Convolutional Neural Networks

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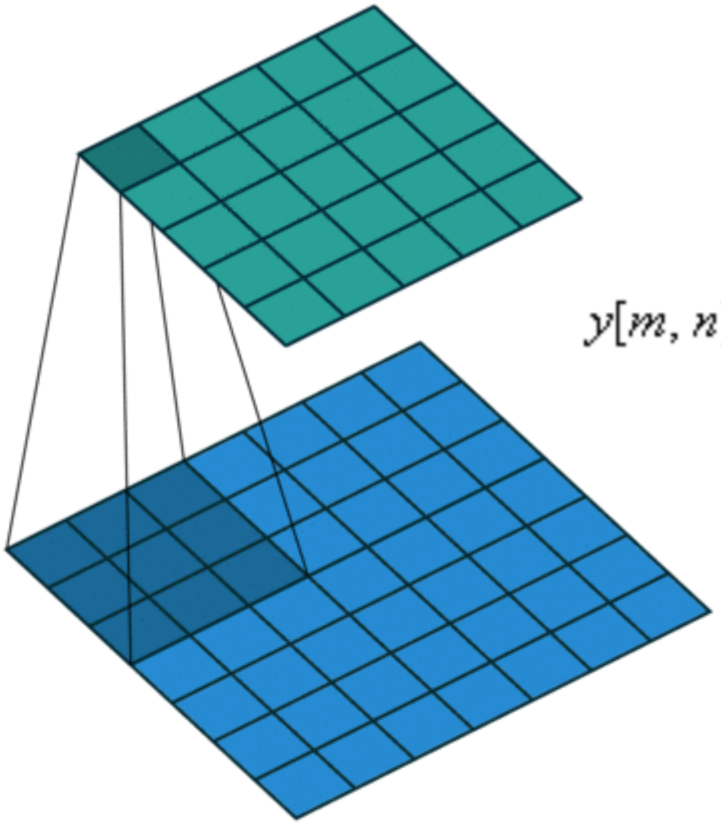
Outline

- Discussing conv. filters from traditional viewpoints
- The first popular deep CNN: LeNet in 1998
- The second popular deep CNN: AlexNet in 2012
- Why 14 years? Challenges of implementing AlexNet?
- Improving CNNs
  - 1x1 convolution
  - Residual network

Convolutional Filters

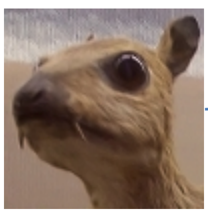
- Image filtering are usually represented by the convolution between an image and a mask.



$$y[m,n] = x[m,n] * h[m,n] = \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} x[i,j] \cdot h[m-i, n-j]$$

Image Filters

- Image filtering are usually represented by the convolution between an image and a mask.



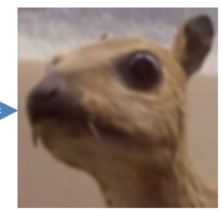
$*$

$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

Edge detection

$*$

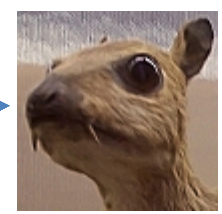
$$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$



Blurring

$*$

$$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$



Sharpen

Discussions

- Filters are powerful for many vision applications

We can use filters for recognition, enhancement…

That is why nowadays CNNs almost dominate all vision applications

Discussions

- Filters are powerful for many vision applications
- Convolutions are expensive
  - At every pixel we need do multi-multiplication with its neighborhood values
  - Algorithms of speedup*: integral image, separable filters, time domain convolution -> frequency multiplication, etc
  - Hardware of speedup: GPU, TPU

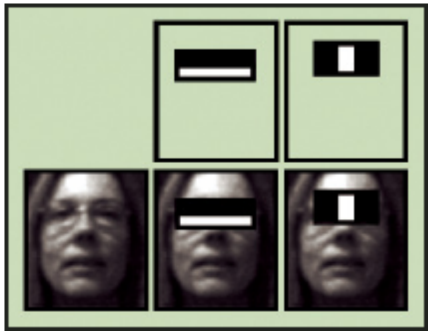
*This suggests a number of research ideas of improving deep cnn

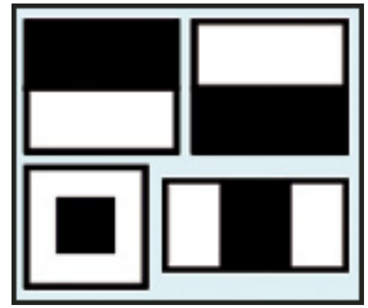
Discussions

- Filters are powerful for many vision applications
- Convolutions are expensive
- How many filters can we learn?
  - Dozens? Hundreds? Millions? More?

