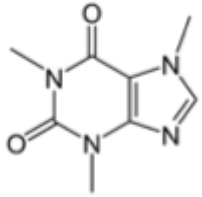
DIY Deep Learning for Vision: a Hands-On Tutorial with Caffe

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



caffe.berkeleyvision.org

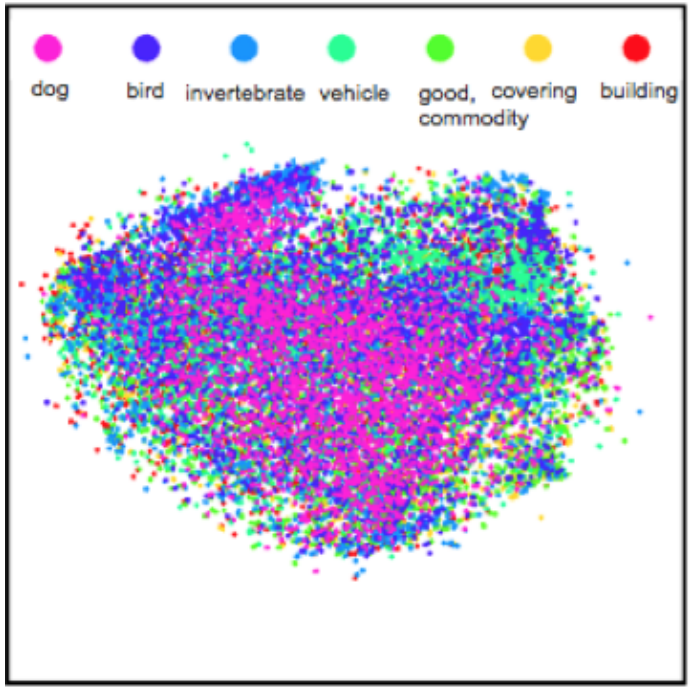
github.com/BVLC/caffe

Evan Shelhamer, Jeff Donahue,
Yangqing Jia, Ross Girshick

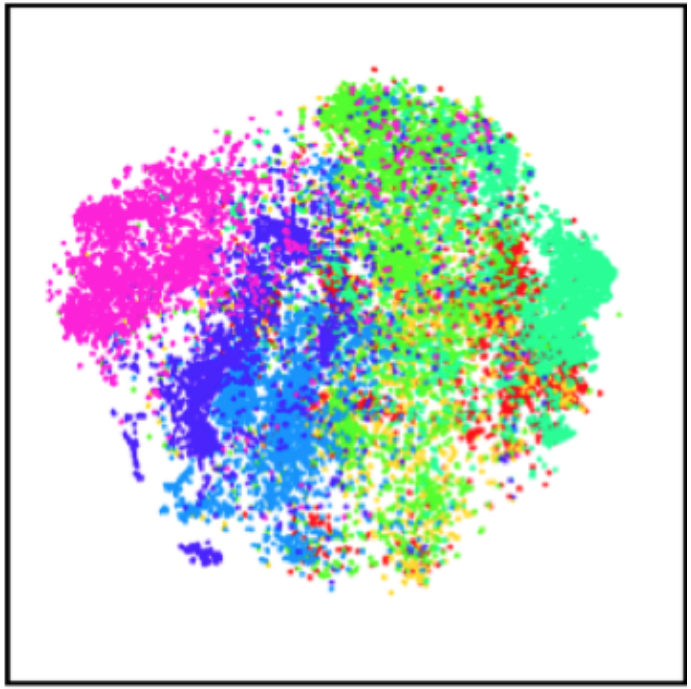
Look for further details in the outline notes

Why Deep Learning?

The Unreasonable Effectiveness of Deep Features



Low-level: $Pool_1$

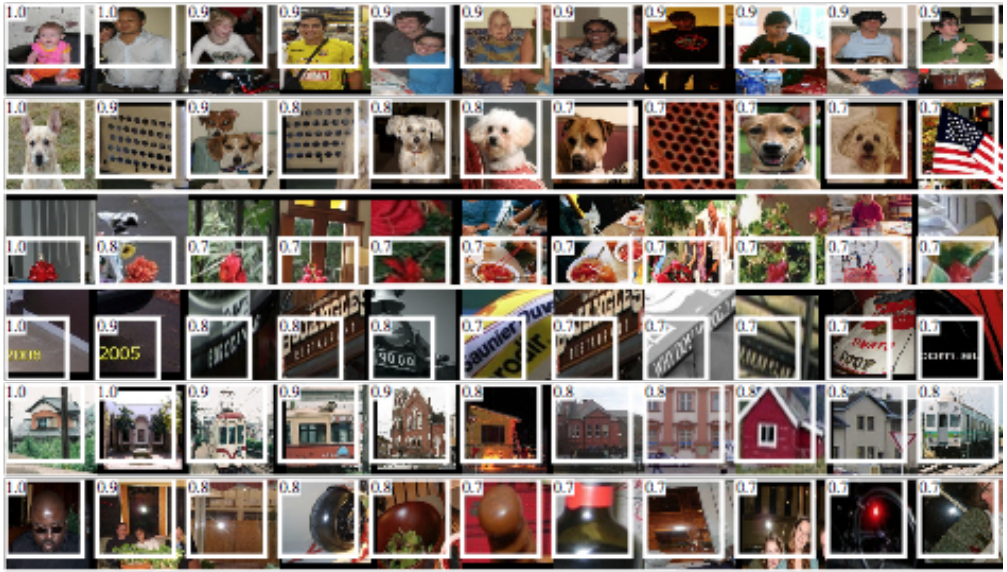


High-level: FC_6

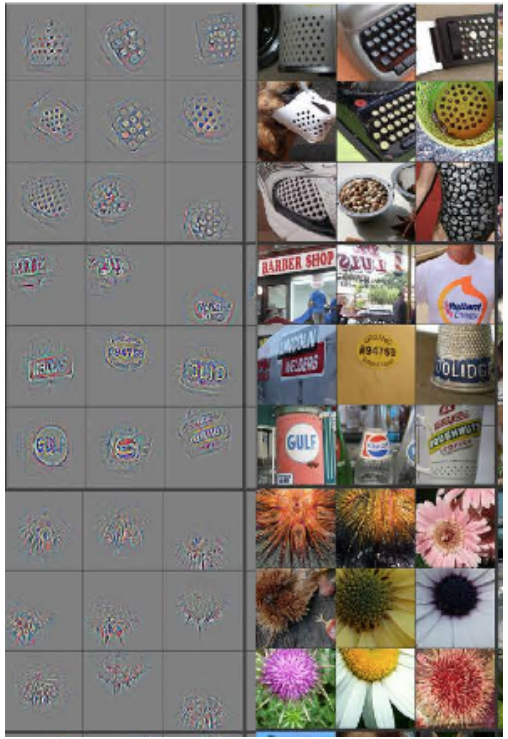
Classes separate in the deep representations and transfer to many tasks.
[DeCAF] [Zeiler-Fergus]

Why Deep Learning?

The Unreasonable Effectiveness of Deep Features



Maximal activations of $pool_5$ units [R-CNN]



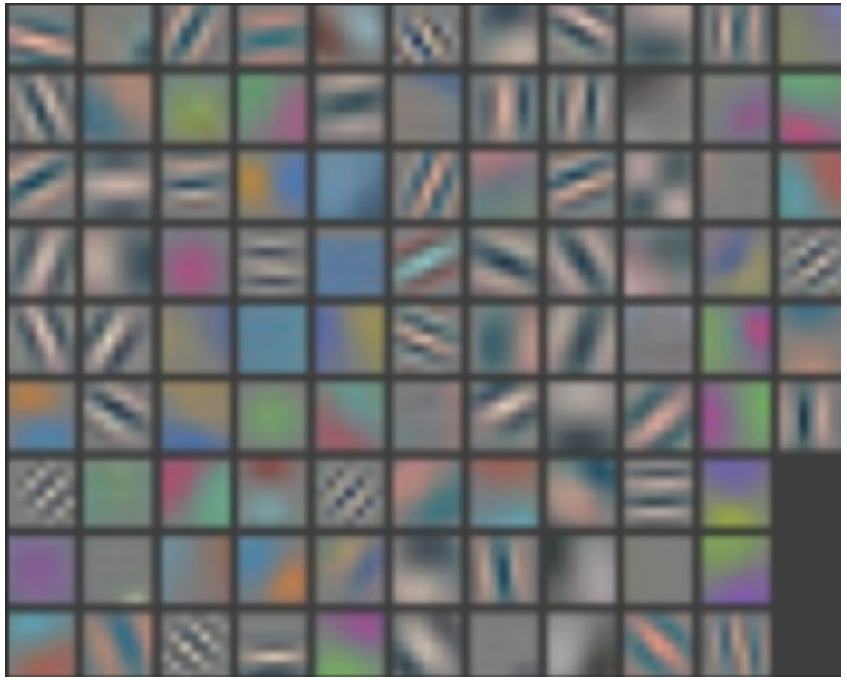
$conv_5$ DeConv visualization [Zeiler-Fergus]

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

What is Deep Learning?

