Convolutional Neural Networks

Liangliang Cao

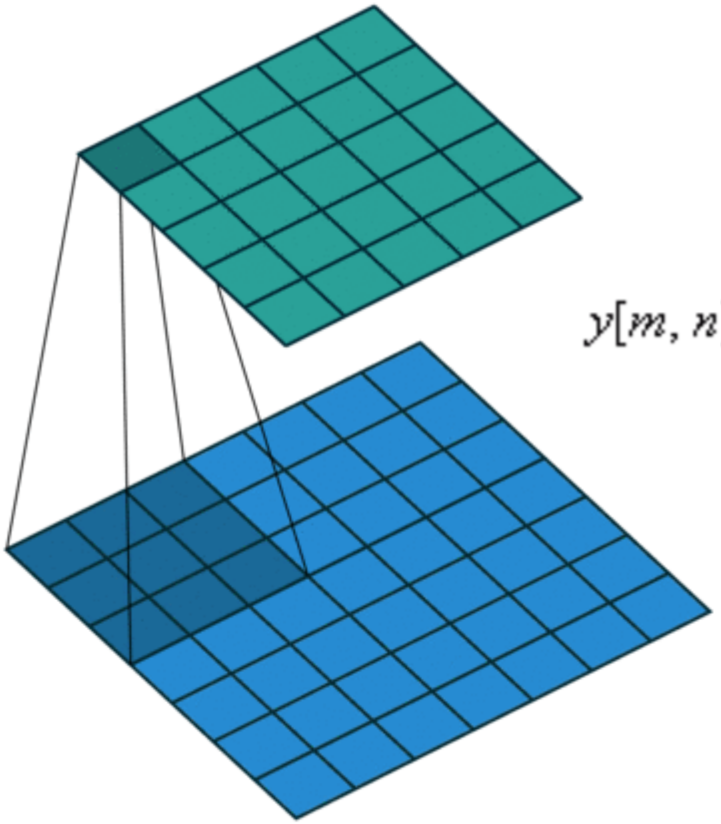
https://columbia6894.github.io/

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

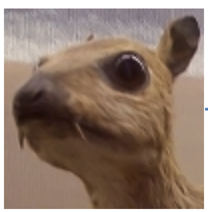
- Image filtering are usually represented by the convolution between an image and a mask.



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

Image Filters

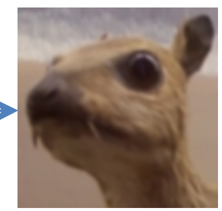
- Image filtering are usually represented by the convolution between an image and a mask.



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

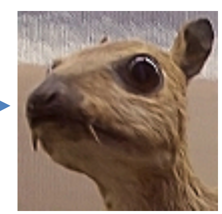
Edge detection

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



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

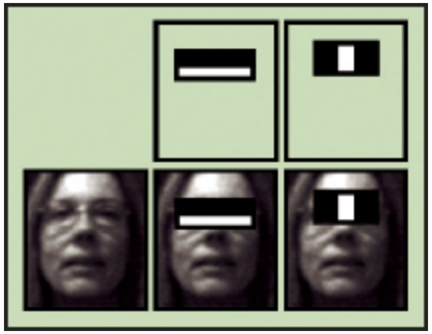
*This suggests a number of research ideas of improving deep cnn