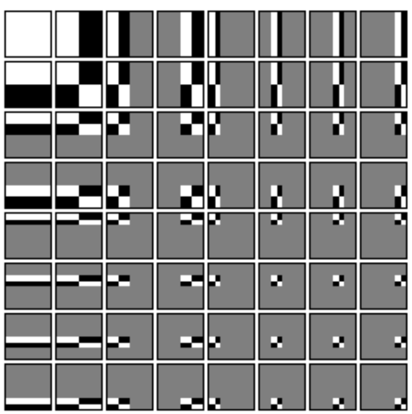
Huge Amount of Filters: An Example

[Viola and Jones]: face detection via <u>millions</u>* of simple filters





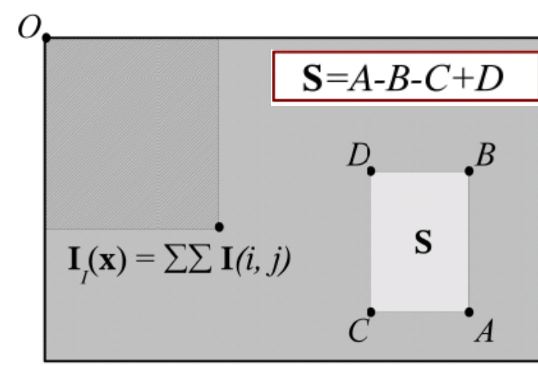
Haar Wavelet



Haar like features

Given two adjacent rectangular regions, sums up the pixel intensities in each region and calculates the difference between the two sums

Efficient computation



*This suggests to find ways to train numerous filters…

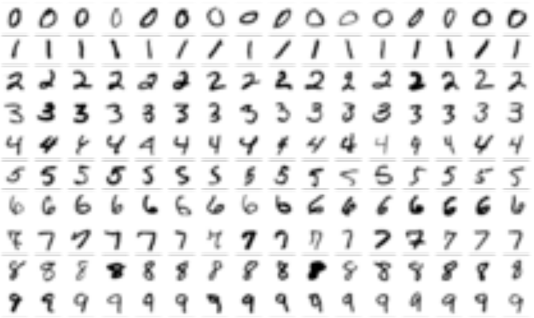
Discussions

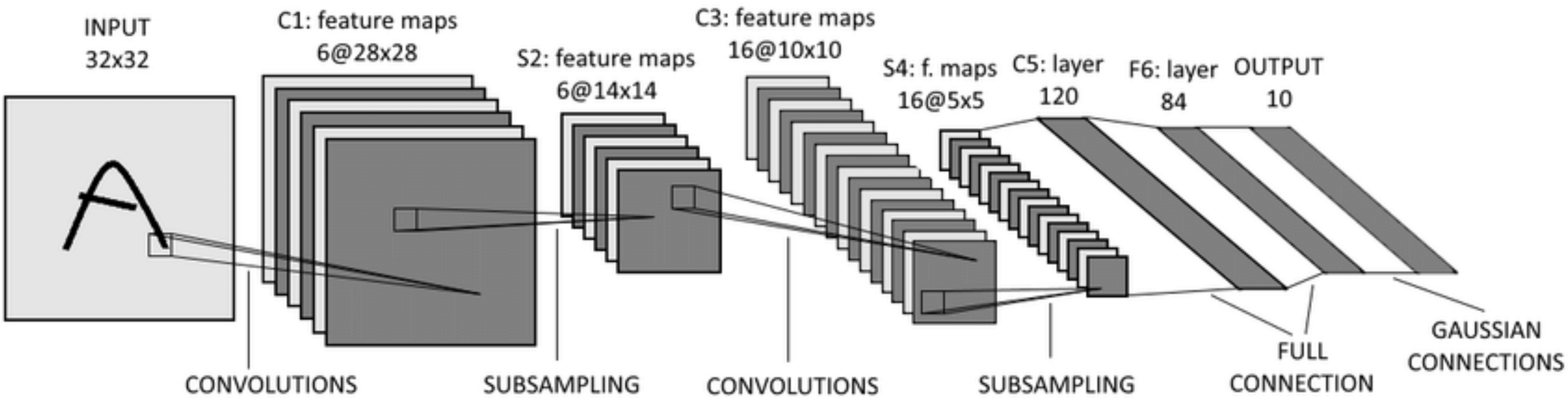
- Filters are powerful for many vision applications
- Convolutions are expensive
- How many filters can we learn?
- How to manage larger neighborhood?
  - Sub-sample the image
  - Larger receptive fields (i.e., filter size)
  - Stack multi convolutional layers together -> deep CNNs

