

CS231n: Deep Learning for Computer Vision

Lecture 1: Introduction

Welcome to CS231n



Welcome to CS231n

Course Instructors



Fei-Fei Li
Andrej Karpathy

Teaching Assistants



2015



2016



Instructors



Justin Johnson

Serena Yeung

Teaching Assistants



Albert Haque
(Head TA)
Rohit Bedi
Shyamal Buch
Zhao (Joe) Chen
Timnit Gebru

Agrim Gupta
De-An Huang
Russell Kaplan
Leo Keselman
Nishith Khandwala



Xingyu Liu
Shayne Longpre
Zelin (Alan) Luo
Lane Moinroth



Ben Poole
Luda Zhao

2017

Instructors



Ranjay Krishna

Danfei Xu

Course Coordinator

Amelie Byun

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Fang-Yu Lin
Damian Mrowca
Boxiao Pan
Nishant Rai

Lynne P. Tchamki
Chris Waites
Rui Wang
Yi Wen
Karen Yang

2020

Instructors



Fei-Fei Li
Albert Haque
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Chaitanya Asawa
Josh Beal
Vincent Chen
Edward Chou
John Clow

Justin Johnson
Manik Dhar
Jim (Linxi) Fan
Pedro Pablo Garzon
Michelle Guo
Jingwei Huang

Serena Yeung
Nishith Khandwala
Carolyn Kim
Winnie Lin
Bingbin Liu
Xingyu Liu
Ajay Mandekar

2018



Amani Peddada
Mike Roberts
Praty Sharma
Fei Xia
Danfei Xu
Ben Zhang

Instructors



Fei-Fei Li
Winnie Lin
(Head TA)
Saahil Agrawal
Malavika Bindu
Hanyue Cai
Kaidi Cao
Apoorva Domadia

Justin Johnson
Jim (Linxi) Fan
Pedro Pablo Garzon
Ayush Gupta
Andrew Han
Tien-Ning Hsu
Lars Jebe

Serena Yeung
Nishith Khandwala
Simon Le Cleach
Bingbin Liu
David Morales
Zaid Nabulsi
Boixiao Pan

Ashwini Pokle
Praty Sharma
William Shen
Owen Wang
Danfei Xu

2019

Instructors



Fei-Fei Li
Kevin Zakra
(Head TA)
Haofeng Chen
Rachel Gardner
Samuel Kwong
Yichen Li

Ranjay Krishna
Sean Liu
Mandy Lu
Nishant Rai
Geet Sethi
Lin Shao

2021

Artificial Intelligence

Slide inspiration: Justin Johnson

Artificial Intelligence

Machine Learning

Computer
Vision

Slide inspiration: Justin Johnson

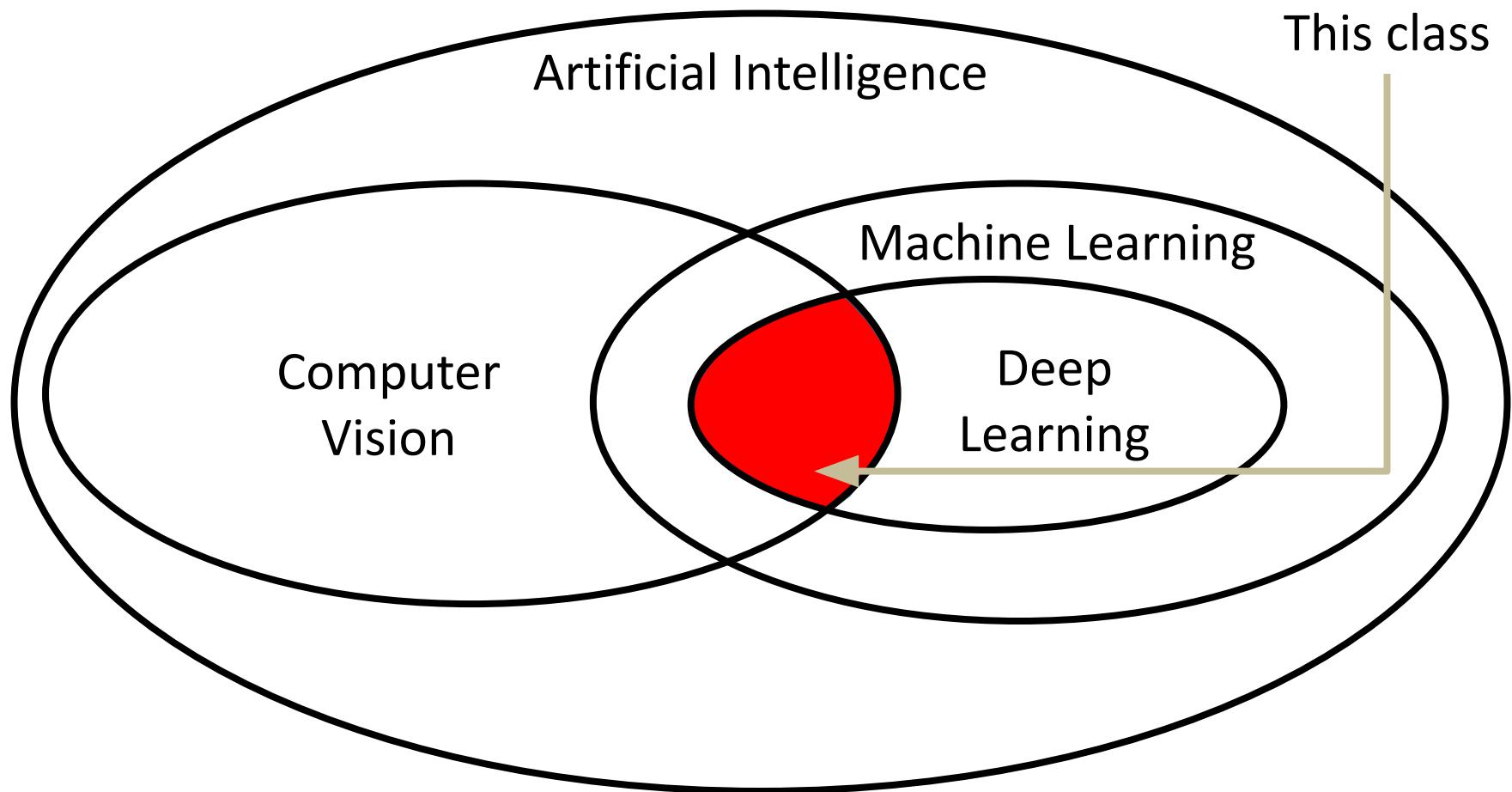
Artificial Intelligence

Machine Learning

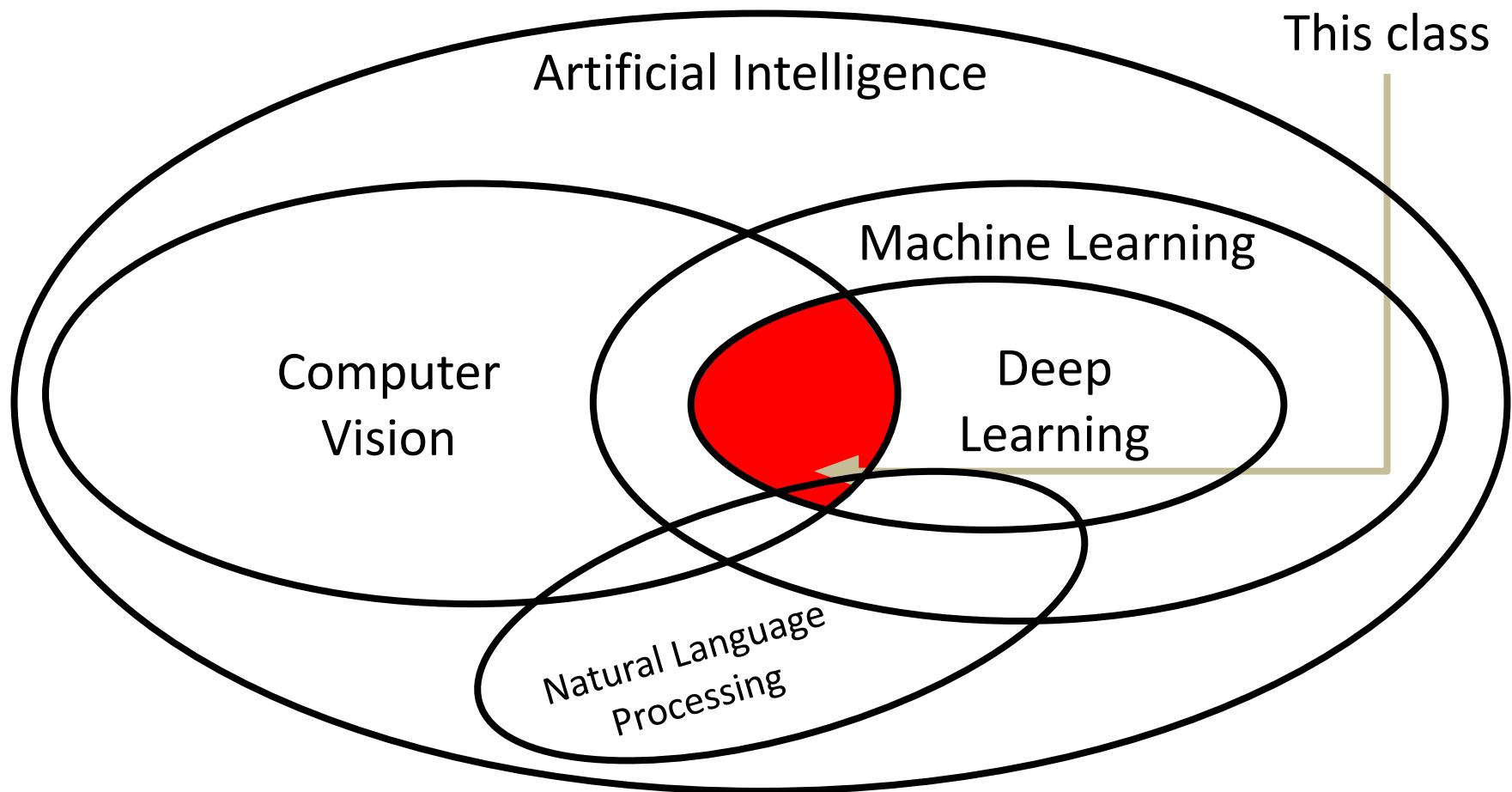
Computer
Vision

Deep
Learning

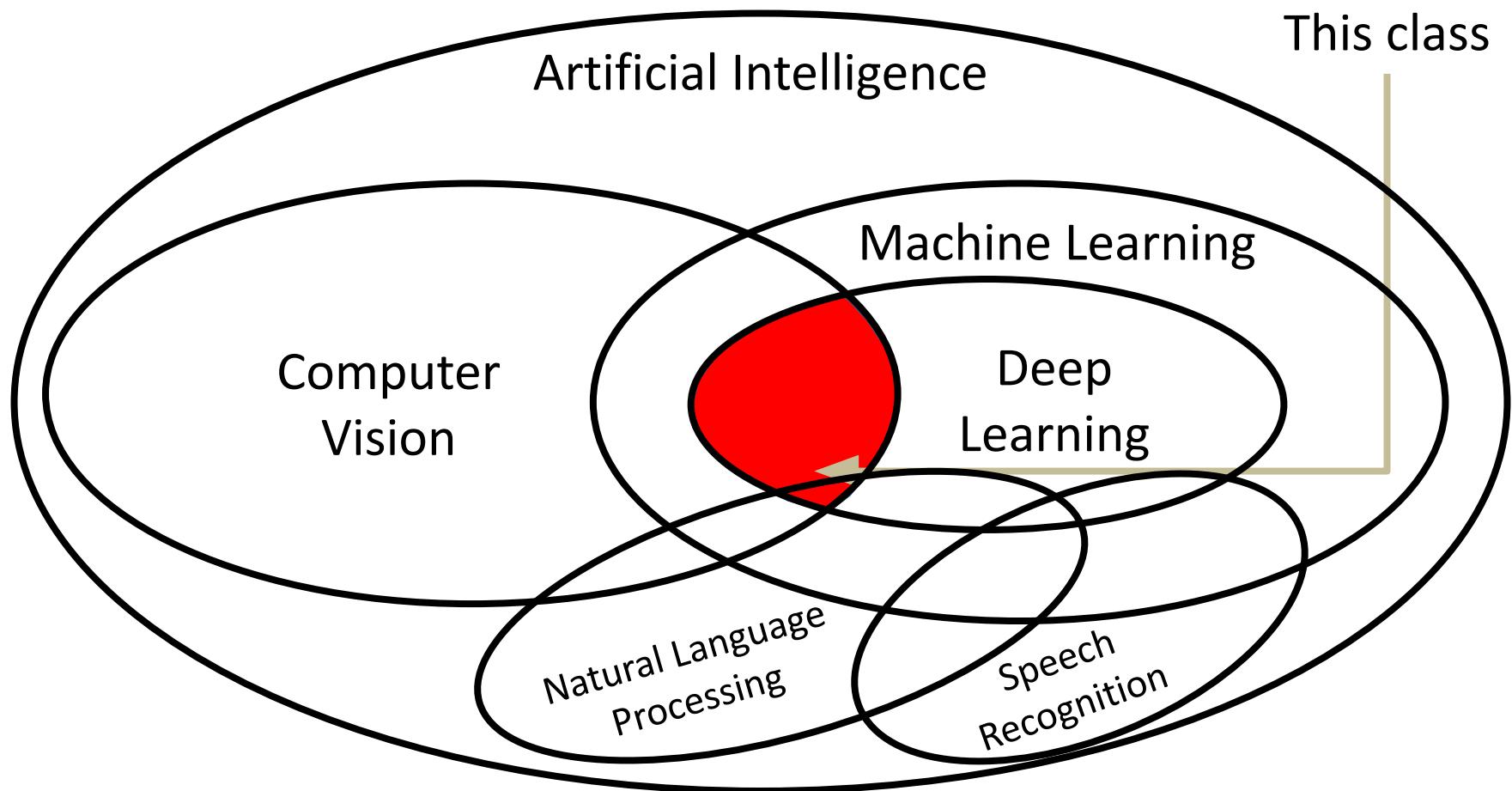
Slide inspiration: Justin Johnson



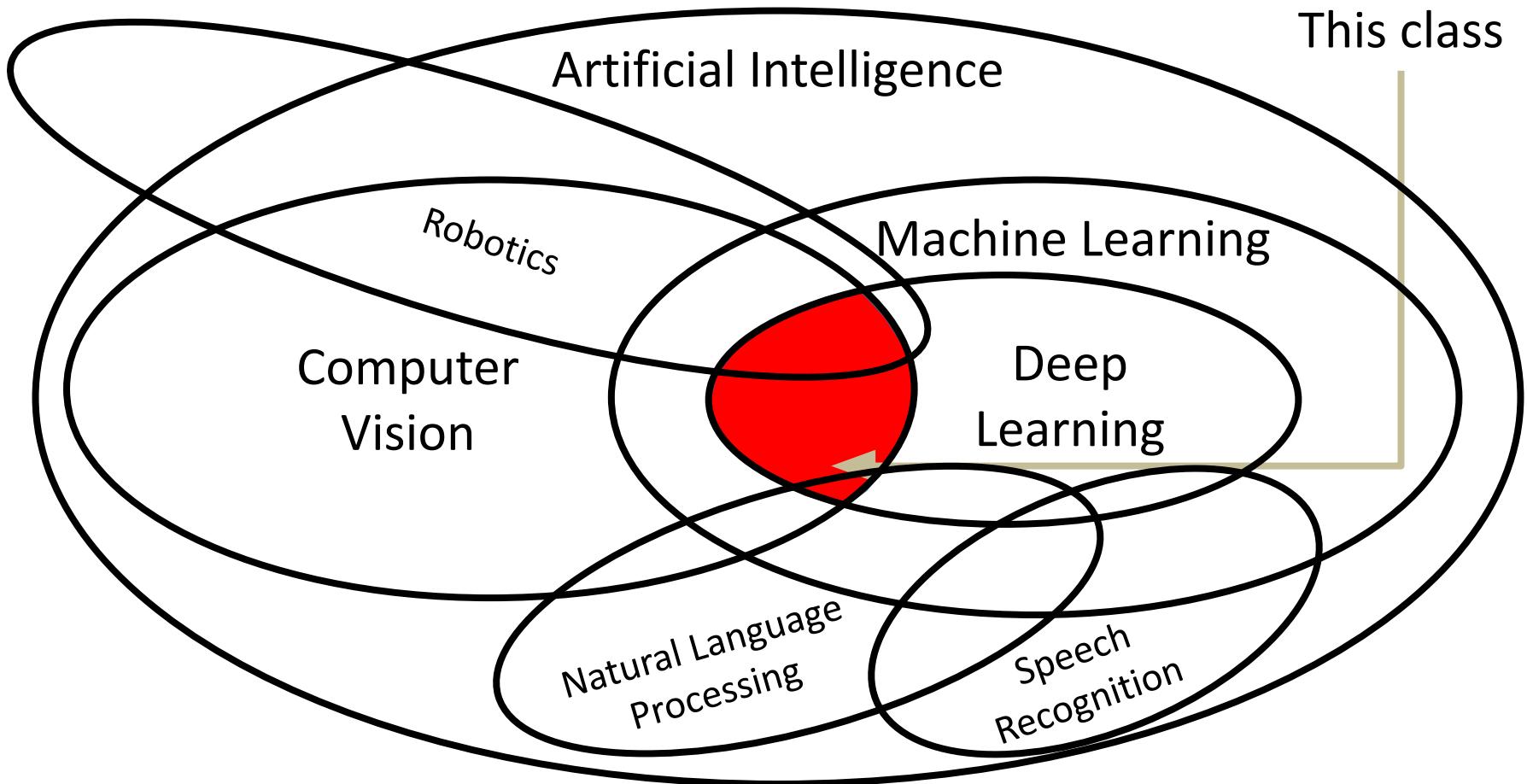
Slide inspiration: Justin Johnson



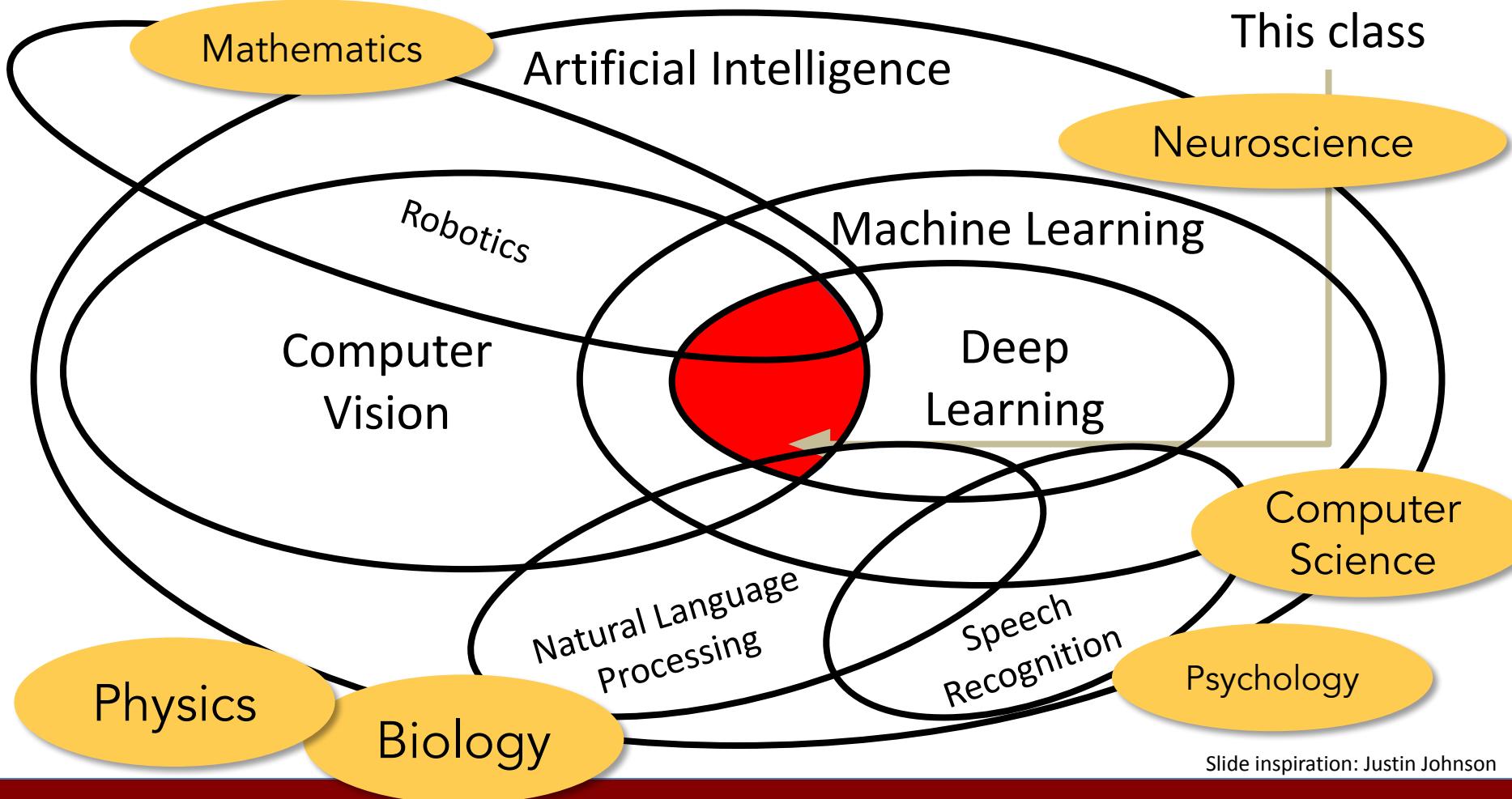
Slide inspiration: Justin Johnson



Slide inspiration: Justin Johnson



Slide inspiration: Justin Johnson



Today's agenda

- A brief history of computer vision and deep learning
- CS231n overview

Evolution's Big Bang: Cambrian Explosion, 530-540million years, B.C.



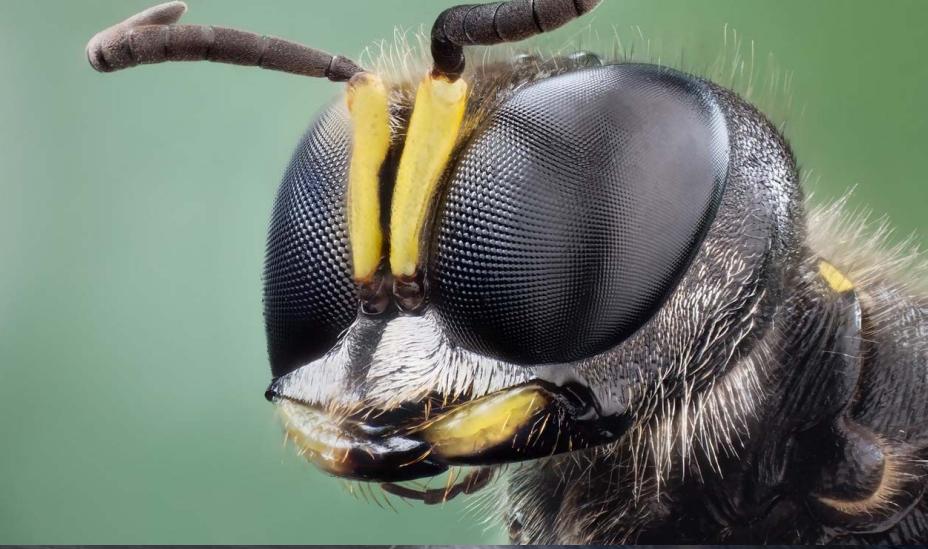
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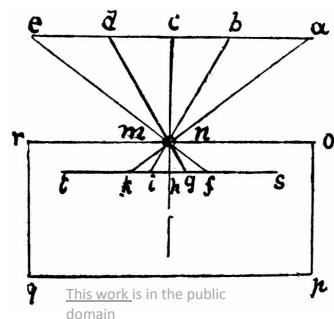
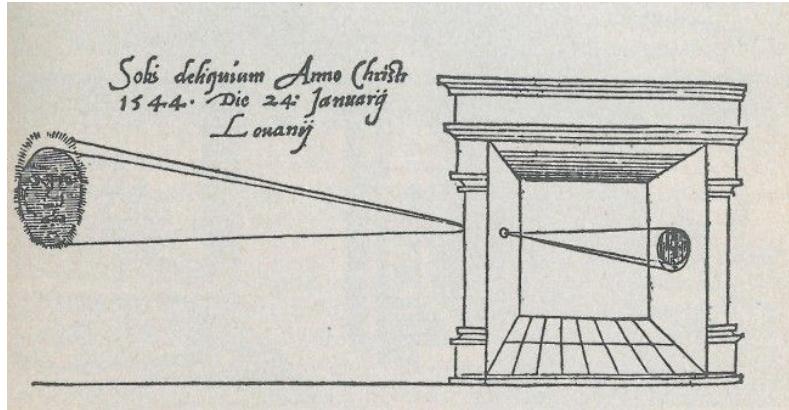


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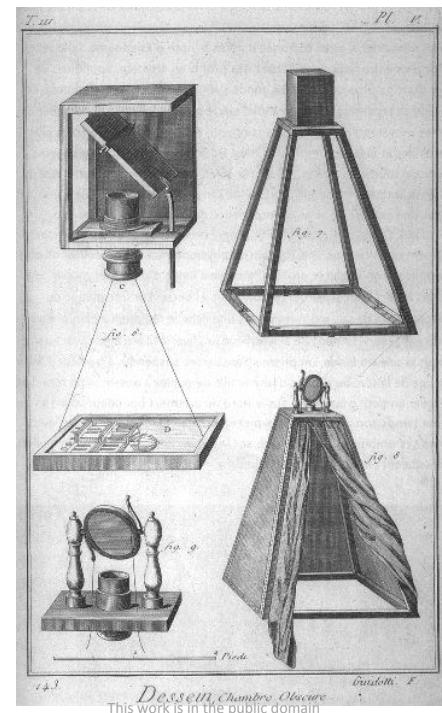
Camera Obscura

Gemma Frisius, 1545



Leonardo da Vinci,
16th Century AD

Encyclopedia, 18th Century



Computer Vision is everywhere!



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Bottom row, left to right
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Where did we come from?

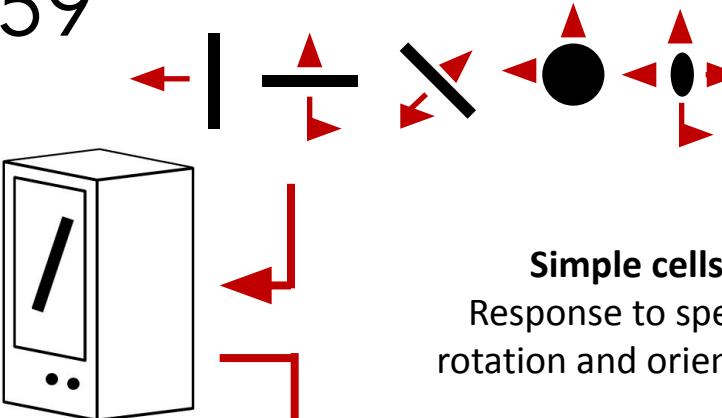
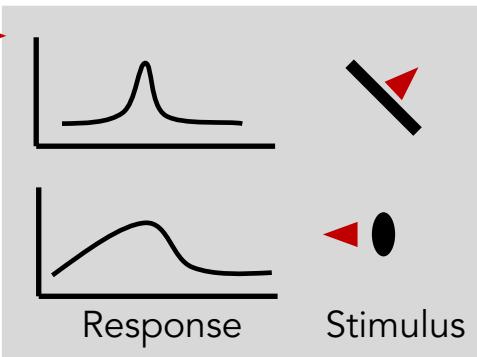
Hubel and Wiesel, 1959

Measure
brain activity



Cat image by CNX OpenStax is licensed under CC BY 4.0; changes made

1959
Hubel & Wiesel



Simple cells:

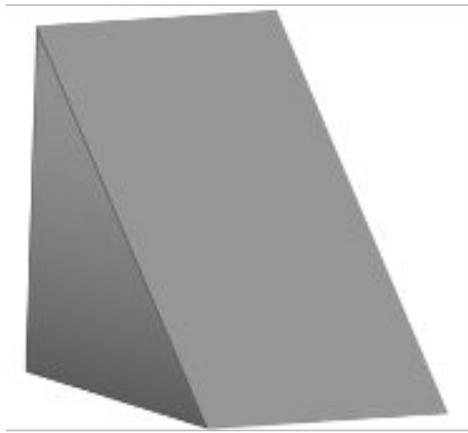
Response to specific rotation and orientation

Complex cells:

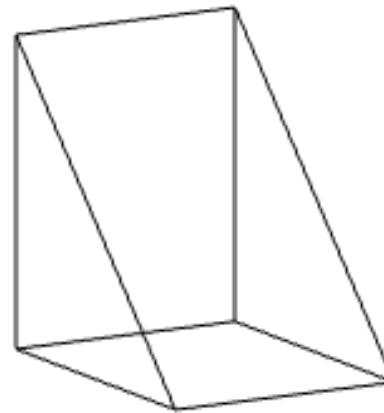
Response to light orientation and movement, some translation invariance



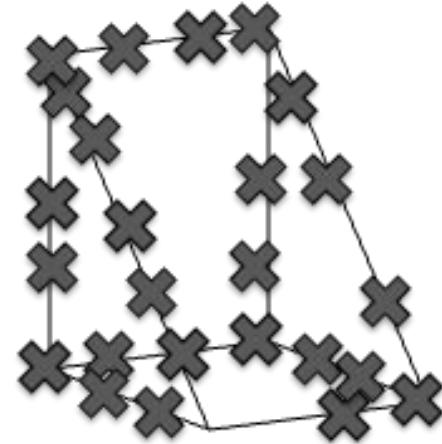
Larry Roberts, 1963



(a) Original picture



(b) Differentiated picture



(c) Feature points selected



Lawrence Gilman Roberts, "Machine Perception of Three-Dimensional Solids", 1963

Slide inspiration: Justin Johnson

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

Artificial Intelligence Group
Vision Memo. No. 100.

July 7, 1966

THE SUMMER VISION PROJECT

Seymour Papert

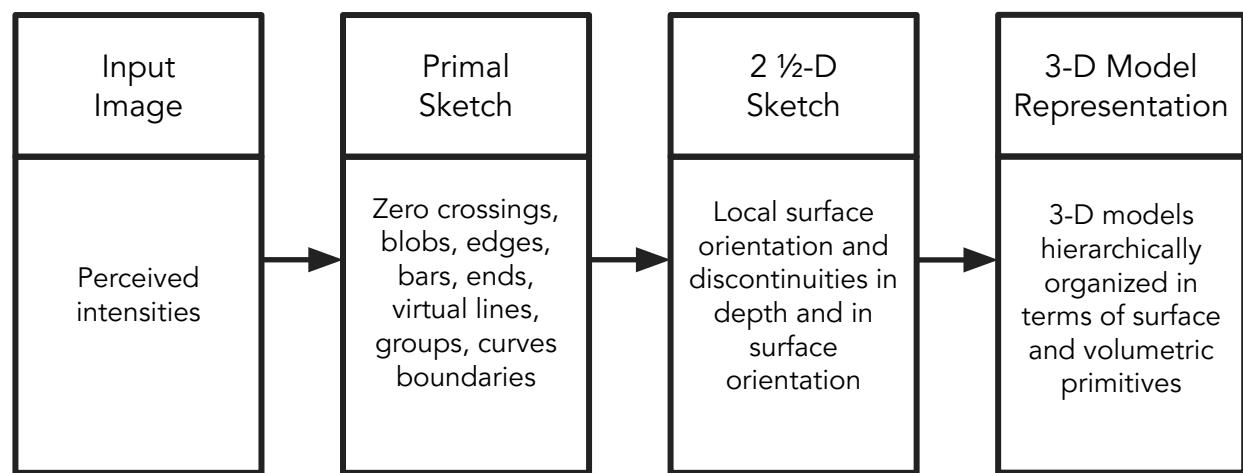
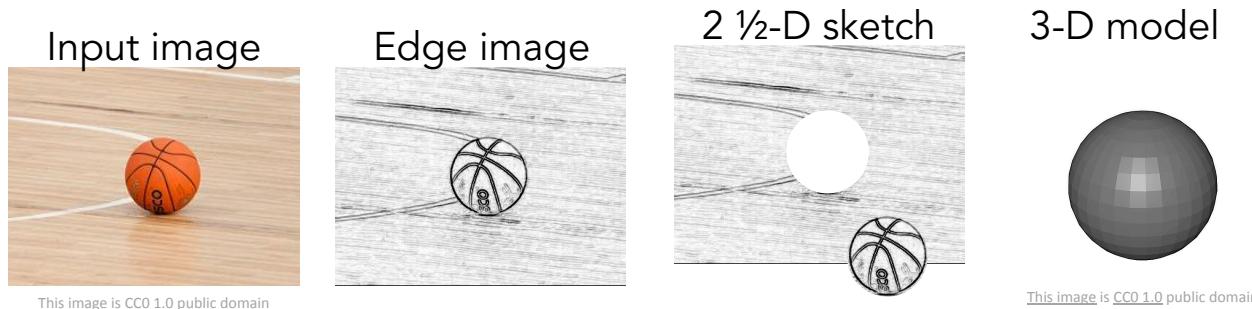
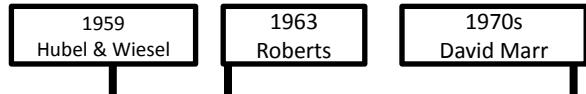
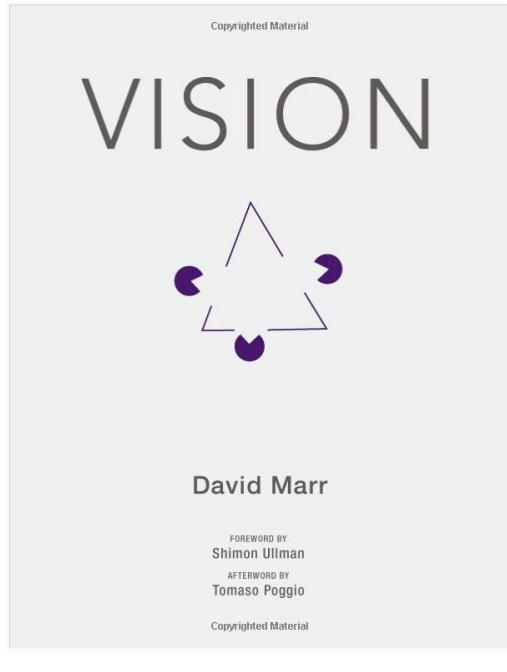
The summer vision project is an attempt to use our summer workers effectively in the construction of a significant part of a visual system. The particular task was chosen partly because it can be segmented into sub-problems which will allow individuals to work independently and yet participate in the construction of a system complex enough to be a real landmark in the development of "pattern recognition".

1959
Hubel & Wiesel

1963
Roberts

<https://dspace.mit.edu/handle/1721.1/6125>

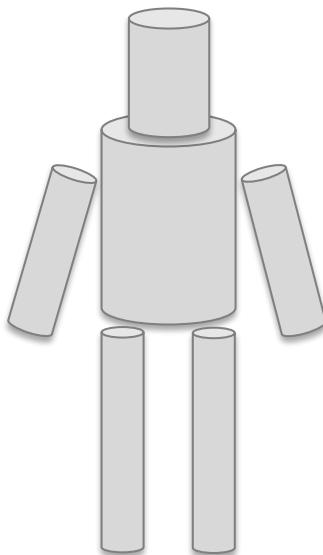
Slide inspiration: Justin Johnson



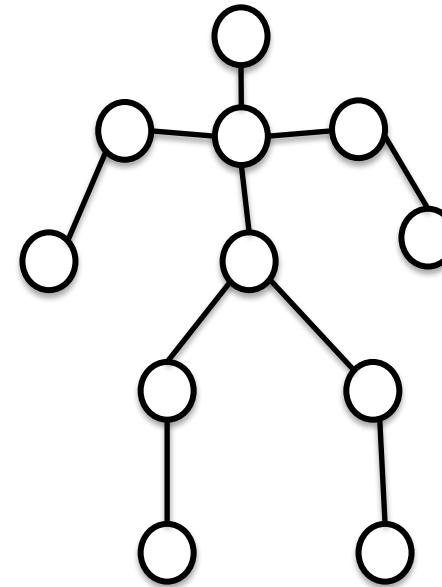
Stages of Visual Representation, David Marr, 1970s

Slide inspiration: Justin Johnson

Recognition via Parts (1970s)



Generalized Cylinders,
Brooks and Binford,
1979



Pictorial Structures,
Fischler and Elshlager, 1973



Slide inspiration: Justin Johnson

Recognition via Edge Detection (1980s)



1959
Hubel & Wiesel

1963
Roberts

1970s
David Marr

1979
Gen. Cylinders

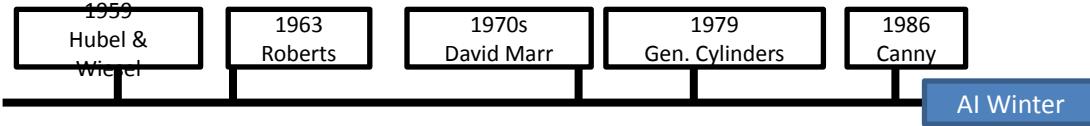
1986
Canny

John Canny, 1986
David Lowe, 1987

Image is CC0 1.0 public domain

Arriving at an “AI winter”

- Enthusiasm (and funding!) for AI research dwindled
- “Expert Systems” failed to deliver on their promises
- But subfields of AI continues to grow
 - Computer vision, NLP, robotics, compbio, etc.



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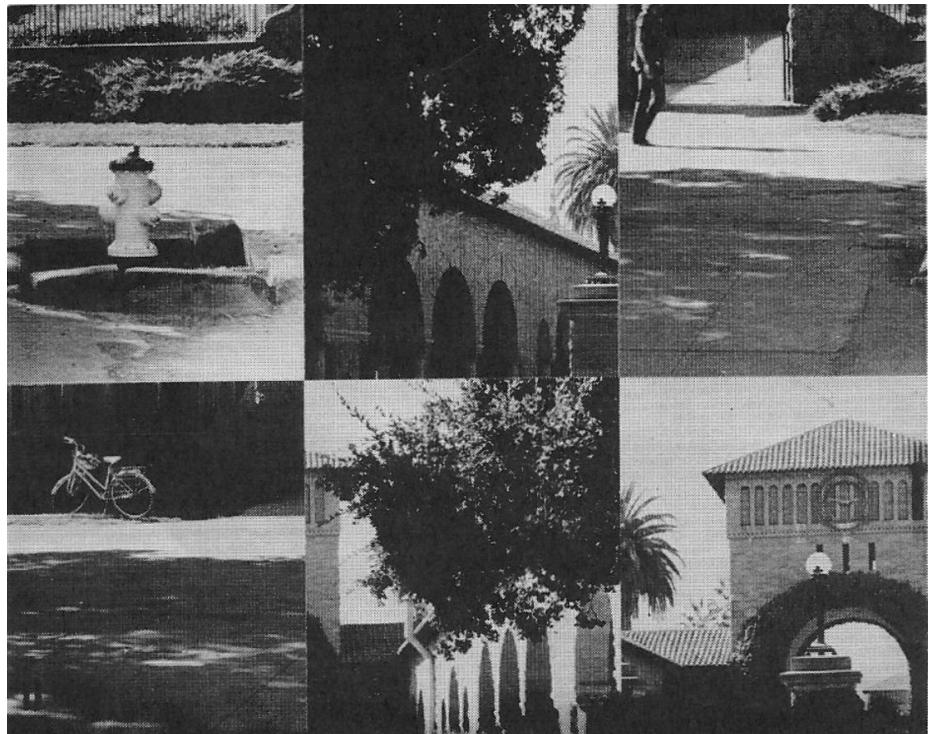
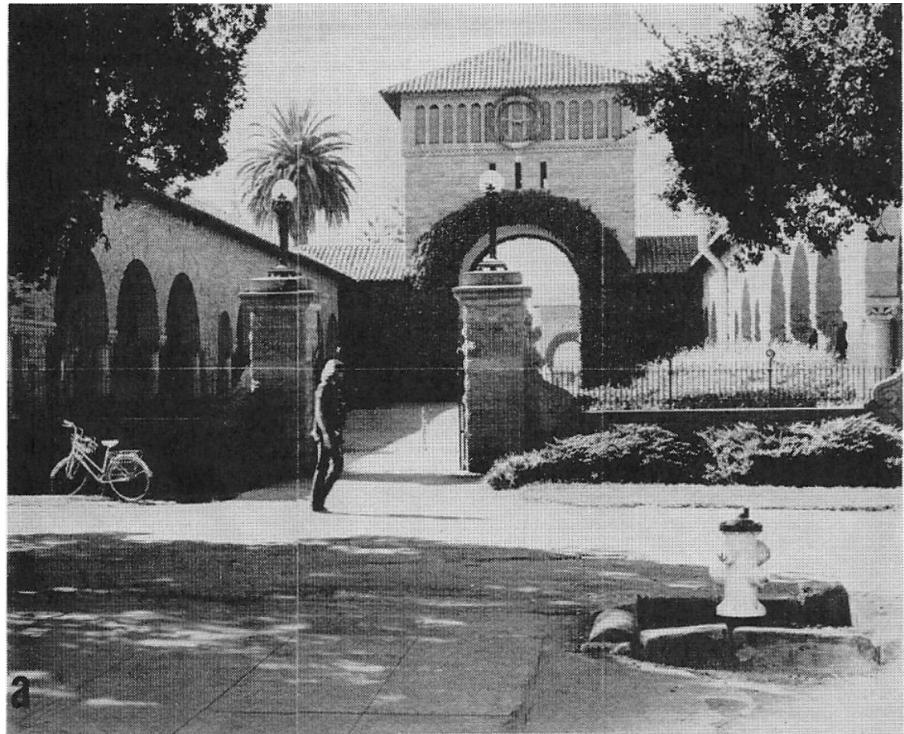
[Right Image](#) is CC-BY 2.0; changes made

Slide inspiration: Justin Johnson

In the meantime...seminal work in
cognitive and neuroscience

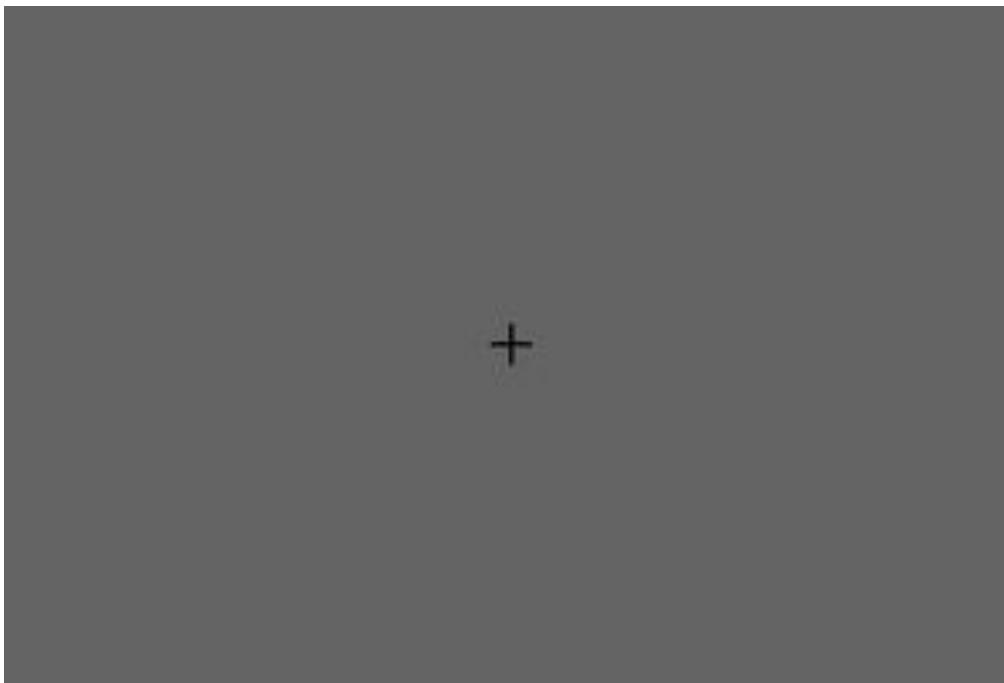
Perceiving Real-World Scenes

Irving Biederman



I. Biederman, *Science*, 1972

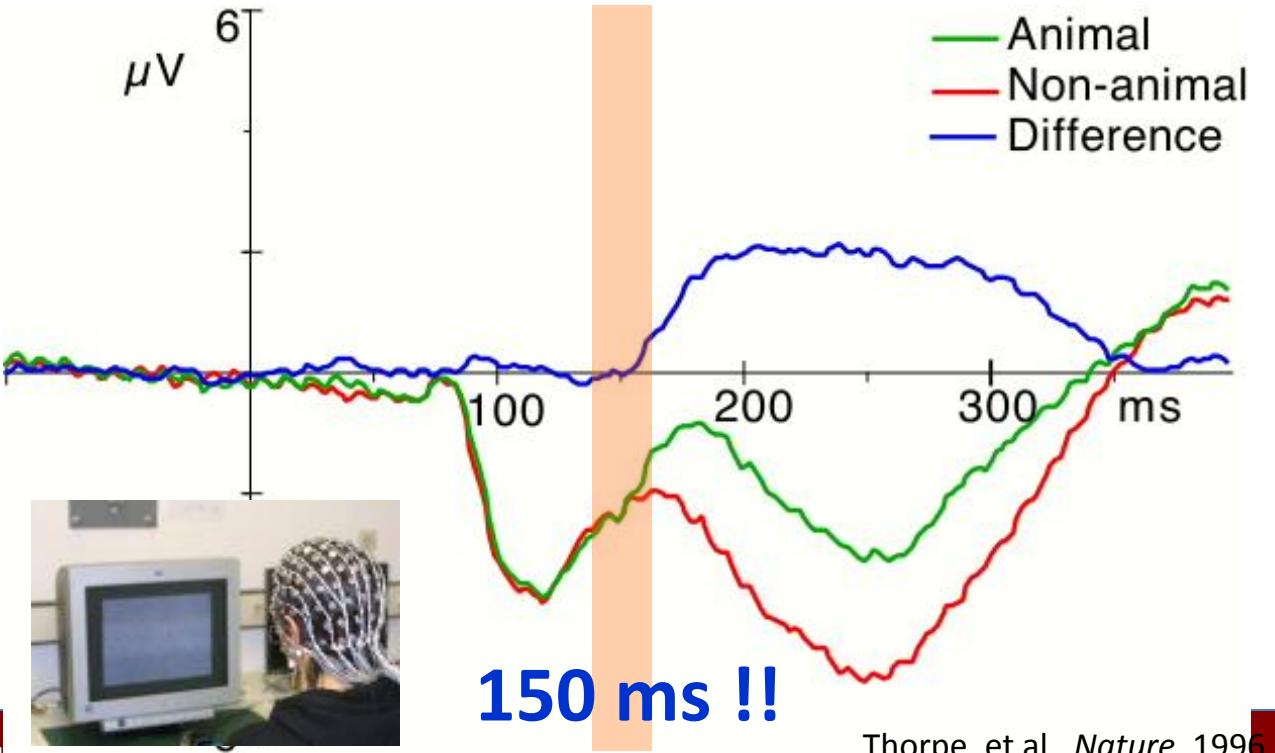
Rapid Serial Visual Perception (RSVP)



Potter, etc. 1970s

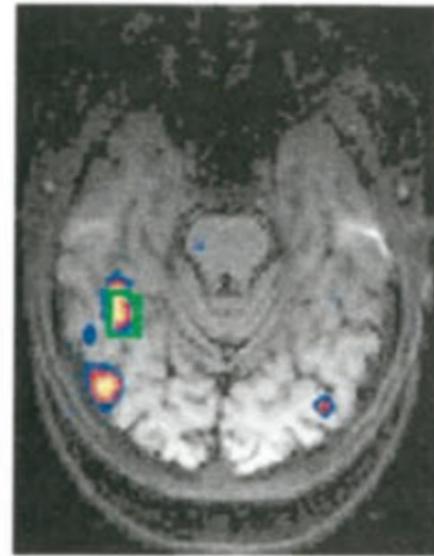
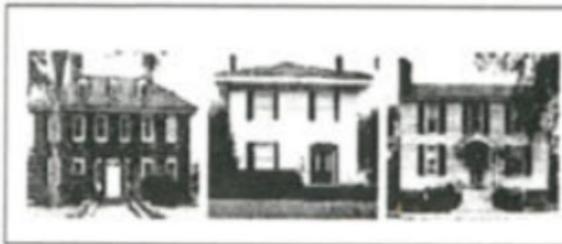
Speed of processing in the human visual system

Simon Thorpe, Denis Fize & Catherine Marlot



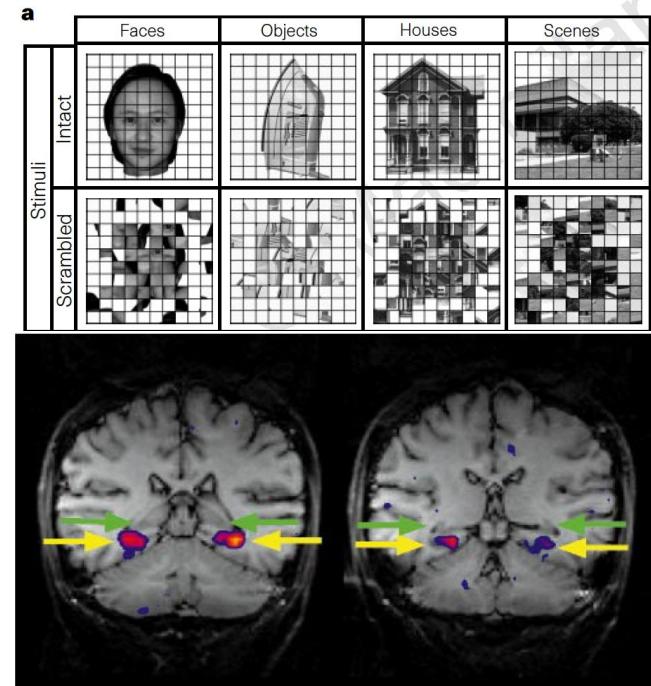
Neural correlates of object & scene recognition

Faces > Houses



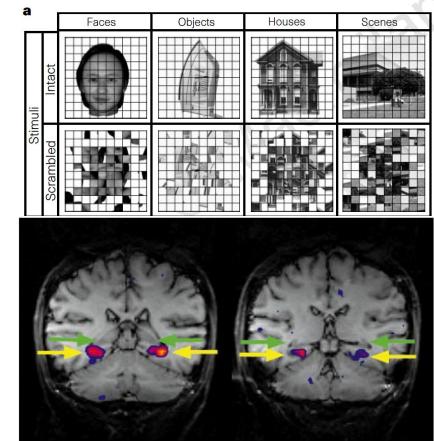
% signal change

Kanwisher et al. J. Neuro. 1997



Epstein & Kanwisher, Nature, 1998

Visual recognition is a fundamental task for visual intelligence



Recognition via Grouping (1990s)



1959
Hubel & Wiesel

1963
Roberts

1970s
David Marr

1979
Gen. Cylinders

1986
Canny

1997
Norm. Cuts

AI Winter

Normalized Cuts, Shi and Malik, 1997

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Recognition via Matching (2000s)



[Image](#) is public domain



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1959
Hubel & Wiesel

1963
Roberts

1970s
David Marr

1979
Gen. Cylinders

1986
Canny

1997
Norm. Cuts

1999
SIFT

AI Winter

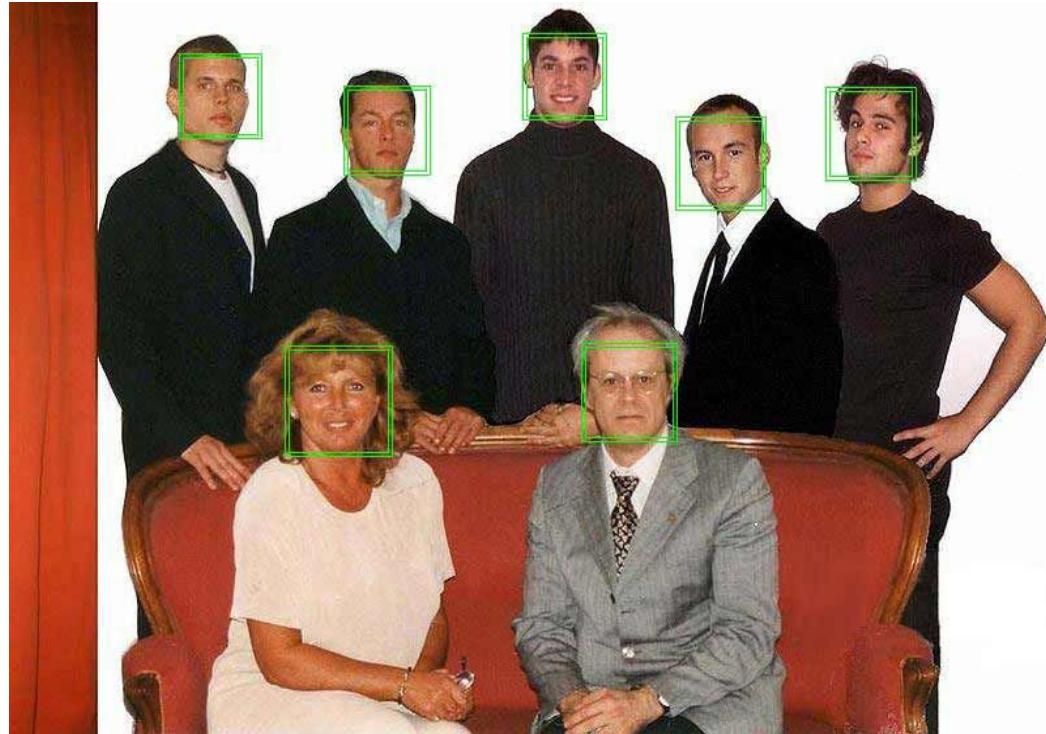
SIFT, David
Lowe, 1999

Slide inspiration: Justin Johnson

Face Detection

Viola and Jones, 2001

One of the first successful applications of machine learning to vision



1959
Hubel & Wiesel

1963
Roberts

1970s
David Marr

1979
Gen. Cylinders

1986
Canny

1997
Norm. Cuts

1999
SIFT

2001
V&J

AI Winter

Slide inspiration: Justin Johnson

Caltech 101 images



1959
Hubel & Wiesel

1963
Roberts

1970s
David Marr

1979
Gen. Cylinders

1986
Canny

1997
Norm. Cuts

1999
SIFT

2001
V&J

2004, 2007
Caltech101;
PASCAL

AI Winter

PASCAL Visual Object Challenge

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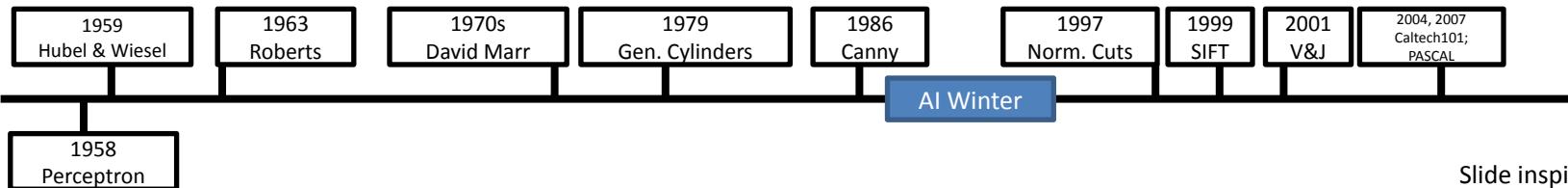
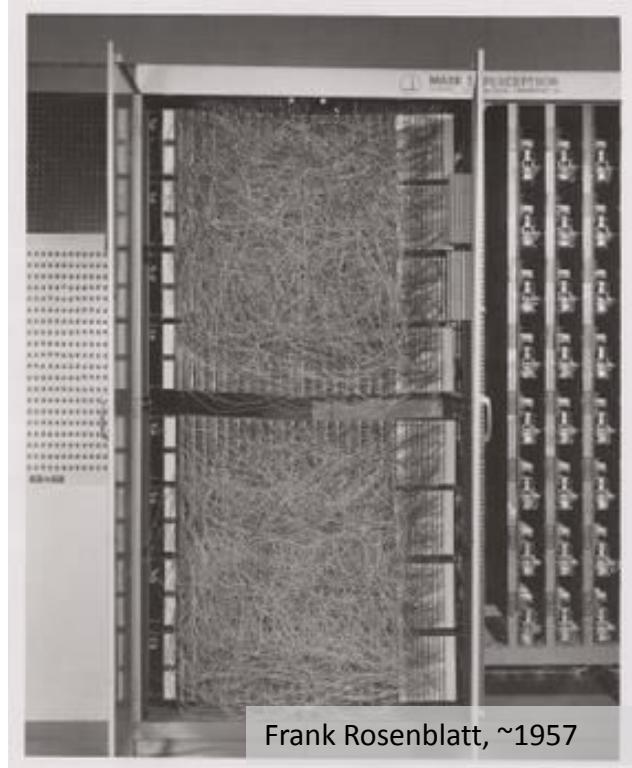
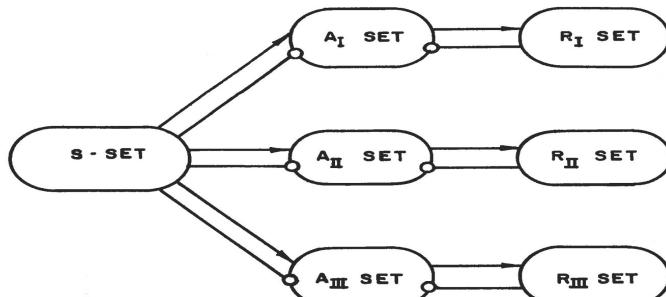
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Learning representations by back-propagating errors

David E. Rumelhart*, Geoffrey E. Hinton†
& Ronald J. Williams*

* Institute for Cognitive Science, C-015, University of California,
San Diego, La Jolla, California 92093, USA

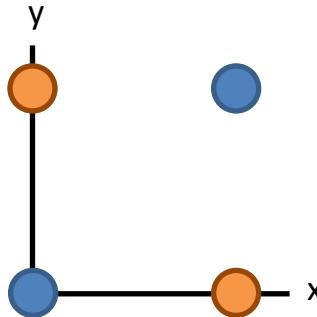
† Department of Computer Science, Carnegie-Mellon University,
Pittsburgh, Philadelphia 15213, USA



Slide inspiration: Justin Johnson

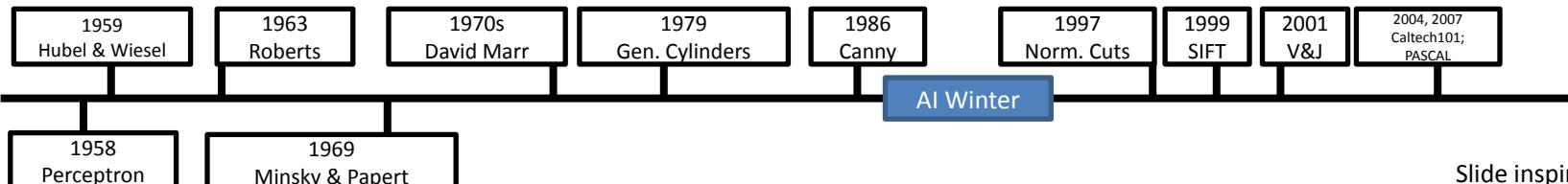
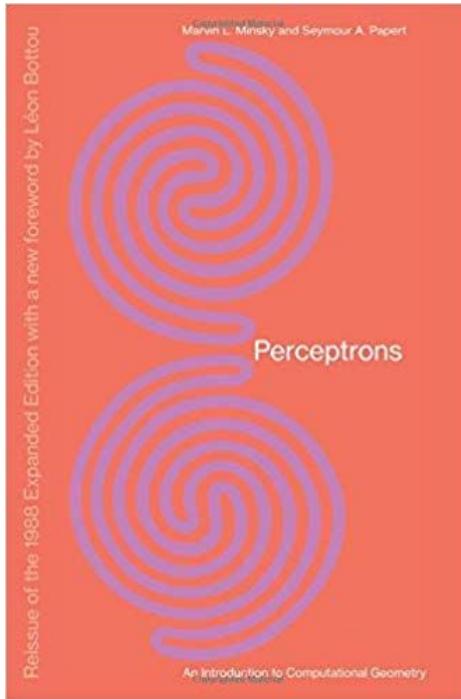
Minsky and Papert, 1969

X	Y	F(x,y)
0	0	0
0	1	1
1	0	1
1	1	0



Showed that Perceptrons could not learn the XOR function

Caused a lot of disillusionment in the field



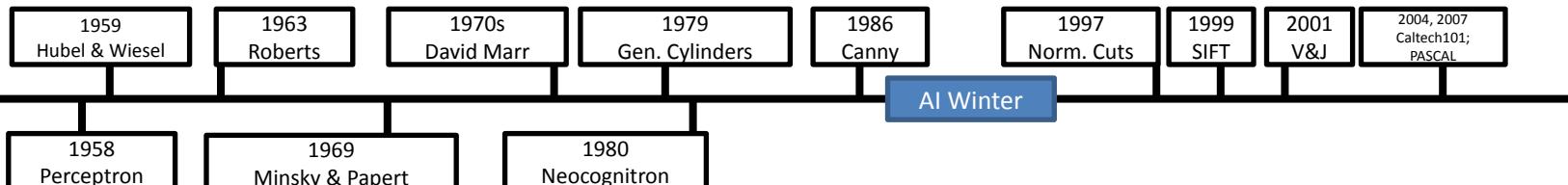
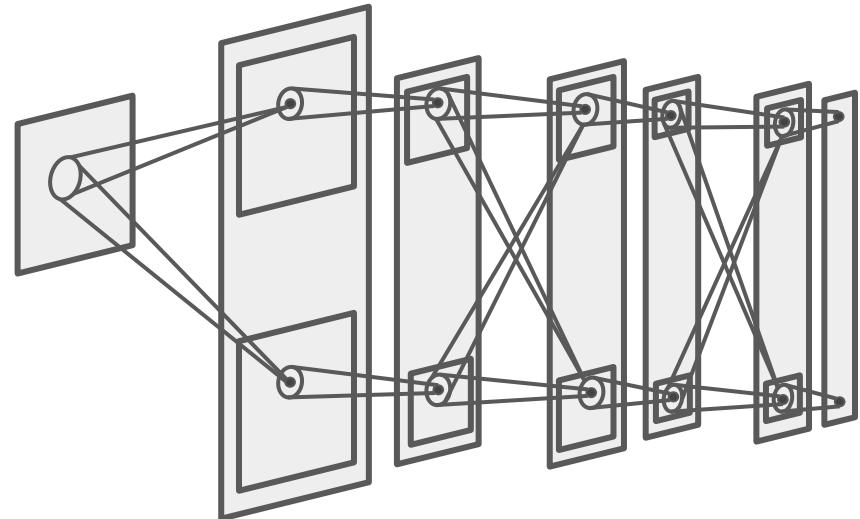
Slide inspiration: Justin Johnson

Neocognitron: Fukushima, 1980

Computational model the visual system,
directly inspired by Hubel and Wiesel's
hierarchy of complex and simple cells

Interleaved simple cells (convolution)
and complex cells (pooling)

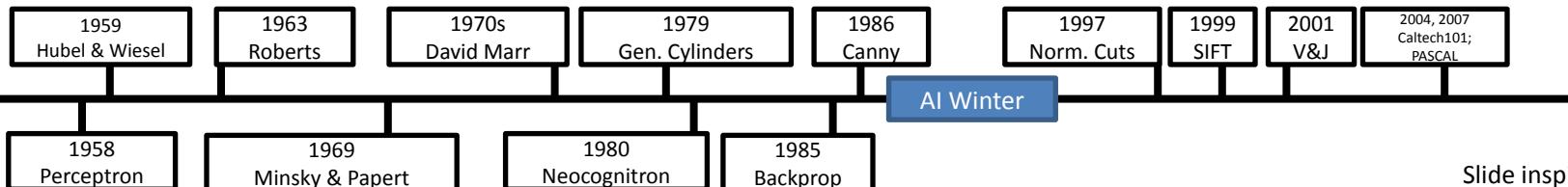
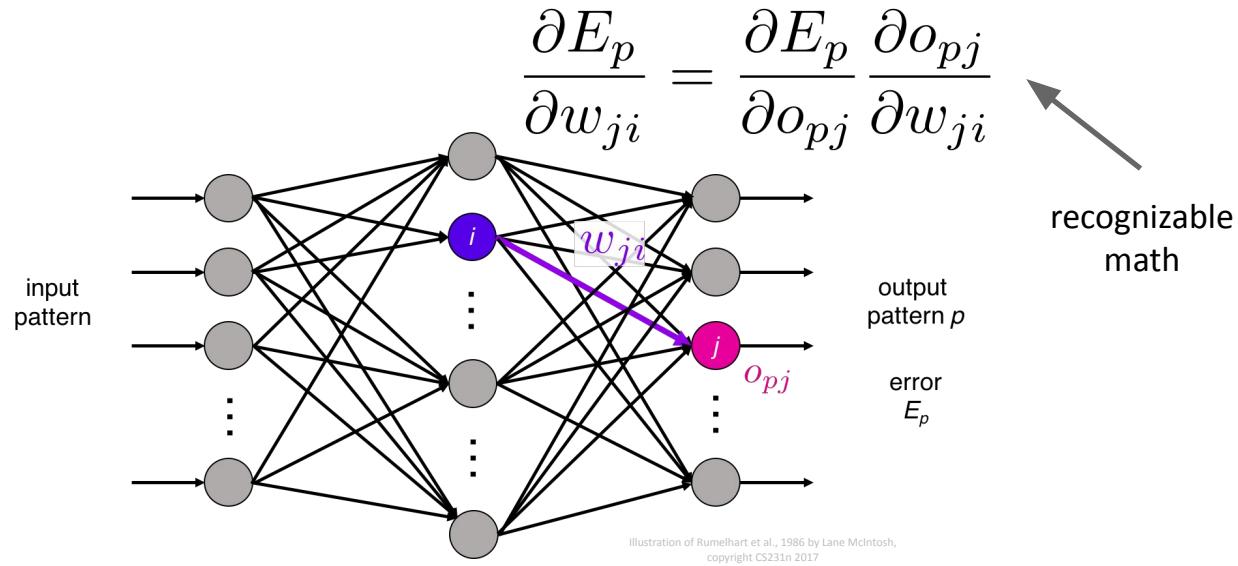
No practical training algorithm



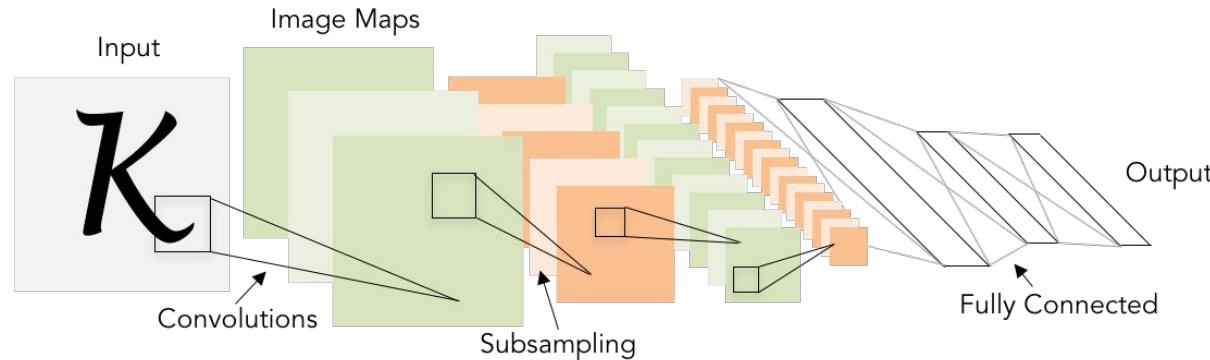
Backprop: Rumelhart, Hinton, and Williams, 1986

Introduced backpropagation for computing gradients in neural networks

Successfully trained perceptrons with multiple layers



Convolutional Networks: LeCun et al, 1998

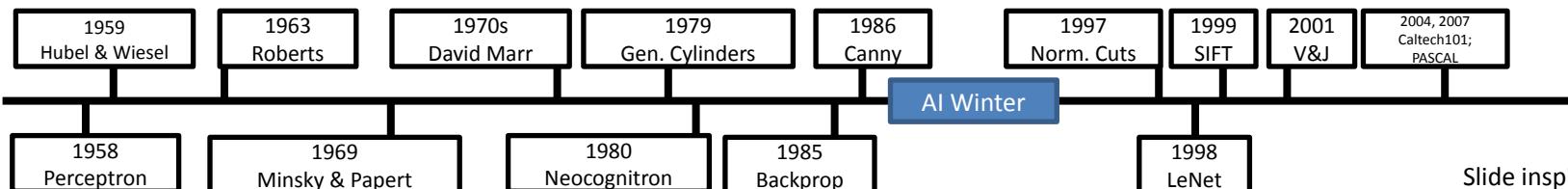


Applied backprop algorithm to a Neocognitron-like architecture

Learned to recognize handwritten digits

Was deployed in a commercial system by NEC, processed handwritten checks

Very similar to our modern convolutional networks!



Slide inspiration: Justin Johnson

2000s: “Deep Learning”

People tried to train neural networks that were deeper and deeper

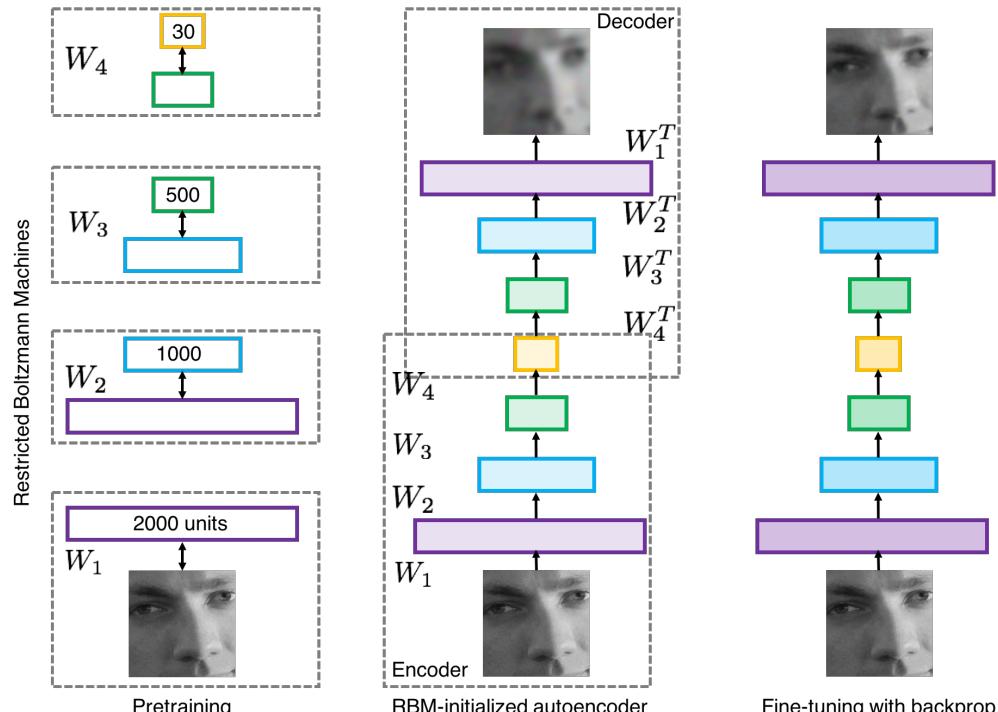
Not a mainstream research topic at this time

Hinton and Salakhutdinov, 2006

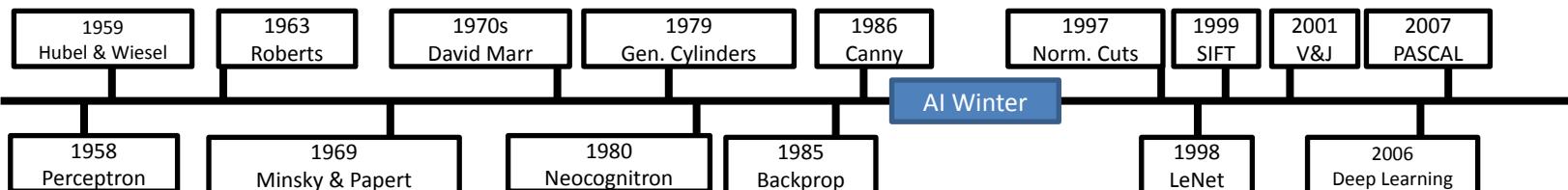
Bengio et al, 2007

Lee et al, 2009

Glorot and Bengio, 2010



Slide inspiration: Justin Johnson



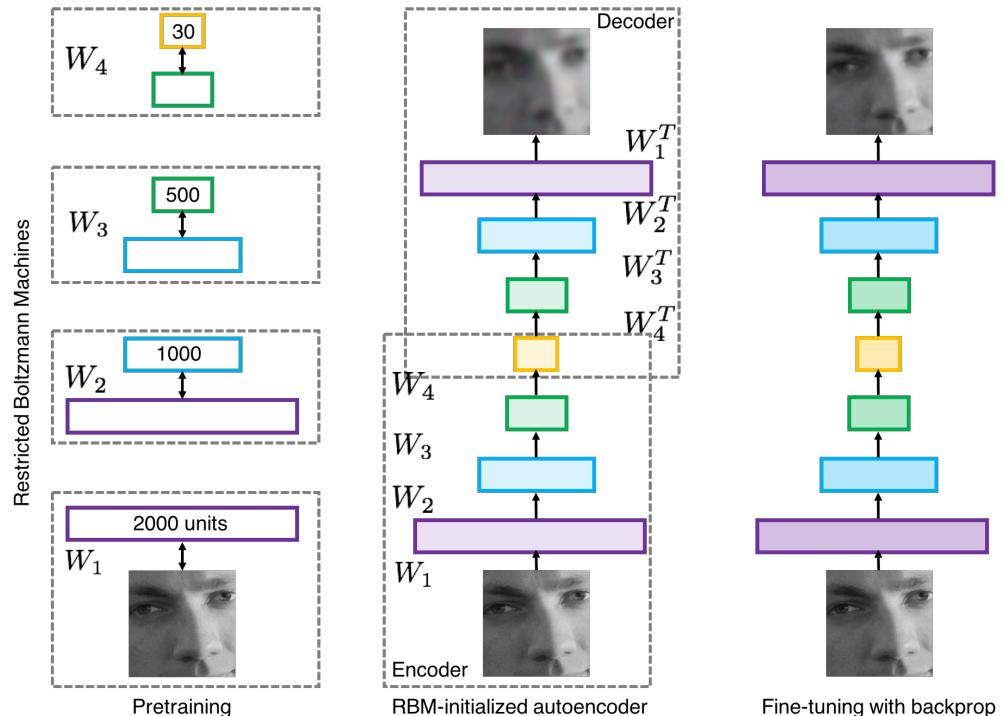
2000s: “Deep Learning”

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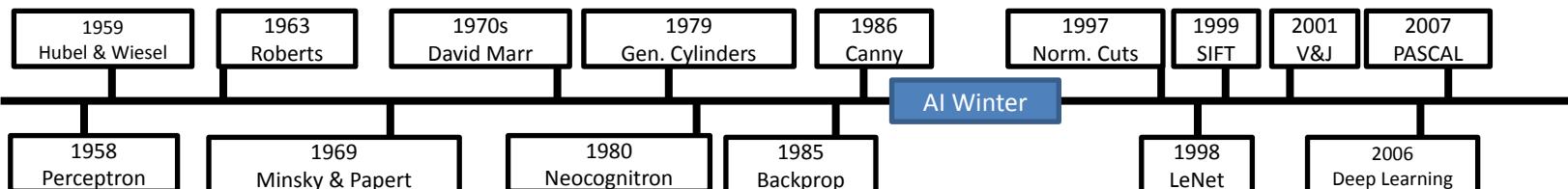
No good dataset to work on

Hinton and Salakhutdinov, 2006
Bengio et al, 2007
Lee et al, 2009
Glorot and Bengio, 2010



Fine-tuning with backprop

Slide inspiration: Justin Johnson



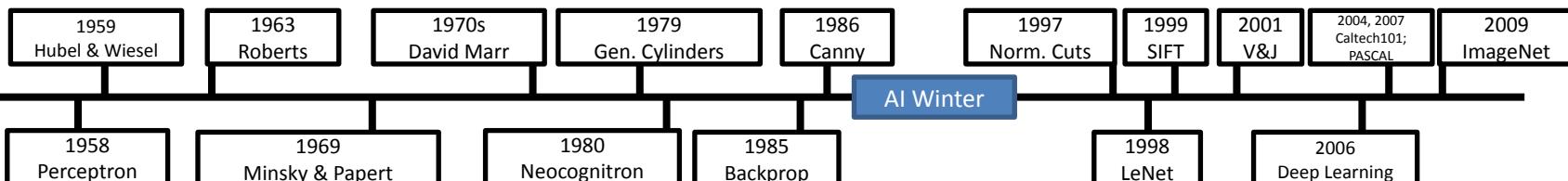
IMAGENET Large Scale Visual Recognition Challenge

The Image Classification Challenge:
1,000 object classes
1,431,167 images

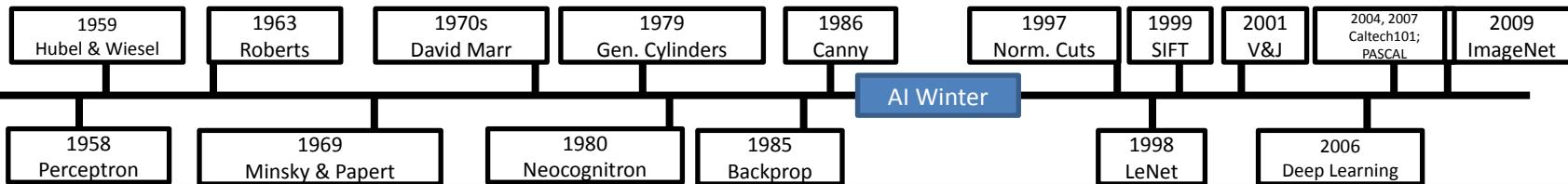
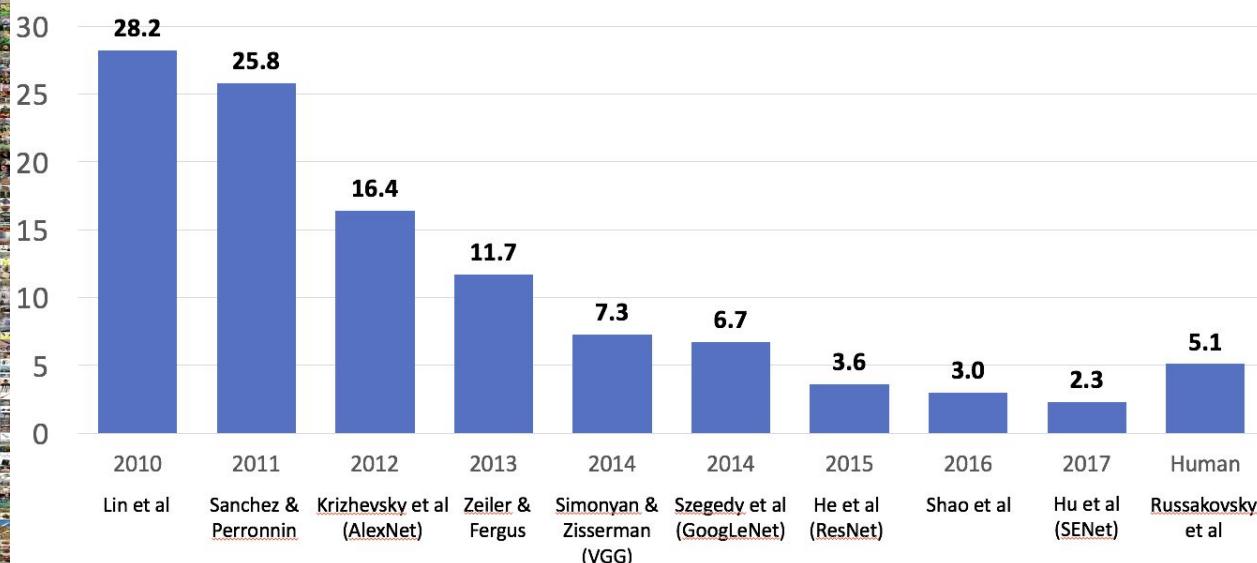


Output:
Scale
T-shirt
Steel drum
Drumstick
Mud turtle

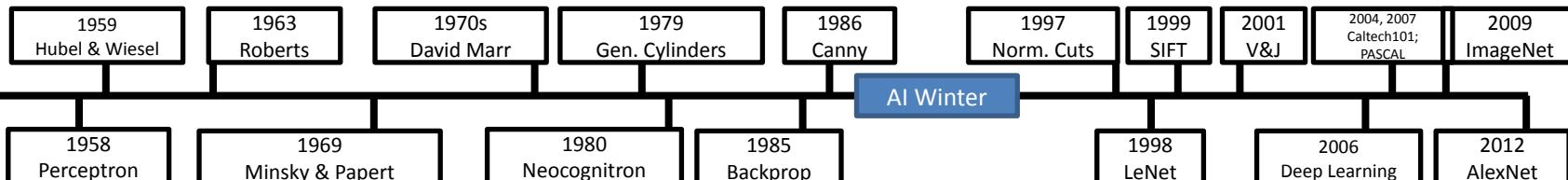
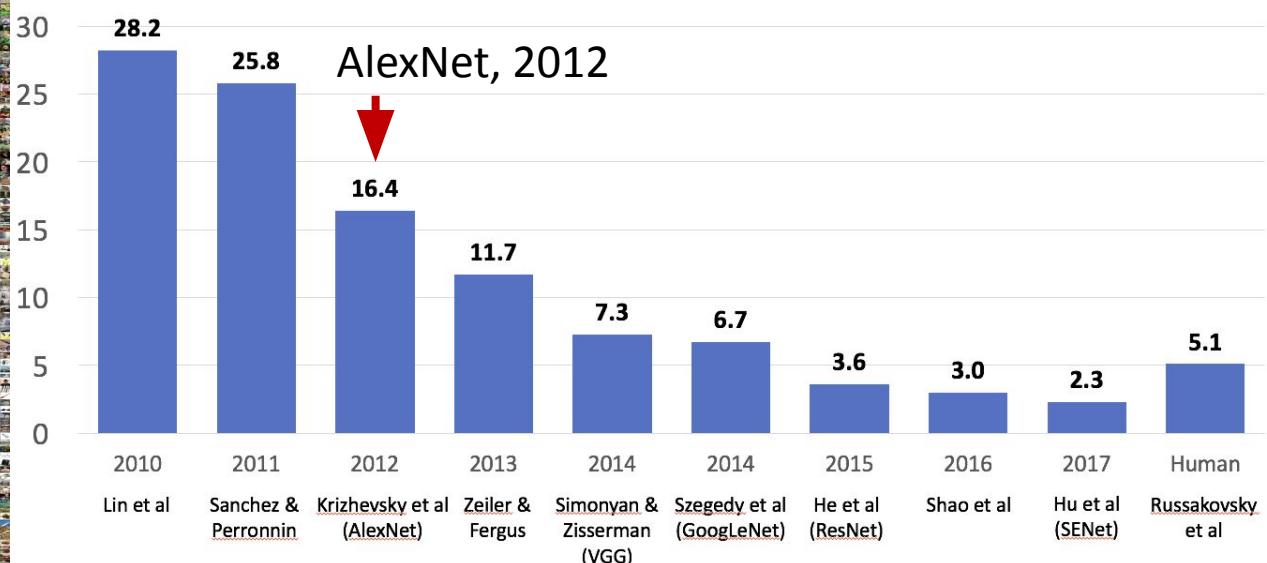
Deng et al, 2009
Russakovsky et al. IJCV 2015



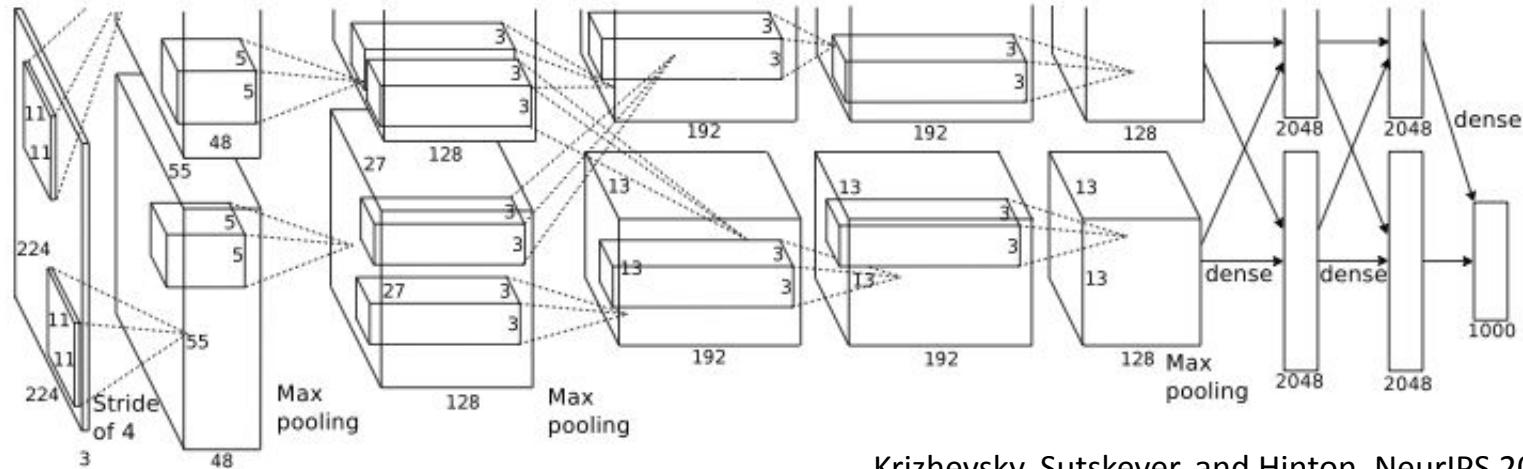
IMAGENET Large Scale Visual Recognition Challenge



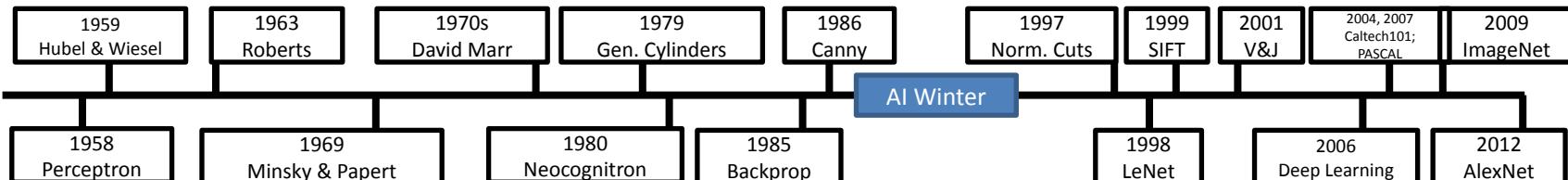
IMAGENET Large Scale Visual Recognition Challenge



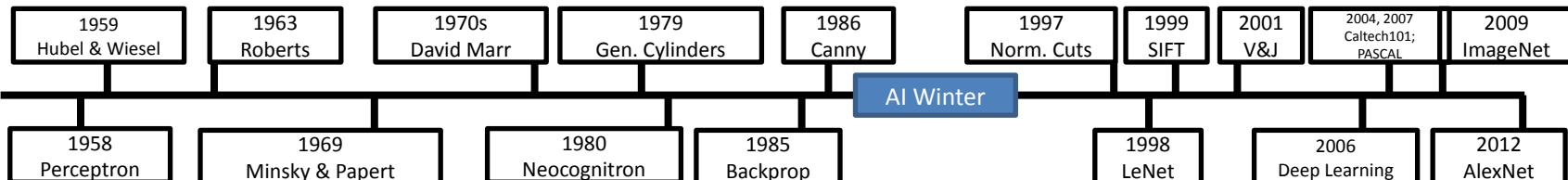
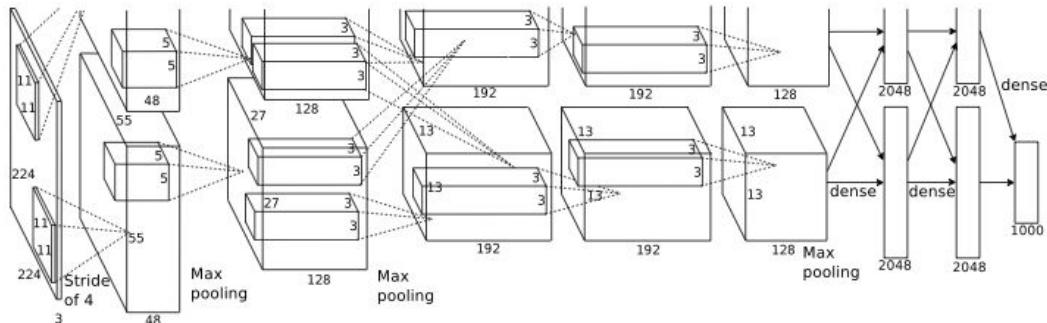
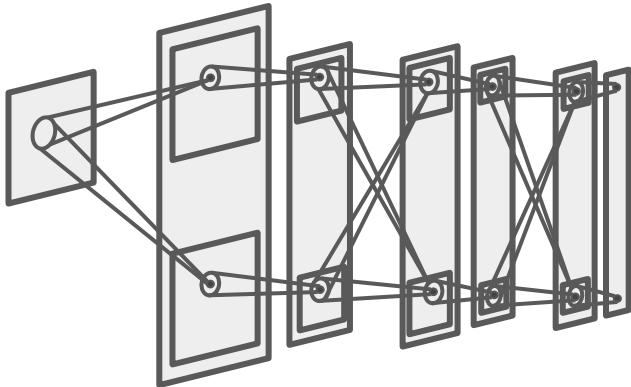
AlexNet: Deep Learning Goes Mainstream



Krizhevsky, Sutskever, and Hinton, NeurIPS 2012



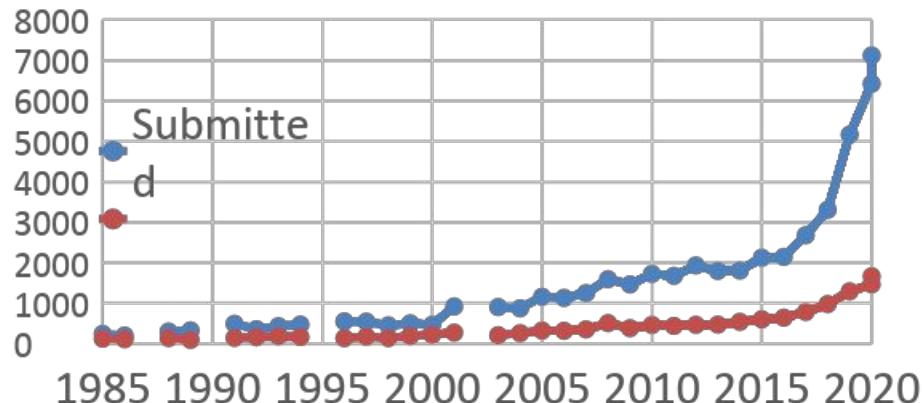
AlexNet vs. Neocognitron: 32 years apart



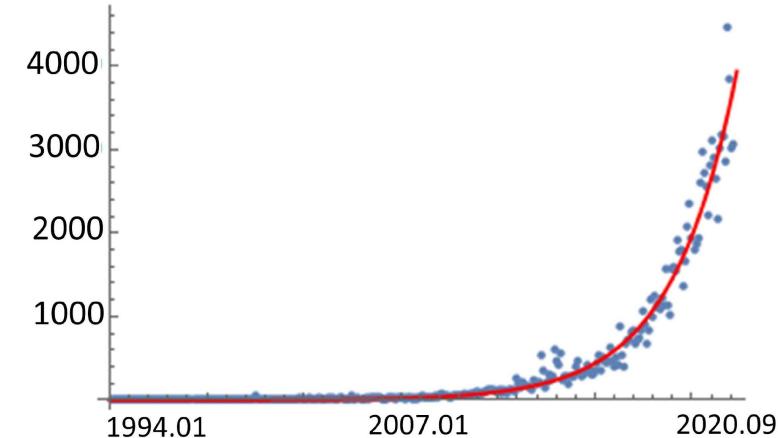
The AI winter thawed,
deep learning revolution arrived

2012 to Present: Deep Learning Explosion

CVPR Papers

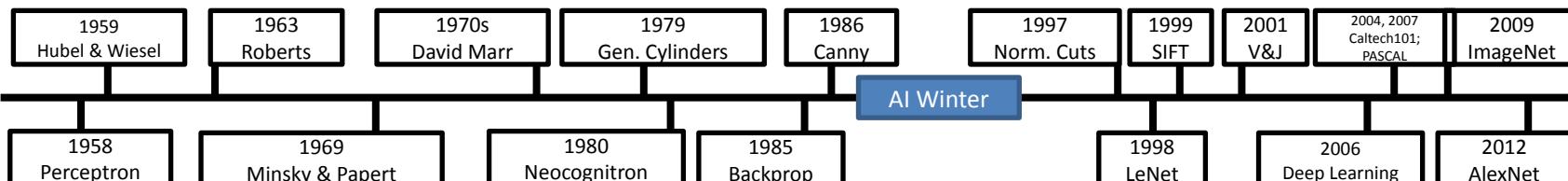


ML+AI arXiv papers per month



Publications at top Computer Vision conference

arXiv papers per month ([source](#))



2012 to Present: Deep Learning is Everywhere

Year 2010

NEC-UIUC



Dense descriptor grid:
HOG, LBP

Coding: local coordinate,
super-vector

Pooling, SPM

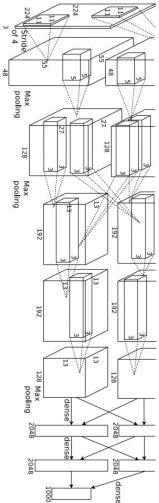
Linear SVM

[Lin CVPR 2011]

Lion image by Swissfrog
is
licensed under CC BY 3.0

Year 2012

SuperVision



[Krizhevsky NIPS 2012]

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.
Reproduced with permission.

Year 2014

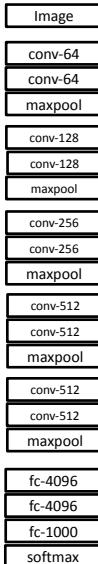
GoogLeNet

- Pooling
- Convolution
- Softmax
- Other



[Szegedy arxiv 2014] [Simonyan arxiv 2014]

VGG



Year 2015

MSRA



[He ICCV 2015]

2012 to Present: Deep Learning is Everywhere

Image Classification



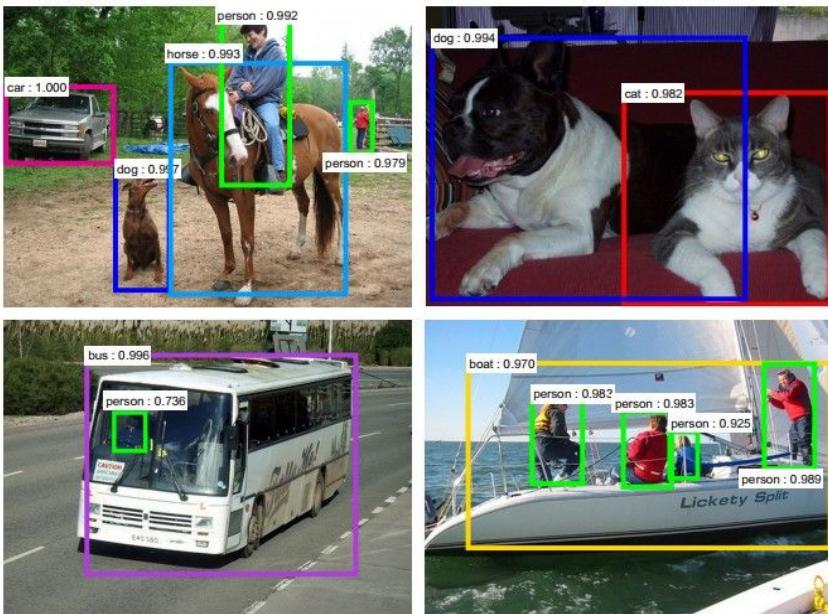
Image Retrieval



Figures copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

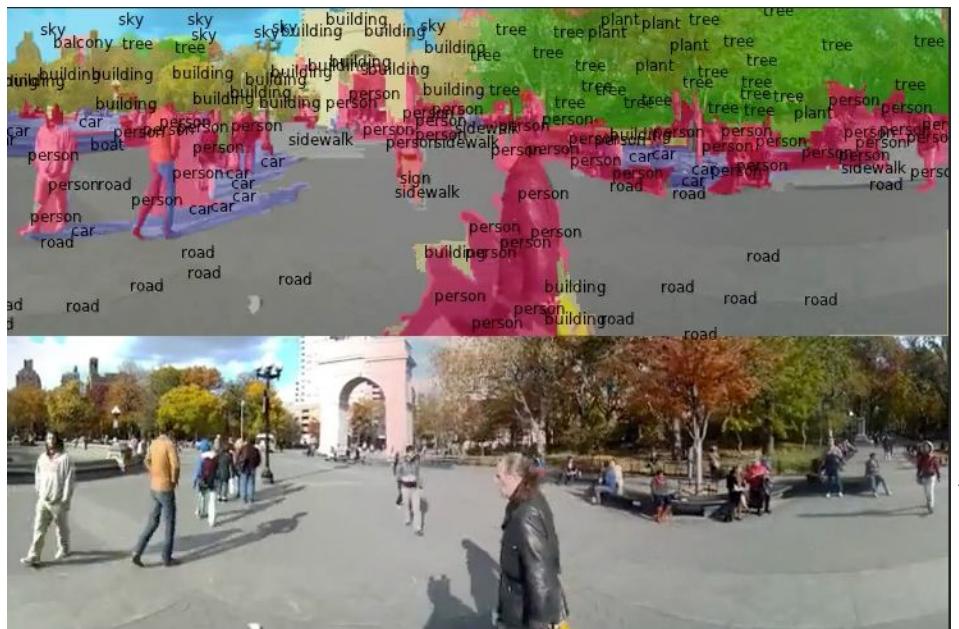
2012 to Present: Deep Learning is Everywhere

Object Detection



Ren, He, Girshick, and Sun, 2015

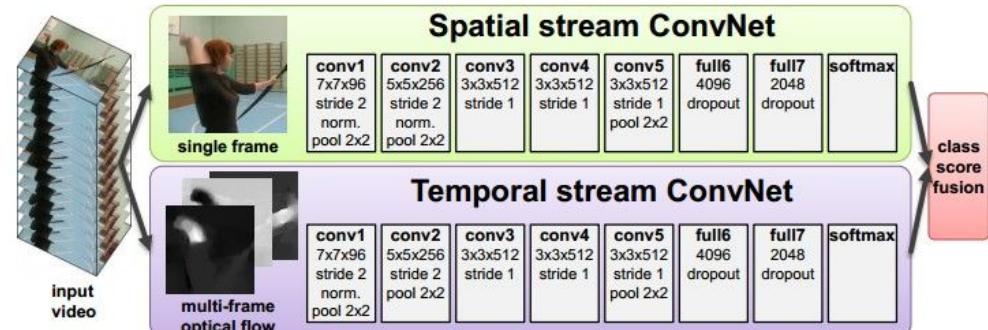
Image Segmentation



Fabaret et al, 2012

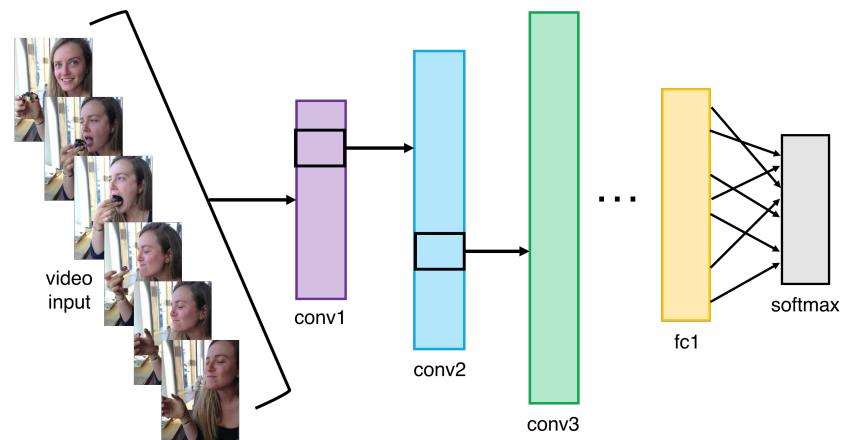
2012 to Present: Deep Learning is Everywhere

Video Classification



Simonyan et al, 2014

Activity Recognition

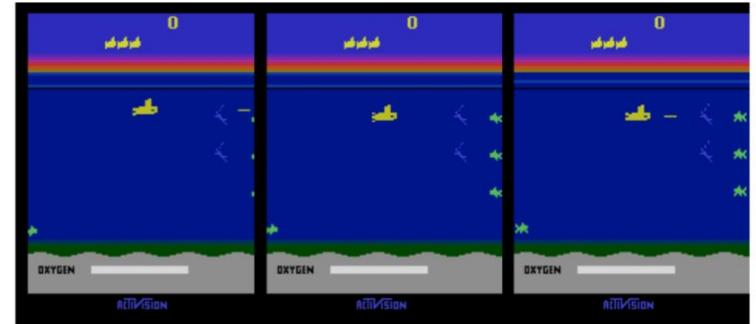
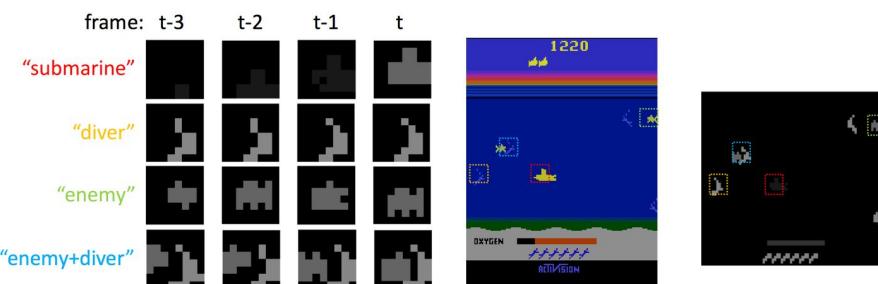


2012 to Present: Deep Learning is Everywhere

Pose Recognition (Toshev and Szegedy, 2014)

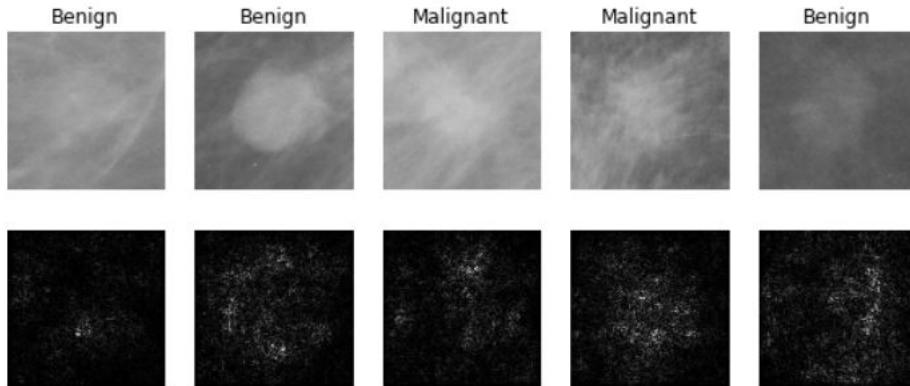


Playing Atari games (Guo et al, 2014)



2012 to Present: Deep Learning is Everywhere

Medical Imaging



Levy et al, 2016

Figure reproduced with permission

Whale recognition



This image by Christin Khan is in the public domain and originally came from the U.S. NOAA.

Galaxy Classification



Dieleman et al, 2014

From left to right: [public domain by NASA](#), usage [permitted](#) by [ESA/Hubble](#); [public domain by NASA](#) and [public domain](#).

Kaggle Challenge

2012 to Present: Deep Learning is Everywhere

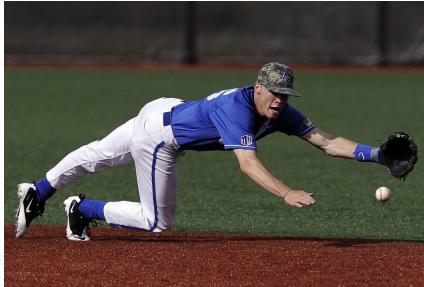


Image Captioning
Vinyals et al, 2015
Karpathy and Fei-Fei, 2015

A white teddy bear sitting in the grass

A man in a baseball uniform throwing a ball

A woman is holding a cat in her hand



A man riding a wave on top of a surfboard



A cat sitting on a suitcase on the floor

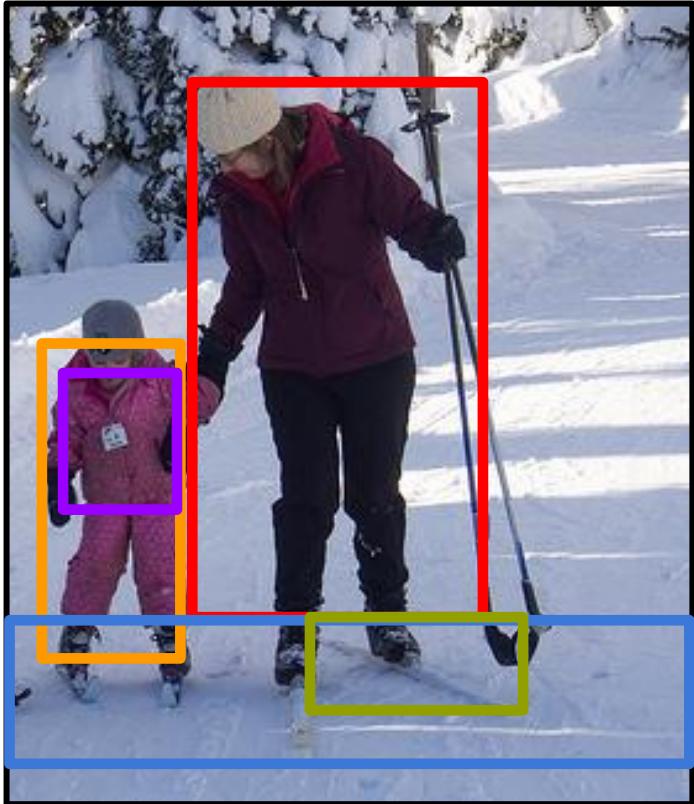


A woman standing on a beach holding a surfboard

All images are CC0 Public domain:
<https://pixabay.com/en/teddy-plush-bear-cute-teddy-bear-1643010/>
<https://pixabay.com/en/teddy-plush-bear-cute-teddy-bear-1623436/>
<https://pixabay.com/en/surf-wave-summer-sport-literal-1668716/>
<https://pixabay.com/en/woman-female-model-portrait-adult-983967/>
<https://pixabay.com/en/handstand-lake-meditation-496008/>
<https://pixabay.com/en/baseball-player-shortstop-infield-1045263/>

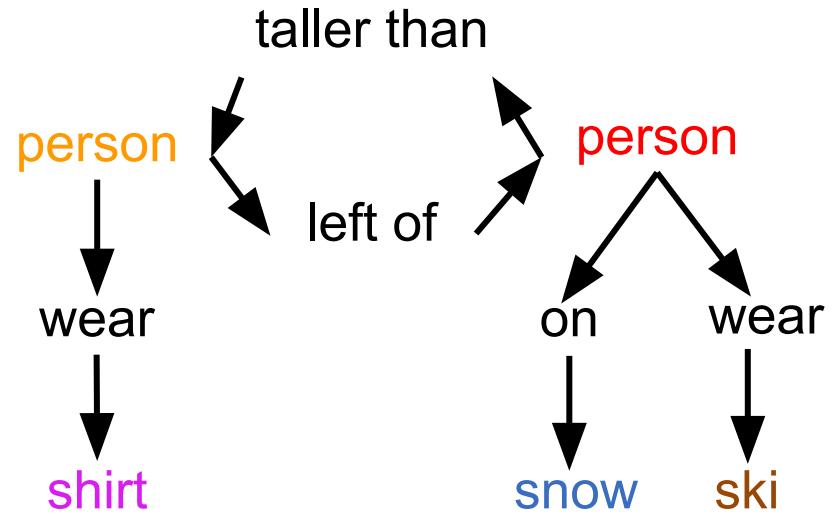
Captions generated by Justin Johnson using NeuralTalk2

2012 to Present: Deep Learning is Everywhere

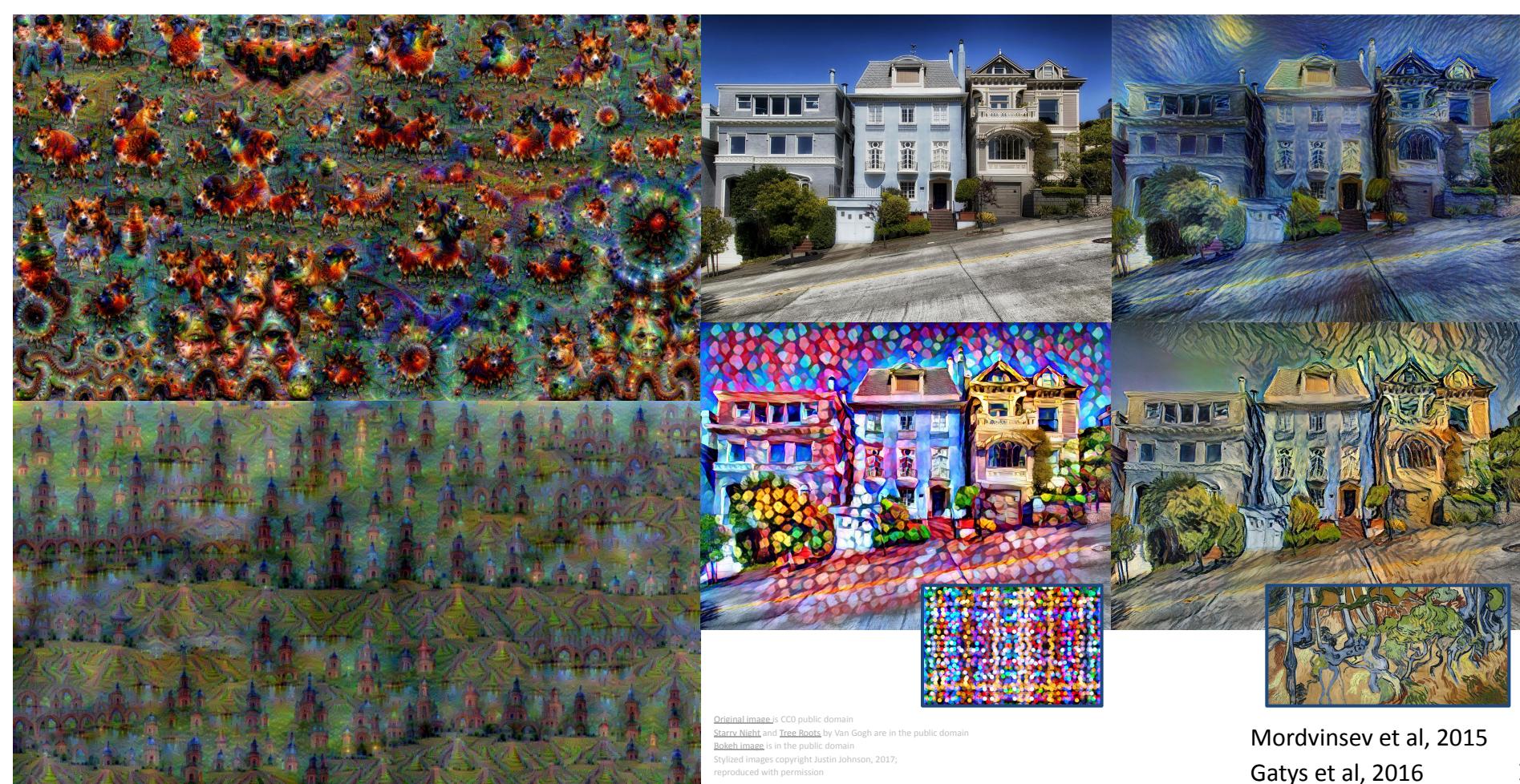


Results:

spatial, comparative, asymmetrical, verb,
prepositional

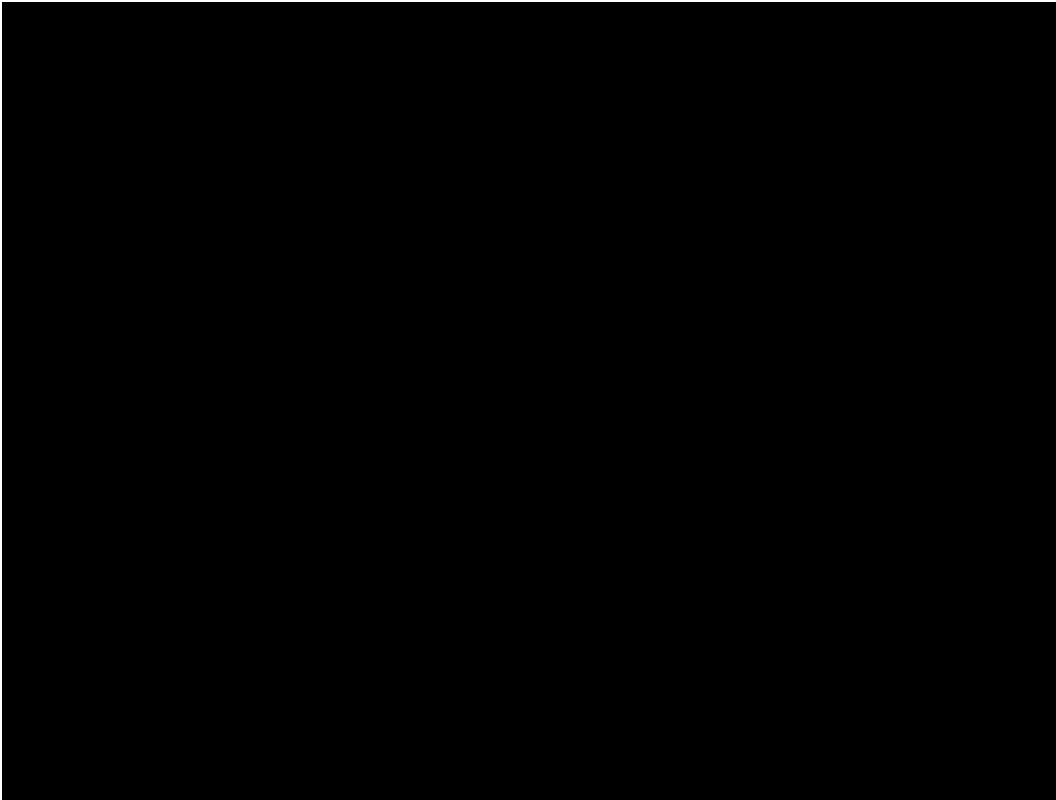


Krishna*, Lu*, Bernstein, Fei-Fei, ECCV 2016



Figures copyright Justin Johnson, 2015. Reproduced with permission. Generated using the Inceptionism approach from a blog post by Google Research.

2012 to Present: Deep Learning is Everywhere



Karras et al, "Progressive Growing of GANs for Improved Quality, Stability, and Variation", ICLR 2018

2012 to Present: Deep Learning is Everywhere

TEXT PROMPT

an armchair in the shape of an avocado. an armchair imitating an avocado.

AI-GENERATED IMAGES



Slide inspiration: Justin Johnson

Ramesh et al., "DALL-E: Creating Images from Text", 2021. <https://openai.com/blog/dall-e/>

2012 to Present: Deep Learning is Everywhere

TEXT PROMPT

an armchair in the shape of a peach. an armchair imitating a peach.

AI-GENERATED IMAGES

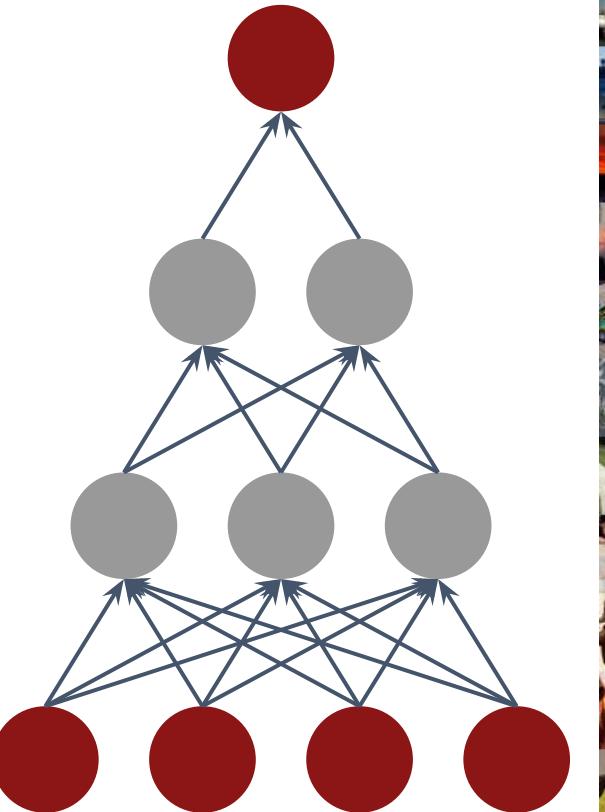


Slide inspiration: Justin Johnson

Ramesh et al., "DALL-E: Creating Images from Text", 2021. <https://openai.com/blog/dall-e/>



Computation



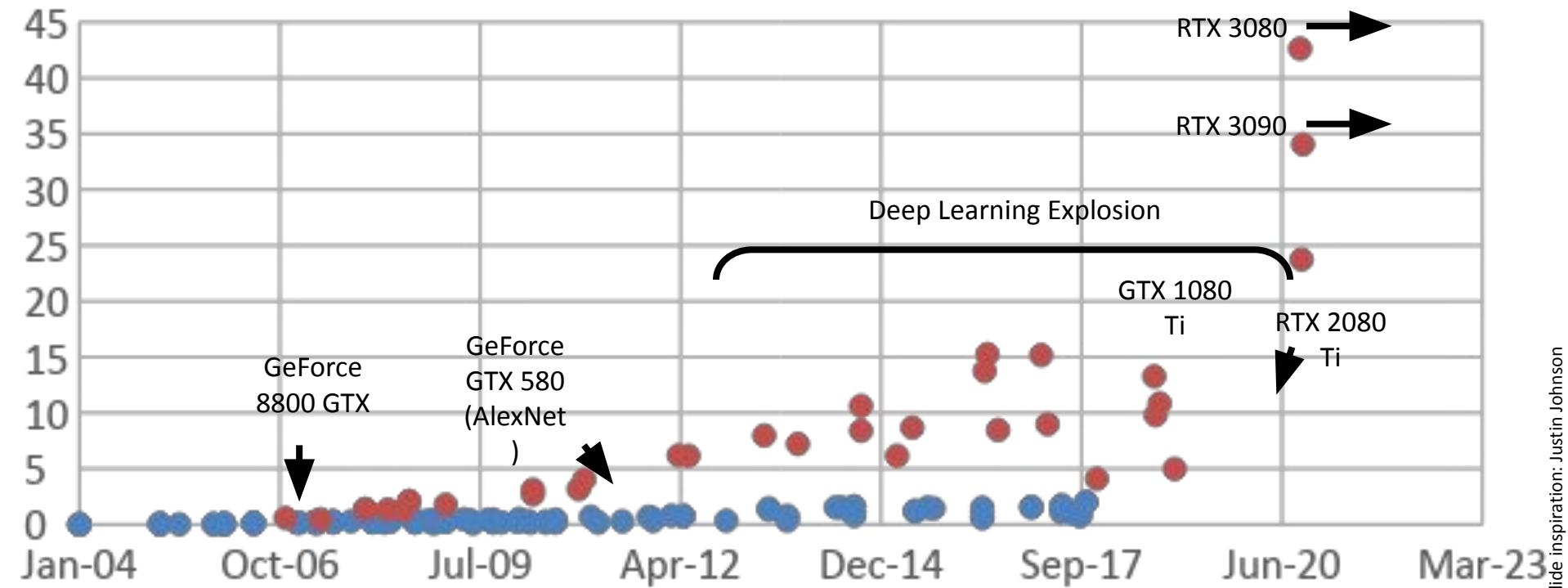
Algorithms



Data

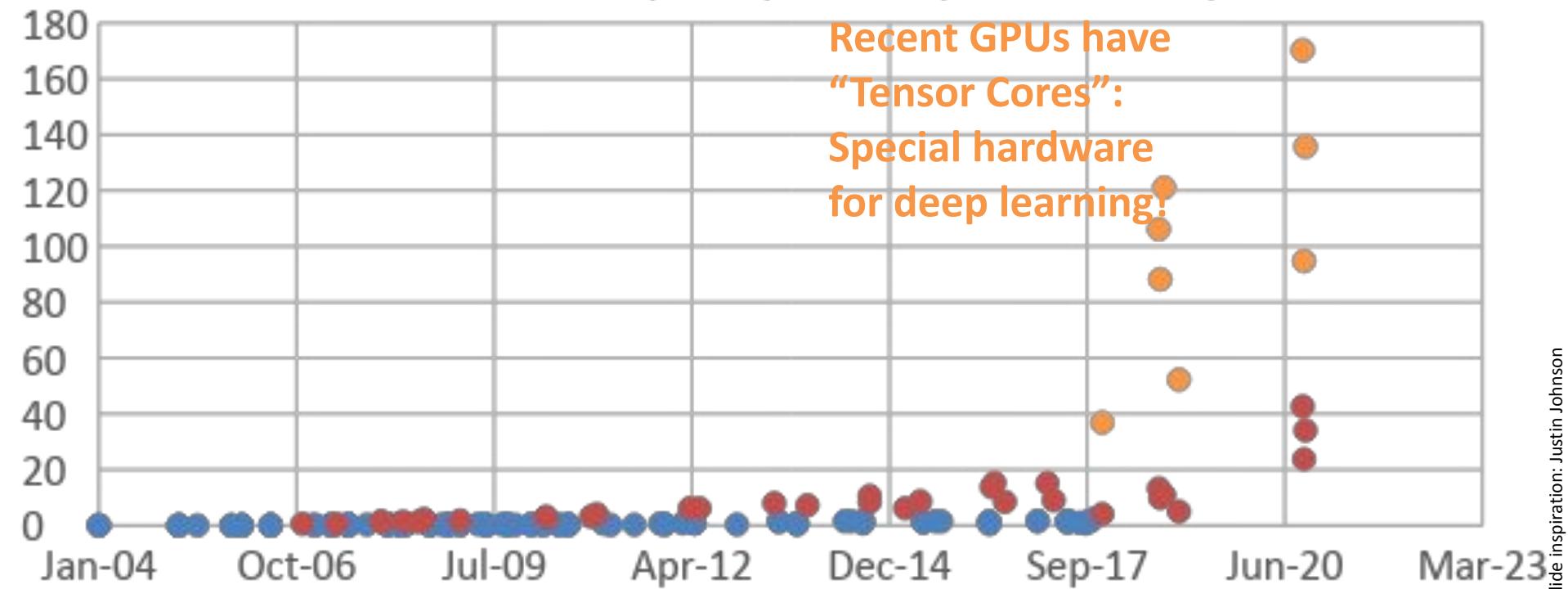
GFLOP per Dollar

• CPU • GPU (FP32)



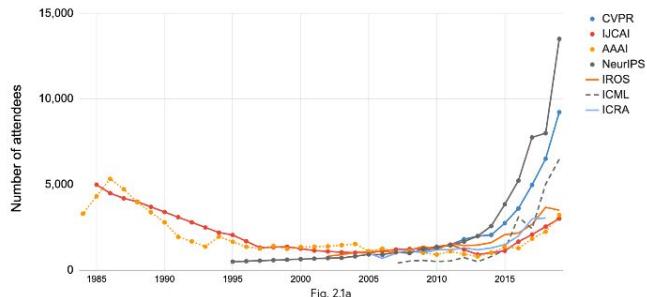
GFLOP per Dollar

- CPU
- GPU (FP32)
- GPU (Tensor Core)



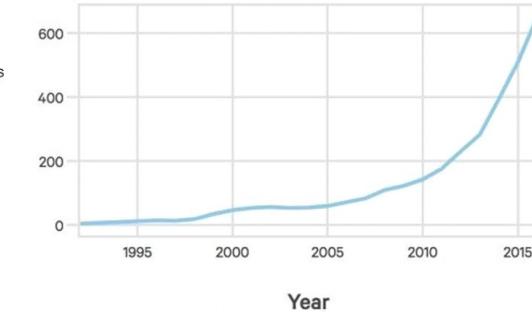
AI's Explosive Growth & Impact

Attendance at large conferences (1984-2019)
Source: Conference provided data.



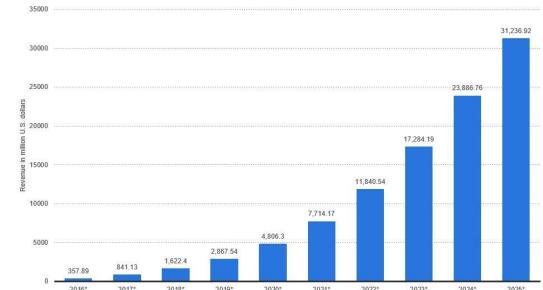
**Number of attendance
At AI conferences**

Source: The Gradient



**Startups Developing AI
Systems**

Source: Crunchbase, VentureSource, Sand
Hill Econometrics



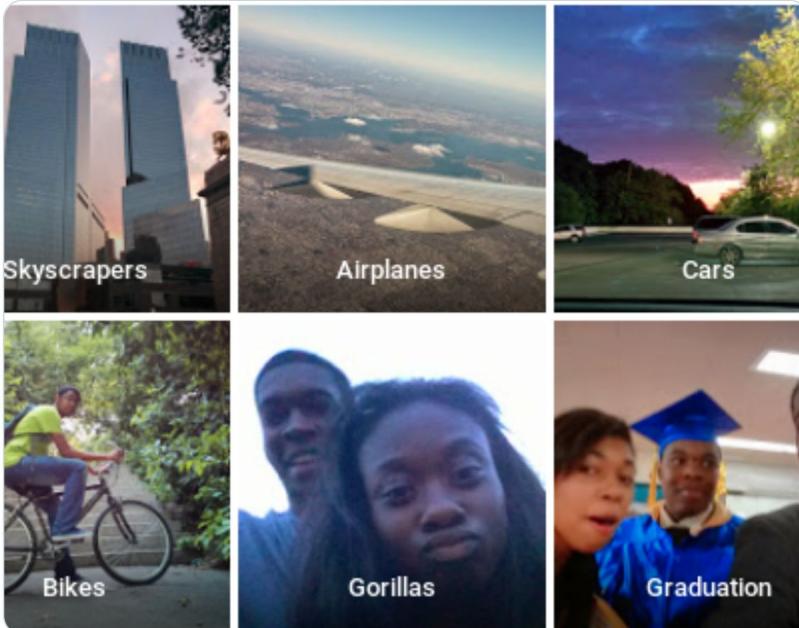
**Enterprise Application AI
Revenue**

Source: Statista

Despite the successes, computer vision still has a long way to go

Computer Vision Can Cause Harm

Harmful Stereotypes



Barocas et al, "The Problem With Bias: Allocative Versus Representational Harms in Machine Learning", SIGCIS 2017

Kate Crawford, "The Trouble with Bias", NeurIPS 2017 Keynote

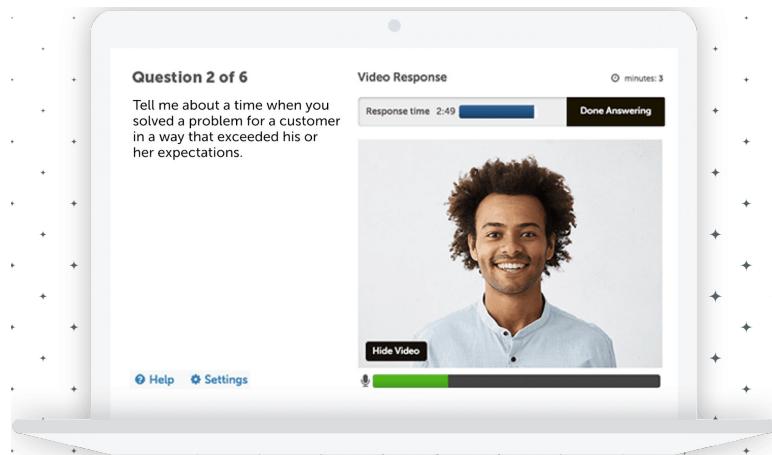
Source: <https://twitter.com/jackyalcine/status/615329515909156865> (2015)

Affect people's lives

Technology

A face-scanning algorithm increasingly decides whether you deserve the job

HireVue claims it uses artificial intelligence to decide who's best for a job. Outside experts call it 'profoundly disturbing.'



Source: <https://www.washingtonpost.com/technology/2019/10/22/ai-hiring-face-scanning-algorithm-increasingly-decides-whether-you-deserve-job/>

<https://www.hirevue.com/platform/online-video-interviewing-software>

Example Credit: Timnit Gebru

Computer Vision Can Save Lives

How to take care of seniors
while keeping them safe?



Early Symptom Detection
of COVID-19



Monitor Patients with
Mild Symptoms



Manage Chronic Conditions



And there is a lot we don't know how to do



https://fedandfit.com/wp-content/uploads/2020/06/summer-activities-for-kids_optimized-scaled.jpeg



This image is
copyright-free United
States government
work

Today's agenda

- A brief history of computer vision & deep learning
- CS231n overview

CS231n: Deep Learning for Computer Vision

Lecture 1 - Overview

Today's agenda

- A brief history of computer vision
- CS231n overview

Today's agenda

- A brief history of computer vision
- CS231n overview

Image Classification: A core task in Computer Vision



cat

This image by [Nikita](#) is
licensed under [CC-BY 2.0](#)

There are many visual recognition problems that are related to image classification, such as object detection, image captioning, image segmentation, visual question answering, visual instruction navigation, video understanding, etc.

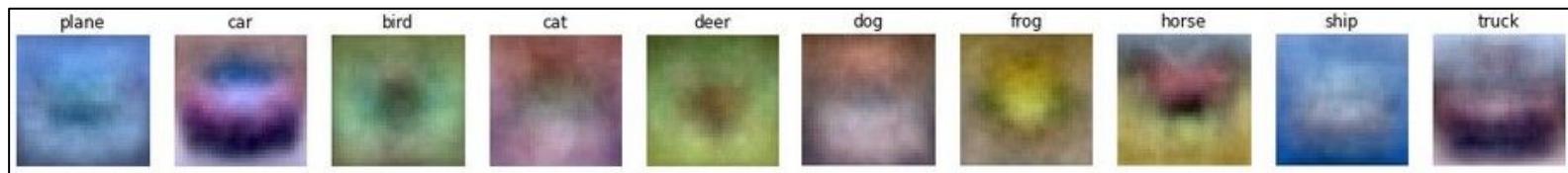
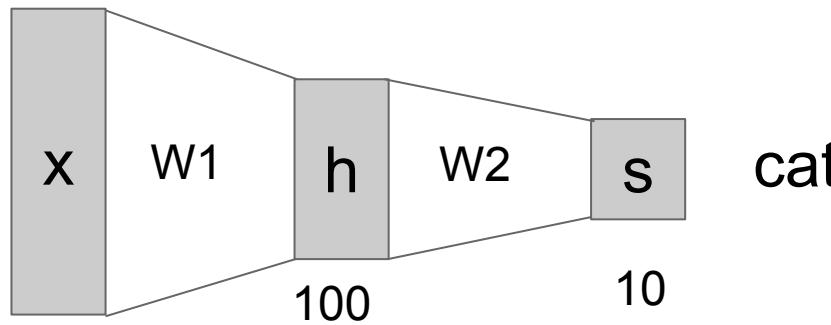
Deep Learning for Computer Vision

Hierarchical computing systems with many “layers”, that are very loosely inspired by Neuroscience

Neural Networks



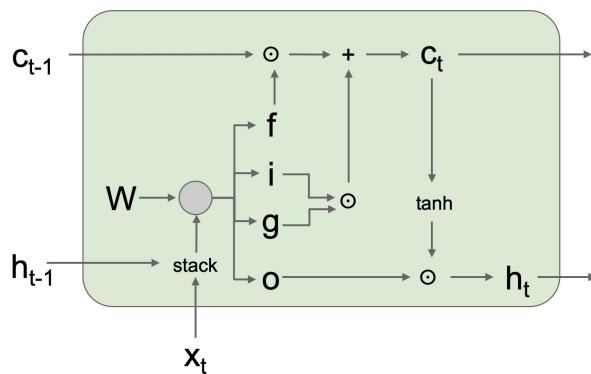
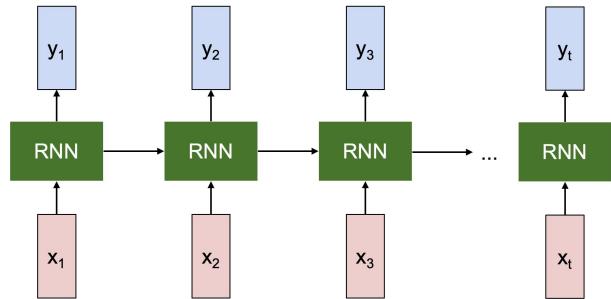
3072



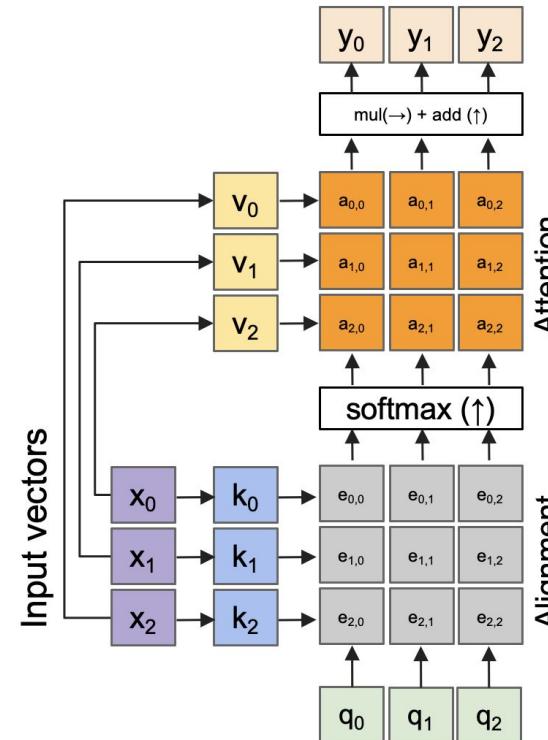
Convolutional Neural Networks for Visual Recognition

A class of Neural Networks that have become an important tool for visual recognition

Beyond Convolutional Neural Networks



Recurrent neural network



Attention mechanism / Transformers

Beyond Image Classification

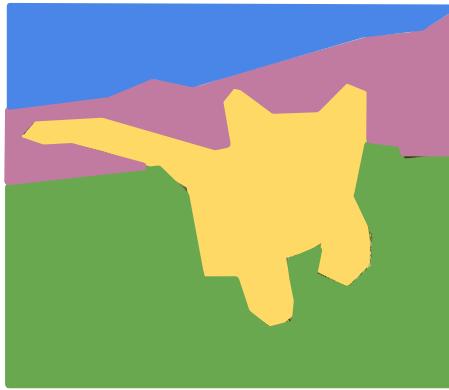
Classification



CAT

No spatial extent

Semantic Segmentation



GRASS, CAT,
TREE, SKY

No objects, just pixels

Object Detection



DOG, DOG, CAT

Multiple Object

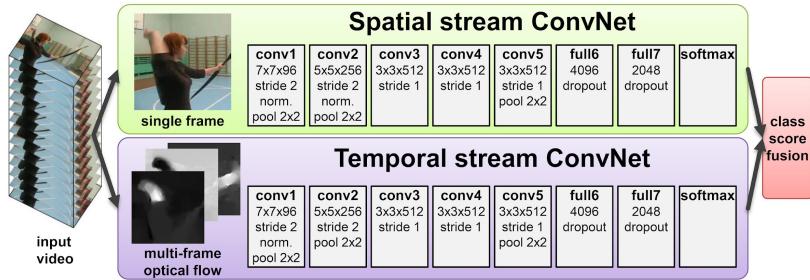
Instance Segmentation



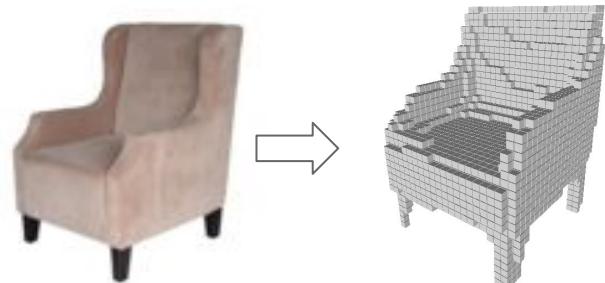
DOG, DOG, CAT

This image is CC0 public domain

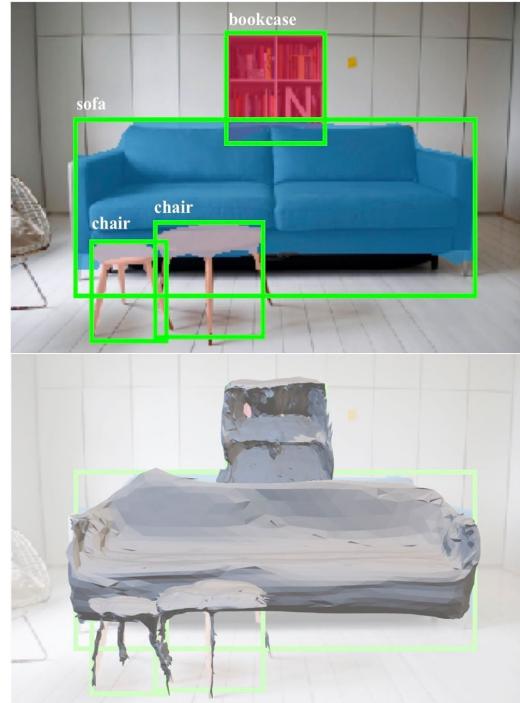
Beyond 2D Images



Simonyan and Zisserman, "Two-stream convolutional networks for action recognition in videos", NeurIPS 2014

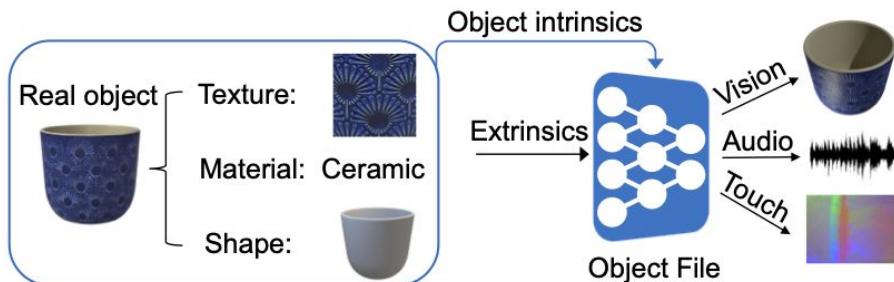


Choy et al., 3D-R2N2: Recurrent Reconstruction Neural Network (2016)

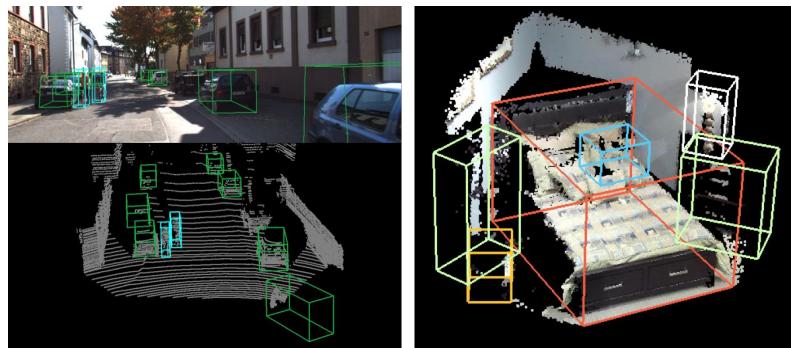


Gkioxari et al., "Mesh R-CNN", ICCV 2019

Beyond Vision



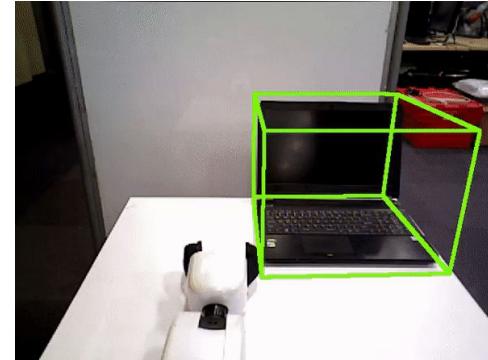
Gao et al., ObjectFolder 2.0: A Multisensory Object Dataset for Sim2Real Transfer (2022)



Xu et al., PointFusion: Deep Sensor Fusion for 3D Bounding Box Estimation (2018)



Mandlekar and Xu et al., Learning to Generalize Across Long-Horizon Tasks from Human Demonstrations (2020)



Wang et al., 6-PACK: Category-level 6D Pose Tracker with Anchor-Based Keypoints (2020)

2018 Turing Award for deep learning

most prestigious technical award, is given for major contributions of lasting importance to computing.



[This image is CC0 public domain](#)

[This image is CC0 public domain](#)

[This image is CC0 public domain](#)

IEEE PAMI Longuet-Higgins Prize

Award recognizes ONE Computer Vision paper from **ten years ago** with **significant impact** on computer vision research.

At CVPR 2019, it was awarded to the 2009 original ImageNet paper

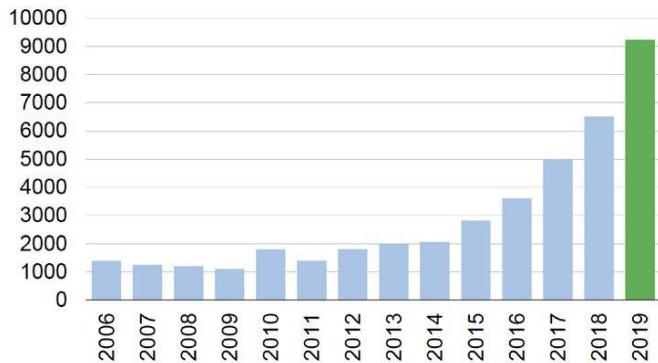


CVPR 2019

Long Beach, CA
June 16th - June 20th



CVPR Attendance Trend



>8k submissions, 2,067 accepted papers

Logistics

Instructors



Fei-Fei Li

Teaching Assistants



Moo Jin Kim
(Head TA)



Dhruba Bansal



Shyamal Buch



Gokul Dharan



Agrim Gupta



Jiajun Wu



Zhiyue Huang



Drew Kaul



Sumith Kulal



Mihir Vipul Patel



Hongyu Ren



Ruohan Gao



Manasi Sharma



William Shen



Haochen Shi



Stephen Su



Bohan Wu



Yinan Zhang

Lectures

- **Tuesdays and Thursdays between 1:30pm to 3:00pm at NVIDIA Auditorium**
- Slides will be posted on the course website shortly before each lecture
- All lectures will be recorded and uploaded to [Canvas](#) after the lecture under the “Panopto Course Videos” Tab.

Course website

CS231n: Deep Learning for Computer Vision

Stanford - Spring 2022

Schedule

- Lectures will occur Tuesday/Thursday from 1:30-3:00pm Pacific Time at [NVIDIA Auditorium](#).
- Discussion sections will (generally) occur Friday from 11:30am-12:30pm Pacific Time on Zoom. Check [Ed](#) for any exceptions.

Updated lecture slides will be posted here shortly before each lecture. For ease of reading, we have color-coded the lecture category titles in [blue](#), discussion sections (and final project poster session) in [yellow](#), and the midterm exam in [red](#). Note that the schedule is subject to change as the quarter progresses.

Date	Description	Course Materials	Events	Deadlines
03/29	Lecture 1: Introduction Computer vision overview Historical context Course logistics			

03/31	Deep Learning Basics Lecture 2: Image Classification with Linear Classifiers The data-driven approach K-nearest neighbor Linear Classifiers Algebraic / Visual / Geometric viewpoints SVM and Softmax loss	Image Classification Problem Linear Classification		
04/01	Python / Numpy Review Session [Colab] [Tutorial]	⌚ 11:30am-12:30pm	Assignment 1 out	

Friday Discussion Sections

6 Discussion sections **Fridays 1:30pm - 2:30pm over Zoom**

04/01	Python / Numpy Review Session
04/08	Backprop Review Session
04/15	Final Project Overview and Guidelines
04/22	PyTorch / TensorFlow Review Session
04/29	Detection software & RNNs
05/06	Midterm Review Session

Hands-on tutorials, with more practical details than the main lecture

Check canvas for the Zoom link of the discussion sessions!

This Friday: Python / numpy / Colab (Presenter: Manasi Sharma)

Ed

For questions about midterm, projects, logistics, etc, use [Ed!](#)

SCPD students: Use your @stanford.edu address to register for Ed; contact scpd-customerservice@stanford.edu for help.

Office Hours

We'll be using Zoom to hold office hours and QueueStatus to setup queues

- please see [Canvas](#) or [Ed](#) for the QueueStatus link
- TAs will admit students to their Zoom meeting rooms for 1-1 conversations when it's your turn using QueueStatus.
- [Office hours is listed on the course webpage!](#)

Optional textbook resources

- [Deep Learning](#)
 - by Goodfellow, Bengio, and Courville
 - Here is a [free version](#)
- Mathematics of deep learning
 - Chapters 5, 6 7 are useful to understand vector calculus and continuous optimization
 - [Free online version](#)
- Dive into deep learning
 - An interactive deep learning book with code, math, and discussions, based on the NumPy interface.
 - [Free online version](#)

Assignments

All assignments will be completed using Google Colab

Assignment 1: Will be out Friday, due 4/15 by 11:59pm

- K-Nearest Neighbor
- Linear classifiers: SVM, Softmax
- Two-layer neural network
- Image features

Grading

All assignments, coding and written portions, will be submitted via [Gradescope](#).

An **auto-grading system**:

- A consistent grading scheme
- Public tests:
 - Students see results of public tests immediately
- Private tests
 - Generalizations of the public tests to thoroughly test your implementation

Grading

3 Assignments: 10% + 20% + 15% = 45%

In-Class Midterm Exam: 20%

Course Project: 35%

- Project Proposal: 1%
- Milestone: 2%
- Final Project Report: 29%
- Poster & Poster Session: 3%

Participation Extra Credit: up to 3%

Late policy

- 4 free late days – use up to 2 late days per assignment
- Afterwards, 25% off per day late
- No late days for project report

AWS

We will have AWS Cloud credits available for projects

- Not for HWs (only for final projects)

We will be distributing coupons to all enrolled students who need it

We will have a tutorial for walking through the AWS setup

Overview on communication

Course Website: <http://cs231n.stanford.edu/>

- Syllabus, lecture slides, links to assignment downloads, etc

Ed:

- Use this for most communication with course staff
- Ask questions about homework, grading, logistics, etc
- Use private questions only if your post will violate honor code if you release publicly.

Gradescope:

- For turning in homework and receiving grades

Canvas:

- For watching recorded lectures
- For watching recorded discussion sessions

Prerequisites

Proficiency in Python

- All class assignments will be in Python (and use numpy)
- Later in the class, you will be using Pytorch and TensorFlow
- [A Python tutorial available on course website](#)

College Calculus, Linear Algebra

No longer need CS229 (Machine Learning)

Collaboration policy

We follow the [Stanford Honor Code](#) and the [CS Department Honor Code](#) – read them!

- **Rule 1:** Don't look at solutions or code that are not your own; everything you submit should be your own work
- **Rule 2:** Don't share your solution code with others; however discussing ideas or general strategies is fine and encouraged
- **Rule 3:** Indicate in your submissions anyone you worked with

Turning in something late / incomplete is better than violating the honor code

Learning objectives

Formalize computer vision applications into tasks

- Formalize inputs and outputs for vision-related problems
- Understand what data and computational requirements you need to train a model

Develop and train vision models

- Learn to code, debug, and train convolutional neural networks.
- Learn how to use software frameworks like PyTorch and TensorFlow

Gain an understanding of where the field is and where it is headed

- What new research has come out in the last 0-5 years?
- What are open research challenges?
- What ethical and societal considerations should we consider before deployment?

Why should you take this class?

Become a vision researcher (an incomplete list of conferences)

- Get involved with [vision research at Stanford](#): apply [using this form](#).
- [CVPR 2022 conference](#)
- [ICCV 2021 conference](#)

Become a vision engineer in industry (an incomplete list of industry teams)

- [Perception team at Google AI](#), [Vision at Google Cloud](#)
- [Vision at Meta AI](#)
- [Vision at Amazon AWS](#)
- [Nvidia](#), [Tesla](#), [Apple](#), [Salesforce](#),

General interest

CS231n: Deep Learning for Computer Vision

- Deep Learning Basics (Lecture 2 – 4)
- Perceiving and Understanding the Visual World (Lecture 5 – 12)
- Reconstructing and Interacting with the Visual World (Lecture 13 – 16)
- Human-Centered Artificial Intelligence (Lecture 17 – 18)

Syllabus

Deep Learning Basics

Data-driven learning
Linear classification & kNN
Loss functions
Optimization
Backpropagation
Multi-layer perceptrons
Neural Networks

Convolutional Neural Networks

Convolutions
PyTorch / TensorFlow
Activation functions
Batch normalization
Transfer learning
Data augmentation
Momentum / RMSProp / Adam
Architecture design

Computer Vision Applications

RNNs / Attention / Transformers
Image captioning
Object detection and segmentation
Style transfer
Video understanding
Generative models
Self-supervised learning
3D vision
Human-centered AI
Fairness & ethics

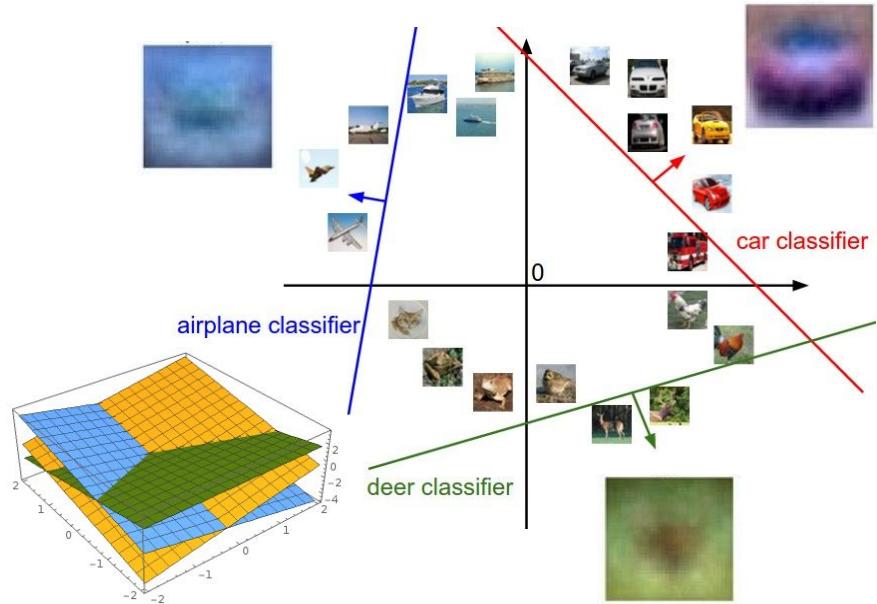


Next time: Image classification with Linear Classifiers

k- nearest neighbor



Linear classification



Plot created using [Wolfram Cloud](#)

Lecture 2: Image Classification with Linear Classifiers

Administrative: Assignment 1

Out tomorrow, Due 4/15 11:59pm

- K-Nearest Neighbor
- Linear classifiers: SVM, Softmax
- Two-layer neural network
- Image features

Administrative: Course Project

Project proposal due 4/18 (Monday) 11:59pm

Find your teammates on Ed (the pinned “Search for Teammates” post)

“Is X a valid project for 231n?” --- Ed private post / TA Office Hours

More info on the website

Administrative: Discussion Sections

This Friday 1:30pm-2:30 pm (recording will be made available)

Python / Numpy, Google Colab

Presenter: Manasi Sharma (TA)

Syllabus

Deep Learning Basics

Data-driven approaches **Linear classification & kNN**

Loss functions
Optimization
Backpropagation
Multi-layer perceptrons
Neural Networks

Convolutional Neural Networks

Convolutions
PyTorch / TensorFlow
Activation functions
Batch normalization
Transfer learning
Data augmentation
Momentum / RMSProp / Adam
Architecture design

Computer Vision Applications

RNNs / Attention / Transformers
Image captioning
Object detection and segmentation
Style transfer
Video understanding
Generative models
Self-supervised learning
3D vision
Human-centered AI
Fairness & ethics



Image Classification

A Core Task in Computer Vision

Today:

- The image classification task
- Two basic data-driven approaches to image classification
 - K-nearest neighbor and linear classifier

Image Classification: A core task in Computer Vision



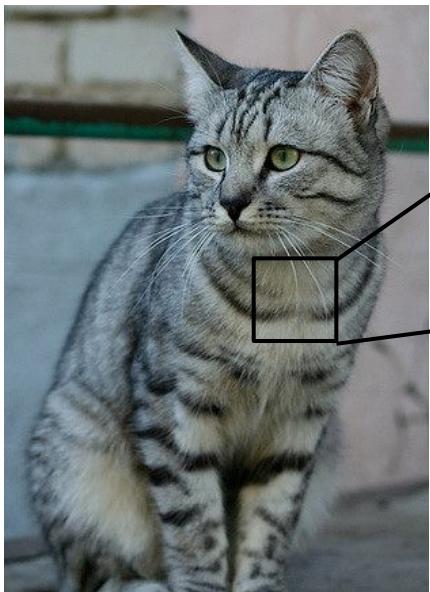
(assume given a set of possible labels)
{dog, cat, truck, plane, ...}



cat

This image by [Nikita](#) is
licensed under [CC-BY 2.0](#)

The Problem: Semantic Gap



[105 112 108 111 104 99 106 99 96 103 112 119 104 97 93 87]
[91 98 102 106 104 79 98 103 99 105 123 136 110 105 94 85]
[76 85 90 105 128 105 87 96 95 99 115 112 106 103 99 85]
[99 81 93 120 131 127 100 95 98 102 99 96 93 101 94]
[106 91 61 64 69 91 88 85 101 107 109 98 75 84 96 95]
[114 108 85 55 55 69 64 54 64 87 112 129 98 74 84 91]
[133 137 147 103 65 81 80 65 52 54 74 84 102 93 85 82]
[128 137 144 140 109 95 86 70 62 65 63 63 60 73 86 101]
[125 133 148 137 119 121 117 94 65 79 80 65 54 64 72 98]
[127 125 131 147 133 127 126 131 111 96 89 75 61 64 72 84]
[115 114 109 123 150 148 131 118 113 109 100 92 74 65 72 78]
[89 93 90 97 108 147 131 118 113 114 113 109 106 95 77 80]
[63 77 86 81 77 79 102 123 117 115 117 125 125 130 115 87]
[62 65 82 89 78 71 80 101 124 126 119 101 107 114 131 119]
[63 65 75 88 89 71 62 81 128 138 135 105 81 98 110 118]
[87 65 71 87 106 95 69 45 76 130 126 107 92 94 105 112]
[118 97 82 86 117 123 116 66 41 51 95 93 89 95 102 107]
[164 146 112 88 82 120 124 104 76 48 45 66 88 101 102 109]
[157 170 157 128 93 86 114 132 112 97 69 55 70 82 99 94]
[130 128 134 161 139 100 109 118 121 134 114 87 65 53 69 86]
[128 112 96 117 150 144 128 115 104 107 102 93 87 81 72 79]
[123 107 96 86 83 112 153 149 122 109 104 75 80 107 112 99]
[122 121 102 88 82 86 94 117 145 148 153 102 58 78 92 107]
[122 164 148 103 71 56 78 83 93 103 119 139 102 61 69 84]]

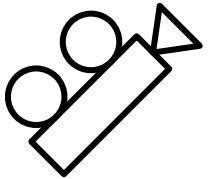
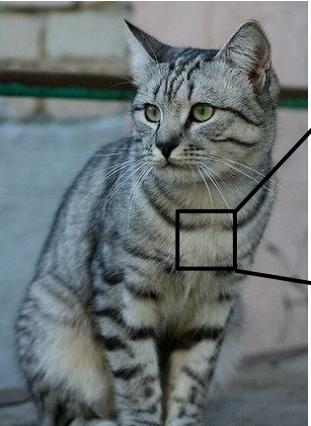
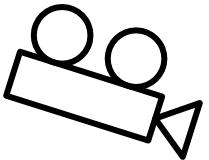
What the computer sees

An image is a tensor of integers between [0, 255]:

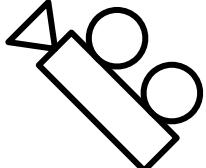
e.g. 800 x 600 x 3
(3 channels RGB)

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licensed under CC-BY 2.0

Challenges: Viewpoint variation



```
[1185 112 188 111 184 99 186 99 96 183 112 119 184 97 93 87]  
[ 91 98 182 106 184 79 98 183 99 185 123 136 118 185 94 85]  
[ 76 85 98 185 128 105 87 96 95 99 115 112 106 183 99 85]  
[ 99 80 81 100 128 103 127 98 98 101 108 109 98 75 84 94]  
[104 91 86 84 60 91 68 85 101 108 109 98 75 84 94 95]  
[114 108 85 55 55 69 64 54 64 87 112 129 98 74 84 94 91]  
[133 137 147 183 65 81 80 65 52 54 74 84 102 93 85 82]  
[128 137 144 148 105 95 86 78 62 65 63 68 68 73 86 101]  
[102 125 131 147 133 127 116 131 111 98 89 75 61 64 72 80]  
[127 125 131 147 133 127 116 131 111 98 89 75 61 64 72 84]  
[115 115 189 123 150 148 131 118 113 109 108 92 74 65 72 78]  
[ 89 93 98 97 108 147 131 118 113 114 113 108 106 95 77 80]  
[ 63 77 86 81 77 79 182 123 137 115 111 125 125 130 115 87]  
[ 62 85 88 89 73 62 81 128 138 135 105 81 98 118 118]  
[ 63 65 75 88 89 73 62 81 128 138 135 105 81 98 118 118]  
[ 87 65 71 87 100 95 69 45 76 126 126 107 92 94 105 112]  
[118 97 82 86 117 123 116 66 41 51 95 93 89 89 95 102 107]  
[164 147 112 88 100 128 126 184 78 48 66 70 101 102 108]  
[157 98 100 118 103 92 86 104 105 128 109 89 75 70 84 94]  
[138 128 134 161 139 180 109 118 121 134 114 87 65 53 69 86]  
[128 112 96 117 150 144 120 115 104 107 102 93 87 81 72 79]  
[123 107 96 86 83 112 153 149 122 189 104 75 88 107 112 99]  
[122 121 102 88 82 86 94 117 145 148 153 105 58 78 92 107]  
[122 164 148 103 71 56 78 83 93 103 119 139 102 61 69 84]
```



All pixels change when
the camera moves!

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Challenges: Illumination



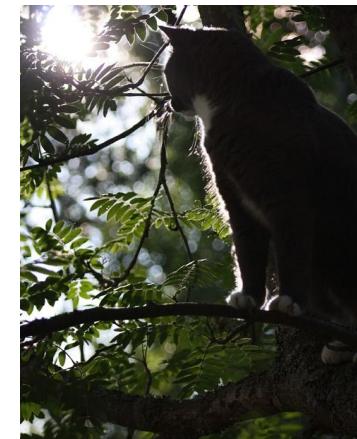
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[This image](#) is CC0 1.0 public domain



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Challenges: Background Clutter



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[This image](#) is [CC0 1.0](#) public domain

Challenges: Occlusion



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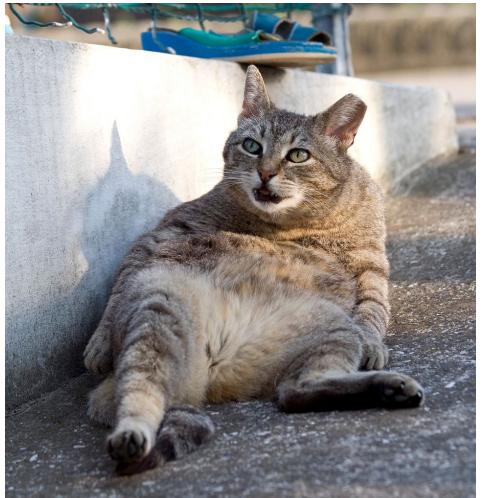


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Challenges: Deformation



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[This image](#) by [sare bear](#) is
licensed under [CC-BY 2.0](#)



[This image](#) by [Tom Thai](#) is
licensed under [CC-BY 2.0](#)

Challenges: Intraclass variation



[This image](#) is [CC0 1.0](#) public domain

Challenges: Context

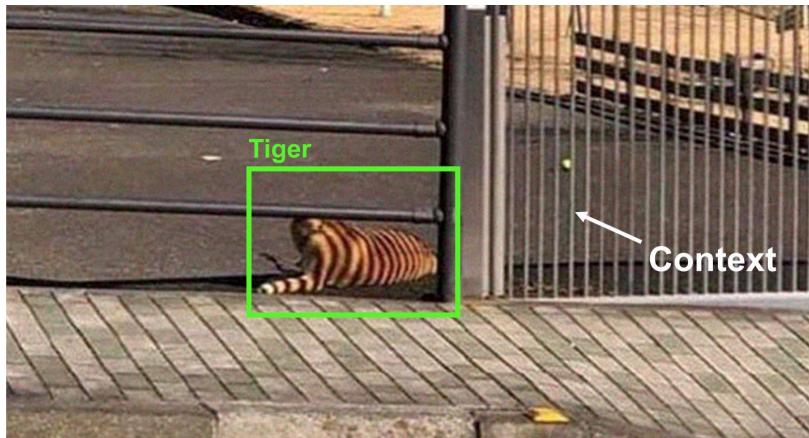
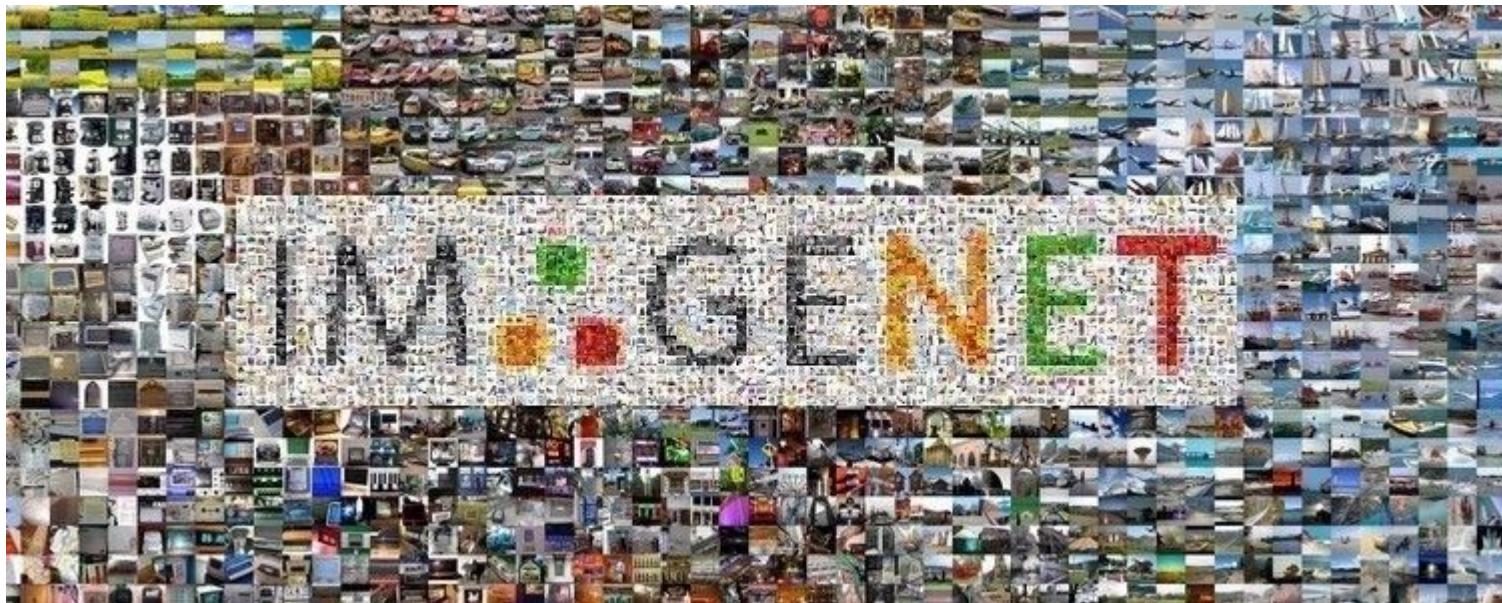


Image source:

https://www.linkedin.com/posts/ralph-aboujaoude-diaz-40838313_technology-artificialintelligence-computervision-activity-6912446088364875776-h-lq/?utm_source=linkedin_share&utm_medium=member_desktop_web

Modern computer vision algorithms



[This image](#) is [CC0 1.0](#) public domain

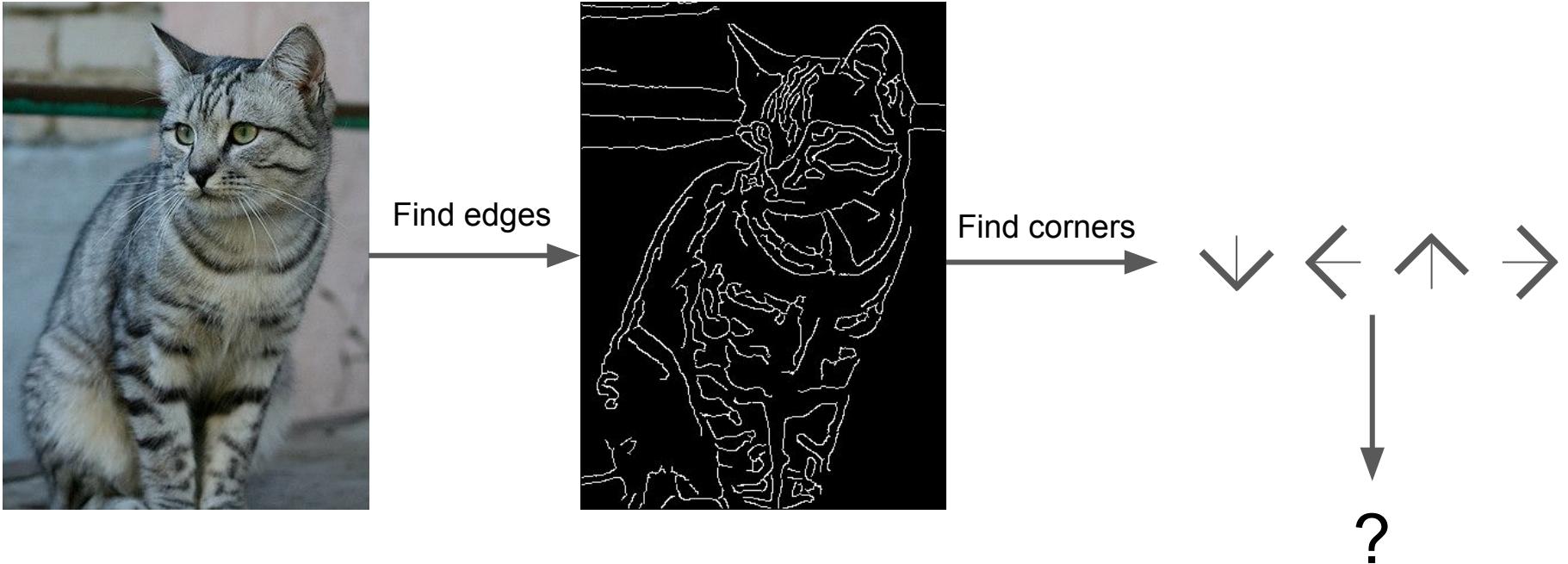
An image classifier

```
def classify_image(image):  
    # Some magic here?  
    return class_label
```

Unlike e.g. sorting a list of numbers,

no obvious way to hard-code the algorithm for
recognizing a cat, or other classes.

Attempts have been made



John Canny, "A Computational Approach to Edge Detection", IEEE TPAMI 1986

Machine Learning: Data-Driven Approach

1. Collect a dataset of images and labels
2. Use Machine Learning algorithms to train a classifier
3. Evaluate the classifier on new images

Example training set

```
def train(images, labels):  
    # Machine learning!  
    return model
```

```
def predict(model, test_images):  
    # Use model to predict labels  
    return test_labels
```

airplane



automobile



bird



cat



deer



Nearest Neighbor Classifier

First classifier: Nearest Neighbor

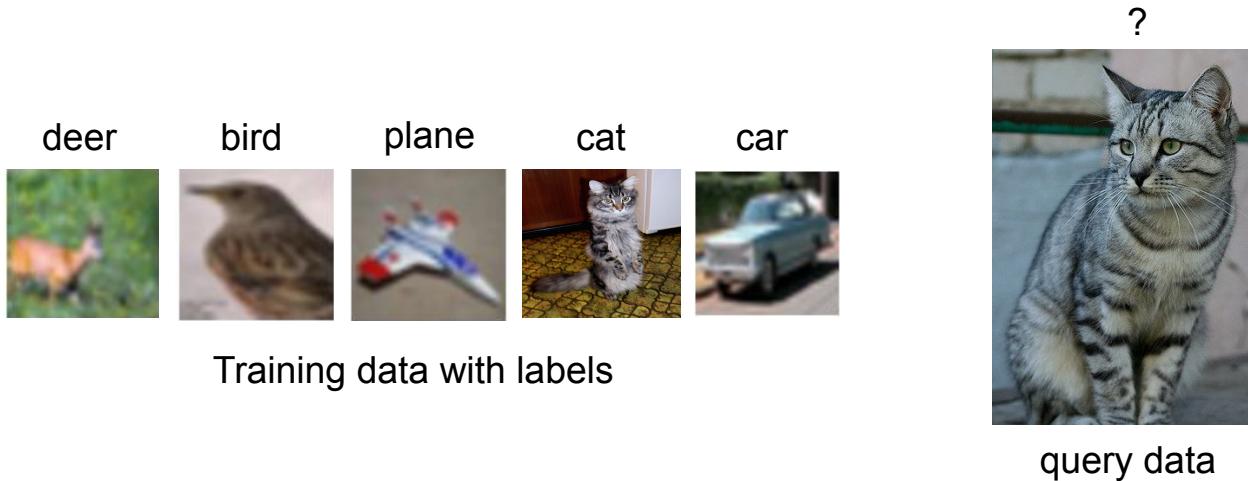
```
def train(images, labels):  
    # Machine learning!  
    return model
```

→ Memorize all
data and labels

```
def predict(model, test_images):  
    # Use model to predict labels  
    return test_labels
```

→ Predict the label
of the most similar
training image

First classifier: Nearest Neighbor



Distance Metric |  | $\rightarrow \mathbb{R}$

Distance Metric to compare images

L1 distance:

$$d_1(I_1, I_2) = \sum_p |I_1^p - I_2^p|$$

test image			
56	32	10	18
90	23	128	133
24	26	178	200
2	0	255	220

training image			
10	20	24	17
8	10	89	100
12	16	178	170
4	32	233	112

-

= pixel-wise absolute value differences

46	12	14	1
82	13	39	33
12	10	0	30
2	32	22	108

add
→ 456

Nearest Neighbor classifier

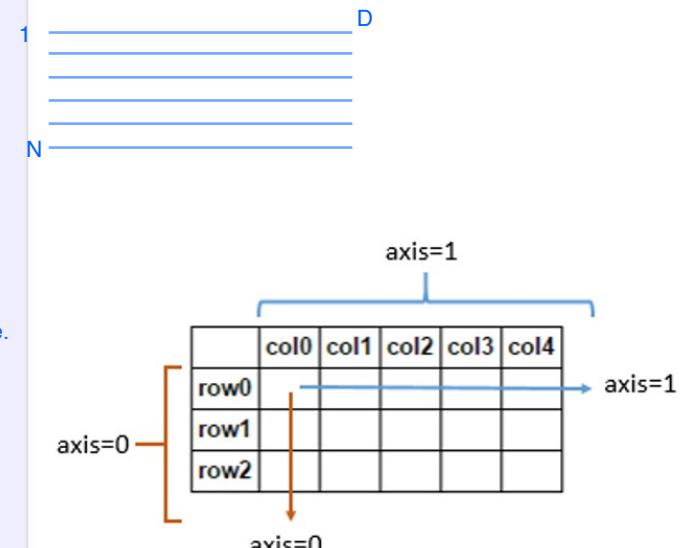
```
import numpy as np

class NearestNeighbor:
    def __init__(self):
        pass
    def train(self, X, y):
        """ X is N x D where each row is an example. Y is 1-dimension of size N """
        # the nearest neighbor classifier simply remembers all the training data
        self.Xtr = X
        self.ytr = y
    def predict(self, X):
        """ X is N x D where each row is an example we wish to predict label for """
        num_test = X.shape[0]
        # lets make sure that the output type matches the input type
        Ypred = np.zeros(num_test, dtype = self.ytr.dtype)

        # loop over all test rows
        for i in xrange(num_test):
            # find the nearest training image to the i'th test image
            # using the L1 distance (sum of absolute value differences)
            distances = np.sum(np.abs(self.Xtr - X[i,:]), axis = 1)
            min_index = np.argmin(distances) # get the index with smallest distance
            Ypred[i] = self.ytr[min_index] # predict the label of the nearest example

        return Ypred
```

subtract a 1d array from a 2d array where each item of 1d array subtracts from respective row in numpy



```

import numpy as np

class NearestNeighbor:
    def __init__(self):
        pass

    def train(self, X, y):
        """ X is N x D where each row is an example. Y is 1-dimension of size N """
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            min_index = np.argmin(distances) # get the index with smallest distance
            Ypred[i] = self.ytr[min_index] # predict the label of the nearest example

        return Ypred

```

Nearest Neighbor classifier

Memorize training data

```

import numpy as np

class NearestNeighbor:
    def __init__(self):
        pass

    def train(self, X, y):
        """ X is N x D where each row is an example. Y is 1-dimension of size N """
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            # find the nearest training image to the i'th test image
            # using the L1 distance (sum of absolute value differences)
            distances = np.sum(np.abs(self.Xtr - X[i,:]), axis = 1)
            min_index = np.argmin(distances) # get the index with smallest distance
            Ypred[i] = self.ytr[min_index] # predict the label of the nearest example

        return Ypred

```

Nearest Neighbor classifier

For each test image:
 Find closest train image
 Predict label of nearest image

```

import numpy as np

class NearestNeighbor:
    def __init__(self):
        pass

    def train(self, X, y):
        """ X is N x D where each row is an example. Y is 1-dimension of size N """
        # the nearest neighbor classifier simply remembers all the training data
        self.Xtr = X
        self.ytr = y

    def predict(self, X):
        """ X is N x D where each row is an example we wish to predict label for """
        num_test = X.shape[0]
        # lets make sure that the output type matches the input type
        Ypred = np.zeros(num_test, dtype = self.ytr.dtype)

        # loop over all test rows
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            # find the nearest training image to the i'th test image
            # using the L1 distance (sum of absolute value differences)
            distances = np.sum(np.abs(self.Xtr - X[i,:]), axis = 1)
            min_index = np.argmin(distances) # get the index with smallest distance
            Ypred[i] = self.ytr[min_index] # predict the label of the nearest example

        return Ypred

```

Nearest Neighbor classifier

Q: With N examples, how fast are training and prediction?

Ans: Train O(1), predict O(N)

This is bad: we want classifiers that are **fast** at prediction; **slow** for training is ok

```

import numpy as np

class NearestNeighbor:
    def __init__(self):
        pass

    def train(self, X, y):
        """ X is N x D where each row is an example. Y is 1-dimension of size N """
        # the nearest neighbor classifier simply remembers all the training data
        self.Xtr = X
        self.ytr = y

    def predict(self, X):
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        num_test = X.shape[0]
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            # using the L1 distance (sum of absolute value differences)
            distances = np.sum(np.abs(self.Xtr - X[i,:]), axis = 1)
            min_index = np.argmin(distances) # get the index with smallest distance
            Ypred[i] = self.ytr[min_index] # predict the label of the nearest example

        return Ypred

```

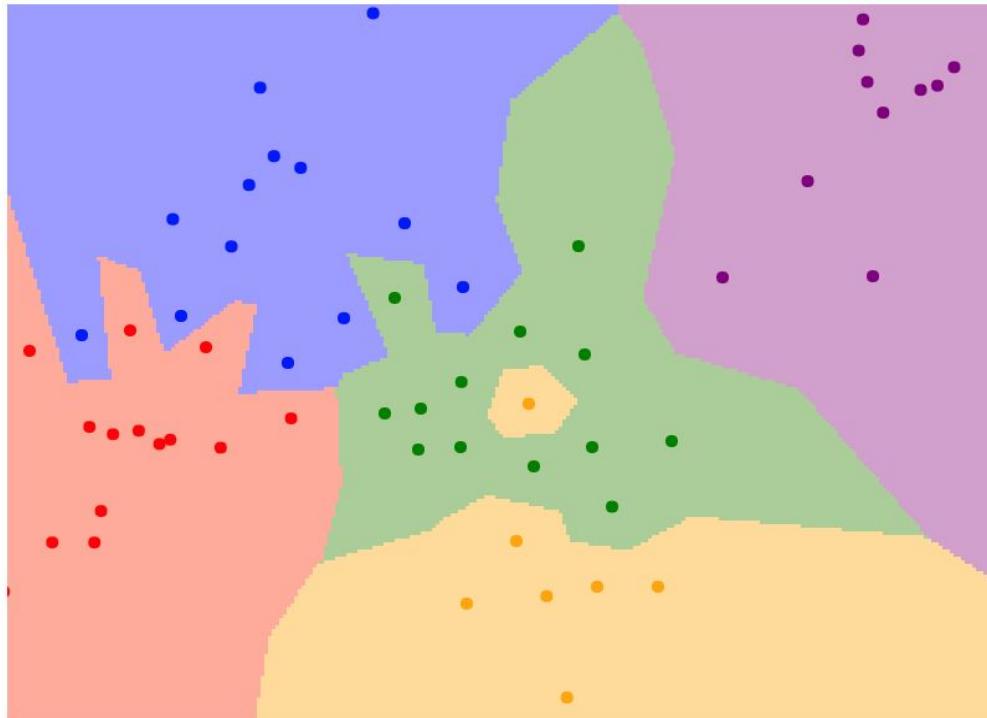
Nearest Neighbor classifier

Many methods exist for fast / approximate nearest neighbor (beyond the scope of 231N!)

A good implementation:
<https://github.com/facebookresearch/faiss>

Johnson et al, “Billion-scale similarity search with GPUs”, arXiv 2017

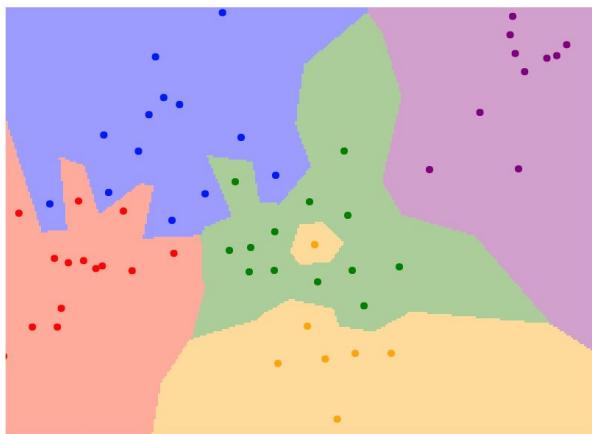
What does this look like?