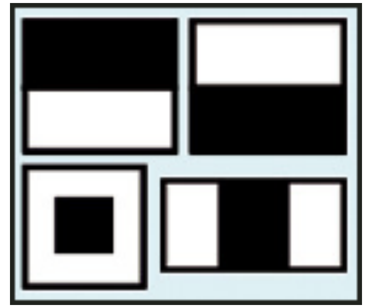
Discussions

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

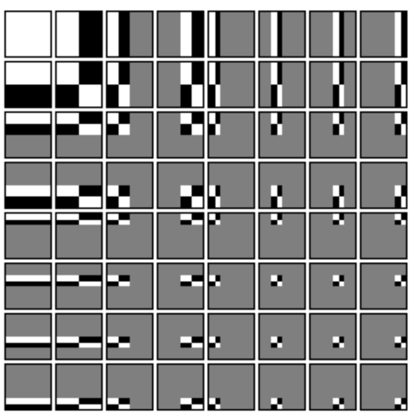
Huge Amount of Filters: An Example

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





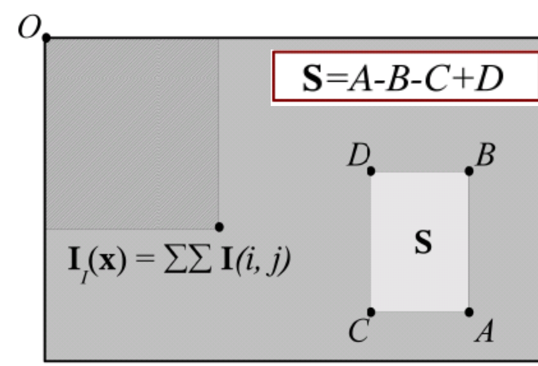
Haar Wavelet



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…

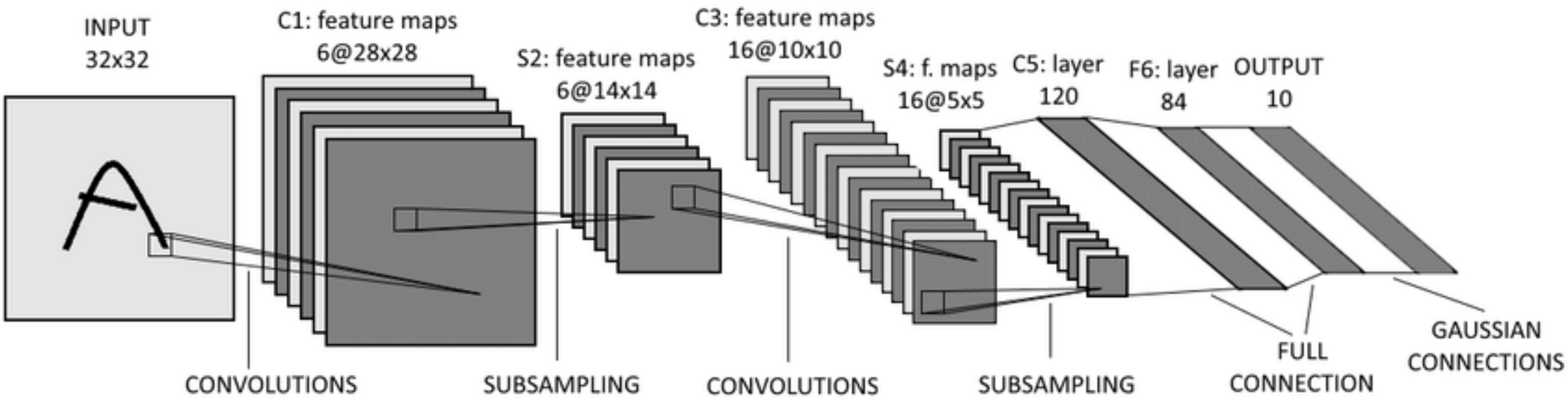
Discussions

- 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)!