Let's Go to Multi-Layer CNNs (deep CNNs)!

The First Popular Deep CNN

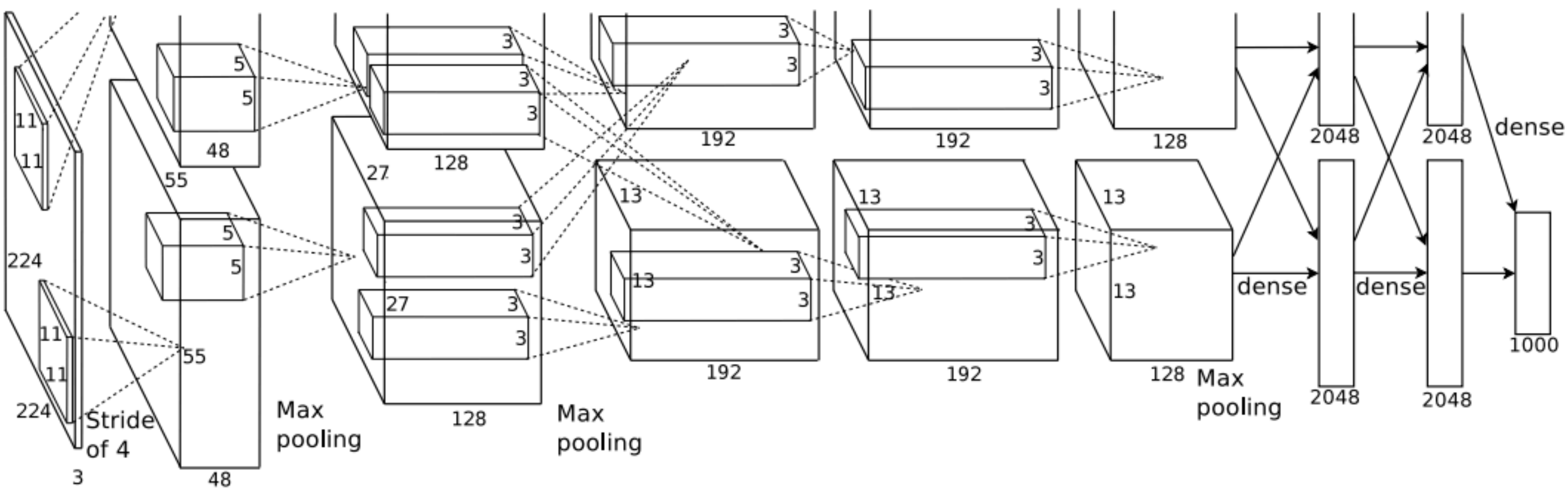
- LeCun, Bottou, Bengio, Haffner, Gradient-based learning applied to document recognition, Proc. IEEE, 1998





The Second Popular Deep CNN

- Krizhevsky, Sutskever, Hinton, ImageNet Classification with Deep Convolutional Neural Networks, NIPS 2012



Why Took 14 years? (1998-2012)

- People do not trust local minimum and may be annoyed by SGD failures.

Which of the following will fail CNNs on MNIST?

- Use the raw pixel values between [0, 255]
- Initialize all the CNN weights as 0
- Use no intercept (i.e., Wx instead of Wx+b) in the fully connect layer
- The batch size is too small (i.e., one sample per batch)
- Use the whole dataset as one batch
- Do not shuffle the data before training

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Which of the following will fail CNNs on MNIST?

