frac{-1}{N} \sum_{n=1}^N \log(\hat{p}_{n,t_n})$$

```
layers {
    name: "recon-loss"
    type: EUCLIDEAN_LOSS
    bottom: "reconstructions"
    bottom: "data"
    top: "recon-loss"
}

layers {
    name: "class-loss"
    type: SOFTMAX_LOSS
    bottom: "class-preds"
    bottom: "class-labels"
    top: "class-loss"
}
```

Multiple loss layers

“*_LOSS” layers have a default loss weight of 1

```
layers {  
    name: "loss"  
    type: SOFTMAX_LOSS  
    bottom: "pred"  
    bottom: "label"  
    top: "loss"  
}
```

==

```
layers {  
    name: "loss"  
    type: SOFTMAX_LOSS  
    bottom: "pred"  
    bottom: "label"  
    top: "loss"  
    loss_weight: 1.0  
}
```

Multiple loss layers

- Give each loss its own weight
- E.g. give higher priority to classification error

$$E = \frac{1}{2N} \sum_{n=1}^N \|\hat{y}_n - y_n\|_2^2 + \textcolor{red}{100^*} \cdot \frac{-1}{N} \sum_{n=1}^N \log(\hat{p}_{n,t_n}),$$

```
layers {
    name: "recon-loss"
    type: EUCLIDEAN_LOSS
    bottom: "reconstructions"
    bottom: "data"
    top: "recon-loss"
}

layers {
    name: "class-loss"
    type: SOFTMAX_LOSS
    bottom: "class-preds"
    bottom: "class-labels"
    top: "class-loss"
    loss_weight: 100.0
}
```

Any layer can produce a loss!

- Just add `loss_weight: 1.0` to have a layer's output be incorporated into the loss

$$E = \|\text{pred} - \text{label}\|_2^2 / (2N)$$

```
layers {
    name: "loss"
    type: EUCLIDEAN_LOSS
    bottom: "pred"
    bottom: "label"
    top: "euclidean_loss"
    loss_weight: 1.0
}
```

==

```
diff = pred - label
layers {
    name: "diff"
    type: ELTWISE
    bottom: "pred"
    bottom: "label"
    top: "diff"
    eltwise_param {
        op: SUM
        coeff: 1
        coeff: -1
    }
}
```

```
E = \| diff \|_2^2 / (2N)
layers {
    name: "loss"
    type: POWER
    bottom: "diff"
    top: "euclidean_loss"
    power_param {
        power: 2
    }
    # = 1/(2N)
    loss_weight: 0.0078125
}
```

SOLVER

Solver

- **Solver** optimizes the network weights W to minimize the loss $L(W)$ over the data D

$$L(W) = \frac{1}{|D|} \sum_i^{|D|} f_W(X^{(i)}) + \lambda r(W)$$

- Coordinates forward / backward, weight updates, and scoring.

Solver

- Computes parameter update ΔW , formed from
 - The stochastic error gradient ∇f_W
 - The regularization gradient $\nabla r(W)$
 - Particulars to each solving method

$$L(W) \approx \frac{1}{N} \sum_i^N f_W(X^{(i)}) + \lambda r(W)$$

SGD Solver

- Stochastic gradient descent, with momentum
- solver_type: SGD

$$V_{t+1} = \mu V_t - \alpha \nabla L(W_t)$$

$$W_{t+1} = W_t + V_{t+1}$$

SGD Solver

- “AlexNet” [1] training strategy:
 - Use momentum 0.9
 - Initialize learning rate at 0.01
 - Periodically drop learning rate by a factor of 10
- Just a few lines of Caffe solver specification:

```
base_lr: 0.01
lr_policy: "step"
gamma: 0.1
stepsize: 100000
max_iter: 350000
momentum: 0.9
```

[1] A. Krizhevsky, I. Sutskever, and G. Hinton. [ImageNet Classification with Deep Convolutional Neural Networks](#). *Advances in Neural Information Processing Systems*, 2012.

NAG Solver

- Nesterov's accelerated gradient [1]
- solver_type: NESTEROV
- Proven to have optimal convergence rate $\mathcal{O}(1/t^2)$ for convex problems

$$V_{t+1} = \mu V_t - \alpha \nabla L(W_t + \mu V_t)$$

$$W_{t+1} = W_t + V_{t+1}$$

[1] Y. Nesterov. A Method of Solving a Convex Programming Problem with Convergence Rate $(1/\sqrt{k})$. *Soviet Mathematics Doklady*, 1983.

