Lecture 8:

Efficiently Evaluating Deep Networks

Visual Computing Systems
Stanford CS348K, Fall 2018

Today

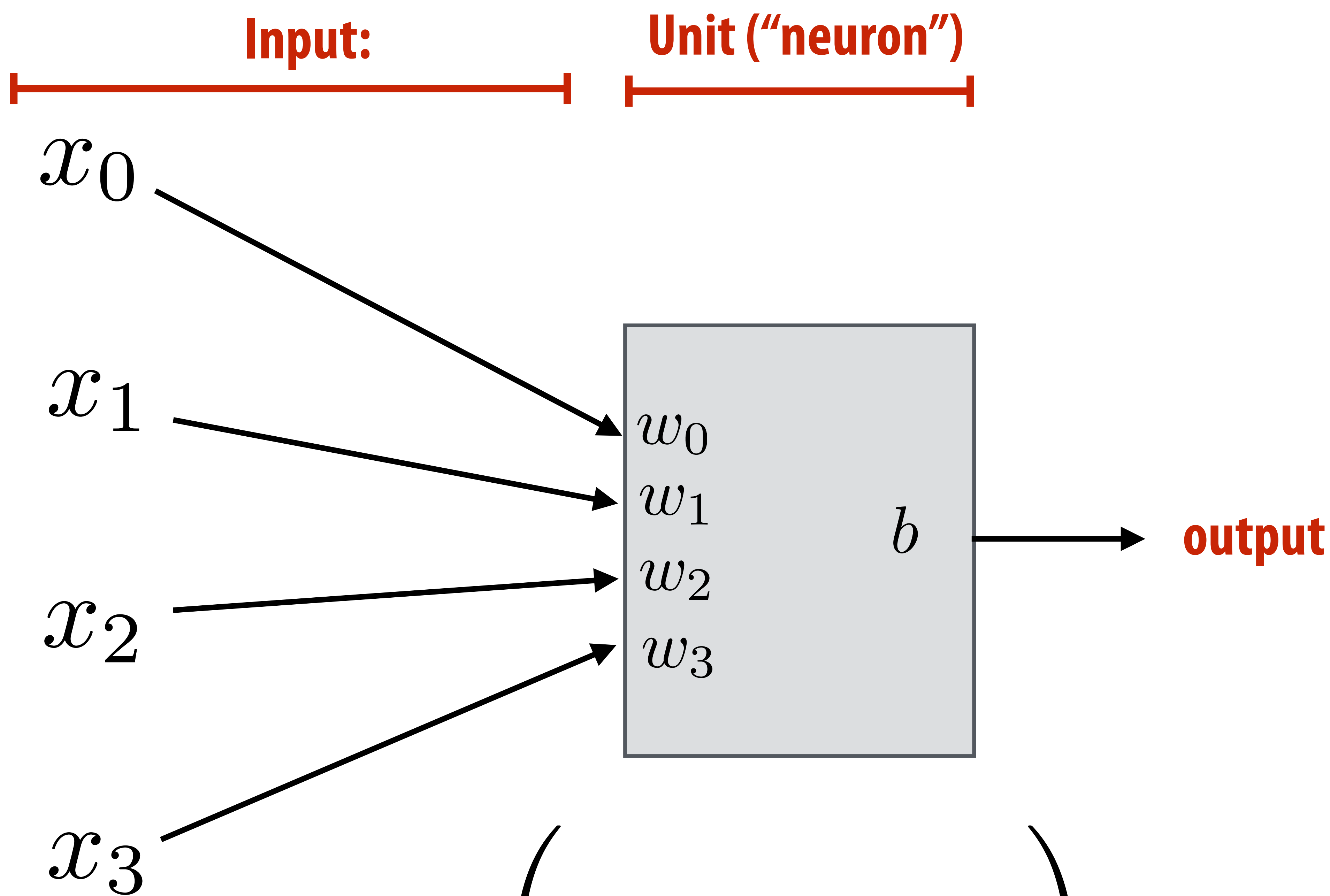
- We will discuss the workload created by need to evaluate deep neural networks (performing "inference") on image datasets

- We will focus on the parallelism challenges of training deep networks next time

What is a deep neural network?

A basic unit:

Unit with *n* inputs described by *n+1* parameters (weights + bias)



$$f\left(\sum_i x_i w_i + b\right)$$

Example: rectified linear unit (ReLU)

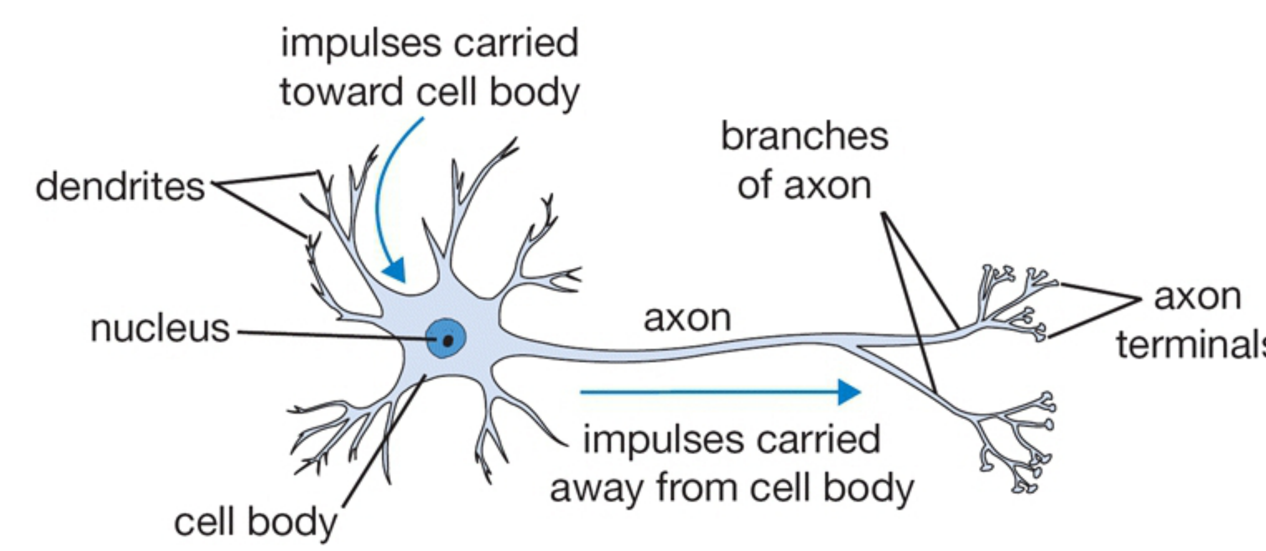
$$f(x) = max(0, x)$$

Basic computational interpretation:

It is just a circuit!

Biological inspiration:

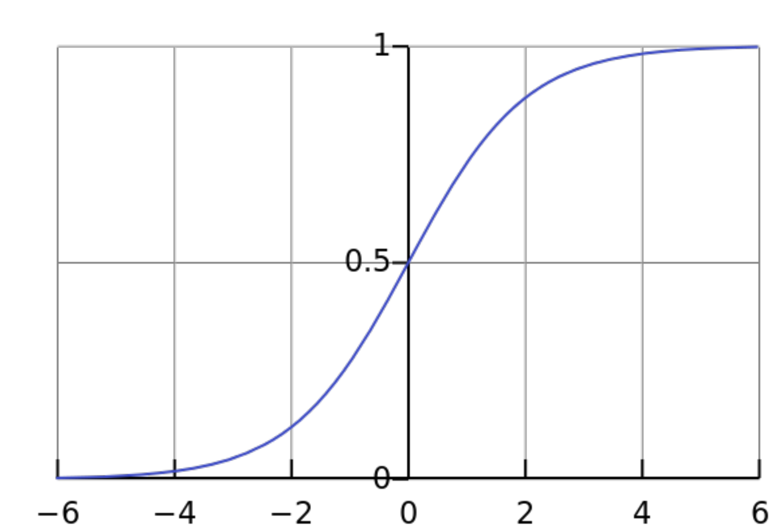
unit output corresponds loosely to activation of neuron



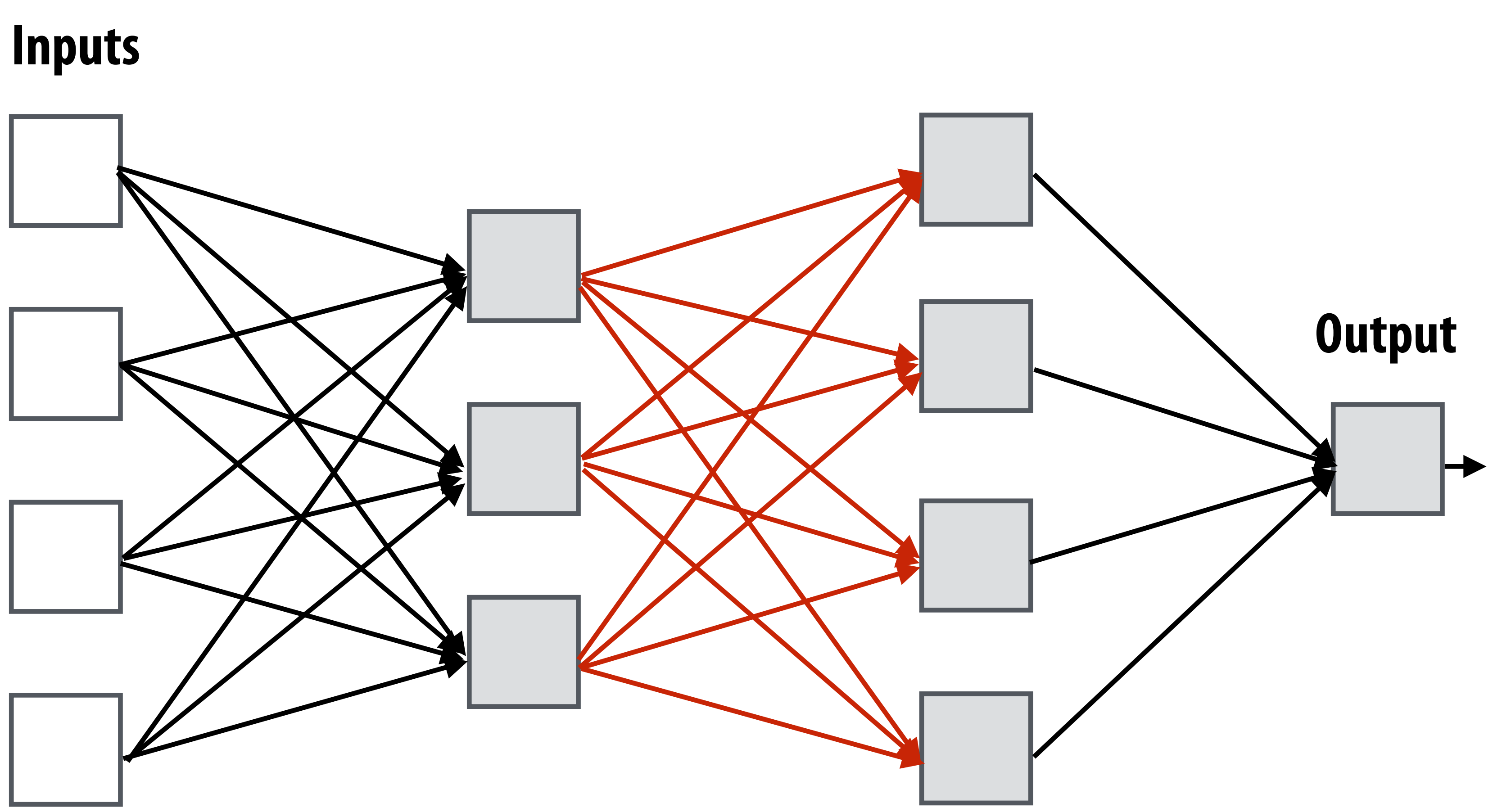
Machine learning interpretation:

binary classifier: interpret output as the probability of one class

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

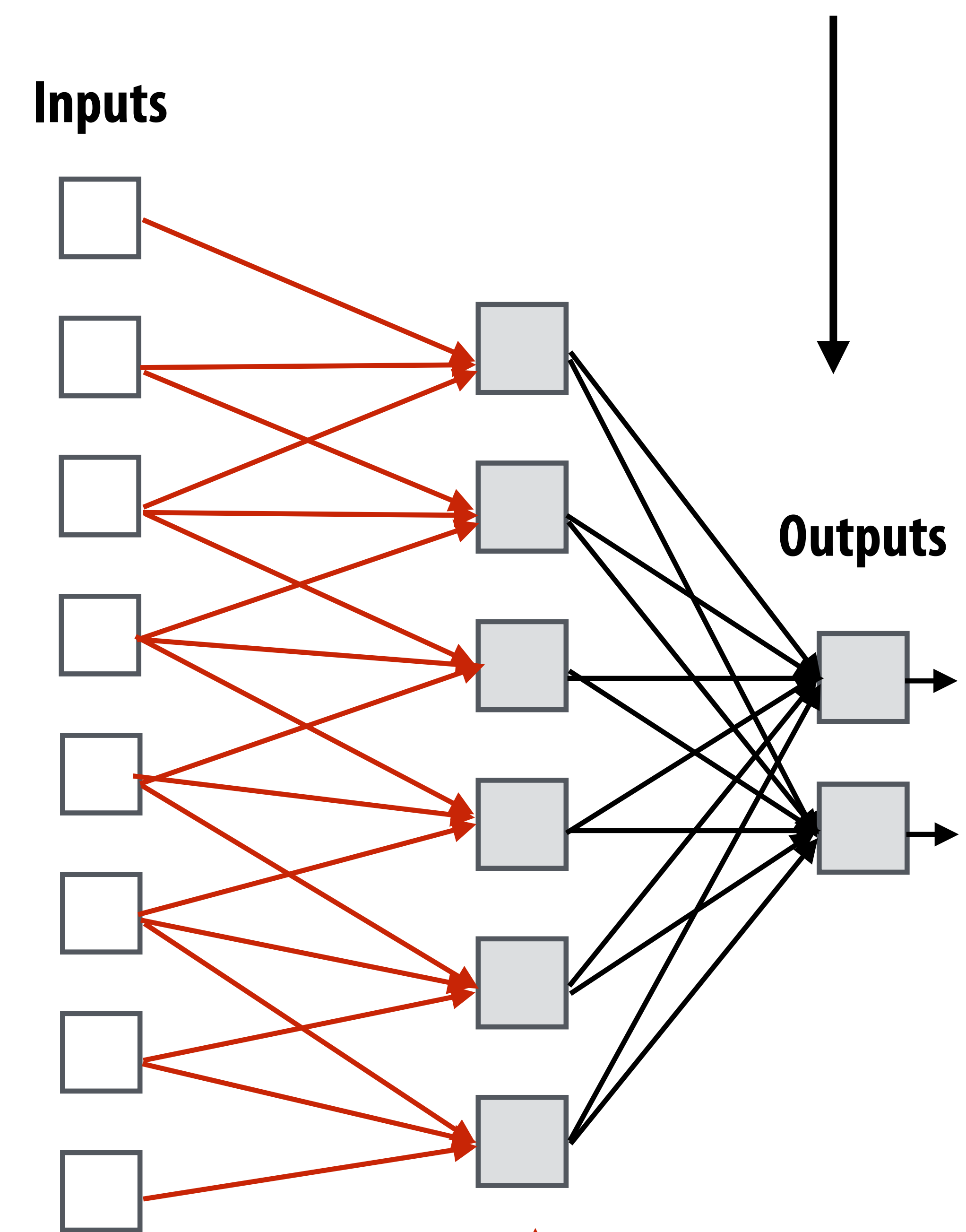


Deep neural network: topology



Fully
connected layer

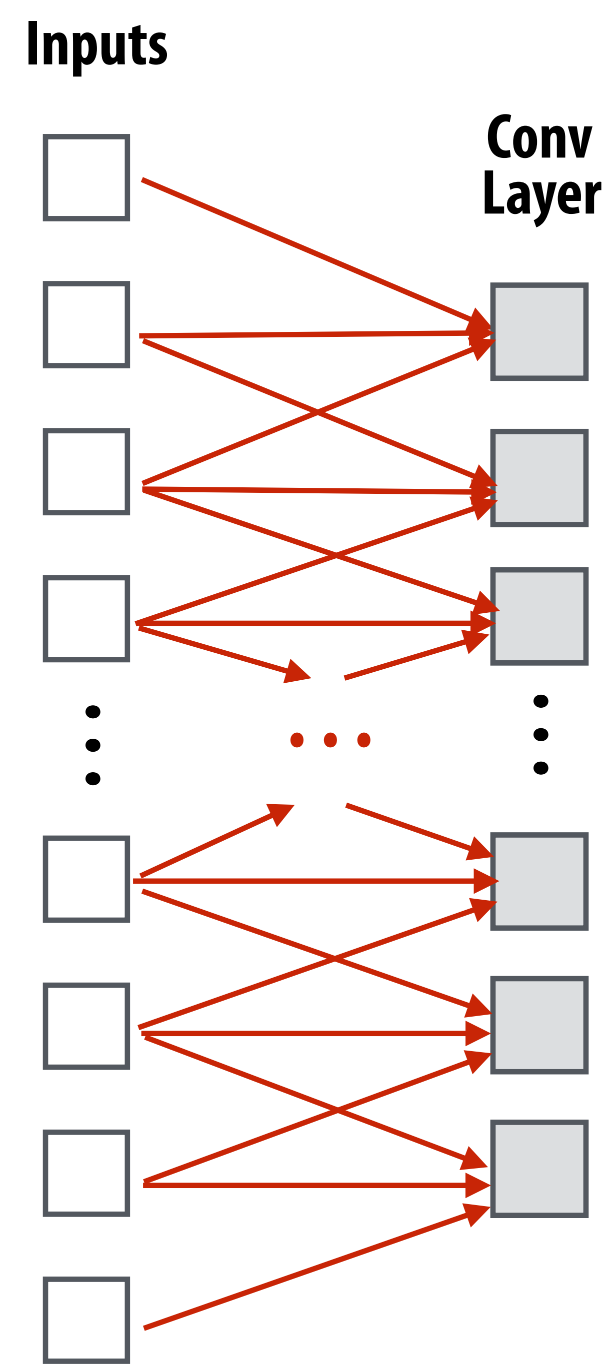
Fully connected layer

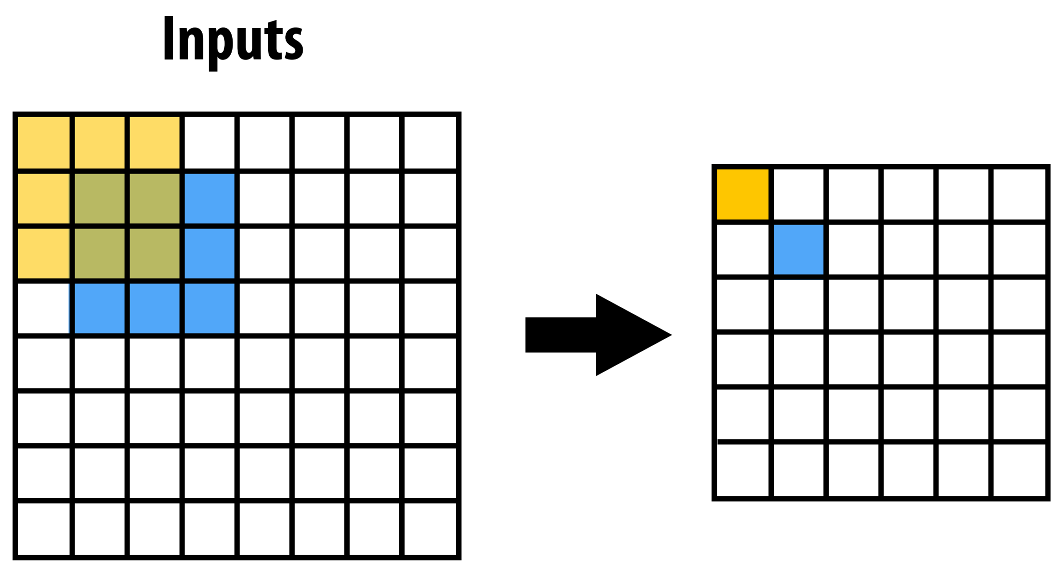


Sparsely (locally)
connected layer
(each unit only received inputs
from three input nodes)

Recall image convolution (3x3 conv)

```
int WIDTH = 1024;
int HEIGHT = 1024;
float input[(WIDTH+2) * (HEIGHT+2)];
float output[WIDTH * HEIGHT];


float weights[] = {1.0/9, 1.0/9, 1.0/9,
                   1.0/9, 1.0/9, 1.0/9,
                   1.0/9, 1.0/9, 1.0/9};


for (int j=0; j<HEIGHT; j++) {
  for (int i=0; i<WIDTH; i++) {
    float tmp = 0.f;
    for (int jj=0; jj<3; jj++)
      for (int ii=0; ii<3; ii++)
        tmp += input[(j+jj)*(WIDTH+2) + (i+ii)] * weights[jj*3 + ii];
    output[j*WIDTH + i] = tmp;
  }
}
```



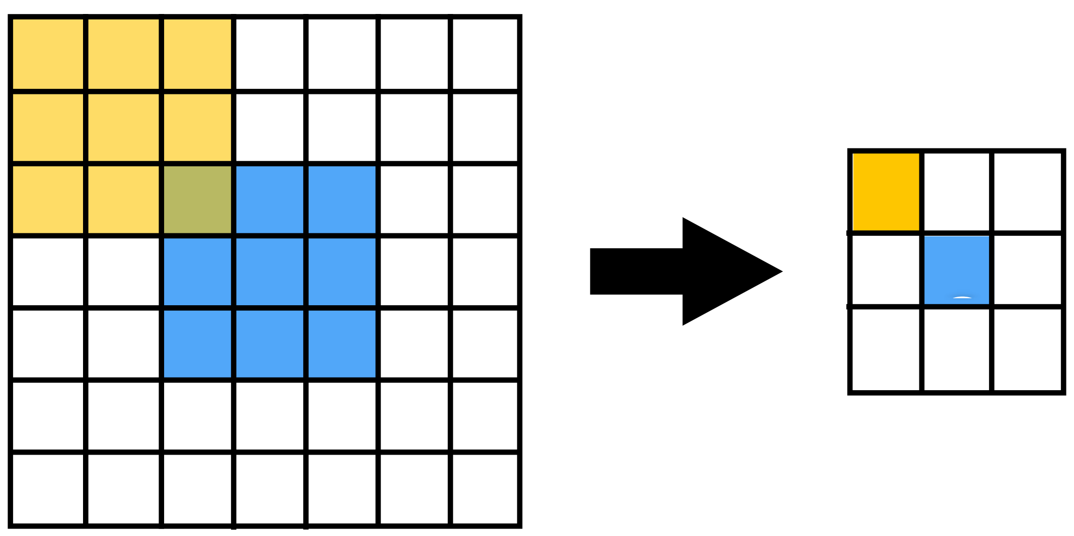


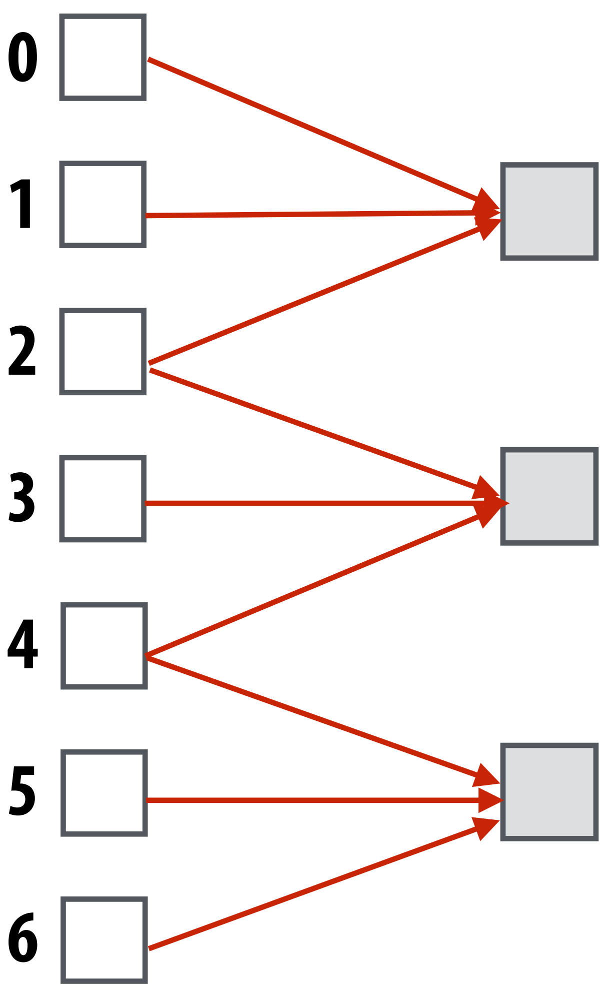
Convolutional layer: locally connected AND all units in layer share the same parameters (same weights + same bias):

(note: network illustration above only shows links for a 1D conv: a.k.a. one iteration of `ii` loop)

Strided 3x3 convolution

```
int WIDTH = 1024;
int HEIGHT = 1024;
int STRIDE = 2;
float input[(WIDTH+2) * (HEIGHT+2)];
float output[(WIDTH/STRIDE) * (HEIGHT/STRIDE)];



float weights[] = {1.0/9, 1.0/9, 1.0/9,
                   1.0/9, 1.0/9, 1.0/9,
                   1.0/9, 1.0/9, 1.0/9};


for (int j=0; j<HEIGHT; j+=STRIDE) {
  for (int i=0; i<WIDTH; i+=STRIDE) {
    float tmp = 0.f;
    for (int jj=0; jj<3; jj++)
      for (int ii=0; ii<3; ii++) {
         tmp += input[(j+jj)*(WIDTH+2) + (i+ii)] * weights[jj*3 + ii];
      output[(j/STRIDE)*WIDTH + (i/STRIDE)] = tmp;
  }
}
```





Convolutional layer with stride 2
(0,1,2) , (2,3,4) , (4,5,6) , …

Recall: what does convolution with these filters do?