- Use the raw pixel values between [0, 255]

Yes. Almost all CNNs prefer to normalize pixel value normalized between [0,1]

Why Took 14 years? (1998-2012)

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Which of the following will fail CNNs on MNIST?

- Initialize all the CNN weights as 0

Yes. network weights should be initialized randomly

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Which of the following will fail CNNs on MNIST?

- Use no intercept (i.e., Wx instead of Wx+b) in the fully connect layer

No. Network with zero intercepts will still work.

Why Took 14 years? (1998-2012)

- People do not trust local minimum and may be annoyed by SGD failures.

Which of the following will fail CNNs on MNIST?

- The batch size is too small (i.e., one sample per batch)

No. Small batch size will still work, but make the optimization smaller

Why Took 14 years? (1998-2012)

- People do not trust local minimum and may be annoyed by SGD failures.

Which of the following will fail CNNs on MNIST?

- – Use the whole dataset as one batch

Yes. We will lose the "stochastic" factor by taking whole dataset as one batch, and the optimization will fall into bad local minimum.

Why Took 14 years? (1998-2012)

- People do not trust local minimum and may be annoyed by SGD failures.

Which of the following will fail CNNs on MNIST?

  - Do not shuffle the data before traiing

Yes. Random shuffling is important.

Why Took 14 years? (1998-2012)

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Which of the following will fail CNNs on MNIST?

- **Use the raw pixel values between [0, 255]**
- **Initialize all the CNN weights as 0**
- Use no intercept (i.e., Wx instead of Wx+b) in the fully connect layer
- The batch size is too small (i.e., one sample per batch)
- **Use the whole dataset as one batch**
- **Do not shuffle the data before training**

Why Took 14 years? (1998-2012)

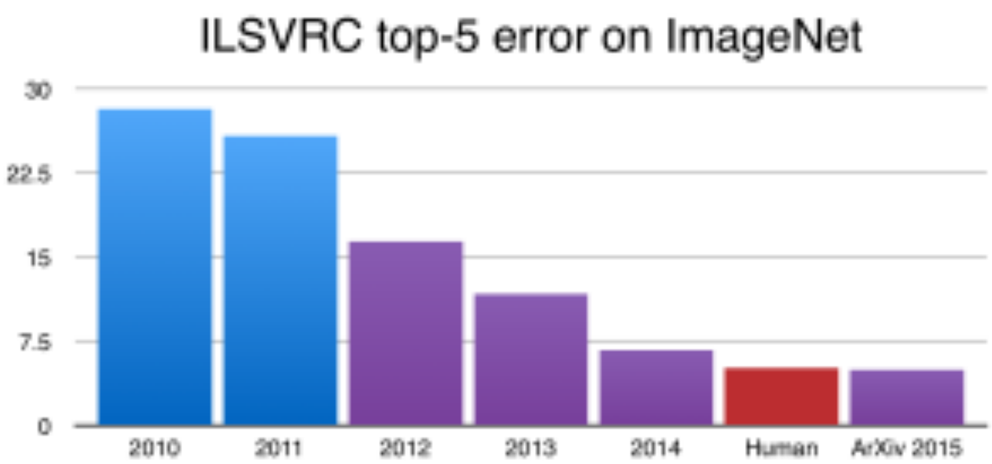
- People do not trust local minimum and may be annoyed by SGD failures.
- On MNIST CNN is not significant better than others

Model	Testing Error
KNN, subsample 16 x 16	1.1%
Boosted tree	1.53%
Non-linear SVM by LeCun'98	1.0%
Non-linear SVM by DeCoste'02	0.56%
2-layer MLP	2.45%
CNN LeNet-5	0.95%

Results from http://yann.lecun.com/exdb/mnist/

Why Took 14 years? (1998-2012)

- People do not trust local minimum and may be annoyed by SGD failures.
- On MNIST CNN is not significant better than others
- But on ImageNet things changed!



Differences between MNIST and ImageNet

	MNIST	ImageNet LSVRC
Image size	28 x 28 x 1	224 x 224 x 3*
Num of images	60K	1,200K
Num of category	10	1000
In-class variation	small	large

*Resized size. Can be as large as 512 x 512

Differences between MNIST and ImageNet

	MNIST	ImageNet LSVRC
Image size	28 x 28 x 1	224 x 224 x 3
Num of images	60K	1,200K
Num of category	10	1000
In-class variation	small	large

SVMs → **More data** → **Bigger model** → **CNNs**

Let’s implement these two popular models.