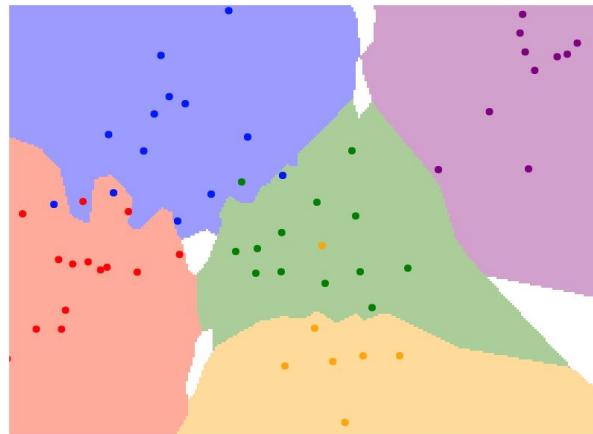
1-nearest neighbor

K-Nearest Neighbors

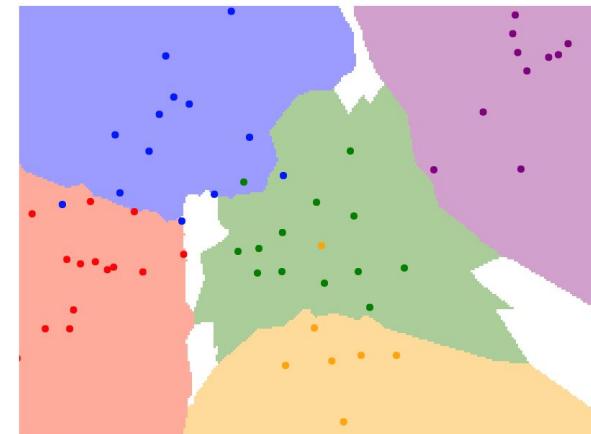
Instead of copying label from nearest neighbor,
take **majority vote** from K closest points



$K = 1$



$K = 3$

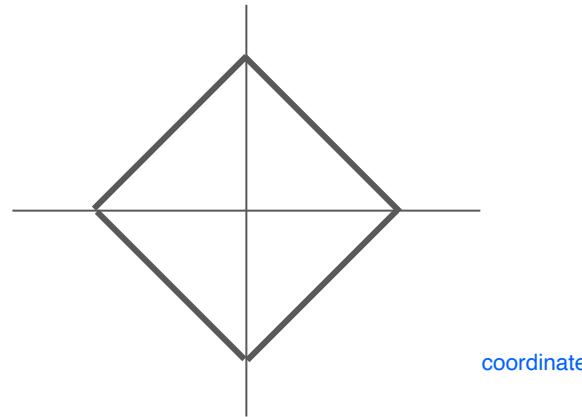


$K = 5$

K-Nearest Neighbors: Distance Metric

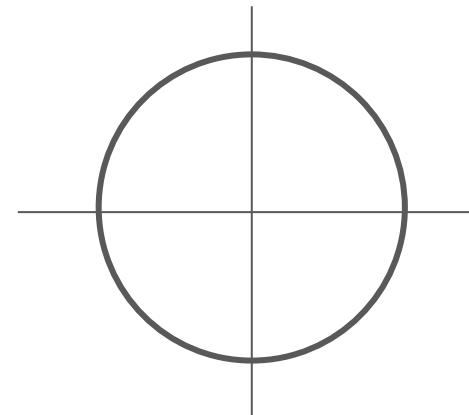
L1 (Manhattan) distance

$$d_1(I_1, I_2) = \sum_p |I_1^p - I_2^p|$$



L2 (Euclidean) distance

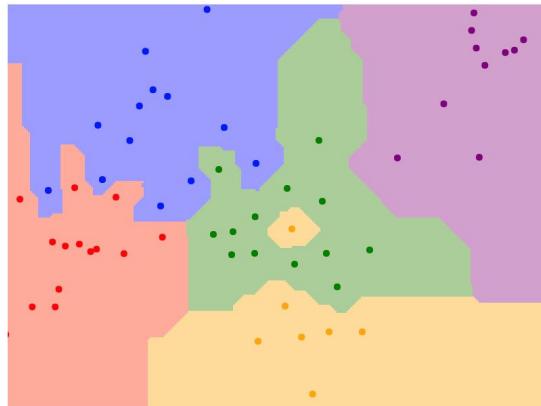
$$d_2(I_1, I_2) = \sqrt{\sum_p (I_1^p - I_2^p)^2}$$



K-Nearest Neighbors: Distance Metric

L1 (Manhattan) distance

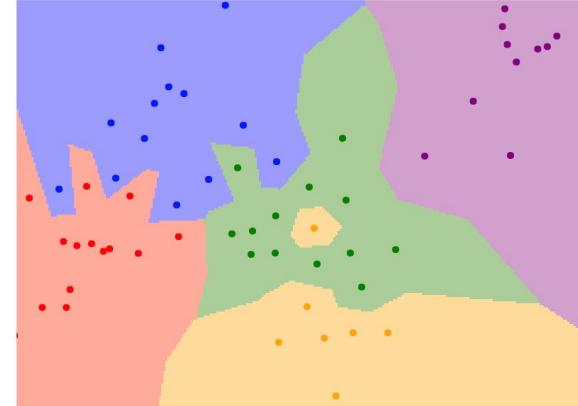
$$d_1(I_1, I_2) = \sum_p |I_1^p - I_2^p|$$



$K = 1$

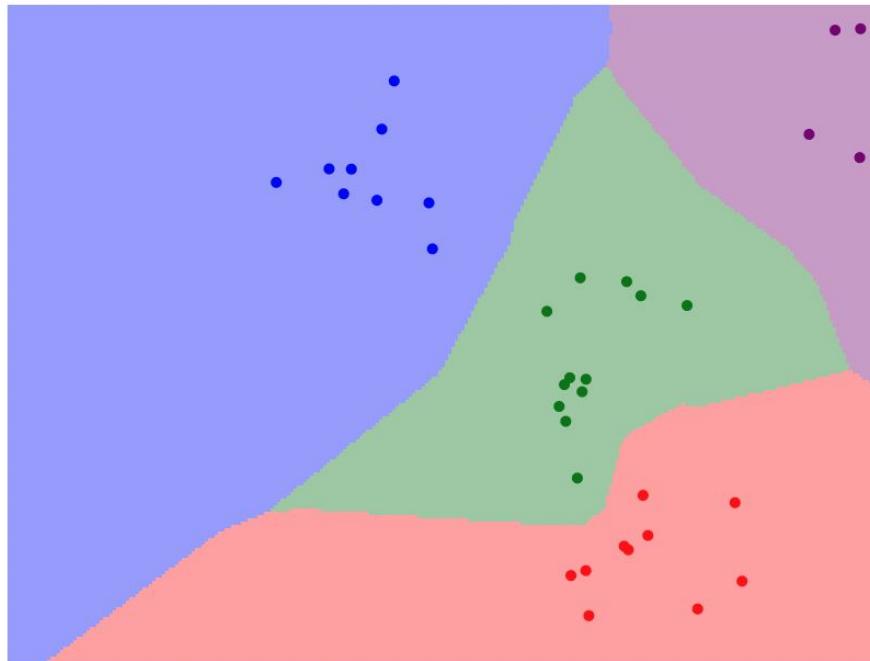
L2 (Euclidean) distance

$$d_2(I_1, I_2) = \sqrt{\sum_p (I_1^p - I_2^p)^2}$$



$K = 1$

K-Nearest Neighbors: try it yourself!



<http://vision.stanford.edu/teaching/cs231n-demos/knn/>

Hyperparameters

What is the best value of k to use?

What is the best **distance** to use?

These are **hyperparameters**: choices about the algorithms themselves.

we set rather than learn

Very problem/dataset-dependent.

Must try them all out and see what works best.

Setting Hyperparameters

Idea #1: Choose hyperparameters
that work best on the **training data**

train

Setting Hyperparameters

Idea #1: Choose hyperparameters
that work best on the **training data**

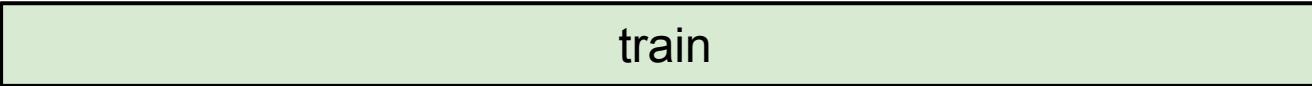
BAD: $K = 1$ always works
perfectly on training data

train

Setting Hyperparameters

Idea #1: Choose hyperparameters that work best on the **training data**

BAD: $K = 1$ always works perfectly on training data



train

Idea #2: choose hyperparameters that work best on **test data**

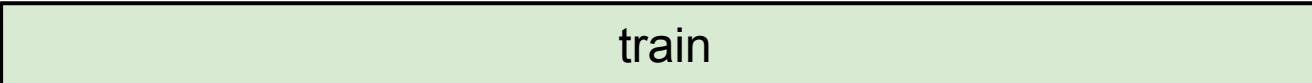


train

test

Setting Hyperparameters

Idea #1: Choose hyperparameters that work best on the **training data**



train

BAD: $K = 1$ always works perfectly on training data

Idea #2: choose hyperparameters that work best on **test data**



train

BAD: No idea how algorithm will perform on new data

Never do this!

Setting Hyperparameters

Idea #1: Choose hyperparameters that work best on the **training data**

BAD: $K = 1$ always works perfectly on training data



train

Idea #2: choose hyperparameters that work best on **test data**

BAD: No idea how algorithm will perform on new data



train

test

Idea #3: Split data into **train**, **val**; choose hyperparameters on val and evaluate on test

Better!



train

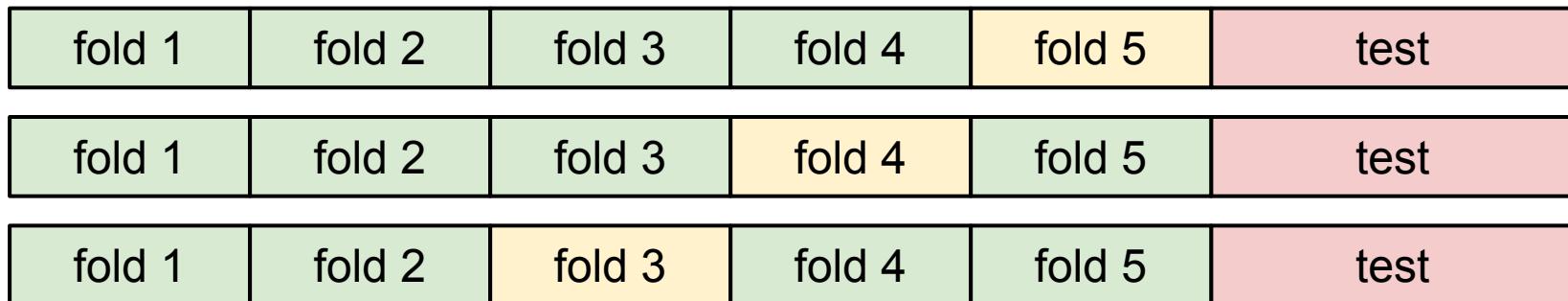
validation

test

Setting Hyperparameters

train

Idea #4: Cross-Validation: Split data into **folds**,
try each fold as validation and average the results



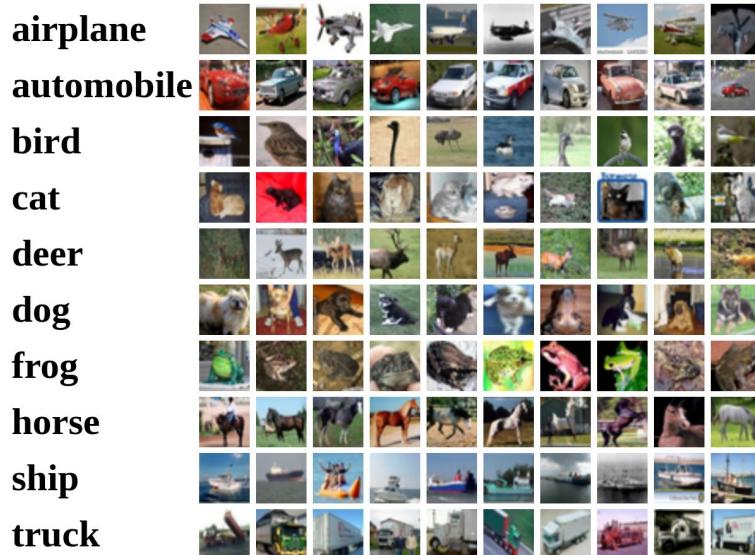
Useful for small datasets, but not used too frequently in deep learning

Example Dataset: CIFAR10

10 classes

50,000 training images

10,000 testing images



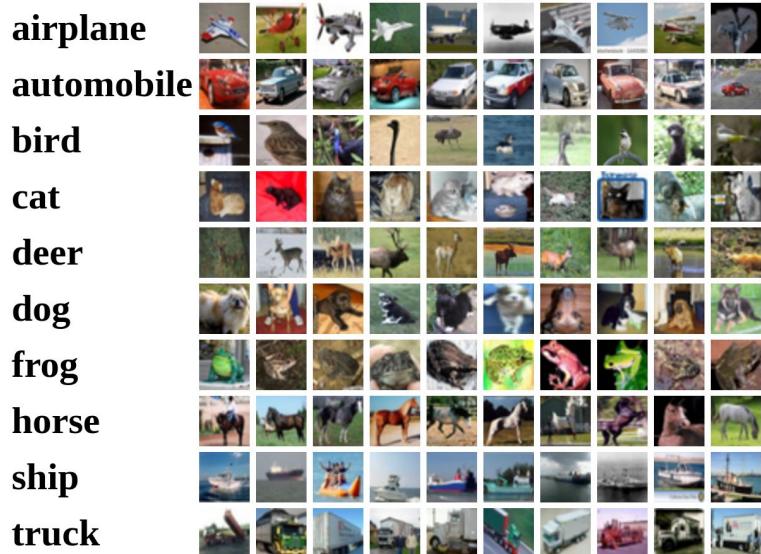
Alex Krizhevsky, "Learning Multiple Layers of Features from Tiny Images", Technical Report, 2009.

Example Dataset: CIFAR10

10 classes

50,000 training images

10,000 testing images

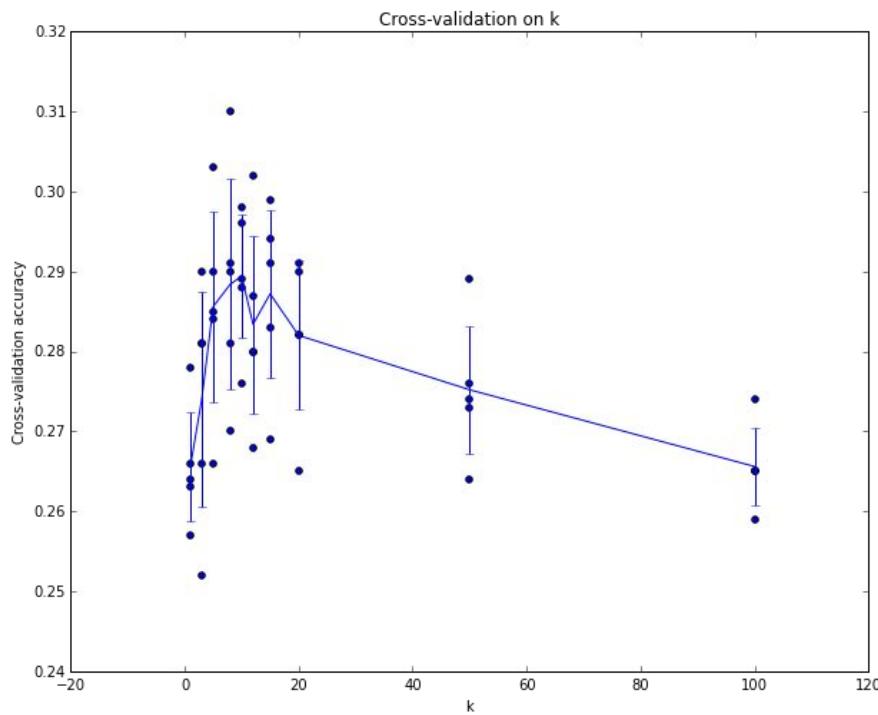


Test images and nearest neighbors



Alex Krizhevsky, "Learning Multiple Layers of Features from Tiny Images", Technical Report, 2009.

Setting Hyperparameters



Example of
5-fold cross-validation
for the value of k .

Each point: single
outcome.

The line goes
through the mean, bars
indicated standard
deviation

(Seems that $k \approx 7$ works best
for this data)

What does this look like?



What does this look like?



k-Nearest Neighbor with pixel distance **never used**.

- Distance metrics on pixels are not informative

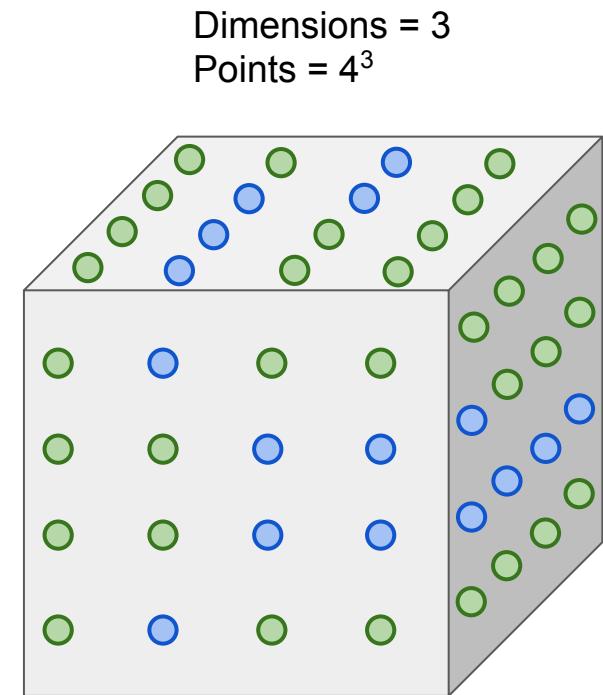
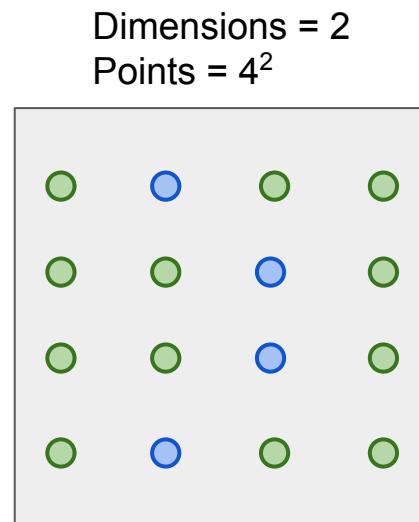
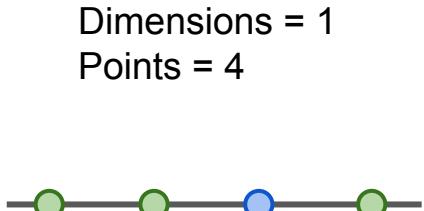
[Original image](#) is
CC0 public domain



(All three images on the right have the same pixel distances to the one on the left)

k-Nearest Neighbor with pixel distance **never used**.

- Curse of dimensionality



K-Nearest Neighbors: Summary

In **image classification** we start with a **training set** of images and labels, and must predict labels on the **test set**

The **K-Nearest Neighbors** classifier predicts labels based on the K nearest training examples

Distance metric and K are **hyperparameters**

Choose hyperparameters using the **validation set**;

Only run on the test set once at the very end!

Linear Classifier

Parametric Approach

Image



Array of **32x32x3** numbers
(3072 numbers total)

$$\xrightarrow{f(x, W)}$$

W
parameters
or weights

10 numbers giving
class scores

Parametric Approach: Linear Classifier

Image



$$f(x, W) = Wx$$

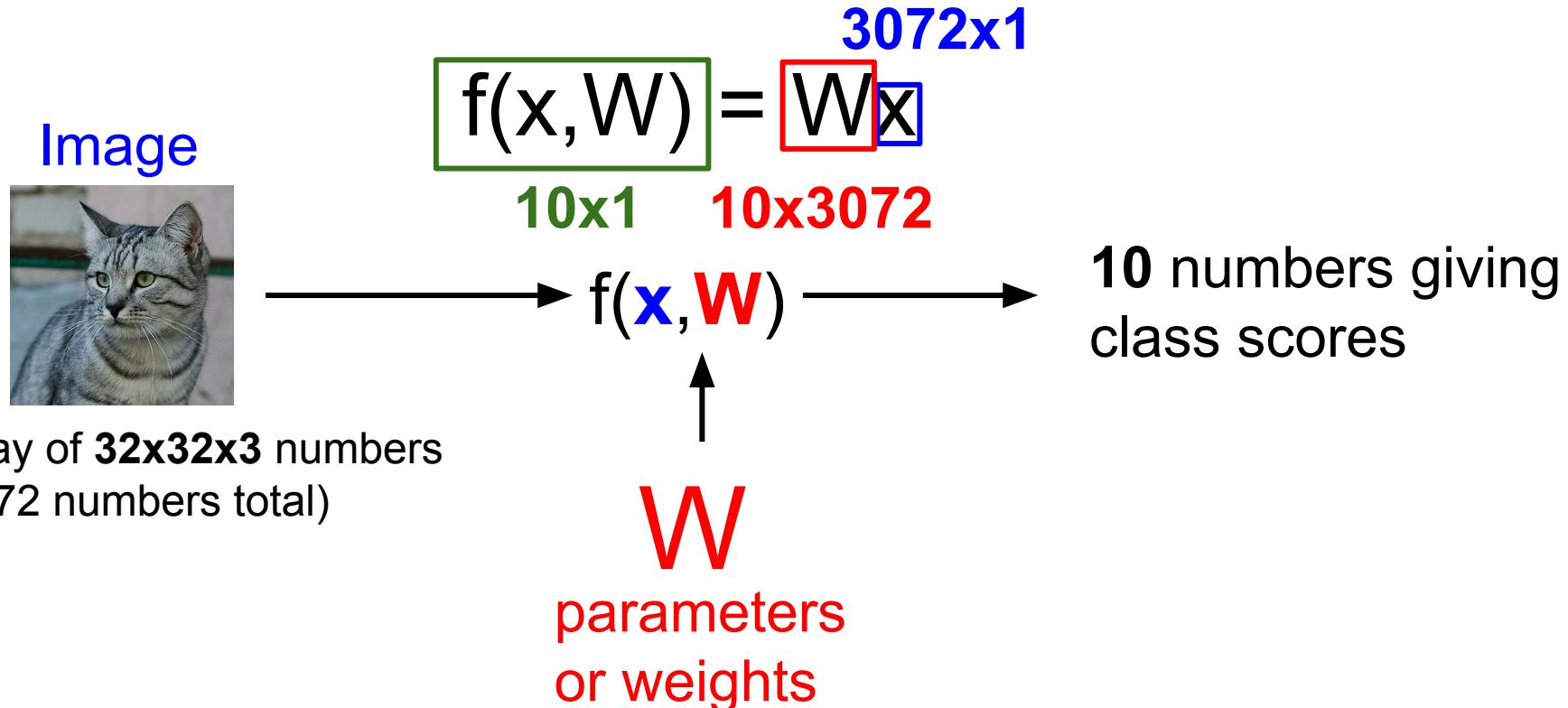
Array of **32x32x3** numbers
(3072 numbers total)

$$f(\mathbf{x}, \mathbf{W})$$

10 numbers giving
class scores

W
parameters
or weights

Parametric Approach: Linear Classifier



Parametric Approach: Linear Classifier



Image

Array of **32x32x3** numbers
(3072 numbers total)

$$f(x, W) = \boxed{W} \underset{10 \times 1}{\boxed{x}} + \boxed{b} \underset{10 \times 1}{}$$

10×1 10×3072

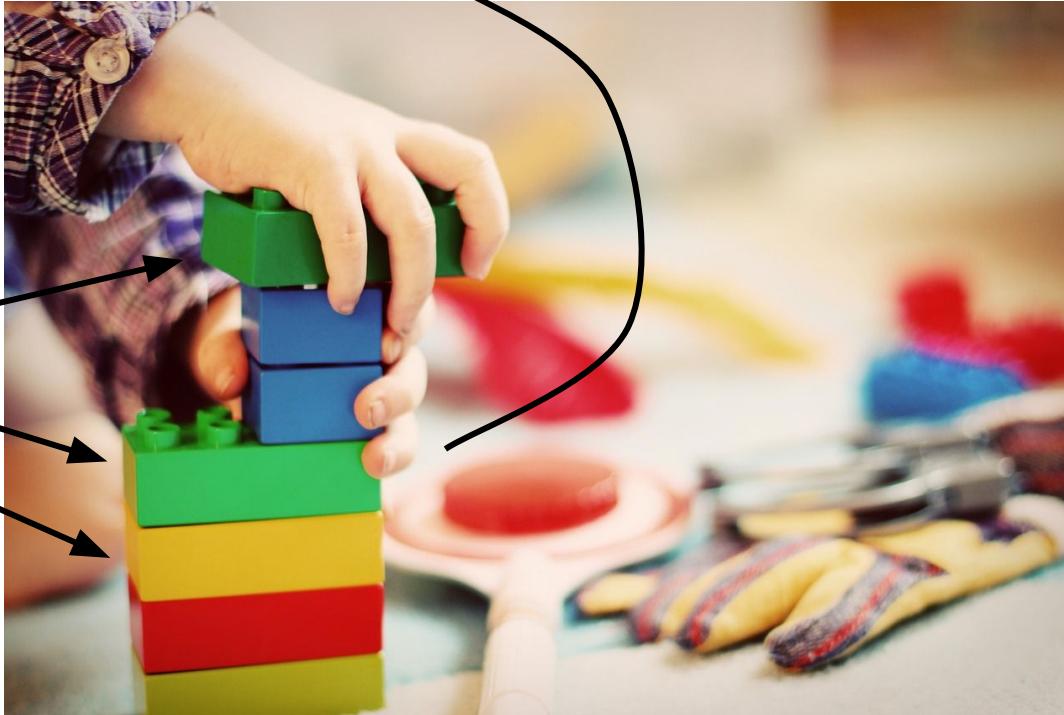
$$f(\underset{\text{blue}}{x}, \underset{\text{red}}{W})$$

10 numbers giving
class scores

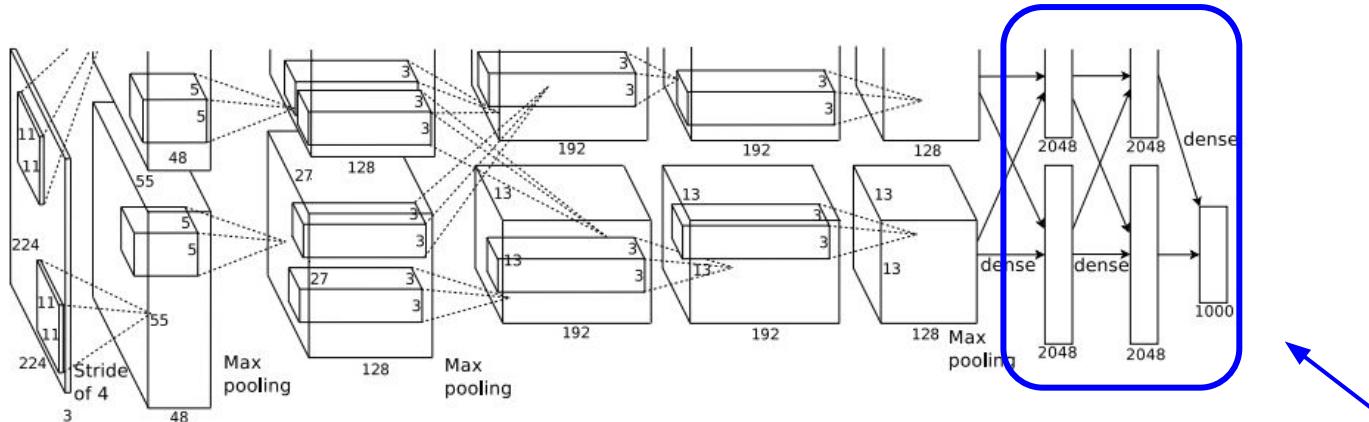
W
parameters
or weights

Neural Network

Linear
classifiers

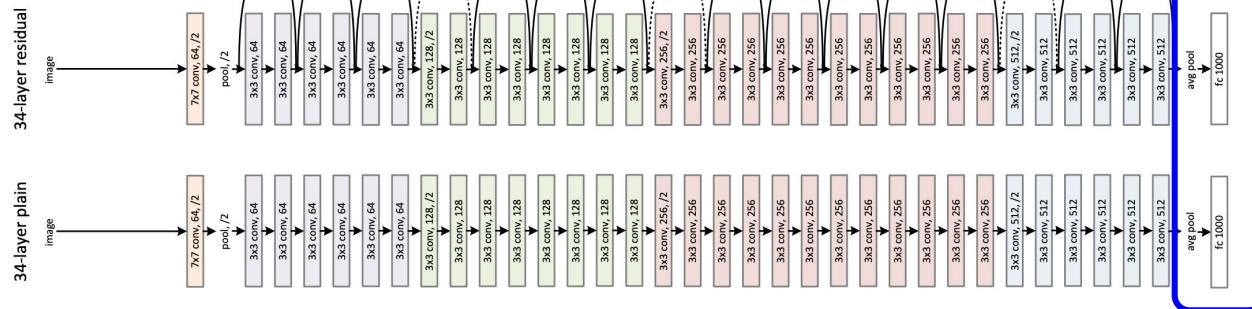


[This image](#) is [CC0 1.0](#) public domain



[Krizhevsky et al. 2012]

Linear layers



[He et al. 2015]

Recall CIFAR10

airplane



automobile



bird



cat



deer



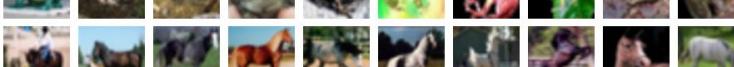
dog



frog



horse



ship



truck

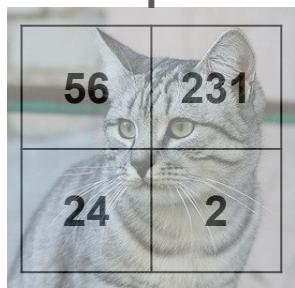


50,000 training images
each image is **32x32x3**

10,000 test images.

Example with an image with 4 pixels, and 3 classes (**cat/dog/ship**)

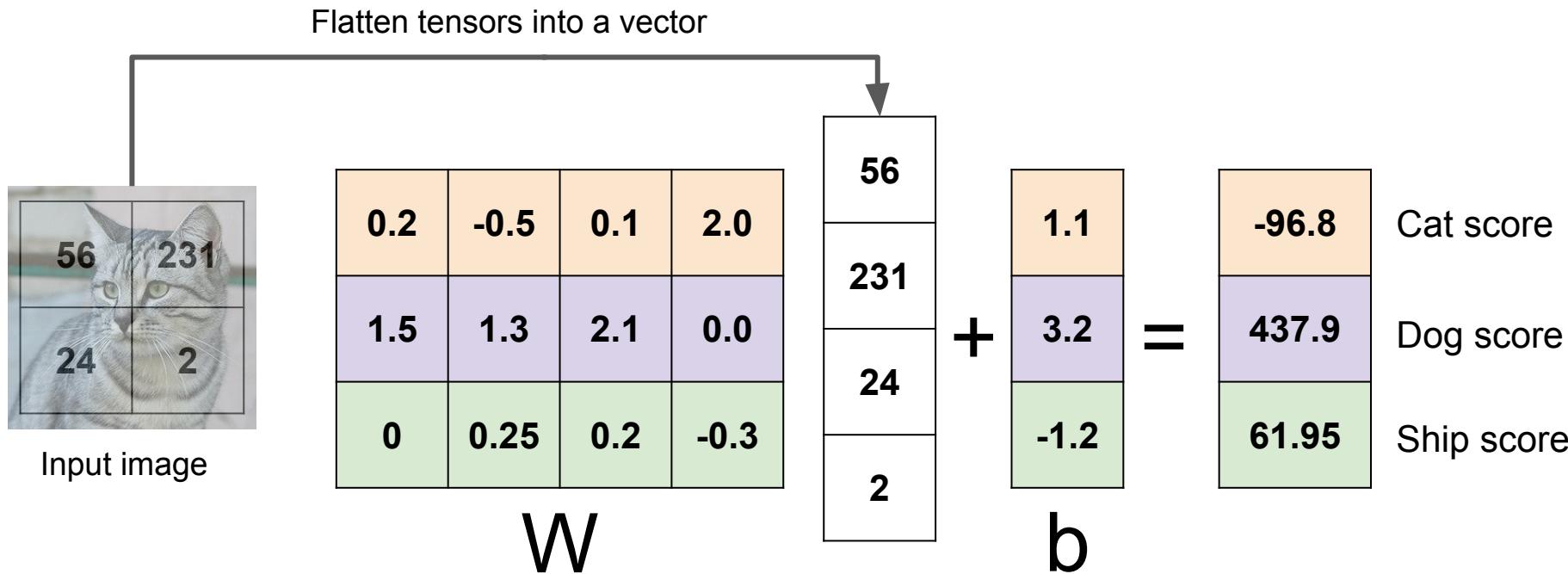
Flatten tensors into a vector



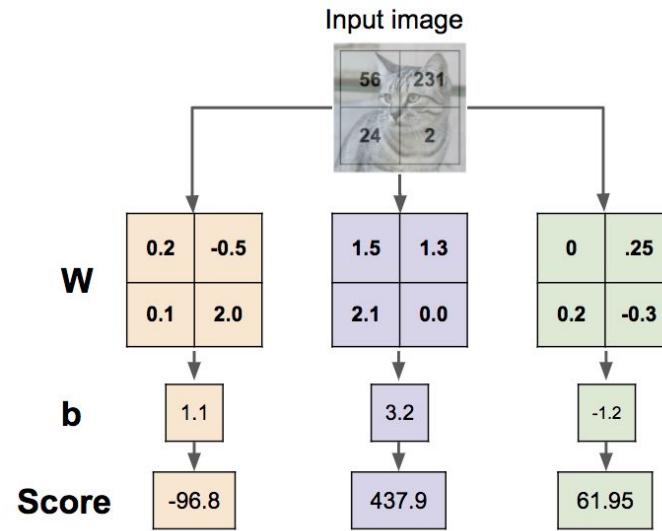
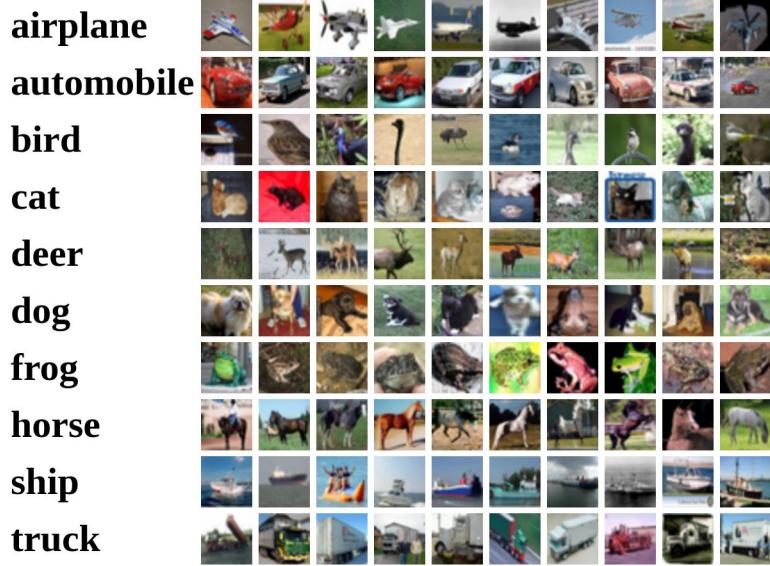
Input image



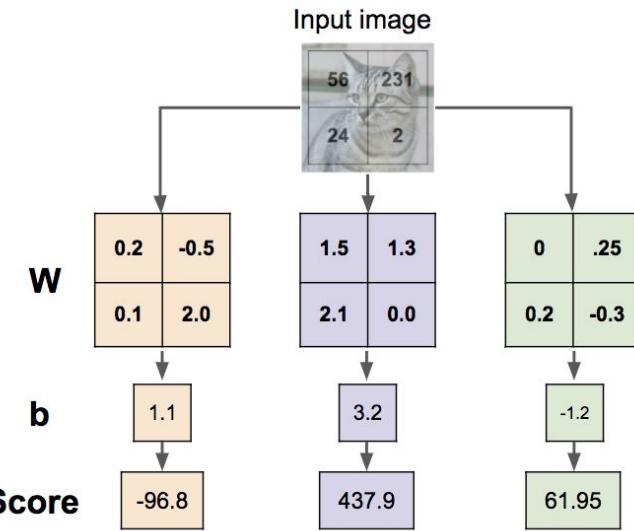
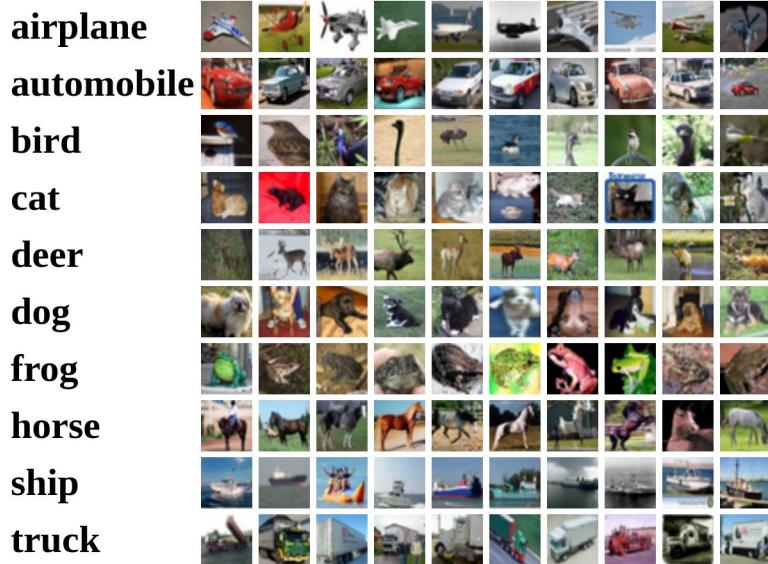
Example with an image with 4 pixels, and 3 classes (cat/dog/ship) Algebraic Viewpoint



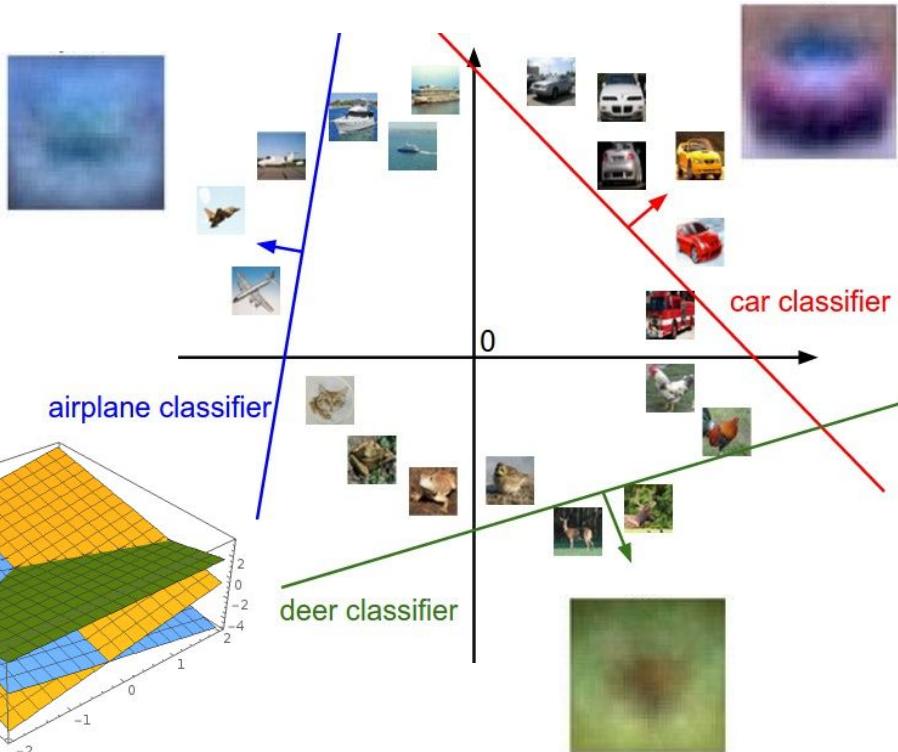
Interpreting a Linear Classifier



Interpreting a Linear Classifier: Visual Viewpoint



Interpreting a Linear Classifier: Geometric Viewpoint



$$f(x, W) = Wx + b$$



Array of **32x32x3** numbers
(3072 numbers total)

Plot created using [Wolfram Cloud](#)

[Cat image](#) by [Nikita](#) is licensed under [CC-BY 2.0](#)

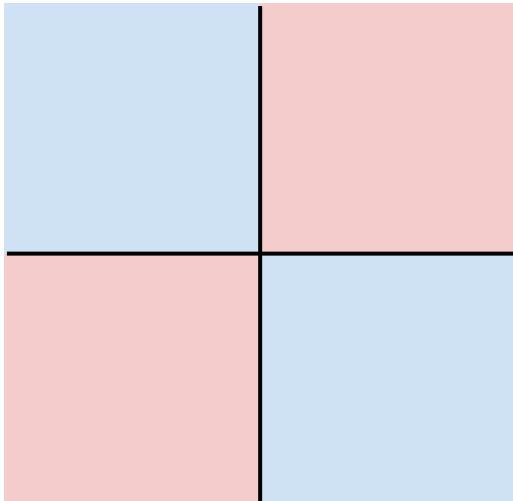
Hard cases for a linear classifier

Class 1:

First and third quadrants

Class 2:

Second and fourth quadrants

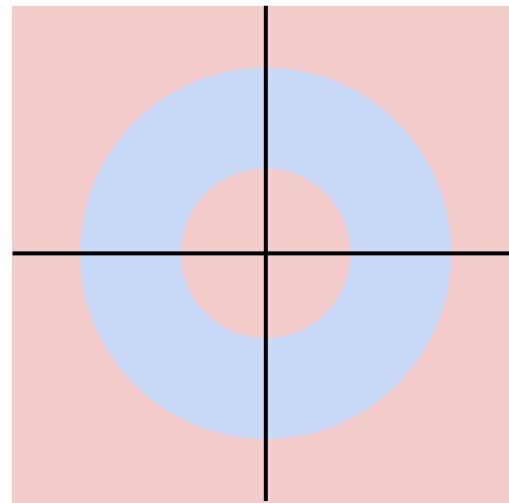


Class 1:

$1 \leq L_2 \text{ norm} \leq 2$

Class 2:

Everything else

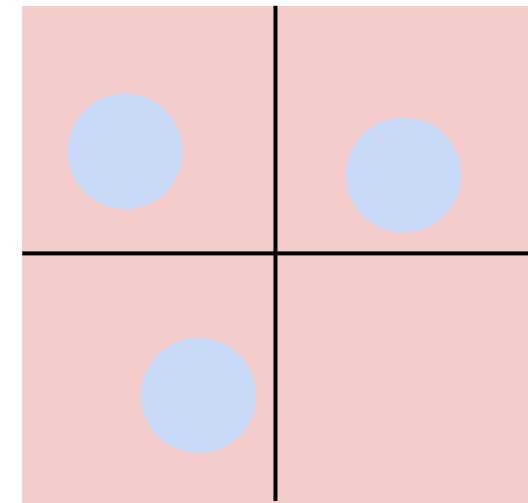


Class 1:

Three modes

Class 2:

Everything else



Linear Classifier – Choose a good W



airplane	-3.45	-0.51	3.42
automobile	-8.87	6.04	4.64
bird	0.09	5.31	2.65
cat	2.9	-4.22	5.1
deer	4.48	-4.19	2.64
dog	8.02	3.58	5.55
frog	3.78	4.49	-4.34
horse	1.06	-4.37	-1.5
ship	-0.36	-2.09	-4.79
truck	-0.72	-2.93	6.14

TODO:

1. Define a **loss function** that quantifies our unhappiness with the scores across the training data.
2. Come up with a way of efficiently finding the parameters that minimize the loss function. (**optimization**)

[Cat image](#) by [Nikita](#) is licensed under [CC-BY 2.0](#); [Car image](#) is [CC0 1.0](#) public domain; [Frog image](#) is in the public domain

Suppose: 3 training examples, 3 classes.

With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:

A **loss function** tells how good our current classifier is



cat	3.2	1.3	2.2
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A **loss function** tells how good our current classifier is

Given a dataset of examples

$$\{(x_i, y_i)\}_{i=1}^N$$

Where x_i is image and
 y_i is (integer) label

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A **loss function** tells how good our current classifier is

Given a dataset of examples

$$\{(x_i, y_i)\}_{i=1}^N$$

Where x_i is image and
 y_i is (integer) label

Loss over the dataset is a average of loss over examples:

$$L = \frac{1}{N} \sum_i L_i(f(x_i, W), y_i)$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
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Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

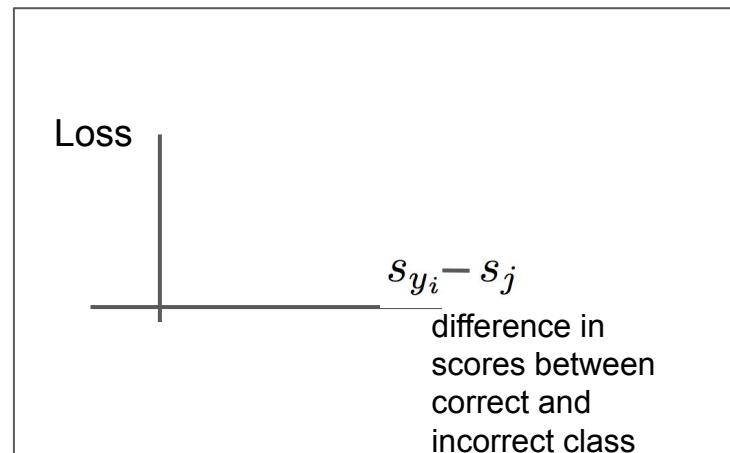
$$\begin{aligned} L_i &= \sum_{j \neq y_i} \begin{cases} 0 & \text{if } s_{y_i} \geq s_j + 1 \\ s_j - s_{y_i} + 1 & \text{otherwise} \end{cases} \\ &= \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \end{aligned}$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



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Interpreting Multiclass SVM loss:



$$L_i = \sum_{j \neq y_i} \begin{cases} 0 & \text{if } s_{y_i} \geq s_j + 1 \\ s_j - s_{y_i} + 1 & \text{otherwise} \end{cases}$$

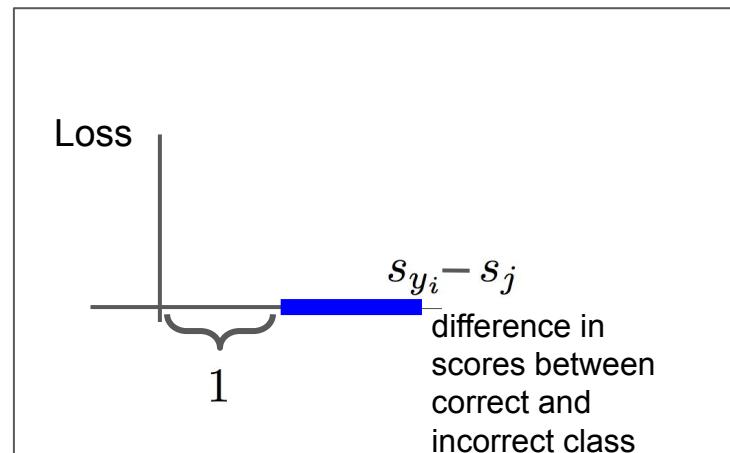
$$= \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
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Interpreting Multiclass SVM loss:



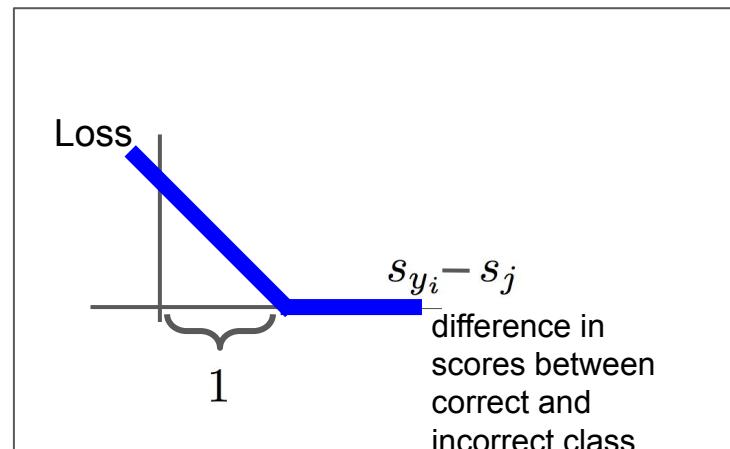
$$\begin{aligned}
 L_i &= \sum_{j \neq y_i} \begin{cases} 0 & \text{if } s_{y_i} \geq s_j + 1 \\ s_j - s_{y_i} + 1 & \text{otherwise} \end{cases} \\
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Interpreting Multiclass SVM loss:



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cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9		

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$\begin{aligned}
 L_i &= \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \\
 &= \max(0, 5.1 - 3.2 + 1) \\
 &\quad + \max(0, -1.7 - 3.2 + 1) \\
 &= \max(0, 2.9) + \max(0, -3.9) \\
 &= 2.9 + 0 \\
 &= 2.9
 \end{aligned}$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
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frog	-1.7	2.0	-3.1
Losses:	2.9	0	

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$\begin{aligned}
 L_i &= \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \\
 &= \max(0, 1.3 - 4.9 + 1) \\
 &\quad + \max(0, 2.0 - 4.9 + 1) \\
 &= \max(0, -2.6) + \max(0, -1.9) \\
 &= 0 + 0 \\
 &= 0
 \end{aligned}$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9	0	12.9

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$\begin{aligned}
 L_i &= \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \\
 &= \max(0, 2.2 - (-3.1) + 1) \\
 &\quad + \max(0, 2.5 - (-3.1) + 1) \\
 &= \max(0, 6.3) + \max(0, 6.6) \\
 &= 6.3 + 6.6 \\
 &= 12.9
 \end{aligned}$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
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Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Loss over full dataset is average:

$$L = \frac{1}{N} \sum_{i=1}^N L_i$$

$$\begin{aligned} L &= (2.9 + 0 + 12.9)/3 \\ &= 5.27 \end{aligned}$$

Suppose: 3 training examples, 3 classes.

With some W the scores $f(x, W) = Wx$ are:

Multiclass SVM loss:

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$



cat	1.3
car	4.9
frog	2.0
Losses:	0

Q1: What happens to loss if car scores decrease by 0.5 for this training example?

Q2: what is the min/max possible SVM loss L_i ?

Q3: At initialization W is small so all $s \approx 0$. What is the loss L_i , assuming N examples and C classes?

1-0; debugging

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
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Losses:	2.9	0	12.9

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Q4: What if the sum was over all classes?
(including $j = y_i$)

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9	0	12.9

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Q5: What if we used mean instead of sum?

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9	0	12.9

Multiclass SVM loss:

Given an example (x_i, y_i) where x_i is the image and where y_i is the (integer) label,

and using the shorthand for the scores vector: $s = f(x_i, W)$

the SVM loss has the form:

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Q6: What if we used

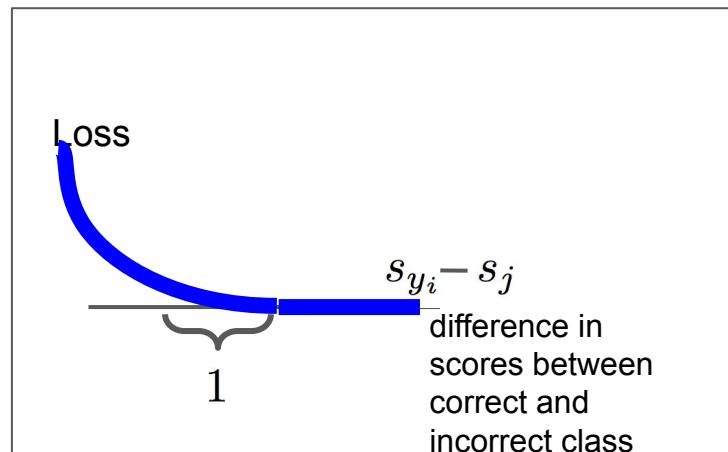
$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)^2$$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9	0	12.9

Multiclass SVM loss:



Q6: What if we used

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)^2$$

Multiclass SVM Loss: Example code

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

```
def L_i_vectorized(x, y, W):
    scores = W.dot(x)                                     # First calculate scores
    margins = np.maximum(0, scores - scores[y] + 1)      # Then calculate the margins  $s_j - s_{y_i} + 1$ 
    margins[y] = 0                                         # only sum j is not  $y_i$ , so when  $j = y_i$ , set to zero.
    loss_i = np.sum(margins)                               # sum across all j
    return loss_i
```

Softmax classifier

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



cat	3.2
car	5.1
frog	-1.7

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

$$P(Y = k | X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

cat	3.2
car	5.1
frog	-1.7

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



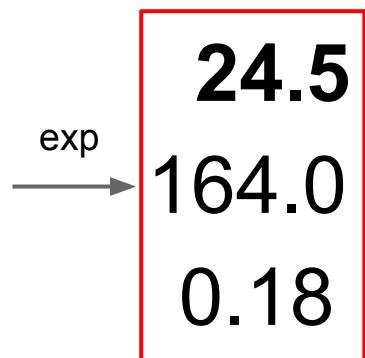
$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

Probabilities
must be ≥ 0

cat	3.2
car	5.1
frog	-1.7



unnormalized
probabilities

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

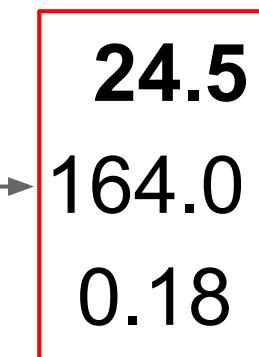
Probabilities
must be ≥ 0

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

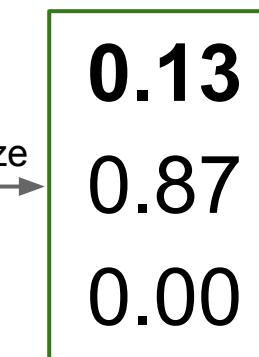
cat	3.2
car	5.1
frog	-1.7

exp



unnormalized
probabilities

normalize



probabilities

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax Function

Probabilities
must be ≥ 0

Probabilities
must sum to 1

cat
car
frog

3.2
5.1
-1.7

Unnormalized
log-probabilities / logits

exp

24.5
164.0
0.18

unnormalized
probabilities

normalize

0.13
0.87
0.00

probabilities

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$
 Softmax Function

Probabilities
must be ≥ 0

Probabilities
must sum to 1

cat
car
frog

3.2
5.1
-1.7

Unnormalized
log-probabilities / logits

exp

24.5
164.0
0.18

unnormalized
probabilities

normalize

0.13
0.87
0.00

probabilities

$$L_i = -\log P(Y = y_i|X = x_i)$$

$$\rightarrow L_i = -\log(0.13) \\ = 2.04$$

Softmax Classifier (Multinomial Logistic Regression)



Want to interpret raw classifier scores as **probabilities**

$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax Function

cat
car
frog

3.2
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Unnormalized
log-probabilities / logits

exp

24.5
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unnormalized
probabilities

normalize

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0.00

probabilities

Probabilities
must sum to 1

$$L_i = -\log P(Y = y_i|X = x_i)$$

$$\rightarrow L_i = -\log(0.13) \\ = 2.04$$

Maximum Likelihood Estimation
Choose weights to maximize the likelihood of the observed data
(See CS 229 for details)

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

Probabilities
must be ≥ 0

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

cat
car
frog

3.2
5.1
-1.7

Unnormalized
log-probabilities / logits

exp

24.5
164.0
0.18

unnormalized
probabilities

normalize

0.13
0.87
0.00

probabilities

compare

1.00
0.00
0.00

Correct
probs

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax Function

cat
car
frog

3.2
5.1
-1.7

Unnormalized
log-probabilities / logits

exp

24.5
164.0
0.18

unnormalized
probabilities

normalize

0.13
0.87
0.00

probabilities

$$D_{KL}(P\|Q) = \sum_y P(y) \log \frac{P(y)}{Q(y)}$$

1.00

0.00

0.00

Correct
probs

$$L_i = -\log P(Y = y_i|X = x_i)$$

Probabilities
must sum to 1

compare

Kullback–Leibler
divergence

$$D_{KL}(P\|Q) = \sum_y P(y) \log \frac{P(y)}{Q(y)}$$

Softmax Classifier (Multinomial Logistic Regression)



Want to interpret raw classifier scores as **probabilities**

$$s = f(x_i; W)$$

Probabilities
must be ≥ 0

cat
car
frog

3.2
5.1
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Unnormalized
log-probabilities / logits

exp

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unnormalized
probabilities

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

Probabilities
must sum to 1

0.13
0.87
0.00

probabilities

$$L_i = -\log P(Y = y_i|X = x_i)$$

compare

1.00

0.00

0.00

Cross Entropy

$$H(P, Q) = H(p) + D_{KL}(P||Q)$$

Correct
probs

Softmax Classifier (Multinomial Logistic Regression)

Want to interpret raw classifier scores as **probabilities**



$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

Maximize probability of correct class

cat	3.2
car	5.1
frog	-1.7

Putting it all together:

$$L_i = -\log P(Y = y_i|X = x_i)$$

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

Softmax Classifier (Multinomial Logistic Regression)



Want to interpret raw classifier scores as **probabilities**

$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax
Function

Maximize probability of correct class

Putting it all together:

$$L_i = -\log P(Y = y_i|X = x_i)$$

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

cat	3.2
car	5.1
frog	-1.7

Q1: What is the min/max possible softmax loss L_i ?

(0, infinity)

Q2: At initialization all s_j will be approximately equal;
what is the softmax loss L_i , assuming C classes?

Softmax Classifier (Multinomial Logistic Regression)



Want to interpret raw classifier scores as **probabilities**

$$s = f(x_i; W)$$

$$P(Y = k|X = x_i) = \frac{e^{s_k}}{\sum_j e^{s_j}}$$

Softmax Function

Maximize probability of correct class

Putting it all together:

$$L_i = -\log P(Y = y_i|X = x_i)$$

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

cat	3.2
car	5.1
frog	-1.7

Q2: At initialization all s will be approximately equal; what is the loss?
A: $-\log(1/C) = \log(C)$,
If $C = 10$, then $L_i = \log(10) \approx 2.3$

Softmax vs. SVM

matrix multiply + bias offset

0.01	-0.05	0.1	0.05
0.7	0.2	0.05	0.16
0.0	-0.45	-0.2	0.03

W

-15
22
-44
56

x_i

y_i 2

2

hinge loss (SVM)

$$\begin{aligned} & \max(0, -2.85 - 0.28 + 1) + \\ & \max(0, 0.86 - 0.28 + 1) \\ & = \\ & \quad \textcolor{red}{1.58} \end{aligned}$$

cross-entropy loss (Softmax)

$$\begin{array}{c} \text{exp} \longrightarrow \begin{array}{c} -2.85 \\ 0.86 \\ 0.28 \end{array} \xrightarrow{\text{normalize}} \begin{array}{c} 0.058 \\ 2.36 \\ 1.32 \end{array} \xrightarrow{\text{- log(0.353)}} \begin{array}{c} 0.016 \\ 0.631 \\ 0.353 \end{array} \\ \text{to sum to one} \end{array} = \textcolor{green}{0.452}$$

Softmax vs. SVM

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Softmax vs. SVM

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

assume scores:

[10, -2, 3]

[10, 9, 9]

[10, -100, -100]

and $y_i = 0$

Q: What is the **softmax loss** and the **SVM** loss?

Softmax vs. SVM

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right)$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

assume scores:

[20, -2, 3]

[20, 9, 9]

[20, -100, -100]

and

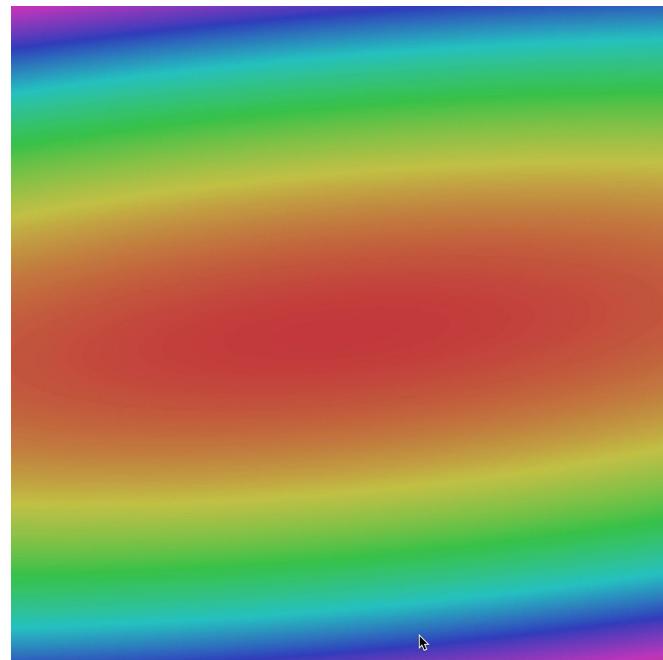
$$y_i = 0$$

Q: What is the **softmax loss** and the **SVM loss if I double the correct class score from 10 -> 20?**

Coming up:

- Regularization
- Optimization

$$f(x, W) = Wx + b$$



Lecture 3: Regularization and Optimization

Administrative: Assignment 1

Released last week, due **Fri 4/15 at 11:59pm**

Administrative: Project proposal

Due **Mon 4/18**

TA expertise are posted on the webpage.

(http://cs231n.stanford.edu/office_hours.html)

Administrative: Ed

Please make sure to check and read all pinned Ed posts.

Image Classification: A core task in Computer Vision



This image by [Nikita](#) is
licensed under [CC-BY 2.0](#)

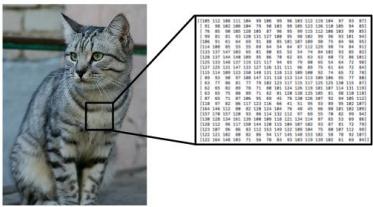
(assume given a set of labels)
{dog, cat, truck, plane, ...}



cat
dog
bird
deer
truck

Recall from last time: Challenges of recognition

Viewpoint



Illumination



[This image](#) is CC0 1.0 public domain

Deformation



[This image](#) by Umberto Salvagnin
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Occlusion



[This image](#) by jonsson is licensed
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Clutter



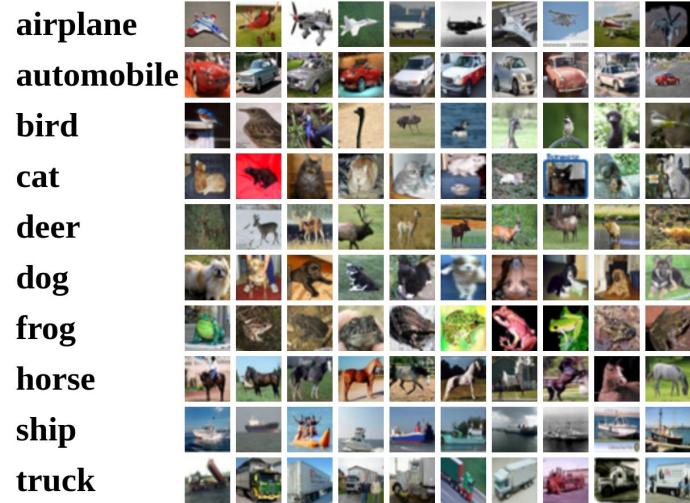
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Intraclass Variation

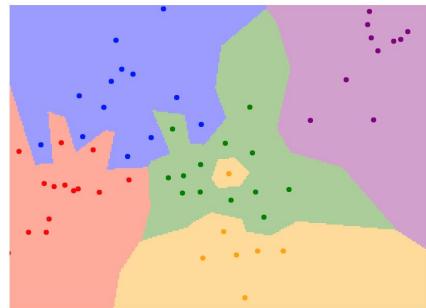


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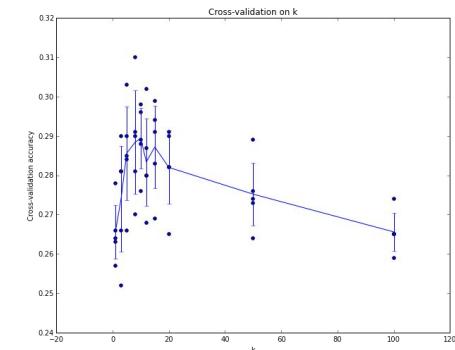
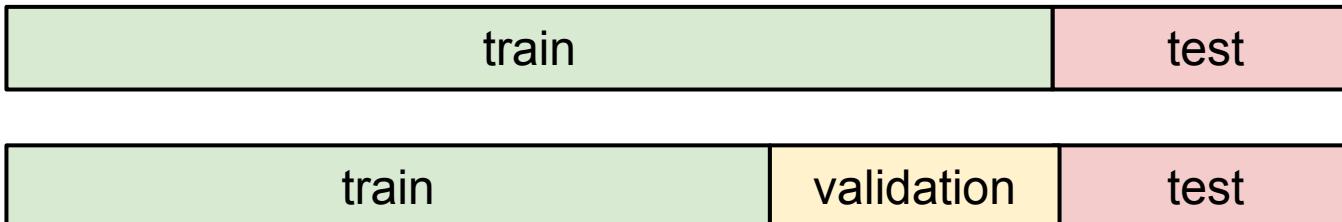
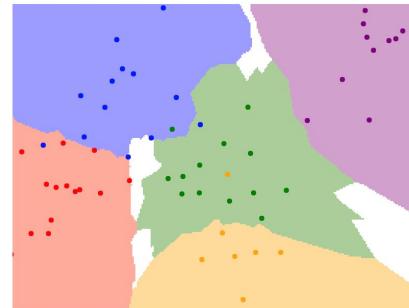
Recall from last time: data-driven approach, kNN



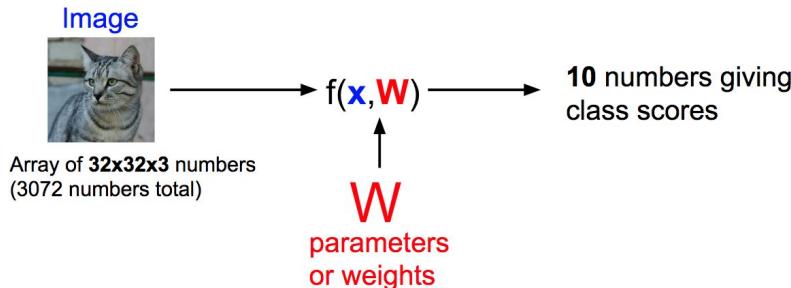
1-NN classifier



5-NN classifier



Recall from last time: Linear Classifier



$$f(\mathbf{x}, \mathbf{W}) = \mathbf{W}\mathbf{x} + \mathbf{b}$$

Algebraic Viewpoint

$$f(\mathbf{x}, \mathbf{W}) = \mathbf{W}\mathbf{x}$$

Stretch pixels into column:

Input image

$\begin{matrix} 56 & 231 \\ 24 & 2 \end{matrix}$

$\begin{matrix} 0.2 & -0.5 & 0.1 & 2.0 \\ 1.5 & 1.3 & 2.1 & 0.0 \\ 0 & 0.25 & 0.2 & -0.3 \end{matrix}$

$\begin{matrix} 56 \\ 231 \\ 24 \\ 2 \end{matrix}$

$\begin{matrix} 1.1 \\ 3.2 \\ -1.2 \end{matrix}$

$\begin{matrix} -96.8 \\ 437.9 \\ 61.95 \end{matrix}$

\mathbf{W}

\mathbf{b}

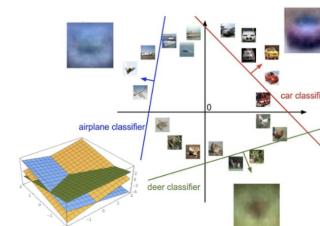
Visual Viewpoint

One template per class



Geometric Viewpoint

Hyperplanes cutting up space

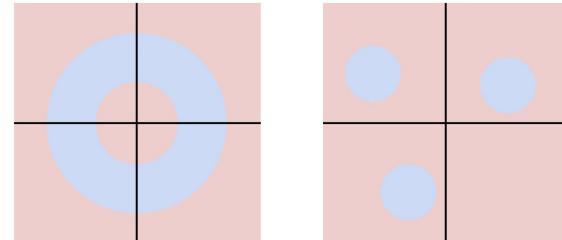


Class 1:
 $1 \leq L_2 \text{ norm} \leq 2$

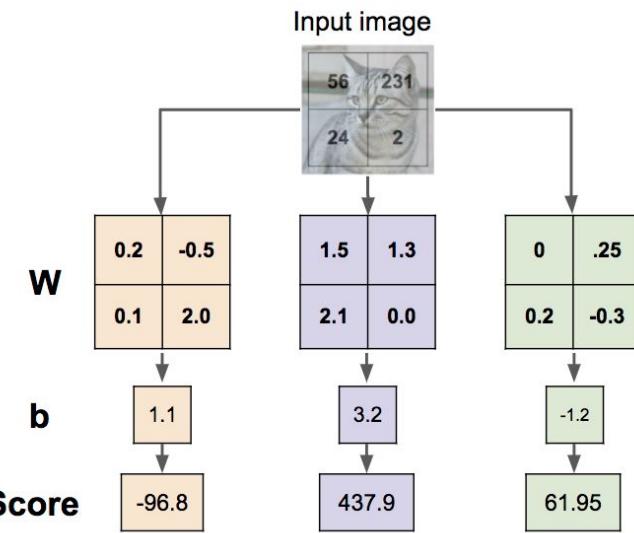
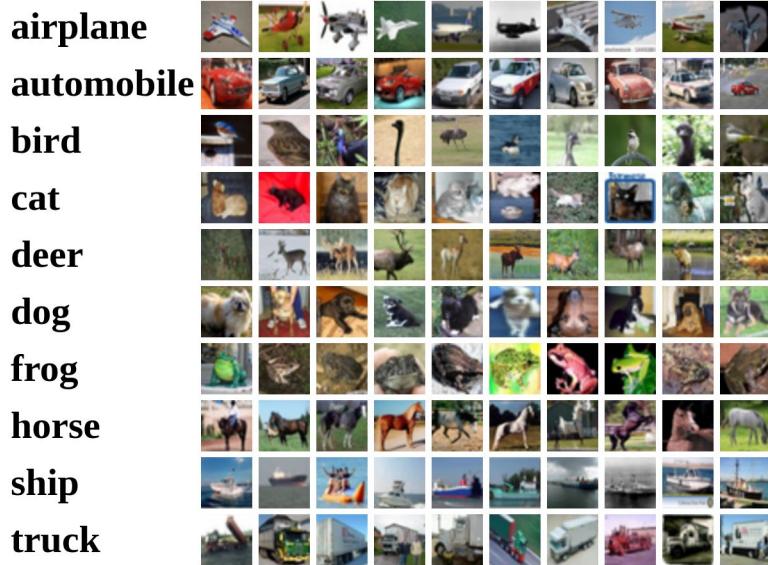
Class 2:
Everything else

Class 1:
Three modes

Class 2:
Everything else



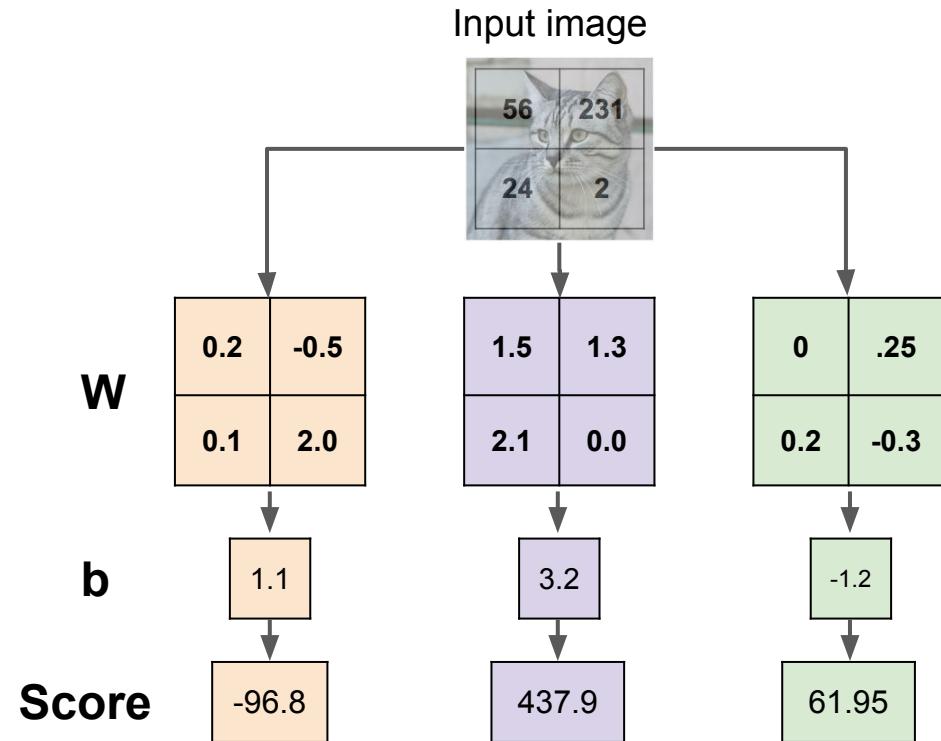
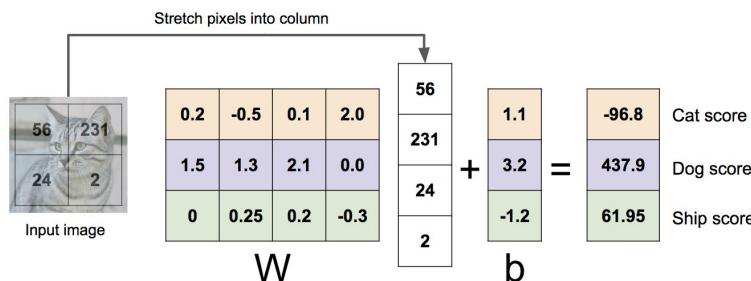
Interpreting a Linear Classifier: Visual Viewpoint



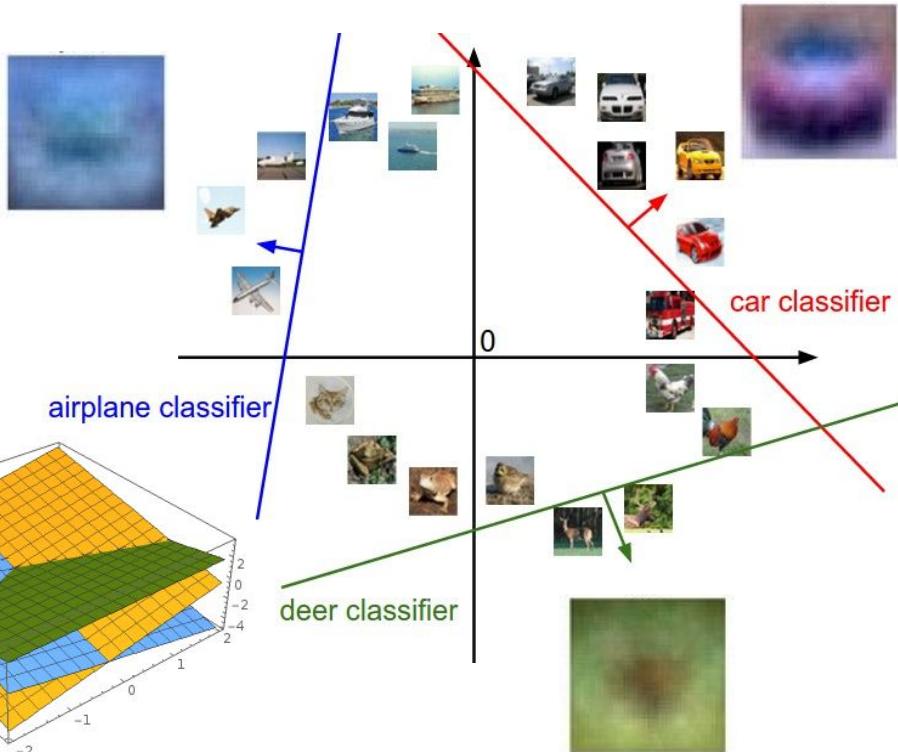
Example with an image with 4 pixels, and 3 classes (**cat/dog/ship**)

Algebraic Viewpoint

$$f(x, W) = Wx$$



Interpreting a Linear Classifier: Geometric Viewpoint



$$f(\mathbf{x}, \mathbf{W}) = \mathbf{W}\mathbf{x} + \mathbf{b}$$



Array of **32x32x3** numbers
(3072 numbers total)

Plot created using [Wolfram Cloud](#)

[Cat image](#) by [Nikita](#) is licensed under [CC-BY 2.0](#)

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1

A **loss function** tells how good our current classifier is

Given a dataset of examples

$$\{(x_i, y_i)\}_{i=1}^N$$

Where x_i is image and
 y_i is (integer) label

Loss over the dataset is a average of loss over examples:

$$L = \frac{1}{N} \sum_i L_i(f(x_i, W), y_i)$$

Softmax vs. SVM

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right) \quad L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

matrix multiply + bias offset

0.01	-0.05	0.1	0.05
0.7	0.2	0.05	0.16
0.0	-0.45	-0.2	0.03

W

-15
22
-44
56

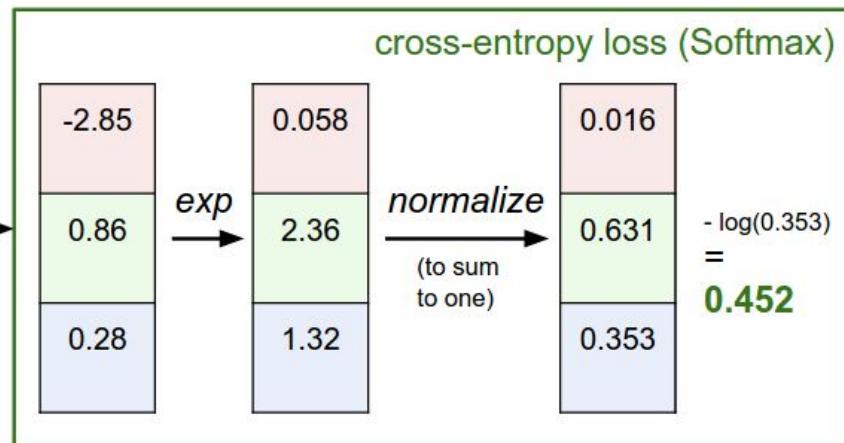
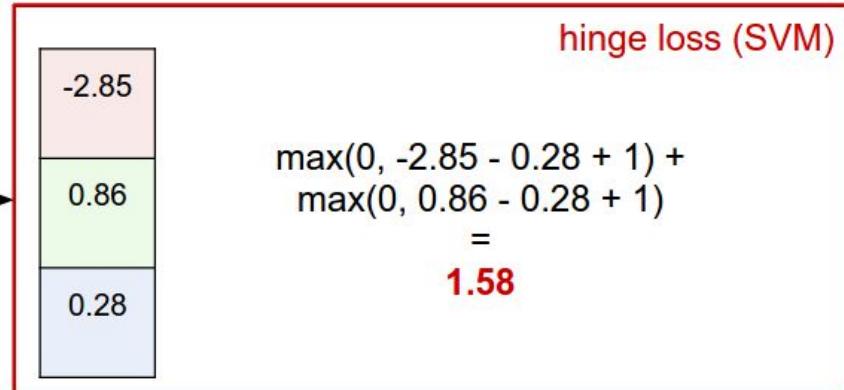
x_i

y_i

2

0.0
0.2
-0.3

b



$$f(x, W) = Wx$$

$$L = \frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, f(x_i; W)_j - f(x_i; W)_{y_i} + 1)$$

Q: Suppose that we found a W such that $L = 0$.
Is this W unique?

$$f(x, W) = Wx$$

$$L = \frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, f(x_i; W)_j - f(x_i; W)_{y_i} + 1)$$

E.g. Suppose that we found a W such that $L = 0$.
Is this W unique?

No! $2W$ is also has $L = 0!$

Suppose: 3 training examples, 3 classes.
With some W the scores $f(x, W) = Wx$ are:



cat	3.2	1.3	2.2
car	5.1	4.9	2.5
frog	-1.7	2.0	-3.1
Losses:	2.9	0	

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Before:

$$\begin{aligned}
 &= \max(0, 1.3 - 4.9 + 1) \\
 &\quad + \max(0, 2.0 - 4.9 + 1) \\
 &= \max(0, -2.6) + \max(0, -1.9) \\
 &= 0 + 0 \\
 &= 0
 \end{aligned}$$

With W twice as large:

$$\begin{aligned}
 &= \max(0, 2.6 - 9.8 + 1) \\
 &\quad + \max(0, 4.0 - 9.8 + 1) \\
 &= \max(0, -6.2) + \max(0, -4.8) \\
 &= 0 + 0 \\
 &= 0
 \end{aligned}$$

$$f(x, W) = Wx$$

$$L = \frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, f(x_i; W)_j - f(x_i; W)_{y_i} + 1)$$

E.g. Suppose that we found a W such that $L = 0$.
Is this W unique?

No! $2W$ is also has $L = 0$!

How do we choose between W and $2W$?

Regularization -

$$L(W) = \frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)$$

Data loss: Model predictions
should match training data

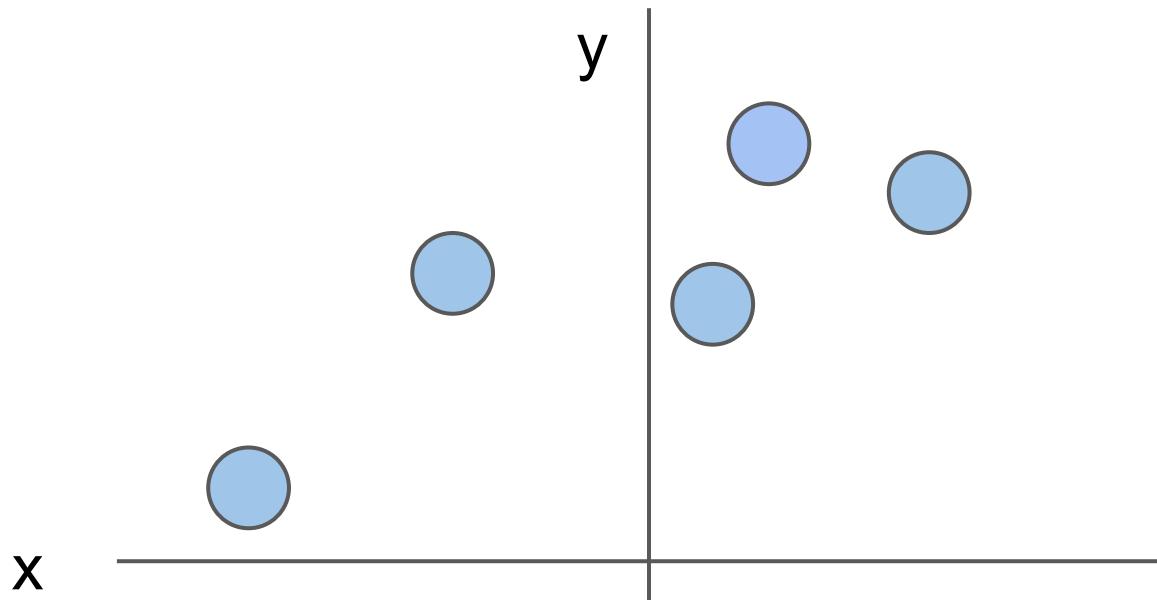
Regularization

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss: Model predictions should match training data}} + \lambda R(W)$$

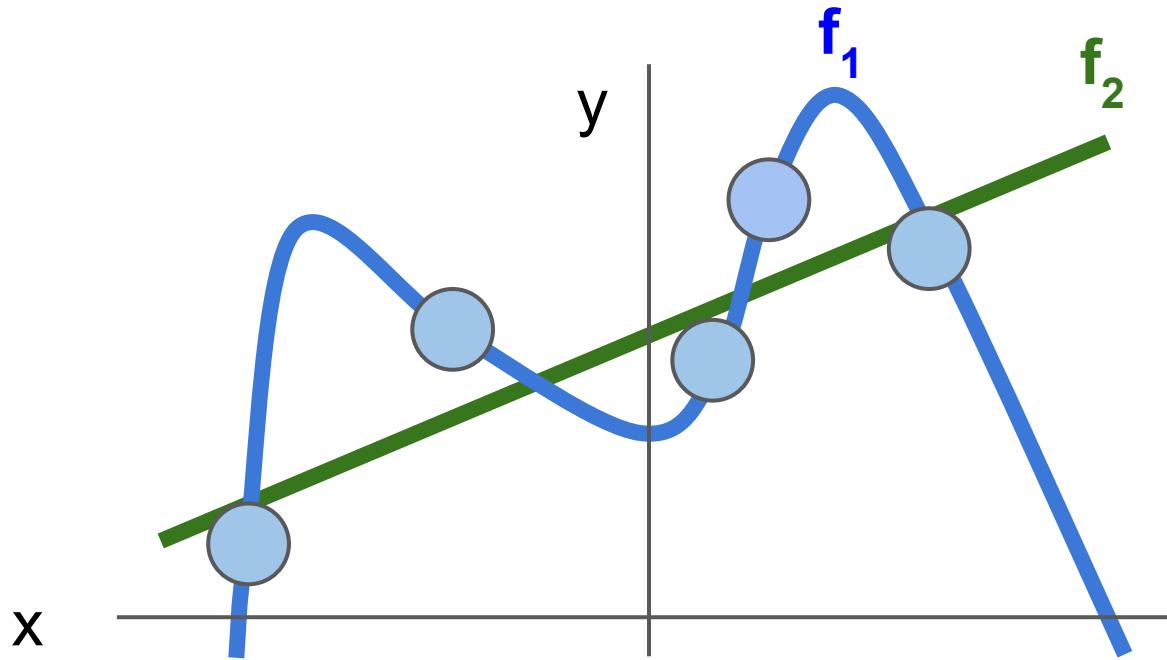

Data loss: Model predictions should match training data

Regularization: Prevent the model from doing *too well* on training data

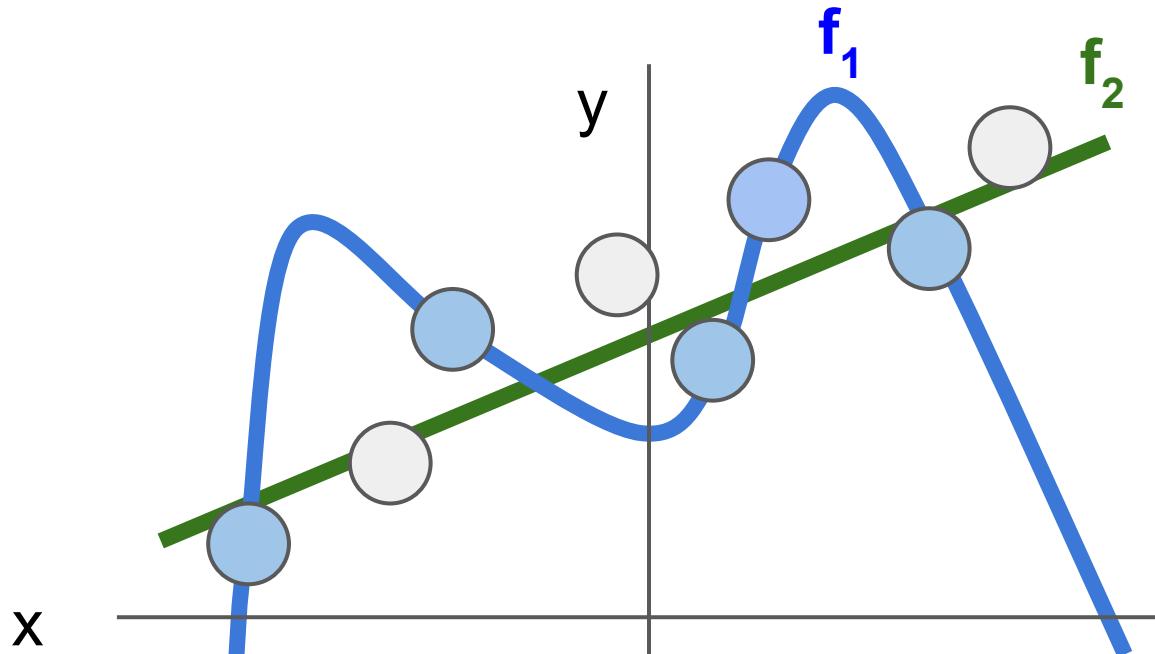
Regularization intuition: toy example training data



Regularization intuition: Prefer Simpler Models



Regularization: Prefer Simpler Models



Regularization pushes against fitting the data
too well so we don't fit noise in the data

Regularization

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss: Model predictions should match training data}} + \lambda R(W)$$


Data loss: Model predictions should match training data

Regularization: Prevent the model from doing *too well* on training data

Occam's Razor: Among multiple competing hypotheses, the simplest is the best,
William of Ockham 1285-1347

Regularization

λ = regularization strength
(hyperparameter)

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss: Model predictions should match training data}} + \lambda R(W)$$



Data loss: Model predictions should match training data

Regularization: Prevent the model from doing *too well* on training data

Regularization

λ = regularization strength
(hyperparameter)

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss: Model predictions should match training data}} + \lambda R(W)$$



Data loss: Model predictions should match training data

Regularization: Prevent the model from doing *too well* on training data

Simple examples

L2 regularization: $R(W) = \sum_k \sum_l W_{k,l}^2$

L1 regularization: $R(W) = \sum_k \sum_l |W_{k,l}|$

Elastic net (L1 + L2): $R(W) = \sum_k \sum_l \beta W_{k,l}^2 + |W_{k,l}|$

Regularization

λ = regularization strength
(hyperparameter)

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss}} + \lambda R(W)$$

Data loss: Model predictions should match training data



Regularization: Prevent the model from doing *too well* on training data

Simple examples

L2 regularization: $R(W) = \sum_k \sum_l W_{k,l}^2$

L1 regularization: $R(W) = \sum_k \sum_l |W_{k,l}|$

Elastic net (L1 + L2): $R(W) = \sum_k \sum_l \beta W_{k,l}^2 + |W_{k,l}|$

More complex:

Dropout

Batch normalization

Stochastic depth, fractional pooling, etc

Regularization

λ = regularization strength
(hyperparameter)

$$L(W) = \underbrace{\frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i)}_{\text{Data loss}} + \lambda R(W)$$

Data loss: Model predictions should match training data

Regularization: Prevent the model from doing *too well* on training data

Why regularize?

- Express preferences over weights
- Make the model *simple* so it works on test data
- Improve optimization by adding curvature

Regularization: Expressing Preferences

$$x = [1, 1, 1, 1]$$

$$w_1 = [1, 0, 0, 0]$$

$$w_2 = [0.25, 0.25, 0.25, 0.25]$$

L2 Regularization

$$R(W) = \sum_k \sum_l W_{k,l}^2$$

Which of w1 or w2 will
the L2 regularizer prefer?

$$w_1^T x = w_2^T x = 1$$

Regularization: Expressing Preferences

$$x = [1, 1, 1, 1]$$

$$w_1 = [1, 0, 0, 0]$$

$$w_2 = [0.25, 0.25, 0.25, 0.25]$$

L2 Regularization

$$R(W) = \sum_k \sum_l W_{k,l}^2$$

Which of w1 or w2 will
the L2 regularizer prefer?

L2 regularization likes to
“spread out” the weights

$$w_1^T x = w_2^T x = 1$$

Regularization: Expressing Preferences

$$x = [1, 1, 1, 1]$$

$$w_1 = [1, 0, 0, 0]$$

$$w_2 = [0.25, 0.25, 0.25, 0.25]$$

L2 Regularization

$$R(W) = \sum_k \sum_l W_{k,l}^2$$

Which of w1 or w2 will
the L2 regularizer prefer?

L2 regularization likes to
“spread out” the weights

$$w_1^T x = w_2^T x = 1$$

Which one would L1
regularization prefer?

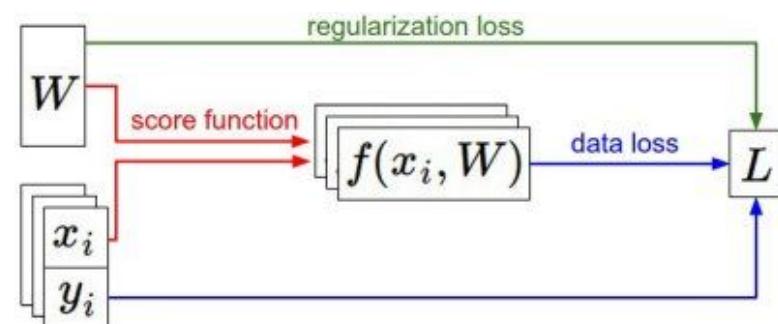
Recap

- We have some dataset of (x, y)
- We have a **score function**: $s = f(x; W) = Wx$ e.g.
- We have a **loss function**:

$$L_i = -\log\left(\frac{e^{sy_i}}{\sum_j e^{sj}}\right) \quad \text{Softmax}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \quad \text{SVM}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W) \quad \text{Full loss}$$



Recap

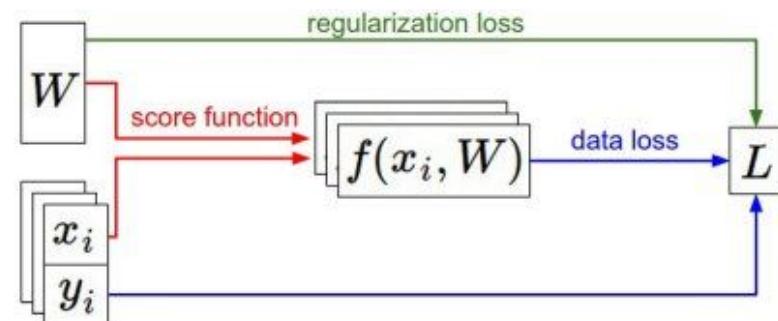
How do we find the best W ?

- We have some dataset of (x, y)
- We have a **score function**: $s = f(x; W) = Wx$ e.g.
- We have a **loss function**:

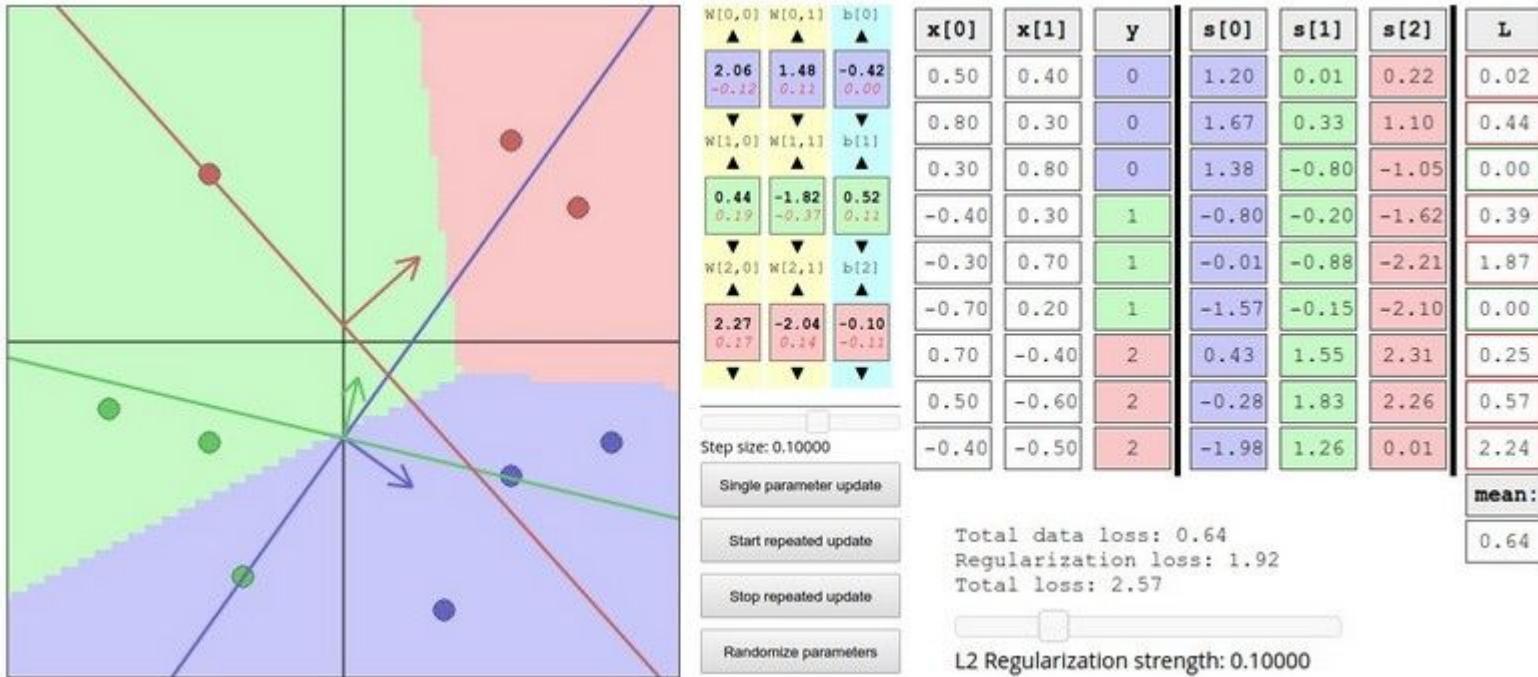
$$L_i = -\log\left(\frac{e^{sy_i}}{\sum_j e^{sj}}\right) \quad \text{Softmax}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \quad \text{SVM}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W) \quad \text{Full loss}$$



Interactive Web Demo



<http://vision.stanford.edu/teaching/cs231n-demos/linear-classify/>

Optimization



[This image](#) is [CC0 1.0](#) public domain



[Walking man image](#) is CC0 1.0 public domain

Strategy #1: A first very bad idea solution: Random search

```
# assume X_train is the data where each column is an example (e.g. 3073 x 50,000)
# assume Y_train are the labels (e.g. 1D array of 50,000)
# assume the function L evaluates the loss function

bestloss = float("inf") # Python assigns the highest possible float value
for num in xrange(1000):
    W = np.random.randn(10, 3073) * 0.0001 # generate random parameters
    loss = L(X_train, Y_train, W) # get the loss over the entire training set
    if loss < bestloss: # keep track of the best solution
        bestloss = loss
        bestW = W
    print 'in attempt %d the loss was %f, best %f' % (num, loss, bestloss)

# prints:
# in attempt 0 the loss was 9.401632, best 9.401632
# in attempt 1 the loss was 8.959668, best 8.959668
# in attempt 2 the loss was 9.044034, best 8.959668
# in attempt 3 the loss was 9.278948, best 8.959668
# in attempt 4 the loss was 8.857370, best 8.857370
# in attempt 5 the loss was 8.943151, best 8.857370
# in attempt 6 the loss was 8.605604, best 8.605604
# ... (truncated: continues for 1000 lines)
```

Lets see how well this works on the test set...

```
# Assume X_test is [3073 x 10000], Y_test [10000 x 1]
scores = wbest.dot(Xte_cols) # 10 x 10000, the class scores for all test examples
# find the index with max score in each column (the predicted class)
Yte_predict = np.argmax(scores, axis = 0)
# and calculate accuracy (fraction of predictions that are correct)
np.mean(Yte_predict == Yte)
# returns 0.1555
```

15.5% accuracy! not bad!
(SOTA is ~99.7%)

Strategy #2: Follow the slope



Strategy #2: Follow the slope

In 1-dimension, the derivative of a function:

$$\frac{df(x)}{dx} = \lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

In multiple dimensions, the **gradient** is the vector of (partial derivatives) along each dimension

The slope in any direction is the **dot product** of the direction with the gradient
The direction of steepest descent is the **negative gradient**

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

gradient dW:

[?,
?,
?,
?,
?,
?,
?,
?,
?,
?,...]

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

W + h (first dim):

[0.34 + 0.0001,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25322

gradient dW:

[?,
?,
?,
?,
?,
?,
?,
?,
?,...]

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

W + h (first dim):

[0.34 + 0.0001,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25322

gradient dW:

[-2.5,
?,
?,

$$\frac{(1.25322 - 1.25347)}{0.0001} = -2.5$$

$$\frac{df(x)}{dx} = \lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

?,
?,...]

current W:	W + h (second dim):	gradient dW:
[0.34, -1.11, 0.78, 0.12, 0.55, 2.81, -3.1, -1.5, 0.33,...] loss 1.25347	[0.34, -1.11 + 0.0001 , 0.78, 0.12, 0.55, 2.81, -3.1, -1.5, 0.33,...] loss 1.25353	[-2.5, ?, ?, ?, ?, ?, ?, ?, ?, ?,...]

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

W + h (second dim):

[0.34,
-1.11 + 0.0001,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25353

gradient dW:

[-2.5,
0.6,
?,
?]

$$\frac{(1.25353 - 1.25347)}{0.0001} = 0.6$$

$$\frac{df(x)}{dx} = \lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

?,...]

current W:	W + h (third dim):	gradient dW:
[0.34, -1.11, 0.78, 0.12, 0.55, 2.81, -3.1, -1.5, 0.33,...]	[0.34, -1.11, 0.78 + 0.0001 , 0.12, 0.55, 2.81, -3.1, -1.5, 0.33,...]	[-2.5, 0.6, ?, ?, ?, ?, ?, ?, ?, ?,...]
loss 1.25347	loss 1.25347	

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

W + h (third dim):

[0.34,
-1.11,
0.78 + 0.0001,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

gradient dW:

[-2.5,
0.6,
0,
?,
0,...]

$$\frac{(1.25347 - 1.25347)}{0.0001} = 0$$

$$\frac{df(x)}{dx} = \lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

?,...

current W:

[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

W + h (third dim):

[0.34,
-1.11,
0.78 + **0.0001**,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

gradient dW:

[-2.5,
0.6,
0,
?,
?]

Numeric Gradient

- Slow! Need to loop over all dimensions
- Approximate

[,...]

This is silly. The loss is just a function of W :

$$L = \frac{1}{N} \sum_{i=1}^N L_i + \sum_k W_k^2$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

$$s = f(x; W) = Wx$$

want $\nabla_W L$

This is silly. The loss is just a function of W:

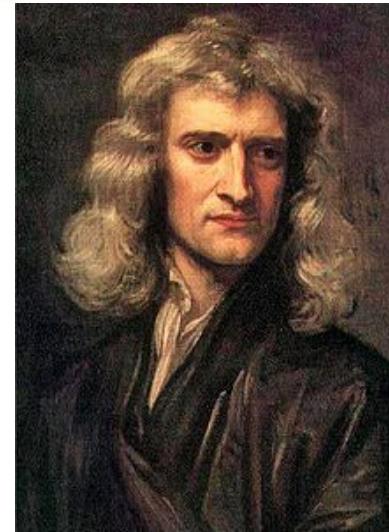
$$L = \frac{1}{N} \sum_{i=1}^N L_i + \sum_k W_k^2$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

$$s = f(x; W) = Wx$$

want $\nabla_W L$

Use calculus to compute an analytic gradient



[This image](#) is in the public domain



[This image](#) is in the public domain

current W:

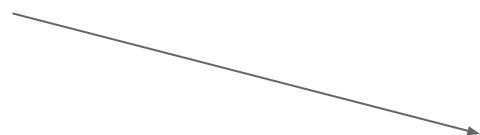
[0.34,
-1.11,
0.78,
0.12,
0.55,
2.81,
-3.1,
-1.5,
0.33,...]

loss 1.25347

gradient dW:

[-2.5,
0.6,
0,
0.2,
0.7,
-0.5,
1.1,
1.3,
-2.1,...]

dW = ...
(some function
data and W)



In summary:

- Numerical gradient: approximate, slow, easy to write
- Analytic gradient: exact, fast, error-prone

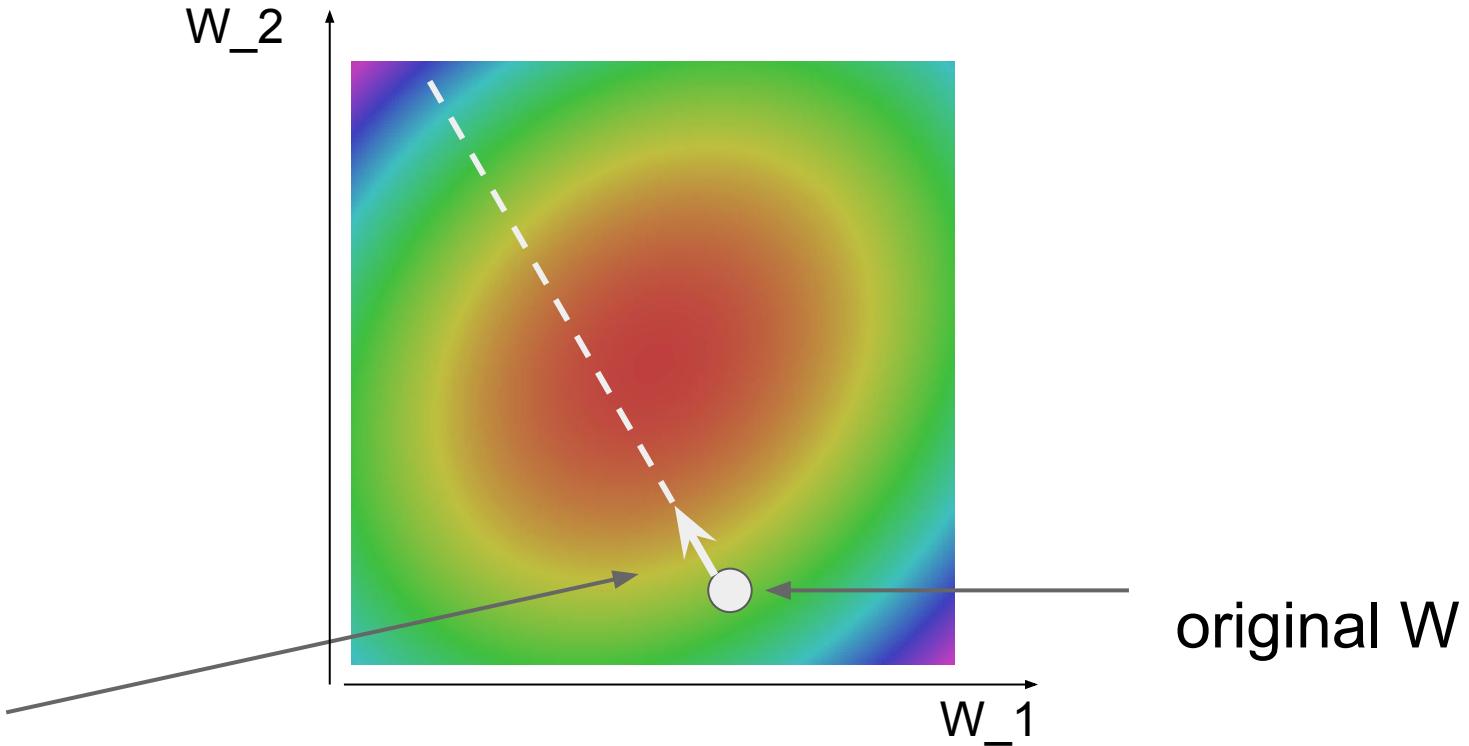
=>

In practice: Always use analytic gradient, but check debug implementation with numerical gradient. This is called a **gradient check**.

Gradient Descent

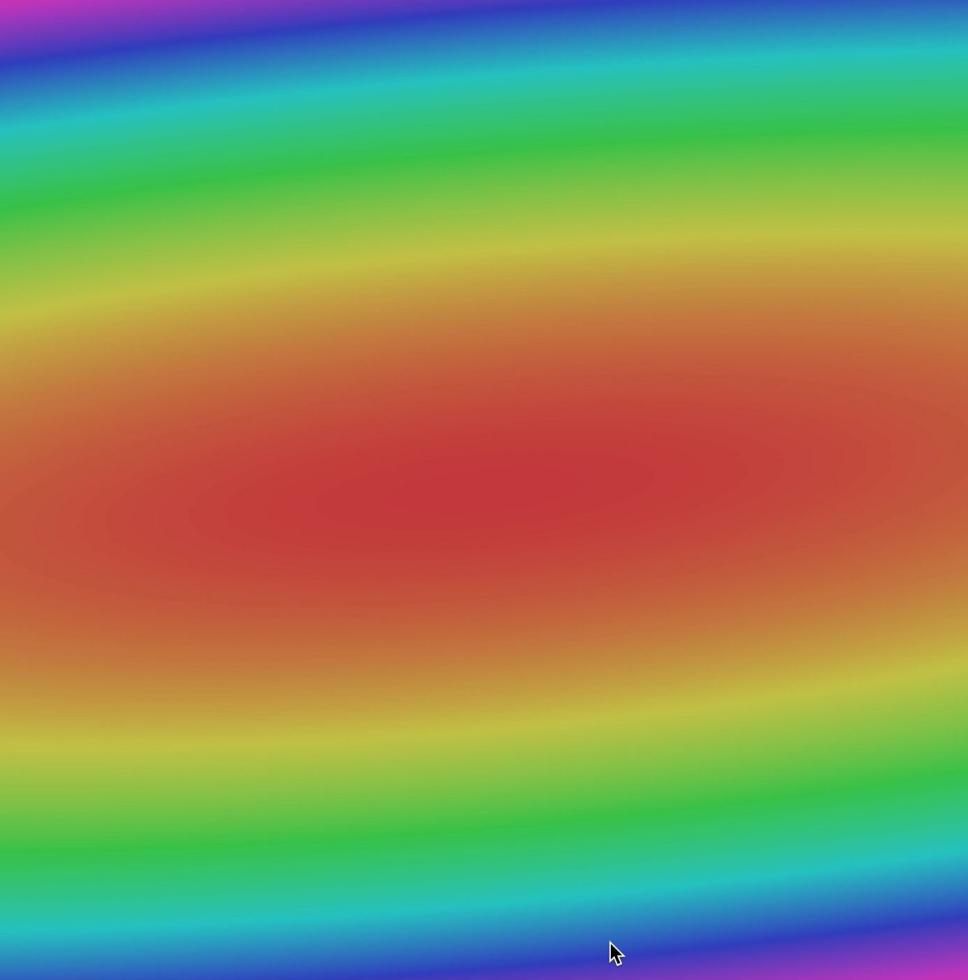
```
# Vanilla Gradient Descent

while True:
    weights_grad = evaluate_gradient(loss_fun, data, weights)
    weights += - step_size * weights_grad # perform parameter update
```



negative gradient direction

original W



Stochastic Gradient Descent (SGD)

$$L(W) = \frac{1}{N} \sum_{i=1}^N L_i(x_i, y_i, W) + \lambda R(W)$$

$$\nabla_W L(W) = \frac{1}{N} \sum_{i=1}^N \nabla_W L_i(x_i, y_i, W) + \lambda \nabla_W R(W)$$

Full sum expensive
when N is large!

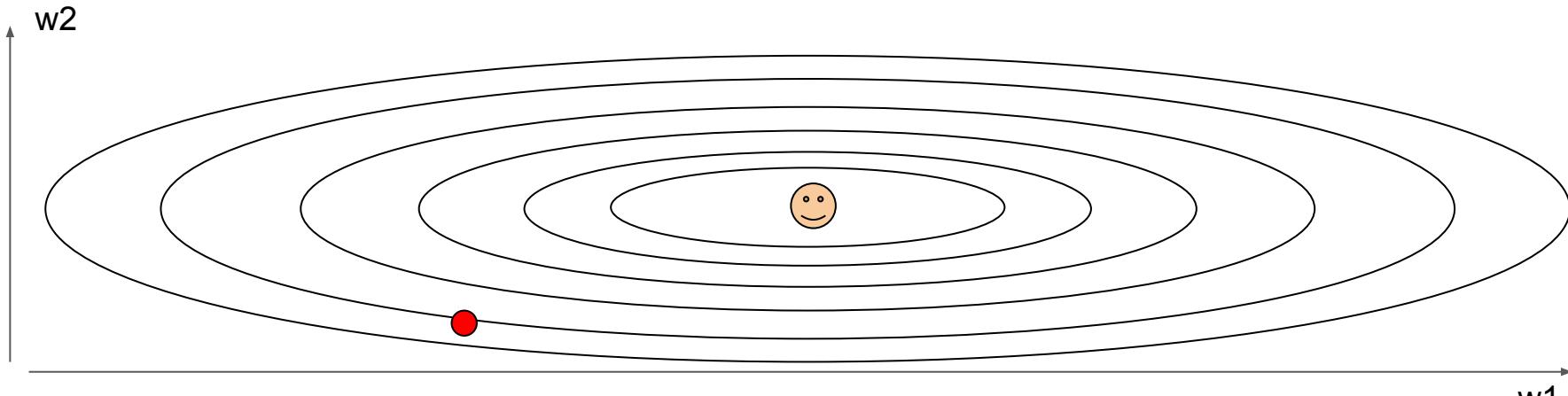
Approximate sum
using a **minibatch** of
examples
32 / 64 / 128 common

```
# Vanilla Minibatch Gradient Descent
```

```
while True:  
    data_batch = sample_training_data(data, 256) # sample 256 examples  
    weights_grad = evaluate_gradient(loss_fun, data_batch, weights)  
    weights += - step_size * weights_grad # perform parameter update
```

Optimization: Problem #1 with SGD

What if loss changes quickly in one direction and slowly in another?
What does gradient descent do?



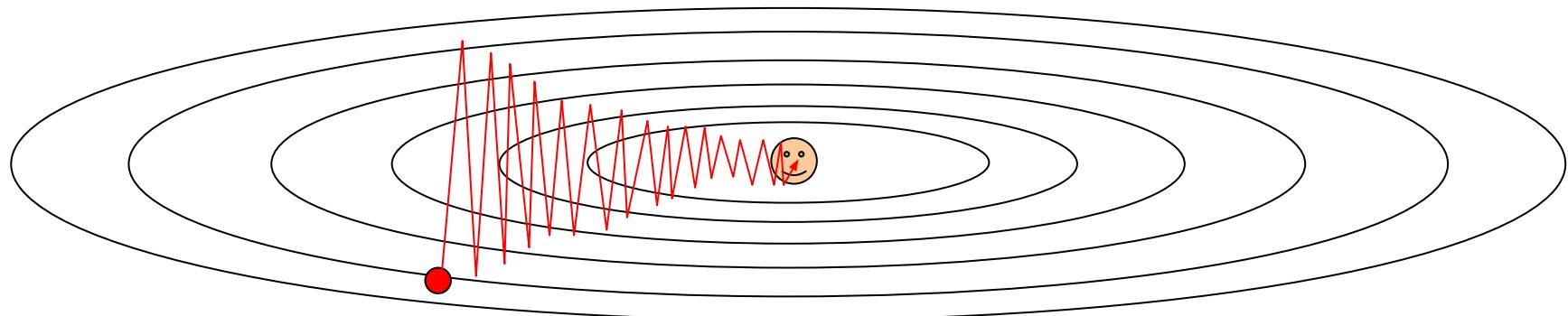
Aside: Loss function has high **condition number**: ratio of largest to smallest singular value of the Hessian matrix is large

Optimization: Problem #1 with SGD

What if loss changes quickly in one direction and slowly in another?

What does gradient descent do?

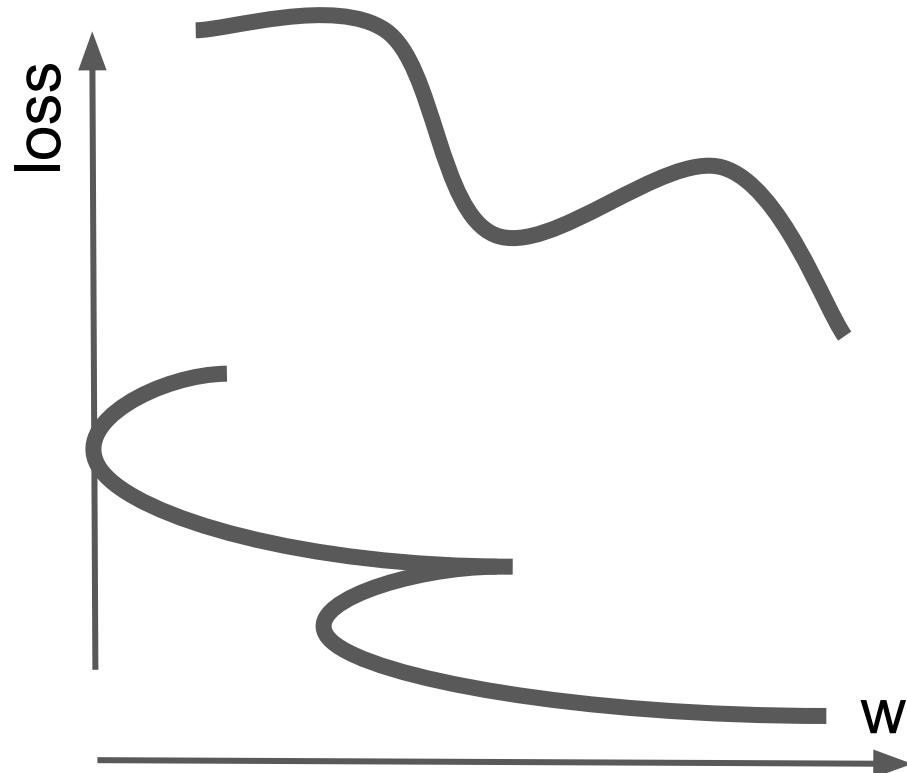
Very slow progress along shallow dimension, jitter along steep direction



Loss function has high **condition number**: ratio of largest to smallest singular value of the Hessian matrix is large

Optimization: Problem #2 with SGD

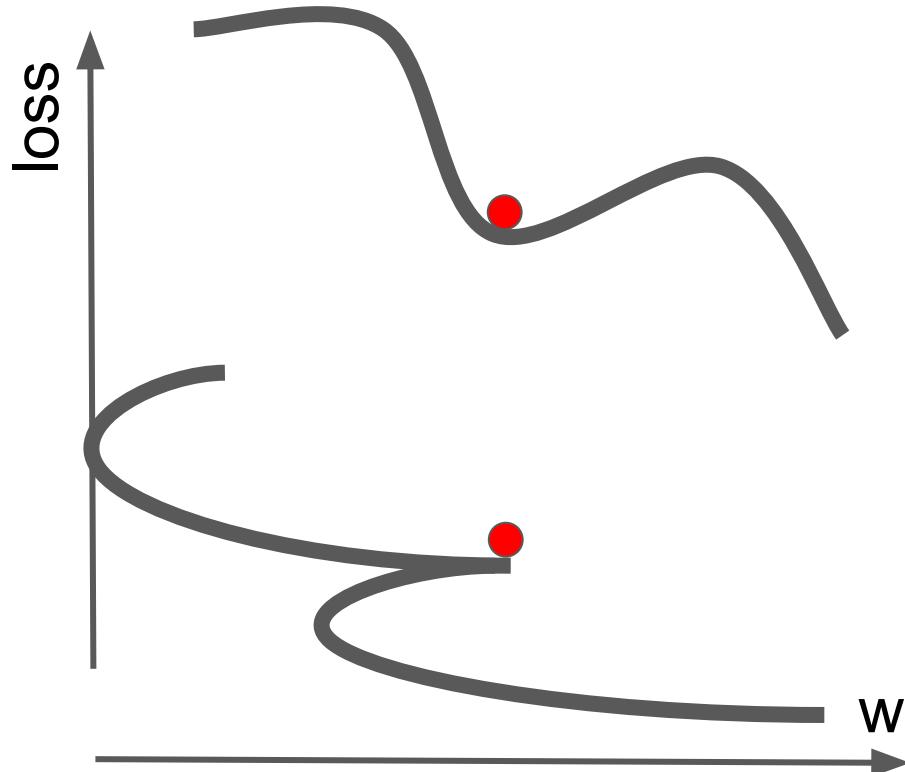
What if the loss
function has a
local minima or
saddle point?



Optimization: Problem #2 with SGD

What if the loss
function has a
local minima or
saddle point?

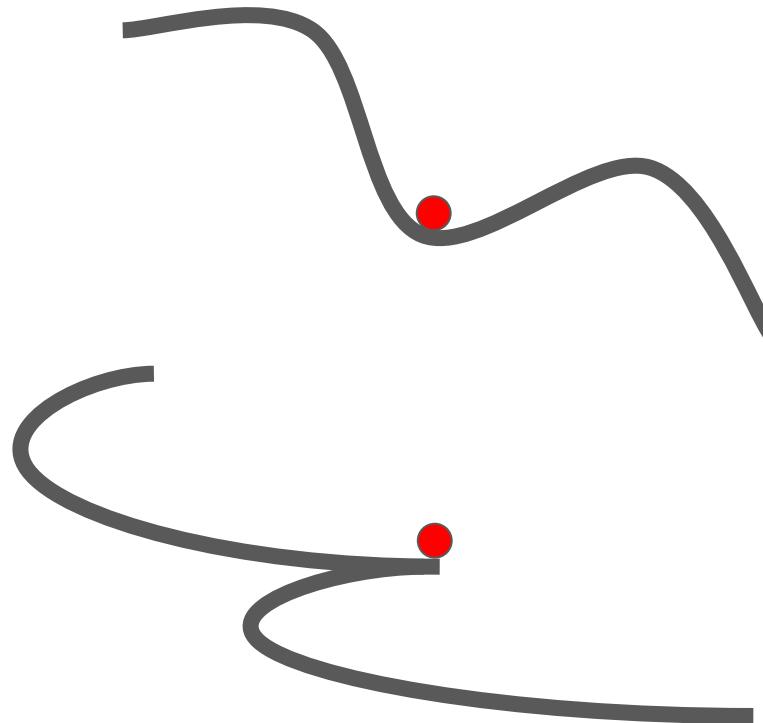
Zero gradient,
gradient descent
gets stuck



Optimization: Problem #2 with SGD

What if the loss
function has a
local minima or
saddle point?

Saddle points much
more common in
high dimension



Dauphin et al, "Identifying and attacking the saddle point problem in high-dimensional non-convex optimization", NIPS 2014

Optimization: Problem #2 with SGD

saddle point in two dimension

$$f(x, y) = x^2 - y^2$$

$$\frac{\partial}{\partial \textcolor{teal}{x}} (\textcolor{teal}{x}^2 - y^2) = 2x \rightarrow 2(\textcolor{teal}{0}) = 0$$

$$\frac{\partial}{\partial \textcolor{red}{y}} (x^2 - \textcolor{red}{y}^2) = -2y \rightarrow -2(\textcolor{red}{0}) = 0$$

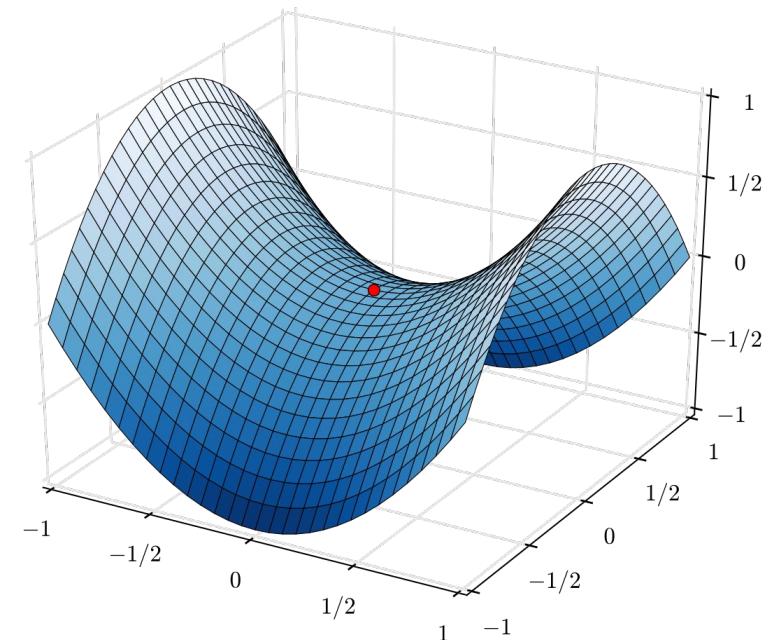


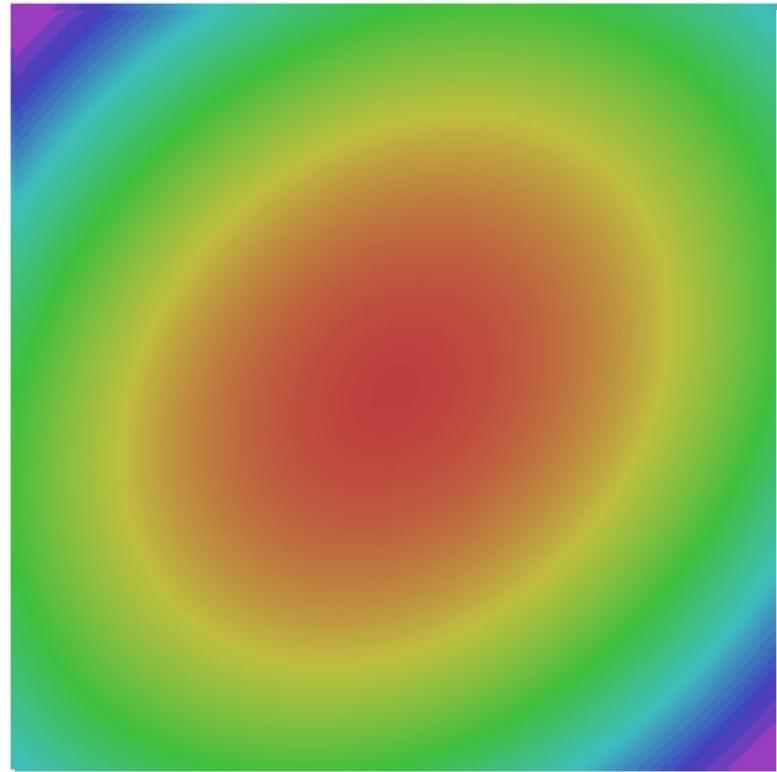
Image source: https://en.wikipedia.org/wiki/Saddle_point

Optimization: Problem #3 with SGD

Our gradients come from
minibatches so they can be noisy!

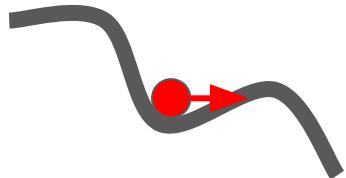
$$L(W) = \frac{1}{N} \sum_{i=1}^N L_i(x_i, y_i, W)$$

$$\nabla_W L(W) = \frac{1}{N} \sum_{i=1}^N \nabla_W L_i(x_i, y_i, W)$$

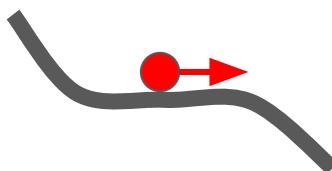


SGD + Momentum

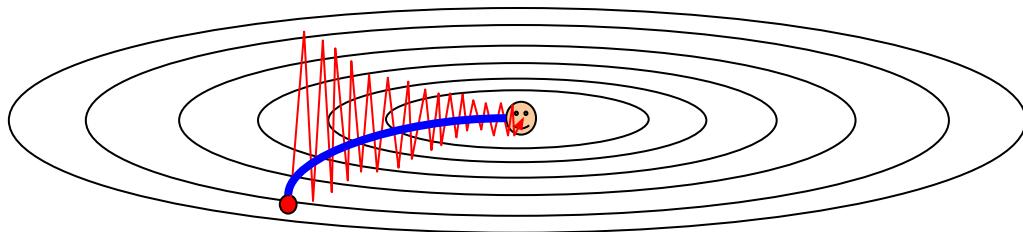
Local Minima



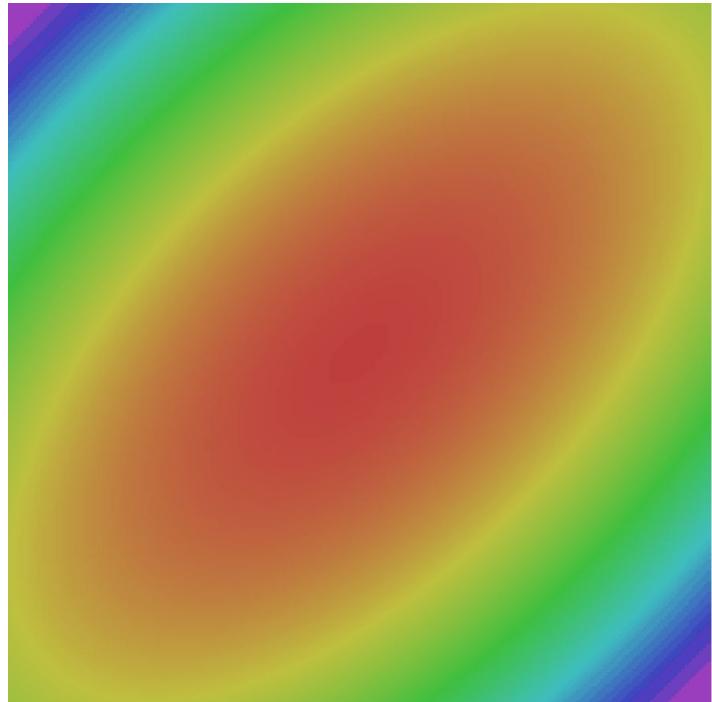
Saddle points



Poor Conditioning



Gradient Noise



SGD

SGD+Momentum

SGD: the simple two line update code

SGD

$$x_{t+1} = x_t - \alpha \nabla f(x_t)$$

```
while True:  
    dx = compute_gradient(x)  
    x -= learning_rate * dx
```

SGD + Momentum:

continue moving in the general direction as the previous iterations

SGD

$$x_{t+1} = x_t - \alpha \nabla f(x_t)$$

SGD+Momentum

$$v_{t+1} = \rho v_t + \nabla f(x_t)$$

$$x_{t+1} = x_t - \alpha v_{t+1}$$

```
while True:  
    dx = compute_gradient(x)  
    x -= learning_rate * dx
```

- Build up “velocity” as a running mean of gradients
- Rho gives “friction”; typically rho=0.9 or 0.99

Sutskever et al, “On the importance of initialization and momentum in deep learning”, ICML 2013

SGD + Momentum:

continue moving in the general direction as the previous iterations

SGD

$$x_{t+1} = x_t - \alpha \nabla f(x_t)$$

```
while True:  
    dx = compute_gradient(x)  
    x -= learning_rate * dx
```

SGD+Momentum

$$v_{t+1} = \rho v_t + \nabla f(x_t)$$

$$x_{t+1} = x_t - \alpha v_{t+1}$$

```
vx = 0  
while True:  
    dx = compute_gradient(x)  
    vx = rho * vx + dx  
    x -= learning_rate * vx
```

- Build up “velocity” as a running mean of gradients
- Rho gives “friction”; typically rho=0.9 or 0.99

Sutskever et al, “On the importance of initialization and momentum in deep learning”, ICML 2013

SGD + Momentum:

alternative equivalent formulation

SGD+Momentum

$$v_{t+1} = \rho v_t - \alpha \nabla f(x_t)$$

$$x_{t+1} = x_t + v_{t+1}$$

```
vx = 0
while True:
    dx = compute_gradient(x)
    vx = rho * vx - learning_rate * dx
    x += vx
```

SGD+Momentum

$$v_{t+1} = \rho v_t + \nabla f(x_t)$$

$$x_{t+1} = x_t - \alpha v_{t+1}$$

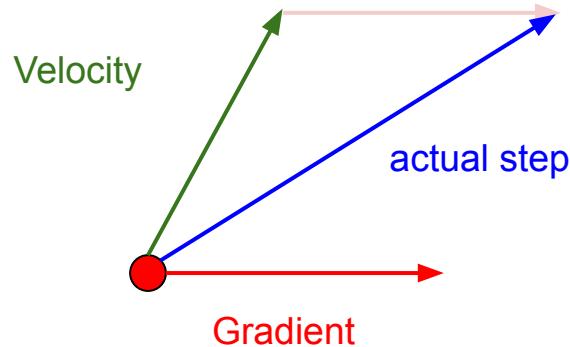
```
vx = 0
while True:
    dx = compute_gradient(x)
    vx = rho * vx + dx
    x -= learning_rate * vx
```

You may see SGD+Momentum formulated different ways,
but they are equivalent - give same sequence of x

Sutskever et al, "On the importance of initialization and momentum in deep learning", ICML 2013

SGD+Momentum

Momentum update:



Combine gradient at current point with velocity to get step used to update weights

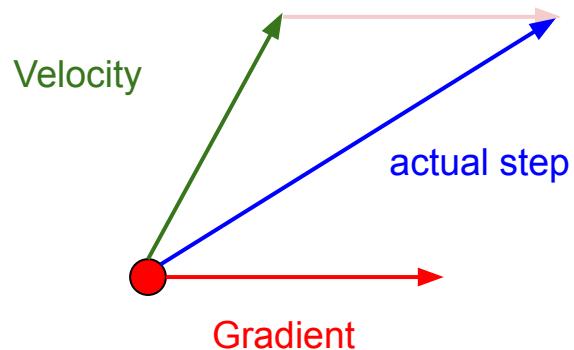
Nesterov, "A method of solving a convex programming problem with convergence rate $O(1/k^2)$ ", 1983

Nesterov, "Introductory lectures on convex optimization: a basic course", 2004

Sutskever et al, "On the importance of initialization and momentum in deep learning", ICML 2013

Nesterov Momentum

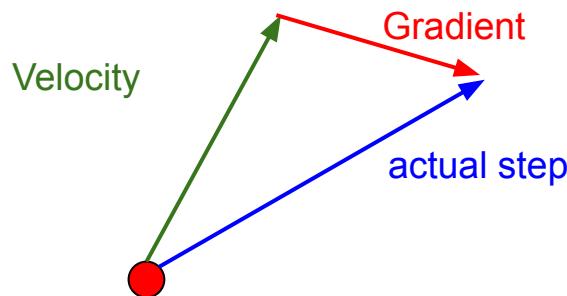
Momentum update:



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Nesterov Momentum

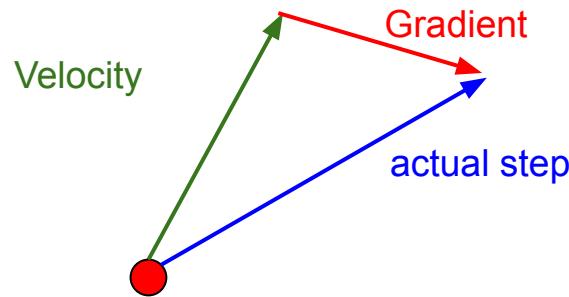


"Look ahead" to the point where updating using velocity would take us; compute gradient there and mix it with velocity to get actual update direction

Nesterov Momentum

$$v_{t+1} = \rho v_t - \alpha \nabla f(x_t + \rho v_t)$$

$$x_{t+1} = x_t + v_{t+1}$$



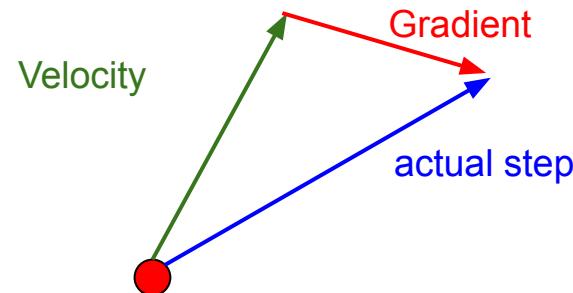
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$$v_{t+1} = \rho v_t - \alpha \nabla f(x_t + \rho v_t)$$

$$x_{t+1} = x_t + v_{t+1}$$

Annoying, usually we want update in terms of $x_t, \nabla f(x_t)$



“Look ahead” to the point where updating using velocity would take us; compute gradient there and mix it with velocity to get actual update direction

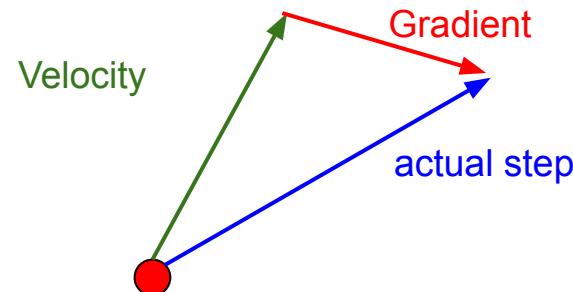
Nesterov Momentum

$$v_{t+1} = \rho v_t - \alpha \nabla f(x_t + \rho v_t)$$

$$x_{t+1} = x_t + v_{t+1}$$

Change of variables $\tilde{x}_t = x_t + \rho v_t$ and
rearrange:

Annoying, usually we want update in terms of $x_t, \nabla f(x_t)$



“Look ahead” to the point where updating using velocity would take us; compute gradient there and mix it with velocity to get actual update direction

Nesterov Momentum

$$v_{t+1} = \rho v_t - \alpha \nabla f(x_t + \rho v_t)$$

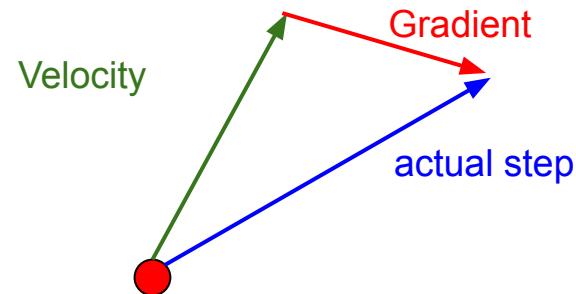
$$x_{t+1} = x_t + v_{t+1}$$

Change of variables $\tilde{x}_t = x_t + \rho v_t$ and rearrange:

$$v_{t+1} = \rho v_t - \alpha \nabla f(\tilde{x}_t)$$

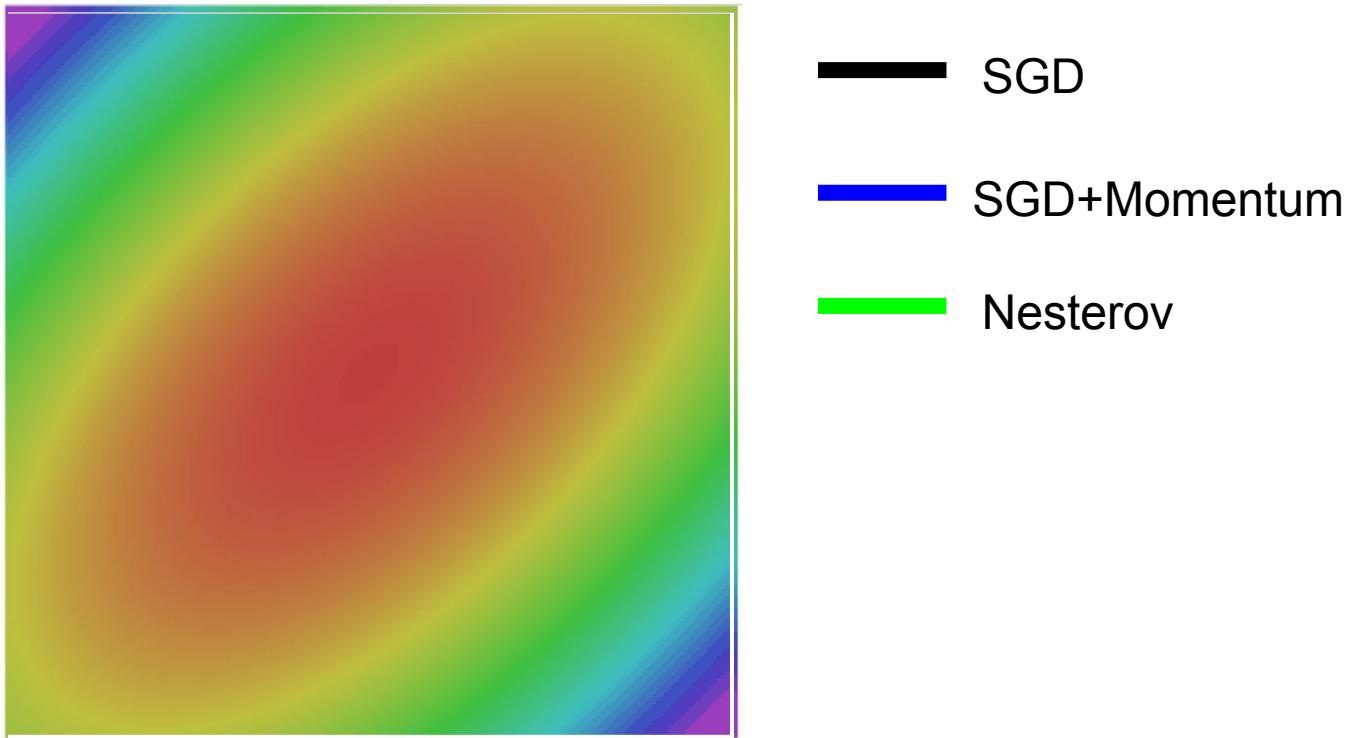
$$\begin{aligned}\tilde{x}_{t+1} &= \tilde{x}_t - \rho v_t + (1 + \rho)v_{t+1} \\ &= \tilde{x}_t + v_{t+1} + \rho(v_{t+1} - v_t)\end{aligned}$$

Annoying, usually we want update in terms of $x_t, \nabla f(x_t)$



“Look ahead” to the point where updating using velocity would take us; compute gradient there and mix it with velocity to get actual update direction

Nesterov Momentum



AdaGrad

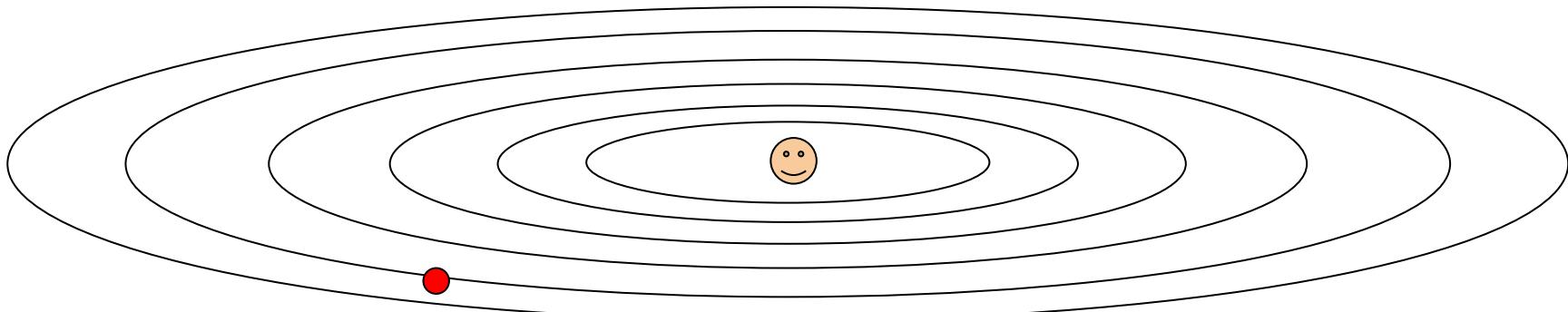
```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```

Added element-wise scaling of the gradient based on the historical sum of squares in each dimension

“Per-parameter learning rates”
or “adaptive learning rates”

AdaGrad

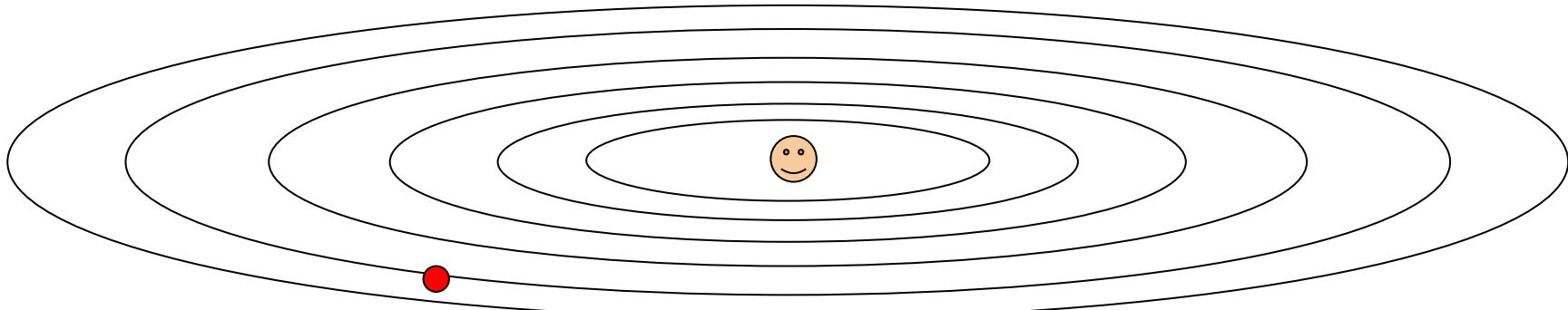
```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```



Q: What happens with AdaGrad?

AdaGrad

```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```

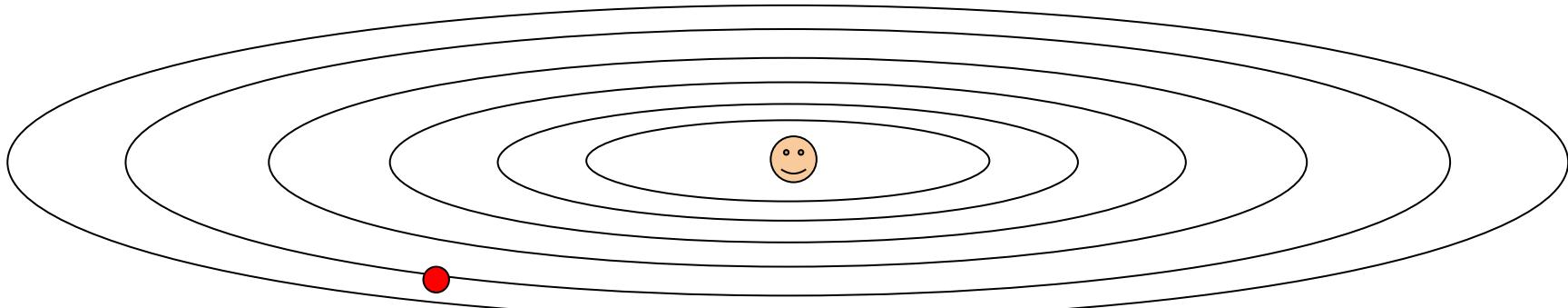


Q: What happens with AdaGrad?

Progress along “steep” directions is damped;
progress along “flat” directions is accelerated

AdaGrad

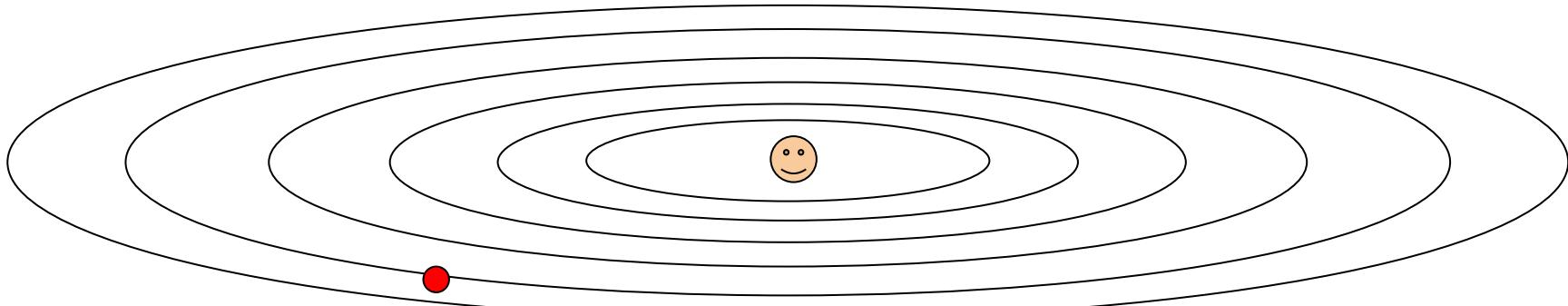
```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```



Q2: What happens to the step size over long time?

AdaGrad

```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```



Q2: What happens to the step size over long time? Decays to zero

RMSProp: “Leaky AdaGrad”

AdaGrad

```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared += dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```

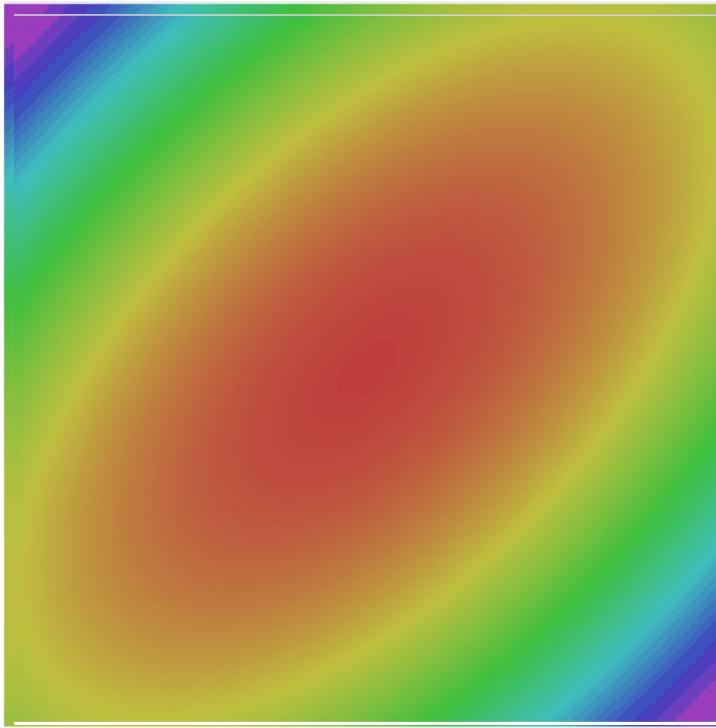


RMSProp

```
grad_squared = 0
while True:
    dx = compute_gradient(x)
    grad_squared = decay_rate * grad_squared + (1 - decay_rate) * dx * dx
    x -= learning_rate * dx / (np.sqrt(grad_squared) + 1e-7)
```

Tieleman and Hinton, 2012

RMSProp



- SGD
- SGD+Momentum
- RMSProp
- AdaGrad
(stuck due to decaying lr)

Adam (almost)

```
first_moment = 0
second_moment = 0
while True:
    dx = compute_gradient(x)
    first_moment = beta1 * first_moment + (1 - beta1) * dx
    second_moment = beta2 * second_moment + (1 - beta2) * dx * dx
    x -= learning_rate * first_moment / (np.sqrt(second_moment) + 1e-7))
```

Kingma and Ba, "Adam: A method for stochastic optimization", ICLR 2015

Adam (almost)

```
first_moment = 0
second_moment = 0
while True:
    dx = compute_gradient(x)
    first_moment = beta1 * first_moment + (1 - beta1) * dx
    second_moment = beta2 * second_moment + (1 - beta2) * dx * dx
    x -= learning_rate * first_moment / (np.sqrt(second_moment) + 1e-7))
```

Momentum

AdaGrad / RMSProp

Sort of like RMSProp with momentum

Q: What happens at first timestep?

Kingma and Ba, "Adam: A method for stochastic optimization", ICLR 2015

Adam (full form)

```
first_moment = 0
second_moment = 0
for t in range(1, num_iterations):
    dx = compute_gradient(x)
    first_moment = beta1 * first_moment + (1 - beta1) * dx
    second_moment = beta2 * second_moment + (1 - beta2) * dx * dx
    first_unbias = first_moment / (1 - beta1 ** t)
    second_unbias = second_moment / (1 - beta2 ** t)
    x -= learning_rate * first_unbias / (np.sqrt(second_unbias) + 1e-7))
```

Momentum

Bias correction

AdaGrad / RMSProp

Bias correction for the fact that
first and second moment
estimates start at zero

Kingma and Ba, "Adam: A method for stochastic optimization", ICLR 2015

Adam (full form)

```
first_moment = 0
second_moment = 0
for t in range(1, num_iterations):
    dx = compute_gradient(x)
    first_moment = beta1 * first_moment + (1 - beta1) * dx
    second_moment = beta2 * second_moment + (1 - beta2) * dx * dx
    first_unbias = first_moment / (1 - beta1 ** t)
    second_unbias = second_moment / (1 - beta2 ** t)
    x -= learning_rate * first_unbias / (np.sqrt(second_unbias) + 1e-7))
```

Momentum

Bias correction

AdaGrad / RMSProp

Bias correction for the fact that
first and second moment
estimates start at zero

Adam with $\text{beta1} = 0.9$,
 $\text{beta2} = 0.999$, and $\text{learning_rate} = 1e-3$ or $5e-4$
is a great starting point for many models!

Kingma and Ba, "Adam: A method for stochastic optimization", ICLR 2015

Adam



- SGD
- SGD+Momentum
- RMSProp
- Adam

Learning rate schedules

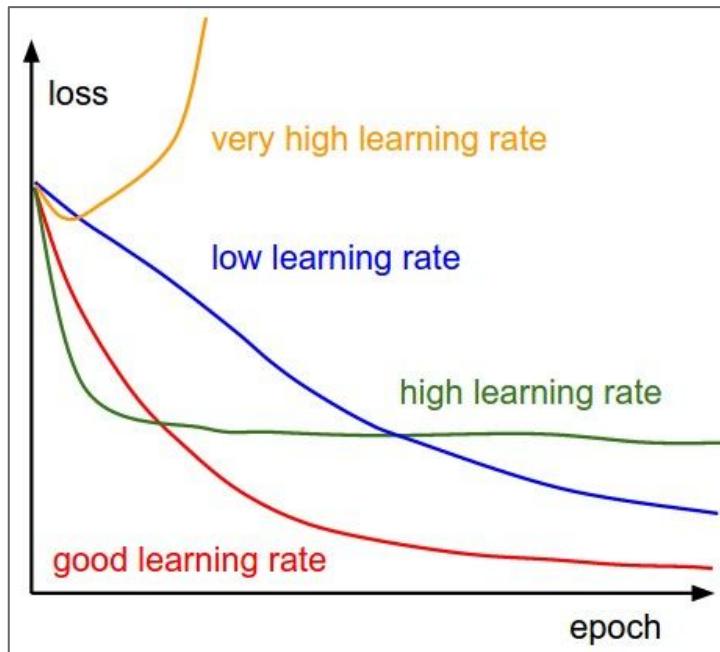
```
# Vanilla Gradient Descent

while True:
    weights_grad = evaluate_gradient(loss_fun, data, weights)
    weights += - step_size * weights_grad # perform parameter update
```



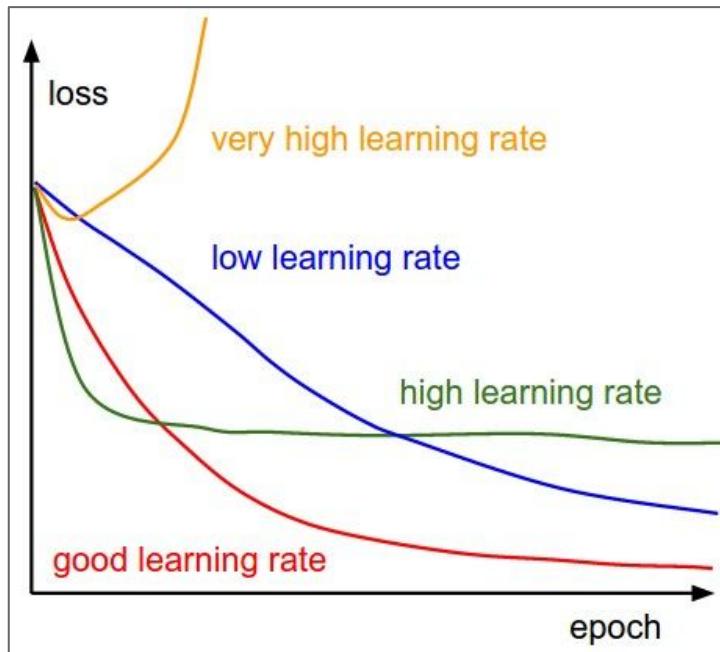
Learning rate

SGD, SGD+Momentum, Adagrad, RMSProp, Adam all have **learning rate** as a hyperparameter.



Q: Which one of these learning rates is best to use?

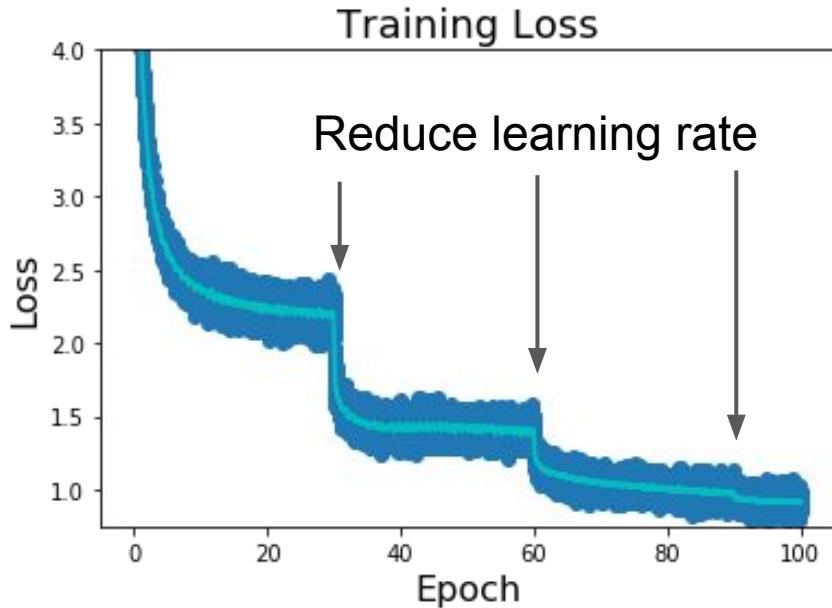
SGD, SGD+Momentum, Adagrad, RMSProp, Adam all have **learning rate** as a hyperparameter.



Q: Which one of these learning rates is best to use?

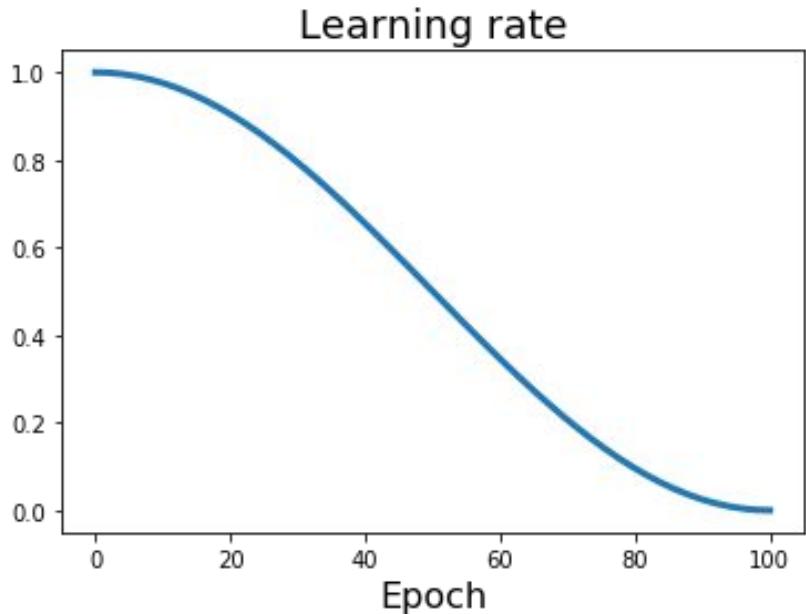
A: In reality, all of these are good learning rates.

Learning rate decays over time



Step: Reduce learning rate at a few fixed points. E.g. for ResNets, multiply LR by 0.1 after epochs 30, 60, and 90.

Learning Rate Decay



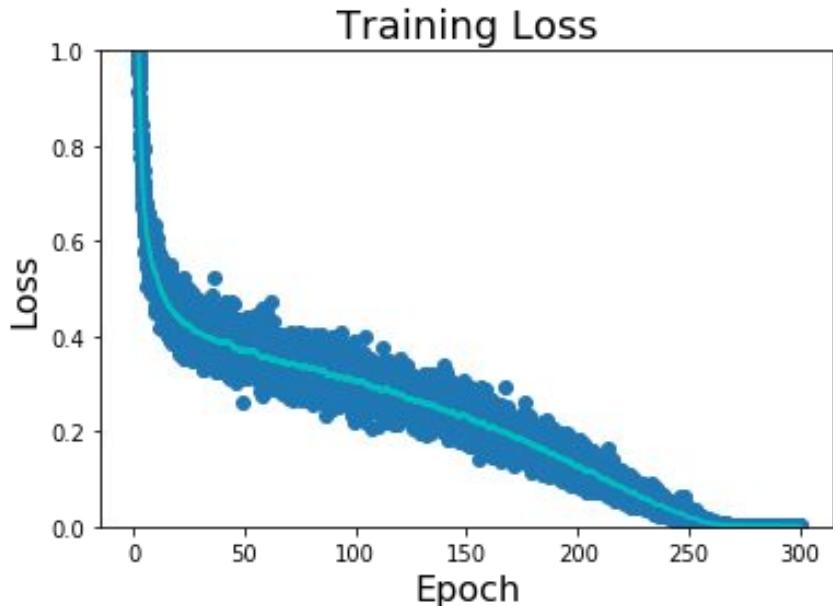
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Cosine: $\alpha_t = \frac{1}{2}\alpha_0 (1 + \cos(t\pi/T))$

α_0 : Initial learning rate
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 T : Total number of epochs

Loshchilov and Hutter, "SGDR: Stochastic Gradient Descent with Warm Restarts", ICLR 2017
Radford et al, "Improving Language Understanding by Generative Pre-Training", 2018
Feichtenhofer et al, "SlowFast Networks for Video Recognition", arXiv 2018
Child et al, "Generating Long Sequences with Sparse Transformers", arXiv 2019

Learning Rate Decay



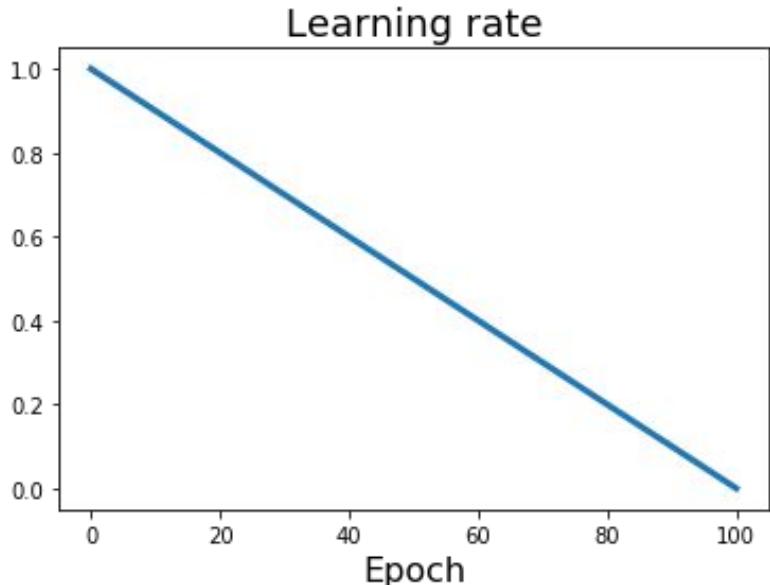
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Learning Rate Decay



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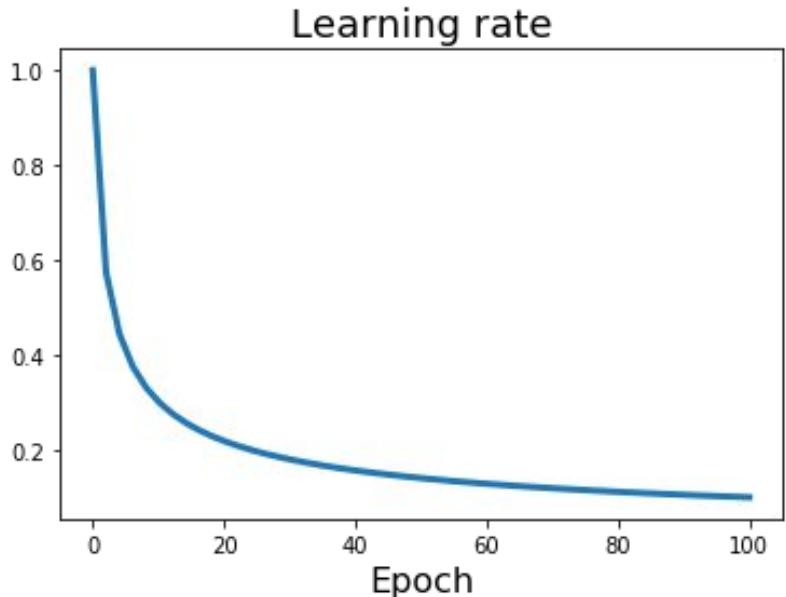
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Devlin et al, "BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding", 2018

Learning Rate Decay



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Inverse sqrt: $\alpha_t = \alpha_0/\sqrt{t}$

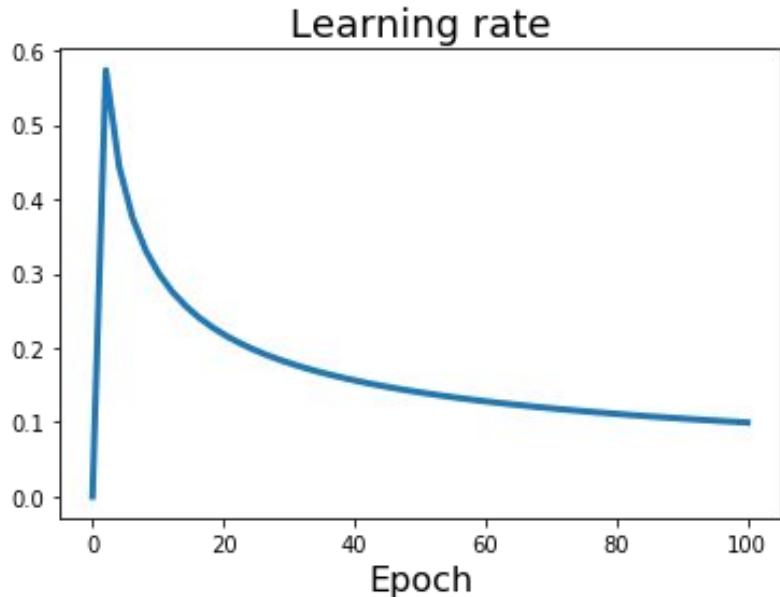
α_0 : Initial learning rate

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Vaswani et al, "Attention is all you need", NIPS 2017

Learning Rate Decay: Linear Warmup

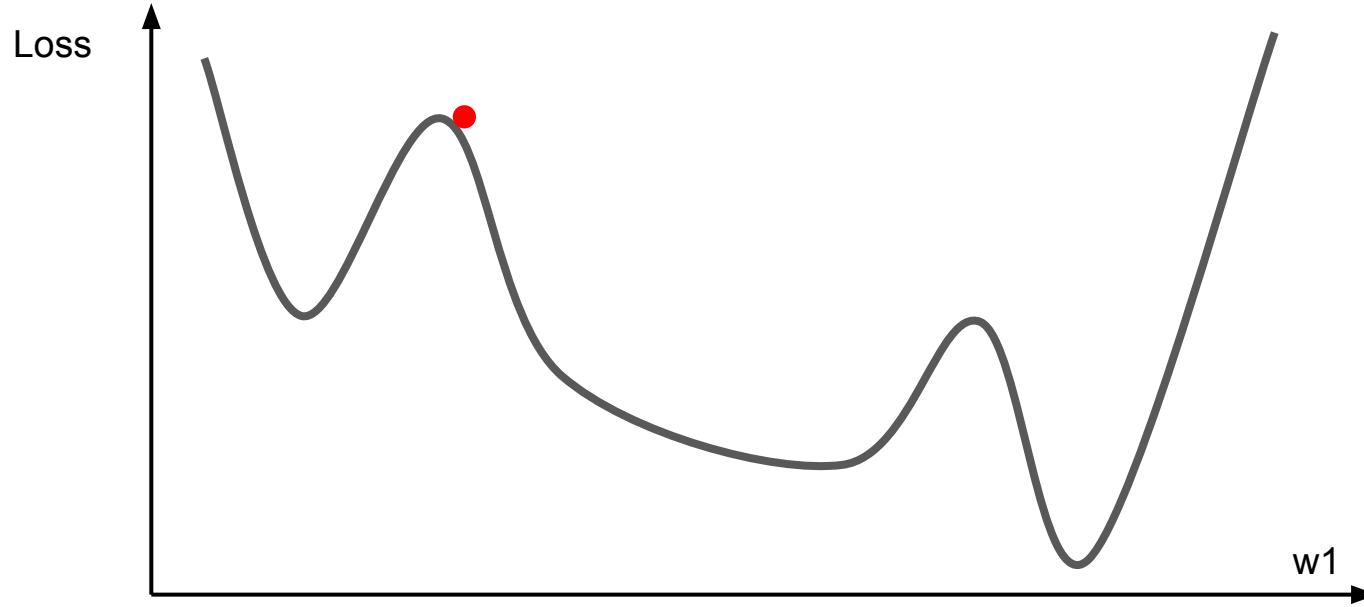


High initial learning rates can make loss explode; linearly increasing learning rate from 0 over the first ~5,000 iterations can prevent this.

Empirical rule of thumb: If you increase the batch size by N, also scale the initial learning rate by N

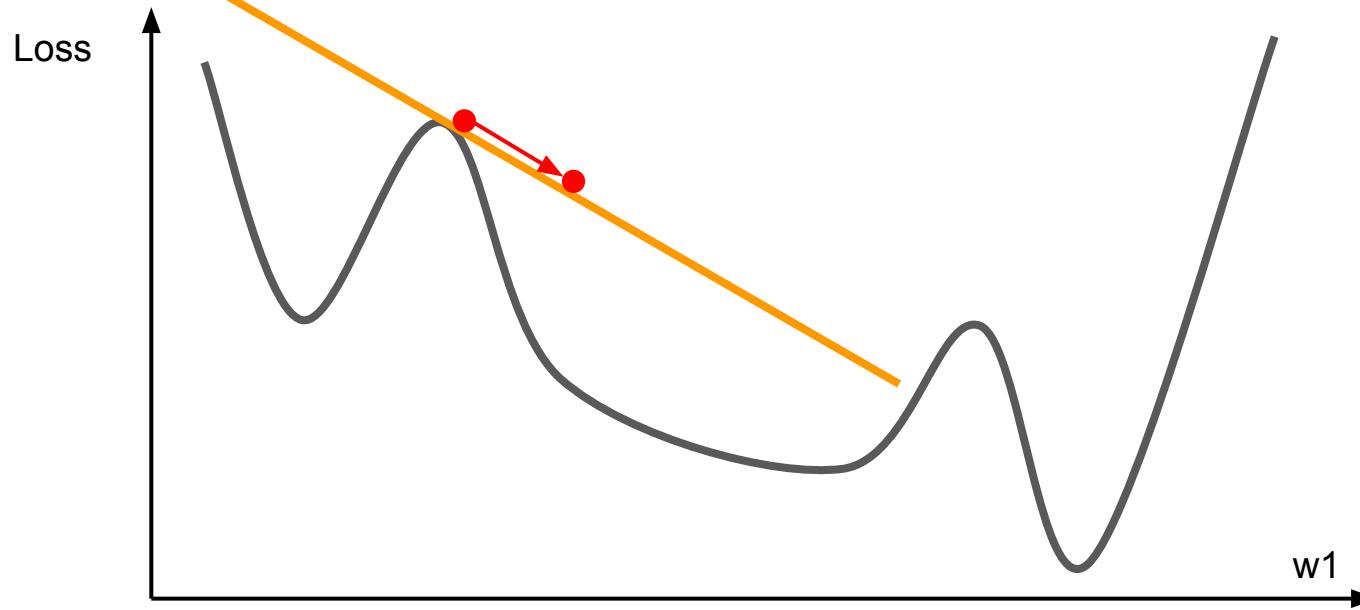
Goyal et al, "Accurate, Large Minibatch SGD: Training ImageNet in 1 Hour", arXiv 2017

First-Order Optimization



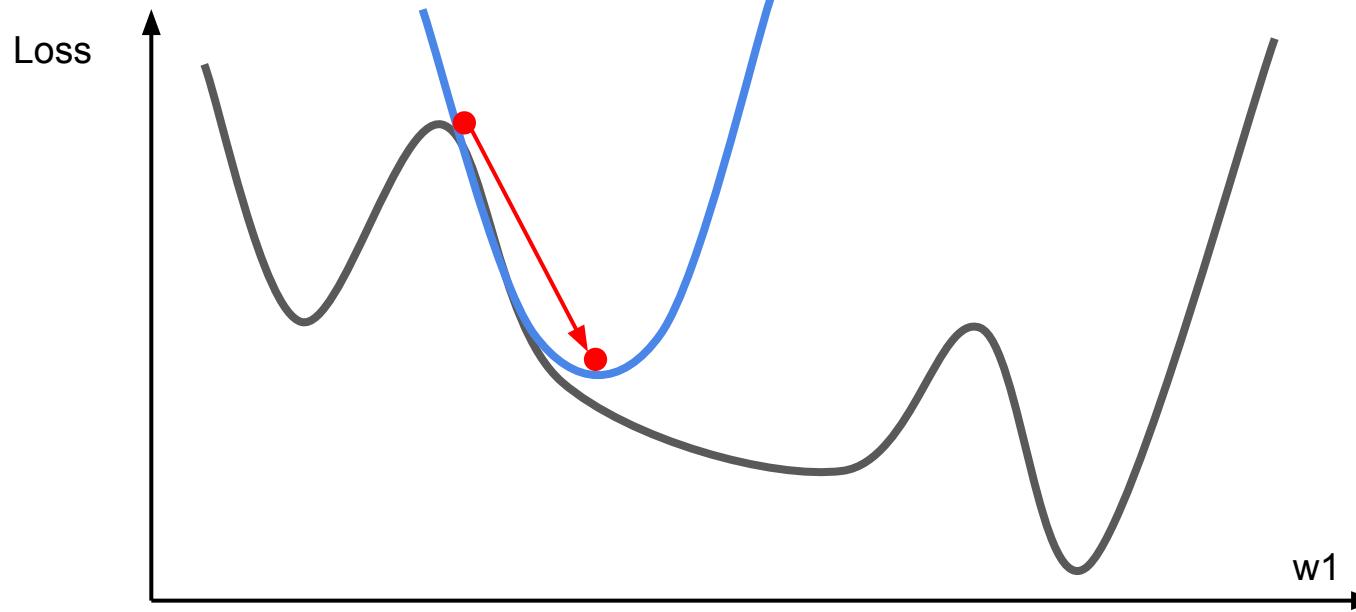
First-Order Optimization

- (1) Use gradient form linear approximation
- (2) Step to minimize the approximation



Second-Order Optimization

- (1) Use gradient **and Hessian** to form **quadratic approximation**
- (2) Step to the **minima** of the approximation



Second-Order Optimization

second-order Taylor expansion:

$$J(\boldsymbol{\theta}) \approx J(\boldsymbol{\theta}_0) + (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^\top \nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}_0) + \frac{1}{2} (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^\top \mathbf{H}(\boldsymbol{\theta} - \boldsymbol{\theta}_0)$$

Solving for the critical point we obtain the Newton parameter update:

$$\boldsymbol{\theta}^* = \boldsymbol{\theta}_0 - \mathbf{H}^{-1} \nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}_0)$$

Q: Why is this bad for deep learning?

Second-Order Optimization

second-order Taylor expansion:

$$J(\boldsymbol{\theta}) \approx J(\boldsymbol{\theta}_0) + (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^\top \nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}_0) + \frac{1}{2} (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^\top \mathbf{H} (\boldsymbol{\theta} - \boldsymbol{\theta}_0)$$

Solving for the critical point we obtain the Newton parameter update:

$$\boldsymbol{\theta}^* = \boldsymbol{\theta}_0 - \mathbf{H}^{-1} \nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}_0)$$

Hessian has $O(N^2)$ elements
Inverting takes $O(N^3)$
 $N = (\text{Tens or Hundreds of}) \text{ Millions}$

Q: Why is this bad for deep learning?

Second-Order Optimization

$$\boldsymbol{\theta}^* = \boldsymbol{\theta}_0 - \boldsymbol{H}^{-1} \nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}_0)$$

- Quasi-Newton methods (**BGFS** most popular):
instead of inverting the Hessian ($O(n^3)$), approximate inverse Hessian with rank 1 updates over time ($O(n^2)$ each).
- **L-BFGS** (Limited memory BFGS):
Does not form/store the full inverse Hessian.

L-BFGS

- **Usually works very well in full batch, deterministic mode**
i.e. if you have a single, deterministic $f(x)$ then L-BFGS will probably work very nicely
- **Does not transfer very well to mini-batch setting.** Gives bad results. Adapting second-order methods to large-scale, stochastic setting is an active area of research.

Le et al, "On optimization methods for deep learning, ICML 2011"

Ba et al, "Distributed second-order optimization using Kronecker-factored approximations", ICLR 2017

In practice:

- **Adam** is a good default choice in many cases; it often works ok even with constant learning rate
- **SGD+Momentum** can outperform Adam but may require more tuning of LR and schedule
- If you can afford to do full batch updates then try out **L-BFGS** (and don't forget to disable all sources of noise)

Next time:

Introduction to neural networks

Backpropagation

Lecture 4: Neural Networks and Backpropagation

Announcements: Assignment 1

Assignment 1 due Fri 4/15 at 11:59pm

Administrative: Project Proposal

Due **Mon 4/18**

TA expertise are posted on the webpage.

(http://cs231n.stanford.edu/office_hours.html)

Administrative: Discussion Section

Discussion section tomorrow:

Backpropagation

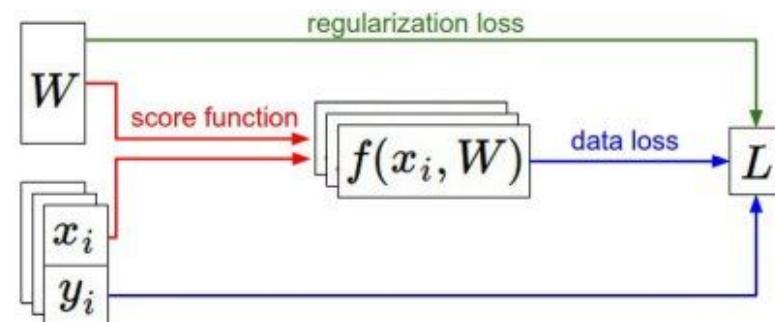
Recap

- We have some dataset of (x, y)
- We have a **score function**: $s = f(x; W) = Wx$ e.g.
- We have a **loss function**:

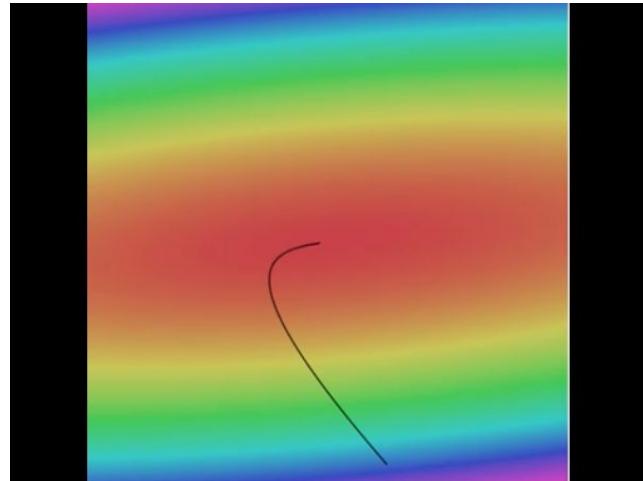
$$L_i = -\log\left(\frac{e^{sy_i}}{\sum_j e^{sj}}\right) \text{ Softmax}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \text{ SVM}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W) \text{ Full loss}$$



Finding the best W: Optimize with Gradient Descent



```
# Vanilla Gradient Descent

while True:
    weights_grad = evaluate_gradient(loss_fun, data, weights)
    weights += - step_size * weights_grad # perform parameter update
```

Landscape image is [CC0 1.0](#) public domain
Walking man image is [CC0 1.0](#) public domain

Gradient descent

$$\frac{df(x)}{dx} = \lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

Numerical gradient: slow :, approximate :, easy to write :)

Analytic gradient: fast :), exact :), error-prone :(

In practice: Derive analytic gradient, check your implementation with numerical gradient

Stochastic Gradient Descent (SGD)

$$L(W) = \frac{1}{N} \sum_{i=1}^N L_i(x_i, y_i, W) + \lambda R(W)$$

$$\nabla_W L(W) = \frac{1}{N} \sum_{i=1}^N \nabla_W L_i(x_i, y_i, W) + \lambda \nabla_W R(W)$$

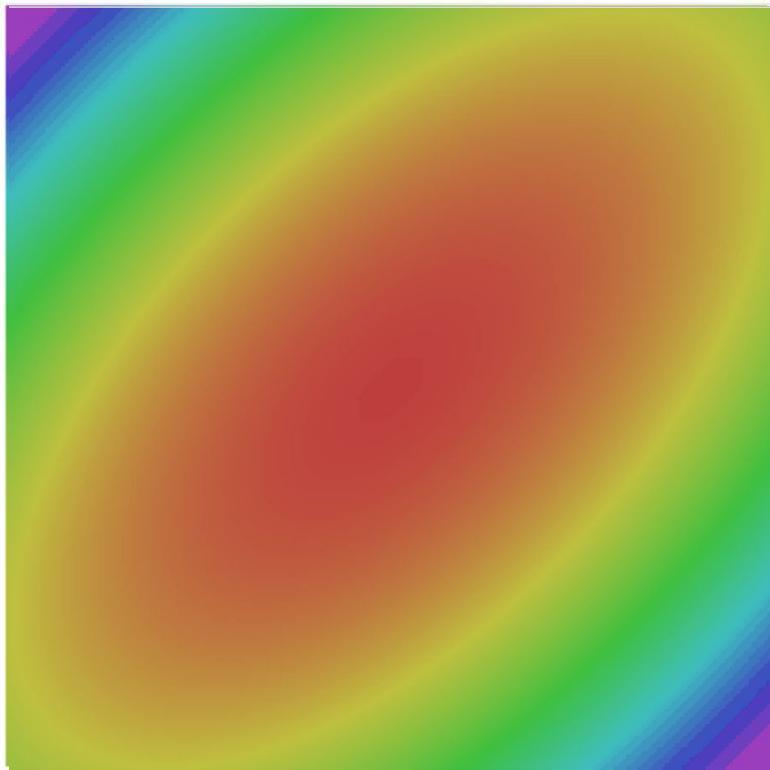
Full sum expensive
when N is large!

