Deep Residual Networks

Deep Learning Gets Way Deeper

8:30-10:30am, June 19

ICML 2016 tutorial

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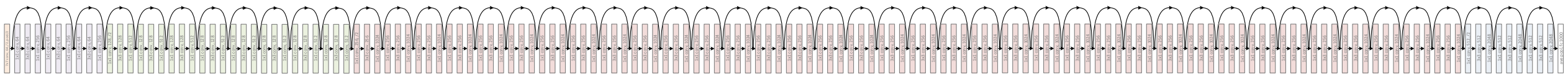


Overview

- Introduction
- Background
  - From shallow to deep
- Deep Residual Networks
  - From 10 layers to 100 layers
  - From 100 layers to 1000 layers
- Applications
- Q & A

Introduction

Introduction

Deep Residual Networks (ResNets)

- "Deep Residual Learning for Image Recognition". CVPR 2016 (next week)
- A simple and clean framework of training "very" deep nets
- State-of-the-art performance for
  - Image classification
  - Object detection
  - Semantic segmentation
  - and more…

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

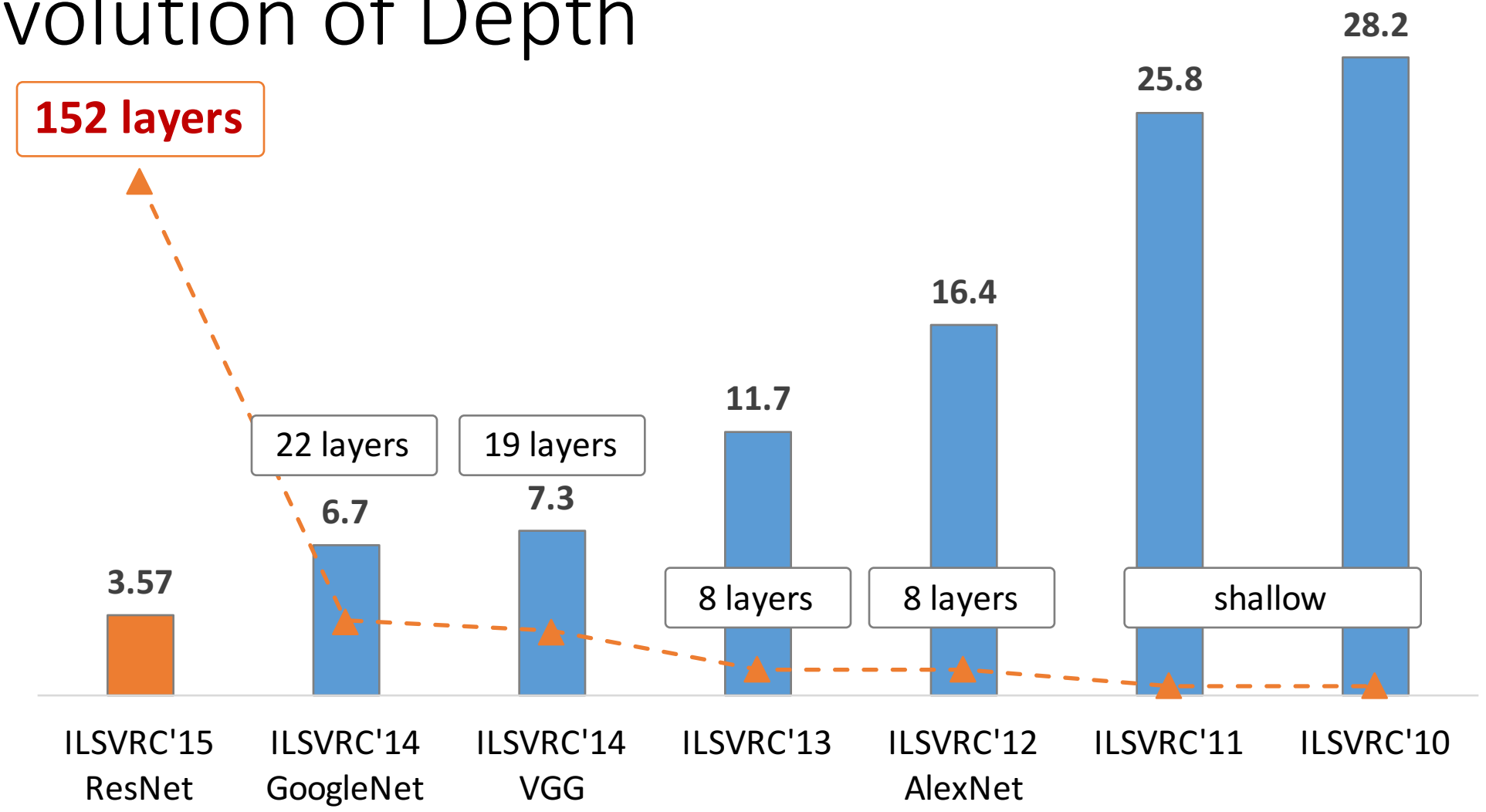
ResNets @ ILSVRC & COCO 2015 Competitions

- **1st places in all five main tracks**
  - ImageNet Classification: "*Ultra-deep*" 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

*improvements are relative numbers

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

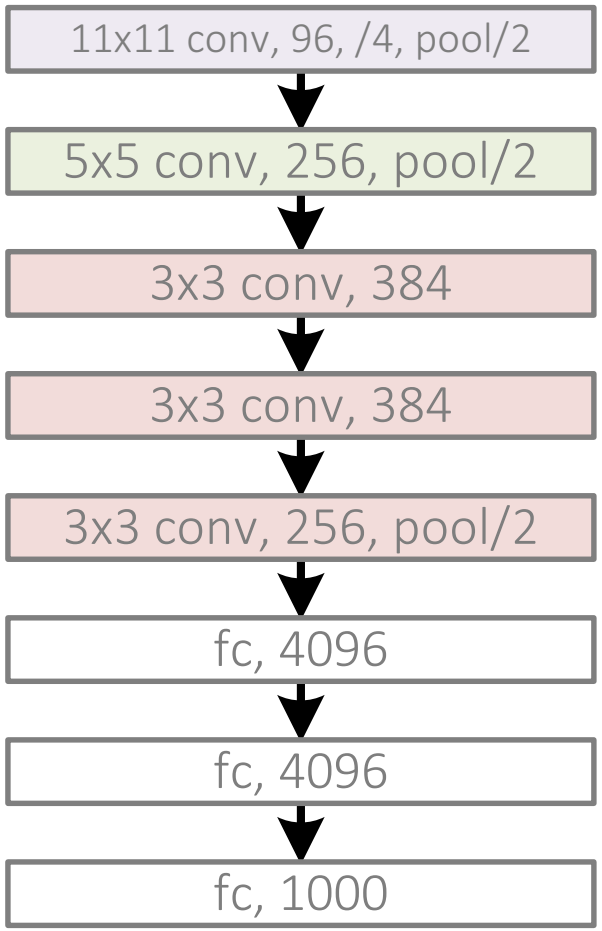
Revolution of Depth



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Revolution of Depth

AlexNet, 8 layers
(ILSVRC 2012)



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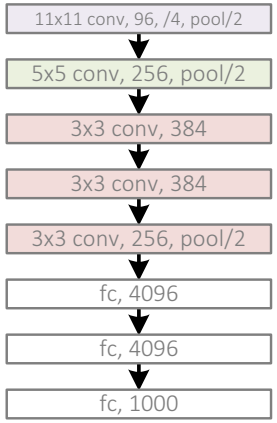
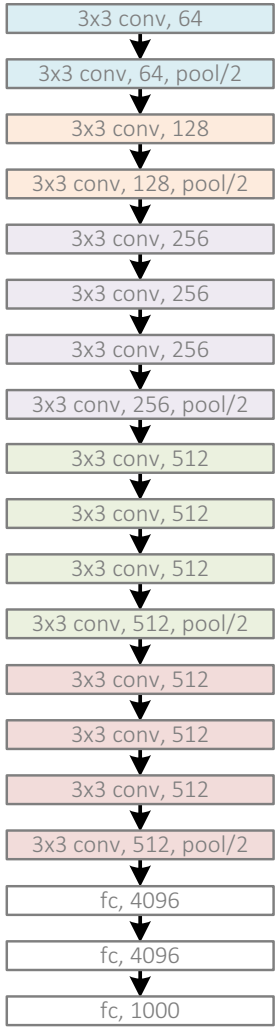


VGG, 19 layers
(ILSVRC 2014)



GoogleNet, 22 layers
(ILSVRC 2014)

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Revolution of Depth

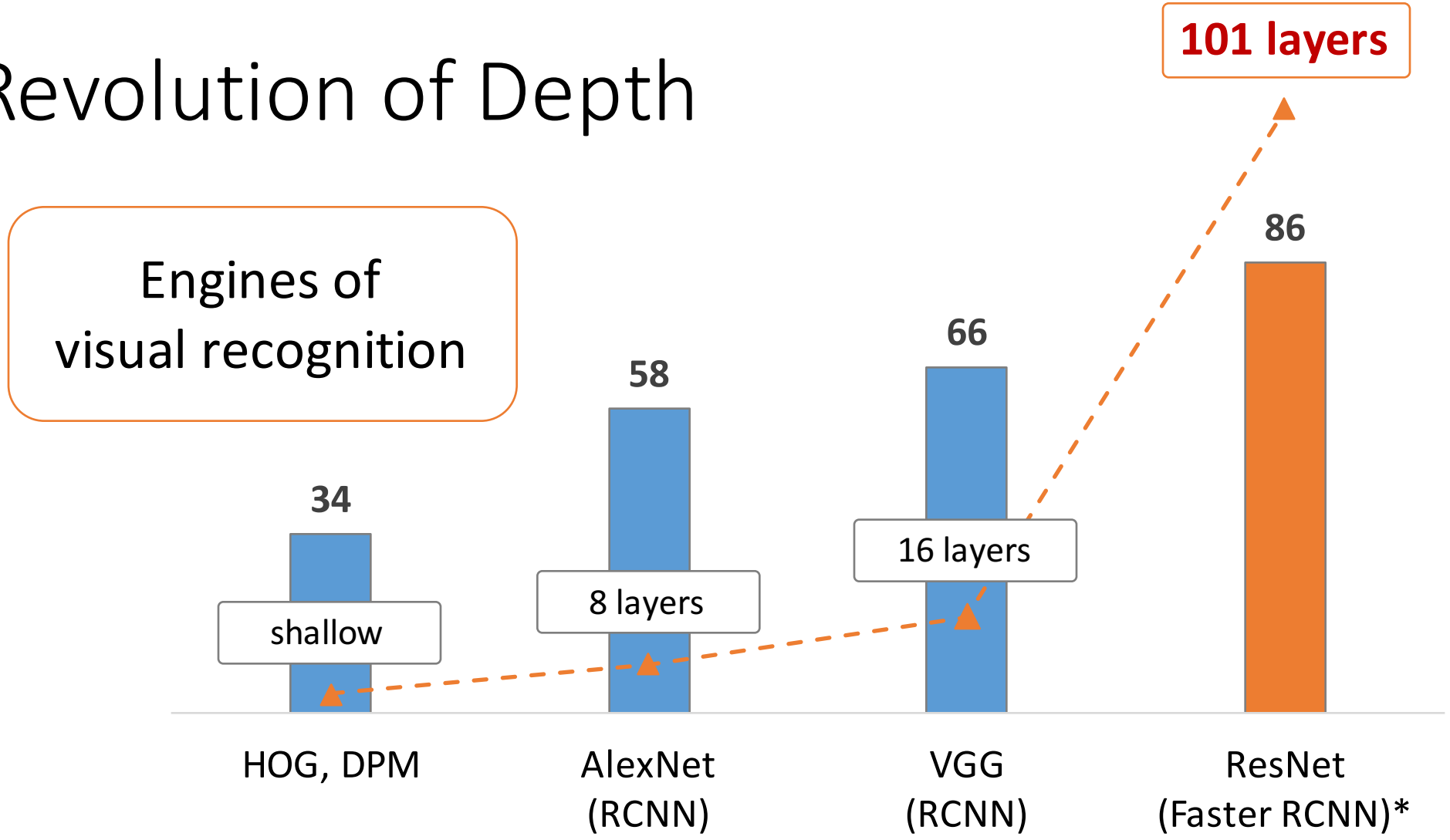
AlexNet, 8 layers
(ILSVRC 2012)

VGG, 19 layers
(ILSVRC 2014)

ResNet, 152 layers
(ILSVRC 2015)

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

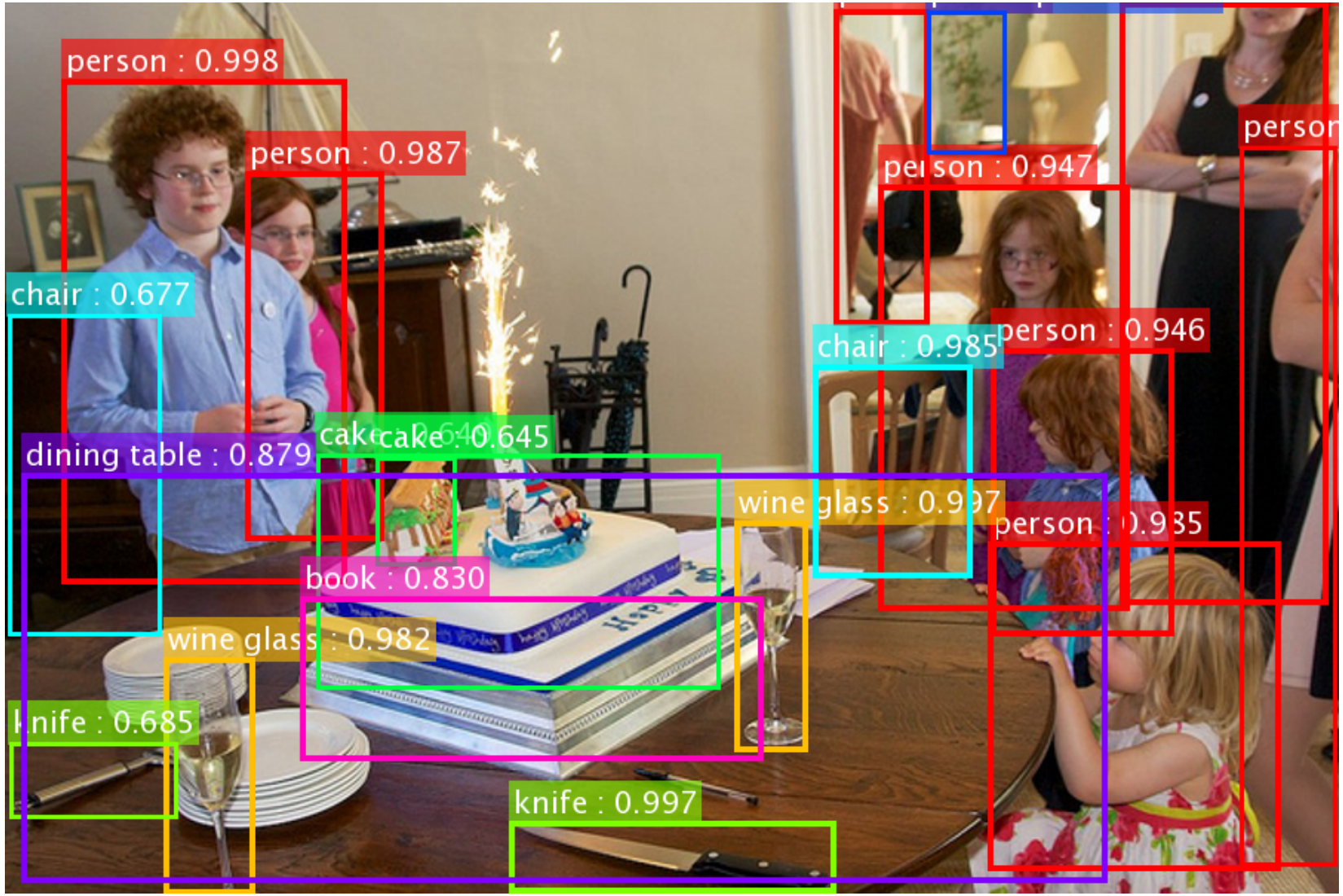
Revolution of Depth



PASCAL VOC 2007 **Object Detection** mAP (%)

*w/ other improvements & more data

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.



ResNet's object detection result on COCO

*the original image is from the COCO dataset

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Very simple, easy to follow

- Many third-party implementations (list in https://github.com/KaimingHe/deep-residual-networks)
  - Facebook AI Research's Torch ResNet:
  - Torch, CIFAR-10, with ResNet-20 to ResNet-110, training code, and curves: code
  - Lasagne, CIFAR-10, with ResNet-32 and ResNet-56 and training code: code
  - Neon, CIFAR-10, with pre-trained ResNet-32 to ResNet-110 models, training code, and curves: code
  - Torch, MNIST, 100 layers: blog, code
  - A winning entry in Kaggle's right whale recognition challenge: blog, code
  - Neon, Place2 (mini), 40 layers: blog, code
  - …
- Easily reproduced results (e.g. Torch ResNet: https://github.com/facebook/fb.resnet.torch)
- A series of extensions and follow-ups
  - > 200 citations in 6 months after posted on arXiv (Dec. 2015)

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Background

From shallow to deep

Traditional recognition

But what's next?

pixels → classifier → "bus"?

edges → classifier → "bus"?

SIFT/HOG

edges → histogram → classifier → "bus"?

edges → histogram → K-means/ sparse code → classifier → "bus"?

shallower

deeper

Deep Learning

Specialized components, domain knowledge required

edges → histogram → K-means/ sparse code → classifier → "bus"?

Generic components ("layers"), less domain knowledge

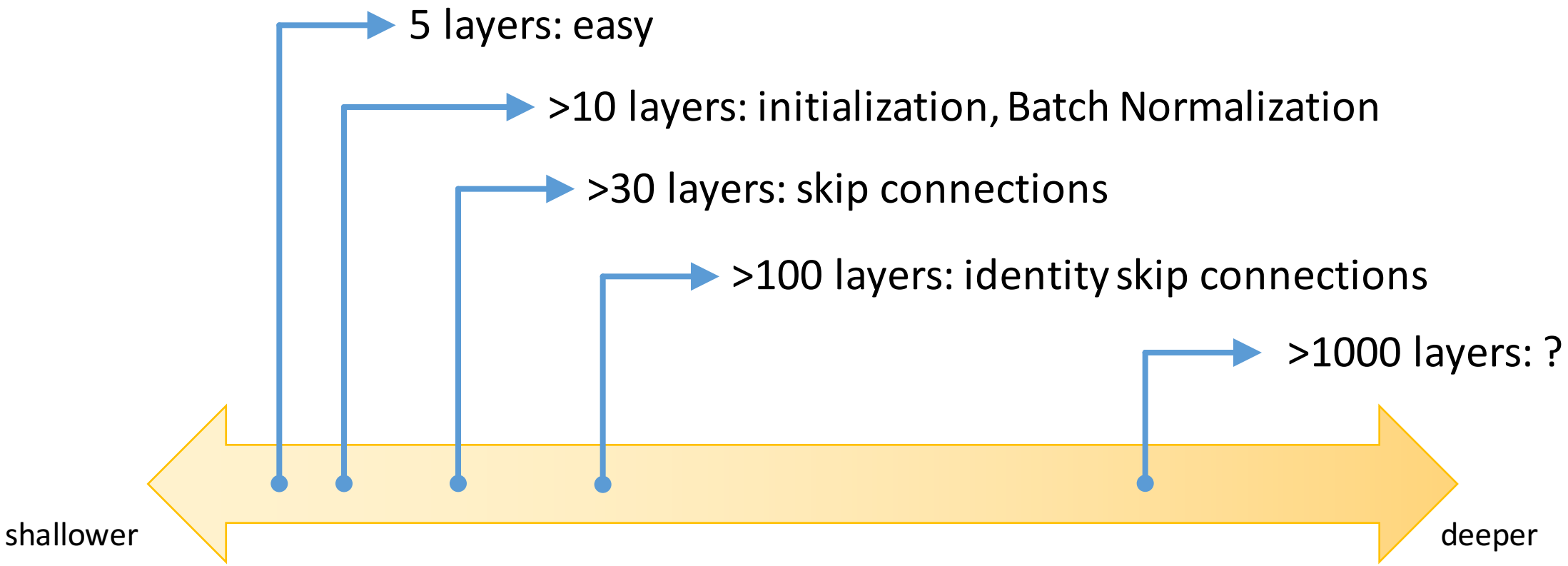
→ □ → □ → □ → □ → "bus"?

Repeat elementary layers => Going deeper

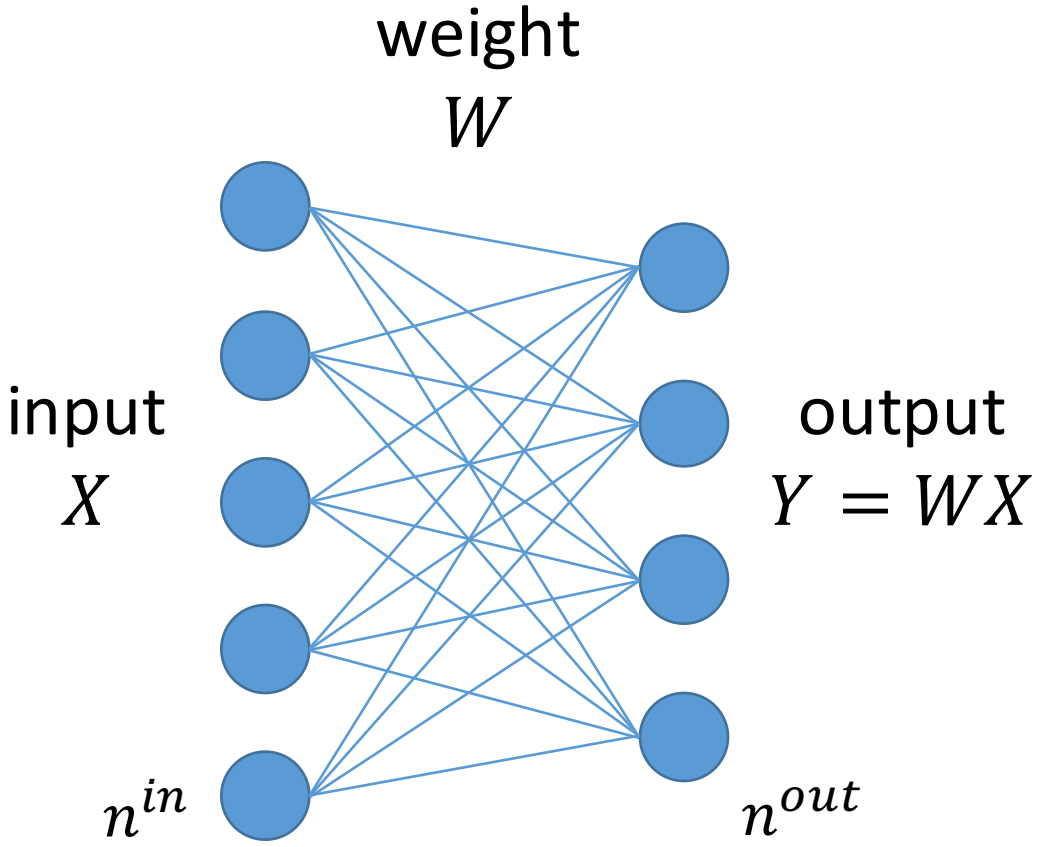
→ □ → □ → □ → □ → □ → □ → "bus"?