To implement LeNet is easy …

1. Download MNIST data and load them into memory
2. Build a 5 layer CNN model
3. Train model and evaluate

You can even run on your laptop without GPU

Implement LeNet-5 using Keras

```
model = Sequential()
model.add(Conv2D(filters = 6, kernel_size = 5, strides = 1, activation = 'relu',
          input_shape = (32,32,1)))
model.add(MaxPooling2D(pool_size = 2, strides = 2))
model.add(Conv2D(filters = 16, kernel_size = 5, strides = 1, activation = 'relu',
          input_shape = (14,14,6)))
model.add(MaxPooling2D(pool_size = 2, strides = 2))
model.add(Flatten())
model.add(Dense(units = 120, activation = 'relu'))
model.add(Dense(units = 84, activation = 'relu'))
model.add(Dense(units = 10, activation = 'softmax'))
model.compile(optimizer = 'adam', loss = 'categorical_crossentropy', metrics
          = ['accuracy'])
model.fit(X_train ,Y_train, steps_per_epoch = 10, epochs = 40)
```

Explain LeNet-5

- filters
- kernel_size
- Strides
- pool_size
- model.add(Flattern())
- activation=relu/sigmoid/softmax

But to implement AlexNet is hard…

Alex Krizhevsky was working on CNNs in 2011. He recalled:

"Ilya convinced me that with **an additional week** of effort, we could get equally good results on ImageNet. It actually took **five months** to match the 2010 state-of-the-art, and **several more months** to improve on it convincingly."

"Time scales aside, his intuition was correct."

But to implement AlexNet is hard…

Suppose you are the chief architect, what is the solution for

- load 1.2M images into memory
- do convolution via GPUs
- AlexNet model: two stream using 2 GPUs (not necessary though)

Challenge 1: Cannot Load All ImageNet Data into Memory

- Can not load into memory: 1.2M x 224 x 224 x 3 = 180G
- Keras' solution: use data iterator

```
class NaiveImageNetIterator:
        def __init__(self, total_batches):
                self.ib, self.nb = 0, total_batches
        def __iter__(self):
                return self
        def next(self): # Python 3: def __next__(self)
                if self.ib >= self.nb: raise StopIteration
                else:
                        self.ib += 1
                        return Load_Batch_from_Disk(self.ib)
```

Challenge 1: Cannot Load All ImageNet Data into Memory

Can not directly load into mem: 1.2M x 224 x 224 x 3 = 180G

- Keras' solution: use data iterator

```
class NaiveImageNetIterator: ….

data_iterator = NaiveImageNetIterator(120)
model.fit_generator(data_iterator, sample_per_epoch=1000)
```

Challenge 1: Cannot Load All ImageNet Data into Memory

Can not directly load into mem: 1.2M x 224 x 224 x 3 = 180G

- Keras' solution: use data iterator
- Tensorflow's low level API: use tf.data.Dataset

- tf.data.Dataset can generate an iterator of Tensor objects
https://www.tensorflow.org/api_docs/python/tf/data

- Many detection toolkits use TFRecord to organize many images

- tensorpack provides an efficient & easy to use 3^{rd} party implementation

https://github.com/tensorpack/tensorpack

Challenge 1: Cannot Load All ImageNet Data into Memory

Can not directly load into mem: 1.2M x 224 x 224 x 3 = 180G

- Keras' solution: use data iterator
- Tensorflow's native solution: use tf.data.Dataset
- 3rd Party implementation: Tensorpack (https://github.com/tensorpack/tensorpack)
  - Use Tensorpack.dataflow
  - See example: ImageNetModels/imagenet_utils.py
  - The most efficient solution so far

I may provide a note with more details after the class.

