



CS 540 Introduction to Artificial Intelligence
Deep Learning III

University of Wisconsin-Madison
Spring 2025

Announcements

- **Homeworks:**

- HW7 online, due on Monday **April 7th at 11:59 PM**

- Class roadmap and schedule:

Machine Learning: Deep Learning III

Machine Learning: Deep Learning and Neural Network's Summary

Outline

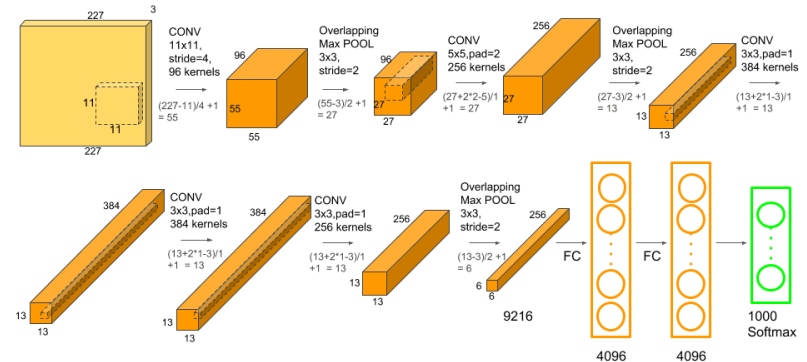
- CNNs with more layers: ResNets
 - Layer problems, residual connections, identity maps
- Data Augmentation & Regularization
 - Expanding the dataset, avoiding overfitting
- More Signal From our Data
 - Graph-structured data, graph neural networks

Last Time: CNNs

We talked about CNN components & architectures

- **Components:** convolutional layers, pooling layers (recall kernels, channels, strides, padding)
- **Architectures:** LeNet, AlexNet, VGG

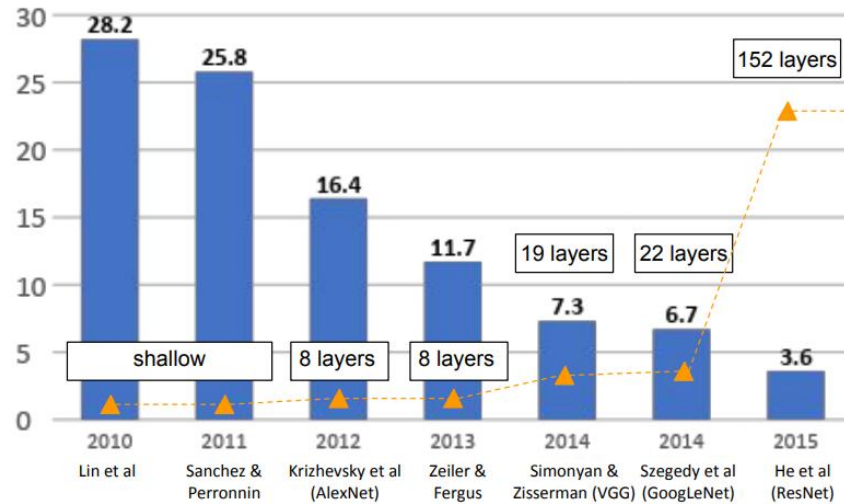
- Trend: bigger, deeper.



Credit: Mathworks

Evolution of CNNs

ImageNet competition (error rate)



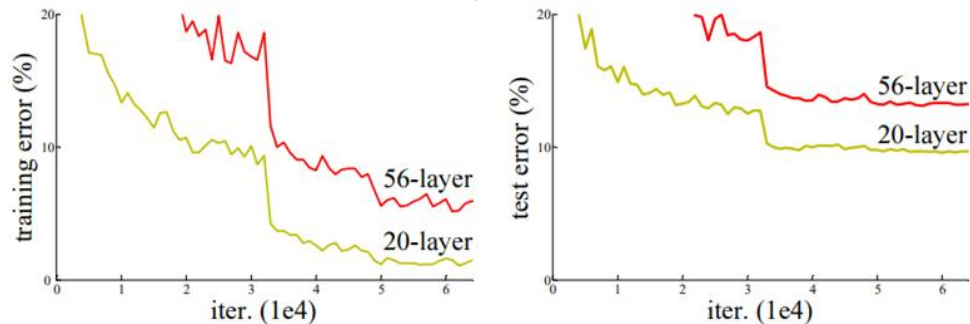
Credit: Stanford CS 231n

Simple Idea: Add More Layers

VGG: 19 layers. ResNet: 152 layers. **Add more layers...**
sufficient?