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

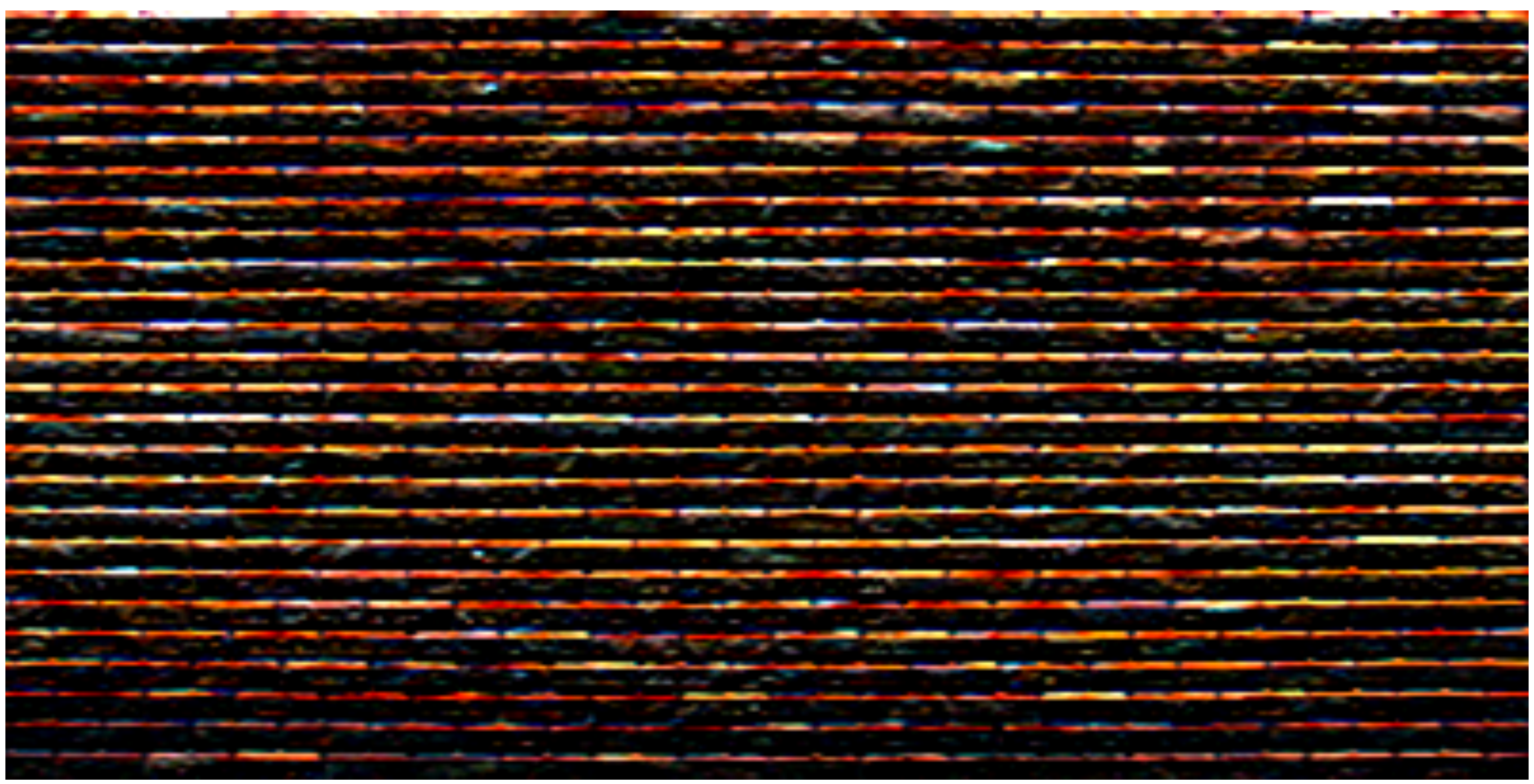
Extracts horizontal gradients

$$\begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

Extracts vertical gradients

Gradient detection filters

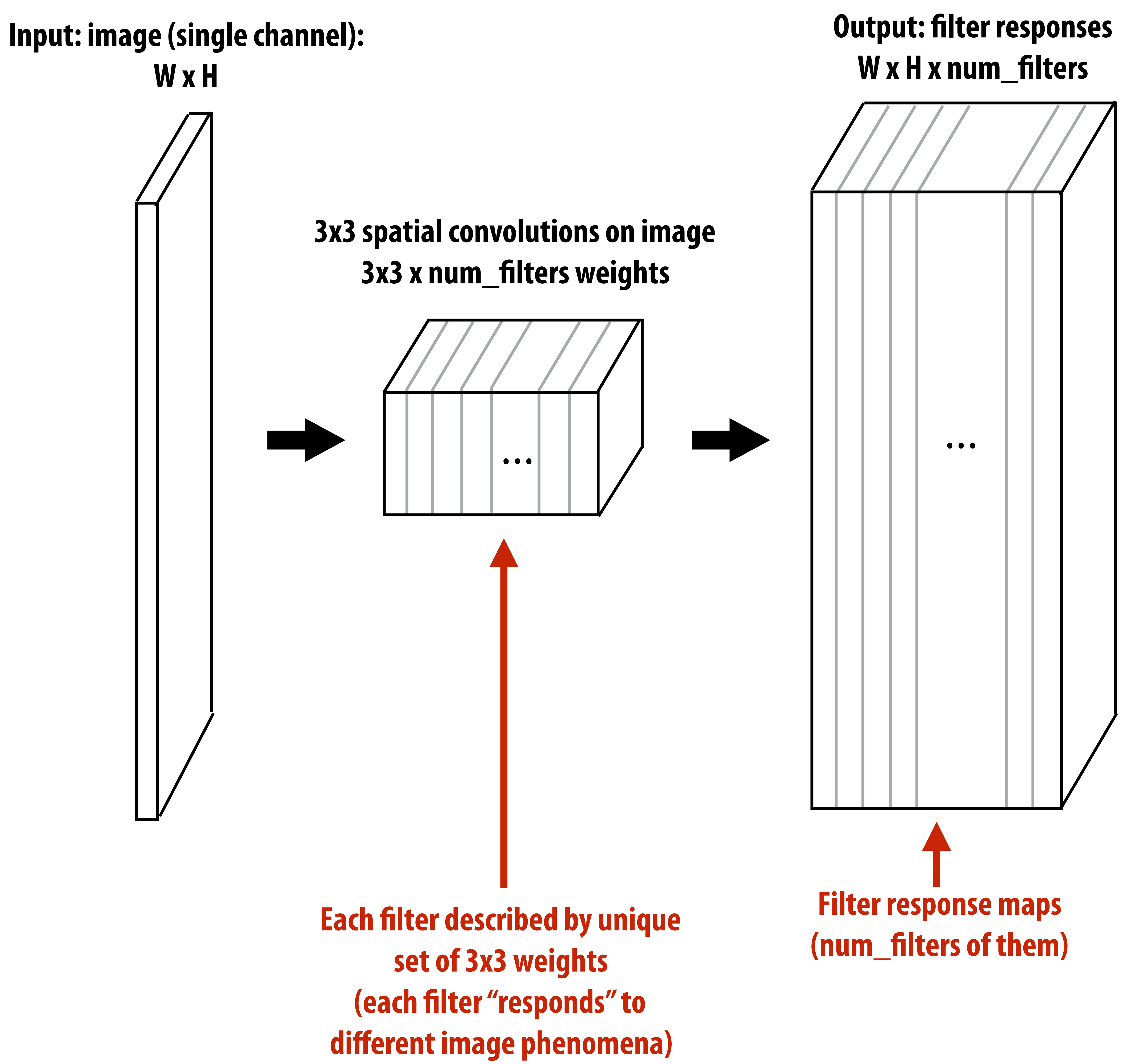
Horizontal gradients



Vertical gradients

Note: you can think of a filter as a "detector" of a pattern, and the magnitude of a pixel in the output image as the "response" of the filter to the region surrounding each pixel in the input image

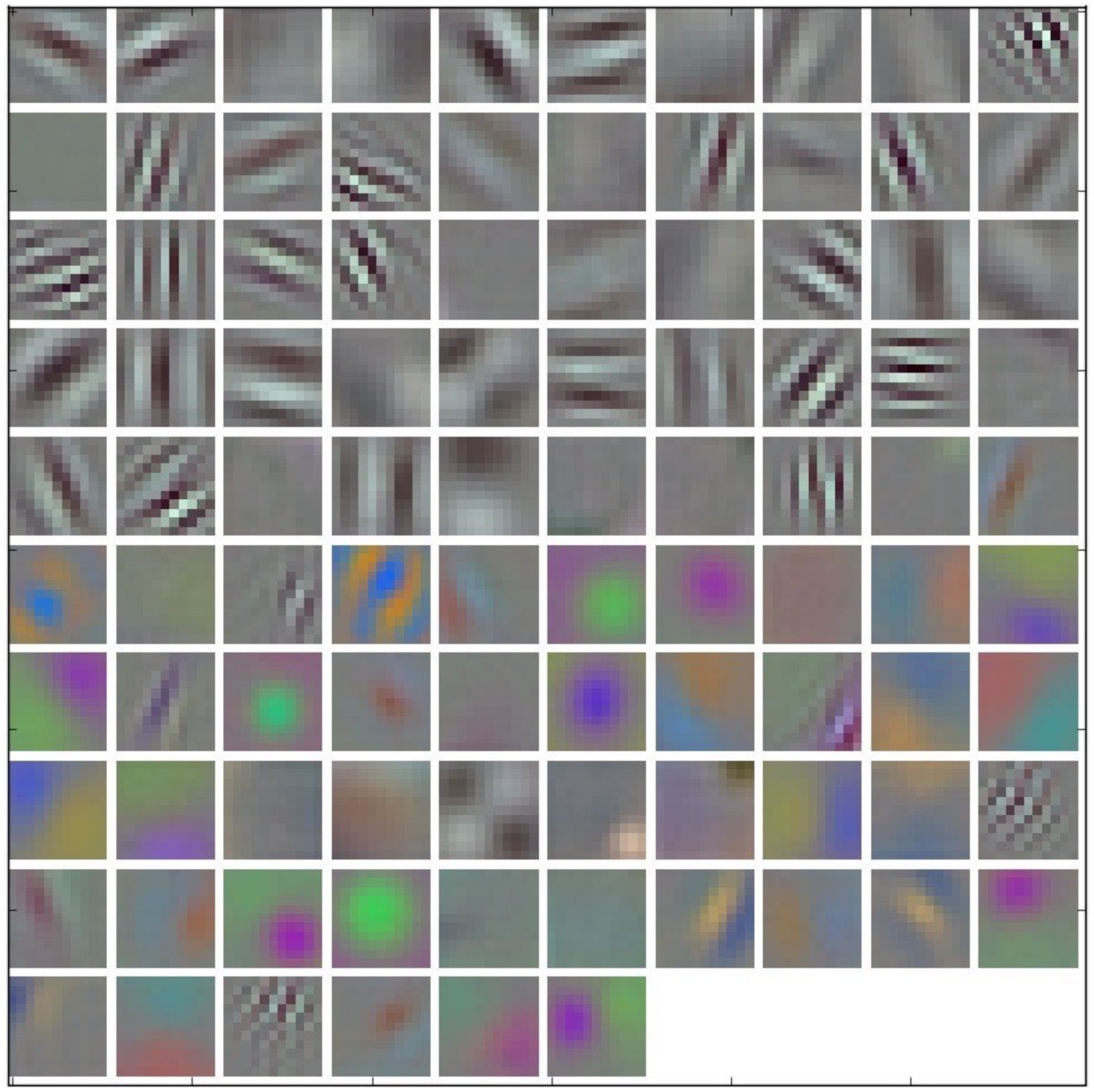
Applying many filters to an image at once



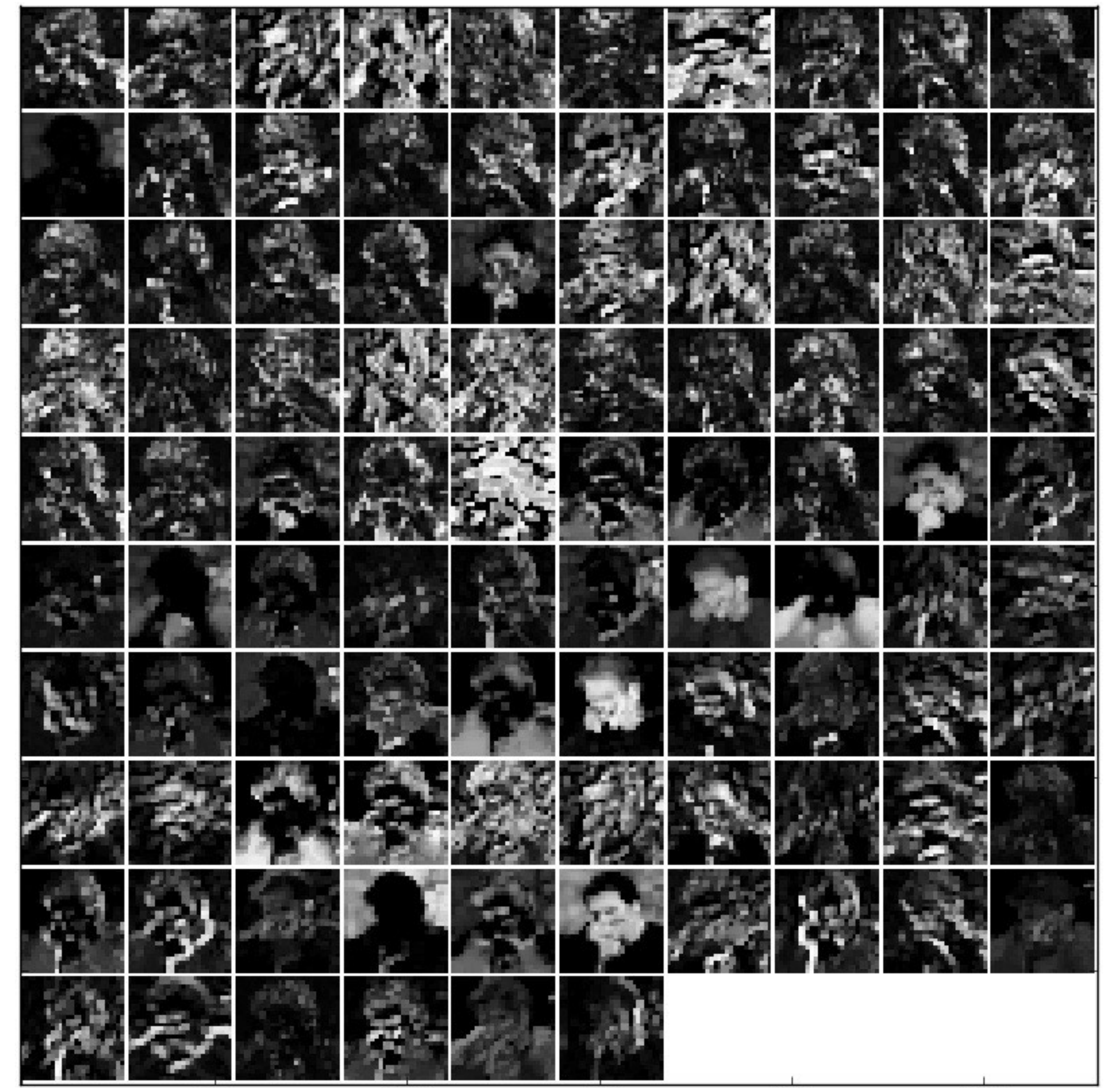
Applying many filters to an image at once

Input RGB image (W x H x 3)

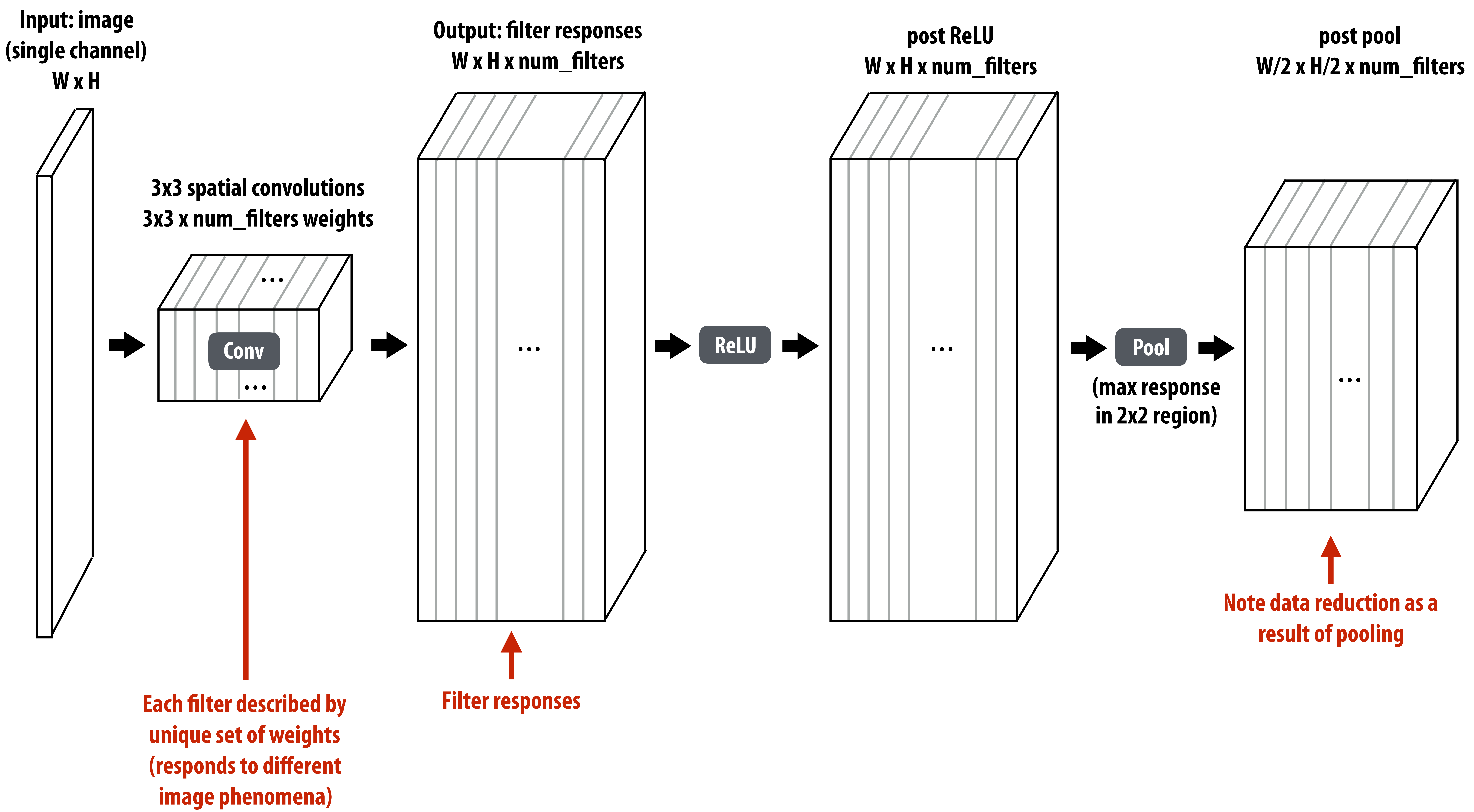
96 11x11x3 filters
(operate on RGB)