But you may have to dig into these examples to play with these solutions

Challenge 2: Convolution via GPUs

Convolution in GPU is not trivial

- Multi-channel (traditional CV do single channel)
- Multi kernel size (optimization of 5x5 filter differs from 7x7)

See Alex's dizzying code
https://code.google.com/archive/p/cuda-convnet/

Challenge 2: Convolution via GPUs

Convolution in GPU is not trivial

- Multi-channel (traditional CV do single channel)
- Multi kernel size (optimization of 5x5 filter differs from 7x7)

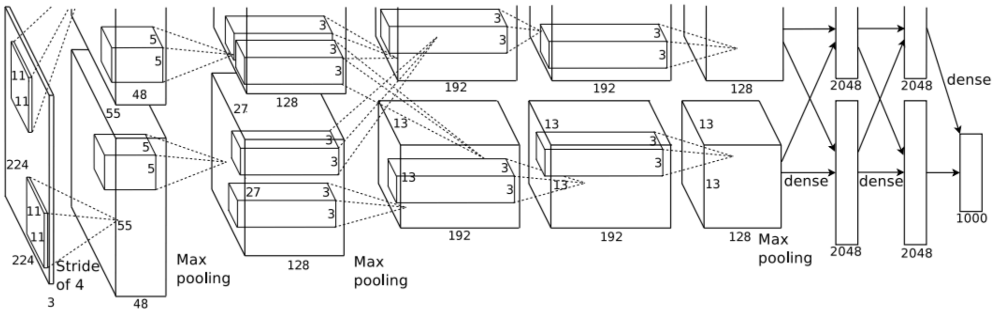
Use NVida's library:

- cuBLAS in early days (converting conv to matrix multiply)
- cuDNN: Nvidia's dominant weapon in GPU market

Challenge 3: Two Stream CNN

Amazing hacks in 2012

No longer necessary with the new GPU cards



Implement AlexNet with Keras

```
# layer 1
alexnet.add(Conv2D(96, (11, 11),
    input_shape=img_shape,
    padding='same',
    kernel_regularizer=l2(l2_reg)))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
    alexnet.add(MaxPooling2D(pool_
    size=(2, 2)))
# layer 2
alexnet.add(Conv2D(256, (5, 5),
    padding='same'))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(MaxPooling2D(pool_siz
    e=(2, 2)))
```

What is the number of para. in Layer 1

- (11 x 11 x 3) * 96 = 35K

What is the output size of layer 1?

- 224 /4 = 55
- Output size (55 x 55 x 96)

What is the number of para in layer 2?

- (5 x 5 x 96) * 256 = 710K

What is the output size of layer 2?

- 55/2 = 27
- Output size (27 x 27 x 256)

Implement AlexNet with Keras

```
# layer 1
alexnet.add(Conv2D(96, (11, 11),
    input_shape=img_shape,
    padding='same',
    kernel_regularizer=l2(l2_reg)))
alexnet.add(BatchNormalization())
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    size=(2, 2)))
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    padding='same'))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(MaxPooling2D(pool_siz
    e=(2, 2)))
```

```
# layer 3
alexnet.add(ZeroPadding2D((1, 1)))
    alexnet.add(Conv2D(512, (3, 3),
    padding='same'))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(MaxPooling2D(pool_siz
    e=(2, 2)))

# layer 4
alexnet.add(ZeroPadding2D((1, 1)))
alexnet.add(Conv2D(1024, (3, 3),
    padding='same'))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
```

Implement AlexNet in Keras (con't)

```
# layer 5
alexnet.add(ZeroPadding2D((1, 1)))
alexnet.add(Conv2D(1024, (3, 3),
  padding='same'))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(MaxPooling2D(pool_size=(2,
  2)))

# layer 6
alexnet.add(Flatten())
alexnet.add(Dense(3072))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(Dropout(0.5))

# layer 7
alexnet.add(Dense(4096))
alexnet.add(BatchNormalization())
alexnet.add(Activation('relu'))
alexnet.add(Dropout(0.5)) #

# layer 8
alexnet.add(Dense(n_classes))
alexnet.add(BatchNormalization())
alexnet.add(Activation('softmax'))
```

From Keras to TF Estimator

Keras is easy to use but not efficient

- Large memory consumption
- Difficulty to scale to multiple GPUs

Use tensorflow's estimator for large datasets:

- TF Estimator can use Keras' layers
- TF Estimator can replace Keras Sequential() model in large scale

Improving AlexNet

Try smaller receptive fields, more filters, with more layers

- Matt Zeiler Network
- VggNet

Concatenate multiple size of filters

- GoogLeNet

Two techniques are important:

- 1x1 conv (aka "network in network")
- Residual Network

1x1 convolution

Consider two layers of CNN

- Input: 56x 56 x 3
- Layer A: (11x11)*96 filters, output (56 x 56 x 96),
- Layer B: (5 x 5) *256 filters output (56 x 56 x 256)

Layer B has (5 x 5 x 96)* 256 parameters, also consumes a lot of GPU memory. How to reduce the parameter?