- End-to-end learning
- Richer solution space

Spectrum of Depth



Initialization



If:

- Linear activation
- x, y, w: independent

Then:

1-layer:

$$Var[y] = (n^{in} Var[w]) Var[x]$$

Multi-layer:

$$Var[y] = (\prod_d n_d^{in} Var[w_d]) Var[x]$$

LeCun et al 1998 “Efficient Backprop”

Glorot & Bengio 2010 “Understanding the difficulty of training deep feedforward neural networks”

Initialization

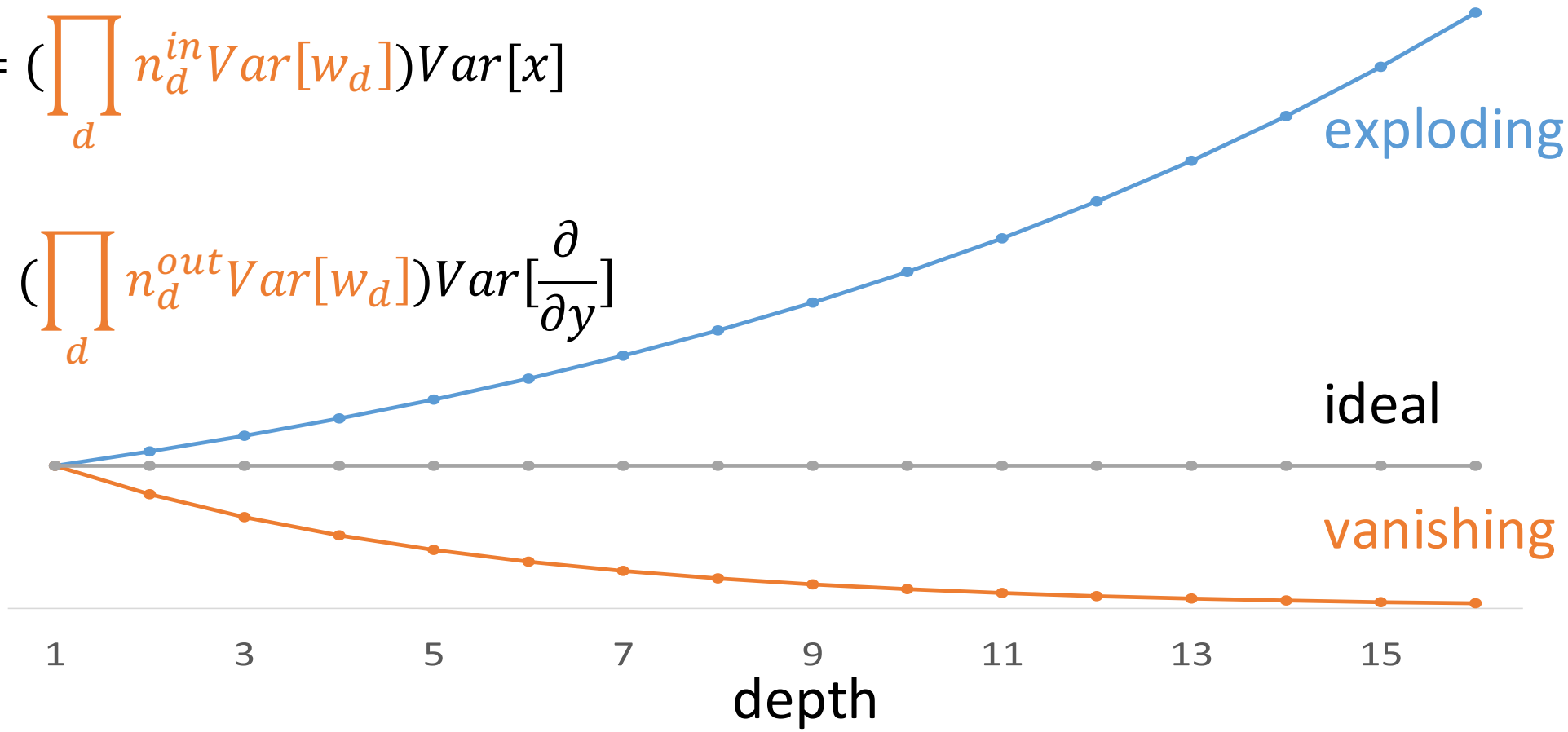
Both forward (response) and backward (gradient) signal can vanish/explode

Forward:

$$Var[y] = (\prod_d n_d^{in} Var[w_d])Var[x]$$

Backward:

$$Var\left[\frac{\partial}{\partial x}\right] = (\prod_d n_d^{out} Var[w_d])Var[\frac{\partial}{\partial y}]$$



LeCun et al 1998 “Efficient Backprop”

Glorot & Bengio 2010 “Understanding the difficulty of training deep feedforward neural networks”

Initialization

- Initialization under **linear** assumption

$$\prod_d n_d^{in} Var[w_d] = const_{\text{fw}} \text{ (healthy forward)}$$

and

$$\prod_d n_d^{out} Var[w_d] = const_{\text{bw}} \text{(healthy backward)}$$

➡ $\boxed{\begin{array}{c} n_d^{in} Var[w_d] = 1 \\ \text{or*} \\ n_d^{out} Var[w_d] = 1 \end{array}}$

*: $n_d^{out} = n_{d+1}^{in}$, so $\frac{const_{\text{bw}}}{const_{\text{fw}}} = \frac{n_{\text{last}}^{out}}{n_{\text{first}}^{in}} < \infty$.

It is sufficient to use either form.

"*Xavier*" init in Caffe

LeCun et al 1998 "Efficient Backprop"

Glorot & Bengio 2010 "Understanding the difficulty of training deep feedforward neural networks"

Initialization

- Initialization under **ReLU** activation

$$\prod_d \frac{1}{2} n_d^{in} Var[w_d] = const_{\text{fw}} \text{ (healthy forward)}$$

and

$$\prod_d \frac{1}{2} n_d^{out} Var[w_d] = const_{\text{bw}} \text{(healthy backward)}$$

➡

$$\frac{1}{2} n_d^{in} Var[w_d] = 1$$

or

$$\frac{1}{2} n_d^{out} Var[w_d] = 1$$

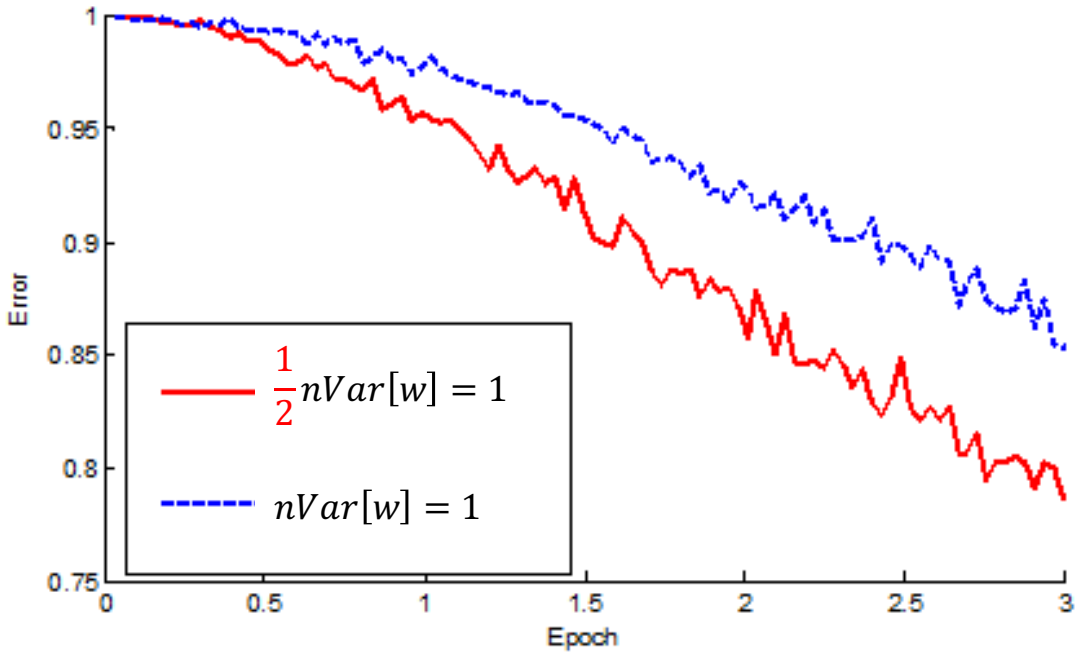
"*MSRA*" init in Caffe

With D layers, a factor of 2 per layer has exponential impact of 2^D

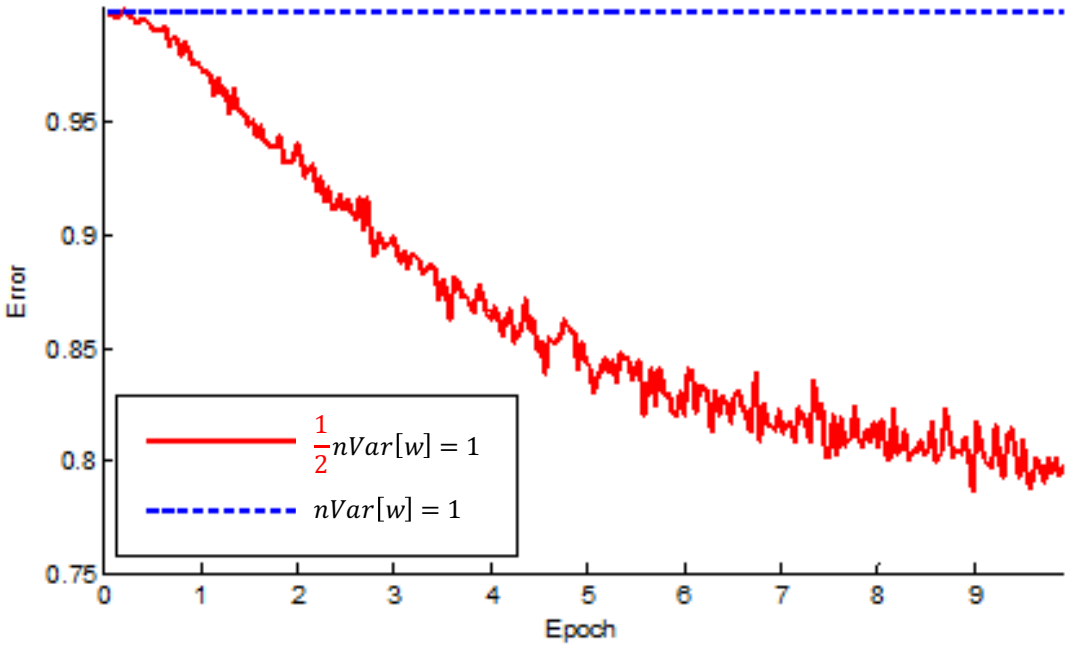
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification". ICCV 2015.

Initialization

22-layer ReLU net:
good init converges faster



30-layer ReLU net:
good init is able to converge



*Figures show the beginning of training

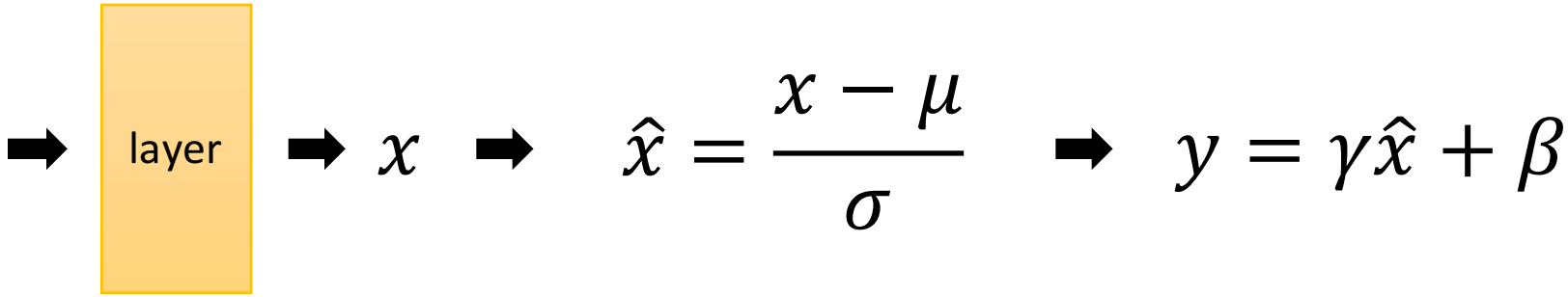
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification". ICCV 2015.

Batch Normalization (BN)

- Normalizing input (LeCun et al 1998 “Efficient Backprop”)
- BN: normalizing each layer, for each mini-batch
- Greatly accelerate training
- Less sensitive to initialization
- Improve regularization

S. Ioffe & C. Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. ICML 2015

Batch Normalization (BN)

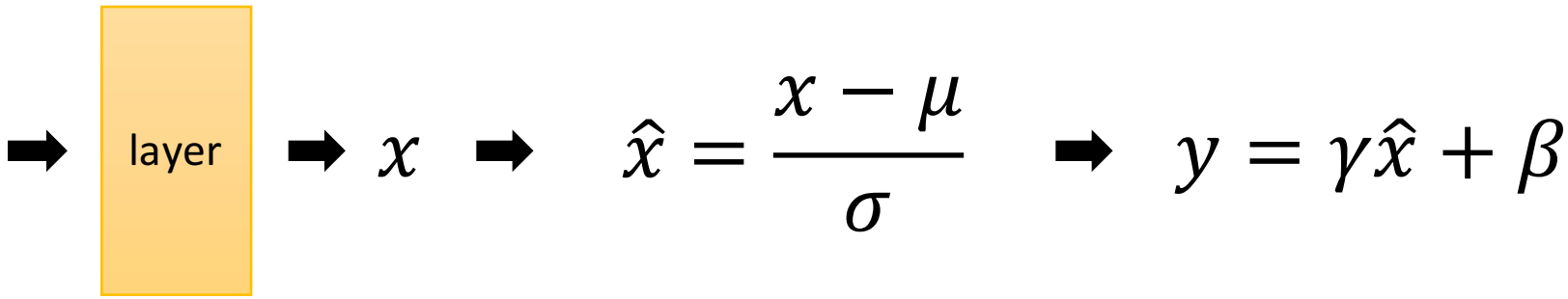


- μ: mean of x in mini-batch
- σ: std of x in mini-batch
- γ: scale
- β: shift

- μ, σ: functions of x, analogous to responses
- γ, β: parameters to be learned, analogous to weights

S. Ioffe & C. Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. ICML 2015

Batch Normalization (BN)



2 modes of BN:

- Train mode:
  - μ, σ are functions of x; backprop gradients
- Test mode:
  - μ, σ are pre-computed* on training set

Caution: make sure your BN is in a correct mode

*: by running average, or post-processing after training

S. Ioffe & C. Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. ICML 2015

Batch Normalization (BN)

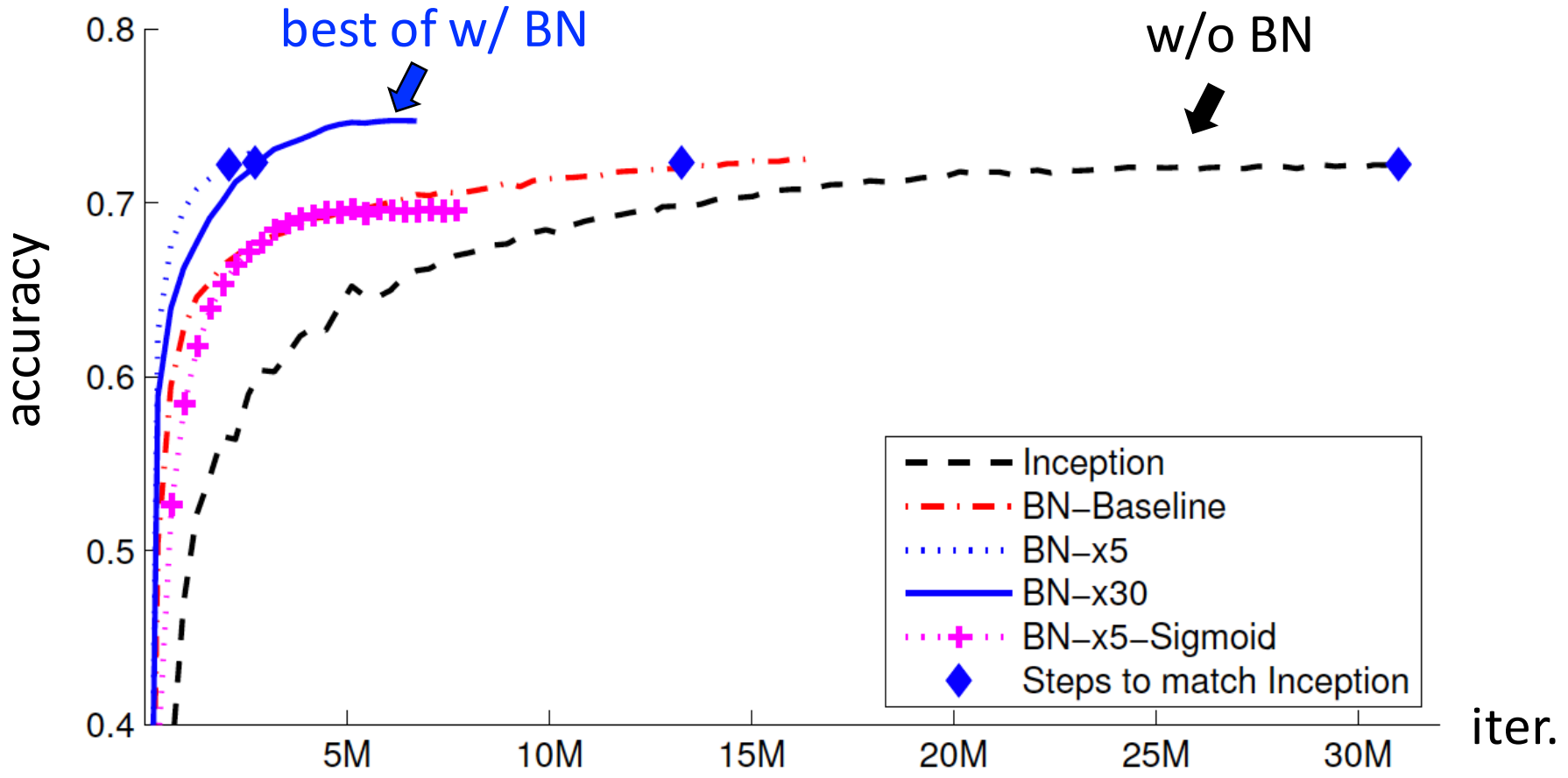


Figure taken from [S. Ioffe & C. Szegedy]

S. Ioffe & C. Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. ICML 2015

Deep Residual Networks

From 10 layers to 100 layers

Going Deeper

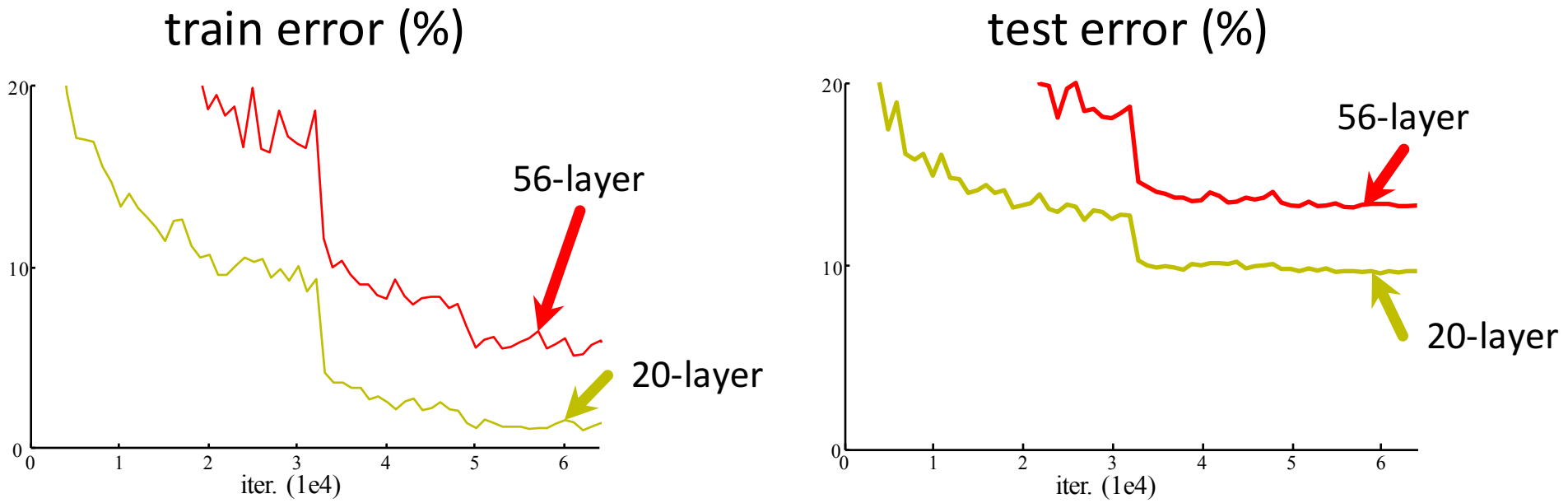
- Initialization algorithms ✓
- Batch Normalization ✓

- **Is learning better networks as simple as stacking more layers?**

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. CVPR 2016.

Simply stacking layers?