AdaGrad Solver

- Adaptive gradient (Duchi et al. [1])
- solver_type: ADAGRAD
- Attempts to automatically scale gradients based on historical gradients

$$(W_{t+1})_i = (W_t)_i - \alpha \frac{(\nabla L(W_t))_i}{\sqrt{\sum_{t'=1}^t (\nabla L(W_{t'}))_i^2}}$$

[1] J. Duchi, E. Hazan, and Y. Singer. *Adaptive Subgradient Methods for Online Learning and Stochastic Optimization*. *The Journal of Machine Learning Research*, 2011.

Solver Showdown: MNIST Autoencoder

AdaGrad

```
I0901 13:36:30.007884 24952 solver.cpp:232] Iteration 65000, loss = 64.1627
I0901 13:36:30.007922 24952 solver.cpp:251] Iteration 65000, Testing net (#0) # train set
I0901 13:36:33.019305 24952 solver.cpp:289] Test loss: 63.217
I0901 13:36:33.019356 24952 solver.cpp:302]      Test net output #0: cross_entropy_loss = 63.217 (* 1 = 63.217 loss)
I0901 13:36:33.019773 24952 solver.cpp:302]      Test net output #1: l2_error = 2.40951
```

SGD

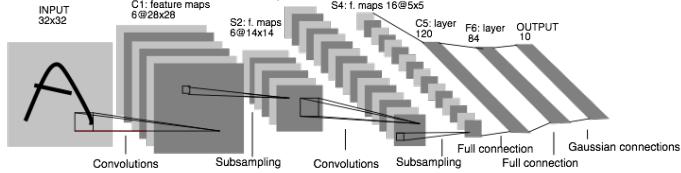
```
I0901 13:35:20.426187 20072 solver.cpp:232] Iteration 65000, loss = 61.5498
I0901 13:35:20.426218 20072 solver.cpp:251] Iteration 65000, Testing net (#0) # train set
I0901 13:35:22.780092 20072 solver.cpp:289] Test loss: 60.8301
I0901 13:35:22.780138 20072 solver.cpp:302]      Test net output #0: cross_entropy_loss = 60.8301 (* 1 = 60.8301 loss)
I0901 13:35:22.780146 20072 solver.cpp:302]      Test net output #1: l2_error = 2.02321
```

Nesterov

```
I0901 13:36:52.466069 22488 solver.cpp:232] Iteration 65000, loss = 59.9389
I0901 13:36:52.466099 22488 solver.cpp:251] Iteration 65000, Testing net (#0) # train set
I0901 13:36:55.068370 22488 solver.cpp:289] Test loss: 59.3663
I0901 13:36:55.068410 22488 solver.cpp:302]      Test net output #0: cross_entropy_loss = 59.3663 (* 1 = 59.3663 loss)
I0901 13:36:55.068418 22488 solver.cpp:302]      Test net output #1: l2_error = 1.79998
```

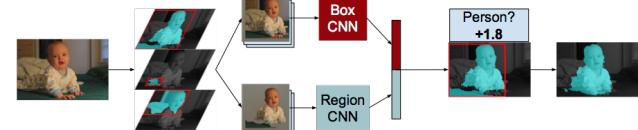
DAG

Many current deep models have linear structure

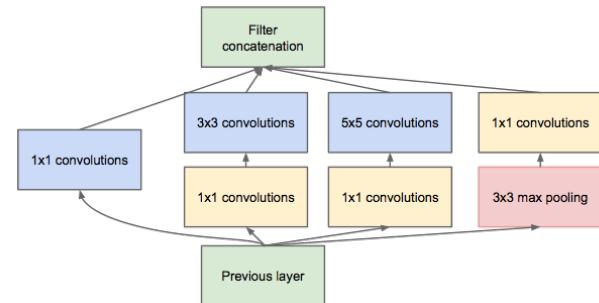


but Caffe nets can have any directed acyclic graph (DAG) structure.