Approximate sum
using a **minibatch** of
examples
32 / 64 / 128 common

```
# Vanilla Minibatch Gradient Descent
```

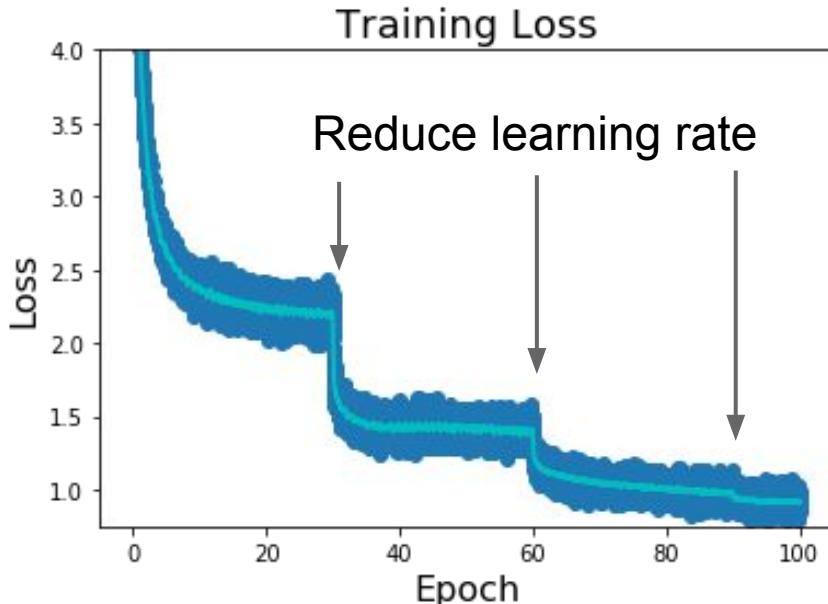
```
while True:  
    data_batch = sample_training_data(data, 256) # sample 256 examples  
    weights_grad = evaluate_gradient(loss_fun, data_batch, weights)  
    weights += - step_size * weights_grad # perform parameter update
```

Last time: fancy optimizers



- SGD
- SGD+Momentum
- RMSProp
- Adam

Last time: learning rate scheduling



Step: Reduce learning rate at a few fixed points. E.g. for ResNets, multiply LR by 0.1 after epochs 30, 60, and 90.

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T : Total number of epochs

Today:

Deep Learning

Released yesterday: dall-e-2

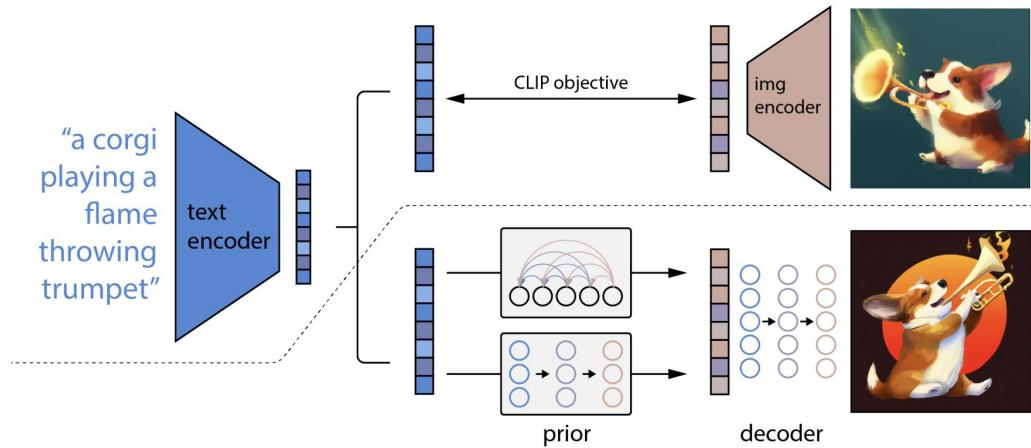
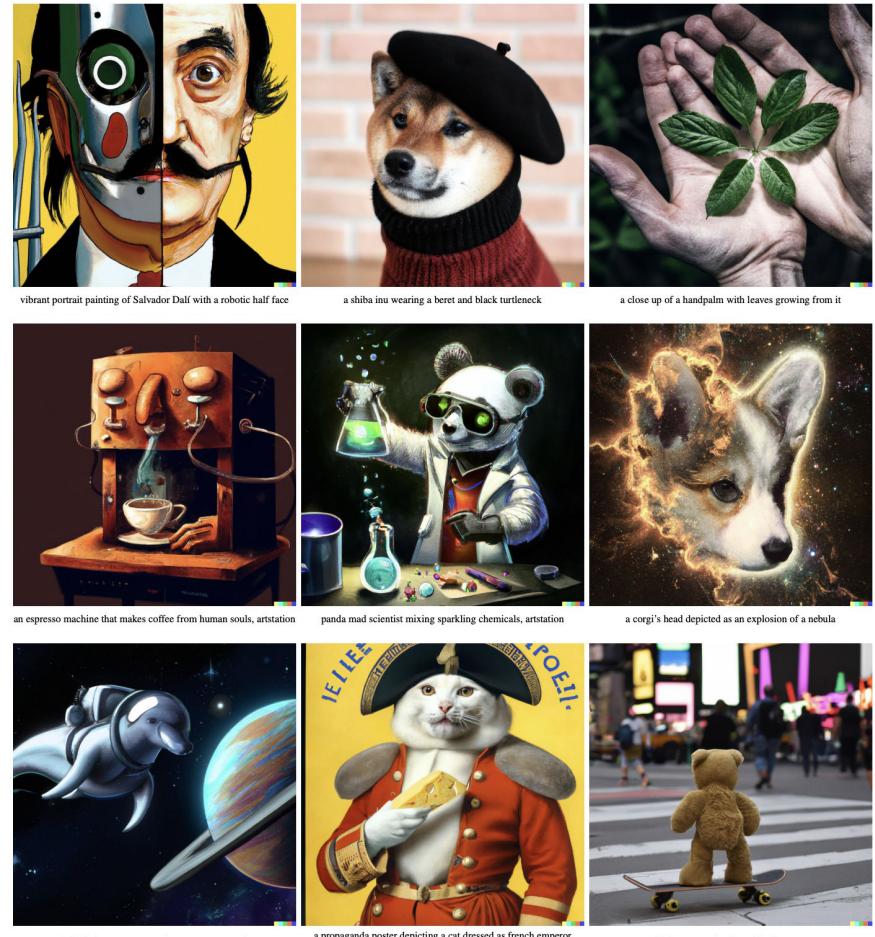


“Teddy bears working on new AI research on the moon in the 1980s.”

“Rabbits attending a college seminar on human anatomy.”

“A wise cat meditating in the Himalayas searching for enlightenment.”

Image source: Sam Altman, <https://openai.com/dall-e-2/>, <https://twitter.com/sama/status/1511724264629678084>



Ramesh et al., Hierarchical Text-Conditional Image Generation with CLIP Latents, 2022.

Neural Networks

Neural networks: the original linear classifier

(Before) Linear score function: $f = Wx$

$$x \in \mathbb{R}^D, W \in \mathbb{R}^{C \times D}$$

Neural networks: 2 layers

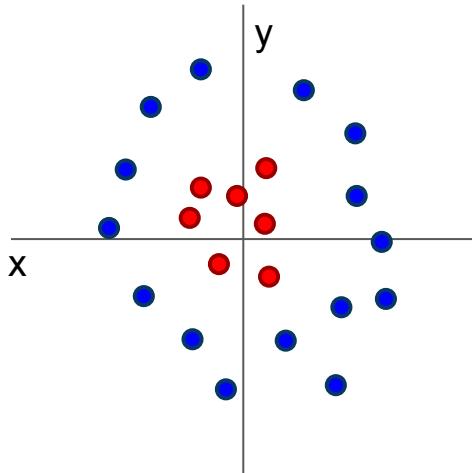
(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

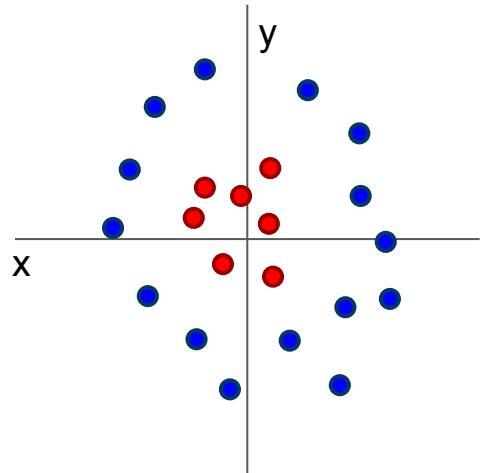
(In practice we will usually add a learnable bias at each layer as well)

Why do we want non-linearity?



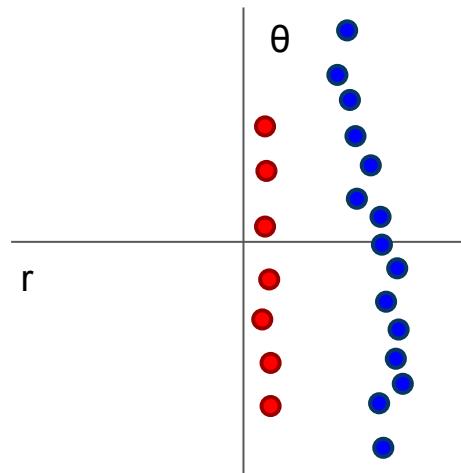
Cannot separate red
and blue points with
linear classifier

Why do we want non-linearity?



Cannot separate red
and blue points with
linear classifier

$$f(x, y) = (r(x, y), \theta(x, y))$$



After applying feature
transform, points can
be separated by linear
classifier

Neural networks: also called fully connected network

(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

“Neural Network” is a very broad term; these are more accurately called “fully-connected networks” or sometimes “multi-layer perceptrons” (MLP)

(In practice we will usually add a learnable bias at each layer as well)

Neural networks: 3 layers

(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$
or 3-layer Neural Network
 $f = W_3 \max(0, W_2 \max(0, W_1 x))$

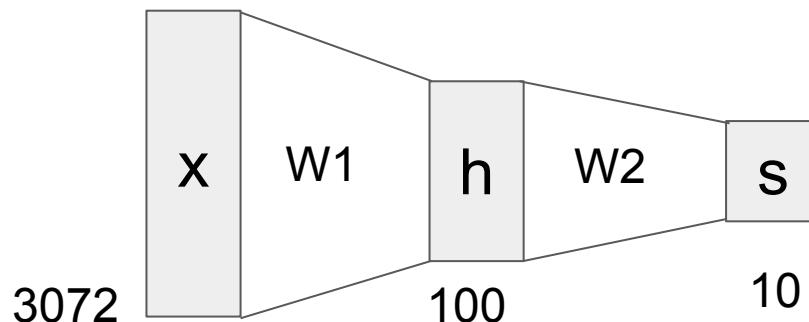
$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H_1 \times D}, W_2 \in \mathbb{R}^{H_2 \times H_1}, W_3 \in \mathbb{R}^{C \times H_2}$$

(In practice we will usually add a learnable bias at each layer as well)

Neural networks: hierarchical computation

(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

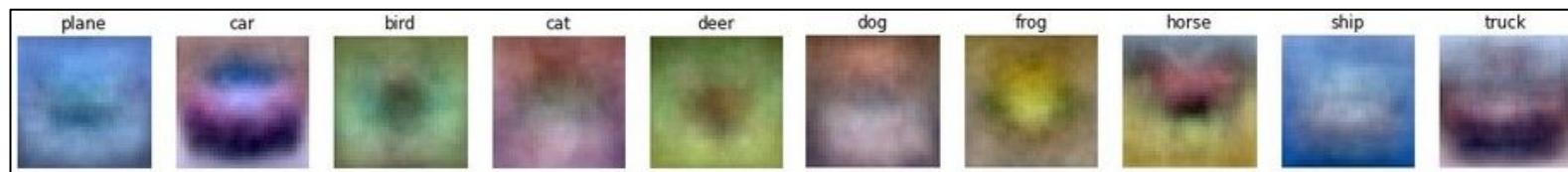
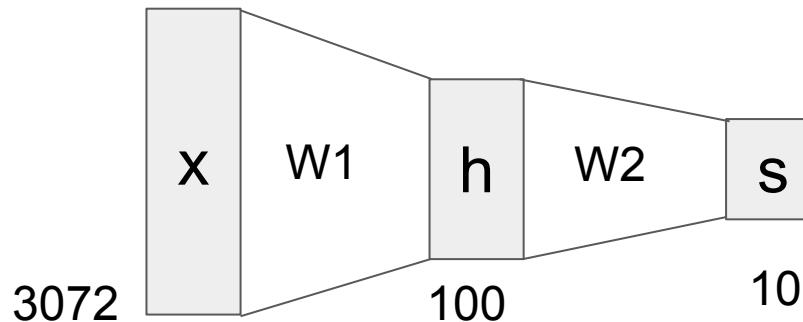


$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

Neural networks: learning 100s of templates

(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$



Learn 100 templates instead of 10.

Share templates between classes

Neural networks: why is max operator important?

(Before) Linear score function: $f = Wx$

(Now) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

The function $\max(0, z)$ is called the **activation function**.

Q: What if we try to build a neural network without one?

$$f = W_2 W_1 x$$

Neural networks: why is max operator important?

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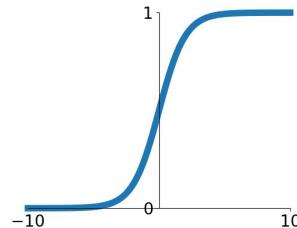
$$f = W_2 W_1 x \quad W_3 = W_2 W_1 \in \mathbb{R}^{C \times H}, f = W_3 x$$

A: We end up with a linear classifier again!

Activation functions

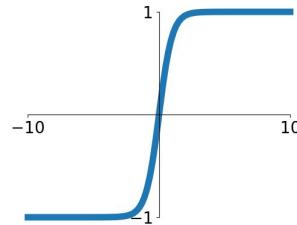
Sigmoid

$$\sigma(x) = \frac{1}{1+e^{-x}}$$



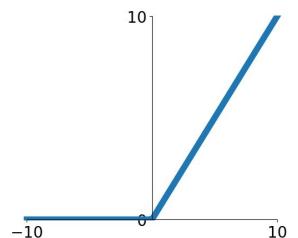
tanh

$$\tanh(x)$$



ReLU

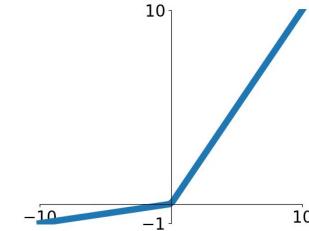
$$\max(0, x)$$



ReLU is a good default choice for most problems

Leaky ReLU

$$\max(0.1x, x)$$

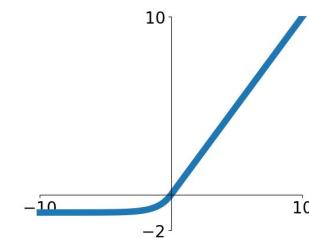


Maxout

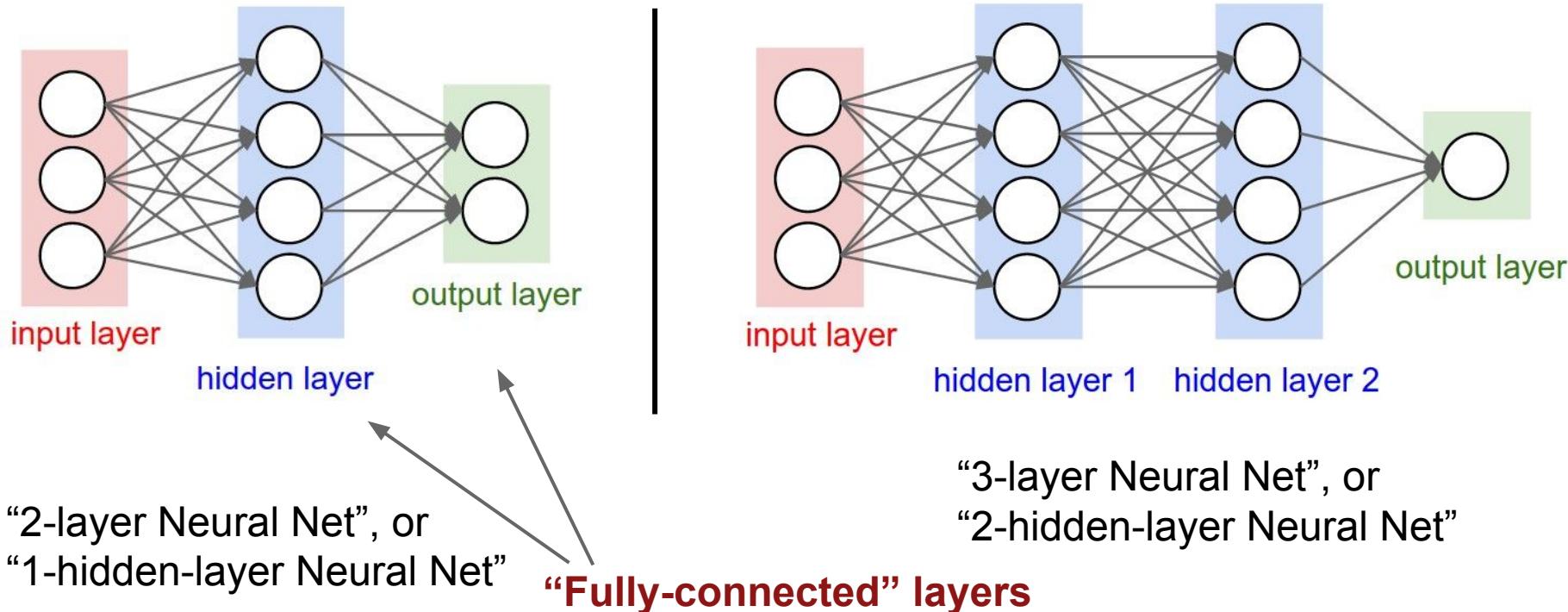
$$\max(w_1^T x + b_1, w_2^T x + b_2)$$

ELU

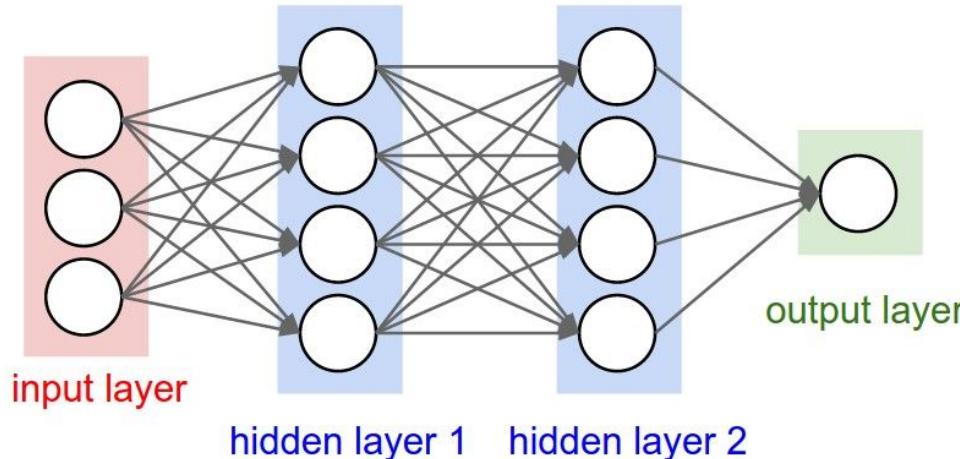
$$\begin{cases} x & x \geq 0 \\ \alpha(e^x - 1) & x < 0 \end{cases}$$



Neural networks: Architectures



Example feed-forward computation of a neural network



```
# forward-pass of a 3-layer neural network:  
f = lambda x: 1.0/(1.0 + np.exp(-x)) # activation function (use sigmoid)  
x = np.random.randn(3, 1) # random input vector of three numbers (3x1)  
h1 = f(np.dot(W1, x) + b1) # calculate first hidden layer activations (4x1)  
h2 = f(np.dot(W2, h1) + b2) # calculate second hidden layer activations (4x1)  
out = np.dot(W3, h2) + b3 # output neuron (1x1)
```

Full implementation of training a 2-layer Neural Network needs ~20 lines:

```
1 import numpy as np
2 from numpy.random import randn
3
4 N, D_in, H, D_out = 64, 1000, 100, 10
5 x, y = randn(N, D_in), randn(N, D_out)
6 w1, w2 = randn(D_in, H), randn(H, D_out)
7
8 for t in range(2000):
9     h = 1 / (1 + np.exp(-x.dot(w1)))
10    y_pred = h.dot(w2)
11    loss = np.square(y_pred - y).sum()
12    print(t, loss)
13
14    grad_y_pred = 2.0 * (y_pred - y)
15    grad_w2 = h.T.dot(grad_y_pred)
16    grad_h = grad_y_pred.dot(w2.T)
17    grad_w1 = x.T.dot(grad_h * h * (1 - h))
18
19    w1 -= 1e-4 * grad_w1
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Define the network

Full implementation of training a 2-layer Neural Network needs ~20 lines:

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Define the network

Forward pass

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Define the network

Forward pass

Calculate the analytical gradients

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```

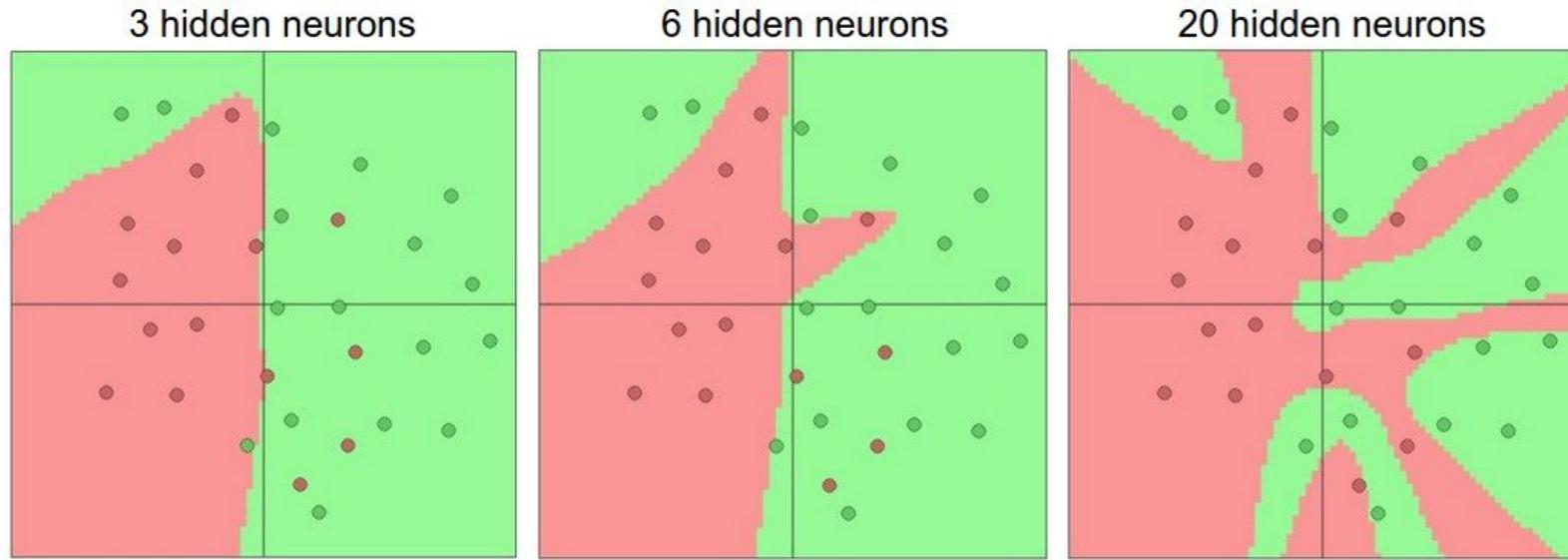
Define the network

Forward pass

Calculate the analytical gradients

Gradient descent

Setting the number of layers and their sizes



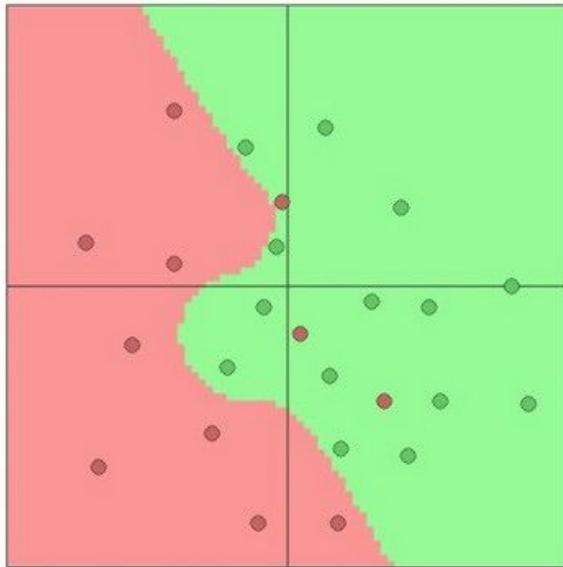
more neurons = more capacity

Do not use size of neural network as a regularizer. Use stronger regularization instead:

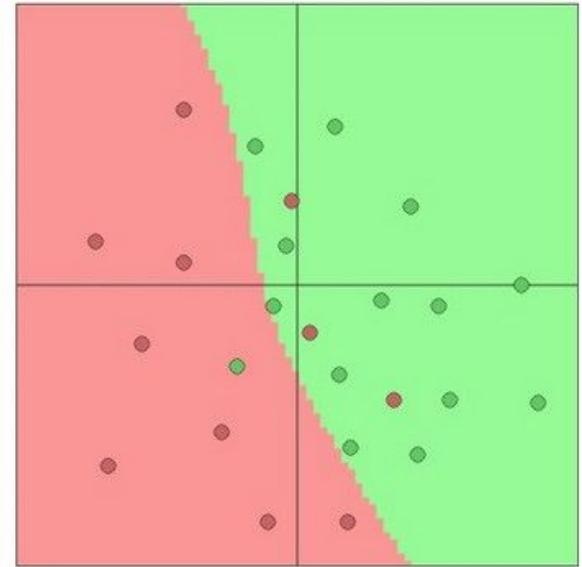
$\lambda = 0.001$



$\lambda = 0.01$



$\lambda = 0.1$



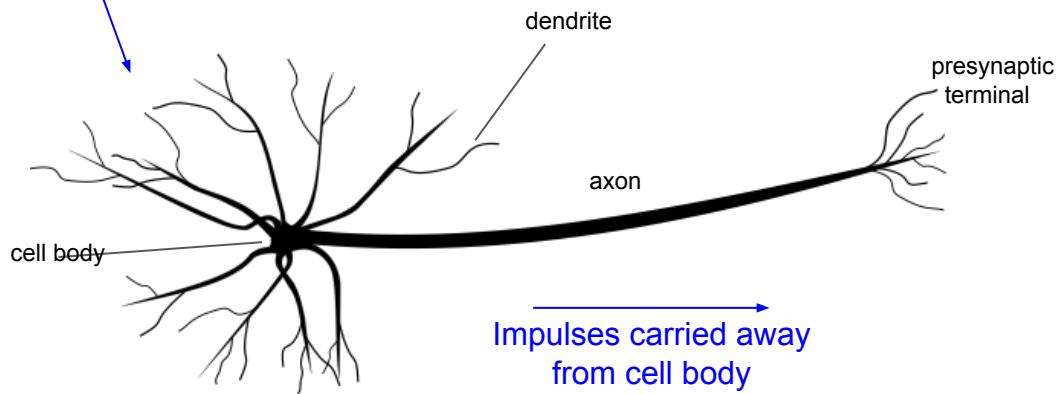
(Web demo with ConvNetJS:
[http://cs.stanford.edu/people/karpathy/convnetjs/demo
/classify2d.html](http://cs.stanford.edu/people/karpathy/convnetjs/demo/classify2d.html))

$$L(W) = \frac{1}{N} \sum_{i=1}^N L_i(f(x_i, W), y_i) + \lambda R(W)$$



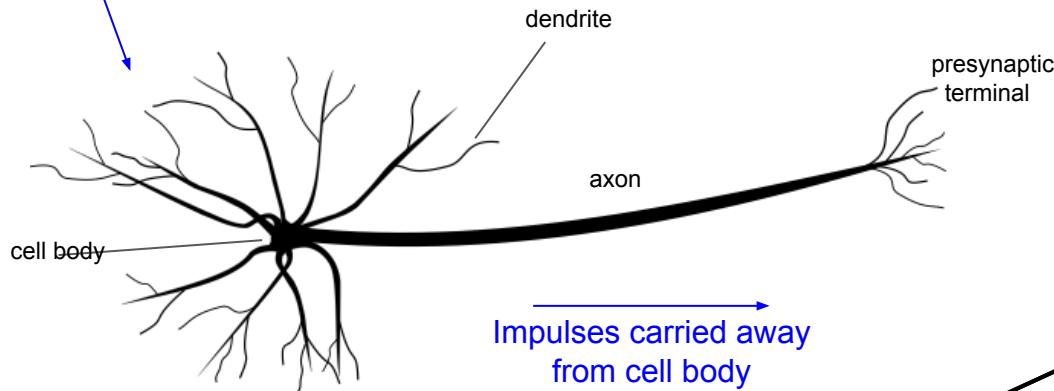
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Impulses carried toward cell body



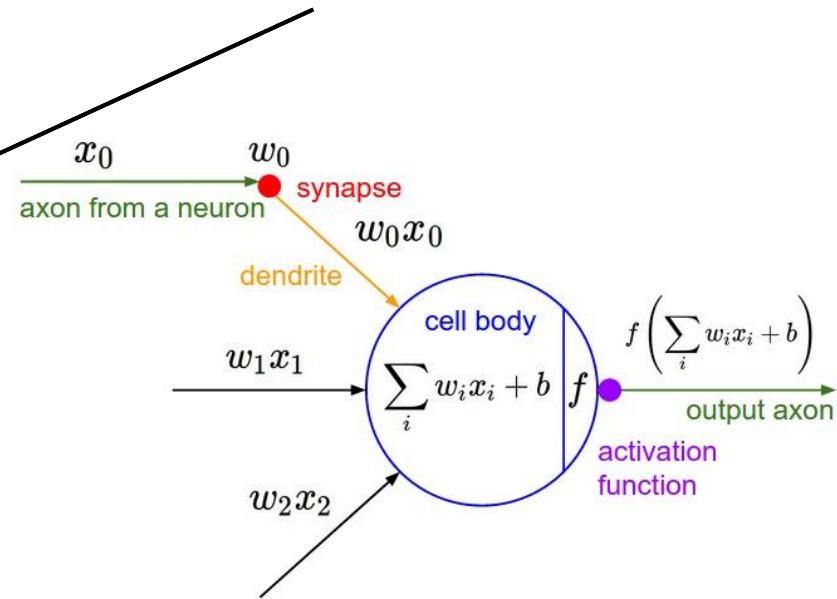
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Impulses carried toward cell body

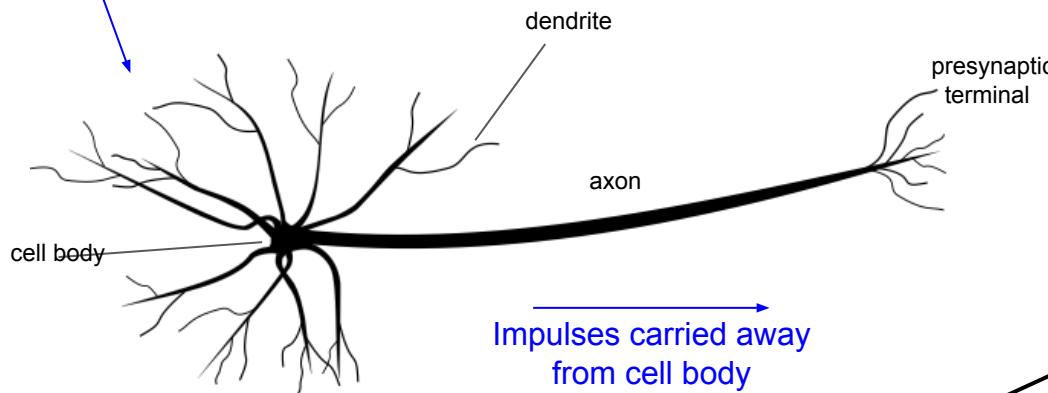


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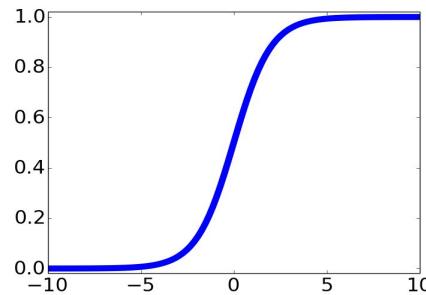
Impulses carried away
from cell body



Impulses carried toward cell body

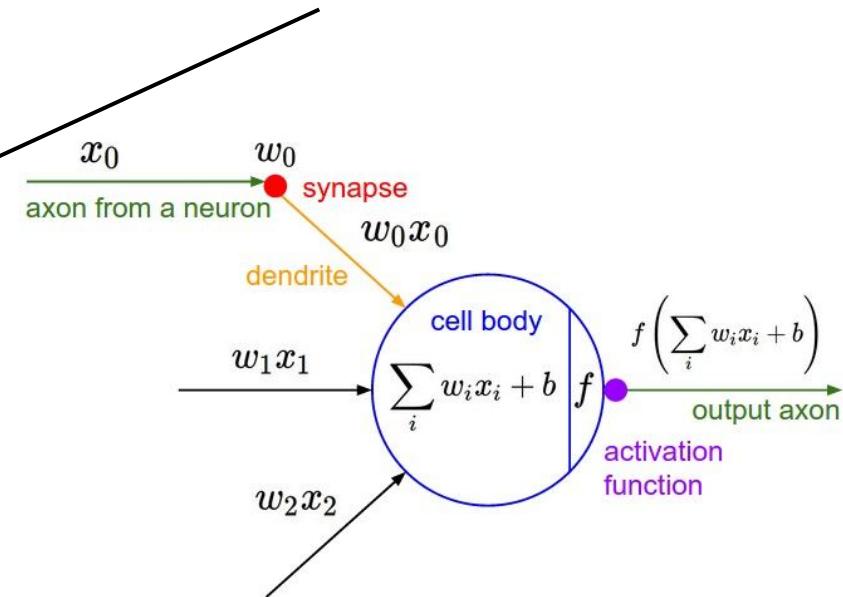


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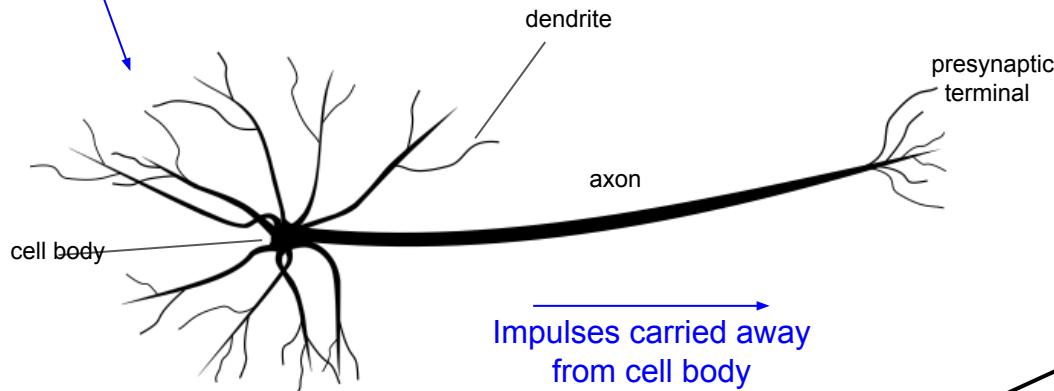


sigmoid activation function

$$\frac{1}{1 + e^{-x}}$$

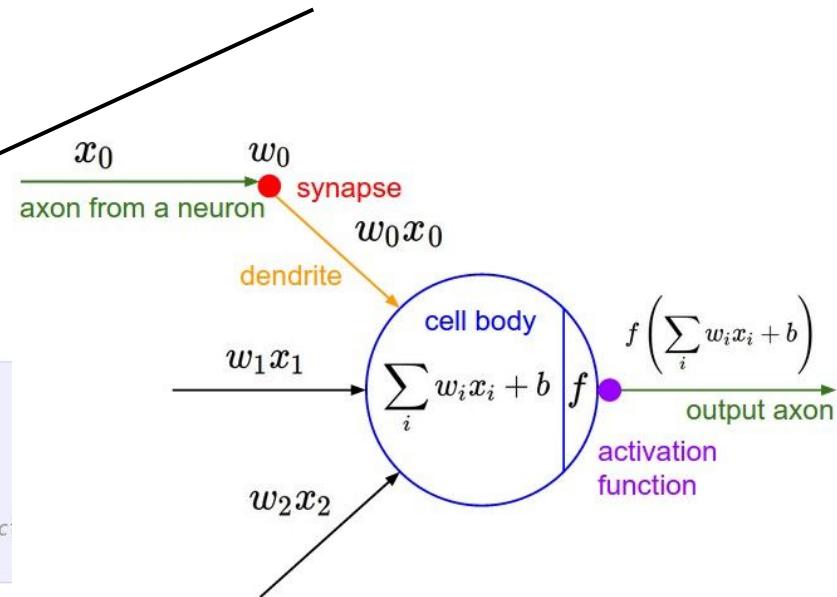


Impulses carried toward cell body

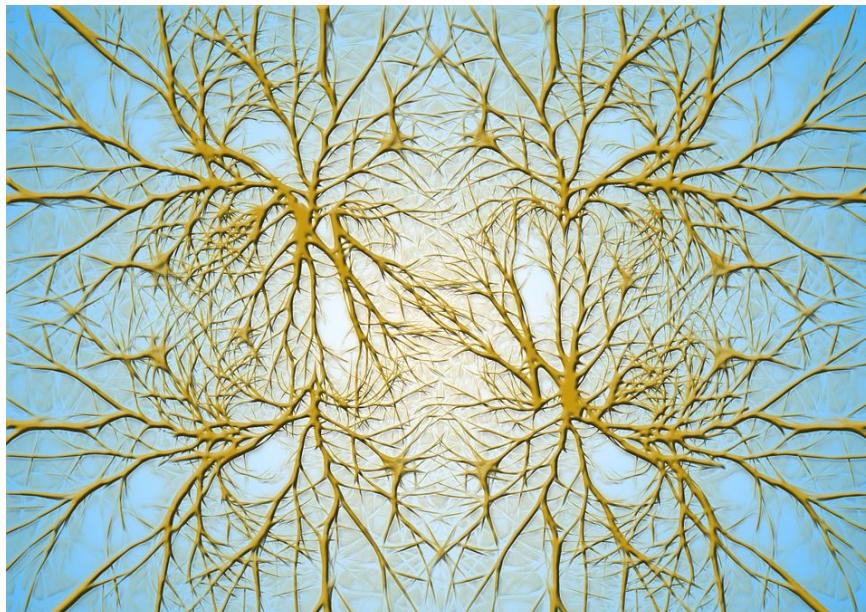


This image by Felipe Perucho
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```
class Neuron:  
    # ...  
    def neuron_tick(inputs):  
        """ assume inputs and weights are 1-D numpy arrays and bias is a number """  
        cell_body_sum = np.sum(inputs * self.weights) + self.bias  
        firing_rate = 1.0 / (1.0 + math.exp(-cell_body_sum)) # sigmoid activation function  
        return firing_rate
```

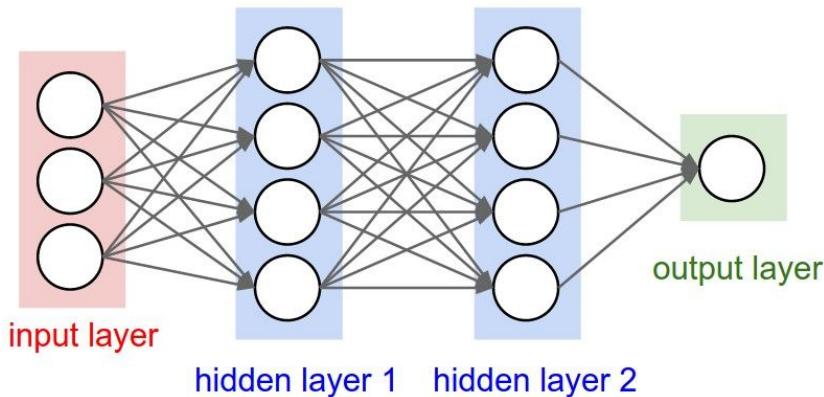


Biological Neurons: Complex connectivity patterns

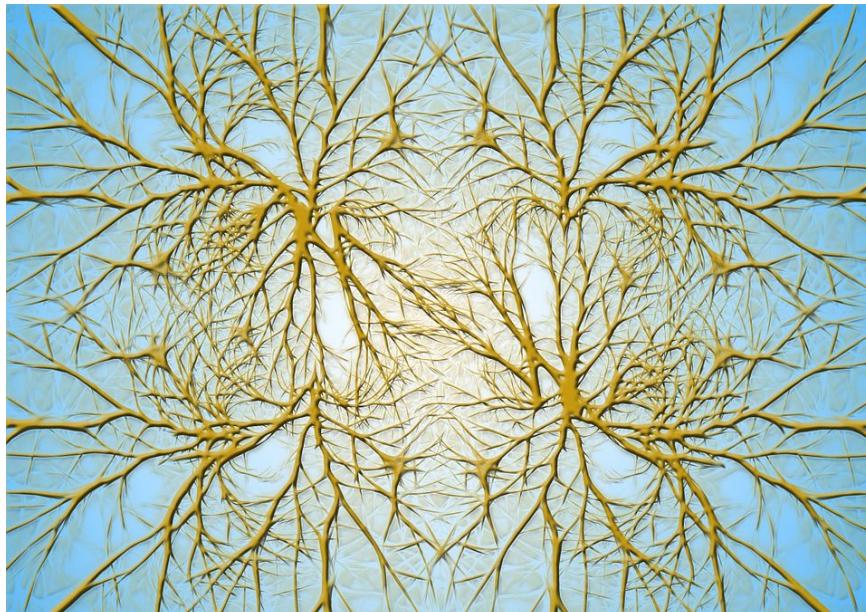


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Neurons in a neural network:
Organized into regular layers for
computational efficiency

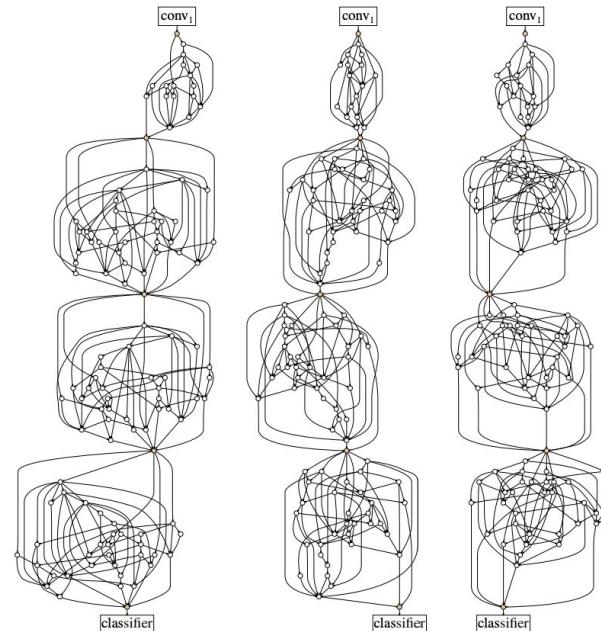


Biological Neurons: Complex connectivity patterns



[This image is CC0 Public Domain](#)

But neural networks with random connections can work too!



Xie et al, "Exploring Randomly Wired Neural Networks for Image Recognition", arXiv 2019

Be very careful with your brain analogies!

Biological Neurons:

- Many different types
- Dendrites can perform complex non-linear computations
- Synapses are not a single weight but a complex non-linear dynamical system

[Dendritic Computation. London and Häusser]

Plugging in neural networks with loss functions

$$s = f(x; W_1, W_2) = W_2 \max(0, W_1 x)$$

Nonlinear score function

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

SVM Loss on predictions

$$R(W) = \sum_k W_k^2$$

Regularization

$$L = \frac{1}{N} \sum_{i=1}^N L_i + \lambda R(W_1) + \lambda R(W_2)$$

Total loss: data loss + regularization

Problem: How to compute gradients?

$$s = f(x; W_1, W_2) = W_2 \max(0, W_1 x) \quad \text{Nonlinear score function}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \quad \text{SVM Loss on predictions}$$

$$R(W) = \sum_k W_k^2 \quad \text{Regularization}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + \lambda R(W_1) + \lambda R(W_2) \quad \text{Total loss: data loss + regularization}$$

If we can compute $\frac{\partial L}{\partial W_1}, \frac{\partial L}{\partial W_2}$ then we can learn W_1 and W_2

(Bad) Idea: Derive $\nabla_W L$ on paper

$$s = f(x; W) = Wx$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

$$= \sum_{j \neq y_i} \max(0, W_{j,:} \cdot x + W_{y_i,:} \cdot x + 1)$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + \lambda \sum_k W_k^2$$

$$= \frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, W_{j,:} \cdot x + W_{y_i,:} \cdot x + 1) + \lambda \sum_k W_k^2$$

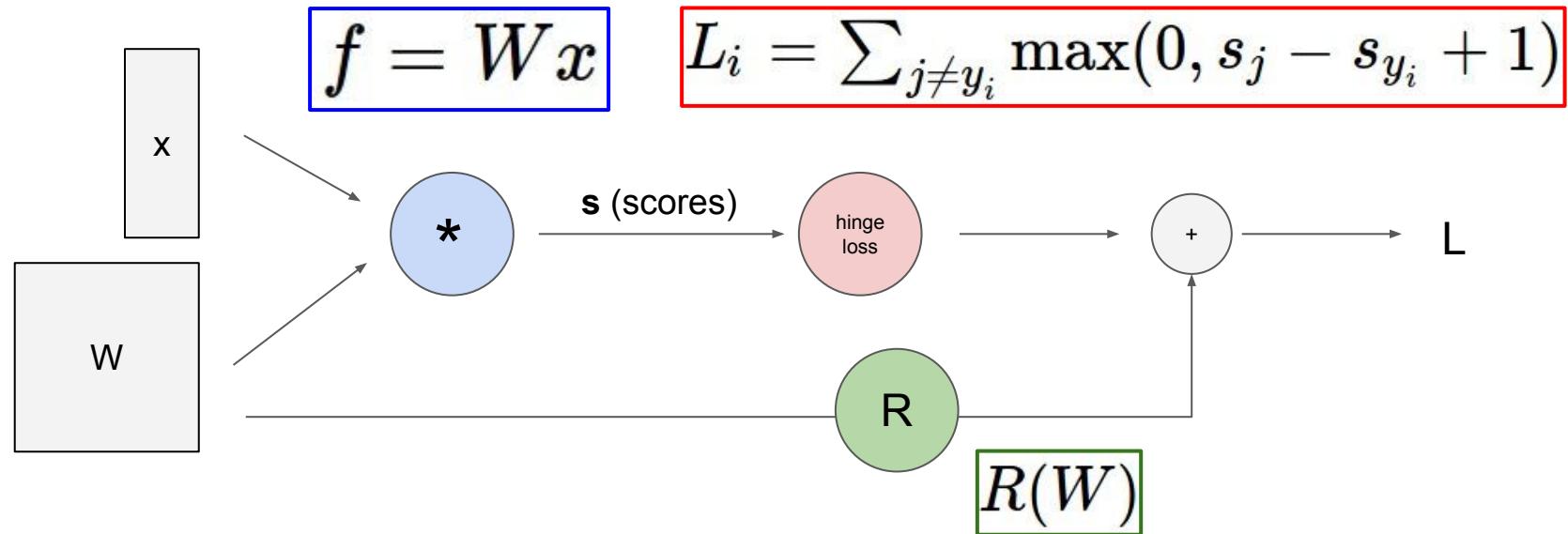
$$\nabla_W L = \nabla_W \left(\frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, W_{j,:} \cdot x + W_{y_i,:} \cdot x + 1) + \lambda \sum_k W_k^2 \right)$$

Problem: Very tedious: Lots of matrix calculus, need lots of paper

Problem: What if we want to change loss? E.g. use softmax instead of SVM? Need to re-derive from scratch =(

Problem: Not feasible for very complex models!

Better Idea: Computational graphs + Backpropagation



Convolutional network (AlexNet)

input image

weights

loss

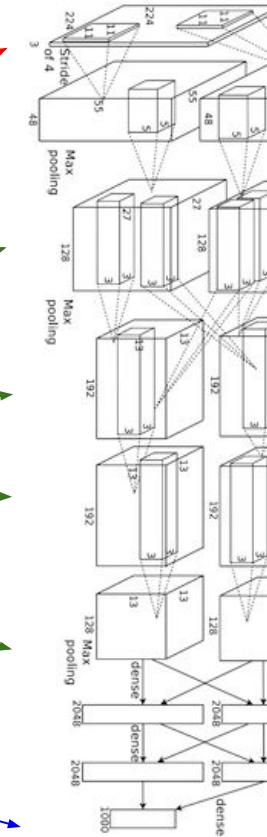


Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Really complex neural networks!!

input image

loss

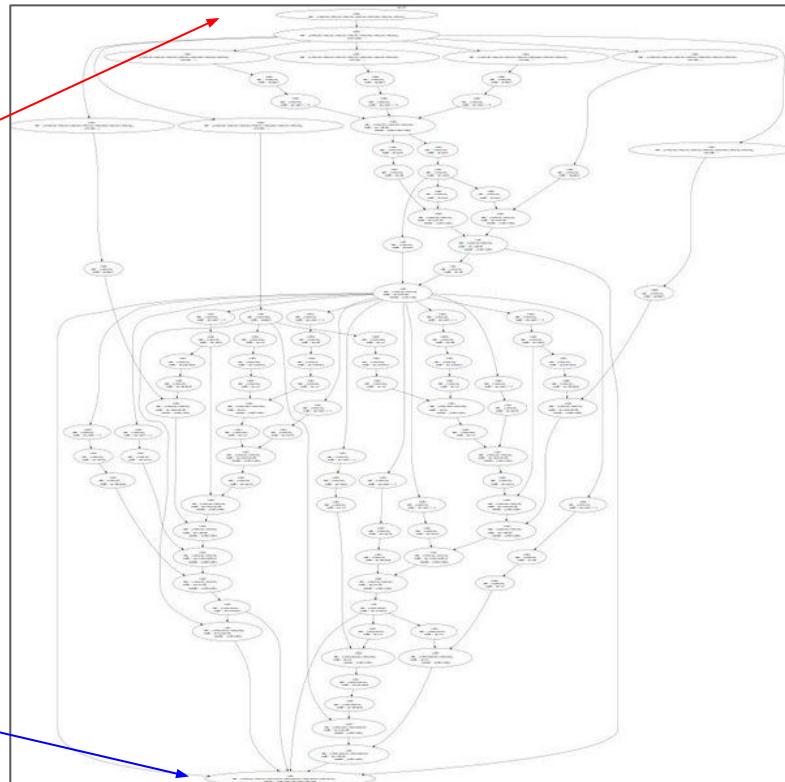


Figure reproduced with permission from a [Twitter post](#) by Andrej Karpathy.

Neural Turing Machine

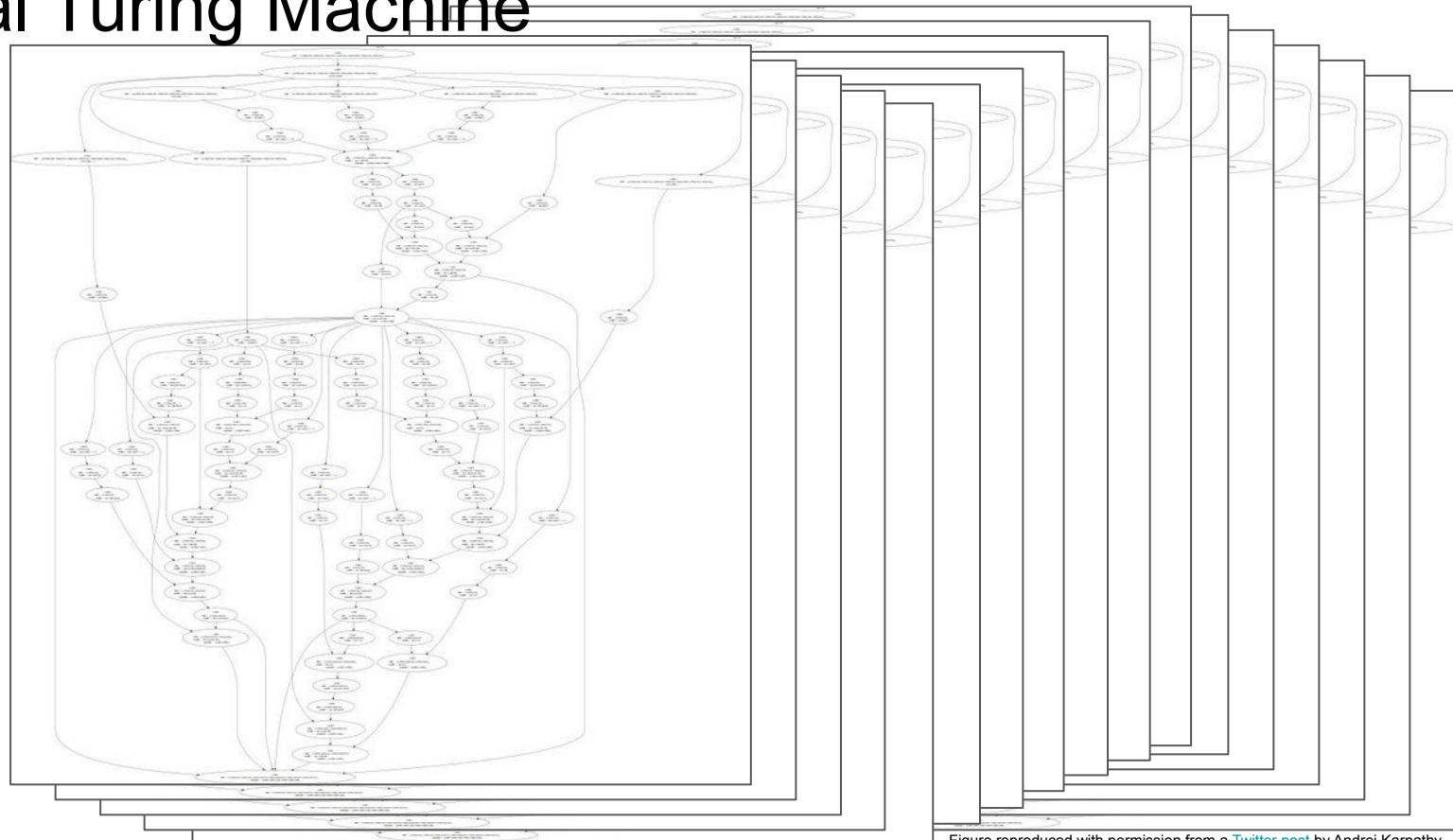


Figure reproduced with permission from a [Twitter post](#) by Andrej Karpathy.

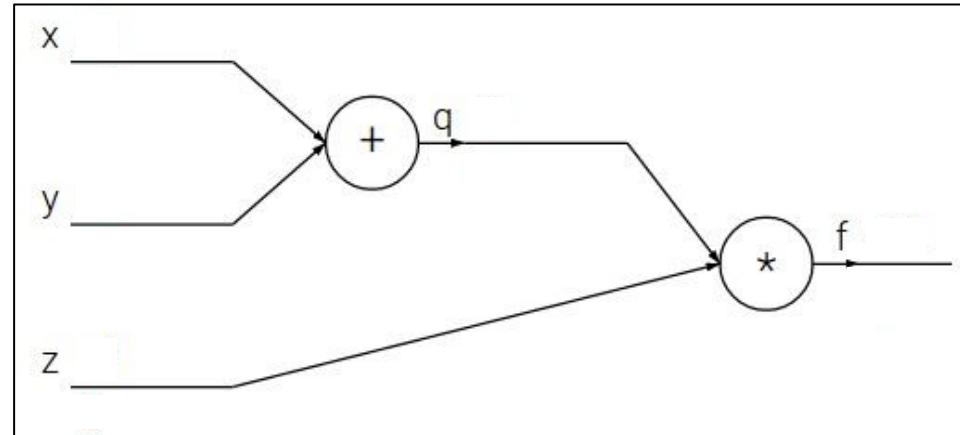
Solution: Backpropagation

Backpropagation: a simple example

$$f(x, y, z) = (x + y)z$$

Backpropagation: a simple example

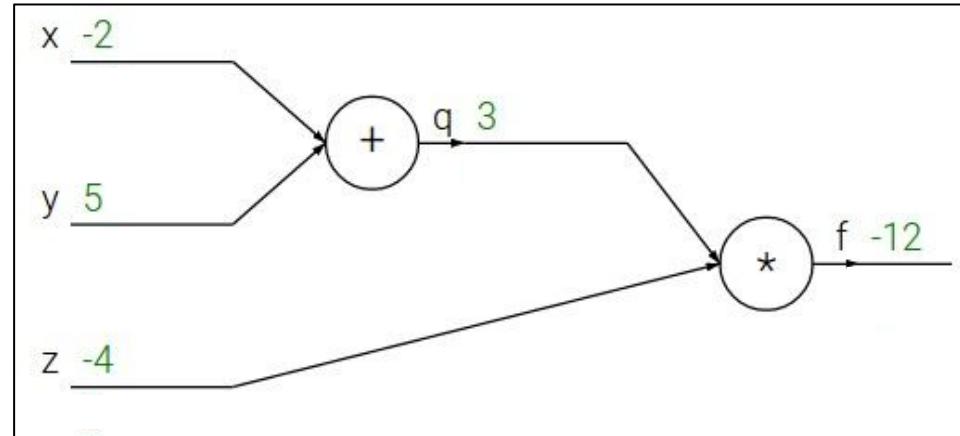
$$f(x, y, z) = (x + y)z$$



Backpropagation: a simple example

$$f(x, y, z) = (x + y)z$$

e.g. $x = -2$, $y = 5$, $z = -4$

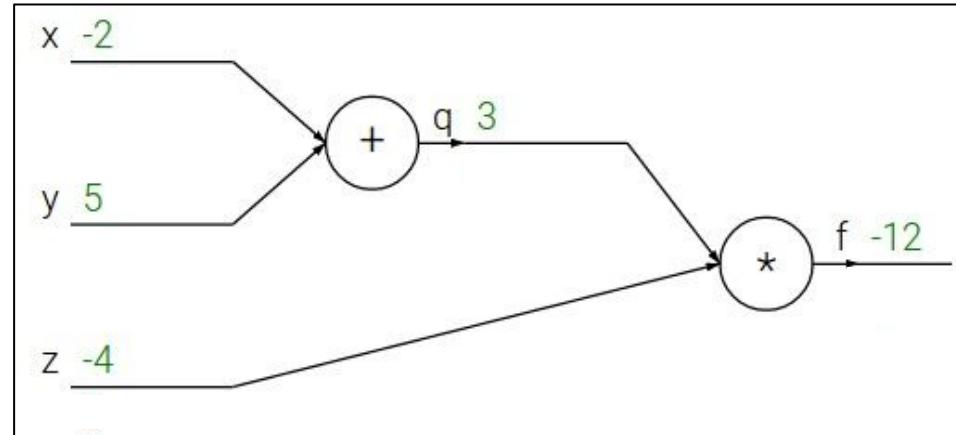


Backpropagation: a simple example

$$f(x, y, z) = (x + y)z$$

e.g. $x = -2, y = 5, z = -4$

$$q = x + y \quad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$



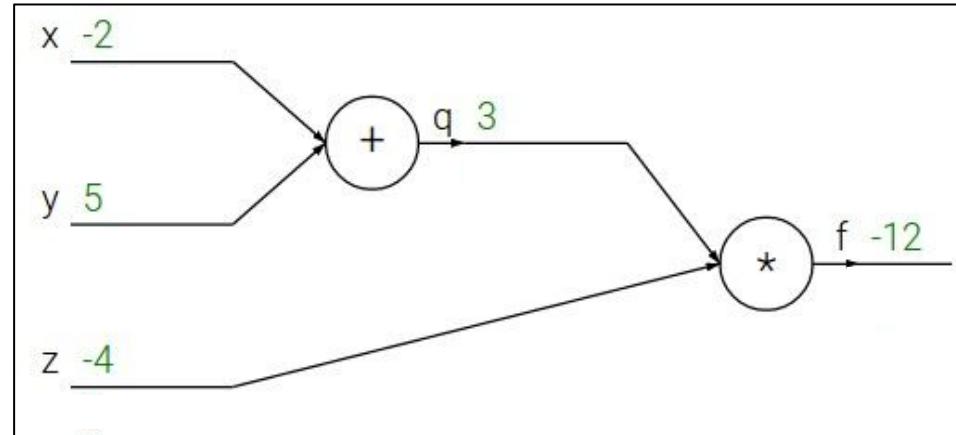
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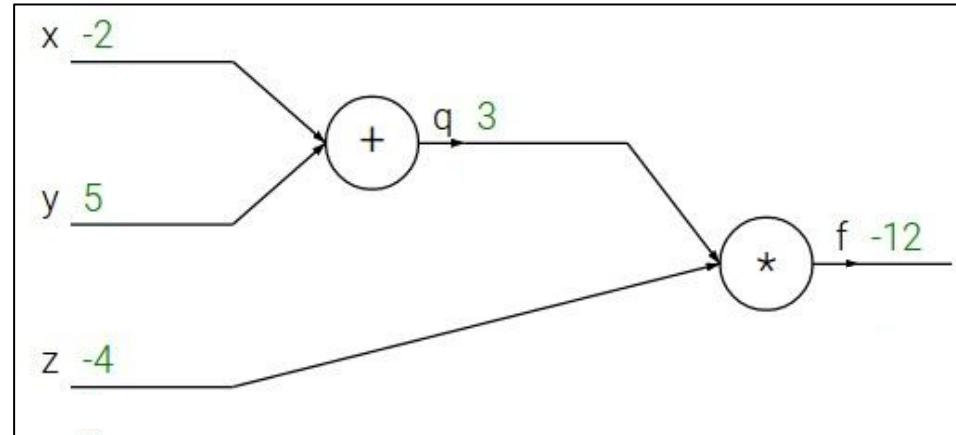
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Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation: a simple example

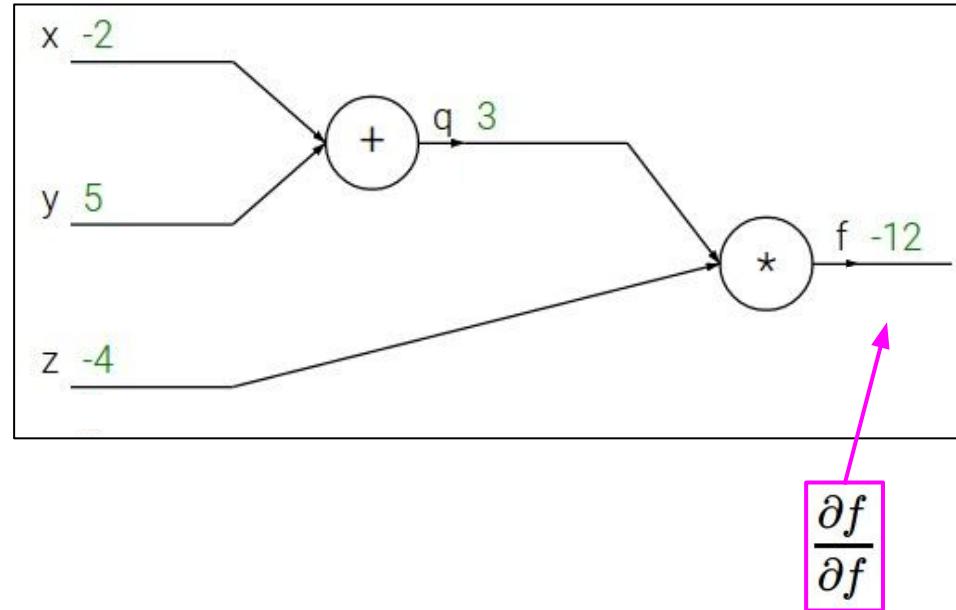
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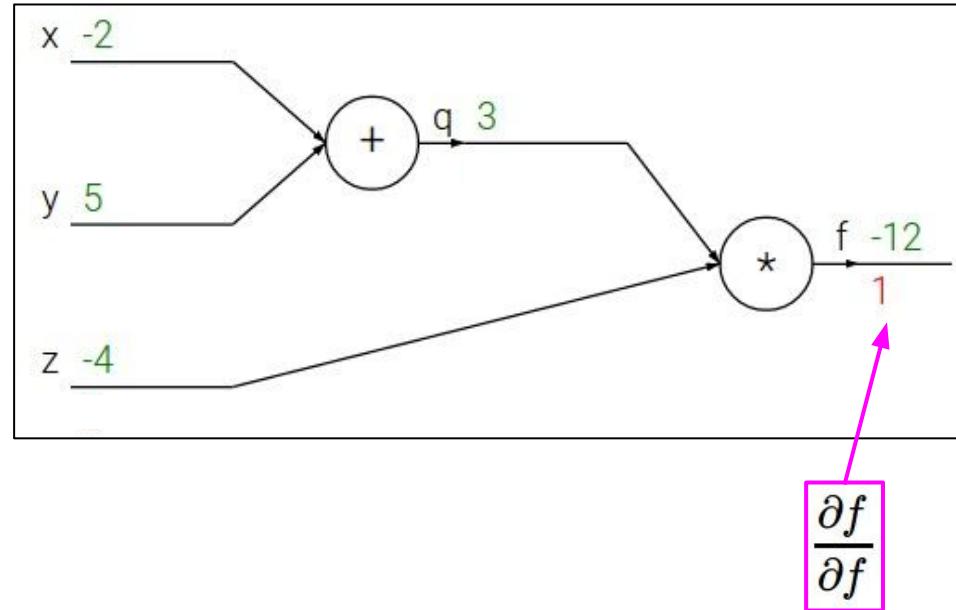
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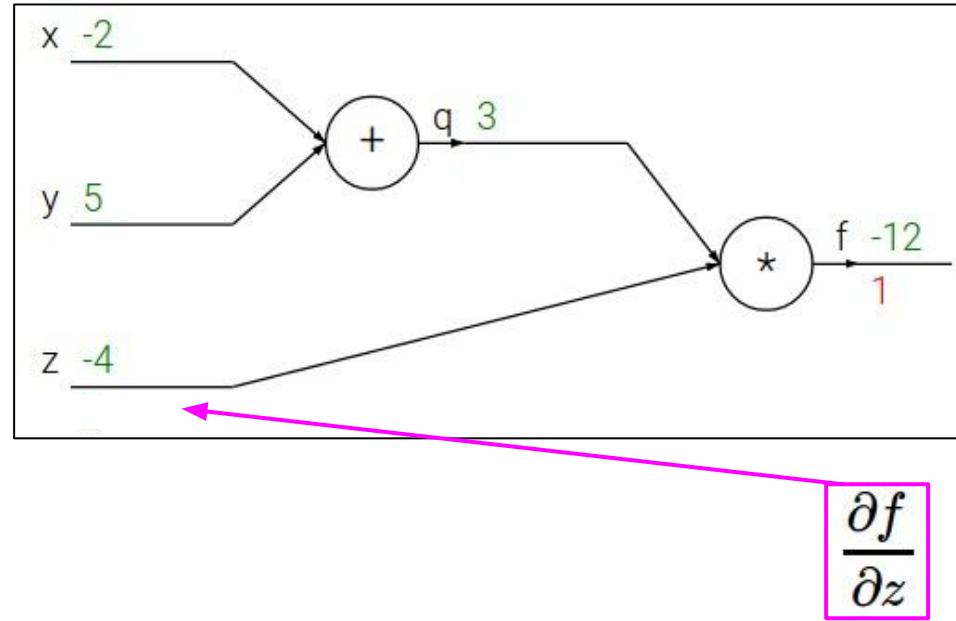
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$$\frac{\partial f}{\partial z}$$

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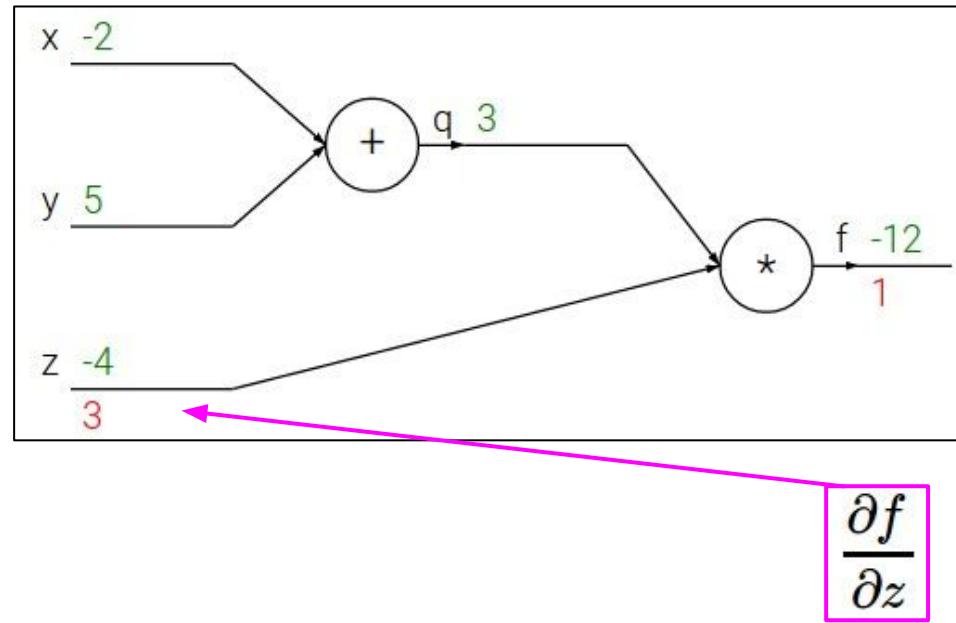
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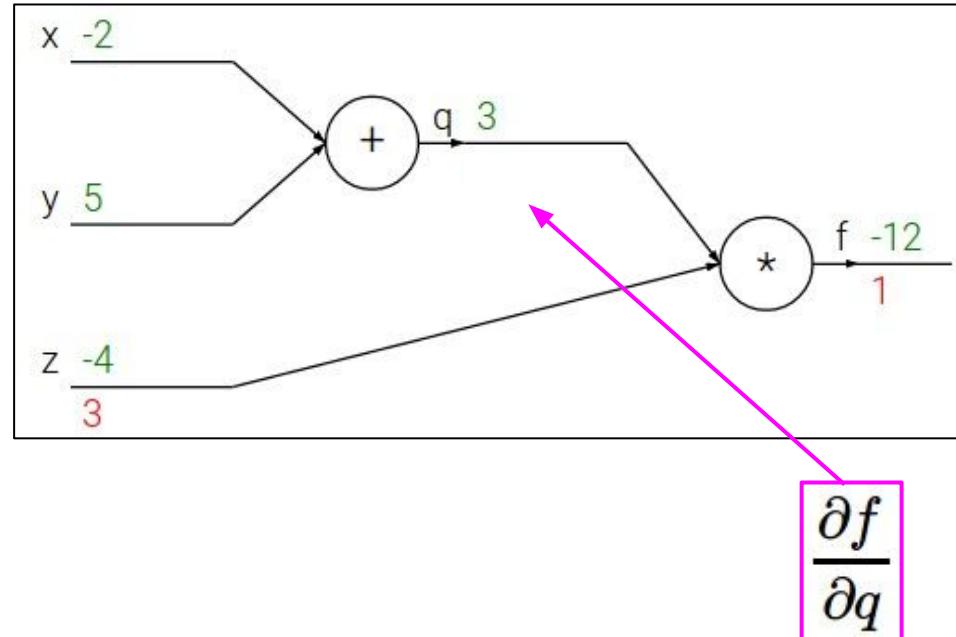
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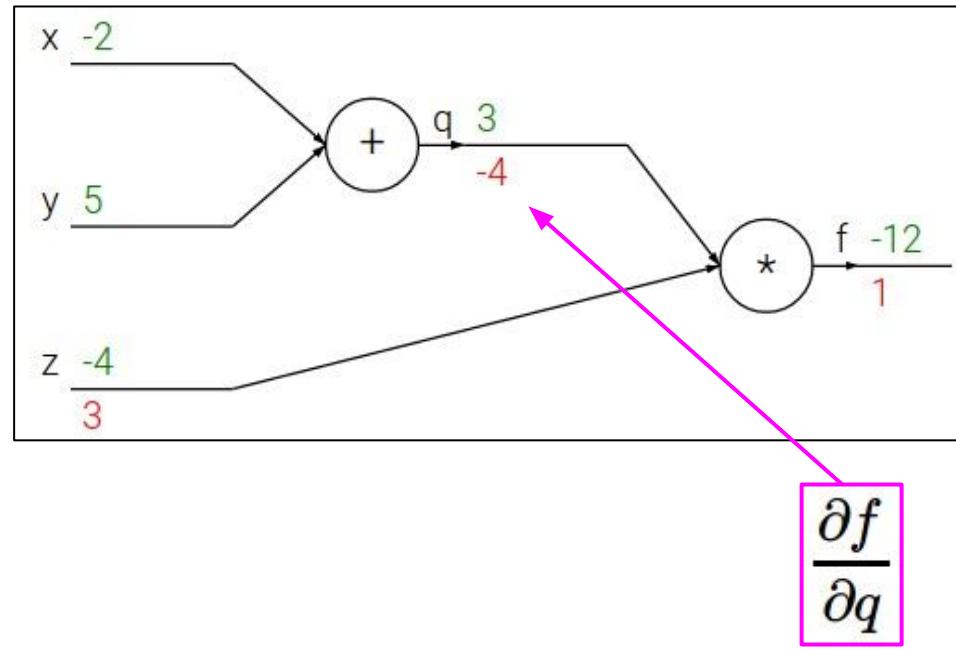
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Backpropagation: a simple example

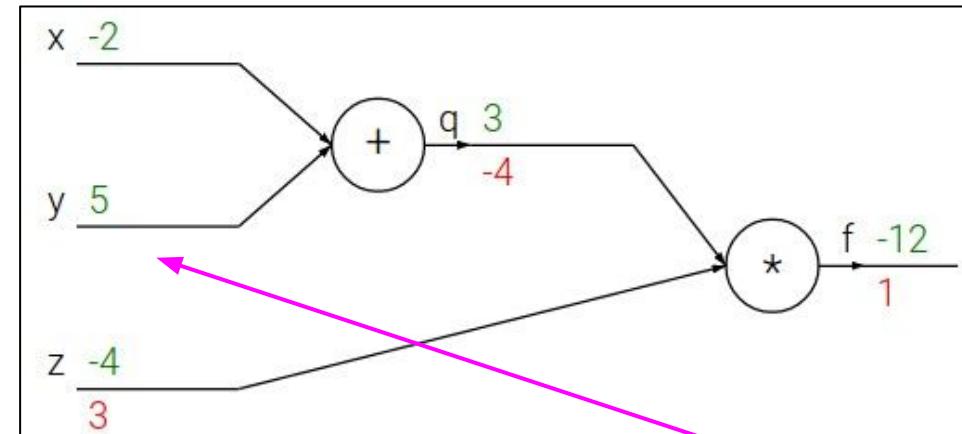
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Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Chain rule:

$$\frac{\partial f}{\partial y} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial y}$$

Upstream
gradient

Local
gradient

$$\frac{\partial f}{\partial y}$$

Backpropagation: a simple example

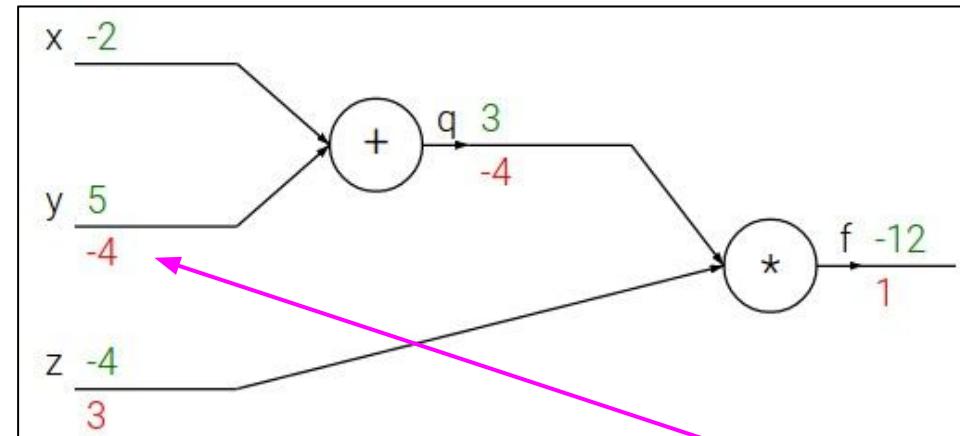
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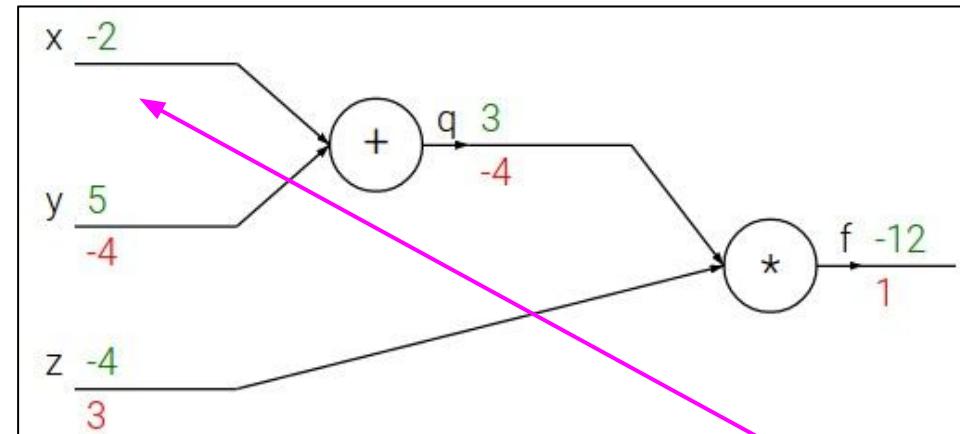
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Local
gradient

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Backpropagation: a simple example

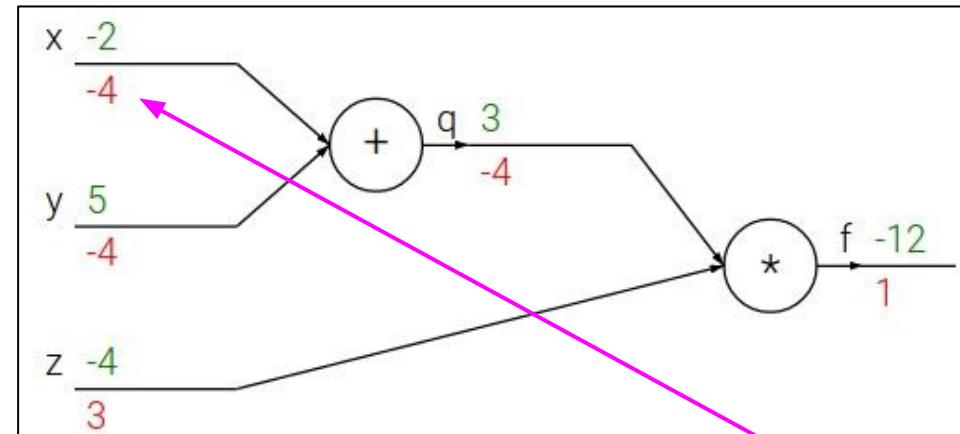
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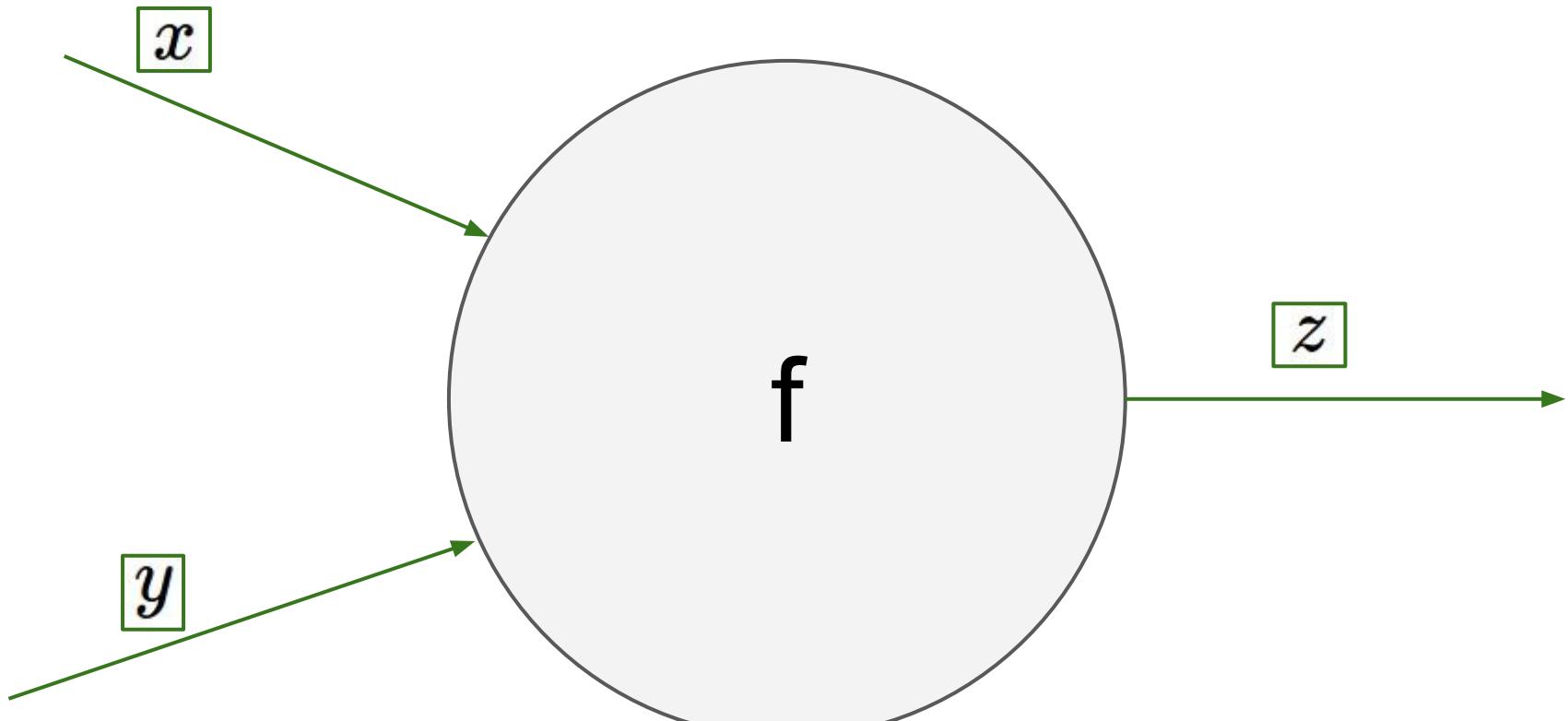


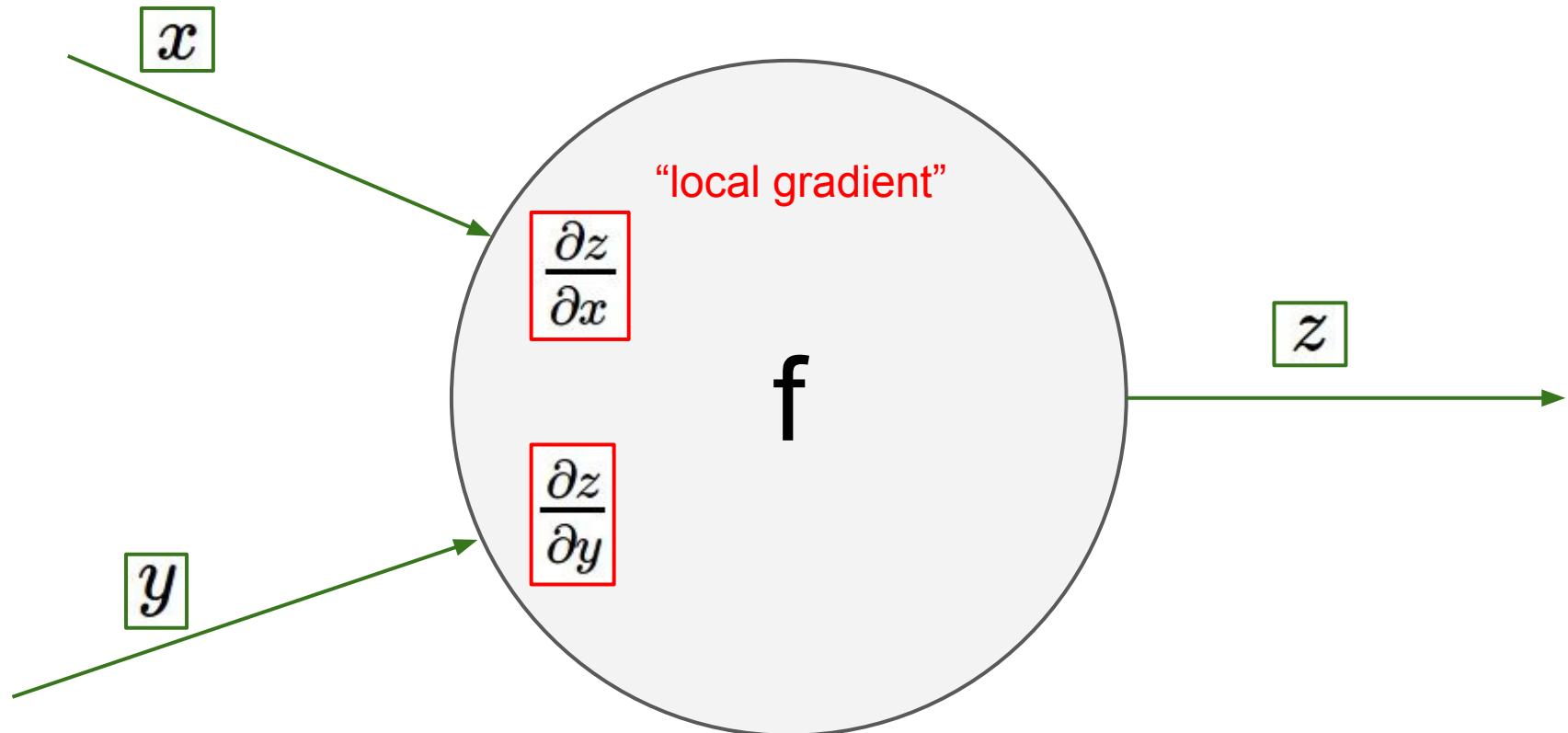
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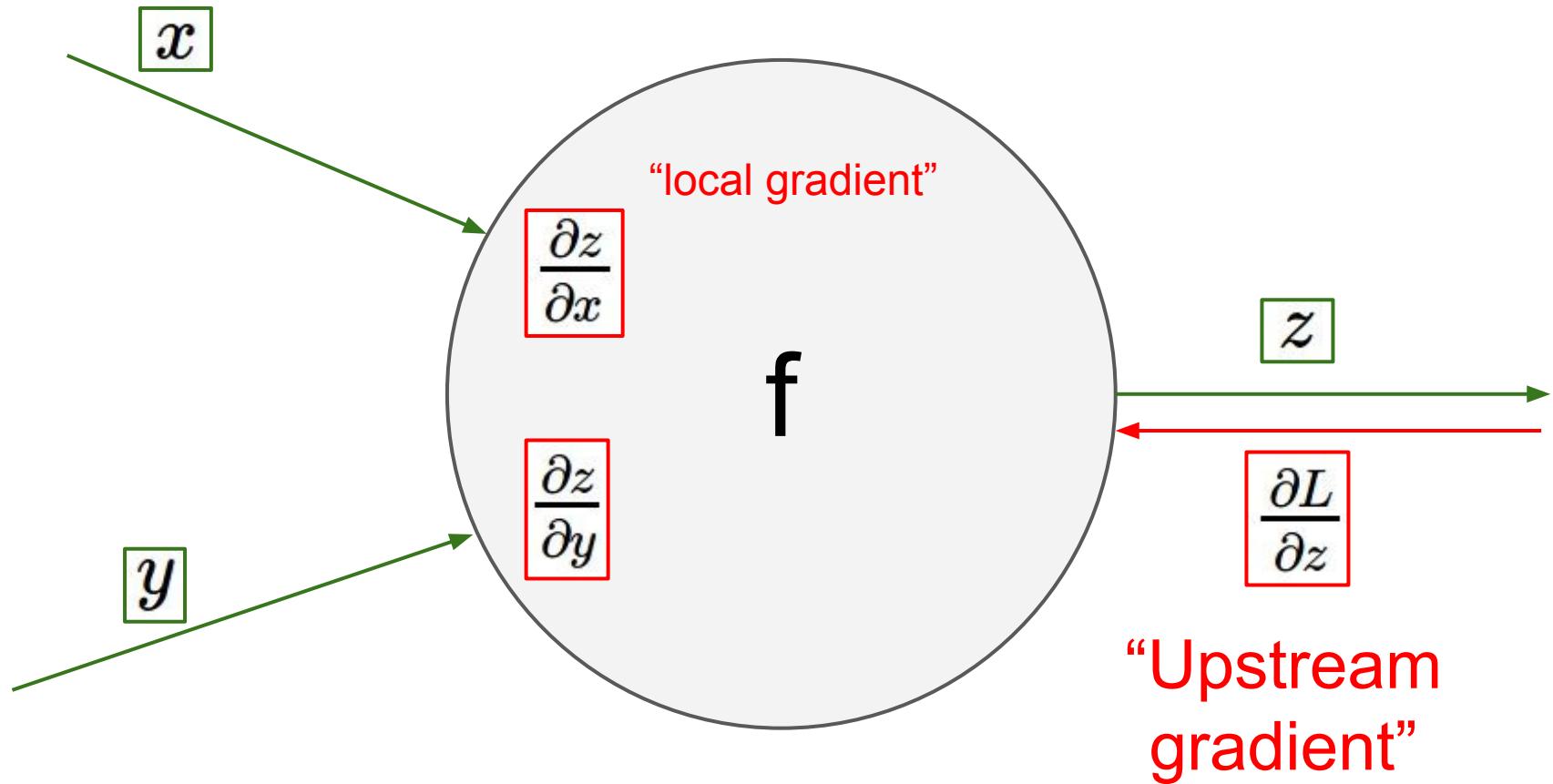
$$\frac{\partial f}{\partial x} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial x}$$

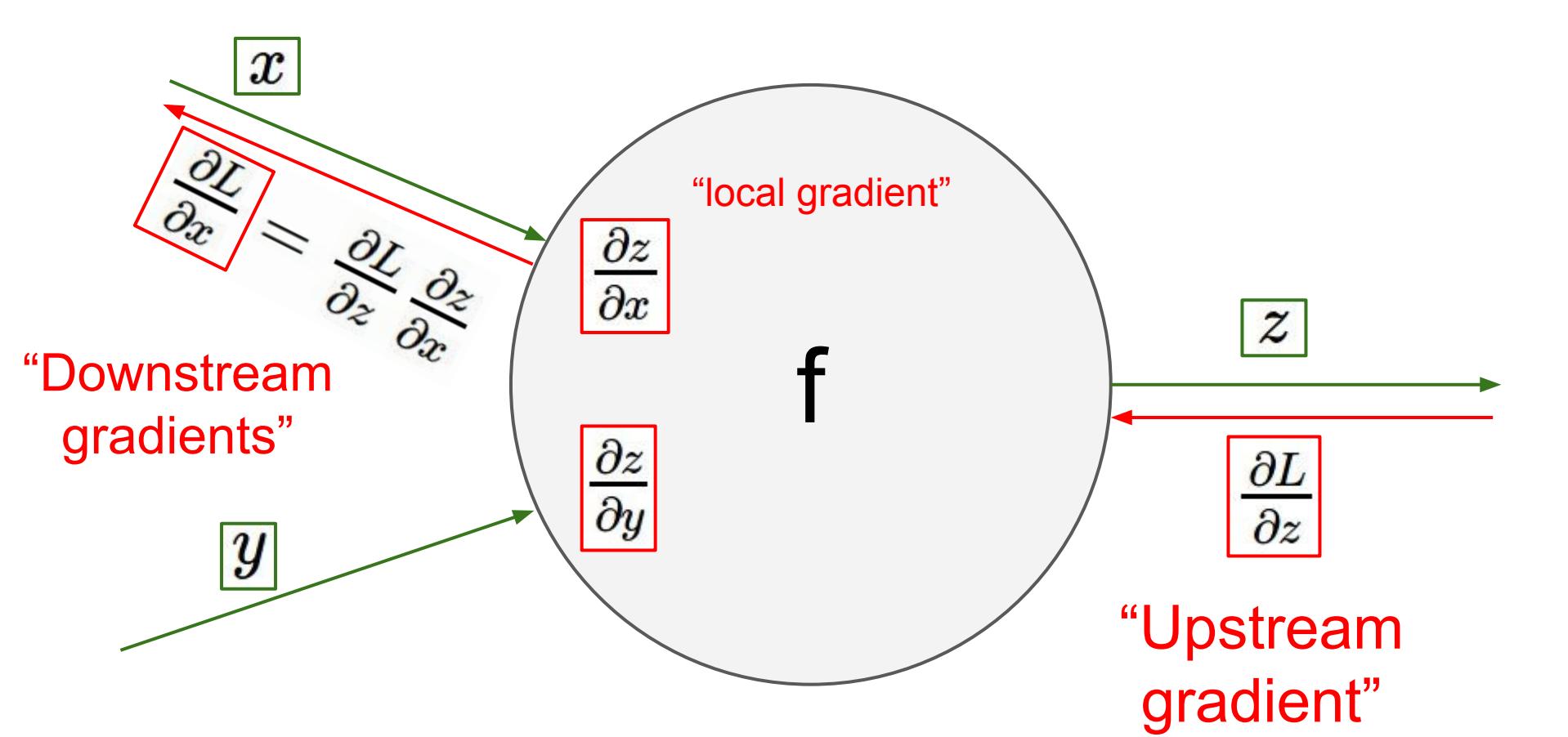
Upstream
gradient

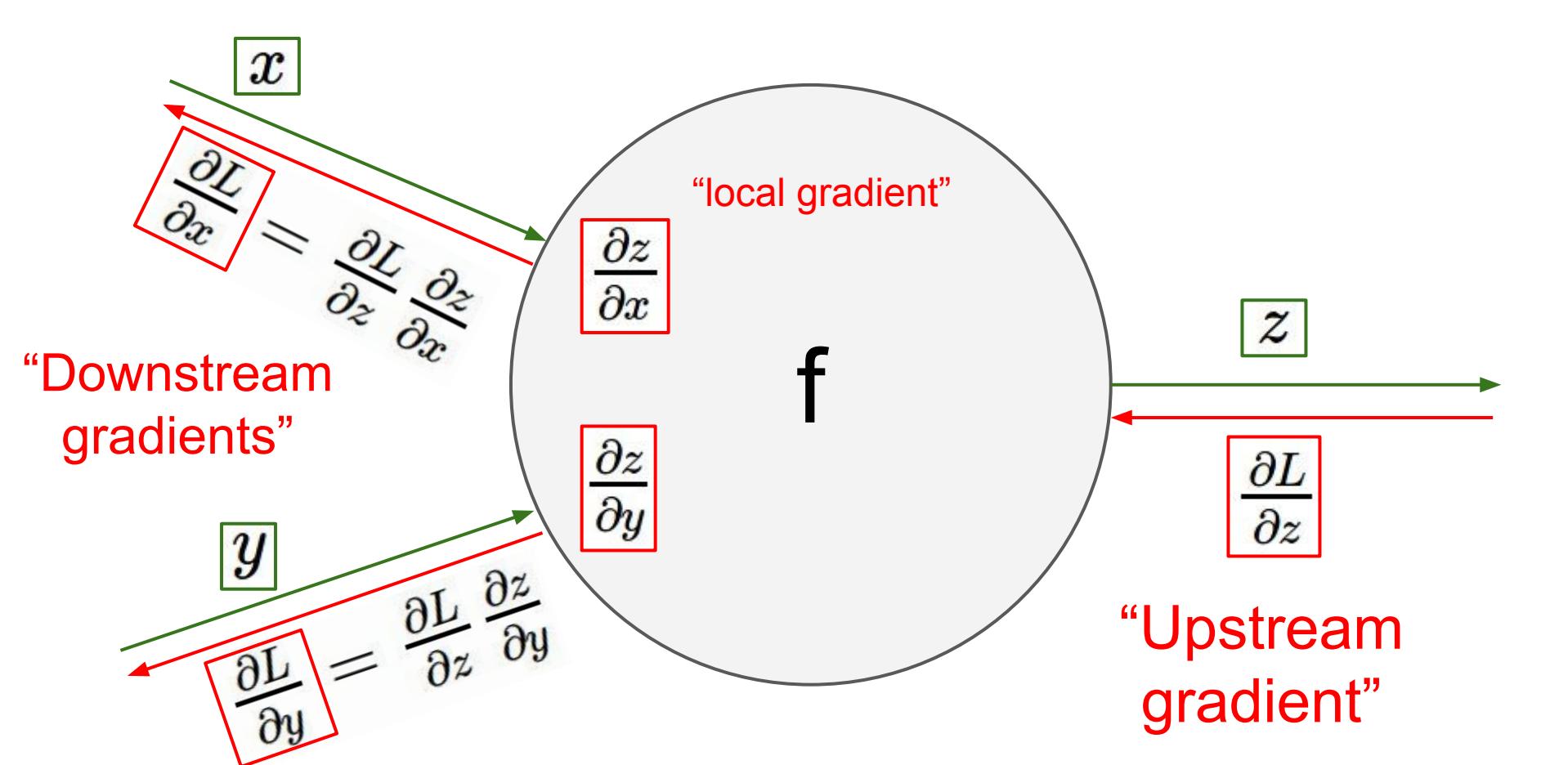
Local
gradient

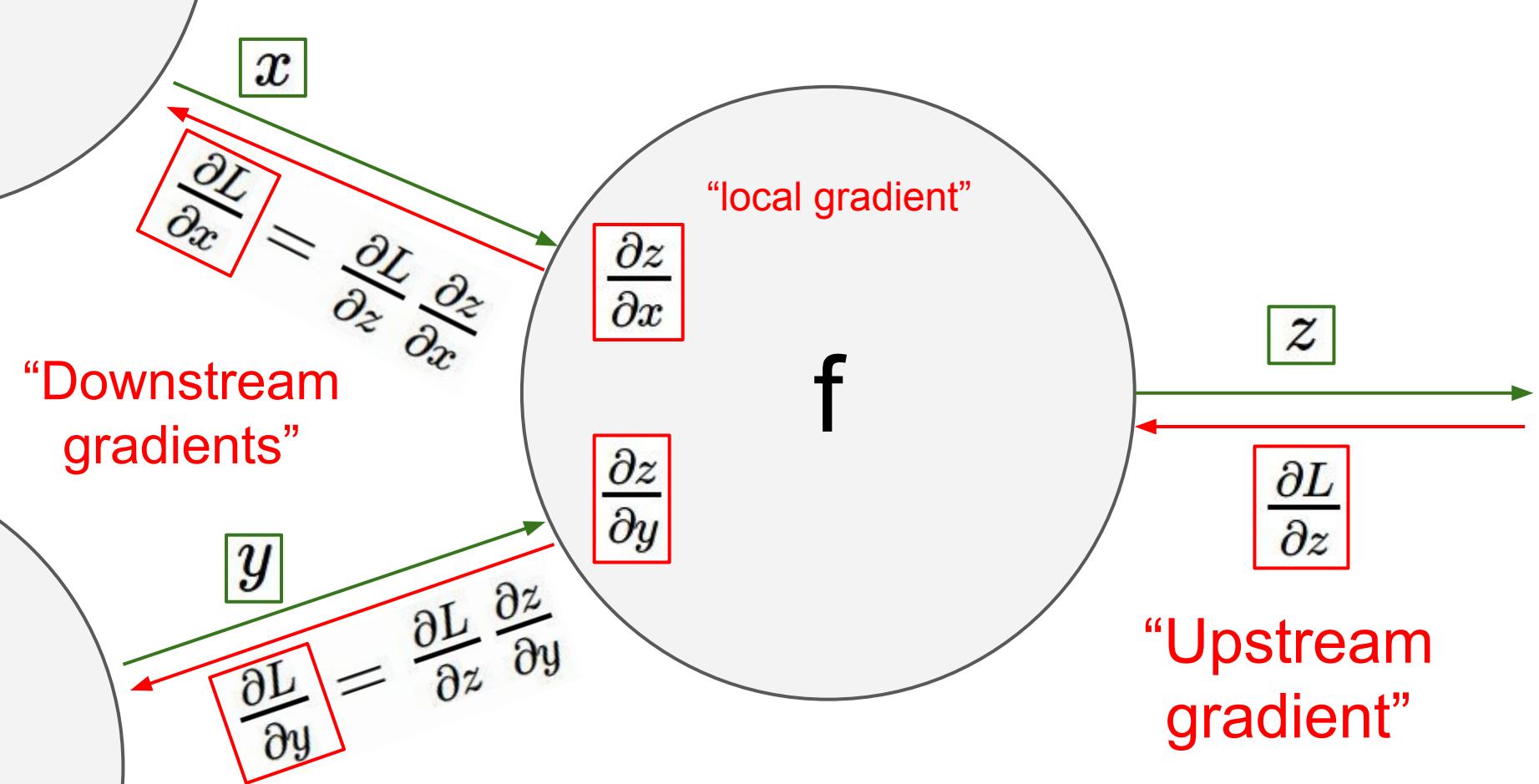






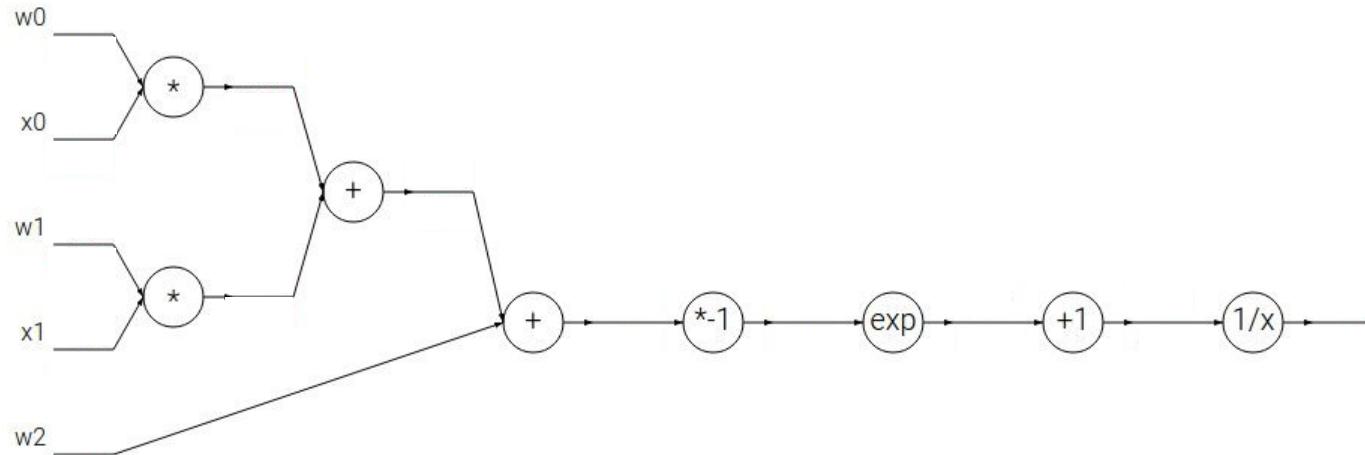






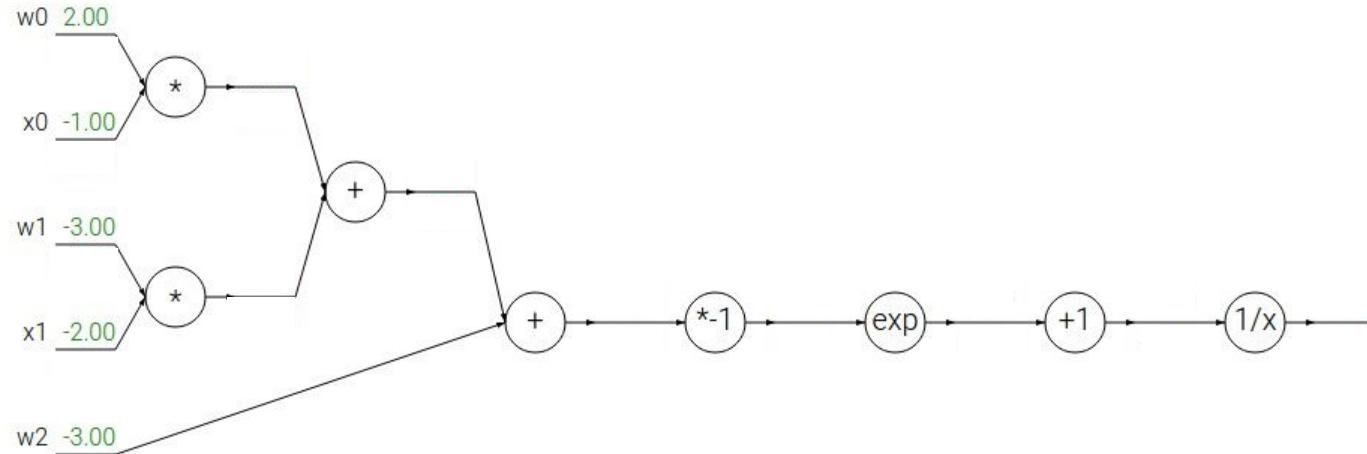
Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



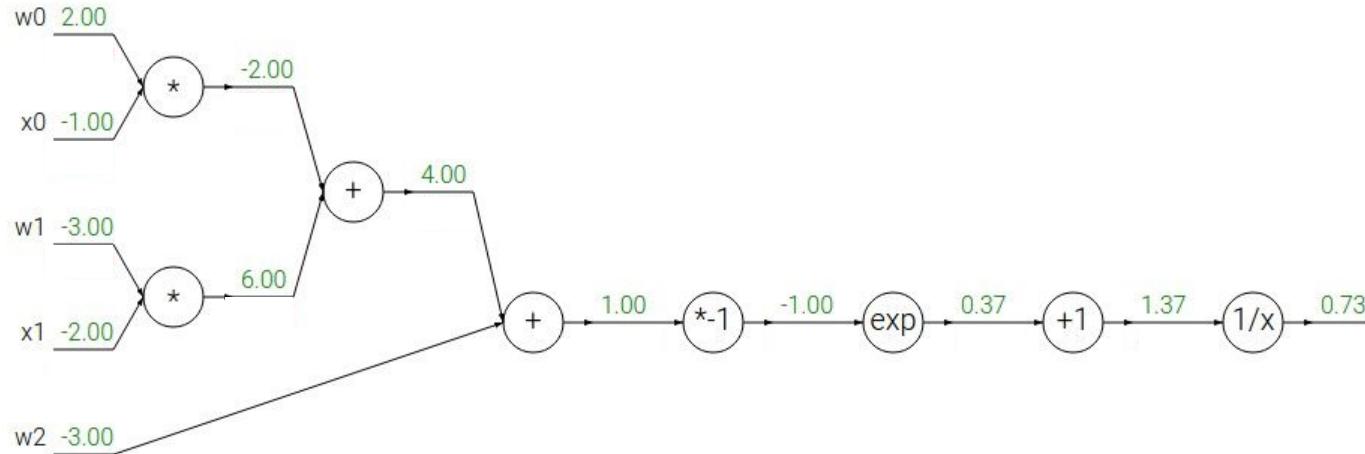
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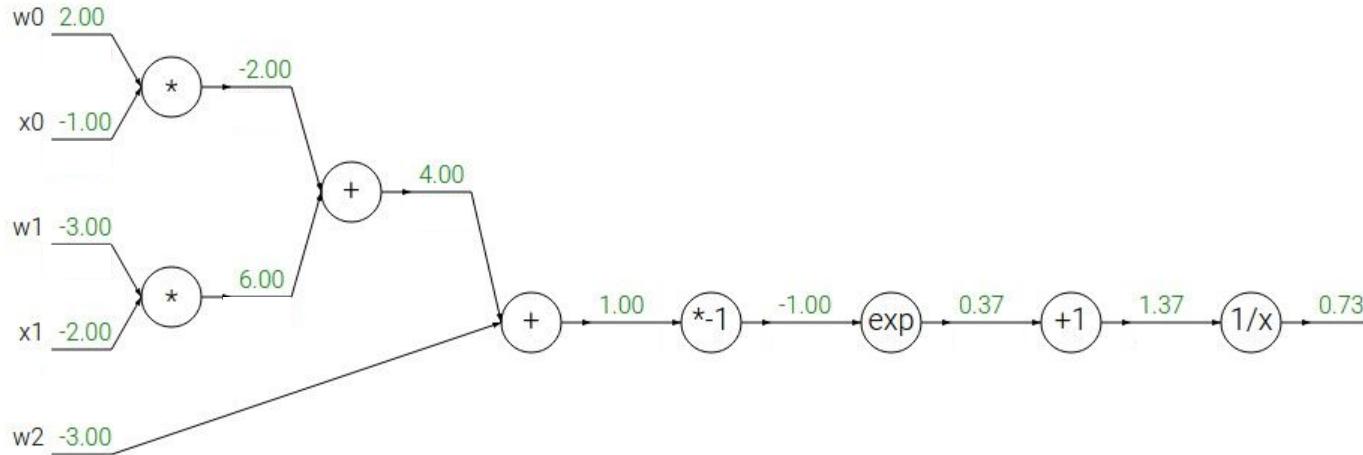
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$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



$$f(x) = e^x$$

\rightarrow

$$\frac{df}{dx} = e^x$$

$$f_a(x) = ax$$

\rightarrow

$$\frac{df}{dx} = a$$

$$f(x) = \frac{1}{x}$$

$$f_c(x) = c + x$$

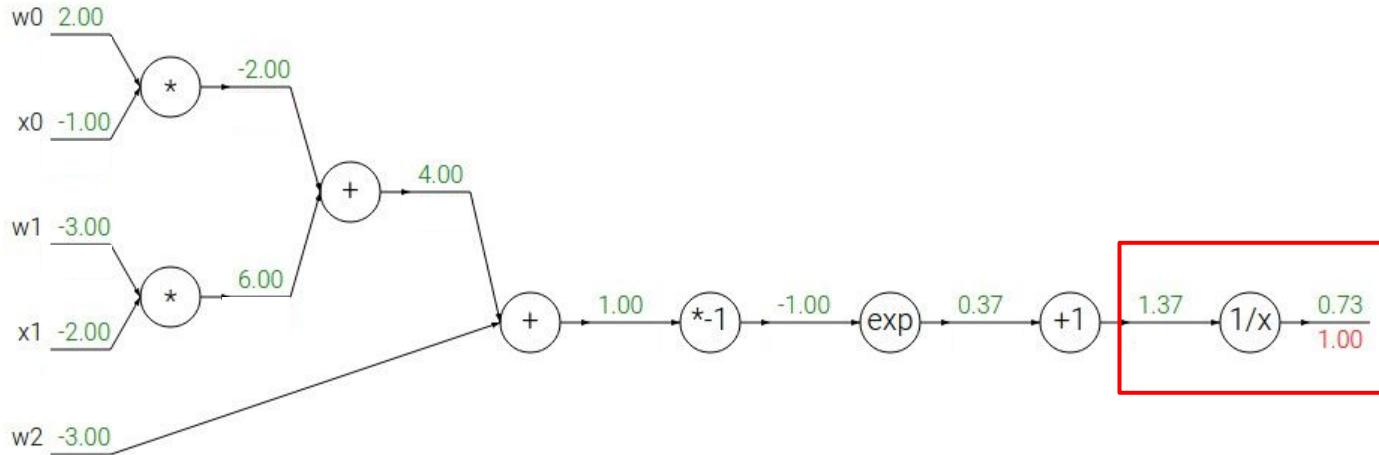
\rightarrow

$$\frac{df}{dx} = -1/x^2$$

$$\frac{df}{dx} = 1$$

Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



$$f(x) = e^x$$

→

$$\frac{df}{dx} = e^x$$

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→

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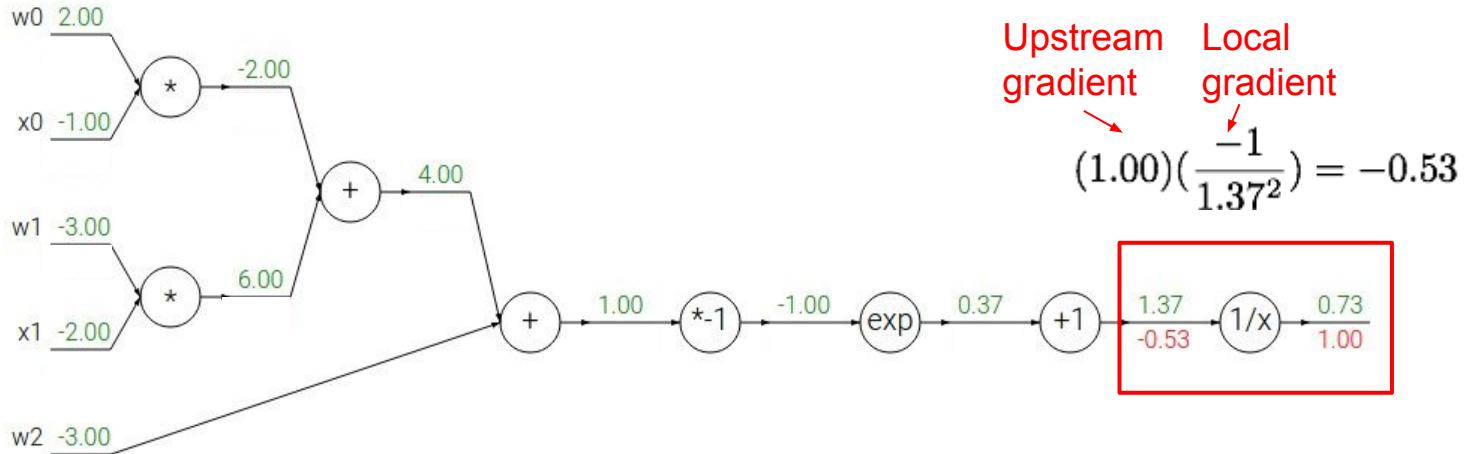
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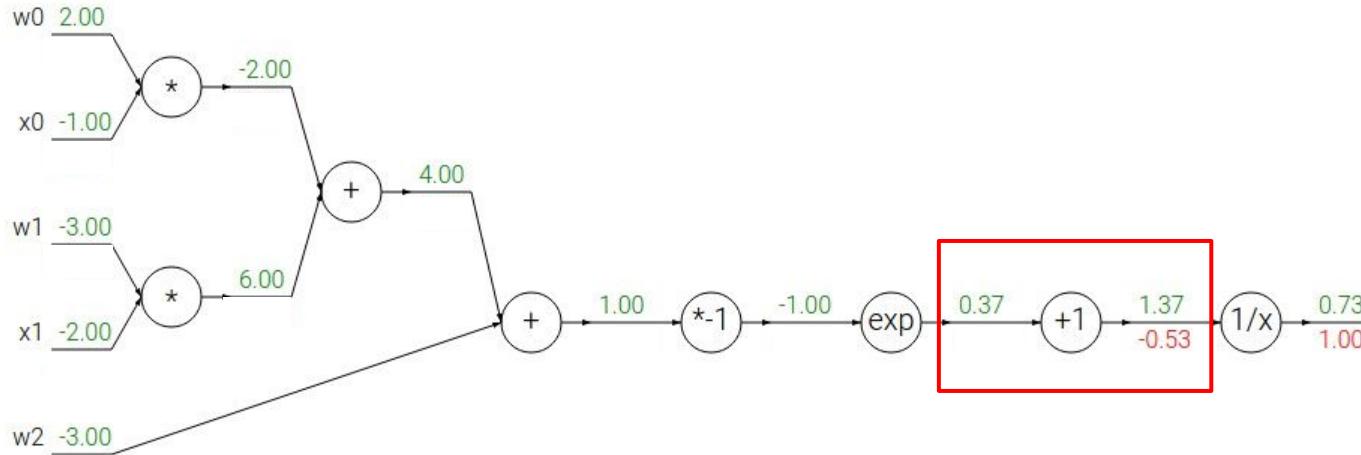
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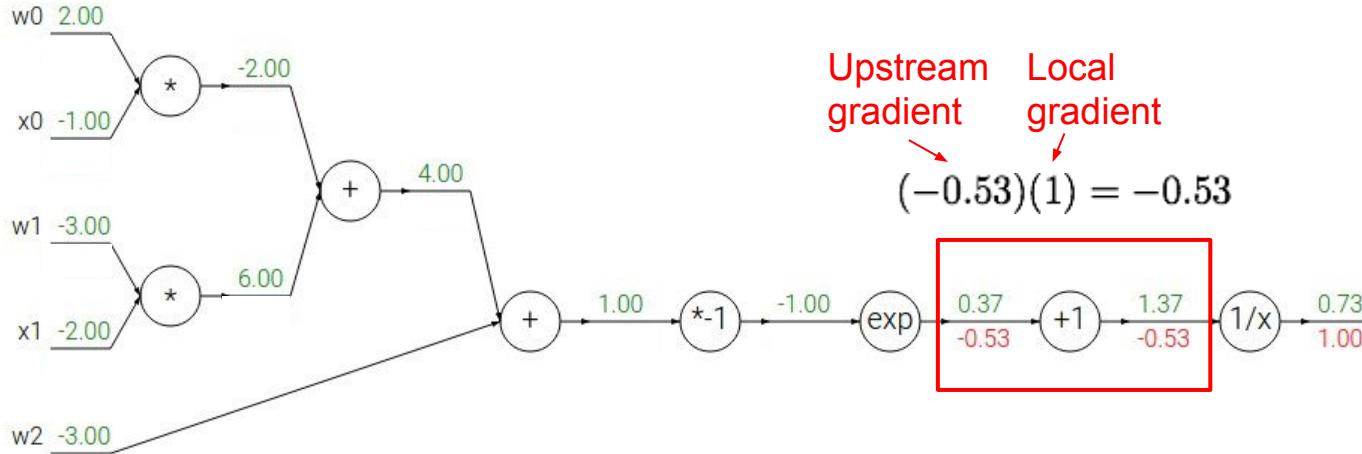
$$f_c(x) = c + x$$

\rightarrow

$$\frac{df}{dx} = 1$$

Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



$$f(x) = e^x$$

\rightarrow

$$\frac{df}{dx} = e^x$$

$$f_a(x) = ax$$

\rightarrow

$$\frac{df}{dx} = a$$

$$f(x) = \frac{1}{x}$$

\rightarrow

$$\frac{df}{dx} = -1/x^2$$

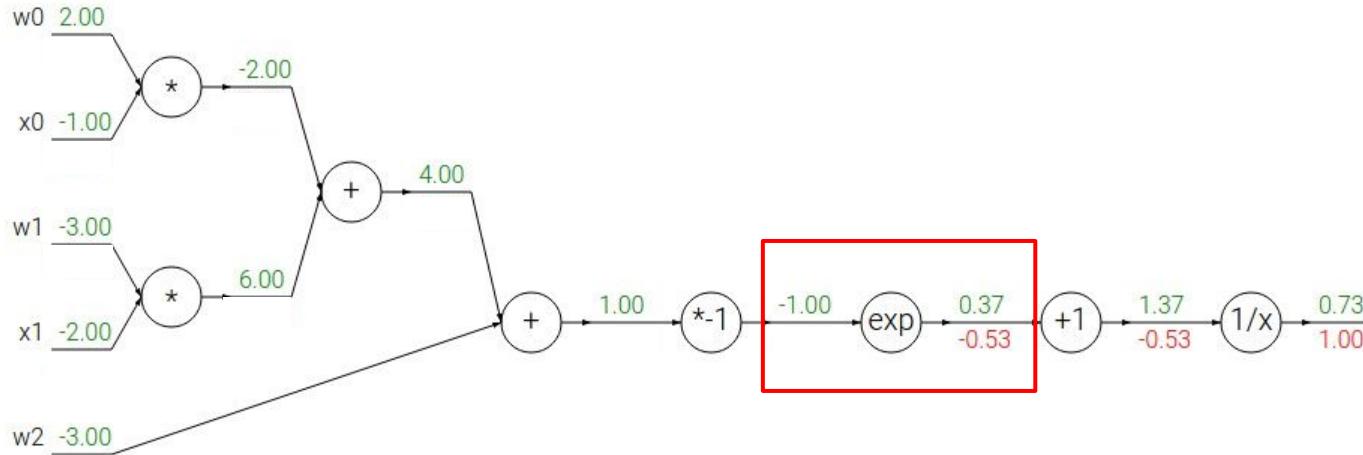
$$f_c(x) = c + x$$

\rightarrow

$$\frac{df}{dx} = 1$$

Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



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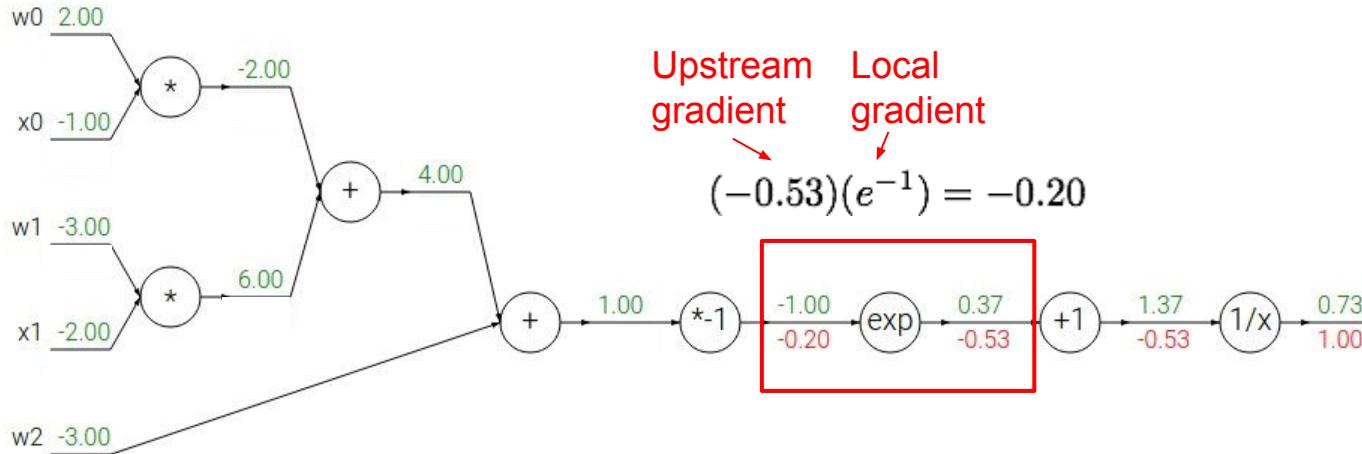
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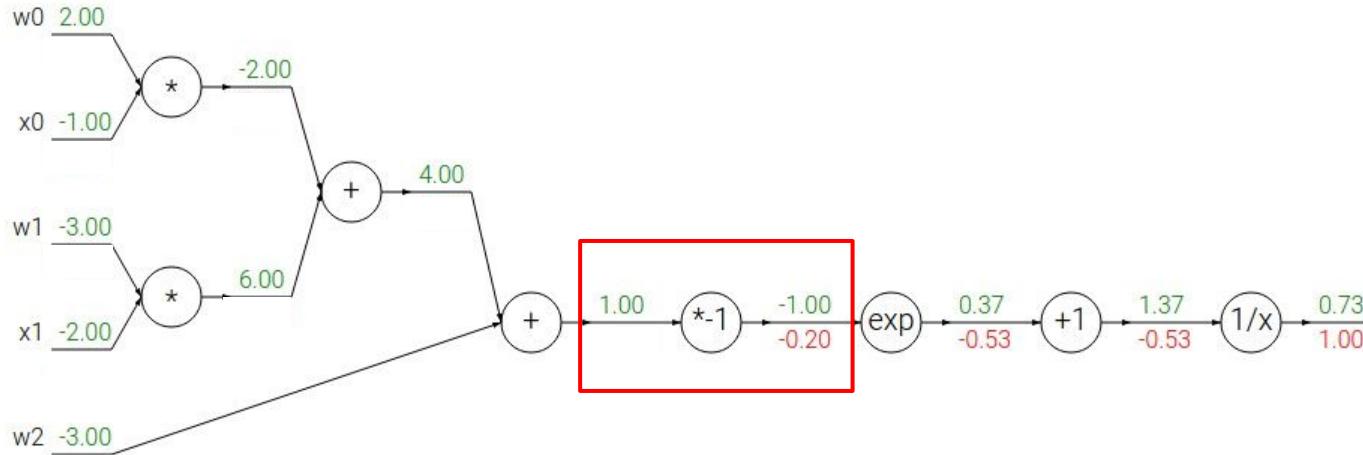
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$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



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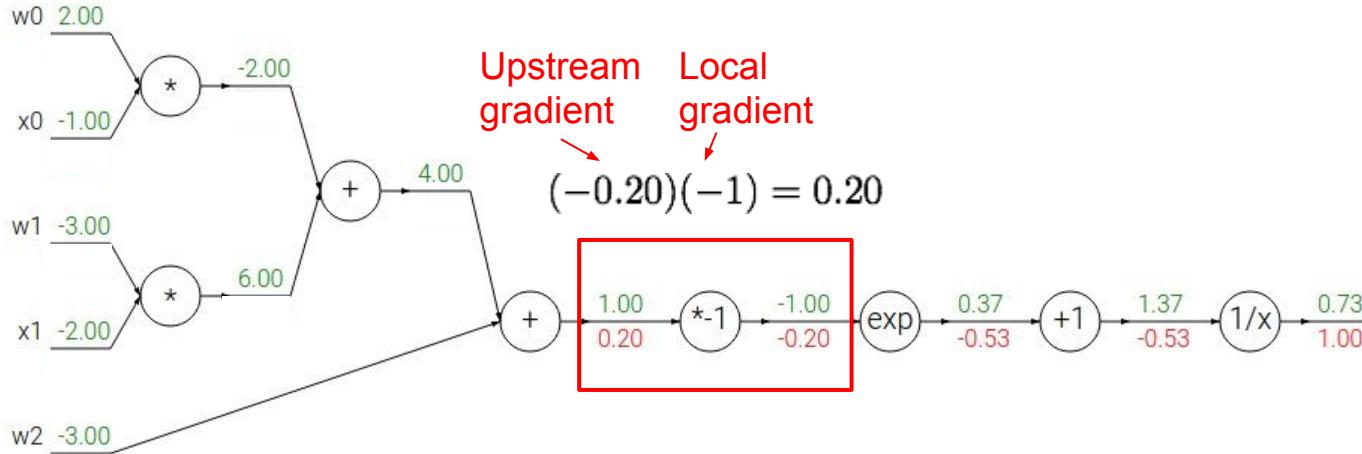
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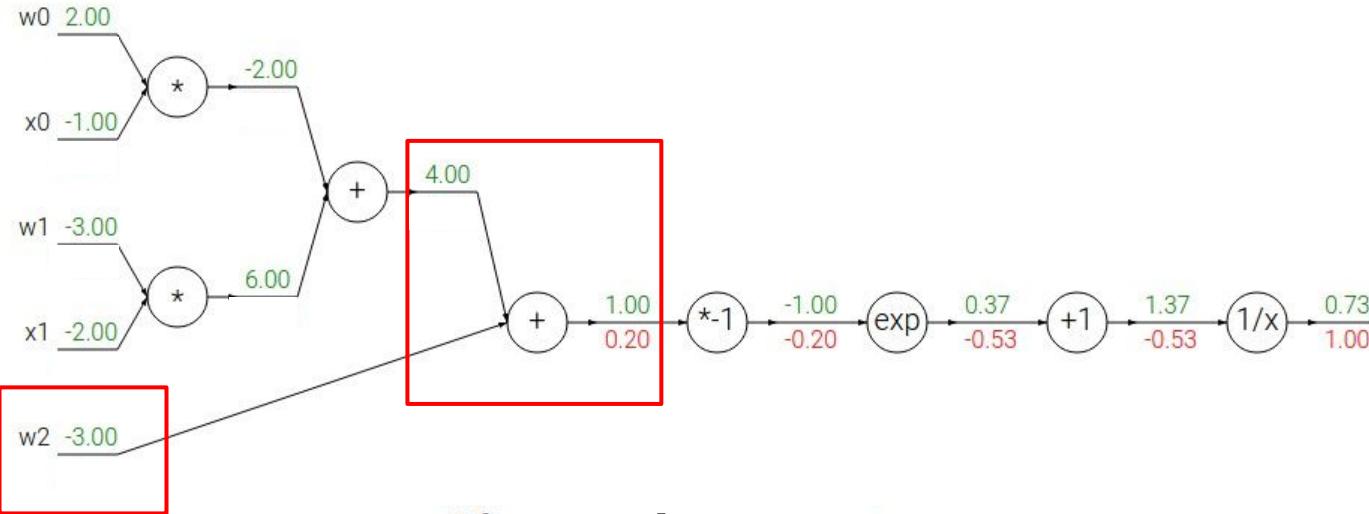
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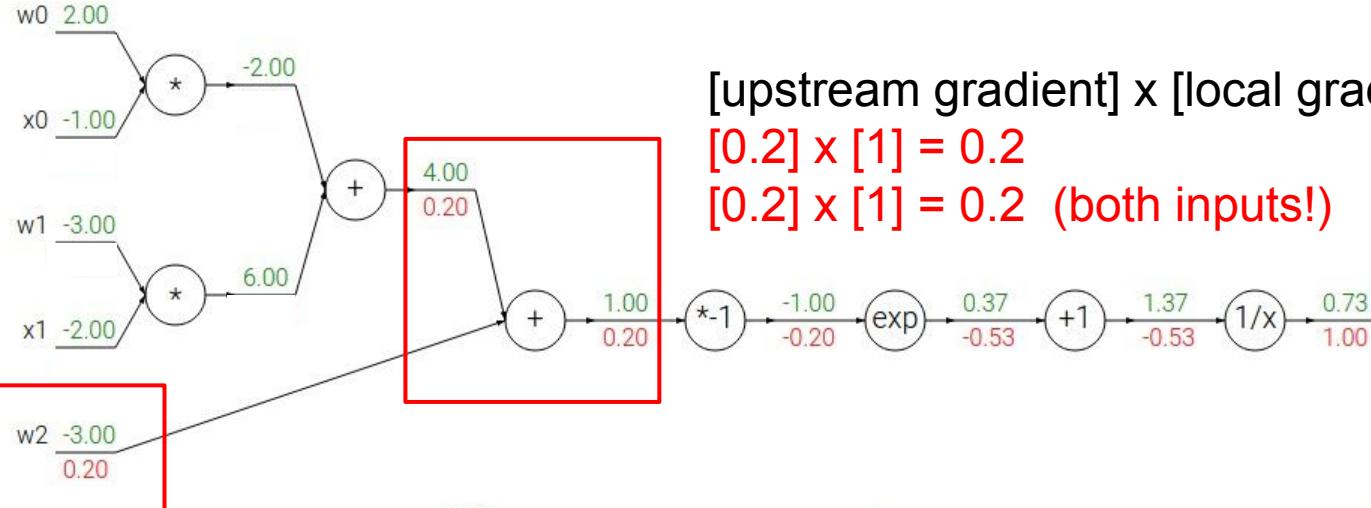
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Another example:

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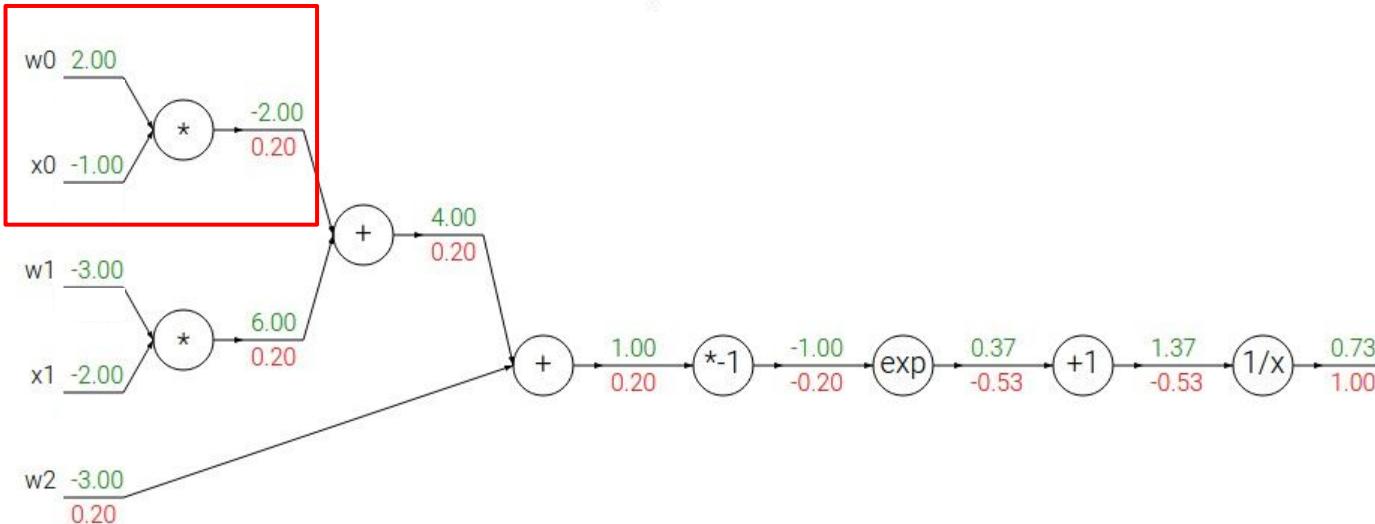
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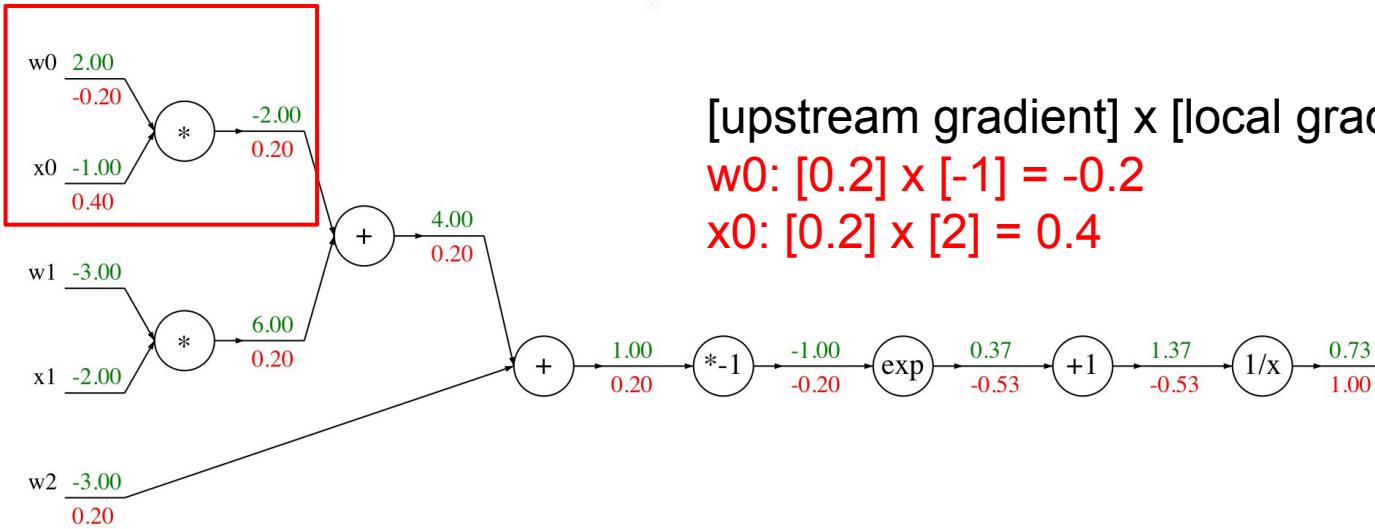
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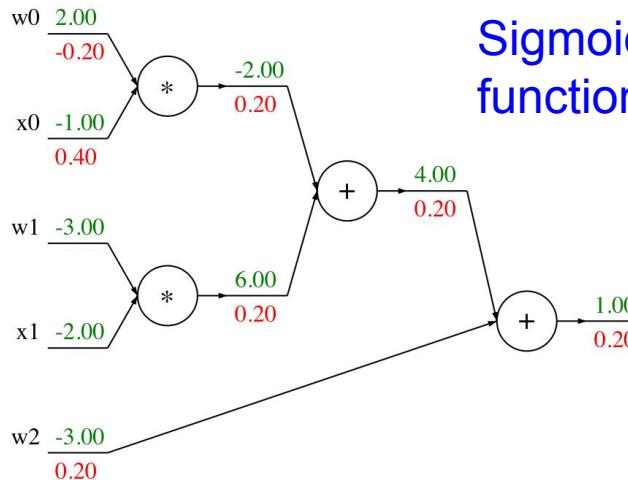
$$f_c(x) = c + x$$

→

$$\frac{df}{dx} = 1$$

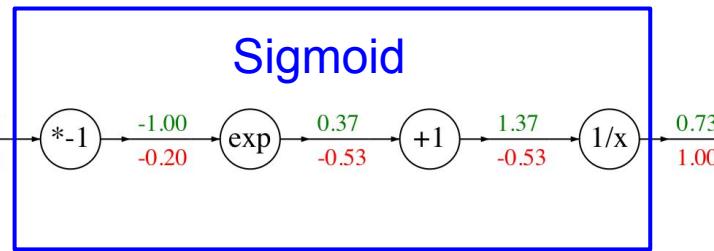
Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



Sigmoid
function

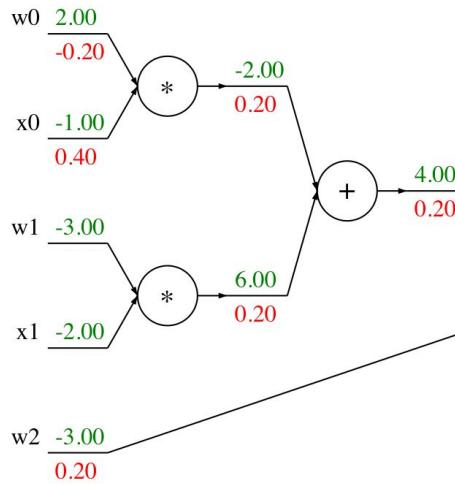
$$\sigma(x) = \frac{1}{1 + e^{-x}}$$



Computational graph representation may not be unique. Choose one where local gradients at each node can be easily expressed!

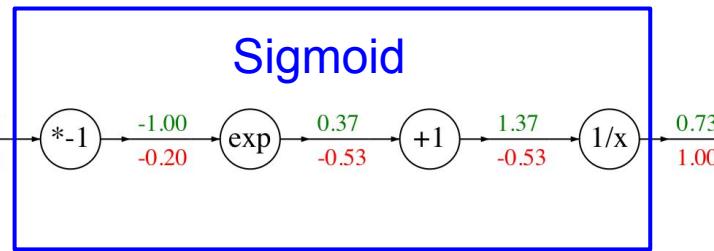
Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



Sigmoid
function

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$



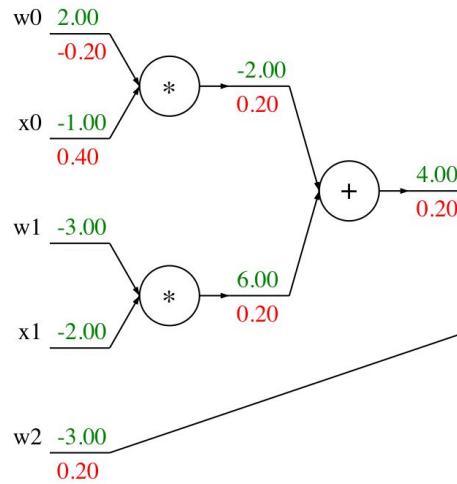
Computational graph representation may not be unique. Choose one where local gradients at each node can be easily expressed!

Sigmoid local gradient:

$$\frac{d\sigma(x)}{dx} = \frac{e^{-x}}{(1 + e^{-x})^2} = \left(\frac{1 + e^{-x} - 1}{1 + e^{-x}} \right) \left(\frac{1}{1 + e^{-x}} \right) = (1 - \sigma(x)) \sigma(x)$$

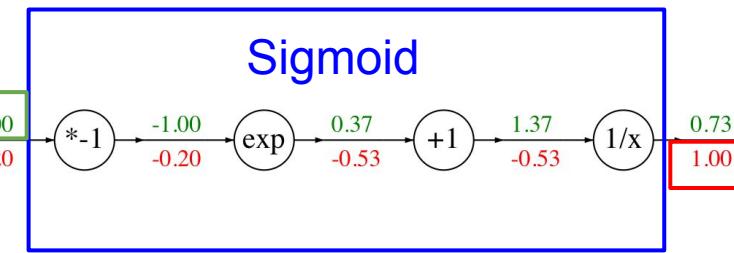
Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



Sigmoid
function

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$



Sigmoid

[upstream gradient] \times [local gradient]

$$[1.00] \times [(1 - 1/(1+e^{-1})) (1/(1+e^{-1}))] = 0.2$$

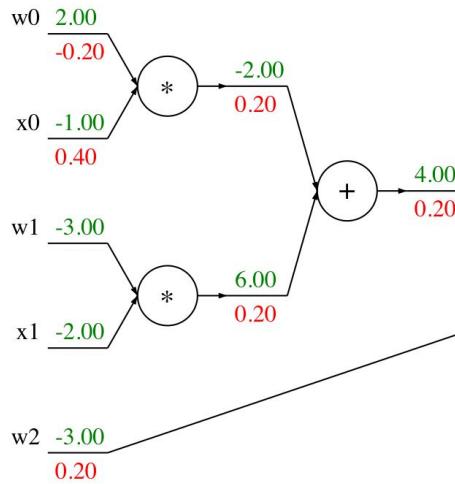
Sigmoid local
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$$\frac{d\sigma(x)}{dx} = \frac{e^{-x}}{(1 + e^{-x})^2} = \left(\frac{1 + e^{-x} - 1}{1 + e^{-x}} \right) \left(\frac{1}{1 + e^{-x}} \right) = (1 - \sigma(x)) \sigma(x)$$

Computational graph representation may not be unique. Choose one where local gradients at each node can be easily expressed!

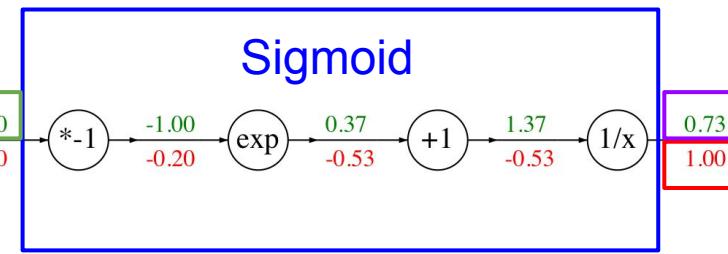
Another example:

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2)}}$$



Sigmoid
function

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$



[upstream gradient] \times [local gradient]
 $[1.00] \times [(1 - 0.73)(0.73)] = 0.2$

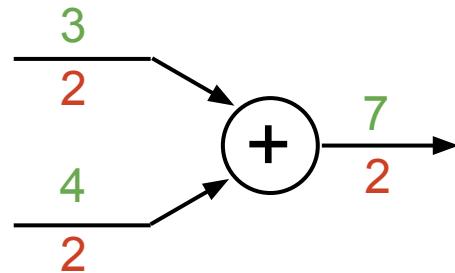
Sigmoid local
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$$\frac{d\sigma(x)}{dx} = \frac{e^{-x}}{(1 + e^{-x})^2} = \left(\frac{1 + e^{-x} - 1}{1 + e^{-x}} \right) \left(\frac{1}{1 + e^{-x}} \right) = (1 - \sigma(x)) \sigma(x)$$

Computational graph representation may not be unique. Choose one where local gradients at each node can be easily expressed!

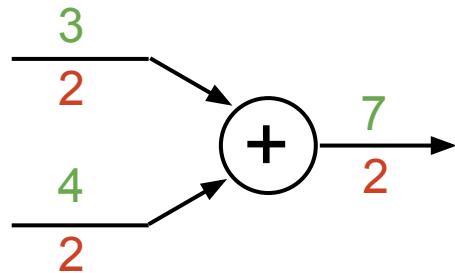
Patterns in gradient flow

add gate: gradient distributor

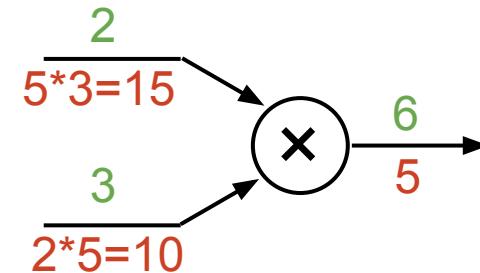


Patterns in gradient flow

add gate: gradient distributor

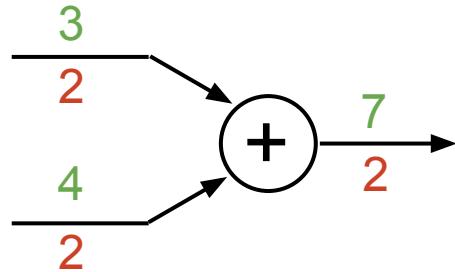


mul gate: “swap multiplier”

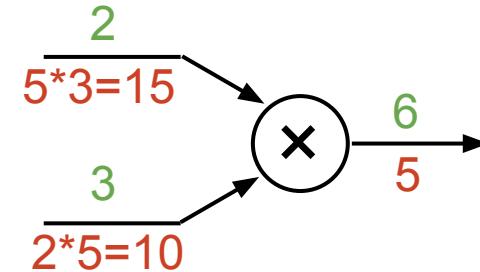


Patterns in gradient flow

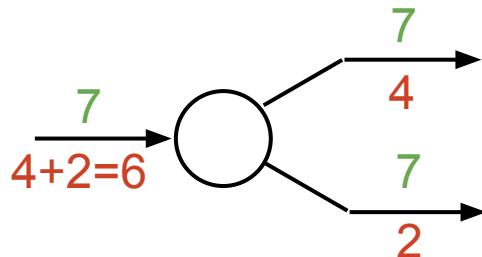
add gate: gradient distributor



mul gate: “swap multiplier”

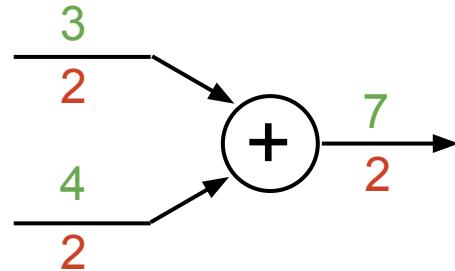


copy gate: gradient adder

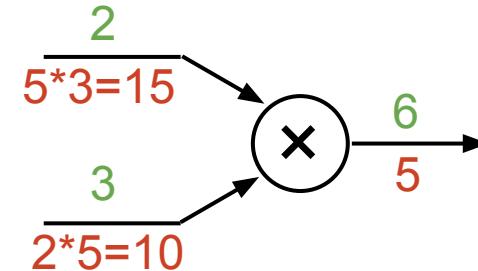


Patterns in gradient flow

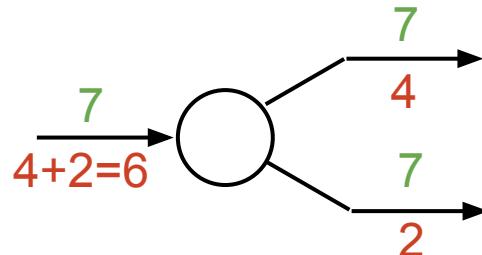
add gate: gradient distributor



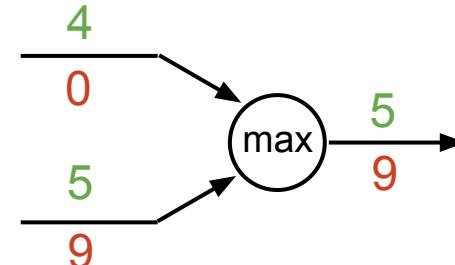
mul gate: “swap multiplier”



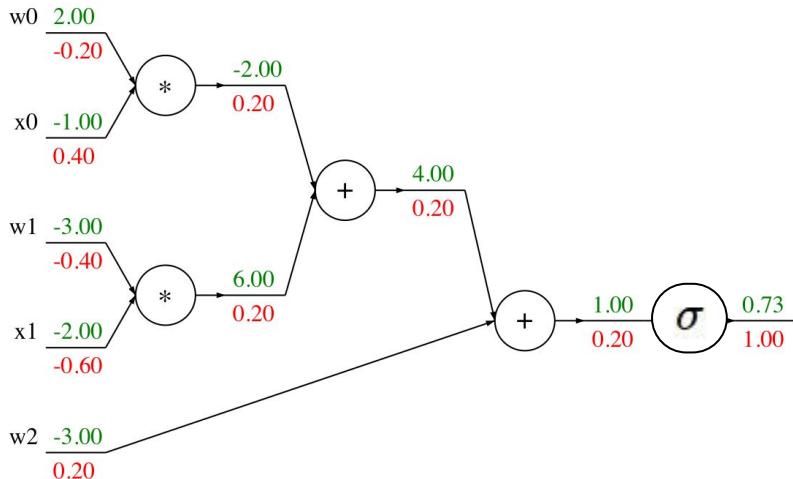
copy gate: gradient adder



max gate: gradient router



Backprop Implementation: “Flat” code



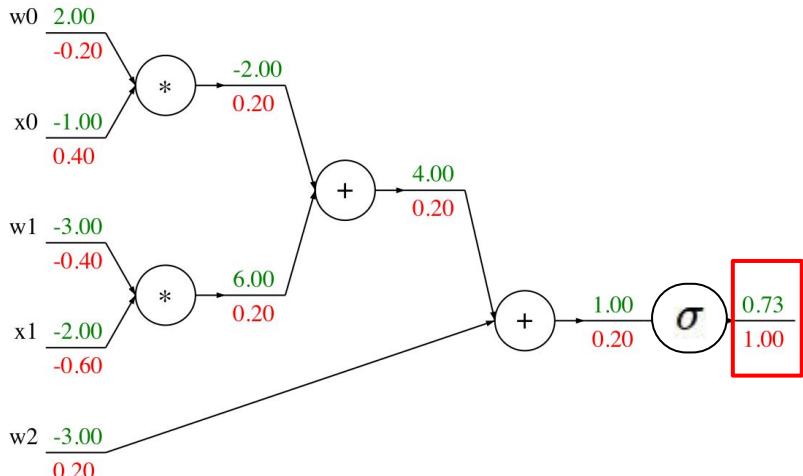
Forward pass:
Compute output

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

Backward pass:
Compute grads

```
grad_L = 1.0  
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Backprop Implementation: “Flat” code



Forward pass:
Compute output

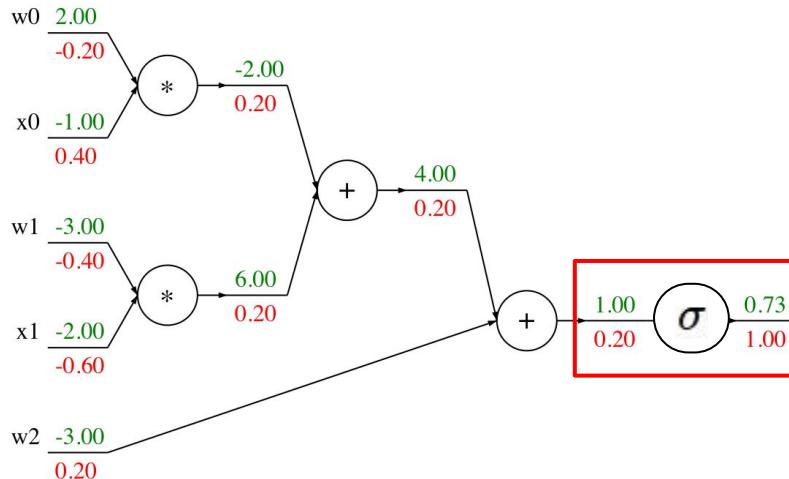
```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

Base case

grad_L = 1.0

```
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Backprop Implementation: “Flat” code



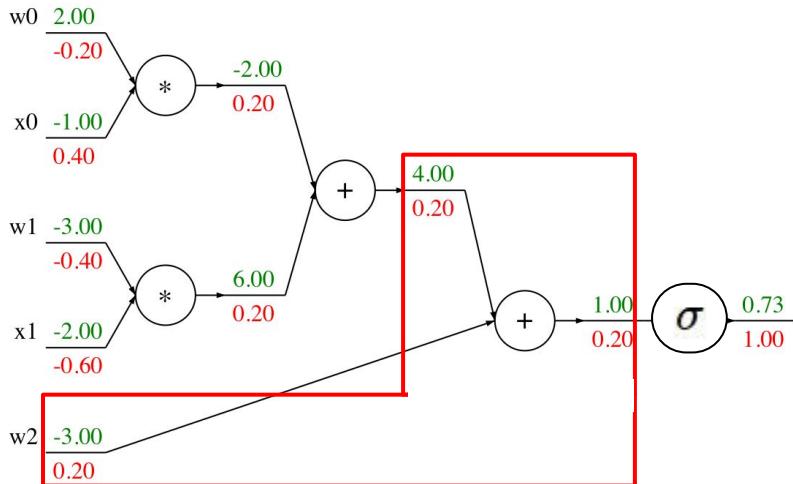
Forward pass:
Compute output

Sigmoid

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
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    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

```
grad_L = 1.0  
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Backprop Implementation: “Flat” code



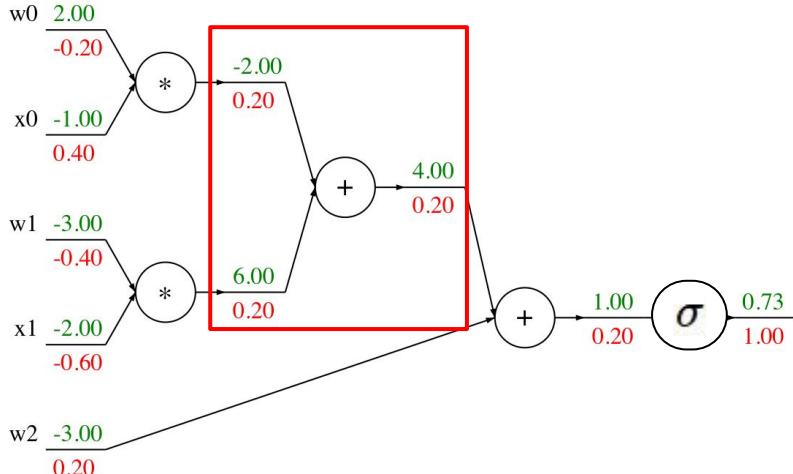
Forward pass:
Compute output

Add gate

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

```
grad_L = 1.0  
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Backprop Implementation: “Flat” code



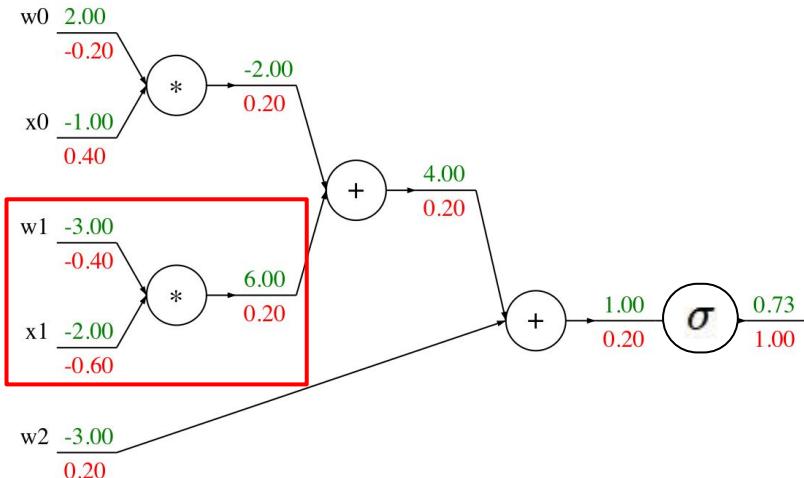
Forward pass:
Compute output

Add gate

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
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```
grad_L = 1.0  
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grad_w2 = grad_s3  
grad_s2 = grad_s3  
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grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Backprop Implementation: “Flat” code



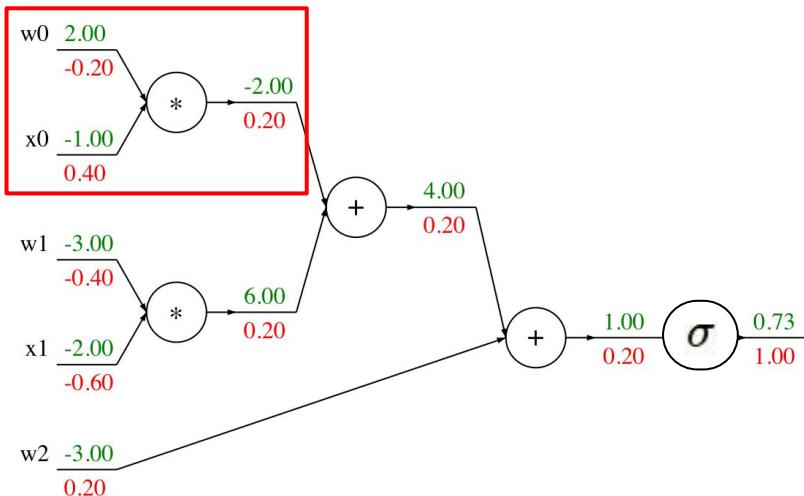
Forward pass:
Compute output

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

```
grad_L = 1.0  
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

Multiply gate

Backprop Implementation: “Flat” code



Forward pass:
Compute output

```
def f(w0, x0, w1, x1, w2):  
    s0 = w0 * x0  
    s1 = w1 * x1  
    s2 = s0 + s1  
    s3 = s2 + w2  
    L = sigmoid(s3)
```

```
grad_L = 1.0  
grad_s3 = grad_L * (1 - L) * L  
grad_w2 = grad_s3  
grad_s2 = grad_s3  
grad_s0 = grad_s2  
grad_s1 = grad_s2  
grad_w1 = grad_s1 * x1  
grad_x1 = grad_s1 * w1  
grad_w0 = grad_s0 * x0  
grad_x0 = grad_s0 * w0
```

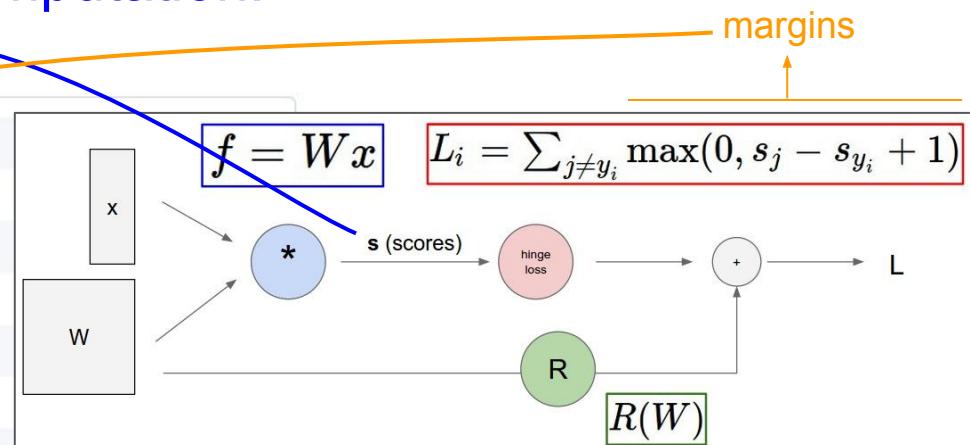
Multiply gate

“Flat” Backprop: Do this for assignment 1!

Stage your forward/backward computation!

E.g. for the SVM:

```
# receive W (weights), X (data)
# forward pass (we have 6 lines)
scores = #...
margins = #...
data_loss = #...
reg_loss = #...
loss = data_loss + reg_loss
# backward pass (we have 5 lines)
dmargins = # ... (optionally, we go direct to dscores)
dscores = #...
dW = #...
```



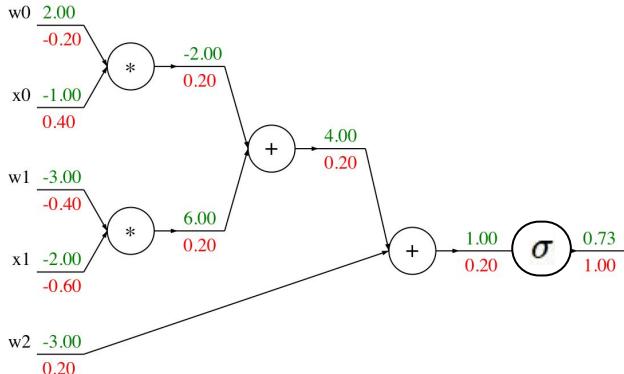
“Flat” Backprop: Do this for assignment 1!