- No! Some problems:
 - i) Vanishing gradients: more layers → more likely
 - ii) Instability: deeper models are harder to optimize

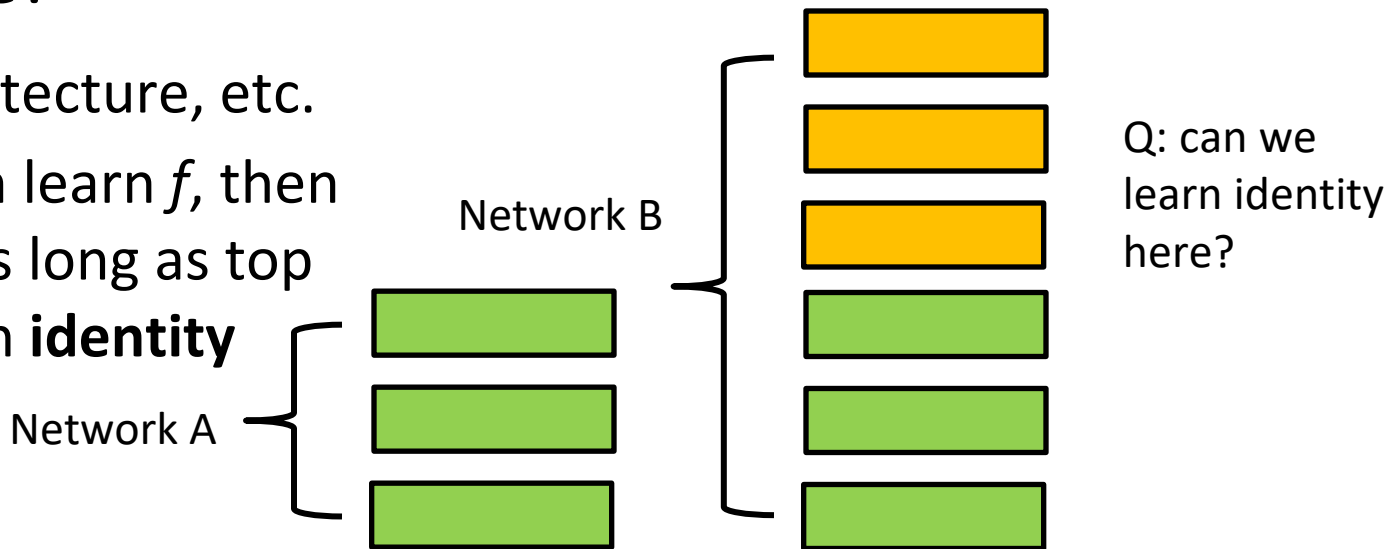
Reflected in training error:



Depth Issues & Learning Identity

Why would more layers result in **worse** performance?

- Same architecture, etc.
- If the A can learn f , then so can B, as long as top layers learn **identity**

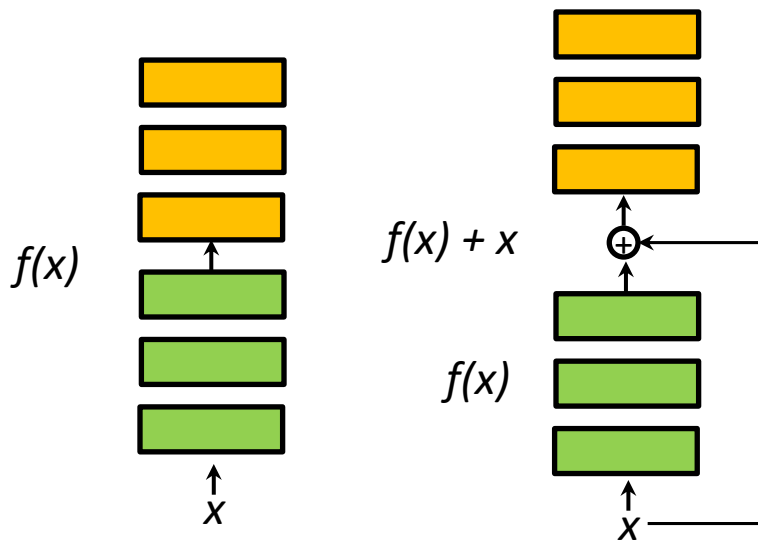


Idea: if layers can learn identity, **can't get worse**.

Residual Connections

Idea: Identity might be hard to learn, but zero is easy!

- Make all the weights tiny, produces zero for output
- Can easily transform learning identity to learning zero:



Left: Conventional layers block

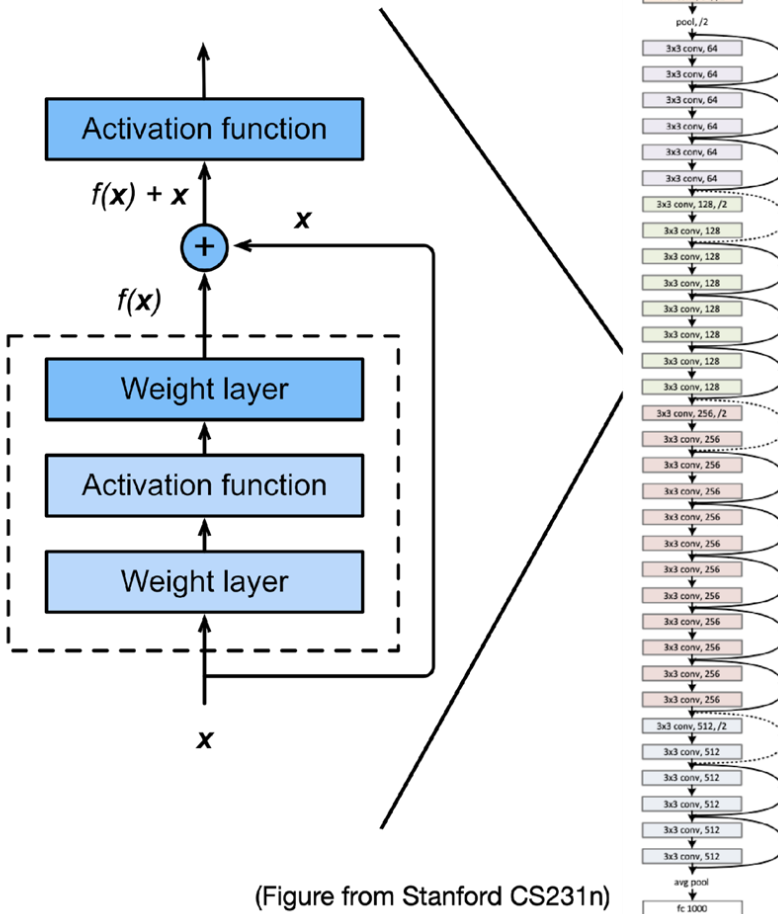
Right: **Residual** layer block

To learn identity $f(x) = x$, layers now need to learn $f(x) = 0 \rightarrow$ easier

Full ResNet Architecture

[He et al. 2015]

- Stack residual blocks
- Every residual block has two 3x3 conv layers
- Periodically, double # of filters and downsample spatially using stride of 2 (/2 in each dimension)

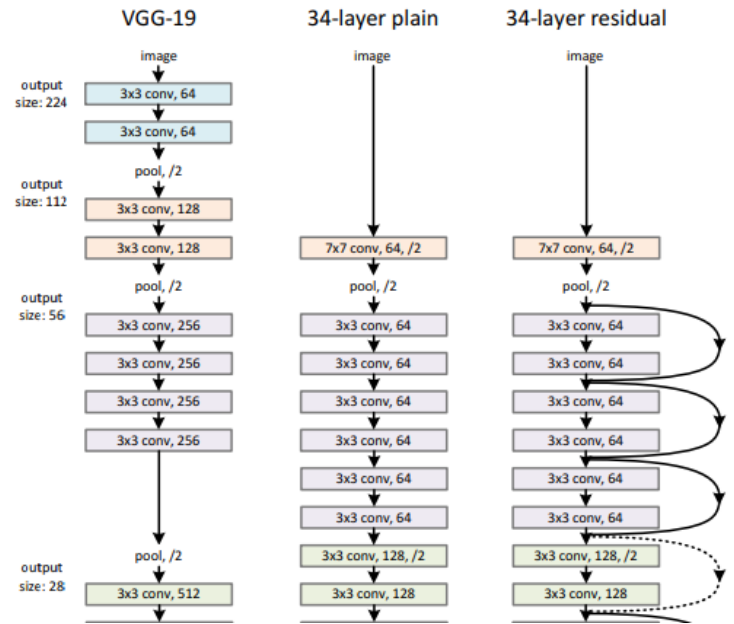


(Figure from Stanford CS231n)

ResNet Architecture

Idea: Residual (skip) connections help make learning easier

- Example architecture:
- Note: residual connections
 - Every two layers for ResNet34
- **Vastly better** performance
 - No additional parameters!
 - Records on many benchmarks



He et al: “Deep Residual Learning for Image Recognition”