96 responses (normalized)



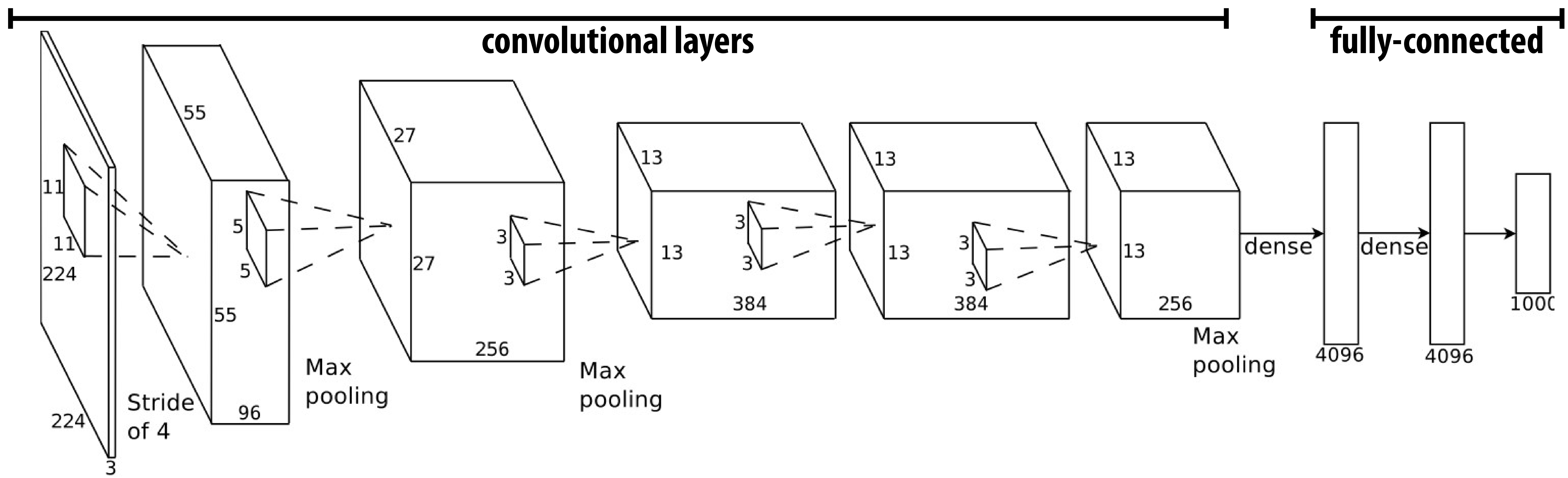
Adding additional layers



Example: "AlexNet" object detection network

Sequences of conv + reLU + pool (optional) layers

Example: AlexNet [Krizhevsky12]: 5 convolutional layers + 3 fully connected layers



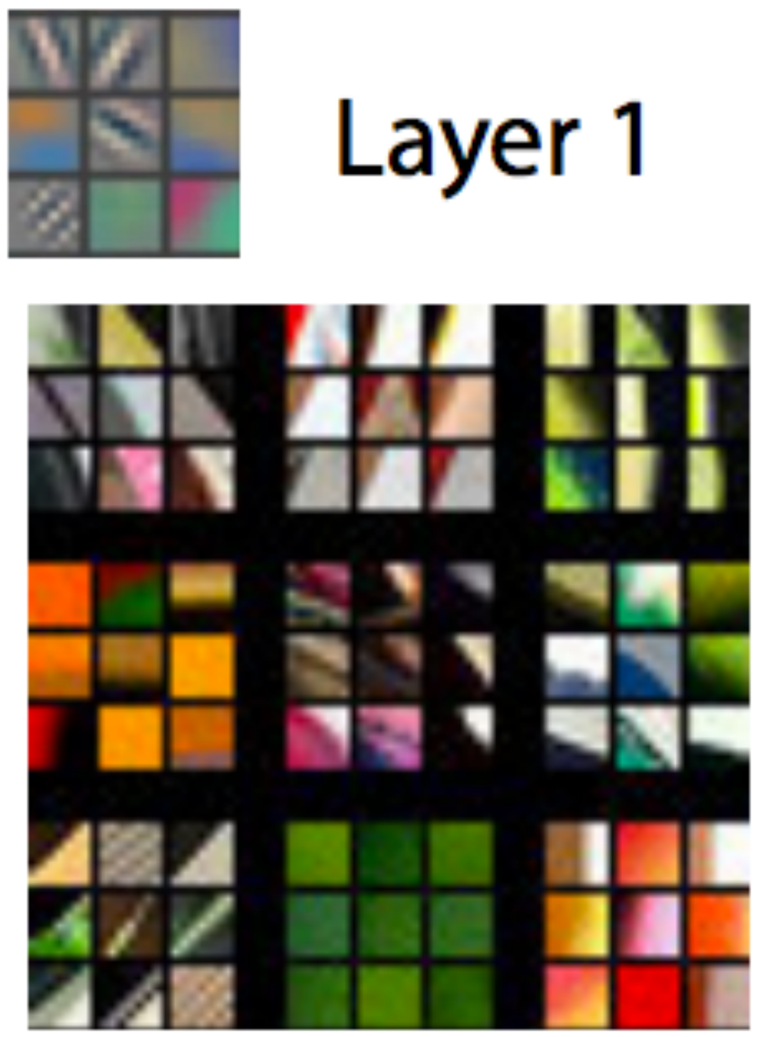
Another example: VGG-16 [Simonyan15]: 13 convolutional layers

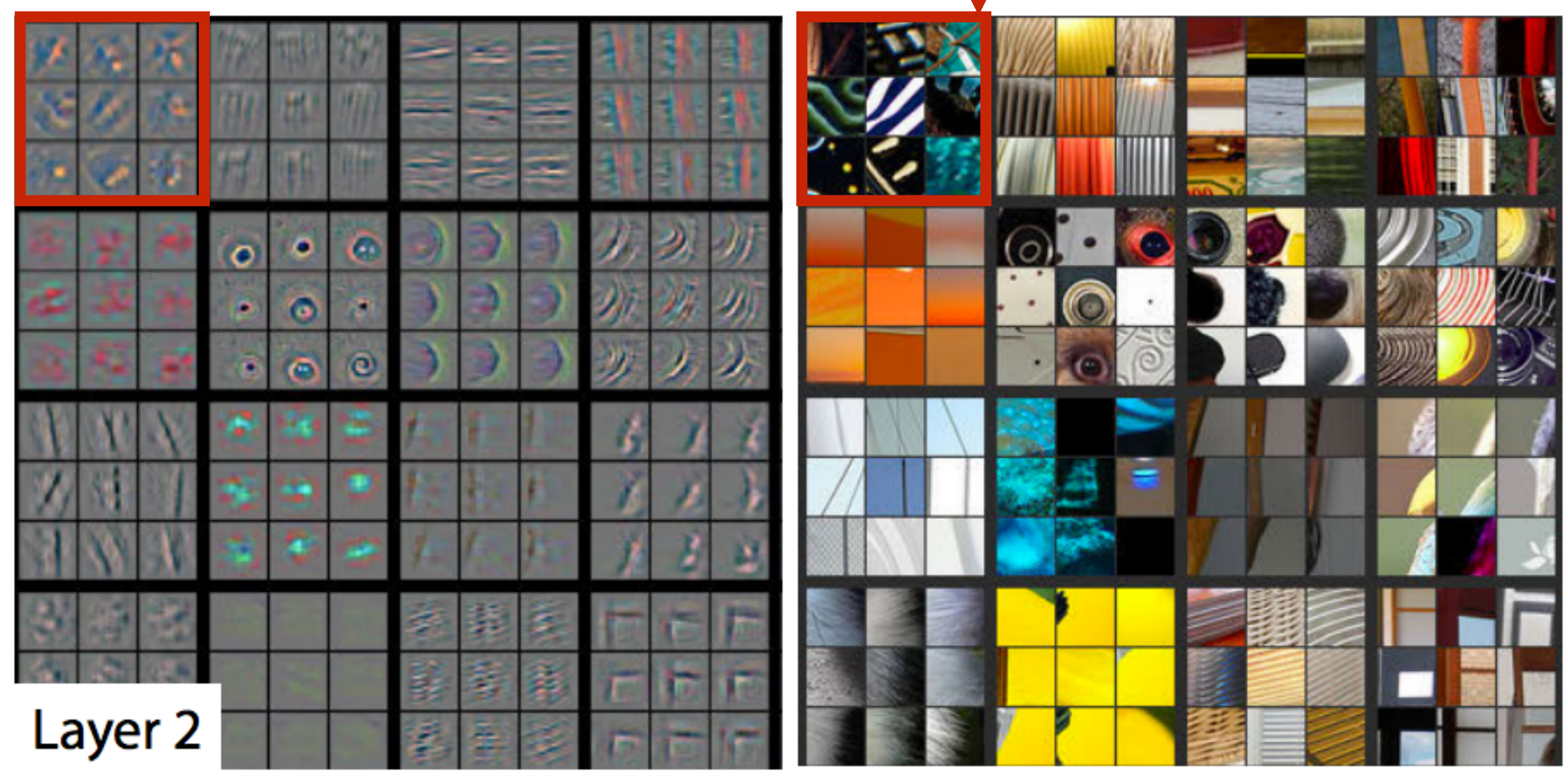
input: 224 x 224 RGB
conv/reLU: 3x3x3x64
conv/reLU: 3x3x64x64
maxpool
conv/reLU: 3x3x64x128
conv/reLU: 3x3x128x128
maxpool
conv/reLU: 3x3x128x256
conv/reLU: 3x3x256x256
conv/reLU: 3x3x256x256
maxpool
conv/reLU: 3x3x256x512
conv/reLU: 3x3x512x512
conv/reLU: 3x3x512x512
maxpool
conv/reLU: 3x3x512x512
conv/reLU: 3x3x512x512
conv/reLU: 3x3x512x512
maxpool
fully-connected 4096
fully-connected 4096
fully-connected 1000
soft-max

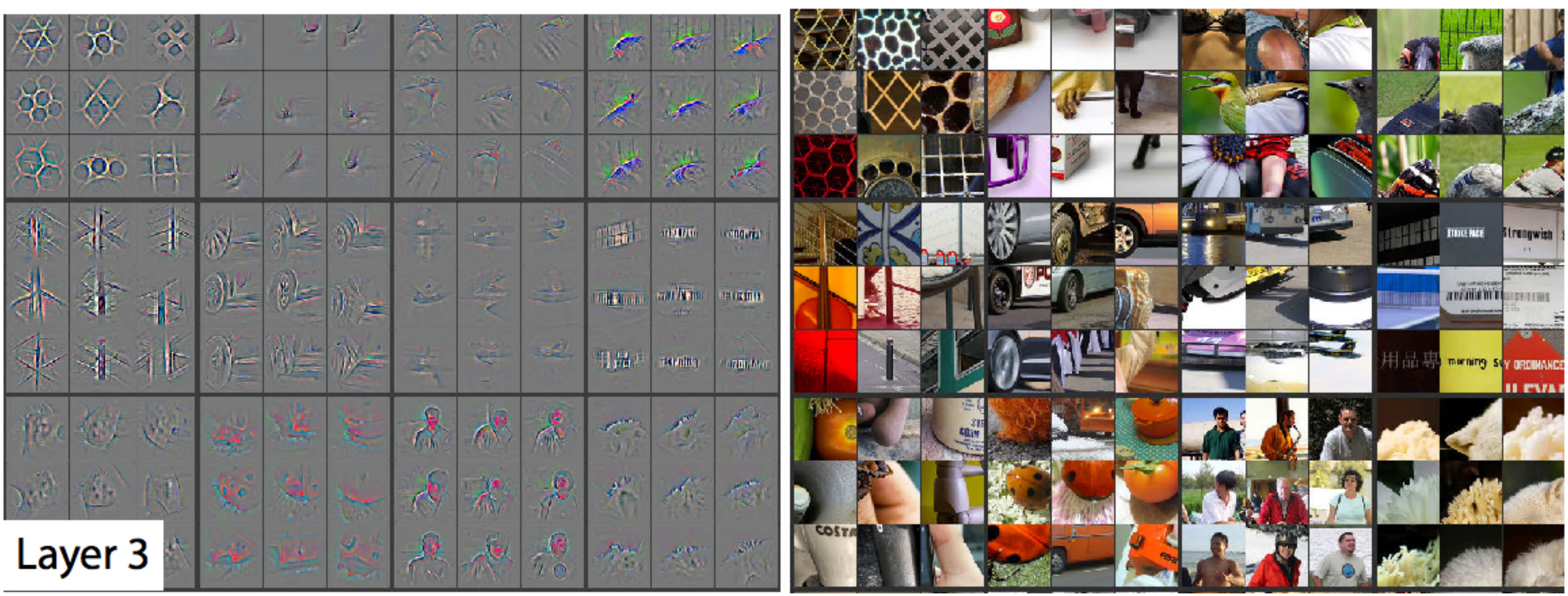
[VGG illustration credit: Yang et al.]

Why deep?