Compositional Models

Learned End-to-End

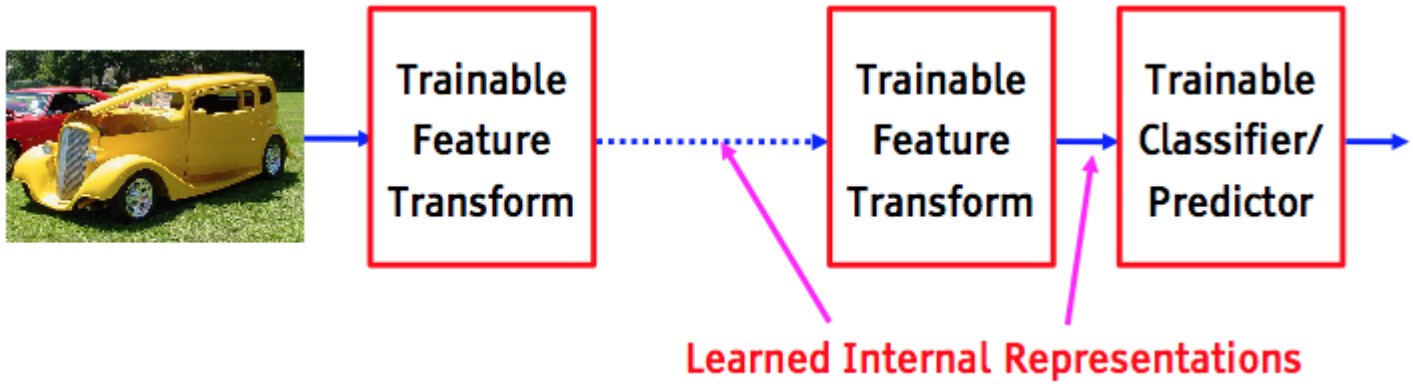


figure credit Yann LeCun, ICML '13 tutorial

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.

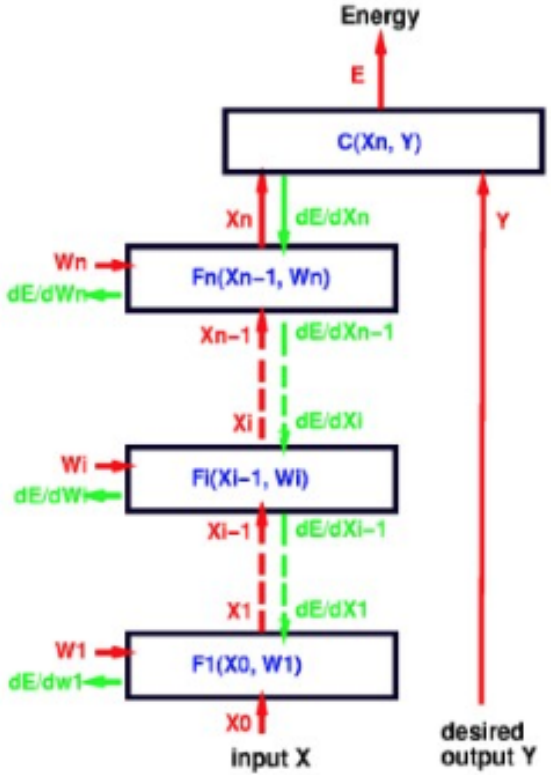
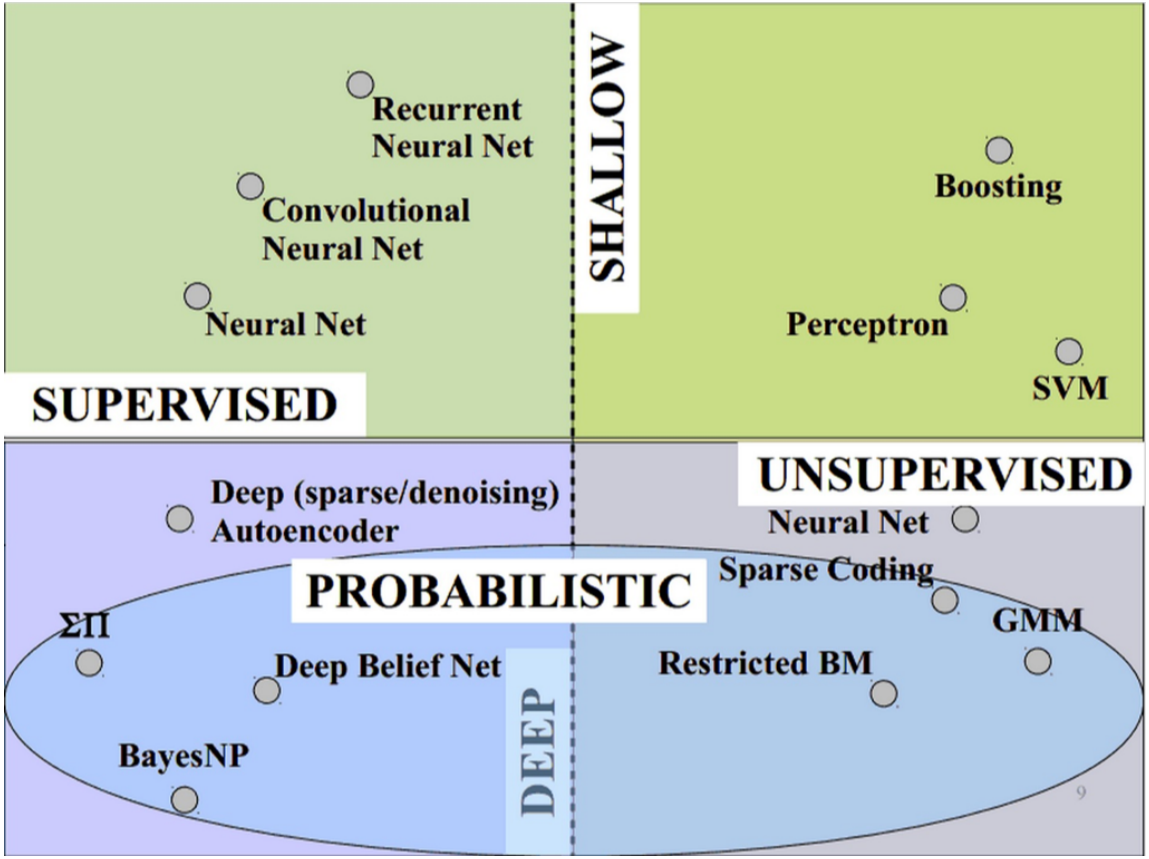


figure credit Yann LeCun, ICML '13 tutorial

What is Deep Learning?



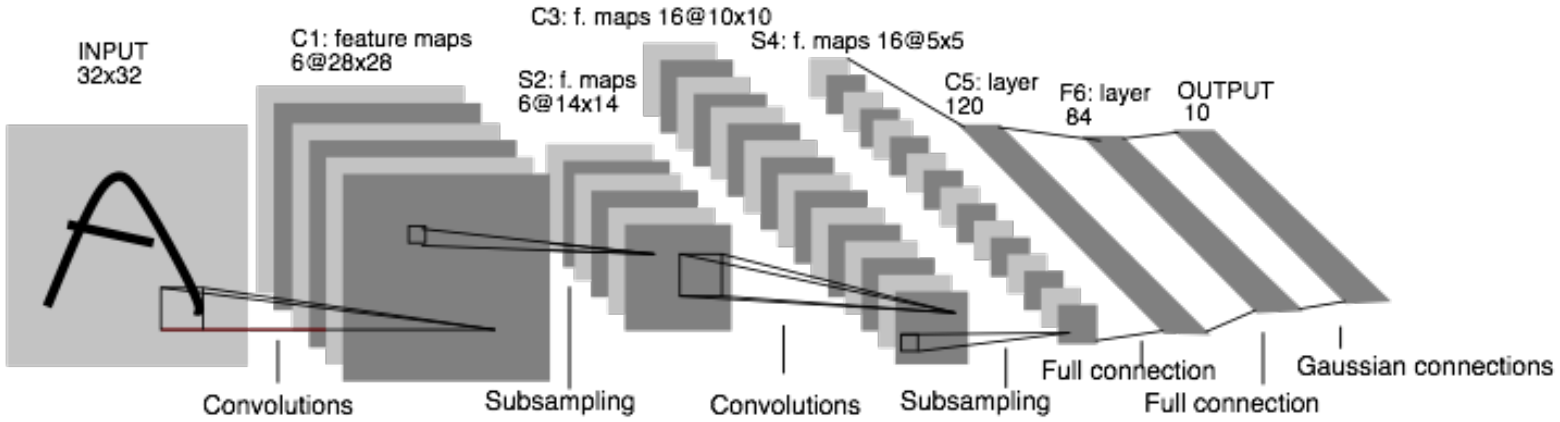
Vast space of models!