ResNet Architecture

Various depth

layer name	output size	18-layer	34-layer	50-layer	101-layer	152-layer
conv1	112×112	7×7, 64, stride 2				
		3×3 max pool, stride 2				
conv2_x	56×56	$\begin{bmatrix} 3\times 3, 64 \\ 3\times 3, 64 \end{bmatrix} \times 2$	$\begin{bmatrix} 3\times 3, 64 \\ 3\times 3, 64 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 64 \\ 3\times 3, 64 \\ 1\times 1, 256 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 64 \\ 3\times 3, 64 \\ 1\times 1, 256 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 64 \\ 3\times 3, 64 \\ 1\times 1, 256 \end{bmatrix} \times 3$
conv3_x	28×28	$\begin{bmatrix} 3\times 3, 128 \\ 3\times 3, 128 \end{bmatrix} \times 2$	$\begin{bmatrix} 3\times 3, 128 \\ 3\times 3, 128 \end{bmatrix} \times 4$	$\begin{bmatrix} 1\times 1, 128 \\ 3\times 3, 128 \\ 1\times 1, 512 \end{bmatrix} \times 4$	$\begin{bmatrix} 1\times 1, 128 \\ 3\times 3, 128 \\ 1\times 1, 512 \end{bmatrix} \times 4$	$\begin{bmatrix} 1\times 1, 128 \\ 3\times 3, 128 \\ 1\times 1, 512 \end{bmatrix} \times 8$
conv4_x	14×14	$\begin{bmatrix} 3\times 3, 256 \\ 3\times 3, 256 \end{bmatrix} \times 2$	$\begin{bmatrix} 3\times 3, 256 \\ 3\times 3, 256 \end{bmatrix} \times 6$	$\begin{bmatrix} 1\times 1, 256 \\ 3\times 3, 256 \\ 1\times 1, 1024 \end{bmatrix} \times 6$	$\begin{bmatrix} 1\times 1, 256 \\ 3\times 3, 256 \\ 1\times 1, 1024 \end{bmatrix} \times 23$	$\begin{bmatrix} 1\times 1, 256 \\ 3\times 3, 256 \\ 1\times 1, 1024 \end{bmatrix} \times 36$
conv5_x	7×7	$\begin{bmatrix} 3\times 3, 512 \\ 3\times 3, 512 \end{bmatrix} \times 2$	$\begin{bmatrix} 3\times 3, 512 \\ 3\times 3, 512 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 512 \\ 3\times 3, 512 \\ 1\times 1, 2048 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 512 \\ 3\times 3, 512 \\ 1\times 1, 2048 \end{bmatrix} \times 3$	$\begin{bmatrix} 1\times 1, 512 \\ 3\times 3, 512 \\ 1\times 1, 2048 \end{bmatrix} \times 3$
	1×1	average pool, 1000-d fc, softmax				
FLOPs		1.8×10 ⁹	3.6×10 ⁹	3.8×10 ⁹	7.6×10 ⁹	11.3×10 ⁹

Table 1. Architectures for ImageNet. Building blocks are shown in brackets (see also Fig. 5), with the numbers of blocks stacked. Down-sampling is performed by conv3_1, conv4_1, and conv5_1 with a stride of 2.

ResNet Architecture

Various depth

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ResNet Architecture

Various depth

Repeat x3 times

of filters

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ResNet Architecture

Various depth

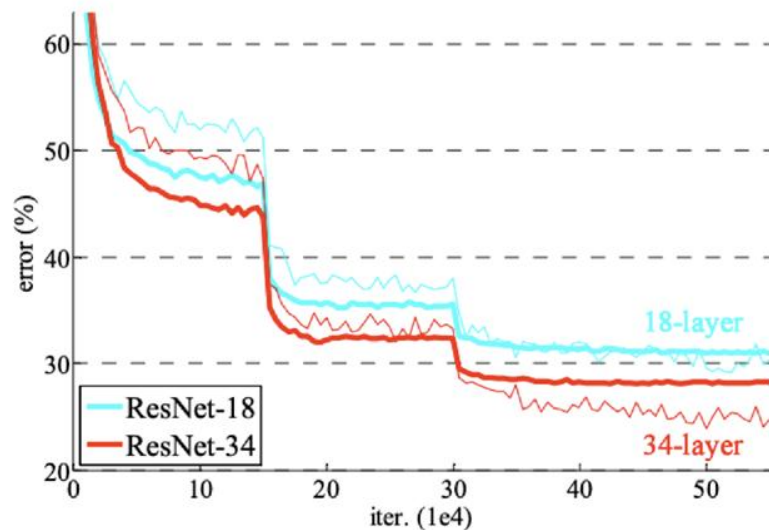
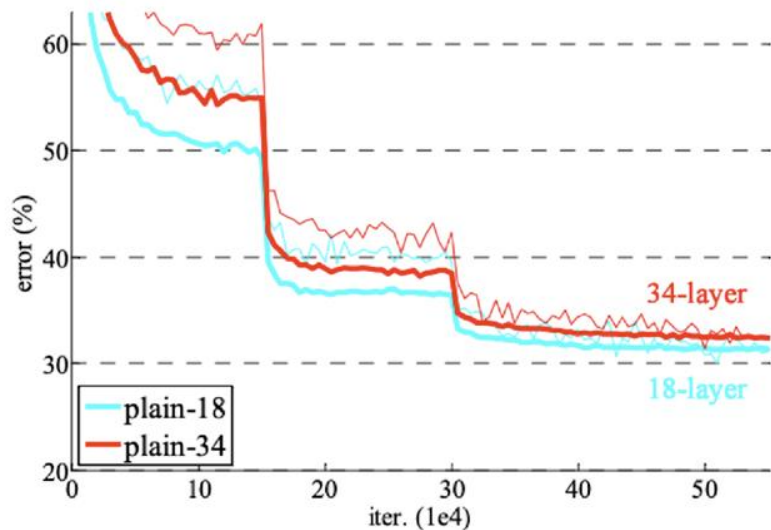
$$1 + 2 \times 3 + 2 \times 4 + 2 \times 6 + 2 \times 3 + 1 = 34$$