E.g. for two-layer neural net:

```
# receive W1,W2,b1,b2 (weights/biases), X (data)
# forward pass:
h1 = #... function of X,W1,b1
scores = #... function of h1,W2,b2
loss = #... (several lines of code to evaluate Softmax loss)
# backward pass:
dscores = #...
dh1,dW2,db2 = #...
dW1,db1 = #...
```

Backprop Implementation: Modularized API

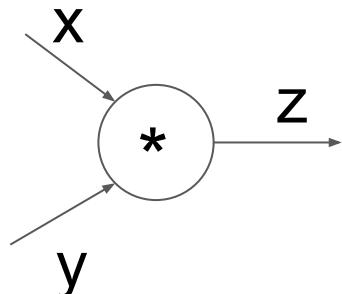
Graph (or Net) object (*rough pseudo code*)



```
class ComputationalGraph(object):  
    ...  
    def forward(inputs):  
        # 1. [pass inputs to input gates...]  
        # 2. forward the computational graph:  
        for gate in self.graph.nodes_topologically_sorted():  
            gate.forward()  
        return loss # the final gate in the graph outputs the loss  
    def backward():  
        for gate in reversed(self.graph.nodes_topologically_sorted()):  
            gate.backward() # little piece of backprop (chain rule applied)  
        return inputs_gradients
```

Modularized implementation: forward / backward API

Gate / Node / Function object: Actual PyTorch code



(x, y, z are scalars)

```
class Multiply(torch.autograd.Function):
    @staticmethod
    def forward(ctx, x, y):
        ctx.save_for_backward(x, y)           # 'context' object
        z = x * y
        return z

    @staticmethod
    def backward(ctx, grad_z):
        x, y = ctx.saved_tensors
        grad_x = y * grad_z    # dz/dx * dL/dz
        grad_y = x * grad_z    # dz/dy * dL/dz
        return grad_x, grad_y
```

Need to cash some values for use in backward

Upstream gradient

Multiply upstream and local gradients

Example: PyTorch operators

pytorch / pytorch		
Code	Issues 2,286	Pull requests 561
Tree: 517c7c9861 → pytorch / aten / src / THNN / generic /	Create new file	Upload files
ezyang and facebook-github-bot Canonicalize all includes in PyTorch. (#14849)	Latest commit 517c7c9 on Dec 8, 2018	
..		
AbsCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
BCECriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
ClassNLLCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
Col2im.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
ELU.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
FeatureLPPooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
GatedLinearUnit.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
HardTanh.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
Im2Col.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
IndexLinear.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
LeakyReLU.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
LogSigmoid.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
MSECriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
MultiLabelMarginCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
MultiMarginCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
RReLU.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
Sigmoid.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SmoothL1Criterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SoftMarginCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SoftPlus.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SoftShrink.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SparseLinear.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialAdaptiveAveragePooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialAdaptiveMaxPooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialAveragePooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialClassNLLCriterion.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialConvolutionMM.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialDilatedConvolution.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialDilatedMaxPooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialFractionalMaxPooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialFullDilatedConvolution.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialMaxUnpooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialReflectionPadding.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialReplicationPadding.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialUpSamplingBilinear.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
SpatialUpSamplingNearest.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
THNN.h	Canonicalize all includes in PyTorch. (#14849)	4 months ago
Tanh.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
TemporalReflectionPadding.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
TemporalReplicationPadding.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
TemporalRowConvolution.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
TemporalUpSamplingLinear.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
TemporalUpSamplingNearest.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
VolumetricAdaptiveAveragePooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
VolumetricAdaptiveMaxPooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
VolumetricAveragePooling.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
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VolumetricReplicationPadding.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
VolumetricUpSamplingNearest.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago
linear_upsampling.h	Implement nn.functional.interpolate based on upsample. (#8591)	9 months ago
pooling_shape.h	Use integer math to compute output size of pooling operations (#14405)	4 months ago
unfold.c	Canonicalize all includes in PyTorch. (#14849)	4 months ago

PyTorch sigmoid layer

```
1 #ifndef TH_GENERIC_FILE
2 #define TH_GENERIC_FILE "THNN/generic/Sigmoid.c"
3 #else
4
5 void THNN_(Sigmoid_updateOutput)(
6     THNNState *state,
7     THTensor *input,
8     THTensor *output)
9 {
10    THTensor_(sigmoid)(output, input);
11 }
12
13 void THNN_(Sigmoid_updateGradInput)(
14     THNNState *state,
15     THTensor *gradOutput,
16     THTensor *gradInput,
17     THTensor *output)
18 {
19     THNN_CHECK_NELEMENT(output, gradOutput);
20     THTensor_(resizeAs)(gradInput, output);
21     TH_TENSOR_APPLY3(scalar_t, gradInput, scalar_t, gradOutput, scalar_t, output,
22         scalar_t z = *output_data;
23         *gradInput_data = *gradOutput_data * (1. - z) * z;
24     );
25 }
26
27 #endif
```

Forward

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

[Source](#)

PyTorch sigmoid layer

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24     );
25 }
26
27 #endif
```

Forward

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

```
static void sigmoid_kernel(TensorIterator& iter) {
    AT_DISPATCH_FLOATING_TYPES(iter.dtype(), "sigmoid_cpu", [&]() {
        unary_kernel_vec(
            iter,
            [=](scalar_t a) -> scalar_t { return (1 / (1 + std::exp((-a)))); },
            [=](Vec256<scalar_t> a) {
                a = Vec256<scalar_t>((scalar_t)(0)) - a;
                a = a.exp();
                a = Vec256<scalar_t>((scalar_t)(1)) + a;
                a = a.reciprocal();
                return a;
            });
    });
}
```

Forward actually defined elsewhere...

return (1 / (1 + std::exp((-a))));

[Source](#)

PyTorch sigmoid layer

```
1 #ifndef TH_GENERIC_FILE
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16     THTensor *gradInput,
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Forward

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

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                a = a.exp();
                a = Vec256<scalar_t>((scalar_t)(1)) + a;
                a = a.reciprocal();
                return a;
            });
    });
}
```

Forward actually defined elsewhere...

Backward

$$(1 - \sigma(x)) \sigma(x)$$

[Source](#)

So far: backprop with scalars

What about **vector-valued** functions?

Recap: Vector derivatives

Scalar to Scalar

$$x \in \mathbb{R}, y \in \mathbb{R}$$

Regular derivative:

$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

If x changes by a small amount, how much will y change?

Recap: Vector derivatives

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Regular derivative:

$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

If x changes by a small amount, how much will y change?

Vector to Scalar

$$x \in \mathbb{R}^N, y \in \mathbb{R}$$

Derivative is **Gradient**:

$$\frac{\partial y}{\partial x} \in \mathbb{R}^N \quad \left(\frac{\partial y}{\partial x} \right)_n = \frac{\partial y}{\partial x_n}$$

For each element of x , if it changes by a small amount then how much will y change?

Recap: Vector derivatives

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Vector to Vector

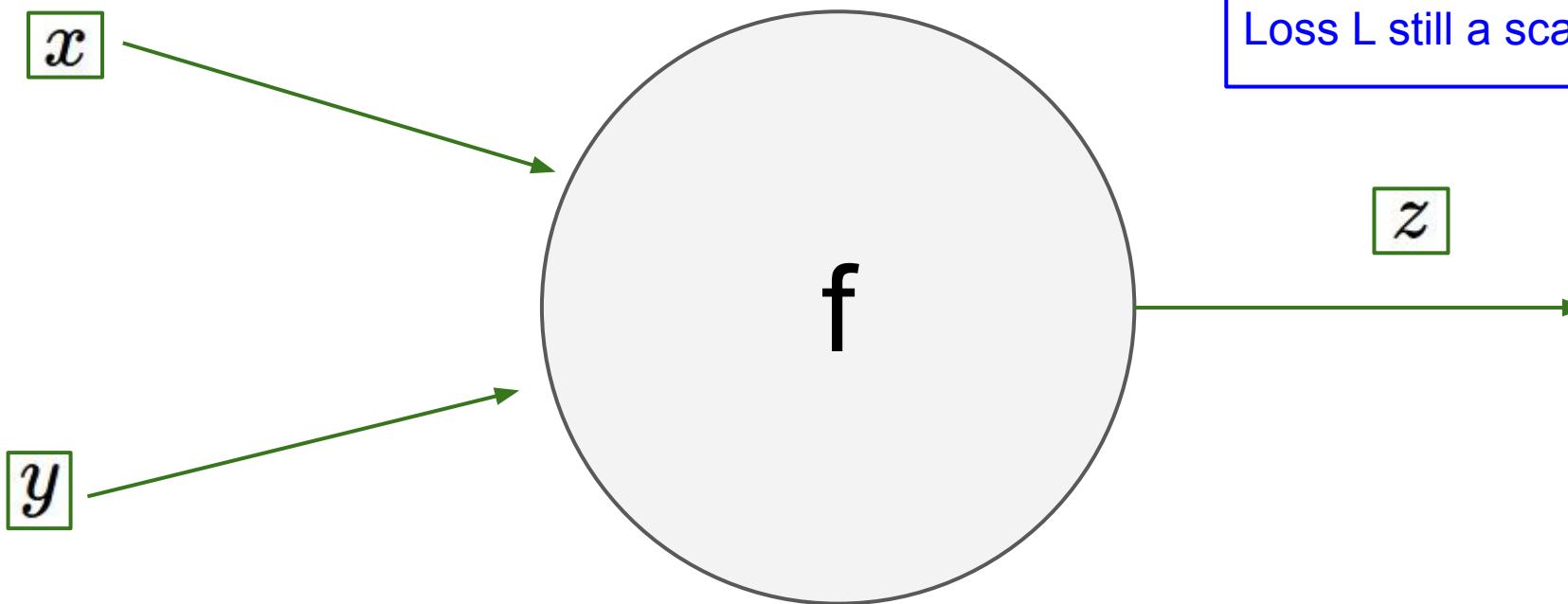
$$x \in \mathbb{R}^N, y \in \mathbb{R}^M$$

Derivative is **Jacobian**:

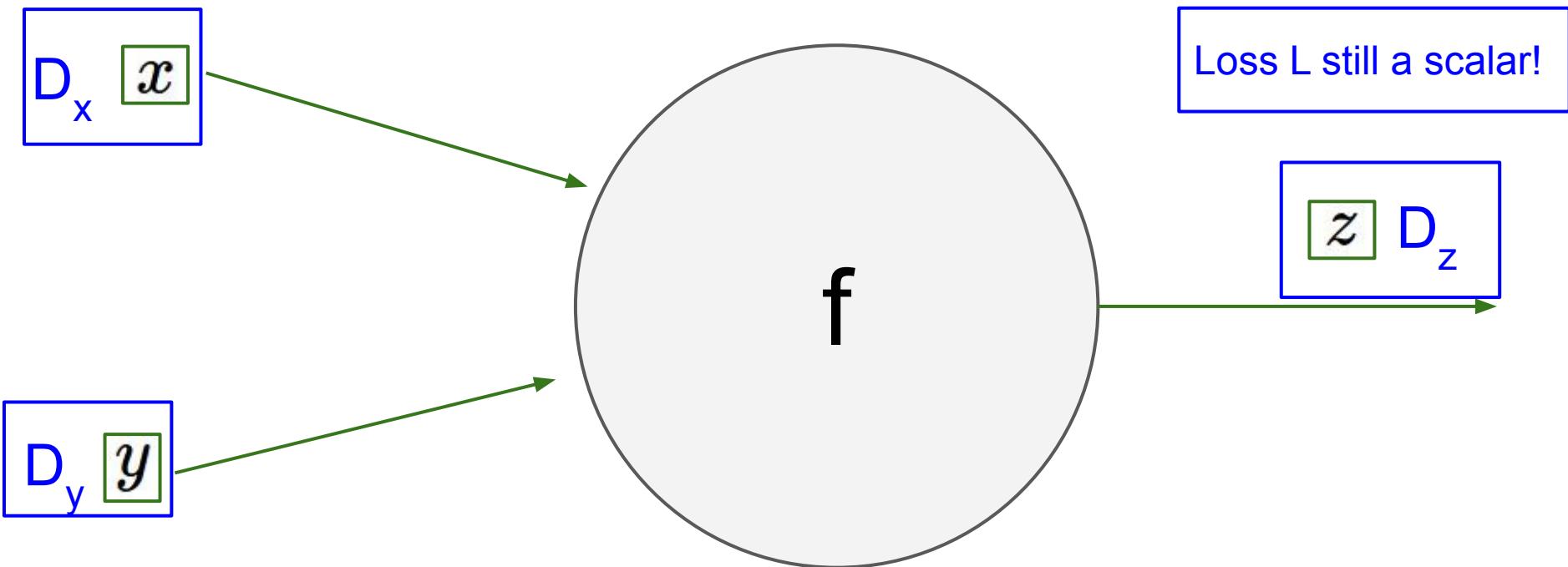
$$\frac{\partial y}{\partial x} \in \mathbb{R}^{N \times M} \quad \left(\frac{\partial y}{\partial x} \right)_{n,m} = \frac{\partial y_m}{\partial x_n}$$

For each element of x , if it changes by a small amount then how much will each element of y change?

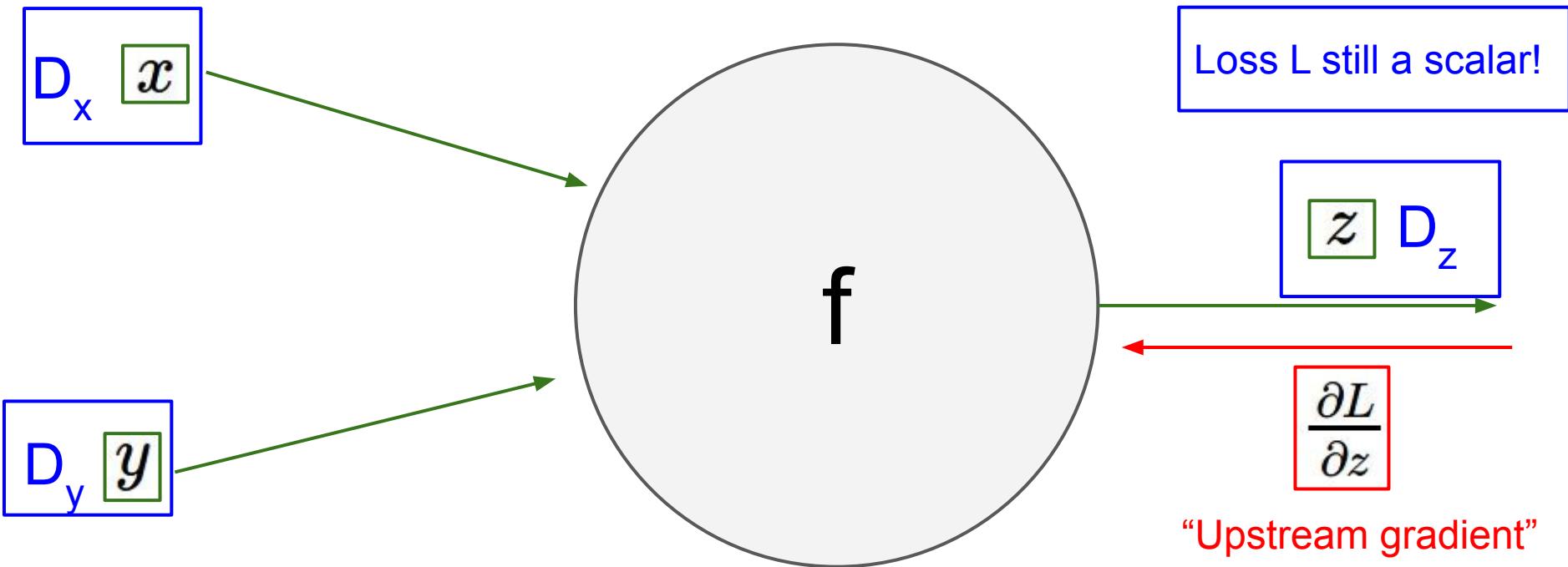
Backprop with Vectors



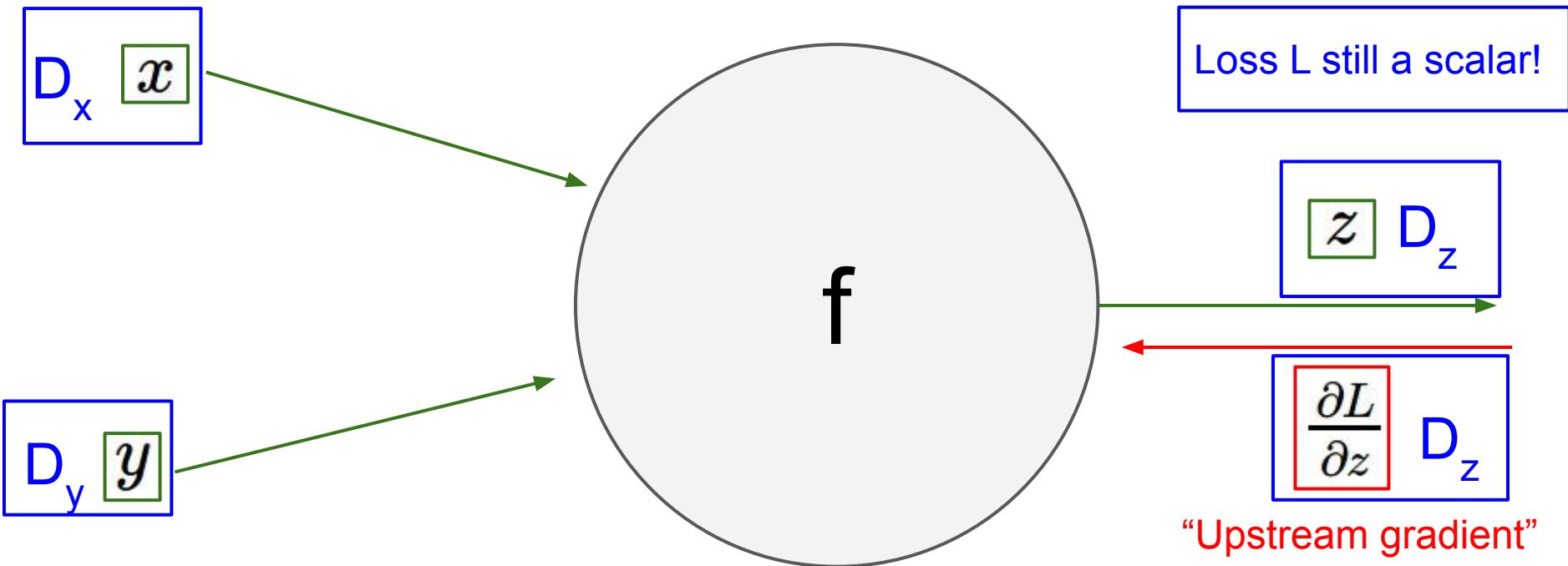
Backprop with Vectors



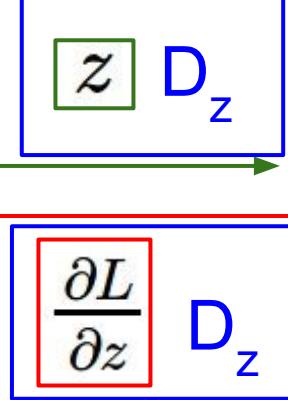
Backprop with Vectors



Backprop with Vectors

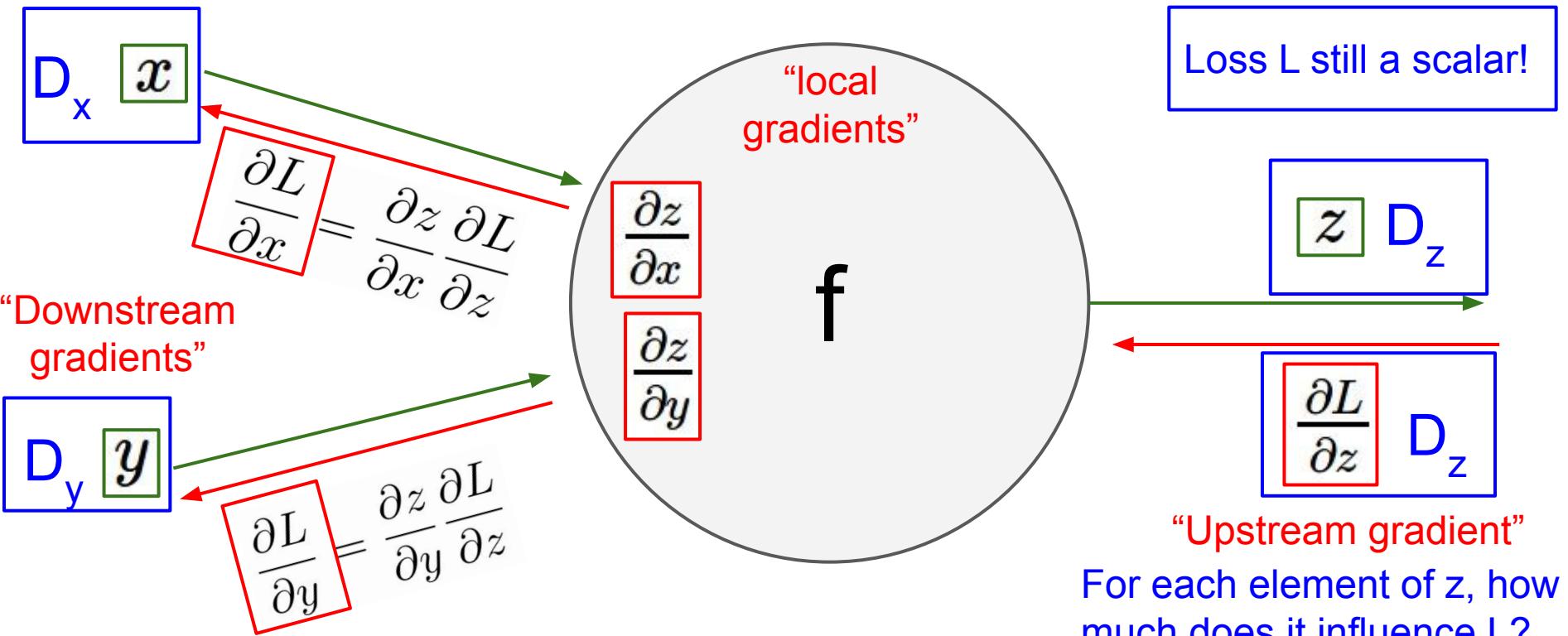


Loss L still a scalar!

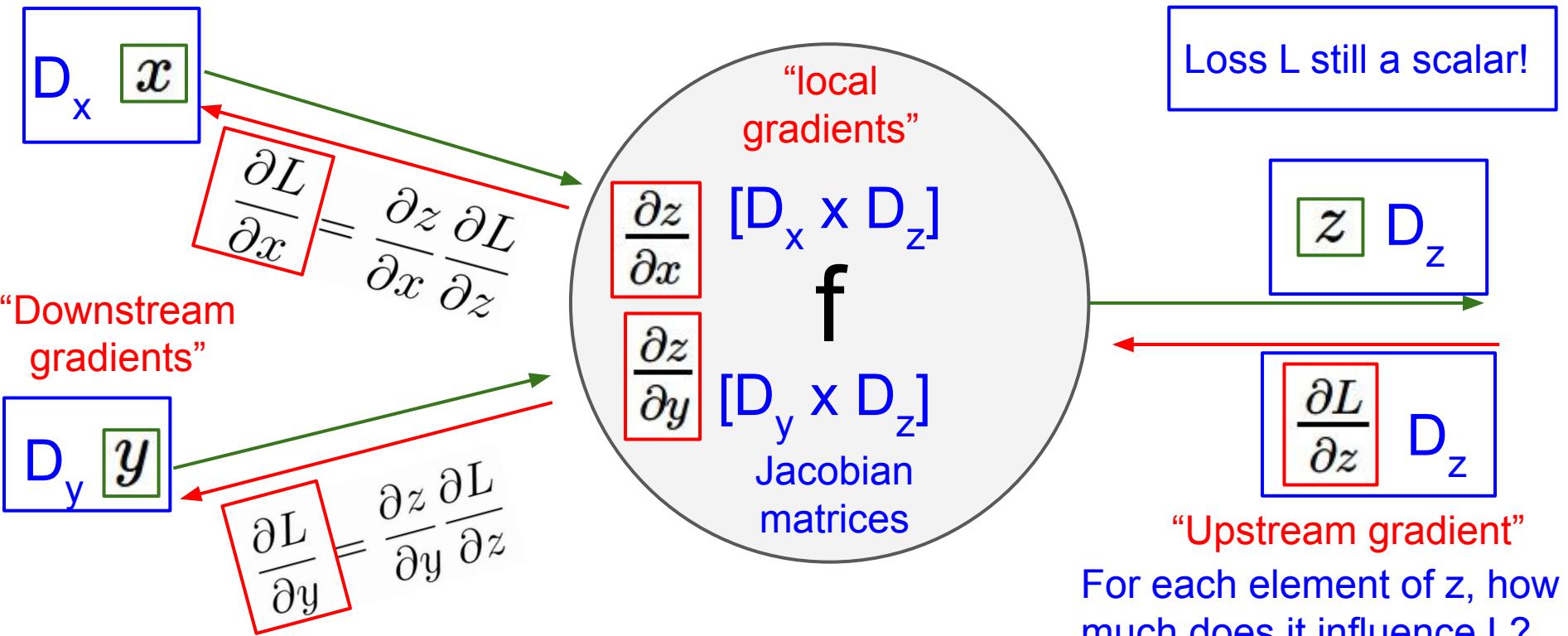


“Upstream gradient”
For each element of z , how
much does it influence L ?

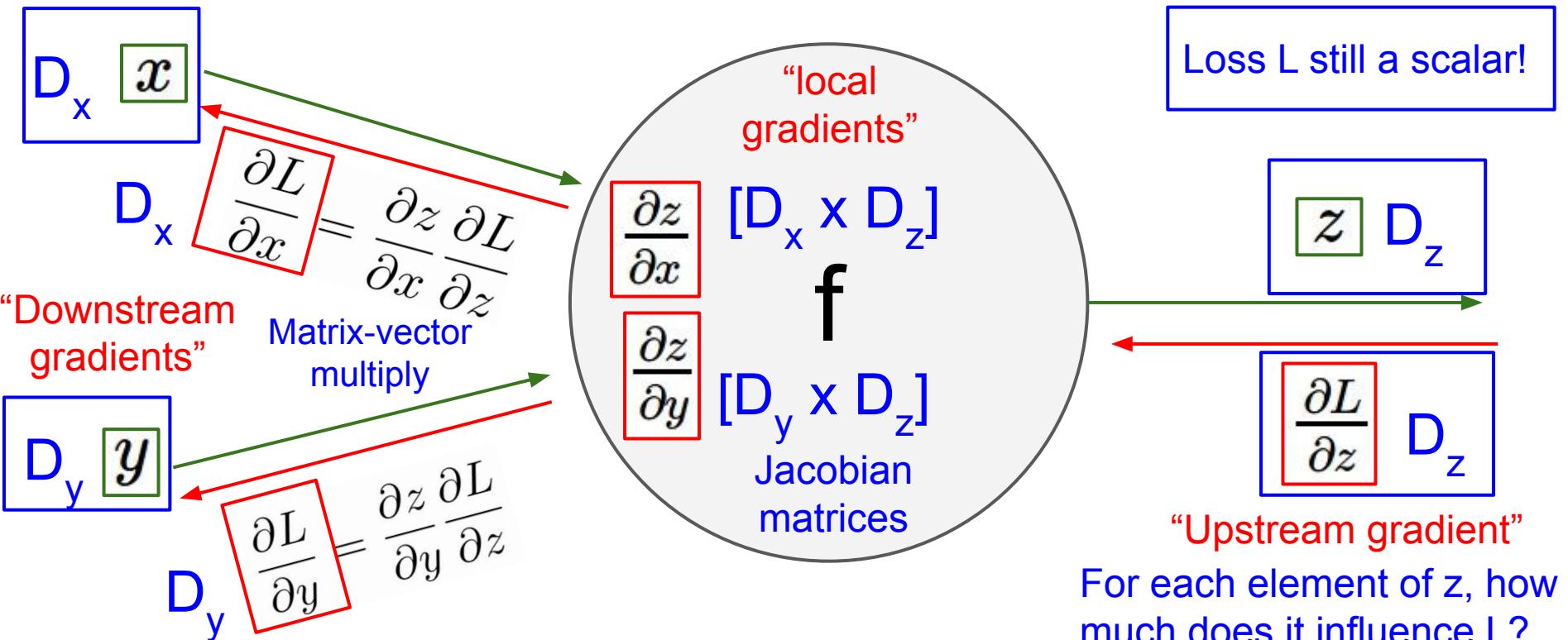
Backprop with Vectors



Backprop with Vectors

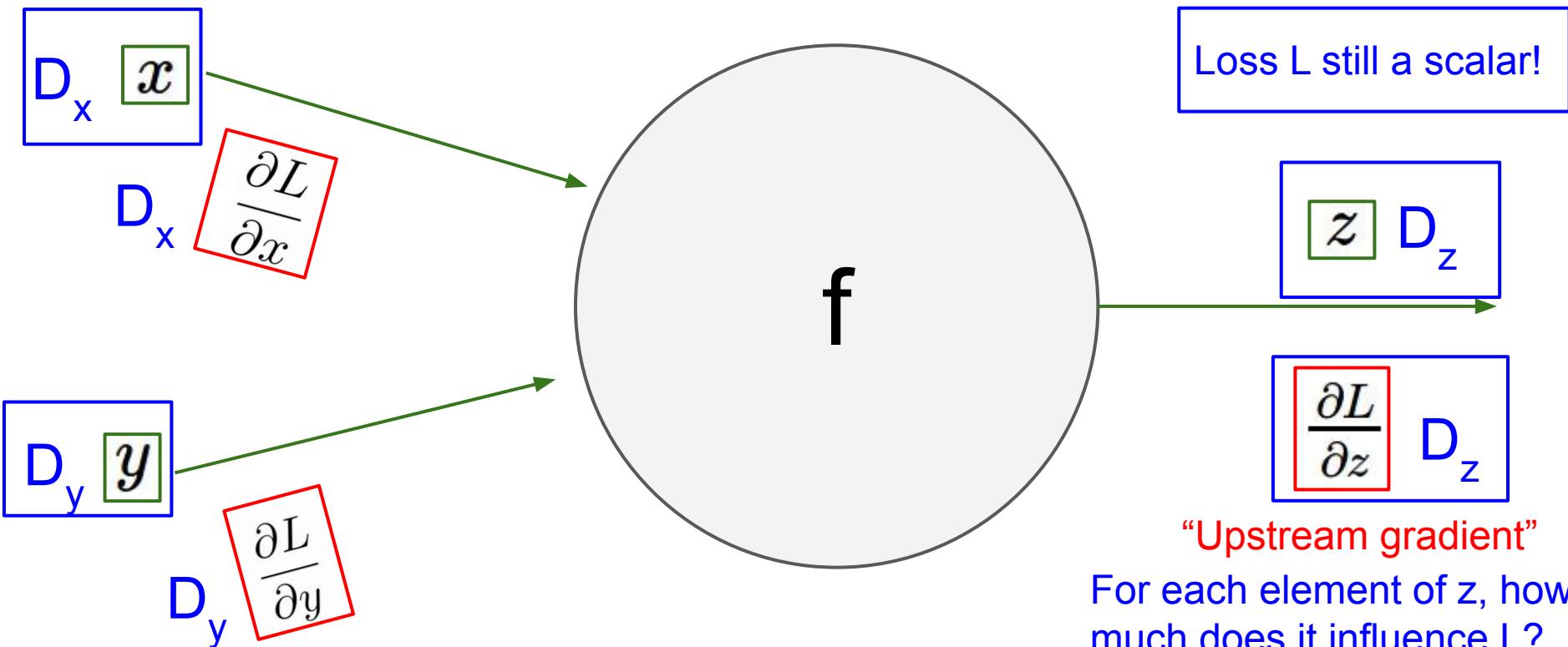


Backprop with Vectors



For each element of z , how much does it influence L ?

Gradients of variables wrt loss have same dims as the original variable



Backprop with Vectors

4D input x :

$$\begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix} \xrightarrow{\hspace{1cm}} \begin{array}{c} \text{f}(x) = \max(0, x) \\ (\text{elementwise}) \end{array}$$

4D output z :

$$\begin{array}{l} \xrightarrow{\hspace{1cm}} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix} \\ \xrightarrow{\hspace{1cm}} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 3 \end{bmatrix} \\ \xrightarrow{\hspace{1cm}} \begin{bmatrix} 3 \\ 0 \\ 0 \\ 1 \end{bmatrix} \\ \xrightarrow{\hspace{1cm}} \begin{bmatrix} 0 \\ 3 \\ 1 \\ 0 \end{bmatrix} \end{array}$$

Backprop with Vectors

4D input x :

$$\begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix} \xrightarrow{\quad} \begin{array}{c} f(x) = \max(0, x) \\ (\text{elementwise}) \end{array}$$

4D output z :

$$\begin{array}{l} \xrightarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix} \\ \xrightarrow{\quad} \\ \xrightarrow{\quad} \\ \xrightarrow{\quad} \end{array}$$

4D dL/dz :

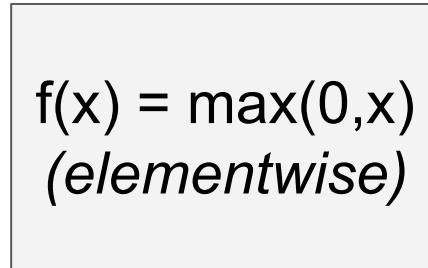
$$\begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

Upstream
gradient

Backprop with Vectors

4D input x :

$$\begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix} \xrightarrow{\quad}$$



4D output z :

$$\xrightarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix}$$

Jacobian $\frac{dz}{dx}$

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

4D $\frac{dL}{dz}$:

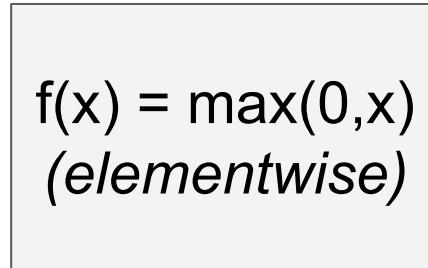
$$\begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

Upstream
gradient

Backprop with Vectors

4D input x :

$$\begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix} \xrightarrow{\quad}$$



4D output z :

$$\xrightarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix}$$

$[dz/dx]$ $[dL/dz]$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} [4]$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} [-1]$$

$$\begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} [5]$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} [9]$$

4D dL/dz :

$$\leftarrow \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

$$\leftarrow \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

$$\leftarrow \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

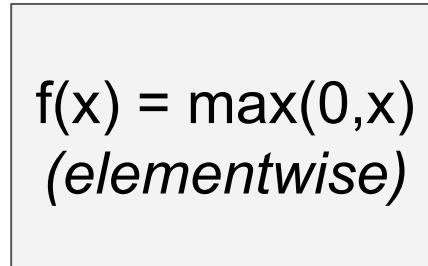
$$\leftarrow \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

Upstream
gradient

Backprop with Vectors

4D input x :

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4D output z :

$$\xrightarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix}$$

4D dL/dx :

$$\begin{bmatrix} 4 \\ 0 \\ 5 \\ 0 \end{bmatrix} \xleftarrow{\quad}$$

$[dz/dx] [dL/dz]$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix}$$

4D dL/dz :

$$\begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \xleftarrow{\quad}$$

Upstream
gradient

Backprop with Vectors

4D input x :

$$\begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix} \xrightarrow{\quad} \begin{bmatrix} 1 \\ -2 \\ 3 \\ -1 \end{bmatrix}$$

Jacobian is **sparse**:
off-diagonal entries
always zero! Never
explicitly form
Jacobian -- instead
use **implicit**
multiplication

4D output z :

$$\begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix} \xleftarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix}$$

$$f(x) = \max(0, x)$$

(elementwise)

4D dL/dx :

$$\begin{bmatrix} 4 \\ 0 \\ 5 \\ 0 \end{bmatrix} \xleftarrow{\quad} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix}$$

4D dL/dz :

$$\begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \xleftarrow{\quad} \begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix}$$

Upstream
gradient

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4D output z :

$$\begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix} \xrightarrow{\quad} \begin{bmatrix} 1 \\ 0 \\ 3 \\ 0 \end{bmatrix}$$

$$f(x) = \max(0, x) \quad (\text{elementwise})$$

4D dL/dx :

$$\begin{bmatrix} 4 \\ 0 \\ 5 \\ 0 \end{bmatrix} \leftarrow$$

$$\left(\frac{\partial L}{\partial x} \right)_i = \begin{cases} \left(\frac{\partial L}{\partial z} \right)_i & \text{if } x_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

$[dz/dx]$ $[dL/dz]$

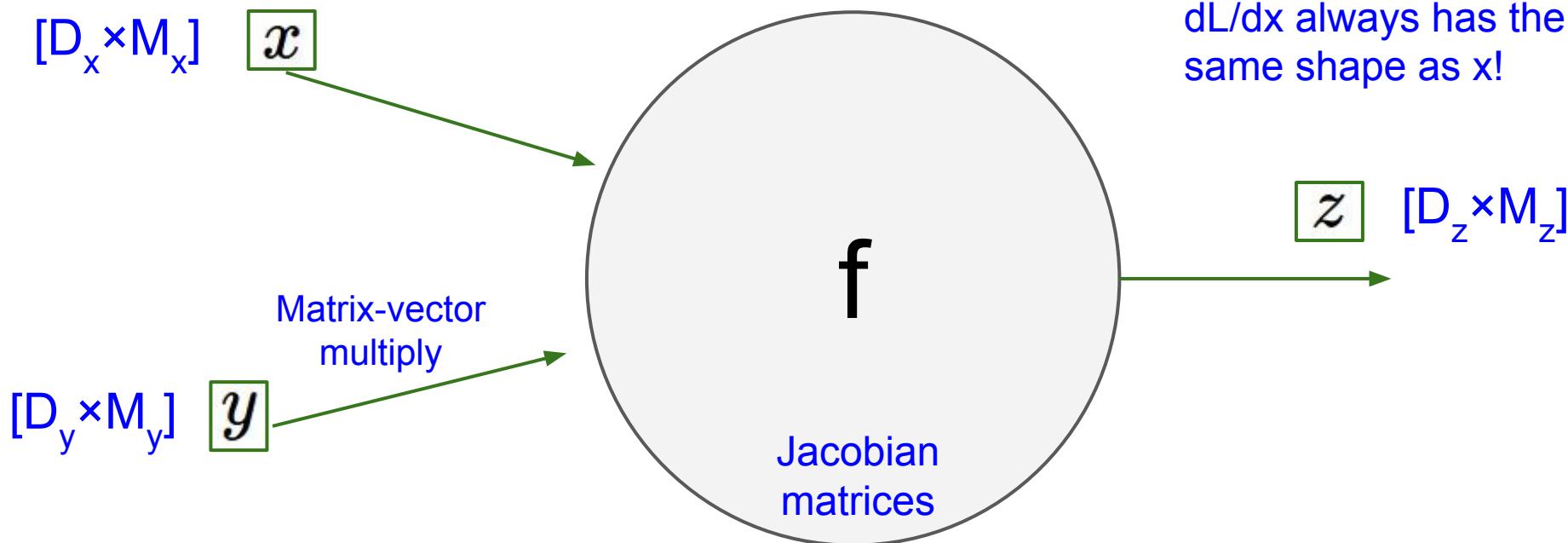
4D dL/dz :

$$\begin{bmatrix} 4 \\ -1 \\ 5 \\ 9 \end{bmatrix} \leftarrow$$

Upstream
gradient

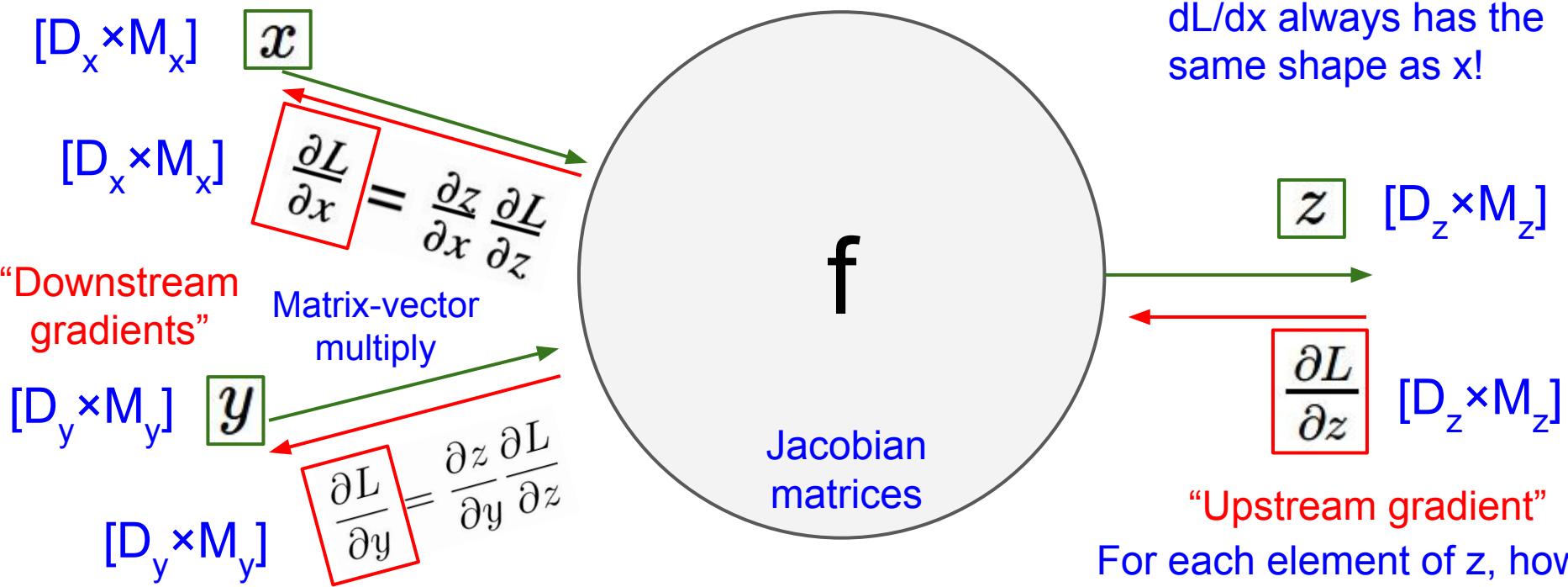
Backprop with Matrices (or Tensors)

Loss L still a scalar!



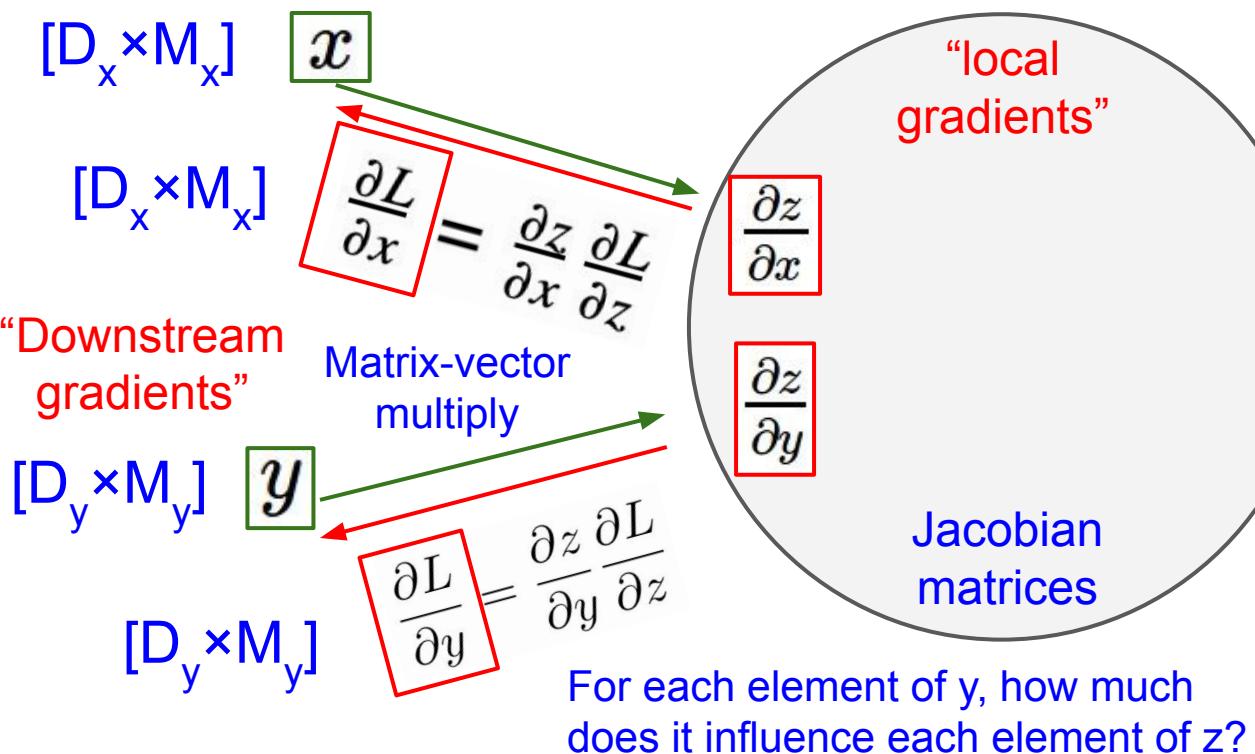
Backprop with Matrices (or Tensors)

Loss L still a scalar!



Backprop with Matrices (or Tensors)

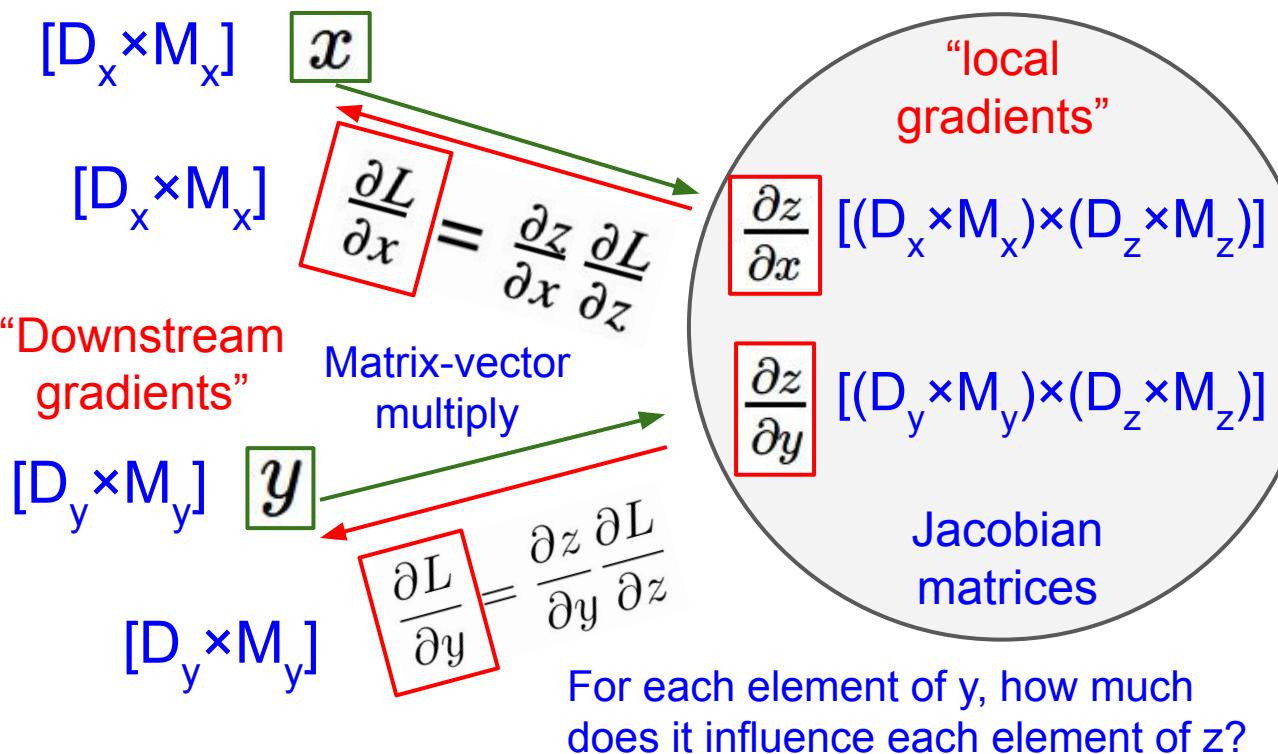
Loss L still a scalar!



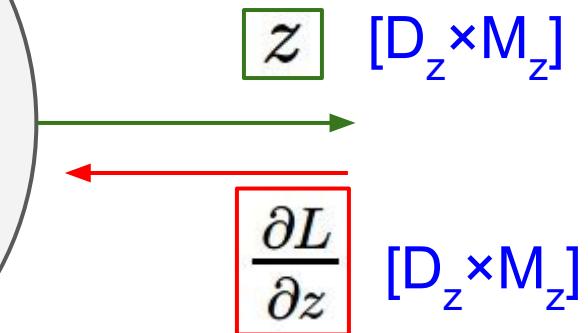
dL/dx always has the same shape as x !

Backprop with Matrices (or Tensors)

Loss L still a scalar!



dL/dx always has the same shape as x !



"Upstream gradient"

For each element of z , how much does it influence L ?

Backprop with Matrices

x: [N×D]

$$\begin{bmatrix} 2 & 1 & -3 \\ -3 & 4 & 2 \end{bmatrix}$$

w: [D×M]

$$\begin{bmatrix} 3 & 2 & 1 & -1 \\ 2 & 1 & 3 & 2 \\ 3 & 2 & 1 & -2 \end{bmatrix}$$

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

y: [N×M]

$$\begin{bmatrix} 13 & 9 & -2 & -6 \\ 5 & 2 & 17 & 1 \end{bmatrix}$$

dL/dy: [N×M]

$$\begin{bmatrix} 2 & 3 & -3 & 9 \\ -8 & 1 & 4 & 6 \end{bmatrix}$$

Also see derivation in the course notes:

<http://cs231n.stanford.edu/handouts/linear-backprop.pdf>

Backprop with Matrices

$x: [N \times D]$

$$\begin{bmatrix} 2 & 1 & -3 \\ -3 & 4 & 2 \end{bmatrix}$$

$w: [D \times M]$

$$\begin{bmatrix} 3 & 2 & 1 & -1 \\ 2 & 1 & 3 & 2 \\ 3 & 2 & 1 & -2 \end{bmatrix}$$

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

Jacobians:

$$\begin{aligned} dy/dx: [(N \times D) \times (N \times M)] \\ dy/dw: [(D \times M) \times (N \times M)] \end{aligned}$$

$y: [N \times M]$

$$\begin{bmatrix} 13 & 9 & -2 & -6 \\ 5 & 2 & 17 & 1 \end{bmatrix}$$

$dL/dy: [N \times M]$

$$\begin{bmatrix} 2 & 3 & -3 & 9 \\ -8 & 1 & 4 & 6 \end{bmatrix}$$

For a neural net we may have

$$N=64, D=M=4096$$

Each Jacobian takes ~ 256 GB of
memory! Must work with them implicitly!

Backprop with Matrices

x: [N×D]

$$\begin{bmatrix} 2 & \boxed{1} & -3 \\ -3 & 4 & 2 \end{bmatrix}$$

w: [D×M]

$$\begin{bmatrix} 3 & 2 & 1 & -1 \\ 2 & 1 & 3 & 2 \\ 3 & 2 & 1 & -2 \end{bmatrix}$$

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$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

Q: What parts of y
are affected by one
element of x?

y: [N×M]

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dL/dy: [N×M]

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Backprop with Matrices

$x: [N \times D]$

[2 **1** -3]

[-3 4 2]

$w: [D \times M]$

[3 2 1 -1]

[2 1 3 2]

[3 2 1 -2]

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

$y: [N \times M]$

[13 9 -2 -6]

[5 2 17 1]

$dL/dy: [N \times M]$

[2 3 -3 9]

[-8 1 4 6]

Q: What parts of y are affected by one element of x ?

A: $x_{n,d}$ affects the whole row $y_{n,:}$

$$\frac{\partial L}{\partial x_{n,d}} = \sum_m \frac{\partial L}{\partial y_{n,m}} \frac{\partial y_{n,m}}{\partial x_{n,d}}$$

Backprop with Matrices

$x: [N \times D]$

[2 **1** -3]

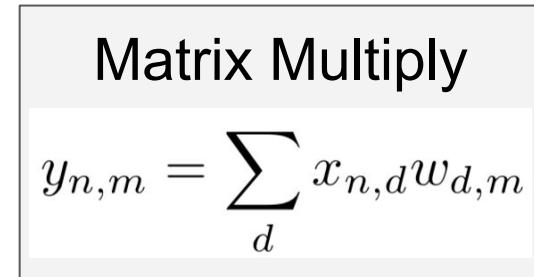
[-3 4 2]

$w: [D \times M]$

[3 2 1 -1]

[2 1 3 2]

[3 2 1 -2]



$y: [N \times M]$

13	9	-2	-6
5	2	17	1

$dL/dy: [N \times M]$

2	3	-3	9
-8	1	4	6

Q: What parts of y are affected by one element of x ?

A: $x_{n,d}$ affects the whole row $y_{n,\cdot}$.

Q: How much does $x_{n,d}$ affect $y_{n,m}$?

$$\frac{\partial L}{\partial x_{n,d}} = \sum_m \frac{\partial L}{\partial y_{n,m}} \frac{\partial y_{n,m}}{\partial x_{n,d}}$$

Backprop with Matrices

$x: [N \times D]$

[2 **1** -3]

[-3 4 2]

$w: [D \times M]$

[3 2 1 -1]

[2 1 **3** 2]

[3 2 1 -2]

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

Q: What parts of y are affected by one element of x ?
A: $x_{n,d}$ affects the whole row $y_{n,:}$.

Q: How much does $x_{n,d}$ affect $y_{n,m}$?
A: $w_{d,m}$

$y: [N \times M]$

[13 9 **-2** -6]

[5 2 17 1]

$dL/dy: [N \times M]$

[2 3 -3 9]

[-8 1 4 6]

$$\frac{\partial L}{\partial x_{n,d}} = \sum_m \frac{\partial L}{\partial y_{n,m}} \frac{\partial y_{n,m}}{\partial x_{n,d}} = \sum_m \frac{\partial L}{\partial y_{n,m}} w_{d,m}$$

Backprop with Matrices

x: [N×D]

$$\begin{bmatrix} 2 & \boxed{1} & -3 \\ -3 & 4 & 2 \end{bmatrix}$$

w: [D×M]

$$\begin{bmatrix} 3 & 2 & 1 & -1 \\ 2 & 1 & \boxed{3} & 2 \\ 3 & 2 & 1 & -2 \end{bmatrix}$$

[N×D] [N×M] [M×D]

$$\frac{\partial L}{\partial x} = \left(\frac{\partial L}{\partial y} \right) w^T$$

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

Q: What parts of y are affected by one element of x?
A: $x_{n,d}$ affects the whole row $y_{n,:}$.

Q: How much does $x_{n,d}$ affect $y_{n,m}$?
A: $w_{d,m}$

y: [N×M]

$$\begin{bmatrix} 13 & 9 & \boxed{-2} & -6 \\ 5 & 2 & 17 & 1 \end{bmatrix}$$

dL/dy: [N×M]

$$\begin{bmatrix} 2 & 3 & -3 & 9 \\ -8 & 1 & 4 & 6 \end{bmatrix}$$

Backprop with Matrices

$x: [N \times D]$

$$\begin{bmatrix} 2 & 1 & -3 \\ -3 & 4 & 2 \end{bmatrix}$$

$w: [D \times M]$

$$\begin{bmatrix} 3 & 2 & 1 & -1 \\ 2 & 1 & 3 & 2 \\ 3 & 2 & 1 & -2 \end{bmatrix}$$

Matrix Multiply

$$y_{n,m} = \sum_d x_{n,d} w_{d,m}$$

$y: [N \times M]$

$$\begin{bmatrix} 13 & 9 & -2 & -6 \\ 5 & 2 & 17 & 1 \end{bmatrix}$$

$dL/dy: [N \times M]$

$$\begin{bmatrix} 2 & 3 & -3 & 9 \\ -8 & 1 & 4 & 6 \end{bmatrix}$$

By similar logic:

$[N \times D] \quad [N \times M] \quad [M \times D]$

$[D \times M] \quad [D \times N] \quad [N \times M]$

$$\frac{\partial L}{\partial x} = \left(\frac{\partial L}{\partial y} \right) w^T$$

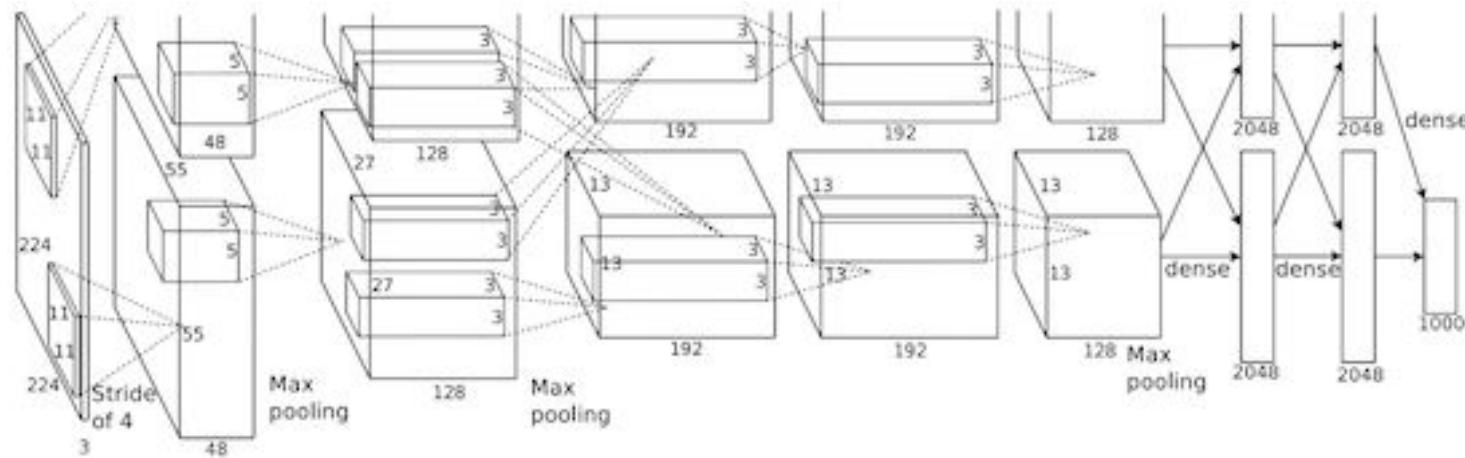
$$\frac{\partial L}{\partial w} = x^T \left(\frac{\partial L}{\partial y} \right)$$

These formulas are easy to remember: they are the only way to make shapes match up!

Summary for today:

- **(Fully-connected) Neural Networks** are stacks of linear functions and nonlinear activation functions; they have much more representational power than linear classifiers
- **backpropagation** = recursive application of the chain rule along a computational graph to compute the gradients of all inputs/parameters/intermediates
- implementations maintain a graph structure, where the nodes implement the **forward()** / **backward()** API
- **forward**: compute result of an operation and save any intermediates needed for gradient computation in memory
- **backward**: apply the chain rule to compute the gradient of the loss function with respect to the inputs

Next Time: Convolutional Neural Networks!

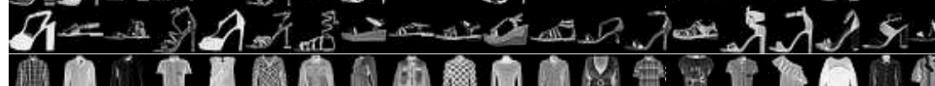




CS 231N PyTorch Tutorial

Drew Kaul
April 22

Fashion-MNIST

Label	Description	Examples
0	T-Shirt/Top	
1	Trouser	
2	Pullover	
3	Dress	
4	Coat	
5	Sandals	
6	Shirt	
7	Sneaker	
8	Bag	
9	Ankle boots	

Xiao et al. Fashion-mnist: a novel image dataset for benchmarking machine learning algorithms.
arXiv preprint arXiv:1708.07747.

Tensors

Initializing a Tensor

Directly from data

Tensors can be created directly from data. The data type is automatically inferred.

```
data = [[1, 2], [3, 4]]  
x_data = torch.tensor(data)
```

From a NumPy array

Tensors can be created from NumPy arrays (and vice versa - see [Bridge with NumPy](#)).

```
np_array = np.array(data)  
x_np = torch.from_numpy(np_array)
```

Initializing a Tensor

From another tensor:

The new tensor retains the properties (shape, datatype) of the argument tensor, unless explicitly overridden.

```
x_ones = torch.ones_like(x_data) # retains the properties of x_data
print(f"Ones Tensor: \n {x_ones} \n")

x_rand = torch.rand_like(x_data, dtype=torch.float) # overrides the datatype of x_data
print(f"Random Tensor: \n {x_rand} \n")
```

Out:

```
Ones Tensor:
tensor([[1, 1],
        [1, 1]])

Random Tensor:
tensor([[0.9152, 0.2666],
        [0.0863, 0.9133]])
```

Attributes of a Tensor

Tensor attributes describe their shape, datatype, and the device on which they are stored.

```
tensor = torch.rand(3,4)

print(f"Shape of tensor: {tensor.shape}")
print(f"Datatype of tensor: {tensor.dtype}")
print(f"Device tensor is stored on: {tensor.device}")
```

Out:

```
Shape of tensor: torch.Size([3, 4])
Datatype of tensor: torch.float32
Device tensor is stored on: cpu
```

Operations on Tensors

By default, tensors are created on the CPU. We need to explicitly move tensors to the GPU using `.to` method (after checking for GPU availability). Keep in mind that copying large tensors across devices can be expensive in terms of time and memory!

```
# We move our tensor to the GPU if available
if torch.cuda.is_available():
    tensor = tensor.to('cuda')
```

Operations on Tensors

Standard numpy-like indexing and slicing:

```
tensor = torch.ones(4, 4)
print('First row: ', tensor[0])
print('First column: ', tensor[:, 0])
print('Last column:', tensor[..., -1])
tensor[:, 1] = 0
print(tensor)
```

Out:

```
First row:  tensor([1., 1., 1., 1.])
First column:  tensor([1., 1., 1., 1.])
Last column: tensor([1., 1., 1., 1.])
tensor([[1., 0., 1., 1.],
        [1., 0., 1., 1.],
        [1., 0., 1., 1.],
        [1., 0., 1., 1.]])
```

Operations on Tensors

Arithmetic operations

```
# This computes the matrix multiplication between two tensors. y1, y2, y3 will have the same value
y1 = tensor @ tensor.T
y2 = tensor.matmul(tensor.T)

y3 = torch.rand_like(tensor)
torch.matmul(tensor, tensor.T, out=y3)

# This computes the element-wise product. z1, z2, z3 will have the same value
z1 = tensor * tensor
z2 = tensor.mul(tensor)

z3 = torch.rand_like(tensor)
torch.mul(tensor, tensor, out=z3)
```

Datasets & DataLoaders

Loading a Dataset

```
import torch
from torch.utils.data import Dataset
from torchvision import datasets
from torchvision.transforms import ToTensor, Lambda
import matplotlib.pyplot as plt

training_data = datasets.FashionMNIST(
    root="data",
    train=True,
    download=True,
    transform=ToTensor()
)

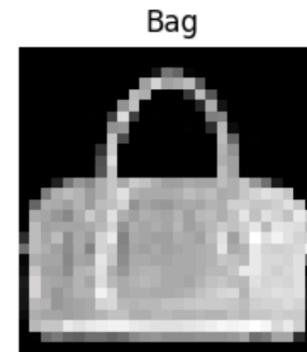
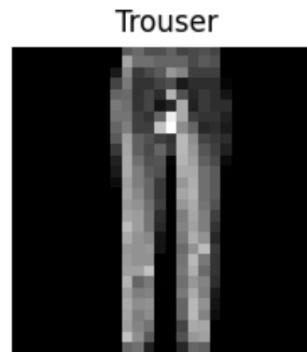
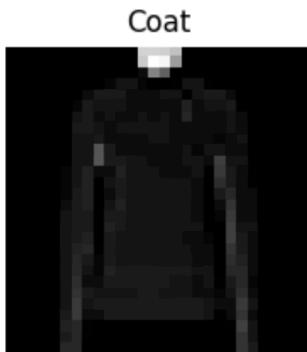
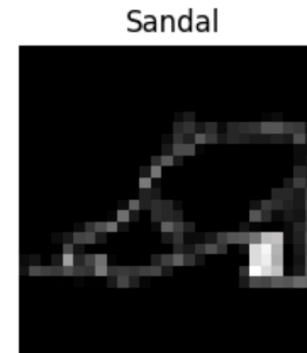
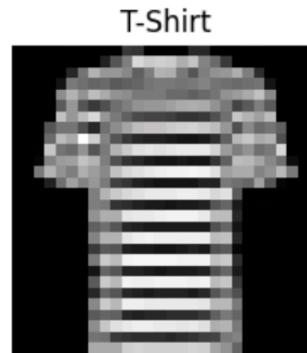
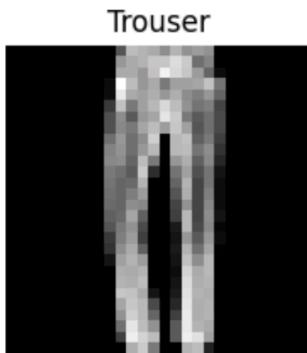
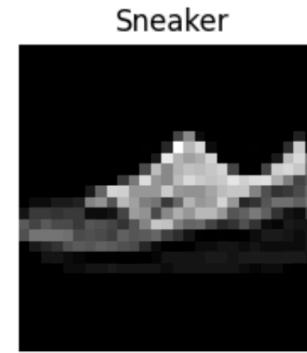
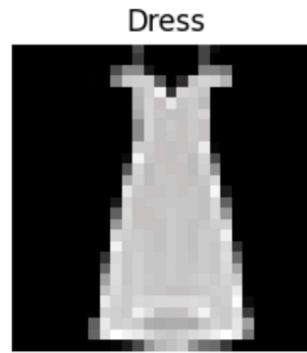
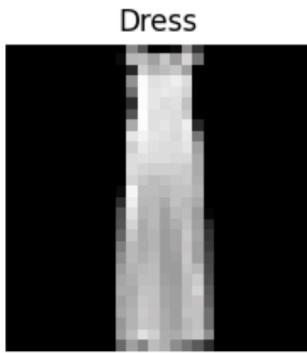
test_data = datasets.FashionMNIST(
    root="data",
    train=False,
    download=True,
    transform=ToTensor()
)
```

Iterating and Visualizing the Dataset

We can index `Datasets` manually like a list: `training_data[index]`. We use `matplotlib` to visualize some samples in our training data.

```
labels_map = {  
    0: "T-Shirt",  
    1: "Trouser",  
    2: "Pullover",  
    3: "Dress",  
    4: "Coat",  
    5: "Sandal",  
    6: "Shirt",  
    7: "Sneaker",  
    8: "Bag",  
    9: "Ankle Boot",  
}  
figure = plt.figure(figsize=(8, 8))  
cols, rows = 3, 3  
for i in range(1, cols * rows + 1):  
    sample_idx = torch.randint(len(training_data), size=(1,)).item()  
    img, label = training_data[sample_idx]  
    figure.add_subplot(rows, cols, i)  
    plt.title(labels_map[label])  
    plt.axis("off")  
    plt.imshow(img.squeeze(), cmap="gray")  
plt.show()
```

Iterating and Visualizing the Dataset



Creating a Custom Dataset for your files

```
import os
import pandas as pd
from torchvision.io import read_image

class CustomImageDataset(Dataset):
    def __init__(self, annotations_file, img_dir, transform=None, target_transform=None):
        self.img_labels = pd.read_csv(annotations_file)
        self.img_dir = img_dir
        self.transform = transform
        self.target_transform = target_transform

    def __len__(self):
        return len(self.img_labels)

    def __getitem__(self, idx):
        img_path = os.path.join(self.img_dir, self.img_labels.iloc[idx, 0])
        image = read_image(img_path)
        label = self.img_labels.iloc[idx, 1]
        if self.transform:
            image = self.transform(image)
        if self.target_transform:
            label = self.target_transform(label)
        sample = {"image": image, "label": label}
        return sample
```

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        self.transform = transform
        self.target_transform = target_transform

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        return len(self.img_labels)

    def __getitem__(self, idx):
        img_path = os.path.join(self.img_dir, self.img_labels.iloc[idx, 0])
        image = read_image(img_path)
        label = self.img_labels.iloc[idx, 1]
        if self.transform:
            image = self.transform(image)
        if self.target_transform:
            label = self.target_transform(label)
        sample = {"image": image, "label": label}
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```

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        self.transform = transform
        self.target_transform = target_transform

    def __len__(self):
        return len(self.img_labels)

    def __getitem__(self, idx):
        img_path = os.path.join(self.img_dir, self.img_labels.iloc[idx, 0])
        image = read_image(img_path)
        label = self.img_labels.iloc[idx, 1]
        if self.transform:
            image = self.transform(image)
        if self.target_transform:
            label = self.target_transform(label)
        sample = {"image": image, "label": label}
        return sample
```

Creating a Custom Dataset for your files

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class CustomImageDataset(Dataset):
    def __init__(self, annotations_file, img_dir, transform=None, target_transform=None):
        self.img_labels = pd.read_csv(annotations_file)
        self.img_dir = img_dir
        self.transform = transform
        self.target_transform = target_transform

    def __len__(self):
        return len(self.img_labels)

    def __getitem__(self, idx):
        img_path = os.path.join(self.img_dir, self.img_labels.iloc[idx, 0])
        image = read_image(img_path)
        label = self.img_labels.iloc[idx, 1]
        if self.transform:
            image = self.transform(image)
        if self.target_transform:
            label = self.target_transform(label)
        sample = {"image": image, "label": label}
        return sample
```

Preparing your data for training with DataLoaders

The `Dataset` retrieves our dataset's features and labels one sample at a time. While training a model, we typically want to pass samples in “minibatches”, reshuffle the data at every epoch to reduce model overfitting, and use Python’s `multiprocessing` to speed up data retrieval.

`DataLoader` is an iterable that abstracts this complexity for us in an easy API.

```
from torch.utils.data import DataLoader

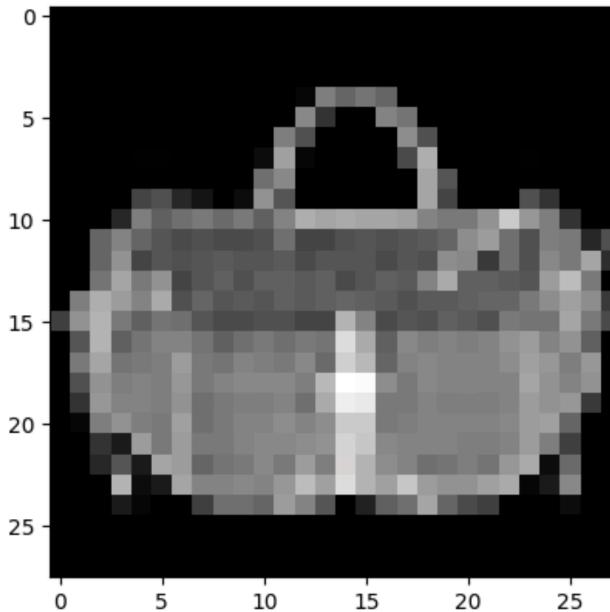
train_dataloader = DataLoader(training_data, batch_size=64, shuffle=True)
test_dataloader = DataLoader(test_data, batch_size=64, shuffle=True)
```

Iterate through the DataLoader

We have loaded that dataset into the `Dataloader` and can iterate through the dataset as needed. Each iteration below returns a batch of `train_features` and `train_labels` (containing ``batch_size=64 features and labels respectively). Because we specified `shuffle=True`, after we iterate over all batches the data is shuffled (for finer-grained control over the data loading order, take a look at [Samplers](#)).

```
# Display image and label.  
train_features, train_labels = next(iter(train_dataloader))  
print(f"Feature batch shape: {train_features.size()}")
print(f"Labels batch shape: {train_labels.size()}")
img = train_features[0].squeeze()  
label = train_labels[0]
plt.imshow(img, cmap="gray")
plt.show()
print(f"Label: {label}")
```

Iterate through the DataLoader



Out:

```
Feature batch shape: torch.Size([64, 1, 28, 28])
Labels batch shape: torch.Size([64])
Label: 8
```

Neural Network

torch.nn.Module

```
import os
import torch
from torch import nn
from torch.utils.data import DataLoader
from torchvision import datasets, transforms
```

Get Device for Training

We want to be able to train our model on a hardware accelerator like the GPU, if it is available. Let's check to see if `torch.cuda` is available, else we continue to use the CPU.

```
device = 'cuda' if torch.cuda.is_available() else 'cpu'  
print('Using {} device'.format(device))
```

Out:

```
Using cuda device
```

Define the Class

We define our neural network by subclassing `nn.Module`, and initialize the neural network layers in `__init__`. Every `nn.Module` subclass implements the operations on input data in the `forward` method.

```
class NeuralNetwork(nn.Module):
    def __init__(self):
        super(NeuralNetwork, self).__init__()
        self.flatten = nn.Flatten()
        self.linear_relu_stack = nn.Sequential(
            nn.Linear(28*28, 512),
            nn.ReLU(),
            nn.Linear(512, 512),
            nn.ReLU(),
            nn.Linear(512, 10),
            nn.ReLU()
        )

    def forward(self, x):
        x = self.flatten(x)
        logits = self.linear_relu_stack(x)
        return logits
```

Define the Class

We create an instance of `NeuralNetwork`, and move it to the `device`, and print it's structure.

```
model = NeuralNetwork().to(device)
print(model)
```

Out:

```
NeuralNetwork(
    (flatten): Flatten(start_dim=1, end_dim=-1)
    (linear_relu_stack): Sequential(
        (0): Linear(in_features=784, out_features=512, bias=True)
        (1): ReLU()
        (2): Linear(in_features=512, out_features=512, bias=True)
        (3): ReLU()
        (4): Linear(in_features=512, out_features=10, bias=True)
        (5): ReLU()
    )
)
```

Define the Class

To use the model, we pass it the input data. This executes the model's `forward`, along with some **background operations**. Do not call `model.forward()` directly!

Calling the model on the input returns a 10-dimensional tensor with raw predicted values for each class. We get the prediction probabilities by passing it through an instance of the `nn.Softmax` module.

```
X = torch.rand(1, 28, 28, device=device)
logits = model(X)
pred_probab = nn.Softmax(dim=1)(logits)
y_pred = pred_probab.argmax(1)
print(f"Predicted class: {y_pred}")
```

Out:

```
Predicted class: tensor([2], device='cuda:0')
```

Optimizing Model Params

Loss Function

Common loss functions include `nn.MSELoss` (Mean Square Error) for regression tasks, and `nn.NLLLoss` (Negative Log Likelihood) for classification. `nn.CrossEntropyLoss` combines `nn.LogSoftmax` and `nn.NLLLoss`.

We pass our model's output logits to `nn.CrossEntropyLoss`, which will normalize the logits and compute the prediction error.

```
# Initialize the loss function
loss_fn = nn.CrossEntropyLoss()
```

Optimizer

We initialize the optimizer by registering the model's parameters that need to be trained, and passing in the learning rate hyperparameter.

```
optimizer = torch.optim.SGD(model.parameters(), lr=learning_rate)
```

Inside the training loop, optimization happens in three steps:

- Call `optimizer.zero_grad()` to reset the gradients of model parameters. Gradients by default add up; to prevent double-counting, we explicitly zero them at each iteration.
- Backpropagate the prediction loss with a call to `loss.backwards()`. PyTorch deposits the gradients of the loss w.r.t. each parameter.
- Once we have our gradients, we call `optimizer.step()` to adjust the parameters by the gradients collected in the backward pass.

Full Implementation – Train Loop

```
def train_loop(dataloader, model, loss_fn, optimizer):
    size = len(dataloader.dataset)
    for batch, (X, y) in enumerate(dataloader):
        # Compute prediction and loss
        pred = model(X)
        loss = loss_fn(pred, y)

        # Backpropagation
        optimizer.zero_grad()
        loss.backward()
        optimizer.step()

        if batch % 100 == 0:
            loss, current = loss.item(), batch * len(X)
            print(f"loss: {loss:>7f} [{current:>5d}/{size:>5d}]")
```

Full Implementation – Test Loop

```
def test_loop(dataloader, model, loss_fn):
    size = len(dataloader.dataset)
    test_loss, correct = 0, 0

    with torch.no_grad():
        for X, y in dataloader:
            pred = model(X)
            test_loss += loss_fn(pred, y).item()
            correct += (pred.argmax(1) == y).type(torch.float).sum().item()

    test_loss /= size
    correct /= size
    print(f"Test Error: \n Accuracy: {(100*correct):>0.1f}%, Avg loss: {test_loss:>8f} \n")
```

Full Implementation

```
loss_fn = nn.CrossEntropyLoss()
optimizer = torch.optim.SGD(model.parameters(), lr=learning_rate)

epochs = 10
for t in range(epochs):
    print(f"Epoch {t+1}\n-----")
    train_loop(train_dataloader, model, loss_fn, optimizer)
    test_loop(test_dataloader, model, loss_fn)
print("Done!")
```

Full Implementation

Out:

Epoch 1

```
-----  
loss: 2.299511  [    0/60000]  
loss: 2.301767  [ 6400/60000]  
loss: 2.289777  [12800/60000]  
loss: 2.291731  [19200/60000]  
loss: 2.269755  [25600/60000]  
loss: 2.261175  [32000/60000]  
loss: 2.258553  [38400/60000]  
loss: 2.240743  [44800/60000]  
loss: 2.260818  [51200/60000]  
loss: 2.243683  [57600/60000]
```

Test Error:

Accuracy: 37.3%, Avg loss: 0.035121

Epoch 2

```
-----  
loss: 2.229830  [    0/60000]  
loss: 2.241497  [ 6400/60000]  
loss: 2.221580  [12800/60000]
```

Save and Load the Model

Saving and Loading Model Weights

PyTorch models store the learned parameters in an internal state dictionary, called `state_dict`. These can be persisted via the `torch.save` method:

```
model = models.vgg16(pretrained=True)
torch.save(model.state_dict(), 'model_weights.pth')
```

To load model weights, you need to create an instance of the same model first, and then load the parameters using `load_state_dict()` method.

```
model = models.vgg16() # we do not specify pretrained=True, i.e. do not load default weights
model.load_state_dict(torch.load('model_weights.pth'))
model.eval()
```

Saving and Loading Models with Shapes

When loading model weights, we needed to instantiate the model class first, because the class defines the structure of a network. We might want to save the structure of this class together with the model, in which case we can pass `model` (and not `model.state_dict()`) to the saving function:

```
torch.save(model, 'model.pth')
```

We can then load the model like this:

```
model = torch.load('model.pth')
```

Acknowledgment

- PyTorch Official Tutorial:
<https://pytorch.org/tutorials/beginner/basics/intro.html>
- Feel free to check out the tutorial for more details!

Lecture 5: Image Classification with CNNs

Administrative

Assignment 1 due Friday April 15, 11:59pm

- Important: tag your solutions with the corresponding hw question in gradescope!

Assignment 2 will also be released on April 15th

Administrative

Project proposal due **Monday Apr 18, 11:59pm**

This week's discussion section is moved to **Wed 3-4pm.**

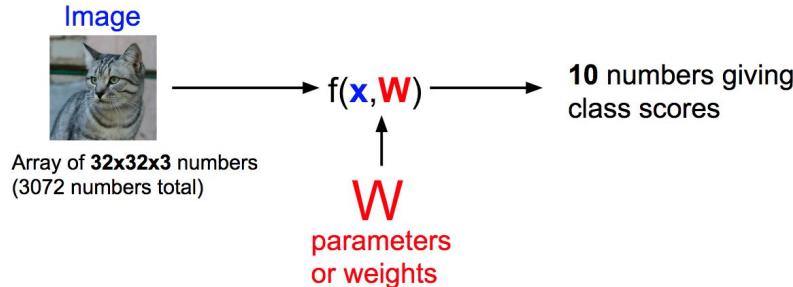
Will discuss how to design a project and guidelines.

Administrative

AWS Credit

- Ed announcement soon
- A Google Doc tutorial will be shared on how to use AWS
- Fill out the Google Form with your AWS account ID if you want AWS cloud credit for your project

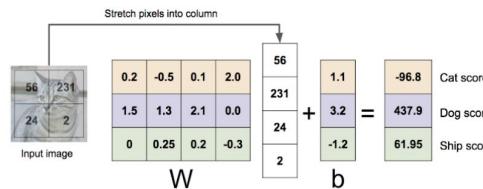
Recap: Image Classification with Linear Classifier



$$f(x, W) = Wx + b$$

Algebraic Viewpoint

$$f(x, W) = Wx$$



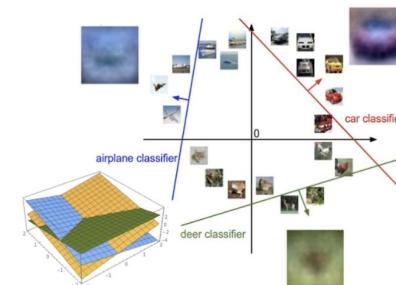
Visual Viewpoint

One template per class



Geometric Viewpoint

Hyperplanes cutting up space



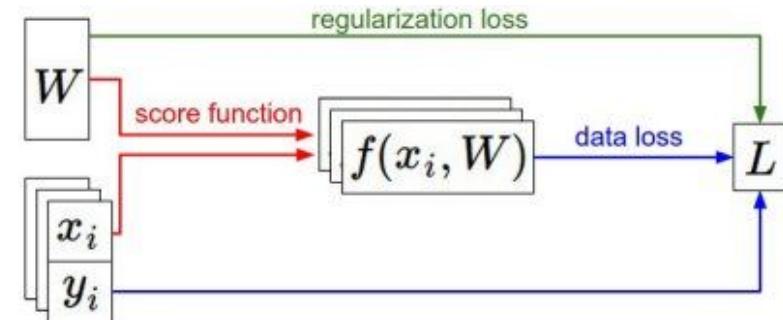
Recap: Loss Function

- We have some dataset of (x, y)
- We have a **score function**: $s = f(x; W) = Wx$
- We have a **loss function**:

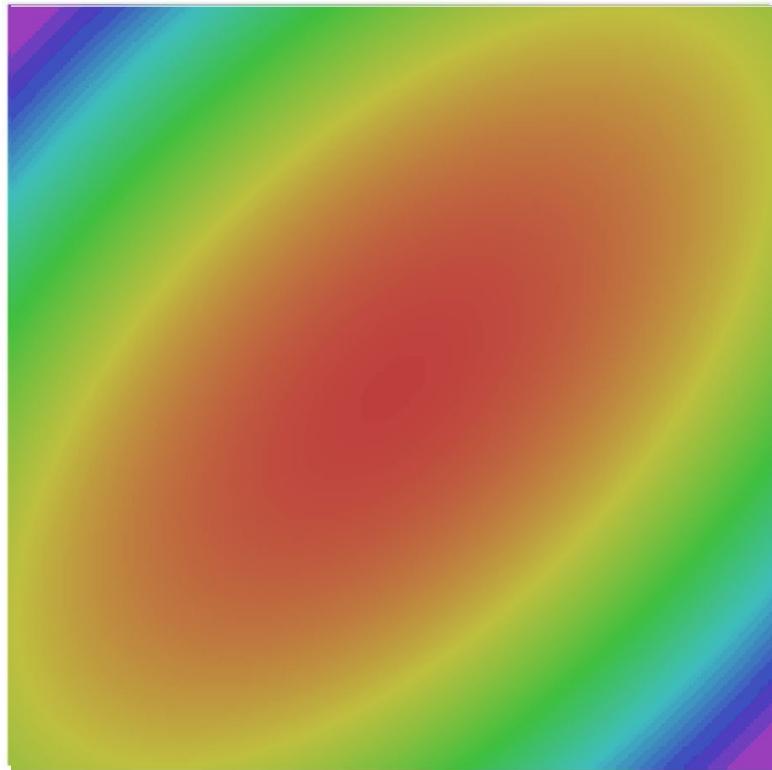
$$L_i = -\log\left(\frac{e^{sy_i}}{\sum_j e^{sj}}\right) \text{ Softmax}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \text{ SVM}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W) \text{ Full loss}$$



Recap: Optimization



- SGD
- SGD+Momentum
- RMSProp
- Adam

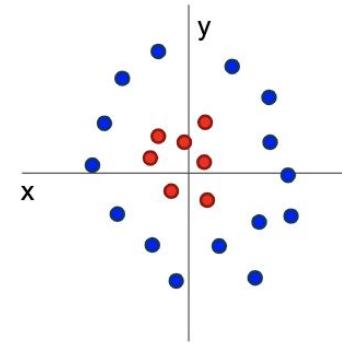
Problem: Linear Classifiers are not very powerful

Visual Viewpoint



Linear classifiers learn
one template per class

Geometric Viewpoint



Linear classifiers
can only draw linear
decision boundaries

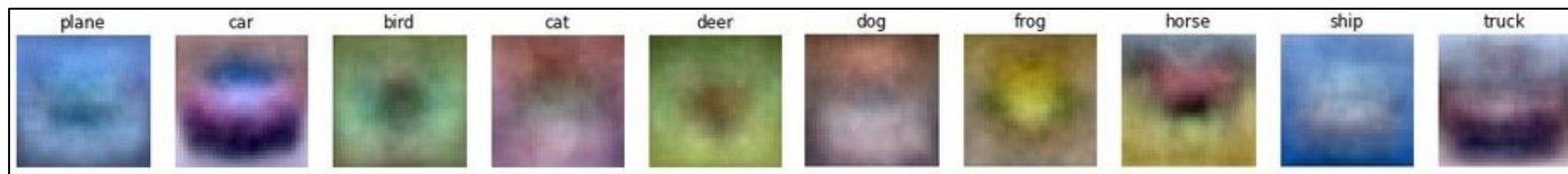
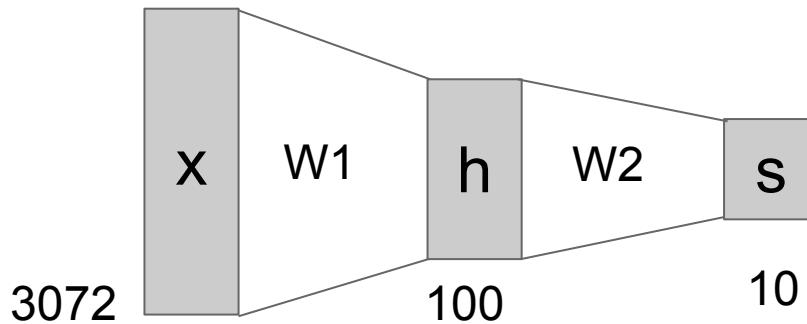
Last time: Neural Networks

Linear score function:

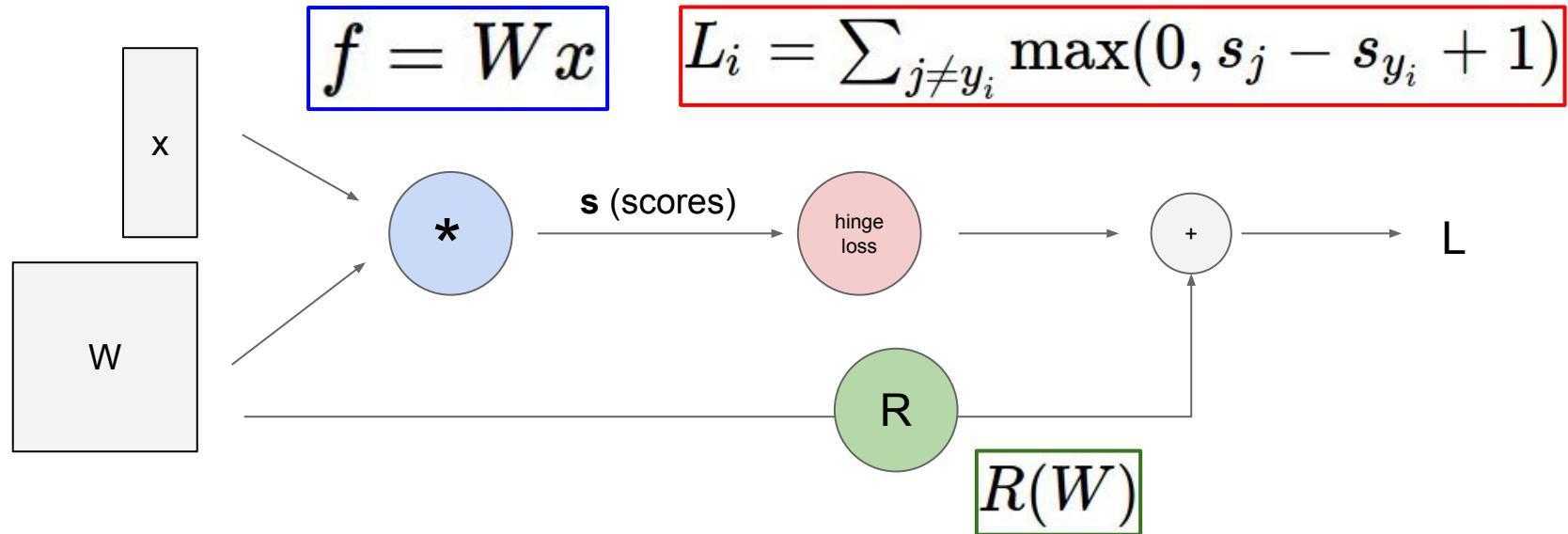
$$f = Wx$$

2-layer Neural Network

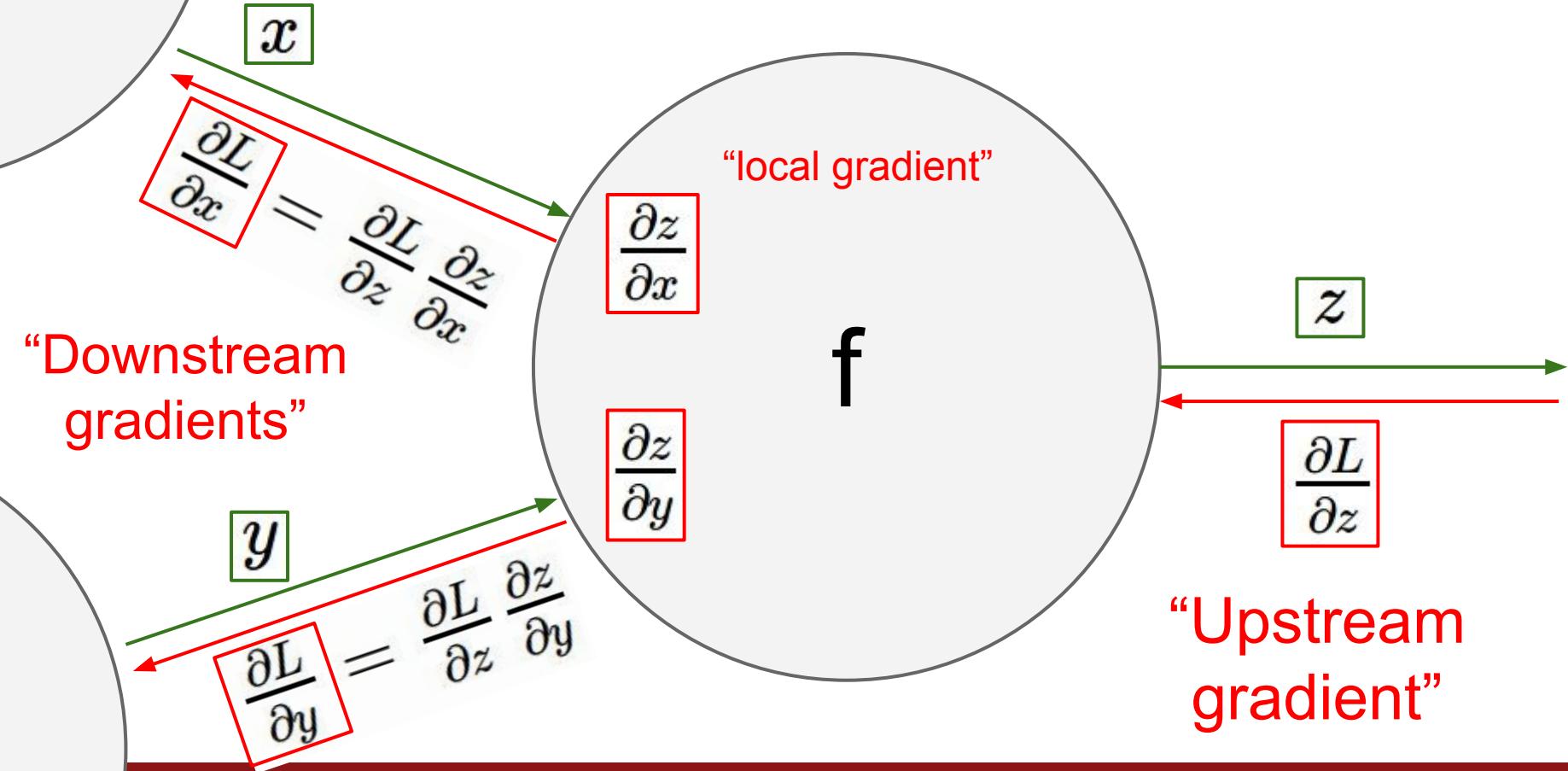
$$f = W_2 \max(0, W_1 x)$$



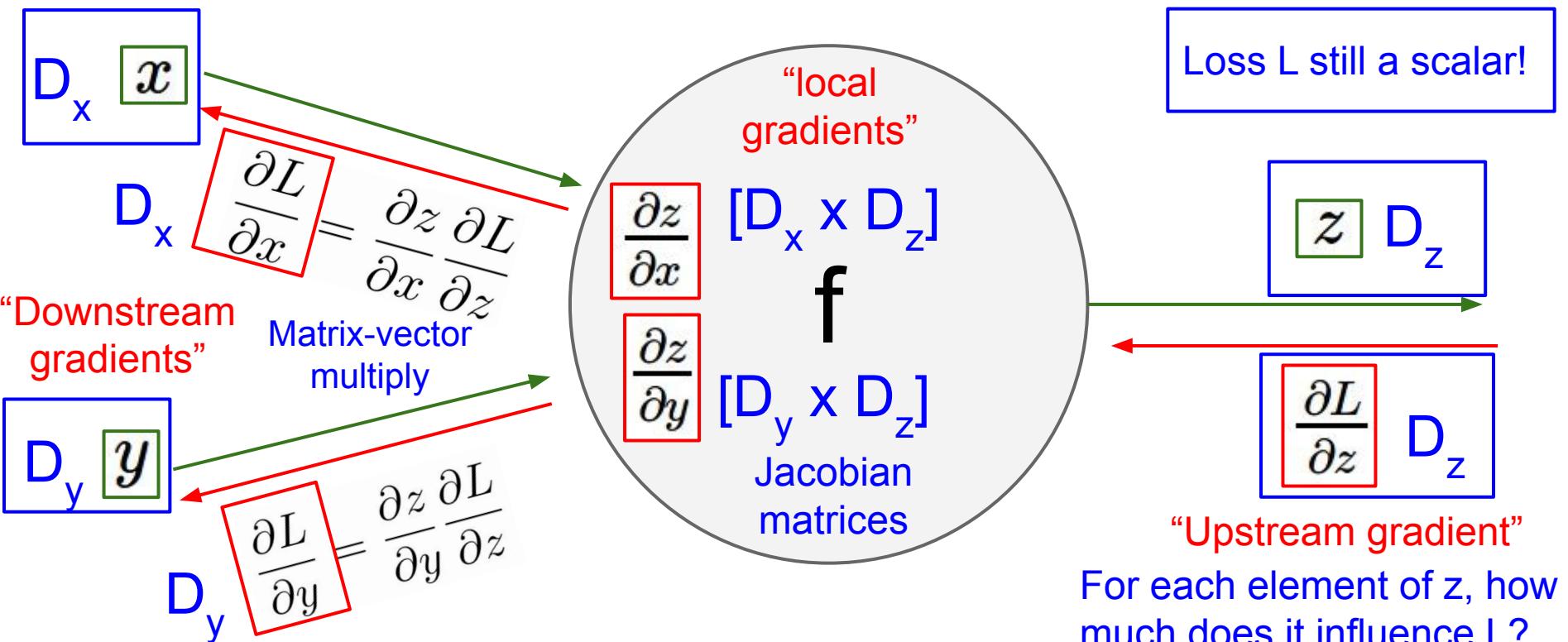
Last time: Computation Graph



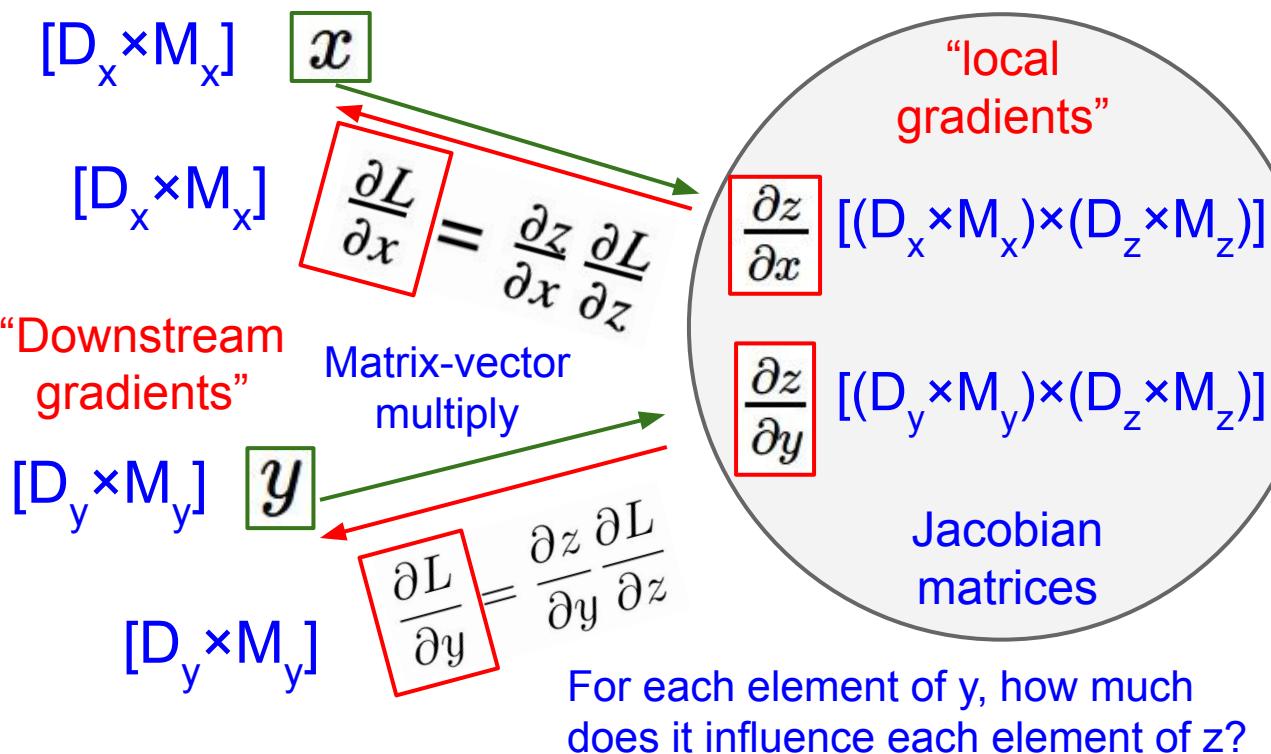
Last time: Backpropagation



Backprop with Vectors

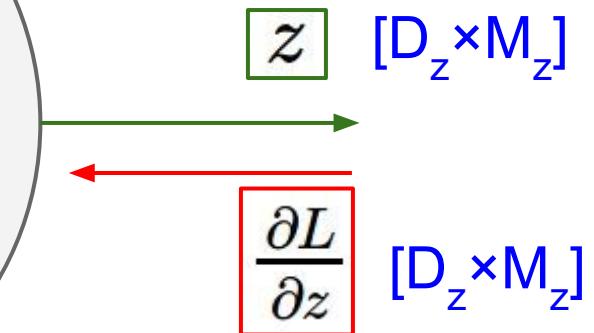


Backprop with Matrices (or Tensors)



Loss L still a scalar!

dL/dx always has the same shape as x !



"Upstream gradient"

For each element of z, how much does it influence L?

CS231n: Deep Learning for Computer Vision

- Deep Learning Basics (Lecture 2 – 4)
- Perceiving and Understanding the Visual World (Lecture 5 – 12)
- Reconstructing and Interacting with the Visual World (Lecture 13 – 16)
- Human-Centered Artificial Intelligence (Lecture 17 – 18)

Image Classification: A core task in Computer Vision



This image by [Nikita](#) is
licensed under [CC-BY 2.0](#)

(assume given a set of labels)
{dog, cat, truck, plane, ...}



cat
dog
bird
deer
truck

Pixel space

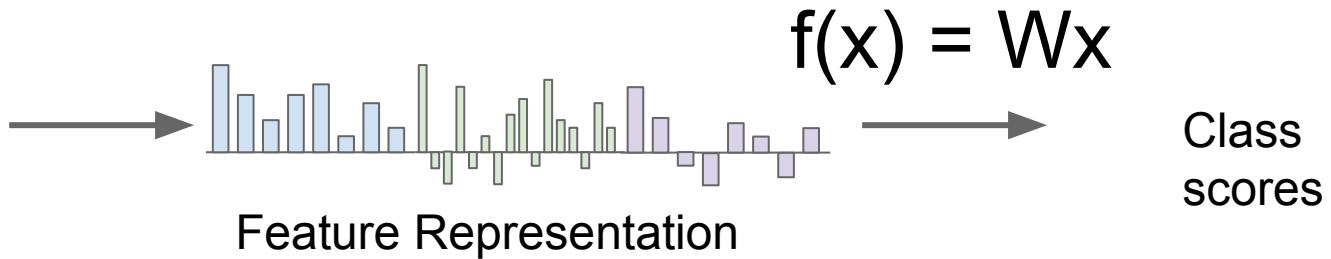


$$f(x) = Wx$$

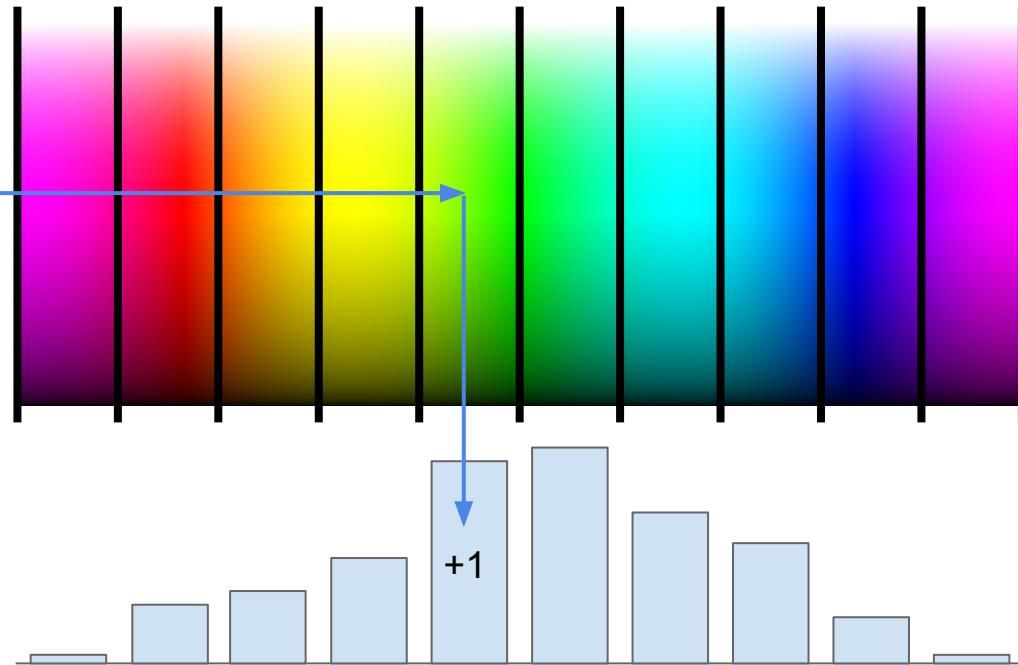
Class
scores



Image features



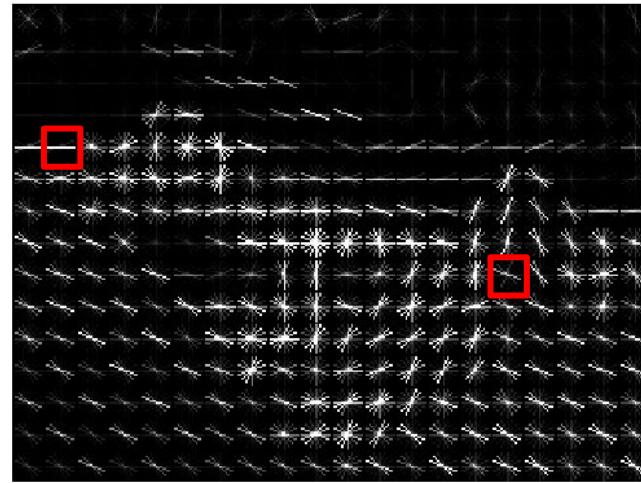
Example: Color Histogram



Example: Histogram of Oriented Gradients (HoG)



Divide image into 8x8 pixel regions
Within each region quantize edge
direction into 9 bins



Example: 320x240 image gets divided
into 40x30 bins; in each bin there are
9 numbers so feature vector has
 $30 \times 40 \times 9 = 10,800$ numbers

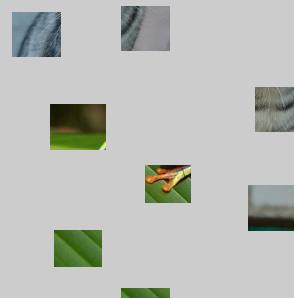
Lowe, "Object recognition from local scale-invariant features", ICCV 1999
Dalal and Triggs, "Histograms of oriented gradients for human detection," CVPR 2005

Example: Bag of Words

Step 1: Build codebook



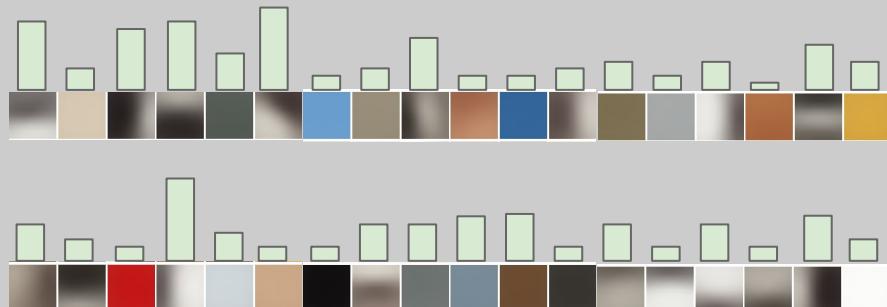
Extract random patches



Cluster patches to form “codebook” of “visual words”



Step 2: Encode images



Fei-Fei and Perona, “A bayesian hierarchical model for learning natural scene categories”, CVPR 2005

Image Features

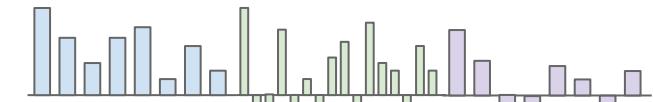
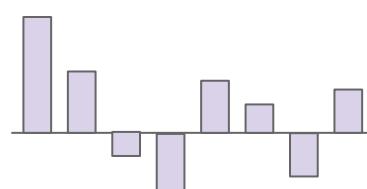
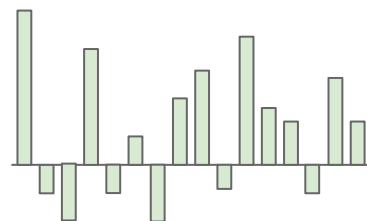
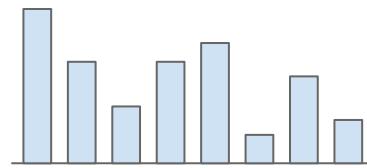
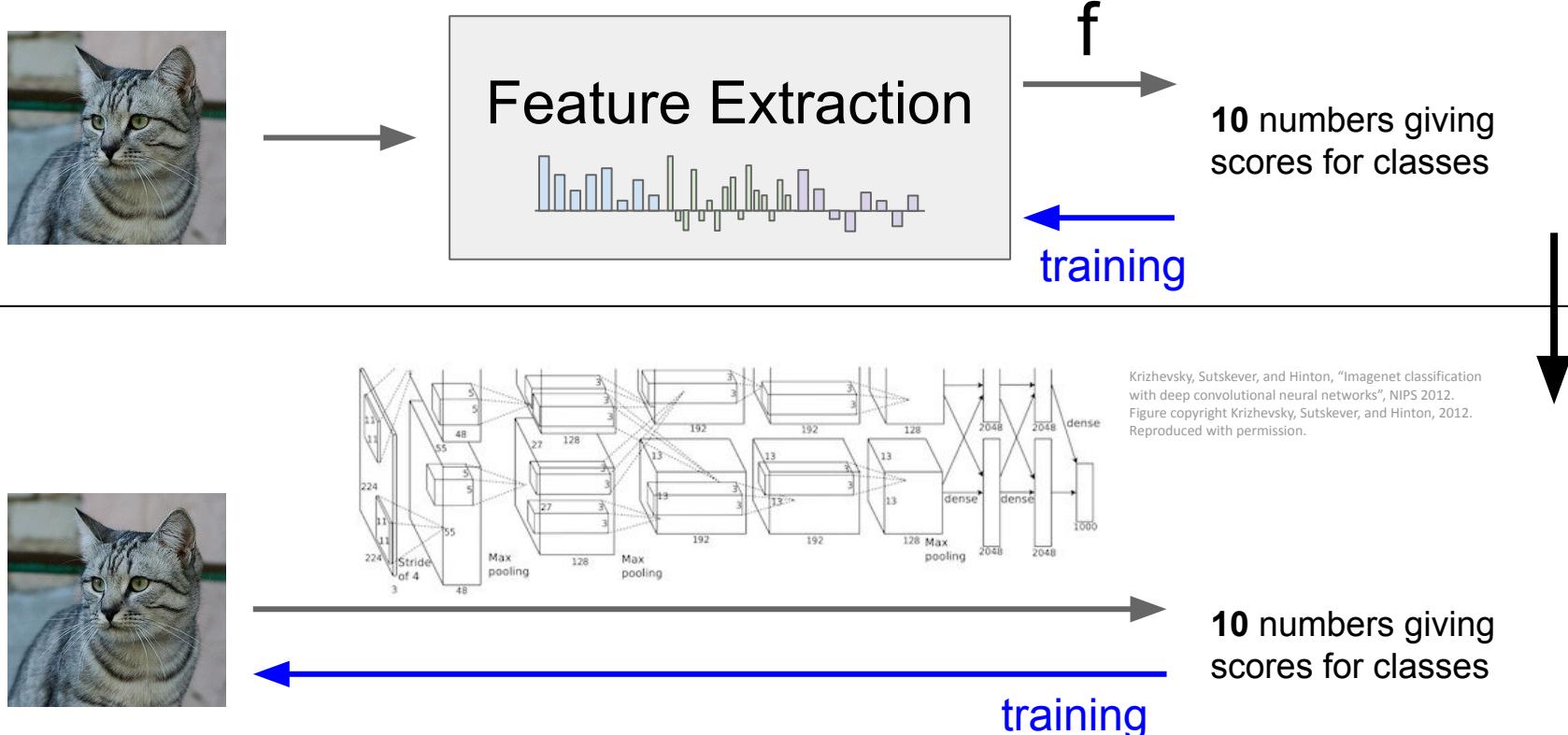


Image features vs. ConvNets



Last Time: Neural Networks

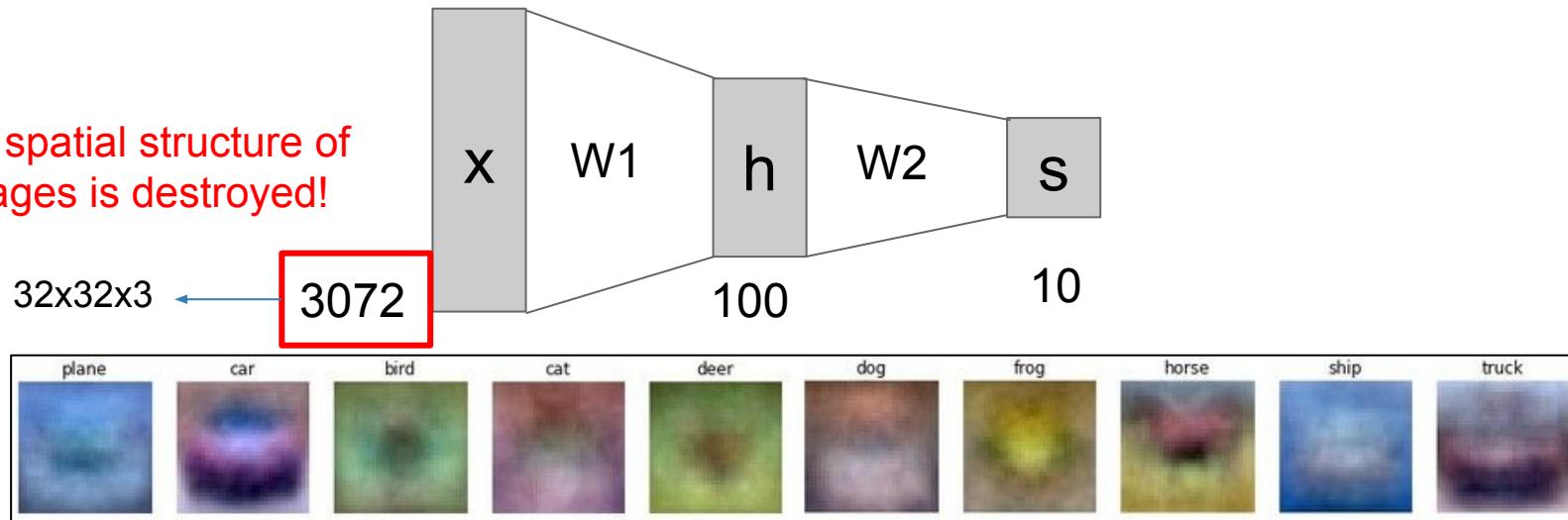
Linear score function:

$$f = Wx$$

2-layer Neural Network

$$f = W_2 \max(0, W_1 x)$$

The spatial structure of images is destroyed!



Next: Convolutional Neural Networks

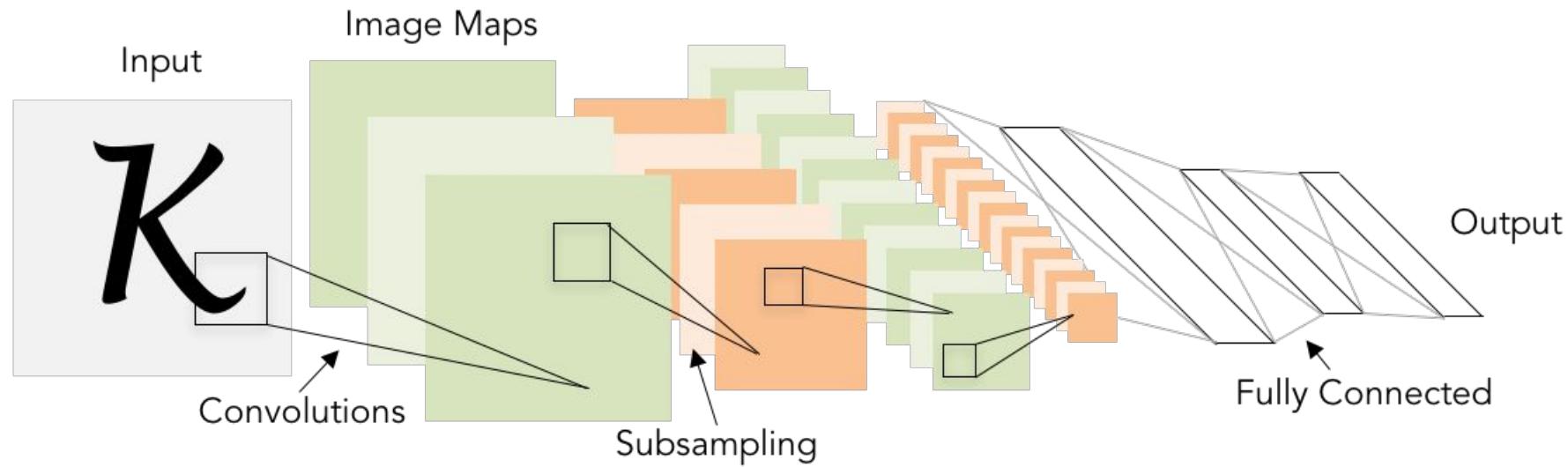


Illustration of LeCun et al. 1998 from CS231n 2017 Lecture 1

A bit of history...

The **Mark I Perceptron** machine was the first implementation of the perceptron algorithm.

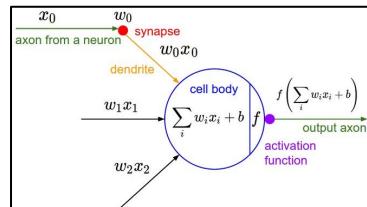
The machine was connected to a camera that used 20×20 cadmium sulfide photocells to produce a 400-pixel image.

recognized
letters of the alphabet

$$f(x) = \begin{cases} 1 & \text{if } w \cdot x + b > 0 \\ 0 & \text{otherwise} \end{cases}$$

update rule:

$$w_i(t+1) = w_i(t) + \alpha(d_j - y_j(t))x_{j,i}$$

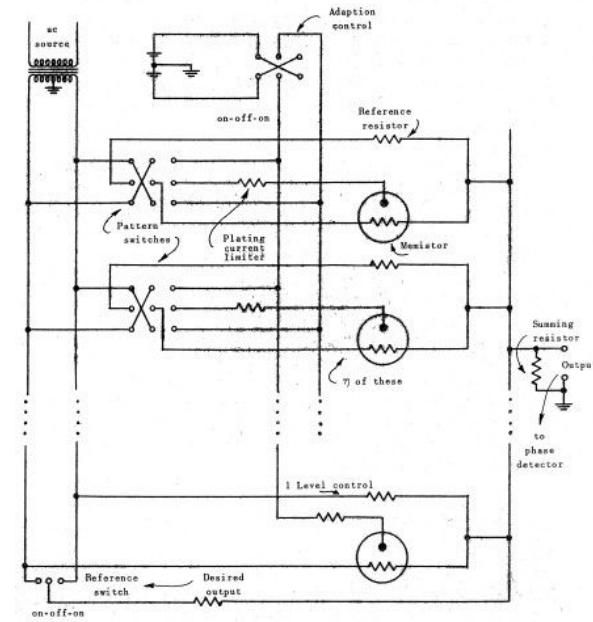
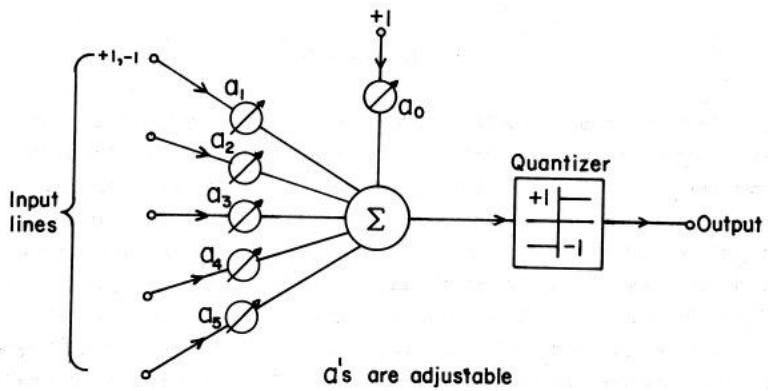


Frank Rosenblatt, ~1957: Perceptron



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A bit of history...

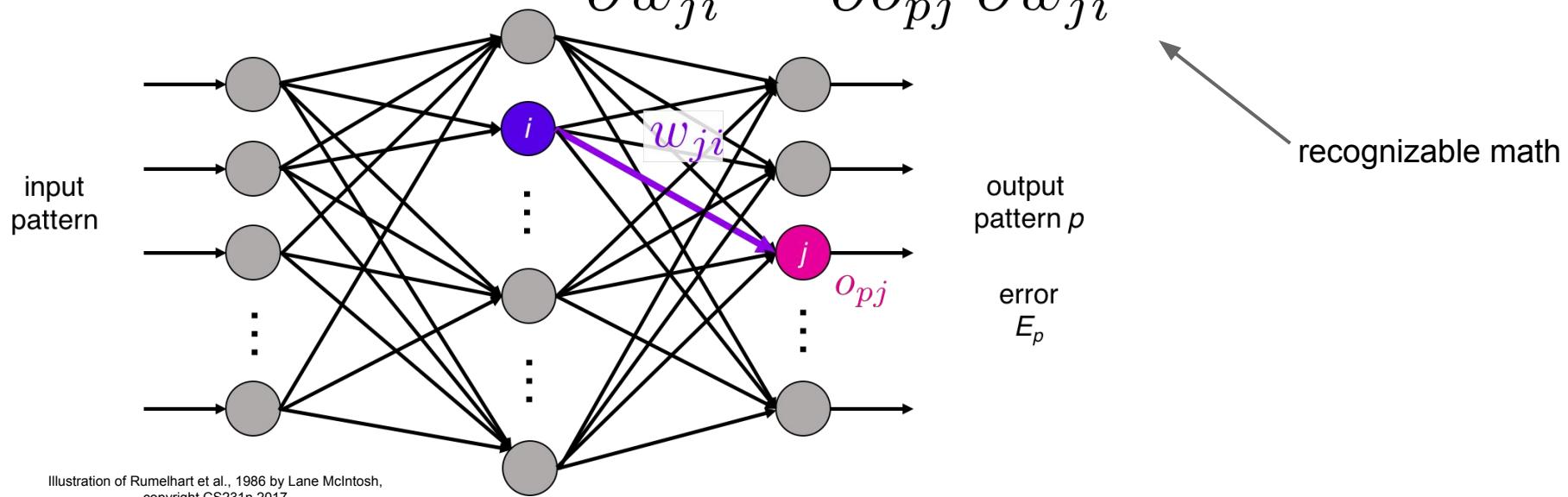


Widrow and Hoff, ~1960: Adaline/Madaline

These figures are reproduced from [Widrow 1960, Stanford Electronics Laboratories Technical Report](#) with permission from [Stanford University Special Collections](#).

A bit of history...

$$\frac{\partial E_p}{\partial w_{ji}} = \frac{\partial E_p}{\partial o_{pj}} \frac{\partial o_{pj}}{\partial w_{ji}}$$



Rumelhart et al., 1986: First time back-propagation became popular

A bit of history...

[Hinton and Salakhutdinov 2006]

Reinvigorated research in
Deep Learning

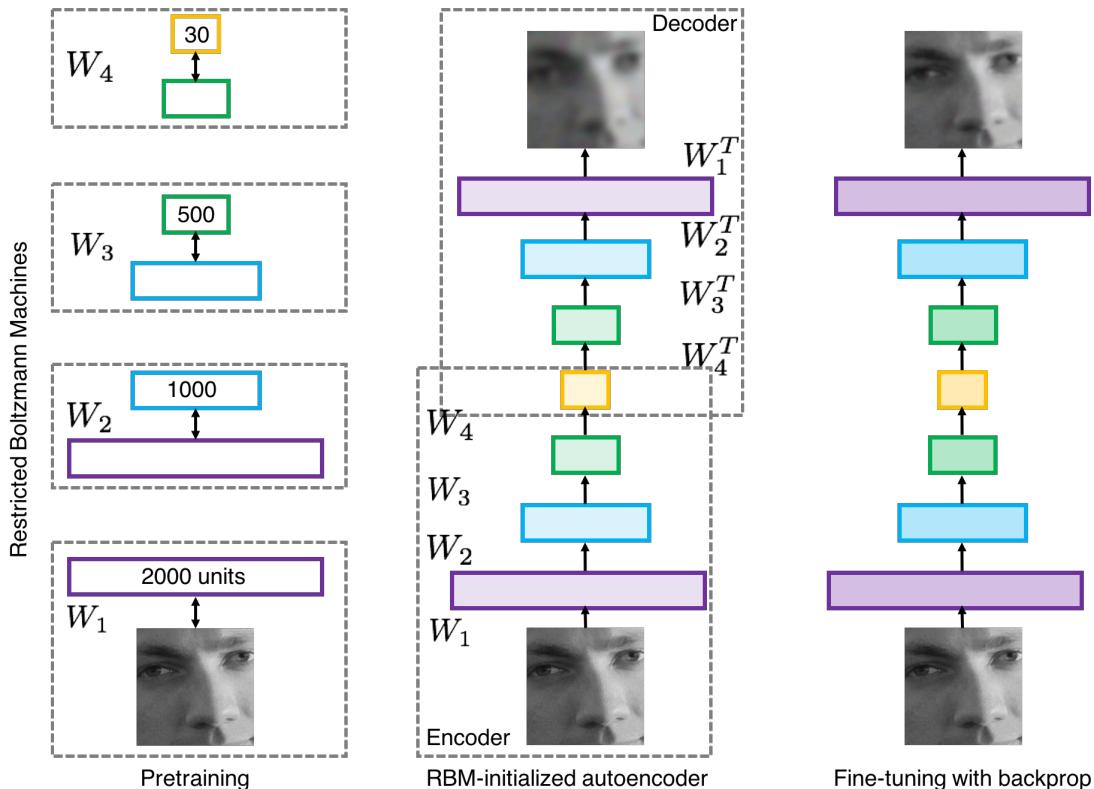


Illustration of Hinton and Salakhutdinov 2006 by Lane McIntosh, copyright CS231n 2017

First strong results

Acoustic Modeling using Deep Belief Networks

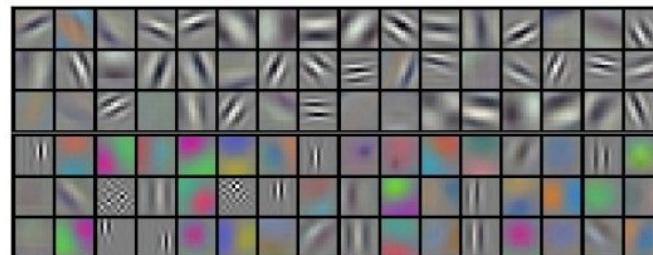
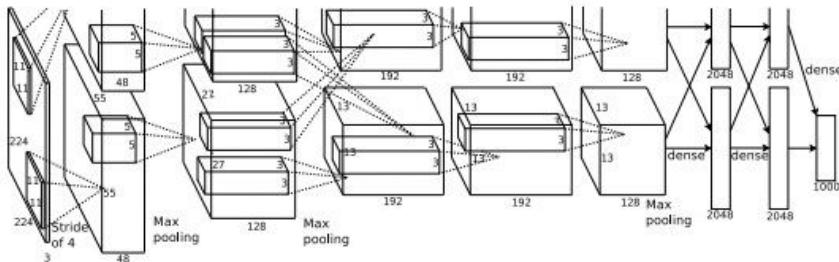
Abdel-rahman Mohamed, George Dahl, Geoffrey Hinton, 2010

Context-Dependent Pre-trained Deep Neural Networks for Large Vocabulary Speech Recognition

George Dahl, Dong Yu, Li Deng, Alex Acero, 2012

Imagenet classification with deep convolutional neural networks

Alex Krizhevsky, Ilya Sutskever, Geoffrey E Hinton, 2012



Figures copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

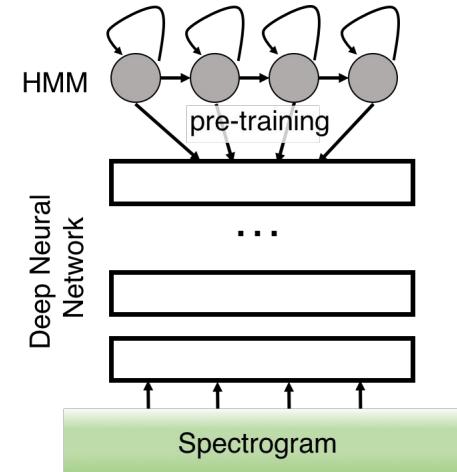


Illustration of Dahl et al. 2012 by Lane McIntosh, copyright CS231n 2017

A bit of history:

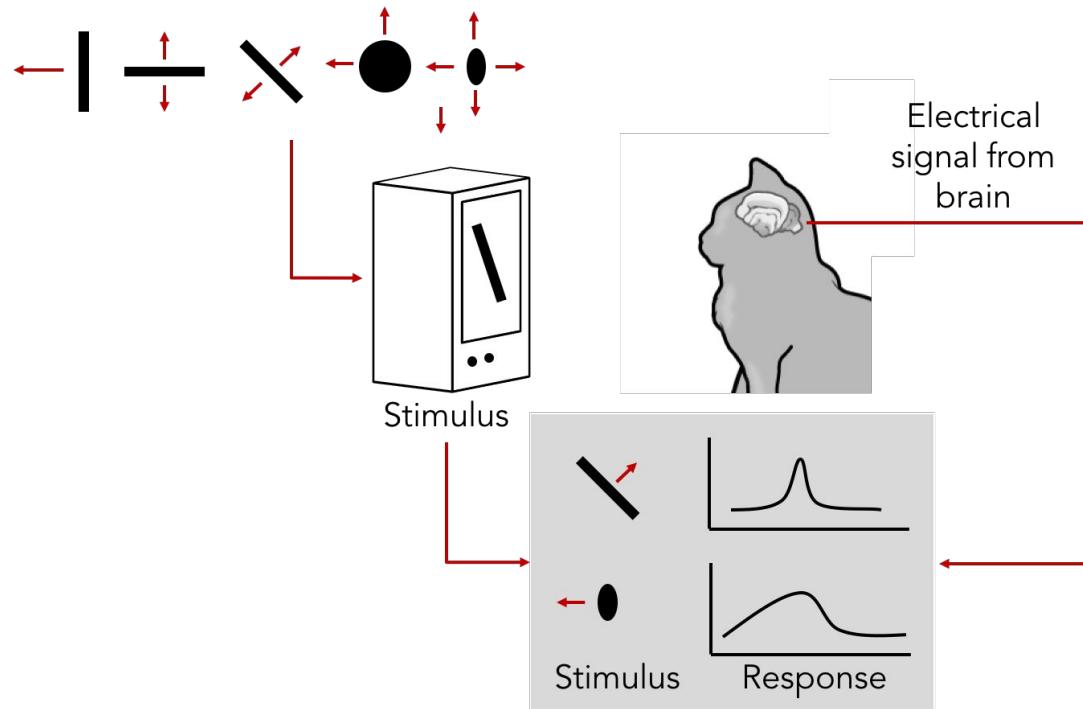
**Hubel & Wiesel,
1959**

RECEPTIVE FIELDS OF SINGLE
NEURONES IN
THE CAT'S STRIATE CORTEX

1962

RECEPTIVE FIELDS, BINOCULAR
INTERACTION
AND FUNCTIONAL ARCHITECTURE IN
THE CAT'S VISUAL CORTEX

1968...

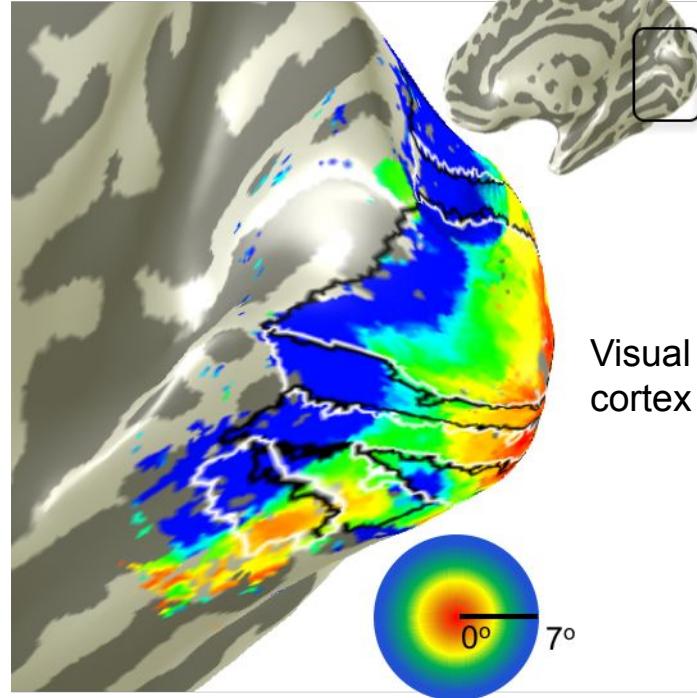
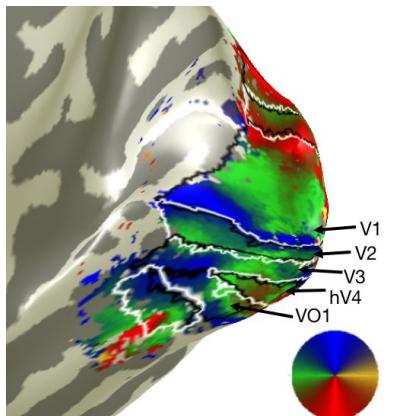


[Cat image](#) by CNX OpenStax is licensed
under CC BY 4.0; changes made

A bit of history

Human brain

Topographical mapping in the cortex:
nearby cells in cortex represent
nearby regions in the visual field



Retinotopy images courtesy of Jesse Gomez in the
Stanford Vision & Perception Neuroscience Lab.

Hierarchical organization

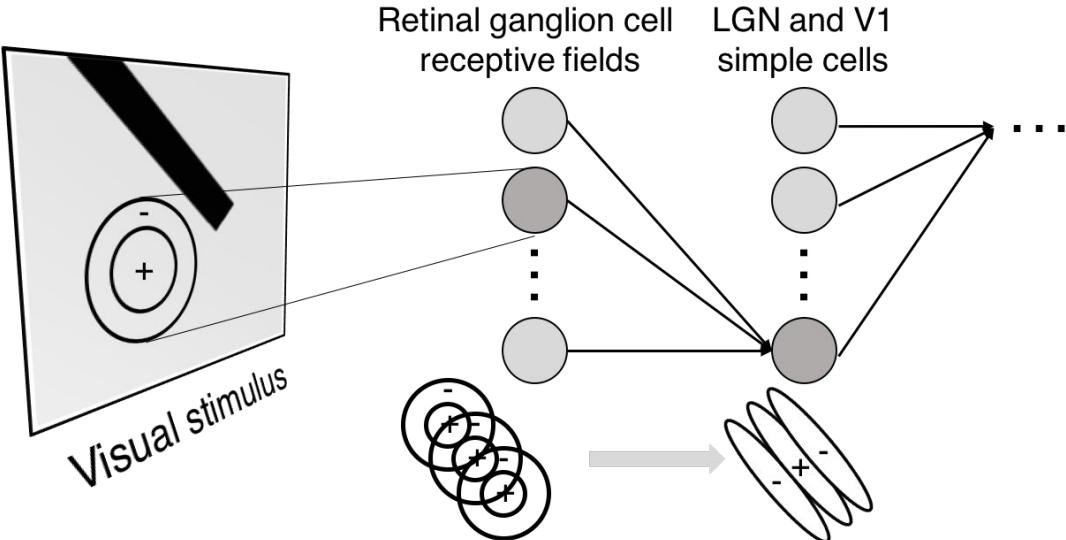
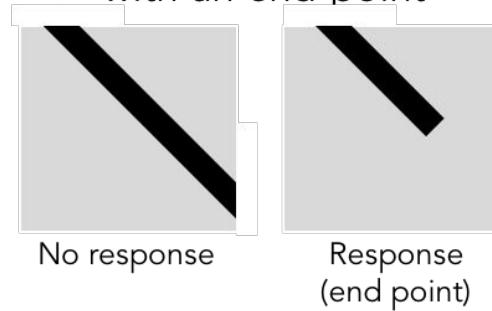


Illustration of hierarchical organization in early visual pathways by Lane McIntosh, copyright CS231n 2017

Simple cells:
Response to light orientation

Complex cells:
Response to light orientation and movement

Hypercomplex cells:
response to movement with an end point



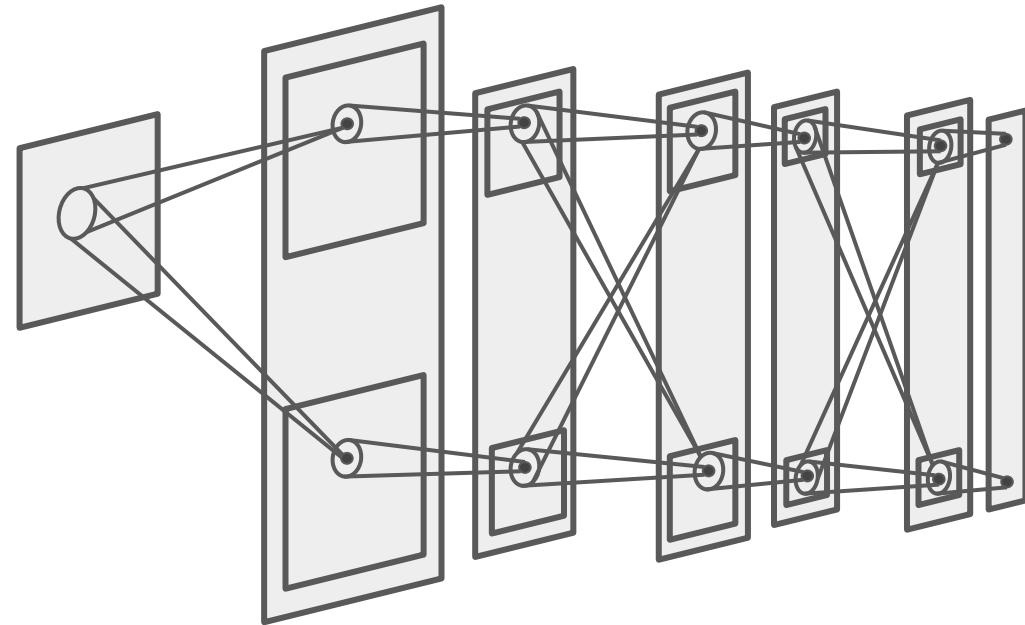
A bit of history:

Neocognitron [Fukushima 1980]

“sandwich” architecture (SCSCSC...)

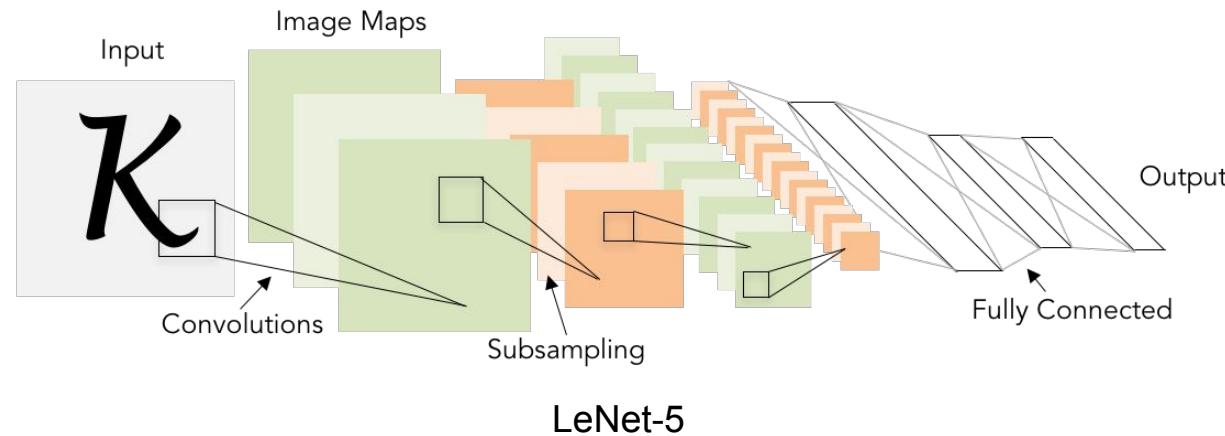
simple cells: modifiable parameters

complex cells: perform pooling



A bit of history: Gradient-based learning applied to document recognition

[LeCun, Bottou, Bengio, Haffner 1998]



A bit of history: ImageNet Classification with Deep Convolutional Neural Networks *[Krizhevsky, Sutskever, Hinton, 2012]*

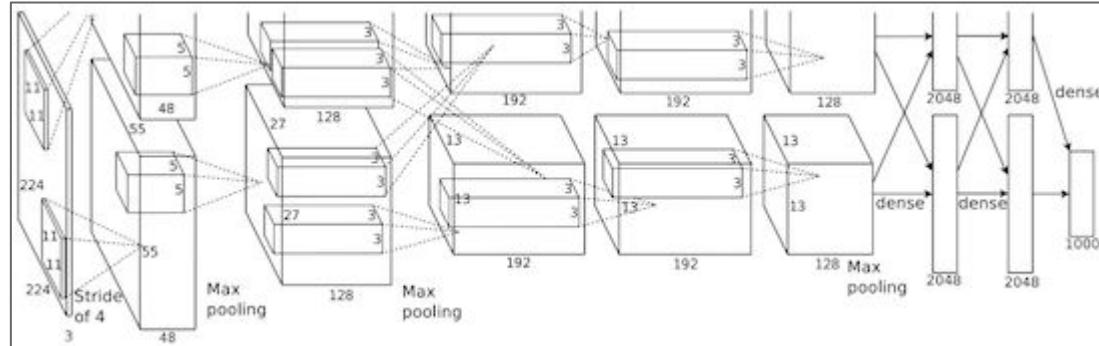
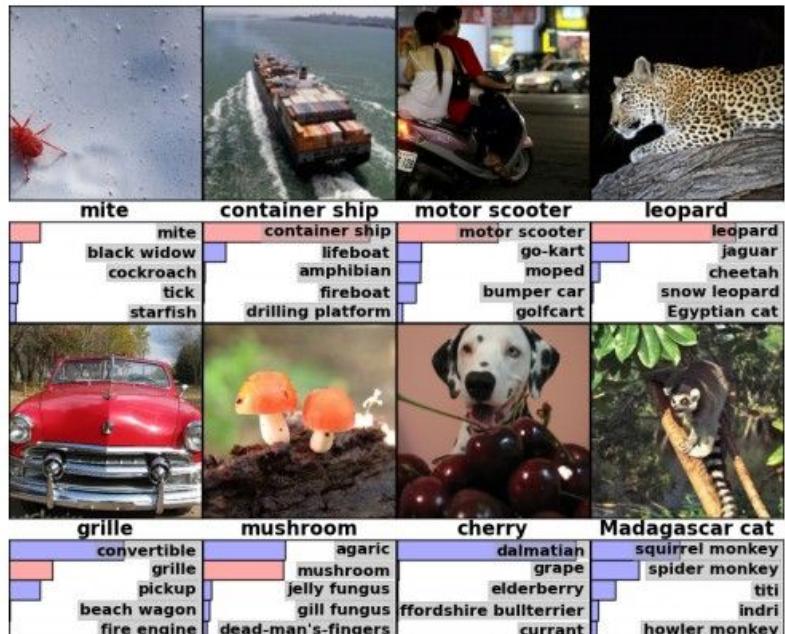


Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

“AlexNet”

Fast-forward to today: ConvNets are everywhere

Classification



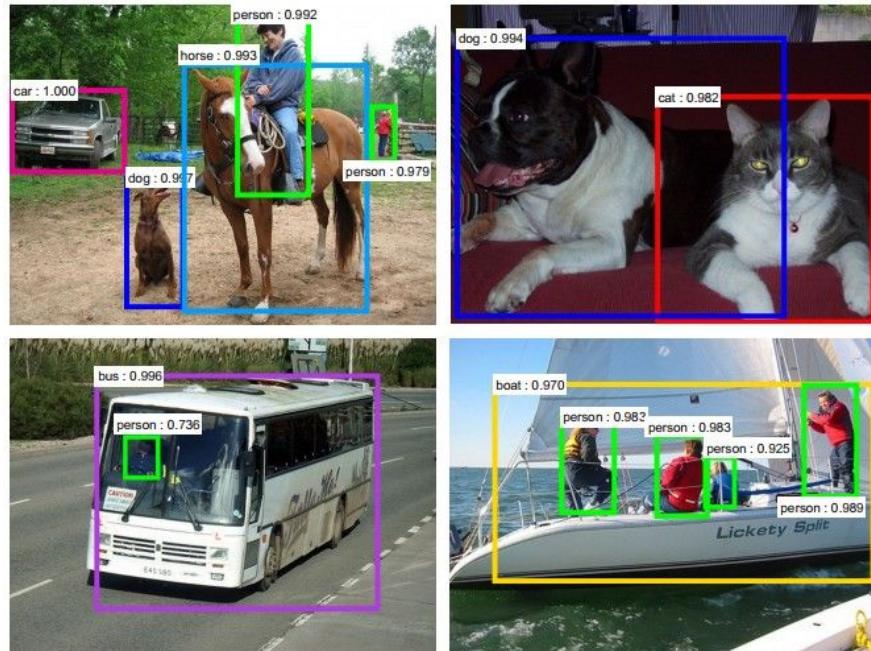
Retrieval



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Fast-forward to today: ConvNets are everywhere

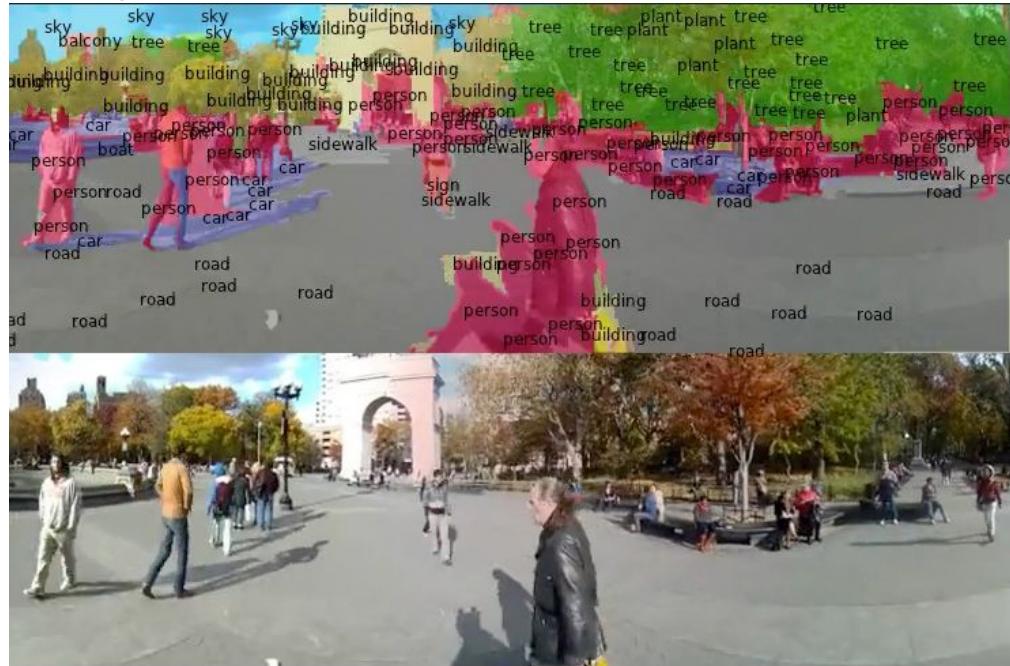
Detection



Figures copyright Shaoqing Ren, Kaiming He, Ross Girshick, Jian Sun, 2015. Reproduced with permission.

[Faster R-CNN: Ren, He, Girshick, Sun 2015]

Segmentation



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[Farabet et al., 2012]

Fast-forward to today: ConvNets are everywhere



self-driving cars

Photo by Lane McIntosh. Copyright CS231n 2017.



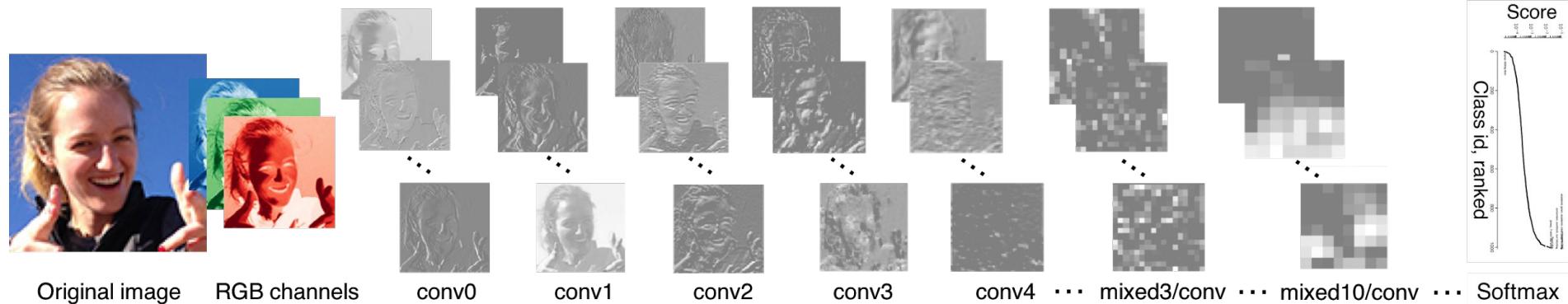
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NVIDIA Tesla line

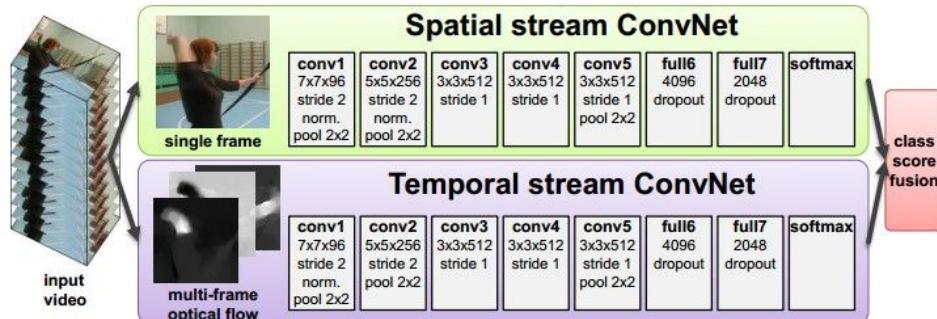
(these are the GPUs on rye01.stanford.edu)

Note that for embedded systems a typical setup would involve NVIDIA Tegras, with integrated GPU and ARM-based CPU cores.

Fast-forward to today: ConvNets are everywhere



[Taigman et al. 2014]



[Simonyan et al. 2014]

Figures copyright Simonyan et al., 2014.
Reproduced with permission.

Activations of [inception-v3 architecture](#) [Szegedy et al. 2015] to image of Emma McIntosh, used with permission. Figure and architecture not from Taigman et al. 2014.

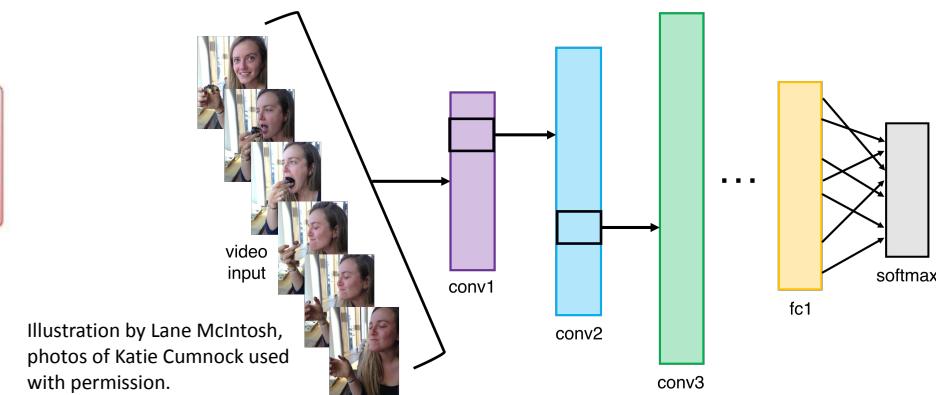


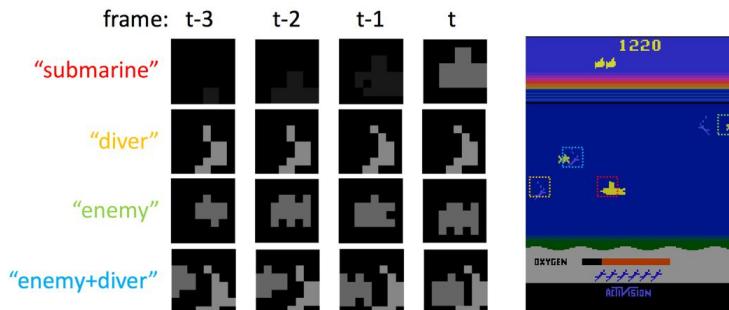
Illustration by Lane McIntosh,
photos of Katie Cumnock used
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Fast-forward to today: ConvNets are everywhere



Images are examples of pose estimation, not actually from Toshev & Szegedy 2014. Copyright Lane McIntosh.

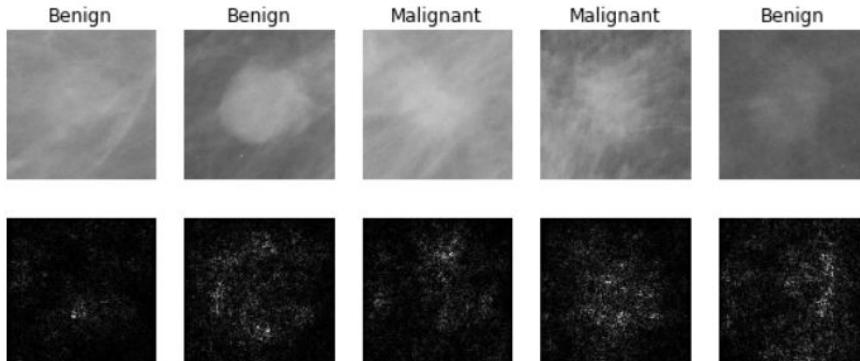
[Toshev, Szegedy 2014]



[Guo et al. 2014]

Figures copyright Xiaoxiao Guo, Satinder Singh, Honglak Lee, Richard Lewis, and Xiaoshi Wang, 2014. Reproduced with permission.

Fast-forward to today: ConvNets are everywhere



[Levy et al. 2016]

Figure copyright Levy et al. 2016.
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[Dieleman et al. 2014]

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Photos by Lane McIntosh.
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[Sermanet et al. 2011]
[Ciresan et al.]

[This image](#) by Christin Khan is in the public domain and originally came from the U.S. NOAA.



Whale recognition, Kaggle Challenge

Photo and figure by Lane McIntosh; not actual example from Mnih and Hinton, 2010 paper.



Mnih and Hinton, 2010

No errors



A white teddy bear sitting in the grass



A man riding a wave on top of a surfboard

Minor errors



A man in a baseball uniform throwing a ball



A cat sitting on a suitcase on the floor

Somewhat related



A woman is holding a cat in her hand



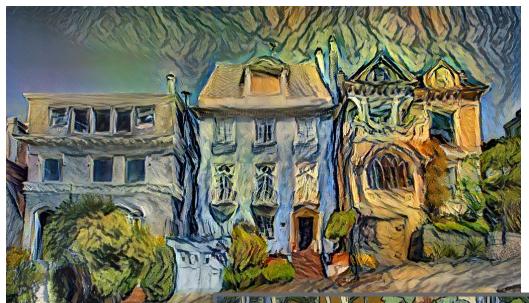
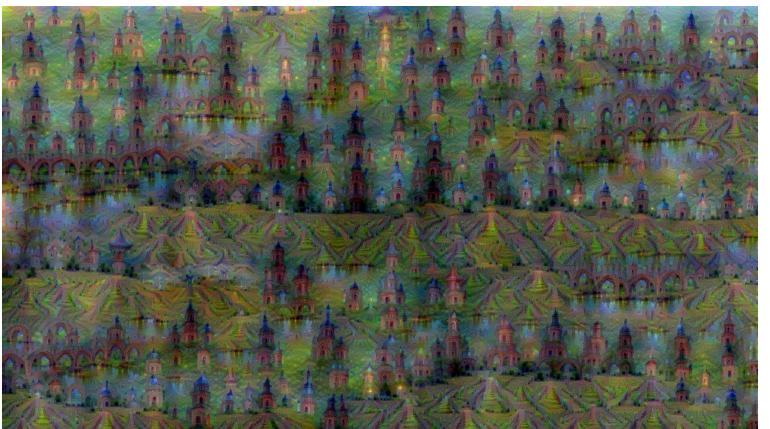
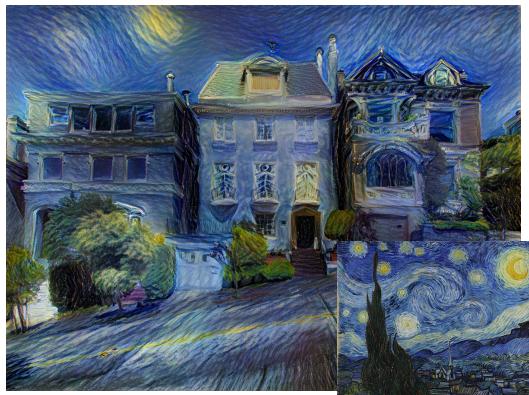
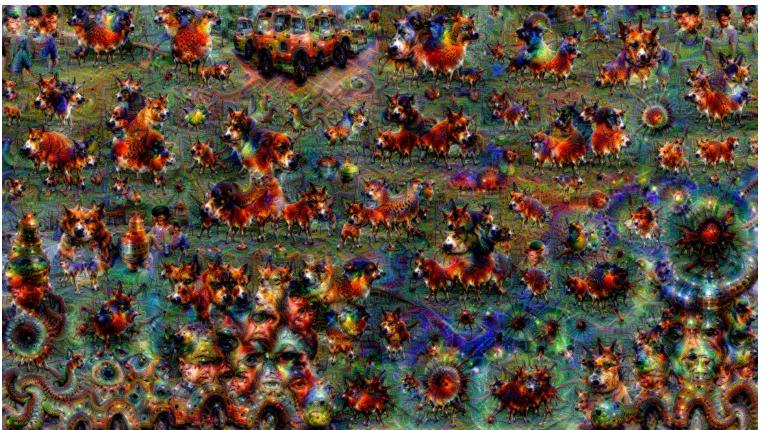
A woman standing on a beach holding a surfboard

Image Captioning

[Vinyals et al., 2015]
[Karpathy and Fei-Fei, 2015]

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<https://pixabay.com/en/handstand-lake-meditation-496008/>
<https://pixabay.com/en/baseball-player-shortstop-infield-1045263/>

Captions generated by Justin Johnson using [NeuralTalk2](#)



Figures copyright Justin Johnson, 2015. Reproduced with permission. Generated using the Inceptionism approach from a [blog post](#) by Google Research.

[Original image](#) is CC0 public domain

[Starry Night](#) and [Tree Roots](#) by Van Gogh are in the public domain

[Bokeh image](#) is in the public domain

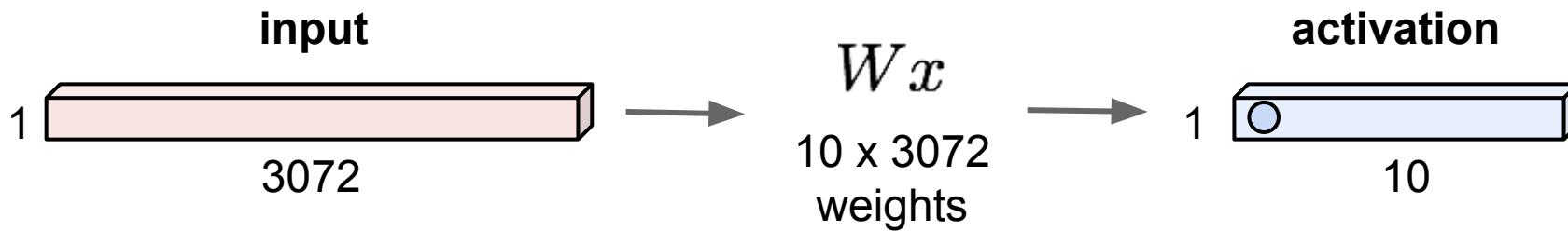
Stylized images copyright Justin Johnson, 2017;
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Gatys et al, "Image Style Transfer using Convolutional Neural Networks", CVPR 2016
Gatys et al, "Controlling Perceptual Factors in Neural Style Transfer", CVPR 2017

Convolutional Neural Networks

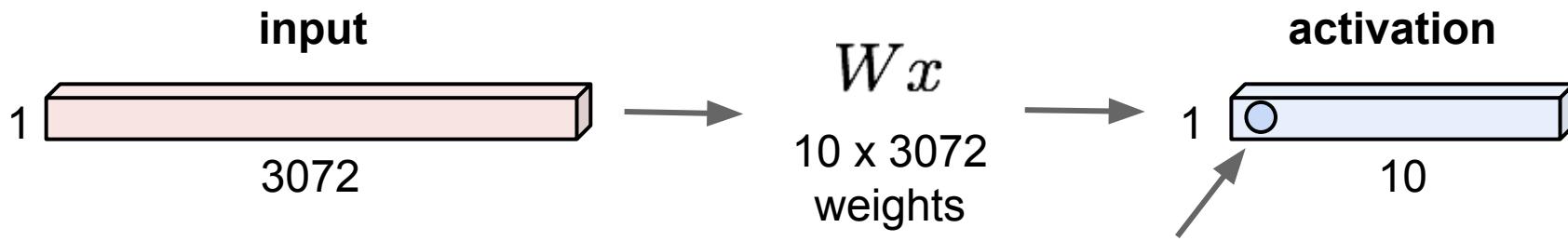
Recap: Fully Connected Layer

32x32x3 image -> stretch to 3072 x 1



Fully Connected Layer

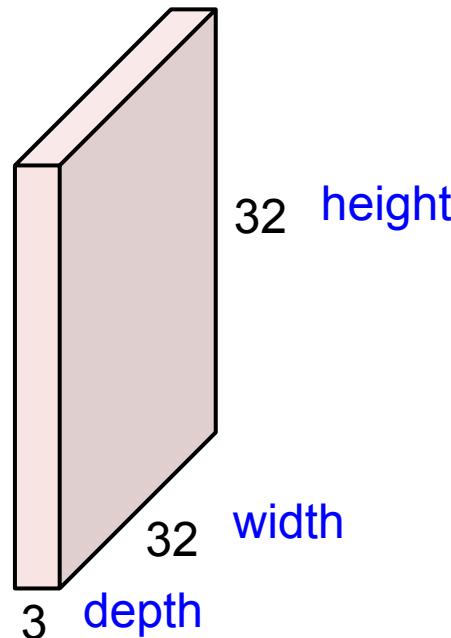
32x32x3 image -> stretch to 3072×1



1 number:
the result of taking a dot product
between a row of W and the input
(a 3072-dimensional dot product)

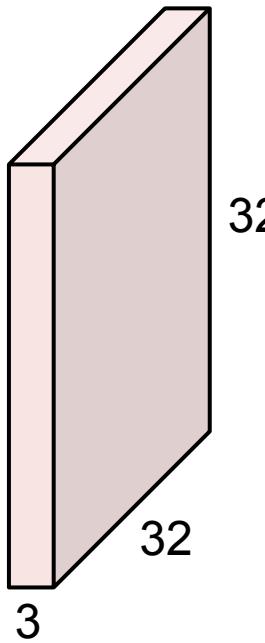
Convolution Layer

32x32x3 image -> preserve spatial structure

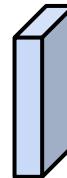


Convolution Layer

32x32x3 image



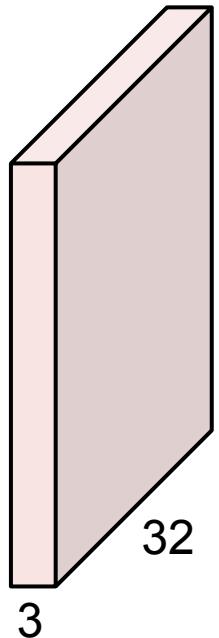
5x5x3 filter



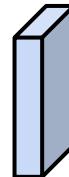
Convolve the filter with the image
i.e. “slide over the image spatially,
computing dot products”

Convolution Layer

32x32x3 image



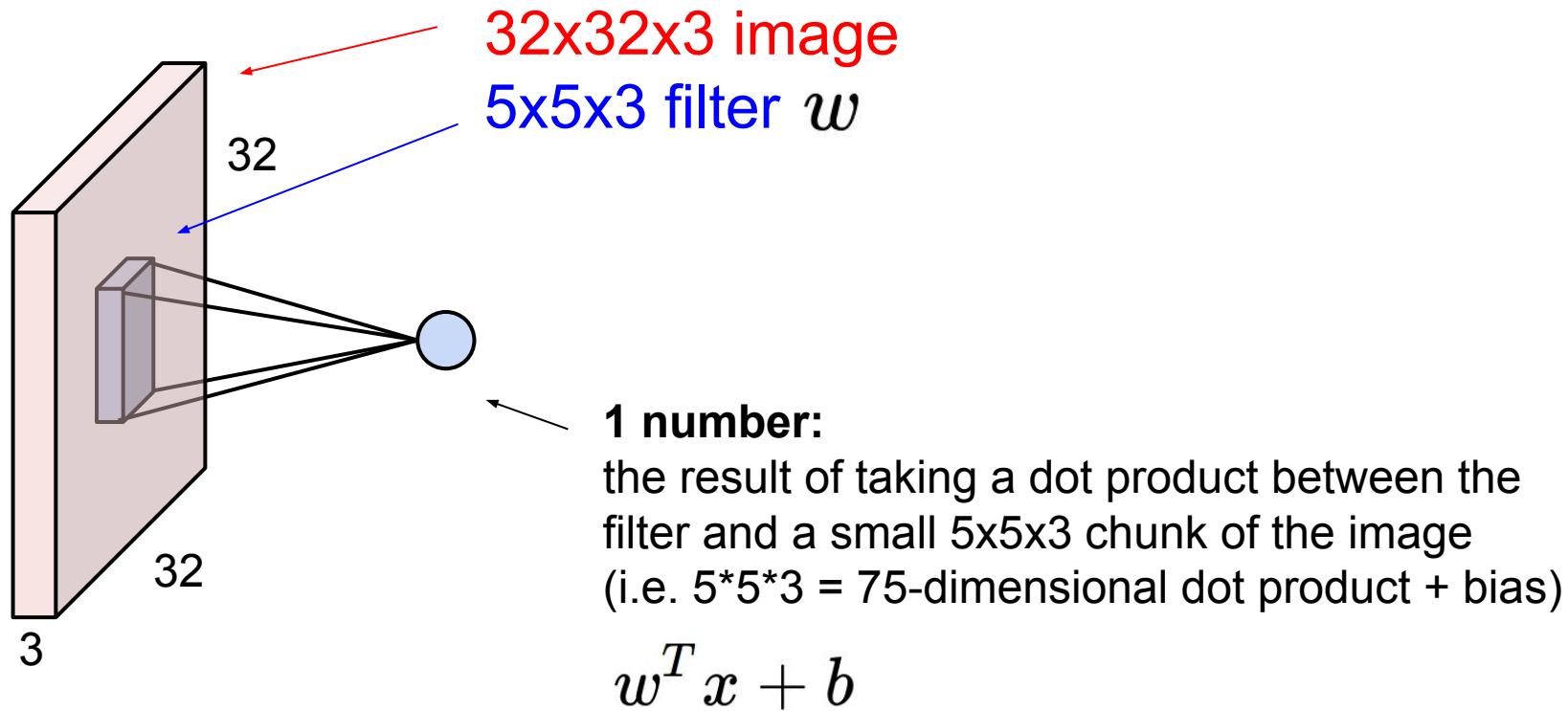
5x5x3 filter



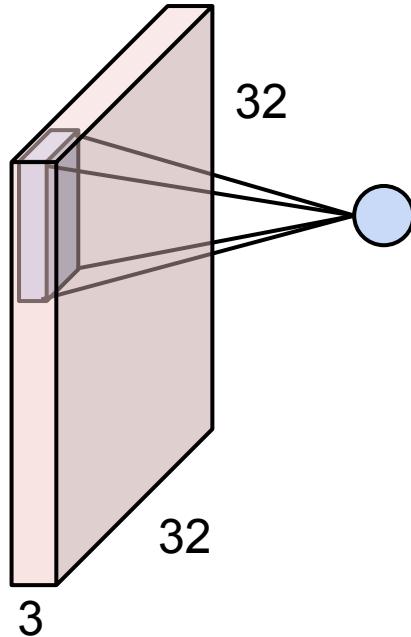
Filters always extend the full depth of the input volume

Convolve the filter with the image
i.e. “slide over the image spatially,
computing dot products”

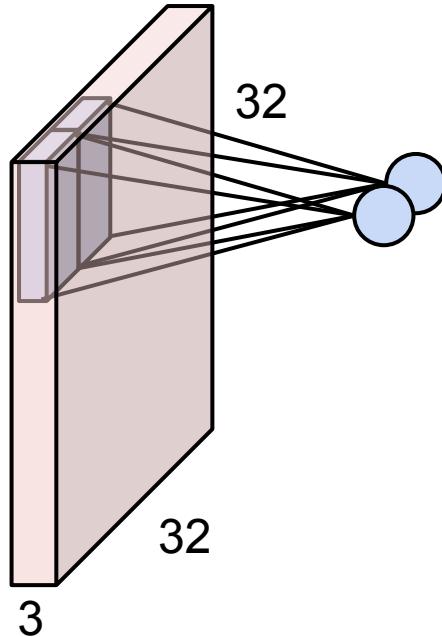
Convolution Layer



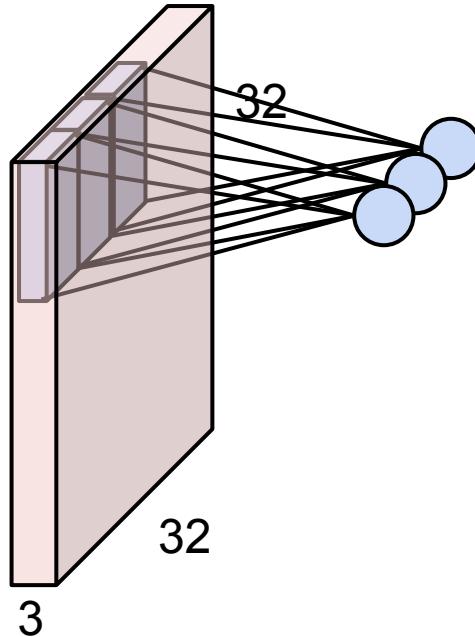
Convolution Layer



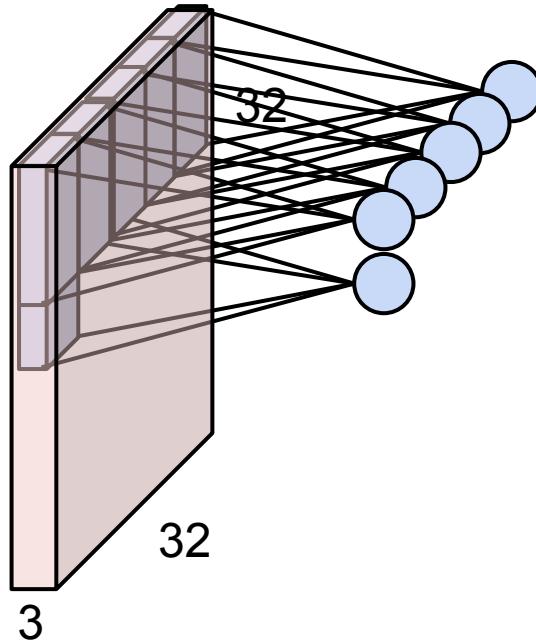
Convolution Layer



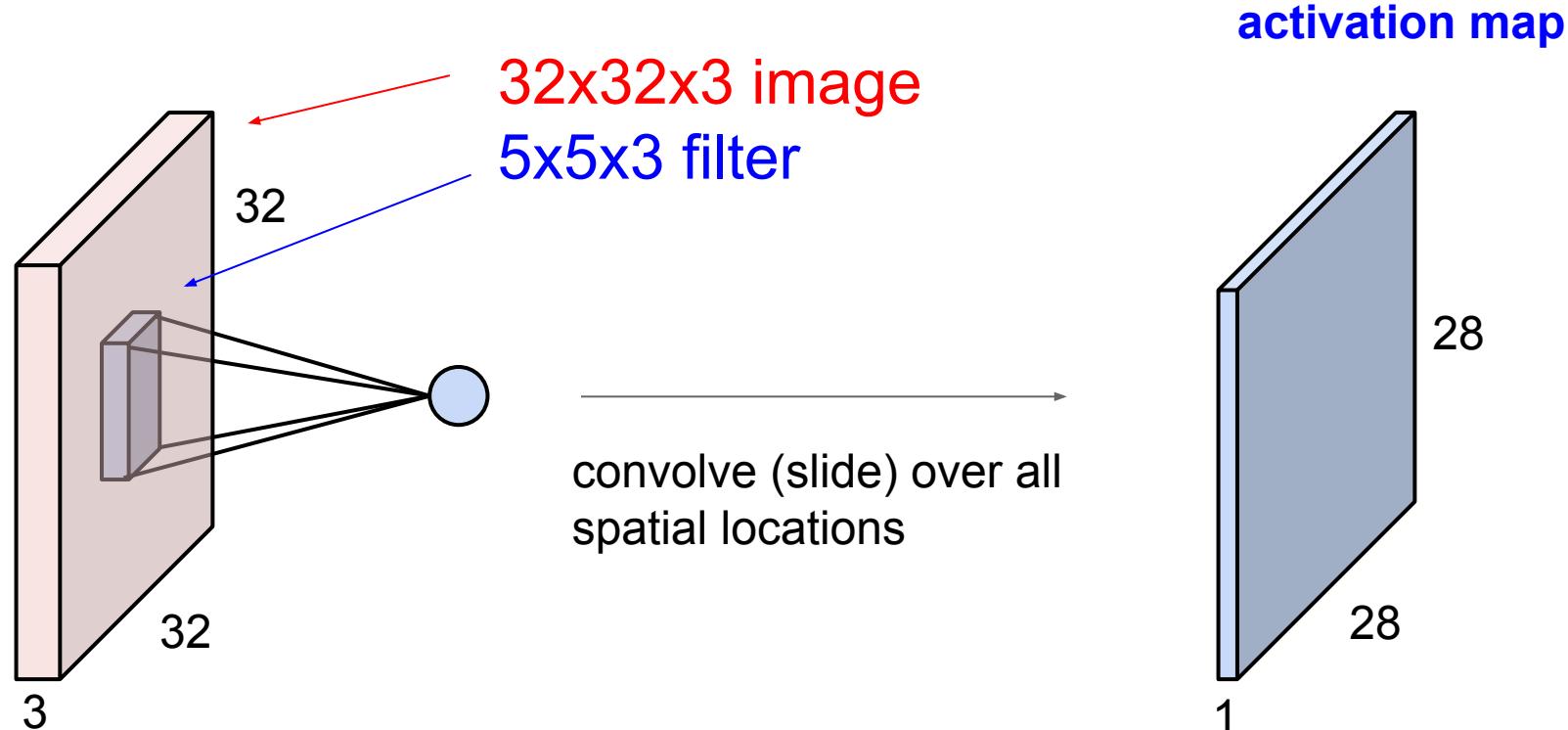
Convolution Layer



Convolution Layer

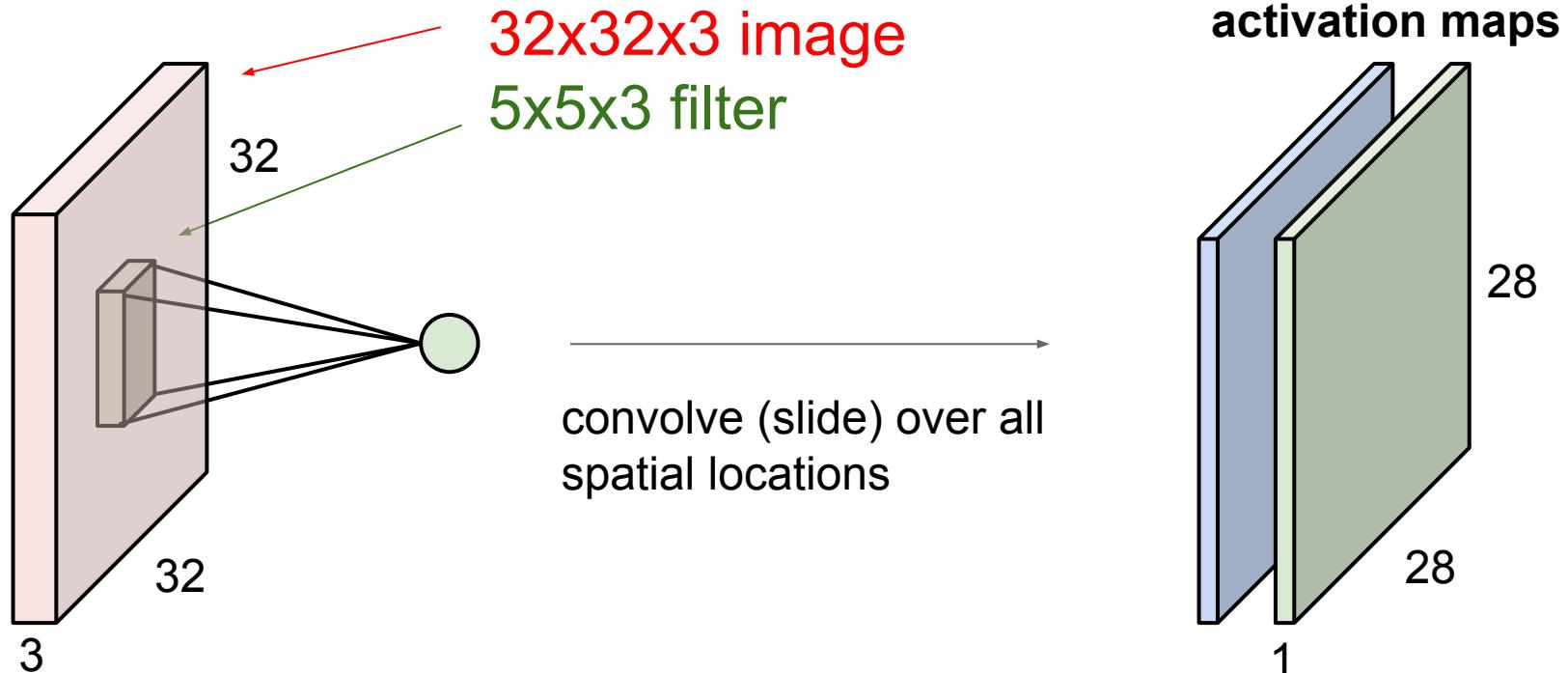


Convolution Layer



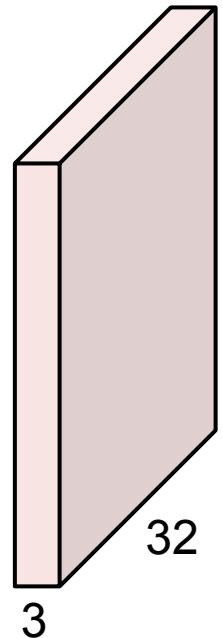
Convolution Layer

consider a second, green filter



Convolution Layer

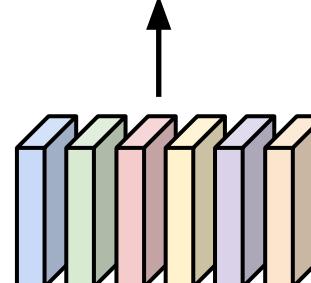
3x32x32 image



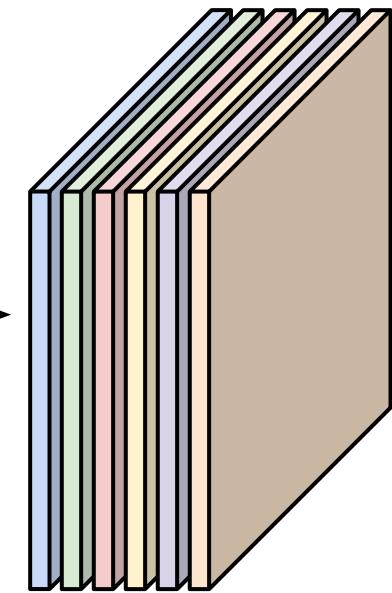
Consider 6 filters,
each 3x5x5

Convolution
Layer

6x3x5x5
filters



6 activation maps,
each 1x28x28

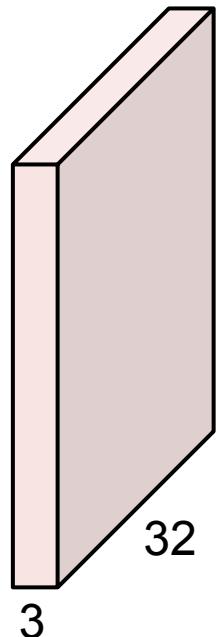


Stack activations to get a
6x28x28 output image!

Slide inspiration: Justin Johnson

Convolution Layer

3x32x32 image

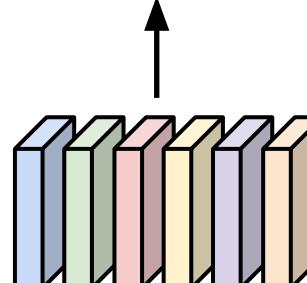


Also 6-dim bias vector:

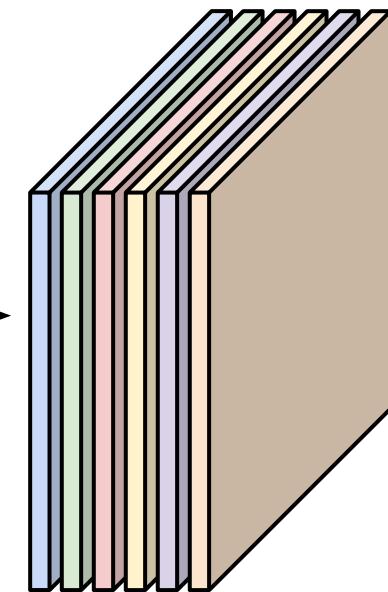


Convolution
Layer

6x3x5x5
filters



6 activation maps,
each 1x28x28



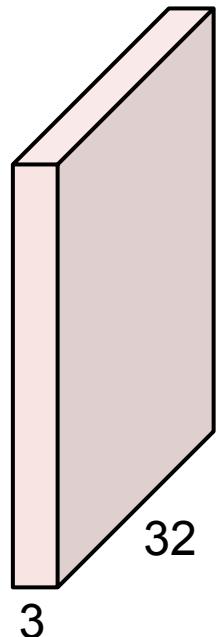
Stack activations to get a
6x28x28 output image!

Slide inspiration: Justin Johnson

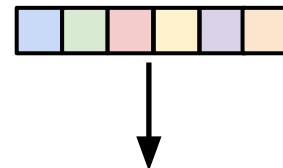
Convolution Layer

28x28 grid, at each point a 6-dim vector

3x32x32 image

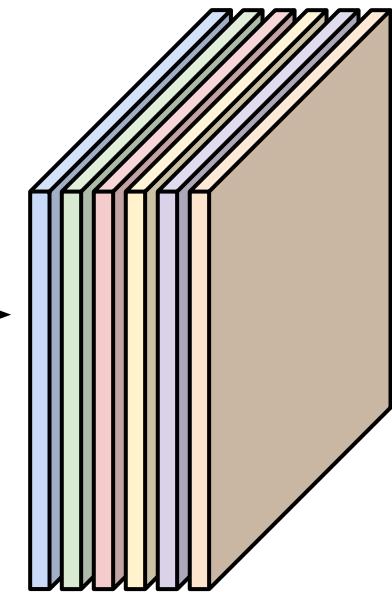
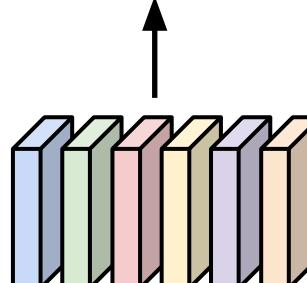


Also 6-dim bias vector:



Convolution
Layer

6x3x5x5
filters

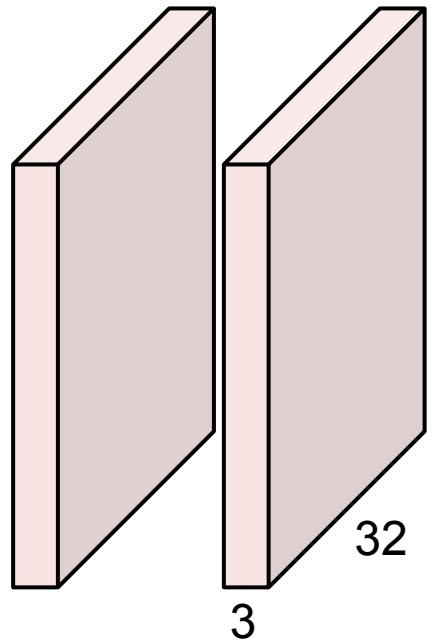


Stack activations to get a 6x28x28 output image!

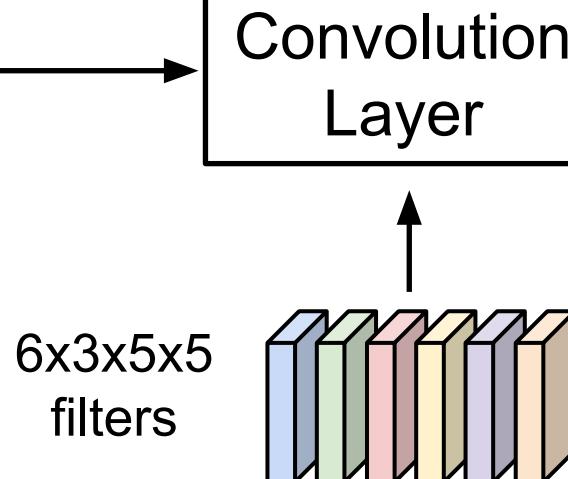
Slide inspiration: Justin Johnson

Convolution Layer

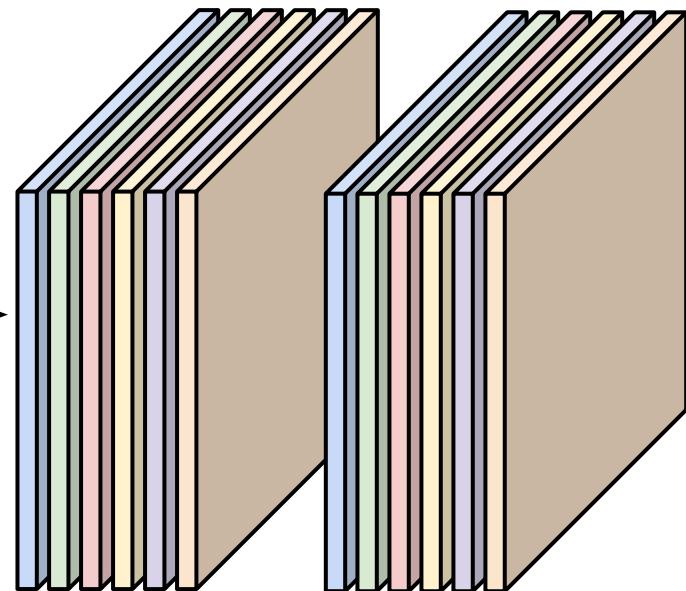
2x3x32x32
Batch of images



Also 6-dim bias vector:



2x6x28x28
Batch of outputs

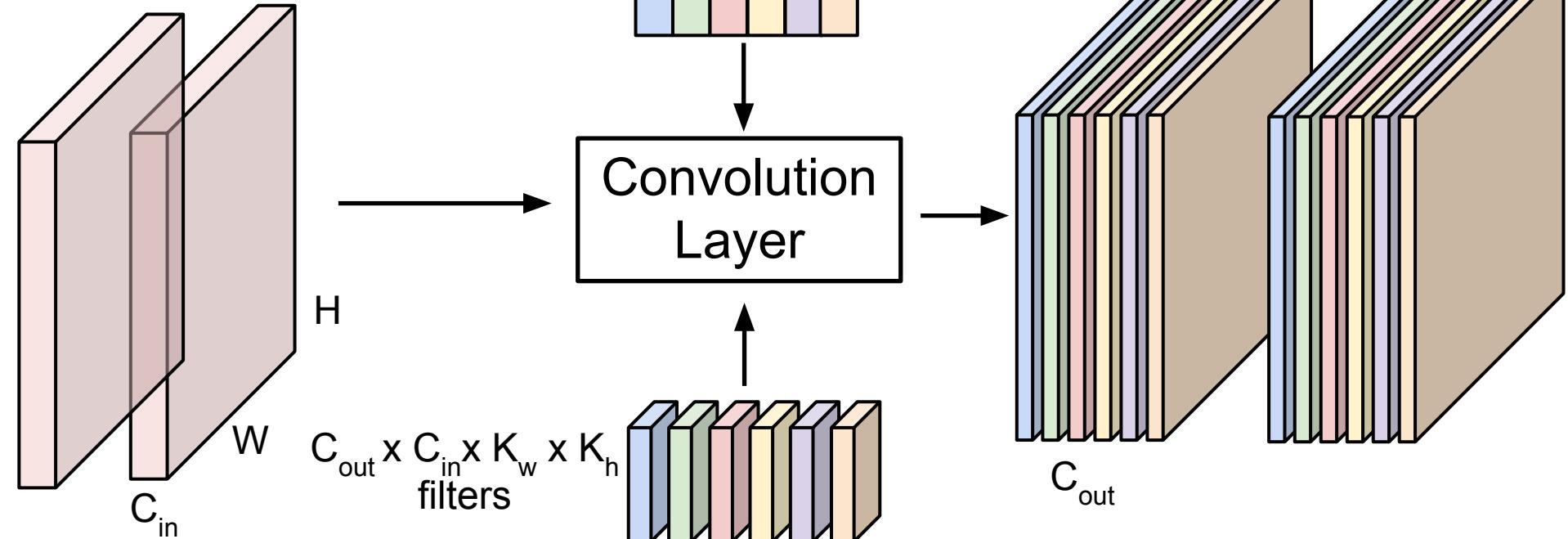


Slide inspiration: Justin Johnson

Convolution Layer

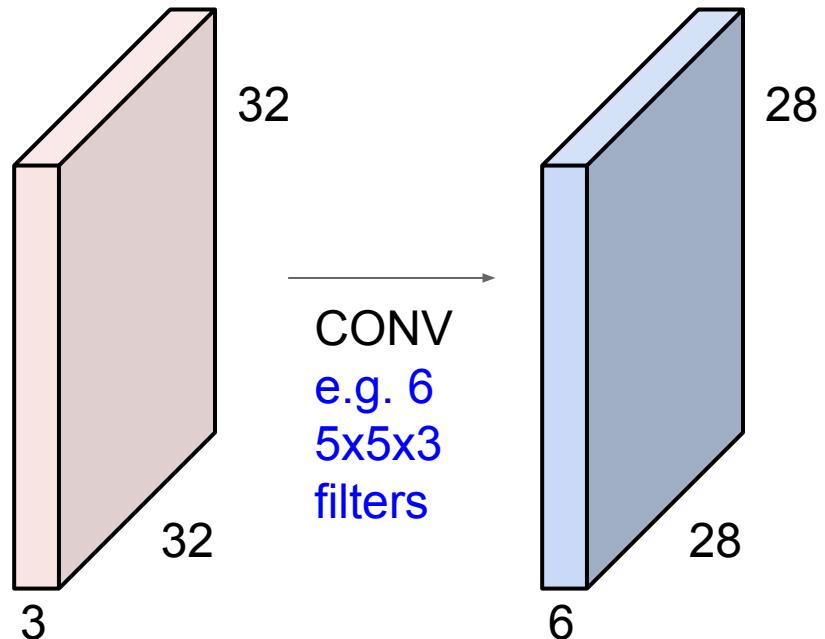
$N \times C_{in} \times H \times W$
Batch of images

$N \times C_{out} \times H' \times W'$
Batch of outputs

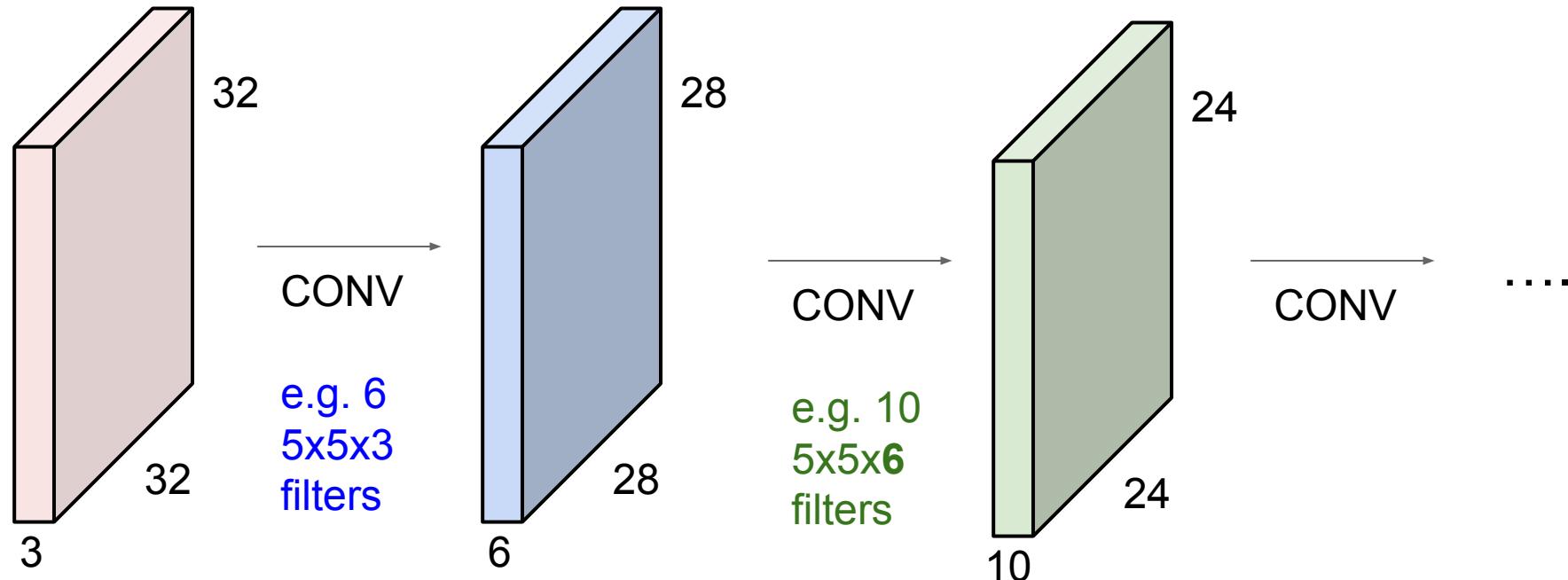


Slide inspiration: Justin Johnson

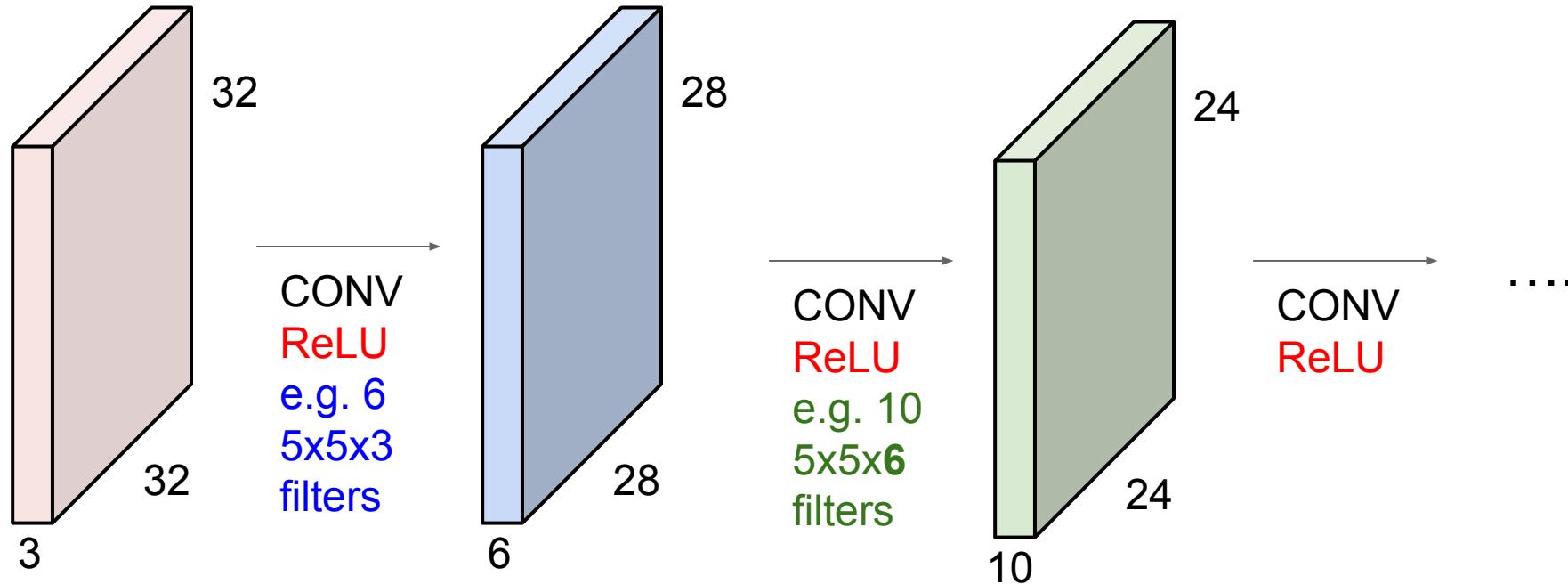
Preview: ConvNet is a sequence of Convolution Layers



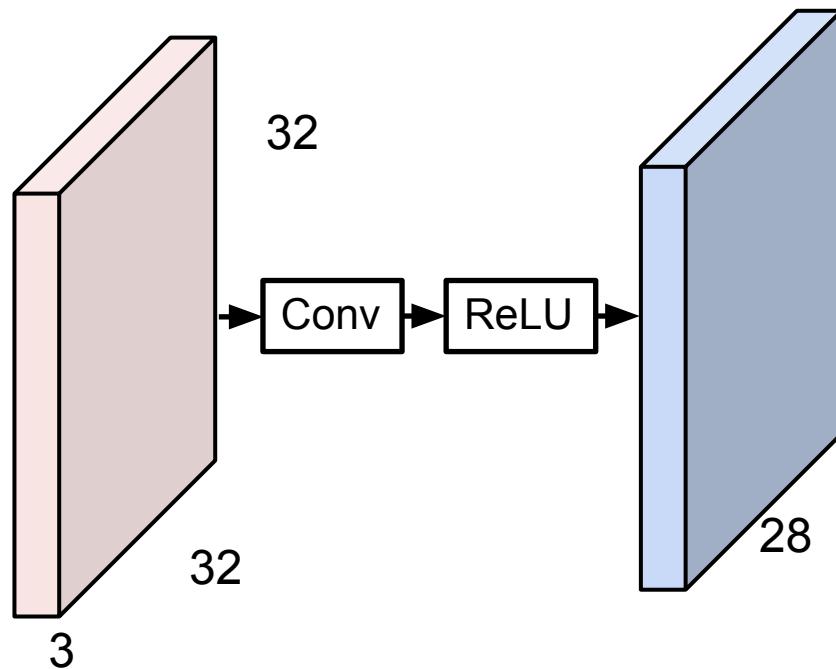
Preview: ConvNet is a sequence of Convolution Layers



Preview: ConvNet is a sequence of Convolution Layers, interspersed with activation functions



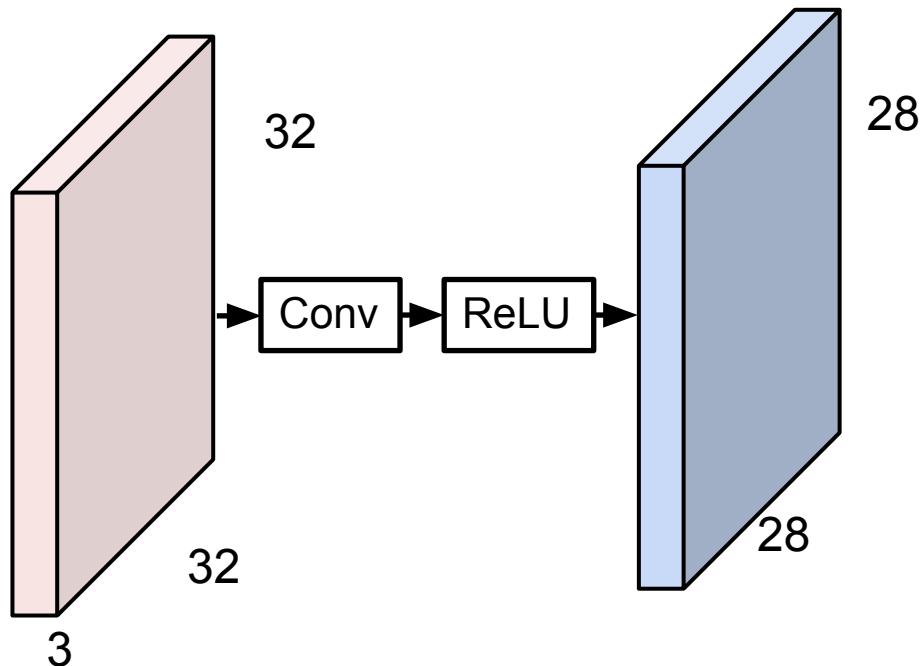
Preview: What do convolutional filters learn?



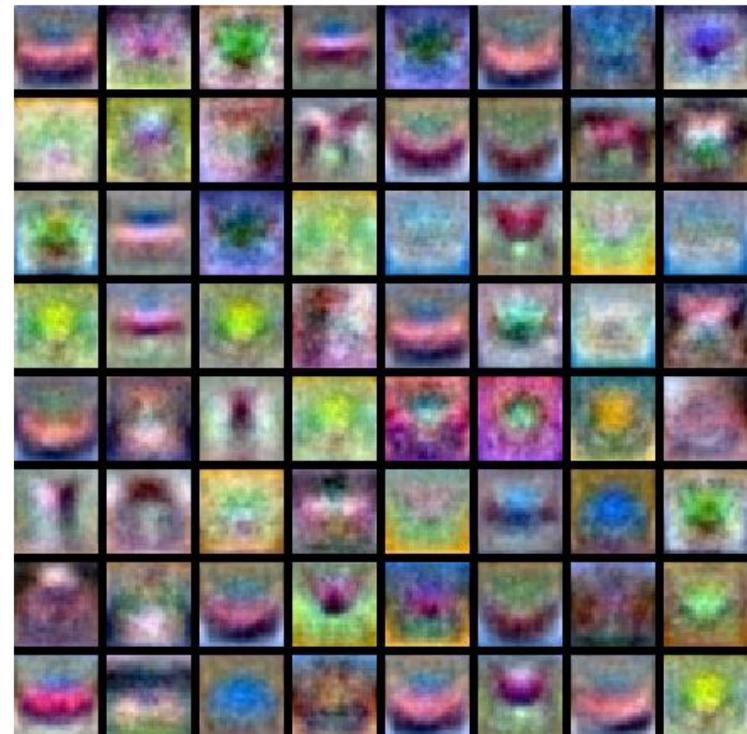
Linear classifier: One template per class



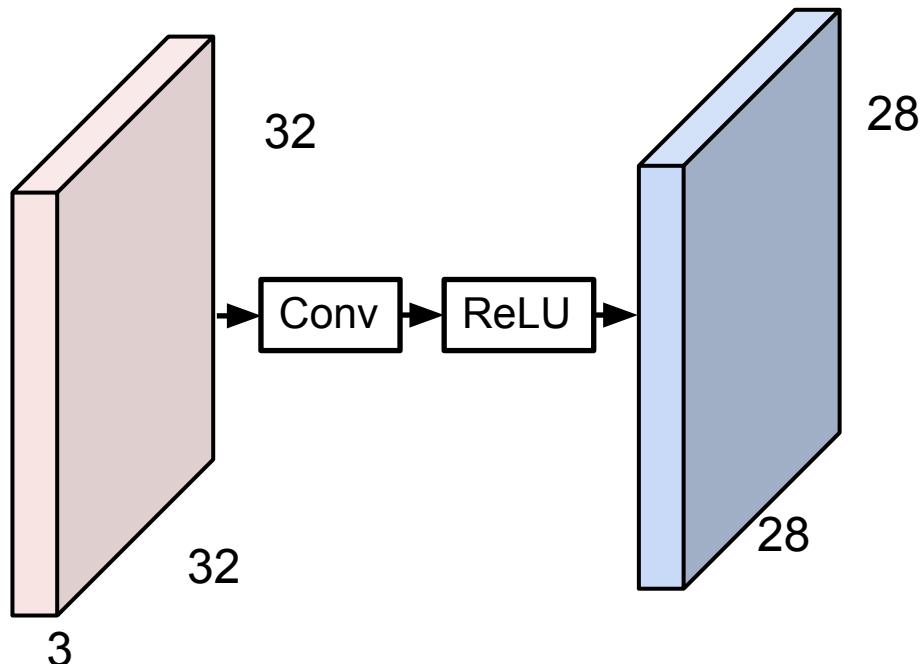
Preview: What do convolutional filters learn?



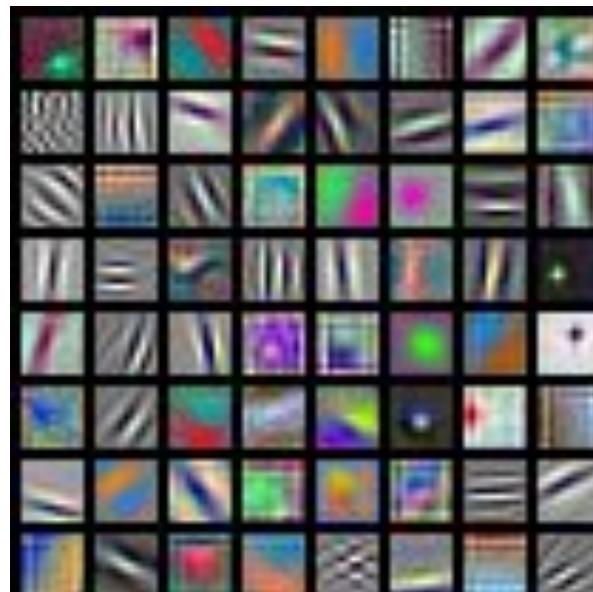
MLP: Bank of whole-image templates



Preview: What do convolutional filters learn?



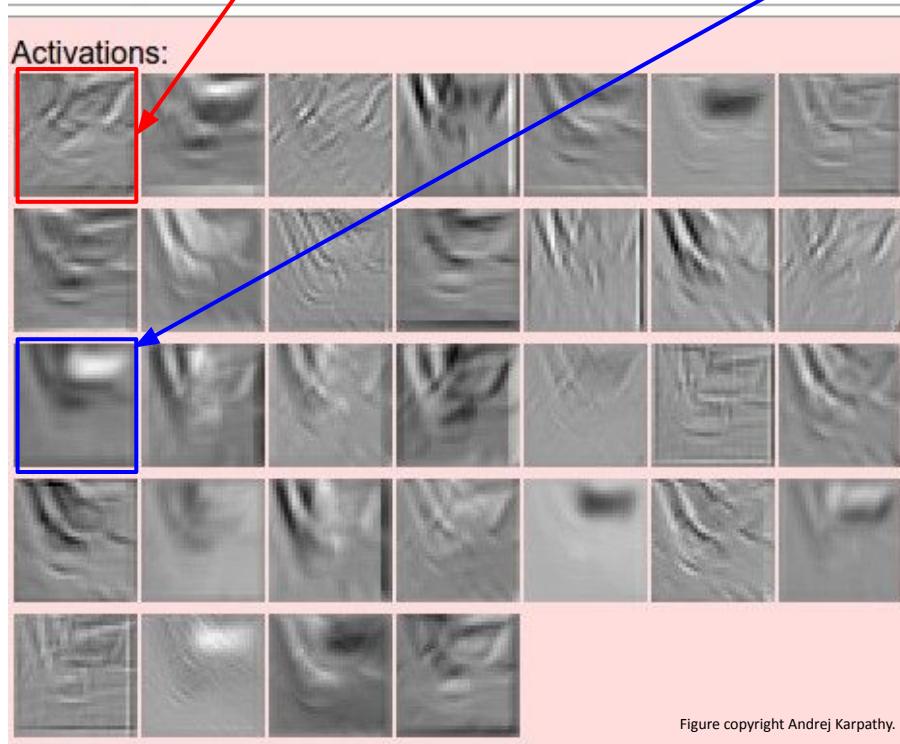
First-layer conv filters: local image templates
(Often learns oriented edges, opposing colors)



AlexNet: 64 filters, each 3x11x11



one filter =>
one activation map



example 5x5 filters
(32 total)

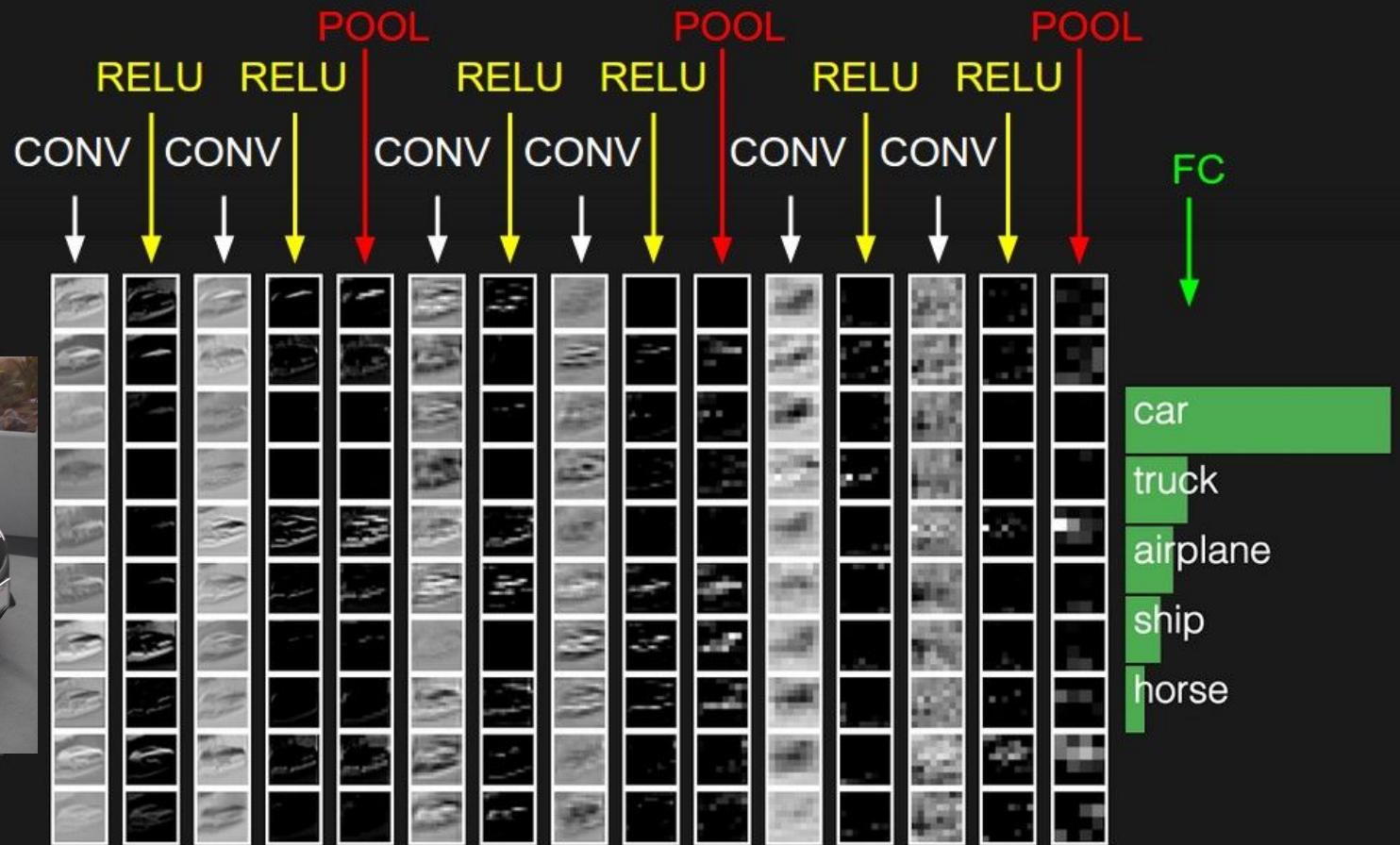
We call the layer convolutional
because it is related to convolution
of two signals:

$$f[x,y] * g[x,y] = \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} f[n_1, n_2] \cdot g[x - n_1, y - n_2]$$

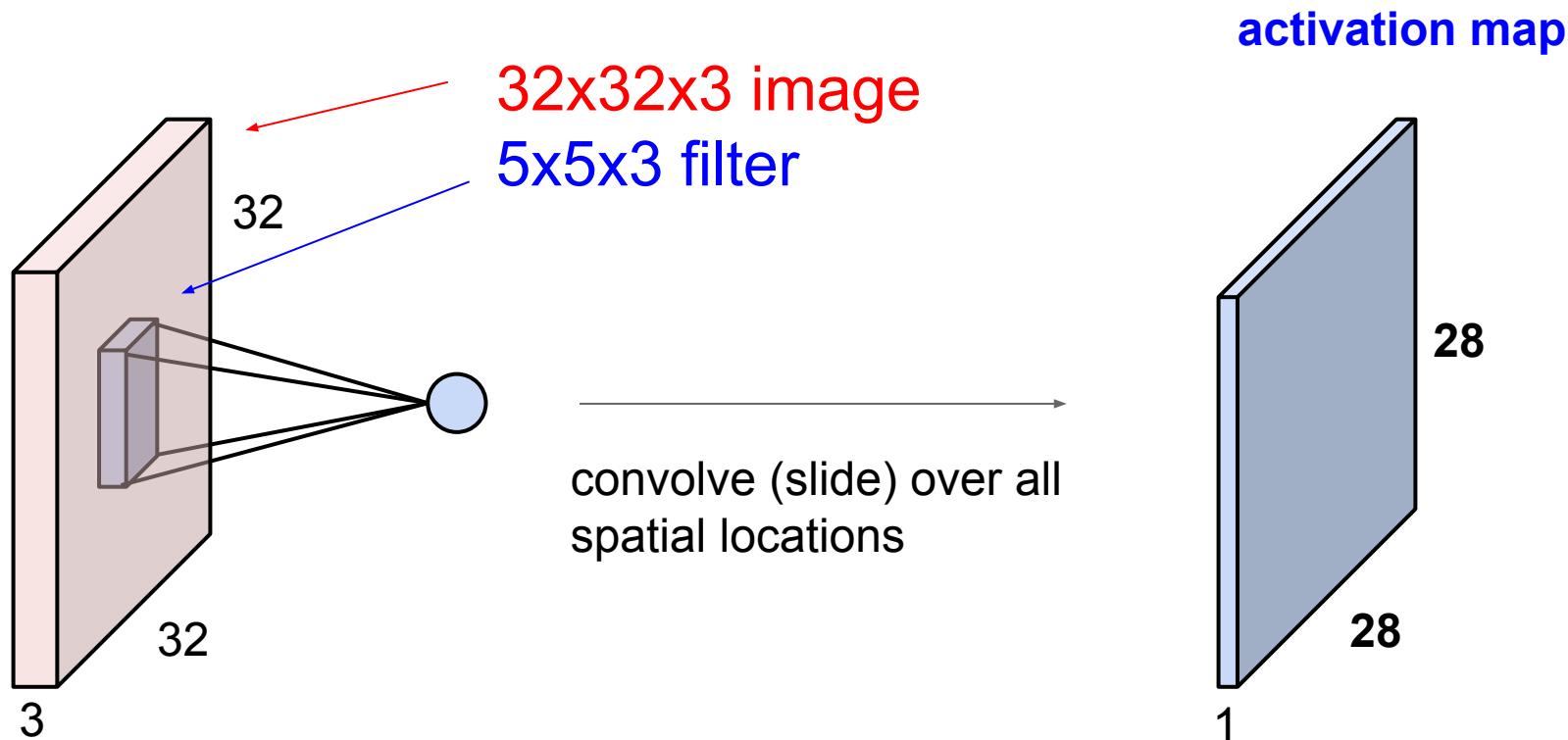


elementwise multiplication and sum of
a filter and the signal (image)

preview:

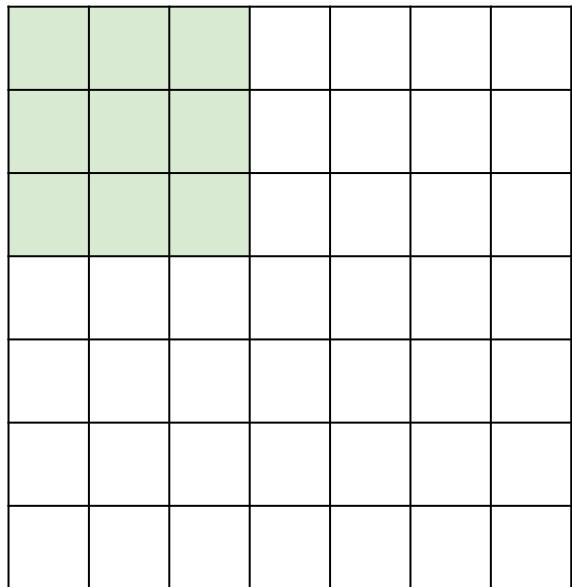


A closer look at spatial dimensions:



A closer look at spatial dimensions:

7

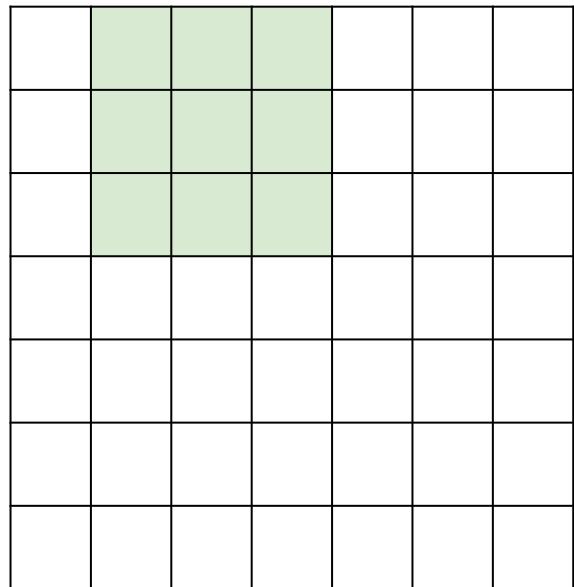


7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

7

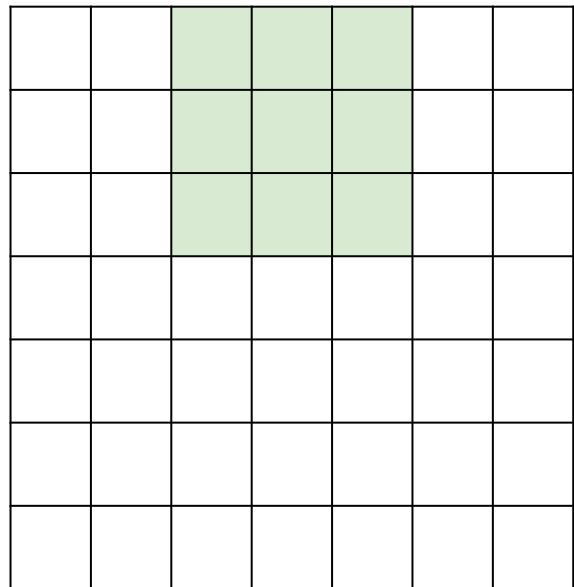


7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

7

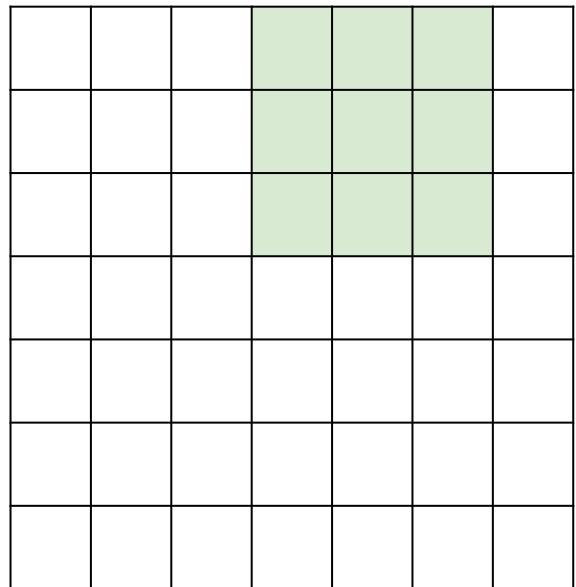


7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

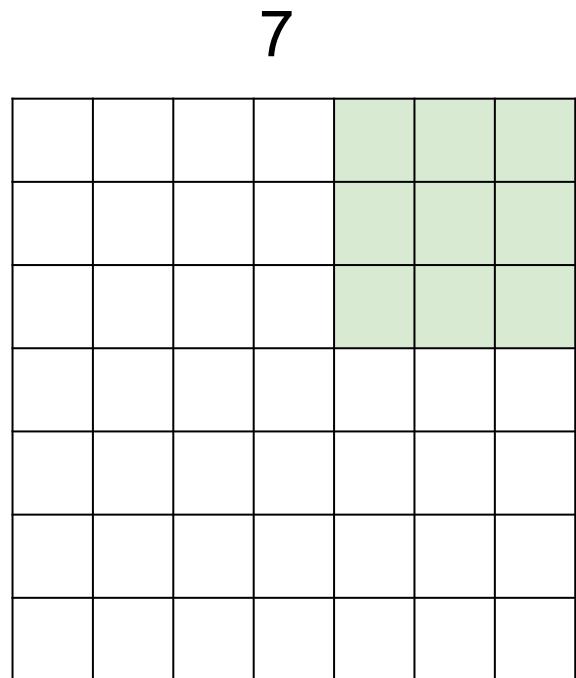
7



7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

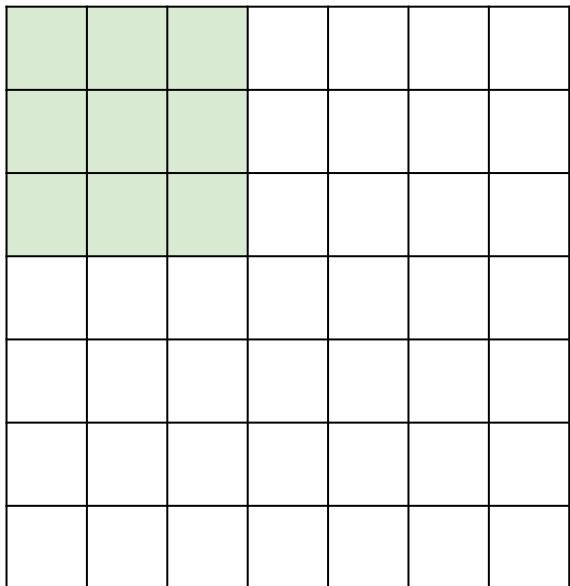


7x7 input (spatially)
assume 3x3 filter

=> 5x5 output

A closer look at spatial dimensions:

7

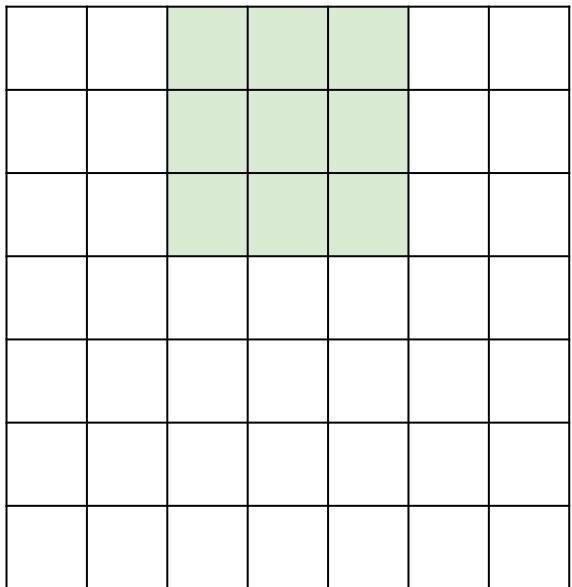


7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

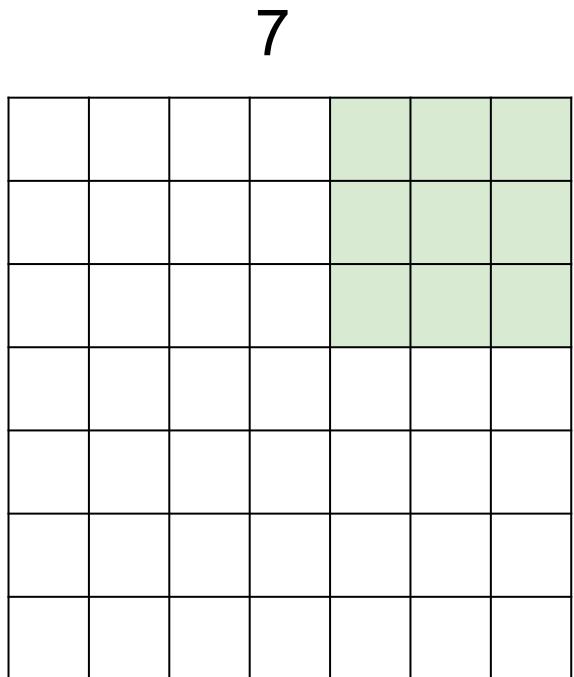
A closer look at spatial dimensions:

7



7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

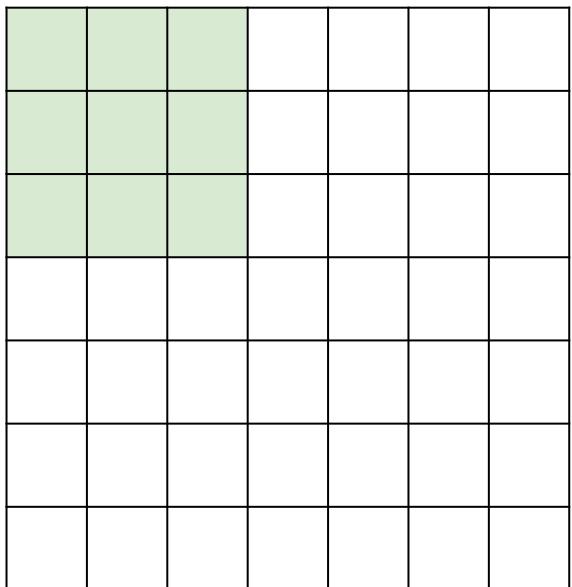
A closer look at spatial dimensions:



7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**
=> 3x3 output!

A closer look at spatial dimensions:

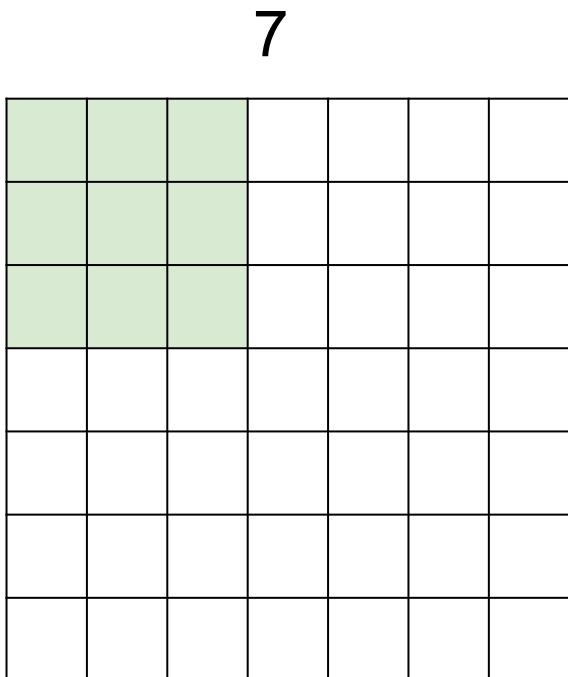
7



7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 3?**

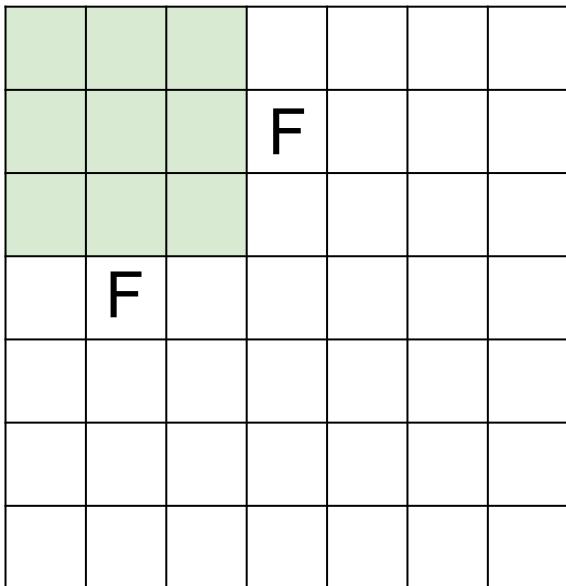
A closer look at spatial dimensions:



7x7 input (spatially)
assume 3x3 filter
applied **with stride 3?**

doesn't fit!
cannot apply 3x3 filter on
7x7 input with stride 3.

N



N

Output size:
(N - F) / stride + 1

e.g. N = 7, F = 3:

$$\text{stride 1} \Rightarrow (7 - 3)/1 + 1 = 5$$

$$\text{stride 2} \Rightarrow (7 - 3)/2 + 1 = 3$$

$$\text{stride 3} \Rightarrow (7 - 3)/3 + 1 = 2.33 : \backslash$$

In practice: Common to zero pad the border

0	0	0	0	0	0		
0							
0							
0							
0							

e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

(recall:)

$$(N - F) / \text{stride} + 1$$

In practice: Common to zero pad the border

0	0	0	0	0	0		
0							
0							
0							
0							

e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

7x7 output!

(recall:)

$$(N + 2P - F) / \text{stride} + 1$$

In practice: Common to zero pad the border

0	0	0	0	0	0		
0							
0							
0							
0							

e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

7x7 output!

in general, common to see CONV layers with stride 1, filters of size $F \times F$, and zero-padding with $(F-1)/2$. (will preserve size spatially)

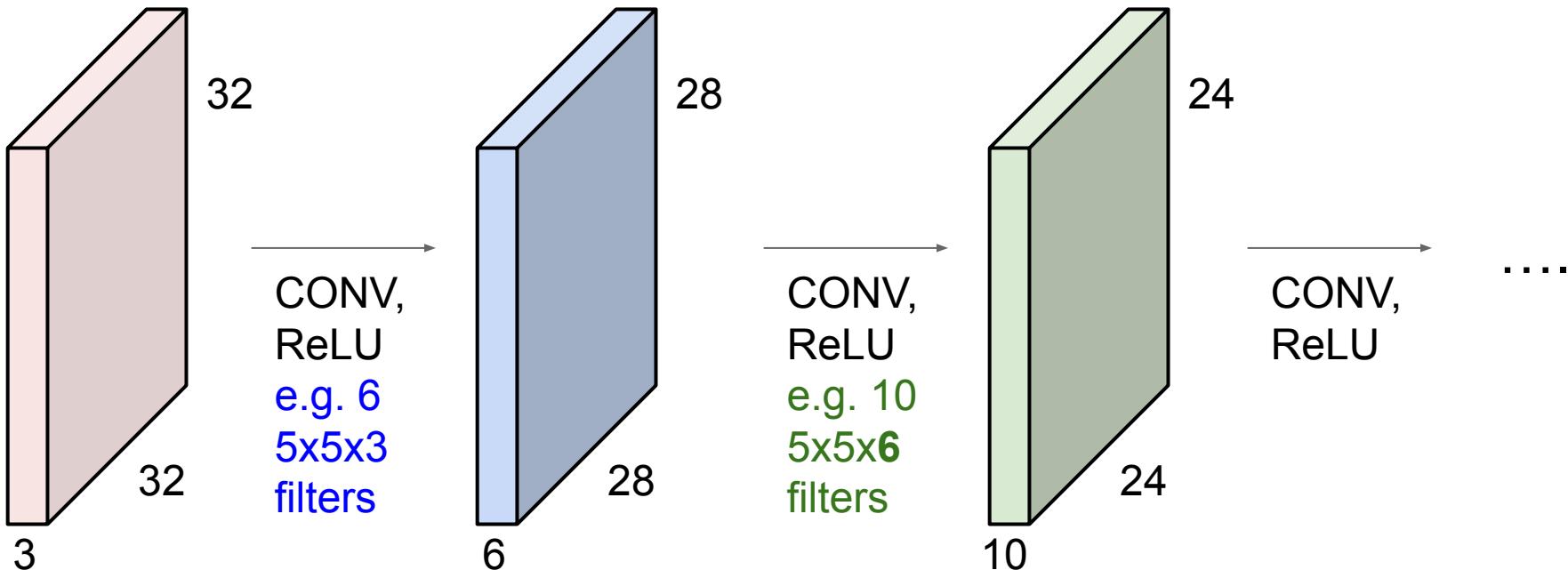
e.g. $F = 3 \Rightarrow$ zero pad with 1

$F = 5 \Rightarrow$ zero pad with 2

$F = 7 \Rightarrow$ zero pad with 3

Remember back to...

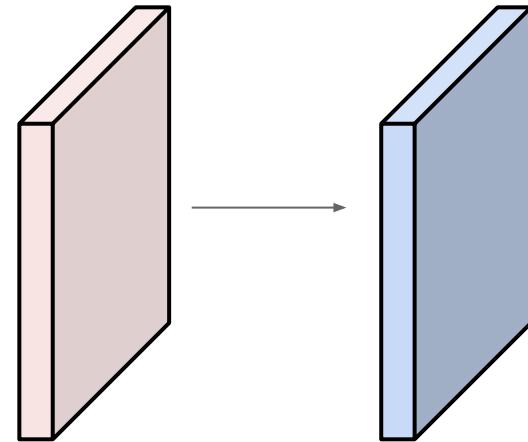
E.g. 32x32 input convolved repeatedly with 5x5 filters shrinks volumes spatially!
(32 -> 28 -> 24 ...). Shrinking too fast is not good, doesn't work well.



Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2

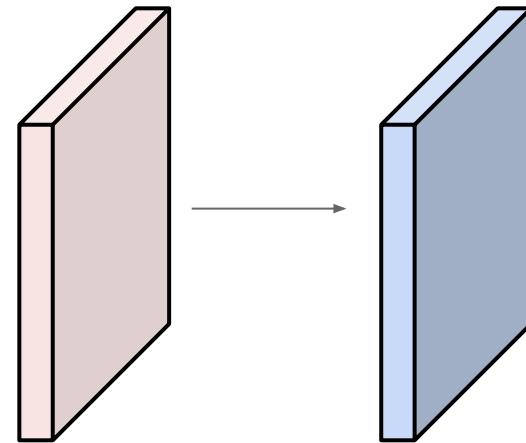


Output volume size: ?

Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad **2**



Output volume size:

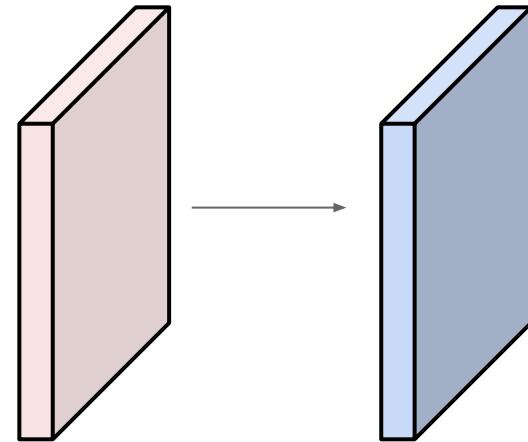
$(32+2*2-5)/1+1 = 32$ spatially, so

32x32x10

Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2

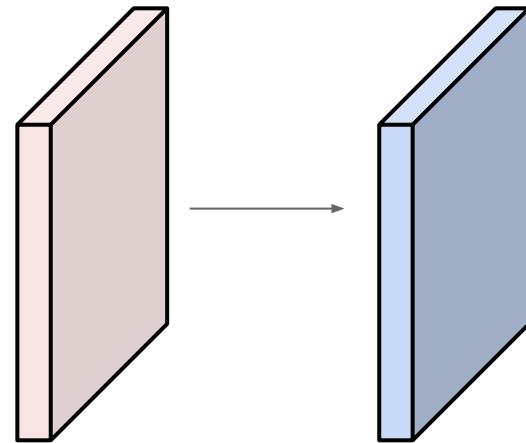


Number of parameters in this layer?

Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2

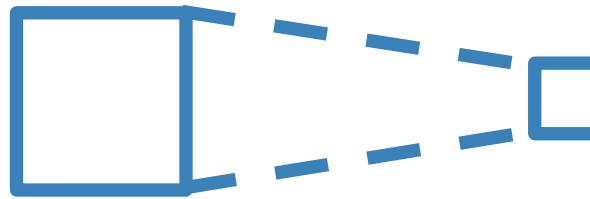


Number of parameters in this layer?

each filter has $5*5*3 + 1 = 76$ params (+1 for bias)
 $\Rightarrow 76*10 = 760$

Receptive Fields

For convolution with kernel size K, each element in the output depends on a $K \times K$ **receptive field** in the input



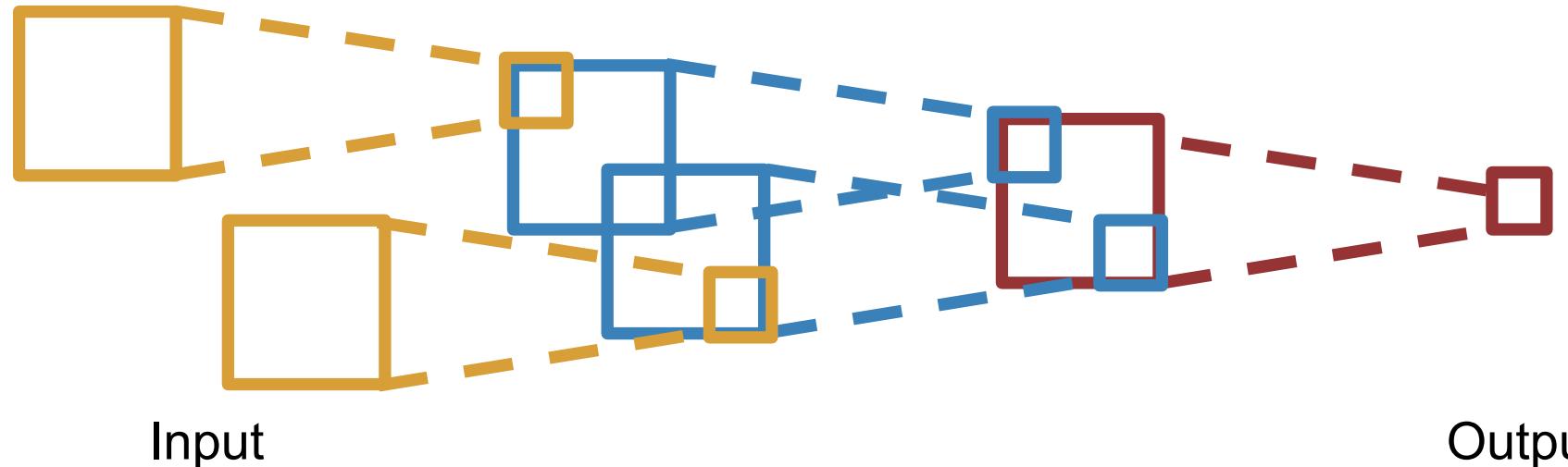
Input

Output

Slide inspiration: Justin Johnson

Receptive Fields

Each successive convolution adds $K - 1$ to the receptive field size
With L layers the receptive field size is $1 + L * (K - 1)$

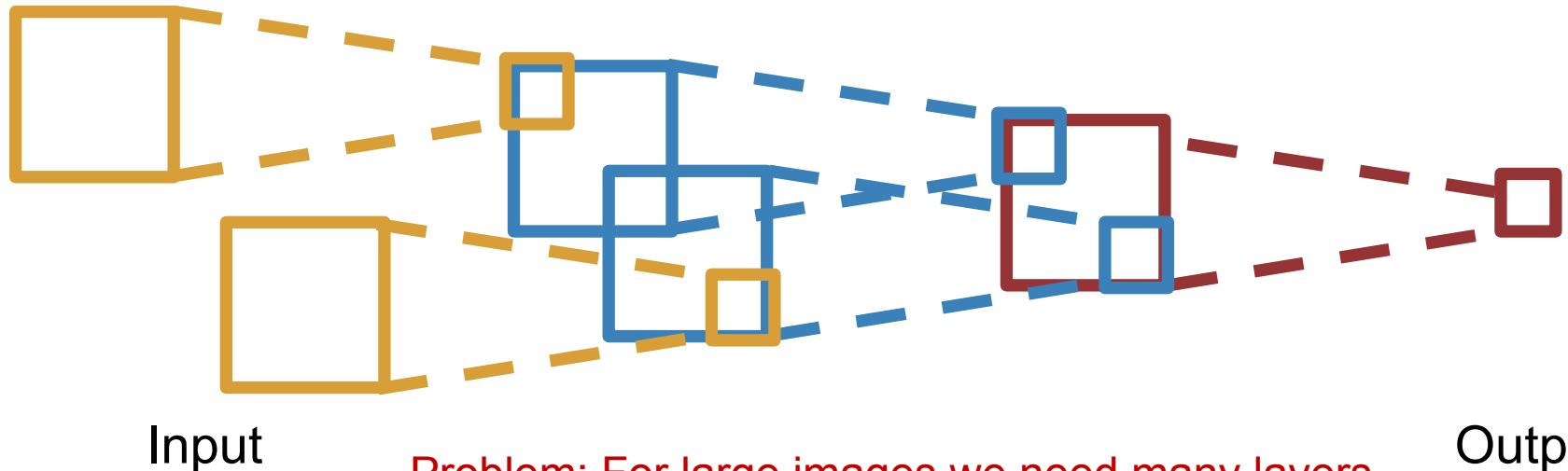


Be careful – “receptive field in the input” vs. “receptive field in the previous layer”

Slide inspiration: Justin Johnson

Receptive Fields

Each successive convolution adds $K - 1$ to the receptive field size
With L layers the receptive field size is $1 + L * (K - 1)$



Input

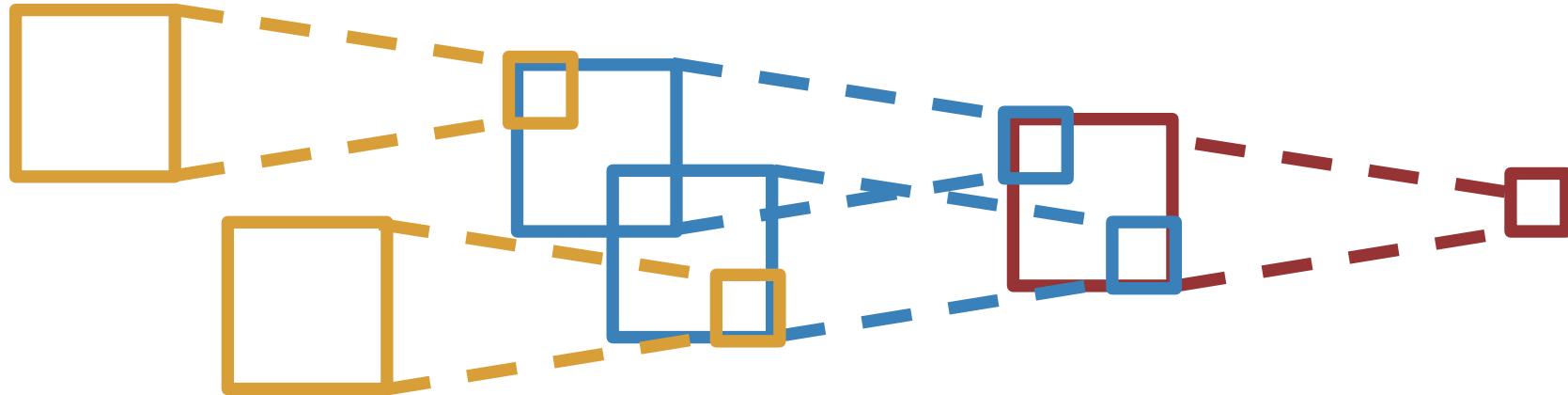
Output

Problem: For large images we need many layers
for each output to “see” the whole image

Slide inspiration: Justin Johnson

Receptive Fields

Each successive convolution adds $K - 1$ to the receptive field size
With L layers the receptive field size is $1 + L * (K - 1)$



Input

Problem: For large images we need many layers
for each output to “see” the whole image

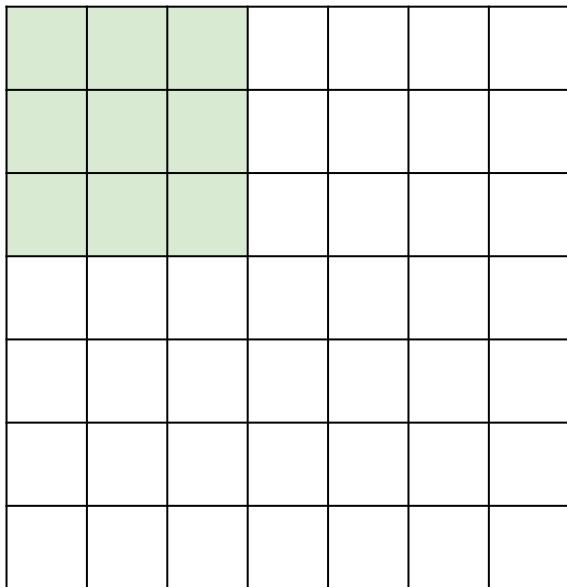
Output

Solution: Downsample inside the network

Slide inspiration: Justin Johnson

Solution: Strided Convolution

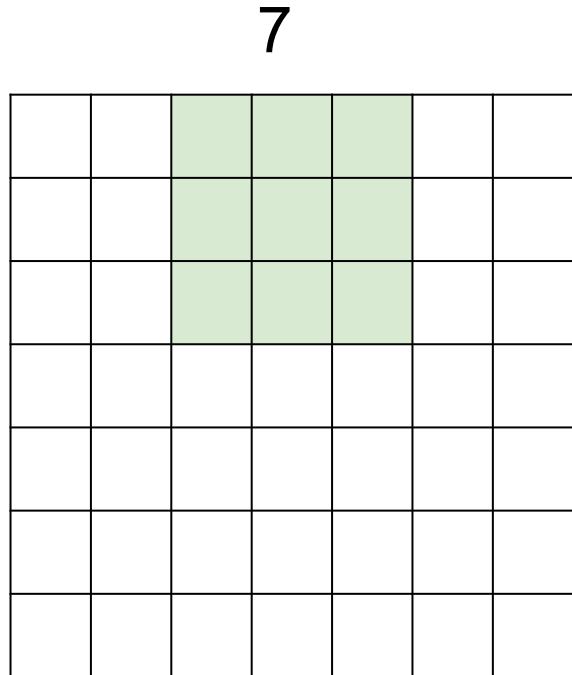
7



7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

Solution: Strided Convolution



7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

=> **3x3 output!**

Convolution layer: summary

Let's assume input is $W_1 \times H_1 \times C$

Conv layer needs 4 hyperparameters:

- Number of filters K
- The filter size F
- The stride S
- The zero padding P

This will produce an output of $W_2 \times H_2 \times K$

where:

- $W_2 = (W_1 - F + 2P)/S + 1$
- $H_2 = (H_1 - F + 2P)/S + 1$

Number of parameters: F^2CK and K biases

Convolution layer: summary

Common settings:

Let's assume input is $W_1 \times H_1 \times C$

Conv layer needs 4 hyperparameters:

- Number of filters **K**
- The filter size **F**
- The stride **S**
- The zero padding **P**

K = (powers of 2, e.g. 32, 64, 128, 512)

- $F = 3, S = 1, P = 1$
- $F = 5, S = 1, P = 2$
- $F = 5, S = 2, P = ?$ (whatever fits)
- $F = 1, S = 1, P = 0$

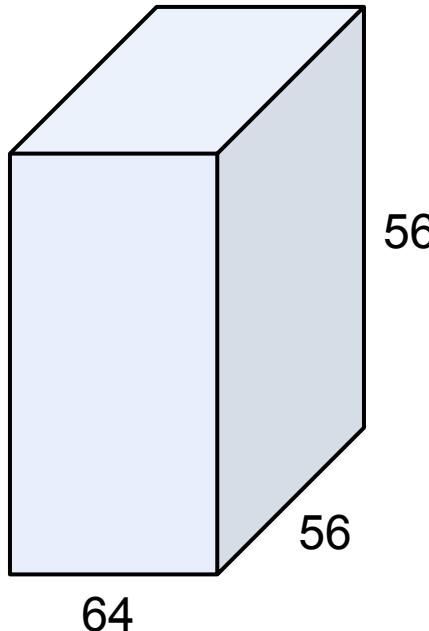
This will produce an output of $W_2 \times H_2 \times K$

where:

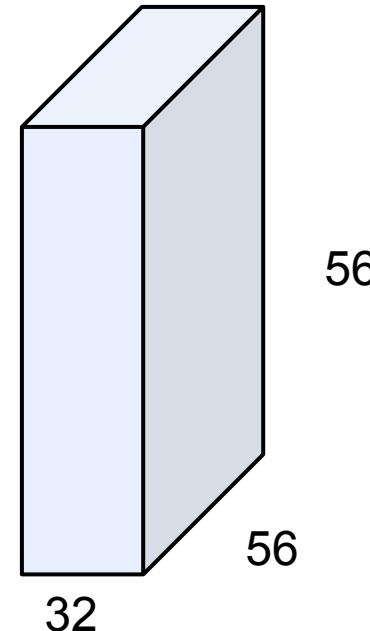
- $W_2 = (W_1 - F + 2P)/S + 1$
- $H_2 = (H_1 - F + 2P)/S + 1$

Number of parameters: F^2CK and K biases

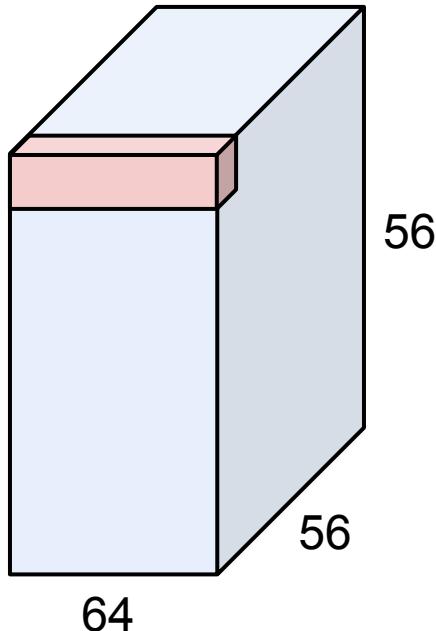
(btw, 1x1 convolution layers make perfect sense)



1x1 CONV
with 32 filters
→
(each filter has size
1x1x64, and performs a
64-dimensional dot
product)



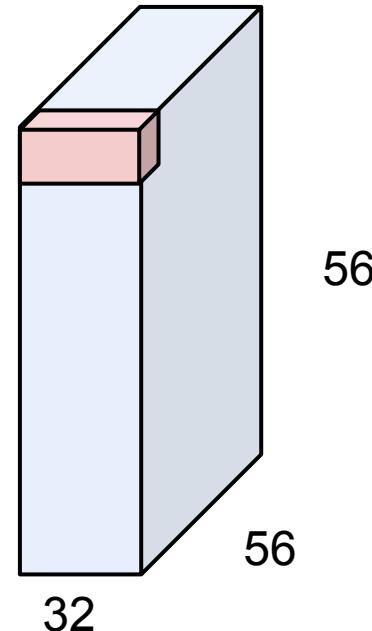
(btw, 1x1 convolution layers make perfect sense)



1x1 CONV
with 32 filters

→

(each filter has size
 $1 \times 1 \times 64$, and performs a
64-dimensional dot
product)



Example: CONV layer in PyTorch

Conv2d