Add a new layer between A and B

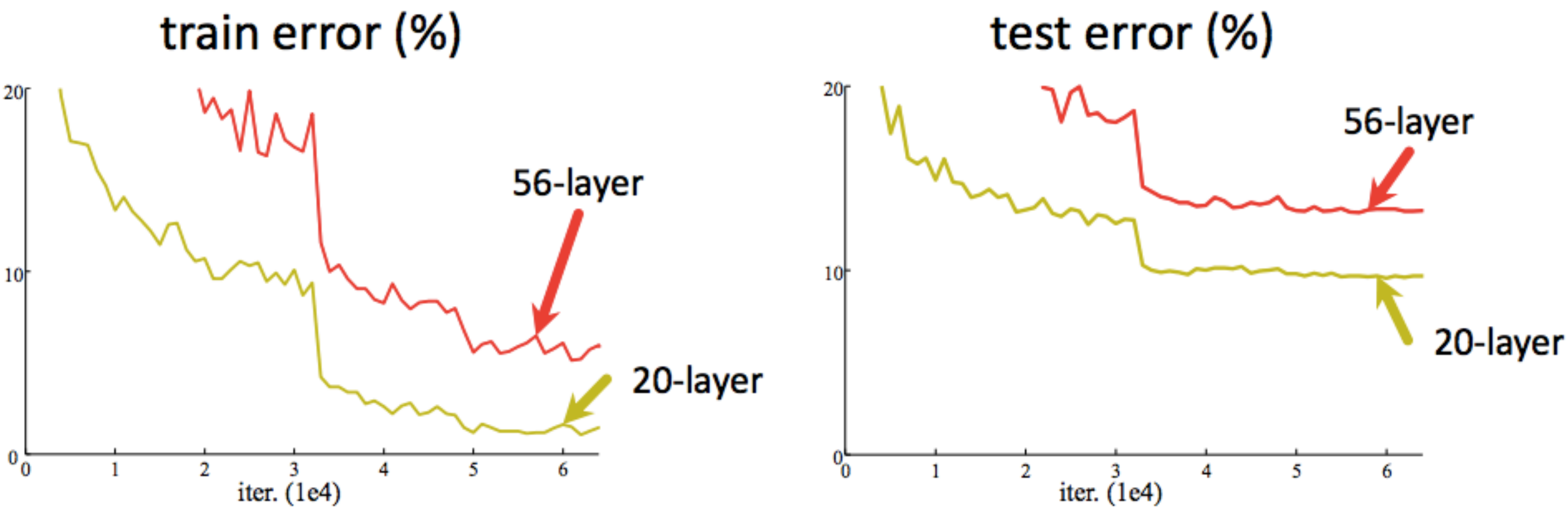
- Layer A': (1x1)*32 filters, output (56 x 56 x 32)

Now layer B has (5 x 5 x 32)*256 filters. 3x less parameters!

Why Residual Network?

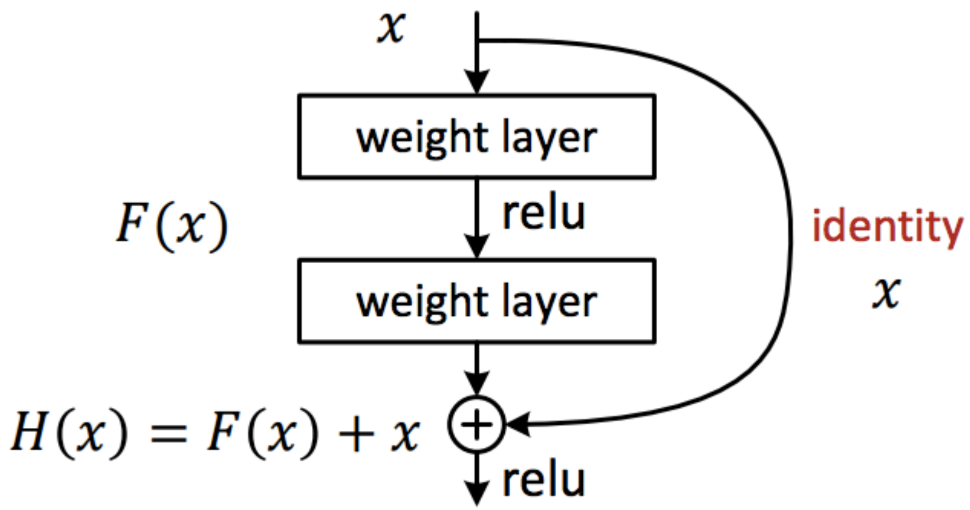
Problem: Is learning better networks as simple as stacking more layers?