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ResNet Training Curves on ImageNet

[He et al., 2015]



A Bit More on ResNets

Idea: Residual (skip) connections help make learning easier

- Note: Can also analyze from **backpropagation** p.o.v
 - Residual connections add paths to computation graph
- Also uses **batch normalization**
 - Normalize the features at each layer to have same mean/variance
 - Common deep learning trick
- Highway networks: learn weights for residual connections

Ioffe and Szegedy: “Batch Normalization: Accelerating Deep Network Training by Reducing Internal Covariate Shift”

Break & Quiz

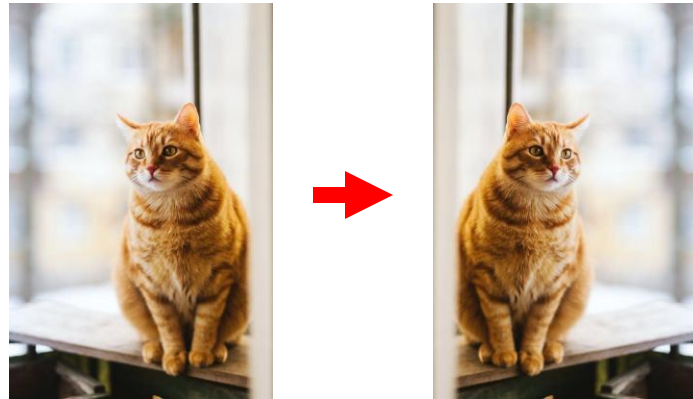
Q 1.1: Which of the following is **not** true?

- A. Adding more layers can improve the performance of a neural network.
- B. Residual connections help deal with vanishing gradients.
- C. CNN architectures use no more than ~ 20 layers to avoid problems such as vanishing gradients.
- D. It is usually easier to learn a zero mapping than the identity mapping.

Data Concerns

What if we don't have a lot of data?

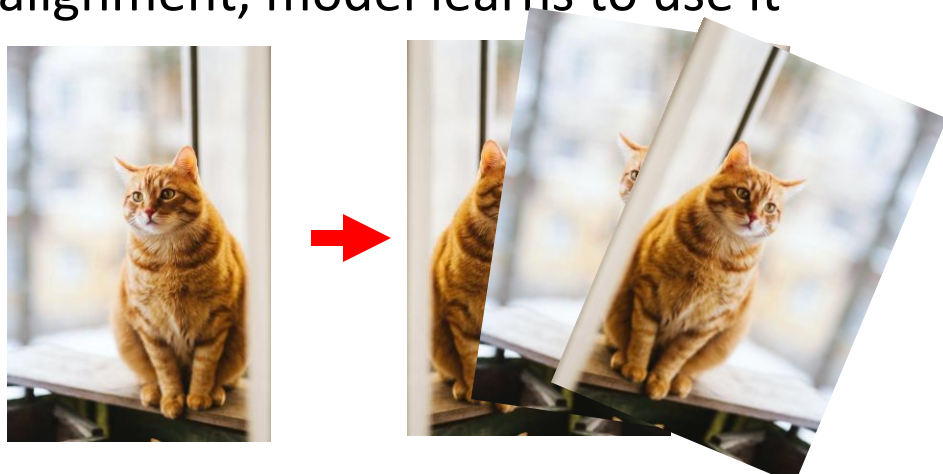
- We risk overfitting
- Avoiding overfitting: **regularization** methods
- Data augmentation: a classic way to regularize



Data Augmentation

Augmentation: transform + add new samples to dataset

- Transformations: based on domain
- Idea: build **invariances** into the model
 - **Ex:** if all images have same alignment, model learns to use it
- Keep the label the same!



Transformations

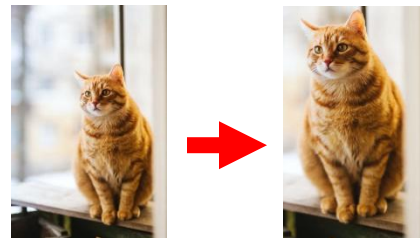
Examples of transformations for images

- **Crop** (and zoom)
- **Color** (change contrast/brightness)
- **Rotations+** (translate, stretch, shear, etc)

Many more possibilities. Combine as well!

Q: how to deal with this at **test time**?