```
CLASS torch.nn.Conv2d(in_channels, out_channels, kernel_size, stride=1, padding=0,  
dilation=1, groups=1, bias=True)
```

[SOURCE]

Applies a 2D convolution over an input signal composed of several input planes.

In the simplest case, the output value of the layer with input size (N, C_{in}, H, W) and output $(N, C_{\text{out}}, H_{\text{out}}, W_{\text{out}})$ can be precisely described as:

$$\text{out}(N_i, C_{\text{out}_j}) = \text{bias}(C_{\text{out}_j}) + \sum_{k=0}^{C_{\text{in}}-1} \text{weight}(C_{\text{out}_j}, k) * \text{input}(N_i, k)$$

where $*$ is the valid 2D cross-correlation operator, N is a batch size, C denotes a number of channels, H is a height of input planes in pixels, and W is width in pixels.

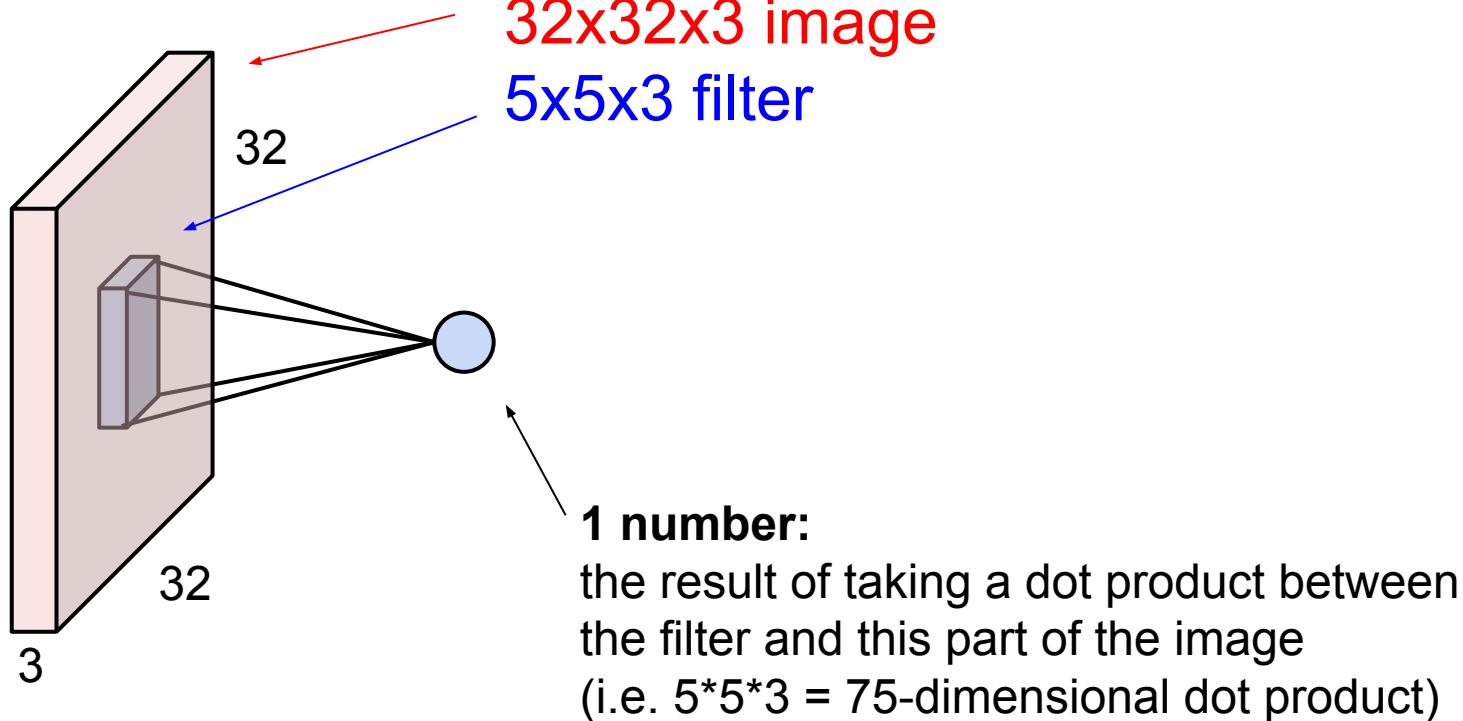
- `stride` controls the stride for the cross-correlation, a single number or a tuple.
- `padding` controls the amount of implicit zero-paddings on both sides for `padding` number of points for each dimension.
- `dilation` controls the spacing between the kernel points; also known as the à trous algorithm. It is harder to describe, but this [link](#) has a nice visualization of what `dilation` does.
- `groups` controls the connections between inputs and outputs. `in_channels` and `out_channels` must both be divisible by `groups`. For example,
 - At `groups=1`, all inputs are convolved to all outputs.
 - At `groups=2`, the operation becomes equivalent to having two conv layers side by side, each seeing half the input channels, and producing half the output channels, and both subsequently concatenated.
 - At `groups= in_channels`, each input channel is convolved with its own set of filters, of size: $\left\lfloor \frac{C_{\text{out}}}{C_{\text{in}}} \right\rfloor$.

The parameters `kernel_size`, `stride`, `padding`, `dilation` can either be:

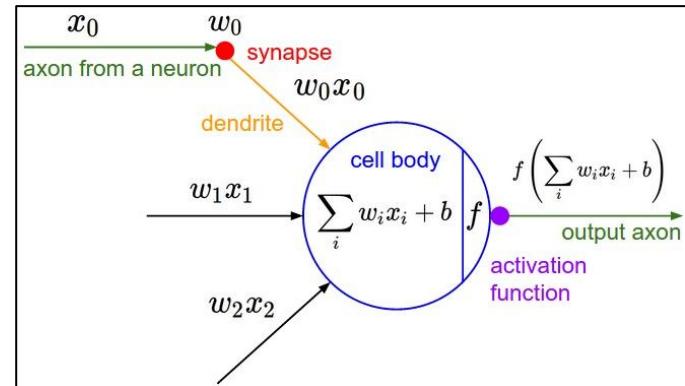
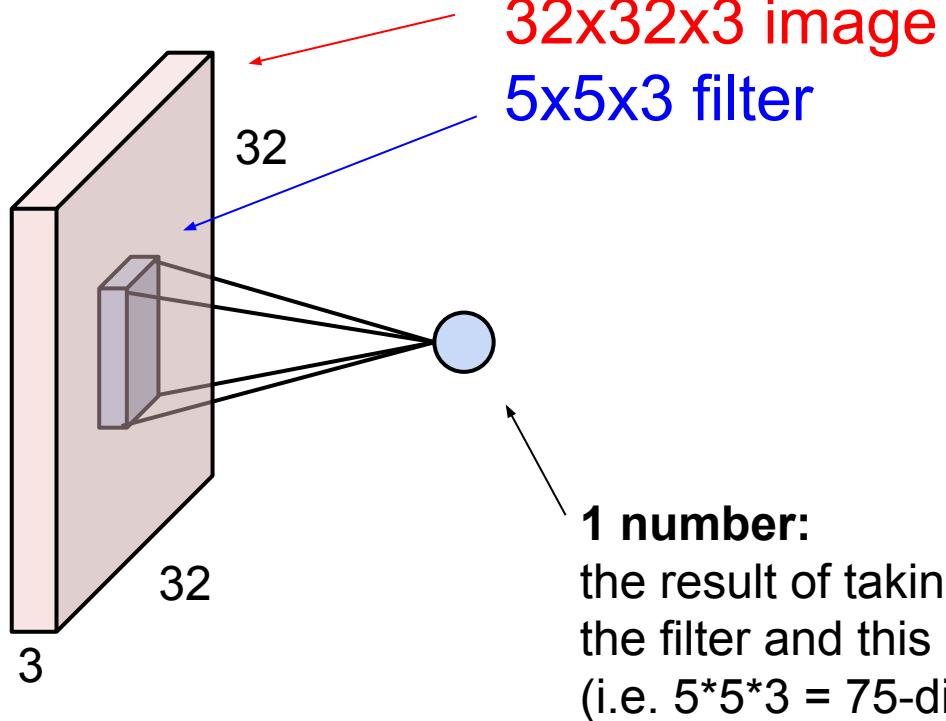
- a single `int` – in which case the same value is used for the height and width dimension
- a `tuple` of two `ints` – in which case, the first `int` is used for the height dimension, and the second `int` for the width dimension

[PyTorch](#) is licensed under [BSD 3-clause](#).

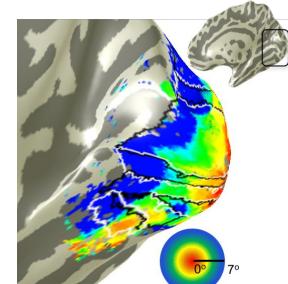
The brain/neuron view of CONV Layer



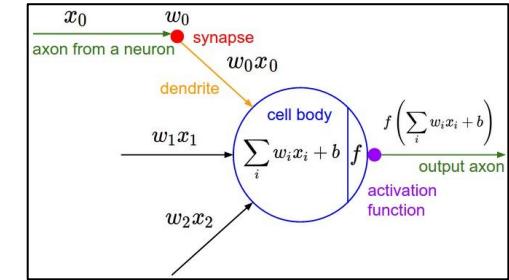
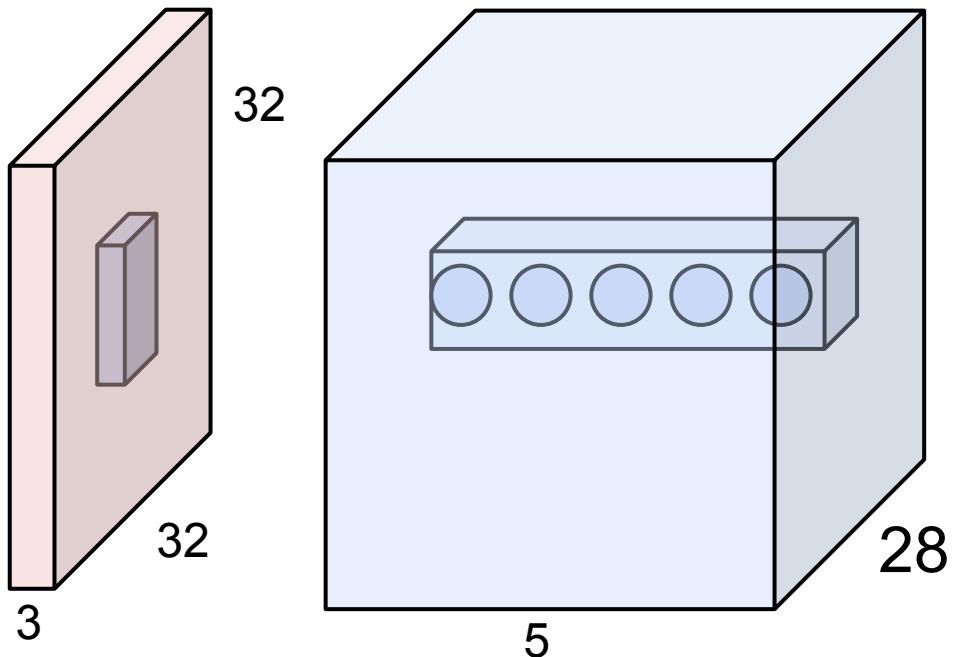
The brain/neuron view of CONV Layer



It's just a neuron with local connectivity...



The brain/neuron view of CONV Layer



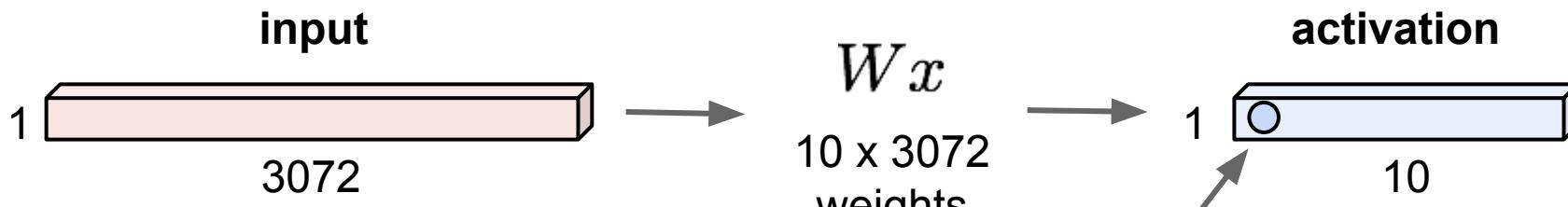
E.g. with 5 filters,
CONV layer consists of
neurons arranged in a 3D grid
($28 \times 28 \times 5$)

There will be 5 different
neurons all looking at the same
region in the input volume

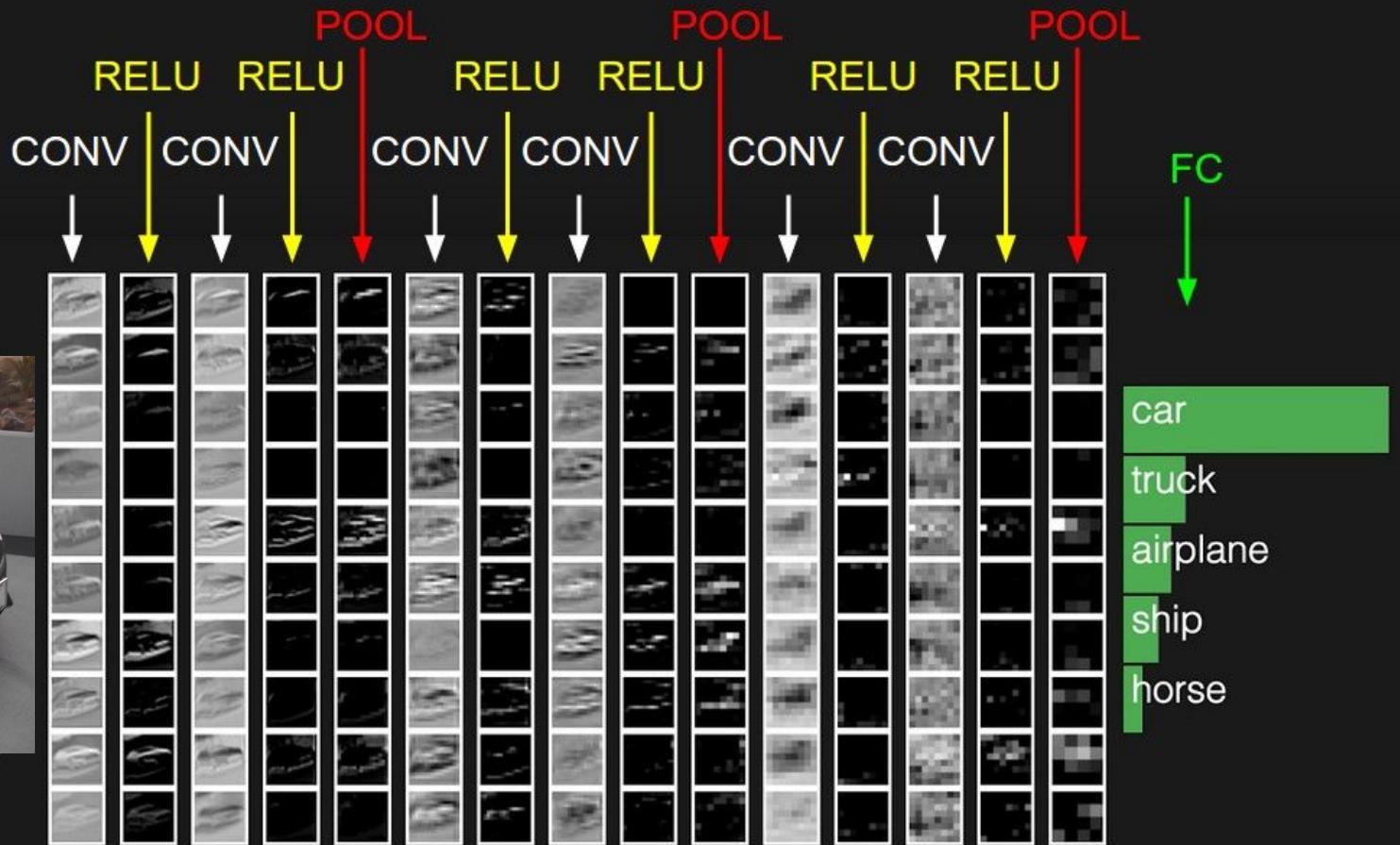
Reminder: Fully Connected Layer

32x32x3 image -> stretch to 3072×1

Each neuron
looks at the full
input volume

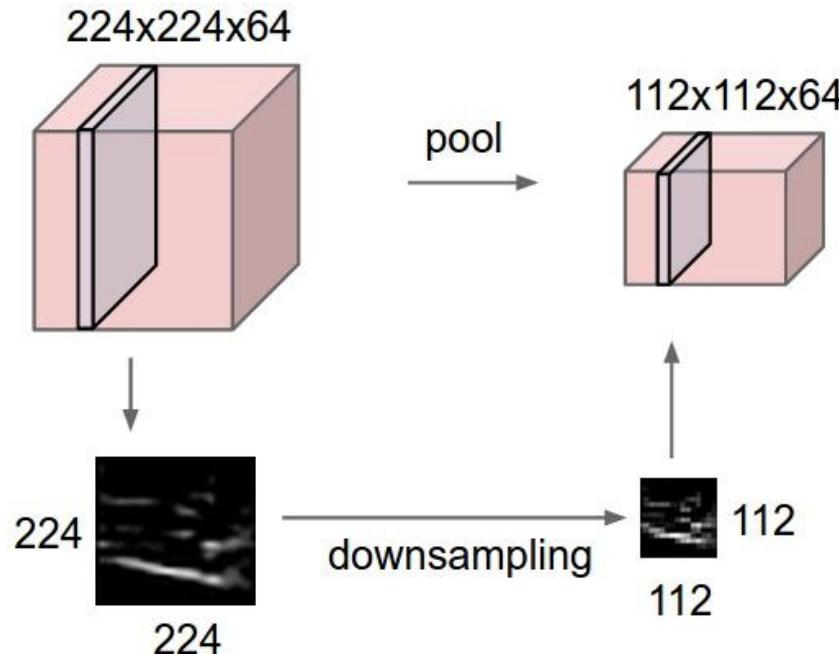


1 number:
the result of taking a dot product
between a row of W and the input
(a 3072-dimensional dot product)

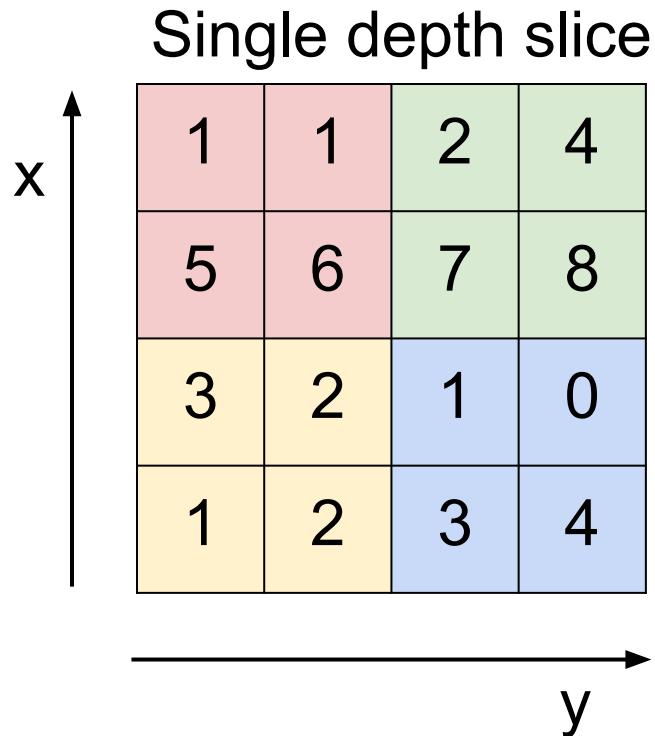


Pooling layer

- makes the representations smaller and more manageable
- operates over each activation map independently



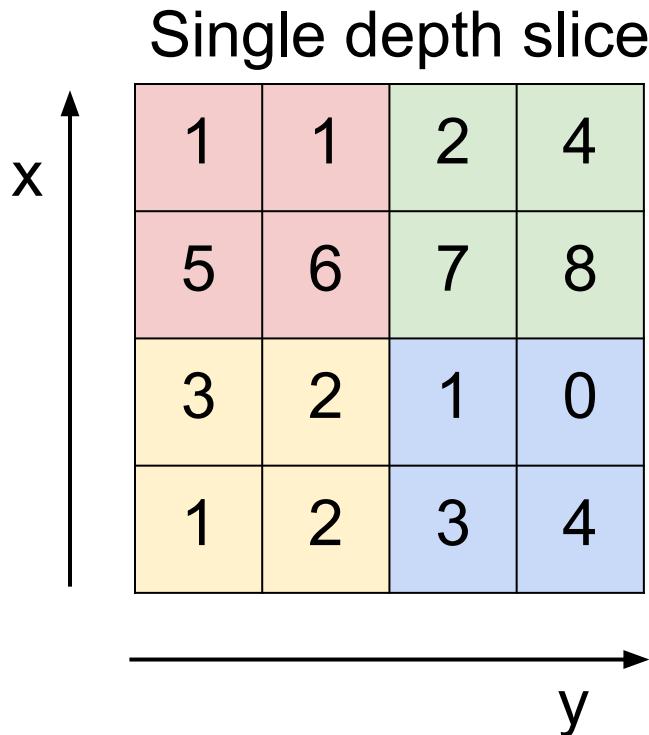
MAX POOLING



max pool with 2x2 filters
and stride 2

6	8
3	4

MAX POOLING



max pool with 2x2 filters
and stride 2

6	8
3	4

- No learnable parameters
- Introduces spatial invariance

Pooling layer: summary

Let's assume input is $W_1 \times H_1 \times C$

Conv layer needs 2 hyperparameters:

- The spatial extent **F**
- The stride **S**

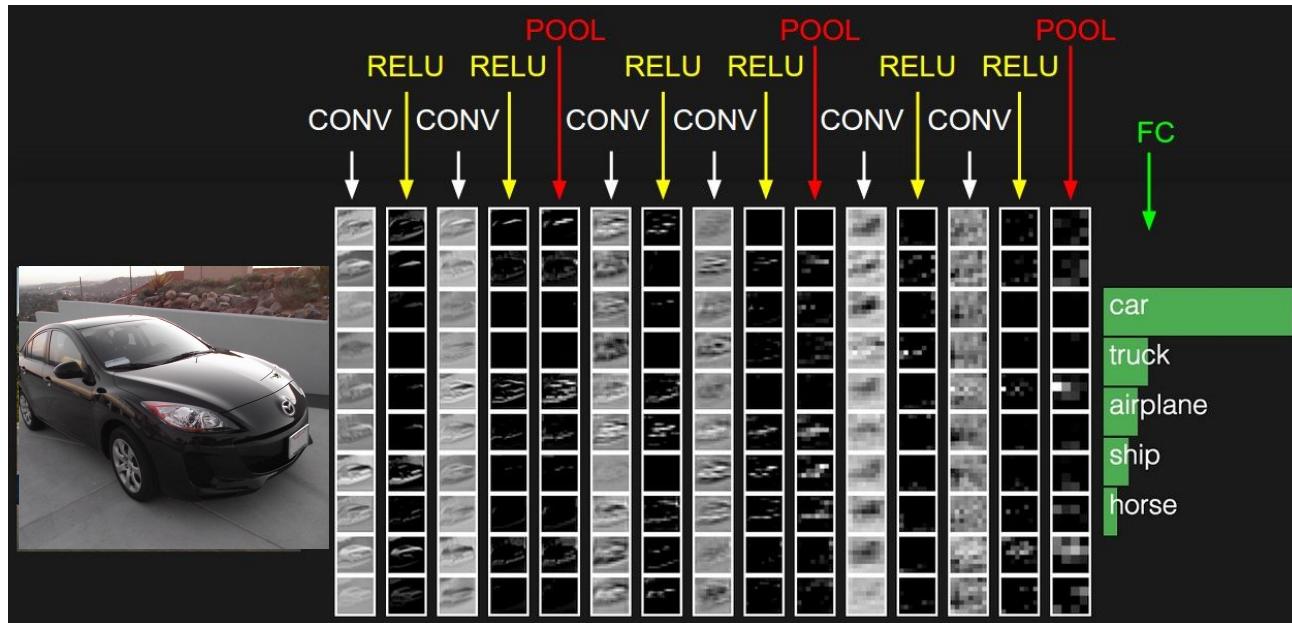
This will produce an output of $W_2 \times H_2 \times C$ where:

- $W_2 = (W_1 - F)/S + 1$
- $H_2 = (H_1 - F)/S + 1$

Number of parameters: 0

Fully Connected Layer (FC layer)

- Contains neurons that connect to the entire input volume, as in ordinary Neural Networks



[ConvNetJS demo: training on CIFAR-10]

ConvNetJS CIFAR-10 demo

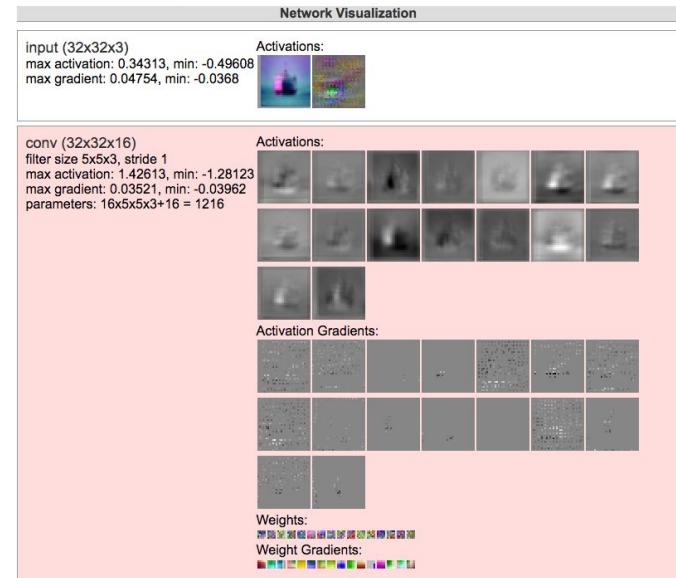
Description

This demo trains a Convolutional Neural Network on the [CIFAR-10 dataset](#) in your browser, with nothing but Javascript. The state of the art on this dataset is about 90% accuracy and human performance is at about 94% (not perfect as the dataset can be a bit ambiguous). I used [this python script](#) to parse the [original files](#) (python version) into batches of images that can be easily loaded into page DOM with img tags.

This dataset is more difficult and it takes longer to train a network. Data augmentation includes random flipping and random image shifts by up to 2px horizontally and vertically.

By default, in this demo we're using Adadelta which is one of per-parameter adaptive step size methods, so we don't have to worry about changing learning rates or momentum over time. However, I still included the text fields for changing these if you'd like to play around with SGD+Momentum trainer.

Report questions/bugs/suggestions to [@karpathy](#).

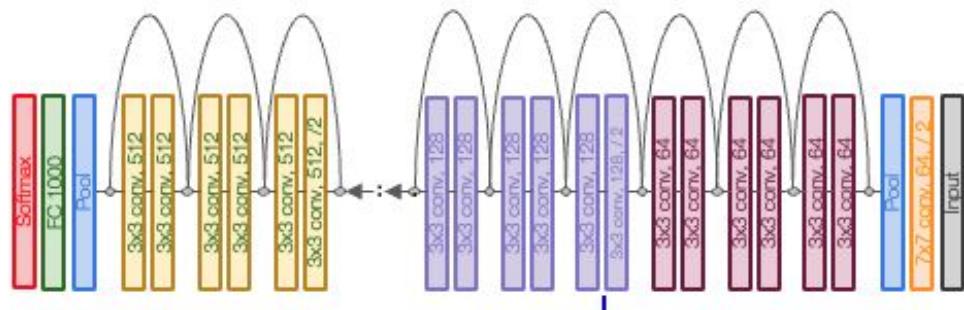
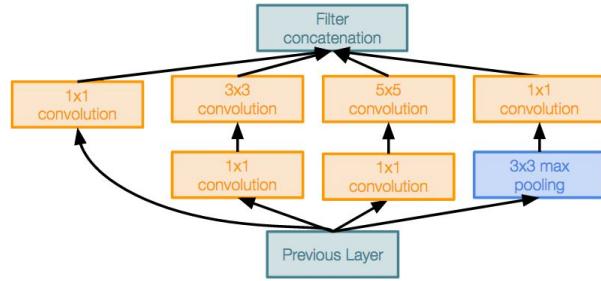
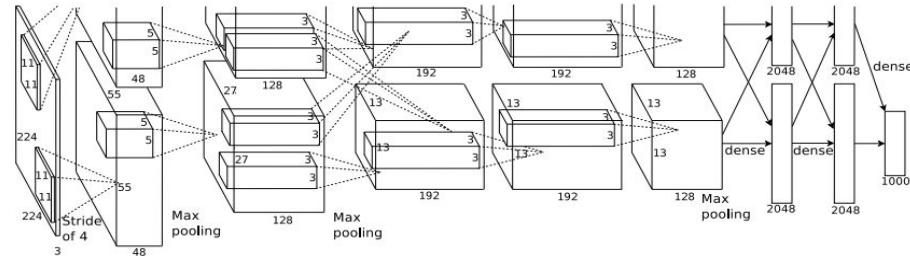
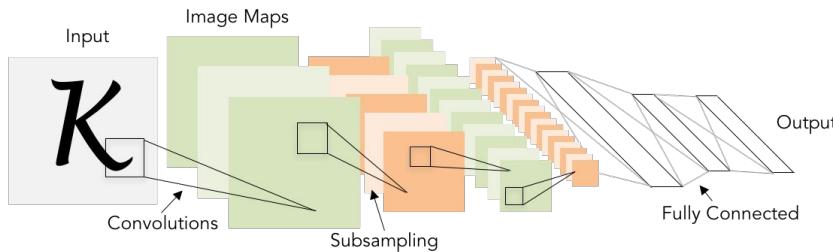


<http://cs.stanford.edu/people/karpathy/convnetjs/demo/cifar10.html>

Summary

- ConvNets stack CONV,POOL,FC layers
- Trend towards smaller filters and deeper architectures
- Trend towards getting rid of POOL/FC layers (just CONV)
- Historically architectures looked like
 $[(\text{CONV-RELU})^* \text{N} - \text{POOL?}]^* \text{M} - (\text{FC-RELU})^* \text{K}, \text{SOFTMAX}$
where N is usually up to ~5, M is large, $0 \leq K \leq 2$.
- But recent advances such as ResNet/GoogLeNet have challenged this paradigm

Next time: CNN Architectures



Agenda

- Motivation
- Backprop Tips & Tricks
- Matrix calculus primer

Agenda

- **Motivation**
- Backprop Tips & Tricks
- Matrix calculus primer

Motivation

Recall: Optimization objective is to minimize loss

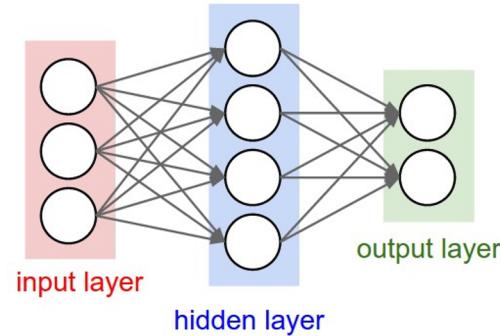
$$Loss = f(x, y; \theta)$$

Motivation

Recall: Optimization objective is to minimize loss

$$Loss = f(x, y; \theta)$$

Goal: how should we tweak the parameters to decrease the loss?



Agenda

- Motivation
- **Backprop Tips & Tricks**
- Matrix calculus primer

A Simple Example

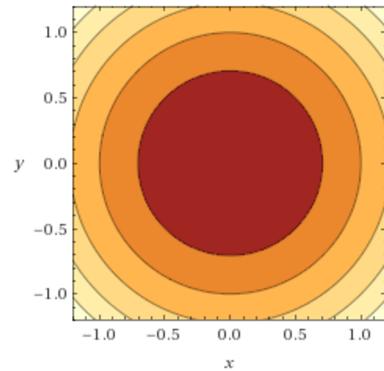
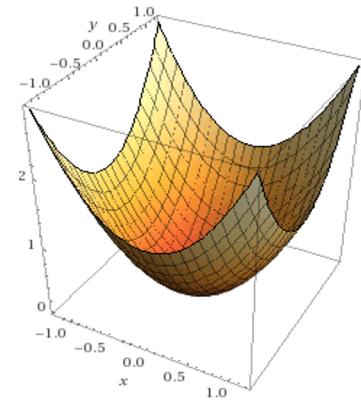
Loss $Loss = f(x, y; \theta)$

Goal: Tweak the parameters to minimize loss

=> minimize a multivariable function in parameter space

A Simple Example

=> minimize a multivariable function



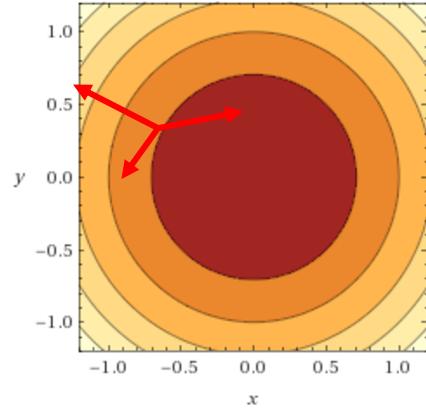
$$f(x, y) = x^2 + y^2$$

Plotted on WolframAlpha

Approach #1: Random Search

Intuition: the step we take in the domain of function

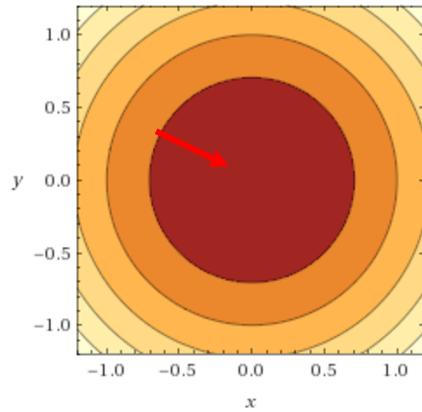
$$f(x, y) = x^2 + y^2$$



Approach #2: Numerical Gradient

Intuition: rate of change of a function with respect to a variable surrounding a small region

$$f(x, y) = x^2 + y^2$$

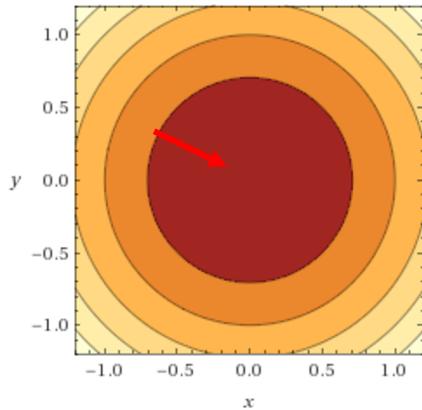


Approach #2: Numerical Gradient

Intuition: rate of change of a function with respect to a variable surrounding a small region

Finite Differences:
$$\frac{f(x + h, y) - f(x, y)}{h}$$

$$f(x, y) = x^2 + y^2$$

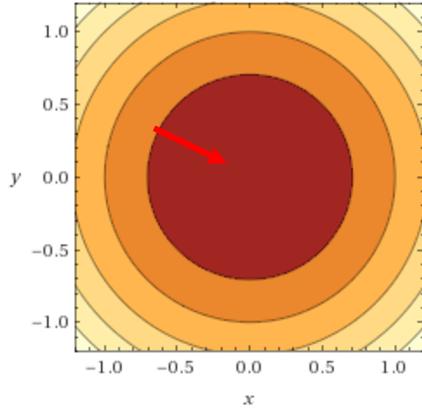


Approach #3: Analytical Gradient

Recall: partial derivative by limit definition

$$\frac{\partial f}{\partial x}(x, y) = \lim_{h \rightarrow 0} \frac{f(x + h, y) - f(x, y)}{h}$$

$$f(x, y) = x^2 + y^2$$



Approach #3: Analytical Gradient

Recall: chain rule $\frac{dz}{dx} = \frac{dz}{dy} \cdot \frac{dy}{dx}.$

Approach #3: Analytical Gradient

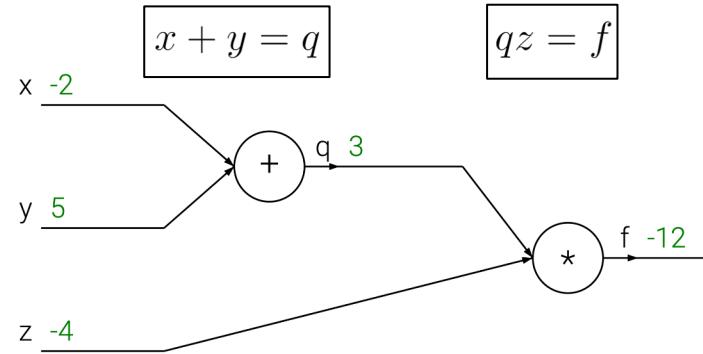
Recall: chain rule $\frac{dz}{dx} = \frac{dz}{dy} \cdot \frac{dy}{dx}$.

E.g. $f(x, y, z) = (x + y)z$

$$\frac{\partial f}{\partial x} =$$

$$\frac{\partial f}{\partial y} =$$

$$\frac{\partial f}{\partial z} =$$



Approach #3: Analytical Gradient

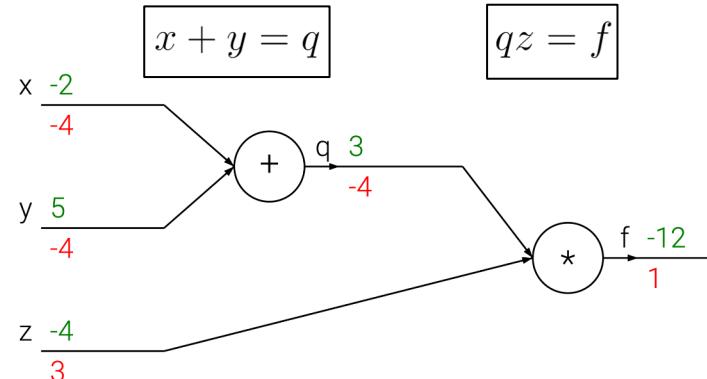
Recall: chain rule $\frac{dz}{dx} = \frac{dz}{dy} \cdot \frac{dy}{dx}$.

E.g. $f(x, y, z) = (x + y)z$

$$\frac{\partial f}{\partial x} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial x} = z \cdot 1 = z = -4$$

$$\frac{\partial f}{\partial y} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial y} = z \cdot 1 = z = -4$$

$$\frac{\partial f}{\partial z} = q = x + y = -2 + 5 = 3$$



Approach #3: Analytical Gradient

Recall: chain rule $\frac{dz}{dx} = \frac{dz}{dy} \cdot \frac{dy}{dx}$.

Intuition: upstream gradient values propagate backwards -- we can reuse them!

Gradient

$$f : R^n \rightarrow R$$

$$\nabla f : R^n \rightarrow R^n$$

$$\mathbf{x} = [x_1, \dots, x_n]^T \in R^n$$

$$\nabla f(\mathbf{x}) = \begin{bmatrix} \frac{\partial f}{\partial x_1}(\mathbf{x}) \\ \vdots \\ \frac{\partial f}{\partial x_n}(\mathbf{x}) \end{bmatrix}$$

“direction and rate of fastest increase”

Numerical Gradient vs Analytical Gradient

What about Autograd?

Q: “Why do we have to write the backward pass when frameworks in the real world, such as TensorFlow, compute them for you automatically?”

A: Problems might surface related to underlying gradients when debugging your model (e.g. vanishing or exploding gradients)

“Yes You Should Understand Backprop”

<https://medium.com/@karpathy/yes-you-should-understand-backprop-e2f06eab496b>

Problem Statement: Backpropagation

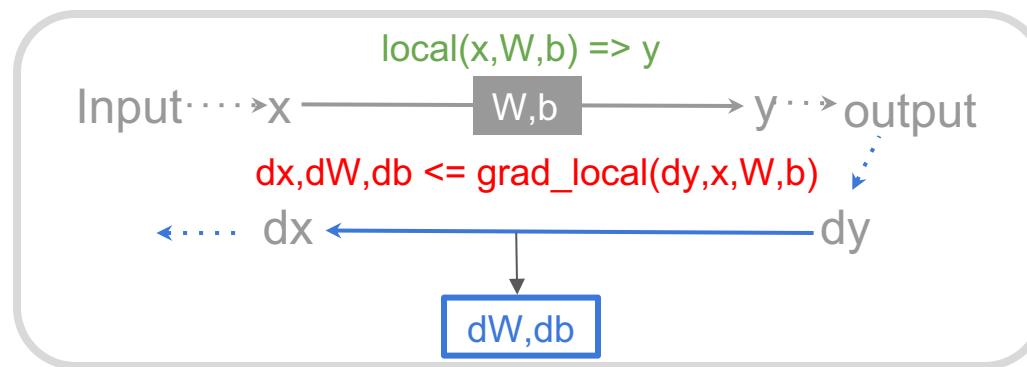
$$Loss = \frac{1}{N} \sum_i L_i(f(x_i, \theta), y_i)$$

Given a function f with respect to inputs x , labels y , and parameters θ
compute the gradient of the $Loss$ with respect to θ

Problem Statement: Backpropagation

An algorithm for computing the gradient of a **compound function** as a series of **local, intermediate gradients**:

1. Identify intermediate functions (forward prop)
2. Compute local gradients (chain rule)
3. Combine with upstream signal to get full gradient



Modularity: Previous Example

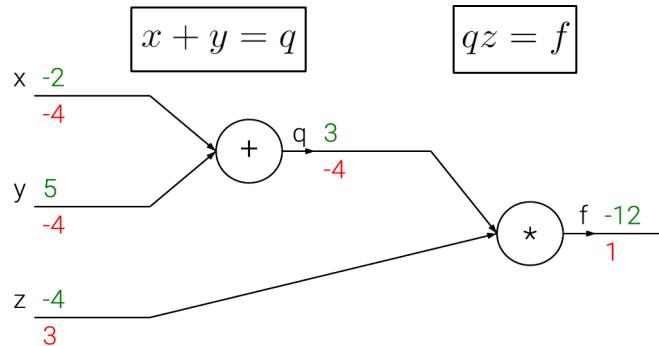
Compound function

$$f(x, y, z) = (x + y)z$$

Intermediate Variables
(forward propagation)

$$q = x + y$$

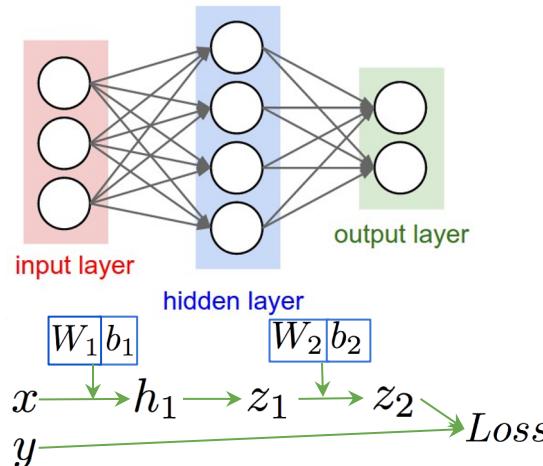
$$f = qz$$



Modularity: 2-Layer Neural Network

Compound function

Intermediate Variables
(forward propagation)



$$Loss = L\left(\sigma(xW_1 + b_1)W_2 + b_2, y\right)$$

$$h_1 = xW_1 + b_1$$

$$z_1 = \sigma(h_1)$$

$$z_2 = z_1 W_2 + b_2$$

$Loss$ = Squared Euclidean Distance
between z_2 and y

Intermediate Variables (forward propagation)

$$h_1 = xW_1 + b_1$$

$$z_1 = \sigma(h_1)$$

$$z_2 = z_1W_2 + b_2$$



? $f(x; W, b) = Wx + b$?

(\uparrow lecture note) Input one feature
vector

(\leftarrow here) Input a batch of data
(matrix)

Intermediate Variables (forward propagation)

$$h_1 = xW_1 + b_1$$

$$z_1 = \sigma(h_1)$$

$$z_2 = z_1W_2 + b_2$$

$$Loss = \frac{1}{N} \|z_2 - y\|_F^2$$

$$\|A\|_F = \sqrt{\sum_{i=1}^m \sum_{j=1}^n |a_{ij}|^2}$$

1. intermediate functions
2. local gradients
3. full gradients

Intermediate Gradients (backward propagation)

$$\frac{\partial h_1}{\partial W_1}, \frac{\partial h_1}{\partial b_1} \quad \frac{\partial h_1}{\partial x} \quad ? \quad ? \quad ? \quad W_1$$

$$\frac{\partial z_1}{\partial h_1} \quad ? \quad ? \quad ? \quad (1 - z_1)$$

$$\frac{\partial z_2}{\partial W_2}, \frac{\partial z_2}{\partial b_2} \quad \frac{\partial z_2}{\partial z_1} \quad ? \quad ? \quad ? \quad W_2$$



$$\frac{\partial Loss}{\partial z_2} = \frac{2}{N}(z_2 - y)$$

Agenda

- Motivation
- Backprop Tips & Tricks
- **Matrix calculus primer**

Derivative w.r.t. Vector

Scalar-by-Vector

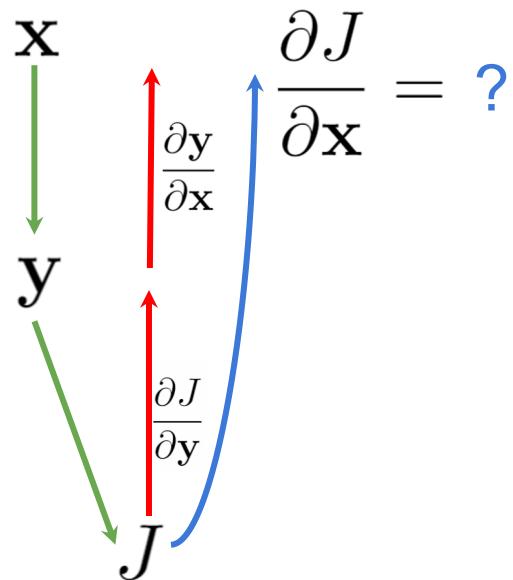
$$\frac{\partial y}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial y}{\partial x_1} & \frac{\partial y}{\partial x_2} & \cdots & \frac{\partial y}{\partial x_n} \end{bmatrix}$$

Vector-by-Vector

$$\frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \cdots & \frac{\partial y_1}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial y_m}{\partial x_1} & \frac{\partial y_m}{\partial x_2} & \cdots & \frac{\partial y_m}{\partial x_n} \end{bmatrix}$$

Derivative w.r.t. Vector: Chain Rule

1. intermediate functions
2. local gradients
3. full gradients



$$\begin{aligned}\frac{\partial J}{\partial x_j} &= \sum_i \frac{\partial J}{\partial y_i} \frac{\partial y_i}{\partial x_j} \\ &= \sum_i \left(\frac{\partial J}{\partial \mathbf{y}} \right)_{1i} \left(\frac{\partial \mathbf{y}}{\partial \mathbf{x}} \right)_{ij}\end{aligned}$$

$$\boxed{\frac{\partial J}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} \frac{\partial \mathbf{y}}{\partial \mathbf{x}}}$$

Derivative w.r.t. Vector: Takeaway

$$\mathbf{y} = A_{m \times n} \mathbf{x} \quad \frac{\partial \mathbf{y}}{\partial \mathbf{x}} = A$$

$$\frac{\partial J}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} \frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} A$$

$$\mathbf{y} = \omega(\mathbf{x}) \quad \frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \begin{bmatrix} \omega'(x_1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \omega'(x_n) \end{bmatrix}$$

$$\frac{\partial J}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} \frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \left[\frac{\partial J}{\partial y_1} \omega'(x_1), \dots, \frac{\partial J}{\partial y_n} \omega'(x_n) \right] = \frac{\partial J}{\partial \mathbf{y}} \circ \omega'(\mathbf{x})^T$$

Derivative w.r.t. Matrix

Scalar-by-Matrix

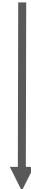
$$\frac{\partial y}{\partial A} = \begin{bmatrix} \frac{\partial y}{\partial A_{11}} & \frac{\partial y}{\partial A_{12}} & \cdots & \frac{\partial y}{\partial A_{1n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial y}{\partial A_{m1}} & \frac{\partial y}{\partial A_{m2}} & \cdots & \frac{\partial y}{\partial A_{mn}} \end{bmatrix}$$

Vector-by-Matrix

?

Derivative w.r.t. Matrix: Dimension Balancing

When you take scalar-by-matrix gradients



The gradient has **shape of denominator**

- Dimension balancing is the “cheap” but **efficient** approach to gradient calculations in most practical settings

Derivative w.r.t. Matrix: Takeaway

$$Y_{m \times l} = A_{m \times n} X_{n \times l}$$

$$\frac{\partial J}{\partial X} = \left. A^T \frac{\partial J}{\partial Y} \right|$$

$$\frac{\partial J}{\partial A} = \left. \frac{\partial J}{\partial Y} X^T \right|$$

$$Y_{m \times n} = \omega(X_{m \times n})$$

$$\frac{\partial J}{\partial X} = \left. \frac{\partial J}{\partial Y} \circ \omega'(X) \right|$$

Intermediate Variables (forward propagation)

$$h_1 = xW_1 + b_1$$

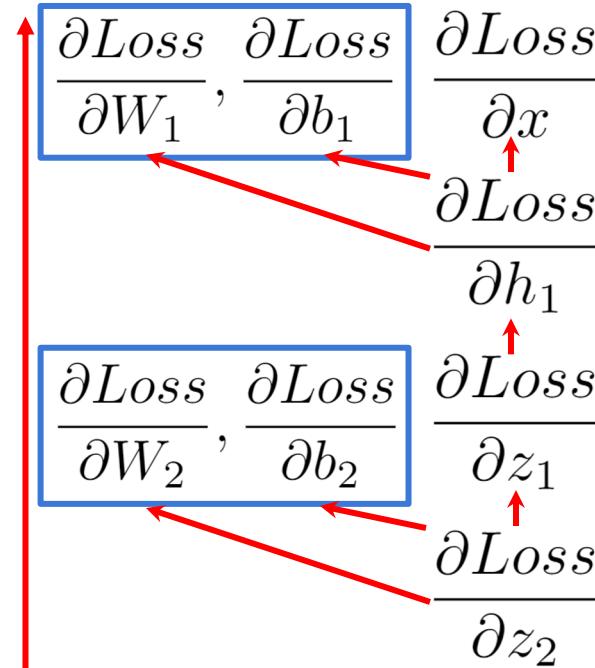
$$z_1 = \sigma(h_1)$$

$$z_2 = z_1W_2 + b_2$$

$$\text{Loss} = \frac{1}{N} \|z_2 - y\|_F^2$$

1. intermediate functions
2. local gradients
3. full gradients

Intermediate Gradients (backward propagation)



Backprop Menu for Success

1. Write down variable graph
2. Keep track of error signals
3. Compute derivative of loss function
4. Enforce shape rule on error signals, especially when deriving
over a linear transformation



Vector-by-vector

$$\mathbf{y} = A_{m \times n} \mathbf{x}$$

$$y_i = \sum_{j=1}^n A_{ij} x_j$$

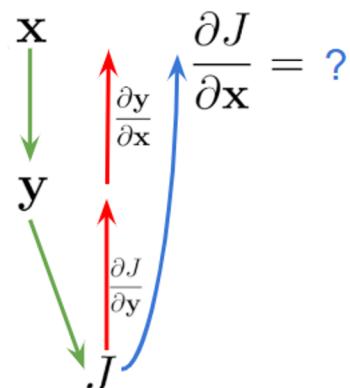
$$\frac{\partial y_i}{\partial x_j} = A_{ij}$$

$$\frac{\partial \mathbf{y}}{\partial \mathbf{x}} = A$$



Vector-by-vector

$$\boxed{\begin{aligned}\mathbf{y} &= A_{m \times n} \mathbf{x} \\ \lambda^T &= \frac{\partial J}{\partial \mathbf{y}}\end{aligned}}$$



$$y_i = \sum_{j=1}^n A_{ij} x_j \quad \frac{\partial y_i}{\partial x_j} = A_{ij}$$
$$\lambda_i = \frac{\partial J}{\partial y_i}$$

$$\frac{\partial J}{\partial x_j} = \sum_i \frac{\partial J}{\partial y_i} \frac{\partial y_i}{\partial x_j} = \sum_{i=1}^m \lambda_i A_{ij}$$

$$\boxed{\frac{\partial J}{\partial \mathbf{x}} = \lambda^T A = \frac{\partial J}{\partial \mathbf{y}} A}$$



Vector-by-vector

$$\mathbf{y} = \omega(\mathbf{x})$$

$$y_i = \omega(x_i)$$

$$\frac{\partial y_i}{\partial x_i} = \omega'(x_i)$$

$$\frac{\partial y_i}{\partial x_j} = 0 \quad (i \neq j)$$

$$\frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \begin{bmatrix} \omega'(x_1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \omega'(x_n) \end{bmatrix}$$



Vector-by-vector

$$\mathbf{y} = \omega(\mathbf{x})$$

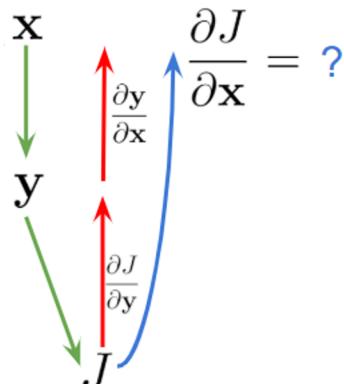
$$\lambda^T = \frac{\partial J}{\partial \mathbf{y}}$$

$$y_i = \omega(x_i)$$

$$\lambda_i = \frac{\partial J}{\partial y_i}$$

$$\frac{\partial y_i}{\partial x_i} = \omega'(x_i)$$

$$\frac{\partial y_i}{\partial x_j} = 0 \quad (i \neq j)$$



$$\frac{\partial J}{\partial x_j} = \sum_i \frac{\partial J}{\partial y_i} \frac{\partial y_i}{\partial x_j} = \frac{\partial J}{\partial y_j} \frac{\partial y_j}{\partial x_j} = \lambda_j \omega'(x_j)$$

$$\frac{\partial J}{\partial \mathbf{x}} = \lambda^T \circ \omega'(\mathbf{x})^T = \frac{\partial J}{\partial \mathbf{y}} \circ \omega'(\mathbf{x})^T$$



$$\mathbf{y} = A_{m \times n} \mathbf{x} \quad \frac{\partial J}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} A$$

$$\frac{\partial J^T}{\partial \mathbf{x}} = A^T \frac{\partial J^T}{\partial \mathbf{y}}$$

Matrix multiplication [Backprop]

$$Y_{m \times l} = A_{m \times n} X_{n \times l}$$

$$\frac{\partial J}{\partial Y} = \Lambda_{m \times l}$$

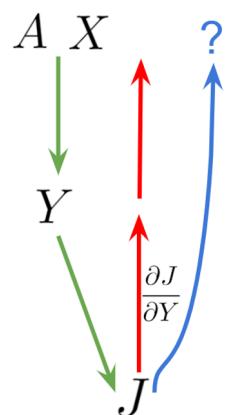
$$\begin{aligned}\frac{\partial J}{\partial X_{ij}} &= \sum_{i',j'} \frac{\partial J}{\partial Y_{i'j'}} \frac{\partial Y_{i'j'}}{\partial X_{ij}} &= \sum_{i'=1}^m \frac{\partial J}{\partial Y_{i'j}} \frac{\partial Y_{i'j}}{\partial X_{ij}} \\ &= \sum_{i'=1}^m A_{i'i} \Lambda_{i'j} &= \sum_{k=1}^m A_{ki} \Lambda_{kj}\end{aligned}$$

$$Y_{ij} = \sum_{k=1}^n A_{ik} X_{kj}$$

$$\Lambda_{ij} = \frac{\partial J}{\partial Y_{ij}}$$

$$\begin{aligned}\frac{\partial J}{\partial A_{ij}} &= \sum_{i',j'} \frac{\partial J}{\partial Y_{i'j'}} \frac{\partial Y_{i'j'}}{\partial A_{ij}} &= \sum_{j'=1}^l \frac{\partial J}{\partial Y_{ij'}} \frac{\partial Y_{ij'}}{\partial A_{ij}} \\ &= \sum_{j'=1}^l \Lambda_{ij'} X_{jj'} &= \sum_{k=1}^l \Lambda_{ik} X_{jk}\end{aligned}$$

$$\frac{\partial J}{\partial A} = \Lambda X^T = \frac{\partial J}{\partial Y} X^T$$





$$\mathbf{y} = \omega(\mathbf{x}) \quad \frac{\partial J}{\partial \mathbf{x}} = \frac{\partial J}{\partial \mathbf{y}} \circ \omega'(\mathbf{x})^T$$

Elementwise function [Backprop]

$$\frac{\partial J^T}{\partial \mathbf{x}} = \frac{\partial J^T}{\partial \mathbf{y}} \circ \omega'(\mathbf{x})$$

$$Y_{m \times n} = \omega(X_{m \times n})$$

$$\frac{\partial J}{\partial Y} = \Lambda_{m \times n}$$

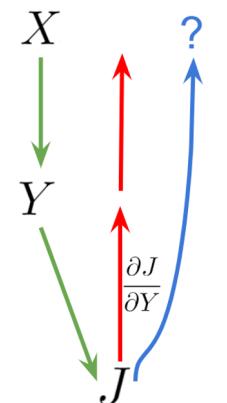
$$Y_{ij} = \omega(X_{ij})$$

$$\Lambda_{ij} = \frac{\partial J}{\partial Y_{ij}}$$

$$\frac{\partial J}{\partial X_{ij}} = \sum_{i',j'} \frac{\partial J}{\partial Y_{i'j'}} \frac{\partial Y_{i'j'}}{\partial X_{ij}}$$

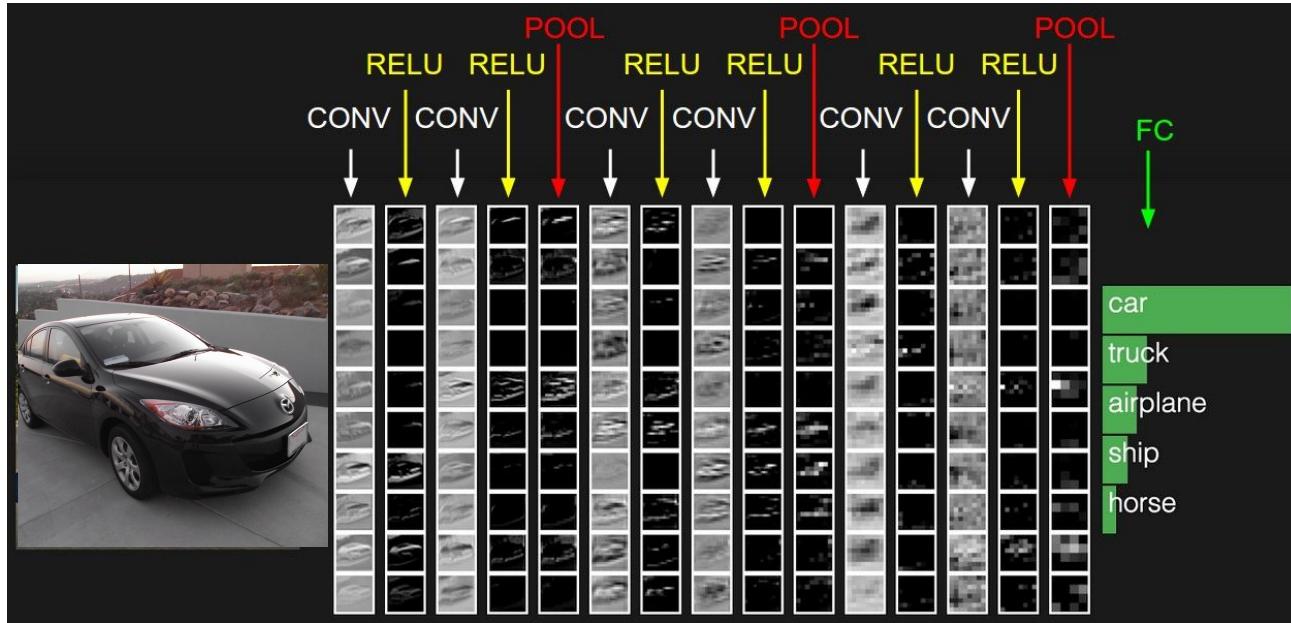
$$= \frac{\partial J}{\partial Y_{ij}} \frac{\partial Y_{ij}}{\partial X_{ij}} = \Lambda_{ij} \omega'(X_{ij})$$

$$\frac{\partial J}{\partial X} = \Lambda \circ \omega'(X) = \frac{\partial J}{\partial Y} \circ \omega'(X)$$



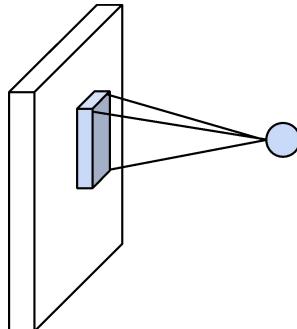
Lecture 6: CNN Architectures

Recap: Convolutional Neural Networks

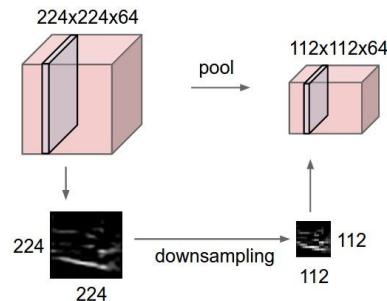


Components of CNNs

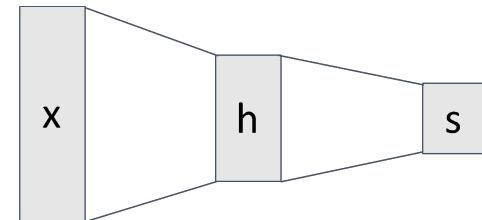
Convolution Layers



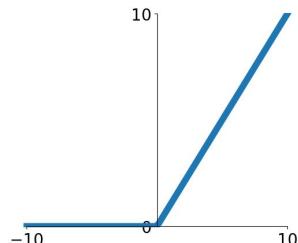
Pooling Layers



Fully-Connected Layers



Activation Function



Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \epsilon}}$$

Batch Normalization

Consider a single layer $y = Wx$

The following could lead to tough optimization:

- Inputs x are not *centered around zero* (need large bias)
- Inputs x have different scaling per-element
(entries in W will need to vary a lot)

Idea: force inputs to be “nicely scaled” at each layer!

Batch Normalization

[Ioffe and Szegedy, 2015]

“you want zero-mean unit-variance activations? just make them so.”

consider a batch of activations at some layer. To make each dimension zero-mean unit-variance, apply:

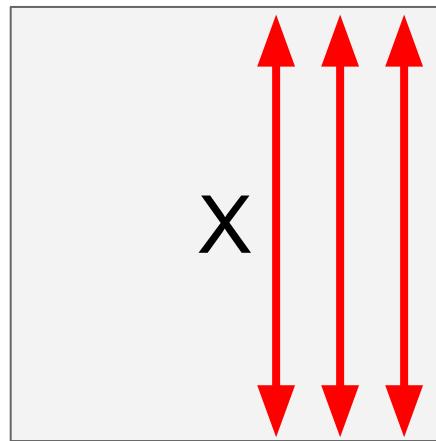
$$\hat{x}^{(k)} = \frac{x^{(k)} - \text{E}[x^{(k)}]}{\sqrt{\text{Var}[x^{(k)}]}}$$

this is a vanilla
differentiable function...

Batch Normalization

[Ioffe and Szegedy, 2015]

Input: $x : N \times D$



$$\mu_j = \frac{1}{N} \sum_{i=1}^N x_{i,j}$$

Per-channel mean,
shape is D

$$\sigma_j^2 = \frac{1}{N} \sum_{i=1}^N (x_{i,j} - \mu_j)^2$$

Per-channel var,
shape is D

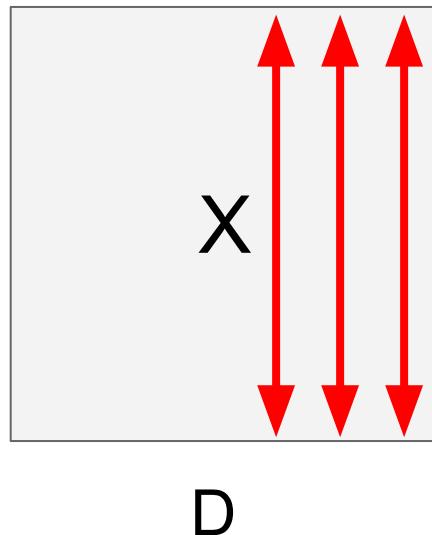
$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Normalized x ,
Shape is $N \times D$

Batch Normalization

[Ioffe and Szegedy, 2015]

Input: $x : N \times D$



$$\mu_j = \frac{1}{N} \sum_{i=1}^N x_{i,j}$$

Per-channel mean,
shape is D

$$\sigma_j^2 = \frac{1}{N} \sum_{i=1}^N (x_{i,j} - \mu_j)^2$$

Per-channel var,
shape is D

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Normalized x,
Shape is $N \times D$

Problem: What if zero-mean, unit variance is too hard of a constraint?

Batch Normalization

[Ioffe and Szegedy, 2015]

Input: $x : N \times D$

$$\mu_j = \frac{1}{N} \sum_{i=1}^N x_{i,j}$$

Per-channel mean,
shape is D

Learnable scale and shift parameters:

$$\gamma, \beta : D$$

$$\sigma_j^2 = \frac{1}{N} \sum_{i=1}^N (x_{i,j} - \mu_j)^2$$

Per-channel var,
shape is D

Learning $\gamma = \sigma$,
 $\beta = \mu$ will recover the identity function!

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Normalized x,
Shape is $N \times D$

$$y_{i,j} = \gamma_j \hat{x}_{i,j} + \beta_j$$

Output,
Shape is $N \times D$

Batch Normalization: Test-Time

Estimates depend on minibatch;
can't do this at test-time!

Input: $x : N \times D$

Learnable scale and shift parameters:

$\gamma, \beta : D$

Learning $\gamma = \sigma$,
 $\beta = \mu$ will recover the identity function!

$$\mu_j = \frac{1}{N} \sum_{i=1}^N x_{i,j}$$

Per-channel mean,
shape is D

$$\sigma_j^2 = \frac{1}{N} \sum_{i=1}^N (x_{i,j} - \mu_j)^2$$

Per-channel var,
shape is D

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Normalized x,
Shape is $N \times D$

$$y_{i,j} = \gamma_j \hat{x}_{i,j} + \beta_j$$

Output,
Shape is $N \times D$

Batch Normalization: Test-Time

Input: $x : N \times D$

$$\mu_j = \text{(Running) average of values seen during training}$$

Per-channel mean,
shape is D

Learnable scale and shift parameters:

$$\gamma, \beta : D$$

$$\sigma_j^2 = \text{(Running) average of values seen during training}$$

Per-channel var,
shape is D

During testing batchnorm becomes a linear operator!
Can be fused with the previous fully-connected or conv layer

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

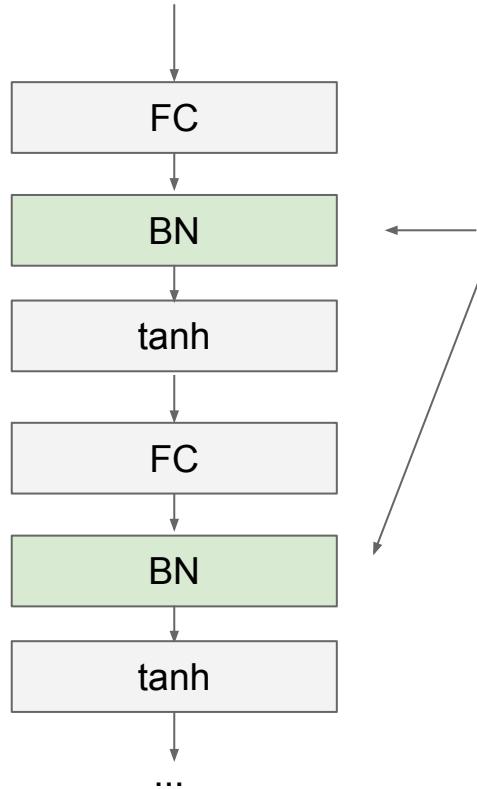
Normalized x,
Shape is N x D

$$y_{i,j} = \gamma_j \hat{x}_{i,j} + \beta_j$$

Output,
Shape is N x D

Batch Normalization

[Ioffe and Szegedy, 2015]

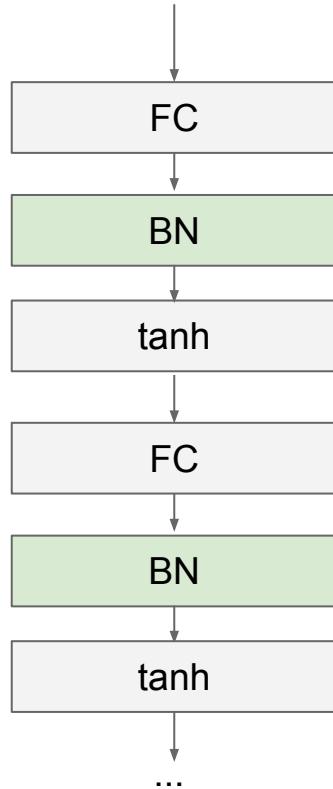


Usually inserted after Fully Connected or Convolutional layers, and before nonlinearity.

$$\hat{x}^{(k)} = \frac{x^{(k)} - \text{E}[x^{(k)}]}{\sqrt{\text{Var}[x^{(k)}]}}$$

Batch Normalization

[Ioffe and Szegedy, 2015]



- Makes deep networks **much** easier to train!
- Improves gradient flow
- Allows higher learning rates, faster convergence
- Networks become more robust to initialization
- Acts as regularization during training
- Zero overhead at test-time: can be fused with conv!
- Behaves differently during training and testing: this is a very common source of bugs!

Batch Normalization for ConvNets

Batch Normalization for
fully-connected networks

$$\begin{aligned}\mathbf{x} &: N \times D \\ \text{Normalize} &\quad \downarrow \\ \boldsymbol{\mu}, \sigma &: 1 \times D \\ \gamma, \beta &: 1 \times D \\ \mathbf{y} &= \gamma(\mathbf{x} - \boldsymbol{\mu}) / \sigma + \beta\end{aligned}$$

Batch Normalization for
convolutional networks
(Spatial Batchnorm, BatchNorm2D)

$$\begin{aligned}\mathbf{x} &: N \times C \times H \times W \\ \text{Normalize} &\quad \downarrow \quad \downarrow \quad \downarrow \\ \boldsymbol{\mu}, \sigma &: 1 \times C \times 1 \times 1 \\ \gamma, \beta &: 1 \times C \times 1 \times 1 \\ \mathbf{y} &= \gamma(\mathbf{x} - \boldsymbol{\mu}) / \sigma + \beta\end{aligned}$$

Layer Normalization

Batch Normalization for
fully-connected networks

Layer Normalization for
fully-connected networks
Same behavior at train and test!
Can be used in recurrent networks

$\mathbf{x}: N \times D$

Normalize



$\mu, \sigma: 1 \times D$

$\gamma, \beta: 1 \times D$

$$\mathbf{y} = \gamma(\mathbf{x} - \boldsymbol{\mu}) / \sigma + \beta$$

$\mathbf{x}: N \times D$

Normalize



$\mu, \sigma: N \times 1$

$\gamma, \beta: 1 \times D$

$$\mathbf{y} = \gamma(\mathbf{x} - \boldsymbol{\mu}) / \sigma + \beta$$

Ba, Kiros, and Hinton, "Layer Normalization", arXiv 2016

Instance Normalization

Batch Normalization for convolutional networks

\mathbf{x} : $N \times C \times H \times W$

Normalize



μ, σ : $1 \times C \times 1 \times 1$

γ, β : $1 \times C \times 1 \times 1$

$$\mathbf{y} = \gamma(\mathbf{x} - \mu) / \sigma + \beta$$

Instance Normalization for convolutional networks
Same behavior at train / test!

\mathbf{x} : $N \times C \times H \times W$

Normalize



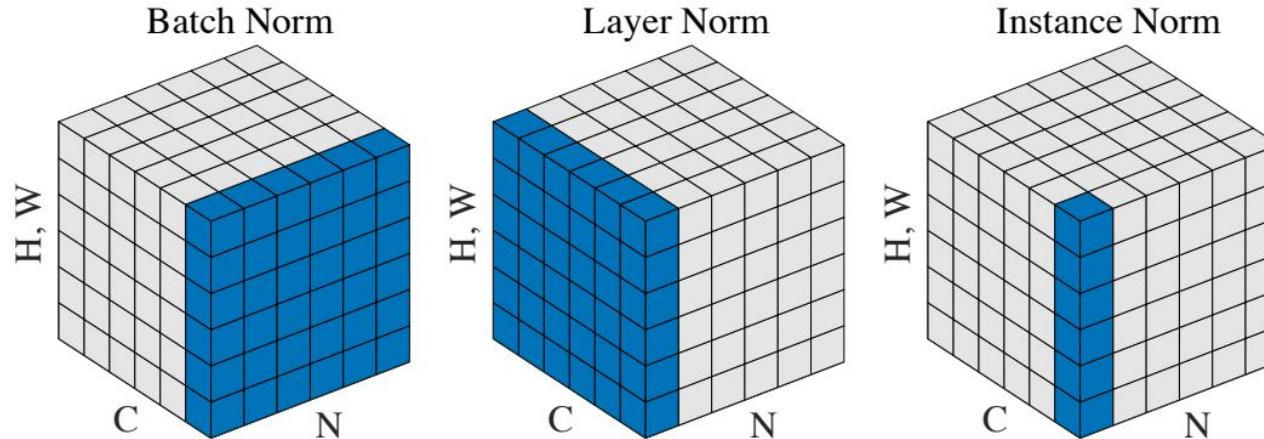
μ, σ : $N \times C \times 1 \times 1$

γ, β : $1 \times C \times 1 \times 1$

$$\mathbf{y} = \gamma(\mathbf{x} - \mu) / \sigma + \beta$$

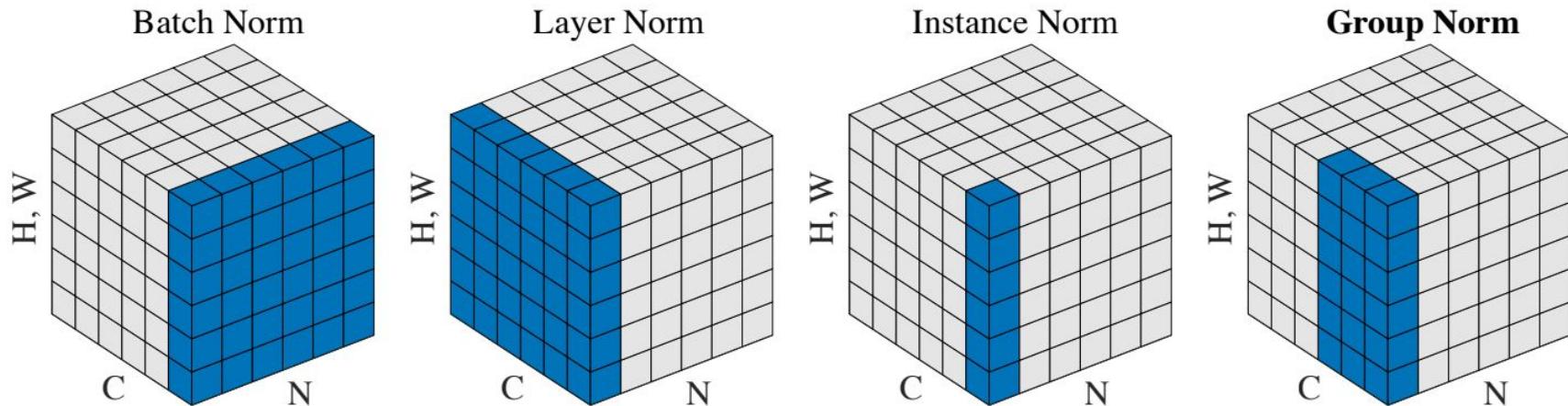
Ulyanov et al, Improved Texture Networks: Maximizing Quality and Diversity in Feed-forward Stylization and Texture Synthesis, CVPR 2017

Comparison of Normalization Layers



Wu and He, "Group Normalization", ECCV 2018

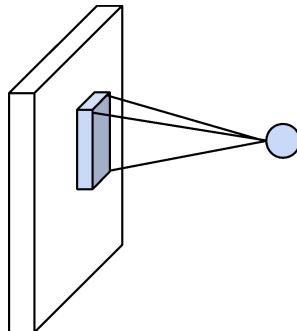
Group Normalization



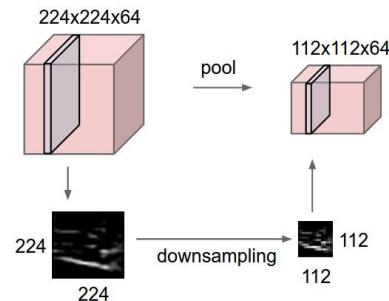
Wu and He, "Group Normalization", ECCV 2018

Components of CNNs

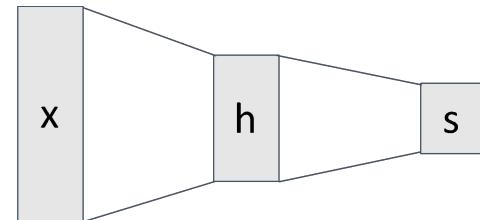
Convolution Layers



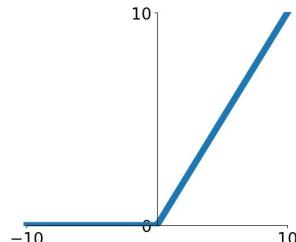
Pooling Layers



Fully-Connected Layers



Activation Function

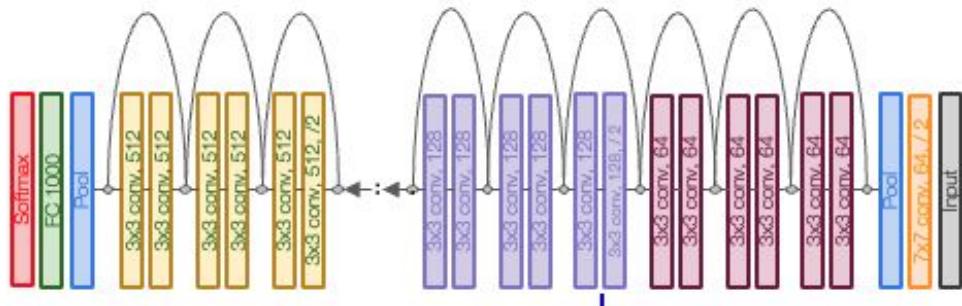
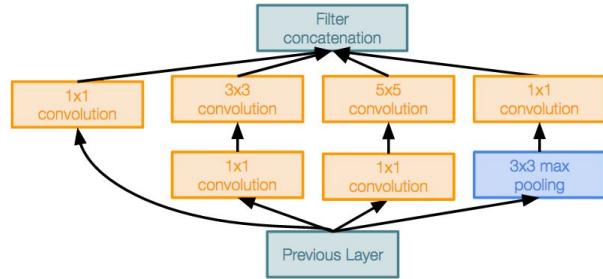
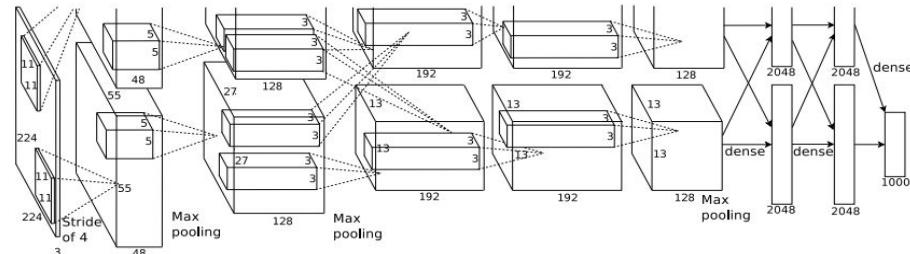
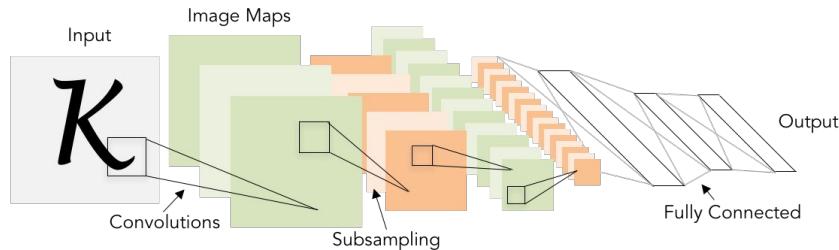


Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \epsilon}}$$

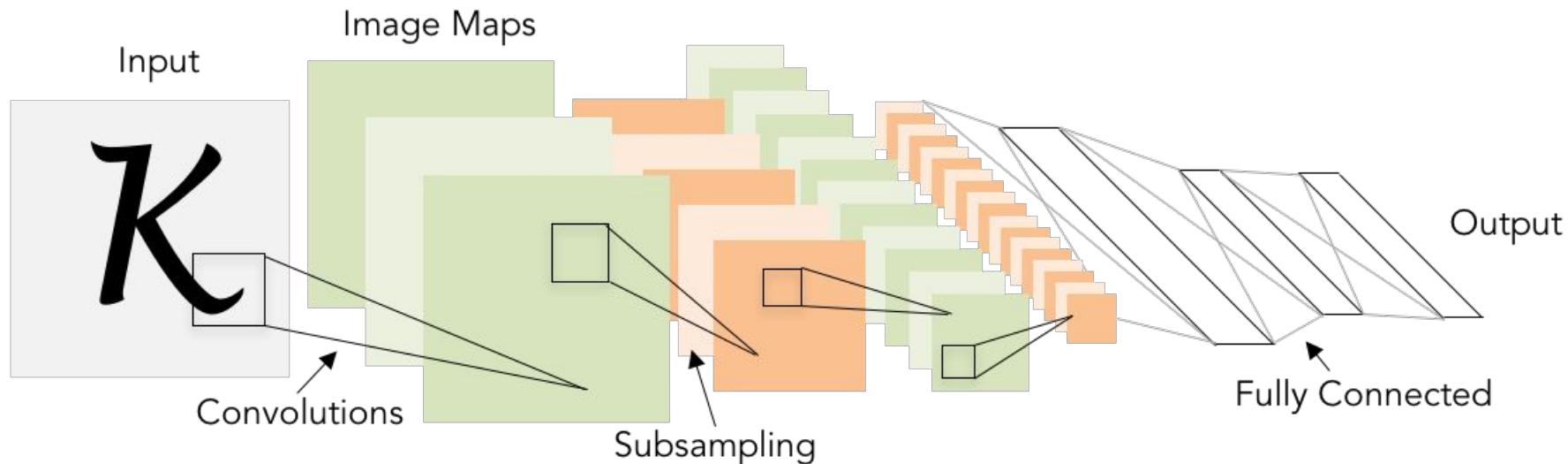
Question: How should we put them together?

Today: CNN Architectures



Review: LeNet-5

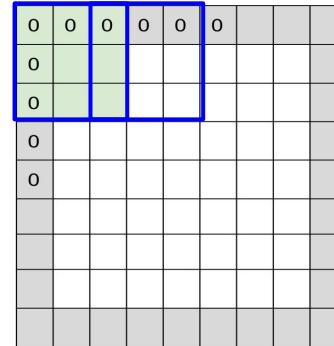
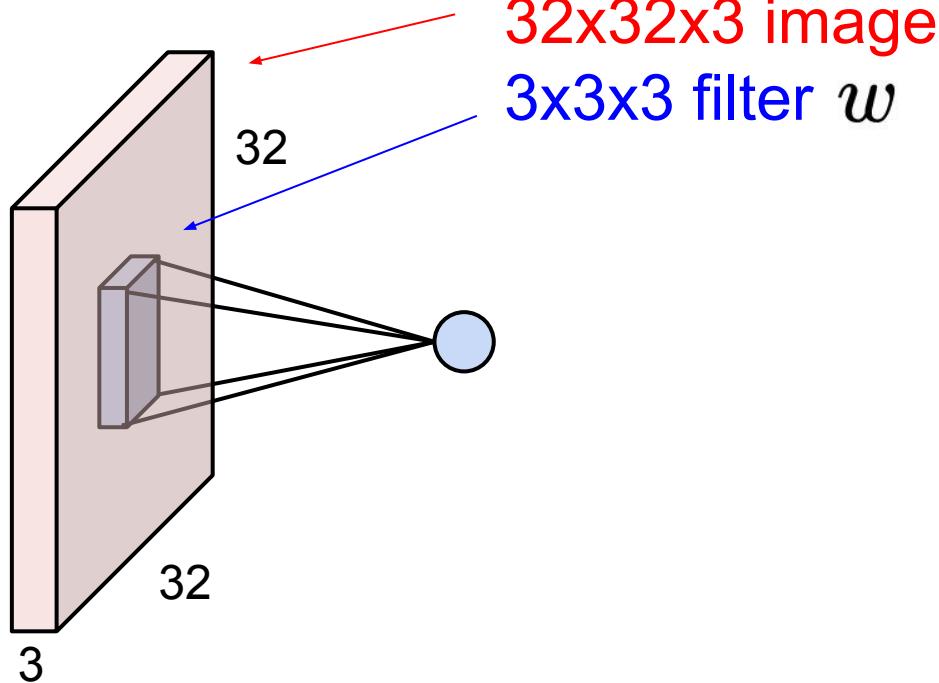
[LeCun et al., 1998]



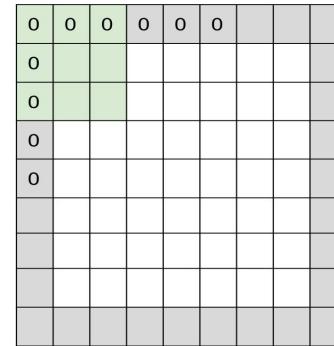
Conv filters were 5x5, applied at stride 1

Subsampling (Pooling) layers were 2x2 applied at stride 2
i.e. architecture is [CONV-POOL-CONV-POOL-FC-FC]

Review: Convolution

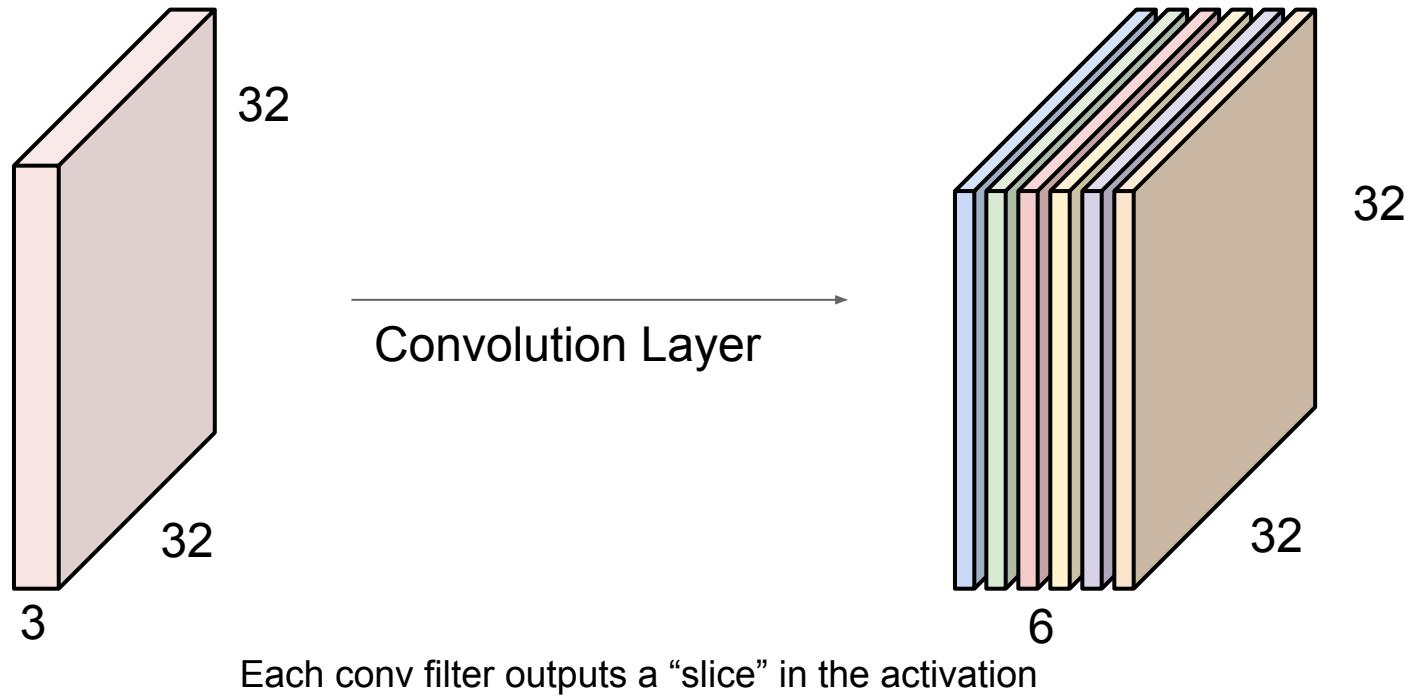


Stride:
Downsample
output activations

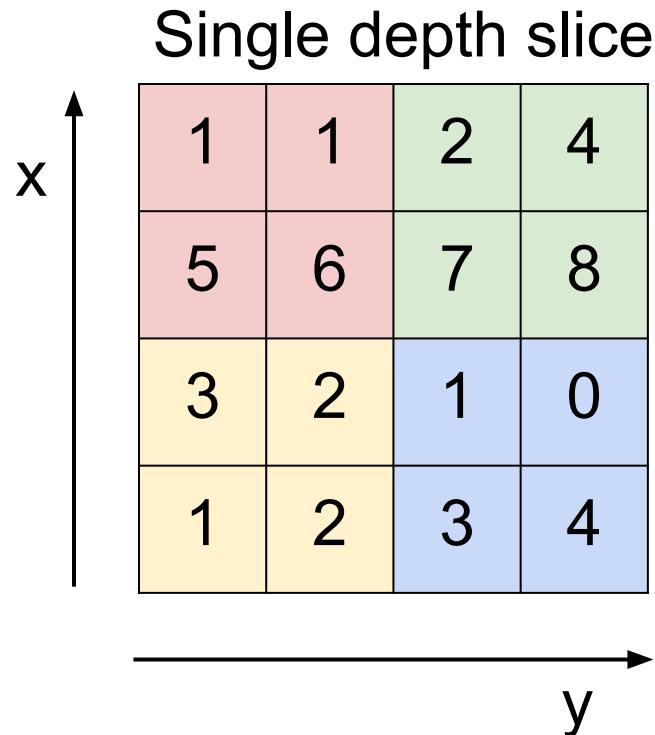


Padding:
Preserve
input spatial
dimensions in
output activations

Review: Convolution



Review: Pooling



max pool with 2x2 filters
and stride 2



6	8
3	4

Today: CNN Architectures

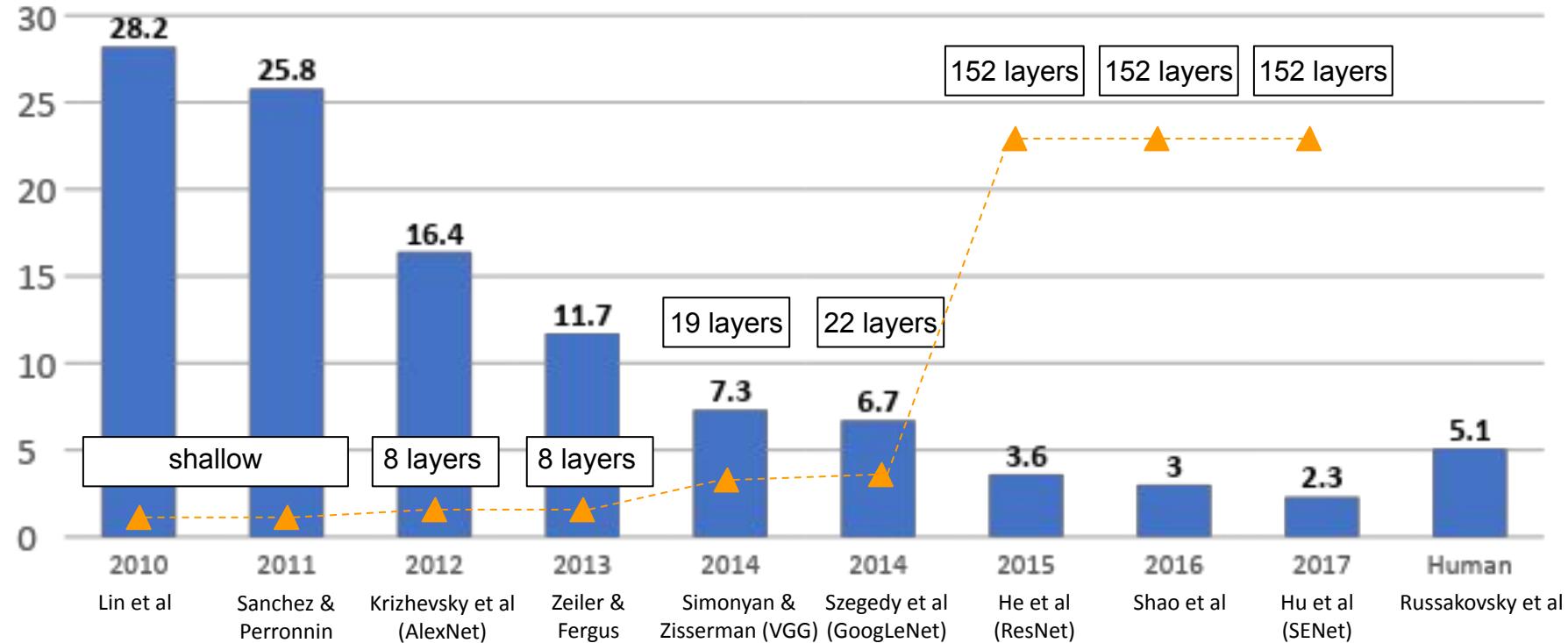
Case Studies

- AlexNet
- VGG
- GoogLeNet
- ResNet

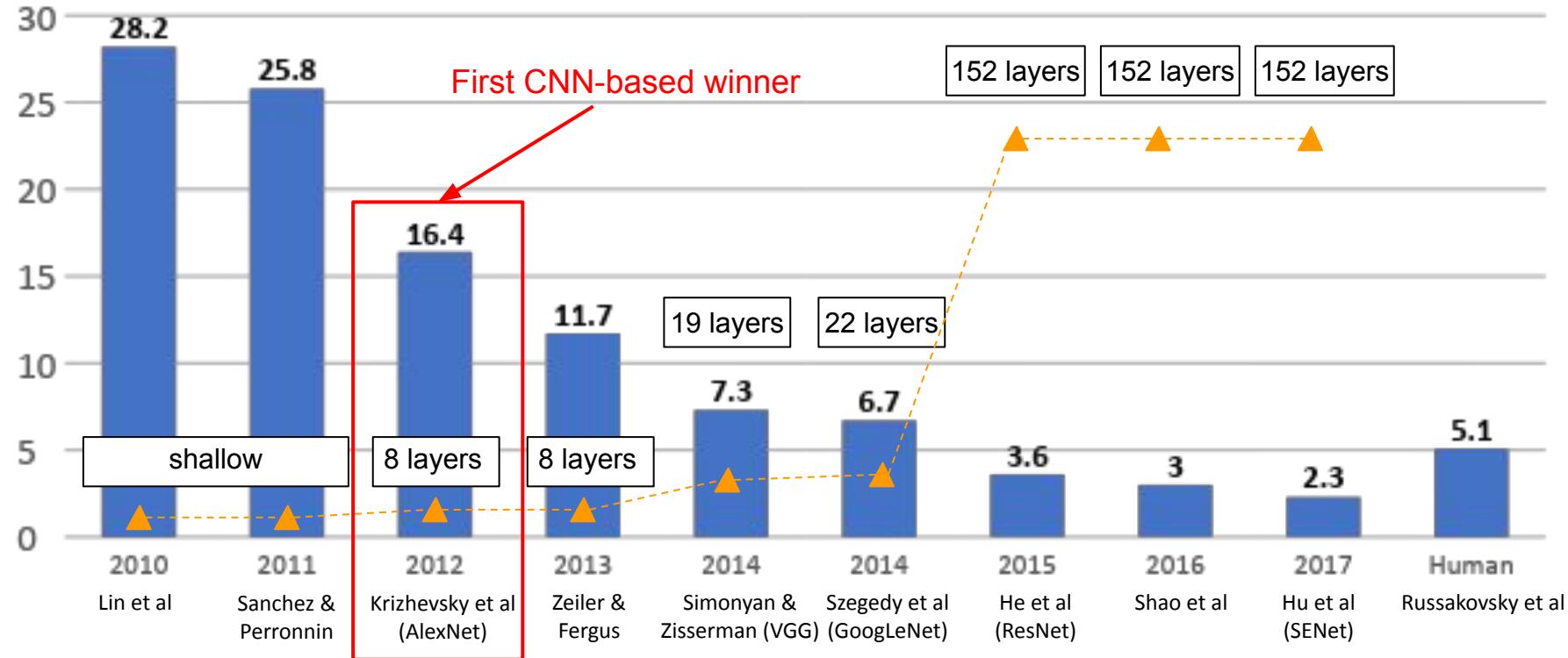
Also....

- SENet
- Wide ResNet
- ResNeXT
- DenseNet
- MobileNets
- NASNet
- EfficientNet

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Case Study: AlexNet

[Krizhevsky et al. 2012]

Architecture:

CONV1

MAX POOL1

NORM1

CONV2

MAX POOL2

NORM2

CONV3

CONV4

CONV5

Max POOL3

FC6

FC7

FC8

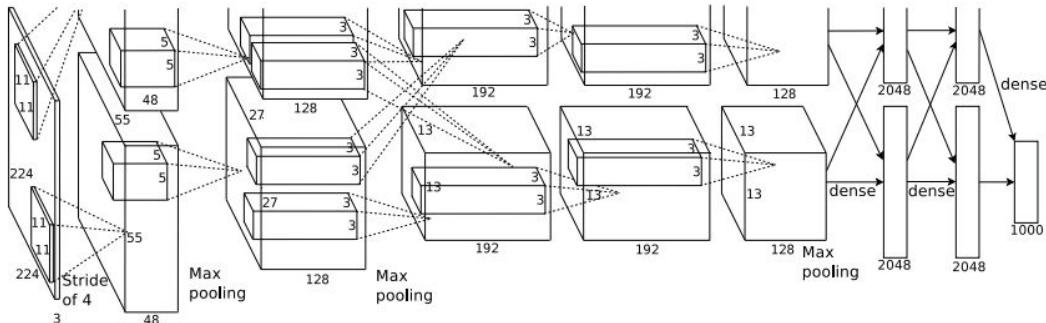
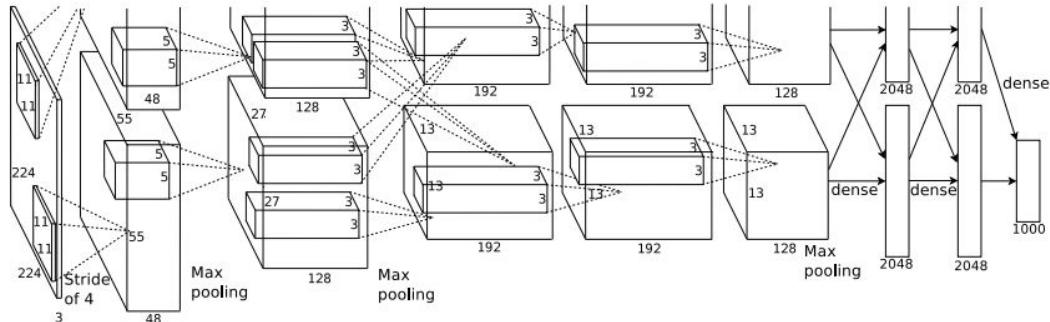


Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

First layer (CONV1): 96 11x11 filters applied at stride 4

=>

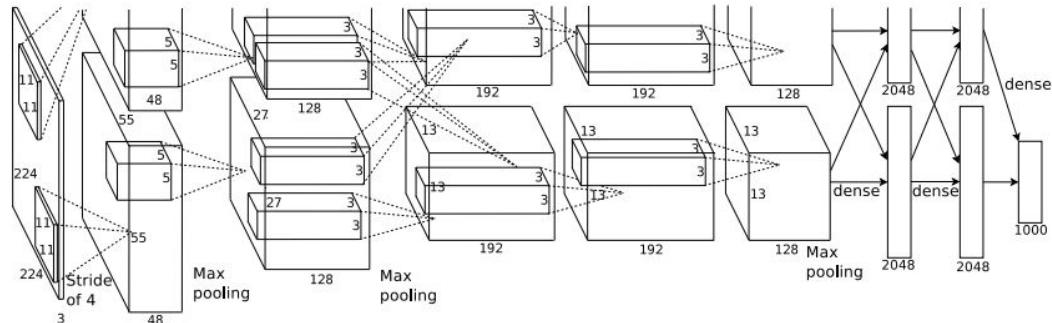
Q: what is the output volume size? Hint: $(227-11)/4+1 = 55$

$$W' = (W - F + 2P) / S + 1$$

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

First layer (CONV1): 96 11x11 filters applied at stride 4

=>

Output volume [55x55x96]

$$W' = (W - F + 2P) / S + 1$$

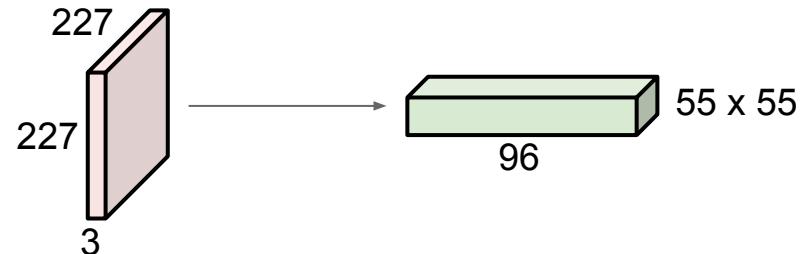
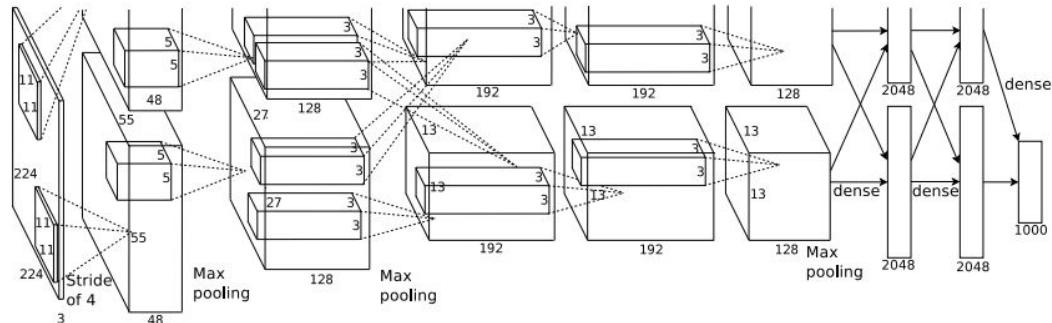


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Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

First layer (CONV1): 96 11x11 filters applied at stride 4

=>

Output volume **[55x55x96]**

Q: What is the total number of parameters in this layer?

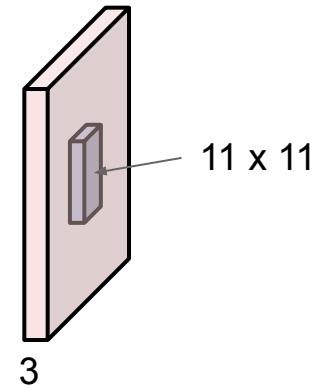
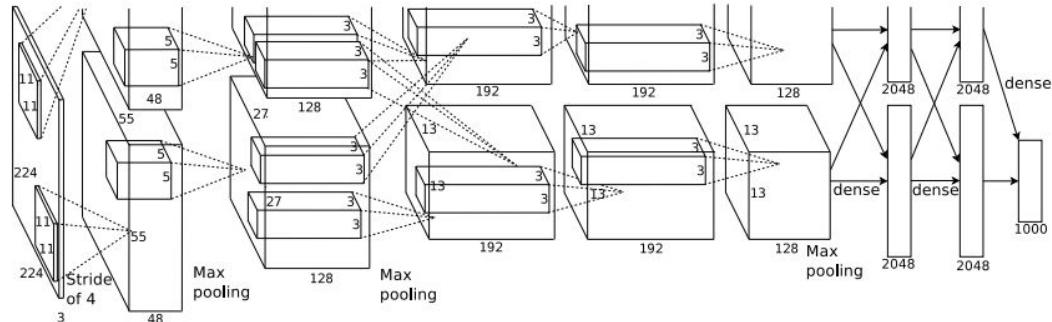


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Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

First layer (CONV1): 96 11x11 filters applied at stride 4

=>

Output volume **[55x55x96]**

Parameters: $(11 \times 11 \times 3 + 1) \times 96 = 35K$

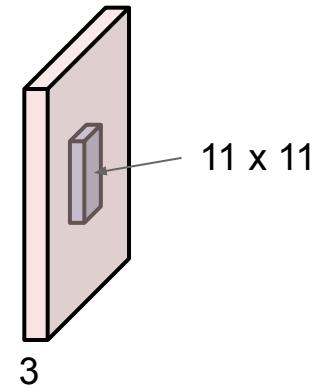
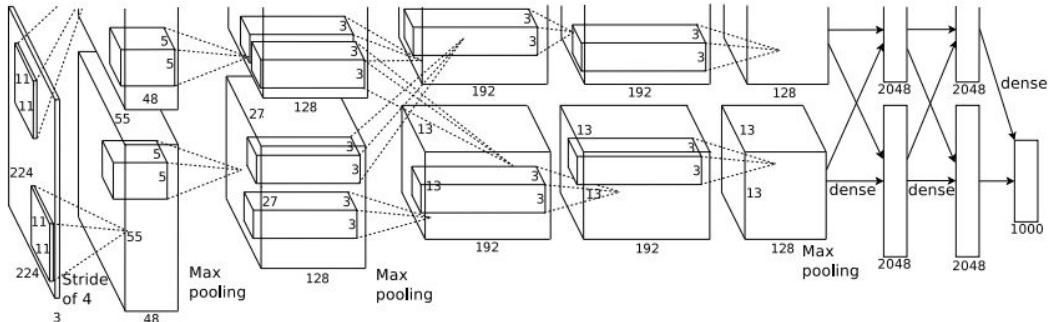


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Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

After CONV1: 55x55x96

$$W' = (W - F + 2P) / S + 1$$

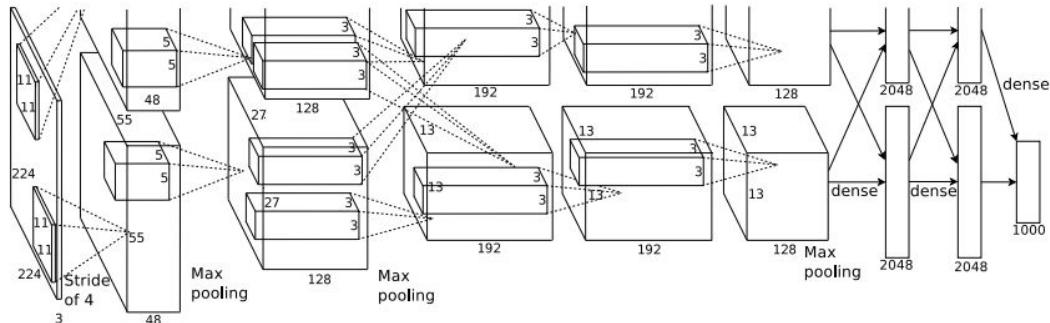
Second layer (POOL1): 3x3 filters applied at stride 2

Q: what is the output volume size? Hint: $(55-3)/2+1 = 27$

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Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

After CONV1: 55x55x96

$$W' = (W - F + 2P) / S + 1$$

Second layer (POOL1): 3x3 filters applied at stride 2

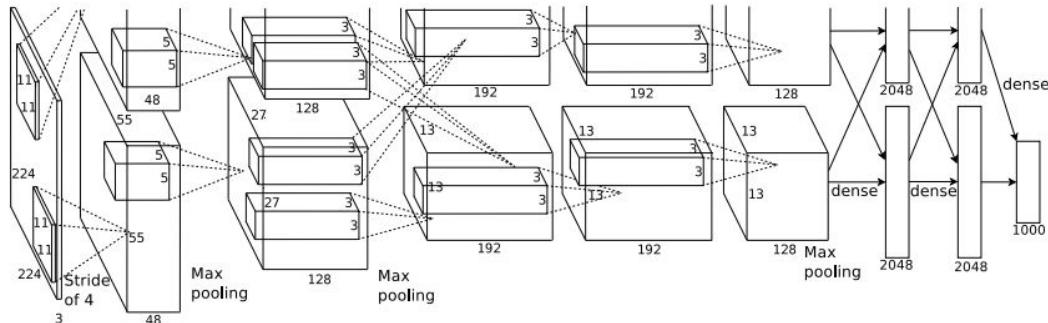
Output volume: 27x27x96

Q: what is the number of parameters in this layer?

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Case Study: AlexNet

[Krizhevsky et al. 2012]



Input: 227x227x3 images

After CONV1: 55x55x96

Second layer (POOL1): 3x3 filters applied at stride 2

Output volume: 27x27x96

Parameters: 0!

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Case Study: AlexNet

[Krizhevsky et al. 2012]

Input: 227x227x3 images

After CONV1: 55x55x96

After POOL1: 27x27x96

...

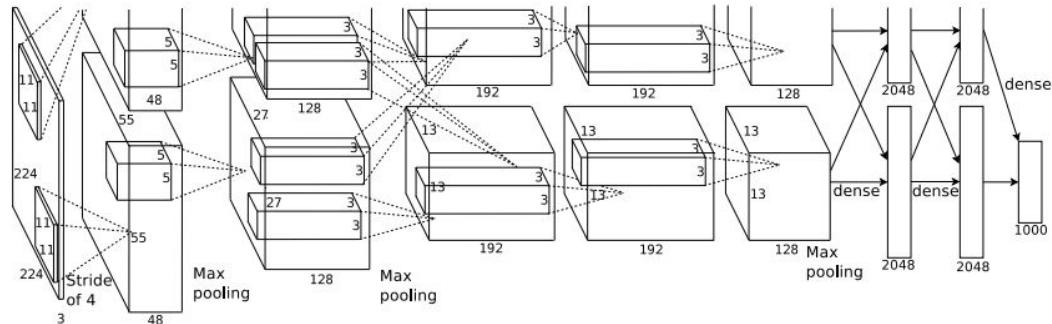


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Case Study: AlexNet

[Krizhevsky et al. 2012]

Full (simplified) AlexNet architecture:

[227x227x3] INPUT

[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0

[27x27x96] MAX POOL1: 3x3 filters at stride 2

[27x27x96] NORM1: Normalization layer

[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2

[13x13x256] MAX POOL2: 3x3 filters at stride 2

[13x13x256] NORM2: Normalization layer

[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1

[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1

[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1

[6x6x256] MAX POOL3: 3x3 filters at stride 2

[4096] FC6: 4096 neurons

[4096] FC7: 4096 neurons

[1000] FC8: 1000 neurons (class scores)

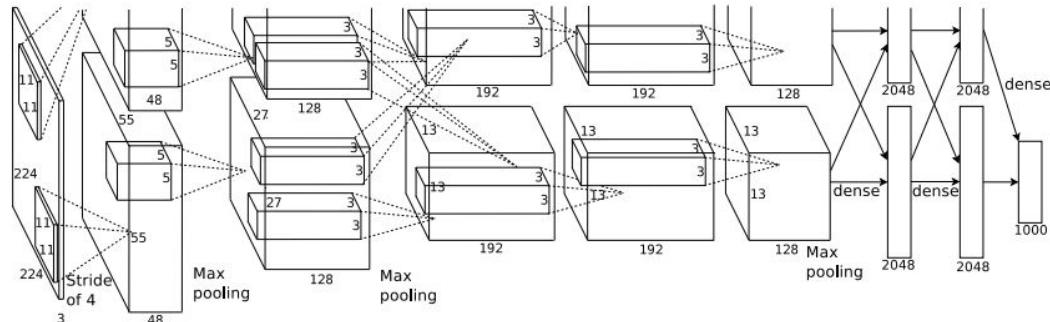


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Case Study: AlexNet

[Krizhevsky et al. 2012]

Full (simplified) AlexNet architecture:

[227x227x3] INPUT

[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0

[27x27x96] MAX POOL1: 3x3 filters at stride 2

[27x27x96] NORM1: Normalization layer

[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2

[13x13x256] MAX POOL2: 3x3 filters at stride 2

[13x13x256] NORM2: Normalization layer

[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1

[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1

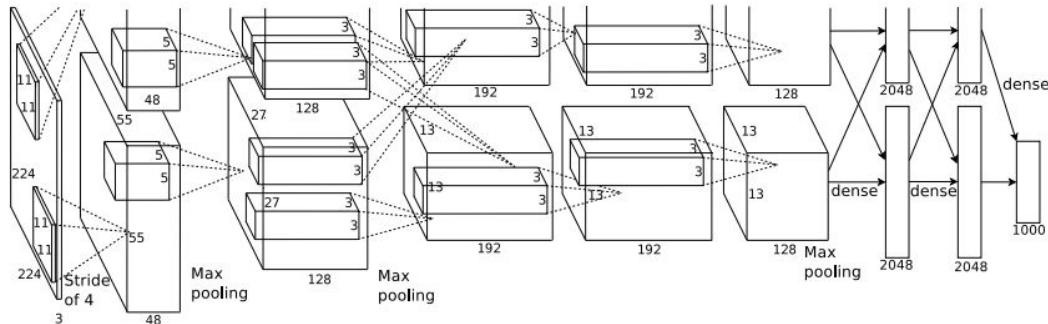
[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1

[6x6x256] MAX POOL3: 3x3 filters at stride 2

[4096] FC6: 4096 neurons

[4096] FC7: 4096 neurons

[1000] FC8: 1000 neurons (class scores)



Details/Retrospectives:

- first use of ReLU
- used LRN layers (not common anymore)
- heavy data augmentation
- dropout 0.5
- batch size 128
- SGD Momentum 0.9
- Learning rate 1e-2, reduced by 10 manually when val accuracy plateaus
- L2 weight decay 5e-4
- 7 CNN ensemble: 18.2% \rightarrow 15.4%

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Case Study: AlexNet

[Krizhevsky et al. 2012]

Full (simplified) AlexNet architecture:

[227x227x3] INPUT

[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0

[27x27x96] MAX POOL1: 3x3 filters at stride 2

[27x27x96] NORM1: Normalization layer

[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2

[13x13x256] MAX POOL2: 3x3 filters at stride 2

[13x13x256] NORM2: Normalization layer

[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1

[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1

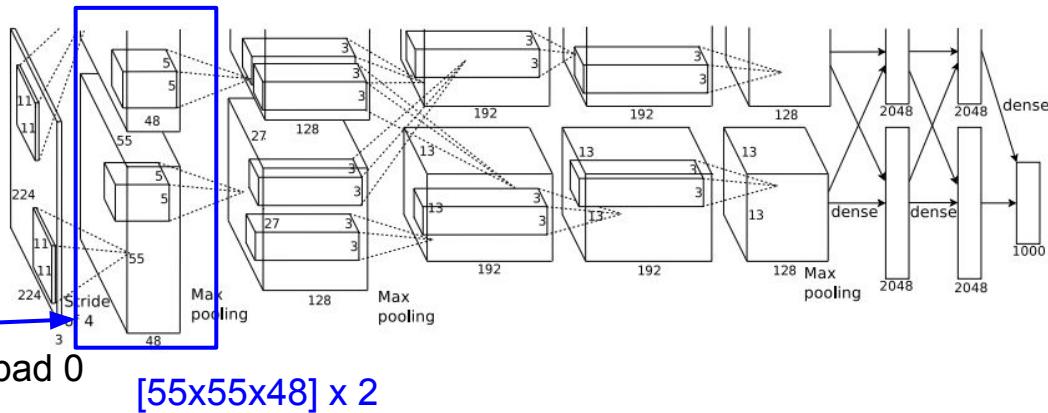
[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1

[6x6x256] MAX POOL3: 3x3 filters at stride 2

[4096] FC6: 4096 neurons

[4096] FC7: 4096 neurons

[1000] FC8: 1000 neurons (class scores)



Historical note: Trained on GTX 580 GPU with only 3 GB of memory.

Network spread across 2 GPUs, half the neurons (feature maps) on each GPU.

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Case Study: AlexNet

[Krizhevsky et al. 2012]

Full (simplified) AlexNet architecture:

[227x227x3] INPUT

[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0

[27x27x96] MAX POOL1: 3x3 filters at stride 2

[27x27x96] NORM1: Normalization layer

[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2

[13x13x256] MAX POOL2: 3x3 filters at stride 2

[13x13x256] NORM2: Normalization layer

[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1

[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1

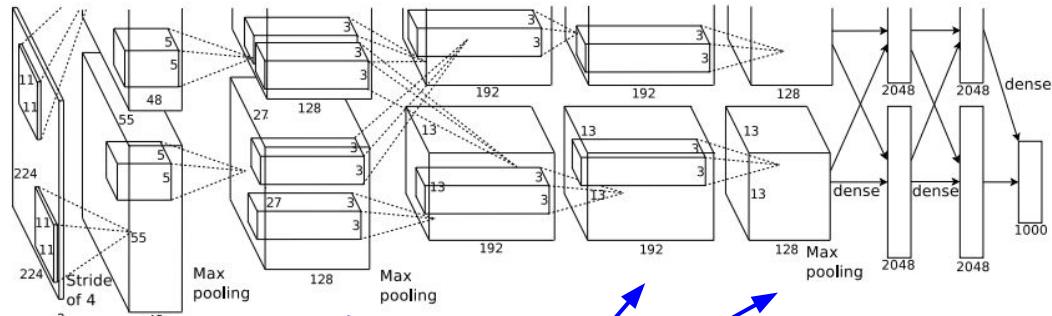
[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1

[6x6x256] MAX POOL3: 3x3 filters at stride 2

[4096] FC6: 4096 neurons

[4096] FC7: 4096 neurons

[1000] FC8: 1000 neurons (class scores)



CONV1, CONV2, CONV4, CONV5:
Connections only with feature maps
on same GPU

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

Case Study: AlexNet

[Krizhevsky et al. 2012]

Full (simplified) AlexNet architecture:

[227x227x3] INPUT

[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0

[27x27x96] MAX POOL1: 3x3 filters at stride 2

[27x27x96] NORM1: Normalization layer

[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2

[13x13x256] MAX POOL2: 3x3 filters at stride 2

[13x13x256] NORM2: Normalization layer

[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1

[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1

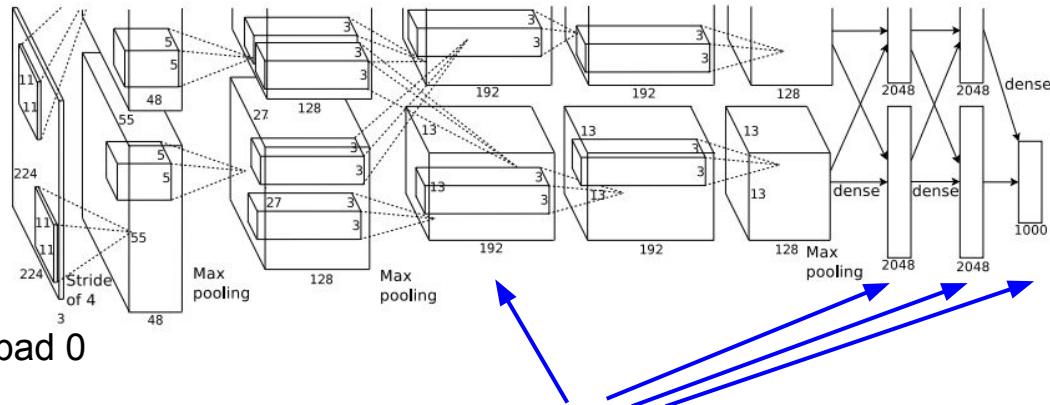
[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1

[6x6x256] MAX POOL3: 3x3 filters at stride 2

[4096] FC6: 4096 neurons

[4096] FC7: 4096 neurons

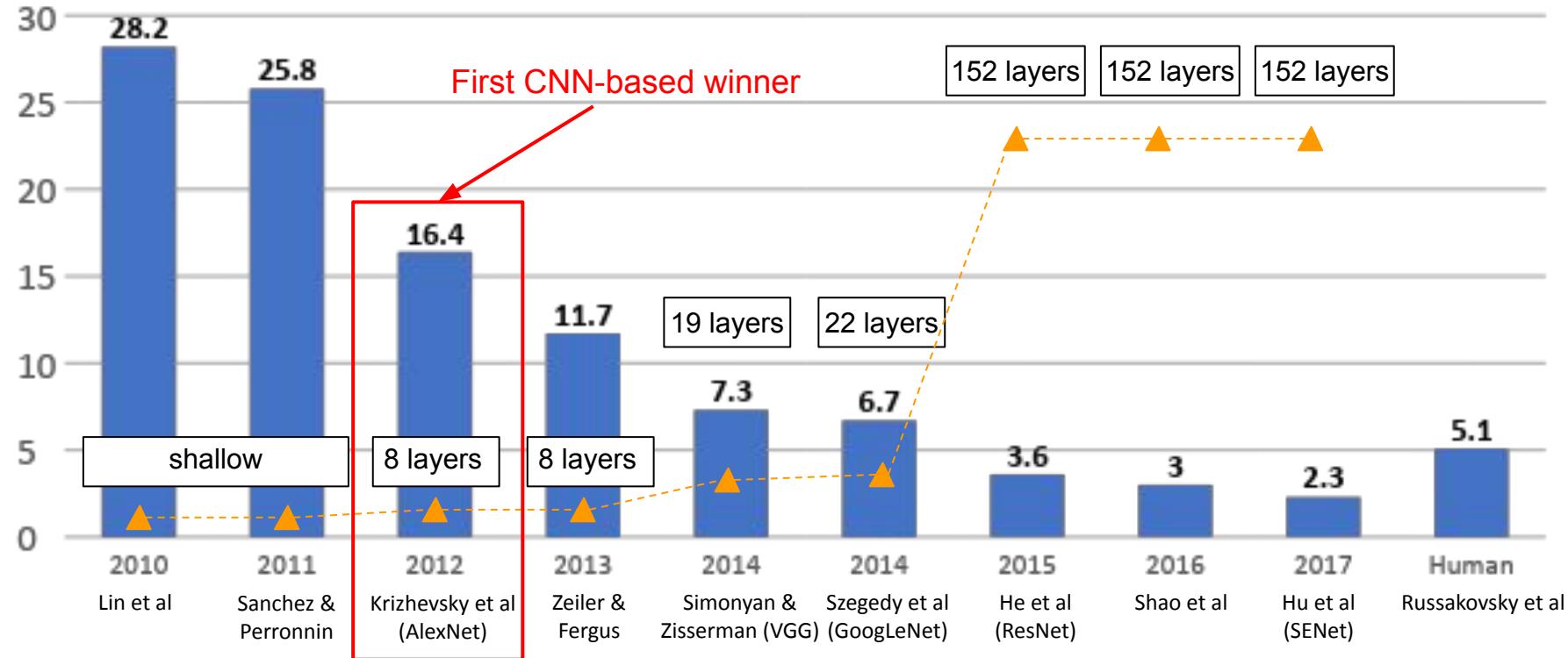
[1000] FC8: 1000 neurons (class scores)



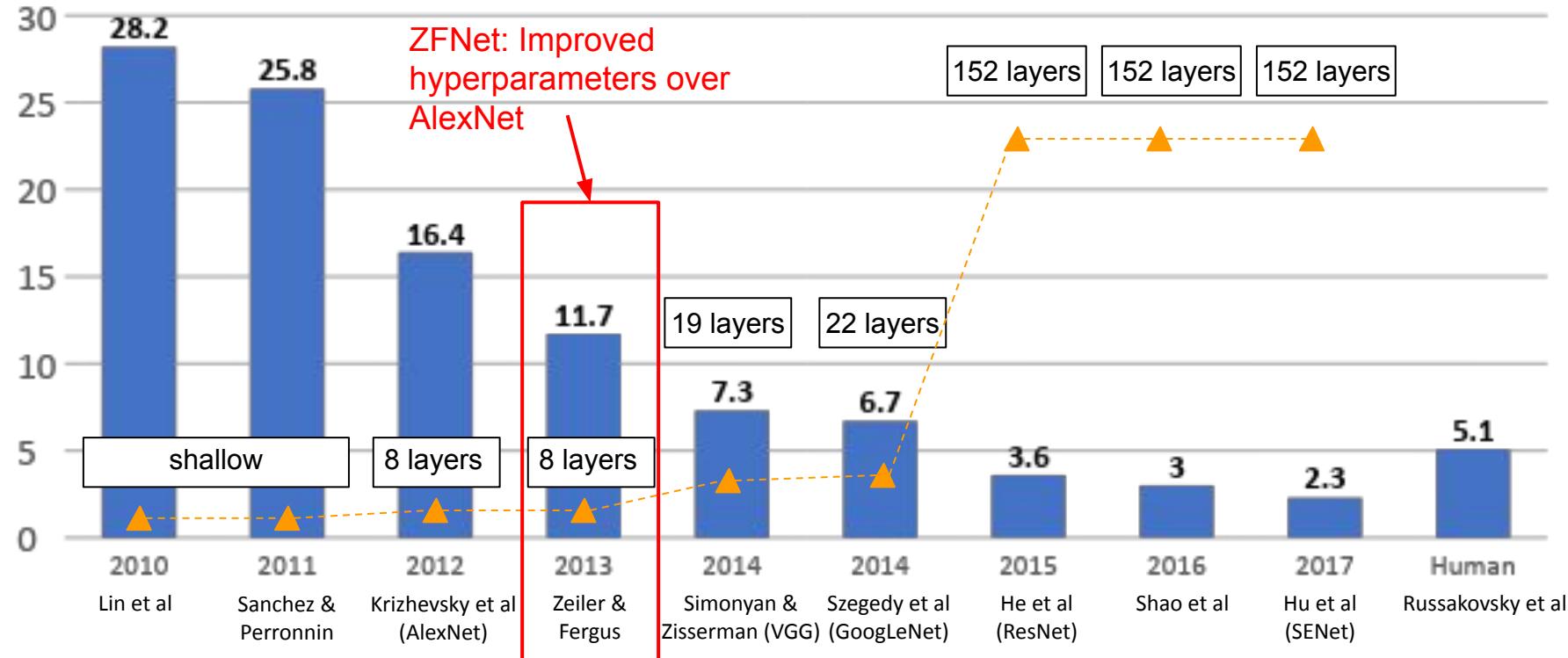
CONV3, FC6, FC7, FC8:
Connections with all feature maps in
preceding layer, communication
across GPUs

Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

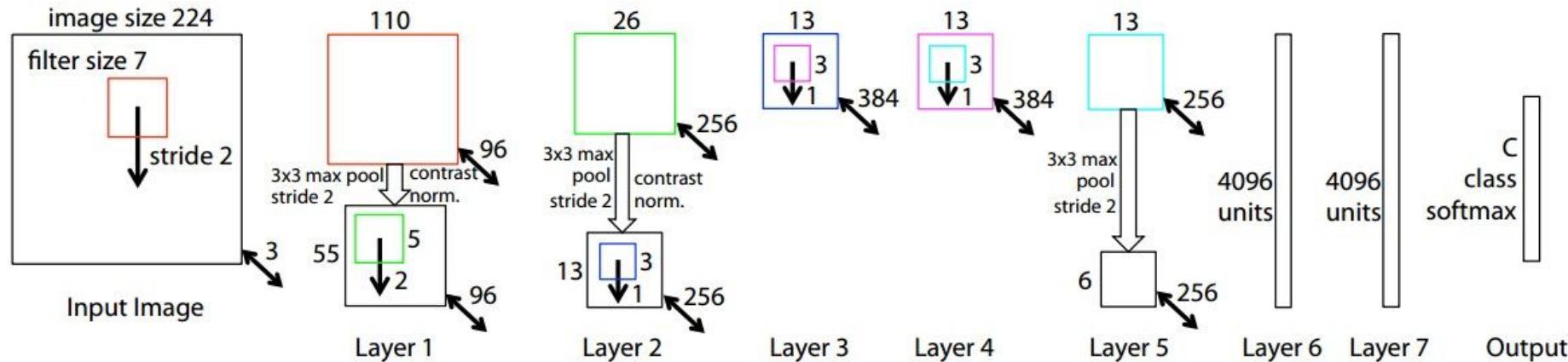


ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



ZFNet

[Zeiler and Fergus, 2013]



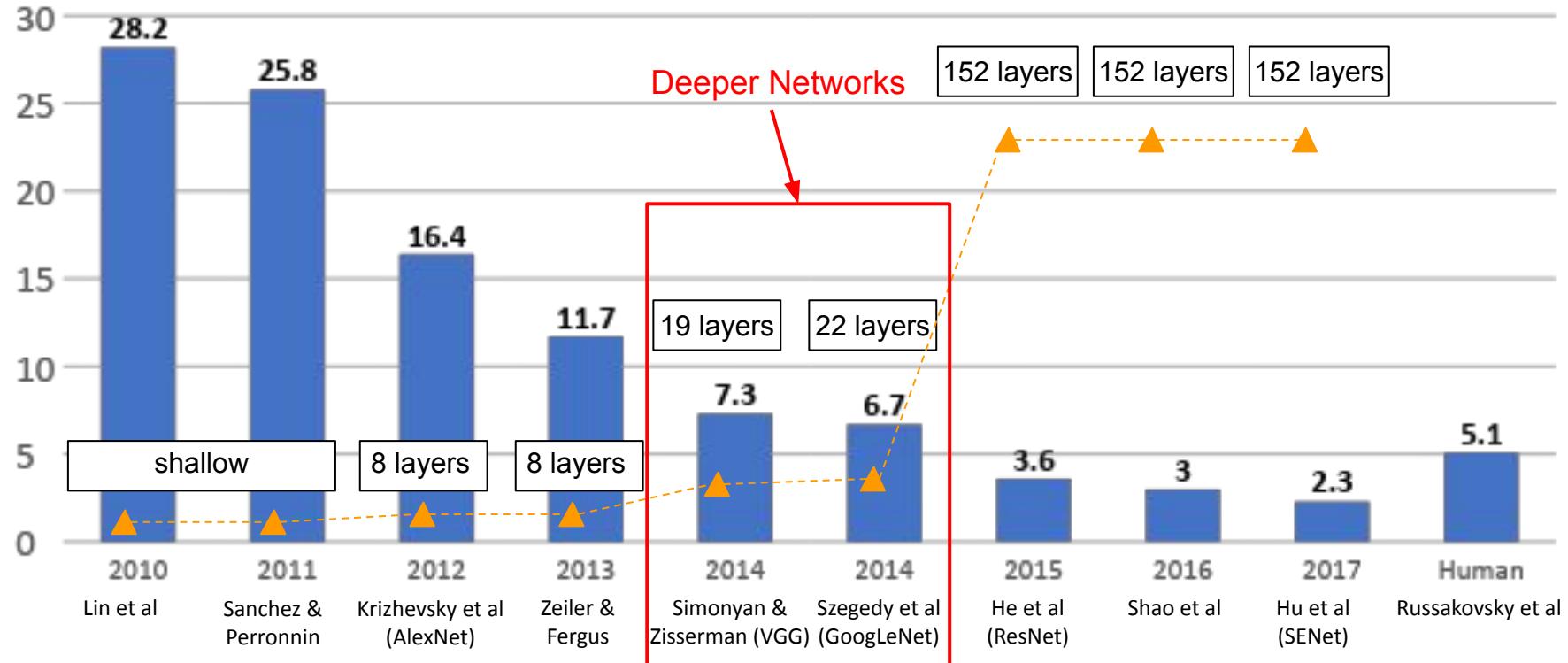
AlexNet but:

CONV1: change from (11x11 stride 4) to (7x7 stride 2)

CONV3,4,5: instead of 384, 384, 256 filters use 512, 1024, 512

ImageNet top 5 error: 16.4% \rightarrow 11.7%

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Case Study: VGGNet

[Simonyan and Zisserman, 2014]

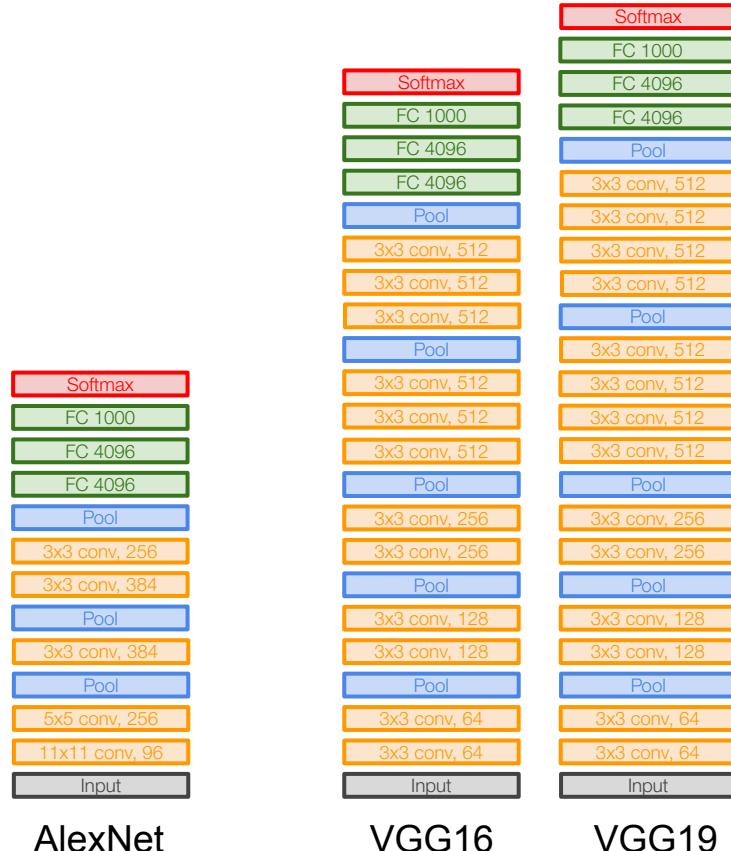
Small filters, Deeper networks

8 layers (AlexNet)

-> 16 - 19 layers (VGG16Net)

Only 3x3 CONV stride 1, pad 1
and 2x2 MAX POOL stride 2

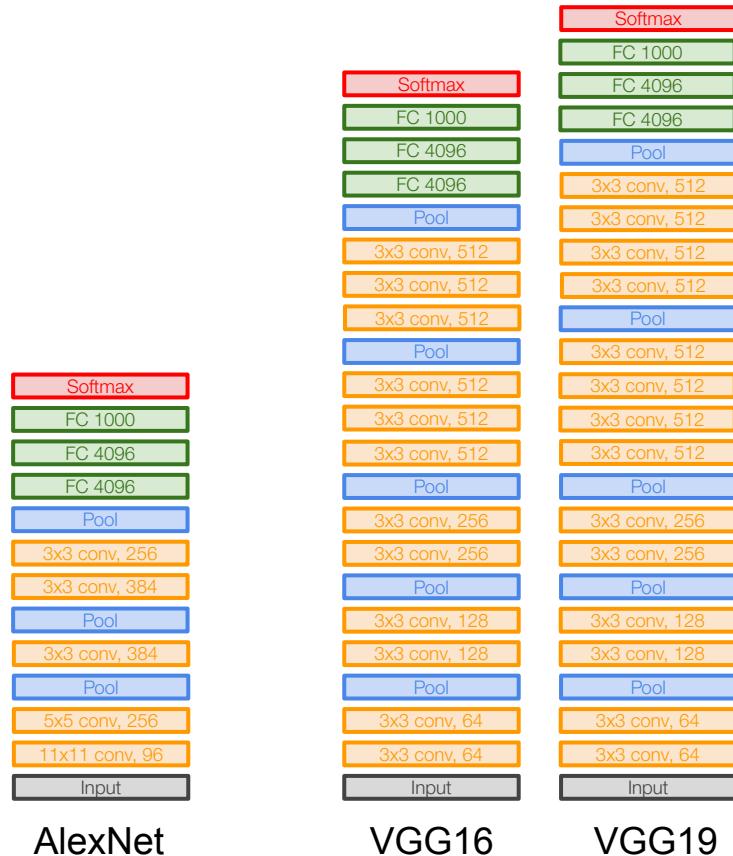
11.7% top 5 error in ILSVRC'13 (ZFNet)
-> 7.3% top 5 error in ILSVRC'14



Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: Why use smaller filters? (3x3 conv)



AlexNet

VGG16

VGG19

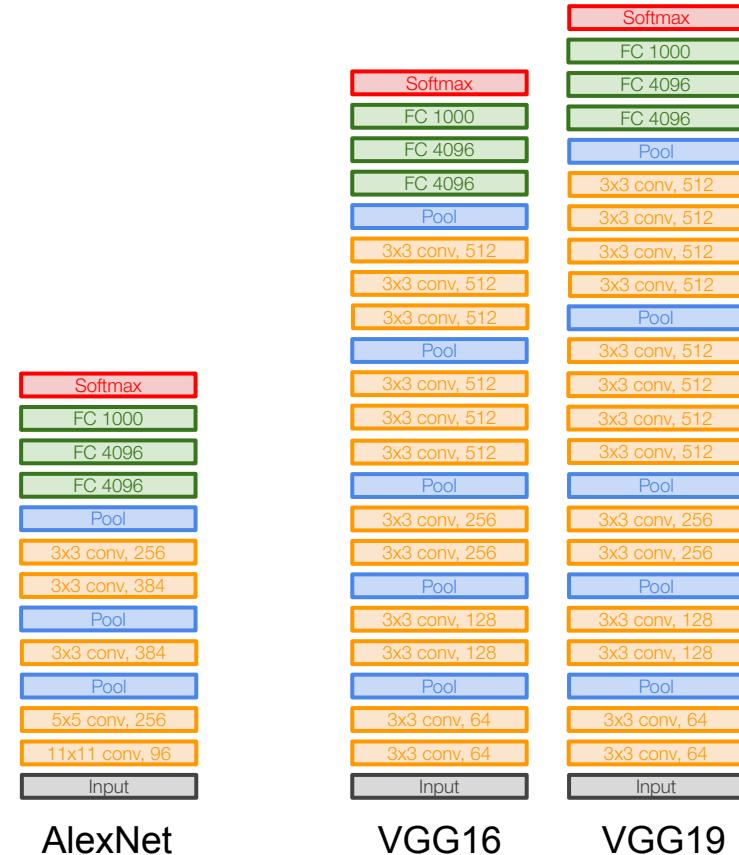
Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: Why use smaller filters? (3x3 conv)

Stack of three 3×3 conv (stride 1) layers
has same **effective receptive field** as
one 7×7 conv layer

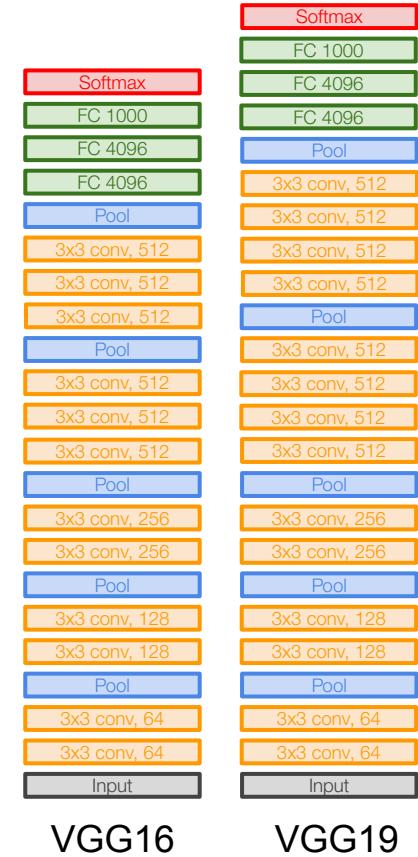
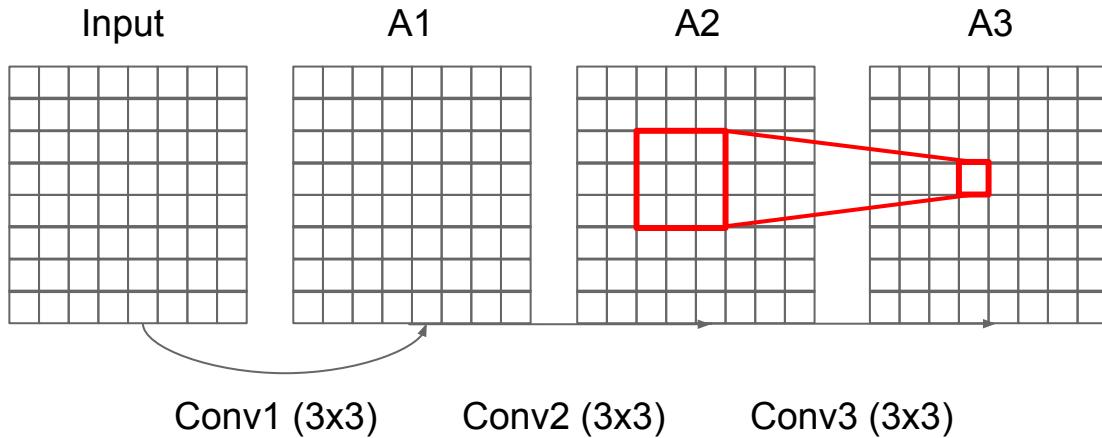
Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



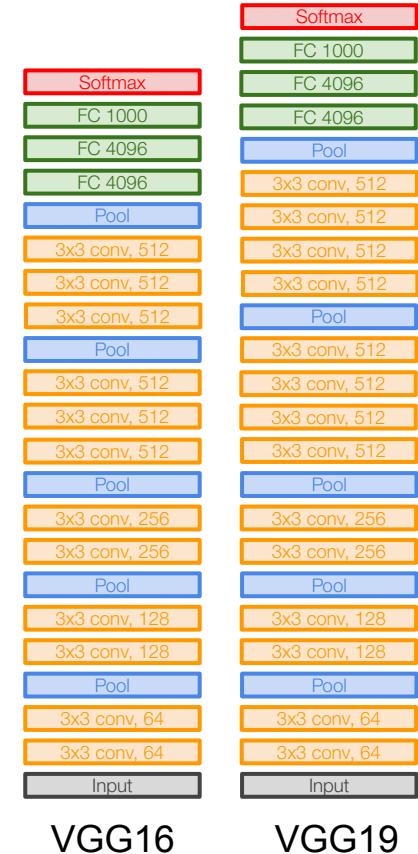
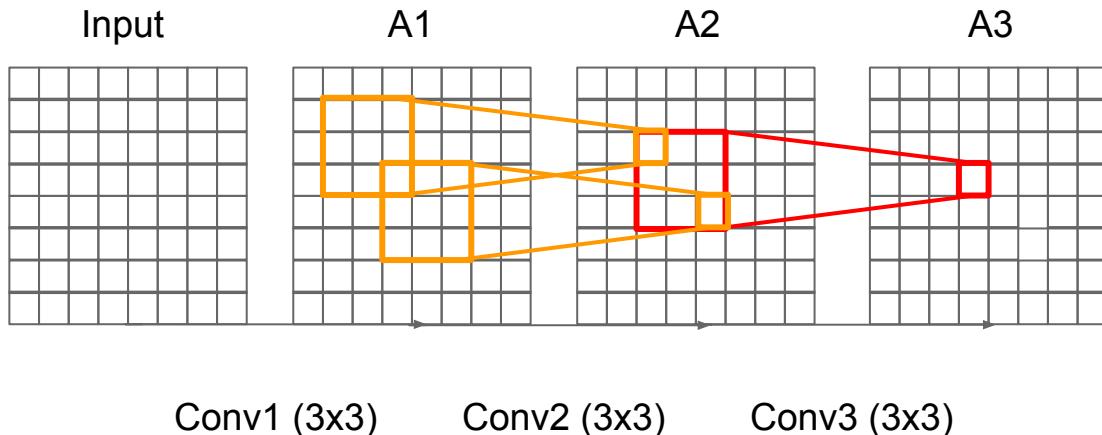
VGG16

VGG19

Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