Caffe models are loss-driven:

- supervised
- unsupervised

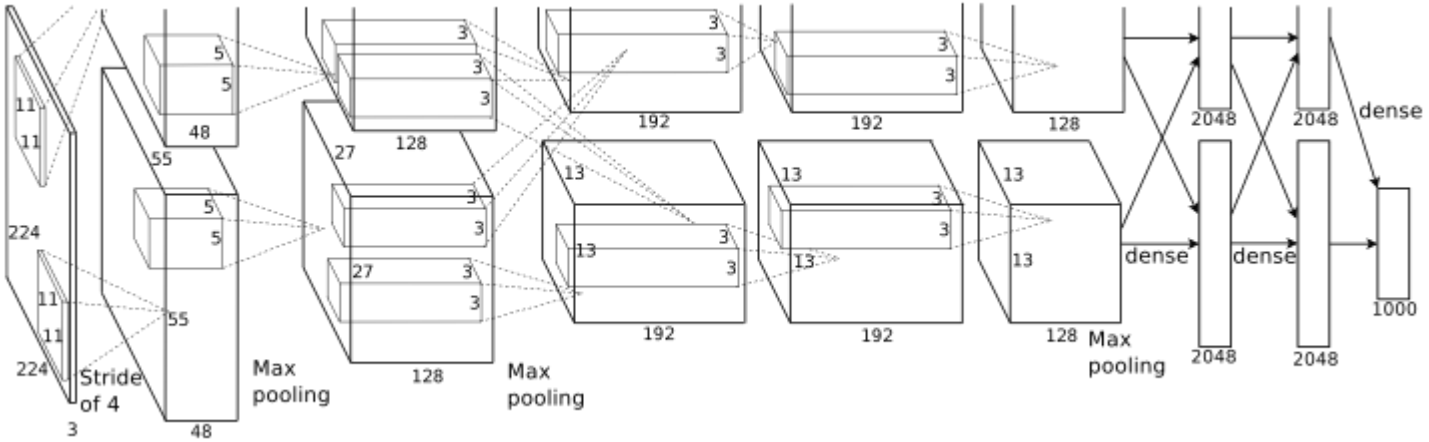
slide credit Marc'aurelio Ranzato, CVPR '14 tutorial.

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]

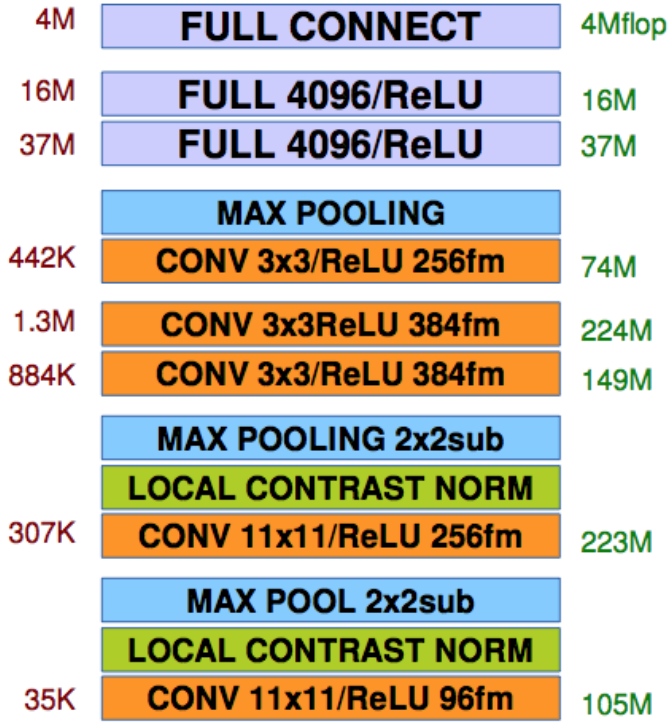
Convolutional Nets: 2012



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

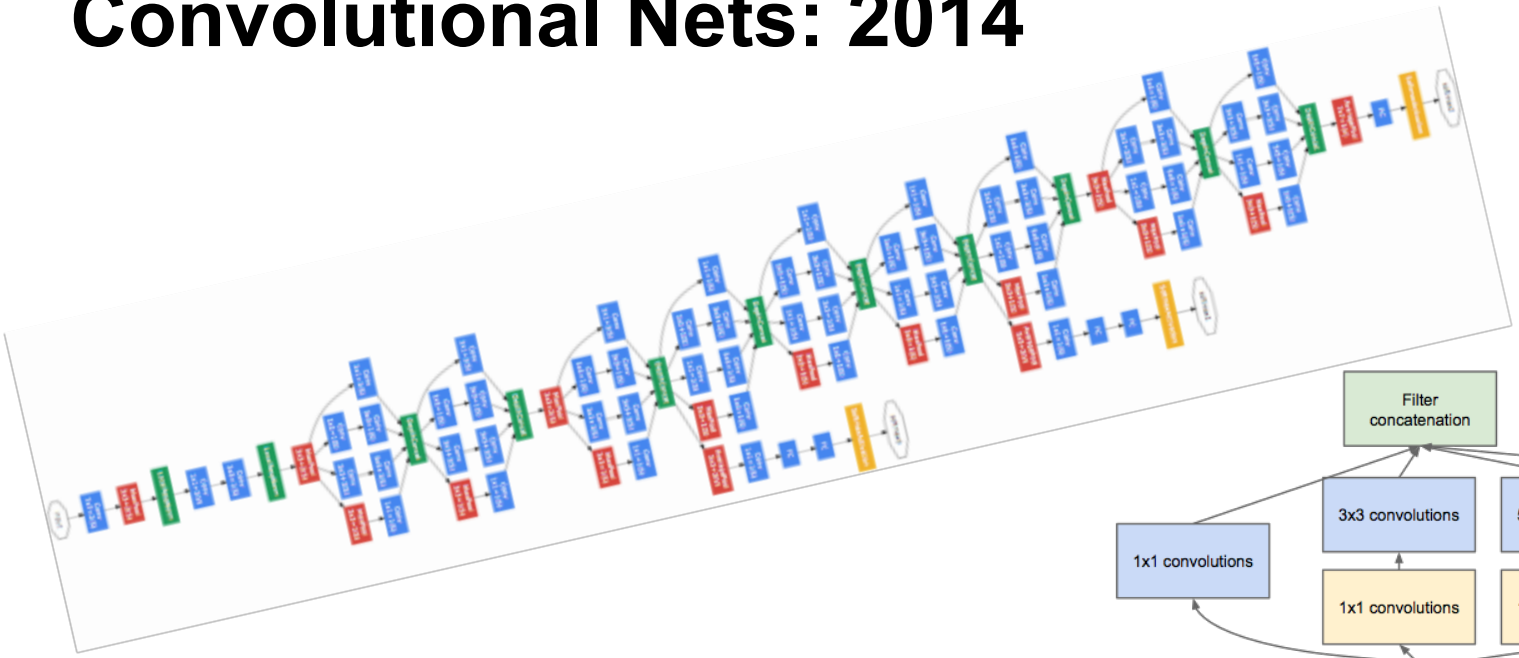


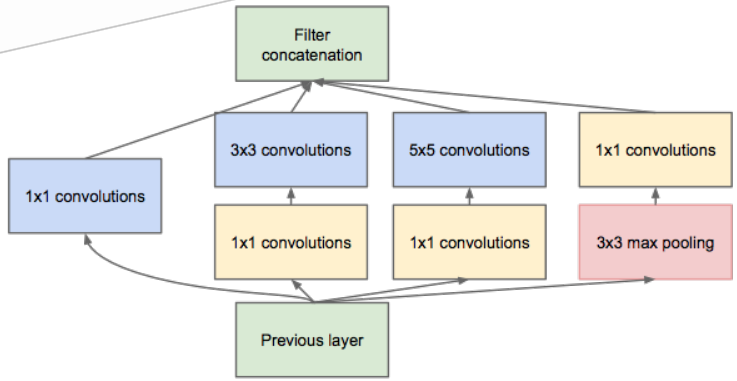
AlexNet: a layered model composed of convolution, pooling, and further operations followed by a holistic representation and all-in-all a landmark classifier on ILSVRC12. [AlexNet]

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

figure credit Y. LeCun and M.A. Ranzato, ICML ‘13 tutorial

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!