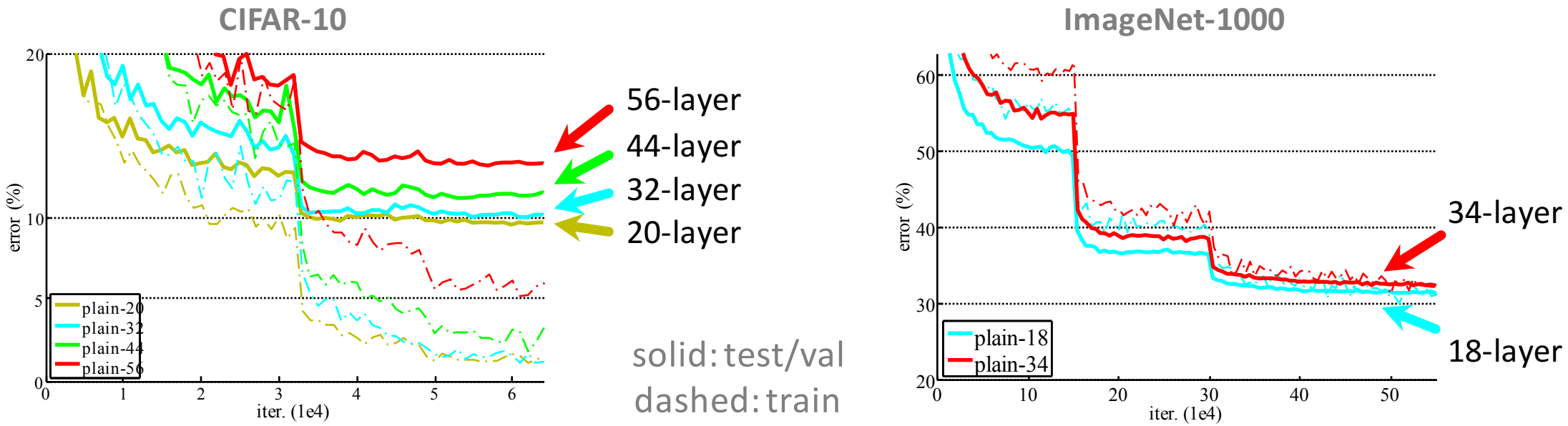
CIFAR-10



- *Plain* nets: stacking 3x3 conv layers…
- 56-layer net has **higher training error** and test error than 20-layer net

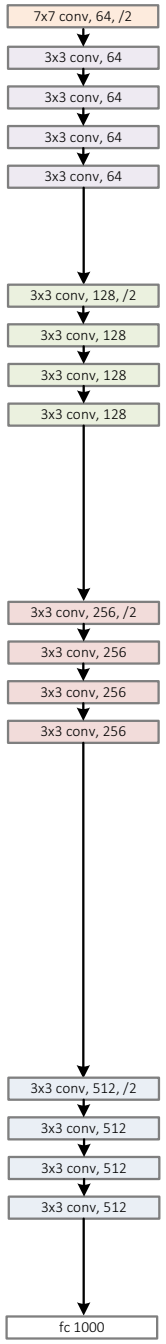
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

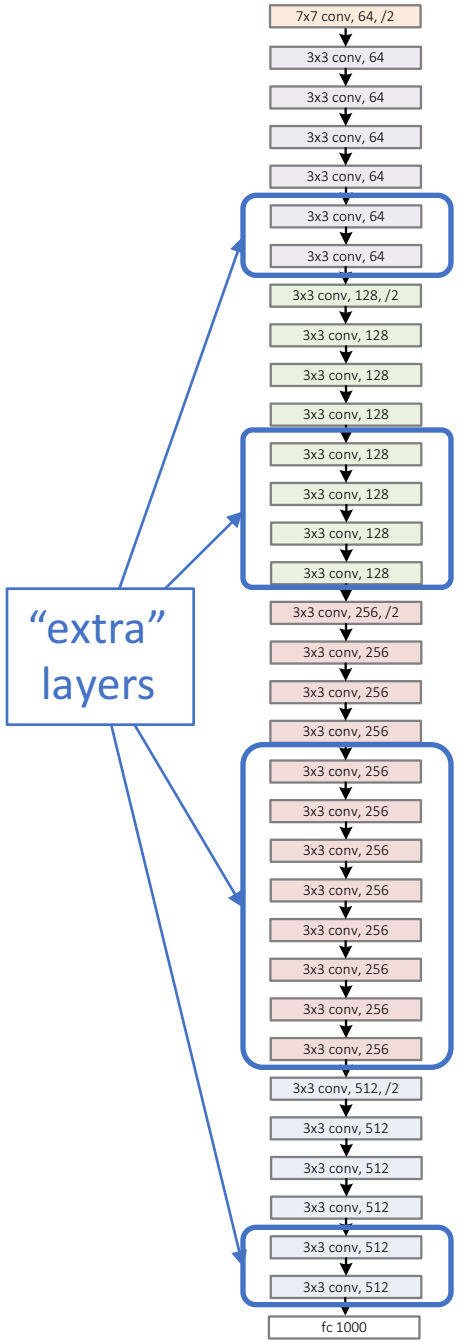
Simply stacking layers?



- "Overly deep" plain nets have **higher training error**
- A general phenomenon, observed in many datasets

a shallower model (18 layers)





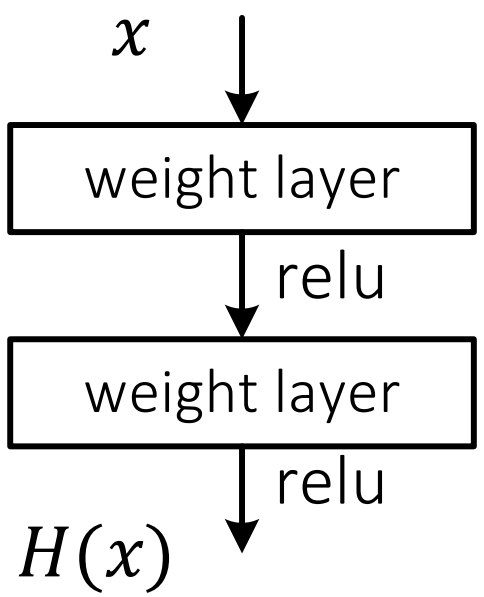
a deeper counterpart (34 layers)

- Richer solution space
- A deeper model should not have **higher training error**
- A solution *by construction*:
  - original layers: copied from a learned shallower model
  - extra layers: set as identity
  - at least the same training error
- Optimization difficulties: solvers cannot find the solution when going deeper…

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Deep Residual Learning

- Plaint net



any two
stacked layers

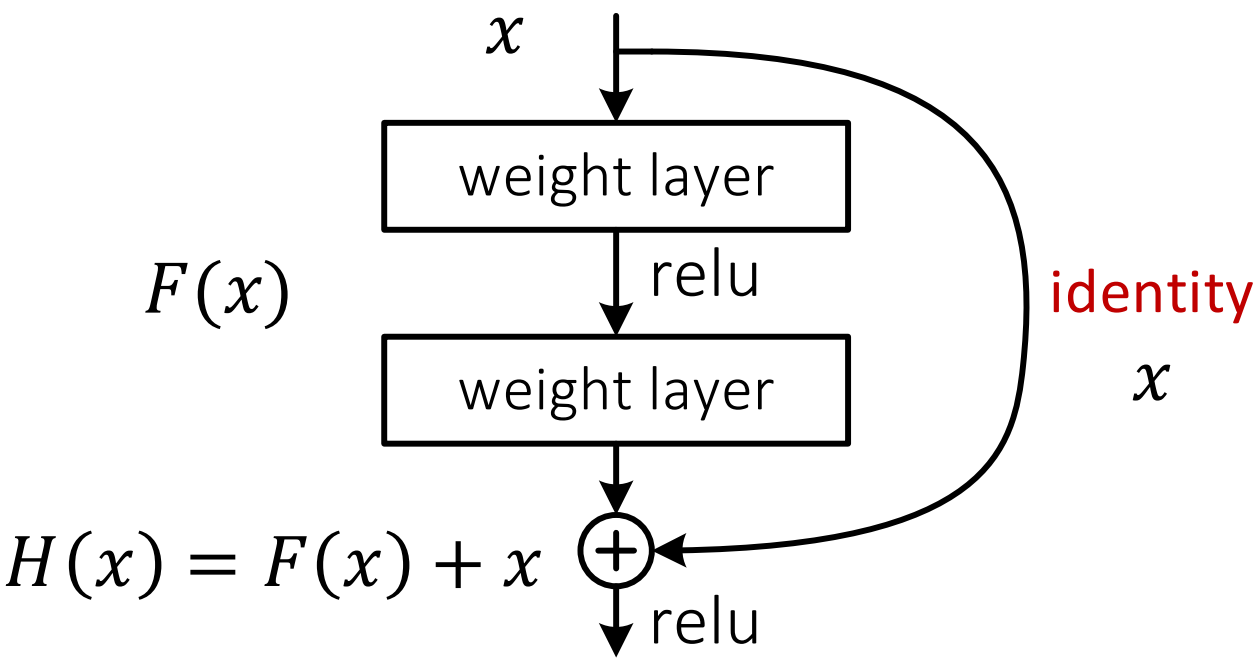
$H(x)$ is any desired mapping,

hope the 2 weight layers fit $H(x)$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Deep Residual Learning

- Residual net



$H(x)$ is any desired mapping,

~~hope the 2 weight layers fit $H(x)$~~

hope the 2 weight layers fit $F(x)$

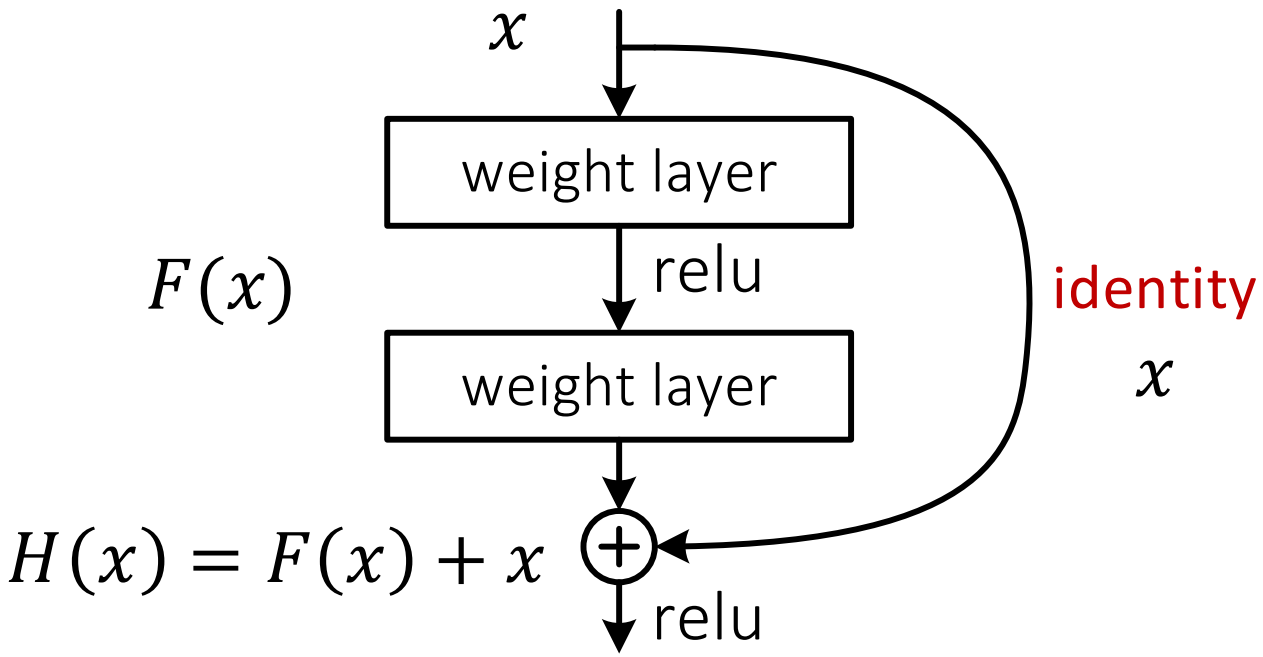
let $H(x) = F(x) + x$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Deep Residual Learning

with reference to, 关于

- $F(x)$ is a residual mapping w.r.t. identity



- If identity were optimal, easy to set weights as 0
- If optimal mapping is closer to identity, easier to find small fluctuations

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

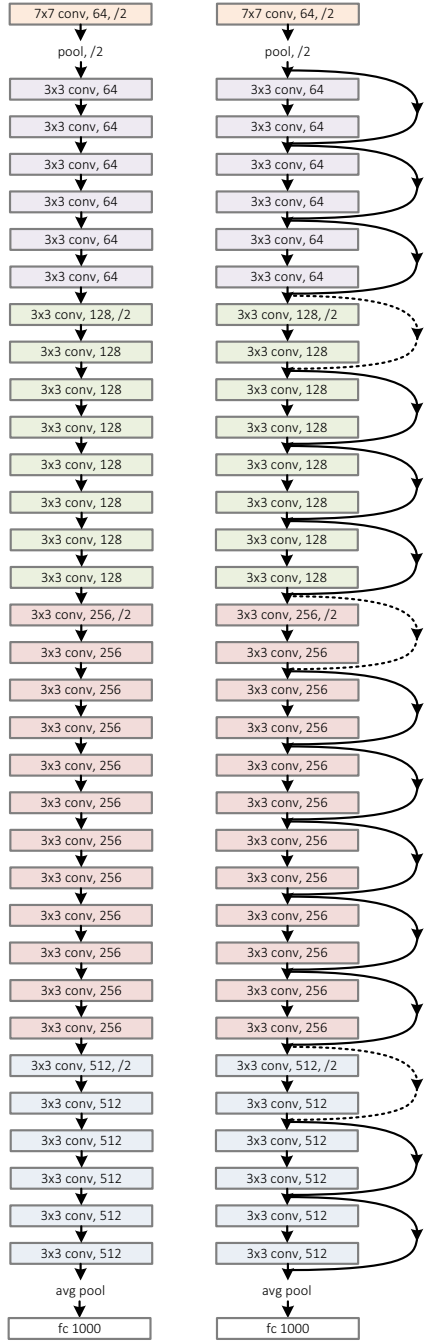
Related Works – Residual Representations

- VLAD & Fisher Vector [Jegou et al 2010], [Perronnin et al 2007]
  - Encoding residual vectors; powerful shallower representations.
- Product Quantization (IVF-ADC) [Jegou et al 2011]
  - Quantizing residual vectors; efficient nearest-neighbor search.
- MultiGrid & Hierarchical Precondition [Briggs, et al 2000], [Szeliski 1990, 2006]
  - Solving residual sub-problems; efficient PDE solvers.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Network “Design”

plain net



ResNet

- Keep it simple
- Our basic design (VGG-style)
  - all 3x3 conv (almost)
  - spatial size /2 => # filters x2 (~same complexity per layer)
  - Simple design; just deep!
- Other remarks:
  - no hidden fc
  - no dropout

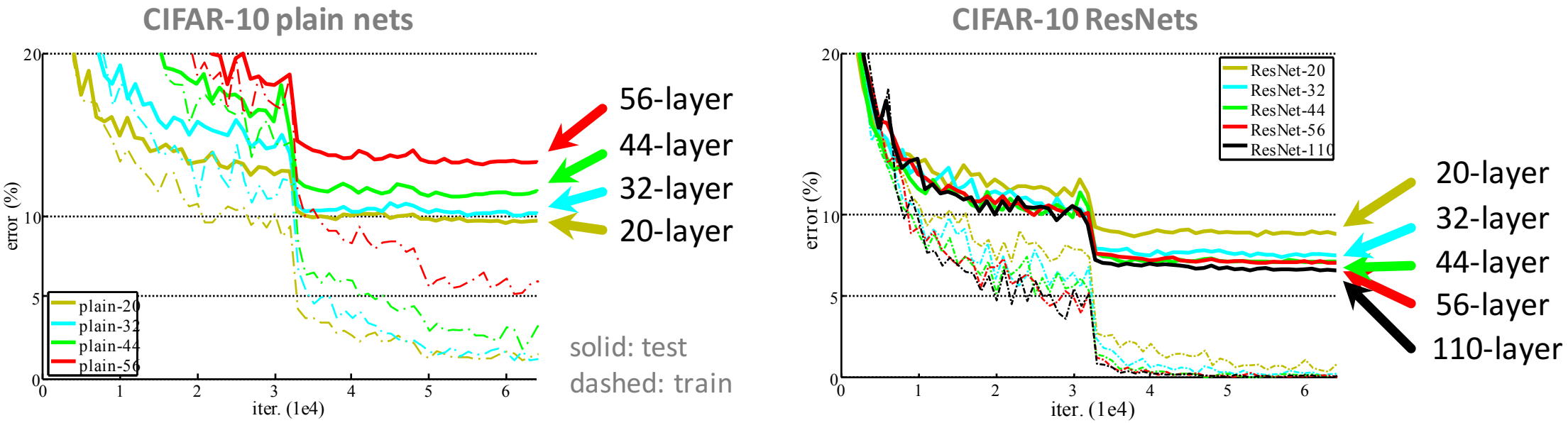
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. CVPR 2016.

Training

- All plain/residual nets are trained from scratch
- All plain/residual nets use Batch Normalization
- Standard hyper-parameters & augmentation

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. CVPR 2016.

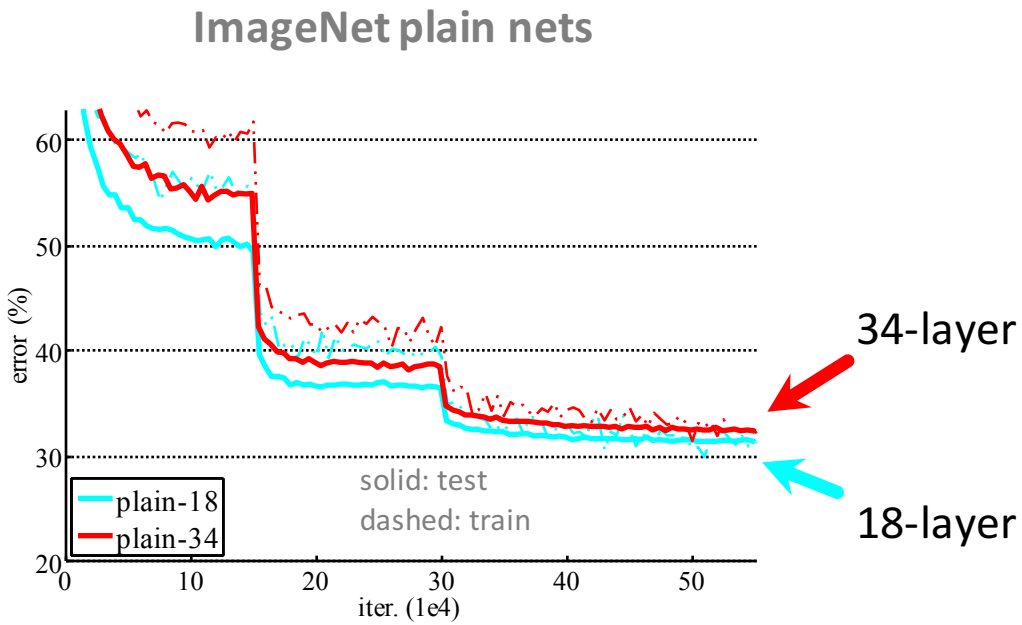
CIFAR-10 experiments

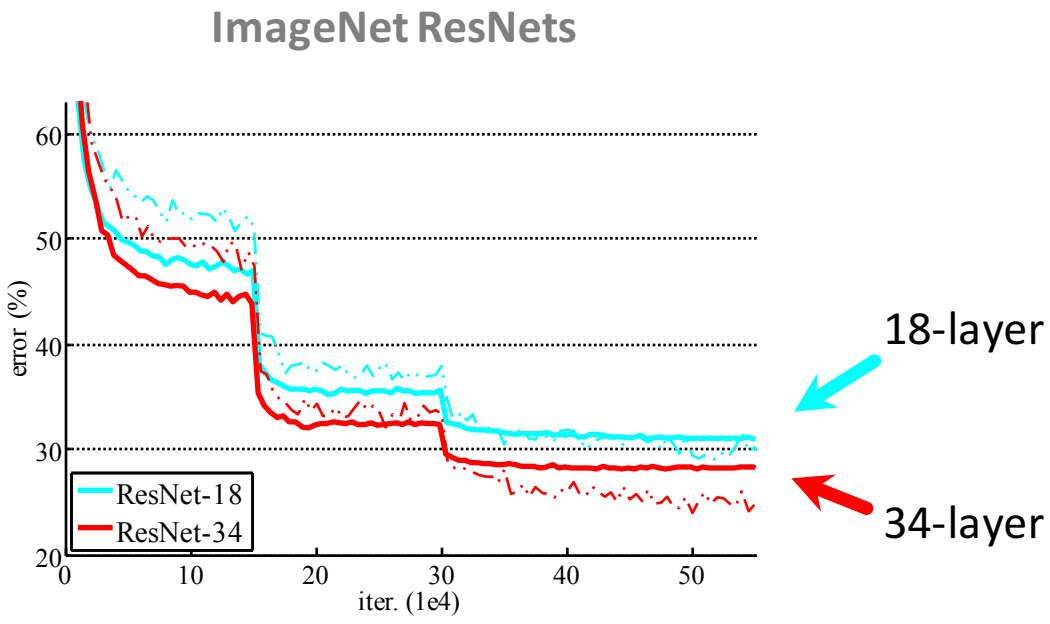


- Deep ResNets can be trained without difficulties
- Deeper ResNets have **lower training error**, and also lower test error

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

ImageNet experiments





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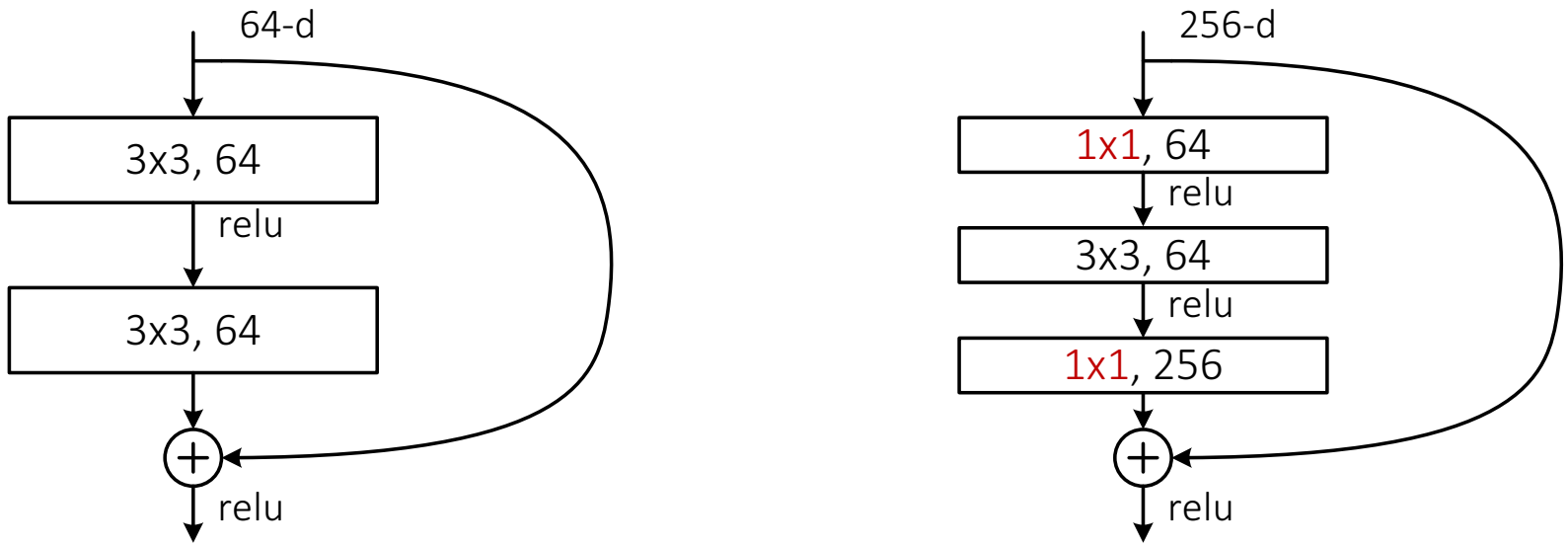
ImageNet experiments