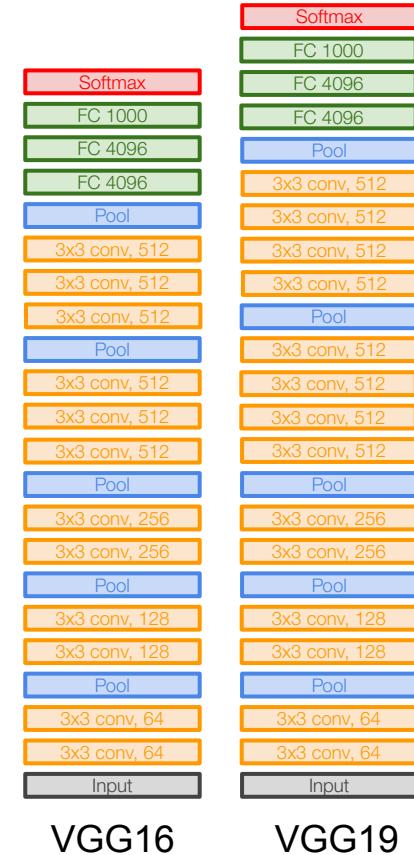
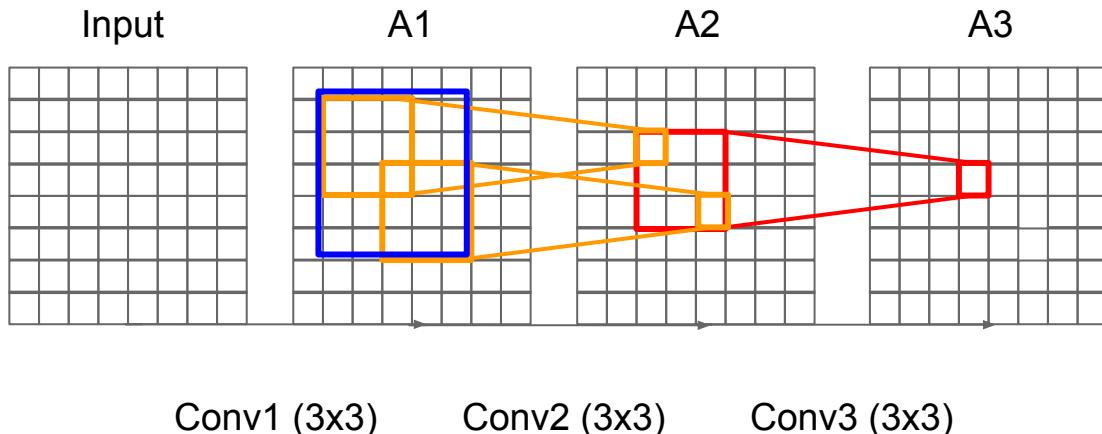
VGG16

VGG19

Case Study: VGGNet

[Simonyan and Zisserman, 2014]

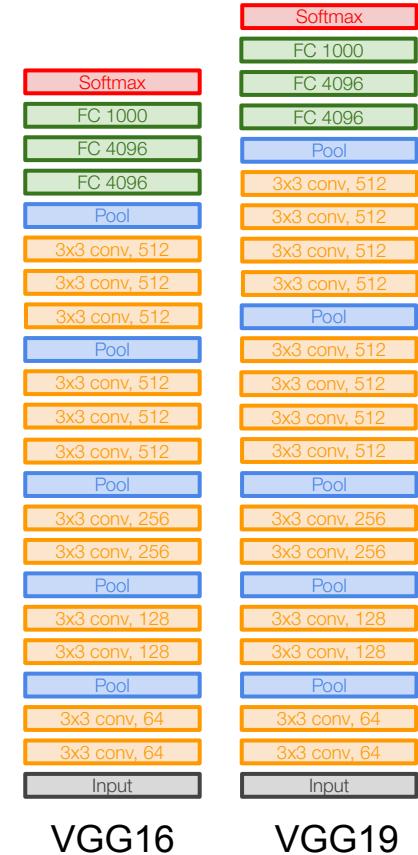
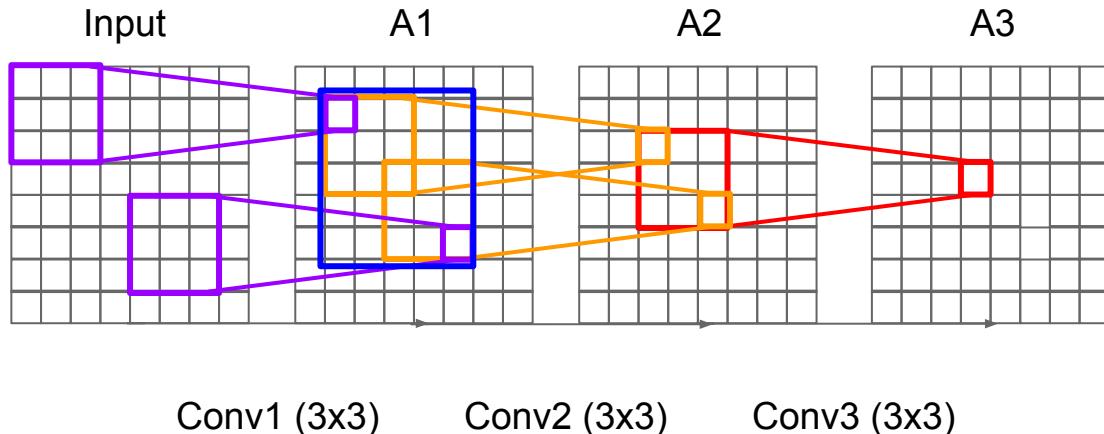
Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



Case Study: VGGNet

[Simonyan and Zisserman, 2014]

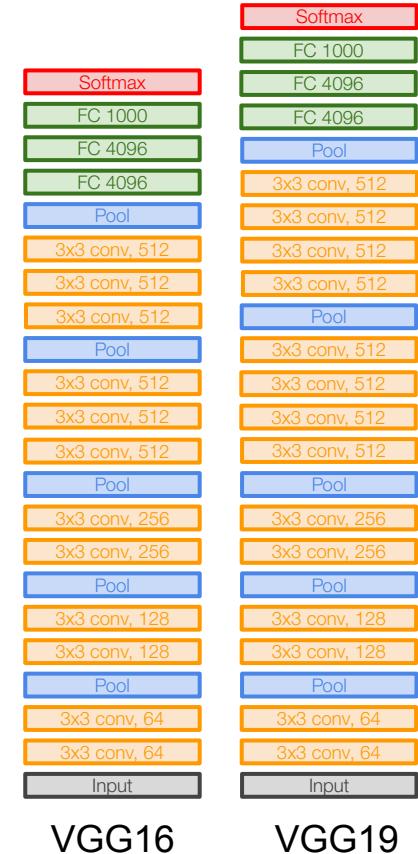
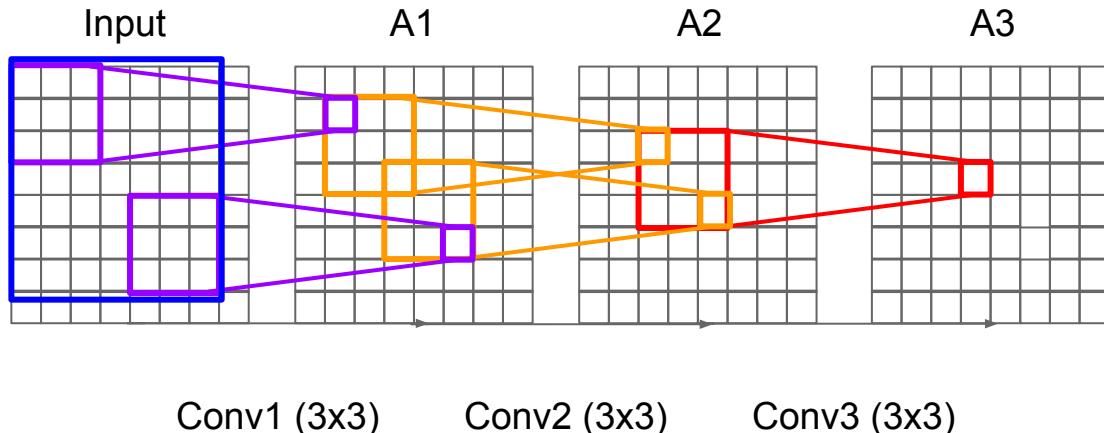
Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: What is the effective receptive field of three 3x3 conv (stride 1) layers?



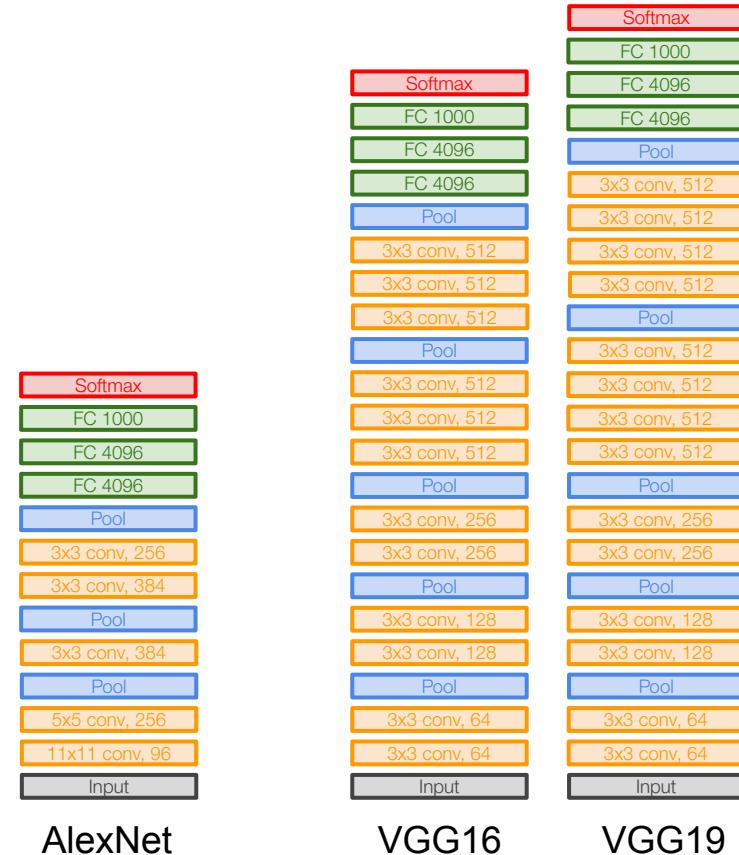
Case Study: VGGNet

[Simonyan and Zisserman, 2014]

Q: Why use smaller filters? (3x3 conv)

Stack of three 3x3 conv (stride 1) layers
has same **effective receptive field** as
one 7x7 conv layer

[7x7]



AlexNet

VGG16

VGG19

Case Study: VGGNet

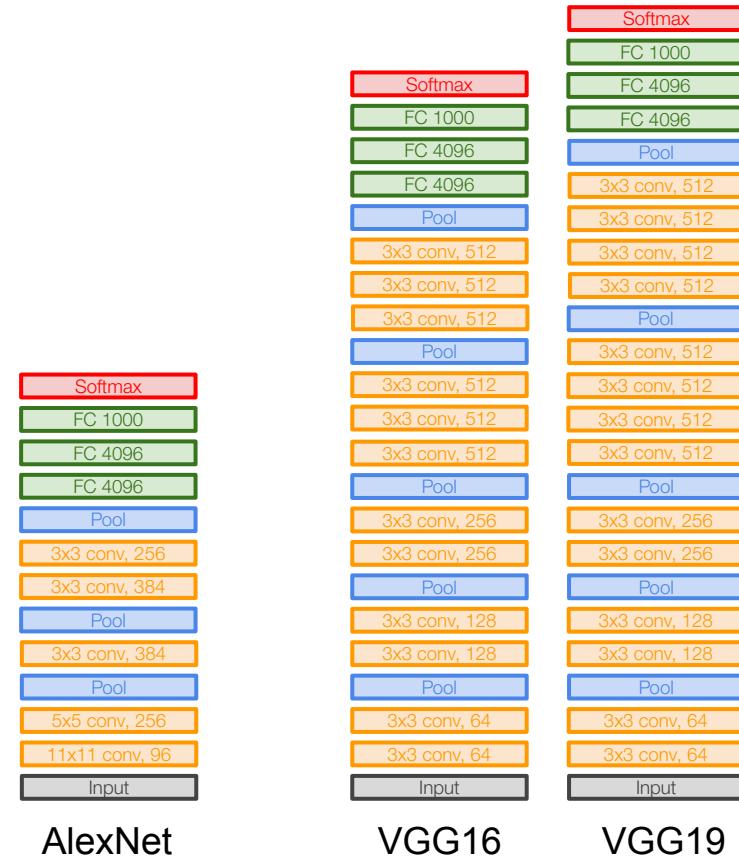
[Simonyan and Zisserman, 2014]

Q: Why use smaller filters? (3x3 conv)

Stack of three 3x3 conv (stride 1) layers
has same **effective receptive field** as
one 7x7 conv layer

But deeper, more non-linearities

And fewer parameters: $3 * (3^2 C^2)$ vs.
 $7^2 C^2$ for C channels per layer



AlexNet

VGG16

VGG19

INPUT: [224x224x3] memory: 224*224*3=150K params: 0 (not counting biases)

CONV3-64: [224x224x64] memory: 224*224*64=3.2M params: (3*3*3)*64 = 1,728

CONV3-64: [224x224x64] memory: 224*224*64=3.2M params: (3*3*64)*64 = 36,864

POOL2: [112x112x64] memory: 112*112*64=800K params: 0

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: (3*3*64)*128 = 73,728

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: (3*3*128)*128 = 147,456

POOL2: [56x56x128] memory: 56*56*128=400K params: 0

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*128)*256 = 294,912

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*256)*256 = 589,824

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*256)*256 = 589,824

POOL2: [28x28x256] memory: 28*28*256=200K params: 0

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*256)*512 = 1,179,648

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*512)*512 = 2,359,296

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*512)*512 = 2,359,296

POOL2: [14x14x512] memory: 14*14*512=100K params: 0

CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

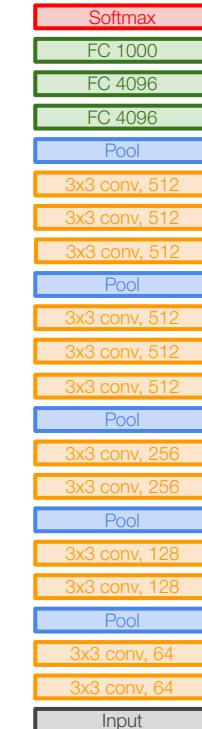
CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

POOL2: [7x7x512] memory: 7*7*512=25K params: 0

FC: [1x1x4096] memory: 4096 params: 7*7*512*4096 = 102,760,448

FC: [1x1x4096] memory: 4096 params: 4096*4096 = 16,777,216

FC: [1x1x1000] memory: 1000 params: 4096*1000 = 4,096,000



VGG16

INPUT: [224x224x3] memory: 224*224*3=150K params: 0 (not counting biases)

CONV3-64: [224x224x64] memory: 224*224*64=3.2M params: (3*3*3)*64 = 1,728

CONV3-64: [224x224x64] memory: 224*224*64=3.2M params: (3*3*64)*64 = 36,864

POOL2: [112x112x64] memory: 112*112*64=800K params: 0

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: (3*3*64)*128 = 73,728

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: (3*3*128)*128 = 147,456

POOL2: [56x56x128] memory: 56*56*128=400K params: 0

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*128)*256 = 294,912

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*256)*256 = 589,824

CONV3-256: [56x56x256] memory: 56*56*256=800K params: (3*3*256)*256 = 589,824

POOL2: [28x28x256] memory: 28*28*256=200K params: 0

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*256)*512 = 1,179,648

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*512)*512 = 2,359,296

CONV3-512: [28x28x512] memory: 28*28*512=400K params: (3*3*512)*512 = 2,359,296

POOL2: [14x14x512] memory: 14*14*512=100K params: 0

CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

CONV3-512: [14x14x512] memory: 14*14*512=100K params: (3*3*512)*512 = 2,359,296

POOL2: [7x7x512] memory: 7*7*512=25K params: 0

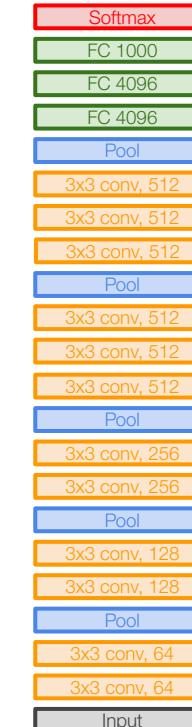
FC: [1x1x4096] memory: 4096 params: 7*7*512*4096 = 102,760,448

FC: [1x1x4096] memory: 4096 params: 4096*4096 = 16,777,216

FC: [1x1x1000] memory: 1000 params: 4096*1000 = 4,096,000

TOTAL memory: 24M * 4 bytes ~= 96MB / image (for a forward pass)

TOTAL params: 138M parameters



VGG16

INPUT: [224x224x3] memory: 224*224*3=150K params: 0 (not counting biases)

CONV3-64: [224x224x64] memory: **224*224*64=3.2M** params: $(3*3*3)*64 = 1,728$

CONV3-64: [224x224x64] memory: **224*224*64=3.2M** params: $(3*3*64)*64 = 36,864$

POOL2: [112x112x64] memory: 112*112*64=800K params: 0

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: $(3*3*64)*128 = 73,728$

CONV3-128: [112x112x128] memory: 112*112*128=1.6M params: $(3*3*128)*128 = 147,456$

POOL2: [56x56x128] memory: 56*56*128=400K params: 0

CONV3-256: [56x56x256] memory: 56*56*256=800K params: $(3*3*128)*256 = 294,912$

CONV3-256: [56x56x256] memory: 56*56*256=800K params: $(3*3*256)*256 = 589,824$

CONV3-256: [56x56x256] memory: 56*56*256=800K params: $(3*3*256)*256 = 589,824$

POOL2: [28x28x256] memory: 28*28*256=200K params: 0

CONV3-512: [28x28x512] memory: 28*28*512=400K params: $(3*3*256)*512 = 1,179,648$

CONV3-512: [28x28x512] memory: 28*28*512=400K params: $(3*3*512)*512 = 2,359,296$

CONV3-512: [28x28x512] memory: 28*28*512=400K params: $(3*3*512)*512 = 2,359,296$

POOL2: [14x14x512] memory: 14*14*512=100K params: 0

CONV3-512: [14x14x512] memory: 14*14*512=100K params: $(3*3*512)*512 = 2,359,296$

CONV3-512: [14x14x512] memory: 14*14*512=100K params: $(3*3*512)*512 = 2,359,296$

CONV3-512: [14x14x512] memory: 14*14*512=100K params: $(3*3*512)*512 = 2,359,296$

POOL2: [7x7x512] memory: 7*7*512=25K params: 0

FC: [1x1x4096] memory: 4096 params: $7*7*512*4096 = \textcolor{red}{102,760,448}$

FC: [1x1x4096] memory: 4096 params: $4096*4096 = 16,777,216$

FC: [1x1x1000] memory: 1000 params: $4096*1000 = 4,096,000$

Note:

Most memory is in early CONV

Most params are in late FC

TOTAL memory: 24M * 4 bytes ~ 96MB / image (only forward! ~*2 for bwd)

TOTAL params: 138M parameters

INPUT: [224x224x3] memory: $224 \times 224 \times 3 = 150K$ params: 0 (not counting biases)

CONV3-64: [224x224x64] memory: $224 \times 224 \times 64 = 3.2M$ params: $(3 \times 3 \times 3) \times 64 = 1,728$

CONV3-64: [224x224x64] memory: $224 \times 224 \times 64 = 3.2M$ params: $(3 \times 3 \times 64) \times 64 = 36,864$

POOL2: [112x112x64] memory: $112 \times 112 \times 64 = 800K$ params: 0

CONV3-128: [112x112x128] memory: $112 \times 112 \times 128 = 1.6M$ params: $(3 \times 3 \times 64) \times 128 = 73,728$

CONV3-128: [112x112x128] memory: $112 \times 112 \times 128 = 1.6M$ params: $(3 \times 3 \times 128) \times 128 = 147,456$

POOL2: [56x56x128] memory: $56 \times 56 \times 128 = 400K$ params: 0

CONV3-256: [56x56x256] memory: $56 \times 56 \times 256 = 800K$ params: $(3 \times 3 \times 128) \times 256 = 294,912$

CONV3-256: [56x56x256] memory: $56 \times 56 \times 256 = 800K$ params: $(3 \times 3 \times 256) \times 256 = 589,824$

CONV3-256: [56x56x256] memory: $56 \times 56 \times 256 = 800K$ params: $(3 \times 3 \times 256) \times 256 = 589,824$

POOL2: [28x28x256] memory: $28 \times 28 \times 256 = 200K$ params: 0

CONV3-512: [28x28x512] memory: $28 \times 28 \times 512 = 400K$ params: $(3 \times 3 \times 256) \times 512 = 1,179,648$

CONV3-512: [28x28x512] memory: $28 \times 28 \times 512 = 400K$ params: $(3 \times 3 \times 512) \times 512 = 2,359,296$

CONV3-512: [28x28x512] memory: $28 \times 28 \times 512 = 400K$ params: $(3 \times 3 \times 512) \times 512 = 2,359,296$

POOL2: [14x14x512] memory: $14 \times 14 \times 512 = 100K$ params: 0

CONV3-512: [14x14x512] memory: $14 \times 14 \times 512 = 100K$ params: $(3 \times 3 \times 512) \times 512 = 2,359,296$

CONV3-512: [14x14x512] memory: $14 \times 14 \times 512 = 100K$ params: $(3 \times 3 \times 512) \times 512 = 2,359,296$

CONV3-512: [14x14x512] memory: $14 \times 14 \times 512 = 100K$ params: $(3 \times 3 \times 512) \times 512 = 2,359,296$

POOL2: [7x7x512] memory: $7 \times 7 \times 512 = 25K$ params: 0

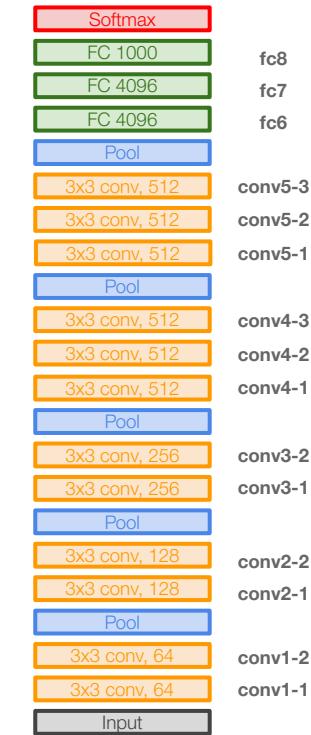
FC: [1x1x4096] memory: 4096 params: $7 \times 7 \times 512 \times 4096 = 102,760,448$

FC: [1x1x4096] memory: 4096 params: $4096 \times 4096 = 16,777,216$

FC: [1x1x1000] memory: 1000 params: $4096 \times 1000 = 4,096,000$

TOTAL memory: $24M \times 4 \text{ bytes} \approx 96\text{MB} / \text{image}$ (only forward! ~ 2 for bwd)

TOTAL params: 138M parameters



VGG16

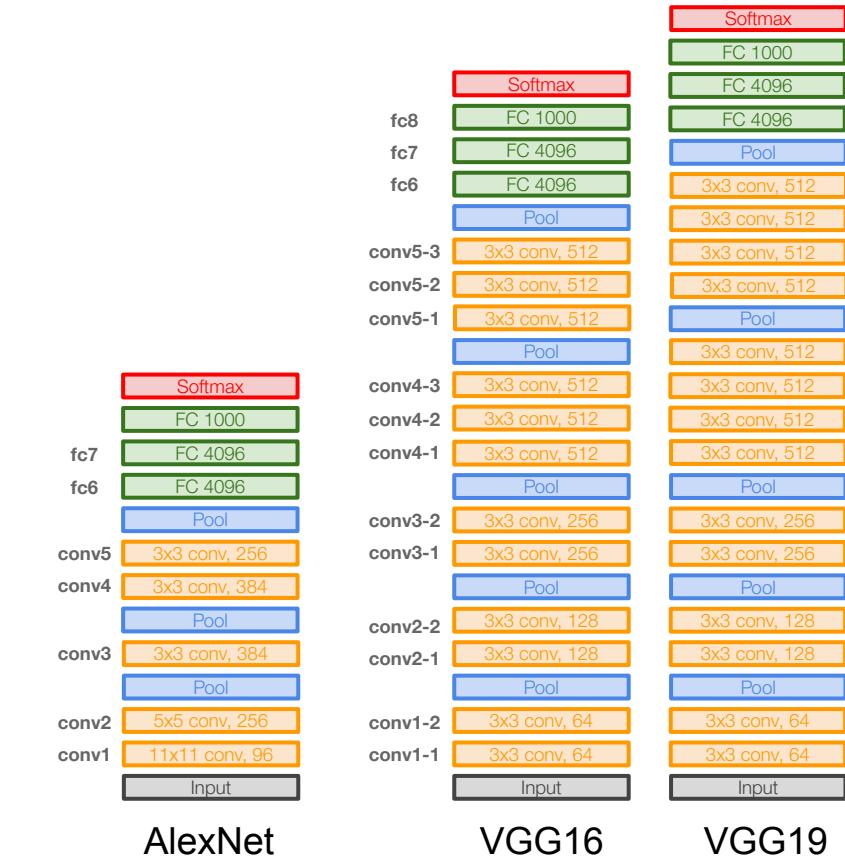
Common names

Case Study: VGGNet

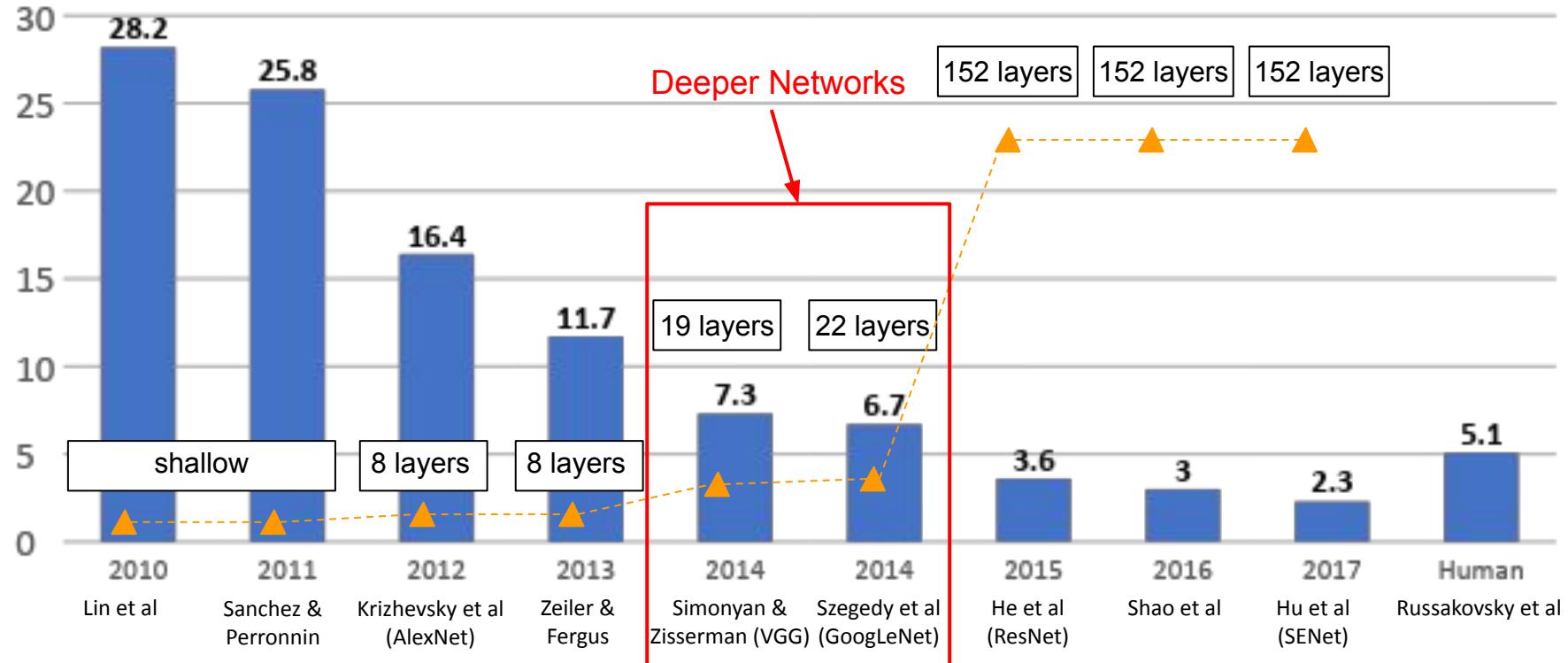
[Simonyan and Zisserman, 2014]

Details:

- ILSVRC'14 2nd in classification, 1st in localization
- Similar training procedure as Krizhevsky 2012
- No Local Response Normalisation (LRN)
- Use VGG16 or VGG19 (VGG19 only slightly better, more memory)
- Use ensembles for best results
- FC7 features generalize well to other tasks



ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

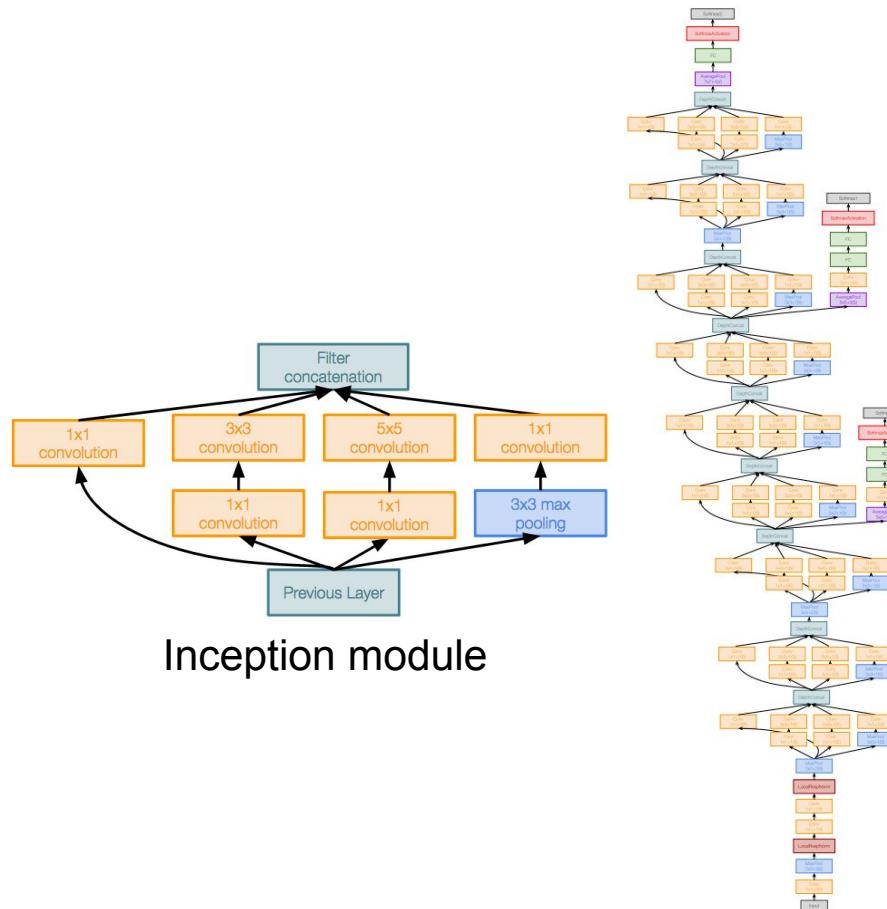


Case Study: GoogLeNet

[Szegedy et al., 2014]

Deeper networks, with computational efficiency

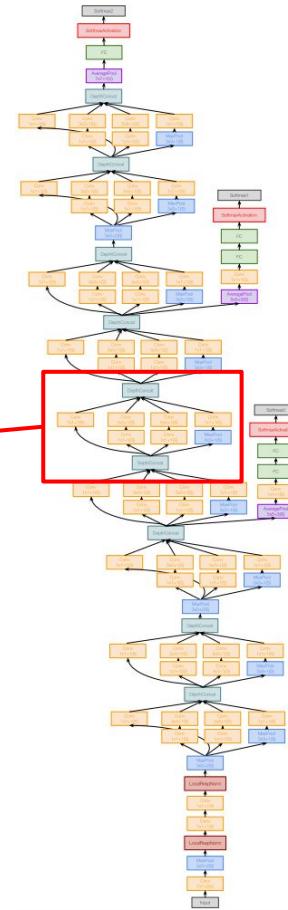
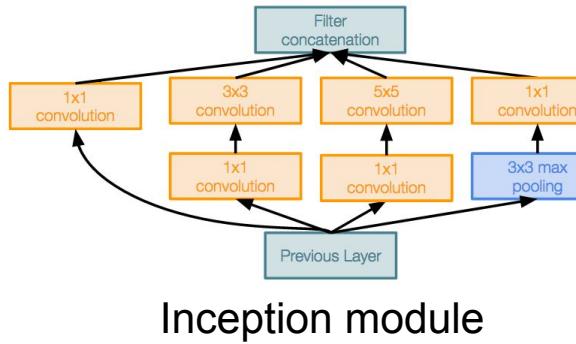
- ILSVRC'14 classification winner (6.7% top 5 error)
- 22 layers
- Only 5 million parameters! 12x less than AlexNet
27x less than VGG-16
- Efficient “Inception” module
- No FC layers



Case Study: GoogLeNet

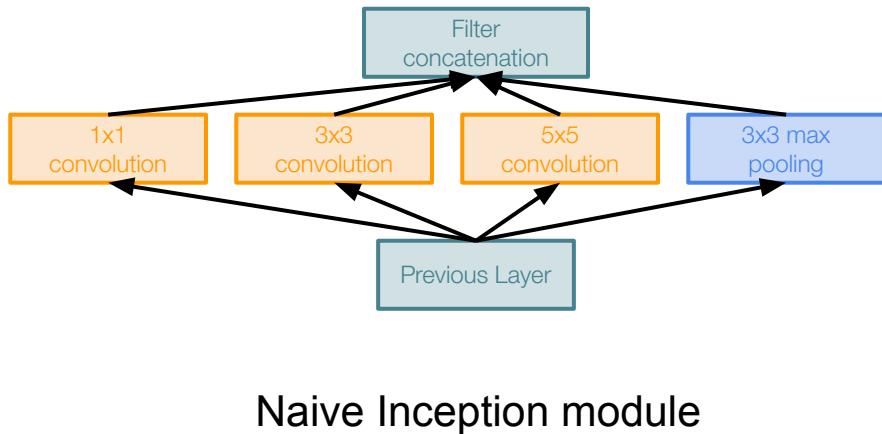
[Szegedy et al., 2014]

“Inception module”: design a good local network topology (network within a network) and then stack these modules on top of each other



Case Study: GoogLeNet

[Szegedy et al., 2014]



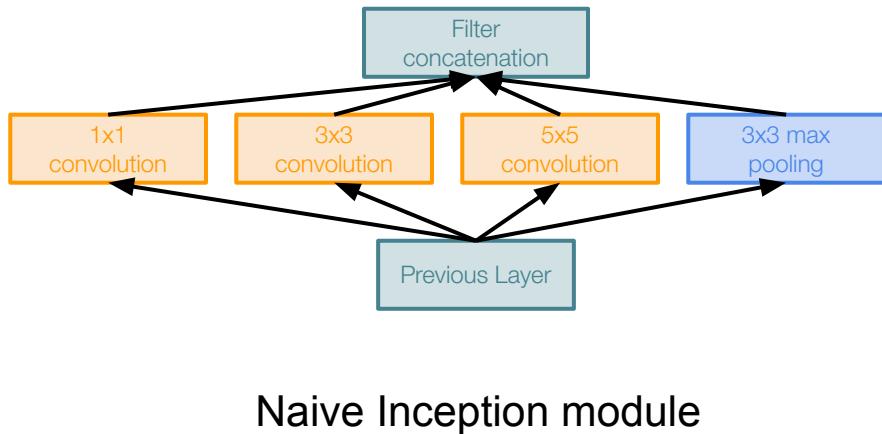
Apply parallel filter operations on the input from previous layer:

- Multiple receptive field sizes for convolution (1×1 , 3×3 , 5×5)
- Pooling operation (3×3)

Concatenate all filter outputs together channel-wise

Case Study: GoogLeNet

[Szegedy et al., 2014]



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- Multiple receptive field sizes for convolution (1×1 , 3×3 , 5×5)
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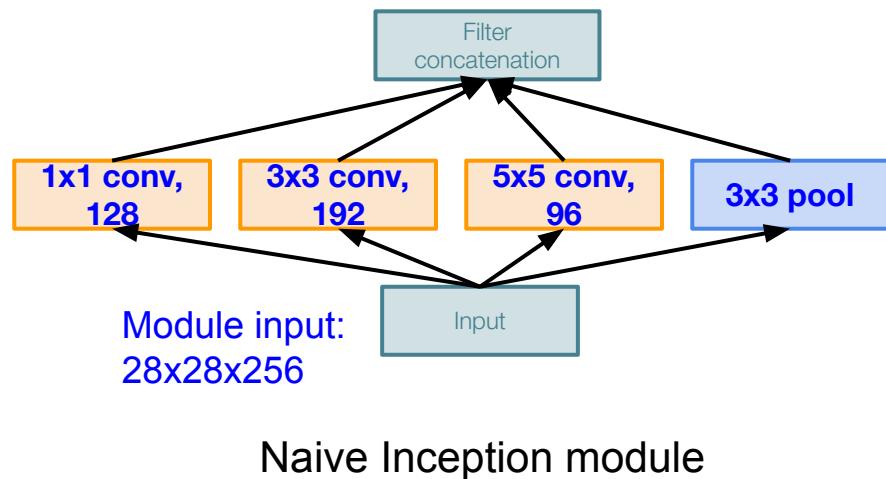
Q: What is the problem with this?
[Hint: Computational complexity]

Case Study: GoogLeNet

[Szegedy et al., 2014]

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Example:



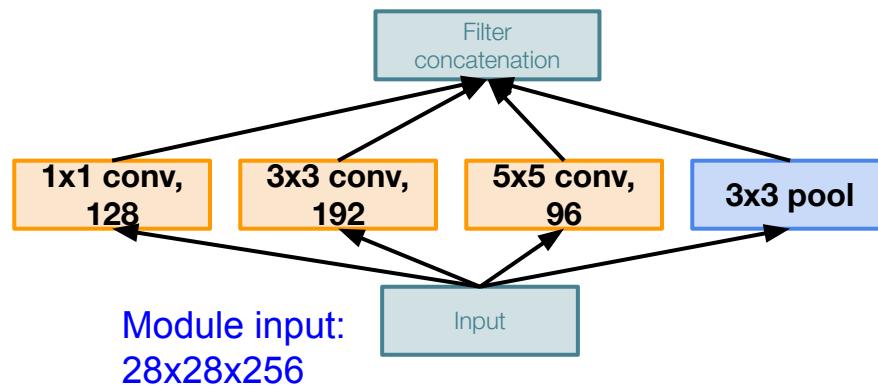
Case Study: GoogLeNet

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[Hint: Computational complexity]

Example:

Q1: What are the output sizes of all different filter operations?



Naive Inception module

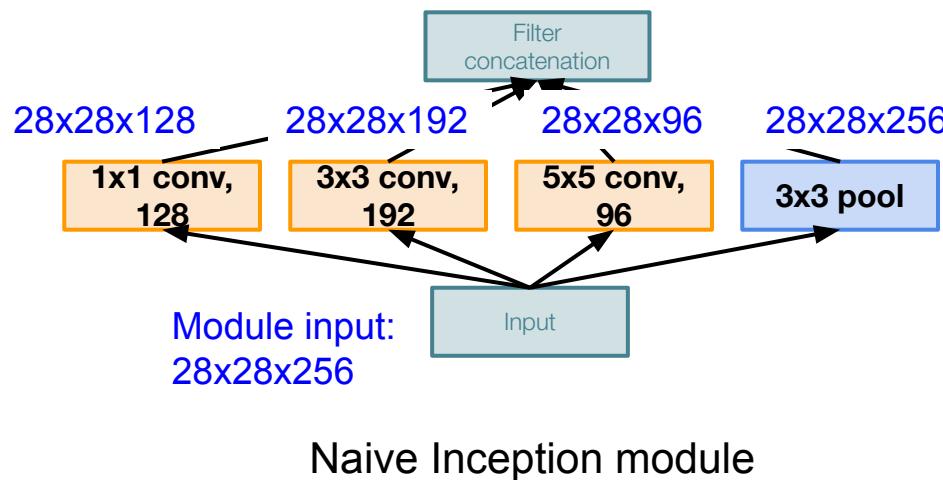
Case Study: GoogLeNet

[Szegedy et al., 2014]

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Example:

Q1: What are the output sizes of all different filter operations?



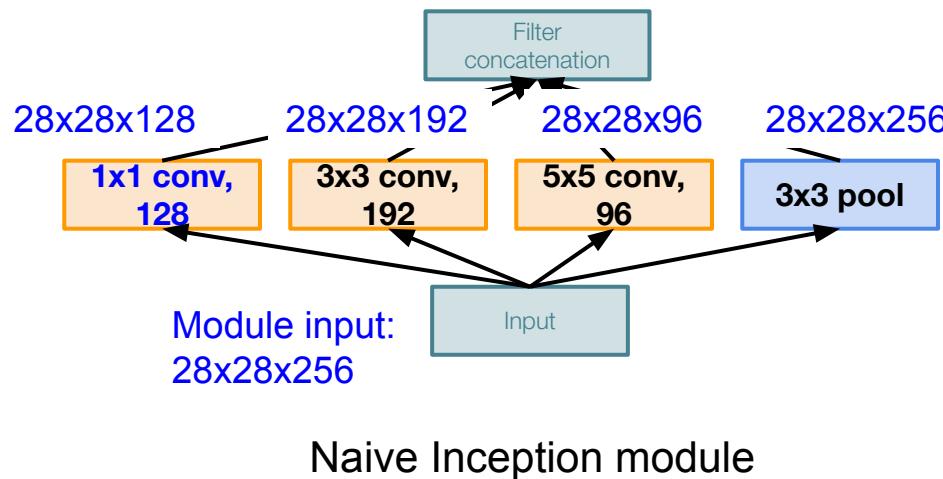
Case Study: GoogLeNet

[Szegedy et al., 2014]

Q: What is the problem with this?
[Hint: Computational complexity]

Example:

Q2: What is output size after
filter concatenation?



Naive Inception module

Case Study: GoogLeNet

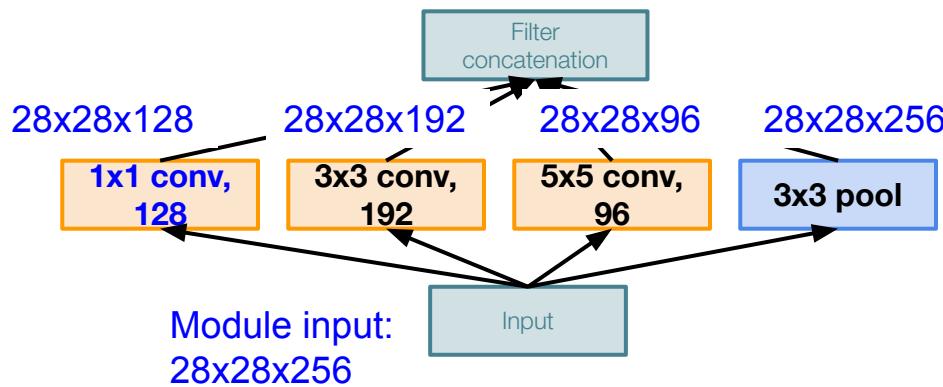
[Szegedy et al., 2014]

Q: What is the problem with this?
[Hint: Computational complexity]

Example:

Q2: What is output size after
filter concatenation?

$$28 \times 28 \times (128 + 192 + 96 + 256) = 28 \times 28 \times 672$$



Naive Inception module

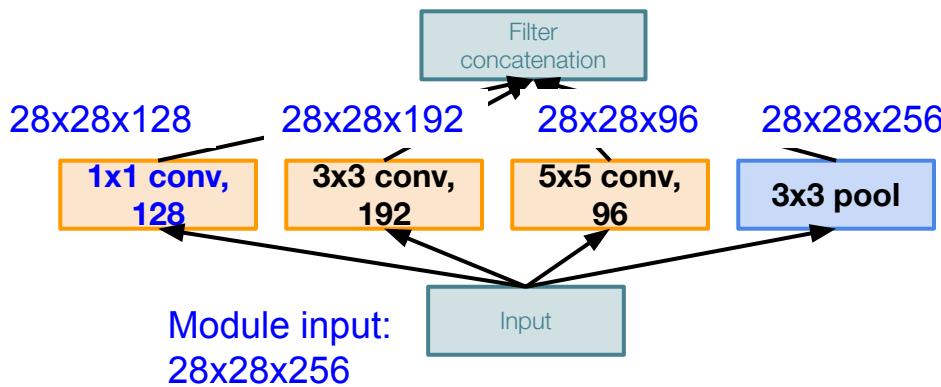
Case Study: GoogLeNet

[Szegedy et al., 2014]

Example:

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$$28 \times 28 \times (128 + 192 + 96 + 256) = 28 \times 28 \times 672$$



Naive Inception module

Q: What is the problem with this?
[Hint: Computational complexity]

Conv Ops:

[1x1 conv, 128] $28 \times 28 \times 128 \times 1 \times 1 \times 256$

[3x3 conv, 192] $28 \times 28 \times 192 \times 3 \times 3 \times 256$

[5x5 conv, 96] $28 \times 28 \times 96 \times 5 \times 5 \times 256$

Total: 854M ops

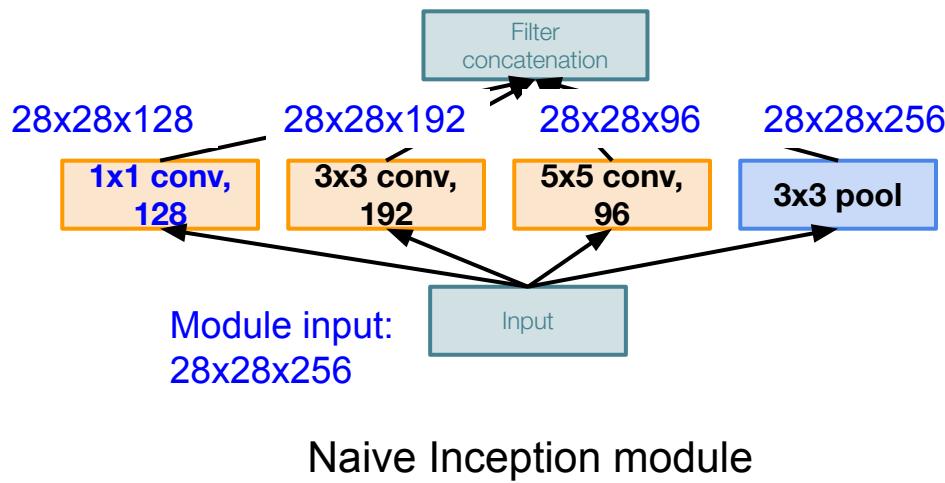
Case Study: GoogLeNet

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Naive Inception module

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Total: 854M ops

Very expensive compute

Pooling layer also preserves feature depth, which means total depth after concatenation can only grow at every layer!

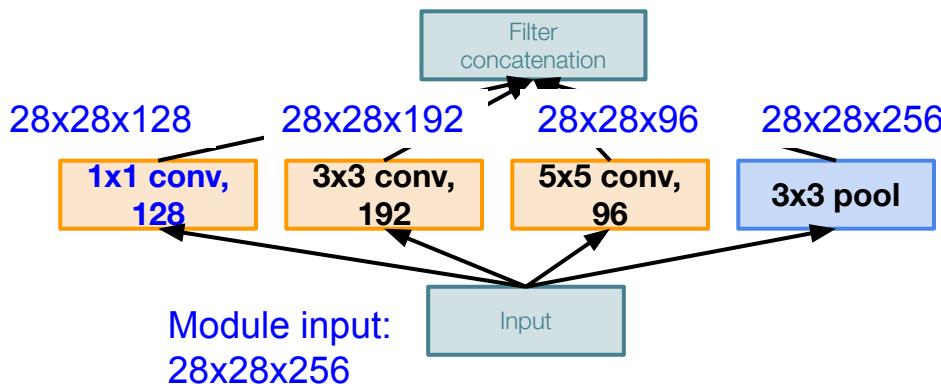
Case Study: GoogLeNet

[Szegedy et al., 2014]

Example:

Q2: What is output size after filter concatenation?

$$28 \times 28 \times (128 + 192 + 96 + 256) = 529k$$

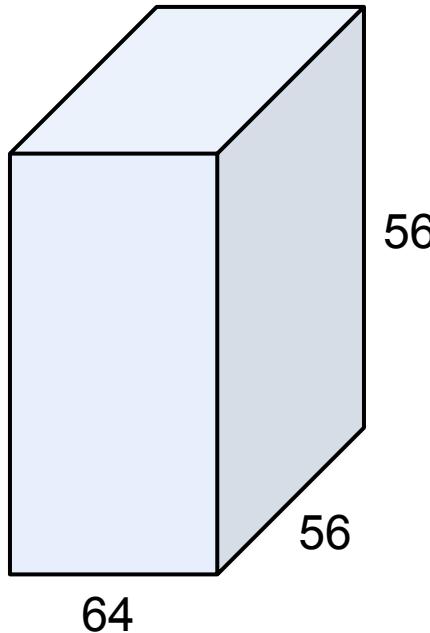


Naive Inception module

Q: What is the problem with this?
[Hint: Computational complexity]

Solution: “bottleneck” layers that use **1x1 convolutions** to reduce feature channel size

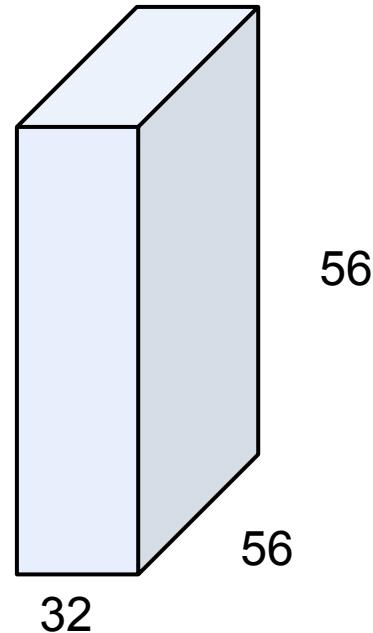
Review: 1x1 convolutions



1x1 CONV
with 32 filters

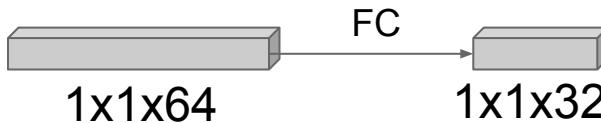
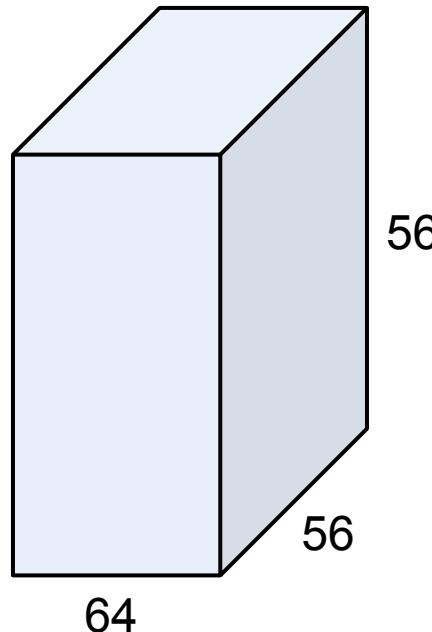
→

(each filter has size
1x1x64, and performs a
64-dimensional dot
product)



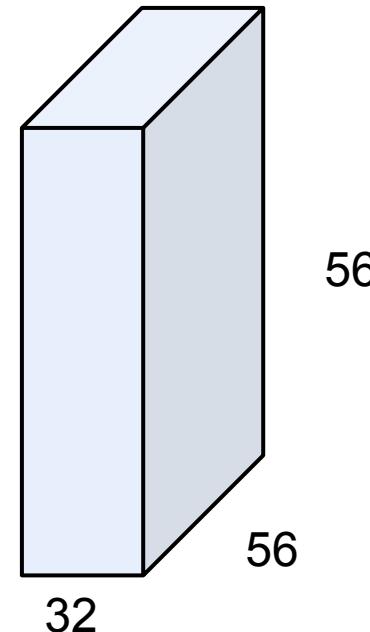
Review: 1x1 convolutions

Alternatively, interpret it as applying the same FC layer on each input pixel



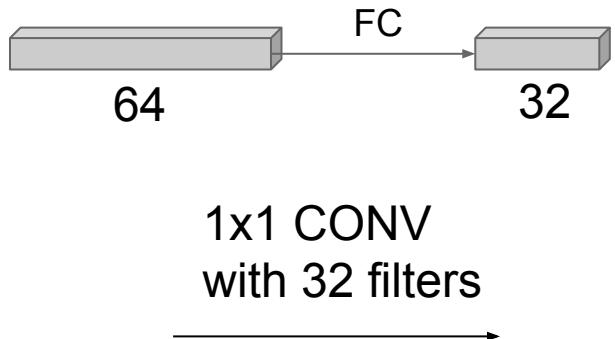
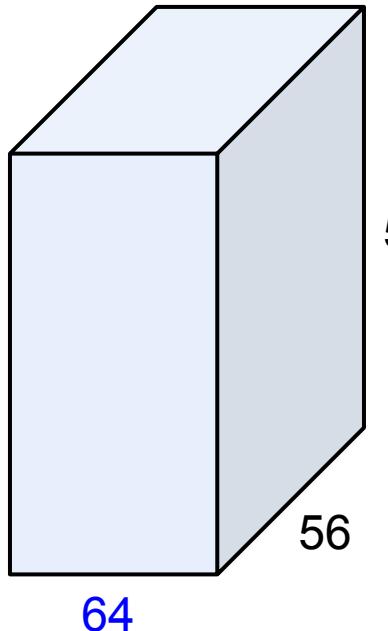
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Review: 1x1 convolutions

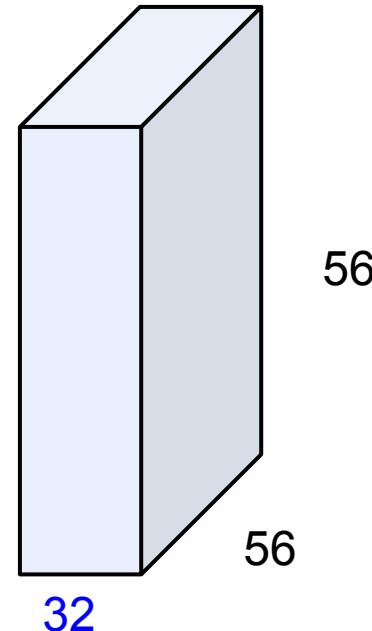
Alternatively, interpret it as applying the same FC layer on each input pixel



1x1 CONV
with 32 filters

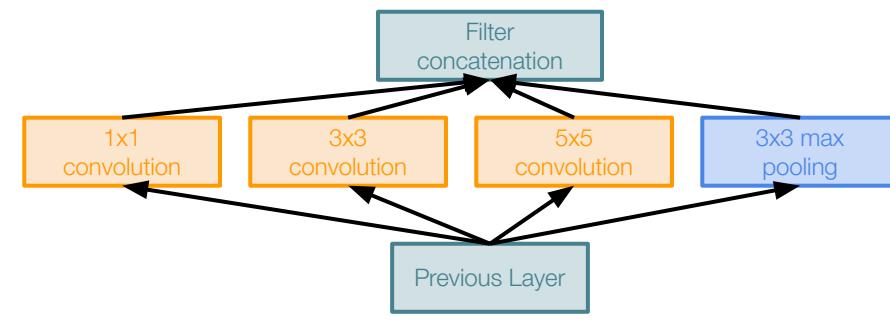
preserves spatial
dimensions, reduces depth!

Projects depth to lower
dimension (combination of
feature maps)

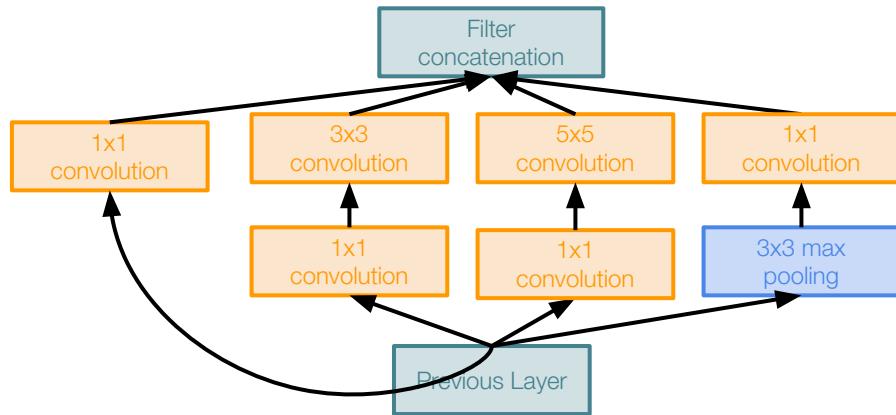


Case Study: GoogLeNet

[Szegedy et al., 2014]



Naive Inception module

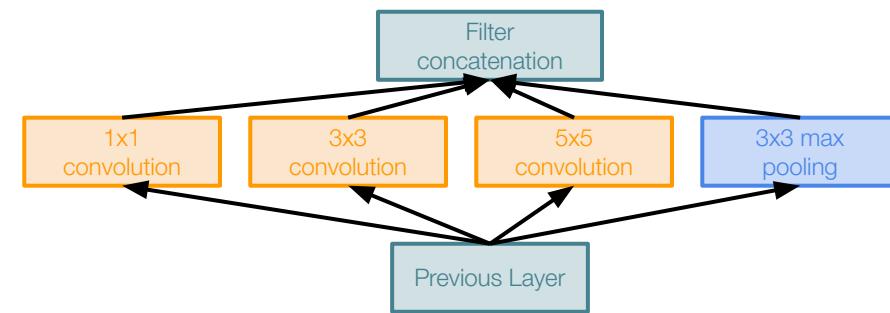


Inception module with dimension reduction

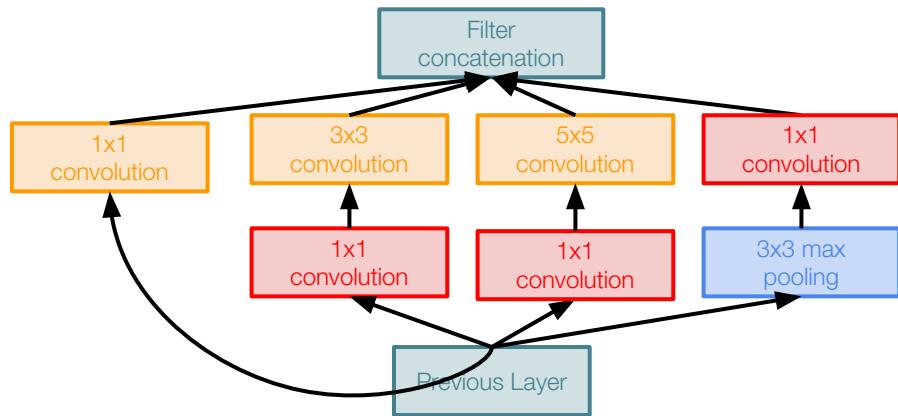
Case Study: GoogLeNet

[Szegedy et al., 2014]

1x1 conv “bottleneck”
layers



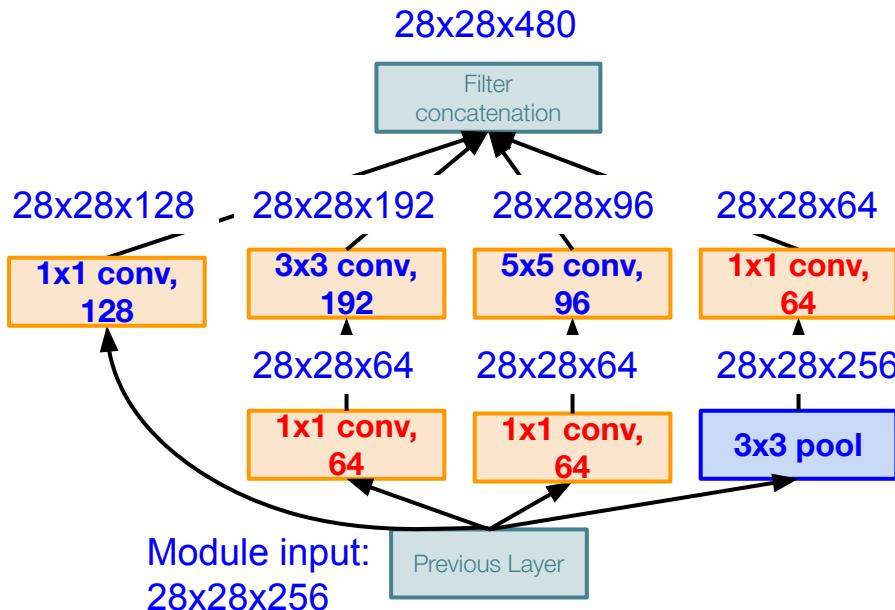
Naive Inception module



Inception module with dimension reduction

Case Study: GoogLeNet

[Szegedy et al., 2014]



Inception module with dimension reduction

Using same parallel layers as naive example, and adding “ 1×1 conv, 64 filter” bottlenecks:

Conv Ops:

[1×1 conv, 64] $28 \times 28 \times 64 \times 1 \times 1 \times 256$
[1×1 conv, 64] $28 \times 28 \times 64 \times 1 \times 1 \times 256$
[1×1 conv, 128] $28 \times 28 \times 128 \times 1 \times 1 \times 256$
[3×3 conv, 192] $28 \times 28 \times 192 \times 3 \times 3 \times 64$
[5×5 conv, 96] $28 \times 28 \times 96 \times 5 \times 5 \times 64$
[1×1 conv, 64] $28 \times 28 \times 64 \times 1 \times 1 \times 256$

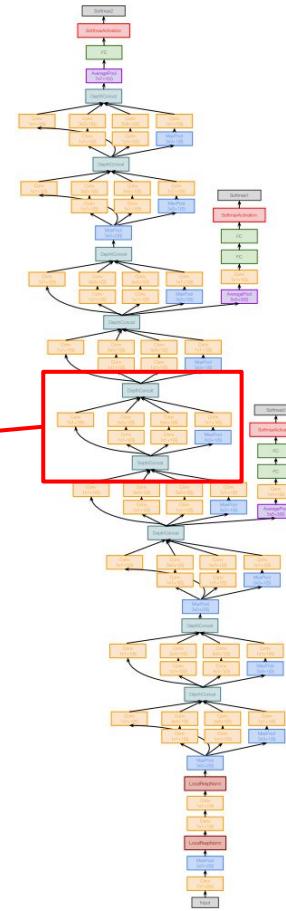
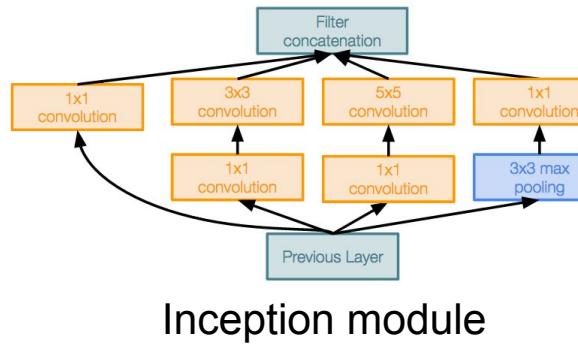
Total: 358M ops

Compared to 854M ops for naive version
Bottleneck can also reduce depth after pooling layer

Case Study: GoogLeNet

[Szegedy et al., 2014]

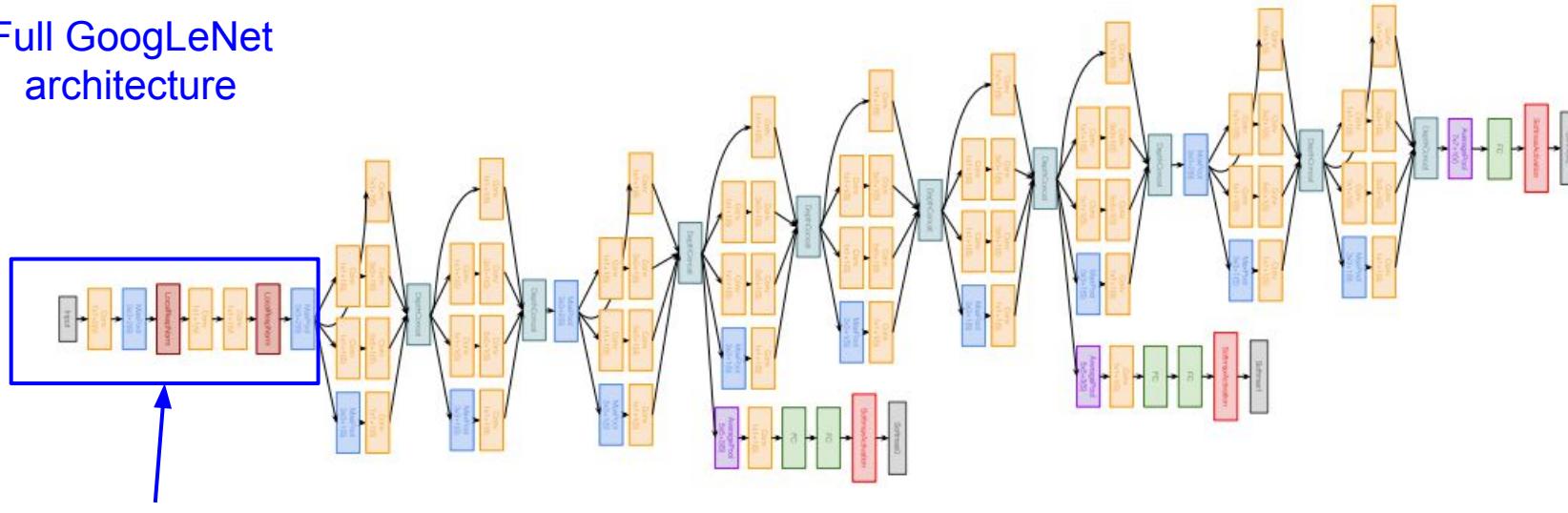
Stack Inception modules
with dimension reduction
on top of each other



Case Study: GoogLeNet

[Szegedy et al., 2014]

Full GoogLeNet
architecture

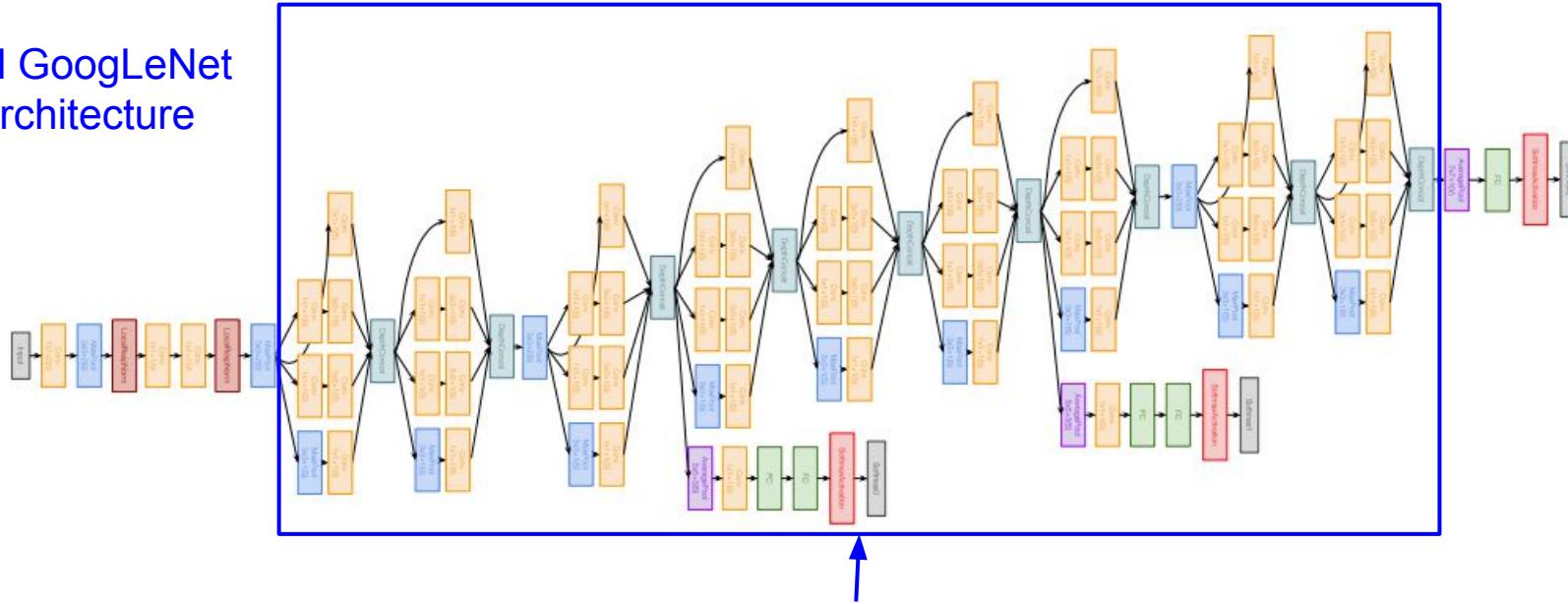


Stem Network:
Conv-Pool-
2x Conv-Pool

Case Study: GoogLeNet

[Szegedy et al., 2014]

Full GoogLeNet
architecture

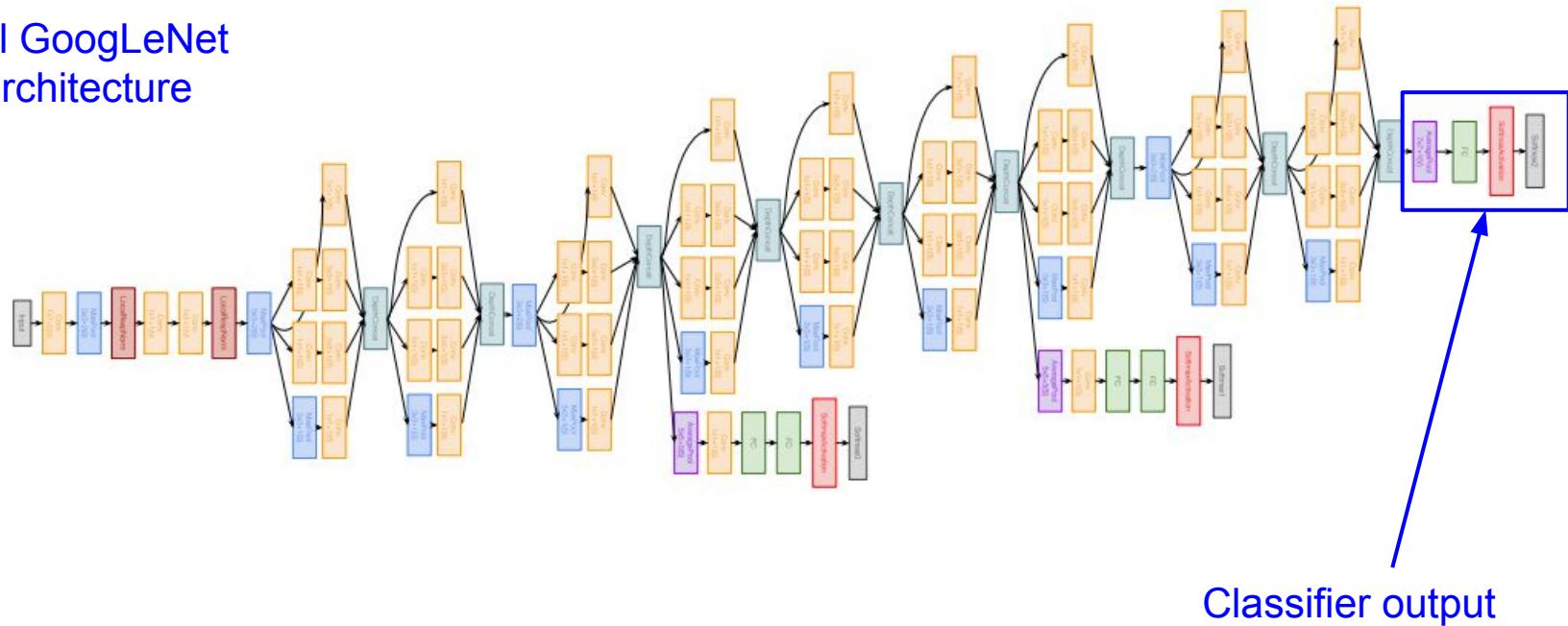


Stacked Inception
Modules

Case Study: GoogLeNet

[Szegedy et al., 2014]

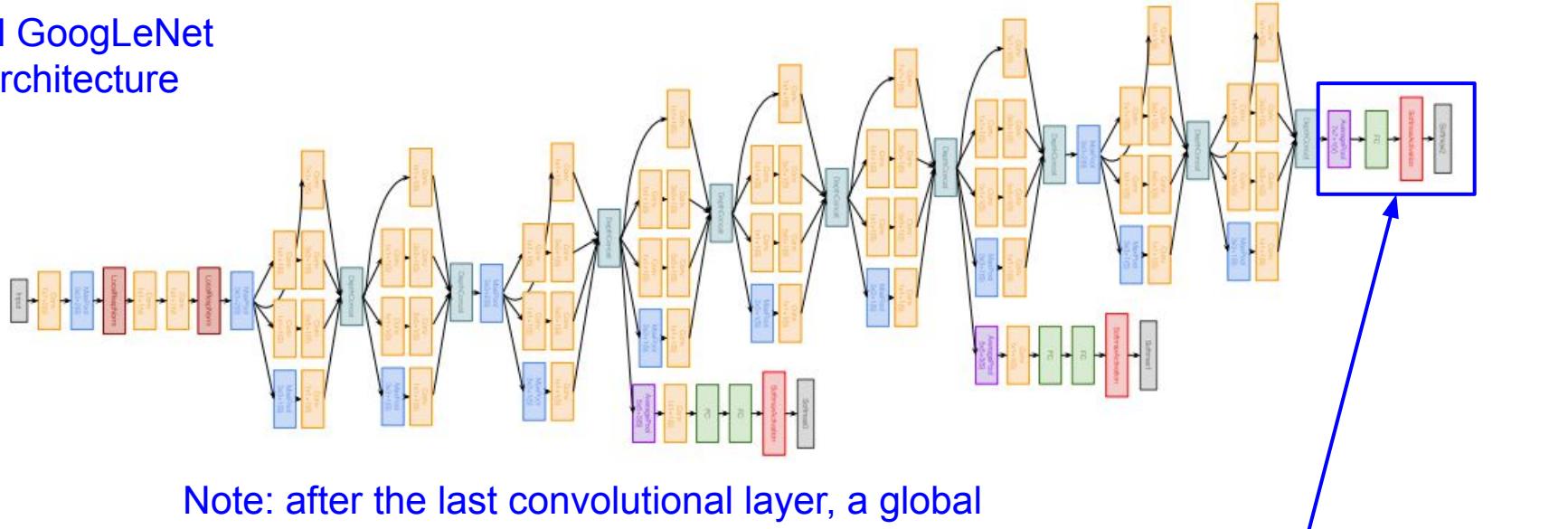
Full GoogLeNet
architecture



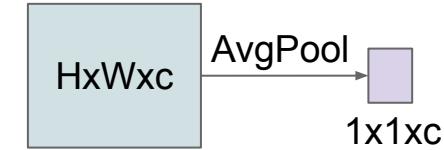
Case Study: GoogLeNet

[Szegedy et al., 2014]

Full GoogLeNet
architecture



Note: after the last convolutional layer, a global average pooling layer is used that spatially averages across each feature map, before final FC layer. No longer multiple expensive FC layers!

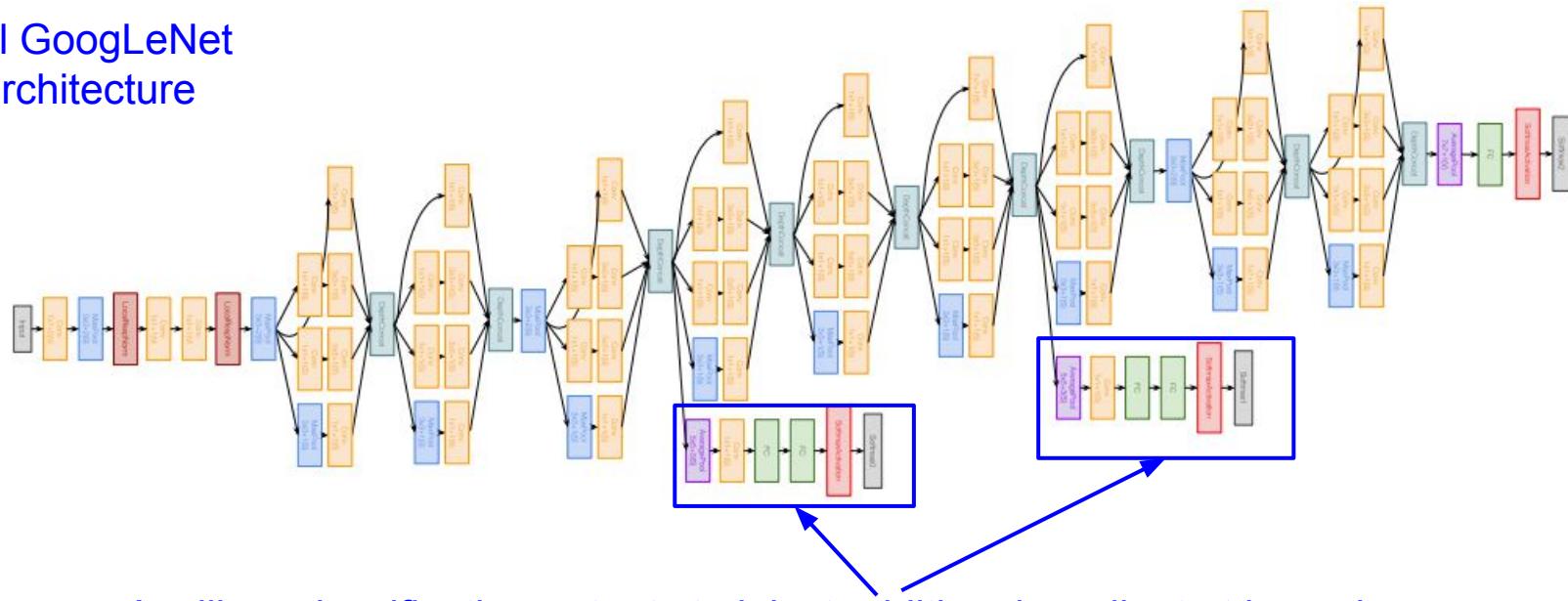


Classifier output

Case Study: GoogLeNet

[Szegedy et al., 2014]

Full GoogLeNet
architecture

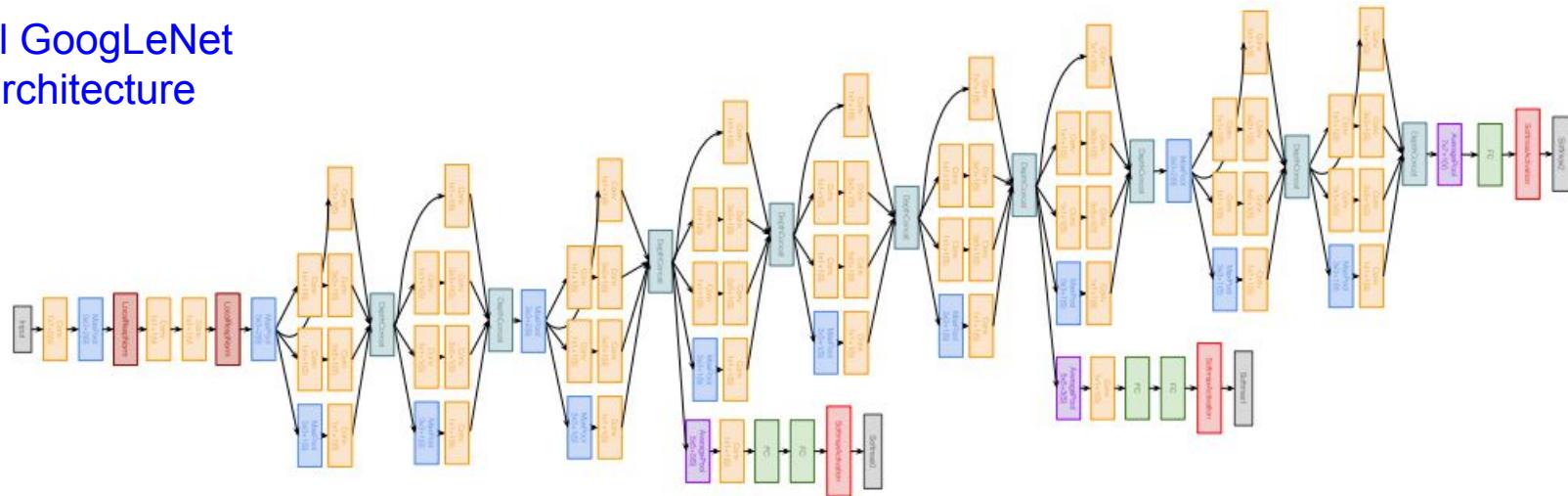


Auxiliary classification outputs to inject additional gradient at lower layers
(AvgPool-1x1Conv-FC-FC-Softmax)

Case Study: GoogLeNet

[Szegedy et al., 2014]

Full GoogLeNet
architecture



22 total layers with weights

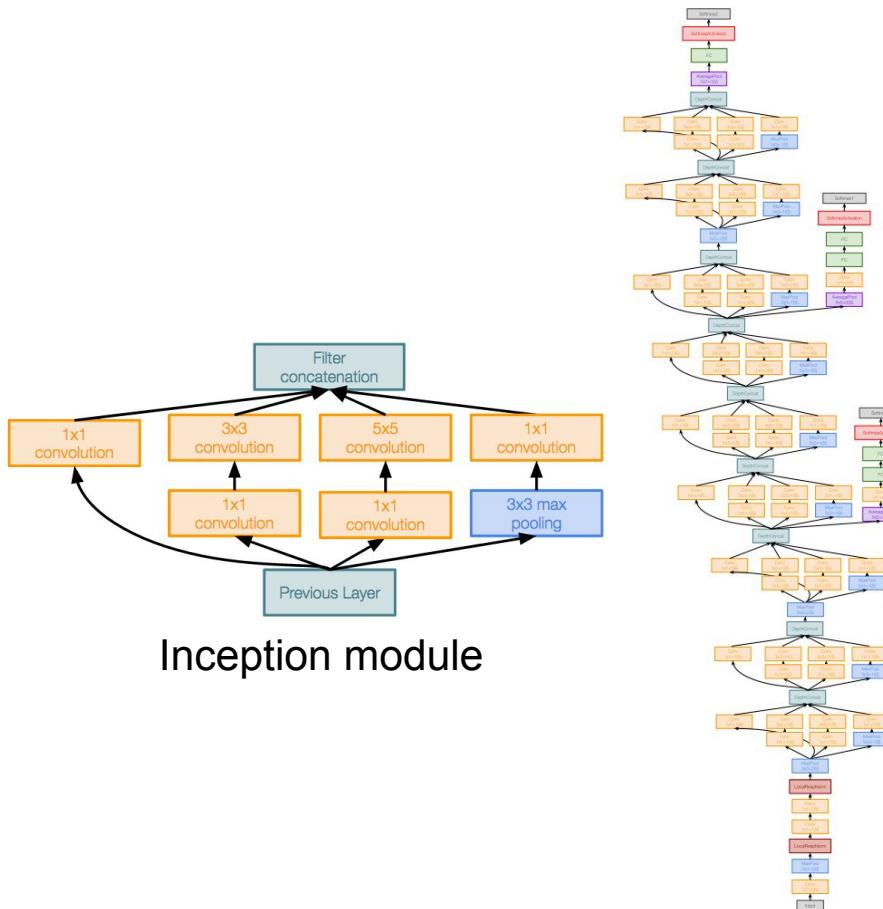
(parallel layers count as 1 layer => 2 layers per Inception module. Don't count auxiliary output layers)

Case Study: GoogLeNet

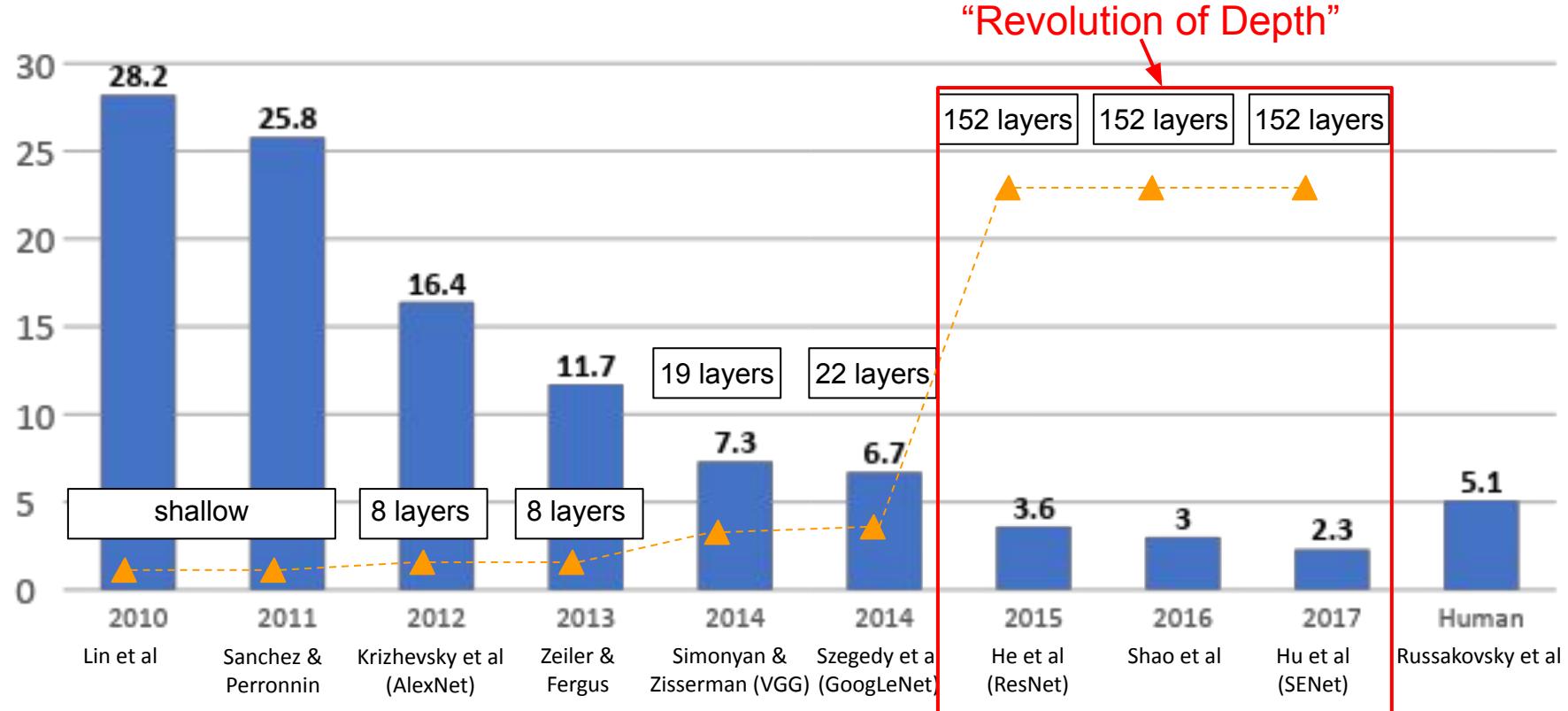
[Szegedy et al., 2014]

Deeper networks, with computational efficiency

- 22 layers
- Efficient “Inception” module
- Avoids expensive FC layers
- 12x less params than AlexNet
- 27x less params than VGG-16
- ILSVRC’14 classification winner (6.7% top 5 error)



ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

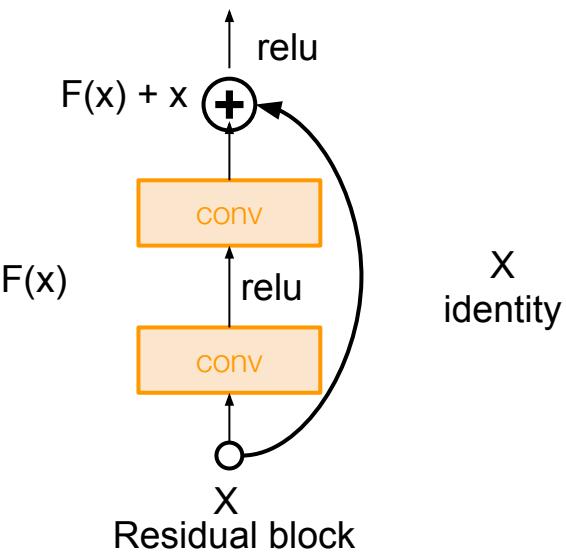


Case Study: ResNet

[He et al., 2015]

Very deep networks using residual connections

- 152-layer model for ImageNet
- ILSVRC'15 classification winner (3.57% top 5 error)
- Swept all classification and detection competitions in ILSVRC'15 and COCO'15!



Case Study: ResNet

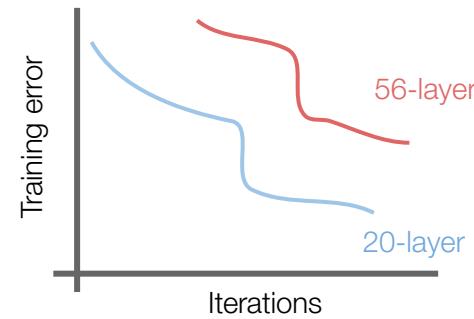
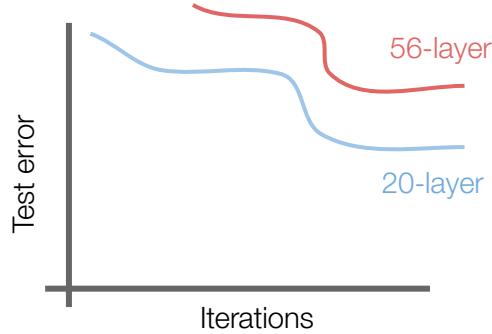
[He et al., 2015]

What happens when we continue stacking deeper layers on a “plain” convolutional neural network?

Case Study: ResNet

[He et al., 2015]

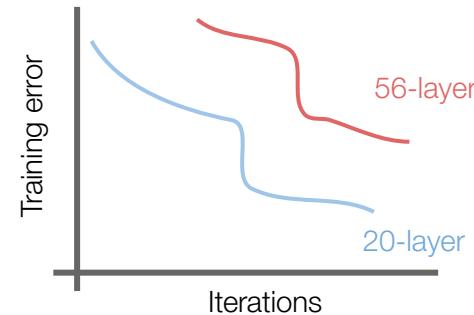
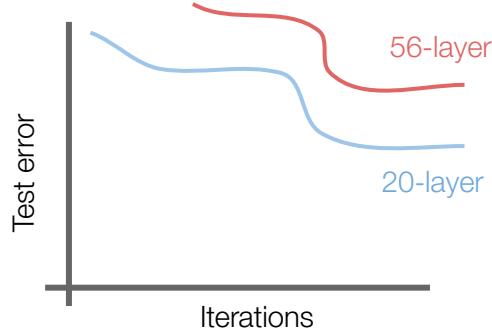
What happens when we continue stacking deeper layers on a “plain” convolutional neural network?



Case Study: ResNet

[He et al., 2015]

What happens when we continue stacking deeper layers on a “plain” convolutional neural network?



56-layer model performs worse on both test and training error
-> The deeper model performs worse, but it's not caused by overfitting!

Case Study: ResNet

[He et al., 2015]

Fact: Deep models have more representation power
(more parameters) than shallower models.

Hypothesis: the problem is an *optimization* problem,
deeper models are harder to optimize

Case Study: ResNet

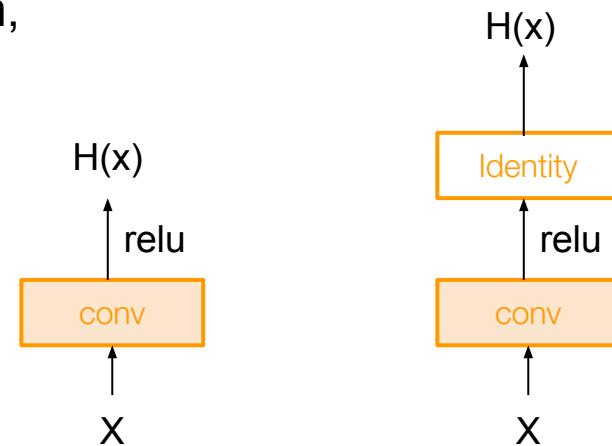
[He et al., 2015]

Fact: Deep models have more representation power (more parameters) than shallower models.

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What should the deeper model learn to be at least as good as the shallower model?

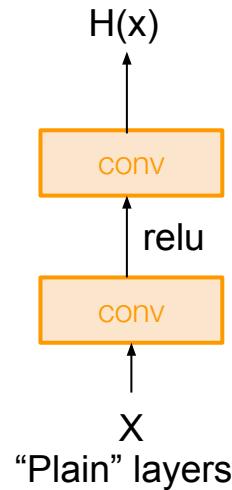
A solution by construction is copying the learned layers from the shallower model and setting additional layers to identity mapping.



Case Study: ResNet

[He et al., 2015]

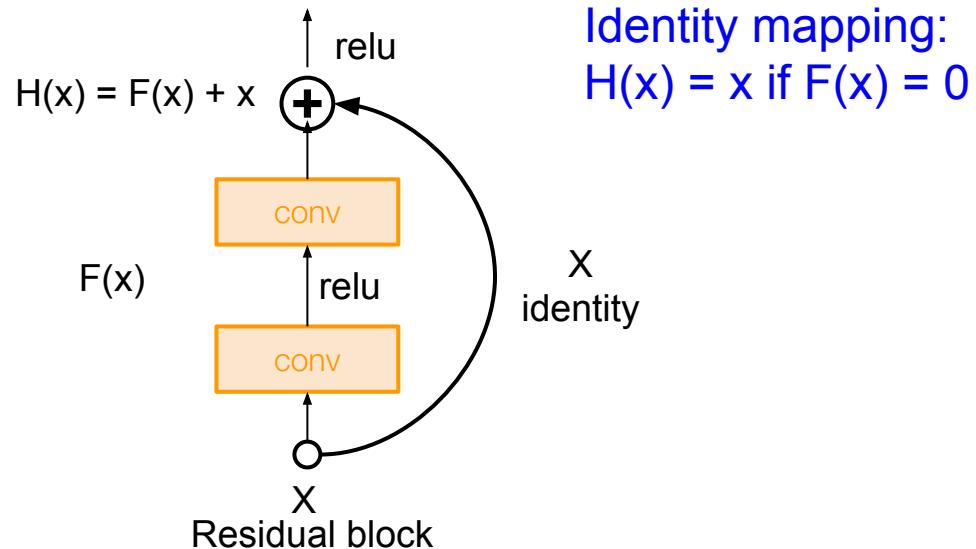
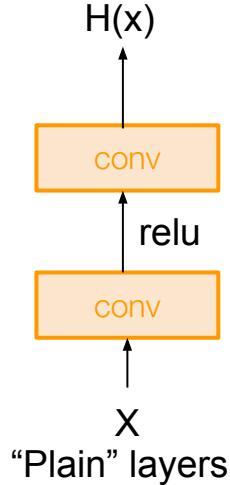
Solution: Use network layers to fit a residual mapping instead of directly trying to fit a desired underlying mapping



Case Study: ResNet

[He et al., 2015]

Solution: Use network layers to fit a residual mapping instead of directly trying to fit a desired underlying mapping

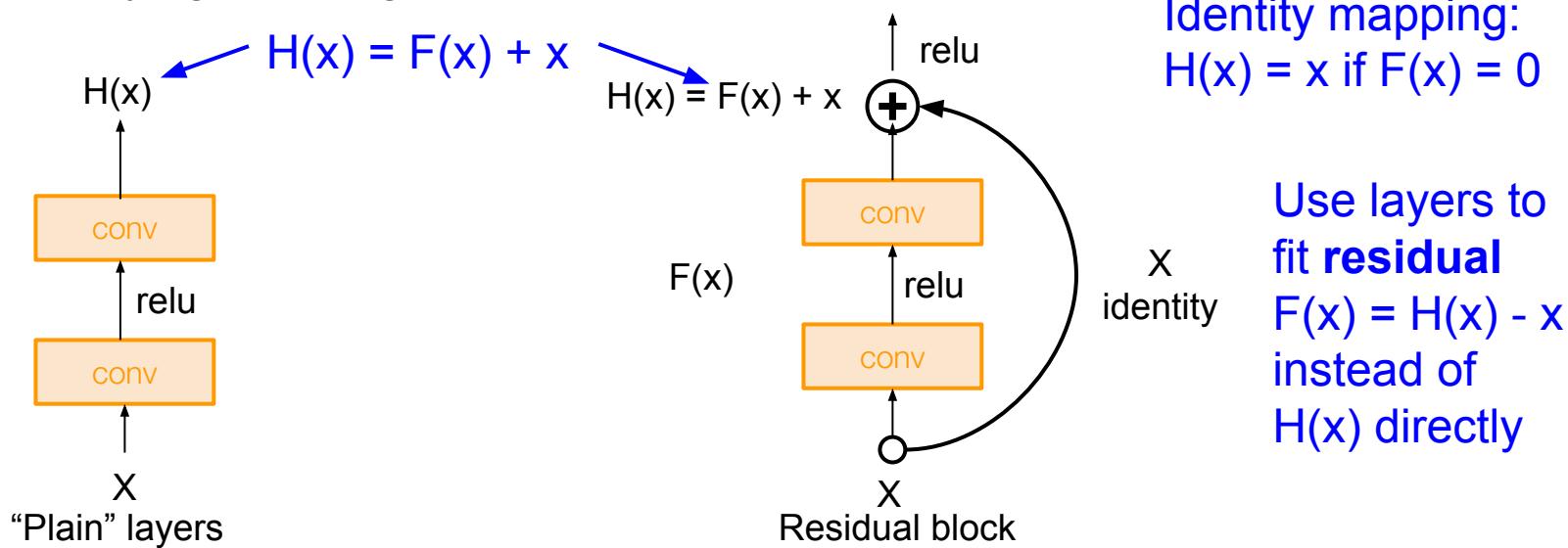


Identity mapping:
 $H(x) = x$ if $F(x) = 0$

Case Study: ResNet

[He et al., 2015]

Solution: Use network layers to fit a residual mapping instead of directly trying to fit a desired underlying mapping

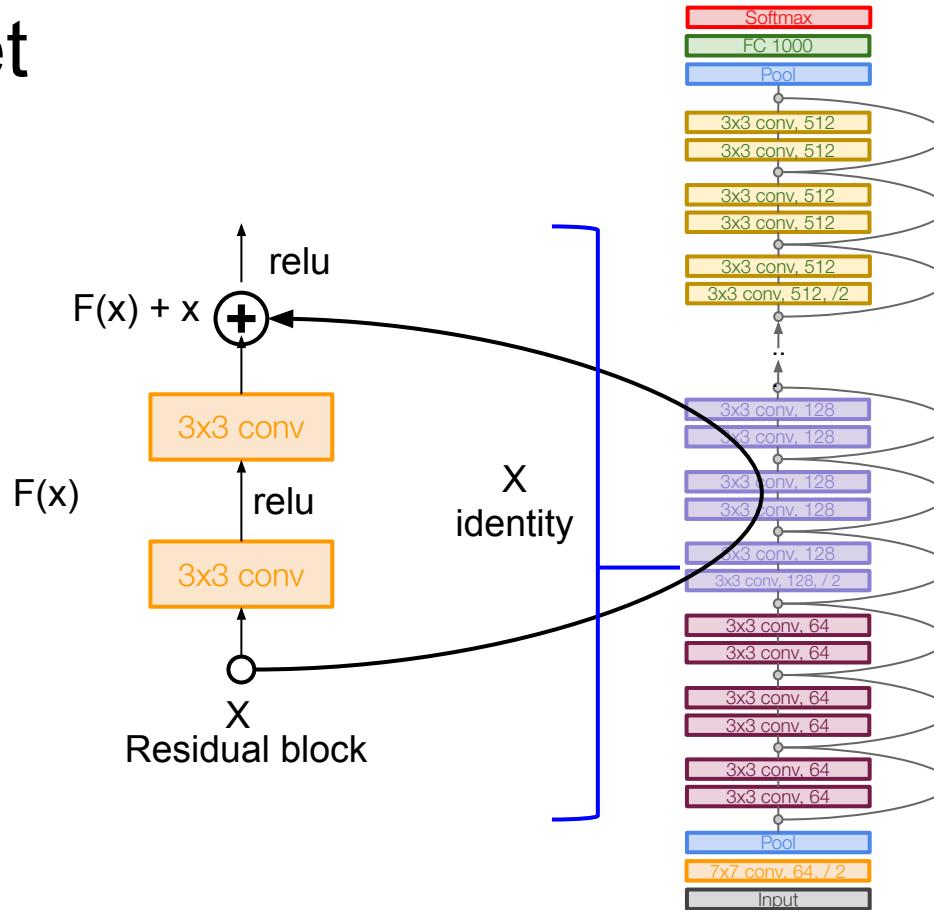


Case Study: ResNet

[He et al., 2015]

Full ResNet architecture:

- Stack residual blocks
- Every residual block has two 3x3 conv layers

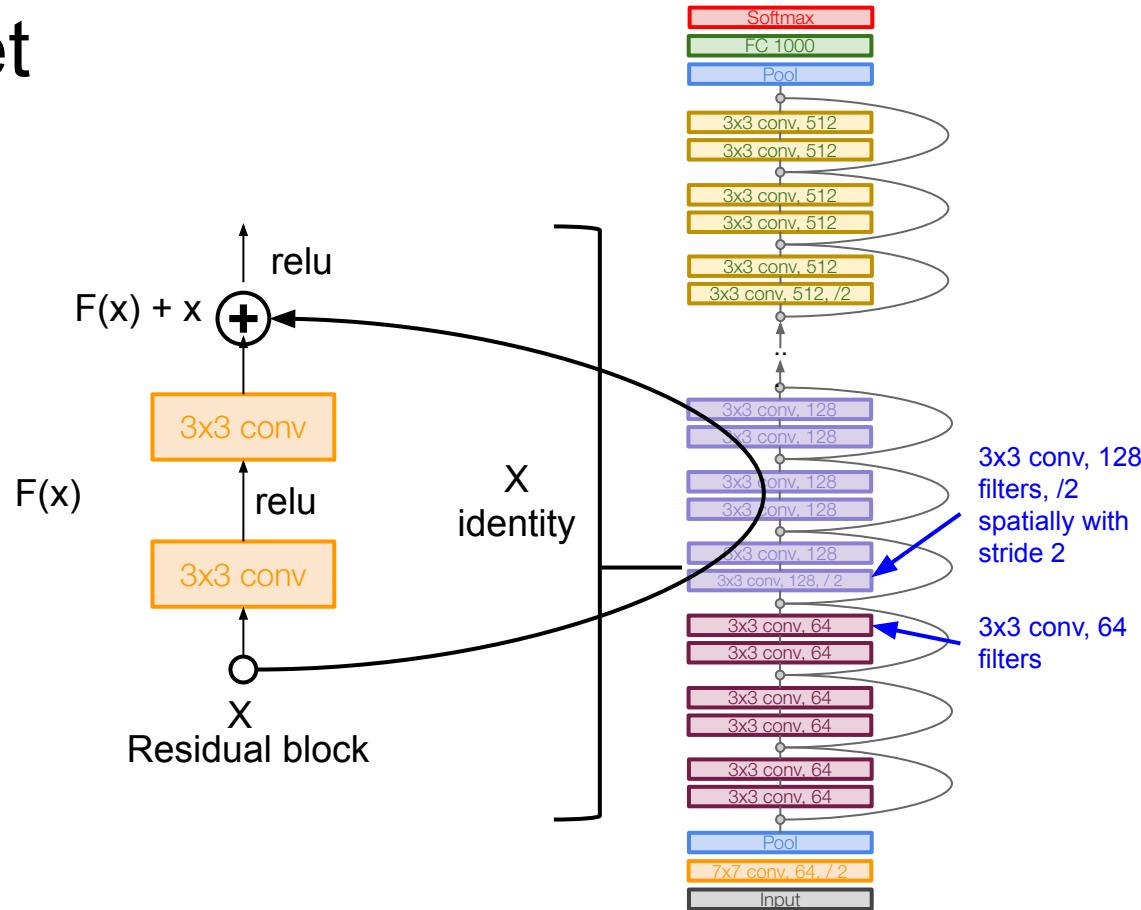


Case Study: ResNet

[He et al., 2015]

Full ResNet architecture:

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

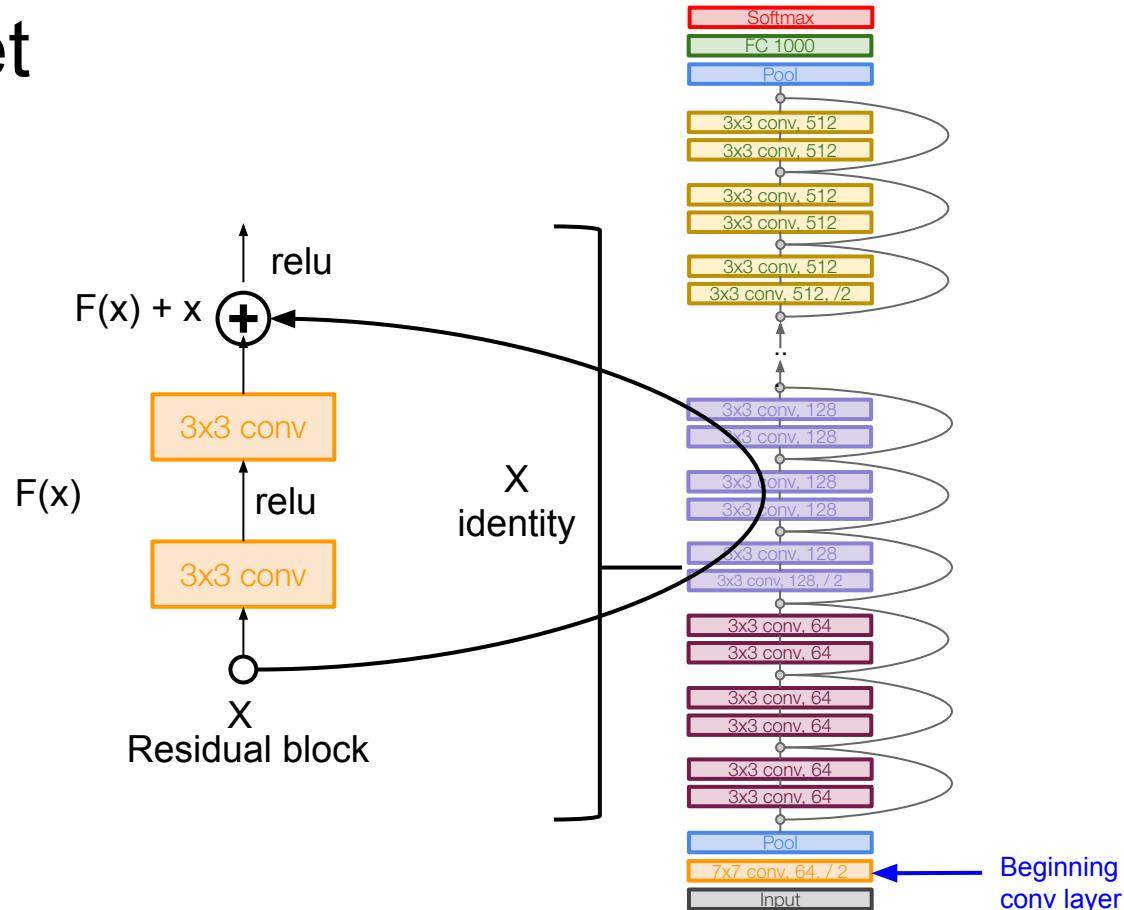


Case Study: ResNet

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- Additional conv layer at the beginning (stem)

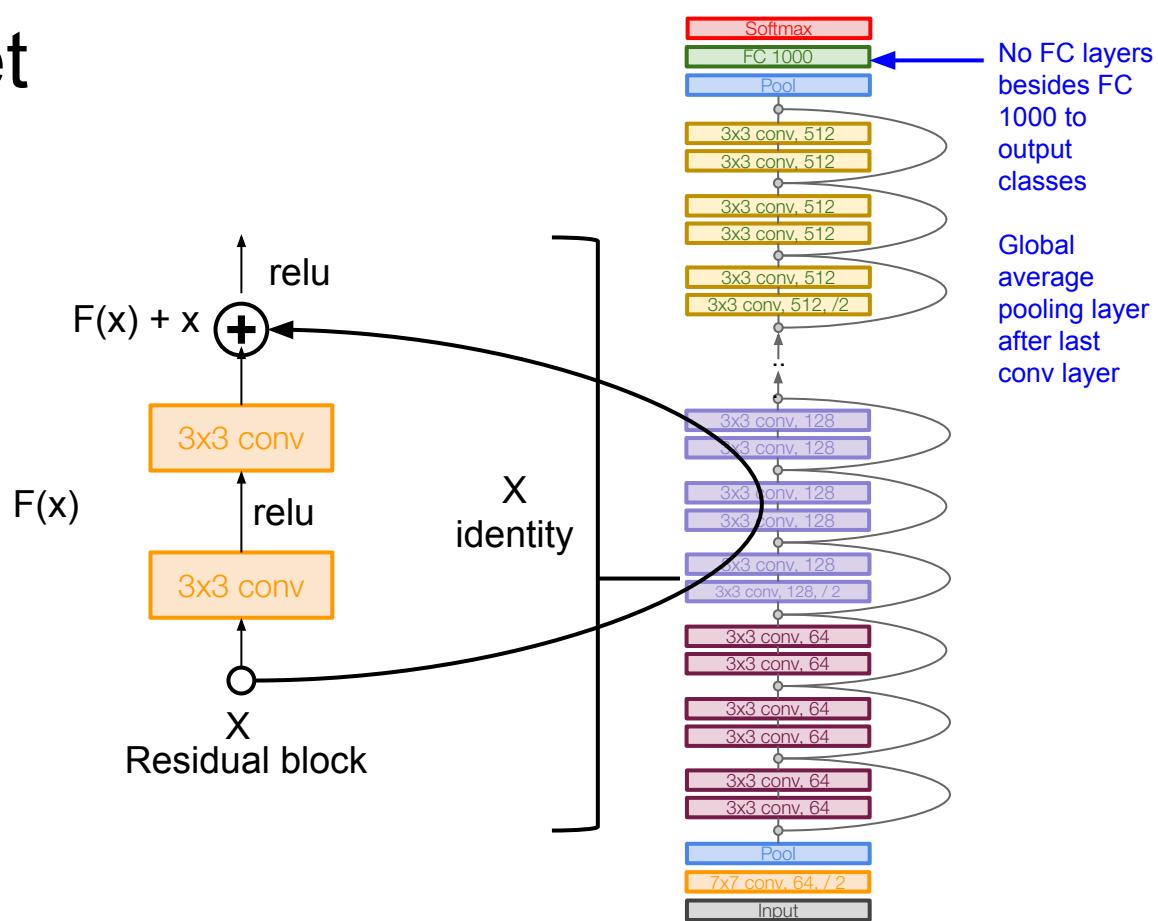


Case Study: ResNet

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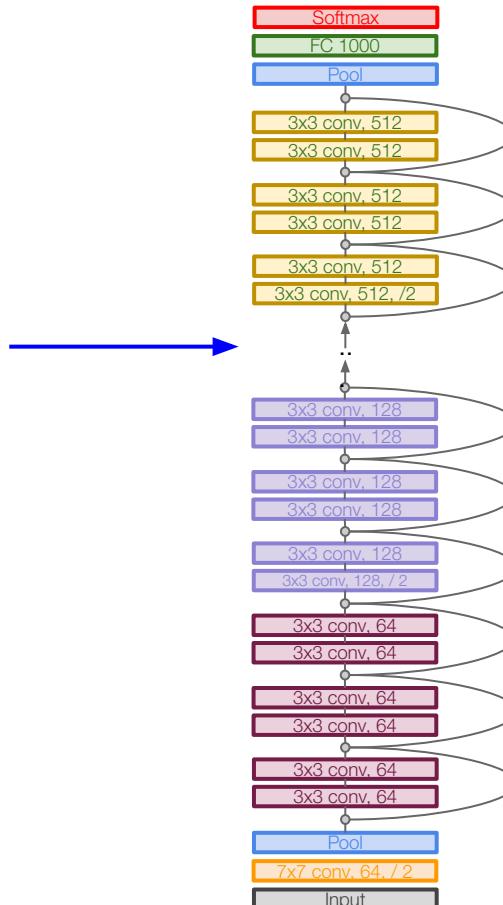
- Stack residual blocks
- Every residual block has two 3x3 conv layers
- Periodically, double # of filters and downsample spatially using stride 2 (/2 in each dimension)
- Additional conv layer at the beginning (stem)
- No FC layers at the end (only FC 1000 to output classes)
- (In theory, you can train a ResNet with input image of variable sizes)



Case Study: ResNet

[He et al., 2015]

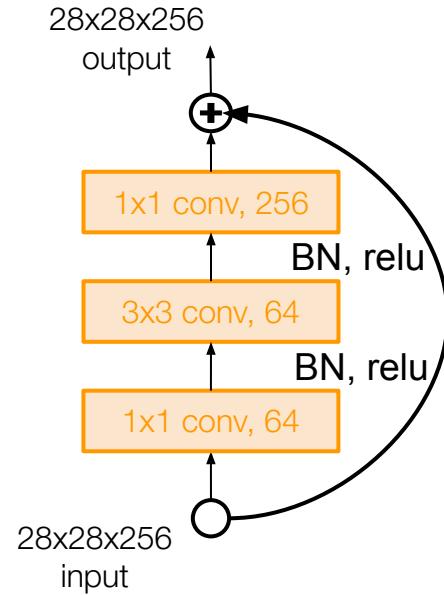
Total depths of 18, 34, 50,
101, or 152 layers for
ImageNet



Case Study: ResNet

[He et al., 2015]

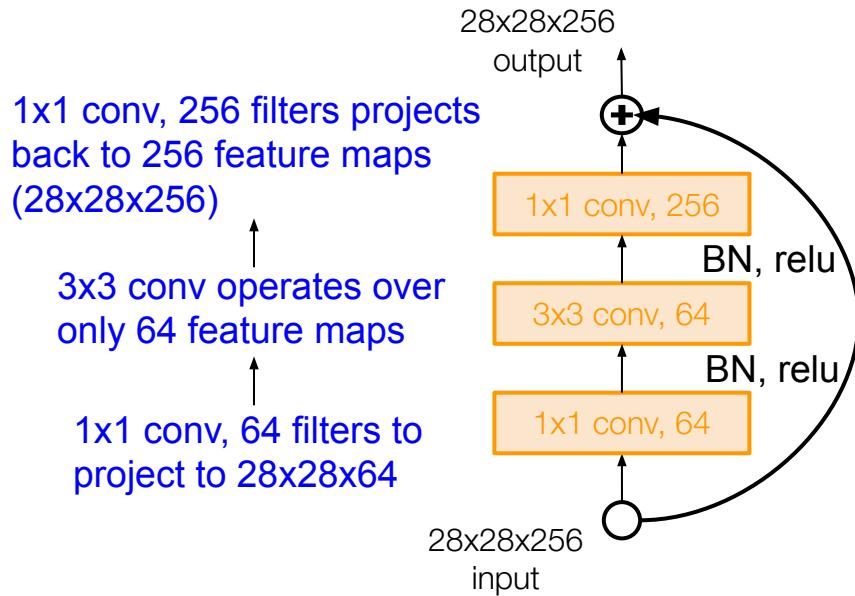
For deeper networks
(ResNet-50+), use “bottleneck”
layer to improve efficiency
(similar to GoogLeNet)



Case Study: ResNet

[He et al., 2015]

For deeper networks
(ResNet-50+), use “bottleneck”
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Case Study: ResNet

[He et al., 2015]

Training ResNet in practice:

- Batch Normalization after every CONV layer
- Xavier initialization from He et al.
- SGD + Momentum (0.9)
- Learning rate: 0.1, divided by 10 when validation error plateaus
- Mini-batch size 256
- Weight decay of 1e-5
- No dropout used

Case Study: ResNet

[He et al., 2015]

Experimental Results

- Able to train very deep networks without degrading (152 layers on ImageNet, 1202 on Cifar)
- Deeper networks now achieve lower training error as expected
- Swept 1st place in all ILSVRC and COCO 2015 competitions

MSRA @ ILSVRC & COCO 2015 Competitions

- **1st places** in all five main tracks
 - ImageNet Classification: “Ultra-deep” (quote Yann) **152-layer** nets
 - ImageNet Detection: **16%** better than 2nd
 - ImageNet Localization: **27%** better than 2nd
 - COCO Detection: **11%** better than 2nd
 - COCO Segmentation: **12%** better than 2nd

Case Study: ResNet

[He et al., 2015]

Experimental Results

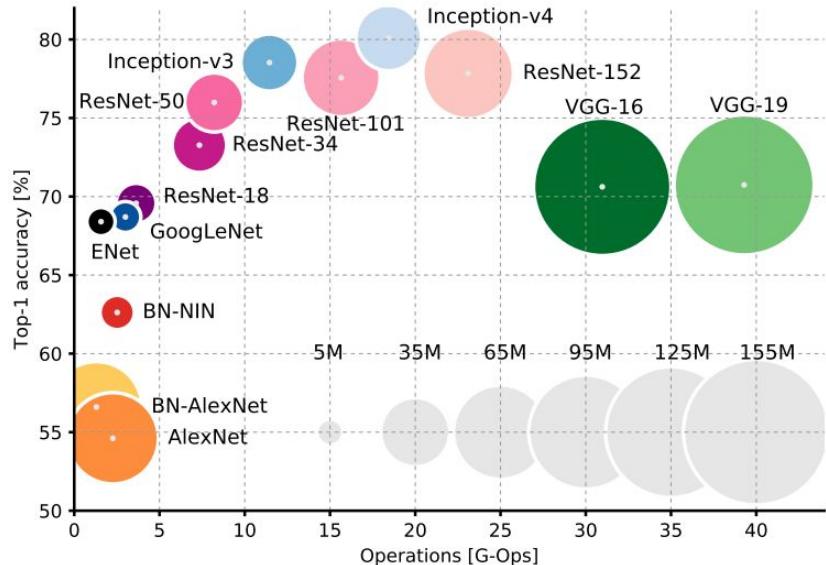
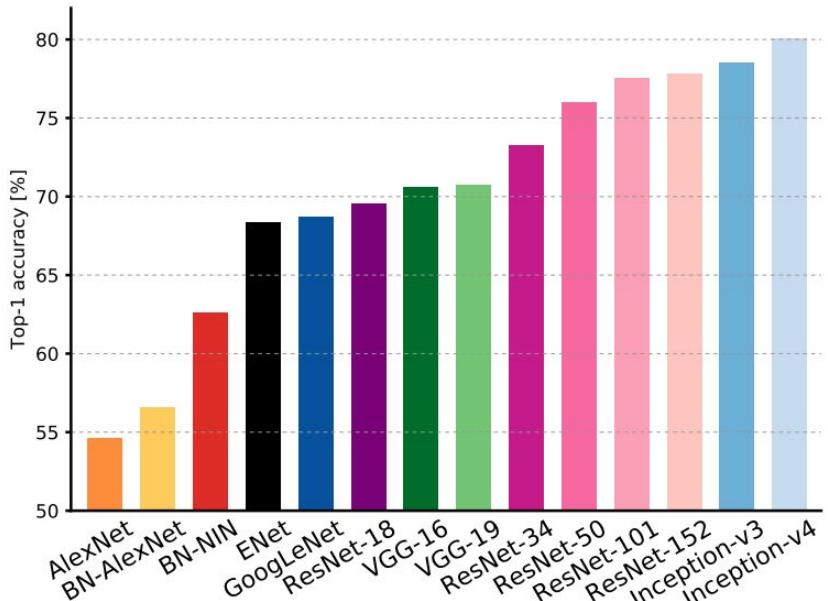
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 - COCO Detection: 11% better than 2nd
 - COCO Segmentation: 12% better than 2nd

ILSVRC 2015 classification winner (3.6% top 5 error) -- better than “human performance”! (Russakovsky 2014)

Comparing complexity...

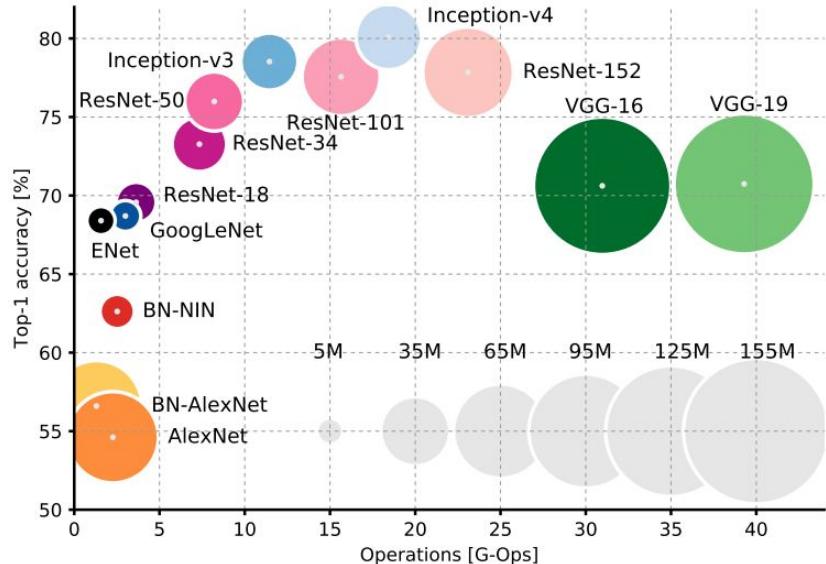
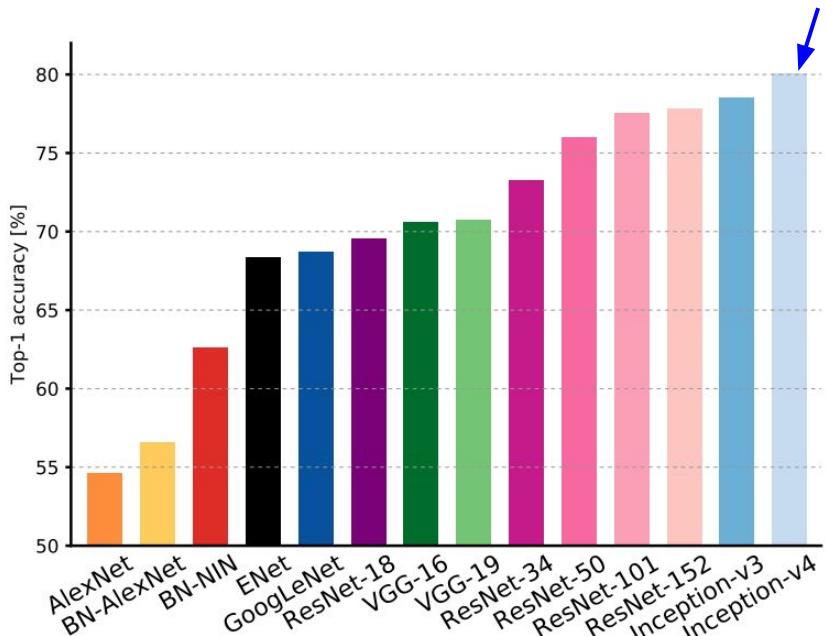


An Analysis of Deep Neural Network Models for Practical Applications, 2017.

Figures copyright Alfredo Canziani, Adam Paszke, Eugenio Culurciello, 2017. Reproduced with permission.

Comparing complexity...

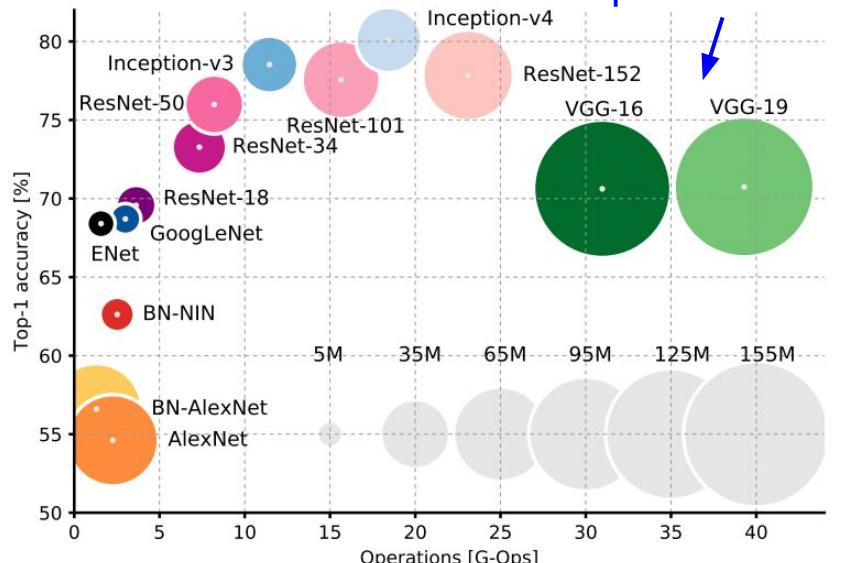
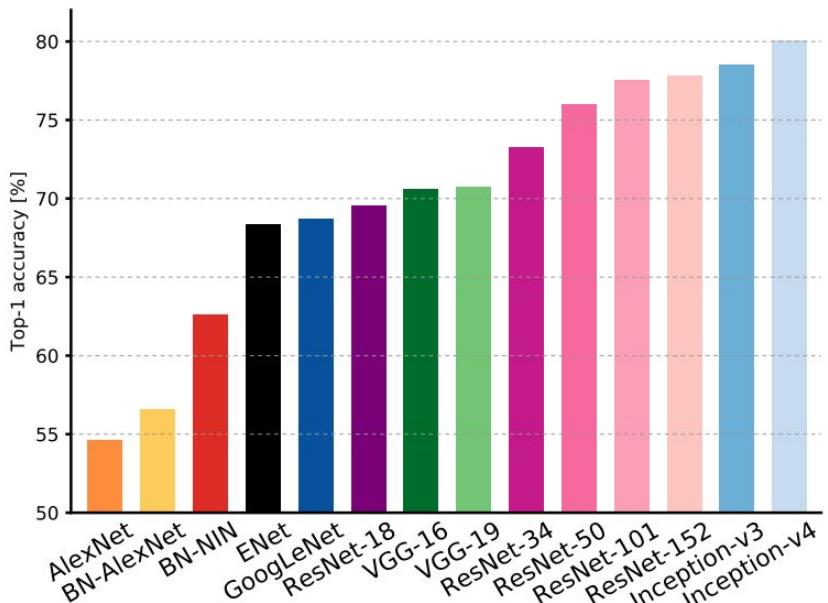
Inception-v4: Resnet + Inception!



An Analysis of Deep Neural Network Models for Practical Applications, 2017.

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Comparing complexity...

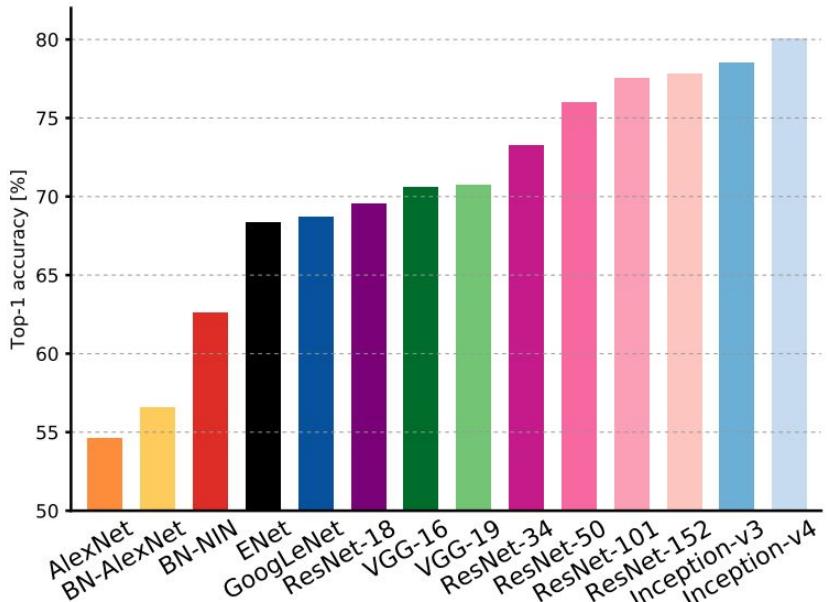


VGG: most parameters, most operations

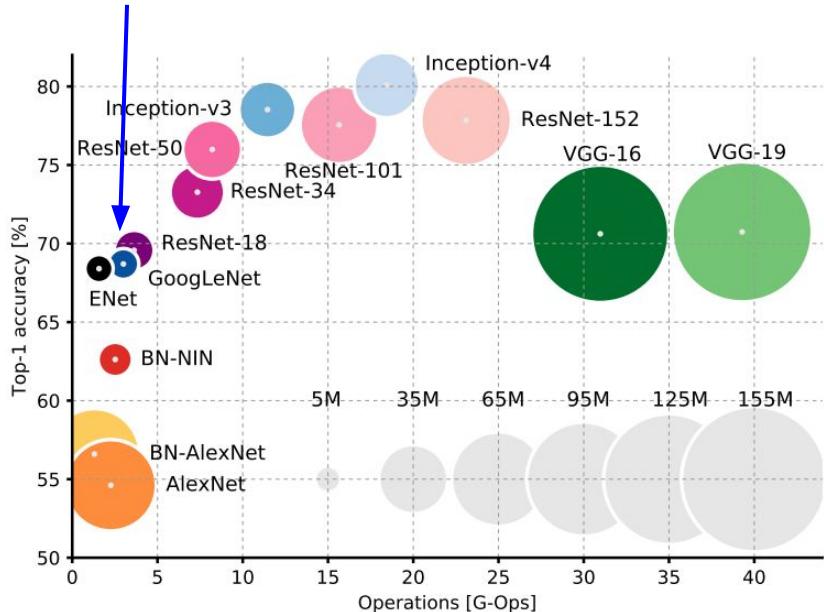
An Analysis of Deep Neural Network Models for Practical Applications, 2017.

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Comparing complexity...



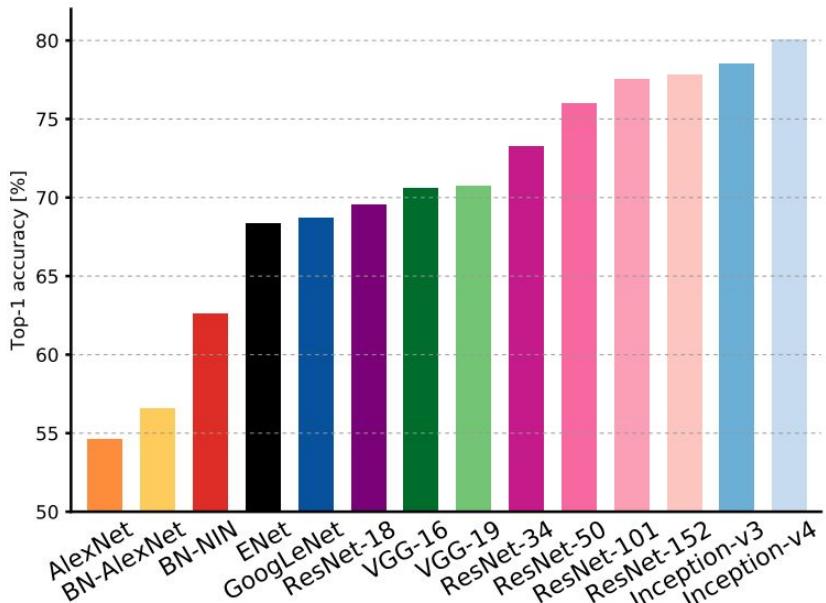
GoogLeNet:
most efficient



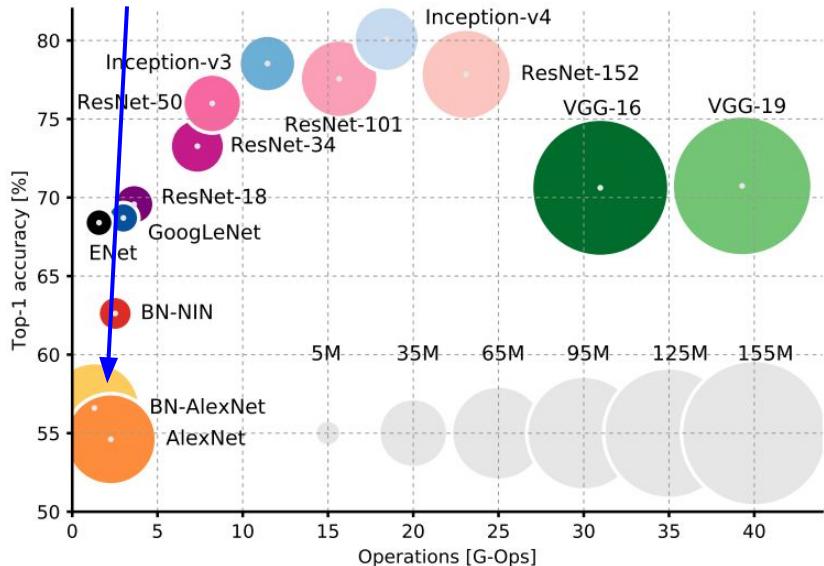
An Analysis of Deep Neural Network Models for Practical Applications, 2017.

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Comparing complexity...



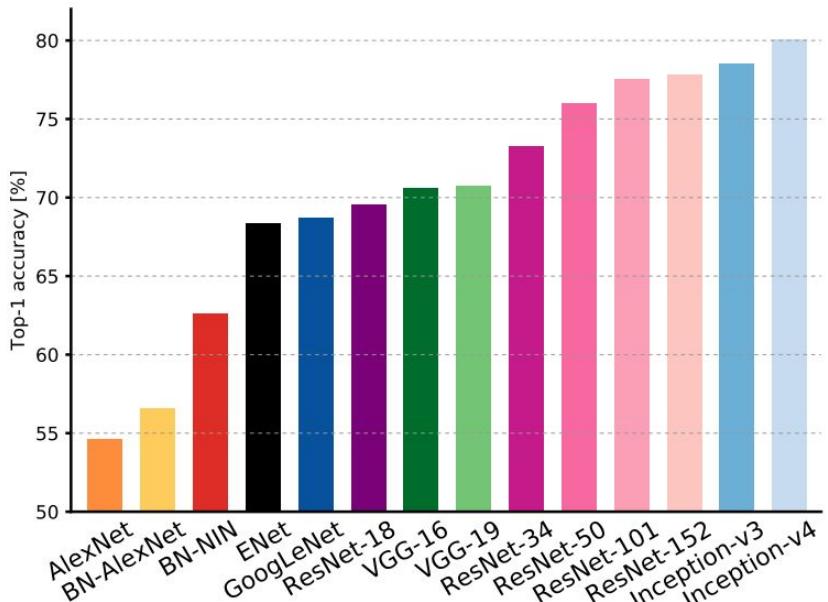
AlexNet:
Smaller compute, still memory heavy, lower accuracy



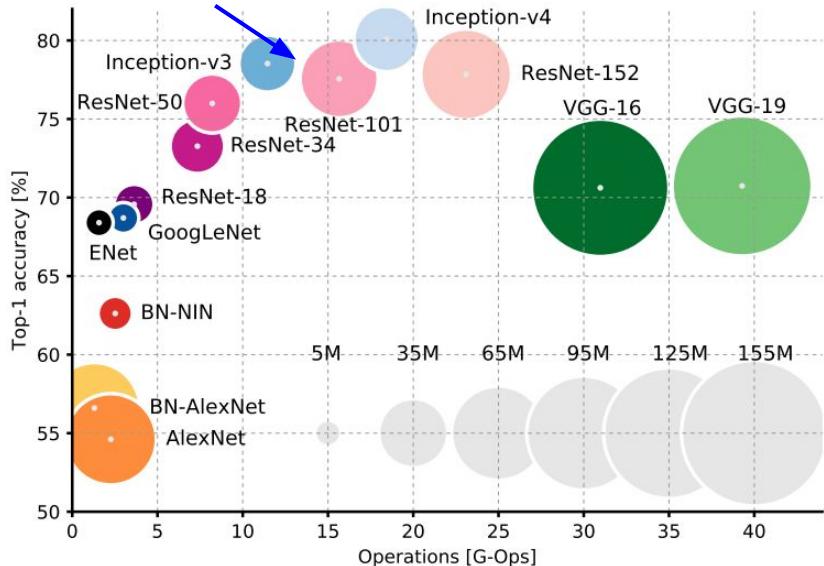
An Analysis of Deep Neural Network Models for Practical Applications, 2017.

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Comparing complexity...



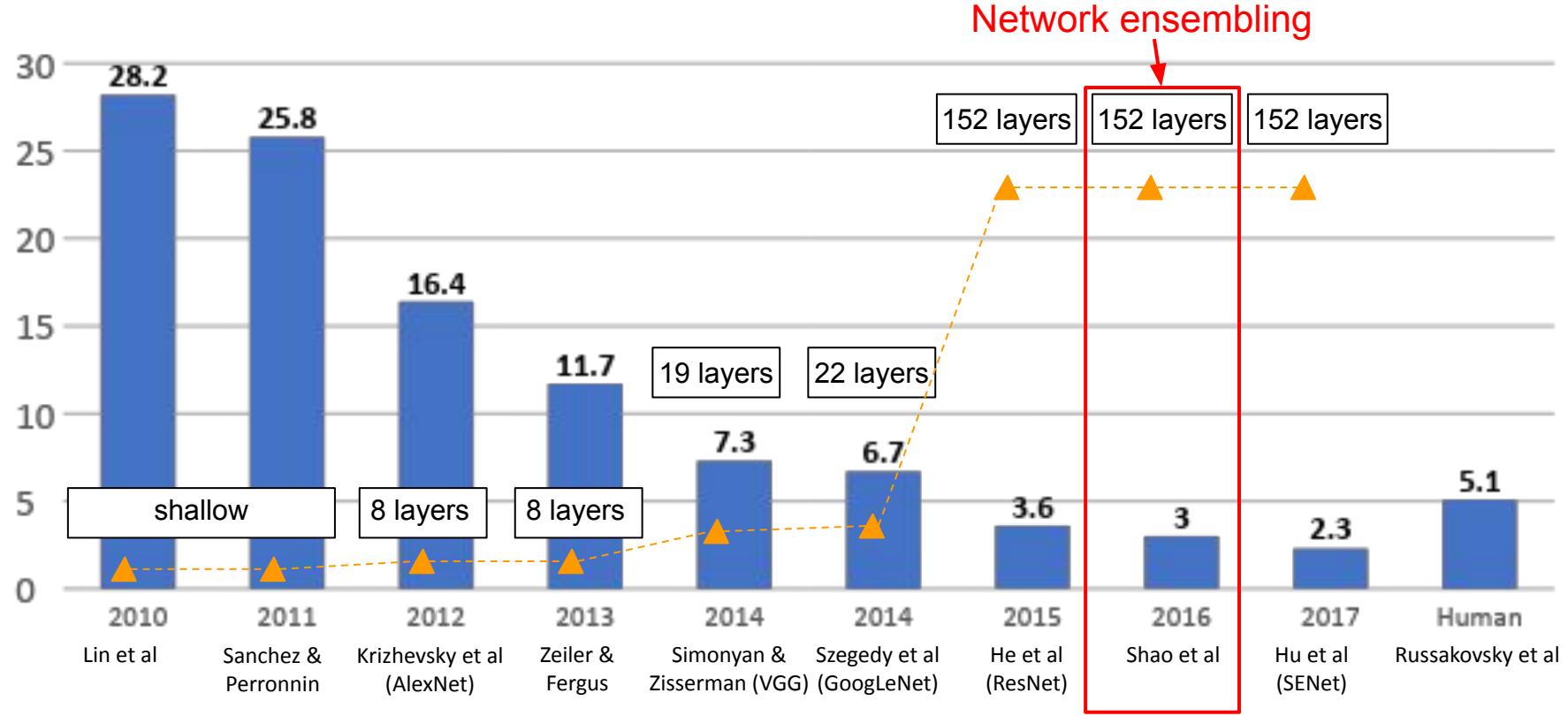
ResNet:
Moderate efficiency depending on
model, highest accuracy



An Analysis of Deep Neural Network Models for Practical Applications, 2017.

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ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Improving ResNets...

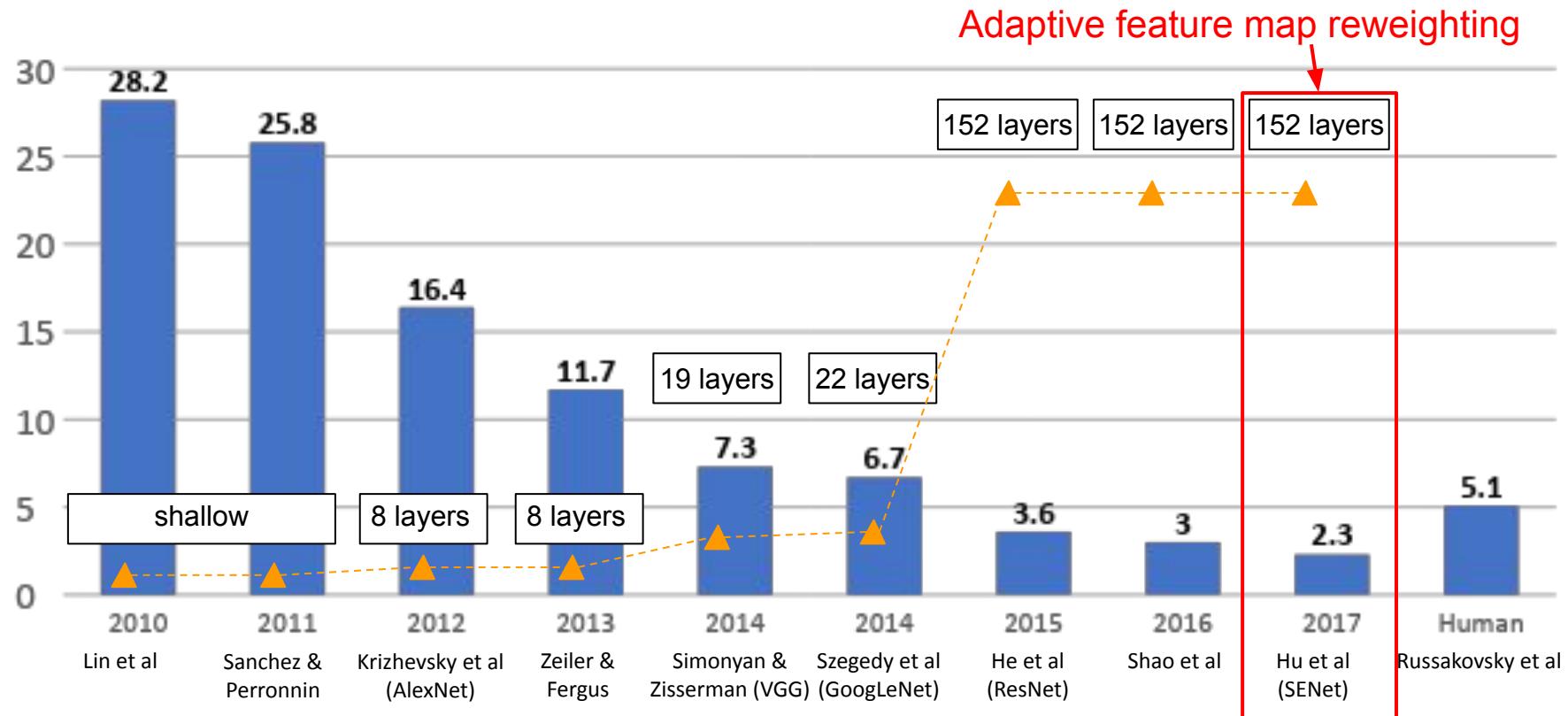
“Good Practices for Deep Feature Fusion”

[Shao et al. 2016]

- Multi-scale ensembling of Inception, Inception-Resnet, Resnet, Wide Resnet models
- ILSVRC'16 classification winner

	Inception-v3	Inception-v4	Inception-Resnet-v2	Resnet-200	Wrn-68-3	Fusion (Val.)	Fusion (Test)
Err. (%)	4.20	4.01	3.52	4.26	4.65	2.92 (-0.6)	2.99

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

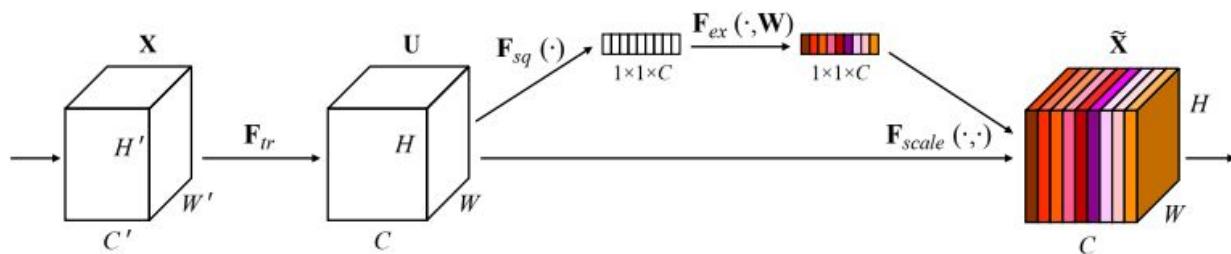
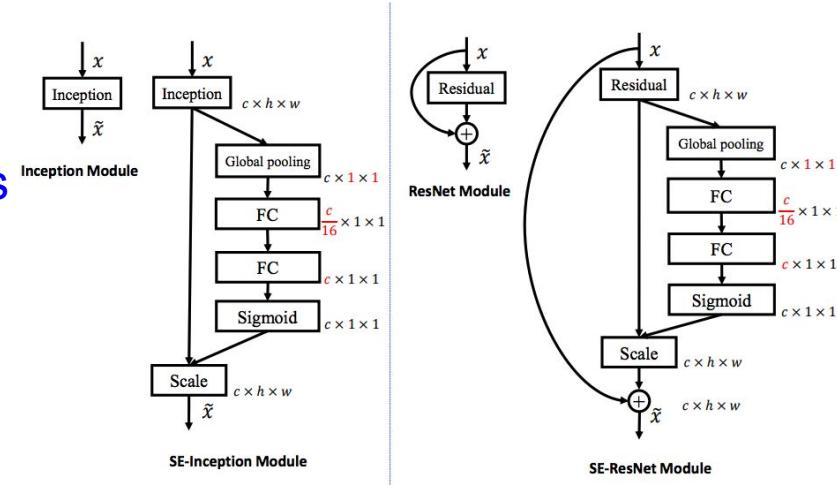


Improving ResNets...

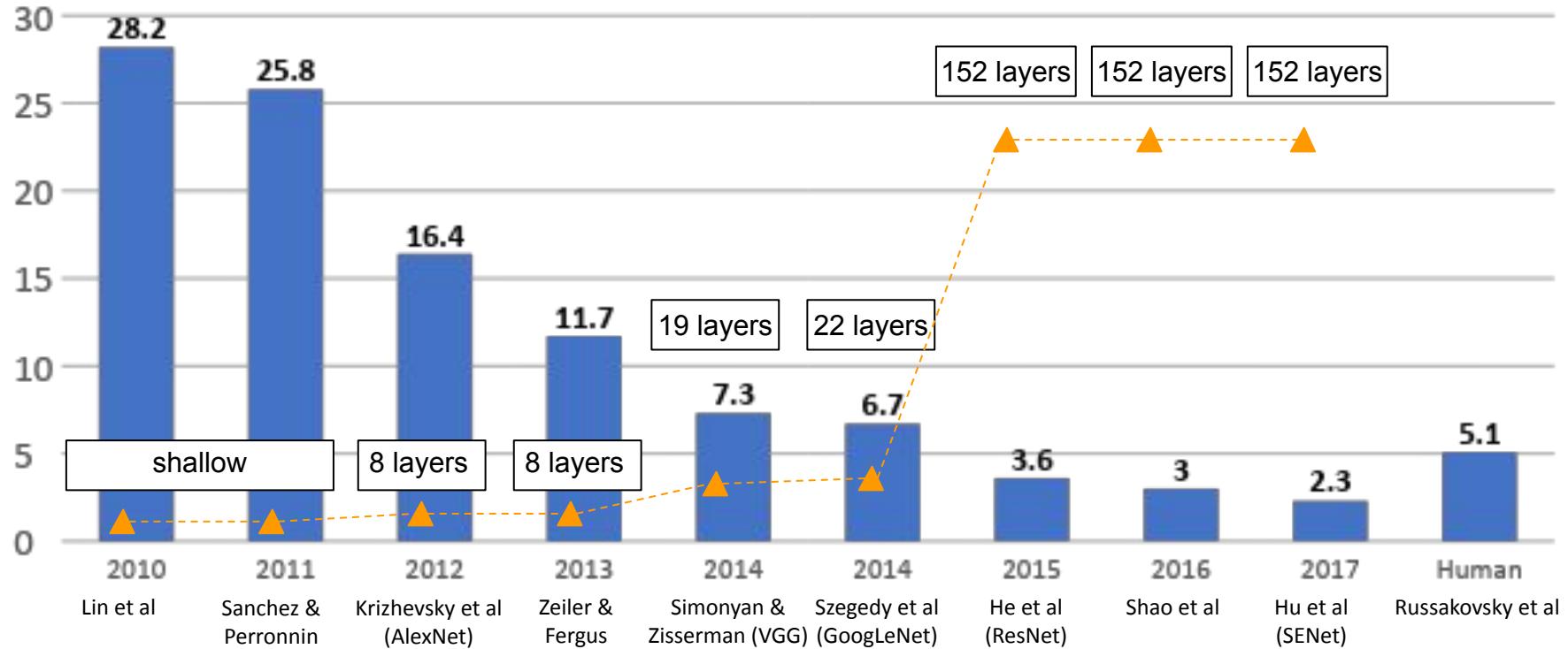
Squeeze-and-Excitation Networks (SENet)

[Hu et al. 2017]

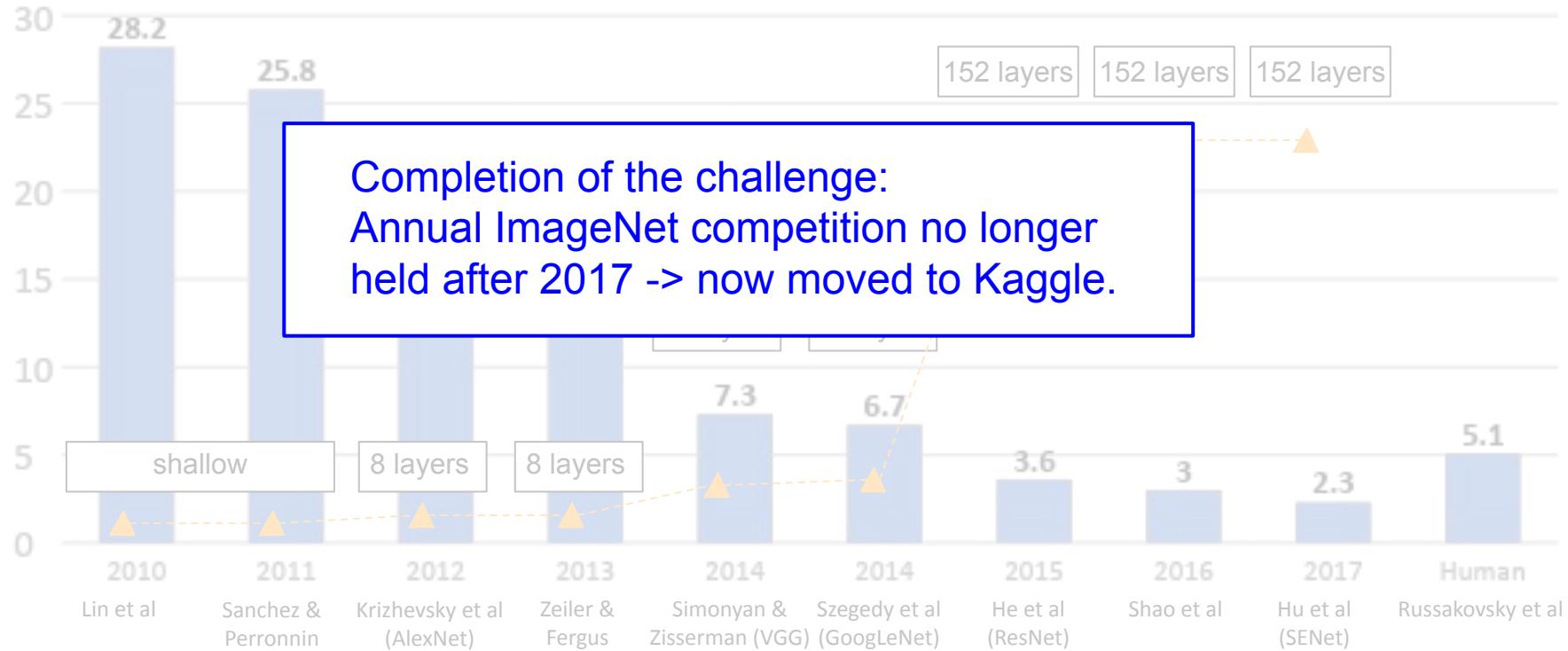
- Add a “feature recalibration” module that learns to adaptively reweight feature maps
- Global information (global avg. pooling layer) + 2 FC layers used to determine feature map weights
- ILSVRC’17 classification winner (using ResNeXt-152 as a base architecture)



ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



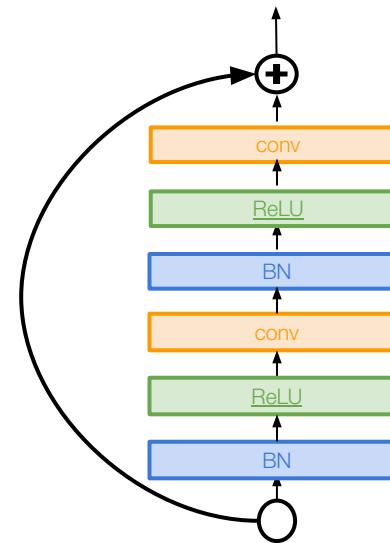
But research into CNN architectures is still flourishing

Improving ResNets...

Identity Mappings in Deep Residual Networks

[He et al. 2016]

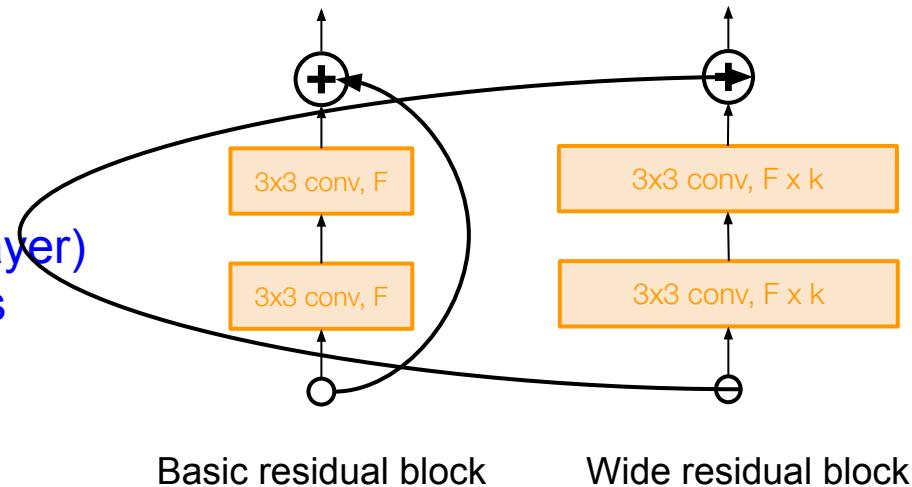
- Improved ResNet block design from creators of ResNet
- Creates a more direct path for propagating information throughout network
- Gives better performance



Wide Residual Networks

[Zagoruyko et al. 2016]

- Argues that residuals are the important factor, not depth
- Use wider residual blocks ($F \times k$ filters instead of F filters in each layer)
- 50-layer wide ResNet outperforms 152-layer original ResNet
- Increasing width instead of depth more computationally efficient (parallelizable)

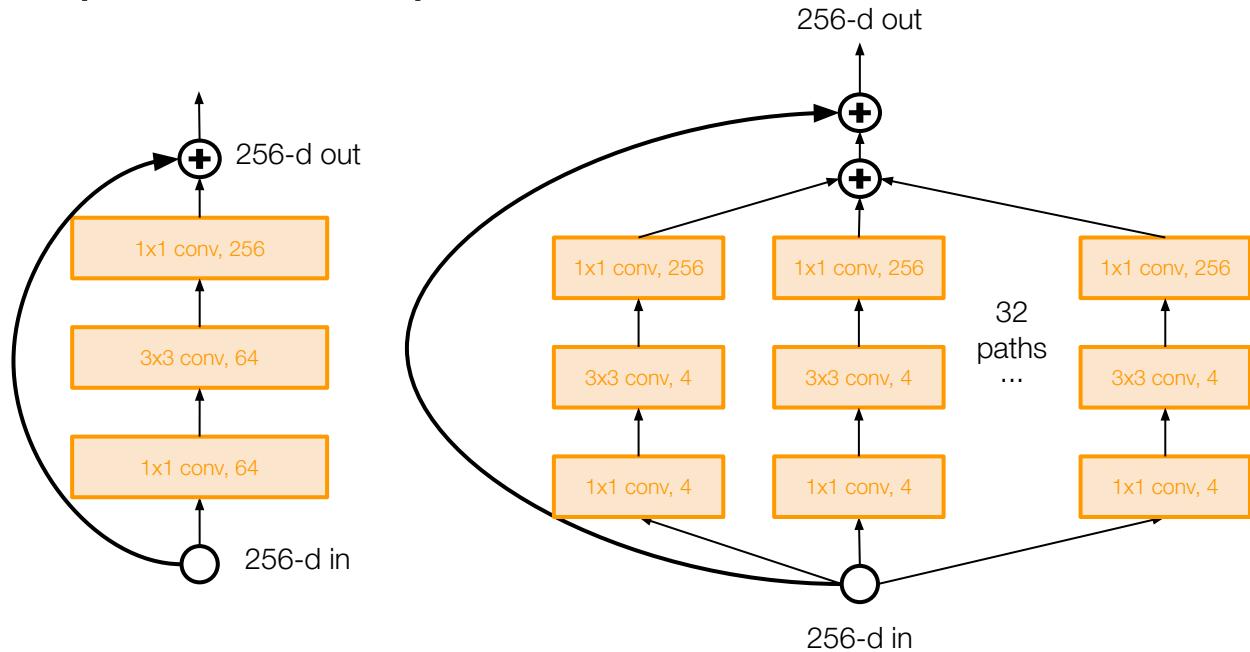


Improving ResNets...

Aggregated Residual Transformations for Deep Neural Networks (ResNeXt)

[Xie et al. 2016]

- Also from creators of ResNet
- Increases width of residual block through multiple parallel pathways (“cardinality”)
- Parallel pathways similar in spirit to Inception module

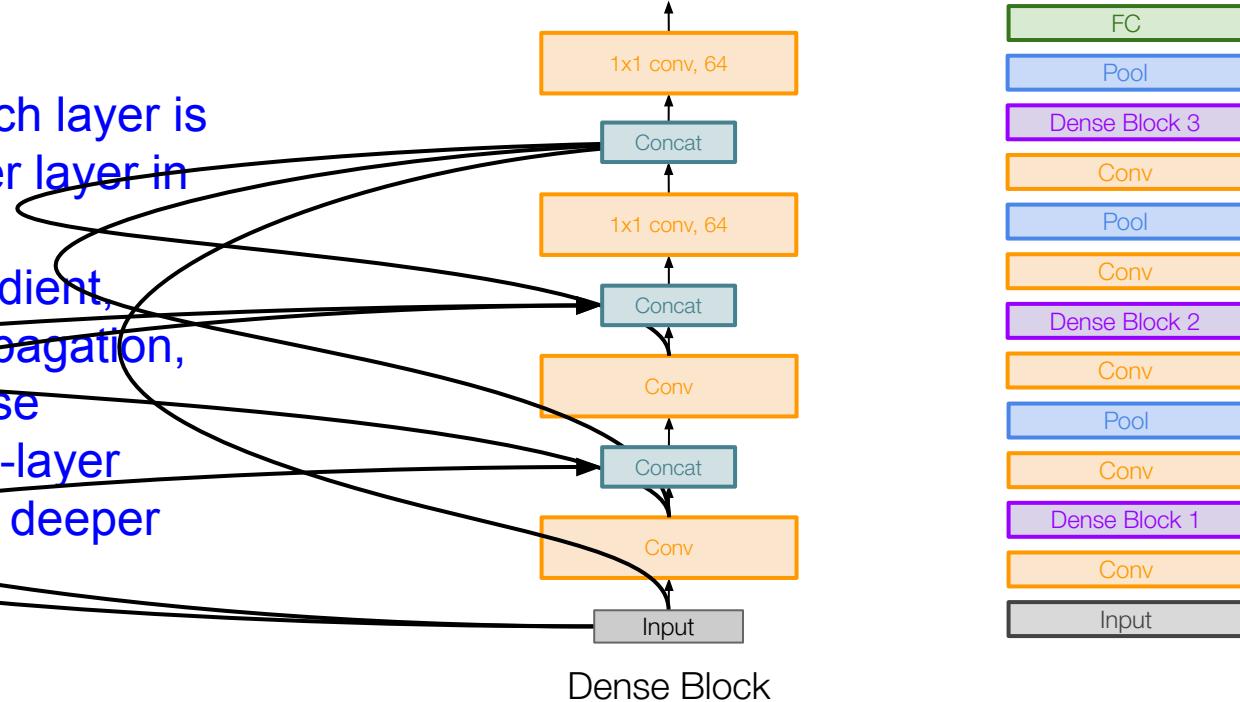


Other ideas...

Densely Connected Convolutional Networks (DenseNet)

[Huang et al. 2017]

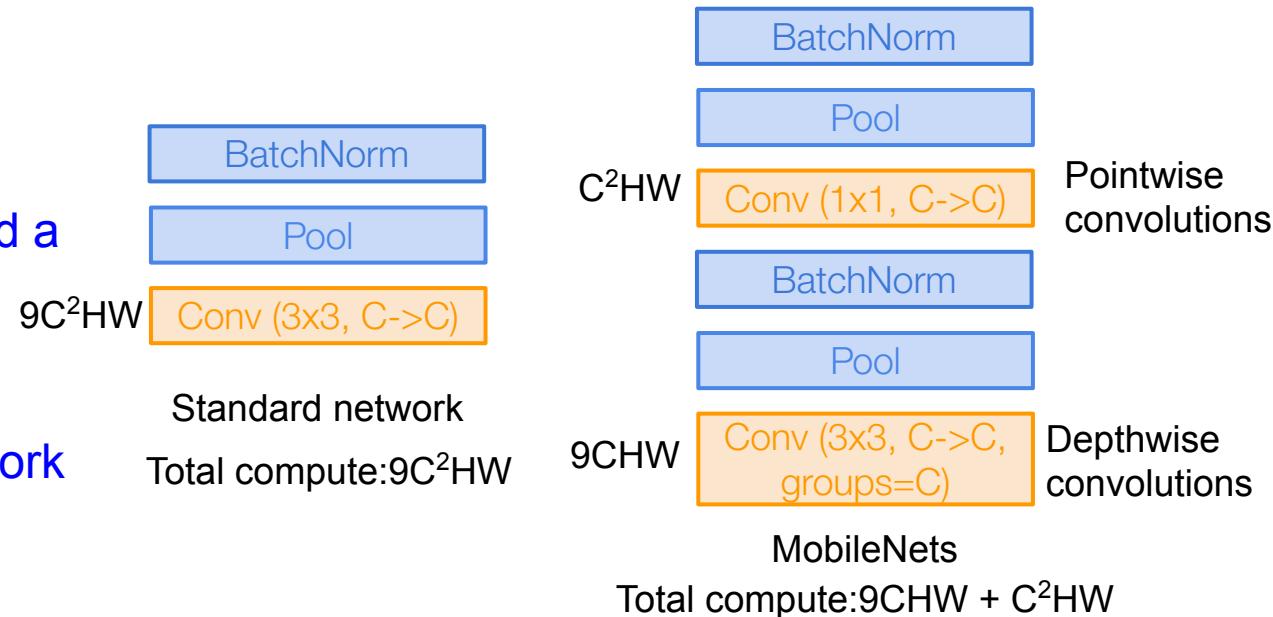
- Dense blocks where each layer is connected to every other layer in feedforward fashion
- Alleviates vanishing gradient, strengthens feature propagation, encourages feature reuse
- Showed that shallow 50-layer network can outperform deeper 152 layer ResNet



Efficient networks...

MobileNets: Efficient Convolutional Neural Networks for Mobile Applications [Howard et al. 2017]

- Depthwise separable convolutions replace standard convolutions by factorizing them into a depthwise convolution and a 1×1 convolution
- Much more efficient, with little loss in accuracy
- Follow-up MobileNetV2 work in 2018 (Sandler et al.)
- ShuffleNet: Zhang et al., CVPR 2018

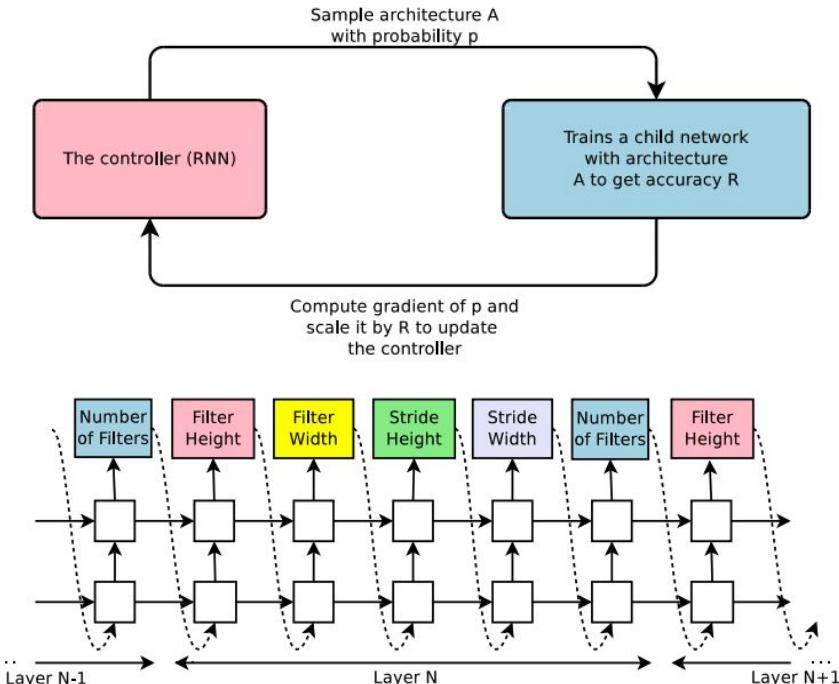


Learning to search for network architectures...

Neural Architecture Search with Reinforcement Learning (NAS)

[Zoph et al. 2016]

- “Controller” network that learns to design a good network architecture (output a string corresponding to network design)
- Iterate:
 - 1) Sample an architecture from search space
 - 2) Train the architecture to get a “reward” R corresponding to accuracy
 - 3) Compute gradient of sample probability, and scale by R to perform controller parameter update (i.e. increase likelihood of good architecture being sampled, decrease likelihood of bad architecture)

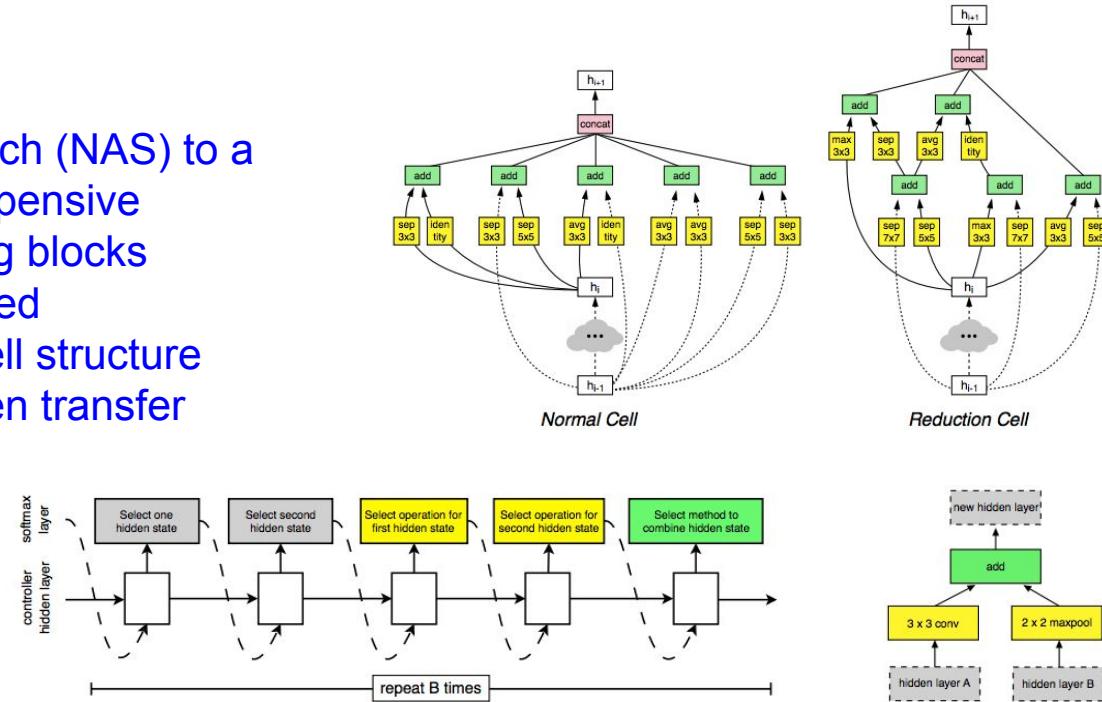


Learning to search for network architectures...

Learning Transferable Architectures for Scalable Image Recognition

[Zoph et al. 2017]

- Applying neural architecture search (NAS) to a large dataset like ImageNet is expensive
- Design a search space of building blocks (“cells”) that can be flexibly stacked
- NASNet: Use NAS to find best cell structure on smaller CIFAR-10 dataset, then transfer architecture to ImageNet
- Many follow-up works in this space e.g. AmoebaNet (Real et al. 2019) and ENAS (Pham, Guan et al. 2018)



But sometimes smart heuristic is better than NAS ...

EfficientNet: Smart Compound Scaling

[Tan and Le. 2019]

- Increase network capacity by scaling width, depth, and resolution, while balancing accuracy and efficiency.
- Search for optimal set of compound scaling factors given a compute budget (target memory & flops).
- Scale up using smart heuristic rules

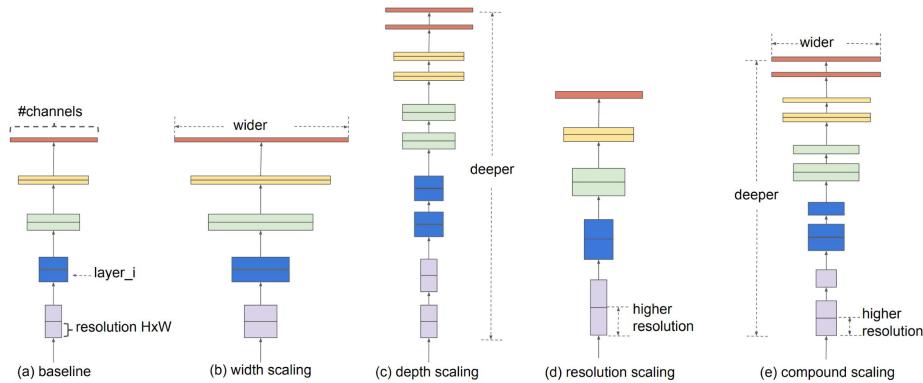
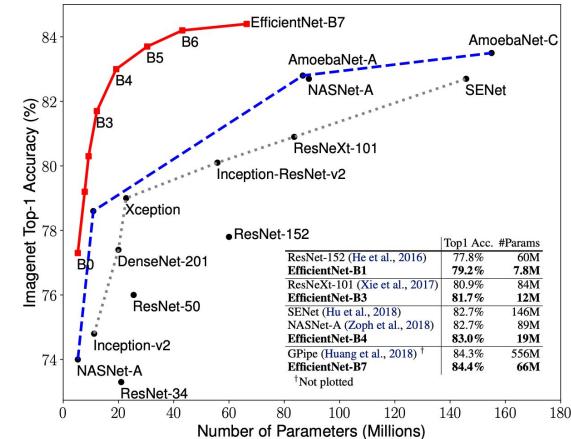
$$\text{depth: } d = \alpha^\phi$$

$$\text{width: } w = \beta^\phi$$

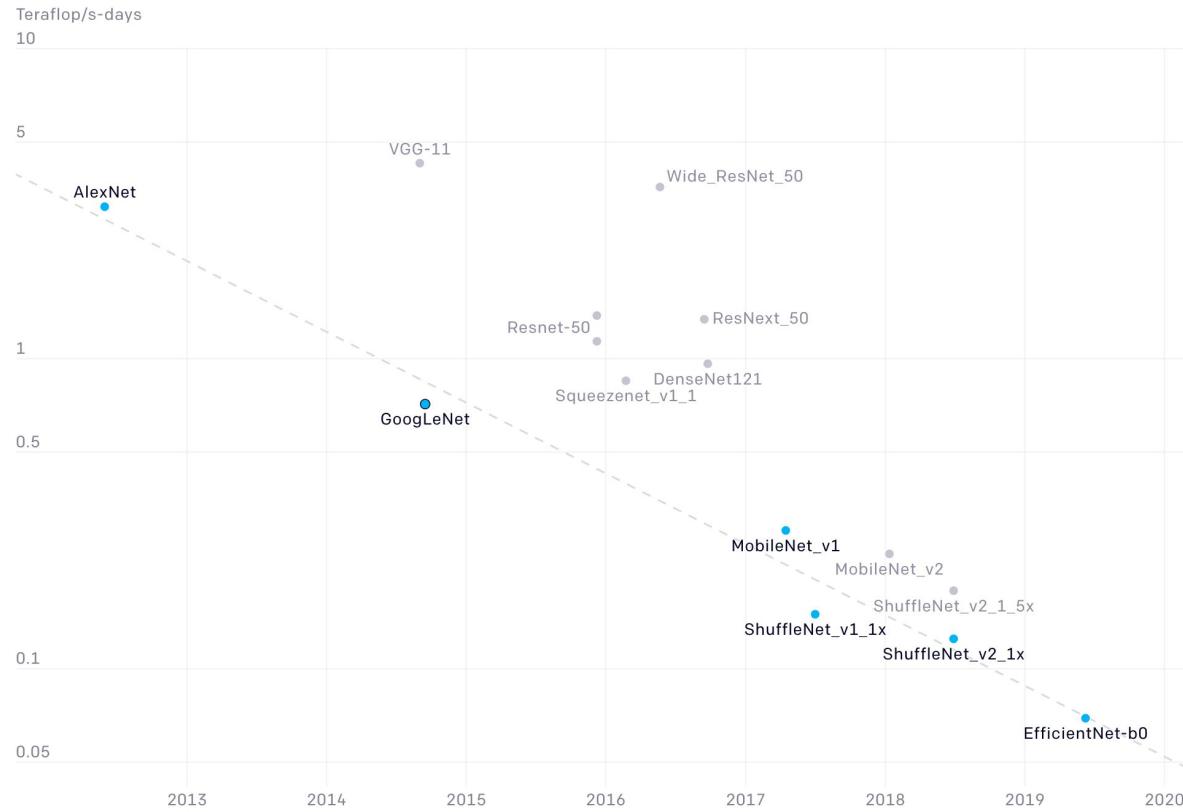
$$\text{resolution: } r = \gamma^\phi$$

$$\text{s.t. } \alpha \cdot \beta^2 \cdot \gamma^2 \approx 2$$

$$\alpha \geq 1, \beta \geq 1, \gamma \geq 1$$



Efficient networks...



<https://openai.com/blog/ai-and-efficiency/>

Summary: CNN Architectures

Case Studies

- AlexNet
- VGG
- GoogLeNet
- ResNet

Also....

- SENet
- Wide ResNet
- ResNeXT
- DenseNet
- MobileNets
- NASNet

Main takeaways

AlexNet showed that you can use CNNs to train Computer Vision models.

ZFNet, VGG shows that bigger networks work better

GoogLeNet is one of the first to focus on efficiency using 1x1 bottleneck convolutions and global avg pool instead of FC layers

ResNet showed us how to train extremely deep networks

- Limited only by GPU & memory!
- Showed diminishing returns as networks got bigger

After ResNet: CNNs were better than the human metric and focus shifted to Efficient networks:

- Lots of tiny networks aimed at mobile devices: **MobileNet, ShuffleNet**

Neural Architecture Search can now automate architecture design

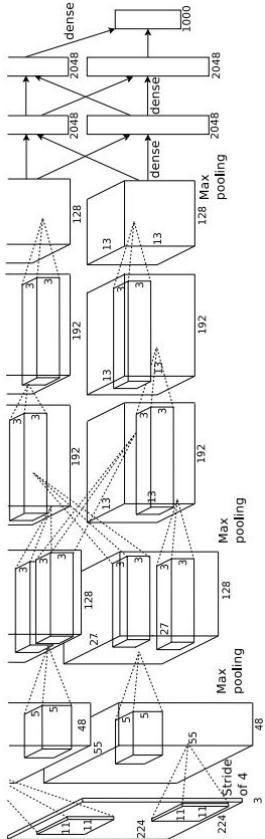
Summary: CNN Architectures

- Many popular architectures are available in model zoos.
- ResNets are currently good defaults to use.
- Networks have gotten increasingly deep over time.
- Many other aspects of network architectures are also continuously being investigated and improved.

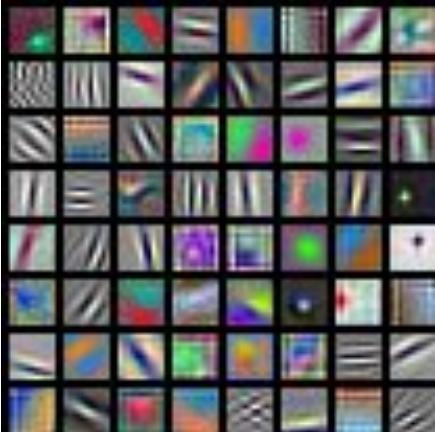
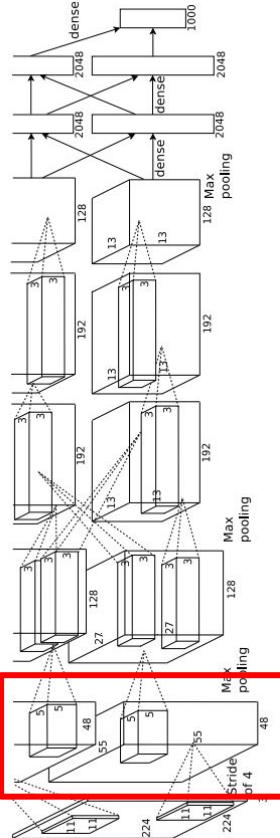
Transfer learning

You need a lot of data if you want to
train/use CNNs?

Transfer Learning with CNNs



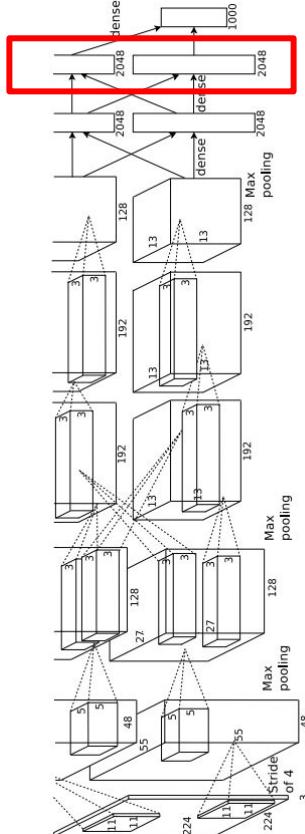
Transfer Learning with CNNs



AlexNet:
64 x 3 x 11 x 11

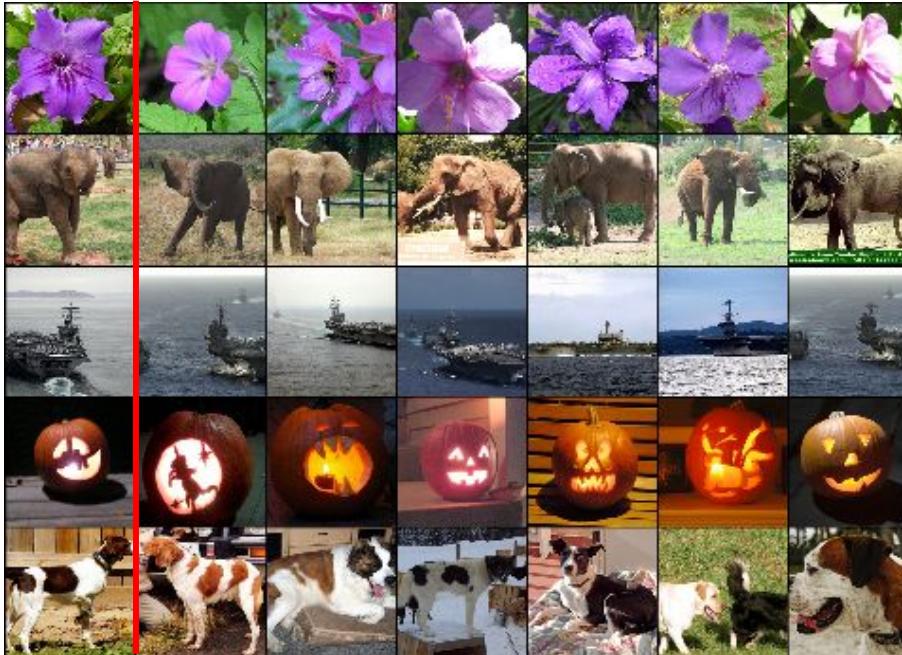
(More on this in Lecture 13)

Transfer Learning with CNNs



Test image

L2 Nearest neighbors in feature space

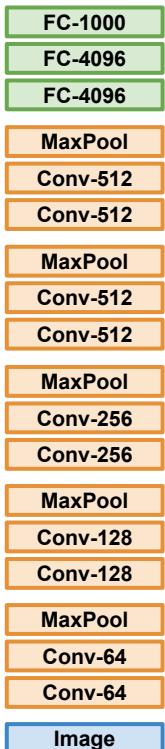


(More on this in Lecture 13)

Transfer Learning with CNNs

Donahue et al, "DeCAF: A Deep Convolutional Activation Feature for Generic Visual Recognition", ICML 2014
Razavian et al, "CNN Features Off-the-Shelf: An Astounding Baseline for Recognition", CVPR Workshops 2014

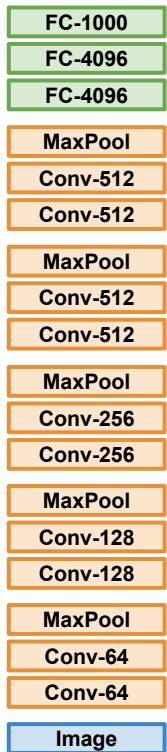
1. Train on Imagenet



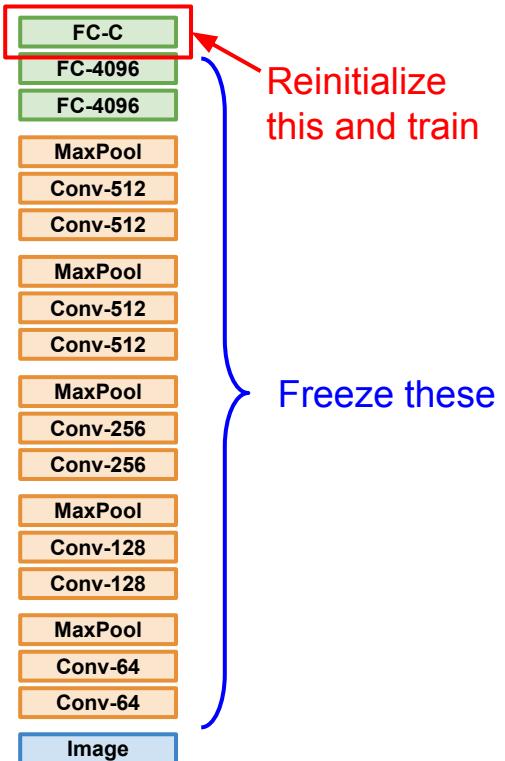
Transfer Learning with CNNs

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1. Train on Imagenet

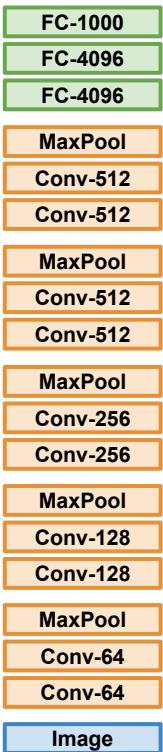


2. Small Dataset (C classes)

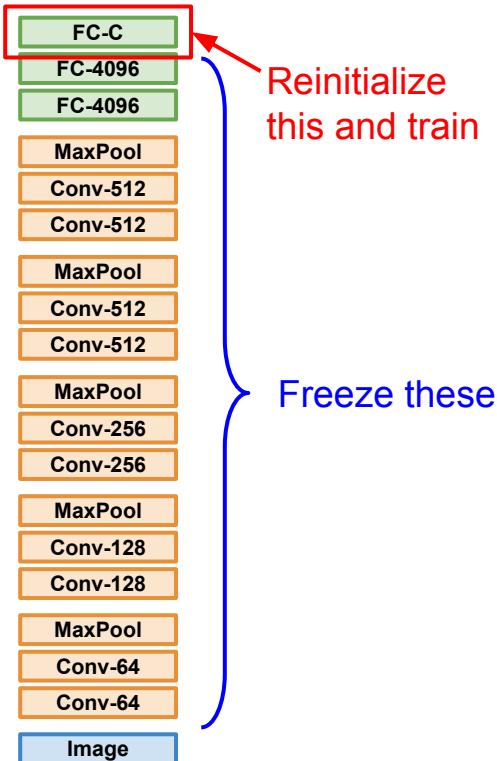


Transfer Learning with CNNs

1. Train on Imagenet

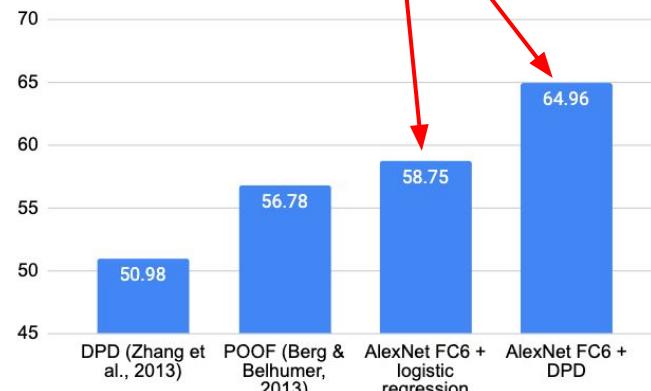


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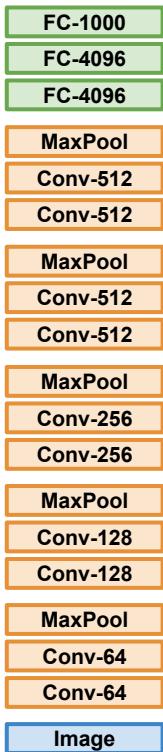
Finetuned from AlexNet



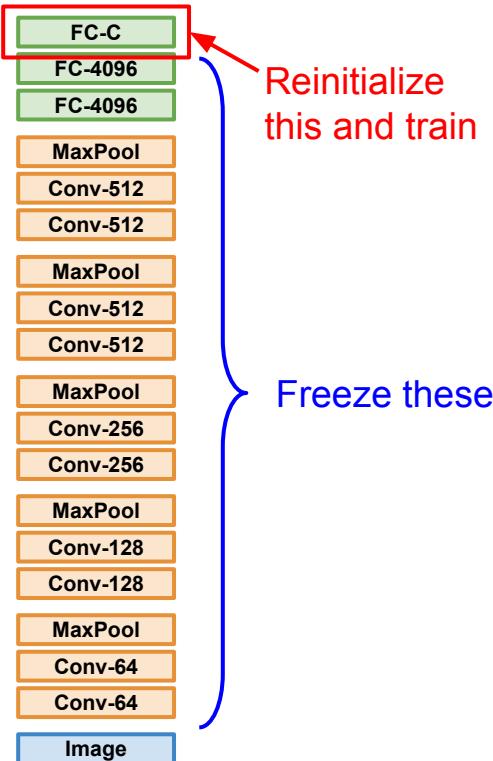
Donahue et al, "DeCAF: A Deep Convolutional Activation Feature for Generic Visual Recognition", ICML 2014

Transfer Learning with CNNs

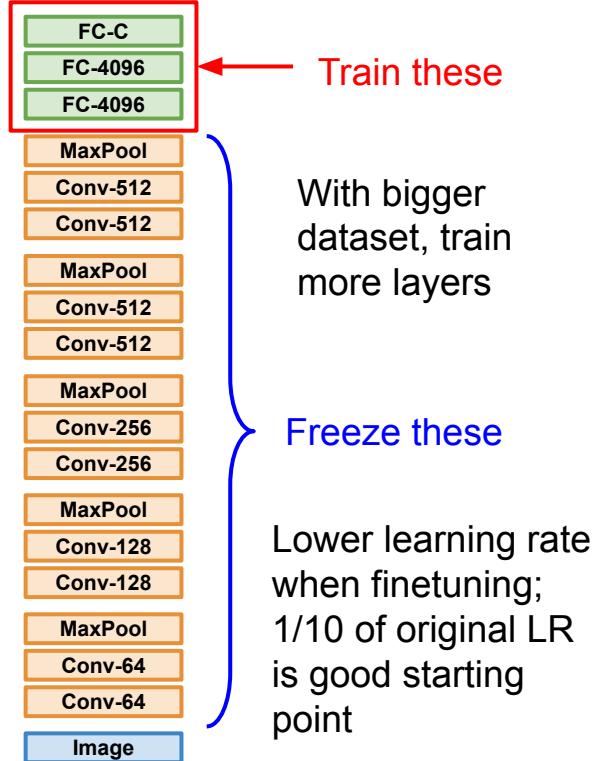
1. Train on Imagenet



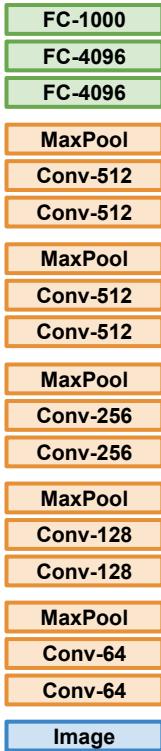
2. Small Dataset (C classes)



3. Bigger dataset



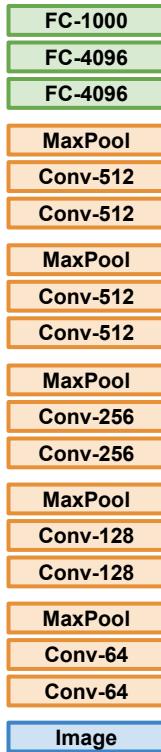
Donahue et al, "DeCAF: A Deep Convolutional Activation Feature for Generic Visual Recognition", ICML 2014
Razavian et al, "CNN Features Off-the-Shelf: An Astounding Baseline for Recognition", CVPR Workshops 2014



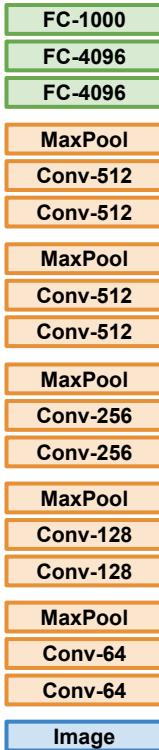
More specific

More generic

	very similar dataset	very different dataset
very little data	?	?
quite a lot of data	?	?



	very similar dataset	very different dataset
very little data	Use Linear Classifier on top layer	?
quite a lot of data	Finetune a few layers	?



	very similar dataset	very different dataset
very little data	Use Linear Classifier on top layer	You're in trouble... Try linear classifier from different stages
quite a lot of data	Finetune a few layers	Finetune a larger number of layers

Transfer learning with CNNs is pervasive... (it's the norm, not an exception)

Object Detection (Fast R-CNN)

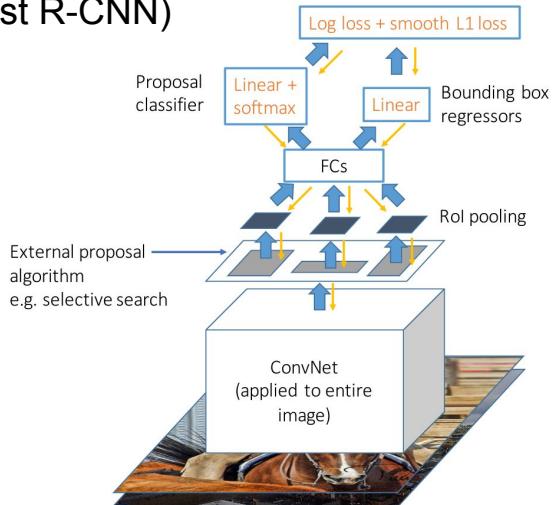
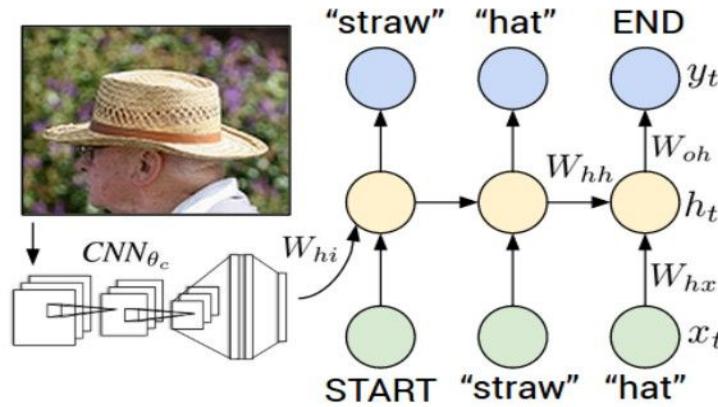


Image Captioning: CNN + RNN

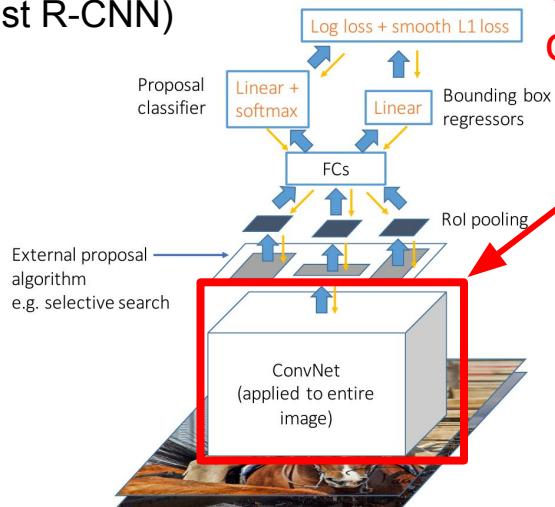


Girshick, "Fast R-CNN", ICCV 2015
Figure copyright Ross Girshick, 2015. Reproduced with permission.

Karpathy and Fei-Fei, "Deep Visual-Semantic Alignments for Generating Image Descriptions", CVPR 2015
Figure copyright IEEE, 2015. Reproduced for educational purposes.

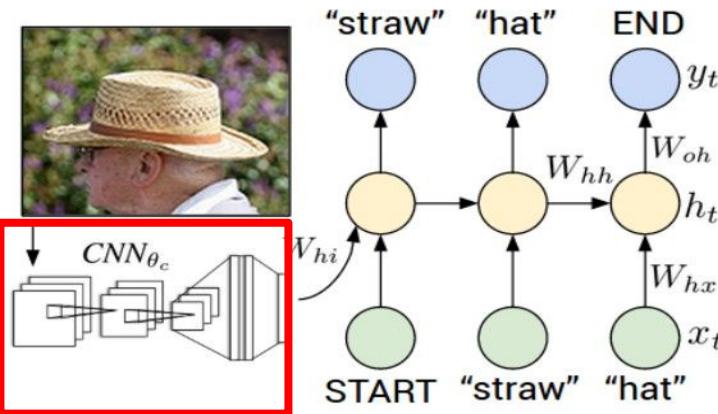
Transfer learning with CNNs is pervasive... (it's the norm, not an exception)

Object Detection
(Fast R-CNN)



CNN pretrained
on ImageNet

Image Captioning: CNN + RNN

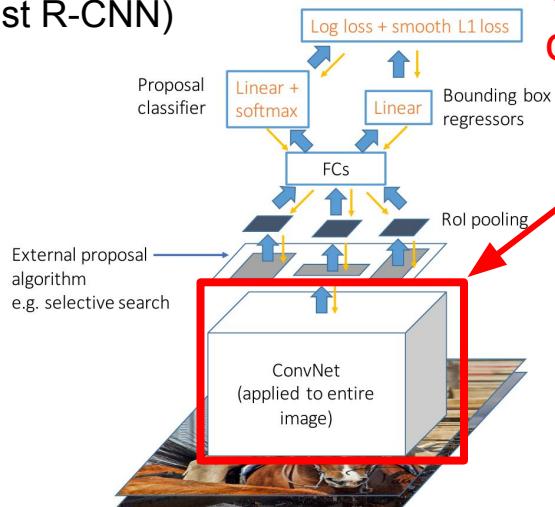


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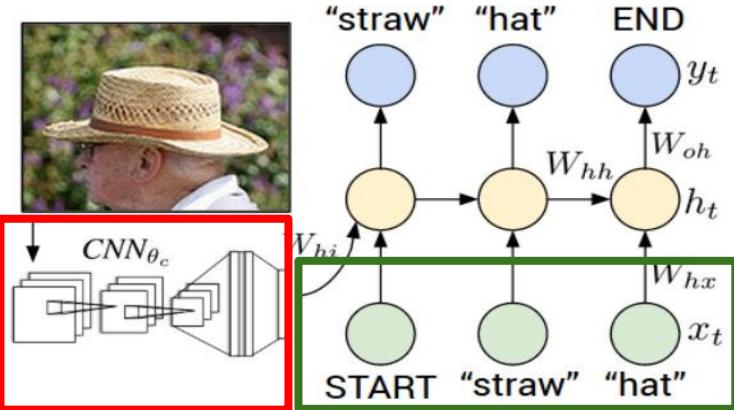
Transfer learning with CNNs is pervasive... (it's the norm, not an exception)

Object Detection
(Fast R-CNN)



CNN pretrained
on ImageNet

Image Captioning: CNN + RNN



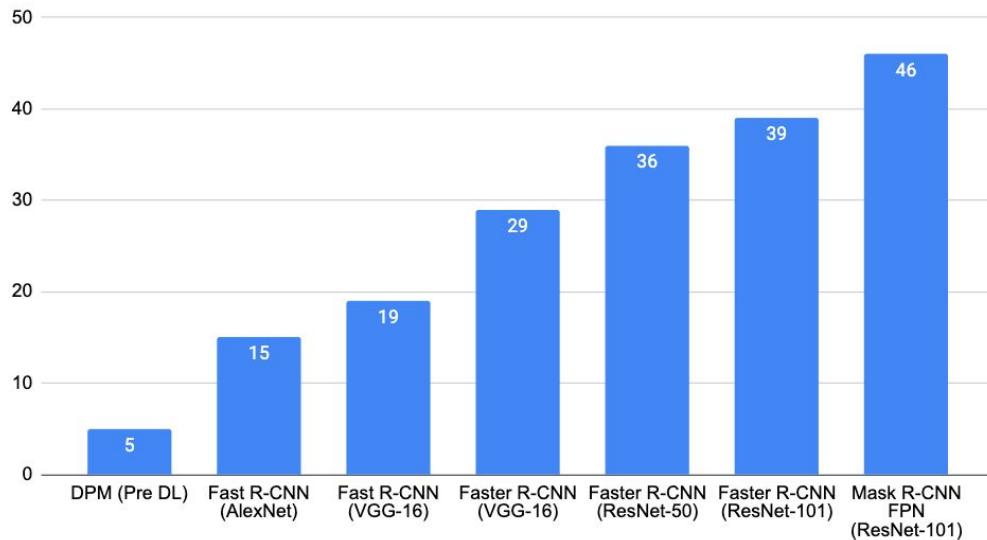
Word vectors pretrained
with word2vec

Girshick, "Fast R-CNN", ICCV 2015
Figure copyright Ross Girshick, 2015. Reproduced with permission.

Karpathy and Fei-Fei, "Deep Visual-Semantic Alignments for Generating Image Descriptions", CVPR 2015
Figure copyright IEEE, 2015. Reproduced for educational purposes.

Transfer learning with CNNs - Architecture matters

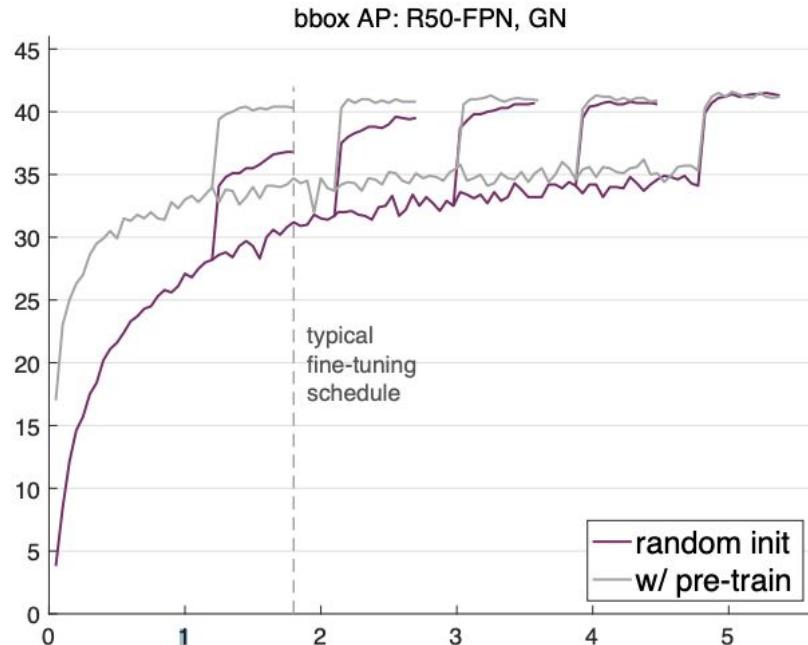
Object detection on MSCOCO



Girshick, "The Generalized R-CNN Framework for Object Detection", ICCV 2017 Tutorial on Instance-Level Visual Recognition

Transfer learning with CNNs is pervasive...

But recent results show it might not always be necessary!



Training from scratch can work just as well as training from a pretrained ImageNet model for object detection

But it takes 2-3x as long to train.

They also find that collecting more data is better than finetuning on a related task

He et al, "Rethinking ImageNet Pre-training", ICCV 2019
Figure copyright Kaiming He, 2019. Reproduced with permission.

Takeaway for your projects and beyond:

Have some dataset of interest but it has < ~1M images?

1. Find a very large dataset that has similar data, train a big ConvNet there
2. Transfer learn to your dataset

Deep learning frameworks provide a “Model Zoo” of pretrained models so you don’t need to train your own

TensorFlow: <https://github.com/tensorflow/models>

PyTorch: <https://github.com/pytorch/vision>

Next time: Training Neural Networks

Lecture 7: Training Neural Networks

Administrative: A2

A2 is out, due Monday May 2nd, 11:59pm

Where we are now...

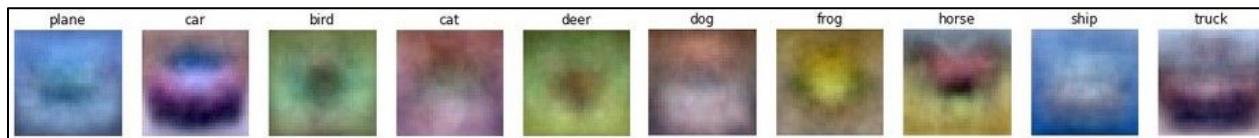
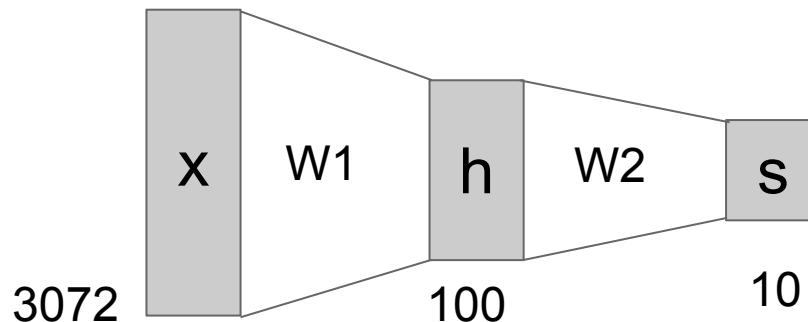
Neural Networks

Linear score function:

$$f = Wx$$

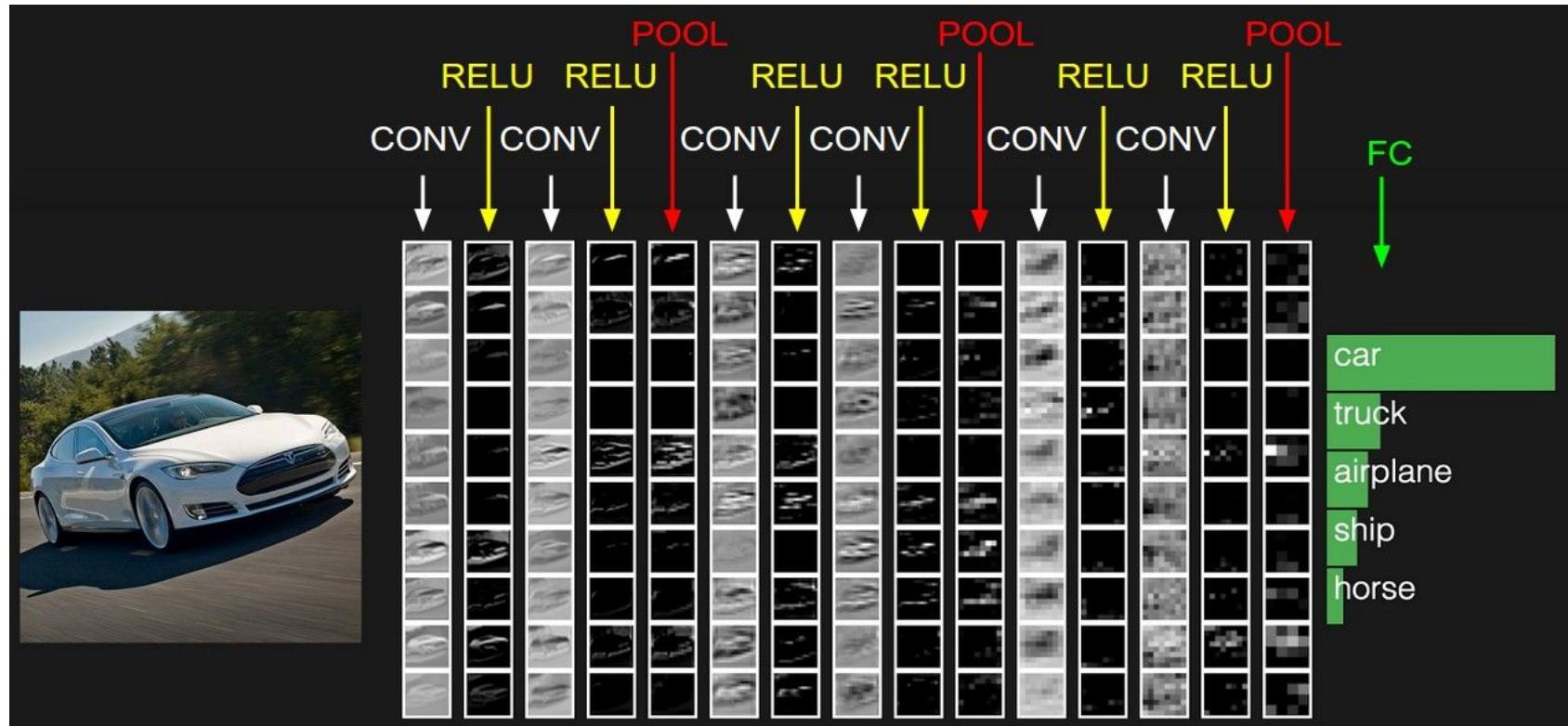
2-layer Neural Network

$$f = W_2 \max(0, W_1 x)$$



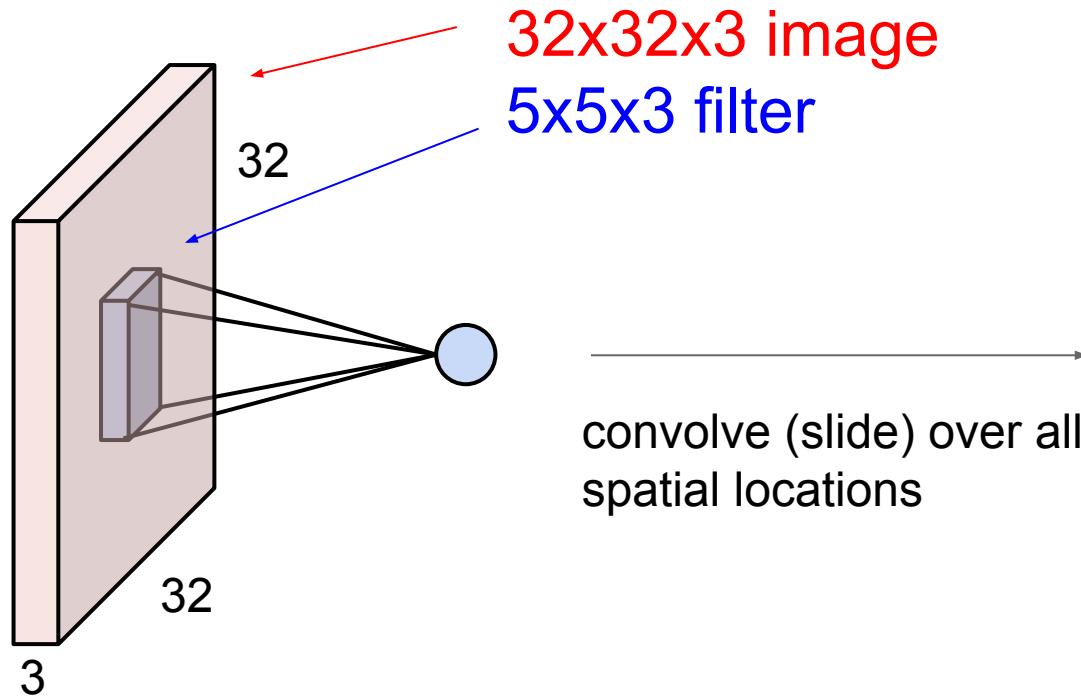
Where we are now...

Convolutional Neural Networks



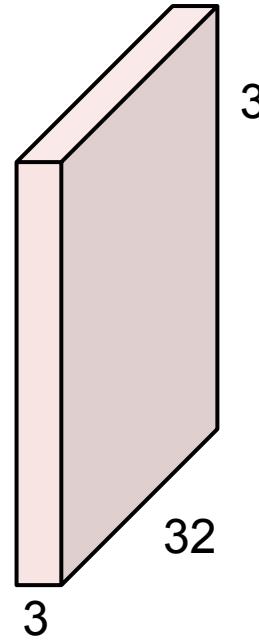
Where we are now...

Convolutional Layer



Where we are now...

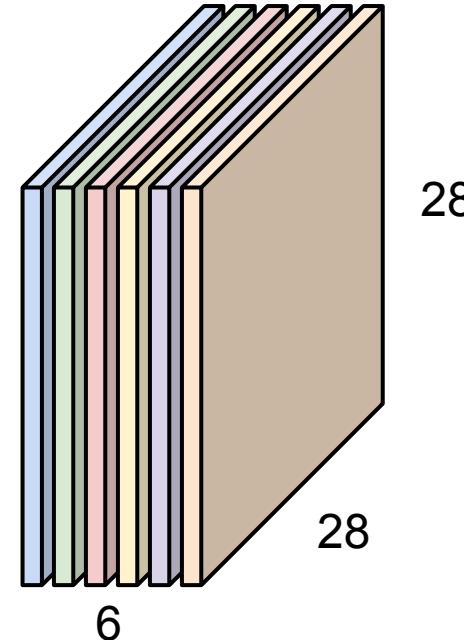
Convolutional Layer



Convolution Layer

For example, if we had 6 5×5 filters, we'll get 6 separate activation maps:

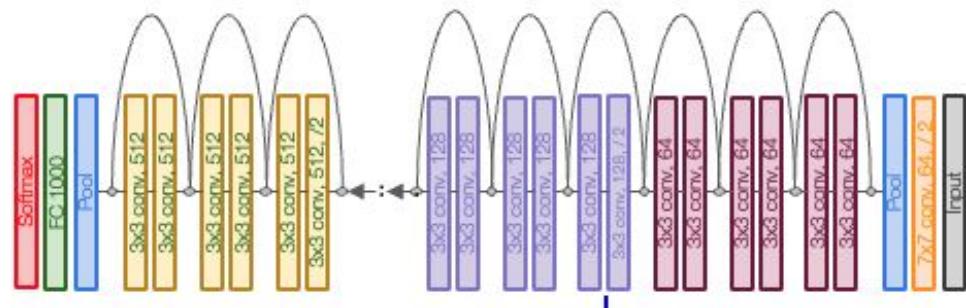
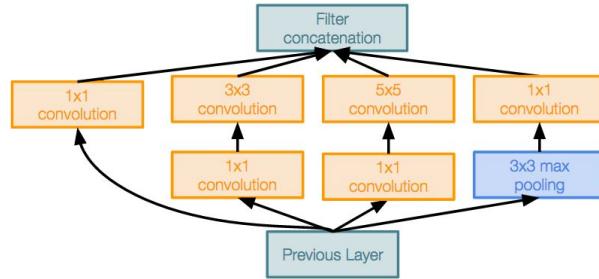
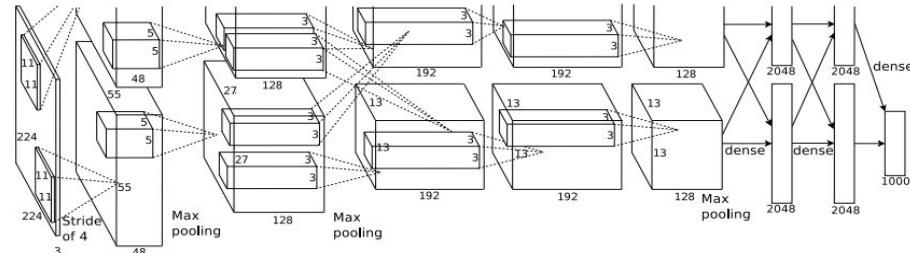
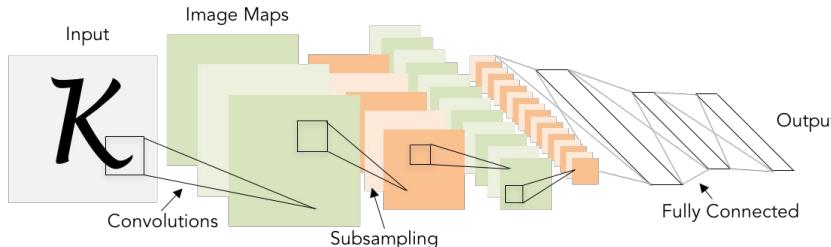
activation maps



We stack these up to get a “new image” of size $28 \times 28 \times 6$!

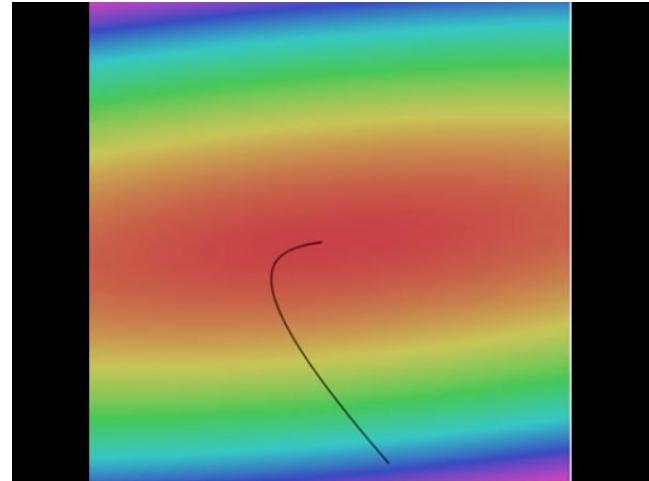
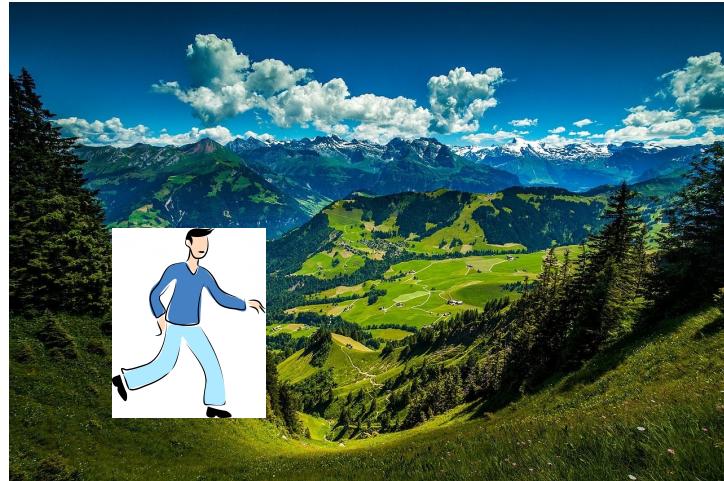
Where we are now...

CNN Architectures



Where we are now...

Learning network parameters through optimization