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

BVLC / caffe

Unwatch 282 | Unstar 1,404 | Fork 750

October 4, 2014 – November 4, 2014

Period: **1 month**

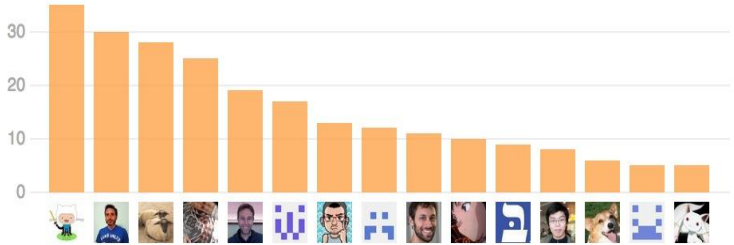
Overview

60 Active Pull Requests

127 Active Issues

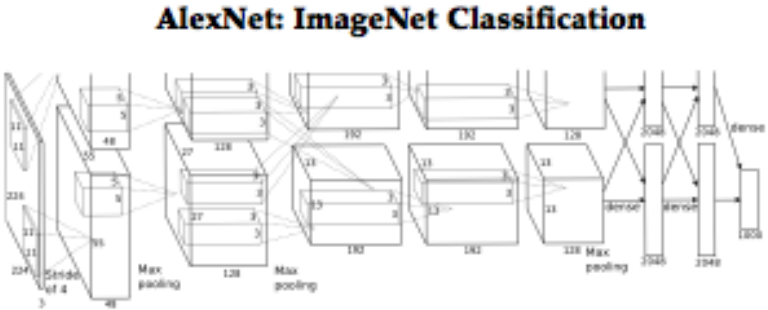
29 Merged Pull Requests	**31** Proposed Pull Requests	**67** Closed Issues	**60** New Issues

Excluding merges, **36 authors** have pushed **16 commits** to master and **274 commits** to all branches. On master, **9 files** have changed and there have been **59 additions** and **55 deletions**.



29 Pull requests merged by **13** people

Reference Models



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

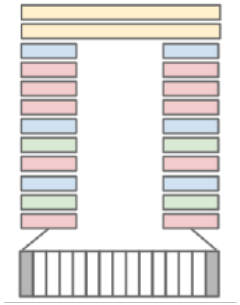
The Caffe Model Zoo

- 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

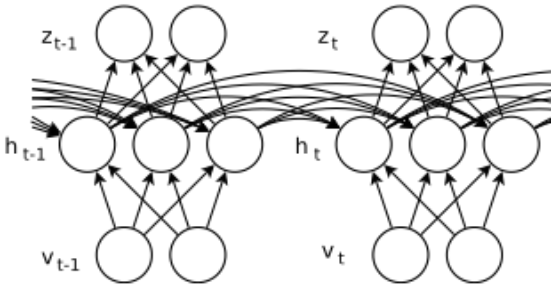
Architectures

DAGs
multi-input
multi-task



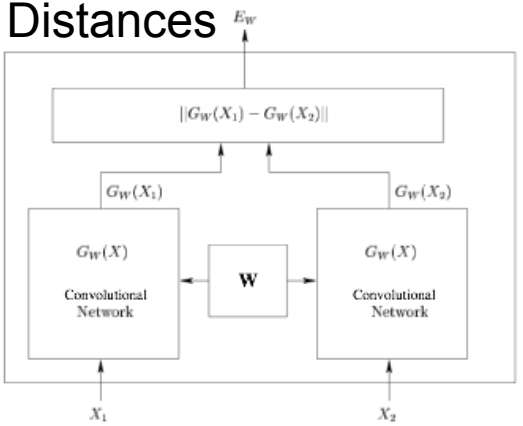
[Karpathy14]

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:
  - K40 / Titan: 2 ms / image, K20: 2.6ms
  - Caffe + cuDNN: **1.17ms / image** on K40
  - 60 million images / day
  - 8-core CPU: ~20 ms/image
- ~ 9K lines of C/C++ code
  - with unit tests ~20k

* Not counting I/O time. Details at http://caffe.berkeleyvision.org/performance_hardware.html