- A practical design of going deeper



all-3x3

similar complexity

bottleneck

(for ResNet-50/101/152)

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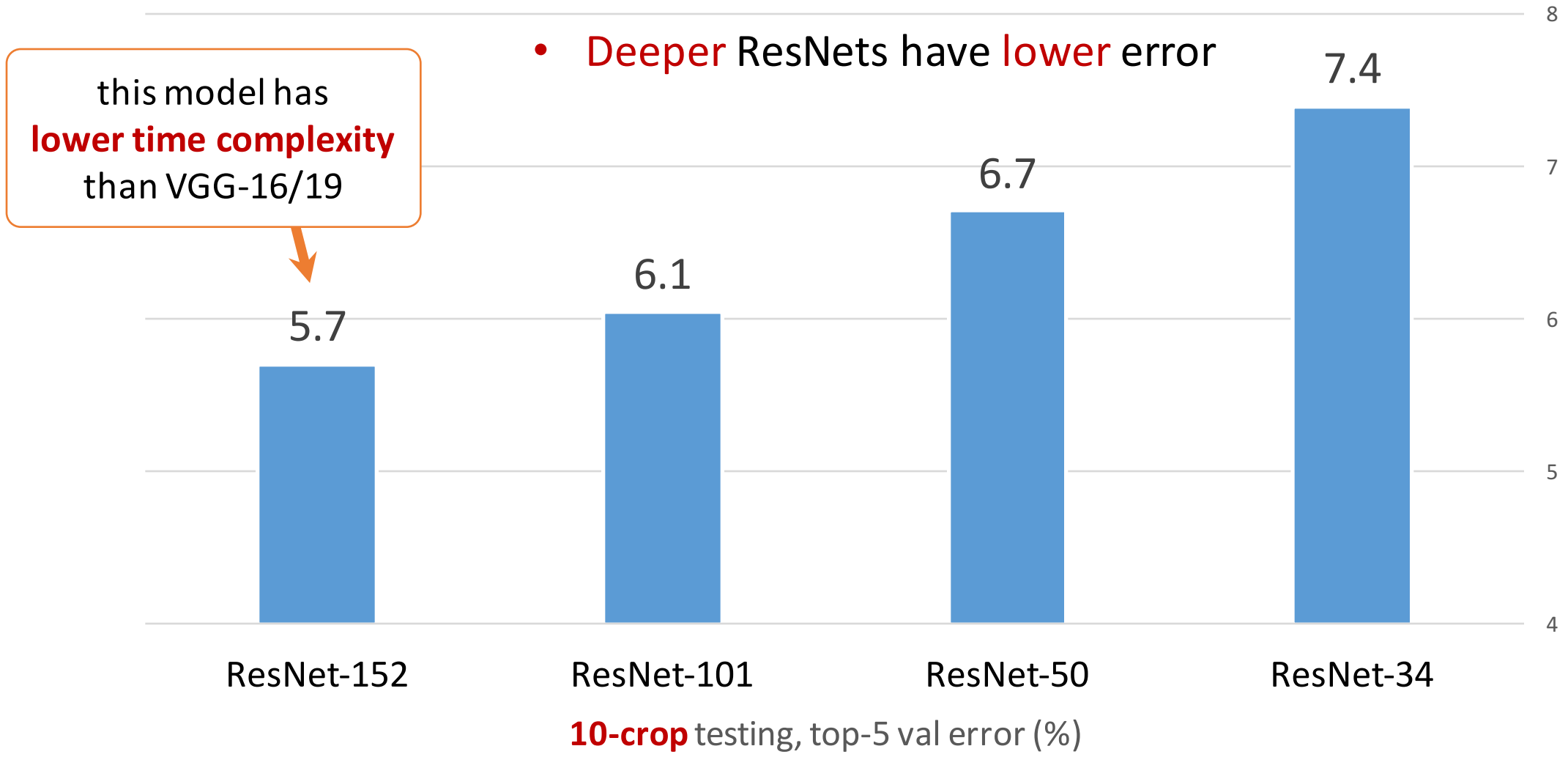
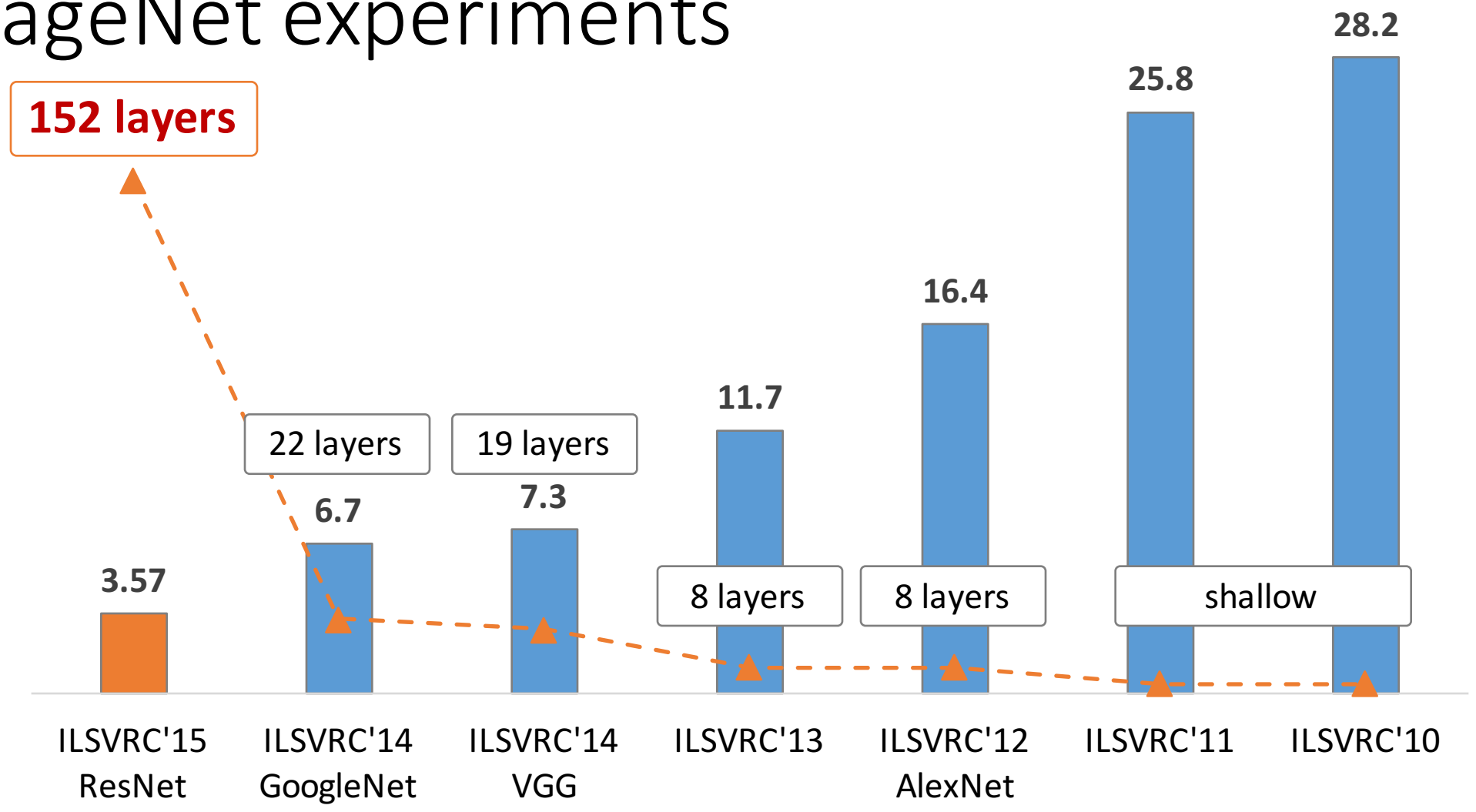
ImageNet experiments



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

ImageNet experiments



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Discussions

Representation, Optimization, Generalization

Issues on learning deep models

- **Representation** ability
  - Ability of model to fit training data, if optimum could be found
  - If model A's solution space is a superset of B's, A should be better.
- **Optimization** ability
  - Feasibility of finding an optimum
  - Not all models are equally easy to optimize
- **Generalization** ability
  - Once training data is fit, how good is the test performance

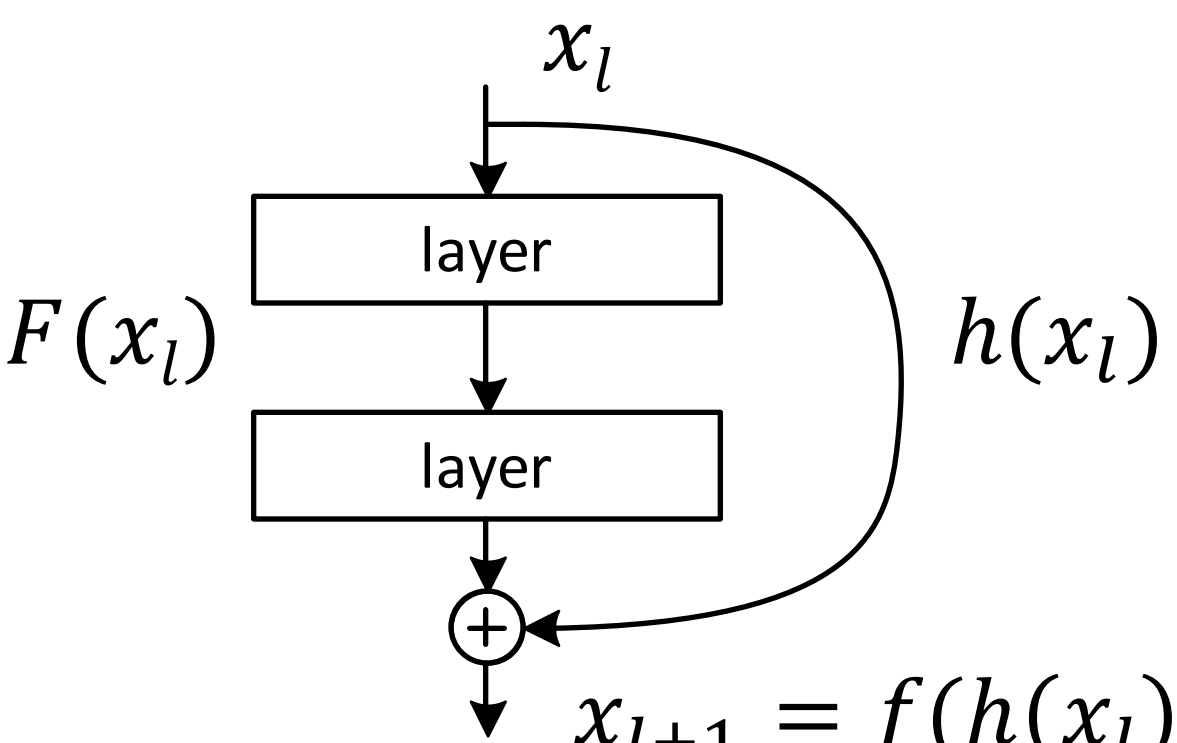
How do ResNets address these issues?

- **Representation** ability
  - No explicit advantage on representation (only re-parameterization), but
  - Allow models to go deeper
- **Optimization** ability
  - Enable very smooth forward/backward prop
  - Greatly ease optimizing deeper models
- **Generalization** ability
  - Not explicitly address generalization, but
  - Deeper+thinner is good generalization

On the Importance of Identity Mapping

From 100 layers to 1000 layers

On identity mappings for **optimization**

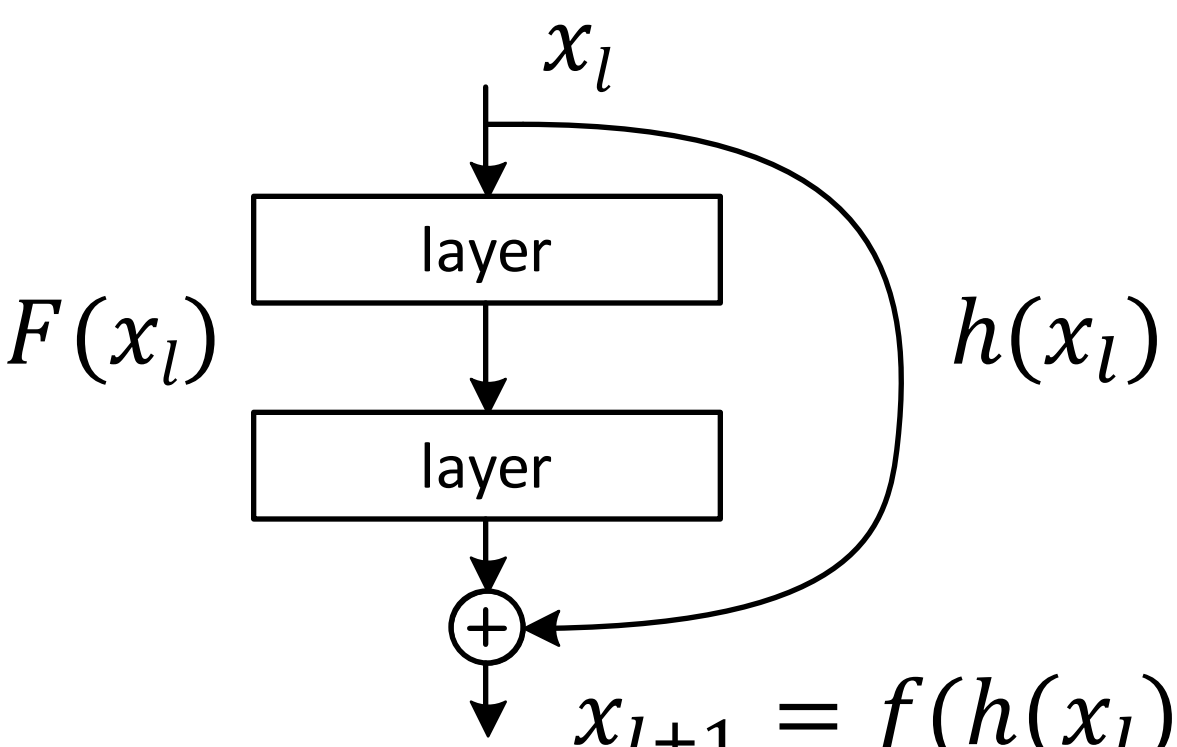


- shortcut mapping: h = identity
- after-add mapping: f = ReLU

$$x_{l+1} = f(h(x_l) + F(x_l))$$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

On identity mappings for **optimization**

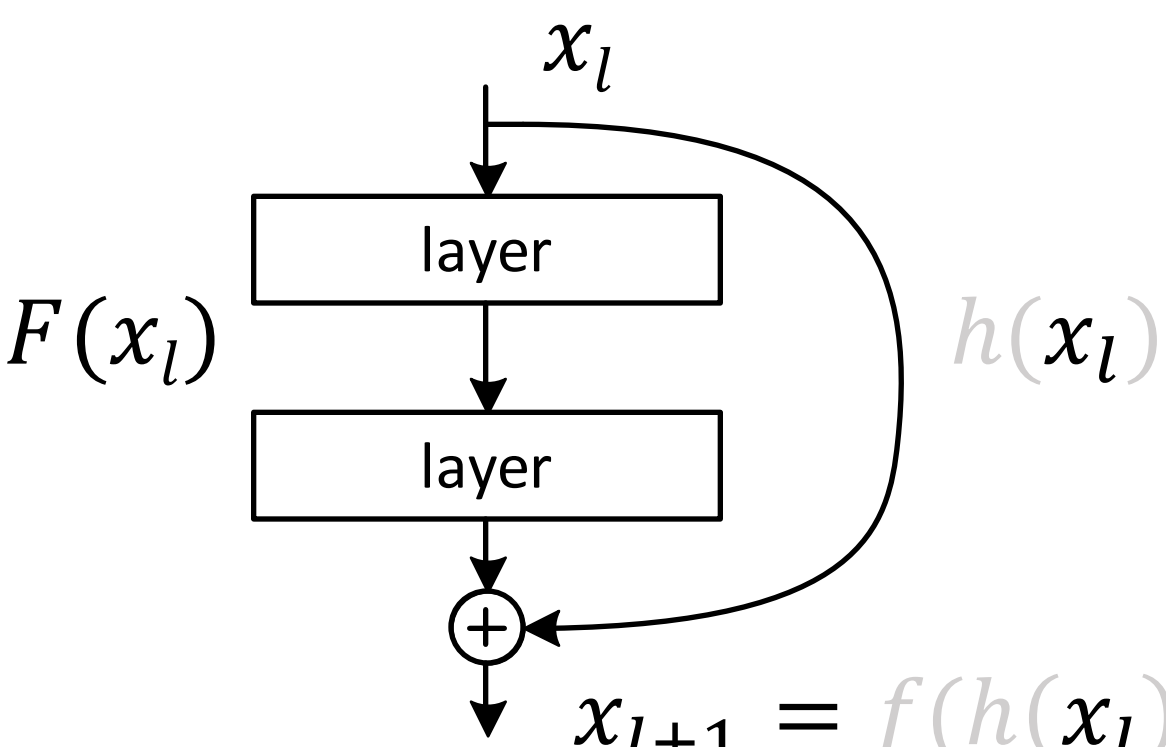


- shortcut mapping: h = identity
- ~~after-add mapping: f = ReLU~~
- What if f = identity?

$$x_{l+1} = f(h(x_l) + F(x_l))$$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

On identity mappings for **optimization**



- shortcut mapping: h = identity
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- What if f = identity?

$$x_{l+1} = f(h(x_l) + F(x_l))$$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

Very smooth forward propagation

$$x_{l+1} = x_l + F(x_l)$$

$$x_{l+2} = x_{l+1} + F(x_{l+1})$$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

Very smooth forward propagation

$$x_{l+1} = x_l + F(x_l)$$

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$$x_{l+2} = x_l + F(x_l) + F(x_{l+1})$$

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Very smooth forward propagation

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$$x_{l+2} = x_l + F(x_l) + F(x_{l+1})$$

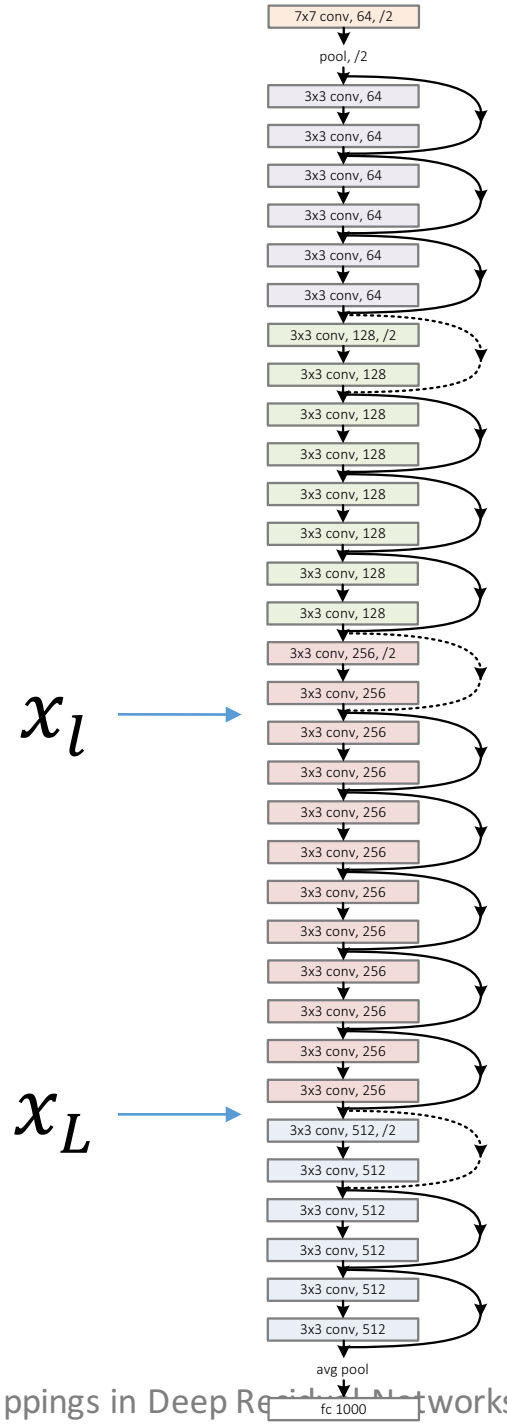
$$x_L = x_l + \sum_{i=l}^{L-1} F(x_i)$$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

Very smooth forward propagation

$$x_L = x_l + \sum_{i=l}^{L-1} F(x_i)$$

- Any x_l is directly forward-prop to any x_L, plus residual.
- Any x_L is an additive outcome.
  - in contrast to multiplicative: $x_L = \prod_{i=l}^{L-1} W_i x_l$

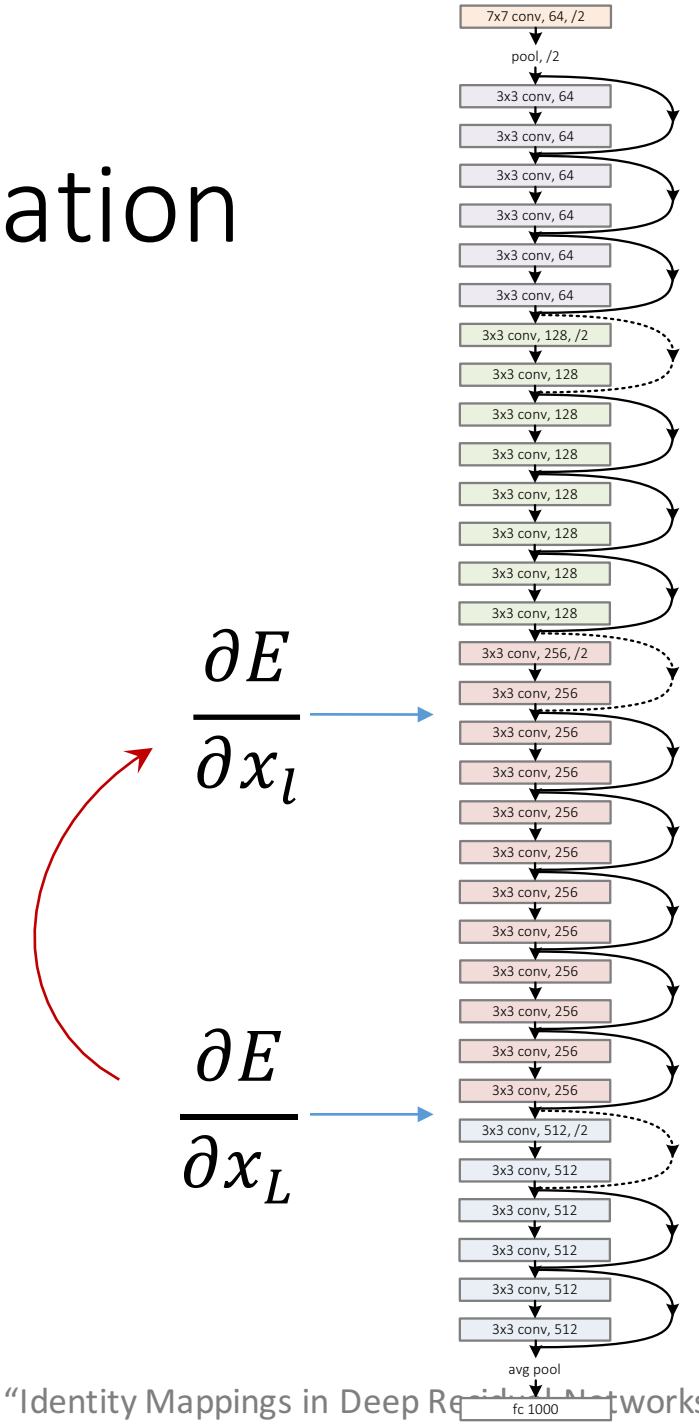


Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Very smooth backward propagation

$$x_L = x_l + \sum_{i=l}^{L-1} F(x_i)$$

$$\frac{\partial E}{\partial x_l} = \frac{\partial E}{\partial x_L}\frac{\partial x_L}{\partial x_l} = \frac{\partial E}{\partial x_L}\left(1 + \frac{\partial}{\partial x_l}\sum_{i=1}^{L-1} F(x_i)\right)$$