```
# Vanilla Gradient Descent  
  
while True:  
    weights_grad = evaluate_gradient(loss_fun, data, weights)  
    weights += - step_size * weights_grad # perform parameter update
```

Landscape image is CC0 1.0 public domain
Walking man image is CC0 1.0 public domain

Where we are now...

Mini-batch SGD

Loop:

1. **Sample** a batch of data
2. **Forward** prop it through the graph
(network), get loss
3. **Backprop** to calculate the gradients
4. **Update** the parameters using the gradient

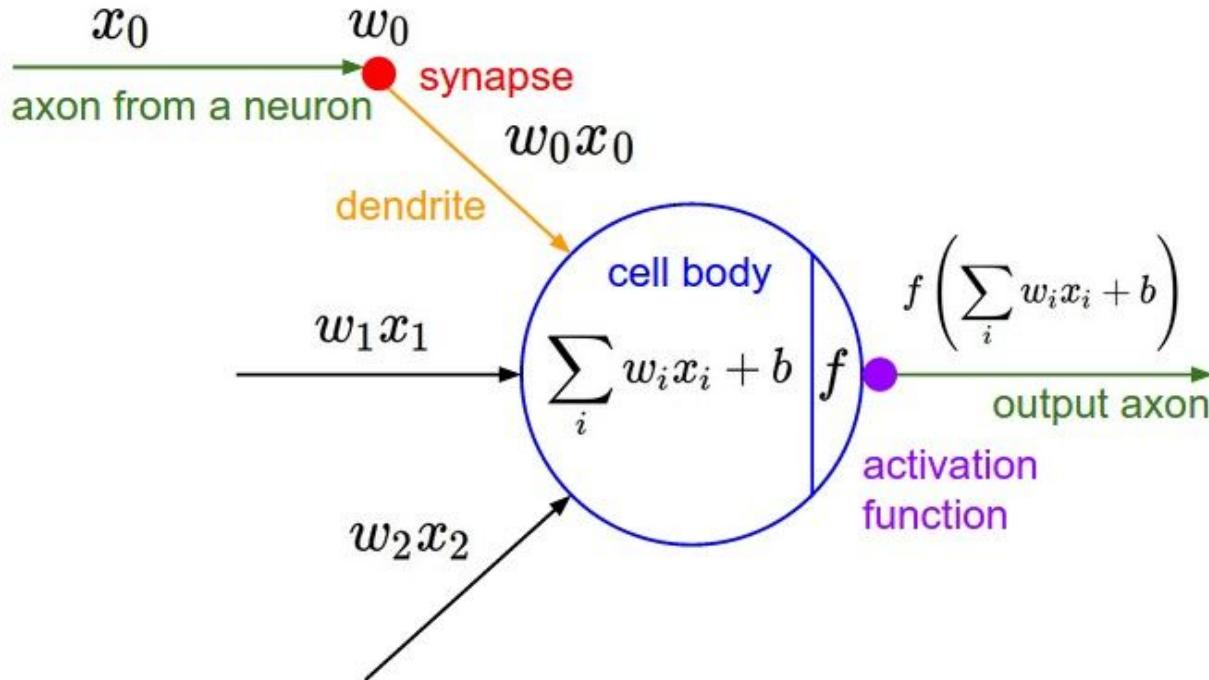
Today: Training Neural Networks

Overview

1. **One time set up:** activation functions, preprocessing, weight initialization, regularization, gradient checking
2. **Training dynamics:** babysitting the learning process, parameter updates, hyperparameter optimization
3. **Evaluation:** model ensembles, test-time augmentation, transfer learning

Activation Functions

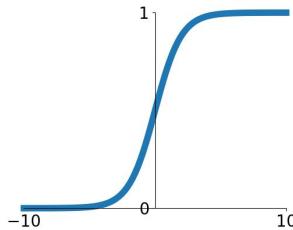
Activation Functions



Activation Functions

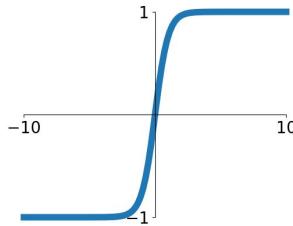
Sigmoid

$$\sigma(x) = \frac{1}{1+e^{-x}}$$



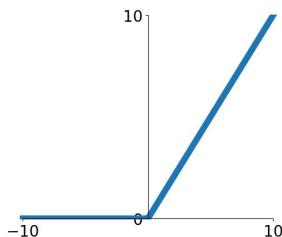
tanh

$$\tanh(x)$$



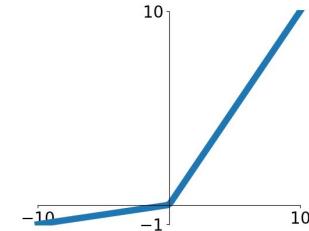
ReLU

$$\max(0, x)$$



Leaky ReLU

$$\max(0.1x, x)$$

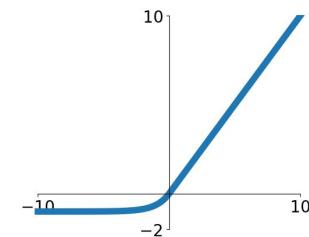


Maxout

$$\max(w_1^T x + b_1, w_2^T x + b_2)$$

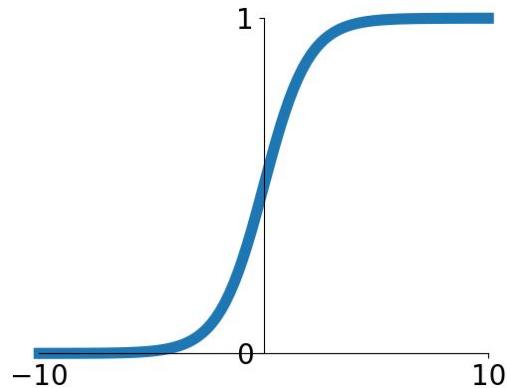
ELU

$$\begin{cases} x & x \geq 0 \\ \alpha(e^x - 1) & x < 0 \end{cases}$$



Activation Functions

$$\sigma(x) = 1/(1 + e^{-x})$$



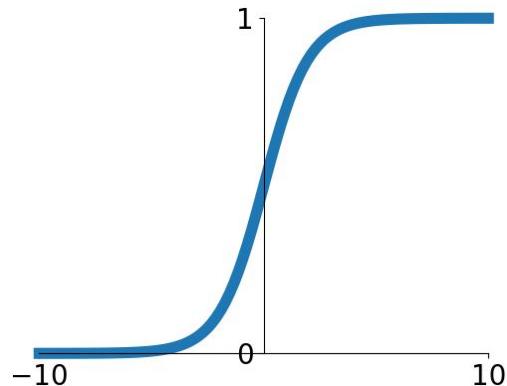
Sigmoid

- Squashes numbers to range [0,1]
- Historically popular since they have nice interpretation as a saturating “firing rate” of a neuron

Activation Functions

$$\sigma(x) = 1/(1 + e^{-x})$$

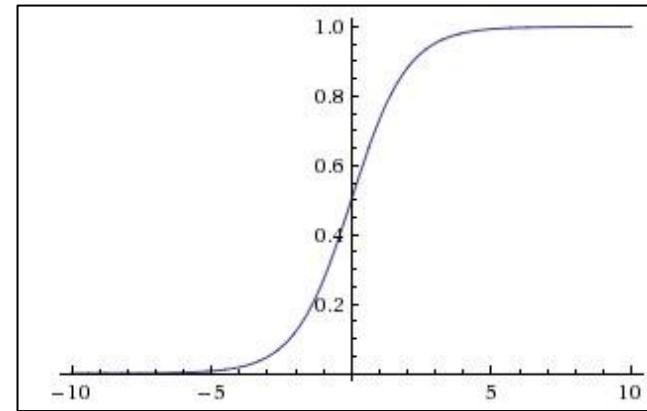
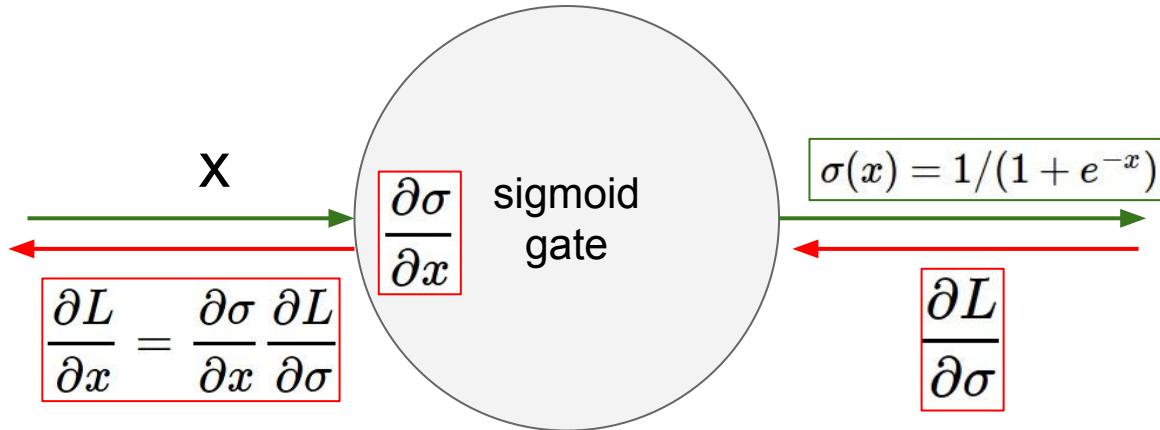
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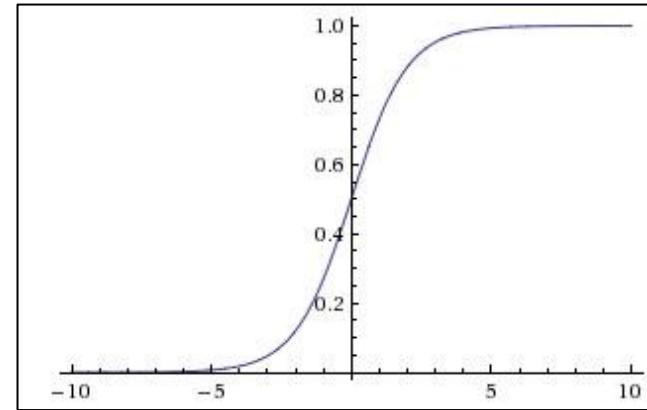
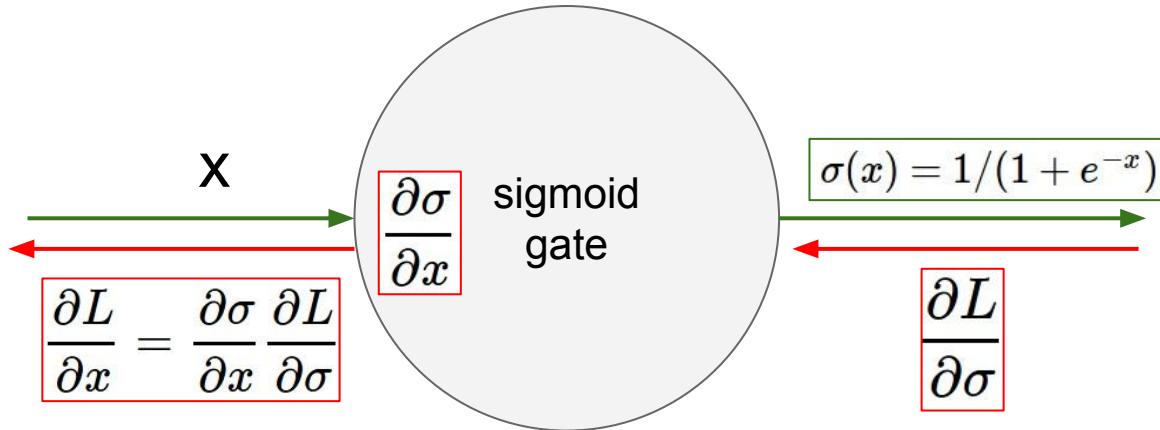
Sigmoid

3 problems:

1. Saturated neurons “kill” the gradients

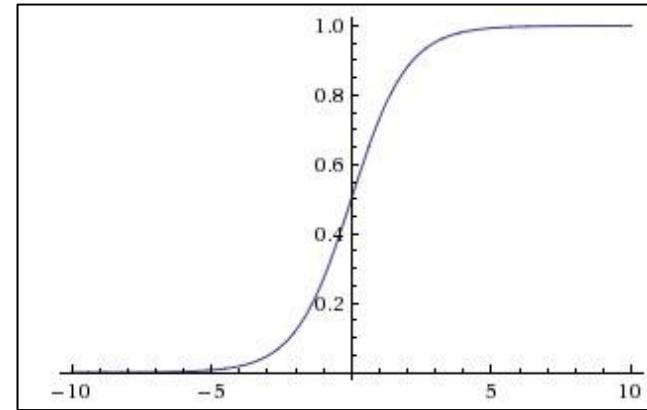
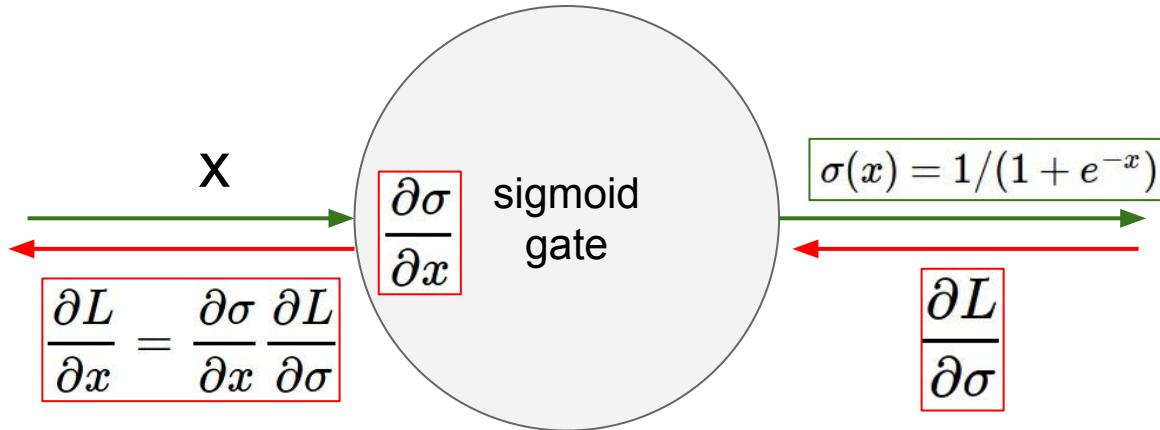


$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x))$$



What happens when $x = -10$?

$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x) (1 - \sigma(x))$$

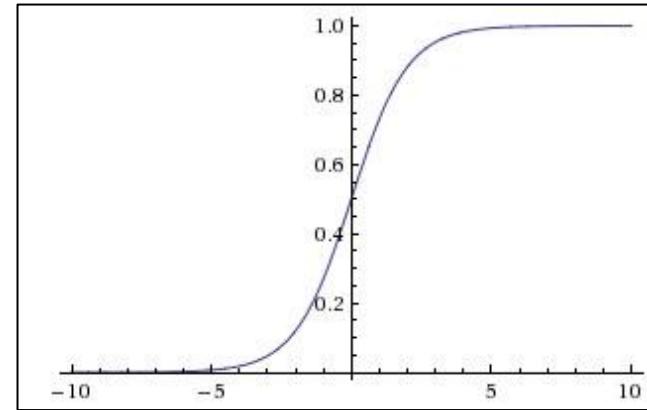
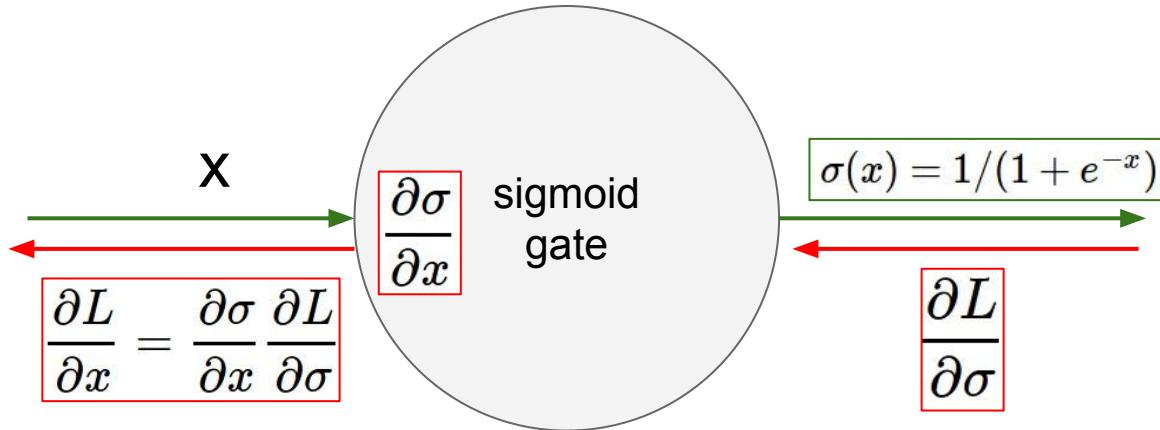


What happens when $x = -10$?

$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x))$$

$$\sigma(x) \approx 0$$

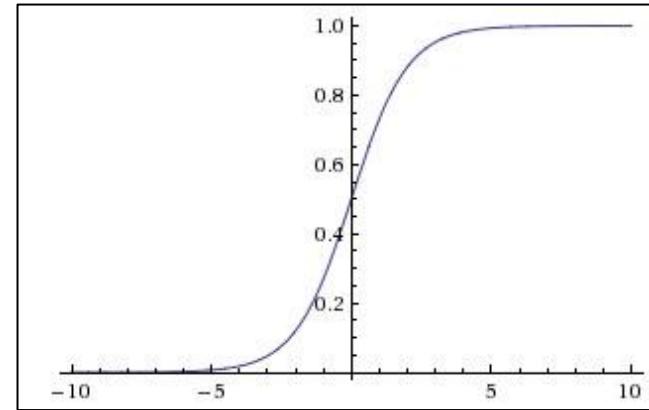
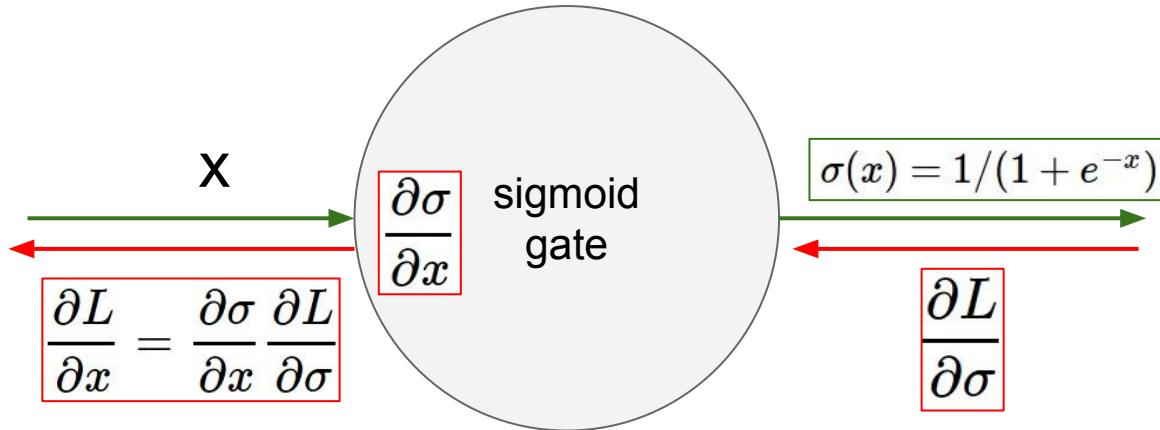
$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x)) = 0(1 - 0) = 0$$



What happens when $x = -10$?

What happens when $x = 0$?

$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x) (1 - \sigma(x))$$



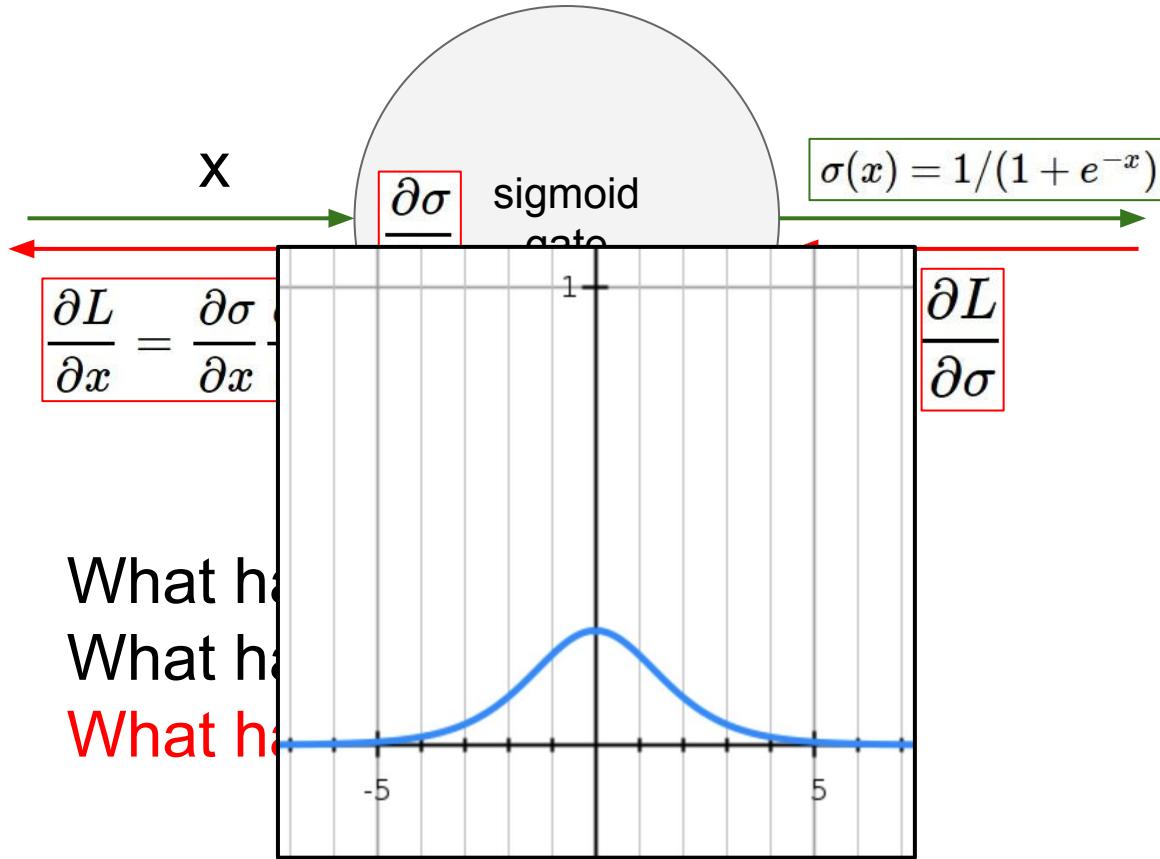
What happens when $x = -10$?

$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x))$$

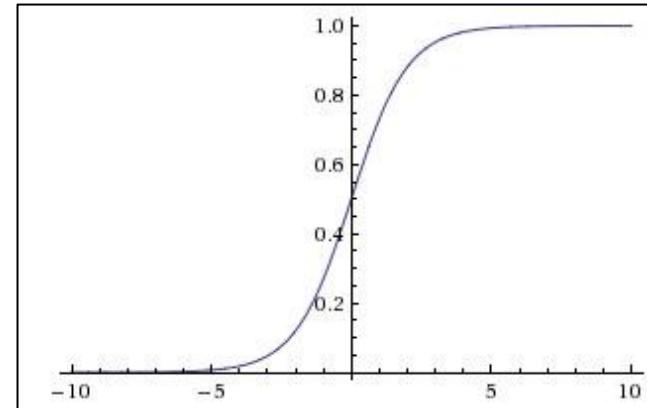
What happens when $x = 0$?

What happens when $x = 10$?

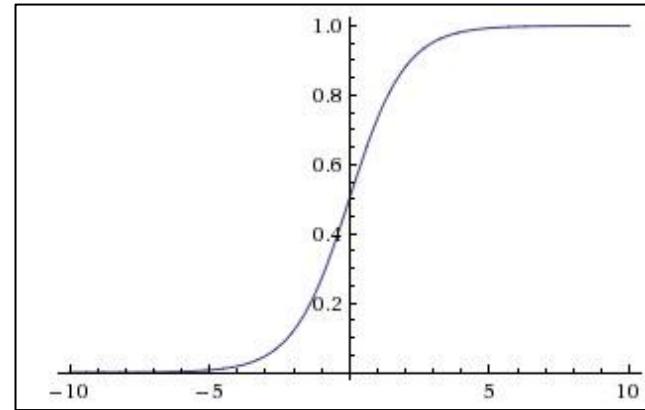
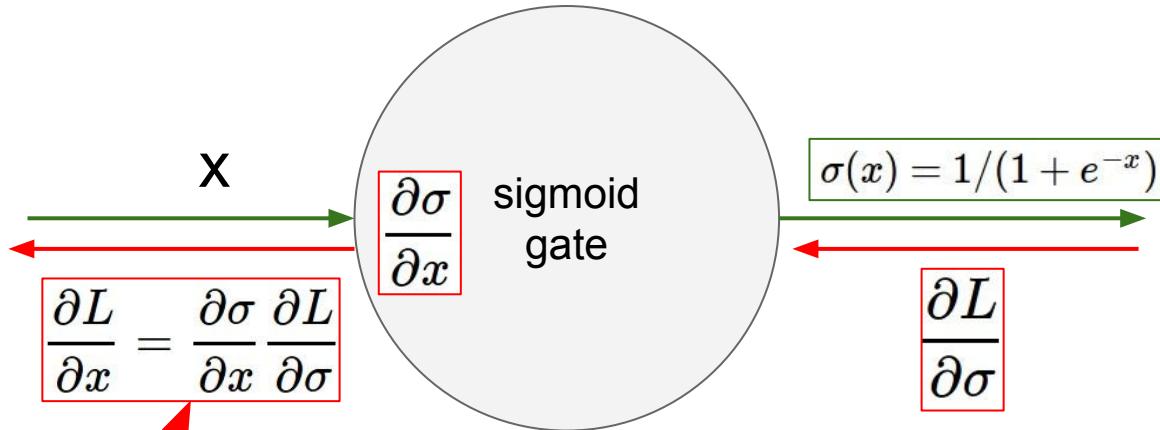
$$\sigma(x) = \sim 1 \quad \frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x)) = 1(1 - 1) = 0$$



What happens if x is large?
 What happens if x is small?
 What happens if x is zero?



$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x))$$



Why is this a problem?

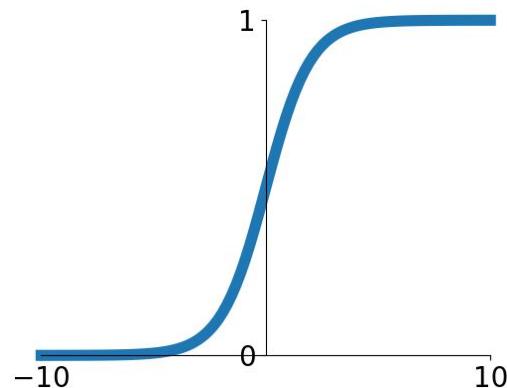
If all the gradients flowing back will be zero and weights will never change

$$\frac{\partial \sigma(x)}{\partial x} = \sigma(x)(1 - \sigma(x))$$

Activation Functions

$$\sigma(x) = 1/(1 + e^{-x})$$

- Squashes numbers to range [0,1]
- Historically popular since they have nice interpretation as a saturating “firing rate” of a neuron



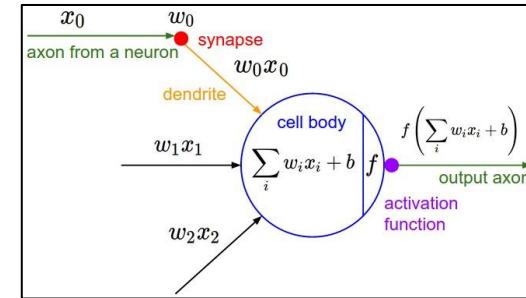
Sigmoid

3 problems:

1. Saturated neurons “kill” the gradients
2. Sigmoid outputs are not zero-centered

Consider what happens when the input to a neuron is always positive...

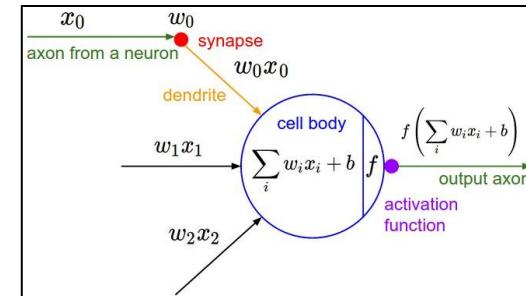
$$f \left(\sum_i w_i x_i + b \right)$$



What can we say about the gradients on w ?

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$

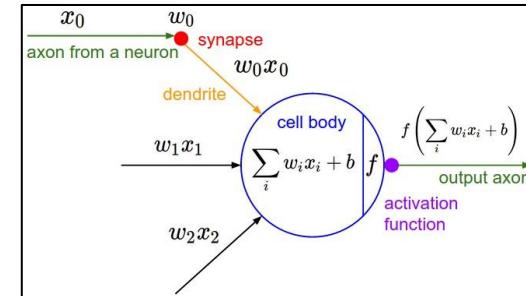


What can we say about the gradients on w ?

$$\frac{\partial L}{\partial w} = \sigma(\sum_i w_i x_i + b)(1 - \sigma(\sum_i w_i x_i + b))x \times \text{upstream_gradient}$$

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



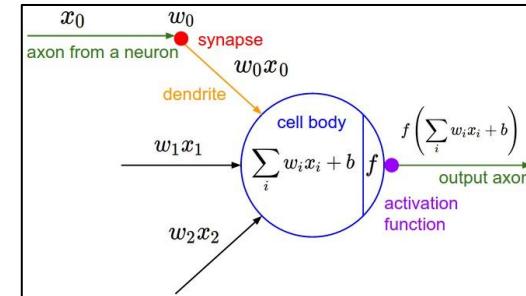
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We know that local gradient of sigmoid is always positive

$$\frac{\partial L}{\partial w} = \boxed{\sigma(\sum_i w_i x_i + b)(1 - \sigma(\sum_i w_i x_i + b))x \times \text{upstream_gradient}}$$

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



What can we say about the gradients on w ?

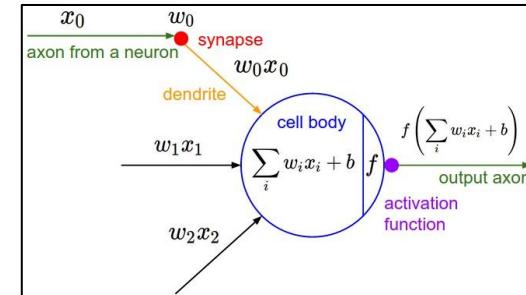
We know that local gradient of sigmoid is always positive

We are assuming x is always positive

$$\frac{\partial L}{\partial w} = \boxed{\sigma(\sum_i w_i x_i + b)(1 - \sigma(\sum_i w_i x_i + b))x} \times \text{upstream_gradient}$$

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



What can we say about the gradients on w ?

We know that local gradient of sigmoid is always positive

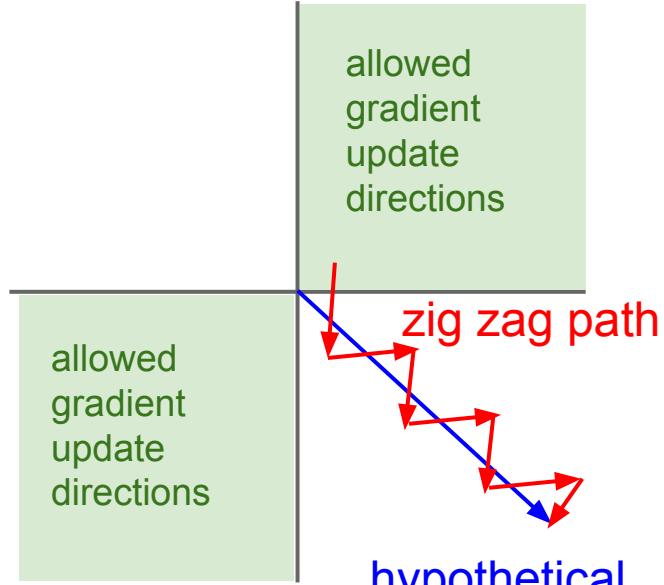
We are assuming x is always positive

So!! Sign of gradient for all w_i is the same as the sign of upstream scalar gradient!

$$\frac{\partial L}{\partial w} = \sigma(\sum_i w_i x_i + b)(1 - \sigma(\sum_i w_i x_i + b))x \times \text{upstream_gradient}$$

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



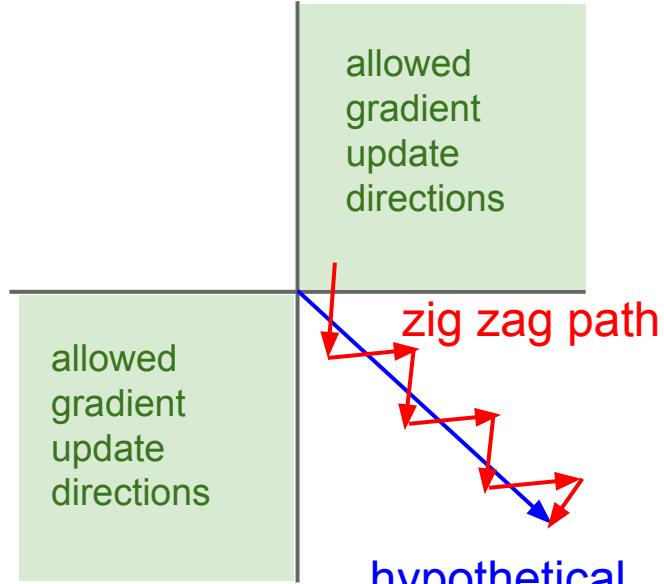
What can we say about the gradients on w ?

Always all positive or all negative :(

hypothetical
optimal w
vector

Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



What can we say about the gradients on w ?

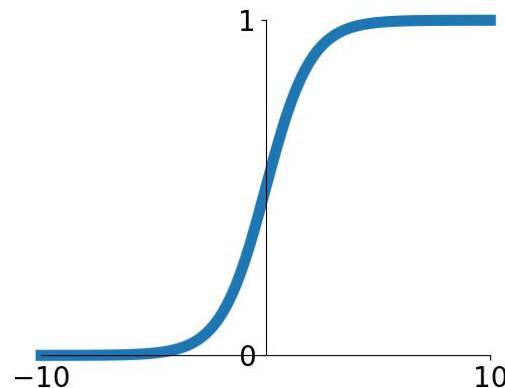
Always all positive or all negative :(

(For a single element! Minibatches help)

Activation Functions

$$\sigma(x) = 1/(1 + e^{-x})$$

- Squashes numbers to range [0,1]
- Historically popular since they have nice interpretation as a saturating “firing rate” of a neuron

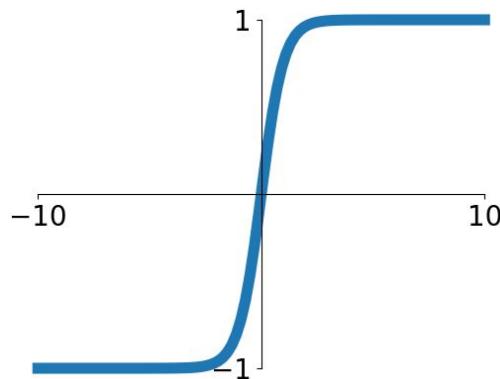


Sigmoid

3 problems:

1. Saturated neurons “kill” the gradients
2. Sigmoid outputs are not zero-centered
3. $\exp()$ is a bit compute expensive

Activation Functions

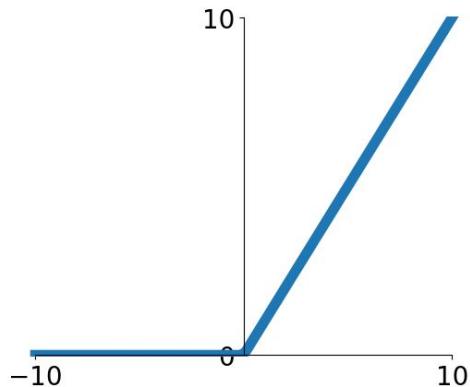


tanh(x)

- Squashes numbers to range [-1,1]
- zero centered (nice)
- still kills gradients when saturated :(

[LeCun et al., 1991]

Activation Functions

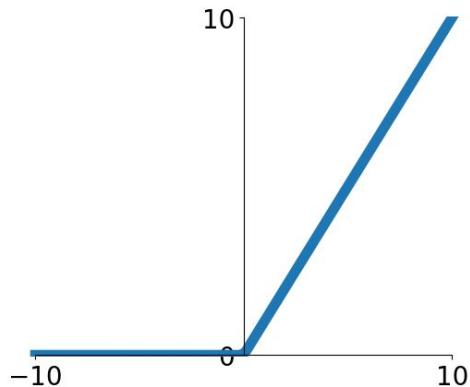


- Computes $f(x) = \max(0, x)$
- Does not saturate (in +region)
- Very computationally efficient
- Converges much faster than sigmoid/tanh in practice (e.g. 6x)

ReLU
(Rectified Linear Unit)

[Krizhevsky et al., 2012]

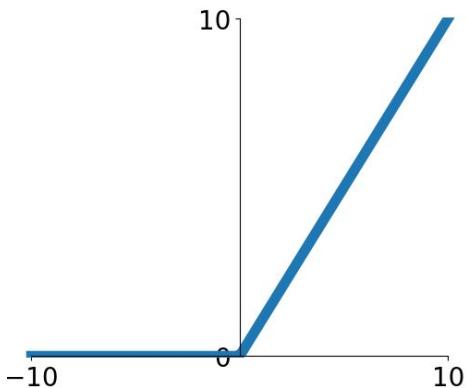
Activation Functions



- Computes $f(x) = \max(0, x)$
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- Not zero-centered output

ReLU
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Activation Functions

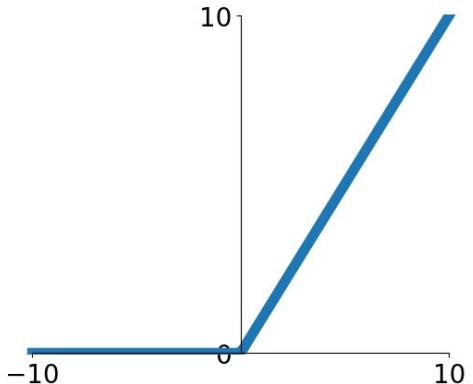
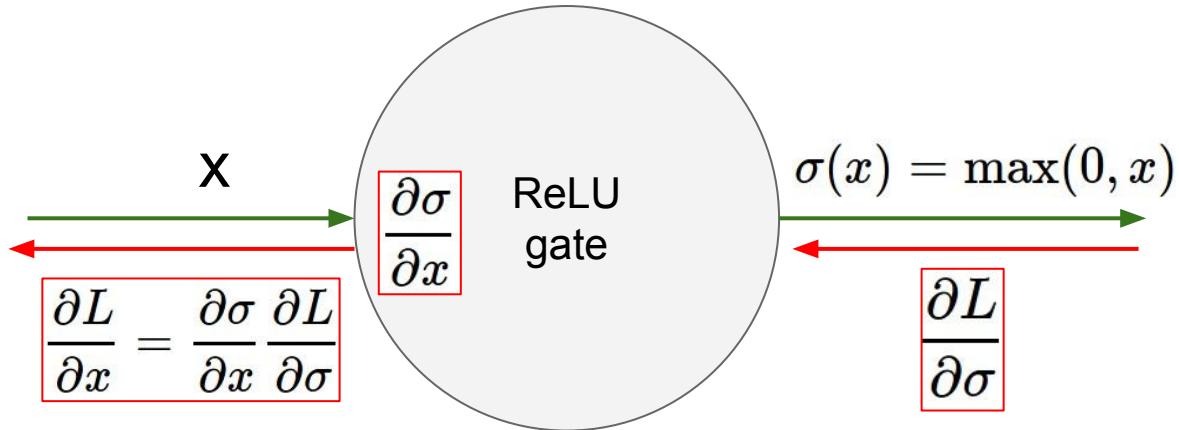


ReLU
(Rectified Linear Unit)

- Computes $f(x) = \max(0, x)$
- Does not saturate (in +region)
- Very computationally efficient
- Converges much faster than sigmoid/tanh in practice (e.g. 6x)

- Not zero-centered output
- An annoyance:

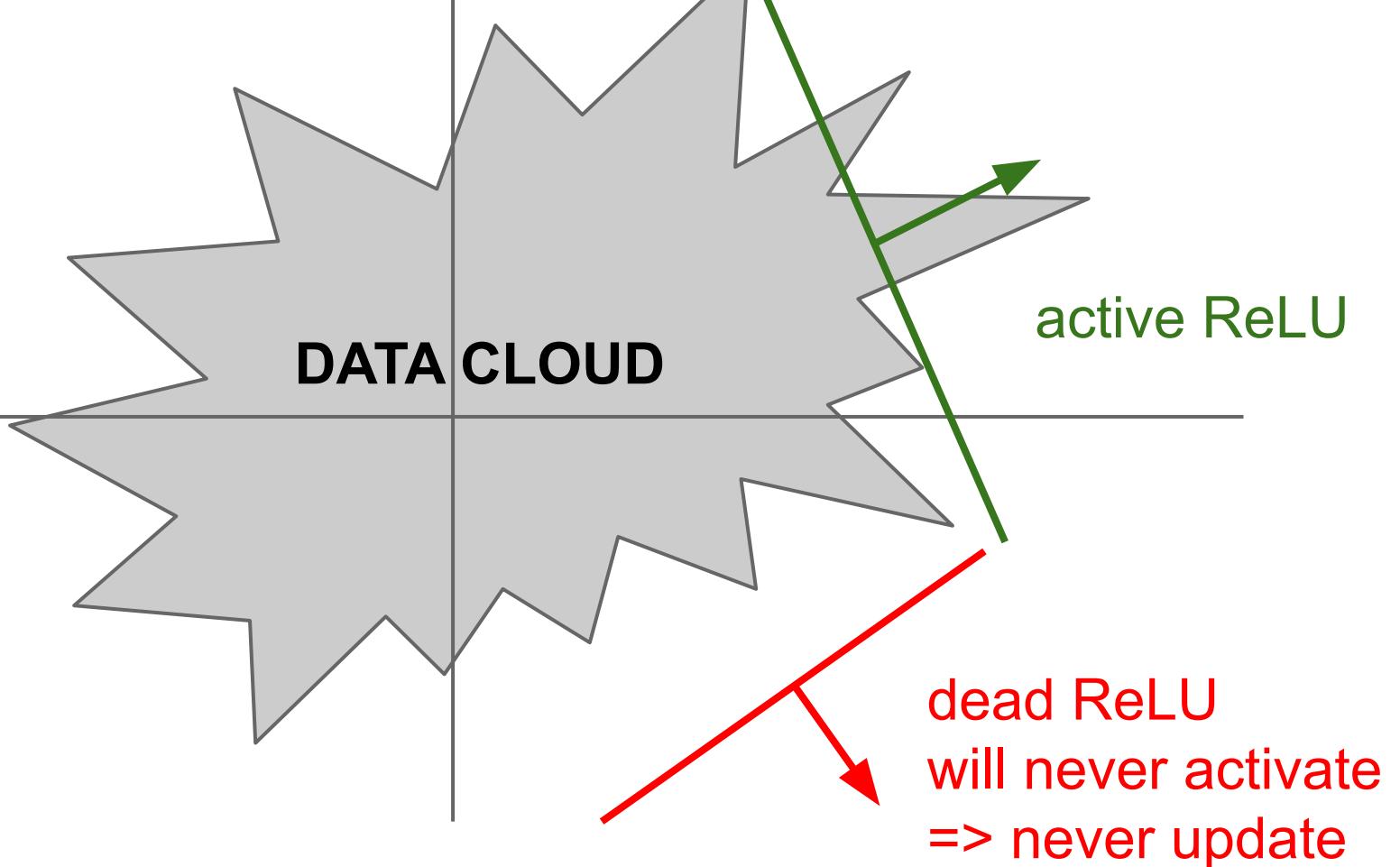
hint: what is the gradient when $x < 0$?

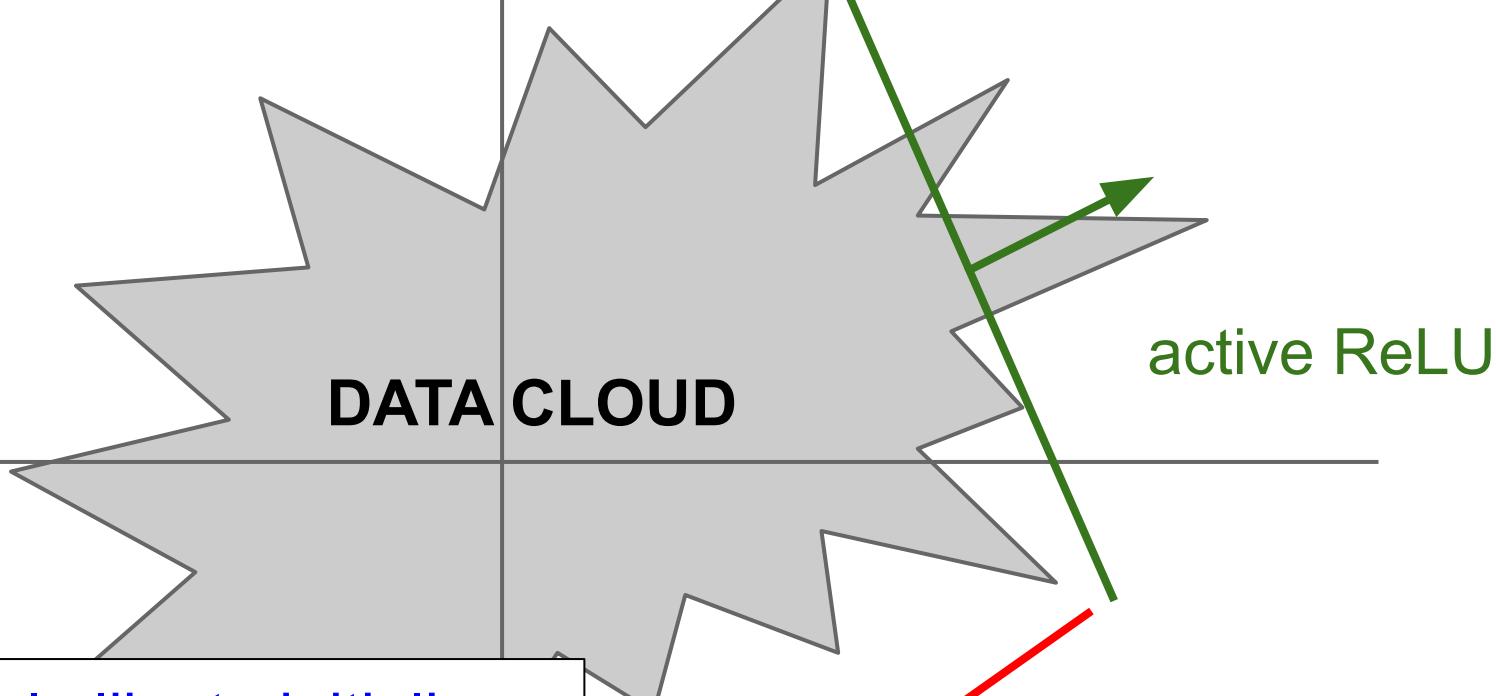


What happens when $x = -10$?

What happens when $x = 0$?

What happens when $x = 10$?



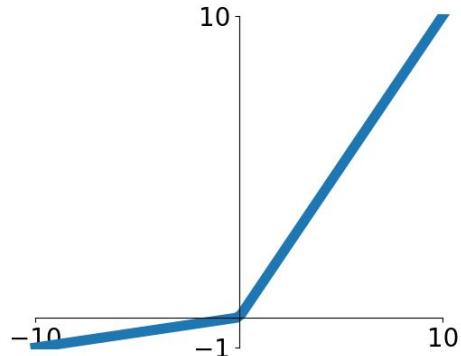


=> people like to initialize
ReLU neurons with slightly
positive biases (e.g. 0.01)

will never activate
=> never update

Activation Functions

[Mass et al., 2013]
[He et al., 2015]



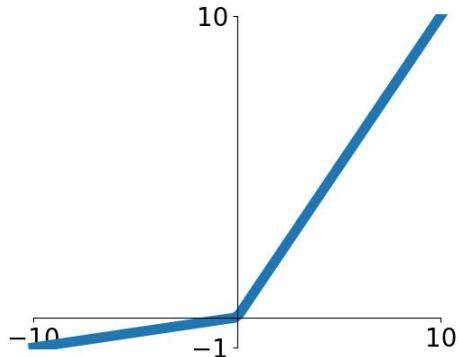
- Does not saturate
- Computationally efficient
- Converges much faster than sigmoid/tanh in practice! (e.g. 6x)
- **will not “die”.**

Leaky ReLU

$$f(x) = \max(0.01x, x)$$

Activation Functions

[Mass et al., 2013]
[He et al., 2015]



Leaky ReLU

$$f(x) = \max(0.01x, x)$$

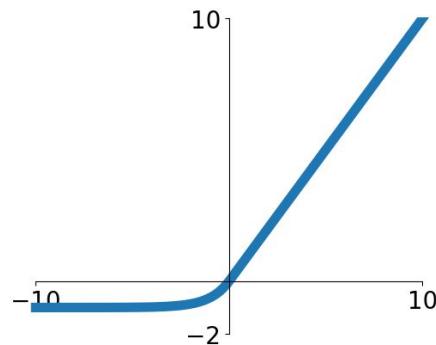
- Does not saturate
- Computationally efficient
- Converges much faster than sigmoid/tanh in practice! (e.g. 6x)
- **will not “die”.**

Parametric Rectifier (PReLU)

$$f(x) = \max(\alpha x, x)$$

backprop into α (parameter)

Exponential Linear Units (ELU)



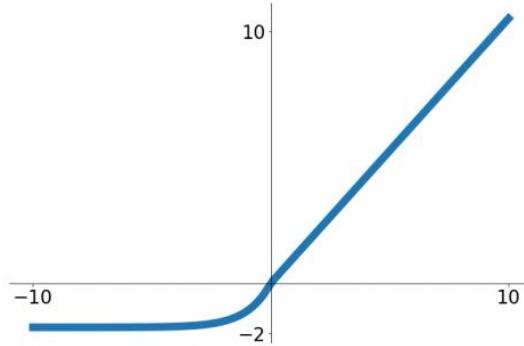
- All benefits of ReLU
- Closer to zero mean outputs
- Negative saturation regime compared with Leaky ReLU adds some robustness to noise

$$f(x) = \begin{cases} x & \text{if } x > 0 \\ \alpha (\exp(x) - 1) & \text{if } x \leq 0 \end{cases}$$

(Alpha default = 1)

- Computation requires $\exp()$

Scaled Exponential Linear Units (SELU)



- Scaled version of ELU that works better for deep networks
- “Self-normalizing” property;
- Can train deep SELU networks without BatchNorm

$$f(x) = \begin{cases} \lambda x & \text{if } x > 0 \\ \lambda \alpha(e^x - 1) & \text{otherwise} \end{cases}$$

$$\alpha = 1.6732632423543772848170429916717$$

$$\lambda = 1.0507009873554804934193349852946$$

Maxout “Neuron”

[Goodfellow et al., 2013]

- Does not have the basic form of dot product -> nonlinearity
- Generalizes ReLU and Leaky ReLU
- Linear Regime! Does not saturate! Does not die!

$$\max(w_1^T x + b_1, w_2^T x + b_2)$$

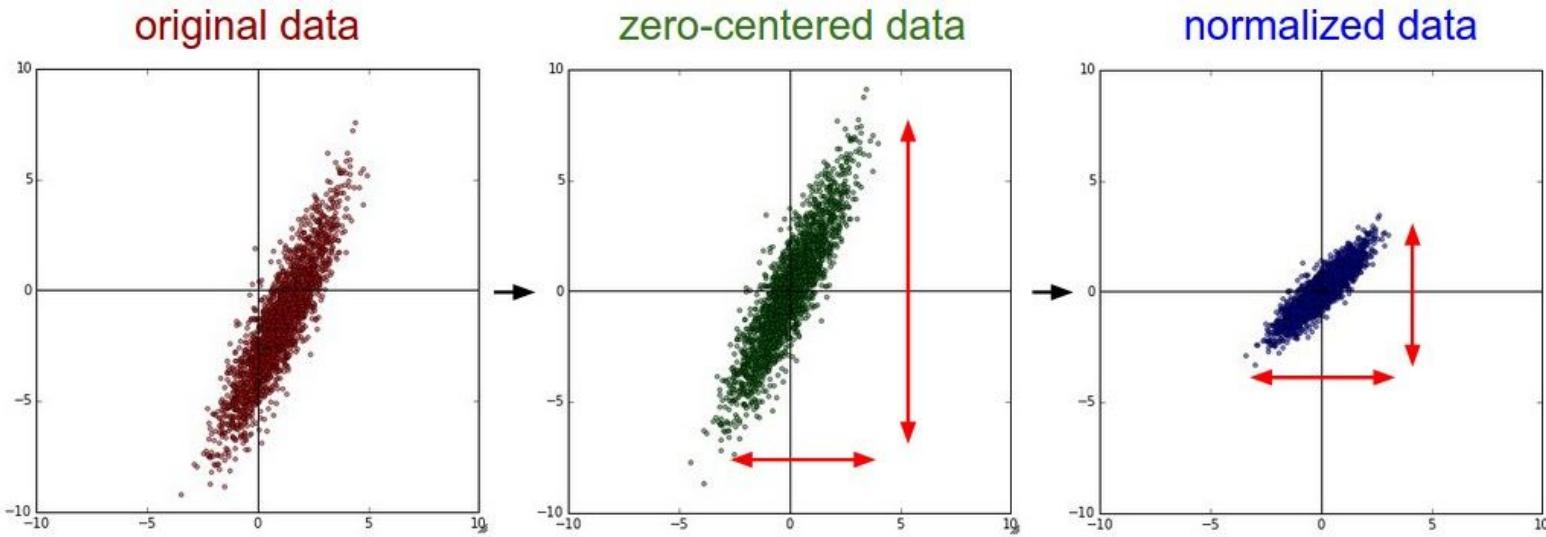
Problem: doubles the number of parameters/neuron :(

TLDR: In practice:

- Use ReLU. Be careful with your learning rates
- Try out Leaky ReLU / Maxout / ELU / SELU
 - To squeeze out some marginal gains
- Don't use sigmoid or tanh

Data Preprocessing

Data Preprocessing



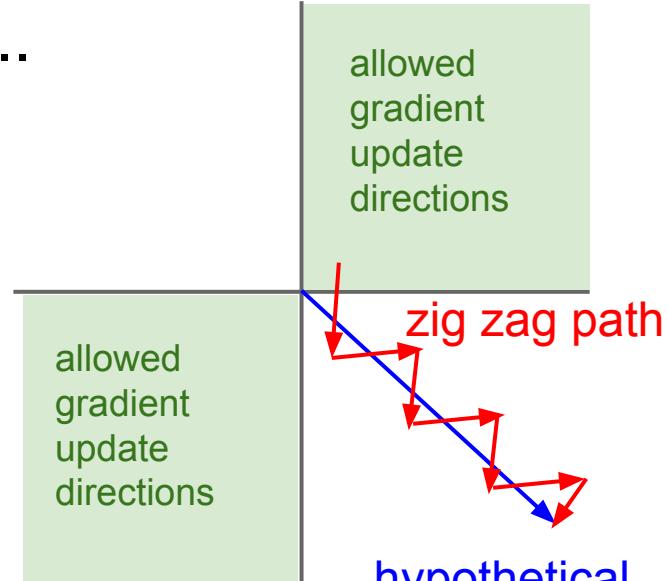
```
X -= np.mean(X, axis = 0)
```

```
X /= np.std(X, axis = 0)
```

(Assume X [NxD] is data matrix,
each example in a row)

Remember: Consider what happens when the input to a neuron is always positive...

$$f \left(\sum_i w_i x_i + b \right)$$



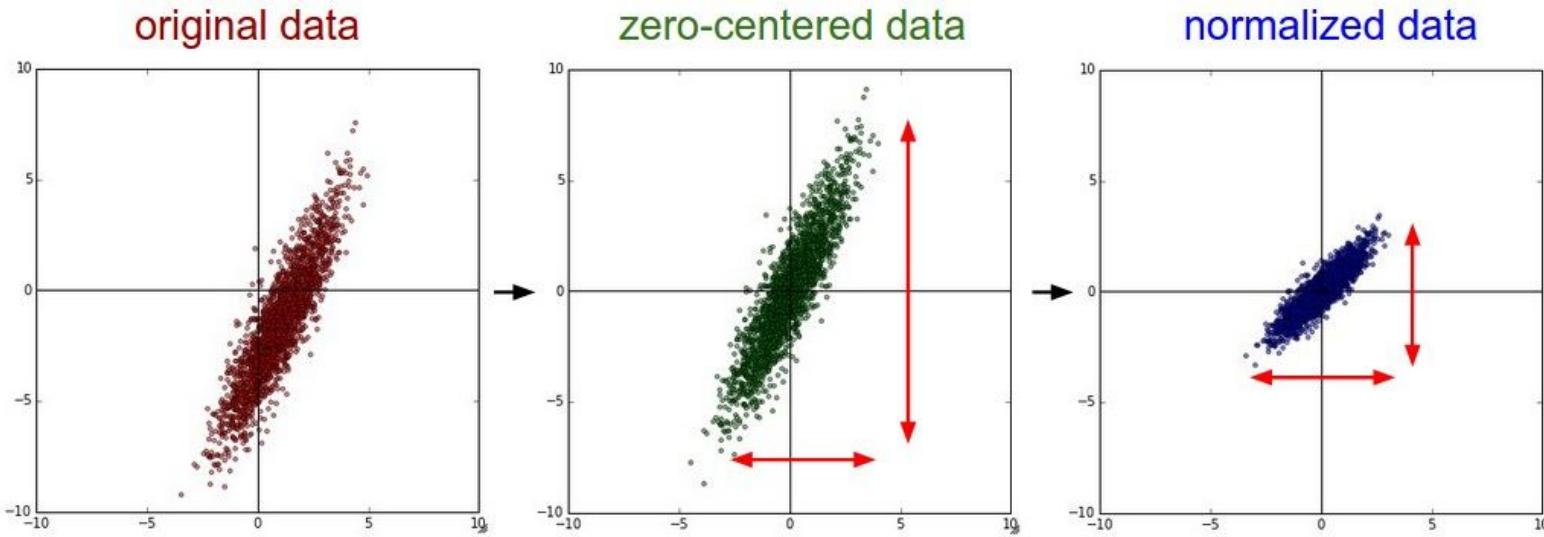
What can we say about the gradients on w ?

Always all positive or all negative :(

(this is also why you want zero-mean data!)

hypothetical
optimal w
vector

Data Preprocessing



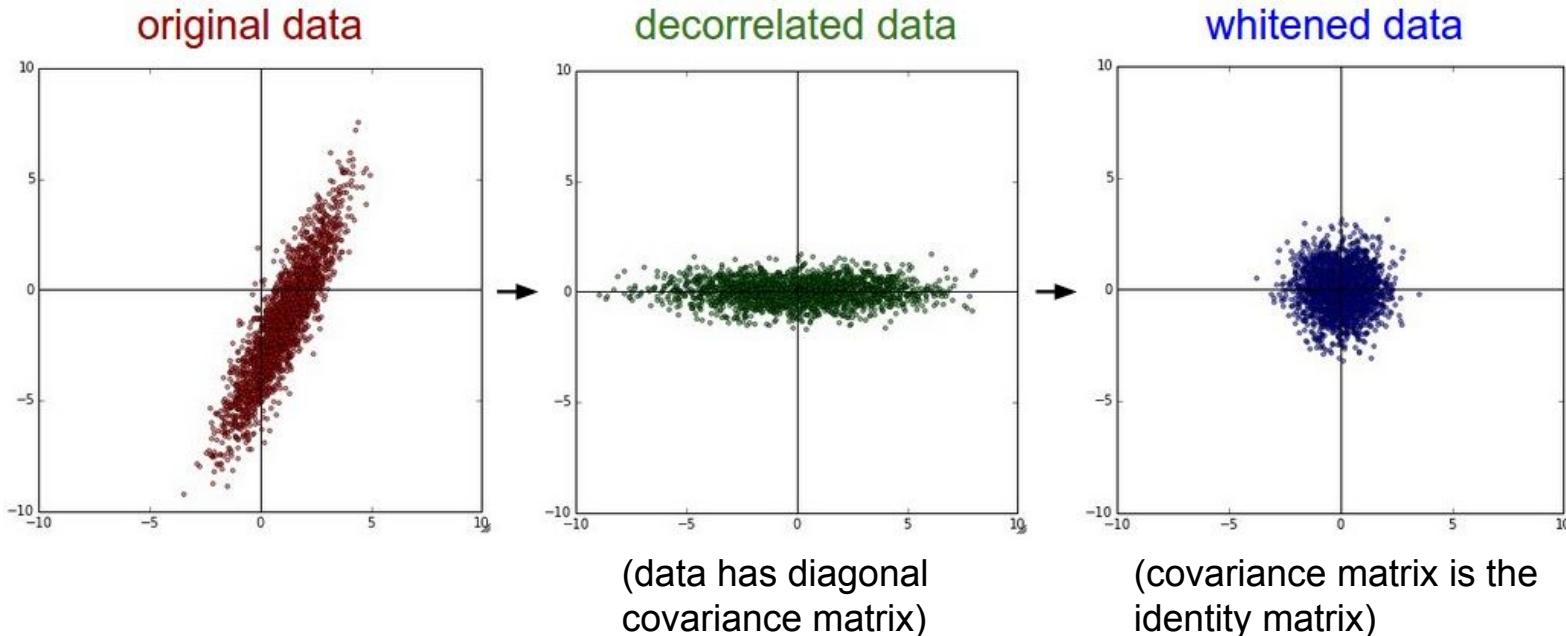
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(Assume X [NxD] is data matrix, each example in a row)

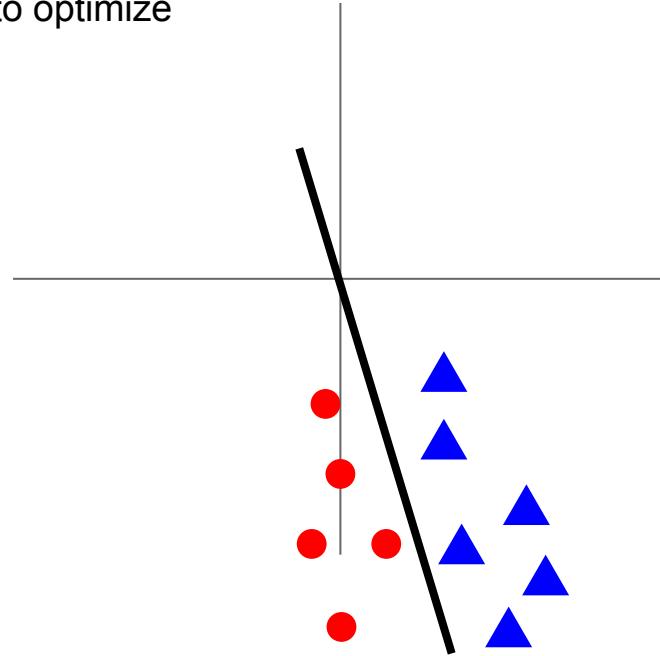
Data Preprocessing

In practice, you may also see **PCA** and **Whitening** of the data

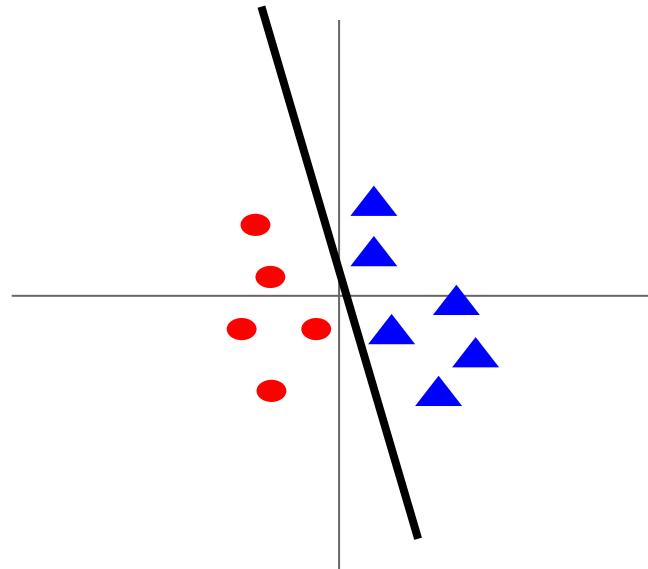


Data Preprocessing

Before normalization: classification loss very sensitive to changes in weight matrix; hard to optimize



After normalization: less sensitive to small changes in weights; easier to optimize



TLDR: In practice for Images: center only

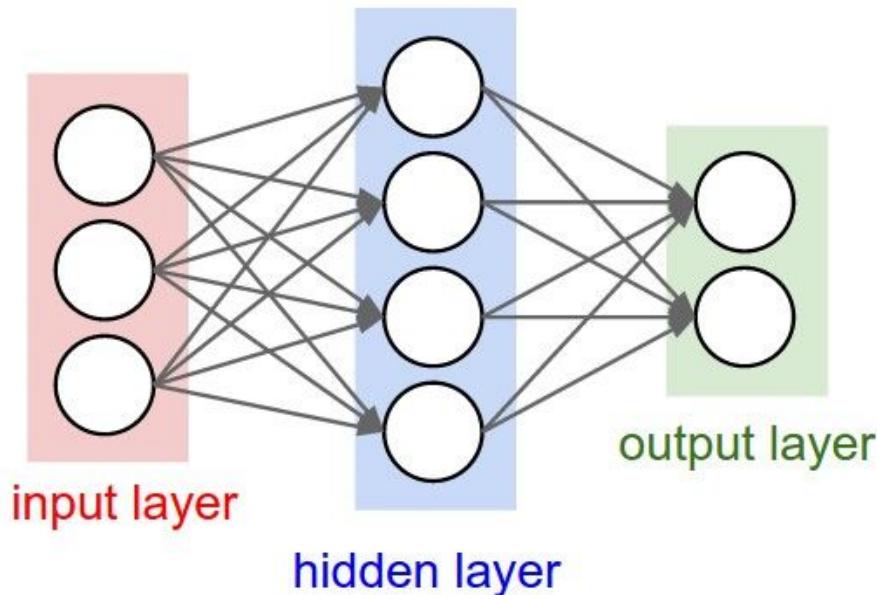
e.g. consider CIFAR-10 example with [32,32,3] images

- Subtract the mean image (e.g. AlexNet)
(mean image = [32,32,3] array)
- Subtract per-channel mean (e.g. VGGNet)
(mean along each channel = 3 numbers)
- Subtract per-channel mean and
Divide by per-channel std (e.g. ResNet)
(mean along each channel = 3 numbers)

Not common
to do PCA or
whitening

Weight Initialization

- Q: what happens when $W=\text{constant init}$ is used?



- First idea: **Small random numbers**
(gaussian with zero mean and 1e-2 standard deviation)

```
W = 0.01 * np.random.randn(Din, Dout)
```

- First idea: **Small random numbers**
(gaussian with zero mean and 1e-2 standard deviation)

```
W = 0.01 * np.random.randn(Din, Dout)
```

Works ~okay for small networks, but problems with deeper networks.

Weight Initialization: Activation statistics

```
dims = [4096] * 7      Forward pass for a 6-layer
hs = []                  net with hidden size 4096
x = np.random.randn(16, dims[0])
for Din, Dout in zip(dims[:-1], dims[1:]):
    W = 0.01 * np.random.randn(Din, Dout)
    x = np.tanh(x.dot(W))
    hs.append(x)
```

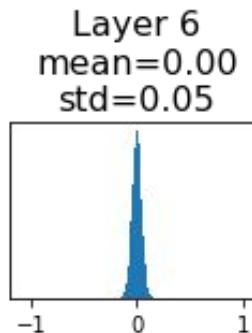
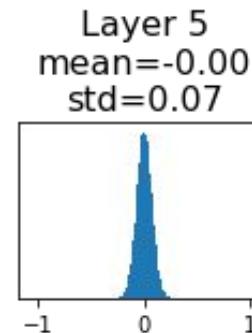
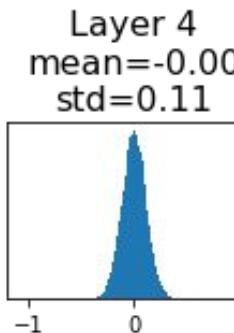
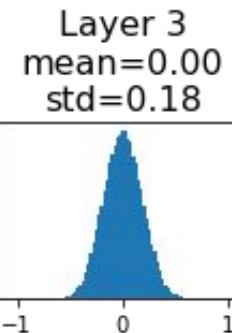
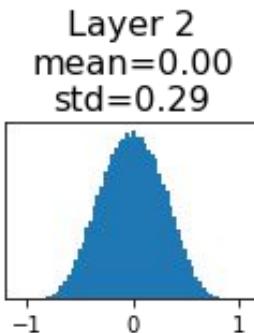
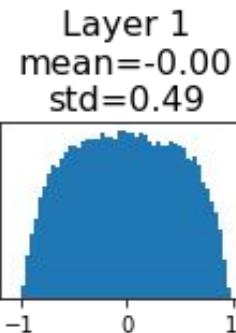
What will happen to the activations for the last layer?

Weight Initialization: Activation statistics

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```

All activations tend to zero for deeper network layers

Q: What do the gradients dL/dW look like?



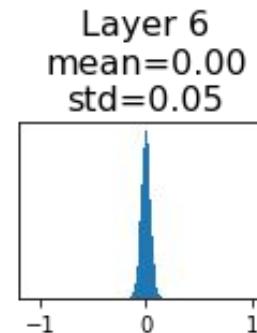
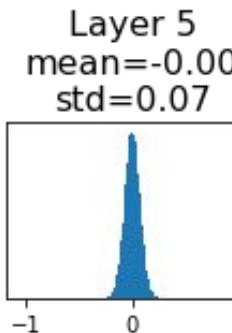
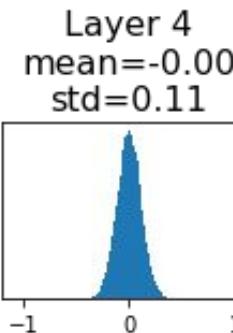
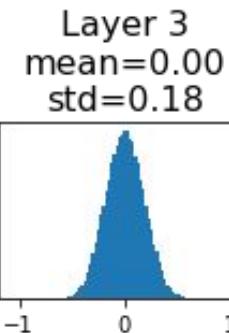
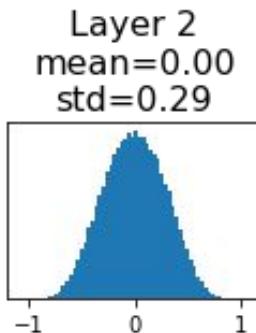
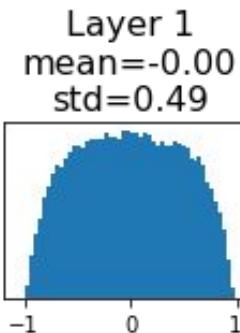
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```

All activations tend to zero for deeper network layers

Q: What do the gradients dL/dW look like?

A: All zero, no learning =(



Weight Initialization: Activation statistics

```
dims = [4096] * 7    Increase std of initial  
hs = []                weights from 0.01 to 0.05  
x = np.random.randn(16, dims[0])  
for Din, Dout in zip(dims[:-1], dims[1:]):  
    W = 0.05 * np.random.randn(Din, Dout)  
    x = np.tanh(x.dot(W))  
    hs.append(x)
```

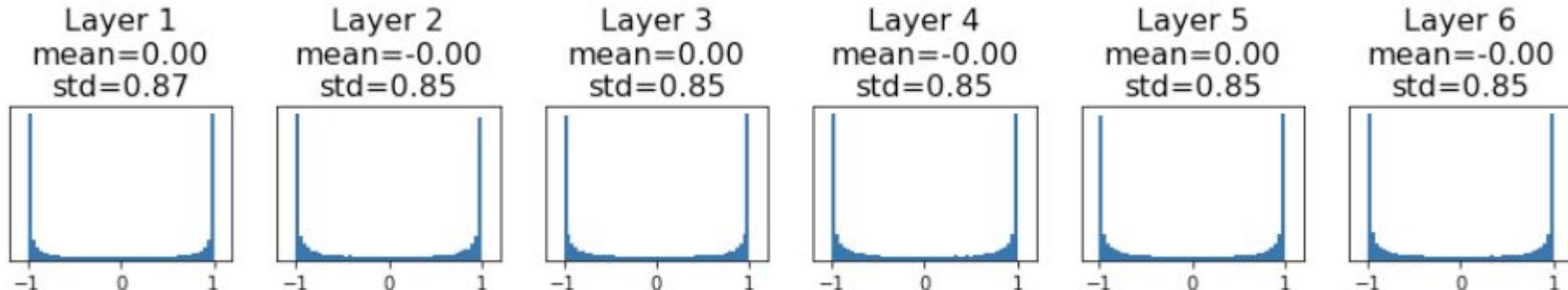
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```

All activations saturate

Q: What do the gradients look like?



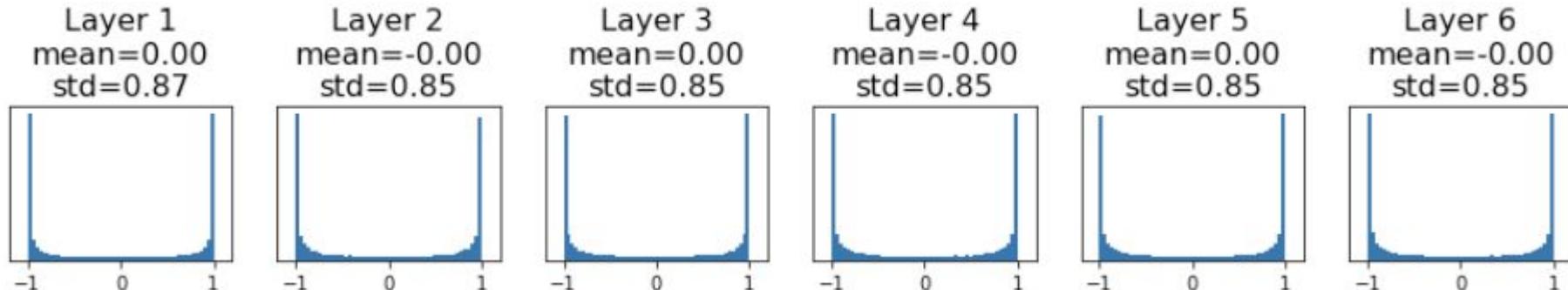
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```

All activations saturate

Q: What do the gradients look like?

A: Local gradients all zero, no learning =(



Weight Initialization: “Xavier” Initialization

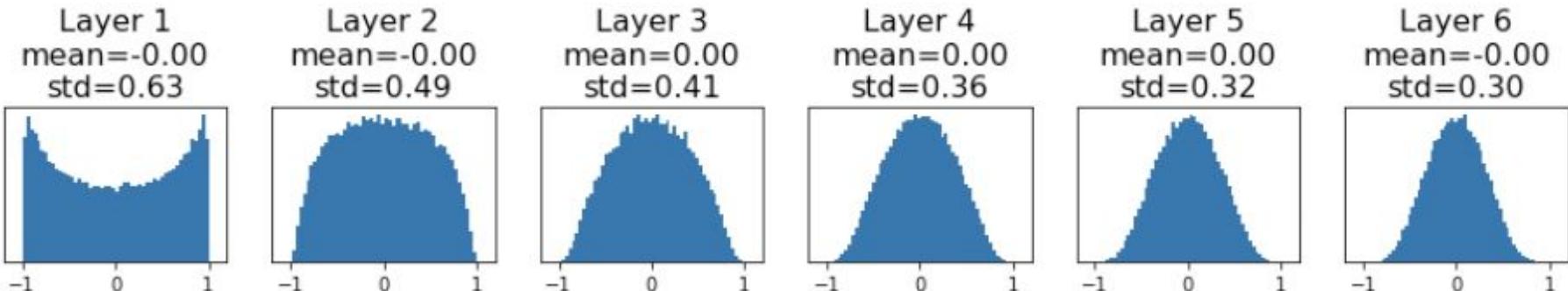
```
dims = [4096] * 7          "Xavier" initialization:  
hs = []                      std = 1/sqrt(Din)  
x = np.random.randn(16, dims[0])  
for Din, Dout in zip(dims[:-1], dims[1:]):  
    W = np.random.randn(Din, Dout) / np.sqrt(Din)  
    x = np.tanh(x.dot(W))  
    hs.append(x)
```

Glorot and Bengio, “Understanding the difficulty of training deep feedforward neural networks”, AISTAT 2010

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```

“Just right”: Activations are nicely scaled for all layers!



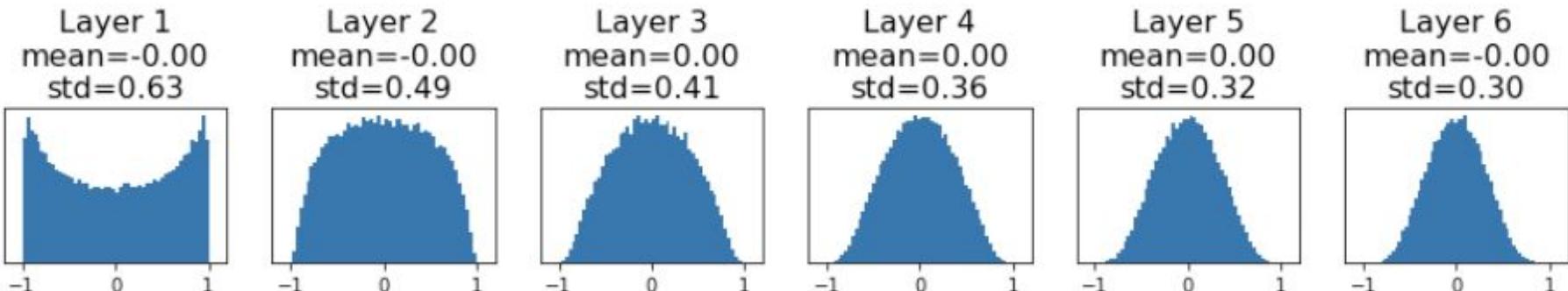
Glorot and Bengio, “Understanding the difficulty of training deep feedforward neural networks”, AISTAT 2010

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For conv layers, Din is $\text{filter_size}^2 * \text{input_channels}$



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For conv layers, Din is $\text{filter_size}^2 * \text{input_channels}$

Let: $y = x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}$

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Assume: $\text{Var}(x_1) = \text{Var}(x_2) = \dots = \text{Var}(x_{Din})$

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We want: $\text{Var}(y) = \text{Var}(x_i)$

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Let: $y = x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}$

Assume: $\text{Var}(x_1) = \text{Var}(x_2) = \dots = \text{Var}(x_{Din})$

We want: $\text{Var}(y) = \text{Var}(x_i)$

$$\text{Var}(y) = \text{Var}(x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din})$$

[substituting value of y]

Weight Initialization: “Xavier” Initialization

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$$\begin{aligned}\text{Var}(y) &= \text{Var}(x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}) \\ &= \text{Din } \text{Var}(x_i w_i)\end{aligned}$$

[Assume all x_i, w_i are iid]

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```
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Let: $y = x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}$

Assume: $\text{Var}(x_1) = \text{Var}(x_2) = \dots = \text{Var}(x_{Din})$

We want: $\text{Var}(y) = \text{Var}(x_i)$

$$\begin{aligned}\text{Var}(y) &= \text{Var}(x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}) \\ &= \text{Din} \text{Var}(x_i w_i) \\ &= \text{Din} \text{Var}(x_i) \text{Var}(w_i)\end{aligned}$$

[Assume all x_i, w_i are zero mean]

Weight Initialization: “Xavier” Initialization

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hs = []                      std = 1/sqrt(Din)  
x = np.random.randn(16, dims[0])  
for Din, Dout in zip(dims[:-1], dims[1:]):  
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We want: $\text{Var}(y) = \text{Var}(x_i)$

$$\begin{aligned}\text{Var}(y) &= \text{Var}(x_1 w_1 + x_2 w_2 + \dots + x_{Din} w_{Din}) \\ &= \text{Din} \text{Var}(x_i w_i) \\ &= \text{Din} \text{Var}(x_i) \text{Var}(w_i)\end{aligned}$$

[Assume all x_i, w_i are iid]

So, $\text{Var}(y) = \text{Var}(x_i)$ only when $\text{Var}(w_i) = 1/\text{Din}$

Glorot and Bengio, “Understanding the difficulty of training deep feedforward neural networks”, AISTAT 2010

Weight Initialization: What about ReLU?

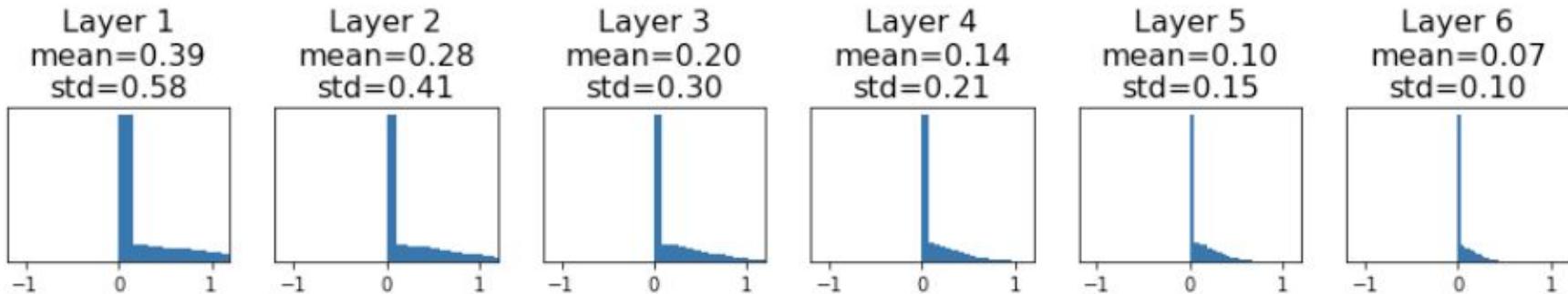
```
dims = [4096] * 7      Change from tanh to ReLU
hs = []
x = np.random.randn(16, dims[0])
for Din, Dout in zip(dims[:-1], dims[1:]):
    W = np.random.randn(Din, Dout) / np.sqrt(Din)
    x = np.maximum(0, x.dot(W))
    hs.append(x)
```

Weight Initialization: What about ReLU?

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hs = []
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for Din, Dout in zip(dims[:-1], dims[1:]):
    W = np.random.randn(Din, Dout) / np.sqrt(Din)
    x = np.maximum(0, x.dot(W))
    hs.append(x)
```

Xavier assumes zero centered activation function

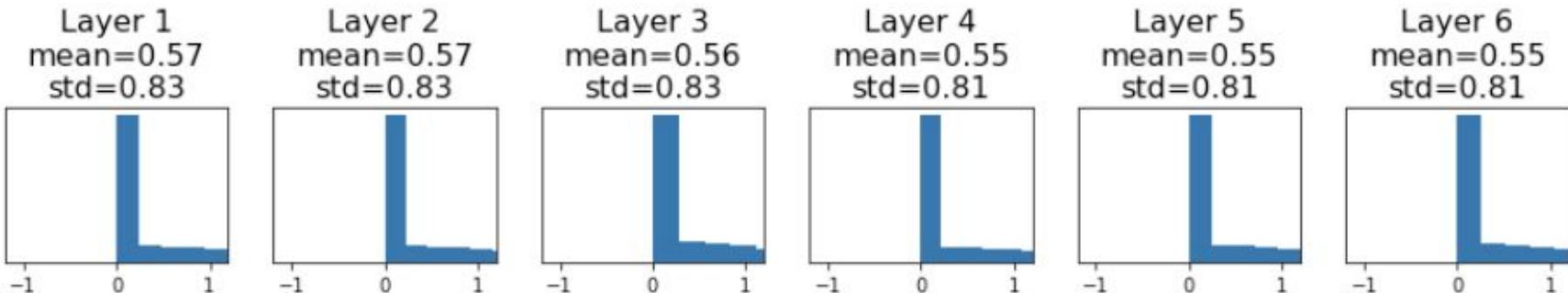
Activations collapse to zero again, no learning =(



Weight Initialization: Kaiming / MSRA Initialization

```
dims = [4096] * 7  ReLU correction: std = sqrt(2 / Din)
hs = []
x = np.random.randn(16, dims[0])
for Din, Dout in zip(dims[:-1], dims[1:]):
    W = np.random.randn(Din, Dout) * np.sqrt(2/Din)
    x = np.maximum(0, x.dot(W))
    hs.append(x)
```

“Just right”: Activations are nicely scaled for all layers!



He et al, “Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification”, ICCV 2015

Proper initialization is an active area of research...

Understanding the difficulty of training deep feedforward neural networks

by Glorot and Bengio, 2010

Exact solutions to the nonlinear dynamics of learning in deep linear neural networks by Saxe et al, 2013

Random walk initialization for training very deep feedforward networks by Sussillo and Abbott, 2014

Delving deep into rectifiers: Surpassing human-level performance on ImageNet classification by He et al., 2015

Data-dependent Initializations of Convolutional Neural Networks by Krähenbühl et al., 2015

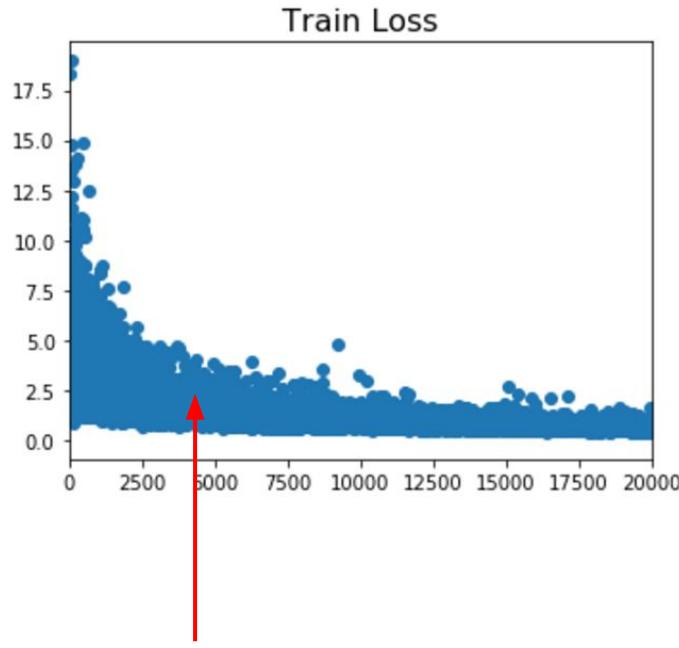
All you need is a good init, Mishkin and Matas, 2015

Fixup Initialization: Residual Learning Without Normalization, Zhang et al, 2019

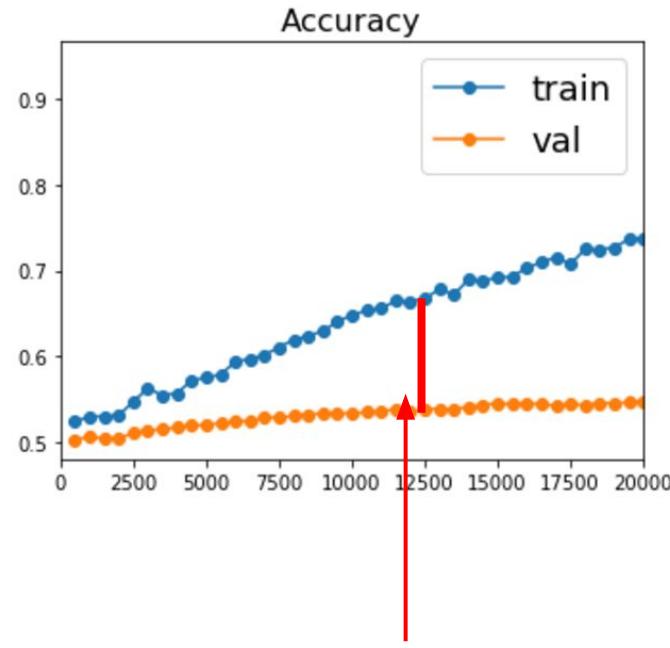
The Lottery Ticket Hypothesis: Finding Sparse, Trainable Neural Networks, Frankle and Carbin, 2019

Training vs. Testing Error

Beyond Training Error

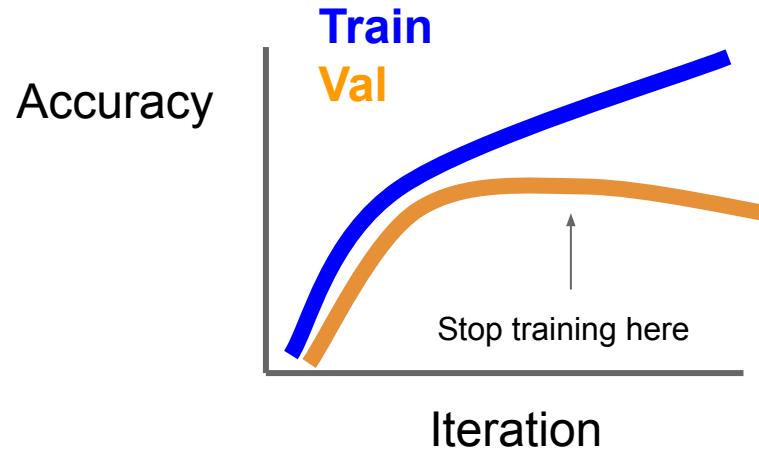
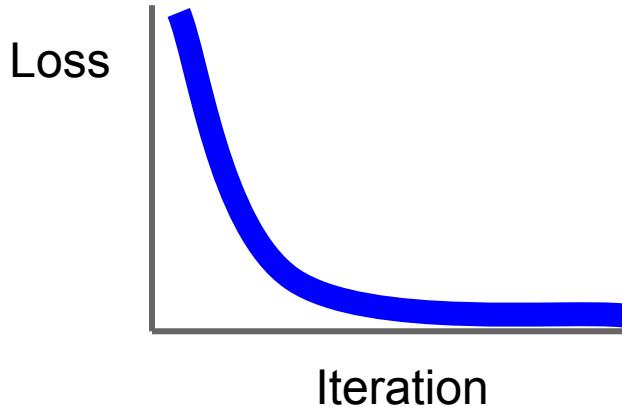


Better optimization algorithms help reduce training loss



But we really care about error on new data - how to reduce the gap?

Early Stopping: Always do this



Stop training the model when accuracy on the validation set decreases
Or train for a long time, but always keep track of the model snapshot
that worked best on val

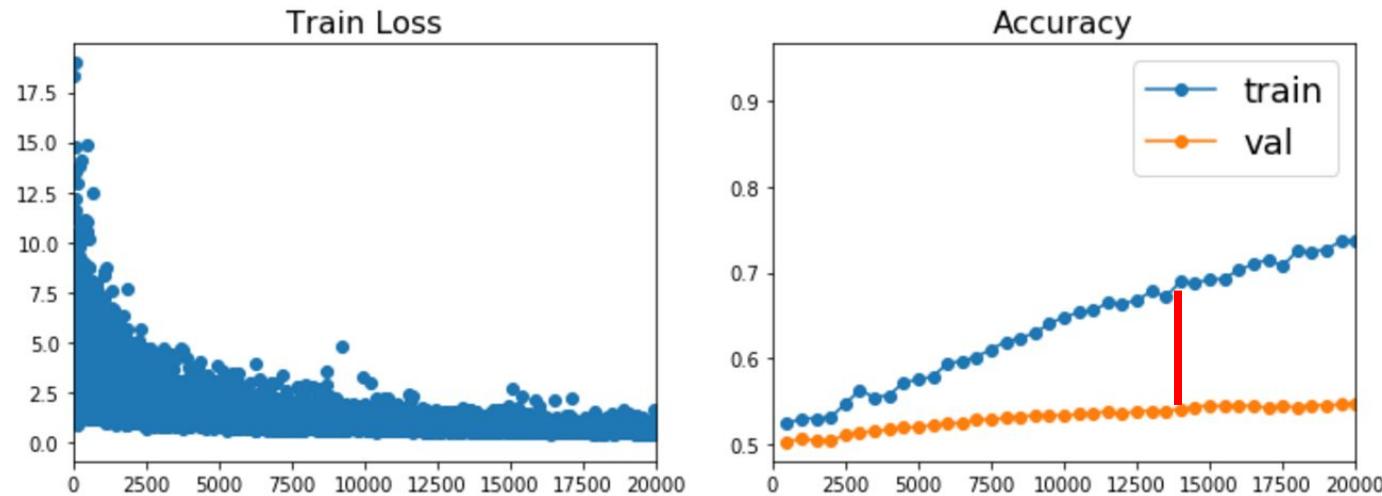
Model Ensembles

1. Train multiple independent models
2. At test time average their results

(Take average of predicted probability distributions, then choose argmax)

Enjoy 2% extra performance

How to improve single-model performance?



Regularization

Regularization: Add term to loss

$$L = \frac{1}{N} \sum_{i=1}^N \sum_{j \neq y_i} \max(0, f(x_i; W)_j - f(x_i; W)_{y_i} + 1) + \boxed{\lambda R(W)}$$

In common use:

L2 regularization

$$R(W) = \sum_k \sum_l W_{k,l}^2 \quad (\text{Weight decay})$$

L1 regularization

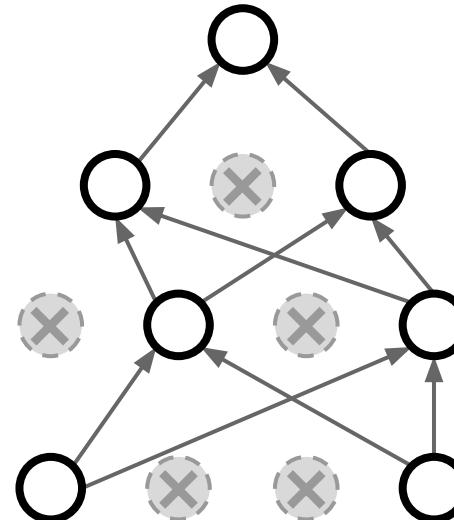
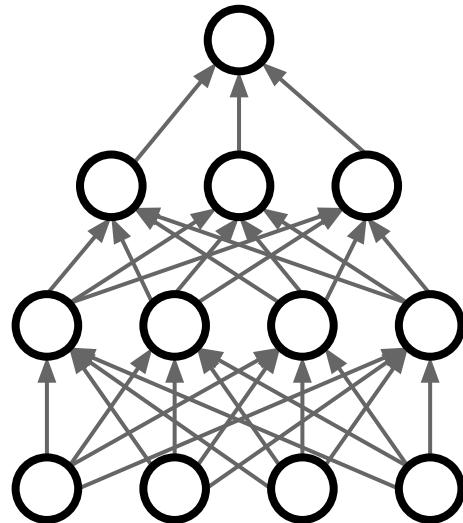
$$R(W) = \sum_k \sum_l |W_{k,l}|$$

Elastic net (L1 + L2)

$$R(W) = \sum_k \sum_l \beta W_{k,l}^2 + |W_{k,l}|$$

Regularization: Dropout

In each forward pass, randomly set some neurons to zero
Probability of dropping is a hyperparameter; 0.5 is common



Srivastava et al, "Dropout: A simple way to prevent neural networks from overfitting", JMLR 2014

Regularization: Dropout

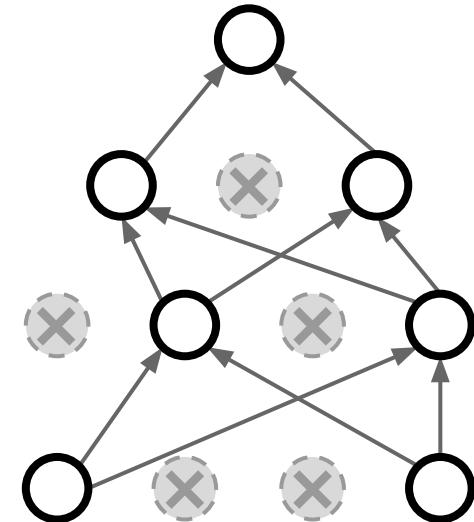
```
p = 0.5 # probability of keeping a unit active. higher = less dropout

def train_step(X):
    """ X contains the data """

    # forward pass for example 3-layer neural network
    H1 = np.maximum(0, np.dot(W1, X) + b1)
    U1 = np.random.rand(*H1.shape) < p # first dropout mask
    H1 *= U1 # drop!
    H2 = np.maximum(0, np.dot(W2, H1) + b2)
    U2 = np.random.rand(*H2.shape) < p # second dropout mask
    H2 *= U2 # drop!
    out = np.dot(W3, H2) + b3

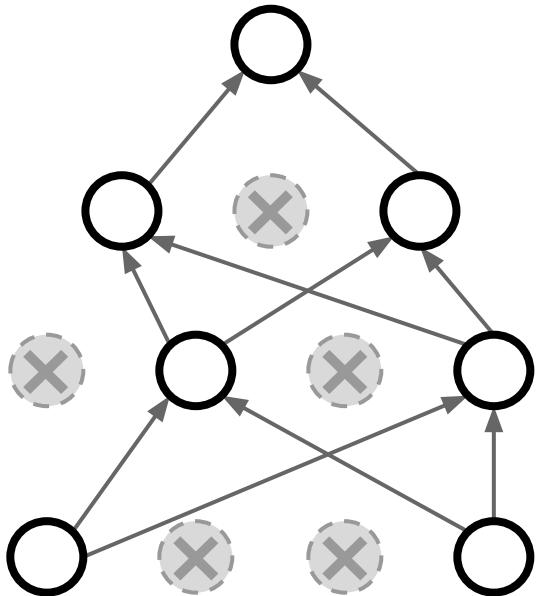
    # backward pass: compute gradients... (not shown)
    # perform parameter update... (not shown)
```

Example forward pass with a 3-layer network using dropout



Regularization: Dropout

How can this possibly be a good idea?

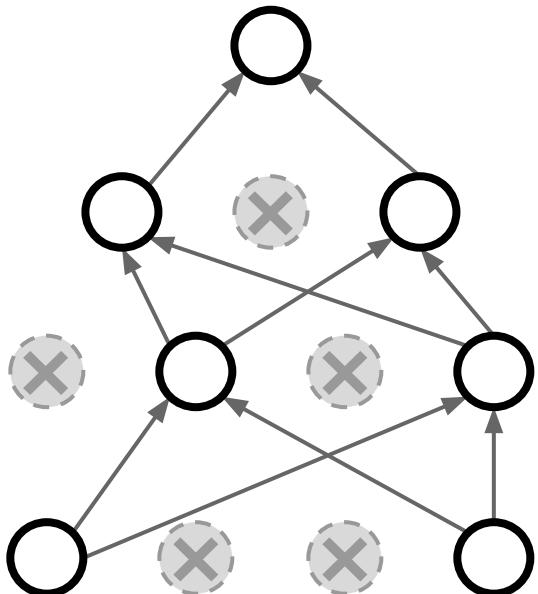


Forces the network to have a redundant representation;
Prevents co-adaptation of features



Regularization: Dropout

How can this possibly be a good idea?



Another interpretation:

Dropout is training a large **ensemble** of models (that share parameters).

Each binary mask is one model

An FC layer with 4096 units has $2^{4096} \sim 10^{1233}$ possible masks!

Only $\sim 10^{82}$ atoms in the universe...

Dropout: Test time

Dropout makes our output random!

$$\boxed{y} = f_W(\boxed{x}, \boxed{z})$$

Output
(label) Input
(image) Random
mask

Want to “average out” the randomness at test-time

$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

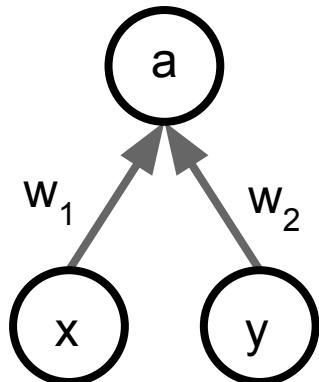
But this integral seems hard ...

Dropout: Test time

Want to approximate
the integral

$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Consider a single neuron.

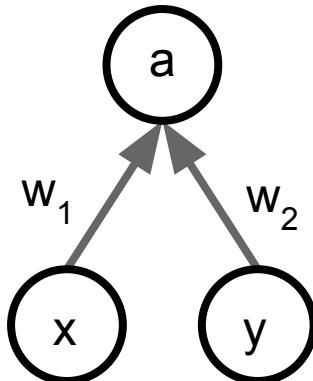


Dropout: Test time

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$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Consider a single neuron.



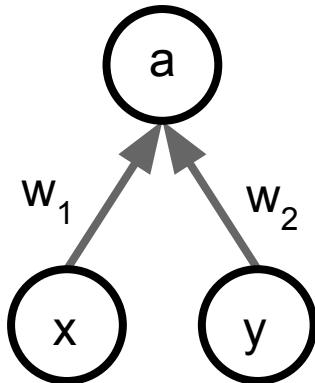
At test time we have: $E[a] = w_1x + w_2y$

Dropout: Test time

Want to approximate
the integral

$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Consider a single neuron.



At test time we have: $E[a] = w_1x + w_2y$

During training we have:

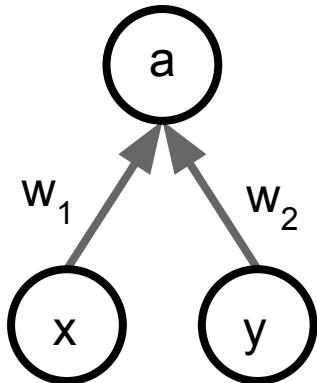
$$\begin{aligned} E[a] &= \frac{1}{4}(w_1x + w_2y) + \frac{1}{4}(w_1x + 0y) \\ &\quad + \frac{1}{4}(0x + 0y) + \frac{1}{4}(0x + w_2y) \\ &= \frac{1}{2}(w_1x + w_2y) \end{aligned}$$

Dropout: Test time

Want to approximate
the integral

$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Consider a single neuron.



At test time we have: $E[a] = w_1x + w_2y$

During training we have:

$$\begin{aligned} E[a] &= \frac{1}{4}(w_1x + w_2y) + \frac{1}{4}(w_1x + 0y) \\ &\quad + \frac{1}{4}(0x + 0y) + \frac{1}{4}(0x + w_2y) \\ &= \frac{1}{2}(w_1x + w_2y) \end{aligned}$$

At test time, multiply
by dropout probability

Dropout: Test time

```
def predict(X):
    # ensembled forward pass
    H1 = np.maximum(0, np.dot(W1, X) + b1) * p # NOTE: scale the activations
    H2 = np.maximum(0, np.dot(W2, H1) + b2) * p # NOTE: scale the activations
    out = np.dot(W3, H2) + b3
```

At test time all neurons are active always

=> We must scale the activations so that for each neuron:

output at test time = expected output at training time

Dropout Summary

```
""" Vanilla Dropout: Not recommended implementation (see notes below) """

p = 0.5 # probability of keeping a unit active. higher = less dropout

def train_step(X):
    """ X contains the data """

    # forward pass for example 3-layer neural network
    H1 = np.maximum(0, np.dot(W1, X) + b1)
    U1 = np.random.rand(*H1.shape) < p # first dropout mask
    H1 *= U1 # drop!
    H2 = np.maximum(0, np.dot(W2, H1) + b2)
    U2 = np.random.rand(*H2.shape) < p # second dropout mask
    H2 *= U2 # drop!
    out = np.dot(W3, H2) + b3

    # backward pass: compute gradients... (not shown)
    # perform parameter update... (not shown)

def predict(X):
    # ensembled forward pass
    H1 = np.maximum(0, np.dot(W1, X) + b1) * p # NOTE: scale the activations
    H2 = np.maximum(0, np.dot(W2, H1) + b2) * p # NOTE: scale the activations
    out = np.dot(W3, H2) + b3
```

drop in train time

scale at test time

More common: “Inverted dropout”

```
p = 0.5 # probability of keeping a unit active. higher = less dropout

def train_step(X):
    # forward pass for example 3-layer neural network
    H1 = np.maximum(0, np.dot(W1, X) + b1)
    U1 = (np.random.rand(*H1.shape) < p) / p # first dropout mask. Notice /p!
    H1 *= U1 # drop!
    H2 = np.maximum(0, np.dot(W2, H1) + b2)
    U2 = (np.random.rand(*H2.shape) < p) / p # second dropout mask. Notice /p!
    H2 *= U2 # drop!
    out = np.dot(W3, H2) + b3

    # backward pass: compute gradients... (not shown)
    # perform parameter update... (not shown)

def predict(X):
    # ensembled forward pass
    H1 = np.maximum(0, np.dot(W1, X) + b1) # no scaling necessary
    H2 = np.maximum(0, np.dot(W2, H1) + b2)
    out = np.dot(W3, H2) + b3
```

test time is unchanged!



Regularization: A common pattern

Training: Add some kind of randomness

$$y = f_W(x, z)$$

Testing: Average out randomness (sometimes approximate)

$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Regularization: A common pattern

Training: Add some kind of randomness

$$y = f_W(x, z)$$

Testing: Average out randomness (sometimes approximate)

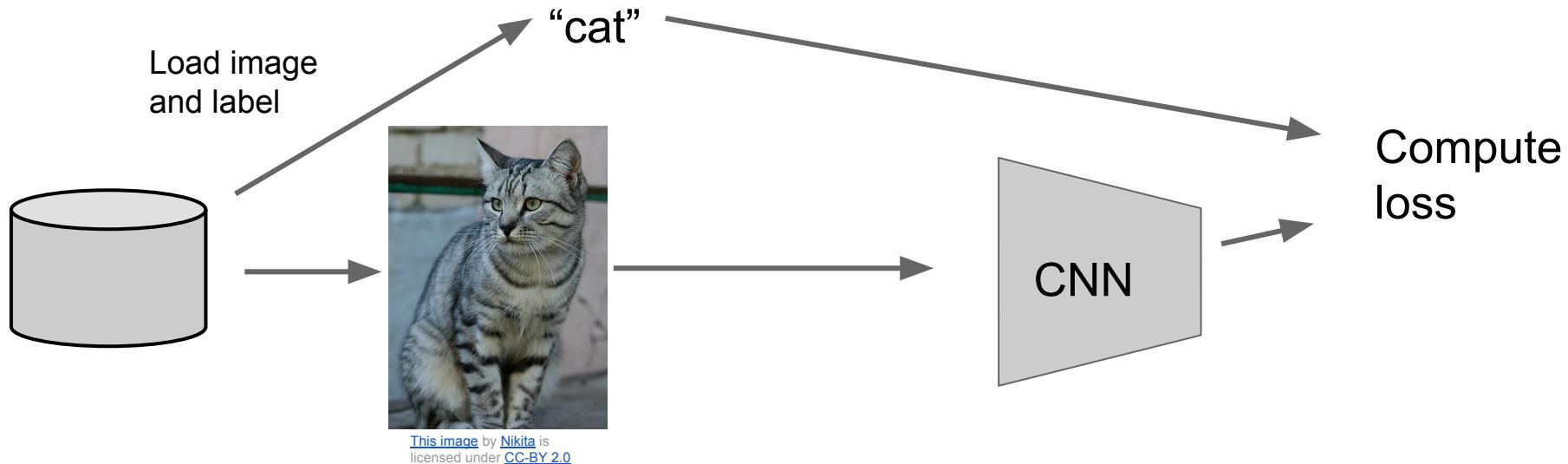
$$y = f(x) = E_z[f(x, z)] = \int p(z)f(x, z)dz$$

Example: Batch Normalization

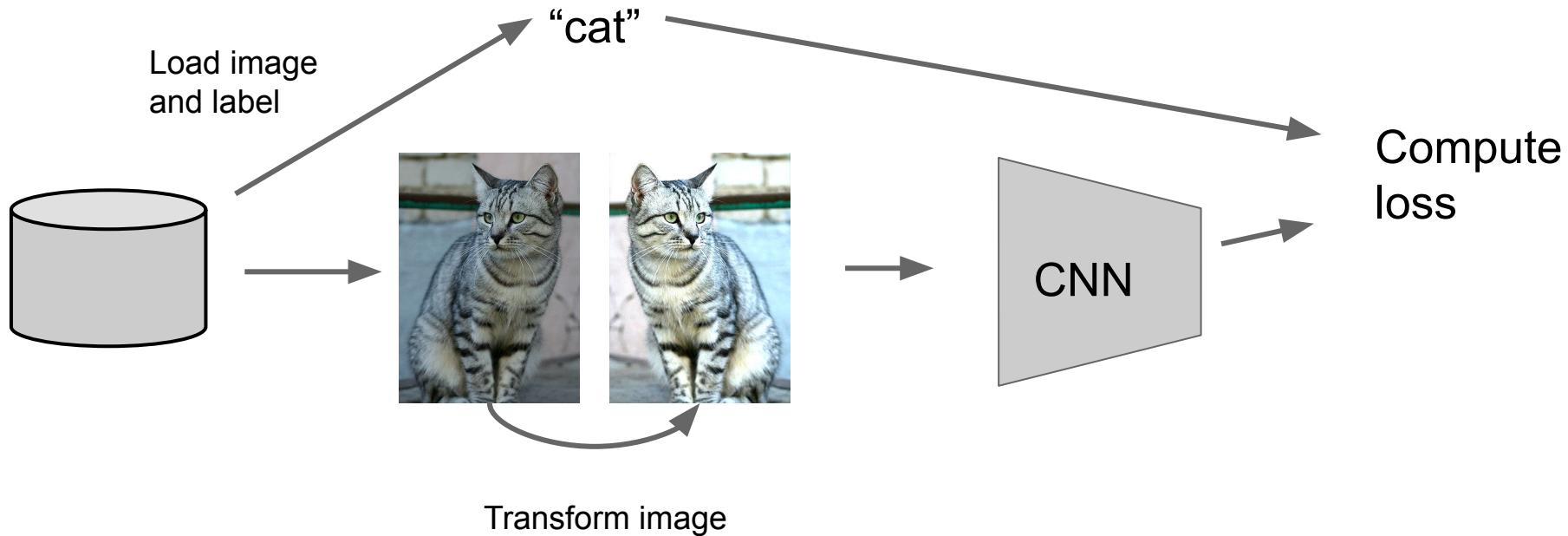
Training: Normalize using stats from random minibatches

Testing: Use fixed stats to normalize

Regularization: Data Augmentation



Regularization: Data Augmentation



Data Augmentation

Horizontal Flips



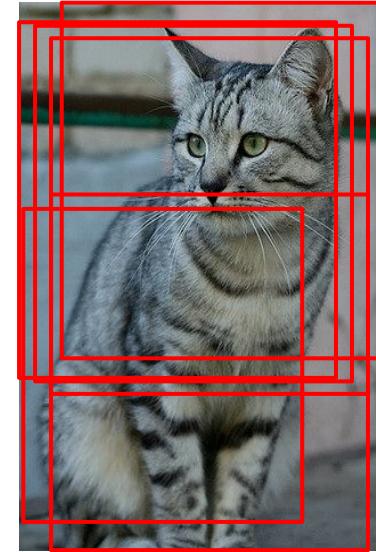
Data Augmentation

Random crops and scales

Training: sample random crops / scales

ResNet:

1. Pick random L in range [256, 480]
2. Resize training image, short side = L
3. Sample random 224×224 patch



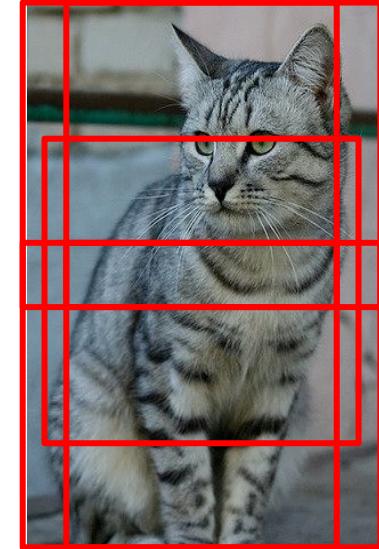
Data Augmentation

Random crops and scales

Training: sample random crops / scales

ResNet:

1. Pick random L in range [256, 480]
2. Resize training image, short side = L
3. Sample random 224×224 patch



Testing: average a fixed set of crops

ResNet:

1. Resize image at 5 scales: {224, 256, 384, 480, 640}
2. For each size, use 10 224×224 crops: 4 corners + center, + flips

Data Augmentation

Color Jitter

Simple: Randomize
contrast and brightness



Data Augmentation

Color Jitter

Simple: Randomize
contrast and brightness



More Complex:

1. Apply PCA to all [R, G, B] pixels in training set
2. Sample a “color offset” along principal component directions
3. Add offset to all pixels of a training image

(As seen in *[Krizhevsky et al. 2012]*, ResNet, etc)

Data Augmentation

Get creative for your problem!

Examples of data augmentations:

- translation
- rotation
- stretching
- shearing,
- lens distortions, ... (go crazy)

Automatic Data Augmentation

	Original	Sub-policy 1	Sub-policy 2	Sub-policy 3	Sub-policy 4	Sub-policy 5
Batch 1						
Batch 2						
Batch 3						
	ShearX, 0.9, 7 Invert, 0.2, 3	ShearY, 0.7, 6 Solarize, 0.4, 8	ShearX, 0.9, 4 AutoContrast, 0.8, 3	Invert, 0.9, 3 Equalize, 0.6, 3	ShearY, 0.8, 5 AutoContrast, 0.7, 3	

Cubuk et al., "AutoAugment: Learning Augmentation Strategies from Data", CVPR 2019

Regularization: A common pattern

Training: Add random noise

Testing: Marginalize over the noise

Examples:

Dropout

Batch Normalization

Data Augmentation

Regularization: DropConnect

Training: Drop connections between neurons (set weights to 0)

Testing: Use all the connections

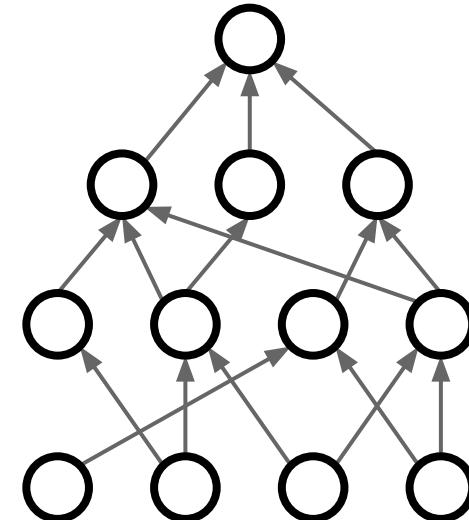
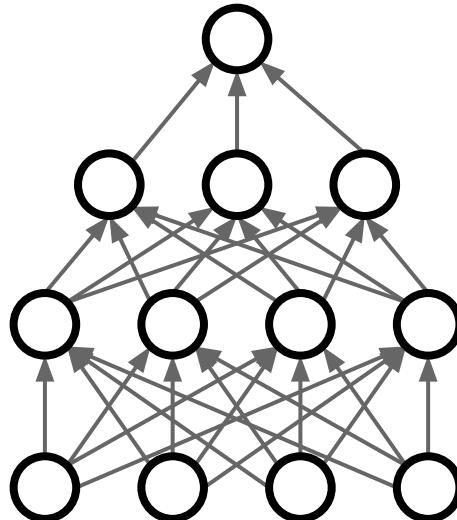
Examples:

Dropout

Batch Normalization

Data Augmentation

DropConnect



Wan et al, "Regularization of Neural Networks using DropConnect", ICML 2013

Regularization: Fractional Pooling

Training: Use randomized pooling regions

Testing: Average predictions from several regions

Examples:

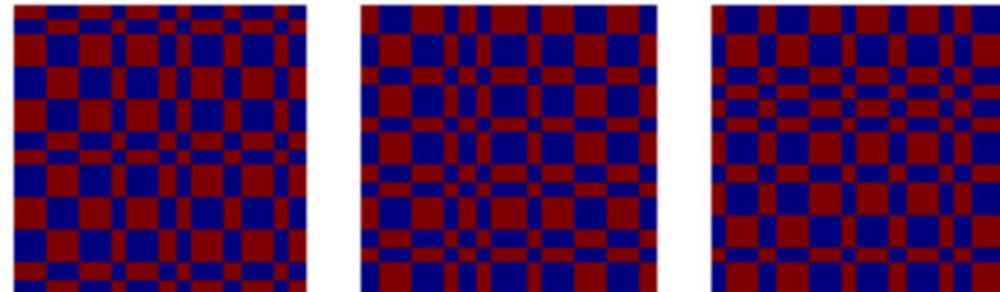
Dropout

Batch Normalization

Data Augmentation

DropConnect

Fractional Max Pooling



Graham, "Fractional Max Pooling", arXiv 2014

Regularization: Stochastic Depth

Training: Skip some layers in the network

Testing: Use all the layer

Examples:

Dropout

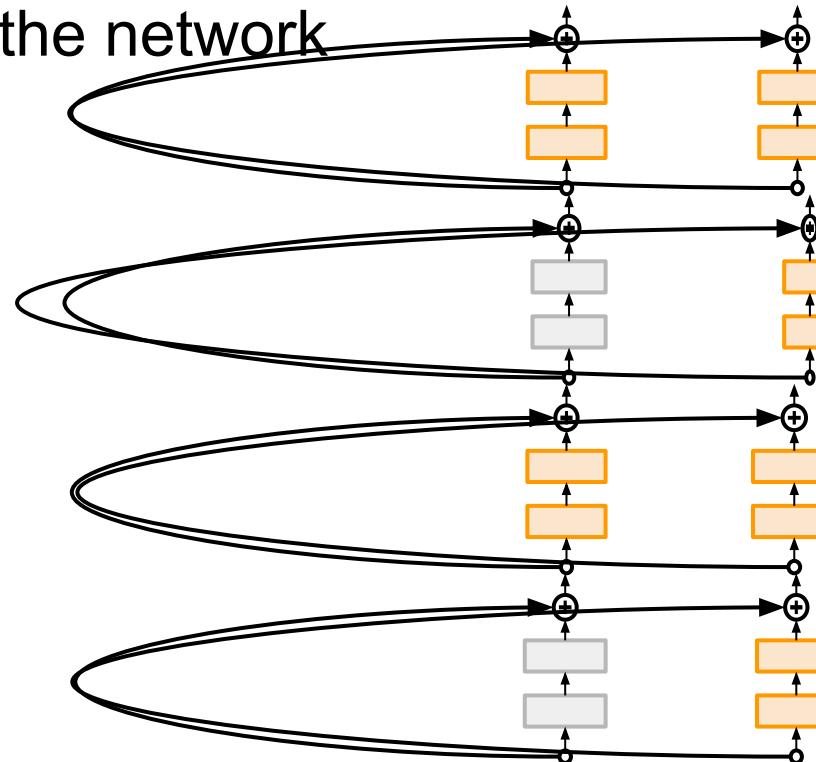
Batch Normalization

Data Augmentation

DropConnect

Fractional Max Pooling

Stochastic Depth



Huang et al, "Deep Networks with Stochastic Depth", ECCV 2016

Regularization: Cutout

Training: Set random image regions to zero

Testing: Use full image

Examples:

Dropout

Batch Normalization

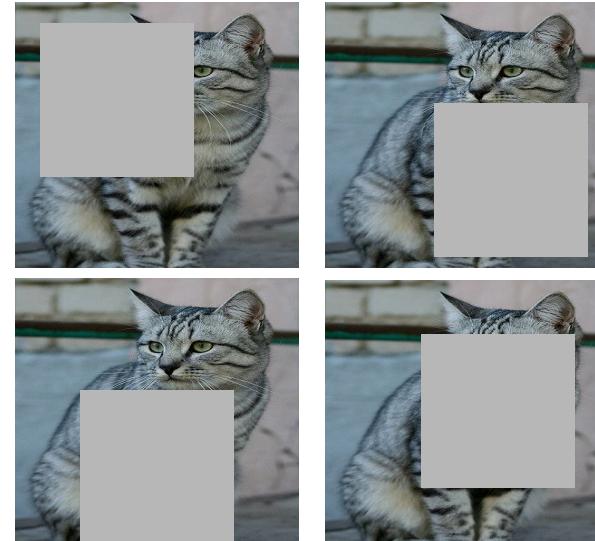
Data Augmentation

DropConnect

Fractional Max Pooling

Stochastic Depth

Cutout / Random Crop



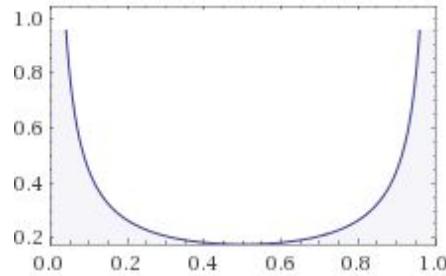
Works very well for small datasets like CIFAR,
less common for large datasets like ImageNet

DeVries and Taylor, "Improved Regularization of
Convolutional Neural Networks with Cutout", arXiv 2017

Regularization: Mixup

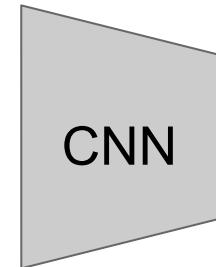
Training: Train on random blends of images

Testing: Use original images



Examples:

- Dropout
- Batch Normalization
- Data Augmentation
- DropConnect
- Fractional Max Pooling
- Stochastic Depth
- Cutout / Random Crop
- Mixup



Target label:
cat: 0.4
dog: 0.6

Randomly blend the pixels
of pairs of training images,
e.g. 40% cat, 60% dog

Zhang et al, "mixup: Beyond Empirical Risk Minimization", ICLR 2018

Regularization - In practice

Training: Add random noise

Testing: Marginalize over the noise

Examples:

Dropout

Batch Normalization

Data Augmentation

DropConnect

Fractional Max Pooling

Stochastic Depth

Cutout / Random Crop

Mixup

- Consider dropout for large fully-connected layers
- Batch normalization and data augmentation almost always a good idea
- Try cutout and mixup especially for small classification datasets

Choosing Hyperparameters

(without tons of GPUs)

Choosing Hyperparameters

Step 1: Check initial loss

Turn off weight decay, sanity check loss at initialization
e.g. $\log(C)$ for softmax with C classes

Choosing Hyperparameters

Step 1: Check initial loss

Step 2: Overfit a small sample

Try to train to 100% training accuracy on a small sample of training data (~5-10 minibatches); fiddle with architecture, learning rate, weight initialization

Loss not going down? LR too low, bad initialization

Loss explodes to Inf or NaN? LR too high, bad initialization

Choosing Hyperparameters

Step 1: Check initial loss

Step 2: Overfit a small sample

Step 3: Find LR that makes loss go down

Use the architecture from the previous step, use all training data, turn on small weight decay, find a learning rate that makes the loss drop significantly within ~100 iterations

Good learning rates to try: 1e-1, 1e-2, 1e-3, 1e-4

Choosing Hyperparameters

Step 1: Check initial loss

Step 2: Overfit a small sample

Step 3: Find LR that makes loss go down

Step 4: Coarse grid, train for ~1-5 epochs

Choose a few values of learning rate and weight decay around what worked from Step 3, train a few models for ~1-5 epochs.