Left: what pixels trigger the response
Right: images that generate strongest response for filters at each layer

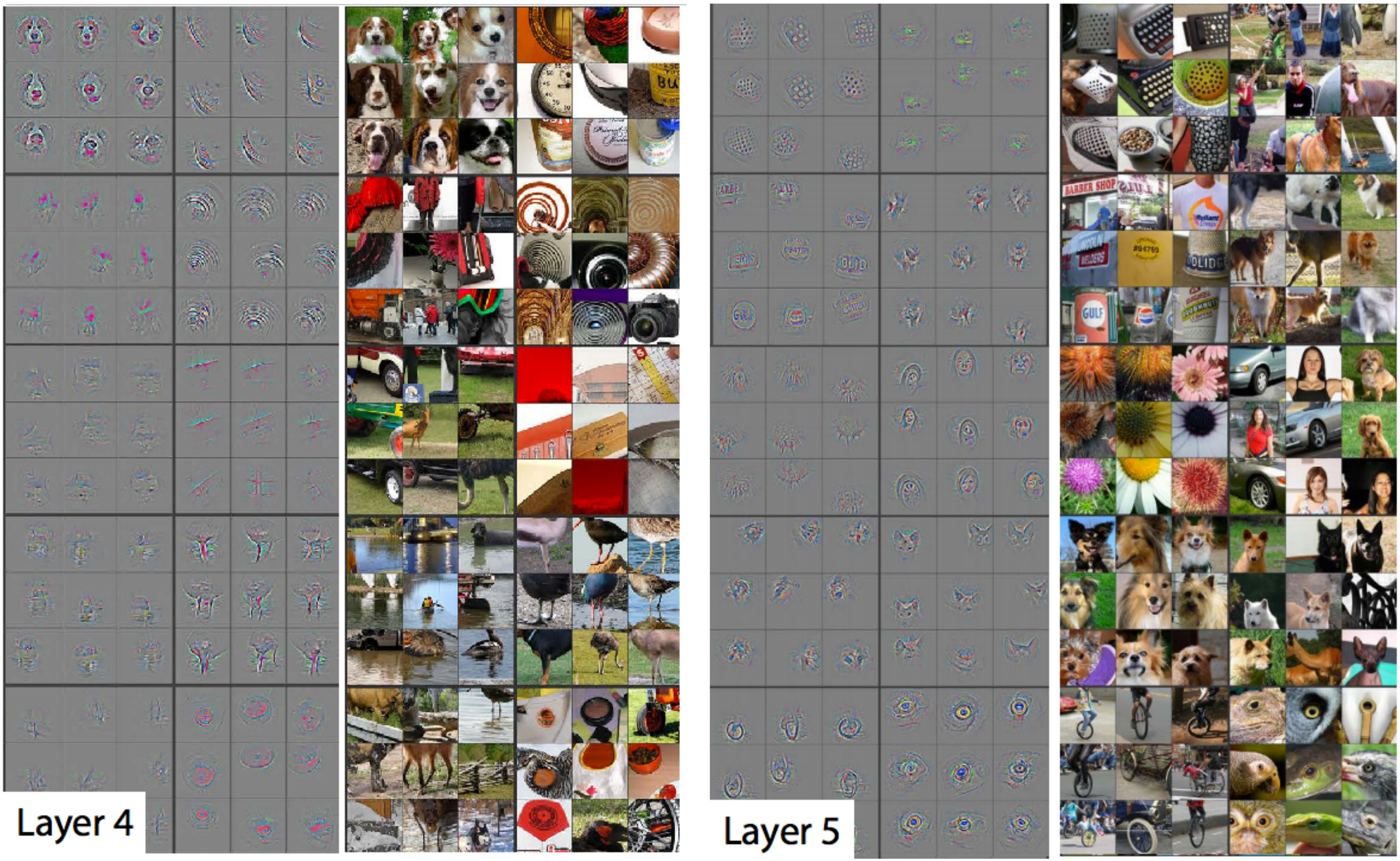






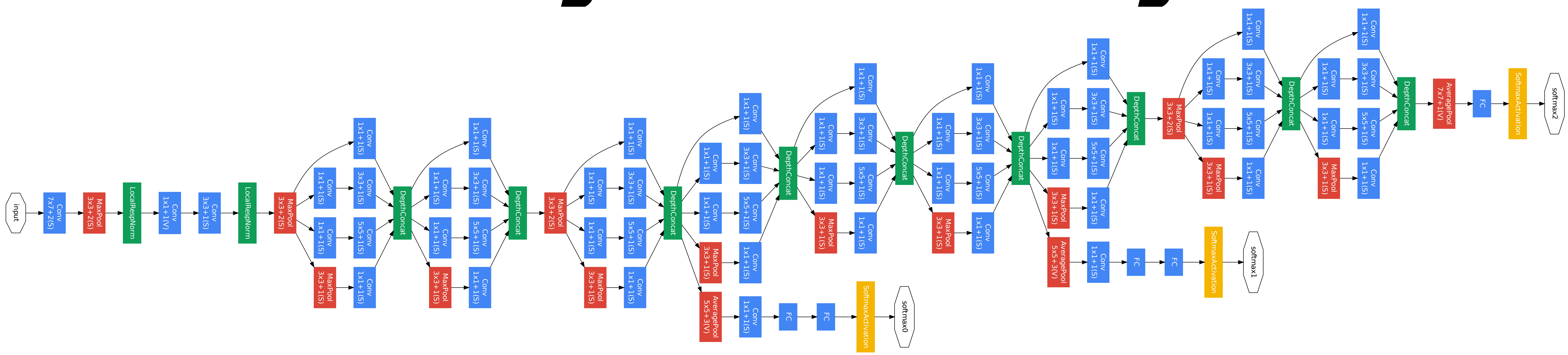
[image credit: Zeiler 14]

Why deep?

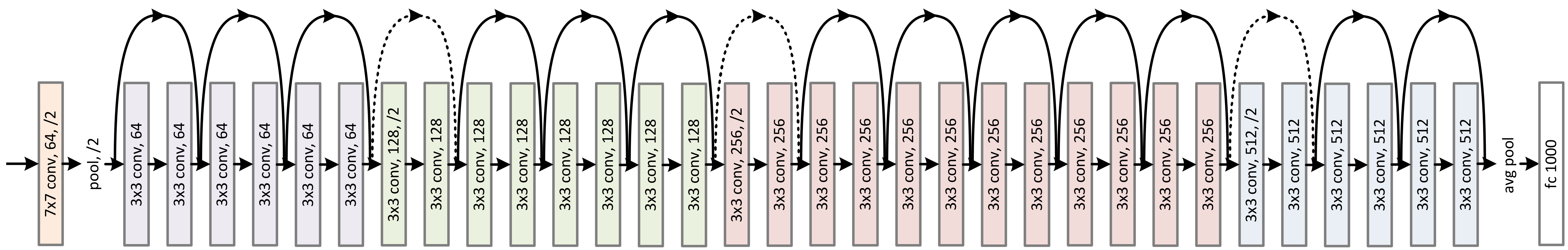


[image credit: Zeiler 14]

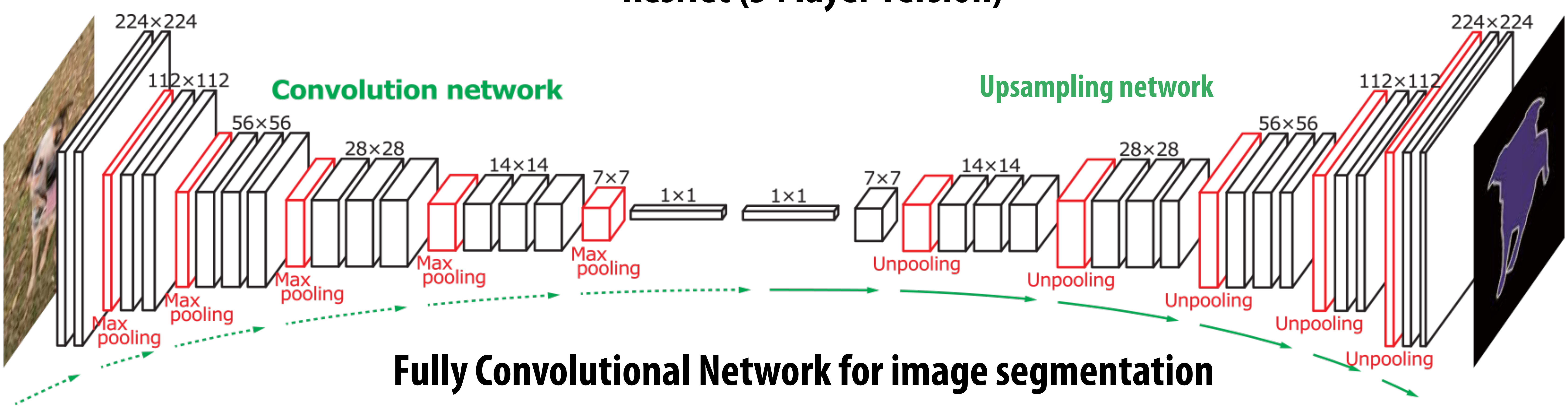
More recent image understanding networks



Inception (GoogleLeNet)



ResNet (34 layer version)



Fully Convolutional Network for image segmentation

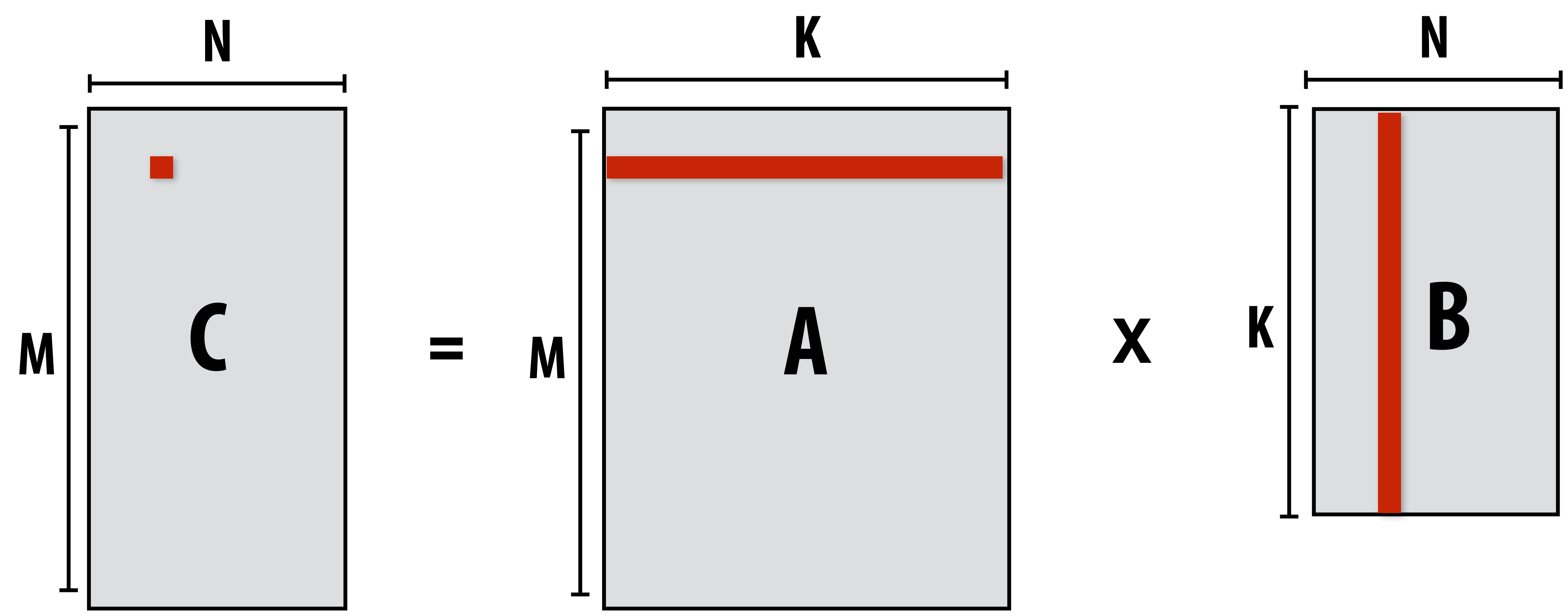
Deep networks learn useful representations

- Simultaneous, multi-scale learning of useful features for the task at hand
  - Example on previous slides: subparts detectors emerged in network for object classification
- But wait… how did you learn the values of all the weights?
  - For today, assume the weights are given (today is about evaluating deep networks, not training them)

Efficiently implementing convolution layers

Dense matrix multiplication

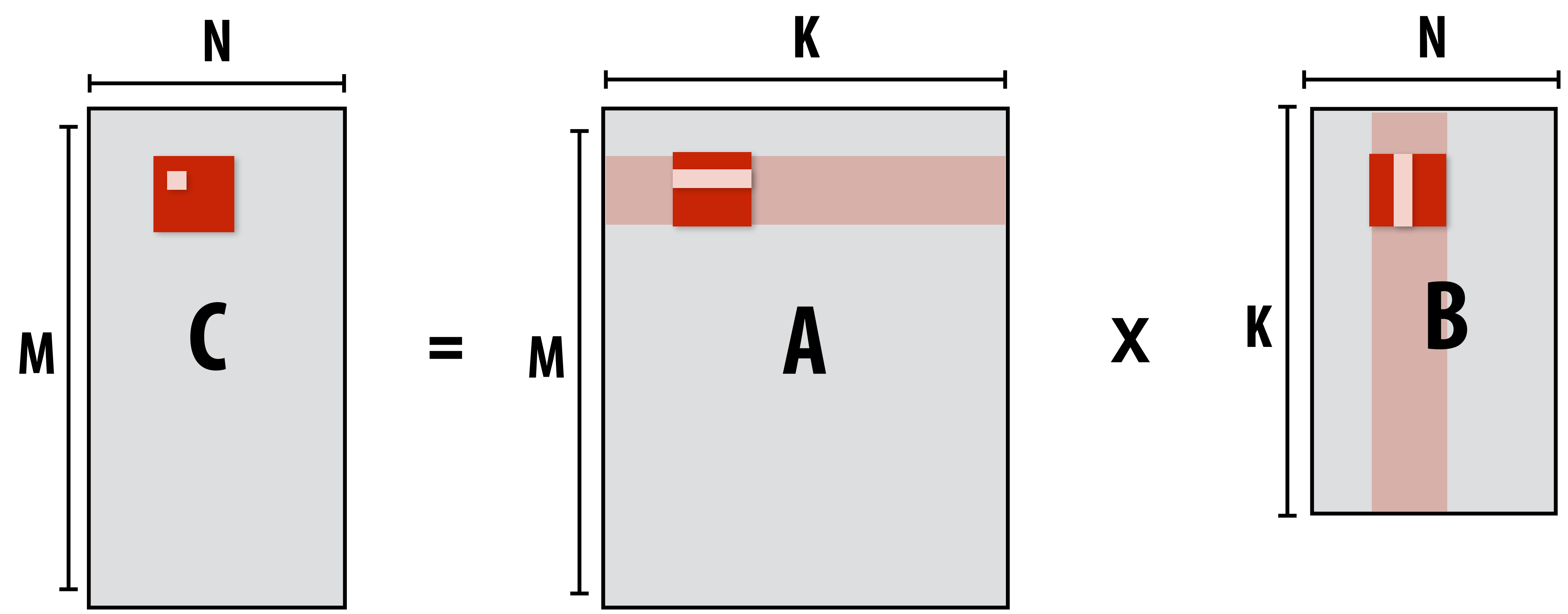
```
float A[M][K];
float B[K][N];
float C[M][N];

// compute C += A * B
#pragma omp parallel for
for (int j=0; j<M; j++)
  for (int i=0; i<N; i++)
     for (int k=0; k<K; k++)
         C[j][i] += A[j][k] * B[k][i];
```



What is the problem with this implementation?

Low arithmetic intensity (does not exploit temporal locality in access to A and B)

Blocked dense matrix multiplication




```
float A[M][K];
float B[K][N];
float C[M][N];

// compute C += A * B
#pragma omp parallel for
for (int jblock=0; jblock<M; jblock+=BLOCKSIZE_J)
  for (int iblock=0; iblock<N; iblock+=BLOCKSIZE_I)
     for (int kblock=0; kblock<K; kblock+=BLOCKSIZE_K)
        for (int j=0; j<BLOCKSIZE_J; j++)
           for (int i=0; i<BLOCKSIZE_I; i++)
              for (int k=0; k<BLOCKSIZE_K; k++)
                 C[jblock+j][iblock+i] += A[jblock+j][kblock+k] * B[kblock+k][iblock+i];
```

Idea: compute partial result for block of C while required blocks of A and B remain in cache
(Assumes BLOCKSIZE chosen to allow block of A, B, and C to remain resident)

Self check: do you want as big a BLOCKSIZE as possible? Why?