- A: transform, test, average



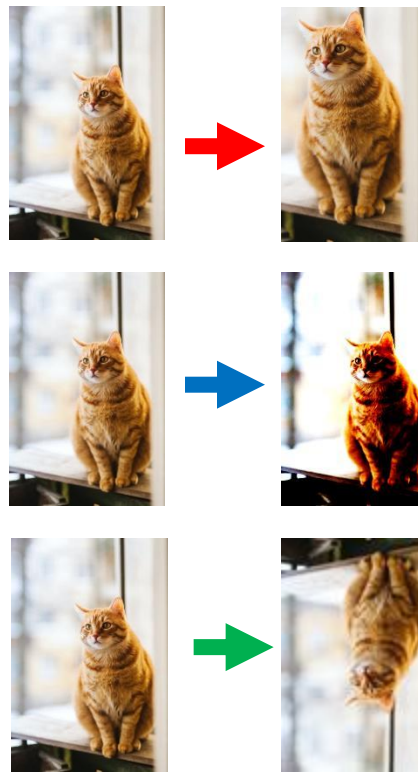
Combining & Automating Transformations

One way to automate the process:

- Apply every transformation and combinations
- **Downside:** most don't help...

Want a good policy, ie,     

- Active area of research: search for good policies
 1. **Ratner et al:** “Learning to Compose Domain-Specific Transformations for Data Augmentation”
 2. **Cubuk et al:** “AutoAugment: Learning Augmentation Strategies from Data”



Other Domains

Not just for image data. For example, on text:

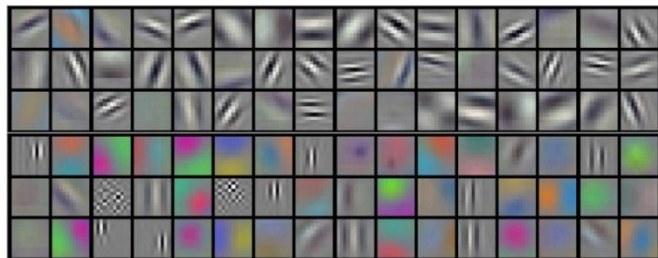
- Substitution
 - E.g., “It is a **great** day” → “It is a **wonderful** day”
 - Use a thesaurus for particular words
 - Or, use a model. Pre-trained word embeddings, language models
- Back-translation
 - “Given the low budget and production limitations, this movie is very good.”
→ “There are few budget items and production limitations to make this film a really good one”

Importance of Augmentation

Data augmentation is critical for top performance!

- You should use it!
- **AlexNet**: used (many papers re-used as well)
 - Random crops, rotations, flips.

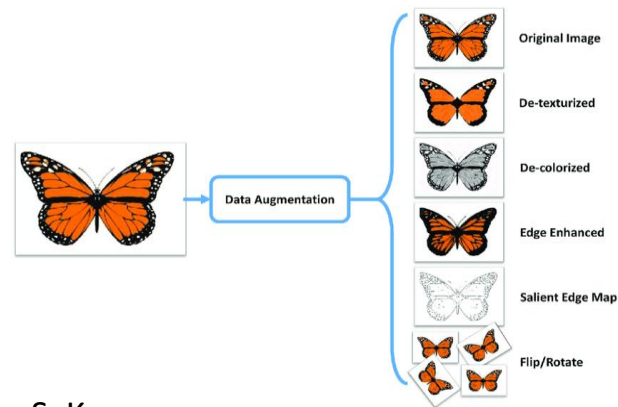
Krizhevsky et al: “ImageNet Classification with Deep Convolutional Neural Networks”



Other Forms of Regularization

Regularization has many interpretations

- **Goodfellow:** “any modification... to a learning algorithm that is intended to reduce its generalization error but not its training error.”
- A way of adding knowledge / side information to model
- Enforcing parsimony/simplicity



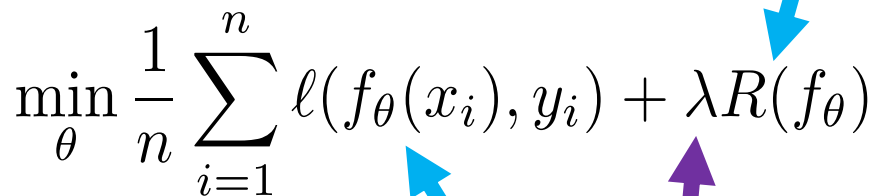
Other Forms of Regularization

Classic regularizations

1. Modify loss functions

Ex: regularized least squares LR

$$\min_{\theta} \frac{1}{n} \sum_{i=1}^n (\theta_0 + x_i^T \theta - y_i)^2 + \lambda \|\theta\|_2^2$$

$$\min_{\theta} \frac{1}{n} \sum_{i=1}^n \ell(f_{\theta}(x_i), y_i) + \lambda R(f_{\theta})$$


Standard
loss

Regularization
parameter

Regularizer

1. Modify architecture/training/data

a) Dropout, batch normalization, augmentation

Break & Quiz

Q 2.1: If we apply data augmentation blindly, we might

(i) Change the label of the data point

(ii) Produce a useless training point

- A. (i) but not (ii)
- B. (ii) but not (i)
- C. Neither
- D. Both

Break & Quiz

Q 2.2: What are some consequences of data augmentation?