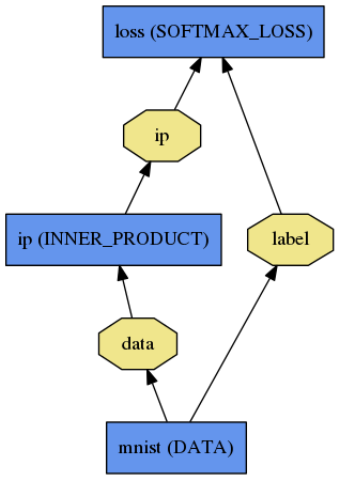
CAFFE INTRO

Net

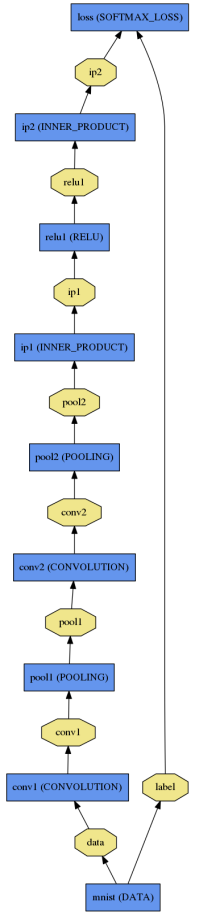
- A network is a set of layers connected as a DAG:

```
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



LogReg ↑

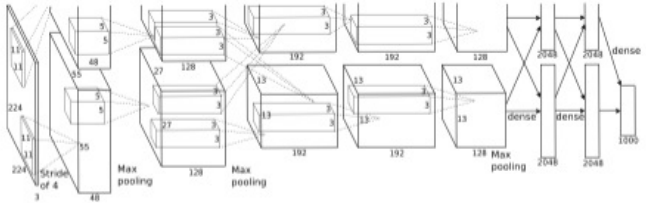


LeNet ⟶

ImageNet, Krizhevsky 2012 ⟶

Forward / Backward the essential Net computations

Forward: inference $f_W(x)$



"espresso" + loss

$\nabla f_W(x)$ Backward: learning

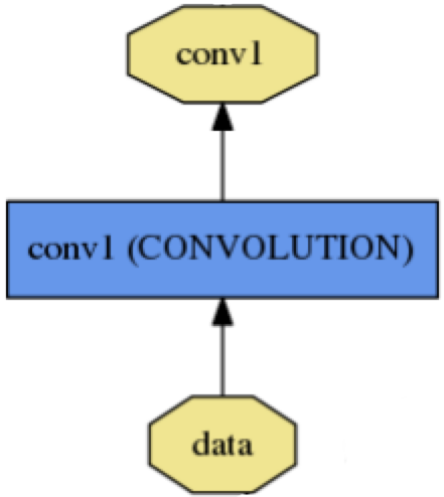
Caffe models are complete machine learning systems for inference and learning. The computation follows from the model definition. Define the model and run.

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**

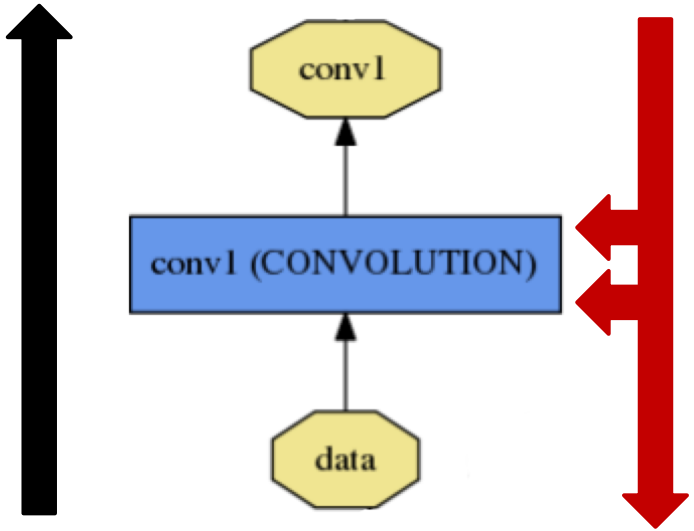
* Nets + Layers are defined by protobuf schema

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)



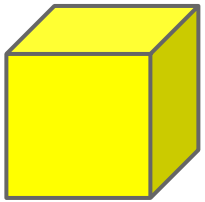
Model Composition
The Net forward and backward passes are the composition the layers'.

Layer Development Checklist

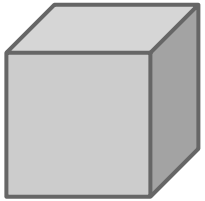
Blob

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

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



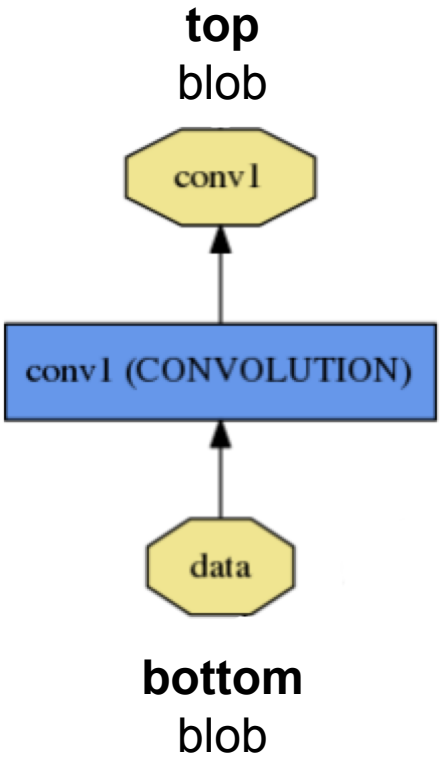
Data
*N*umber x *K* Channel x *H*eight x *W*idth
256 x 3 x 227 x 227 for ImageNet train input



Parameter: Convolution Weight
N Output x *K* Input x *H*eight x *W*idth
96 x 3 x 11 x 11 for CaffeNet conv1

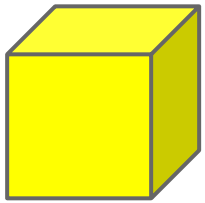
Parameter: Convolution Blas
96 x 1 x 1 x 1 for CaffeNet conv1

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



Blob

Blobs provide a unified memory interface.

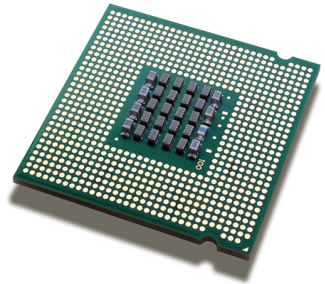


Reshape(num, channel, height, width)
- declare dimensions
- make *SyncedMem* -- but only lazily allocate

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)

End to End Recipe...

- Convert the data to Caffe-format
  - lmdb, 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/build/tools/*`

(Examples)

Logistic Regression

Learn LeNet on MNIST

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 by MIT

Predictions:

- **Type of environment:** outdoor
- **Semantic categories:** rock_arch:0.63, arch:0.30,
- **SUN scene attributes:** rugged, natural light, dry, climbing, far-away horizon, touring, rocky, open area, warm, sand

Places CNN demo

B. Zhou et al. NIPS 14

Object Detection

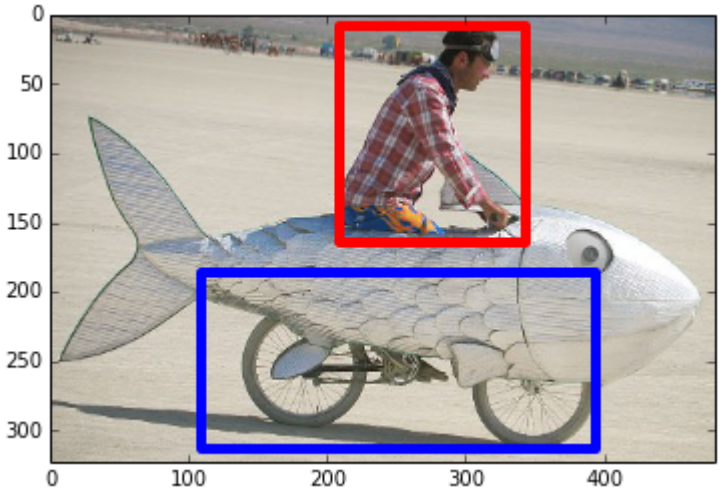
R-CNN: Regions with Convolutional Neural Networks

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).

[Image-Style]

Other Styles:

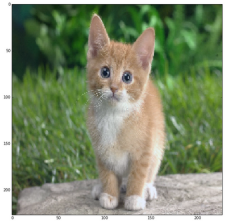
Vintage
Long Exposure
Noir
Pastel
Macro
… and so on.

Embedded Caffe

Caffe on the NVIDIA Jetson TK1 mobile board

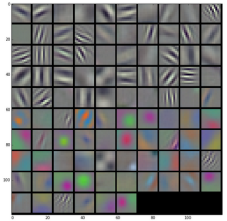
- 10 watts of power
- inference at 35 ms per image
- NVIDIA acceleration just released
- how-to guide
  courtesy of Pete Warden
- cuDNN for TK1 recently released!

Feature Extraction + Visualization



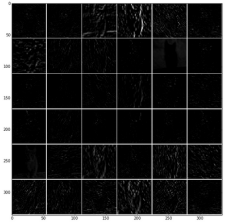
The first layer filters, conv1

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

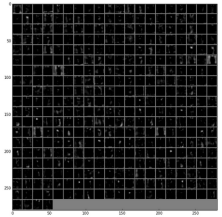


The first layer output, conv1 (rectified responses of the filters above, first 36 only)

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

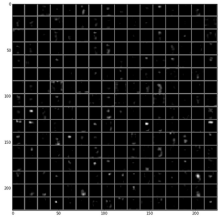


In [13]:
```
feat = net.blobs['conv4'].data[4]
vis_square(feat, padval=0.5)
```



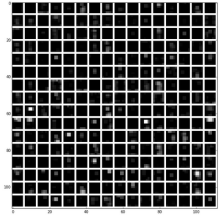
The fifth layer output, conv5 (rectified, all 256 channels)

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

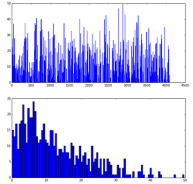


The fifth layer after pooling, pool5

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

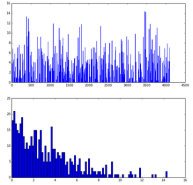


In [16]:
```
feat = net.blobs['fc6'].data[4]
plt.subplot(2, 1, 1)
plt.plot(feat.flat)
plt.subplot(2, 1, 2)
_ = plt.hist(feat.flat[feat.flat > 0], bins=100)
```



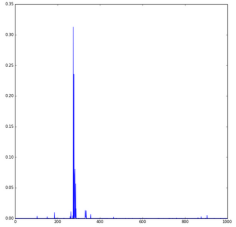
The second fully connected layer, fc7 (rectified)

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)
```

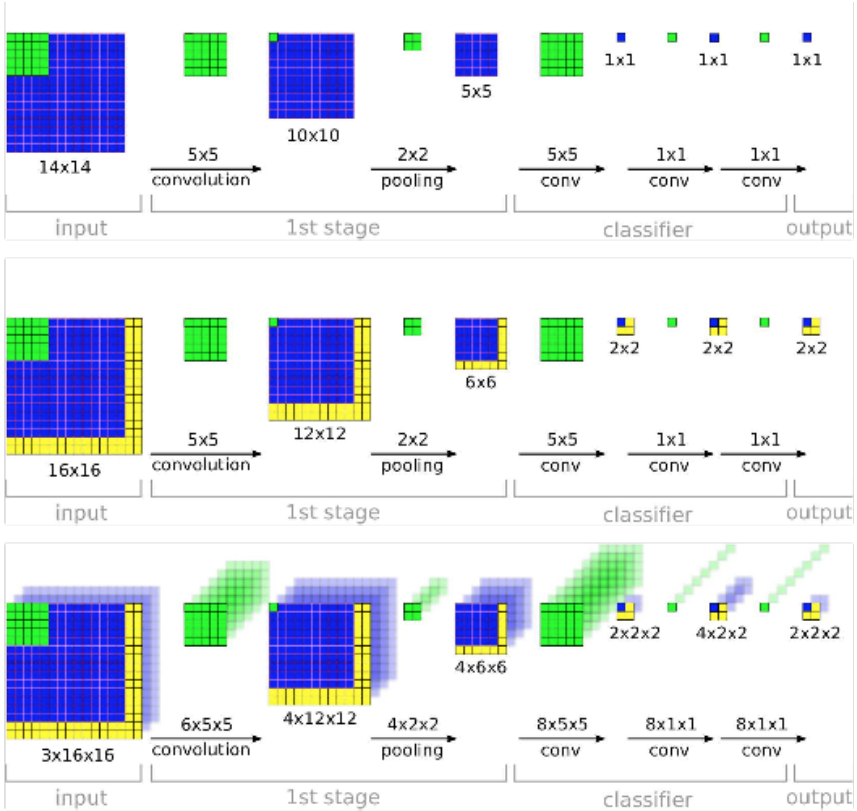


In [18]:
```
feat = net.blobs['prob'].data[4]
plt.plot(feat.flat)
```

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



Editing Model Parameters



[OverFeat]

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

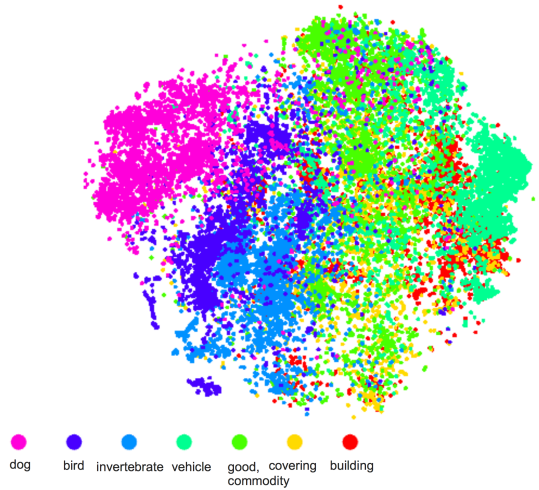
The computation exploits a natural efficiency of convolutional neural network (CNN) structure by dynamic programming in the forward pass from shallow to deep layers and analogously in backward.