CIFAR-10



Deep network + residual learning can solve this problem.

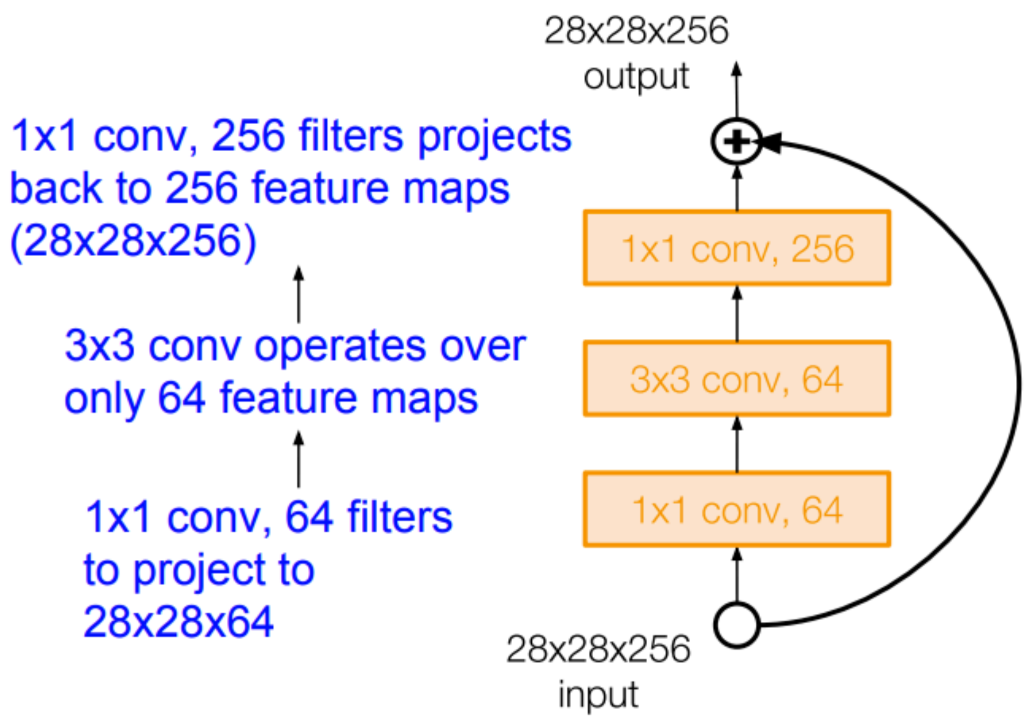
Residual Net




```
from keras.layers import Conv2D, Input

# input tensor for a 3-channel 256x256 image
x = Input(shape=(3, 256, 256))
# 3x3 conv with 3 output channels (same as input channels)
y = Conv2D(3, (3, 3), padding='same')(x)
# this returns x + y.
z = keras.layers.add([x, y])
```

Residual Net With Bottleneck Structure



A number of future improvement

Treasure from ImageNet Dataset

By adapting models trained from ImageNet, we can build a decent classifier with limited data.

IMAGENET

Very few new label

- Tune the last layer
- Or last layer as feature for SVM

Enough new labels

- Tune the whole network

New tasks

<u>Example code :</u>

http://caffe.berkeleyvision.org/gathered/examples/finetune_flickr_style.html

But ImageNet May NOT Be Ideal For Course Projects

- Too crowded in the competition
- Relatively difficulty to find novel ideas

If you want to try a final project on large scale recognition, we recommend Celebrity1M faces

After break (8:30pm), will join us our guest lecture Dr. Lei Zhang, who is the creator of Microsoft Celebrity1M.