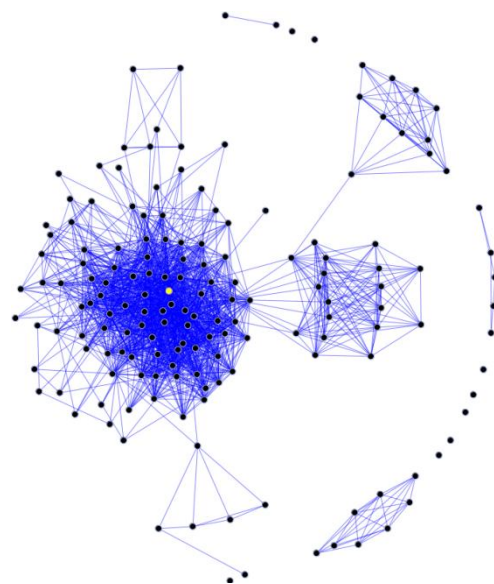
- (i) We have to store a much bigger dataset in memory
- (ii) For a fixed batch size, there will be more batches per epoch

- A. (i) but not (ii)
- B. (ii) but not (i)
- C. Neither
- D. Both

Relationships in Data

So far, all of our data consists of points

- Assume all are independent, “unrelated” in a sense $(\mathbf{x}_1, y_1), (\mathbf{x}_2, y_2), \dots, (\mathbf{x}_n, y_n)$
- Pretty common to have relationships between points
 - **Social networks**: individuals related by friendship
 - **Biology/chemistry**: bonds between compounds, molecules
 - **Citation networks**: Scientific papers cite each other

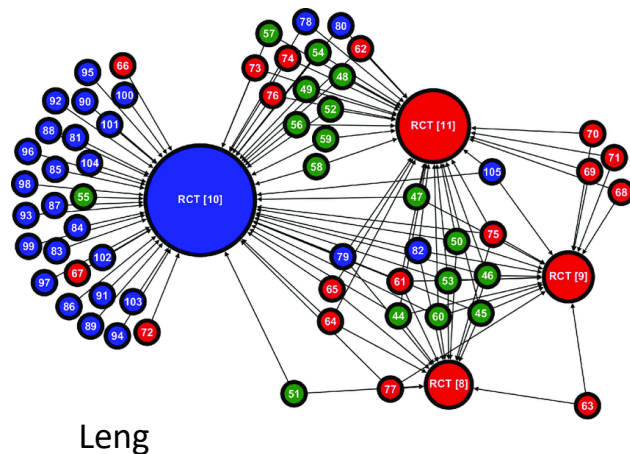


Wiki

Signal from Relationships

Suppose we are classifying scientific papers

- **Features:** title, abstract, authors. **Labels:** math/science/eng.
- Could build a reasonable classifier with the above data
- **More signal** from relationships
 - Cite each other, more likely from the same field
 - Note: citations are not features; they're **links**
 - Need a new type of network to handle

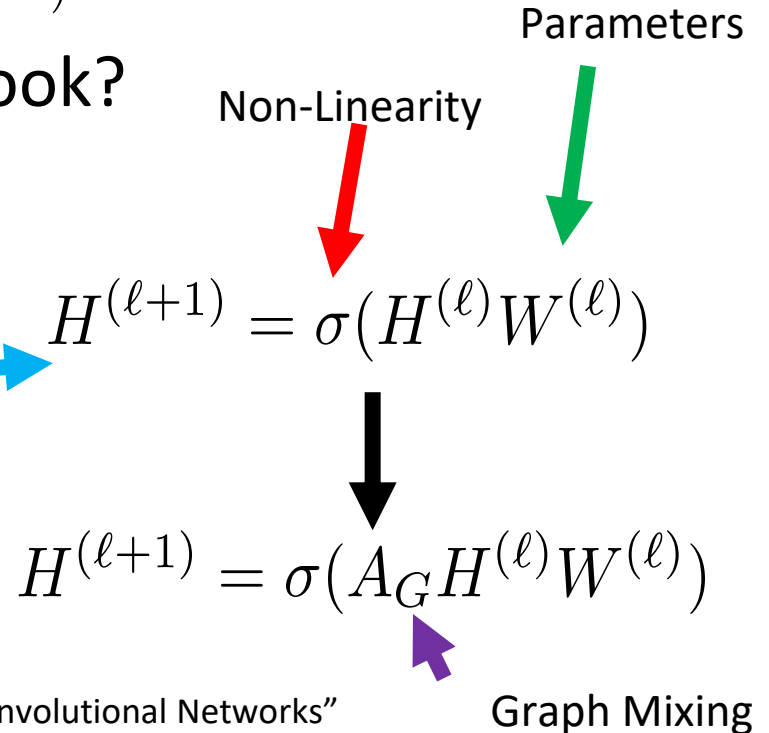


Graph Neural Networks

Have: $(\mathbf{x}_1, y_1), (\mathbf{x}_2, y_2), \dots, (\mathbf{x}_n, y_n), G = (V, E)$

How should our new architecture look?