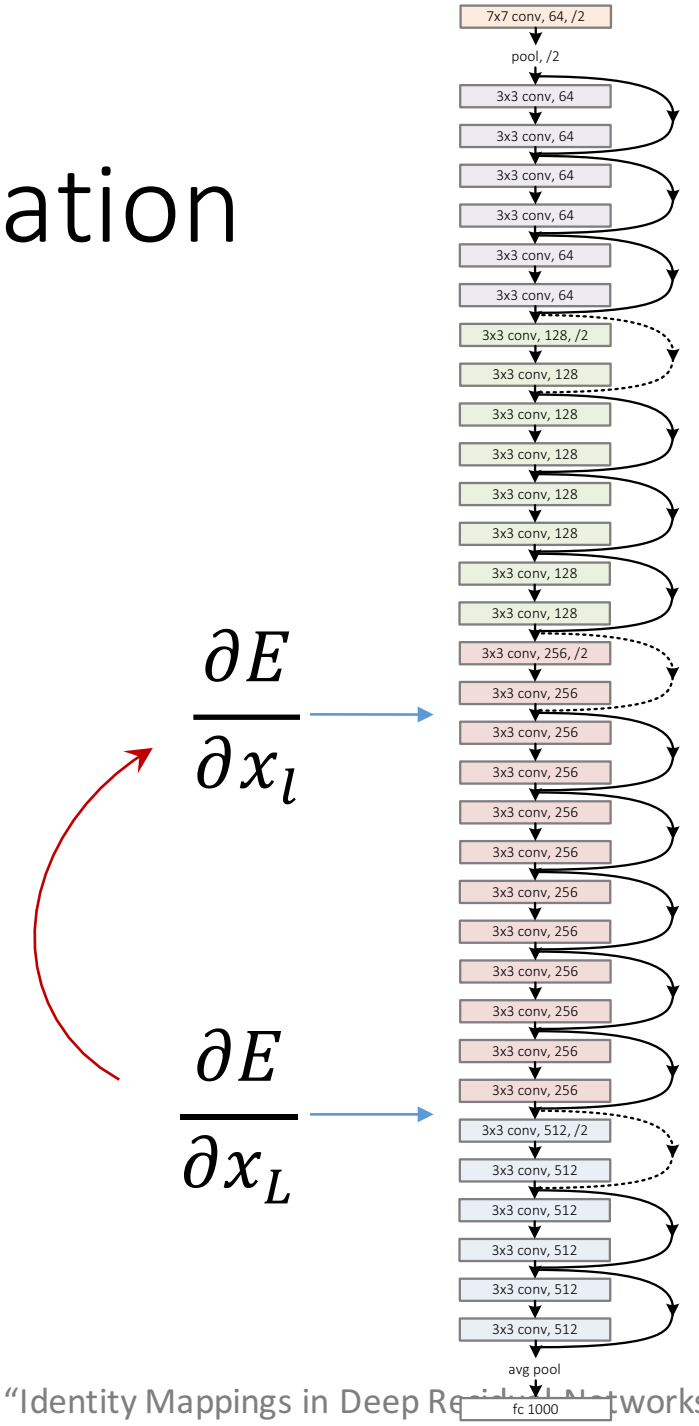


Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Very smooth backward propagation

$$\frac{\partial E}{\partial x_l} = \frac{\partial E}{\partial x_L}\left(1 + \frac{\partial}{\partial x_l}\sum_{i=1}^{L-1} F(x_i)\right)$$

- Any $\frac{\partial E}{\partial x_L}$ is directly back-prop to any $\frac{\partial E}{\partial x_l}$, plus residual.
- Any $\frac{\partial E}{\partial x_l}$ is additive; unlikely to vanish
  - in contrast to multiplicative: $\frac{\partial E}{\partial x_l} = \prod_{i=l}^{L-1} W_i \frac{\partial E}{\partial x_L}$



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Residual for every layer

forward: $x_L = x_l + \sum_{i=l}^{L-1} F(x_i)$

Enabled by:

- shortcut mapping: h = identity
- after-add mapping: f = identity

backward: $\frac{\partial E}{\partial x_l} = \frac{\partial E}{\partial x_L}\left(1 + \frac{\partial}{\partial x_l}\sum_{i=1}^{L-1} F(x_i)\right)$

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

Experiments

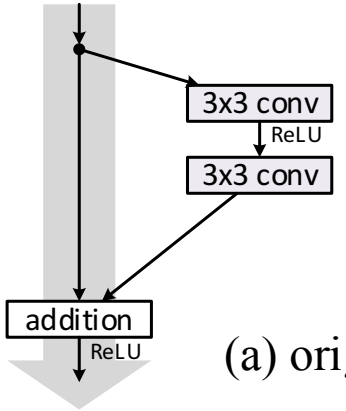
- Set 1: what if shortcut mapping $h \neq$ identity
- Set 2: what if after-add mapping f is identity
- Experiments on ResNets with more than 100 layers
  - deeper models suffer more from optimization difficulty

Experiment Set 1:
what if shortcut mapping h ≠ identity?

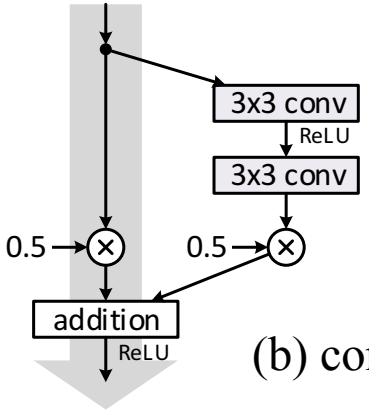
* ResNet-110 on CIFAR-10

$h(x) = x$

error: 6.6%



(a) original



(b) constant scaling

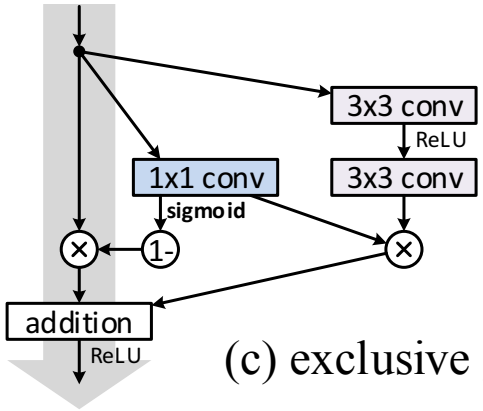
$h(x) = 0.5x$

error: 12.4%

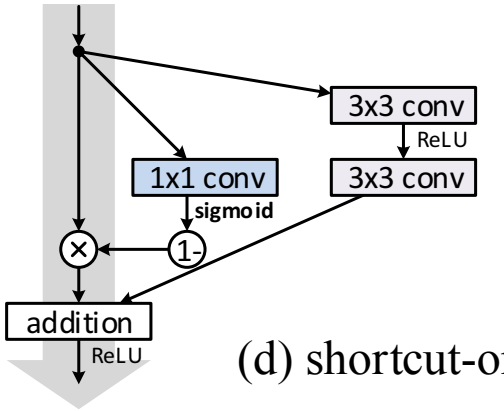
$h(x) = \text{gate} \cdot x$

error: 8.7%

*similar to "Highway Network"



(c) exclusive gating



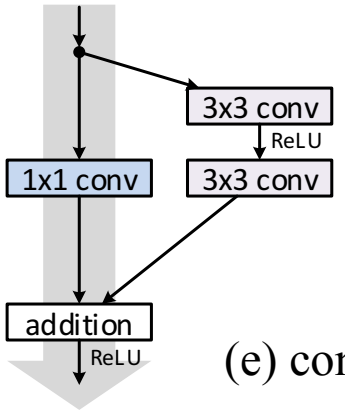
(d) shortcut-only gating

$h(x) = \text{gate} \cdot x$

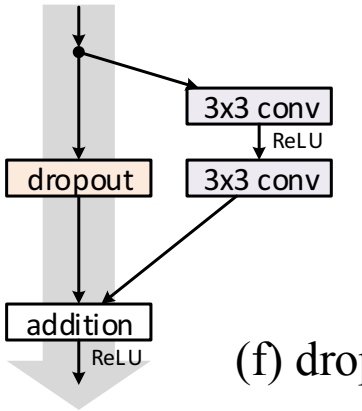
error: 12.9%

$h(x) = \text{conv}(x)$

error: 12.2%



(e) conv shortcut



(f) dropout shortcut

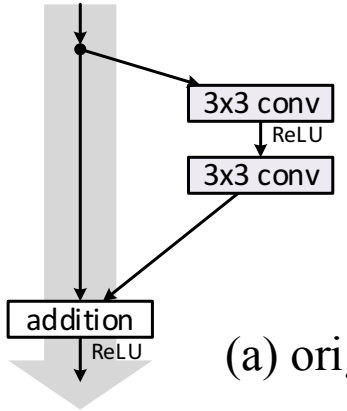
$h(x) = \text{dropout}(x)$

error: > 20%

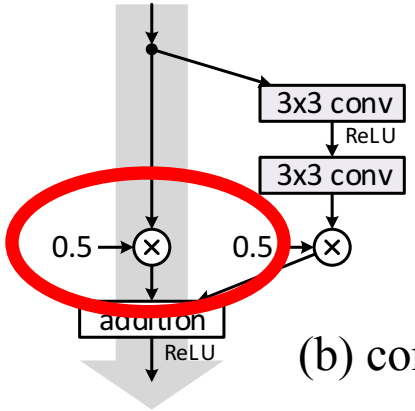
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

* ResNet-110 on CIFAR-10

$h(x) = x$
error: 6.6%



(a) original



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$h(x) = 0.5x$
error: 12.4%

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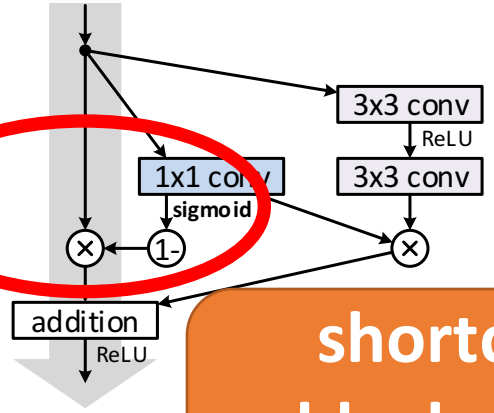
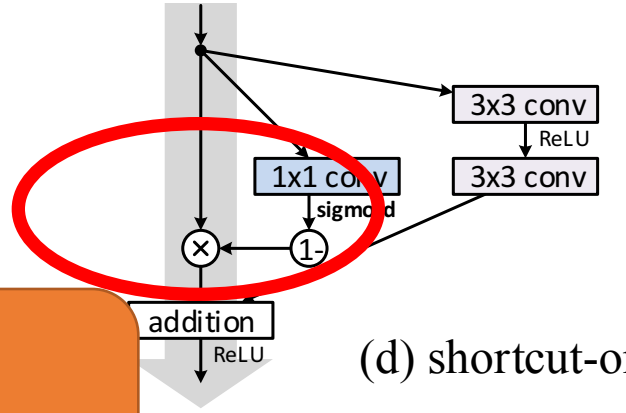
error: 8.7%



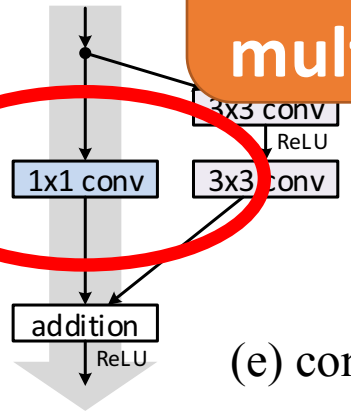


(d) shortcut-only gating

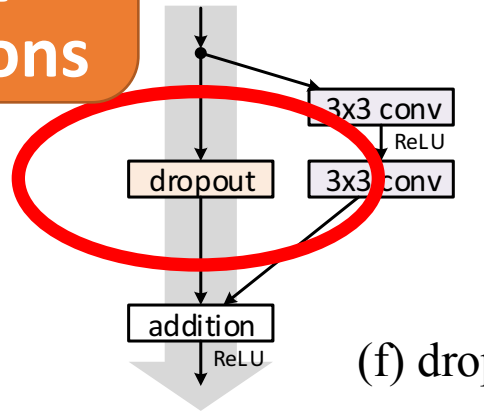
$h(x) = \text{gate} \cdot x$
error: 12.9%

shortcuts blocked by multiplications

$h(x) = \text{conv}(x)$
error: 12.2%



(e) conv shortcut



(f) dropout shortcut

$h(x) = \text{dropout}(x)$
error: > 20%

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

If h is multiplicative, e.g. $h(x) = \lambda x$

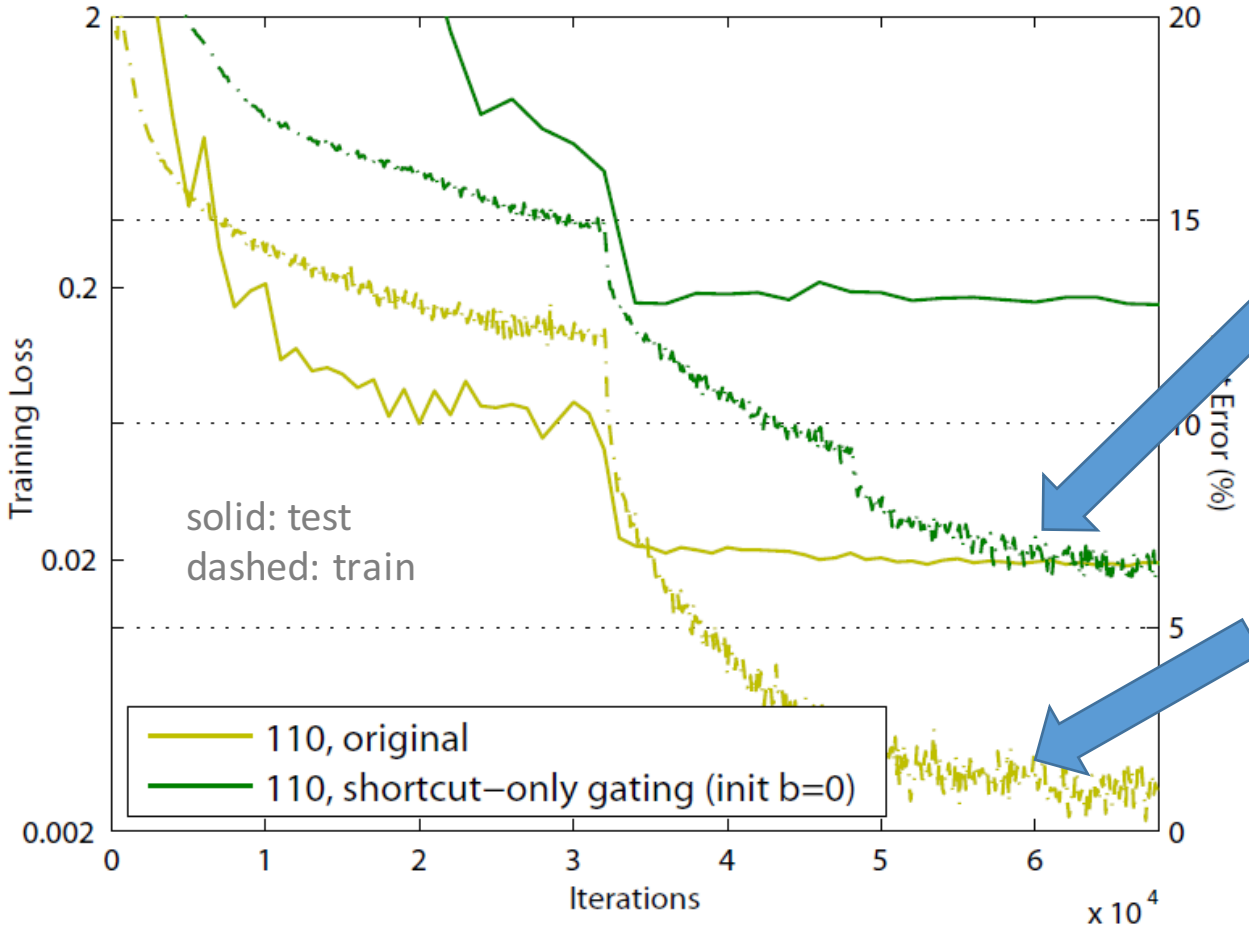
forward: $x_L = \lambda^{L-l} x_l + \sum_{i=l}^{L-1} \hat{F}(x_i)$

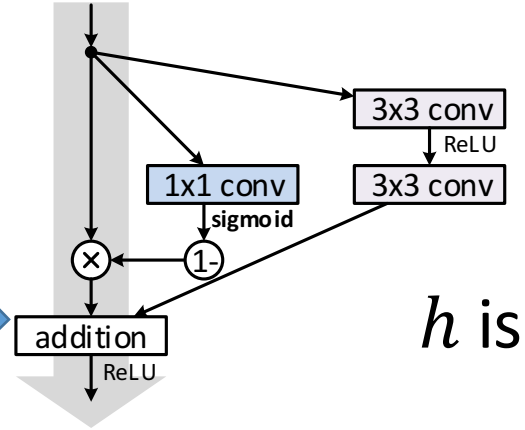
- if h is multiplicative, shortcuts are blocked
- direct propagation is decayed

backward: $\frac{\partial E}{\partial x_l} = \frac{\partial E}{\partial x_L}\left(\lambda^{L-l} + \frac{\partial}{\partial x_l} \sum_{i=1}^{L-1} \hat{F}(x_i)\right)$

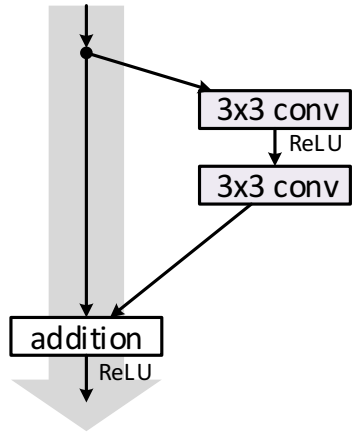
*assuming f = identity

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.





h is gating

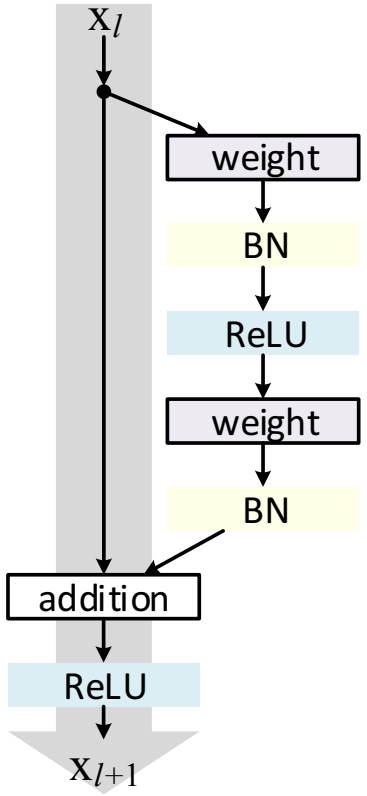


h is identity

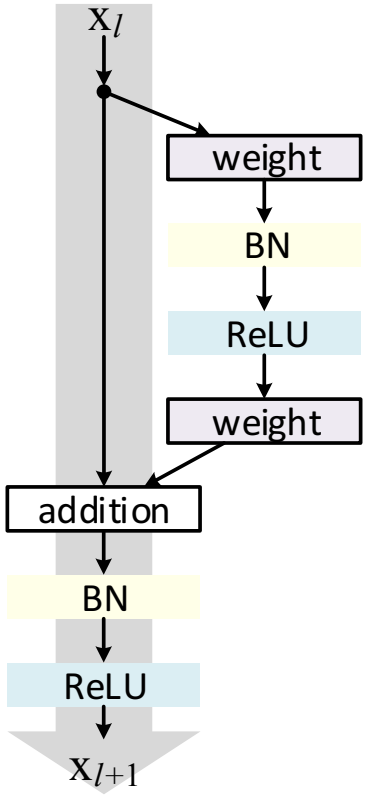
- gating should have better representation ability (identity is a special case), but
- optimization difficulty dominates results

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

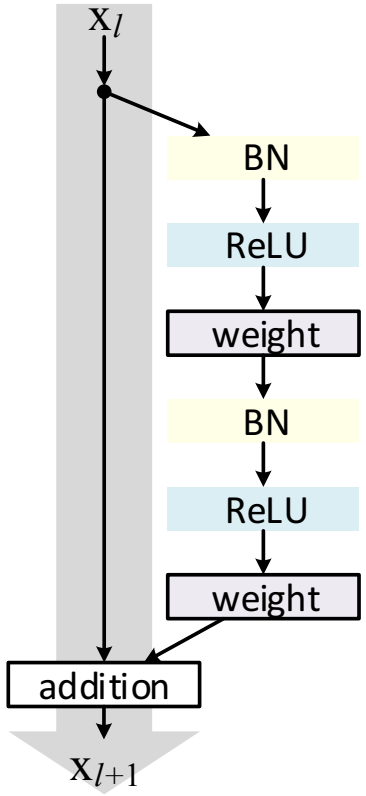
Experiment Set 2:
what if after-add mapping f is identity



f is ReLU
(original ResNet)