Hierarchical blocked matrix mult

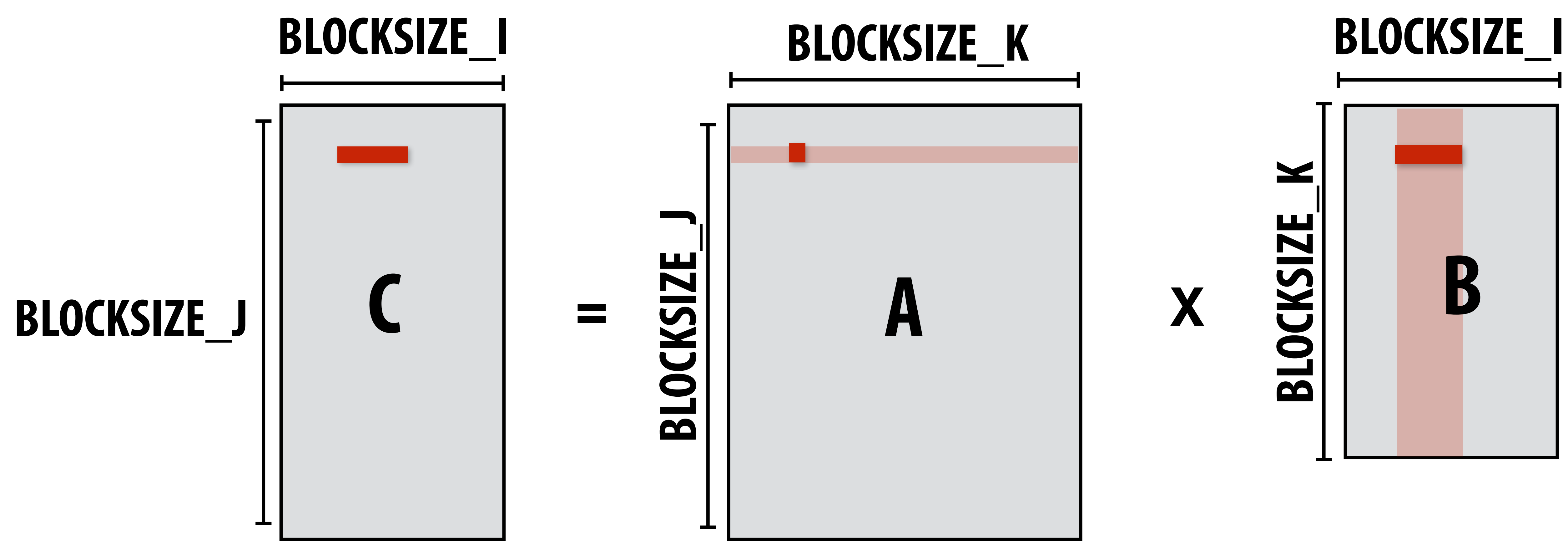
Exploit multiple levels of memory hierarchy

```
float A[M][K];
float B[K][N];
float C[M][N];

// compute C += A * B
#pragma omp parallel for
for (int jblock2=0; jblock2<M; jblock2+=L2_BLOCKSIZE_J)
  for (int iblock2=0; iblock2<N; iblock2+=L2_BLOCKSIZE_I)
     for (int kblock2=0; kblock2<K; kblock2+=L2_BLOCKSIZE_K)
        for (int jblock1=0; jblock1<L1_BLOCKSIZE_J; jblock1+=L1_BLOCKSIZE_J)
           for (int iblock1=0; iblock1<L1_BLOCKSIZE_I; iblock1+=L1_BLOCKSIZE_I)
              for (int kblock1=0; kblock1<L1_BLOCKSIZE_K; kblock1+=L1_BLOCKSIZE_K)
                 for (int j=0; j<BLOCKSIZE_J; j++)
                    for (int i=0; i<BLOCKSIZE_I; i++)
                       for (int k=0; k<BLOCKSIZE_K; k++)
                          ...
```

Not shown: final level of "blocking" for register locality…

Blocked dense matrix multiplication (1)

Consider SIMD parallelism within a block



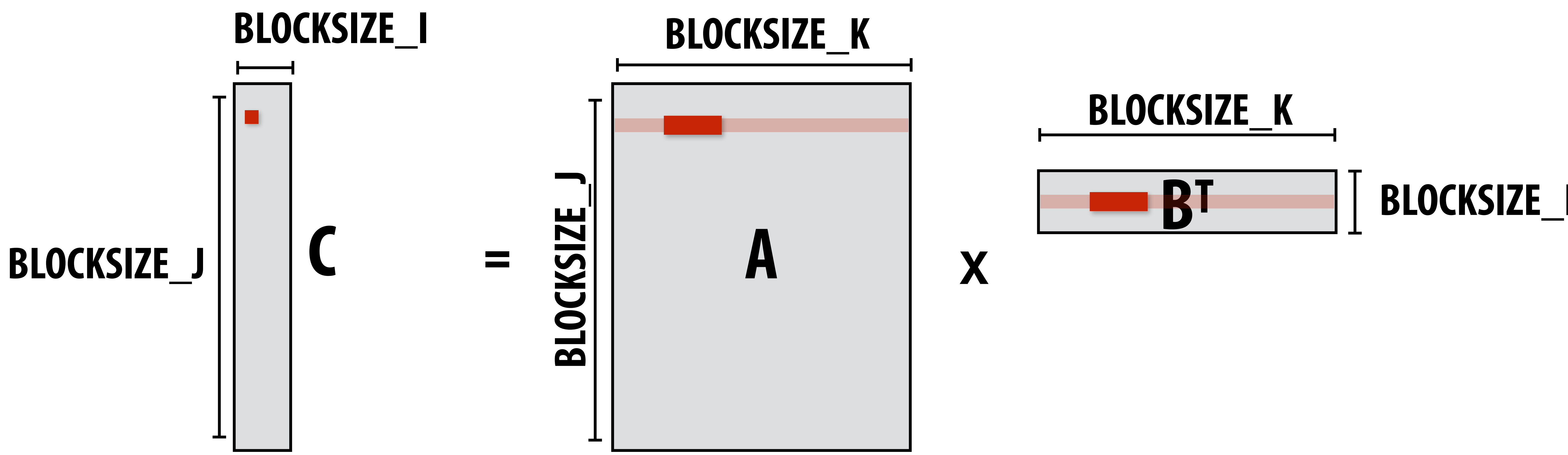

```
...
for (int j=0; j<BLOCKSIZE_J; j++) {
   for (int i=0; i<BLOCKSIZE_I; i+=SIMD_WIDTH) {
      simd_vec C_accum = vec_load(&C[jblock+j][iblock+i]);
      for (int k=0; k<BLOCKSIZE_K; k++) {
         // C = A*B + C
         simd_vec A_val = splat(&A[jblock+j][kblock+k]); // load a single element in vector register
         simd_muladd(A_val, vec_load(&B[kblock+k][iblock+i]), C_accum);
      }
      vec_store(&C[jblock+j][iblock+i], C_accum);
   }
}
```

Vectorize i loop

Good: also improves spatial locality in access to B

Bad: working set increased by SIMD_WIDTH, still walking over B in large steps

Blocked dense matrix multiplication (2)



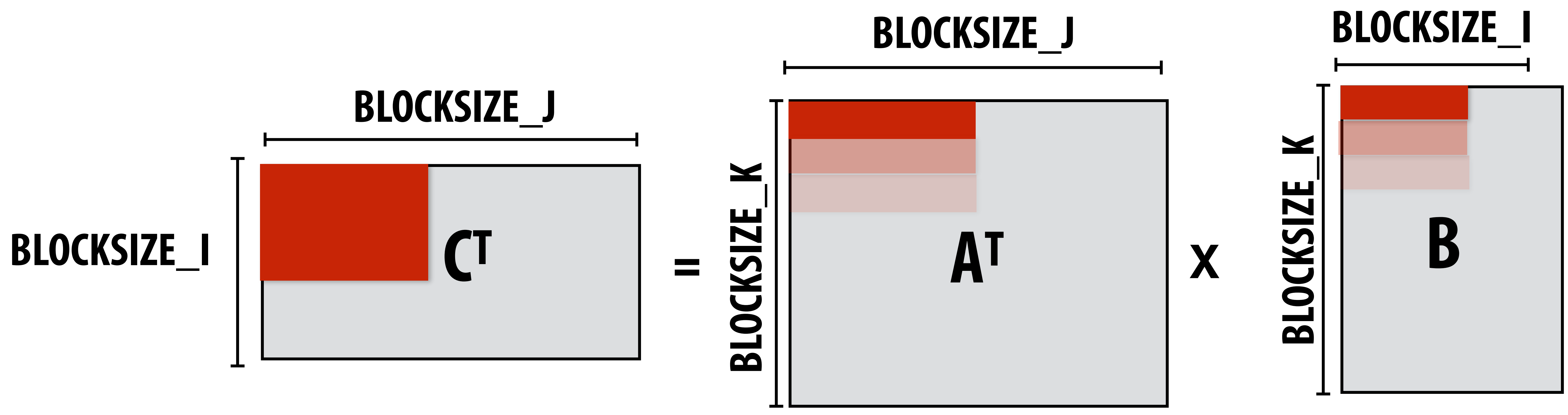

```
...
for (int j=0; j<BLOCKSIZE_J; j++)
   for (int i=0; i<BLOCKSIZE_I; i++) {
      float C_scalar = C[jblock+j][iblock+i];
      // C_scalar += dot(row of A,row of B)
      for (int k=0; k<BLOCKSIZE_K; k+=SIMD_WIDTH) {
        C_scalar += simd_dot(vec_load(&A[jblock+j][kblock+k]), vec_load(&Btrans[iblock+i][[kblock+k]);
      }
      C[jblock+j][iblock+i] = C_scalar;
   }
```

Assume *i* dimension is small. Previous vectorization scheme (1) would not work well.

Pre-transpose block of B (copy block of B to temp buffer in transposed form)

Vectorize innermost loop

Blocked dense matrix multiplication (3)




```
// assume blocks of A and C are pre-transposed as Atrans and Ctrans
for (int j=0; j<BLOCKSIZE_J; j+=SIMD_WIDTH) {
   for (int i=0; i<BLOCKSIZE_I; i+=SIMD_WIDTH) {

      simd_vec C_accum[SIMD_WIDTH];
      for (int k=0; k<SIMD_WIDTH; k++)   // load C_accum for a SIMD_WIDTH x SIMD_WIDTH chunk of C^T
         C_accum[k] = vec_load(&Ctrans[iblock+i+k][jblock+j]);

      for (int k=0; k<BLOCKSIZE_K; k++) {
        simd_vec bvec = vec_load(&B[kblock+k][iblock+i]);
        for (int kk=0; kk<SIMD_WIDTH; kk++)  // innermost loop items not dependent
            simd_muladd(vec_load(&Atrans[kblock+k][jblock+j], splat(bvec[kk]), C_accum[kk]);
      }

      for (int k=0; k<SIMD_WIDTH; k++)
        vec_store(&Ctrans[iblock+i+k][jblock+j], C_accum[k]);
   }
}
```

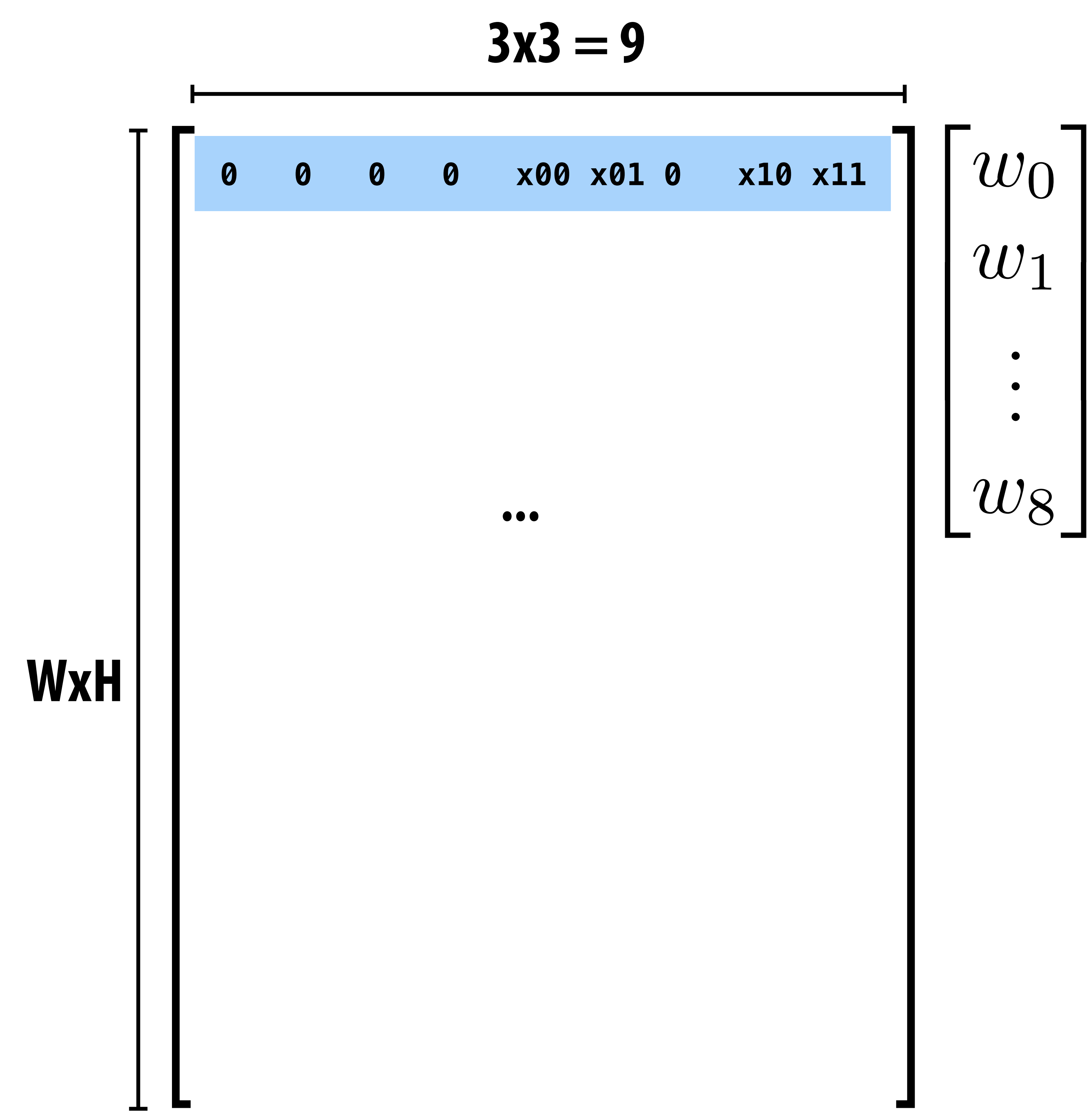
Convolution as matrix-vector product

Construct matrix from elements of input image

X_{00}	X_{01}	X_{02}	X_{03}	...			
X_{10}	X_{11}	X_{12}	X_{13}	...			
X_{20}	X_{21}	X_{22}	X_{23}	...			
X_{30}	X_{31}	X_{32}	X_{33}	...			
...	...	...	...				