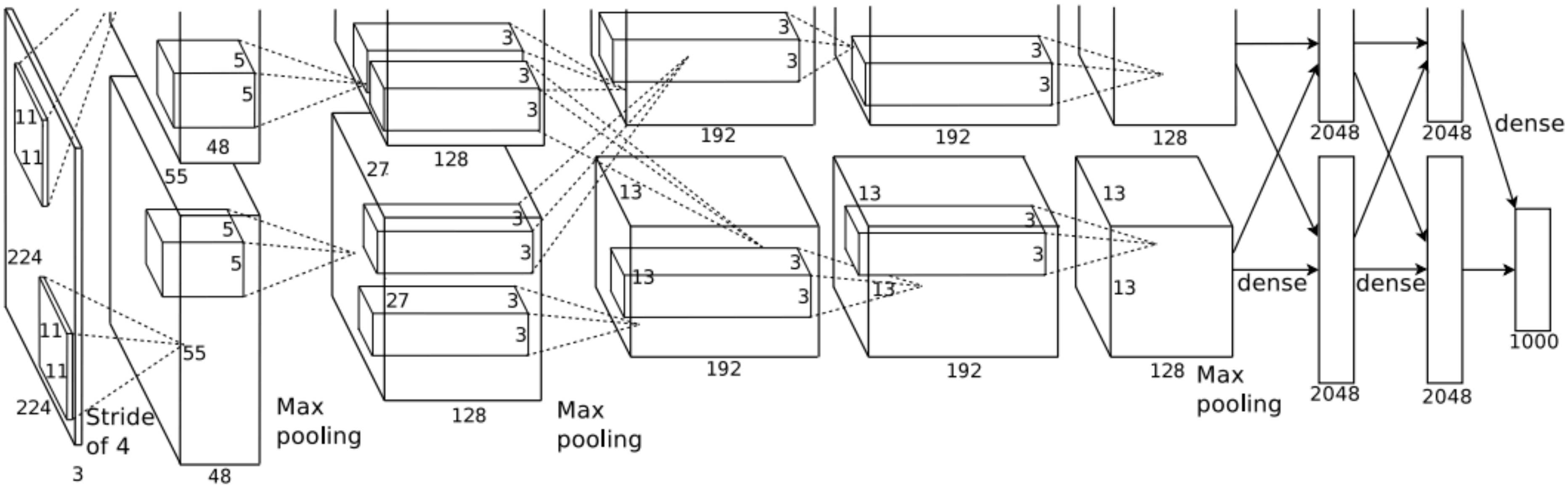
The First Popular Deep CNN

- 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

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**

Why Took 14 years? (1998-2012)

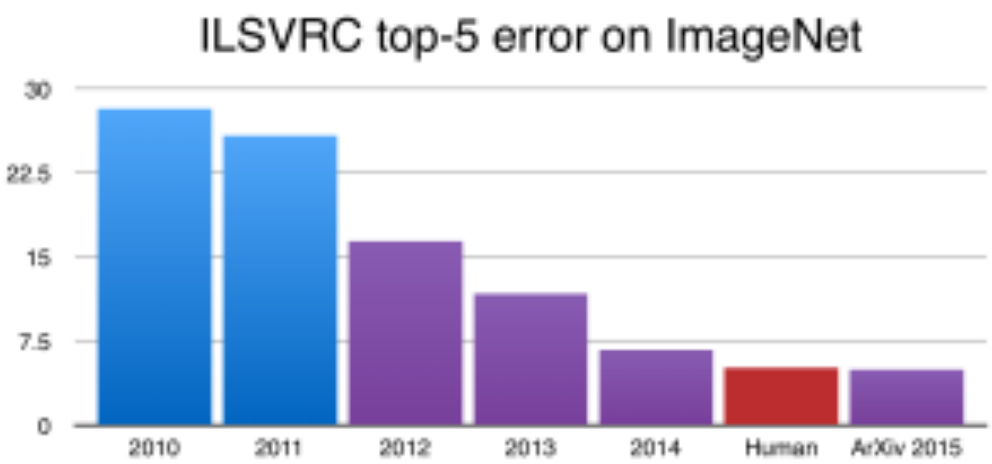
- People do not trust local minimum and may be annoyed by SGD failures.
- On MNIST CNN is not significant better than others

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!



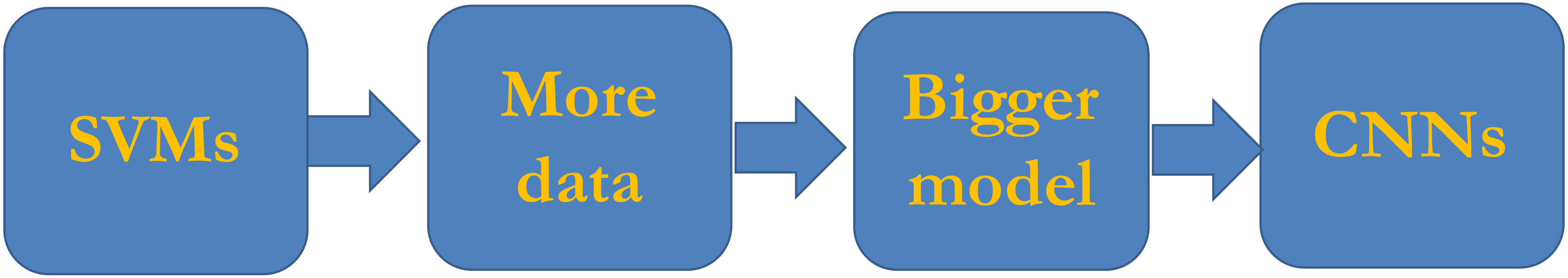
Differences between MNIST and ImageNet

	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



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 native solution: use tf.data.Dataset