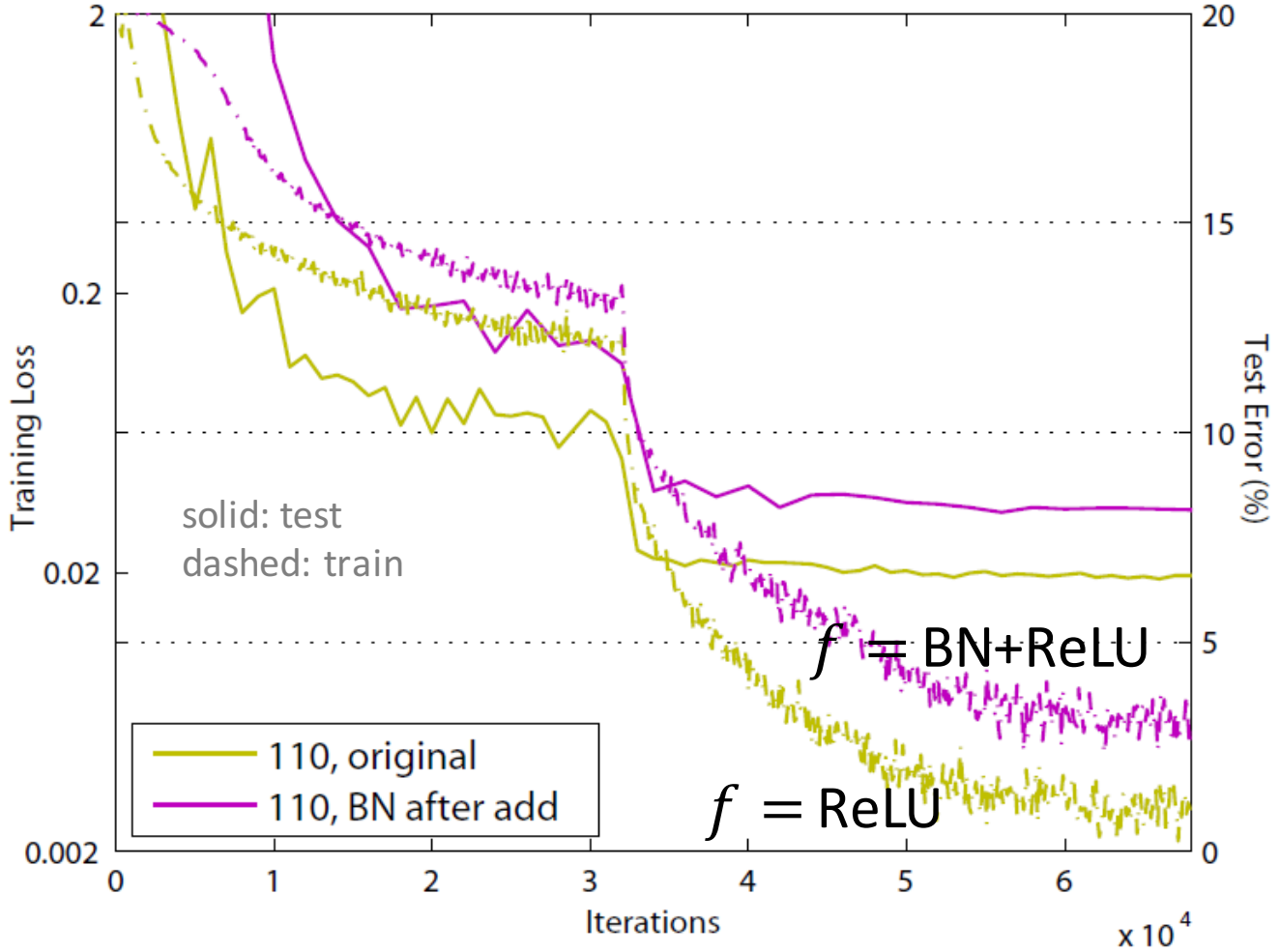


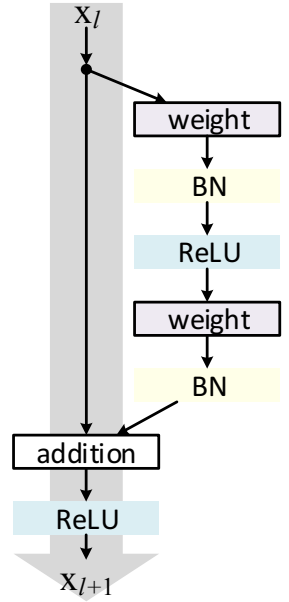
f is BN+ReLU

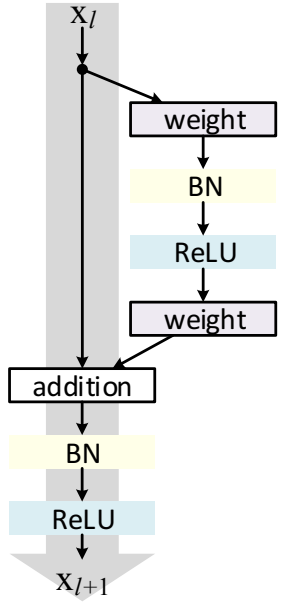


f is identity
(**pre-activation** ResNet)

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.





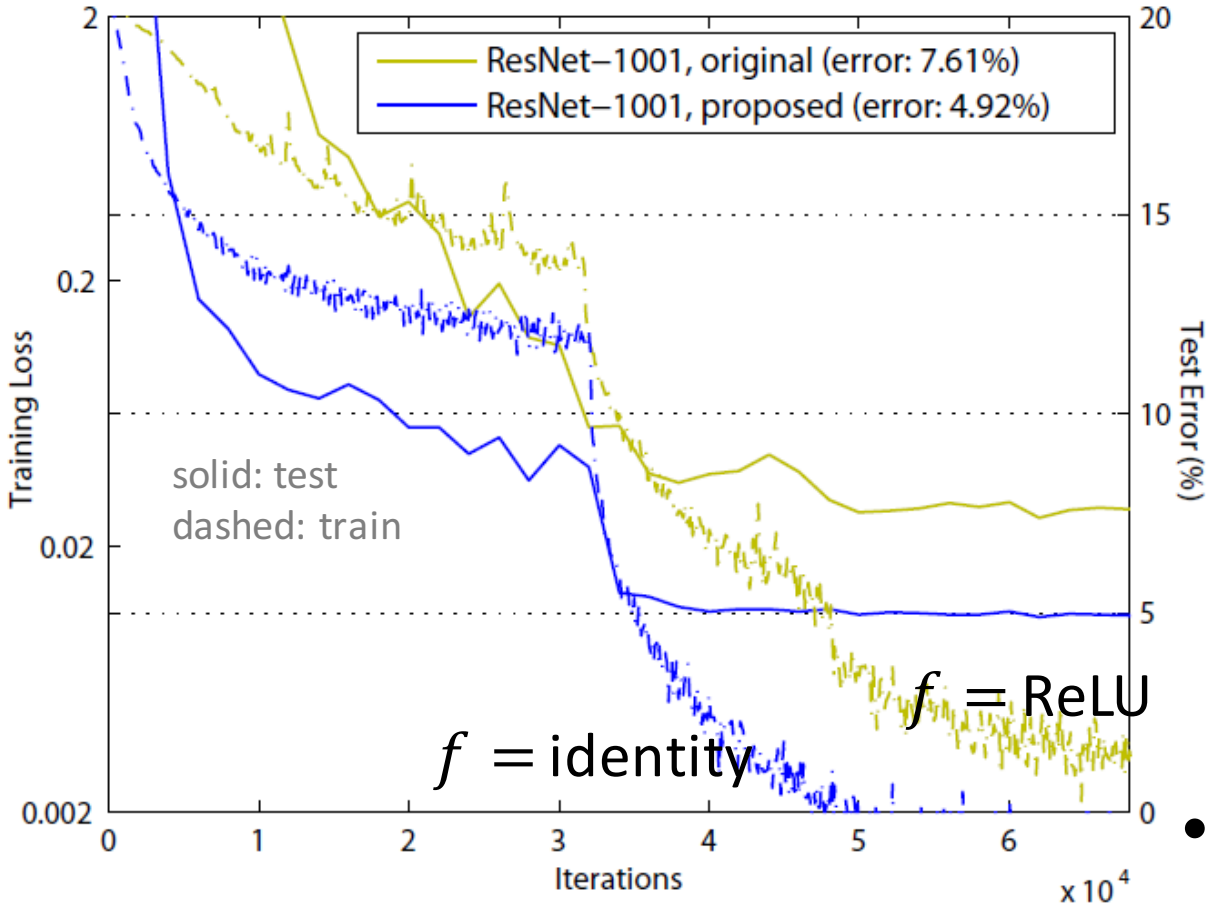


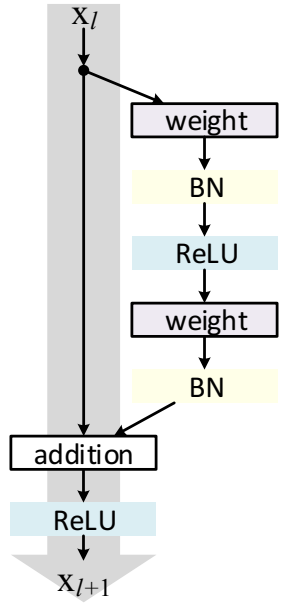
f = ReLU f = BN+ReLU

- BN could block prop
- Keep the shortest pass as smooth as possible

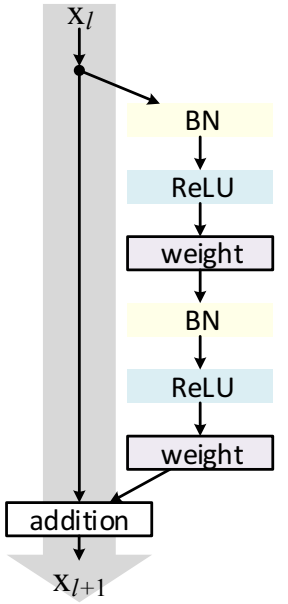
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

1001-layer ResNets on CIFAR-10





f = ReLU



f = identity

- ReLU could block prop when there are 1000 layers
- pre-activation design eases optimization (and improves generalization; see paper)

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Comparisons on CIFAR-10/100

CIFAR-10

method	error (%)
NIN	8.81
DSN	8.22
FitNet	8.39
Highway	7.72
ResNet-110 (1.7M)	6.61
ResNet-1202 (19.4M)	7.93
ResNet-164, pre-activation (1.7M)	5.46
ResNet-1001, pre-activation (10.2M)	**4.92** (4.89±0.14)

CIFAR-100

method	error (%)
NIN	35.68
DSN	34.57
FitNet	35.04
Highway	32.39
ResNet-164 (1.7M)	25.16
ResNet-1001 (10.2M)	27.82
ResNet-164, pre-activation (1.7M)	24.33
ResNet-1001, pre-activation (10.2M)	**22.71** (22.68±0.22)

*all based on moderate augmentation

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

ImageNet Experiments

ImageNet single-crop (320x320) val error

method	data augmentation	top-1 error (%)	top-5 error (%)
ResNet-152, original	scale	21.3	5.5
ResNet-152, pre-activation	scale	21.1	5.5
ResNet-200, original	scale	21.8	6.0
ResNet-200, pre-activation	scale	**20.7**	**5.3**
ResNet-200, pre-activation	scale + aspect ratio	**20.1***	**4.8***

*independently reproduced by:

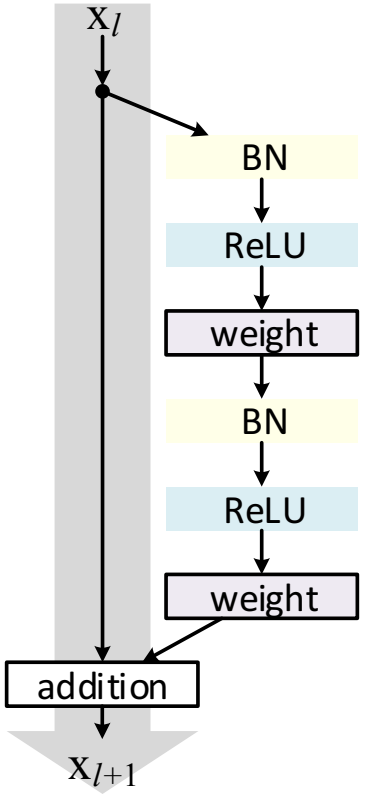
https://github.com/facebook/fb.resnet.torch/tree/master/pretrained#notes

training code and models available.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Summary of observations

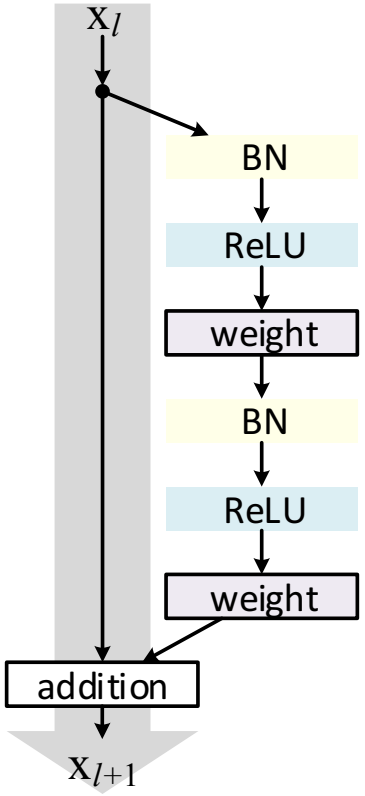
- Keep the shortest path as smooth as possible
  - by making h and f identity
  - forward/backward signals directly flow through this path
- Features of any layers are additive outcomes
- 1000-layer ResNets can be easily trained and have better accuracy



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Future Works

- **Representation**
  - skipping 1 layer vs. multiple layers?
  - Flat vs. Bottleneck?
  - Inception-ResNet [Szegedy et al 2016]
  - ResNet in ResNet [Targ et al 2016]
  - Width vs. Depth [Zagoruyko & Komodakis 2016]
- **Generalization**
  - DropOut, MaxOut, DropConnect, …
  - Drop Layer (Stochastic Depth) [Huang et al 2016]
- **Optimization**
  - Without residual/shortcut?



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.

Applications

“Features matter”

"Features matter." (quote [Girshick et al. 2014], the R-CNN paper)

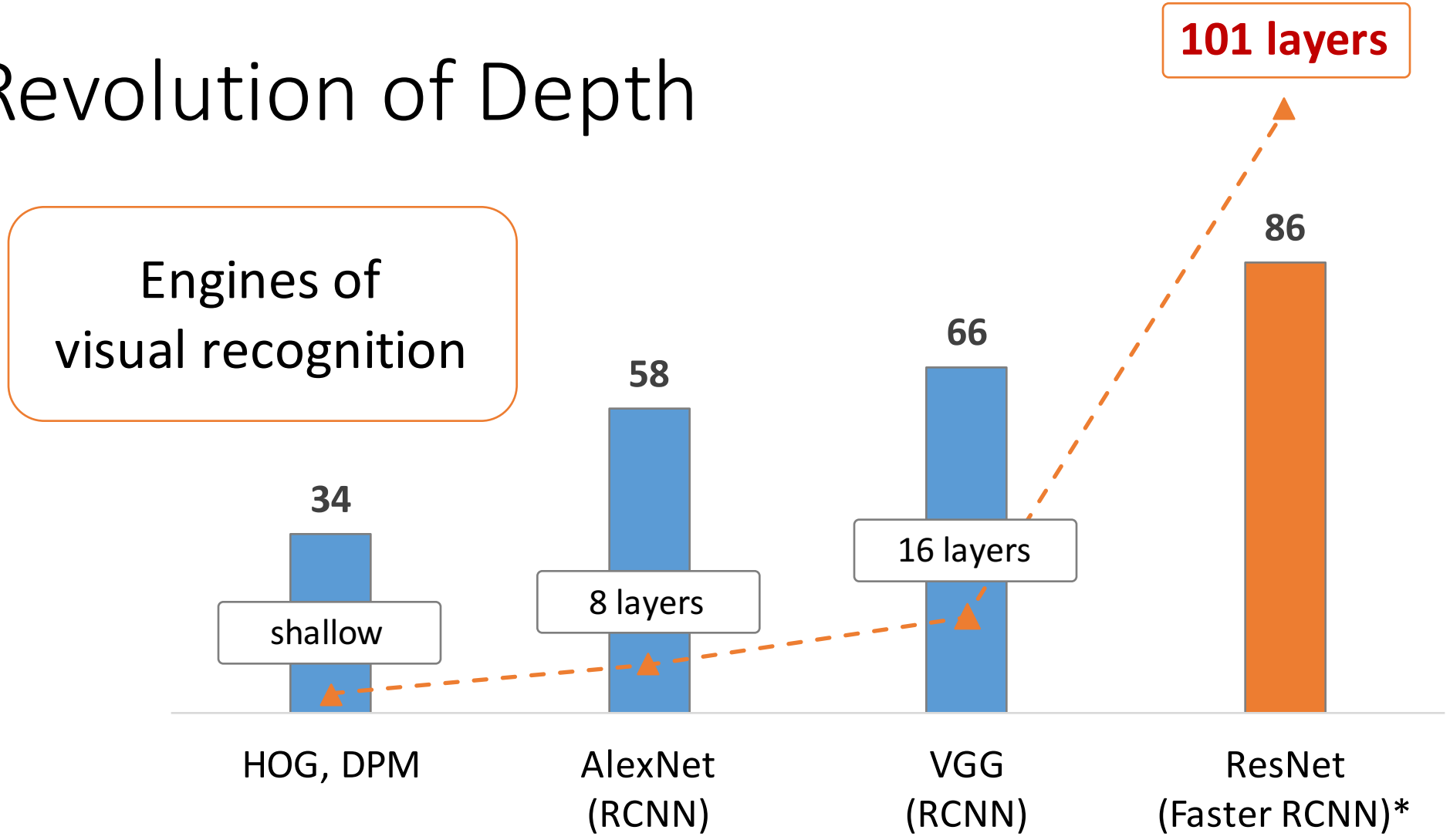
task	2nd-place winner	ResNets	margin (relative)
ImageNet Localization (top-5 error)	12.0	9.0	**27%**
ImageNet Detection (mAP@.5)	53.6	62.1	**16%**
COCO Detection (mAP@.5:.95)	33.5	37.3	**11%**
COCO Segmentation (mAP@.5:.95)	25.1	28.2	**12%**

absolute 8.5% better!

- Our results are all based on ResNet-101
- Deeper features are well transferrable

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Revolution of Depth

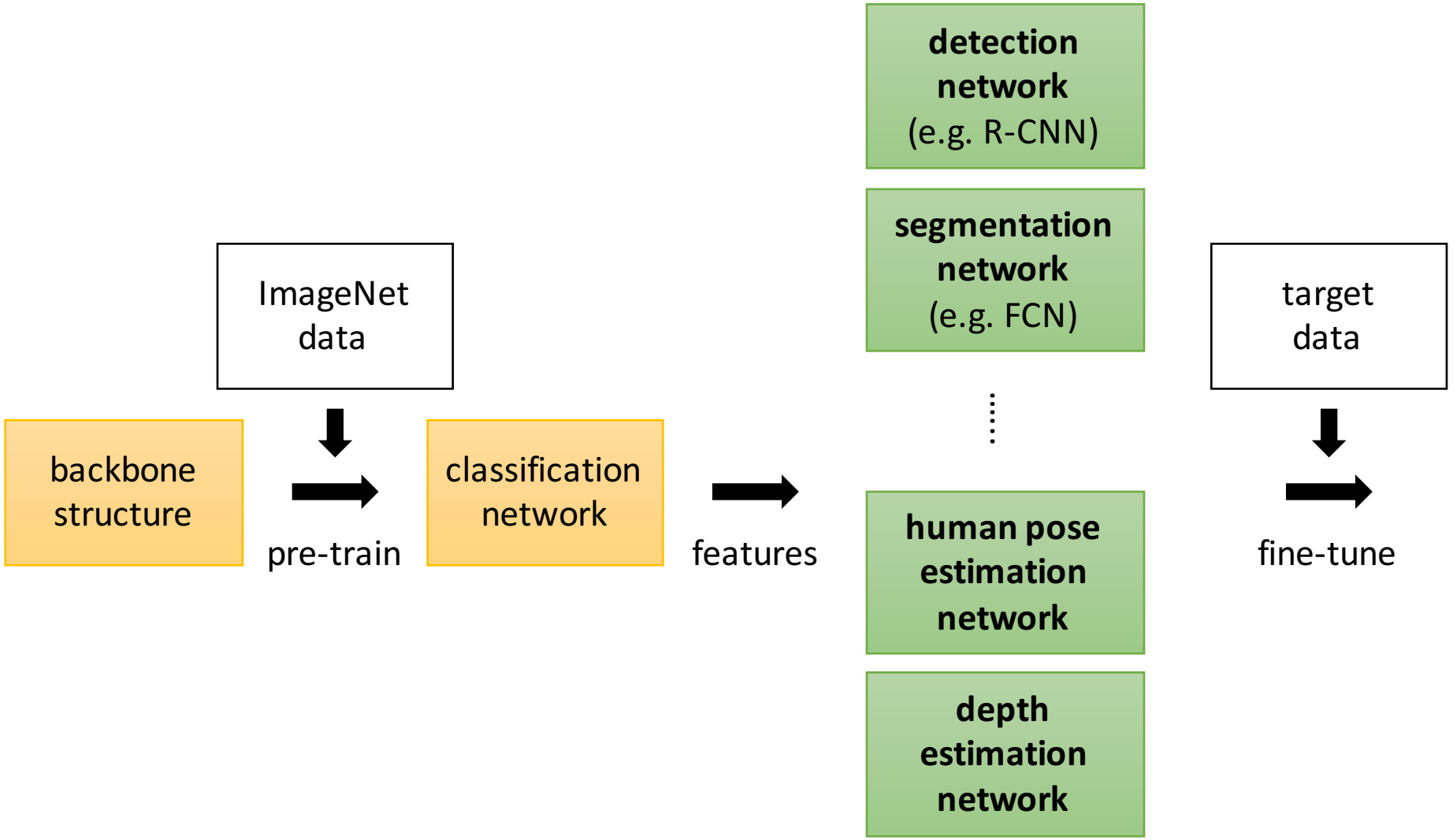


PASCAL VOC 2007 **Object Detection** mAP (%)

*w/ other improvements & more data

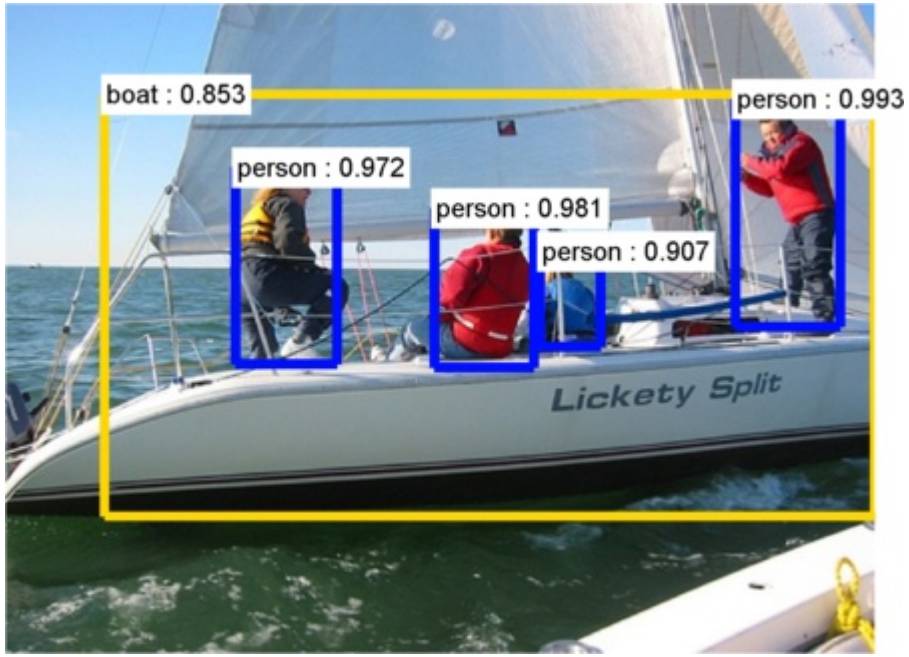
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.