Net surgery in Caffe
how to transform models:
- make fully convolutional
- transplant parameters

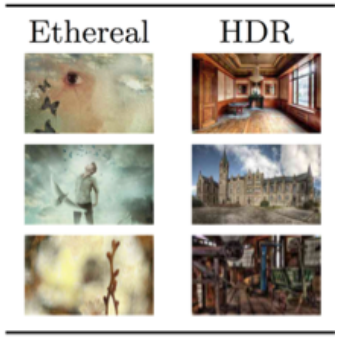
FINE-TUNING

Fine-tuning Transferring learned weights to kick-start models

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



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"
  type: INNER_PRODUCT
  blobs_lr: 1
  blobs_lr: 2
  weight_decay: 1
  weight_decay: 0
  inner_product_param {
    num_output: 20
    ...
  }
}
```

new name = new params

Input:
A different source

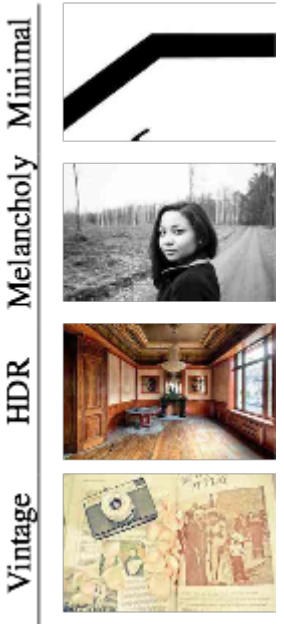
Last Layer:
A different classifier

From ImageNet to Style

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

Under the hood (loosely speaking):

```
net = new Caffe::Net(
    "style_solver.prototxt");
net.CopyTrainedNetFrom(
    pretrained_model);
solver.Solve(net);
```



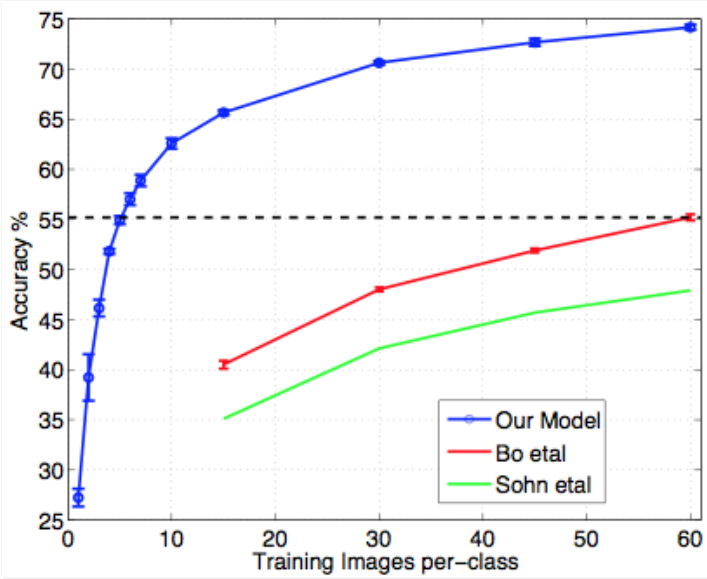
When to Fine-tune?

A good first step!

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

State-of-the-art results in

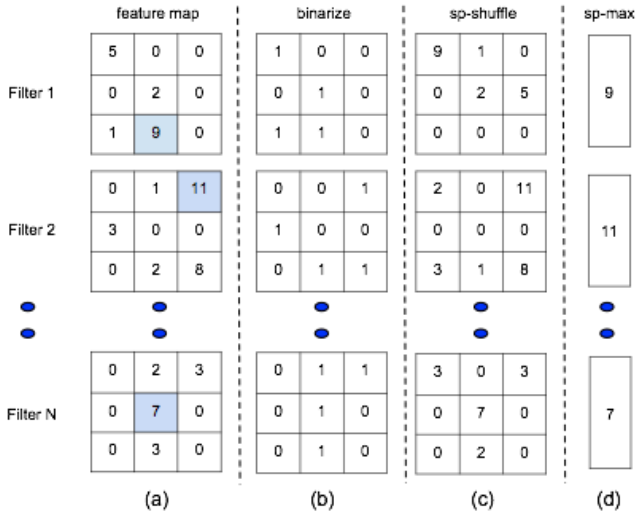
- recognition
- detection
- segmentation

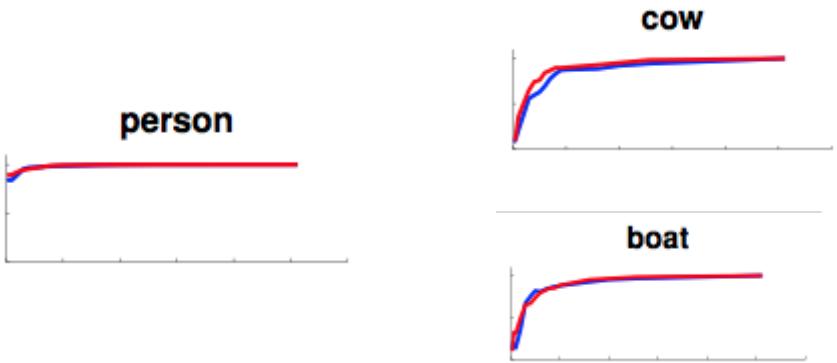


[Zeiler-Fergus]

Training & Fine-tuning Analysis

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





P. Agarwal et al. ECCV 14

Fine-tuning Tricks

Learn the last layer first

- Caffe layers have local learning rates: `blobs_lr`
- 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

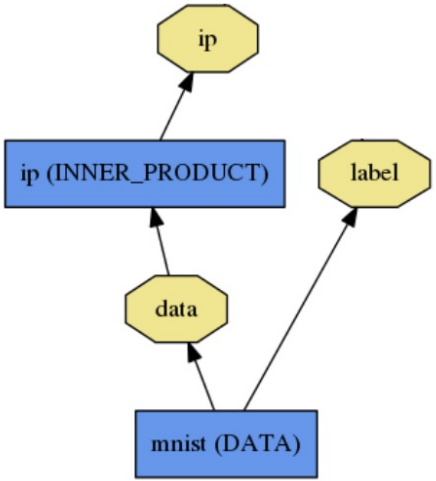
(Example)

Fine-tuning from ImageNet to Style

LOSS

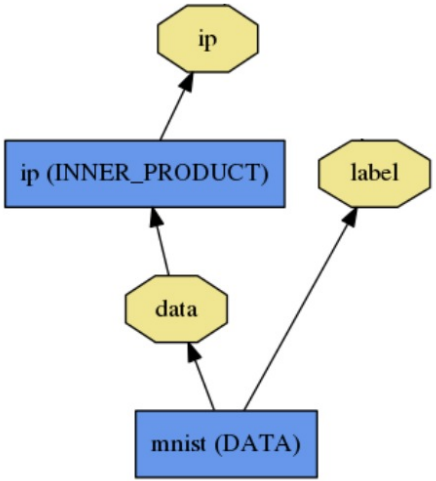
Loss

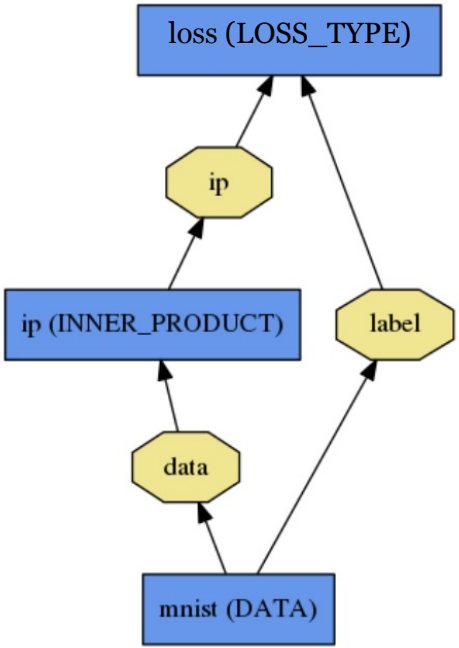
What kind of model is this?



Loss

What kind of model is this?





Classification
`SOFTMAX_LOSS`
`HINGE_LOSS`

Linear Regression
`EUCLIDEAN_LOSS`

Attributes / Multiclassification
`SIGMOID_CROSS_ENTROPY_LOSS`

Others…

New Task
`NEW_LOSS`

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

Loss

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

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

Data term: error averaged over instances

Regularization term: penalize large weights to improve generalization

Loss

- The data error term $f_W\left(X^{(i)}\right)$ 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"
}
```