  - tf.data.Dataset can generate an iterator of Tensor objects

  - see: https://www.tensorflow.org/api_docs/python/tf/data

  - more efficient than Keras

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)

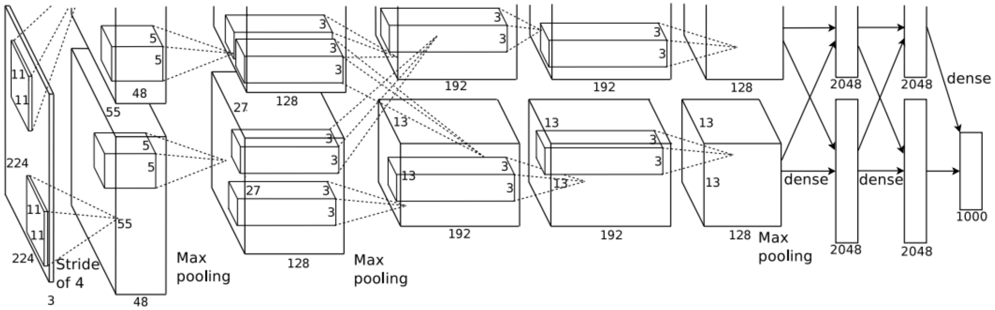
Use NVida's library:

- 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())
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)))
```