Deep Learning for Computer Vision



Example: Object Detection

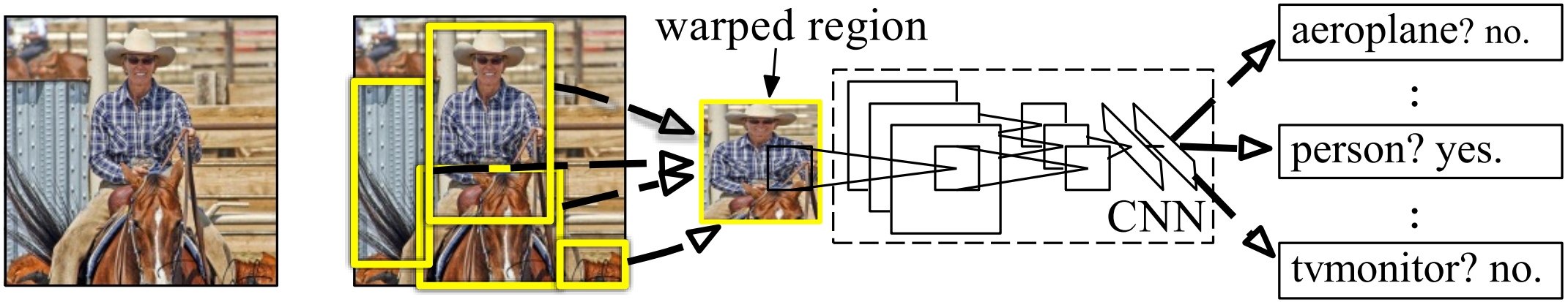
Image Classification
(what?)



Object Detection
(what + where?)

Object Detection: R-CNN

figure credit: R. Girshick et al.



input image

region proposals
~2,000

1 CNN for each region

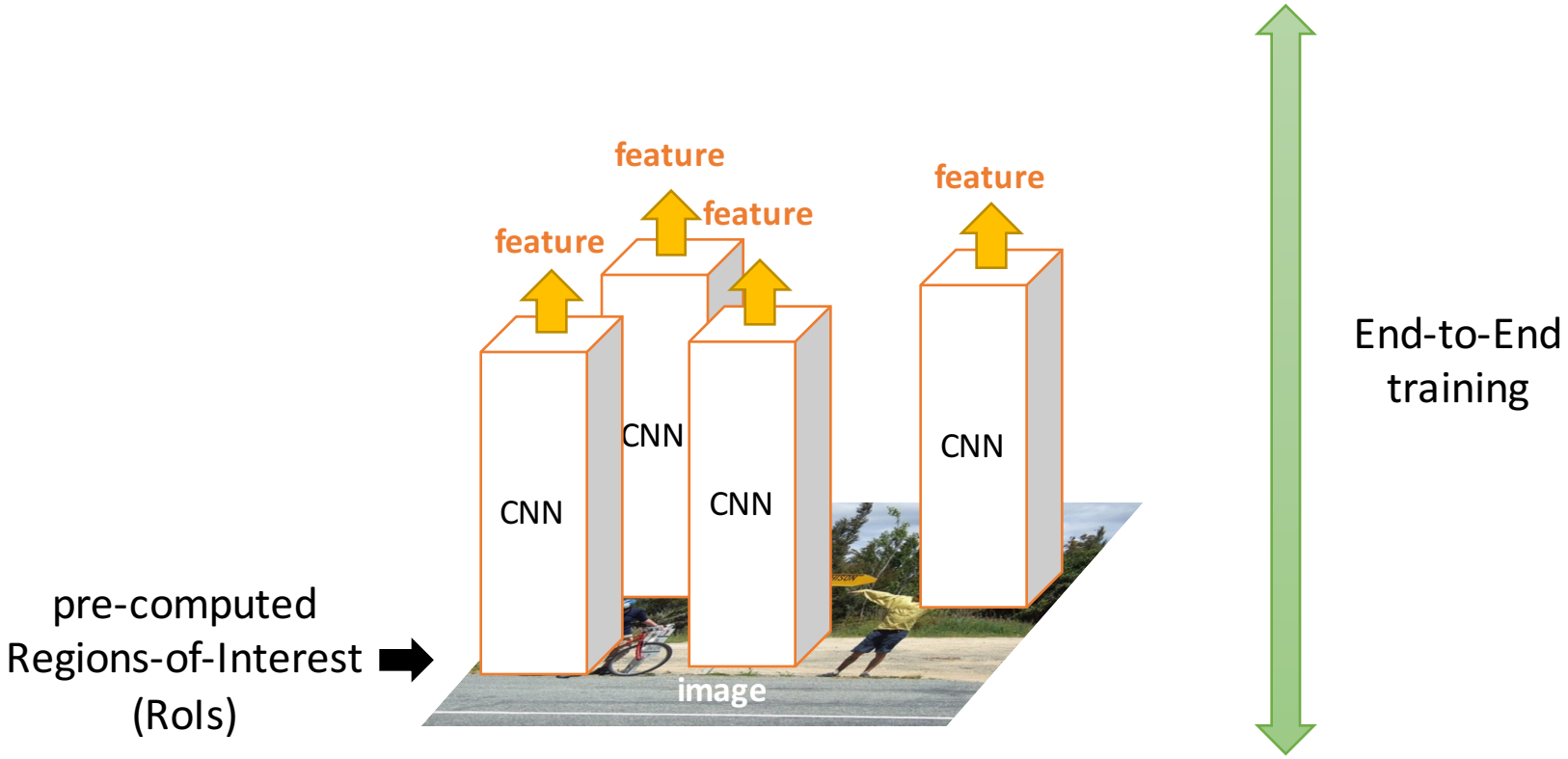
classify regions

Region-based **CNN** pipeline

Girshick, Donahue, Darrell, Malik. Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation. CVPR 2014

Object Detection: R-CNN

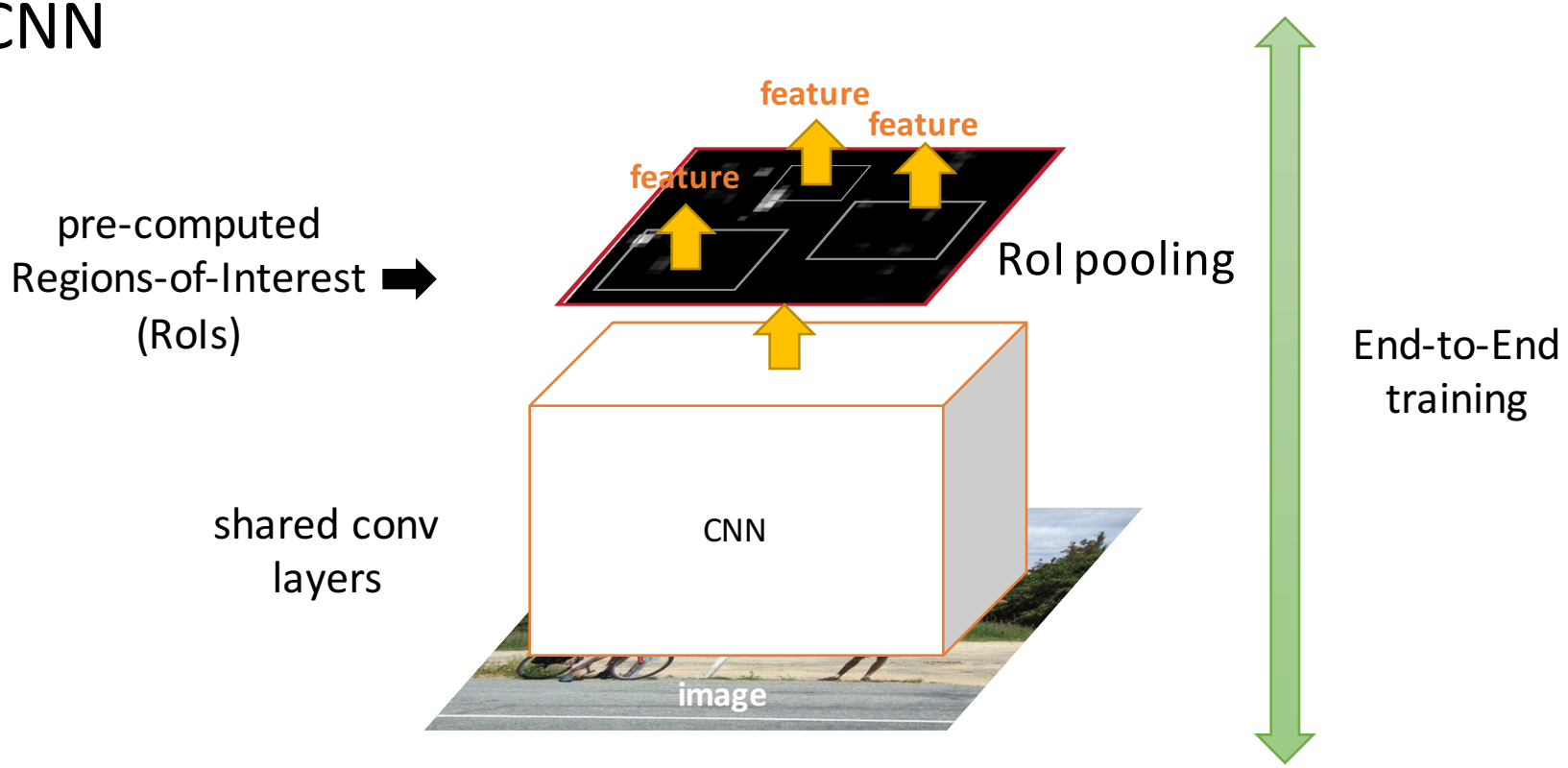
- R-CNN



Girshick, Donahue, Darrell, Malik. Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation. CVPR 2014

Object Detection: Fast R-CNN

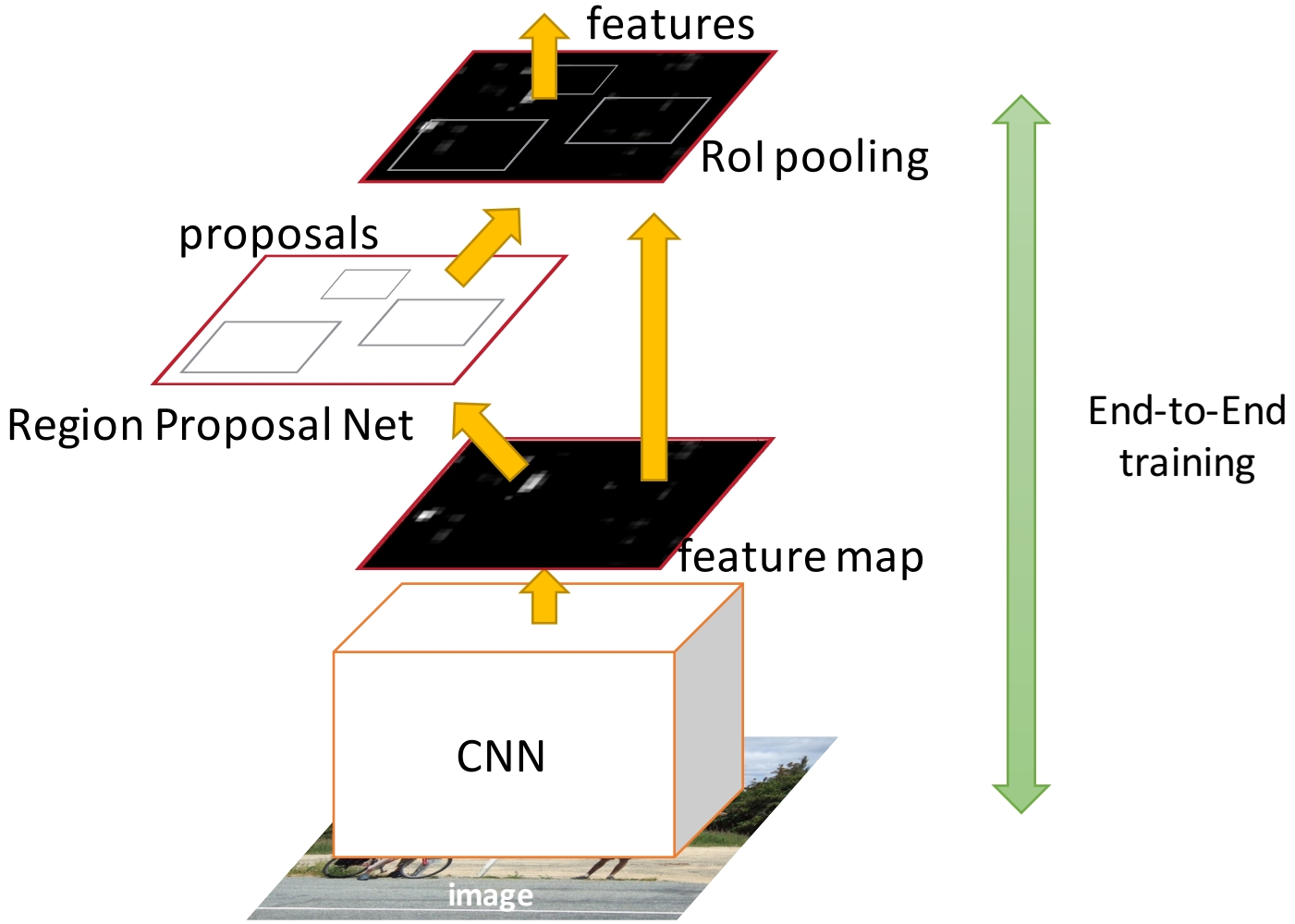
- Fast R-CNN



Girshick. Fast R-CNN. ICCV 2015

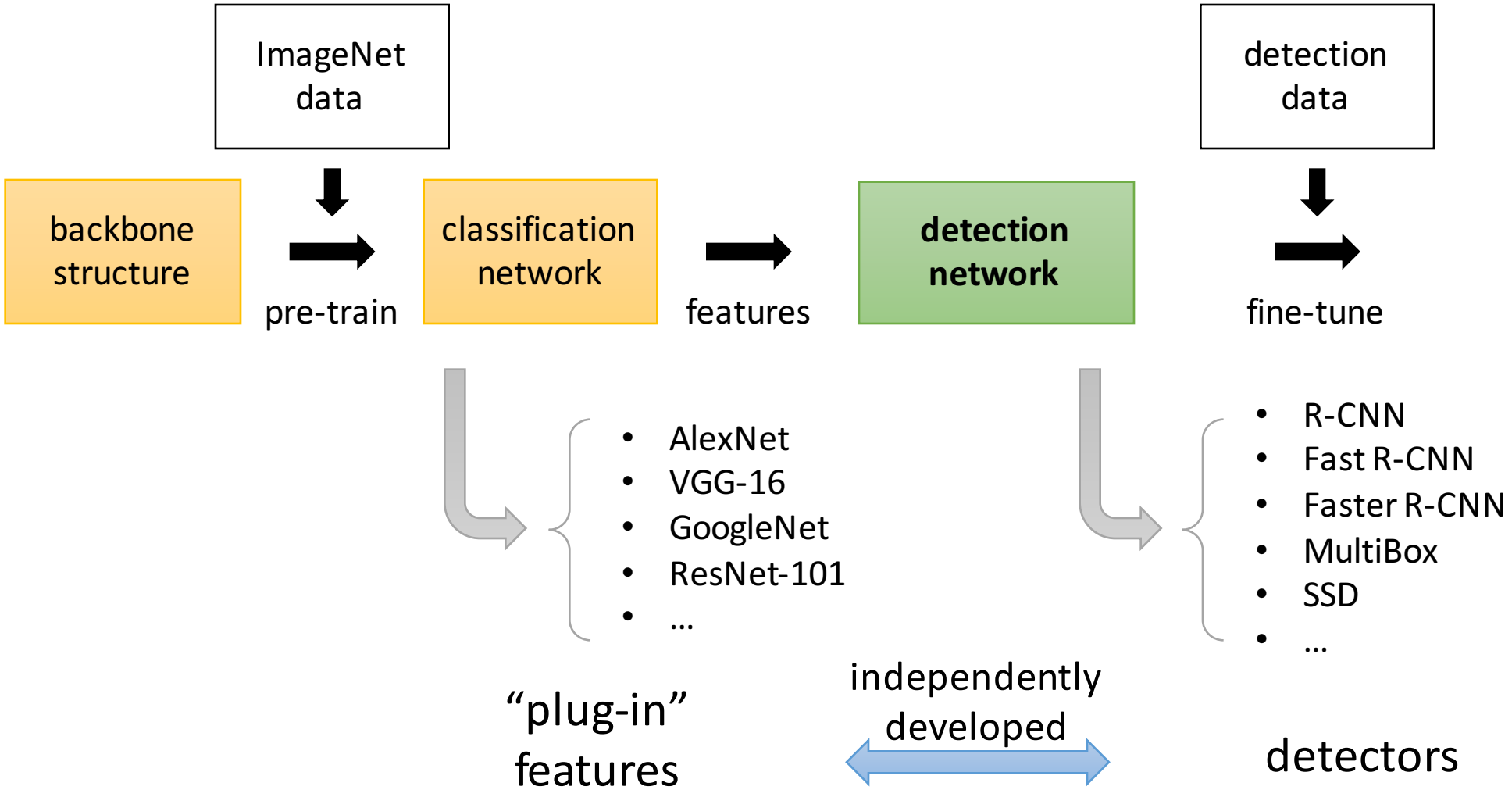
Object Detection: Faster R-CNN

- Faster R-CNN
  - Solely based on CNN
  - No external modules
  - Each step is end-to-end



Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks". NIPS 2015.

Object Detection



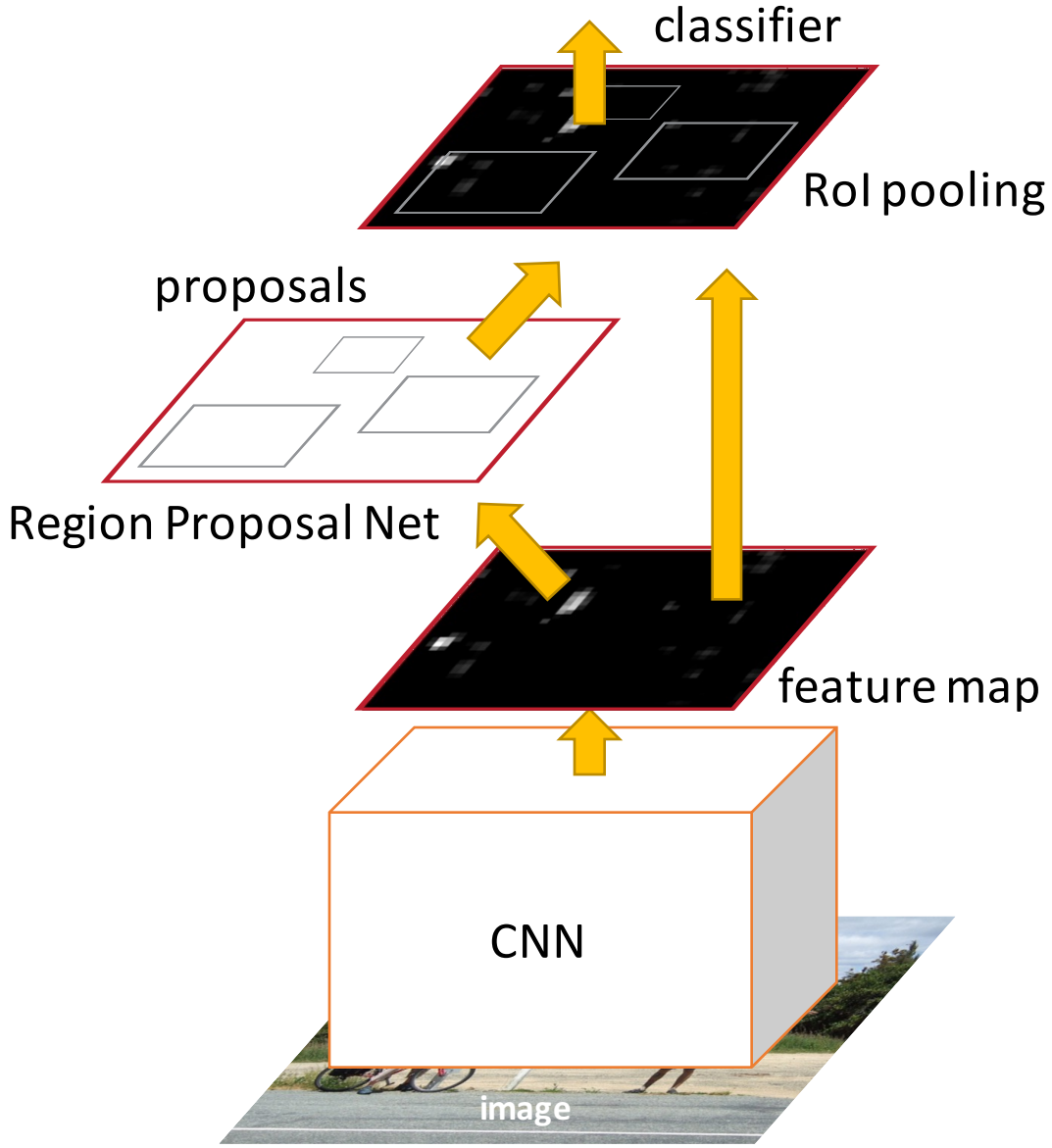
Object Detection

- Simply “Faster R-CNN + ResNet”

Faster R-CNN baseline	mAP@.5	mAP@.5:.95
VGG-16	41.5	21.5
ResNet-101	**48.4**	**27.2**

COCO detection results

ResNet-101 has 28% relative gain vs VGG-16

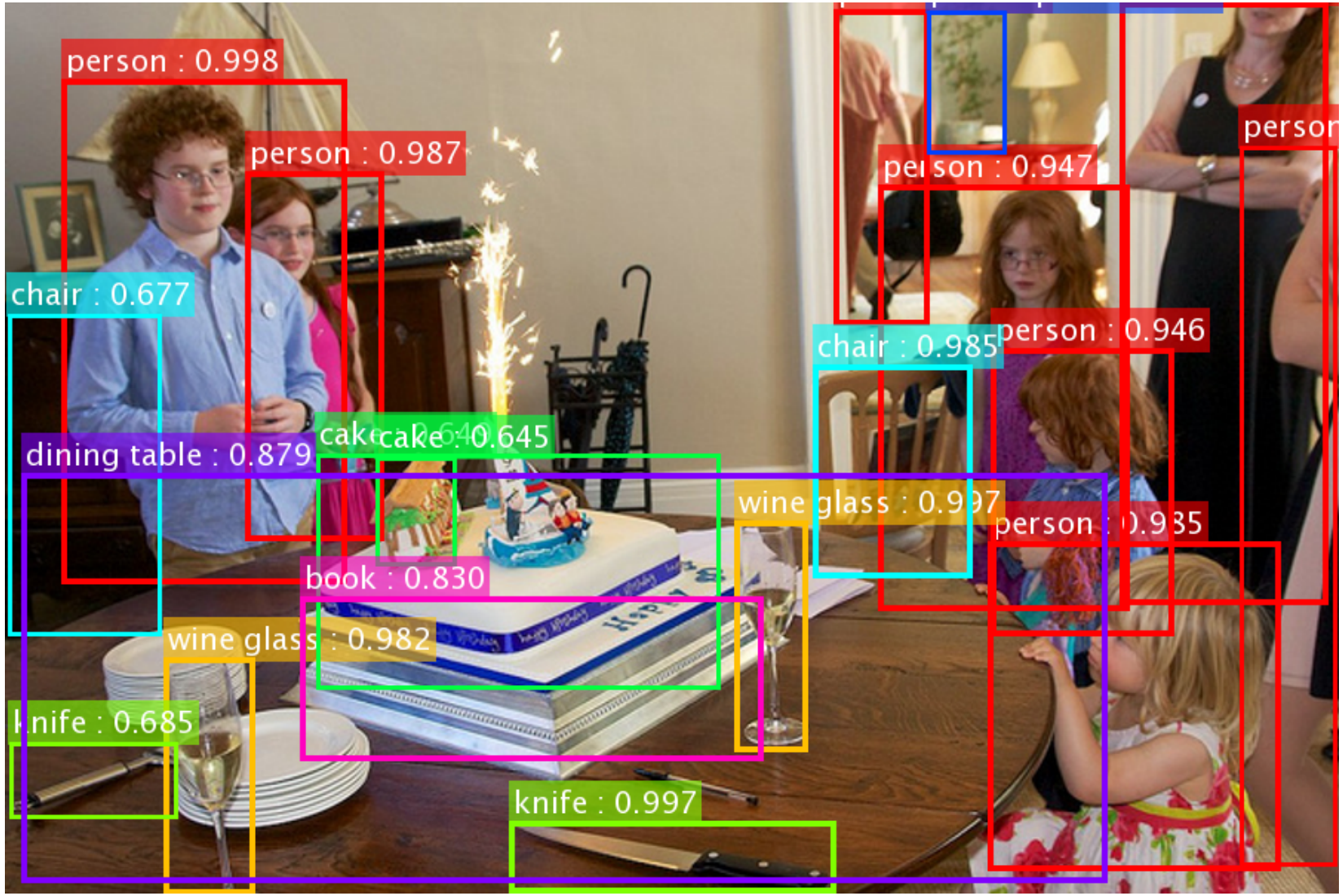


Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. CVPR 2016.
Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”. NIPS 2015.