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

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

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:

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

```
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

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

```
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 = || pred - label ||^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 / (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

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

- 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

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

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

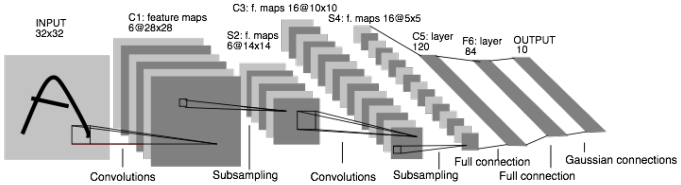
```
I0901 13:35:20.426187 20072 solver.cpp:232] Iteration 65000, loss = 61.5498
I0901 13:35:20.426218 20072 solver.cpp:251] Iteration 65000, Testing net (#0) # train set
I0901 13:35:22.780092 20072 solver.cpp:289] Test loss: 60.8301
I0901 13:35:22.780138 20072 solver.cpp:302]     Test net output #0: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

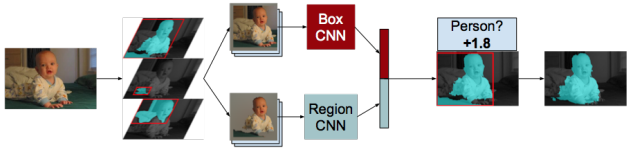
DAG

Many current deep models have linear structure

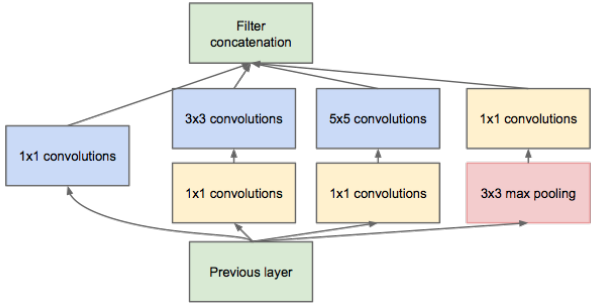


but Caffe nets can have any directed acyclic graph (DAG) structure.

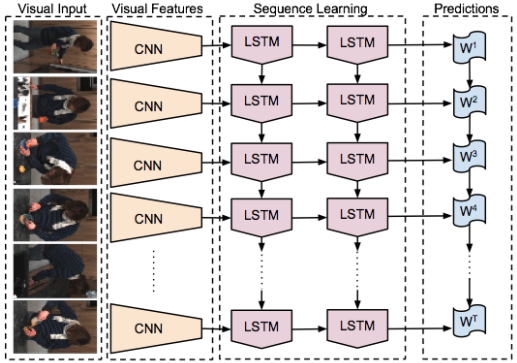
Define `bottoms` and `tops` and Caffe will connect the net.



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

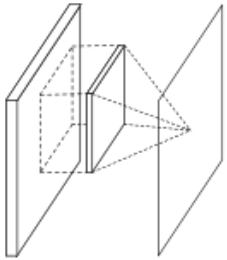
```
layers: {
  name: 'innerproduct1'
  type: INNER_PRODUCT
  inner_product_param {
    num_output: 10
    bias_term: false
    weight_filler {
      type: 'gaussian'
      std: 10
    }
  }
  param: 'sharedweights'
  bottom: 'data'
  top: 'innerproduct1'
}
layers: {
  name: 'innerproduct2'
  type: INNER_PRODUCT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

RECENT MODELS

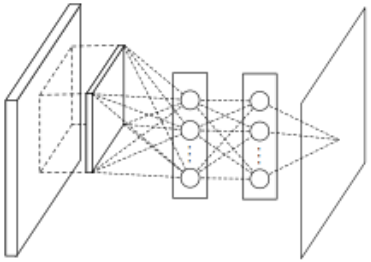
- Network-in-Network (NIN)
- GoogLeNet
- VGG

Network-in-Network

- filter with a nonlinear composition instead of a linear filter
- 1x1 convolution + nonlinearity
- reduce dimensionality, deepen the representation

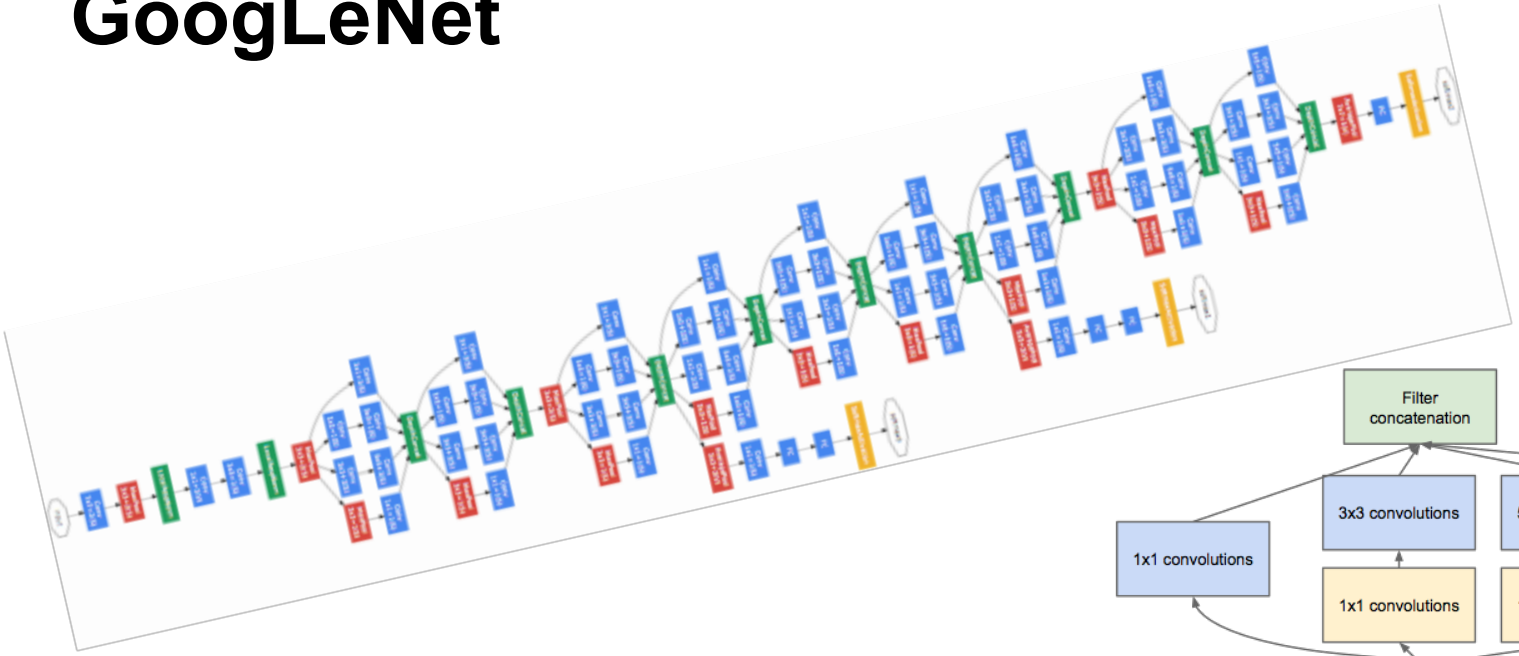


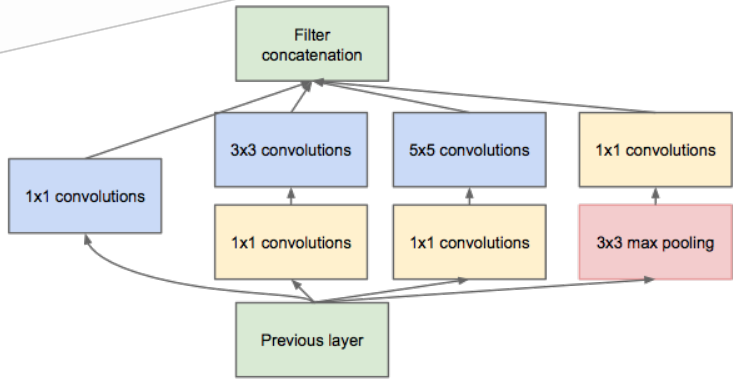
Linear Filter
CONV



NIN / MLP filter
1x1 CONV

GoogLeNet





"Inception" module

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

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 **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 **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 **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
- Fully Convolutional Networks
- Sequences
- cuDNN v2
- Gradient Accumulation
- 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