```
# 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'))
```

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?

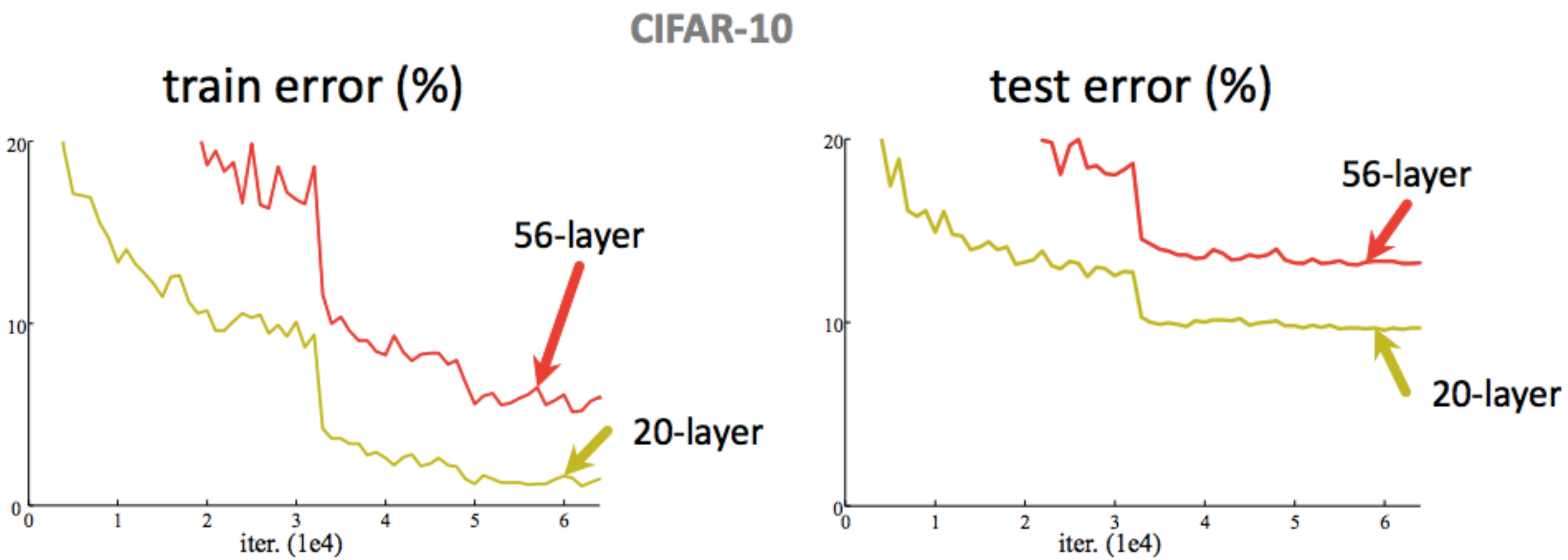
Add a new layer between A and B

- 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!

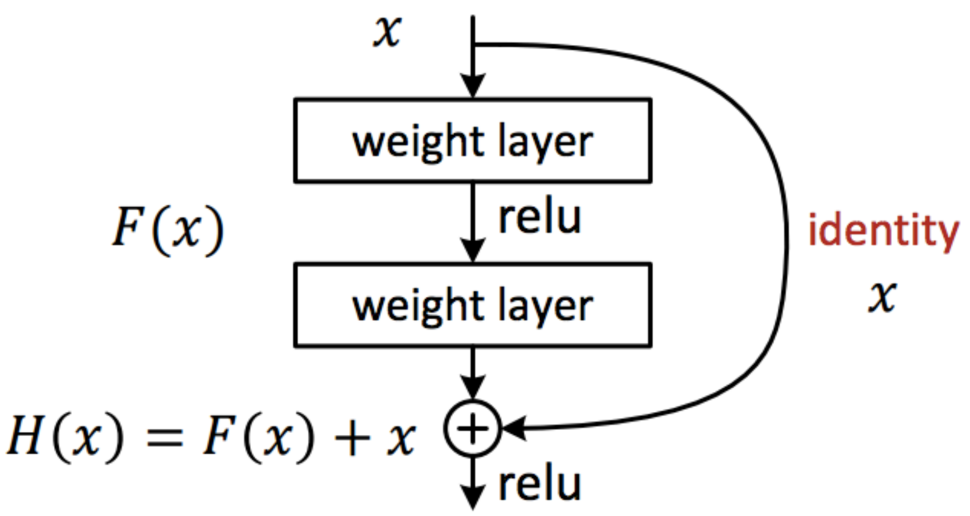
Why Residual Network?

Problem: <u>Is learning better networks as simple as stacking more layers?</u>



Deep network + residual learning can solve this problem.

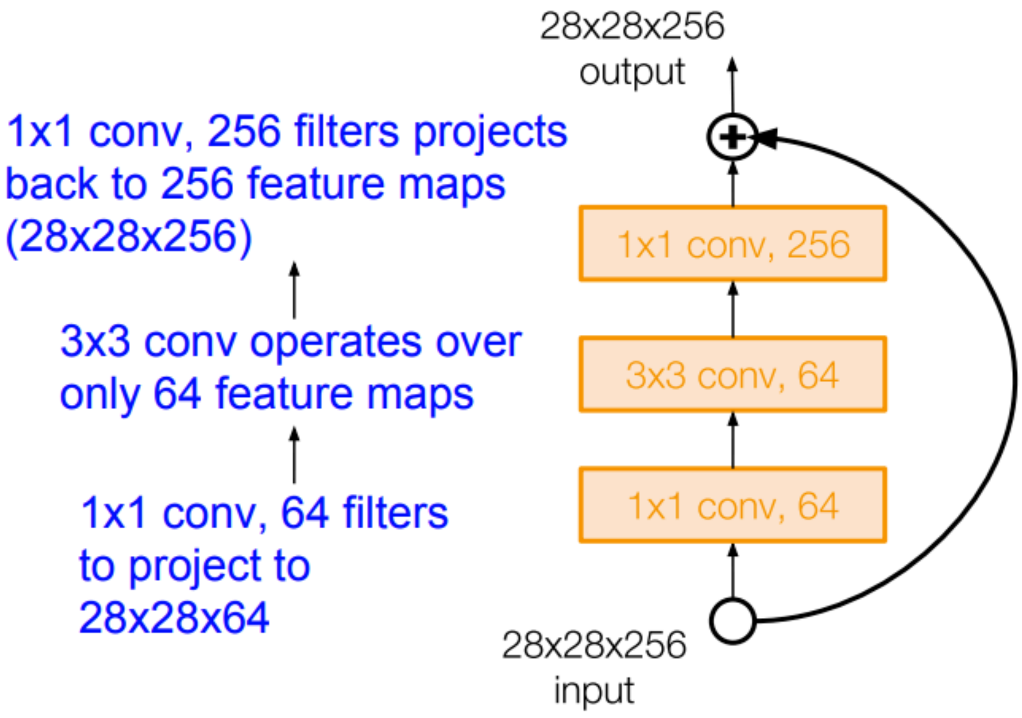
Residual Net




```
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

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

Very few new label

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

Enough new labels

- Tune the whole network

New tasks

But ImageNet May NOT Ideal For Course Projects

- Resource demanding
- Too much competition

But we still hope you can gain experience from large scale problem

Please see Lei Zhang's talk on Celebrity1M faces