Object Detection

- RPN learns proposals by extremely deep nets
  - We use only 300 proposals (no hand-designed proposals)
- Add components:
  - Iterative localization
  - Context modeling
  - Multi-scale testing
- All are based on CNN features; all are end-to-end
- All benefit more from deeper features – cumulative gains!

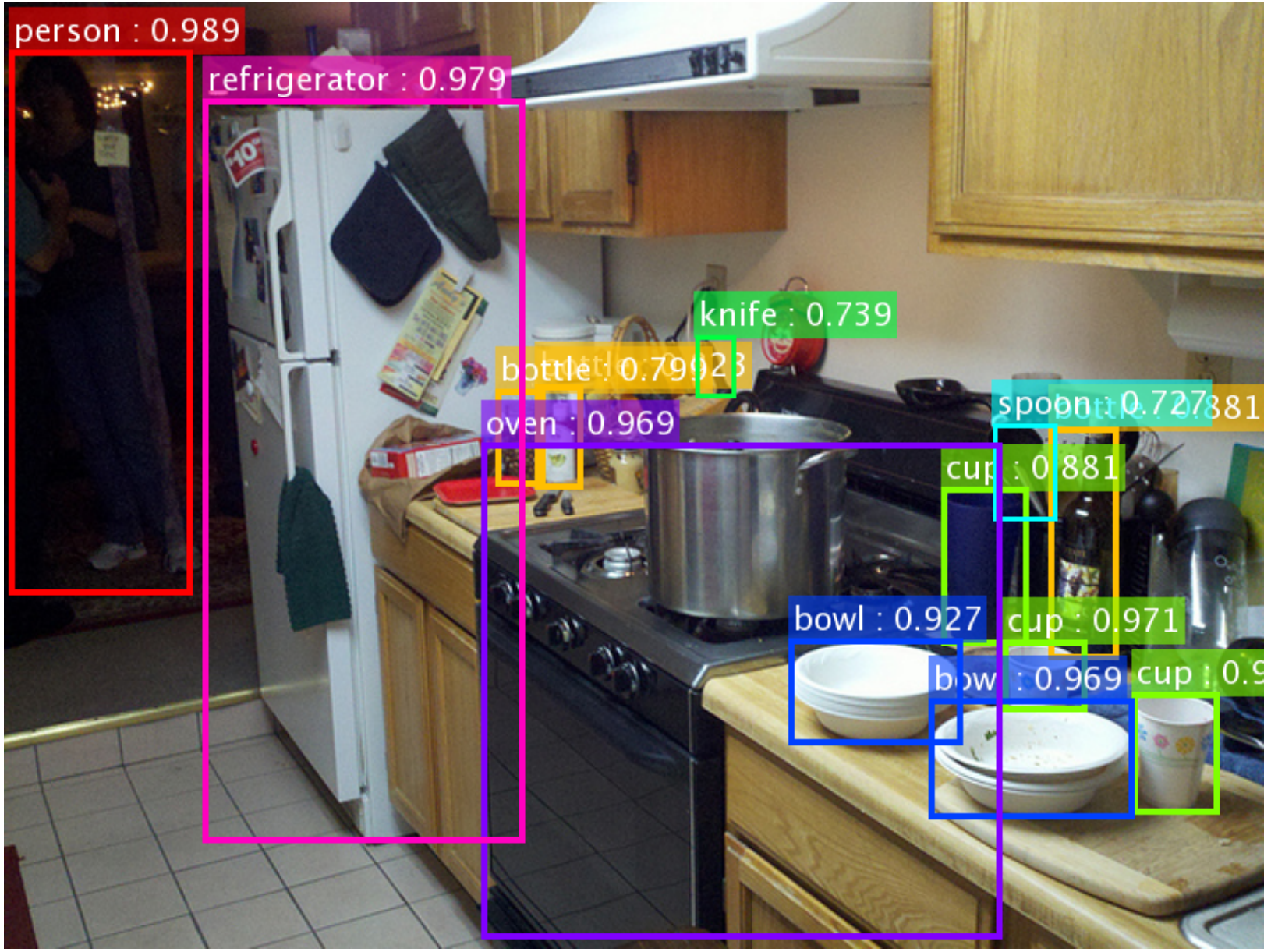
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.
Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks". NIPS 2015.



ResNet's object detection result on COCO

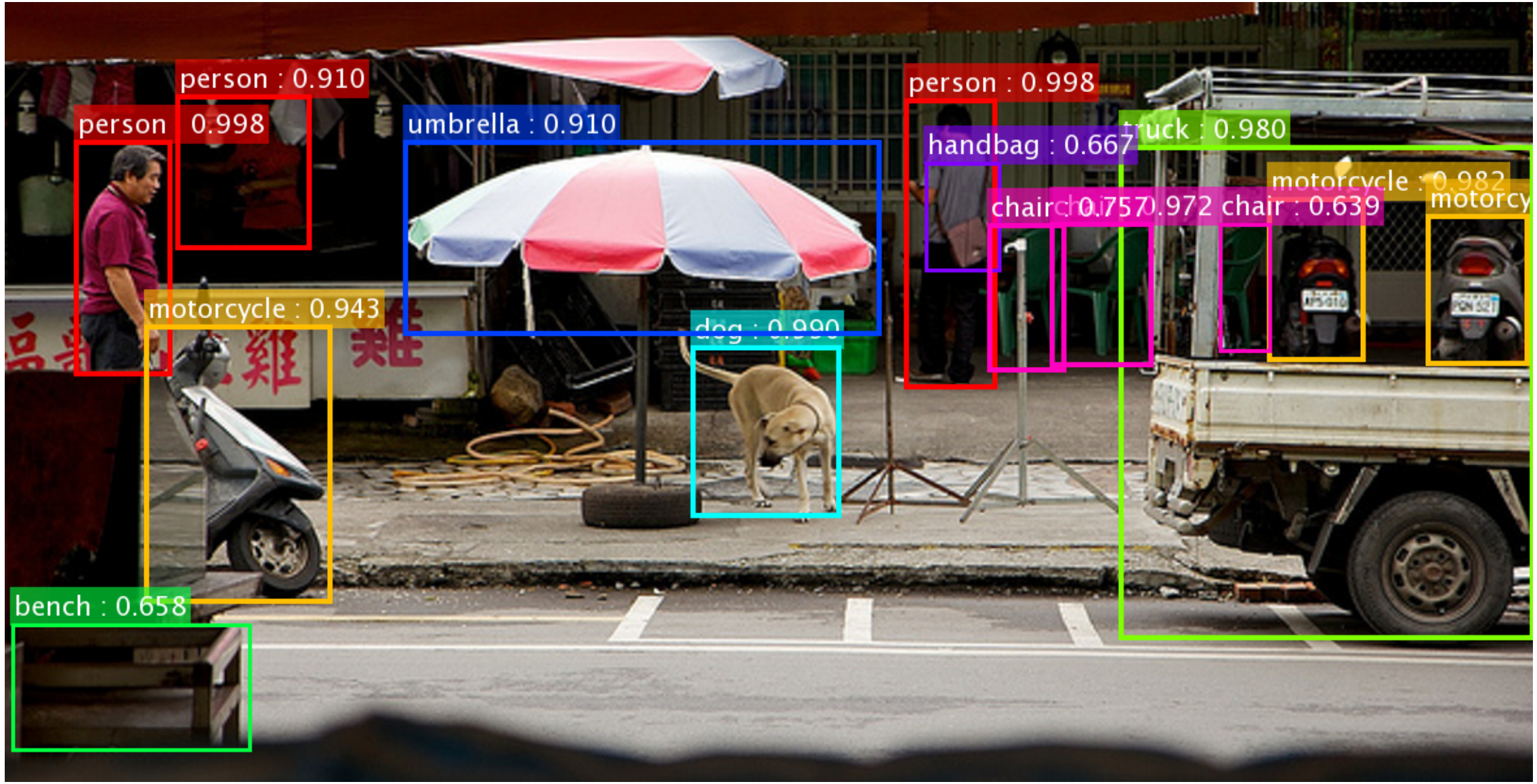
*the original image is from the COCO dataset

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.
Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks". NIPS 2015.



*the original image is from the COCO dataset

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. arXiv 2015.
Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”. NIPS 2015.



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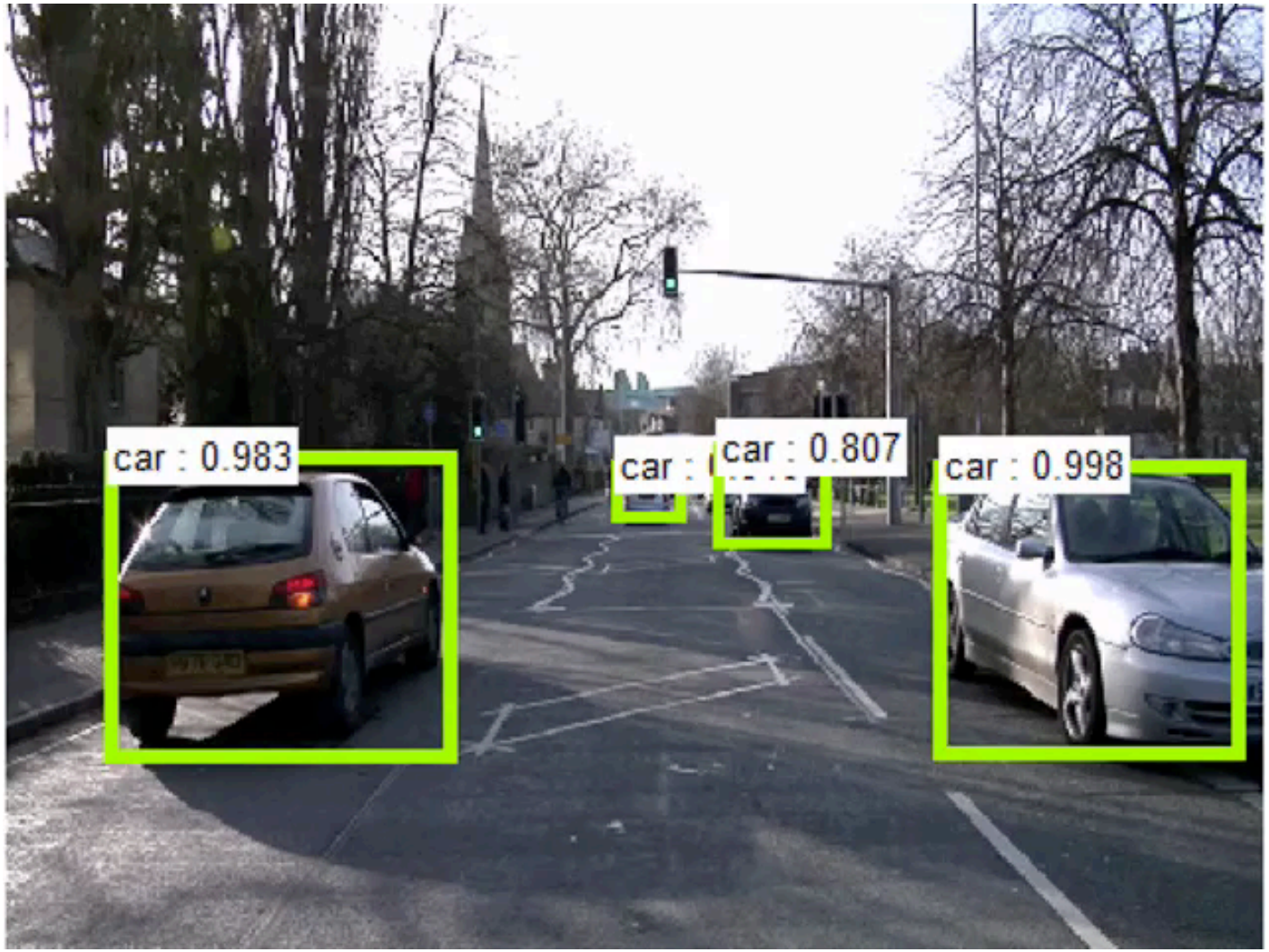


this video is available online: https://youtu.be/WZmSMkK9VuA

Results on real video. Models trained on MS COCO (80 categories).
(frame-by-frame; no temporal processing)

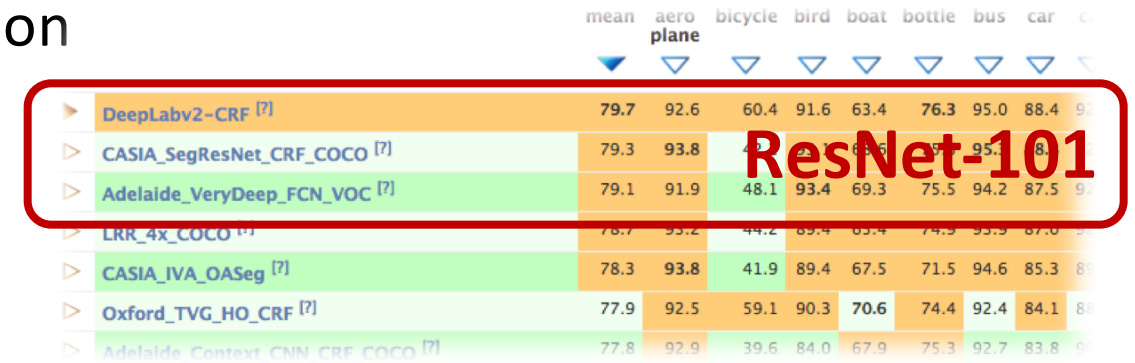
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.
Shaoqing Ren, Kaiming He, Ross Girshick, & Jian Sun. "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks". NIPS 2015.

More Visual Recognition Tasks

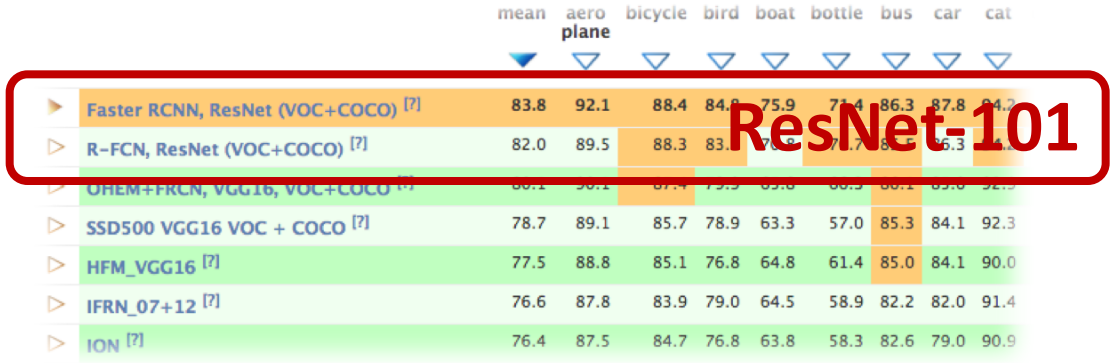
ResNet-based methods lead on these benchmarks (incomplete list):

- ImageNet classification, detection, localization
- MS COCO detection, segmentation
- PASCAL VOC detection, segmentation

- Human pose estimation [Newell et al 2016]
- Depth estimation [Laina et al 2016]
- Segment proposal [Pinheiro et al 2016]
- …

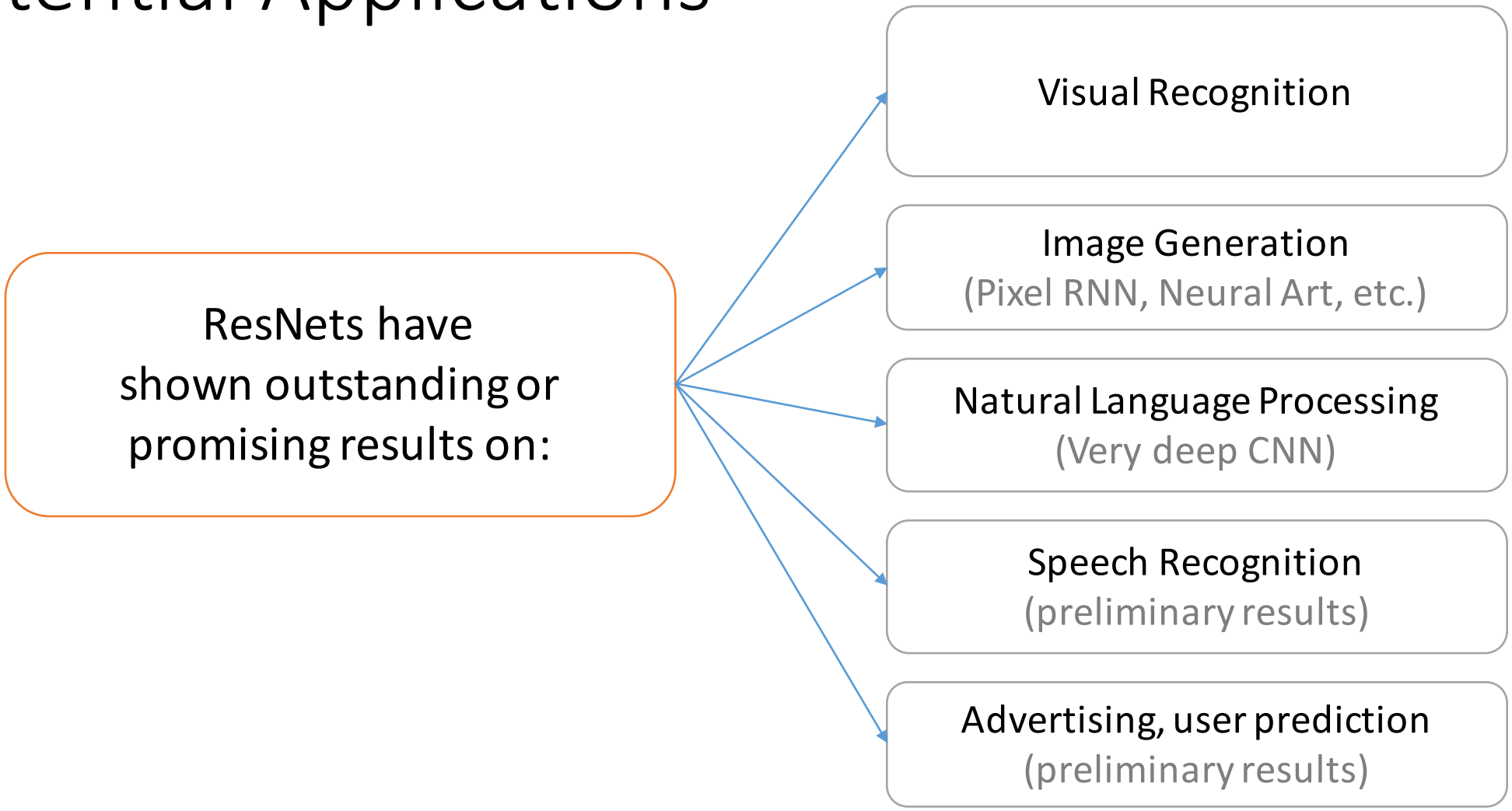


PASCAL **segmentation** leaderboard



PASCAL **detection** leaderboard

Potential Applications



Conclusions of the Tutorial

- Deep Residual Learning:
  - Ultra deep networks can be easy to train
  - Ultra deep networks can gain accuracy from depth
  - Ultra deep representations are well transferrable
  - Now 200 layers on ImageNet and 1000 layers on CIFAR!

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. CVPR 2016.
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Identity Mappings in Deep Residual Networks”. arXiv 2016.

Resources

- Models and Code
  - Our ImageNet models in Caffe: https://github.com/KaimingHe/deep-residual-networks

- Many available implementation
  (list in https://github.com/KaimingHe/deep-residual-networks)
  - Facebook AI Research's Torch ResNet: https://github.com/facebook/fb.resnet.torch
  - Torch, CIFAR-10, with ResNet-20 to ResNet-110, training code, and curves: code
  - Lasagne, CIFAR-10, with ResNet-32 and ResNet-56 and training code: code
  - Neon, CIFAR-10, with pre-trained ResNet-32 to ResNet-110 models, training code, and curves: code
  - Torch, MNIST, 100 layers: blog, code
  - A winning entry in Kaggle's right whale recognition challenge: blog, code
  - Neon, Place2 (mini), 40 layers: blog, code
  - .....

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". CVPR 2016.
Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Identity Mappings in Deep Residual Networks". arXiv 2016.