O(N) storage multiplier for filter with N elements

Must construct input data matrix



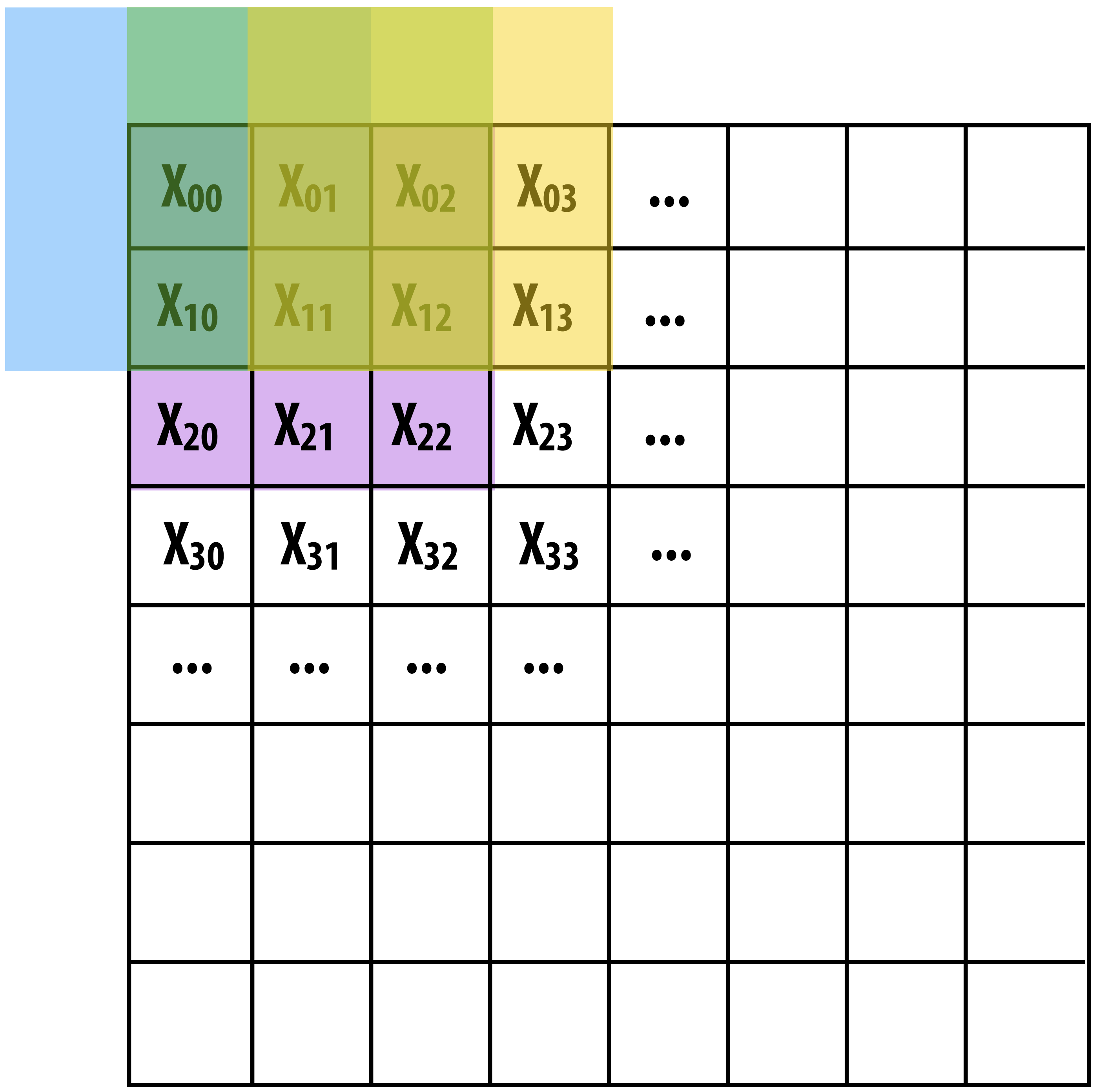
Note: 0-pad matrix

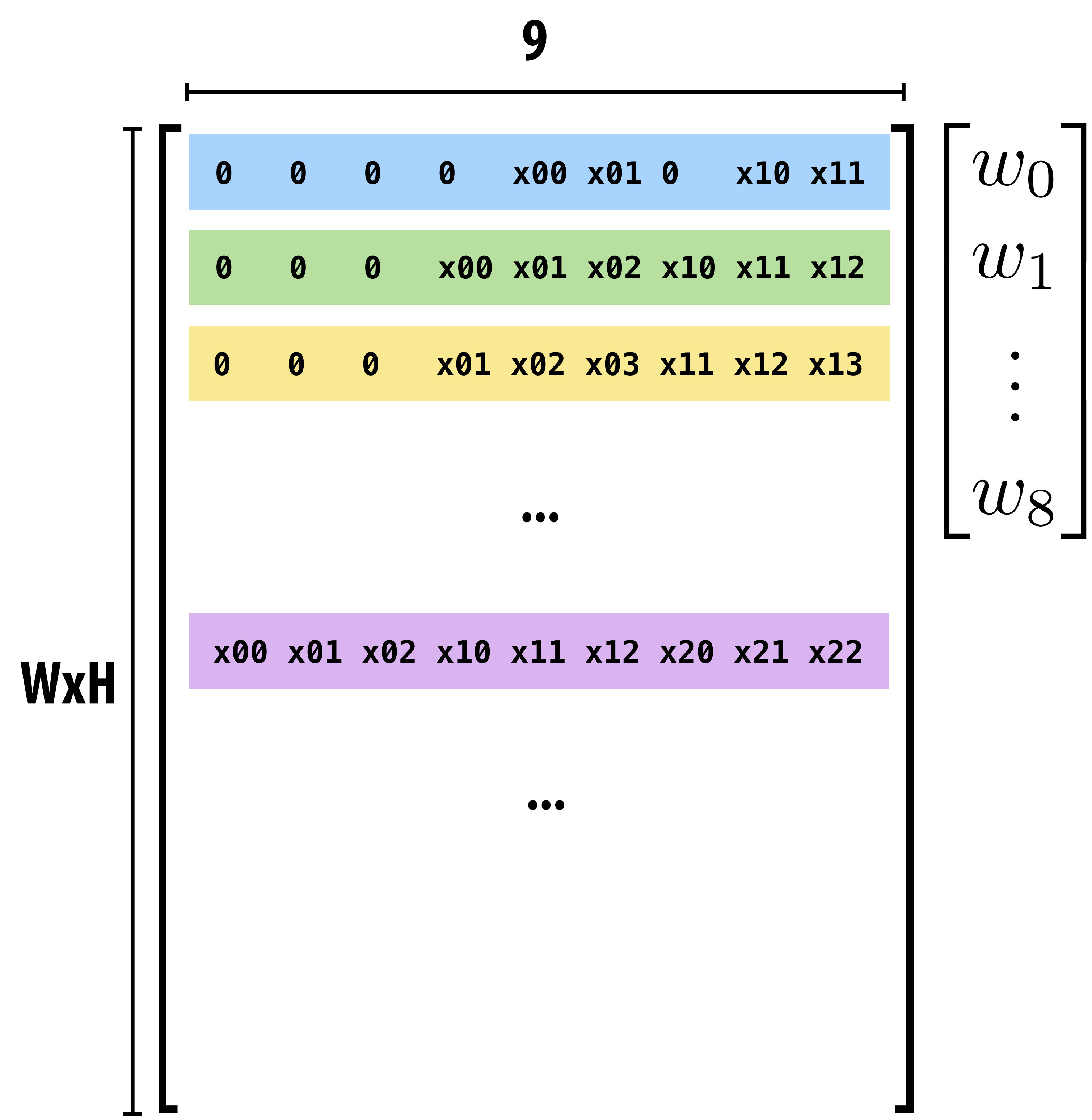
3x3 convolution as matrix-vector product