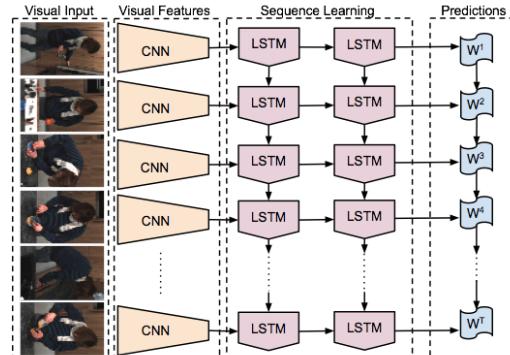
Define bottoms and tops and Caffe will connect the net.



SDS two-stream net



GoogLeNet Inception Module



LRCN joint vision-sequence model

WEIGHT SHARING

Weight sharing

- Parameters can be shared and reused across Layers throughout the Net
- Applications:
 - Convolution at multiple scales / pyramids
 - Recurrent Neural Networks (RNNs)
 - Siamese nets for distance learning

Weight sharing

- Just give the parameter blobs explicit names using the param field
- Layers specifying the same param name will share that parameter, accumulating gradients accordingly

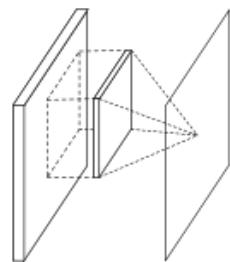
```
layers: {  
    name: 'innerproduct1'  
    type: INNER_PRODUCT  
    inner_product_param {  
        num_output: 10  
        bias_term: false  
        weight_filler {  
            type: 'gaussian'  
            std: 10  
        }  
    }  
    param: 'sharedweights'  
    bottom: 'data'  
    top: 'innerproduct1'  
}  
layers: {  
    name: 'innerproduct2'  
    type: INNER_PRODUCT  
    inner_product_param {  
        num_output: 10  
        bias_term: false  
    }  
    param: 'sharedweights'  
    bottom: 'data'  
    top: 'innerproduct2'  
}
```

RECENT MODELS

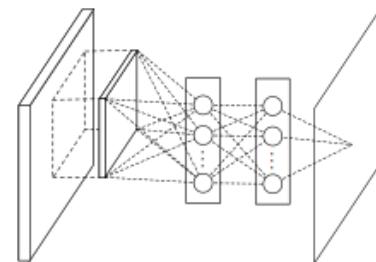
- Network-in-Network (NIN)
- GoogLeNet
- VGG

Network-in-Network

- filter with a nonlinear composition instead of a linear filter
- 1×1 convolution + nonlinearity
- reduce dimensionality, deepen the representation