Good weight decay to try: 1e-4, 1e-5, 0

Choosing Hyperparameters

Step 1: Check initial loss

Step 2: Overfit a small sample

Step 3: Find LR that makes loss go down

Step 4: Coarse grid, train for ~1-5 epochs

Step 5: Refine grid, train longer

Pick best models from Step 4, train them for longer (~10-20 epochs) without learning rate decay

Choosing Hyperparameters

Step 1: Check initial loss

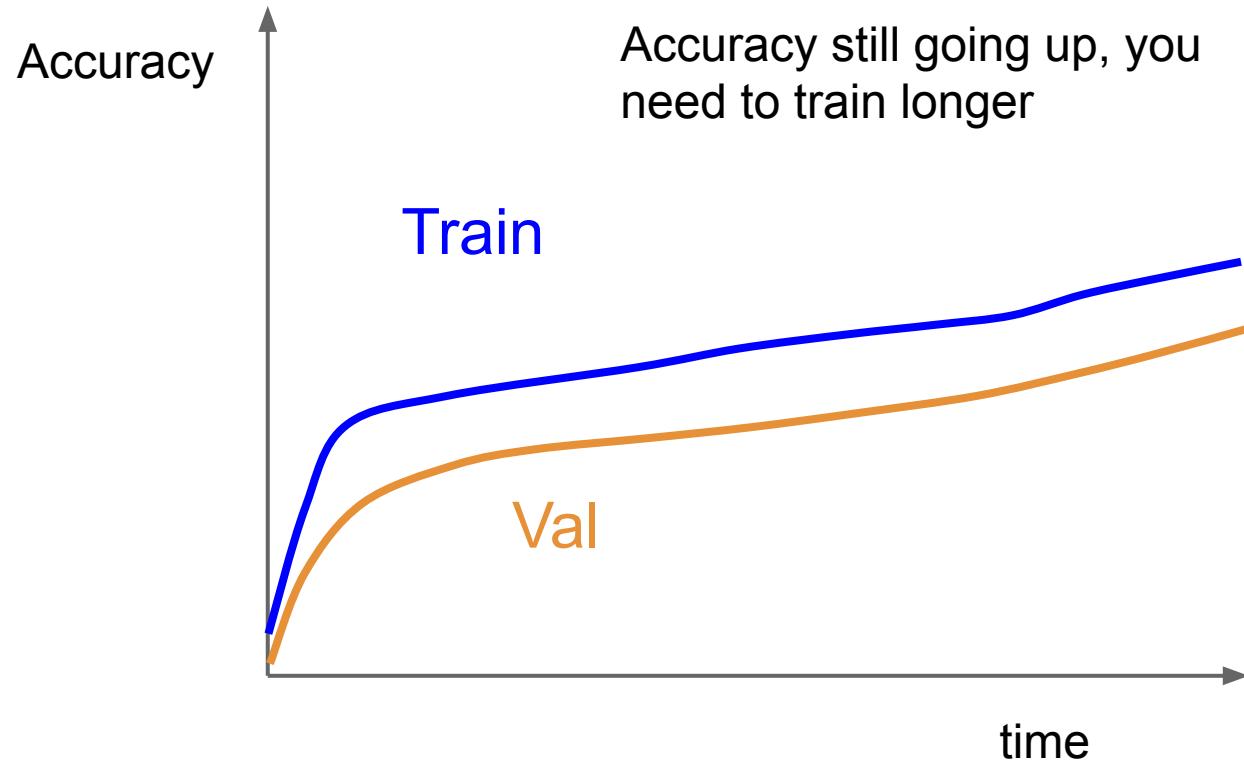
Step 2: Overfit a small sample

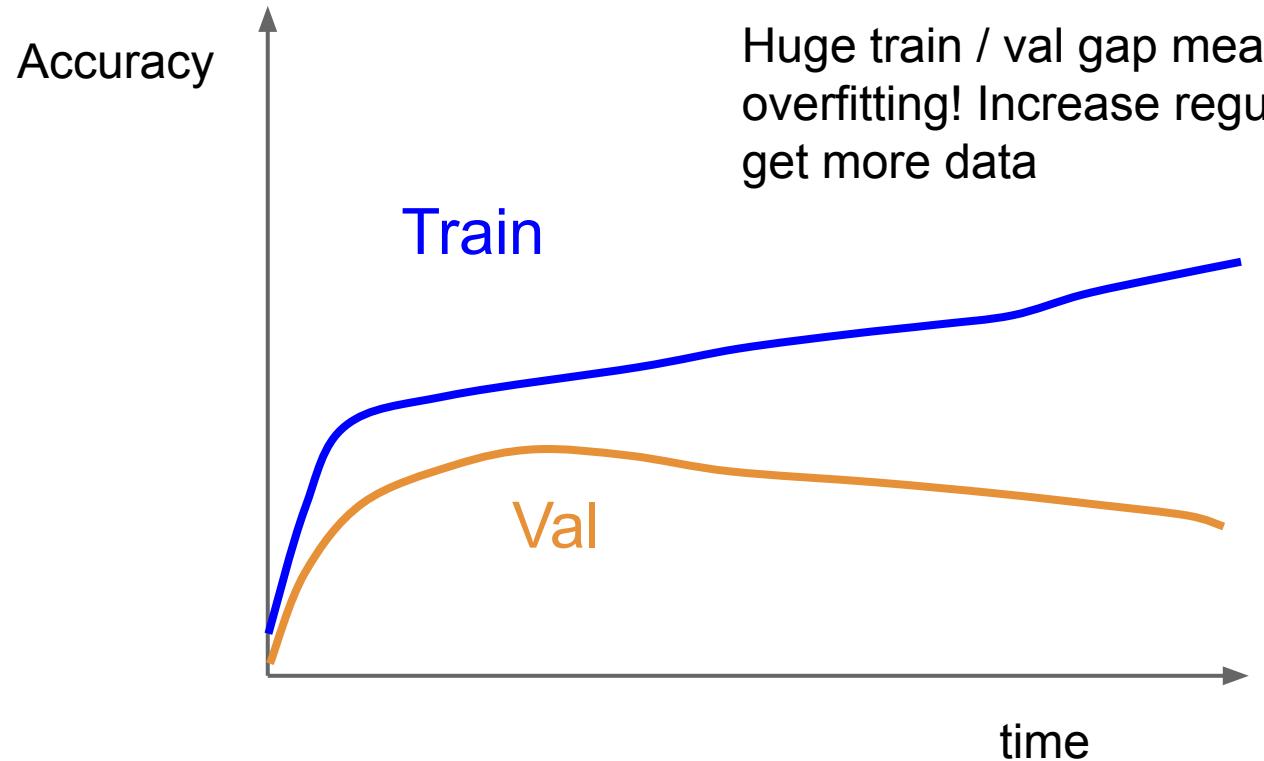
Step 3: Find LR that makes loss go down

Step 4: Coarse grid, train for ~1-5 epochs

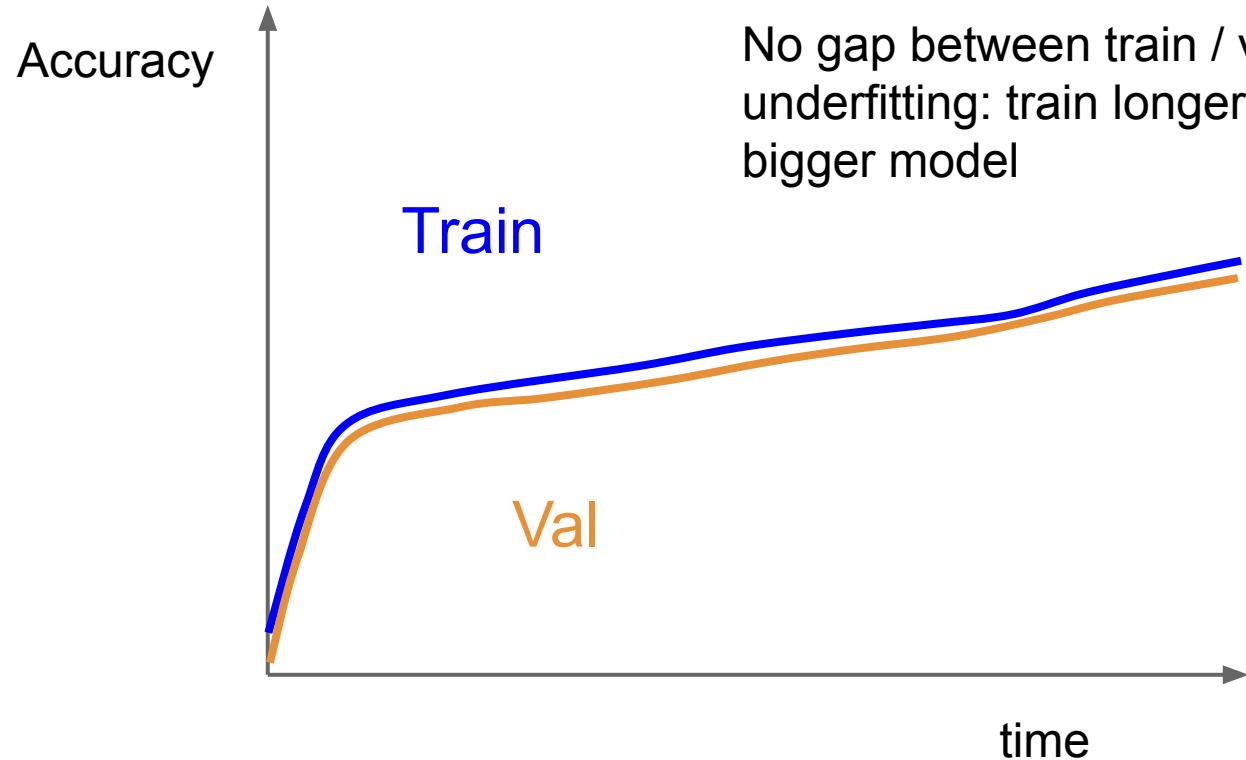
Step 5: Refine grid, train longer

Step 6: Look at loss and accuracy curves



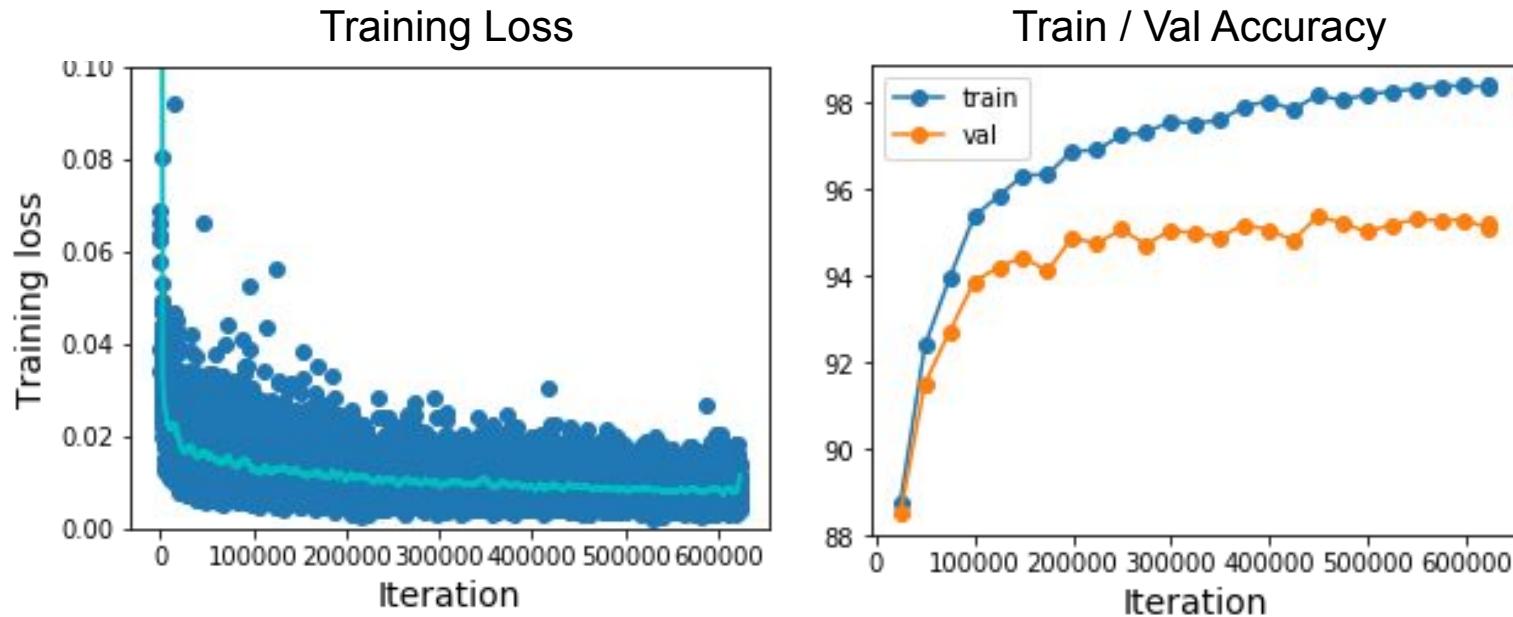


Huge train / val gap means overfitting! Increase regularization, get more data



No gap between train / val means underfitting: train longer, use a bigger model

Look at learning curves!

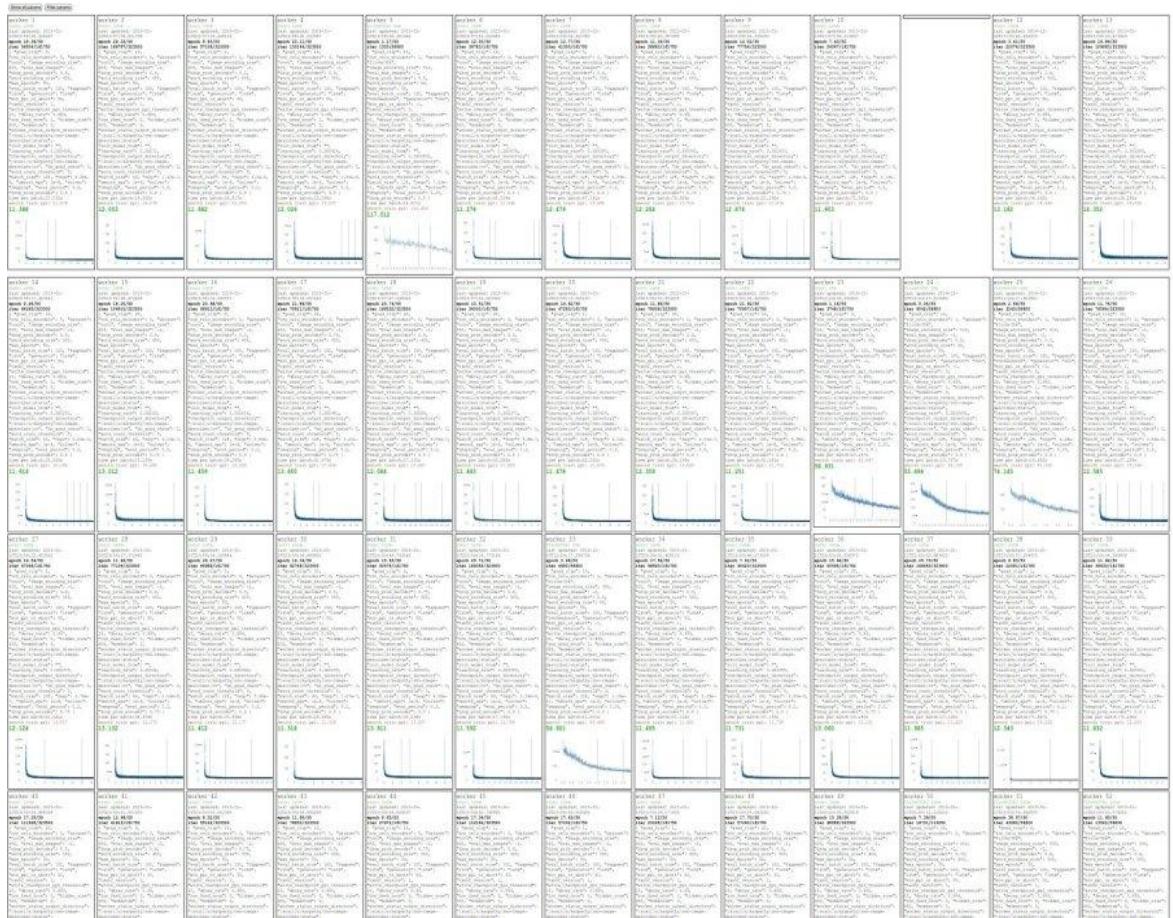


Losses may be noisy, use a scatter plot and also plot moving average to see trends better

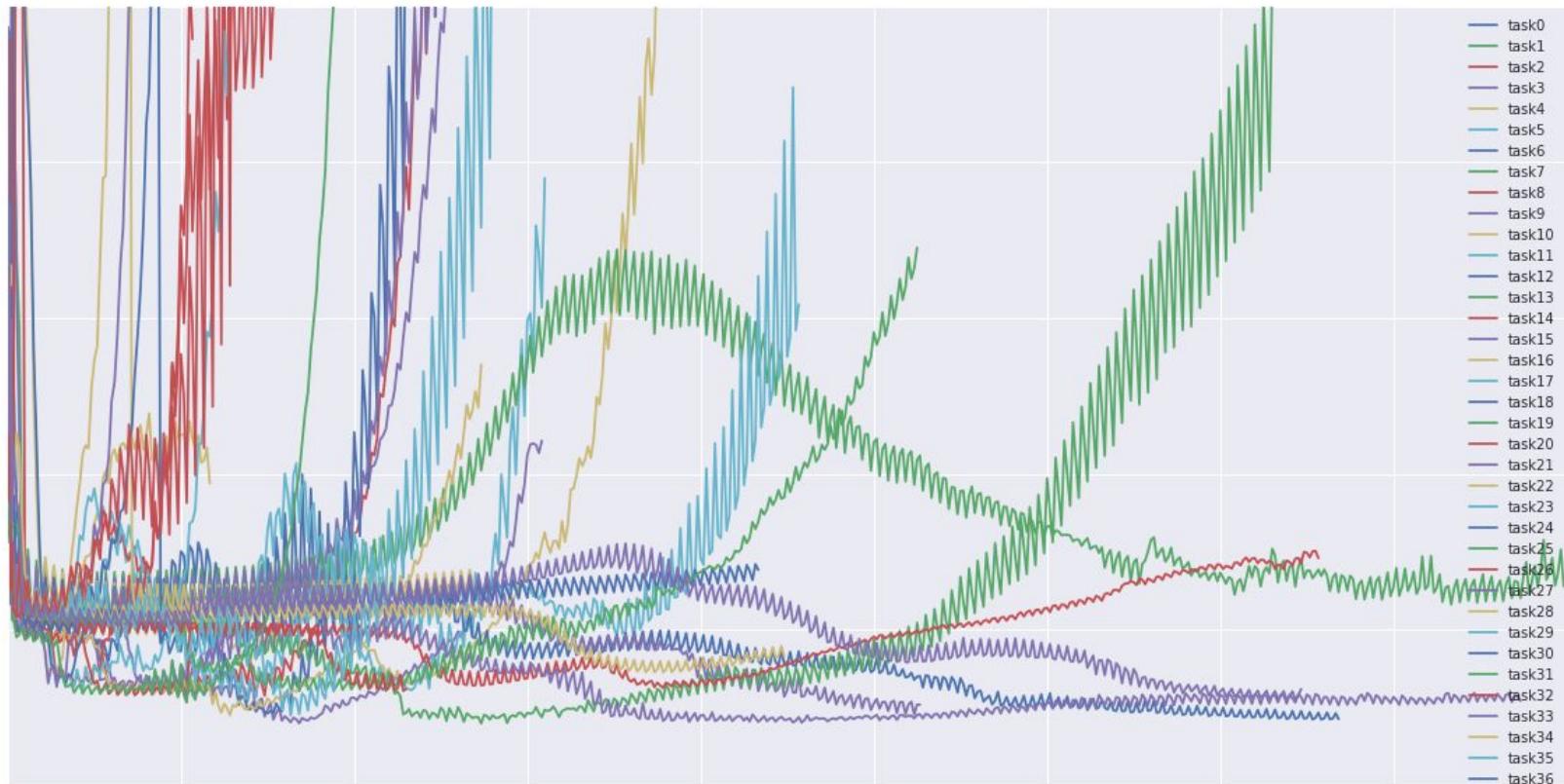
Cross-validation

We develop "command centers" to visualize all our models training with different hyperparameters

check out [weights and biases](#)



You can plot all your loss curves for different hyperparameters on a single plot



Don't look at accuracy or loss curves for too long!



Choosing Hyperparameters

Step 1: Check initial loss

Step 2: Overfit a small sample

Step 3: Find LR that makes loss go down

Step 4: Coarse grid, train for ~1-5 epochs

Step 5: Refine grid, train longer

Step 6: Look at loss and accuracy curves

Step 7: GOTO step 5

Random Search vs. Grid Search

*Random Search for
Hyper-Parameter Optimization
Bergstra and Bengio, 2012*

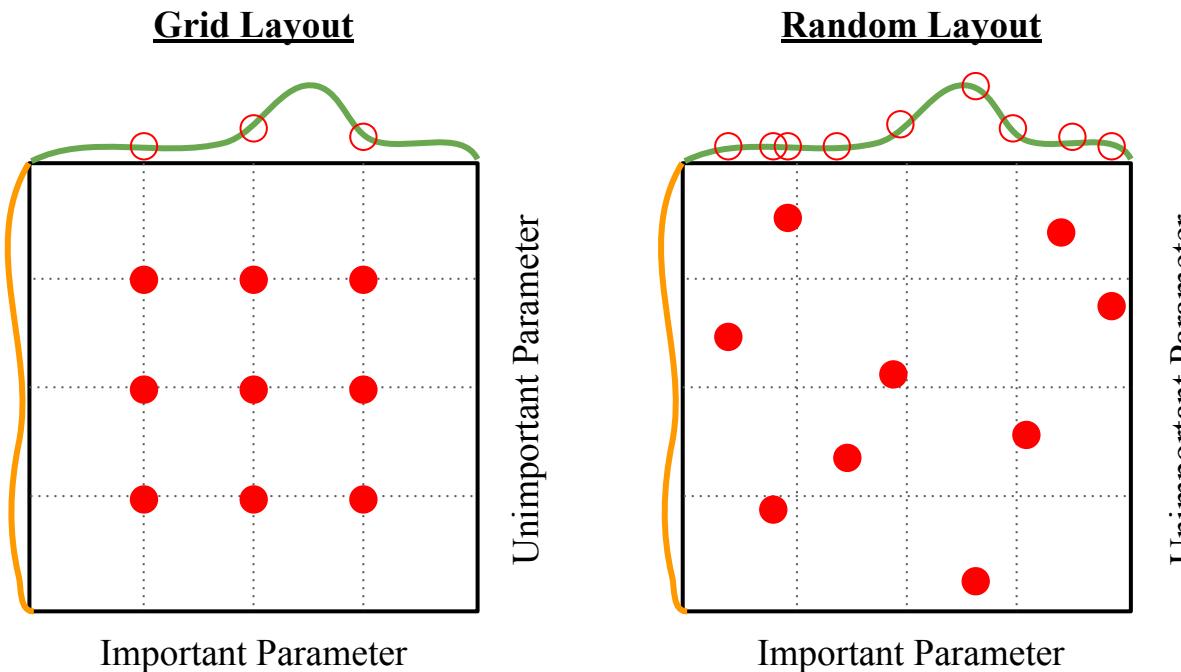


Illustration of Bergstra et al., 2012 by Shayne
Longpre, copyright CS231n 2017

Summary

- Improve your training error:
 - Optimizers
 - Learning rate schedules
- Improve your test error:
 - Regularization
 - Choosing Hyperparameters

Summary

TLDRs

We looked in detail at:

- Activation Functions (use ReLU)
- Data Preprocessing (images: subtract mean)
- Weight Initialization (use Xavier/He init)
- Batch Normalization (use this!)
- Transfer learning (use this if you can!)

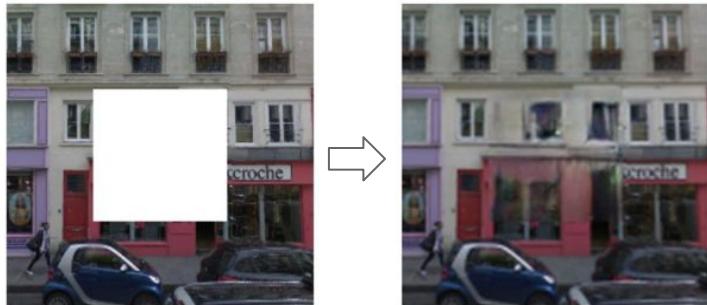
Next time: Visualizing and Understanding

Lecture 14: Visualizing and Understanding

Administrative

- Midterm grades released (regrade policy see Piazza)
 - some questions were removed or updated to reflect student feedback
- Assignment 3 due in a week on May 25
 - A3 has extra credit opportunities
- Final project reports due June 3rd
 - Final project video due June 4th
 - No late days for final project
- A2 and milestone grades will be released by Thursday

Last time: Self-supervised learning



Patch completion



Colorization

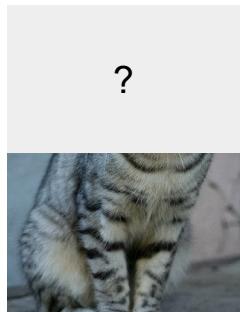


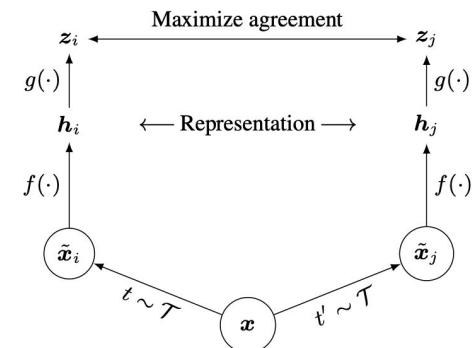
image completion



rotation prediction

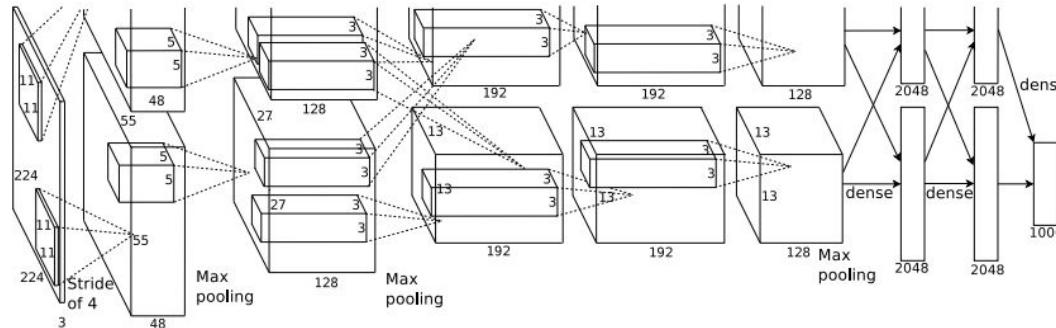


“jigsaw puzzle”



Today: What's going on inside ConvNets?

This image is CC0 public domain



Input Image:
3 x 224 x 224

What are the intermediate features looking for?

Class Scores:
1000 numbers

Krizhevsky et al, "ImageNet Classification with Deep Convolutional Neural Networks", NIPS 2012.
Figure reproduced with permission.

Visualizing what models have learned:

- Visualizing filters
- Visualizing final layer features
- Visualizing activations

Understanding input pixels

- Identifying important pixels
- Saliency via backprop
- Guided backprop to generate images
- Gradient ascent to visualize features

Adversarial perturbations

Style transfer

- Deep dream
- Features inversion
- Texture synthesis
- Neural style transfer

Today's agenda

Visualizing what models have learned:

- Visualizing filters
- Visualizing final layer features
- Visualizing activations

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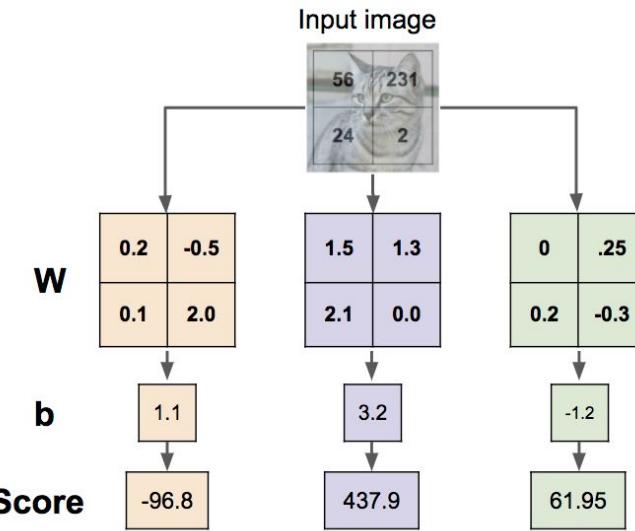
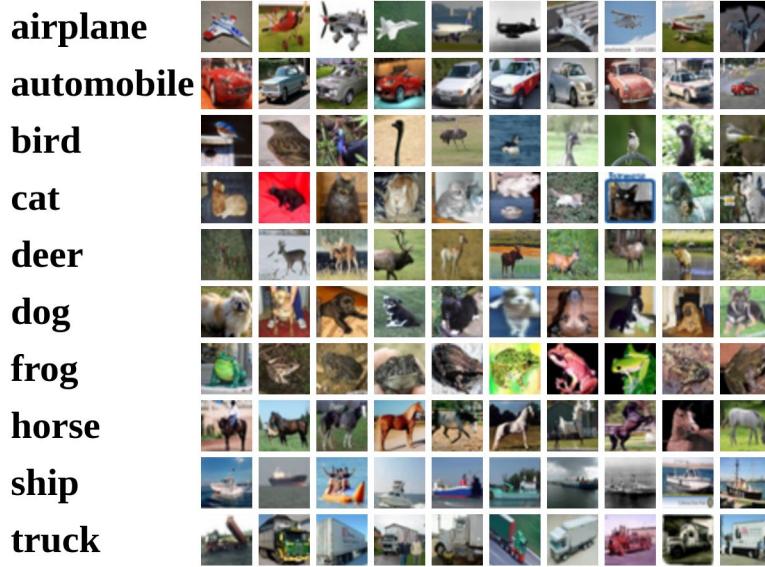
Adversarial perturbations

Style transfer

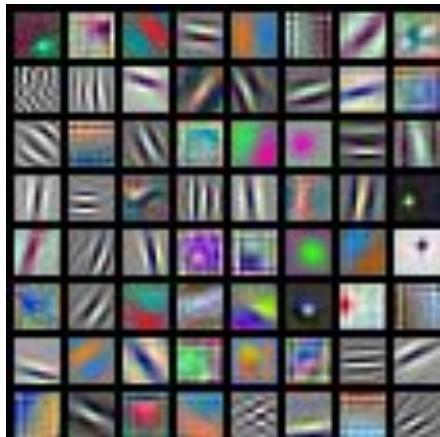
- Deep dream
- Features inversion
- Texture synthesis
- Neural style transfer

Today's agenda

Interpreting a Linear Classifier: Visual Viewpoint



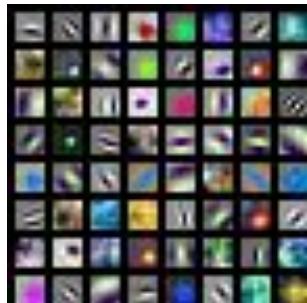
First Layer: Visualize Filters



AlexNet:
 $64 \times 3 \times 11 \times 11$



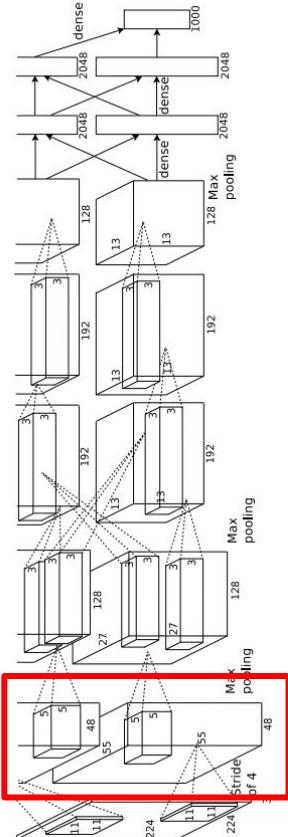
ResNet-18:
 $64 \times 3 \times 7 \times 7$



ResNet-101:
 $64 \times 3 \times 7 \times 7$



DenseNet-121:
 $64 \times 3 \times 7 \times 7$



Krizhevsky, "One weird trick for parallelizing convolutional neural networks", arXiv 2014

He et al, "Deep Residual Learning for Image Recognition", CVPR 2016

Huang et al, "Densely Connected Convolutional Networks", CVPR 2017

Visualize the filters/kernels (raw weights)

We can visualize filters at higher layers, but not that interesting

(these are taken from ConvNetJS CIFAR-10 demo)

Weights:


layer 1 weights

$16 \times 3 \times 7 \times 7$

Weights:


layer 2 weights

$20 \times 16 \times 7 \times 7$

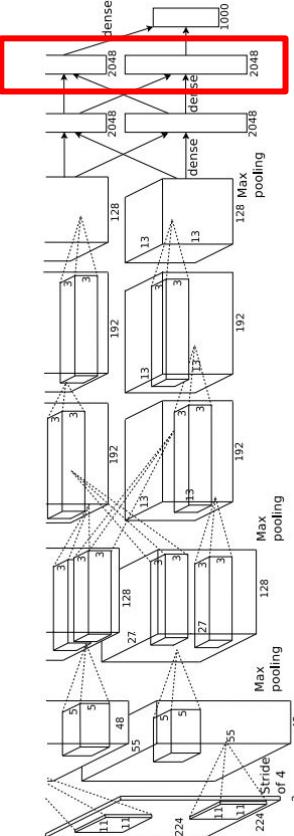
Weights:


layer 3 weights

$20 \times 20 \times 7 \times 7$

Last Layer

FC7 layer

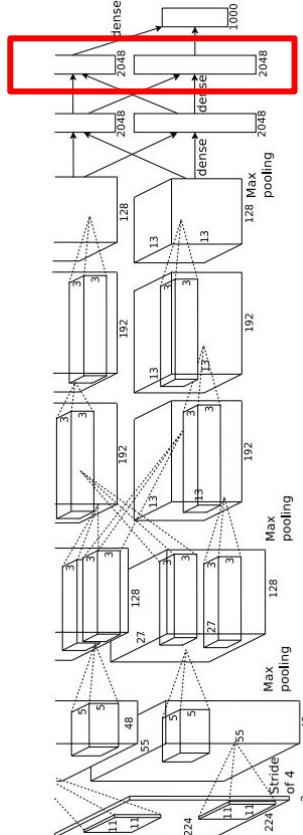


4096-dimensional feature vector for an image
(layer immediately before the classifier)

Run the network on many images, collect the feature vectors

Last Layer: Nearest Neighbors

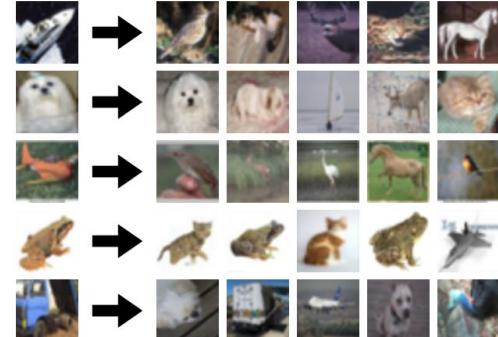
4096-dim vector



Test image L2 Nearest neighbors in feature space



Recall: Nearest neighbors
in pixel space



Krizhevsky et al, "ImageNet Classification with Deep Convolutional Neural Networks", NIPS 2012.

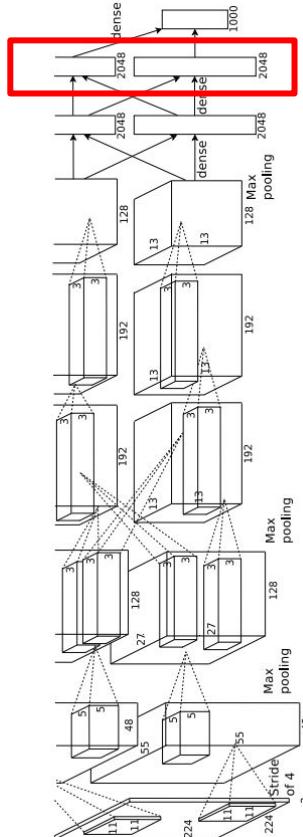
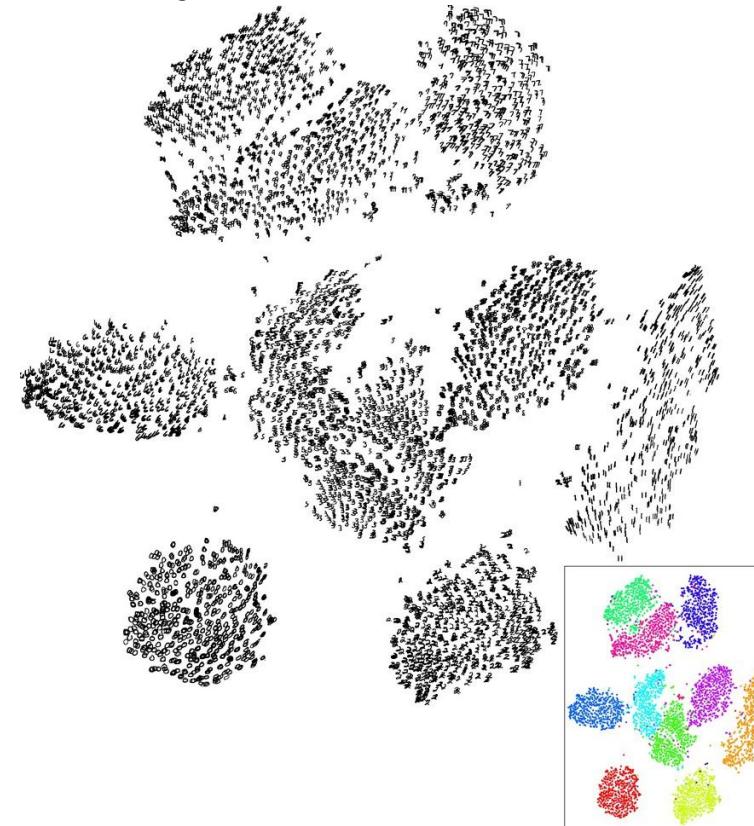
Figures reproduced with permission.

Last Layer: Dimensionality Reduction

Visualize the “space” of FC7 feature vectors by reducing dimensionality of vectors from 4096 to 2 dimensions

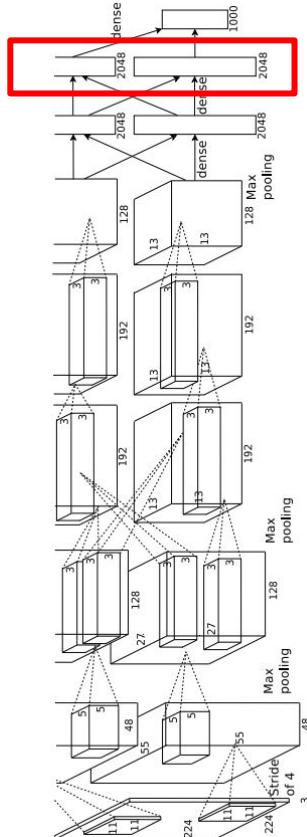
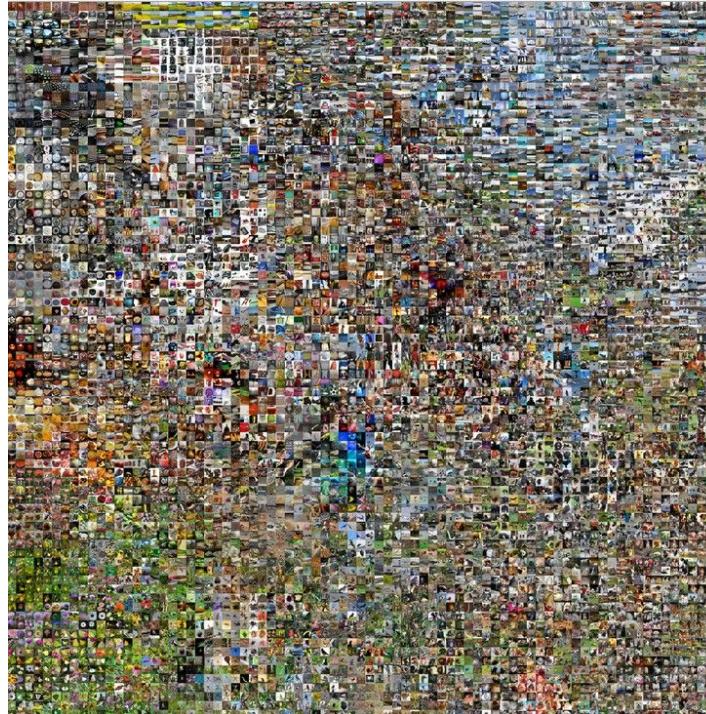
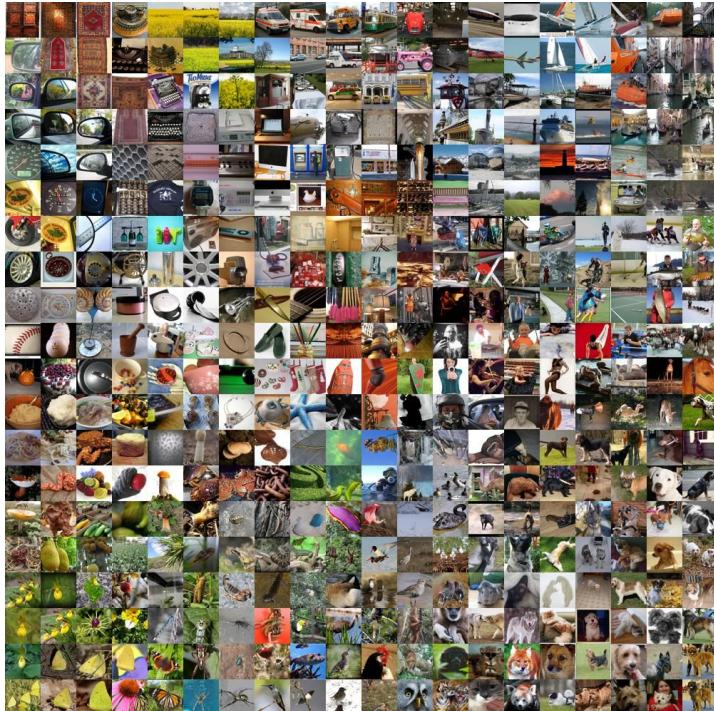
Simple algorithm: Principal Component Analysis (PCA)

More complex: t-SNE



Van der Maaten and Hinton, "Visualizing Data using t-SNE", JMLR 2008
Figure copyright Laurens van der Maaten and Geoff Hinton, 2008. Reproduced with permission.

Last Layer: Dimensionality Reduction

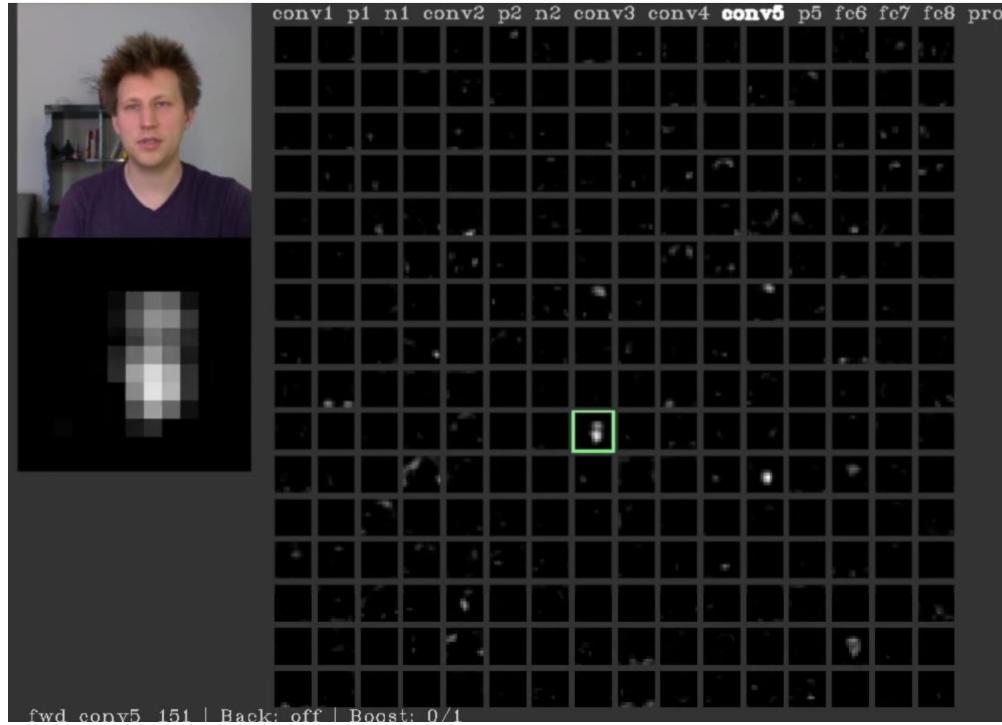


Van der Maaten and Hinton, "Visualizing Data using t-SNE", JMLR 2008
Krizhevsky et al, "ImageNet Classification with Deep Convolutional Neural Networks", NIPS 2012.
Figure reproduced with permission.

See high-resolution versions at
<http://cs.stanford.edu/people/karpathy/cnnembed/>

Visualizing Activations

conv5 feature map is
128x13x13; visualize
as 128 13x13
grayscale images



Yosinski et al, "Understanding Neural Networks Through Deep Visualization", ICML DL Workshop 2014.
Figure copyright Jason Yosinski, 2014. Reproduced with permission.

Visualizing what models have learned:

- Visualizing filters
- Visualizing final layer features
- Visualizing activations

Understanding input pixels

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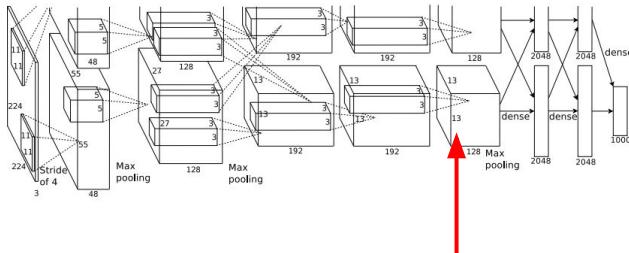
Adversarial perturbations

Style transfer

- Deep dream
- Features inversion
- Texture synthesis
- Neural style transfer

Today's agenda

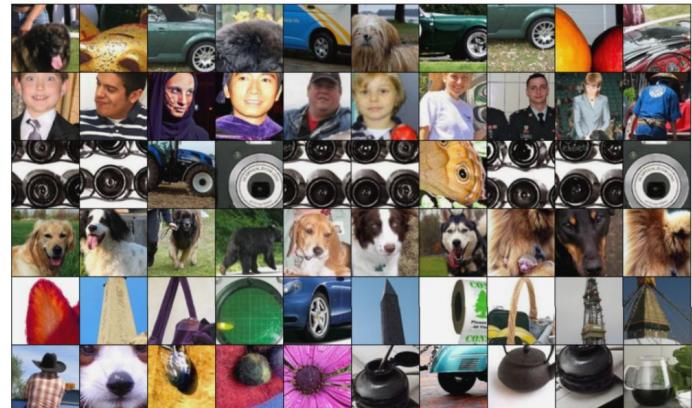
Maximally Activating Patches



Pick a layer and a channel; e.g. conv5 is $128 \times 13 \times 13$, pick channel 17/128

Run many images through the network,
record values of chosen channel

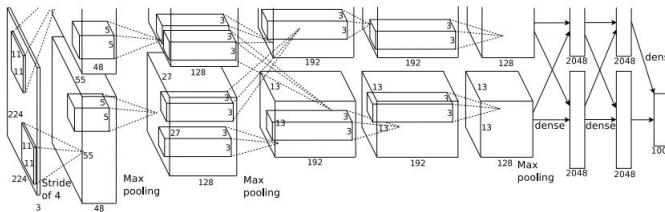
Visualize image patches that correspond
to maximal activations



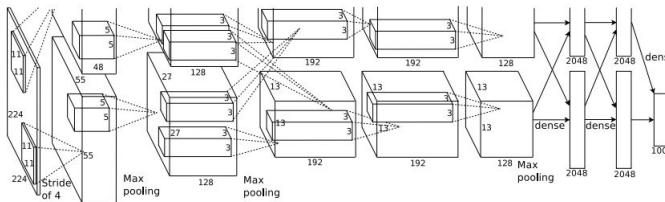
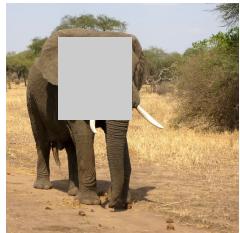
Springenberg et al, "Striving for Simplicity: The All Convolutional Net", ICLR Workshop 2015
Figure copyright Jost Tobias Springenberg, Alexey Dosovitskiy, Thomas Brox, Martin Riedmiller, 2015;
reproduced with permission.

Which pixels matter: Saliency via Occlusion

Mask part of the image before feeding to CNN,
check how much predicted probabilities change



$$P(\text{elephant}) = 0.95$$



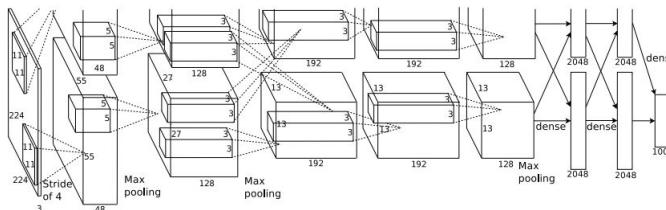
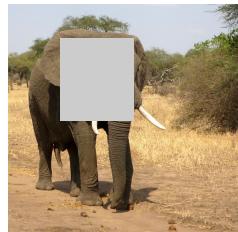
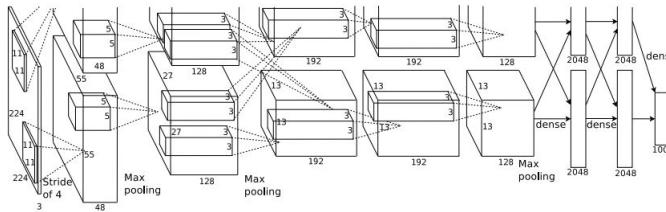
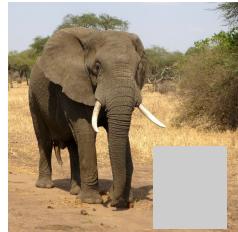
$$P(\text{elephant}) = 0.75$$

Zeiler and Fergus, "Visualizing and Understanding Convolutional Networks", ECCV 2014

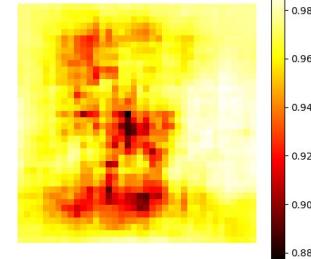
Boat image is CC0 public domain
Elephant image is CC0 public domain
Go-Karts image is CC0 public domain

Which pixels matter: Saliency via Occlusion

Mask part of the image before feeding to CNN,
check how much predicted probabilities change

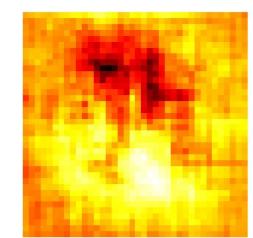
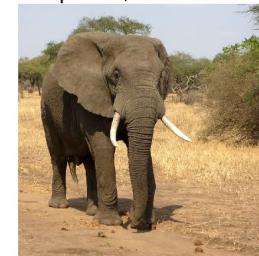


schooner



Color scale: 0.88 to 0.98

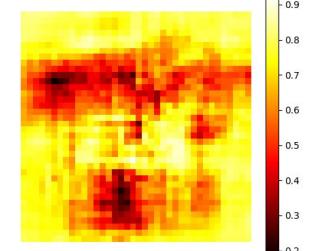
African elephant, *Loxodonta africana*



Color scale: 0.4 to 0.8



go-kart



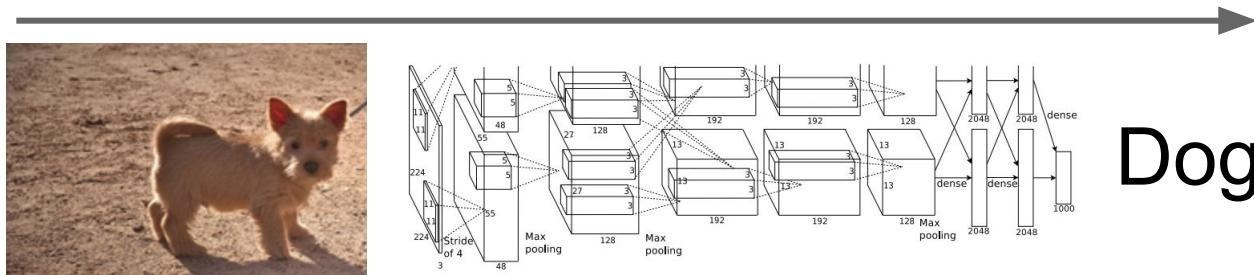
Color scale: 0.2 to 0.9

Zeiler and Fergus, "Visualizing and Understanding Convolutional Networks", ECCV 2014

Boat image is CC0 public domain
Elephant image is CC0 public domain
Go-Karts image is CC0 public domain

Which pixels matter: Saliency via Backprop

Forward pass: Compute probabilities

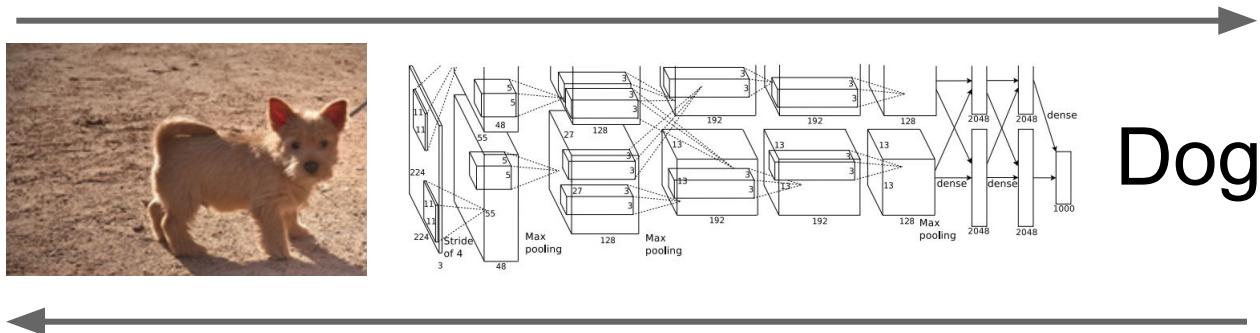


Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.

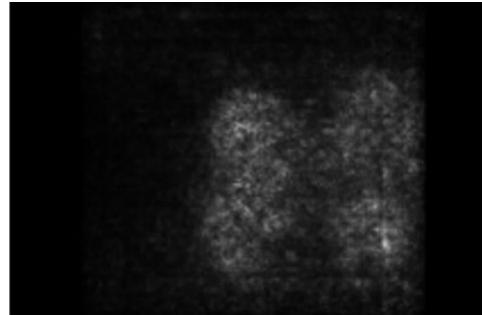
Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.

Which pixels matter: Saliency via Backprop

Forward pass: Compute probabilities



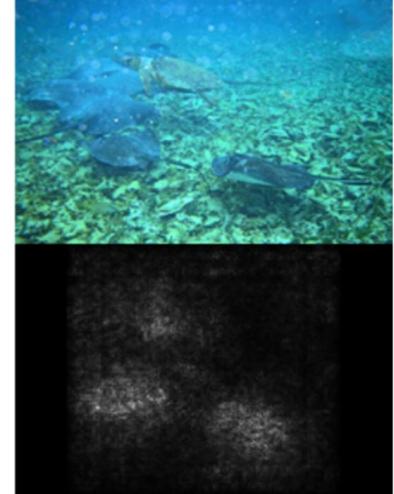
Compute gradient of (unnormalized) class score with respect to image pixels, take absolute value and max over RGB channels



Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.

Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.

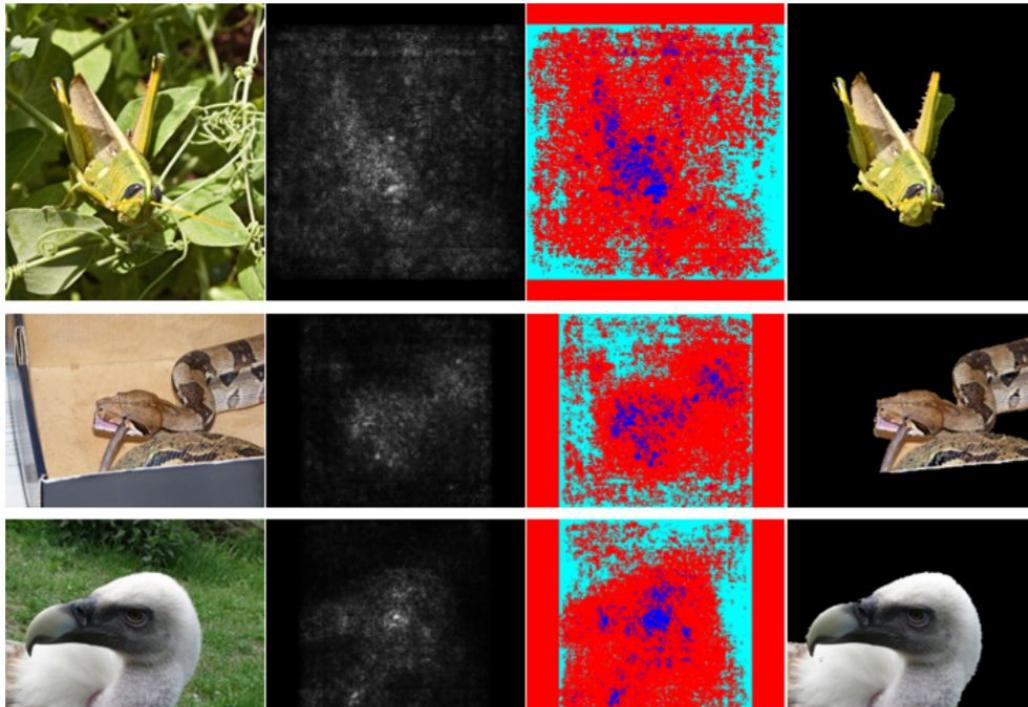
Saliency Maps



Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.

Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.

Saliency Maps: Segmentation without supervision



Use GrabCut on
saliency map

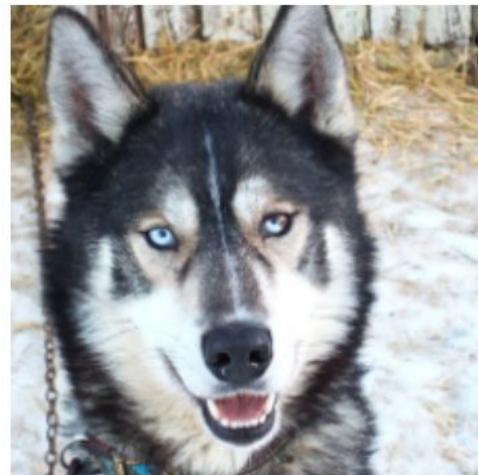
Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.

Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.
Rother et al, "Grabcut: Interactive foreground extraction using iterated graph cuts", ACM TOG 2004

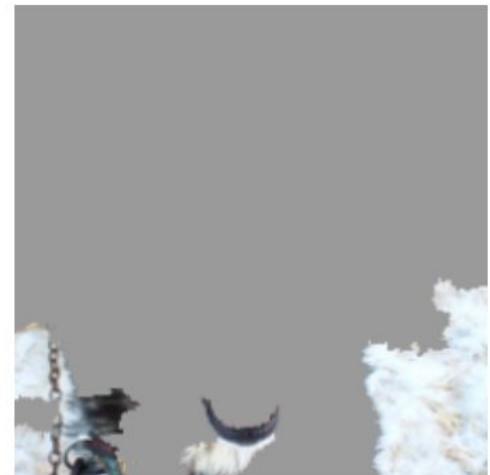
Saliency maps: Uncovers biases

Such methods also find
biases

wolf vs dog classifier looks
is actually a snow vs
no-snow classifier



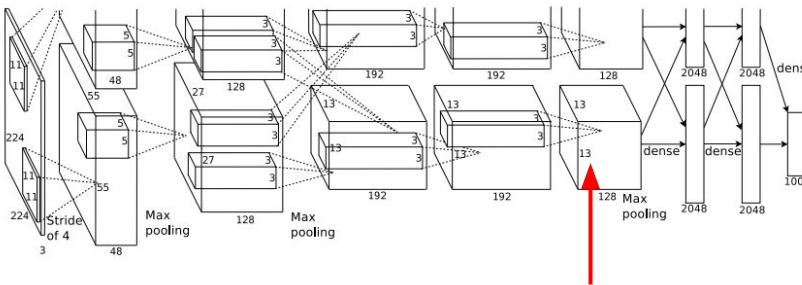
(a) Husky classified as wolf



(b) Explanation

Figures copyright Marco Tulio Ribeiro, Sameer Singh, and Carlos Guestrin, 2016; reproduced with permission.
Ribeiro et al, "Why Should I Trust You?" Explaining the Predictions of Any Classifier", ACM KDD 2016

Intermediate Features via (guided) backprop

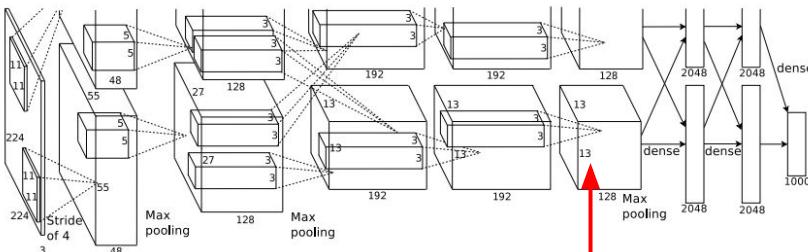


Pick a single intermediate channel, e.g. one value in $128 \times 13 \times 13$ conv5 feature map

Compute gradient of activation value with respect to image pixels

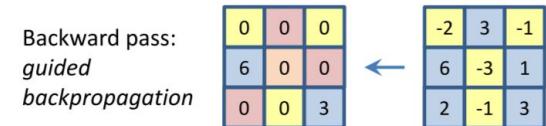
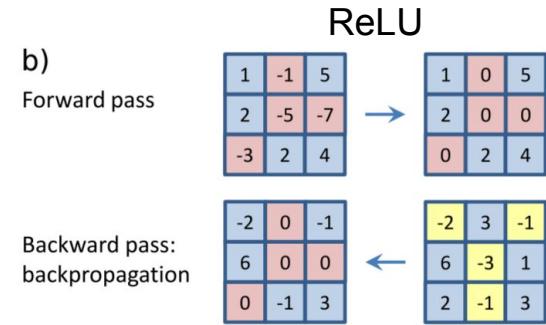
Zeiler and Fergus, "Visualizing and Understanding Convolutional Networks", ECCV 2014
Springenberg et al, "Striving for Simplicity: The All Convolutional Net", ICLR Workshop 2015

Intermediate Features via (guided) backprop



Pick a single intermediate neuron, e.g. one value in $128 \times 13 \times 13$ conv5 feature map

Compute gradient of neuron value with respect to image pixels



Images come out nicer if you only backprop positive gradients through each ReLU (guided backprop)

Figure copyright Jost Tobias Springenberg, Alexey Dosovitskiy, Thomas Brox, Martin Riedmiller, 2015; reproduced with permission.

Intermediate features via (guided) backprop



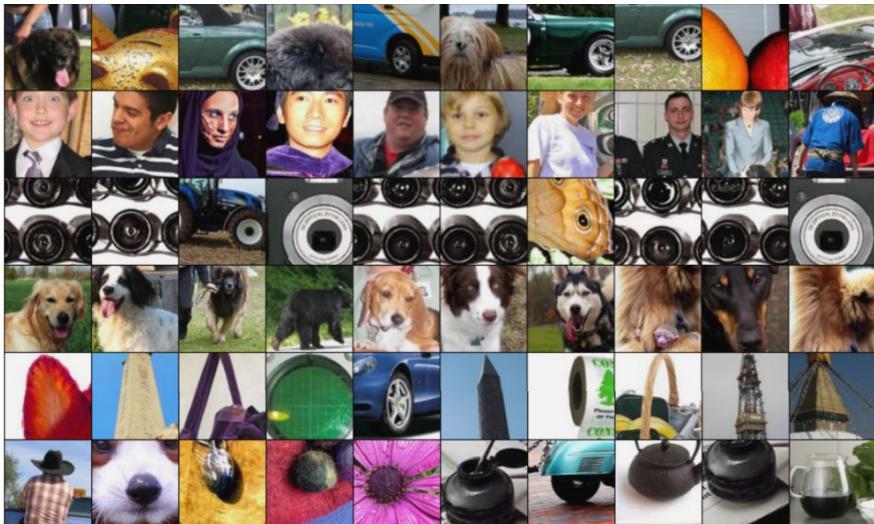
Maximally activating patches
(Each row is a different neuron)



Guided Backprop

Zeiler and Fergus, "Visualizing and Understanding Convolutional Networks", ECCV 2014
Springenberg et al, "Striving for Simplicity: The All Convolutional Net", ICLR Workshop 2015
Figure copyright Jost Tobias Springenberg, Alexey Dosovitskiy, Thomas Brox, Martin Riedmiller, 2015; reproduced with permission.

Intermediate features via (guided) backprop



Maximally activating patches
(Each row is a different neuron)



Guided Backprop

Zeiler and Fergus, "Visualizing and Understanding Convolutional Networks", ECCV 2014
Springenberg et al, "Striving for Simplicity: The All Convolutional Net", ICLR Workshop 2015
Figure copyright Jost Tobias Springenberg, Alexey Dosovitskiy, Thomas Brox, Martin Riedmiller, 2015; reproduced with permission.

Visualizing CNN features: Gradient Ascent

(Guided) backprop:

Find the part of an image that a neuron responds to

Gradient ascent:

Generate a synthetic image that maximally activates a neuron

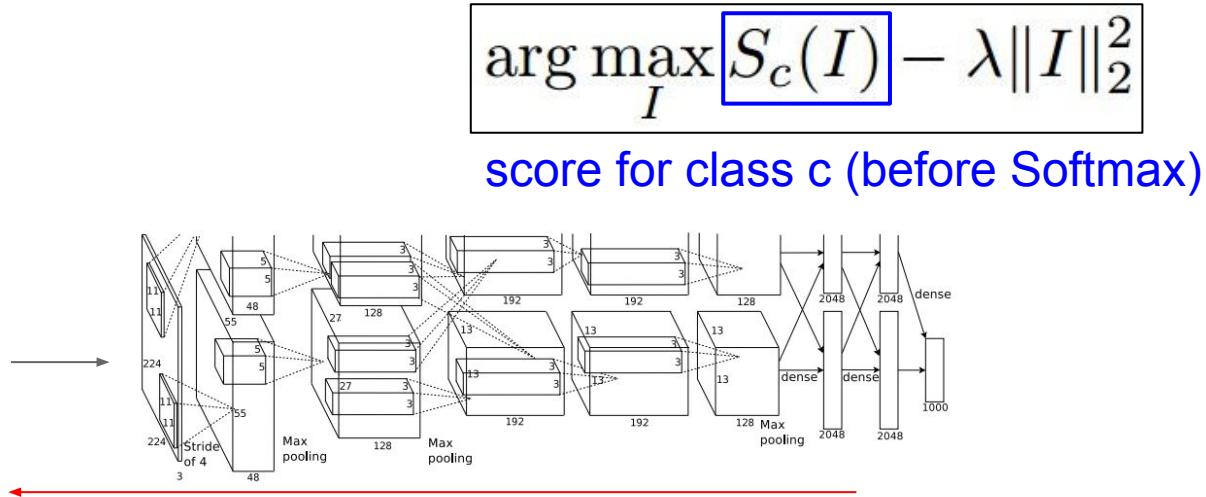
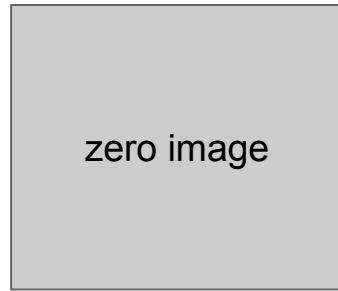
$$I^* = \arg \max_I f(I) + R(I)$$

Neuron value

Natural image regularizer

Visualizing CNN features: Gradient Ascent

1. Initialize image to zeros



Repeat:

2. Forward image to compute current scores
3. Backprop to get gradient of neuron value with respect to image pixels
4. Make a small update to the image

$$\arg \max_I S_c(I) - \lambda \|I\|_2^2$$

score for class c (before Softmax)

Visualizing CNN features: Gradient Ascent

$$\arg \max_I S_c(I) - \boxed{\lambda \|I\|_2^2}$$

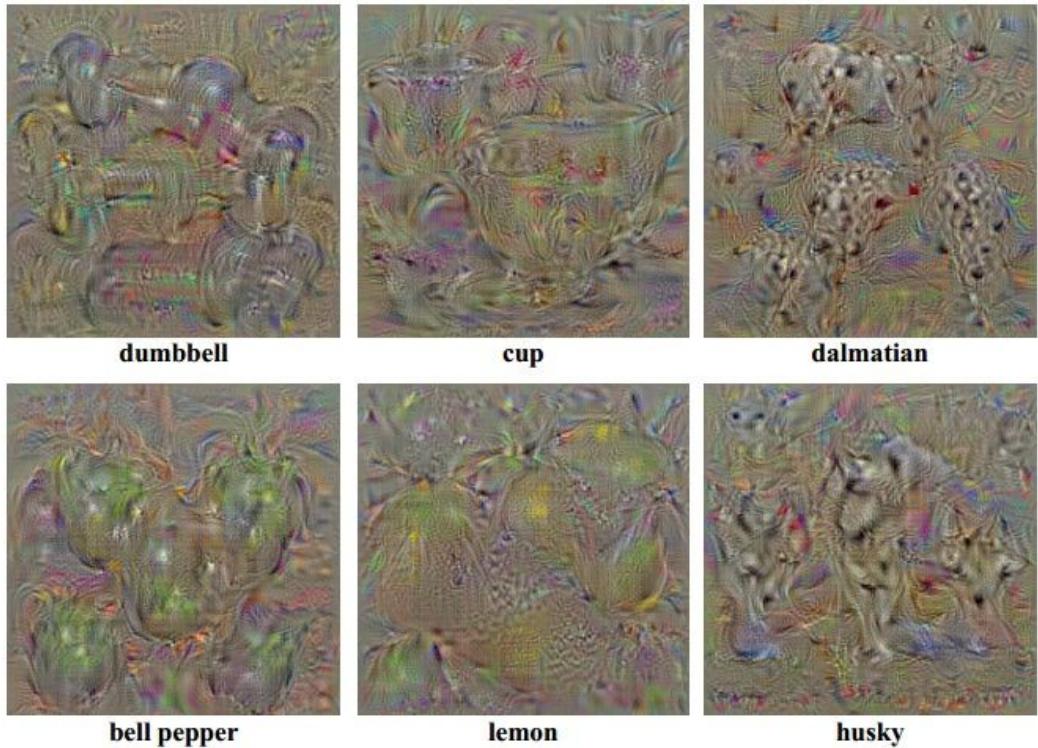
Simple regularizer: Penalize L2
norm of generated image

Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.
Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.

Visualizing CNN features: Gradient Ascent

$$\arg \max_I S_c(I) - \boxed{\lambda \|I\|_2^2}$$

Simple regularizer: Penalize L2
norm of generated image

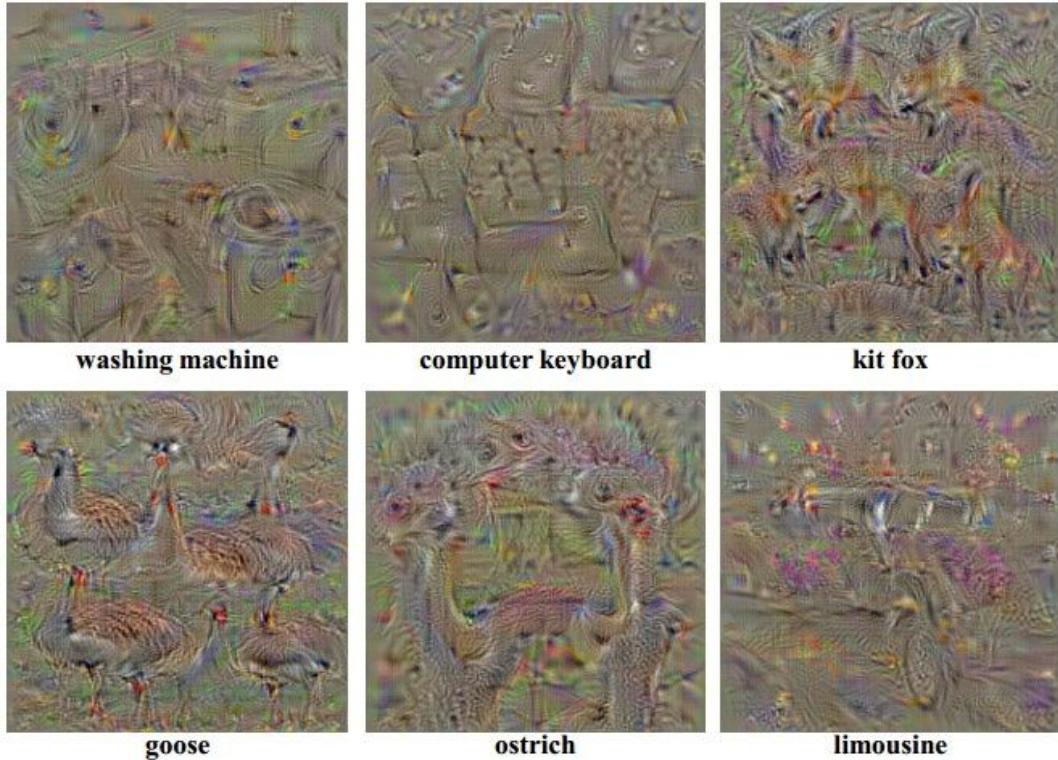


Simonyan, Vedaldi, and Zisserman, "Deep Inside Convolutional Networks: Visualising Image Classification Models and Saliency Maps", ICLR Workshop 2014.
Figures copyright Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman, 2014; reproduced with permission.

Visualizing CNN features: Gradient Ascent

$$\arg \max_I S_c(I) - \boxed{\lambda \|I\|_2^2}$$

Simple regularizer: Penalize L2 norm of generated image



Yosinski et al, "Understanding Neural Networks Through Deep Visualization", ICML DL Workshop 2014.
Figure copyright Jason Yosinski, Jeff Clune, Anh Nguyen, Thomas Fuchs, and Hod Lipson, 2014. Reproduced with permission.

Visualizing CNN features: Gradient Ascent

$$\arg \max_I S_c(I) - \lambda \|I\|_2^2$$

Better regularizer: Penalize L2 norm of image; also during optimization periodically

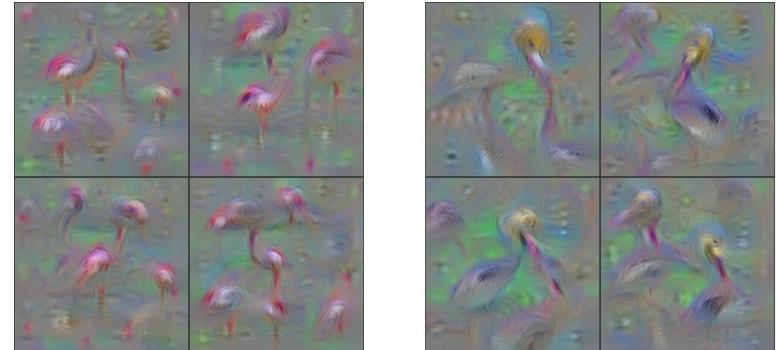
- (1) Gaussian blur image
- (2) Clip pixels with small values to 0
- (3) Clip pixels with small gradients to 0

Visualizing CNN features: Gradient Ascent

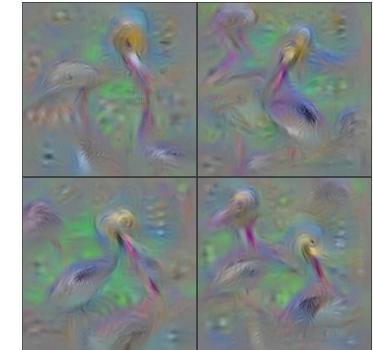
$$\arg \max_I S_c(I) - \lambda \|I\|_2^2$$

Better regularizer: Penalize L2 norm of image; also during optimization periodically

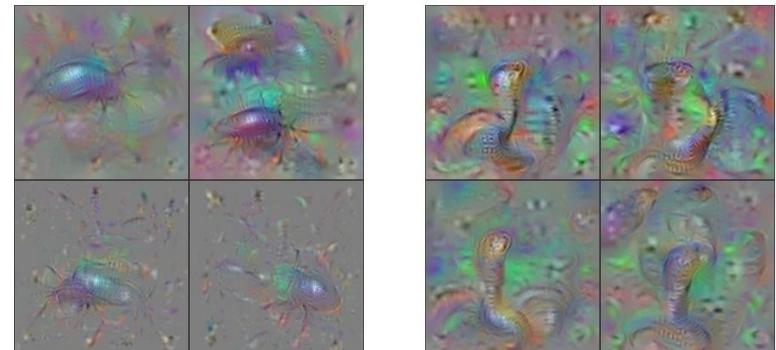
- (1) Gaussian blur image
- (2) Clip pixels with small values to 0
- (3) Clip pixels with small gradients to 0



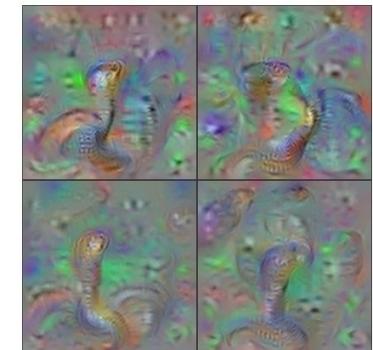
Flamingo



Pelican



Ground Beetle



Indian Cobra

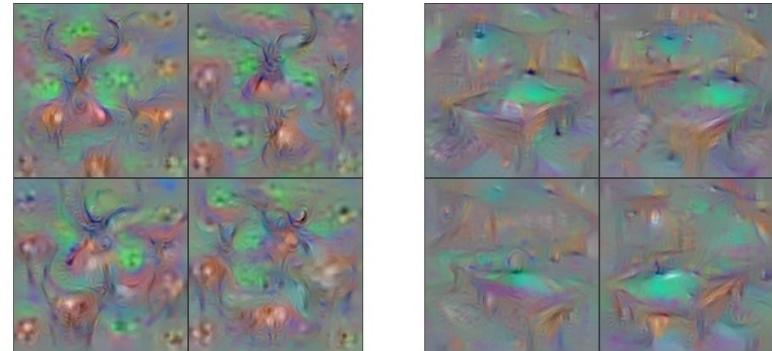
Yosinski et al, "Understanding Neural Networks Through Deep Visualization", ICML DL Workshop 2014.
Figure copyright Jason Yosinski, Jeff Clune, Anh Nguyen, Thomas Fuchs, and Hod Lipson, 2014. Reproduced with permission.

Visualizing CNN features: Gradient Ascent

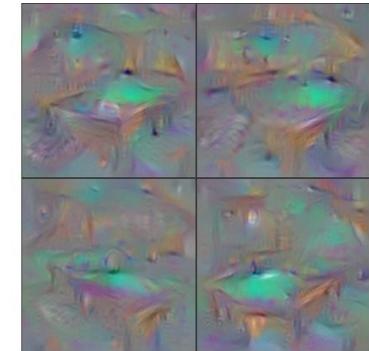
$$\arg \max_I S_c(I) - \lambda \|I\|_2^2$$

Better regularizer: Penalize L2 norm of image; also during optimization periodically

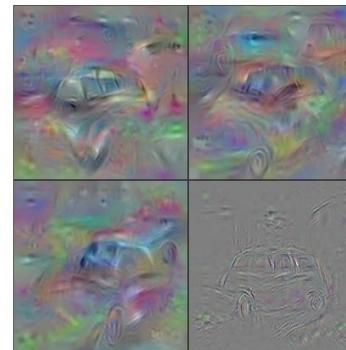
- (1) Gaussian blur image
- (2) Clip pixels with small values to 0
- (3) Clip pixels with small gradients to 0



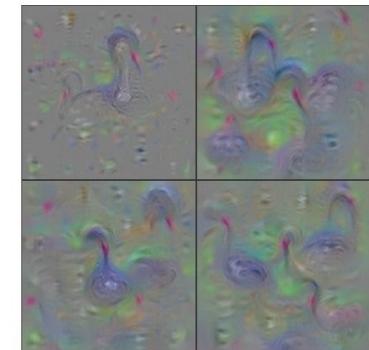
Hartebeest



Billiard Table



Station Wagon

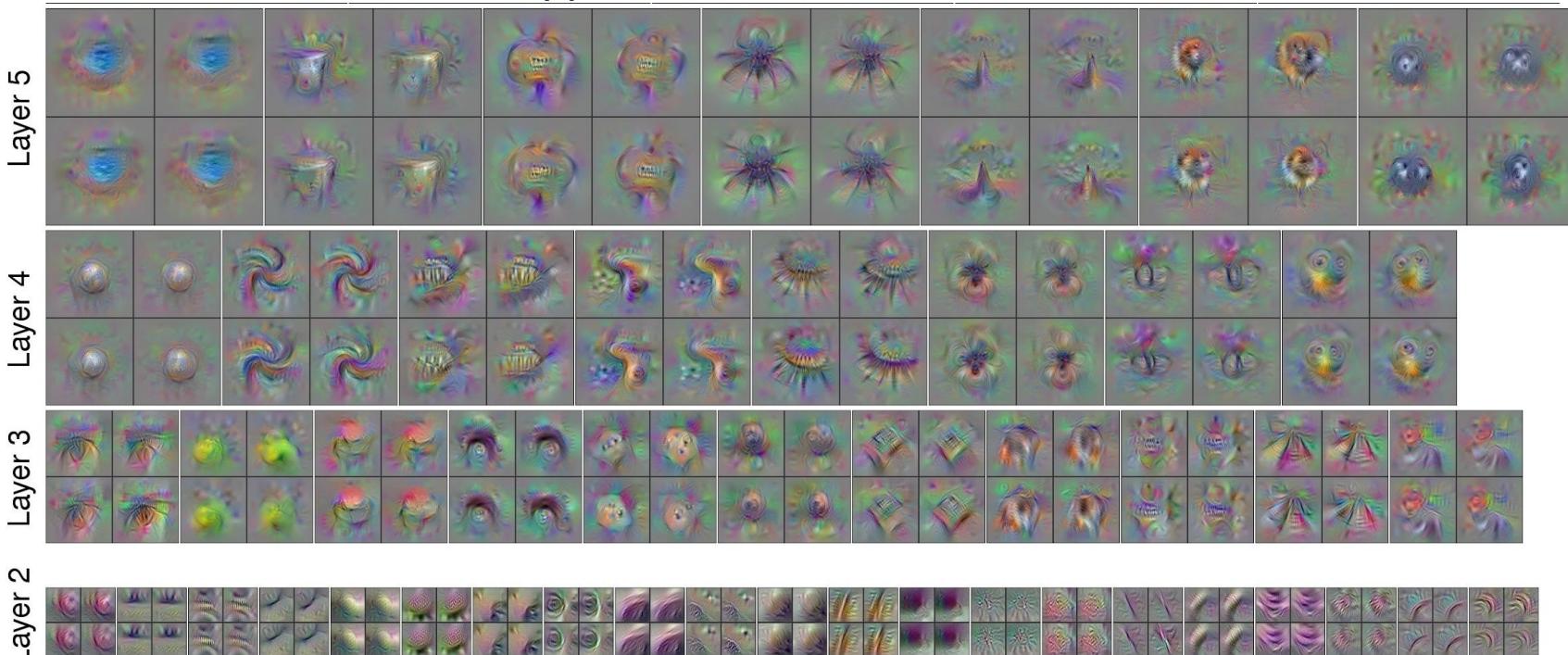


Black Swan

Yosinski et al, "Understanding Neural Networks Through Deep Visualization", ICML DL Workshop 2014.
Figure copyright Jason Yosinski, Jeff Clune, Anh Nguyen, Thomas Fuchs, and Hod Lipson, 2014. Reproduced with permission.

Visualizing CNN features: Gradient Ascent

Use the same approach to visualize intermediate features



Yosinski et al, "Understanding Neural Networks Through Deep Visualization", ICML DL Workshop 2014.

Figure copyright Jason Yosinski, Jeff Clune, Anh Nguyen, Thomas Fuchs, and Hod Lipson, 2014. Reproduced with permission.

Visualizing CNN features: Gradient Ascent

Adding “multi-faceted” visualization gives even nicer results:
(Plus more careful regularization, center-bias)

Reconstructions of multiple feature types (facets) recognized by the same “grocery store” neuron



Corresponding example training set images recognized by the same neuron as in the “grocery store” class



Nguyen et al., “Multifaceted Feature Visualization: Uncovering the Different Types of Features Learned By Each Neuron in Deep Neural Networks”, ICML Visualization for Deep Learning Workshop 2016.
Figures copyright Anh Nguyen, Jason Yosinski, and Jeff Clune, 2016; reproduced with permission.

Visualizing CNN features: Gradient Ascent

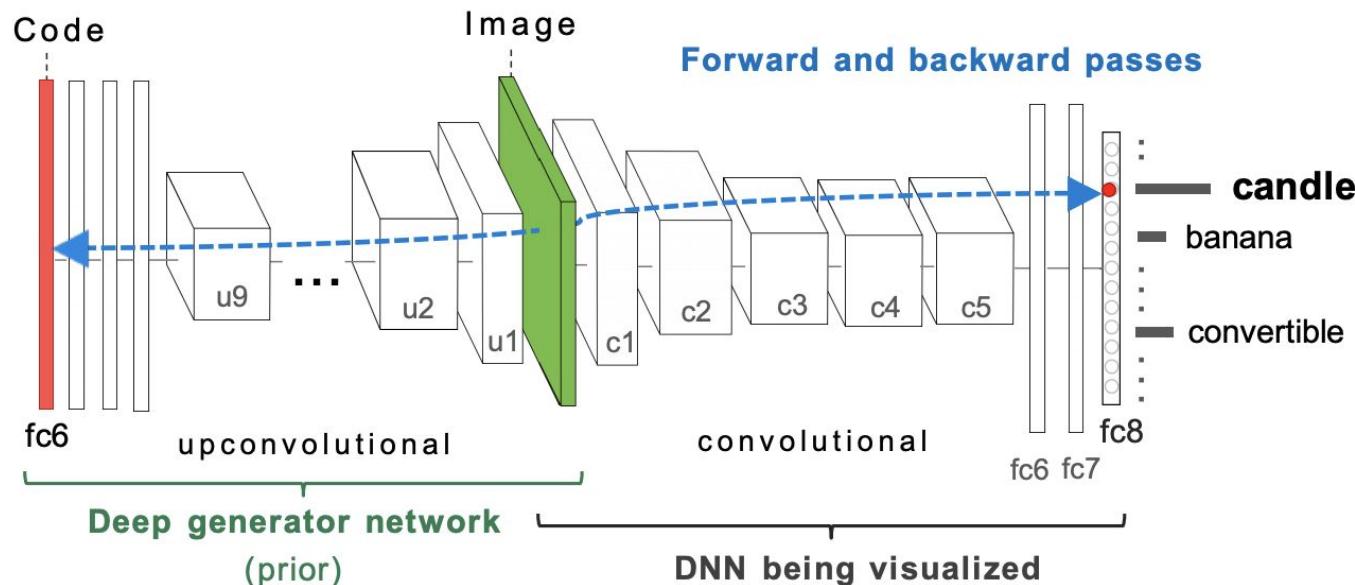


Nguyen et al., "Multifaceted Feature Visualization: Uncovering the Different Types of Features Learned By Each Neuron in Deep Neural Networks", ICML Visualization for Deep Learning Workshop 2016.

Figures copyright Anh Nguyen, Jason Yosinski, and Jeff Clune, 2016; reproduced with permission.

Visualizing CNN features: Gradient Ascent

Optimize in FC6 latent space instead of pixel space:



Nguyen et al., "Synthesizing the preferred inputs for neurons in neural networks via deep generator networks," NIPS 2016
Figure copyright Nguyen et al, 2016; reproduced with permission.

Visualizing CNN features: Gradient Ascent

Optimize in FC6 latent space instead of pixel space:



Nguyen et al., "Synthesizing the preferred inputs for neurons in neural networks via deep generator networks," NIPS 2016
Figure copyright Nguyen et al, 2016; reproduced with permission.

Visualizing what models have learned:

- Visualizing filters
- Visualizing final layer features
- Visualizing activations

Understanding input pixels

- Identifying important pixels
- Saliency via backprop
- Guided backprop to generate images
- Gradient ascent to visualize features

Adversarial perturbations

Style transfer

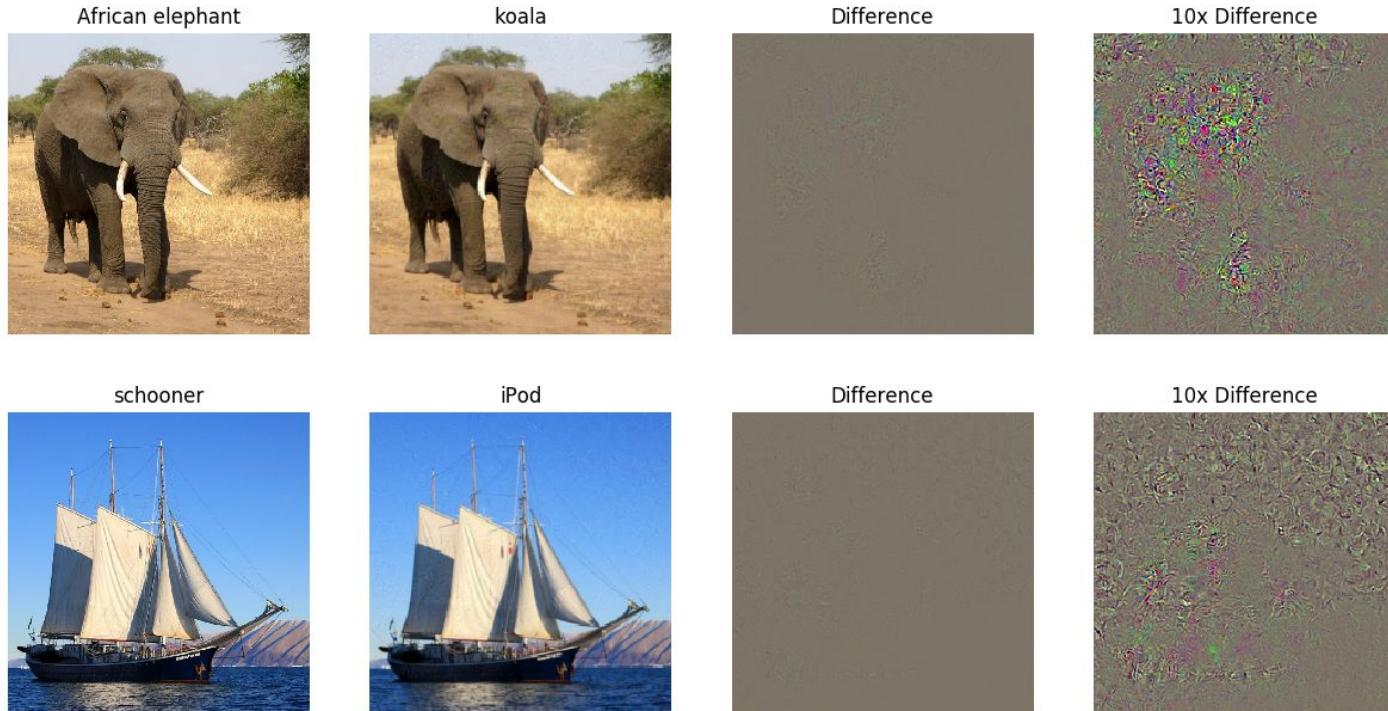
- Deep dream
- Features inversion
- Texture synthesis
- Neural style transfer

Today's agenda

Fooling Images / Adversarial Examples

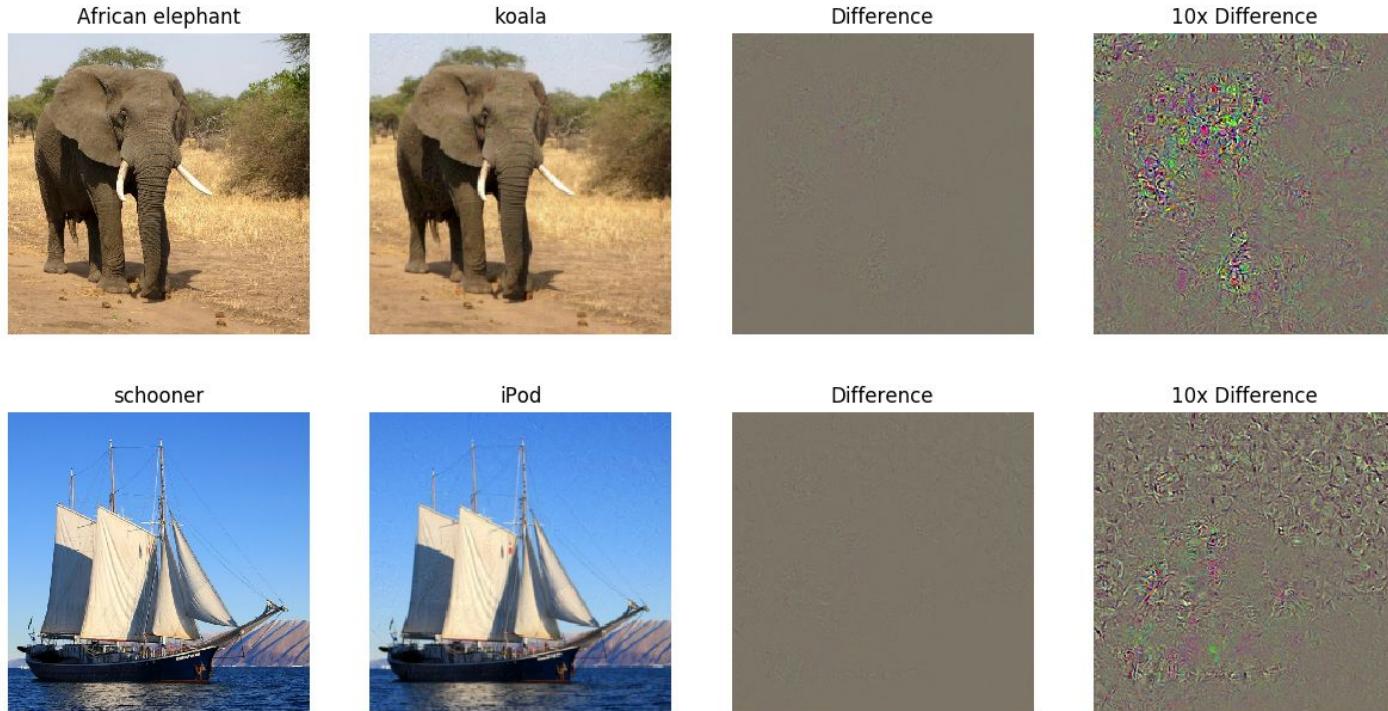
- (1) Start from an arbitrary image
- (2) Pick an arbitrary class
- (3) Modify the image to maximize the class
- (4) Repeat until network is fooled

Fooling Images / Adversarial Examples



Boat image is CC0 public domain
Elephant image is CC0 public domain

Fooling Images / Adversarial Examples



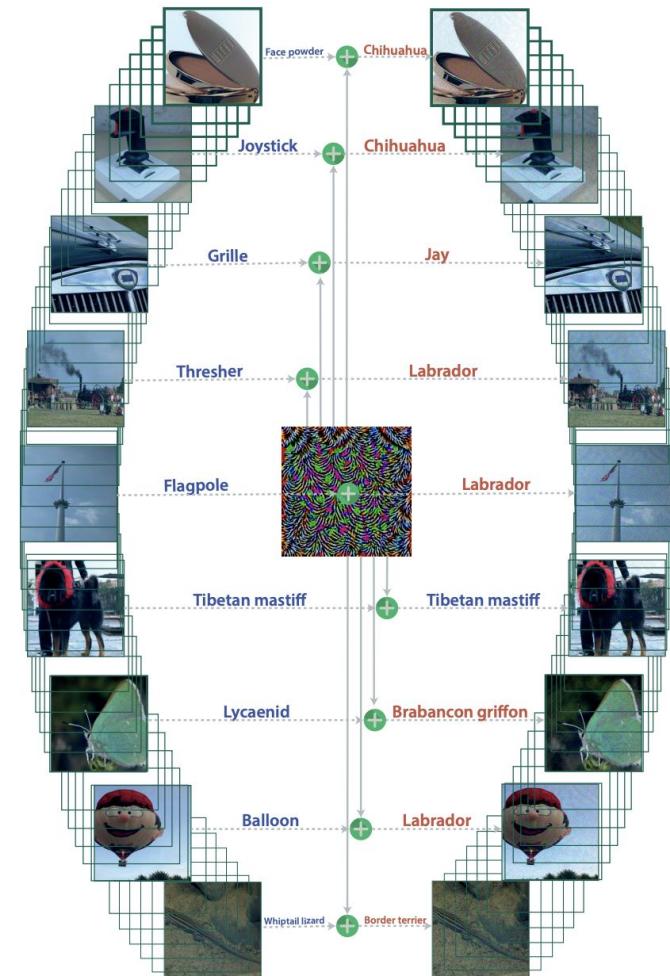
Check out [Ian Goodfellow's lecture from 2017](#)

Boat image is CC0 public domain
Elephant image is CC0 public domain

Fooling Images / Adversarial Examples

Universal perturbations

Moosavi-Dezfooli, Seyed-Mohsen, et al. "Universal adversarial perturbations." Proceedings of the IEEE conference on computer vision and pattern recognition. 2017.
Figure reproduced with permission



Visualizing what models have learned:

- Visualizing filters
- Visualizing final layer features
- Visualizing activations

Understanding input pixels

- Identifying important pixels
- Saliency via backprop
- Guided backprop to generate images
- Gradient ascent to visualize features

Adversarial perturbations

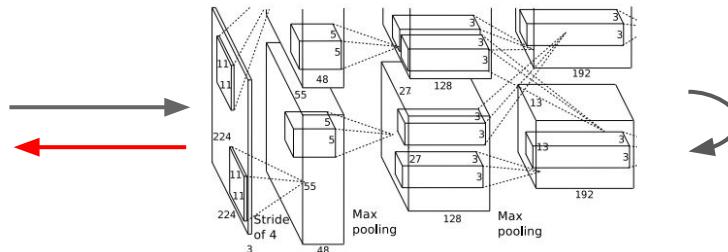
Style transfer

- Deep dream
- Features inversion
- Texture synthesis
- Neural style transfer

Today's agenda

DeepDream: Amplify existing features

Rather than synthesizing an image to maximize a specific neuron, instead try to **amplify** the neuron activations at some layer in the network



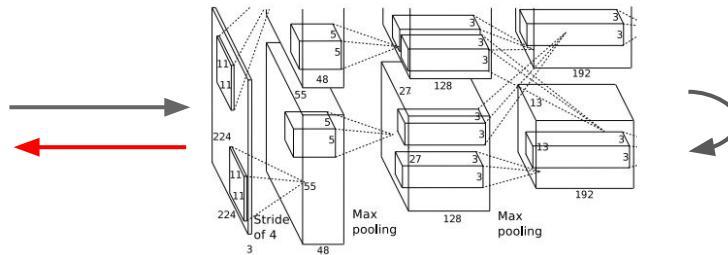
Choose an image and a layer in a CNN; repeat:

1. Forward: compute activations at chosen layer
2. Set gradient of chosen layer *equal to its activation*
3. Backward: Compute gradient on image
4. Update image

Mordvintsev, Olah, and Tyka, "Inceptionism: Going Deeper into Neural Networks", [Google Research Blog](#). Images are licensed under [CC-BY 4.0](#)

DeepDream: Amplify existing features

Rather than synthesizing an image to maximize a specific neuron, instead try to **amplify** the neuron activations at some layer in the network



Choose an image and a layer in a CNN; repeat:

1. Forward: compute activations at chosen layer
2. Set gradient of chosen layer *equal to its activation*
3. Backward: Compute gradient on image
4. Update image

Equivalent to:

$$I^* = \arg \max_I \sum_i f_i(I)^2$$

Mordvintsev, Olah, and Tyka, "Inceptionism: Going Deeper into Neural Networks", [Google Research Blog](#). Images are licensed under [CC-BY 4.0](#)

DeepDream: Amplify existing features

```
def objective_L2(dst):
    dst.diff[:] = dst.data

def make_step(net, step_size=1.5, end='inception_4c/output',
             jitter=32, clip=True, objective=objective_L2):
    '''Basic gradient ascent step.'''
    src = net.blobs['data'] # input image is stored in Net's 'data' blob
    dst = net.blobs[end]

    ox, oy = np.random.randint(-jitter, jitter+1, 2)
    src.data[0] = np.roll(np.roll(src.data[0], ox, -1), oy, -2) # apply jitter shift

    net.forward(end=end)
    objective(dst) # specify the optimization objective
    net.backward(start=end)
    g = src.diff[0]
    # apply normalized ascent step to the input image
    src.data[:] += step_size/np.abs(g).mean() * g

    src.data[0] = np.roll(np.roll(src.data[0], -ox, -1), -oy, -2) # unshift image

    if clip:
        bias = net.transformer.mean['data']
        src.data[:] = np.clip(src.data, -bias, 255-bias)
```

[Code](#) is very simple but it uses a couple tricks:

(Code is licensed under [Apache 2.0](#))

DeepDream: Amplify existing features

```
def objective_L2(dst):
    dst.diff[:] = dst.data

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[Code](#) is very simple but it uses a couple tricks:

(Code is licensed under [Apache 2.0](#))

Jitter image

DeepDream: Amplify existing features

```
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def make_step(net, step_size=1.5, end='inception_4c/output',
             jitter=32, clip=True, objective=objective_L2):
    '''Basic gradient ascent step.'''
    src = net.blobs['data'] # input image is stored in Net's 'data' blob
    dst = net.blobs[end]

    ox, oy = np.random.randint(-jitter, jitter+1, 2)
    src.data[0] = np.roll(np.roll(src.data[0], ox, -1), oy, -2) # apply jitter shift

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```

[Code](#) is very simple but it uses a couple tricks:

(Code is licensed under [Apache 2.0](#))

Jitter image

L1 Normalize gradients

DeepDream: Amplify existing features

```
def objective_L2(dst):
    dst.diff[:] = dst.data

def make_step(net, step_size=1.5, end='inception_4c/output',
             jitter=32, clip=True, objective=objective_L2):
    '''Basic gradient ascent step.'''
    src = net.blobs['data'] # input image is stored in Net's 'data' blob
    dst = net.blobs[end]
```

```
ox, oy = np.random.randint(-jitter, jitter+1, 2)
src.data[0] = np.roll(np.roll(src.data[0], ox, -1), oy, -2) # apply jitter shift
```

```
net.forward(end=end)
objective(dst) # specify the optimization objective
net.backward(start=end)
g = src.diff[0]
```

```
# apply normalized ascent step to the input image
src.data[:] += step_size/np.abs(g).mean() * g
```

```
src.data[0] = np.roll(np.roll(src.data[0], -ox, -1), -oy, -2) # unshift image
```

```
if clip:
    bias = net.transformer.mean['data']
    src.data[:] = np.clip(src.data, -bias, 255-bias)
```

[Code](#) is very simple but it uses a couple tricks:

(Code is licensed under [Apache 2.0](#))

Jitter image

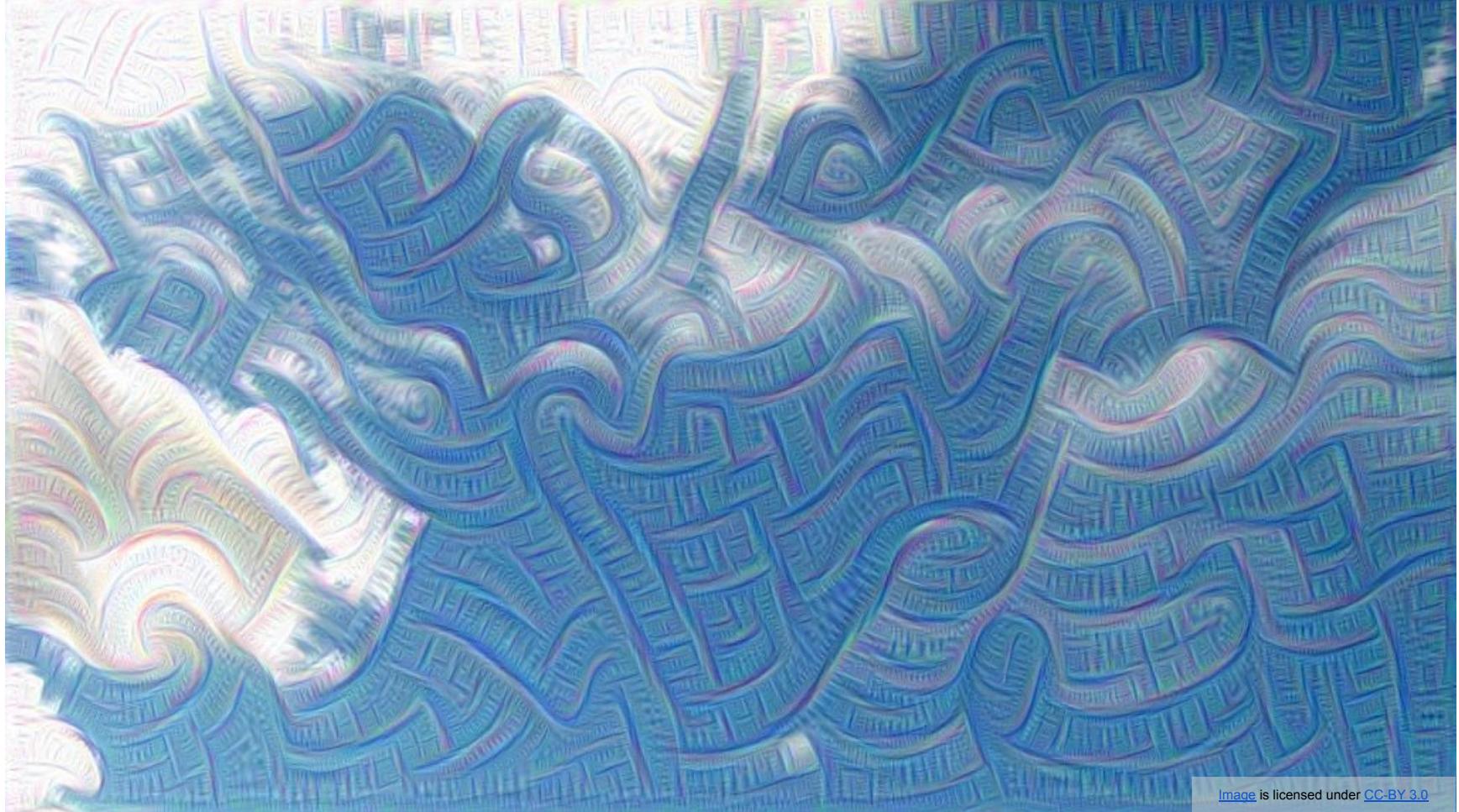
L1 Normalize gradients

Clip pixel values

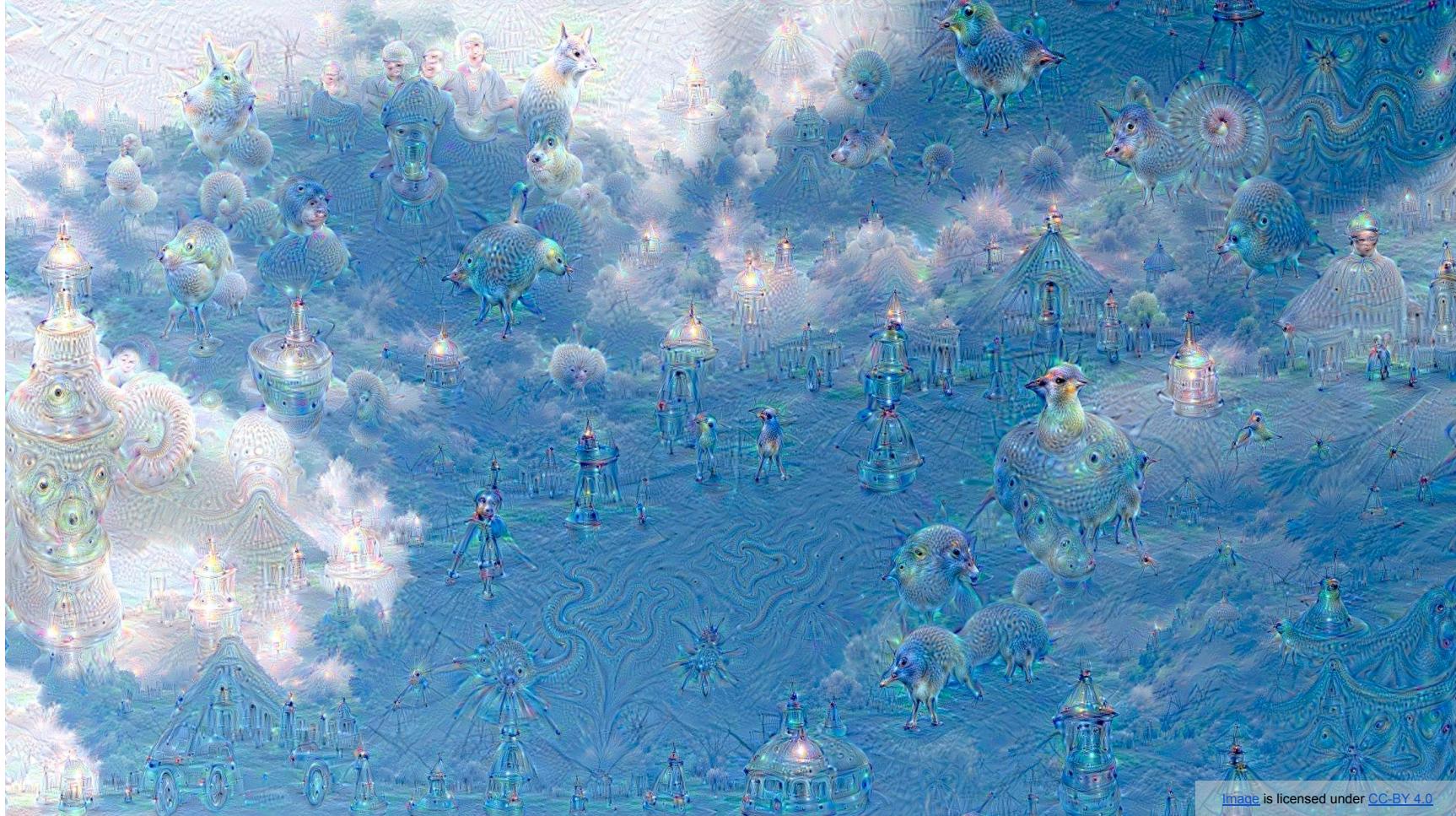
Also uses multiscale processing for a fractal effect (not shown)



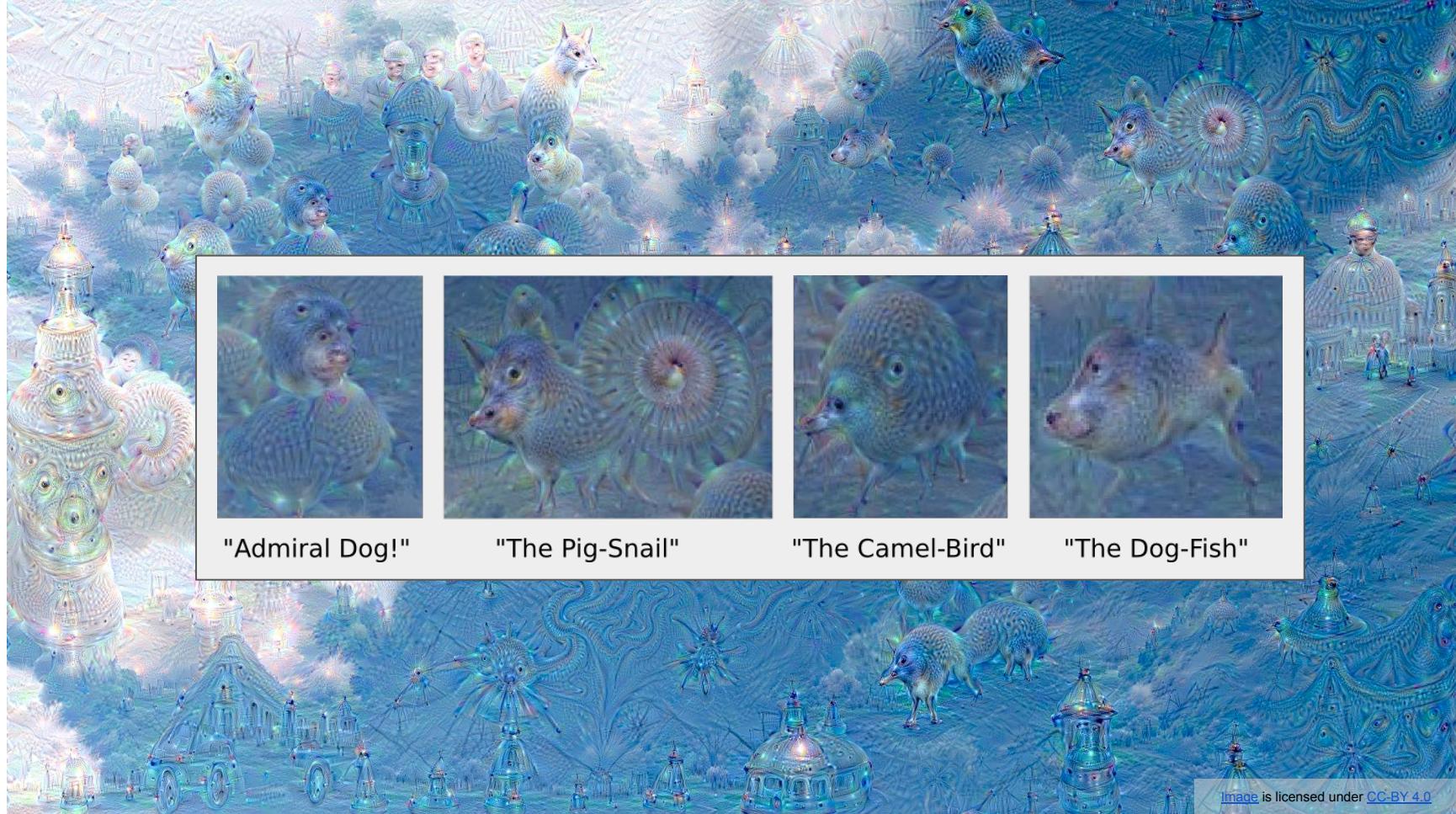
Sky image is licensed under [CC-BY SA 3.0](#)



[Image](#) is licensed under [CC-BY 3.0](#)



[Image](#) is licensed under [CC-BY 4.0](#)



"Admiral Dog!"

"The Pig-Snail"

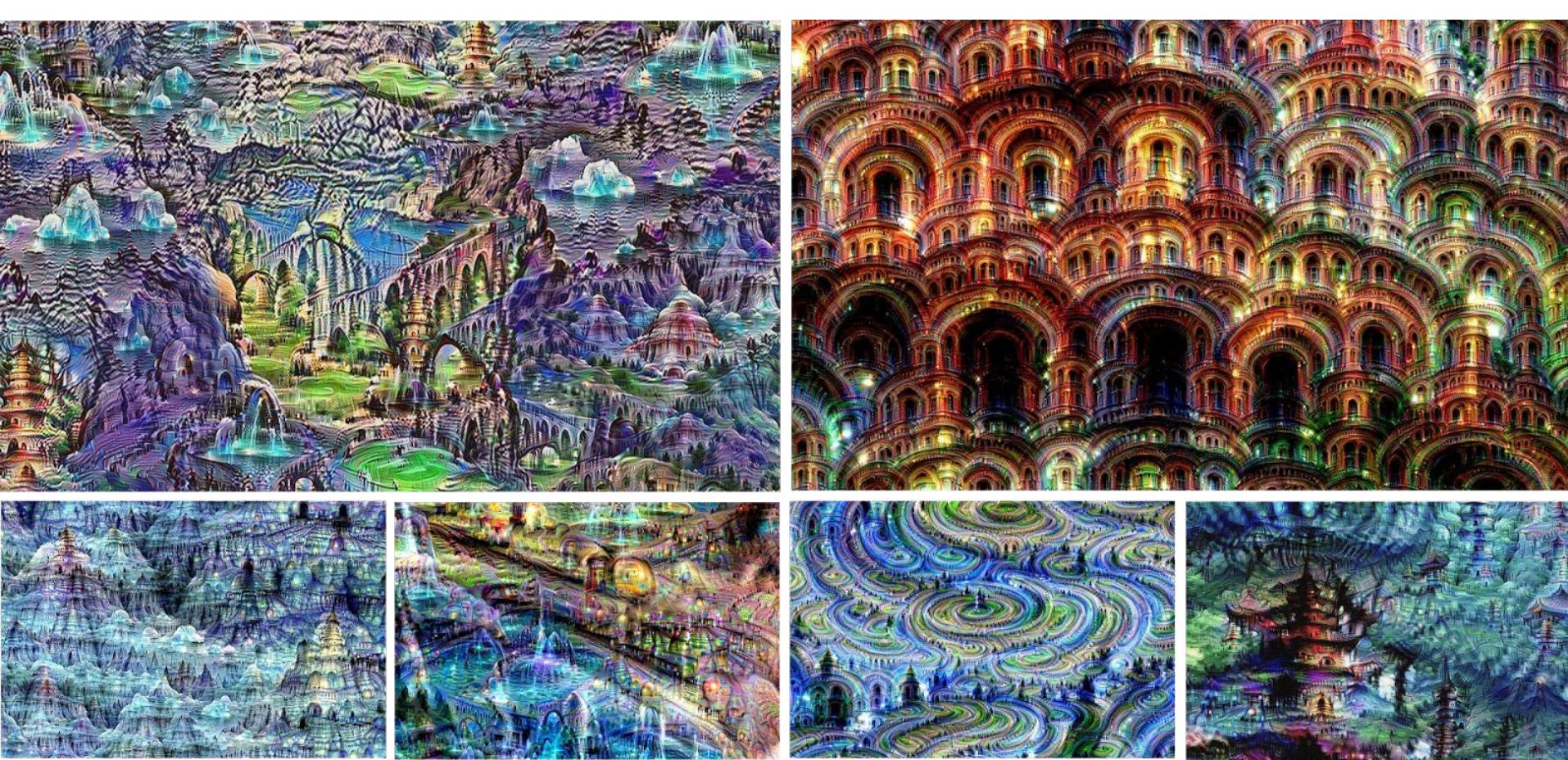
"The Camel-Bird"

"The Dog-Fish"

is licensed under [CC-BY 4.0](#)



[Image](#) is licensed under [CC-BY 3.0](#)



[Image](#) is licensed under CC-BY 4.0

Feature Inversion

Given a CNN feature vector for an image, find a new image that:

- Matches the given feature vector
- “looks natural” (image prior regularization)

$$\mathbf{x}^* = \underset{\mathbf{x} \in \mathbb{R}^{H \times W \times C}}{\operatorname{argmin}} \ell(\Phi(\mathbf{x}), \Phi_0) + \lambda \mathcal{R}(\mathbf{x})$$

Given feature vector

Features of new image

$$\ell(\Phi(\mathbf{x}), \Phi_0) = \|\Phi(\mathbf{x}) - \Phi_0\|^2$$

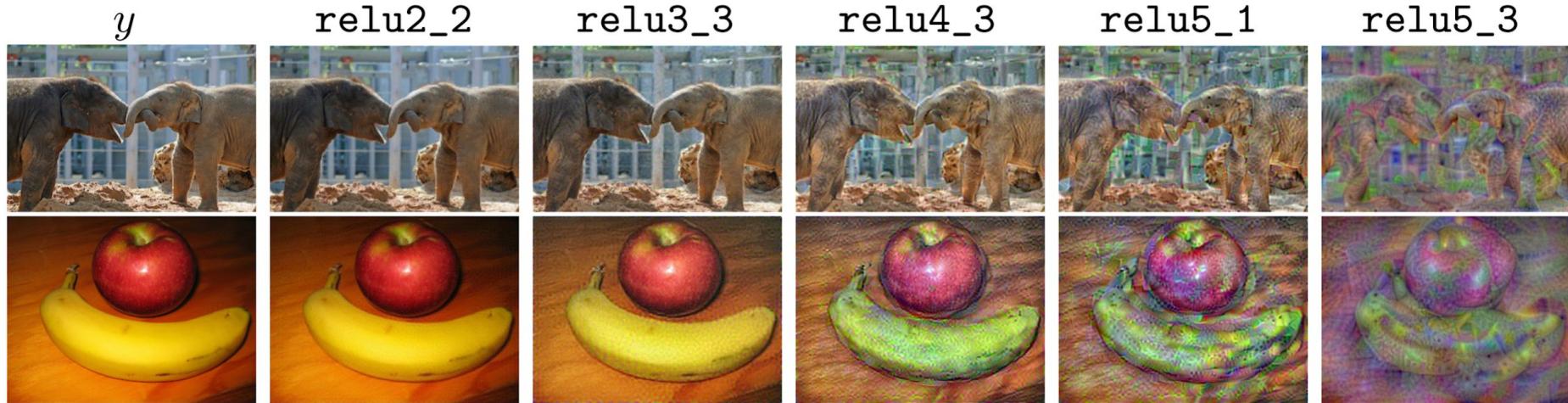
$$\mathcal{R}_{V^\beta}(\mathbf{x}) = \sum_{i,j} \left((x_{i,j+1} - x_{ij})^2 + (x_{i+1,j} - x_{ij})^2 \right)^{\frac{\beta}{2}}$$

Total Variation regularizer
(encourages spatial smoothness)

Mahendran and Vedaldi, “Understanding Deep Image Representations by Inverting Them”, CVPR 2015

Feature Inversion

Reconstructing from different layers of VGG-16



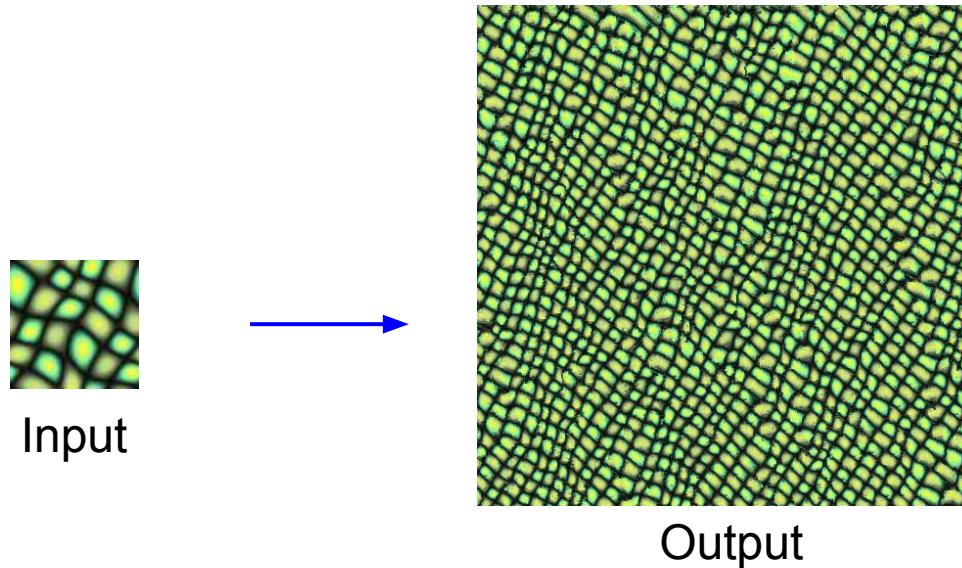
Mahendran and Vedaldi, "Understanding Deep Image Representations by Inverting Them", CVPR 2015

Figure from Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016. Copyright Springer, 2016.

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Texture Synthesis

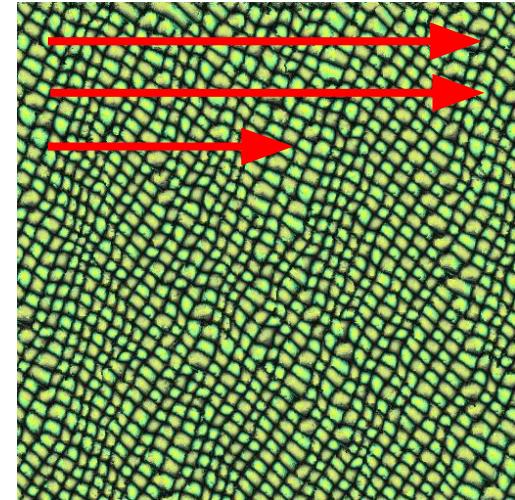
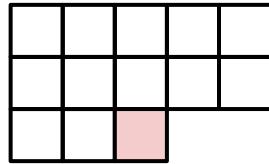
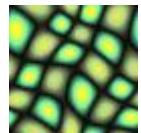
Given a sample patch of some texture, can we generate a bigger image of the same texture?



[Output image](#) is licensed under the [MIT license](#)

Texture Synthesis: Nearest Neighbor

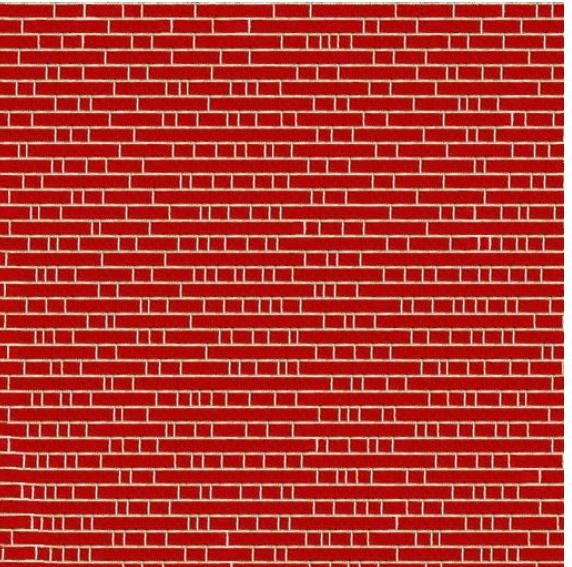
Generate pixels one at a time in scanline order; form neighborhood of already generated pixels and copy nearest neighbor from input



Wei and Levoy, "Fast Texture Synthesis using Tree-structured Vector Quantization", SIGGRAPH 2000

Efros and Leung, "Texture Synthesis by Non-parametric Sampling", ICCV 1999

Texture Synthesis: Nearest Neighbor

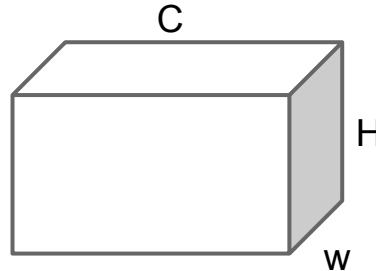
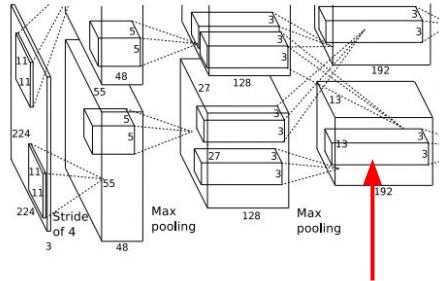


[Images](#) licensed under the MIT license

Neural Texture Synthesis: Gram Matrix



This image is in the public domain.

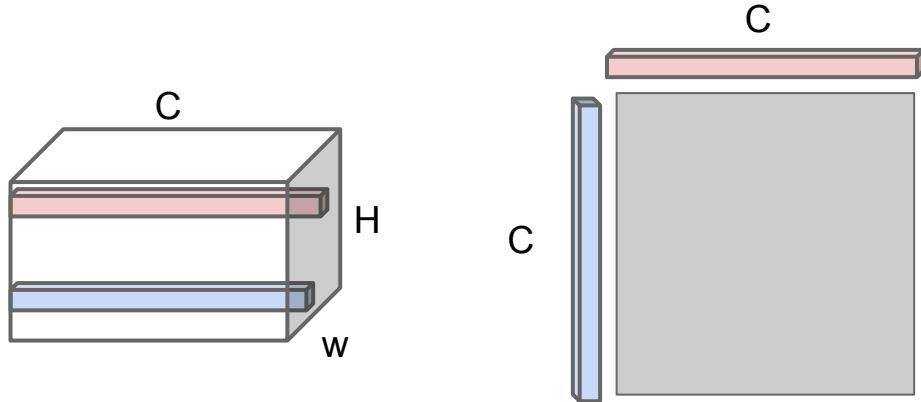
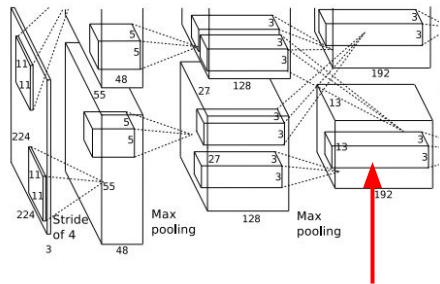


Each layer of CNN gives $C \times H \times W$ tensor of features; $H \times W$ grid of C -dimensional vectors

Neural Texture Synthesis: Gram Matrix



This image is in the public domain.



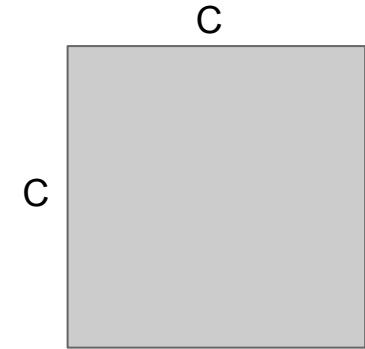
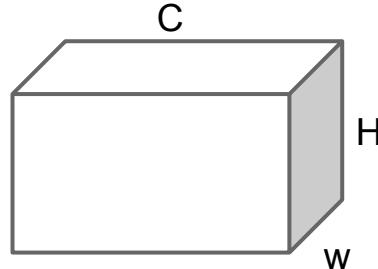
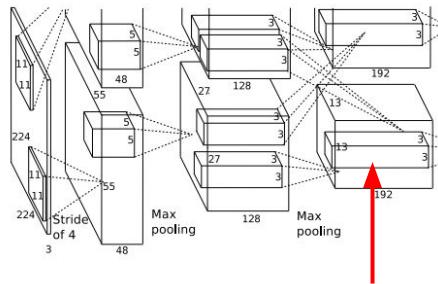
Each layer of CNN gives $C \times H \times W$ tensor of features; $H \times W$ grid of C -dimensional vectors

Outer product of two C -dimensional vectors gives $C \times C$ matrix measuring co-occurrence

Neural Texture Synthesis: Gram Matrix



This image is in the public domain.



Each layer of CNN gives $C \times H \times W$ tensor of features; $H \times W$ grid of C -dimensional vectors

Gram Matrix

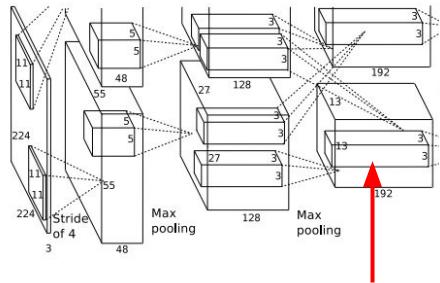
Outer product of two C -dimensional vectors gives $C \times C$ matrix measuring co-occurrence

Average over all HW pairs of vectors, giving **Gram matrix** of shape $C \times C$

Neural Texture Synthesis: Gram Matrix



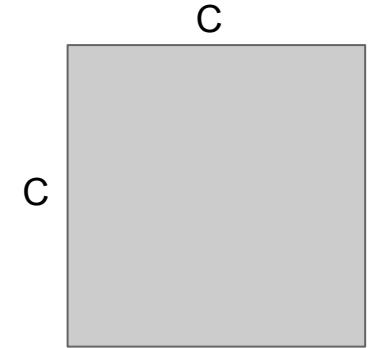
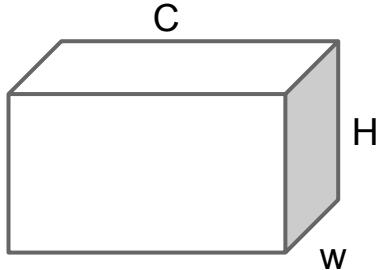
This image is in the public domain.



Each layer of CNN gives $C \times H \times W$ tensor of features; $H \times W$ grid of C -dimensional vectors

Outer product of two C -dimensional vectors gives $C \times C$ matrix measuring co-occurrence

Average over all HW pairs of vectors, giving **Gram matrix** of shape $C \times C$



Efficient to compute; reshape features from

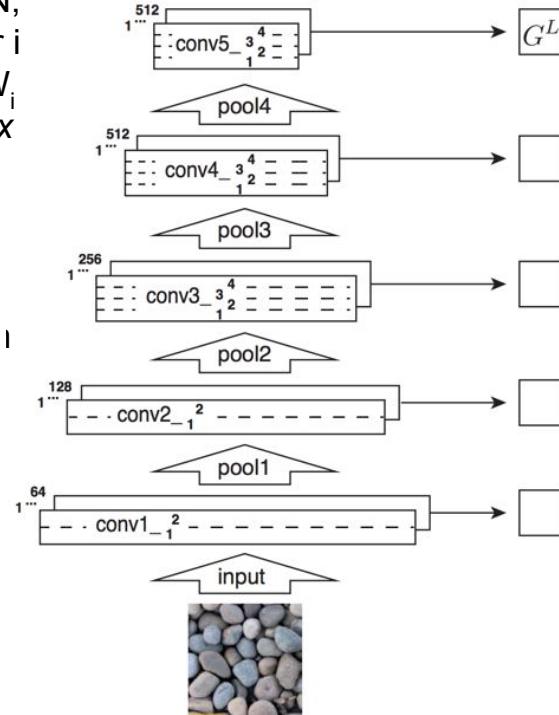
$C \times H \times W$ to $=C \times HW$

then compute $G = FF^T$

Neural Texture Synthesis

1. Pretrain a CNN on ImageNet (VGG-19)
2. Run input texture forward through CNN, record activations on every layer; layer i gives feature map of shape $C_i \times H_i \times W_i$
3. At each layer compute the *Gram matrix* giving outer product of features:

$$G_{ij}^l = \sum_k F_{ik}^l F_{jk}^l \text{ (shape } C_i \times C_i\text{)}$$



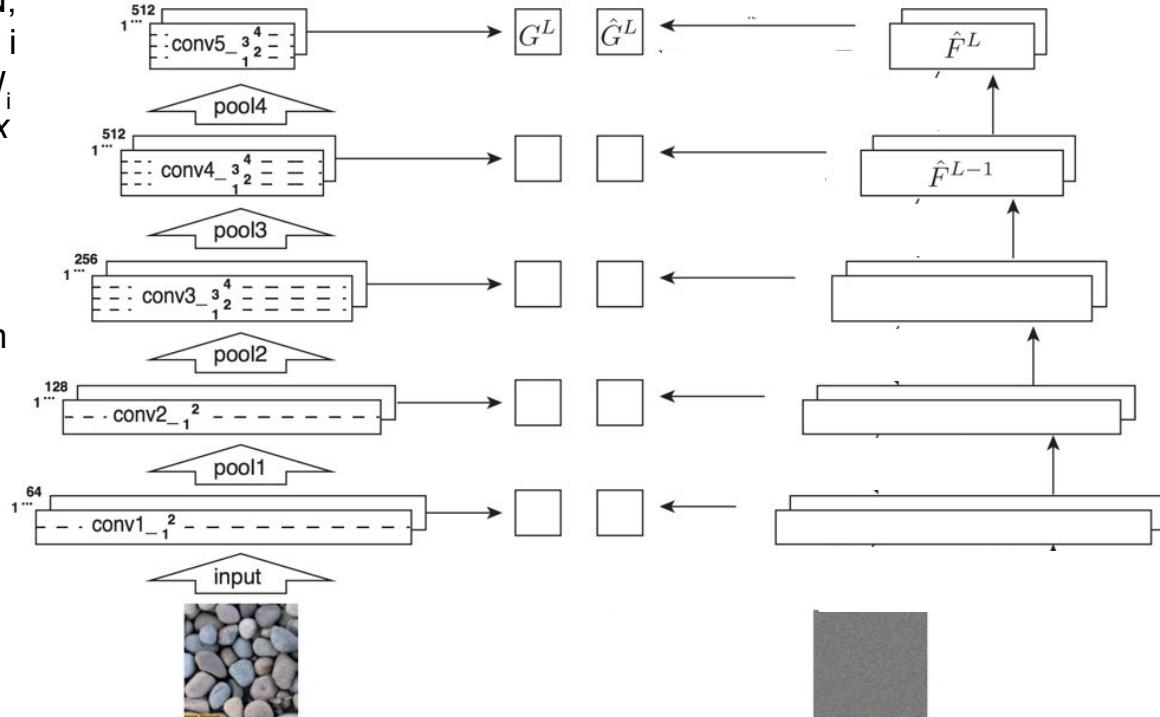
Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015
Figure copyright Leon Gatys, Alexander S. Ecker, and Matthias Bethge, 2015. Reproduced with permission.

Neural Texture Synthesis

1. Pretrain a CNN on ImageNet (VGG-19)
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3. At each layer compute the *Gram matrix* giving outer product of features:

$$G_{ij}^l = \sum_k F_{ik}^l F_{jk}^l \text{ (shape } C_i \times C_i\text{)}$$

4. Initialize generated image from random noise
5. Pass generated image through CNN, compute Gram matrix on each layer



Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015
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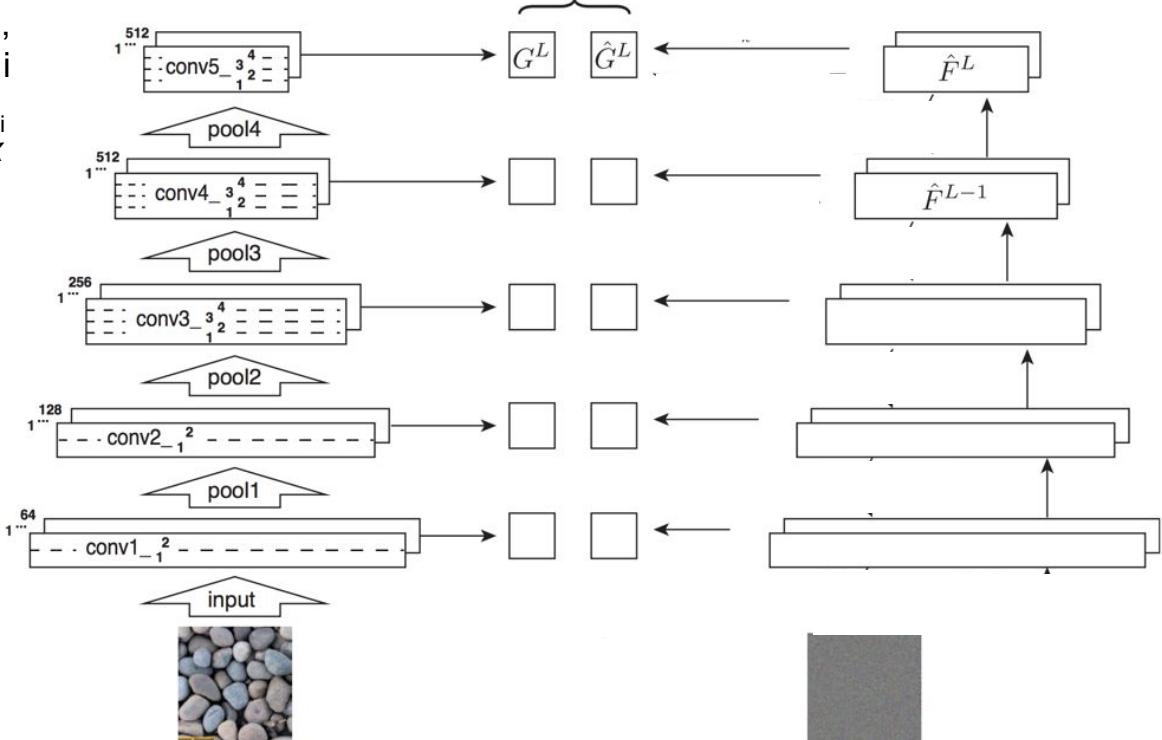
Neural Texture Synthesis

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3. At each layer compute the *Gram matrix* giving outer product of features:

$$G_{ij}^l = \sum_k F_{ik}^l F_{jk}^l \text{ (shape } C_i \times C_i\text{)}$$

4. Initialize generated image from random noise
5. Pass generated image through CNN, compute Gram matrix on each layer
6. Compute loss: weighted sum of L2 distance between Gram matrices

$$E_l = \frac{1}{4N_l^2 M_l^2} \sum_{i,j} \left(G_{ij}^l - \hat{G}_{ij}^l \right)^2 \quad \mathcal{L}(\vec{x}, \hat{\vec{x}}) = \sum_{l=0}^L w_l E_l$$



Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015
Figure copyright Leon Gatys, Alexander S. Ecker, and Matthias Bethge, 2015. Reproduced with permission.

Neural Texture Synthesis

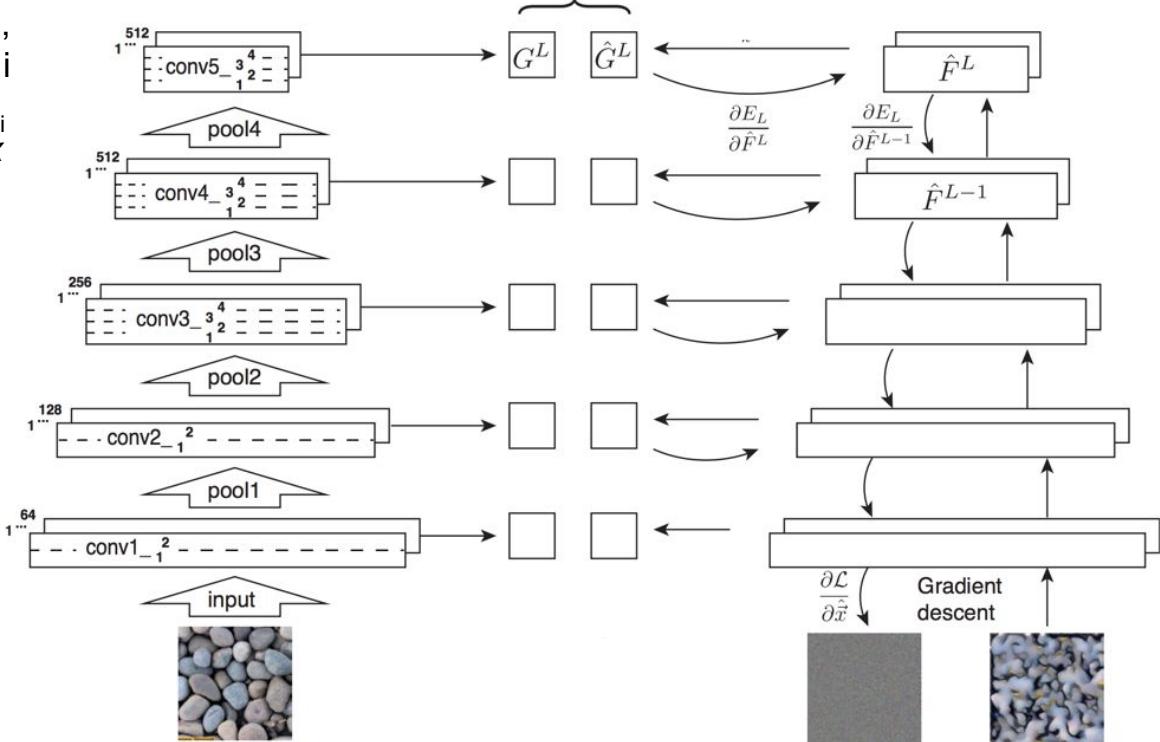
1. Pretrain a CNN on ImageNet (VGG-19)
2. Run input texture forward through CNN, record activations on every layer; layer i gives feature map of shape $C_i \times H_i \times W_i$
3. At each layer compute the *Gram matrix* giving outer product of features:

$$G_{ij}^l = \sum_k F_{ik}^l F_{jk}^l \text{ (shape } C_i \times C_i\text{)}$$

4. Initialize generated image from random noise
5. Pass generated image through CNN, compute Gram matrix on each layer
6. Compute loss: weighted sum of L2 distance between Gram matrices
7. Backprop to get gradient on image
8. Make gradient step on image
9. GOTO 5

$$E_l = \frac{1}{4N_l^2 M_l^2} \sum_{i,j} \left(G_{ij}^l - \hat{G}_{ij}^l \right)^2$$

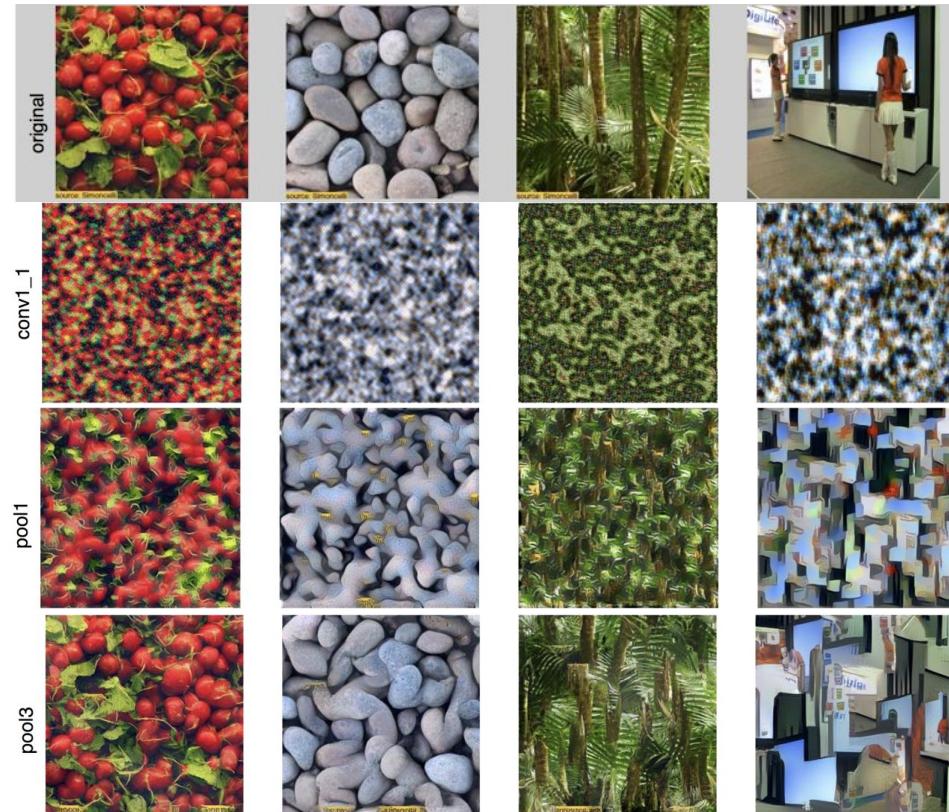
$$\mathcal{L}(\vec{x}, \hat{x}) = \sum_{l=0}^L w_l E_l$$



Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015
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Neural Texture Synthesis

Reconstructing texture from higher layers recovers larger features from the input texture



Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015
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Neural Texture Synthesis: Texture = Artwork

Texture synthesis
(Gram
reconstruction)

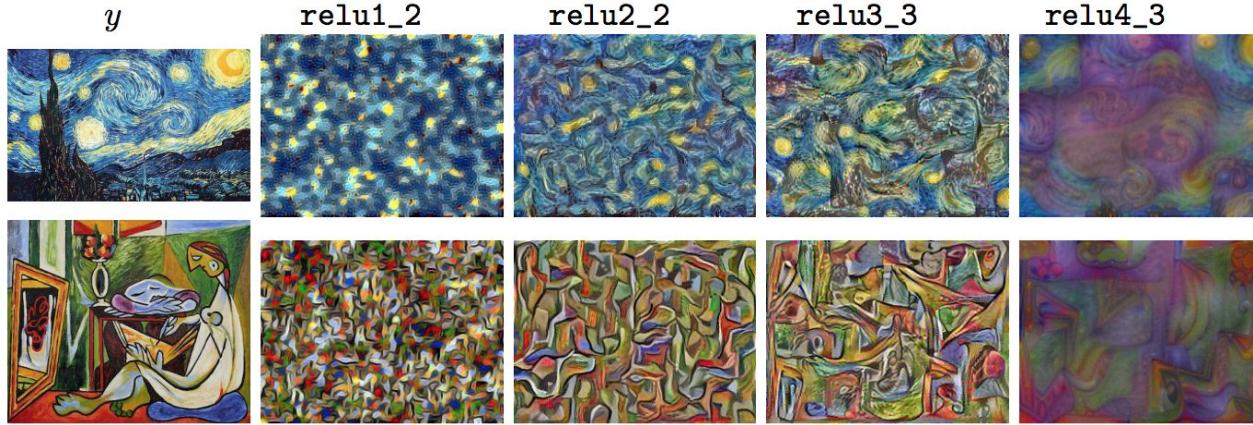
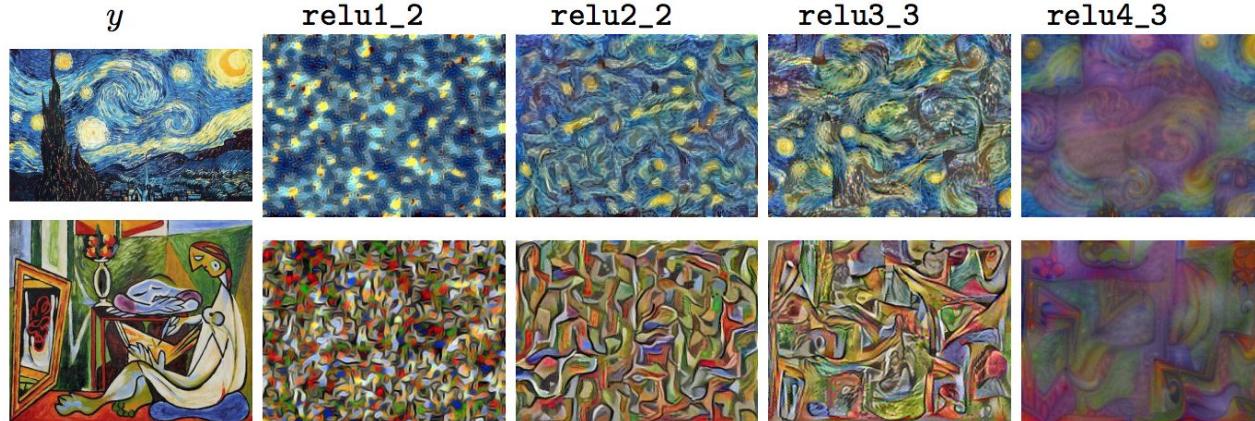


Figure from Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016. Copyright Springer, 2016.
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Neural Style Transfer: Feature + Gram Reconstruction

Texture synthesis
(Gram
reconstruction)



Feature
reconstruction

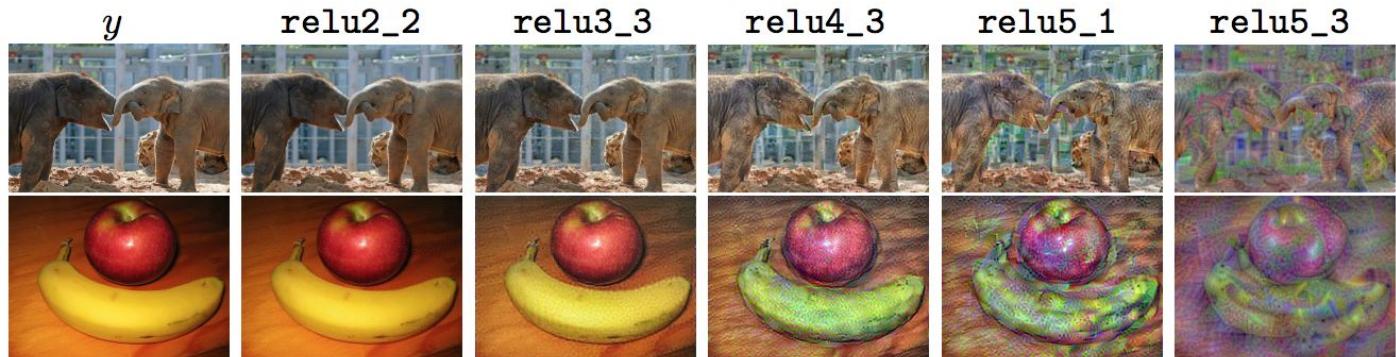


Figure from Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016. Copyright Springer, 2016. Reproduced for educational purposes.

Neural Style Transfer

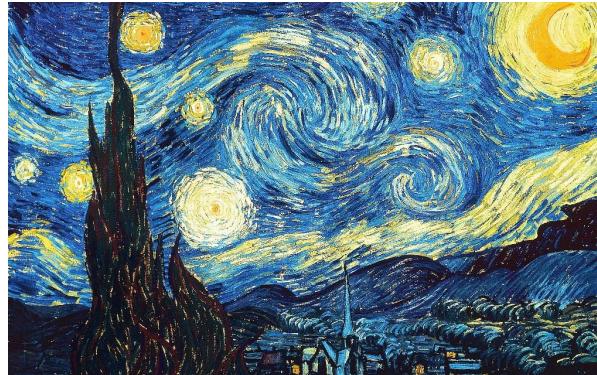
Content Image



[This image is licensed under CC-BY 3.0](#)

+

Style Image



[Starry Night](#) by Van Gogh is in the public domain

Gatys, Ecker, and Bethge, "Texture Synthesis Using Convolutional Neural Networks", NIPS 2015

Neural Style Transfer

Content Image



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Style Image



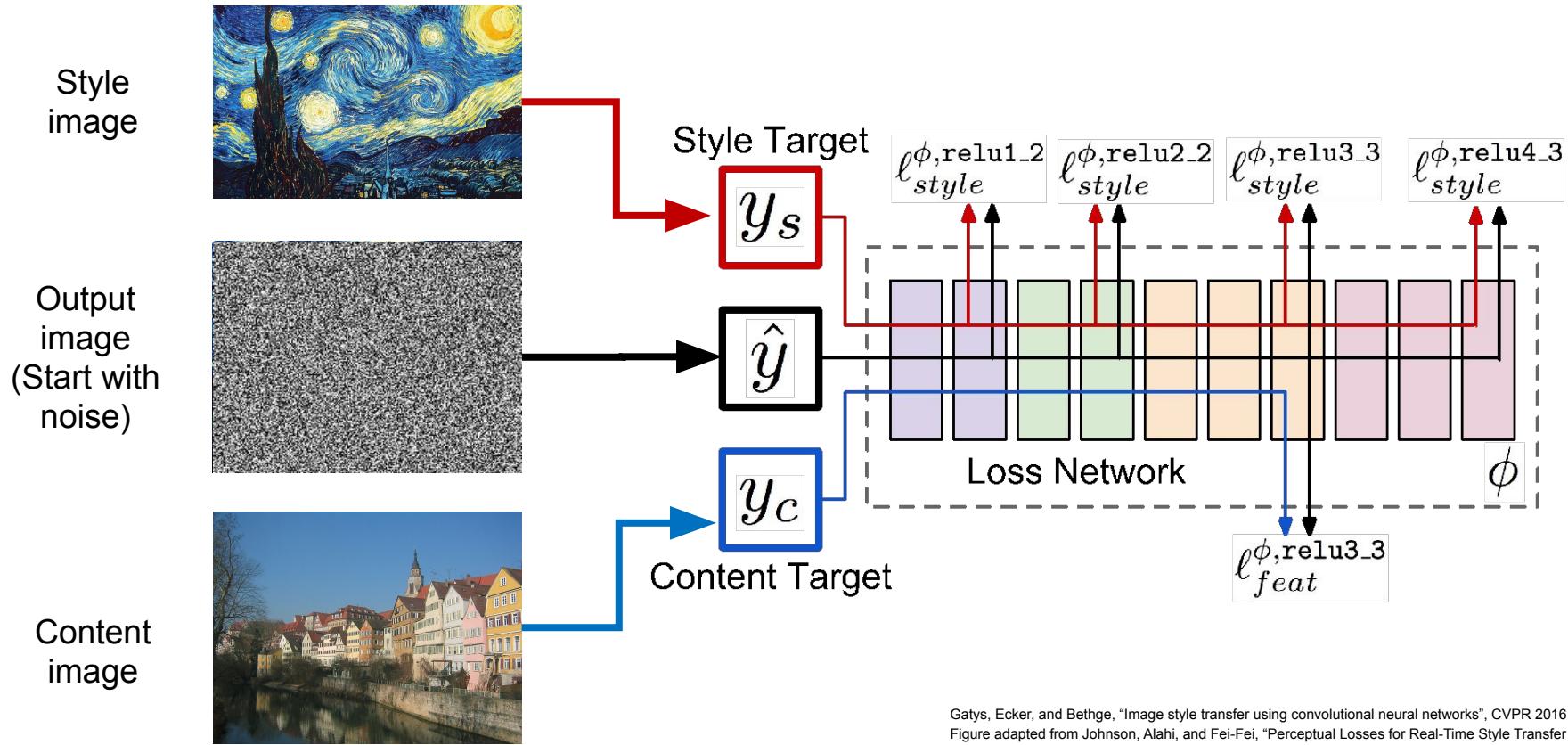
[Starry Night](#) by Van Gogh is in the public domain

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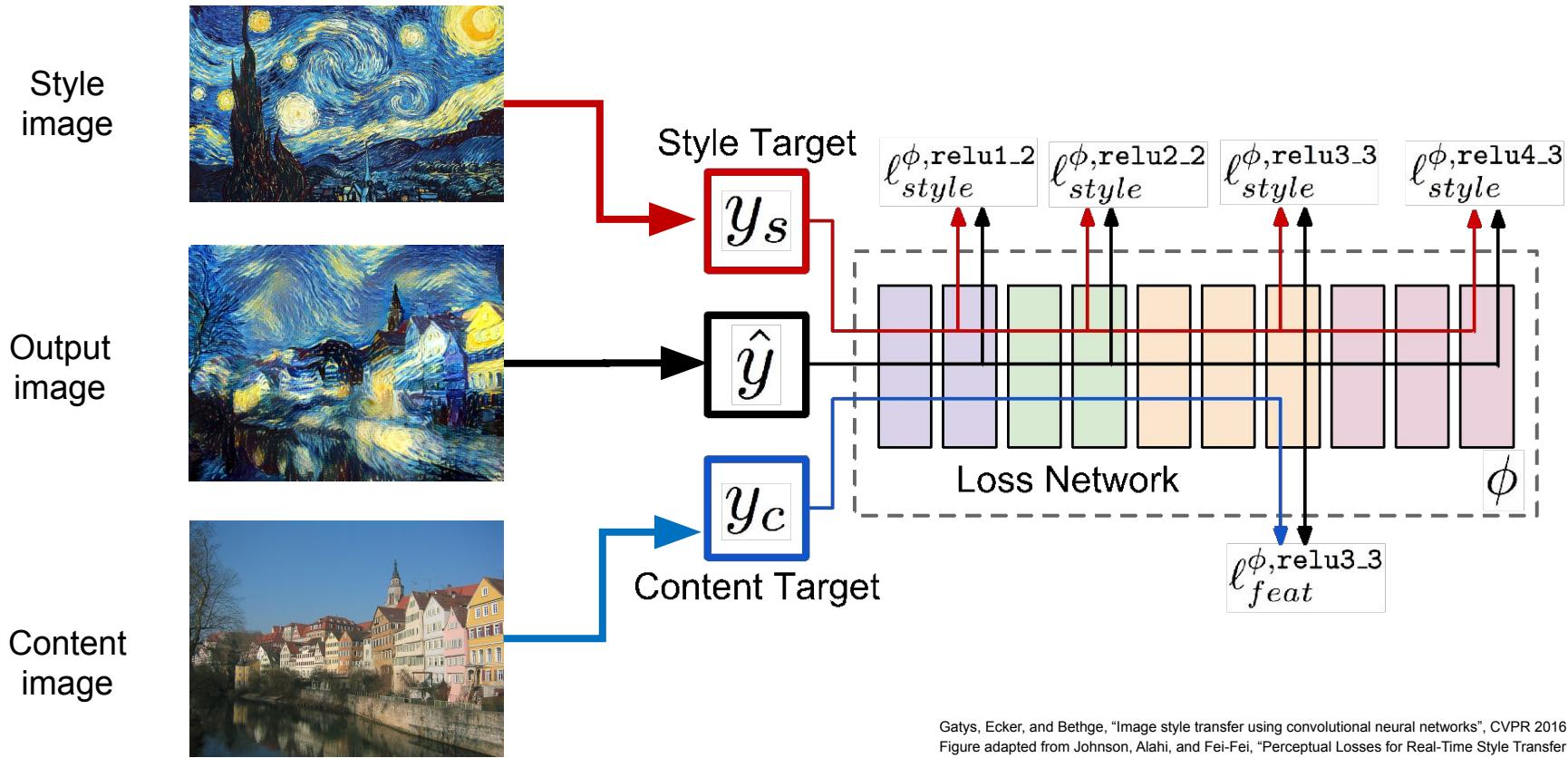


[This image](#) copyright Justin Johnson, 2015. Reproduced with permission.

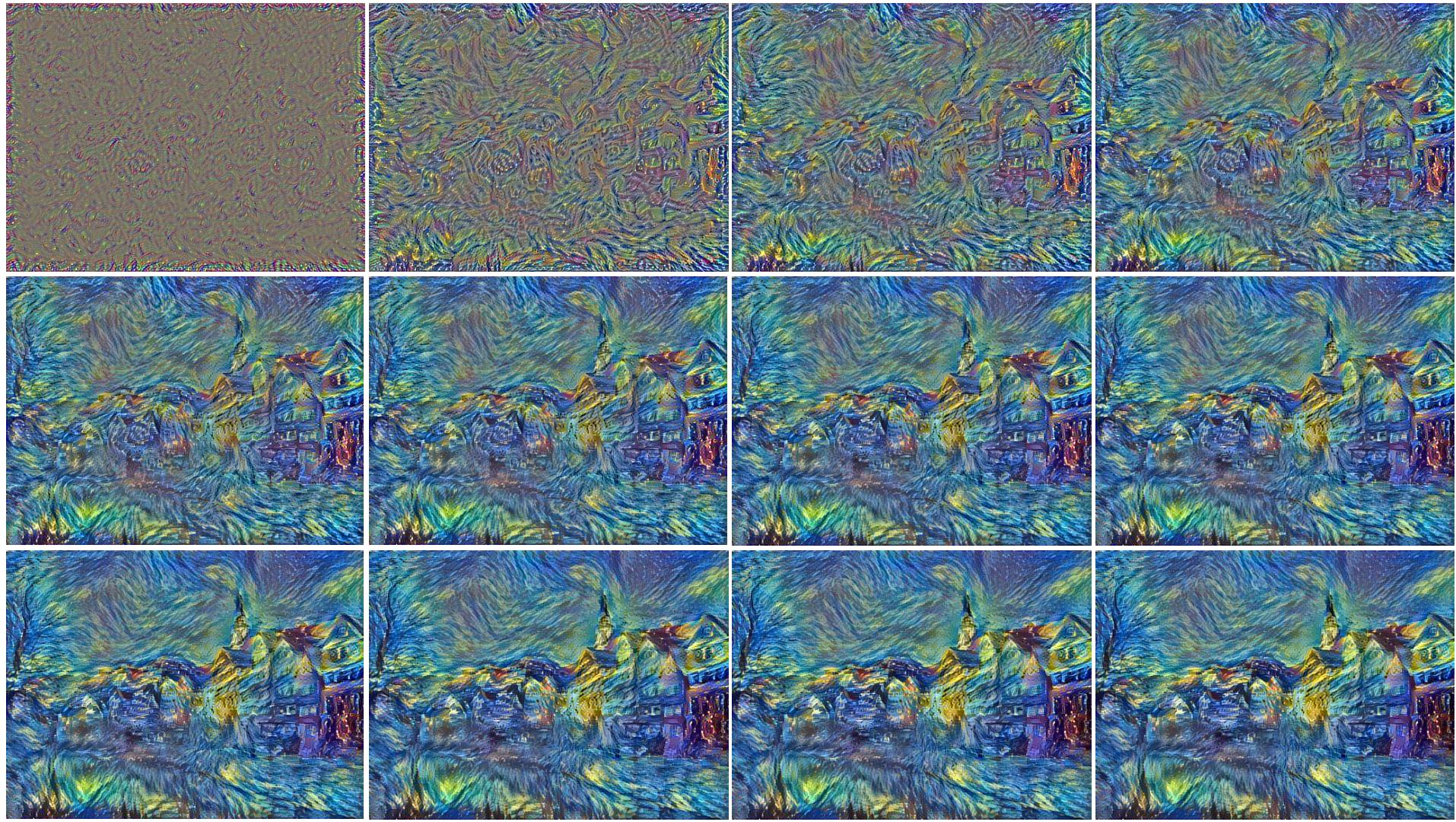
Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016



Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016
 Figure adapted from Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016. Copyright Springer, 2016. Reproduced for educational purposes.



Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016
 Figure adapted from Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016. Copyright Springer, 2016. Reproduced for educational purposes.



Neural Style Transfer

Example outputs from
Lua torch
[implementation](#)



Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016
Figure copyright Justin Johnson, 2015.

Neural Style Transfer



More weight to
content loss



More weight to
style loss

Neural Style Transfer

Resizing style image before running style transfer algorithm can transfer different types of features



Larger style
image

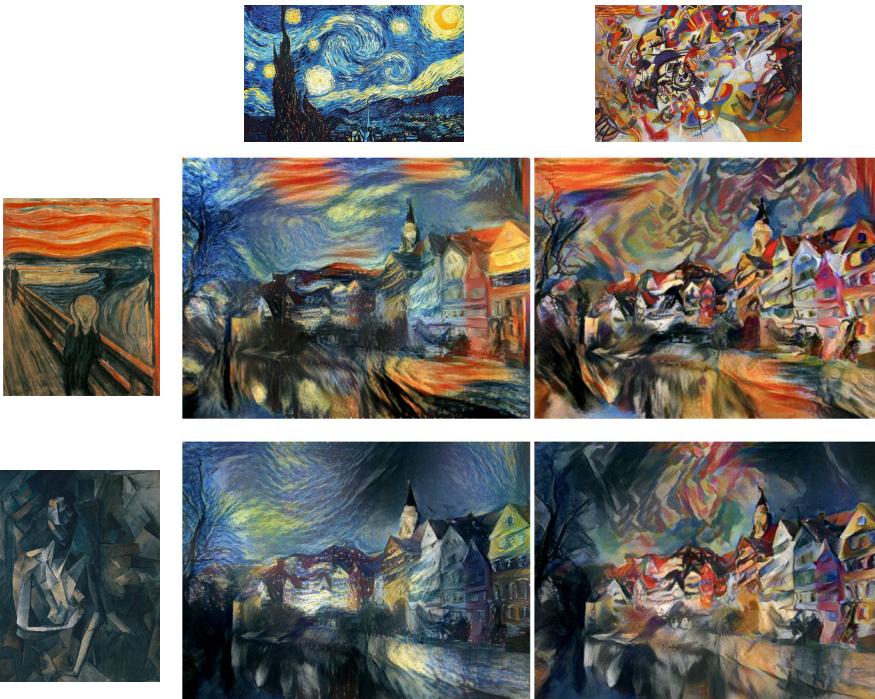


Smaller style
image

Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016
Figure copyright Justin Johnson, 2015.

Neural Style Transfer: Multiple Style Images

Mix style from multiple images by taking a weighted average of Gram matrices



Gatys, Ecker, and Bethge, "Image style transfer using convolutional neural networks", CVPR 2016
Figure copyright Justin Johnson, 2015.









Neural Style Transfer

Problem: Style transfer
requires many forward /
backward passes through
VGG; very slow!

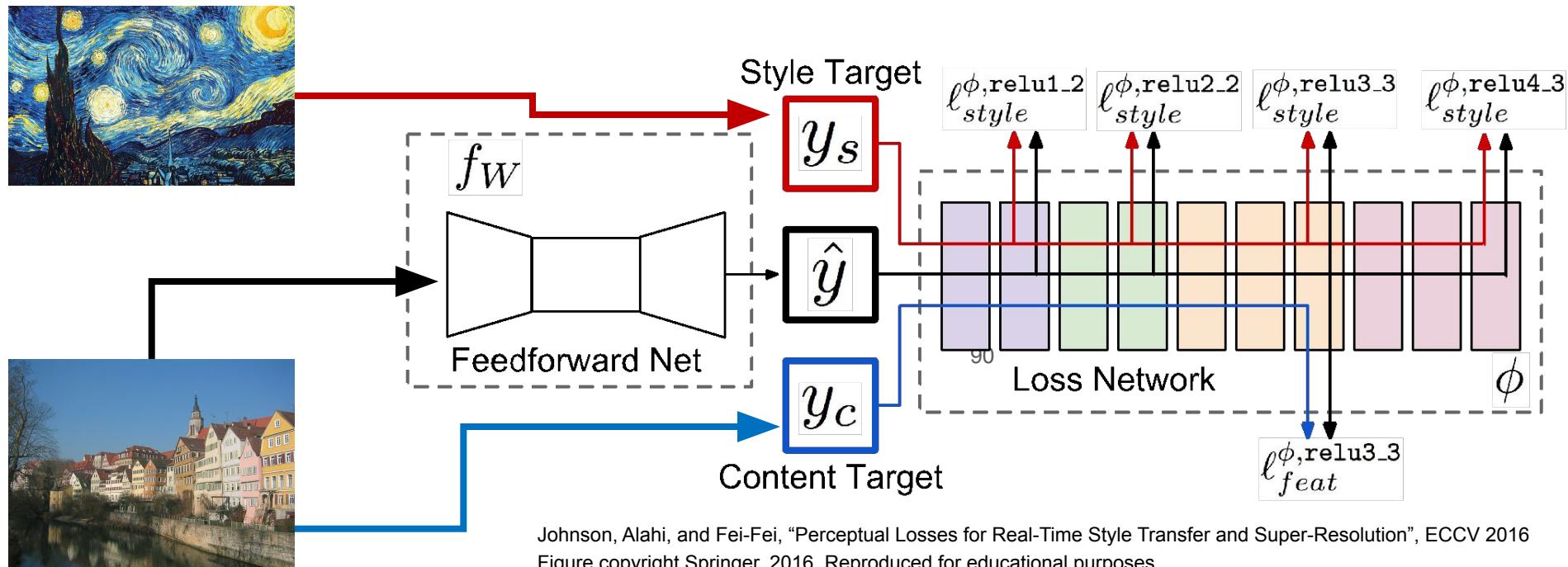
Neural Style Transfer

Problem: Style transfer requires many forward / backward passes through VGG; very slow!

Solution: Train another neural network to perform style transfer for us!

Fast Style Transfer

- (1) Train a feedforward network for each style
- (2) Use pretrained CNN to compute same losses as before
- (3) After training, stylize images using a single forward pass



Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016
Figure copyright Springer, 2016. Reproduced for educational purposes.

Fast Style Transfer

Style
The Starry Night,
Vincent van Gogh,
1889



Slow

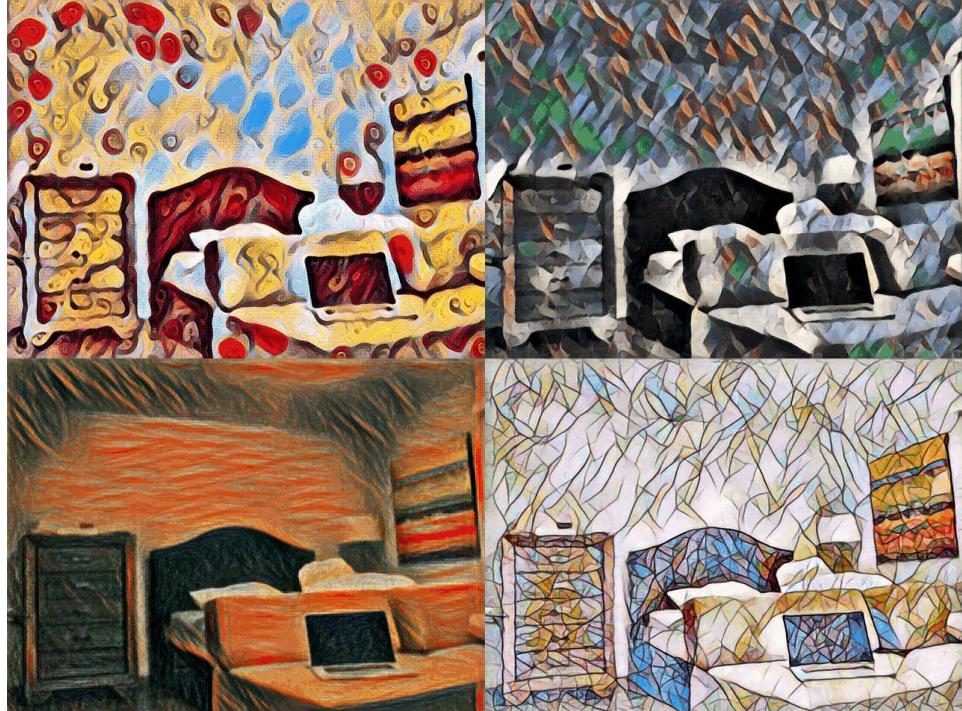
Fast

Style
The Muse,
Pablo Picasso,
1935



Slow

Fast



<https://github.com/jcjohnson/fast-neural-style>

Johnson, Alahi, and Fei-Fei, "Perceptual Losses for Real-Time Style Transfer and Super-Resolution", ECCV 2016
Figure copyright Springer, 2016. Reproduced for educational purposes.

Fast Style Transfer



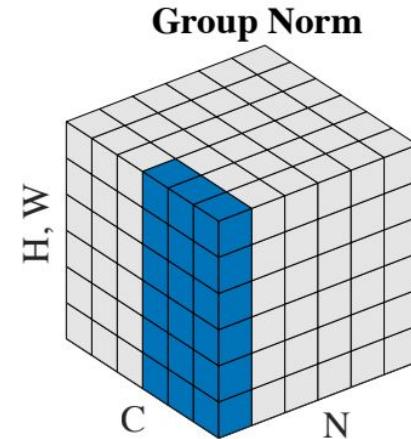
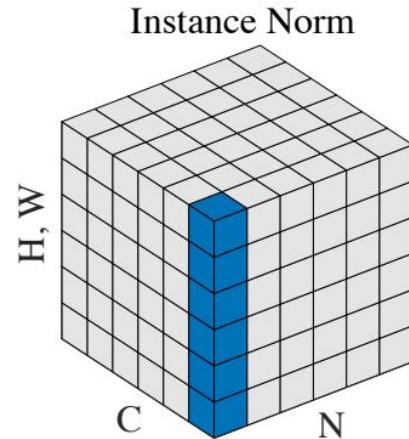
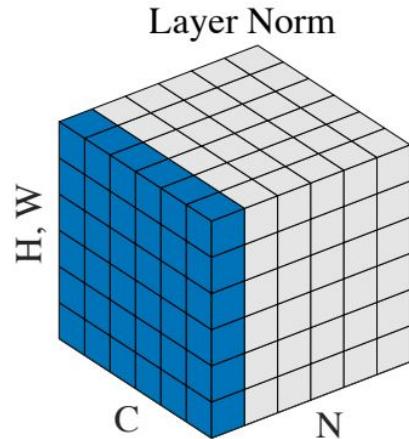
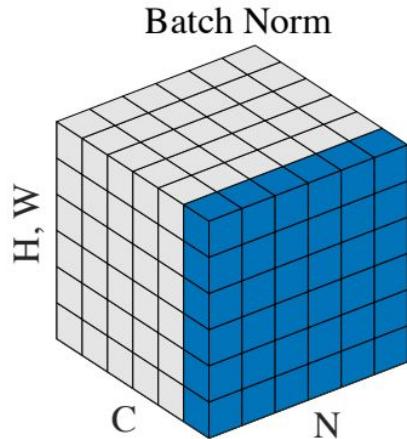
Replacing batch normalization with Instance Normalization improves results

Ulyanov et al. "Texture Networks: Feed-forward Synthesis of Textures and Stylized Images", ICML 2016

Ulyanov et al. "Instance Normalization: The Missing Ingredient for Fast Stylization", arXiv 2016

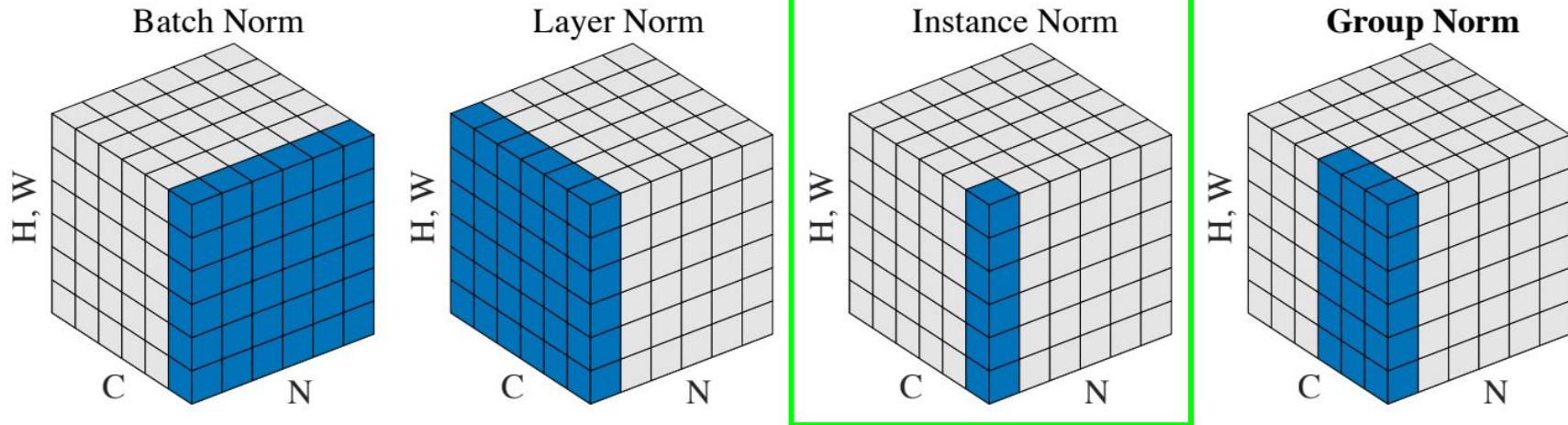
Figures copyright Dmitry Ulyanov, Vadim Lebedev, Andrea Vedaldi, and Victor Lempitsky, 2016. Reproduced with permission.

Remember Normalization Methods?



Remember Normalization Methods?

Instance Normalization was developed for style transfer!



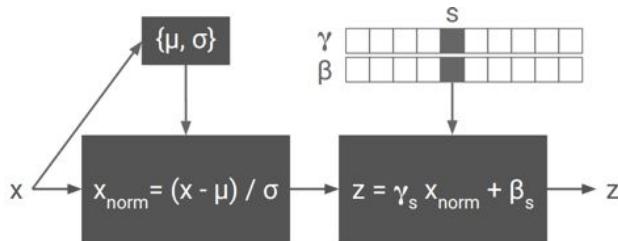
One Network, Many Styles



Dumoulin, Shlens, and Kudlur, "A Learned Representation for Artistic Style", ICLR 2017.
Figure copyright Vincent Dumoulin, Jonathon Shlens, and Manjunath Kudlur, 2016; reproduced with permission.

One Network, Many Styles

Use the same network for multiple styles using conditional instance normalization: learn separate scale and shift parameters per style



Single network can blend styles after training

Dumoulin, Shlens, and Kudlur, "A Learned Representation for Artistic Style", ICLR 2017.
Figure copyright Vincent Dumoulin, Jonathon Shlens, and Manjunath Kudlur, 2016; reproduced with permission.

Summary

Many methods for understanding CNN representations

Activations: Nearest neighbors, Dimensionality reduction, maximal patches, occlusion

Gradients: Saliency maps, class visualization, fooling images, feature inversion

Fun: DeepDream, Style Transfer.

Next time: Detection and Segmentation