Python Layer

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

Complete instrumentation in Python

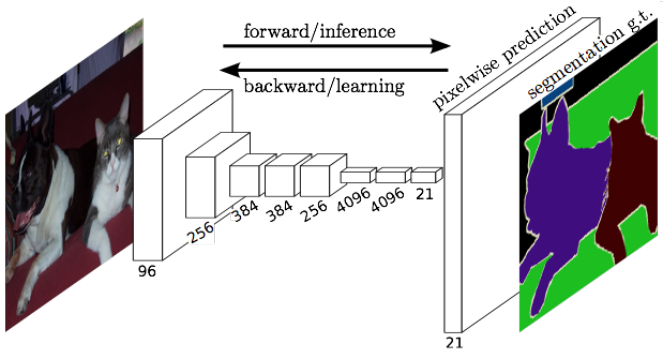
- data preparation
- solving
- inference
- model definition

Fully Convolutional Network: FCN

A framework for spatial prediction by conv. net

applied to semantic segmentation

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



Further applications

- depth estimation
- denoising

arXiv

Jon Long & Evan Shelhamer

Sequences

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

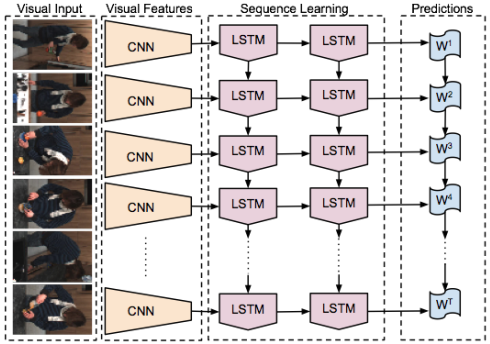
- video
- language
- dynamics

learned by back-propagation through time.

LRCN: Long-term Recurrent Convolutional Network

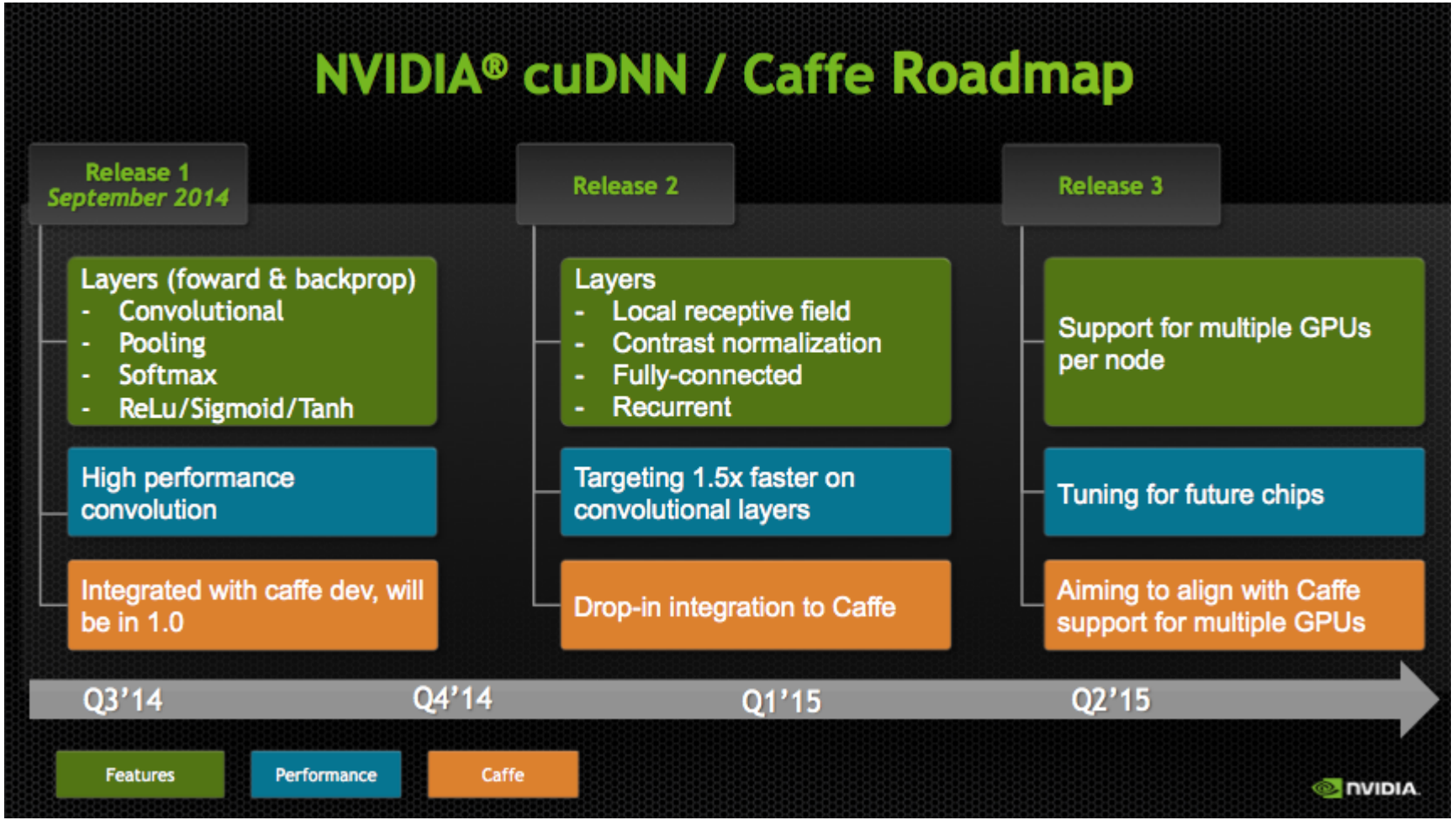
- activity recognition
- image captioning
- video captioning

[arXiv]



A group of young men playing a game of soccer.

Jeff Donahue et al.


NVIDIA® cuDNN / Caffe Roadmap
Release 1
September 2014
Release 2
Release 3
Layers (foward & backprop)
- Convolutional
- Pooling
- Softmax
- ReLu/Sigmoid/Tanh
Layers
- Local receptive field
- Contrast normalization
- Fully-connected
- Recurrent
Support for multiple GPUs per node
High performance convolution
Targeting 1.5x faster on convolutional layers
Tuning for future chips
Integrated with caffe dev, will be in 1.0
Drop-in integration to Caffe
Aiming to align with Caffe support for multiple GPUs
Q3'14
Q4'14
Q1'15
Q2'15
Features
Performance
Caffe
NVIDIA

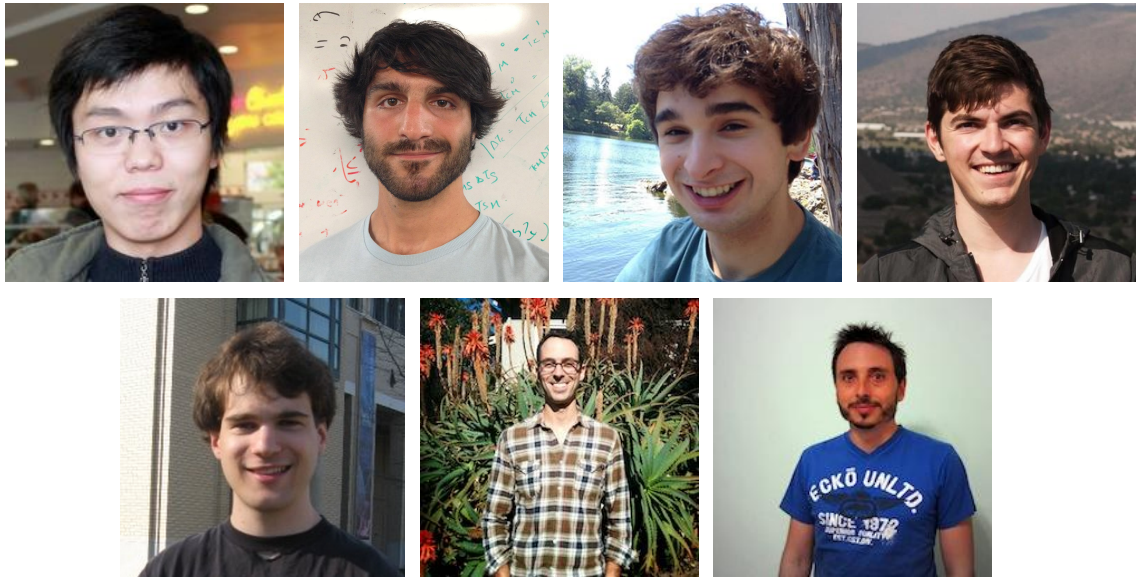
Gradient Accumulation

- decouple computational and learning mini-batch size
- tune optimization independently of resource constraints
- conserve memory

...and share convolution buffers for further memory savings.

Jon Long & Sergio Guadarrama

Thanks to the Caffe crew



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

and our open source contributors!

...plus the cold-brew

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Thank you to our 50+
open source contributors
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