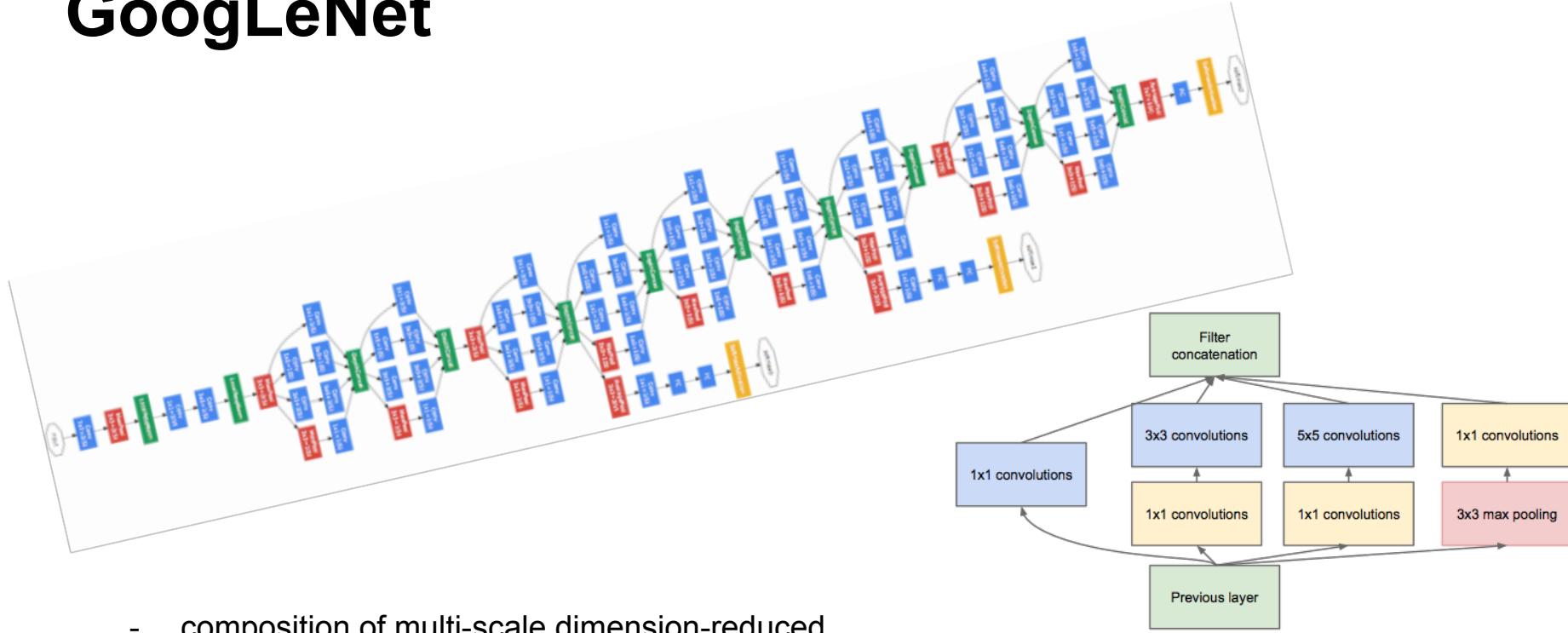


Linear Filter
CONV



NIN / MLP filter
 1×1 CONV

GoogLeNet



- composition of multi-scale dimension-reduced “Inception” modules
- 1x1 conv for dimensionality reduction
- concatenation across filter scales
- multiple losses for training to depth

“Inception” module

VGG

ConvNet Configuration					
A	A-LRN	B	C	D	E
11 weight layers	11 weight layers	13 weight layers	16 weight layers	16 weight layers	19 weight layers
input (224×224 RGB image)					
conv3-64	conv3-64 LRN	conv3-64 conv3-64	conv3-64 conv3-64	conv3-64 conv3-64	conv3-64 conv3-64
maxpool					
conv3-128	conv3-128	conv3-128 conv3-128	conv3-128 conv3-128	conv3-128 conv3-128	conv3-128 conv3-128
maxpool					
conv3-256 conv3-256	conv3-256 conv3-256	conv3-256 conv3-256	conv3-256 conv3-256 conv1-256	conv3-256 conv3-256 conv3-256	conv3-256 conv3-256 conv3-256
maxpool					
conv3-512 conv3-512	conv3-512 conv3-512	conv3-512 conv3-512	conv3-512 conv3-512 conv1-512	conv3-512 conv3-512 conv3-512	conv3-512 conv3-512 conv3-512
maxpool					
conv3-512 conv3-512	conv3-512 conv3-512	conv3-512 conv3-512	conv3-512 conv3-512 conv1-512	conv3-512 conv3-512 conv3-512	conv3-512 conv3-512 conv3-512
maxpool					
FC-4096					
FC-4096					
FC-1000					
soft-max					

Table 2: Number of parameters (in millions).

Network	A,A-LRN	B	C	D	E
Number of parameters	133	133	134	138	144

- 3x3 convolution all the way down...
- fine-tuned progression of deeper models
- 16 and 19 parameter layer variations in the model zoo

NOW ROASTING

- Parallelism
- Pythonification **done in rc2**
- Fully Convolutional Networks **PRs open**
- Sequences **PRs open**
- cuDNN v2 **PR #1731**
- Gradient Accumulation **PR #2016**
- More
 - FFT convolution
 - locally-connected layer
 - ...