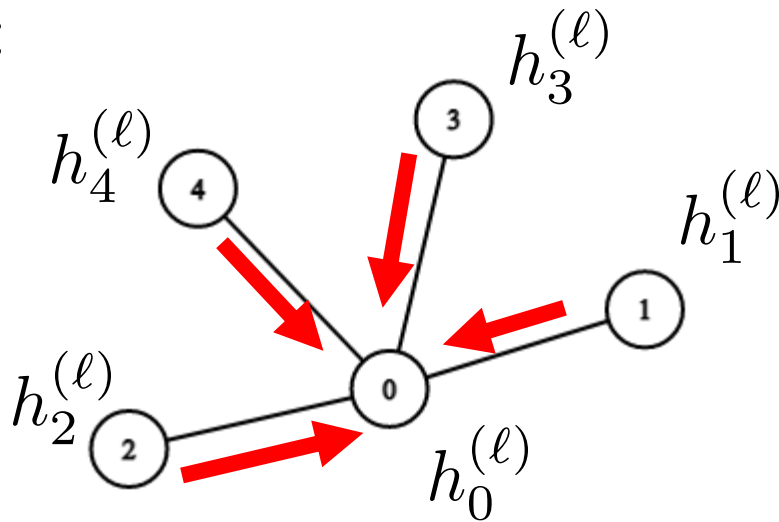
- Still want layers
 - linear transformation + non-linearity
- Now want to integrate neighbors
- Bottom: graph convolutional network



Graph Convolutional Networks

Let's examine the GCN architecture in more detail

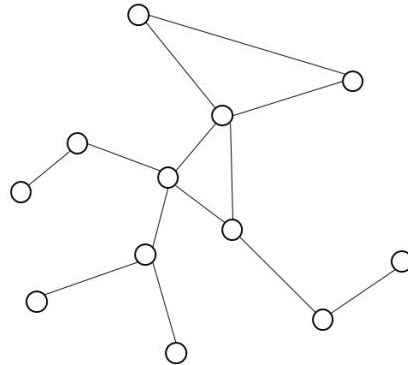
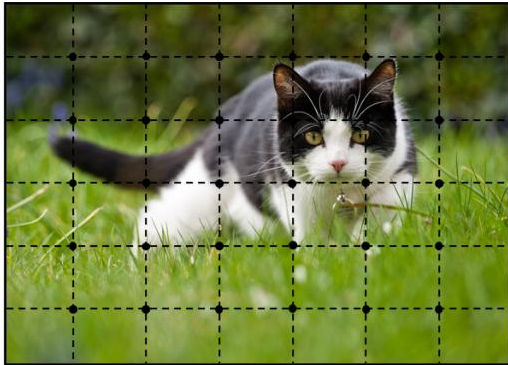
- Difference: “graph mixing” component
- At each layer, get representation at each node
- Combine node's representation with neighboring nodes
- **“Aggregate”** and **“Update”** rules



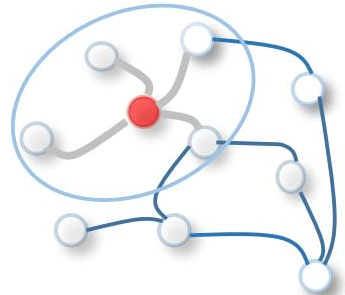
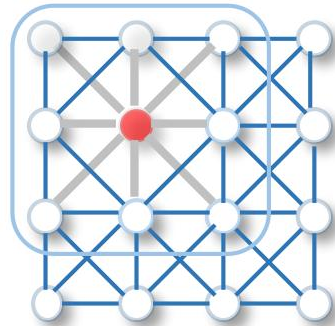
Graph Convolutional Networks

Note the resemblance to CNNs:

- Pixels: arranged as a very regular graph
- Want: more general configurations (less regular)



Wu et al, A Comprehensive Survey on Graph Neural Networks



Summary

- Intro to deeper networks (resnets)
 - Dealing with problems by adding skip connections
- Intro to regularization
 - Data augmentation + other regularizers
- Basic graph neural networks



Acknowledgements: Inspired by materials by Fei-Fei Li, Ranjay Krishna, Danfei Xu (Stanford CS231n)