Parallelism

Parallel / distributed training across
GPUs, CPUs, and cluster nodes

- collaboration with Flickr + open source community
- promoted to official integration branch in [PR #1148](#)
- faster learning and scaling to larger data

Pythonification done in #1703

Python Layer

- layer prototyping and ease of expression
- call Python from C++, C++ from Python,
and around we go

Complete instrumentation in Python

- data preparation
- solving
- inference
- model definition still to come in #1733

Jon Long

Fully Convolutional Network: FCN

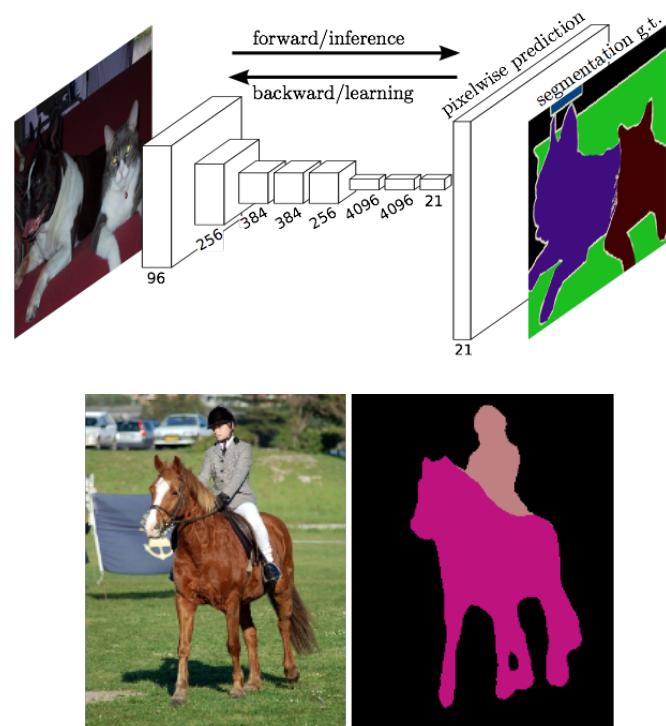
Model family for pixel prediction by conv. net
applied to semantic segmentation

- end-to-end learning
- efficiency in inference and learning
175 ms per-image prediction
- multi-modal, multi-task

Further applications

- depth estimation
- denoising
- ...

[arXiv](#) and [pre-release](#)



Sequences

Recurrent Net RNN and Long Short Term Memory LSTM
are sequential models

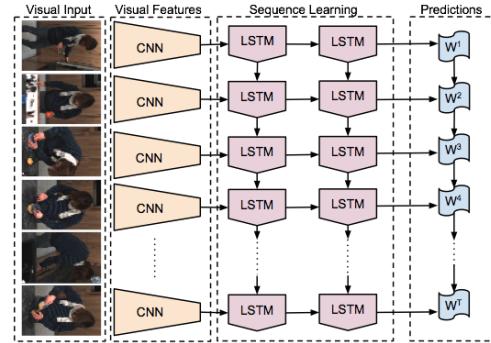
- video
- language
- dynamics

learned by back-propagation through time.

LRCN: Long-term Recurrent Convolutional Network

- activity recognition
- image captioning
- video captioning

[arXiv](#) and [web page & PR](#)



A group of young men playing a game of soccer.

Jeff Donahue et al.

NVIDIA® cuDNN / Caffe Roadmap

Release 1
September 2014

Layers (foward & backprop)

- Convolutional
- Pooling
- Softmax
- ReLu/Sigmoid/Tanh

High performance convolution

Integrated with caffe dev, will be in 1.0

Release 2

Layers

- Local receptive field
- Contrast normalization
- Fully-connected
- Recurrent

Targeting 1.5x faster on convolutional layers

Drop-in integration to Caffe

Release 3

Support for multiple GPUs per node

Tuning for future chips

Aiming to align with Caffe support for multiple GPUs

Q3'14

Q4'14

Q1'15

Q2'15

Features

Performance

Caffe



Thanks to the Caffe crew

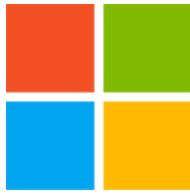


Yangqing Jia, Evan Shelhamer, Jeff Donahue, Sergey Karayev
Jonathan Long, Ross Girshick, Sergio Guadarrama, Trevor Darrell

and our [open source contributors!](#)

...plus the
cold-brew

Acknowledgements



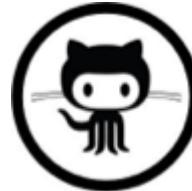
Thank you to the Berkeley Vision and Learning Center Sponsors.



Thank you to NVIDIA
for GPU donation and
collaboration on cuDNN.



Thank you to A9 and AWS
for a research grant for Caffe dev
and reproducible research.



Thank you to our 75+
open source contributors
and vibrant community.

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