Construct matrix from elements of input image

O(N) storage overhead for filter with N elements

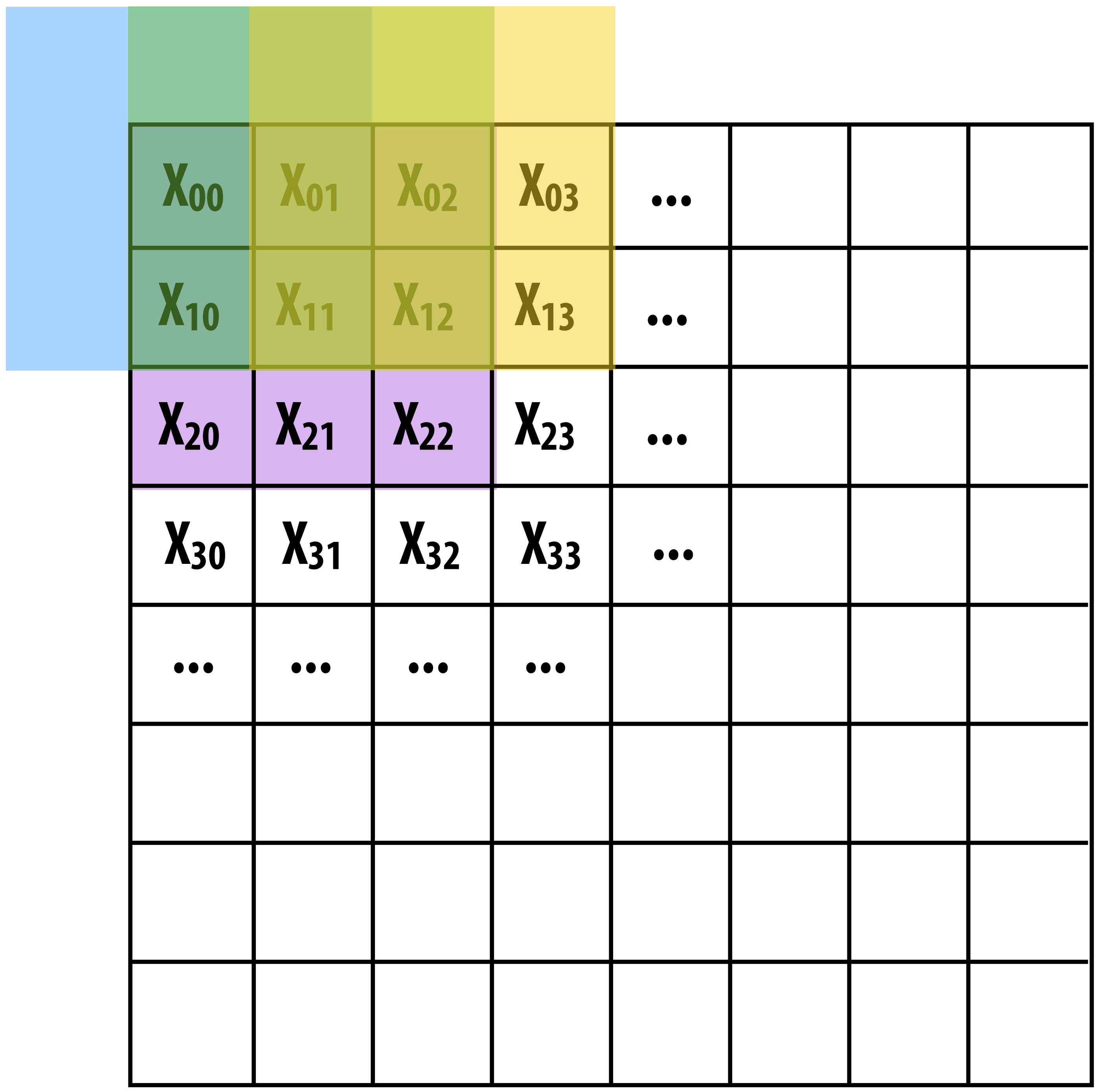
Must construct input data matrix





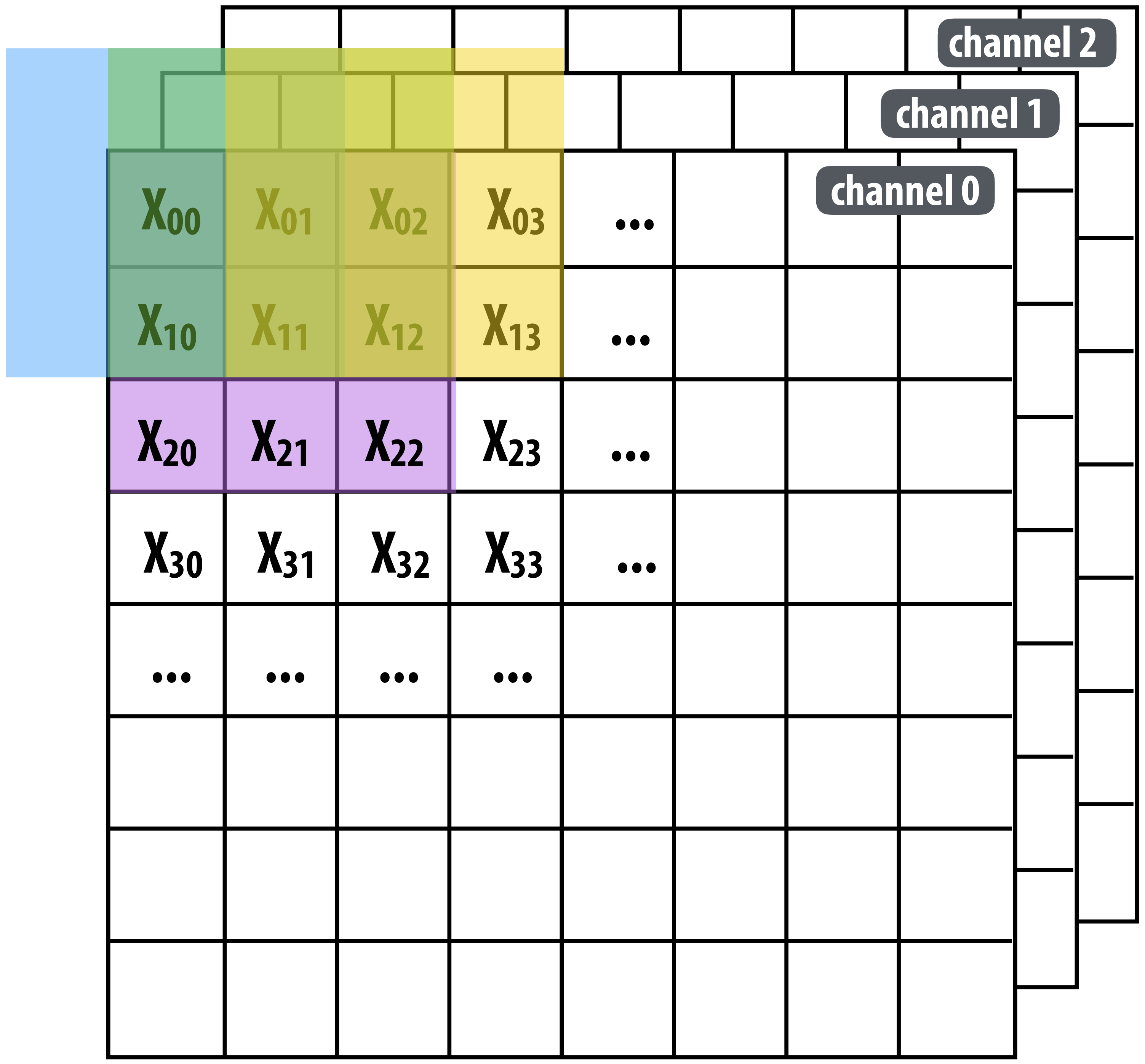
Note: 0-pad matrix

Multiple convolutions as matrix-matrix mult



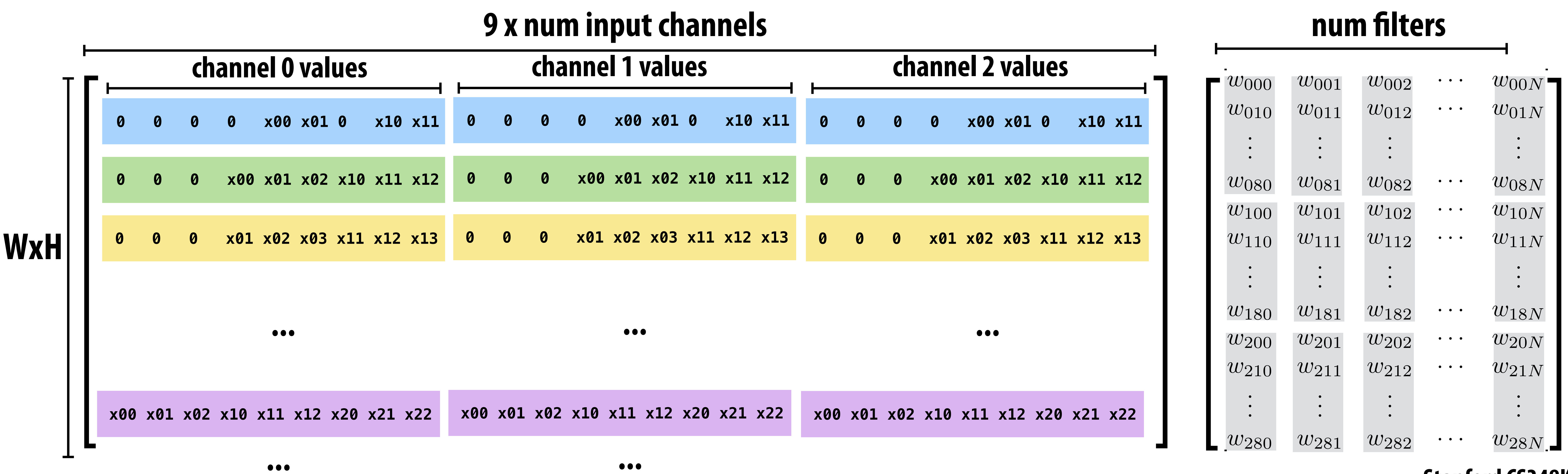
$$
\begin{array}{cc}
 & \text{9} \\
\text{WxH} & \begin{bmatrix}
0 & 0 & 0 & 0 & x00 & x01 & 0 & x10 & x11 \\
0 & 0 & 0 & x00 & x01 & x02 & x10 & x11 & x12 \\
0 & 0 & 0 & x01 & x02 & x03 & x11 & x12 & x13 \\
 & & & & \dots & & & & \\
x00 & x01 & x02 & x10 & x11 & x12 & x20 & x21 & x22 \\
 & & & & \dots & & & &
\end{bmatrix}
\end{array}
\quad
\begin{array}{c}
\text{num filters} \\
\begin{bmatrix}
w_{00} & w_{01} & w_{02} & \cdots & w_{0N} \\
w_{10} & w_{11} & w_{12} & \cdots & w_{0N} \\
\vdots & \vdots & \vdots & & \vdots \\
w_{80} & w_{81} & w_{82} & \cdots & w_{8N}
\end{bmatrix}
\end{array}
$$

Multiple convolutions on multiple input channels



For each filter, sum responses over input channels

Equivalent to (3 x 3 x num_channels) convolution on (W x H x num_channels) input data



Direct implementation of conv layer

```
float input[IMAGE_BATCH_SIZE][INPUT_HEIGHT][INPUT_WIDTH][INPUT_DEPTH];
float output[IMAGE_BATCH_SIZE][INPUT_HEIGHT][INPUT_WIDTH][LAYER_NUM_FILTERS];
float layer_weights[LAYER_NUM_FILTERS][LAYER_CONVY][LAYER_CONVX][INPUT_DEPTH];

// assumes convolution stride is 1
for (int img=0; img<IMAGE_BATCH_SIZE; img++)
   for (int j=0; j<INPUT_HEIGHT; j++)
      for (int i=0; i<INPUT_WIDTH; i++)
         for (int f=0; f<LAYER_NUM_FILTERS; f++) {
            output[img][j][i][f] = 0.f;
            for (int kk=0; kk<INPUT_DEPTH; kk++)       // sum over filter responses of input channels
               for (int jj=0; jj<LAYER_FILTER_Y; jj++)    // spatial convolution (Y)
                  for (int ii=0; ii<LAYER_FILTER_X; ii+)  // spatial convolution (X)
                     output[img][j][i][f] += layer_weights[f][jj][ii][kk] * input[img][j+jj][i+ii][kk];
          }
```

Seven loops with significant input data reuse: reuse of filter weights (during convolution), and reuse of input values (across different filters)

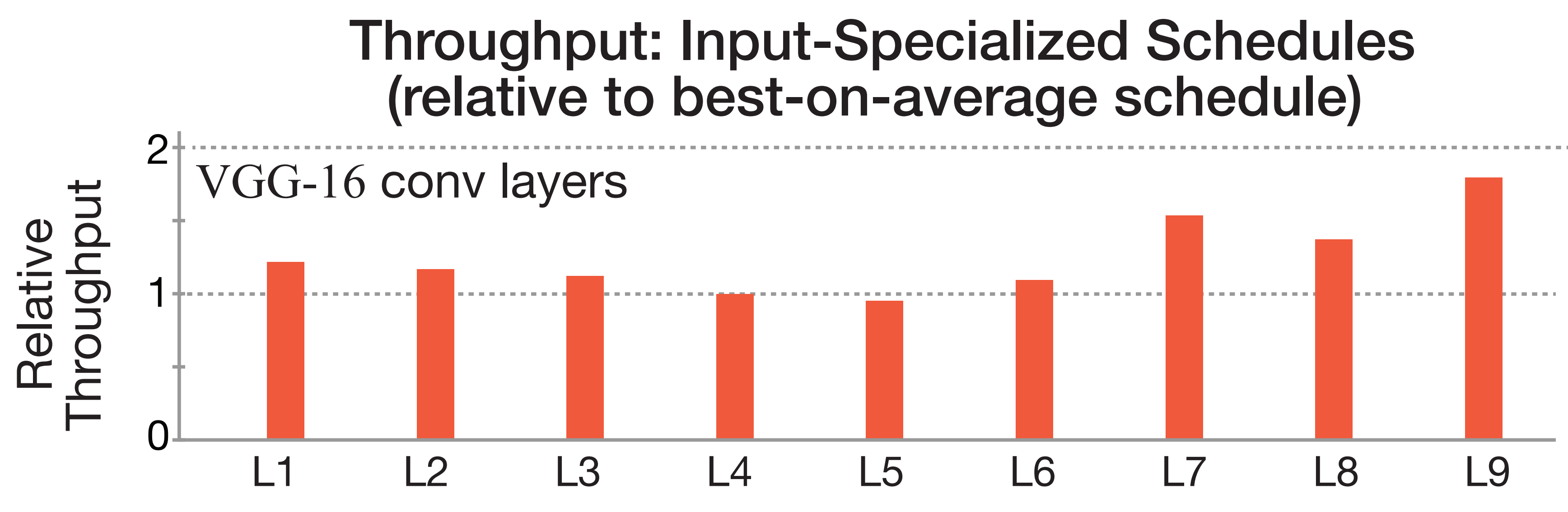
Avoids O(N) footprint increase by avoiding materializing input matrix
In theory loads O(N) times less data (potentially higher arithmetic intensity… but matrix mult is typically compute-bound)
But must roll your own highly optimized implementation of complicated loop nest.

Conv layer in Halide

```
int in_w, in_h, in_ch = 4;            // input params: assume initialized

Func in_func;                         // assume input function is initialized

int num_f, f_w, f_h, pad, stride;     // parameters of the conv layer

Func forward = Func("conv");
Var x, y, z, n;                       // n is minibatch dimension

// This creates a padded input to avoid checking boundary
// conditions while computing the actual convolution
f_in_bound = BoundaryConditions::repeat_edge(in_func, 0, in_w, 0, in_h);

// Create buffers for layer parameters
Halide::Buffer<float> W(f_w, f_h, in_ch, num_f)
Halide::Buffer<float> b(num_f);

// domain of summation for filter with W x H x in_ch
RDom r(0, f_w, 0, f_h, 0, in_ch);

// Initialize to bias
forward(x, y, z, n) =  b(z);
forward(x, y, z, n) += W(r.x, r.y, r.z, z) *
                       f_in_bound(x*stride + r.x - pad, y*stride + r.y - pad, r.z, n);
```

Consider scheduling this seven-dimensional loop nest.

Different layers of a single DNN may benefit from unique scheduling strategies



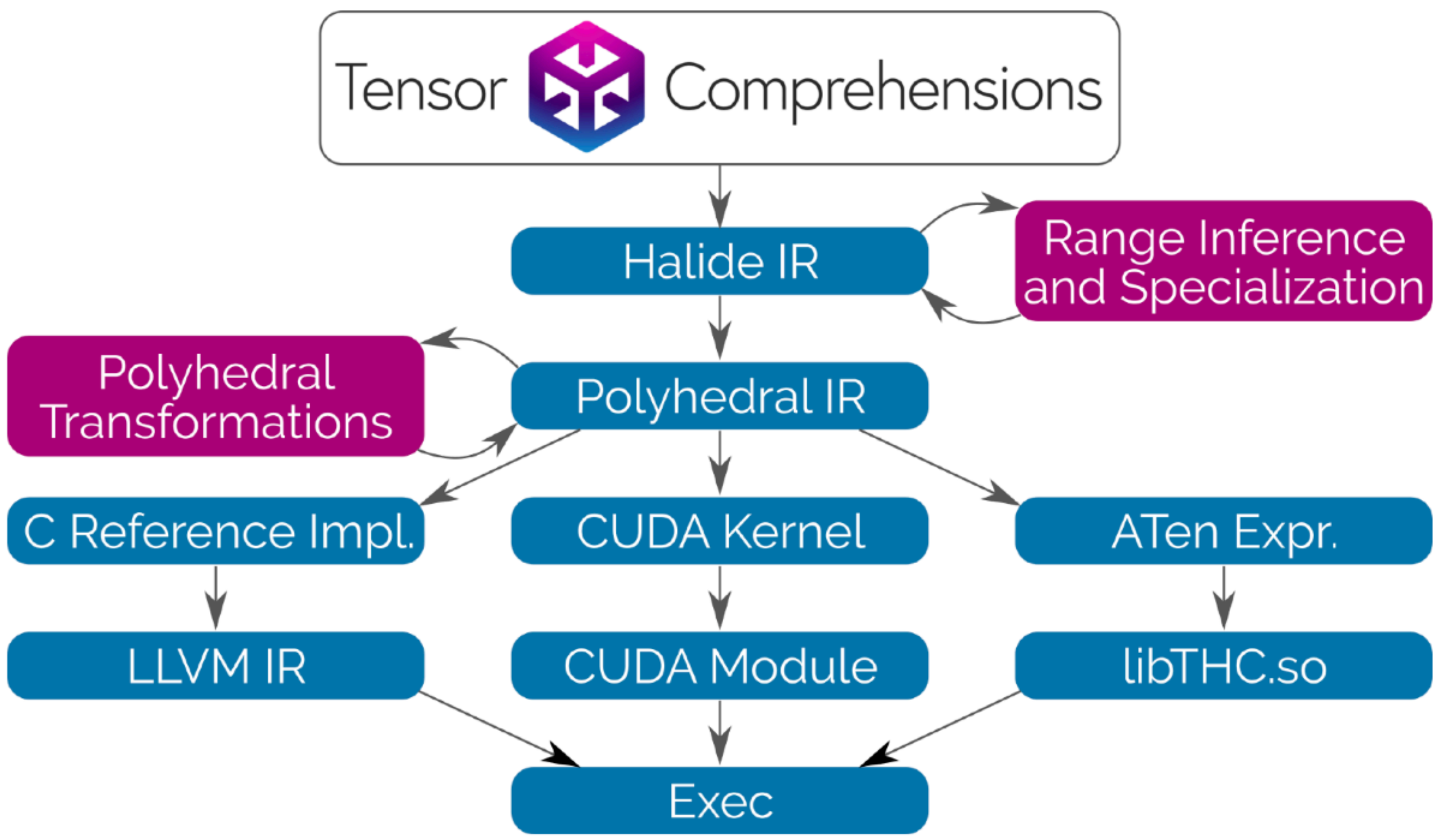
[Figure credit: Mullapudi et al. 2016]

Table 1. MobileNet Body Architecture

Type / Stride	Filter Shape	Input Size
Conv / s2	$3 \times 3 \times 3 \times 32$	$224 \times 224 \times 3$
Conv dw / s1	$3 \times 3 \times 32$ dw	$112 \times 112 \times 32$
Conv / s1	$1 \times 1 \times 32 \times 64$	$112 \times 112 \times 32$
Conv dw / s2	$3 \times 3 \times 64$ dw	$112 \times 112 \times 64$
Conv / s1	$1 \times 1 \times 64 \times 128$	$56 \times 56 \times 64$
Conv dw / s1	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 128$	$56 \times 56 \times 128$
Conv dw / s2	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 256$	$28 \times 28 \times 128$
Conv dw / s1	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 256$	$28 \times 28 \times 256$
Conv dw / s2	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 512$	$14 \times 14 \times 256$
$5\times$ Conv dw / s1	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
$5\times$ Conv / s1	$1 \times 1 \times 512 \times 512$	$14 \times 14 \times 512$
Conv dw / s2	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
Conv / s1	$1 \times 1 \times 512 \times 1024$	$7 \times 7 \times 512$
Conv dw / s2	$3 \times 3 \times 1024$ dw	$7 \times 7 \times 1024$
Conv / s1	$1 \times 1 \times 1024 \times 1024$	$7 \times 7 \times 1024$
Avg Pool / s1	Pool 7×7	$7 \times 7 \times 1024$
FC / s1	1024×1000	$1 \times 1 \times 1024$
Softmax / s1	Classifier	$1 \times 1 \times 1000$

Notice sizes of weights and activations in this network:
(and consider SIMD widths of modern machines)

Significant number of efforts to automatically schedule key DNN operations



tvm Open Deep Learning Compiler Stack

license Apache 2.0 build passing

Documentation | Contributors | Community | Release Notes

TVM is a compiler stack for deep learning systems. It is designed to close the gap between the productivity-focused deep learning frameworks, and the performance- and efficiency-focused hardware backends. TVM works with deep learning frameworks to provide end to end compilation to different backends. Checkout the tvm stack homepage for more information.

Deep Learning Compiler
nGraph

NVIDIA TensorRT

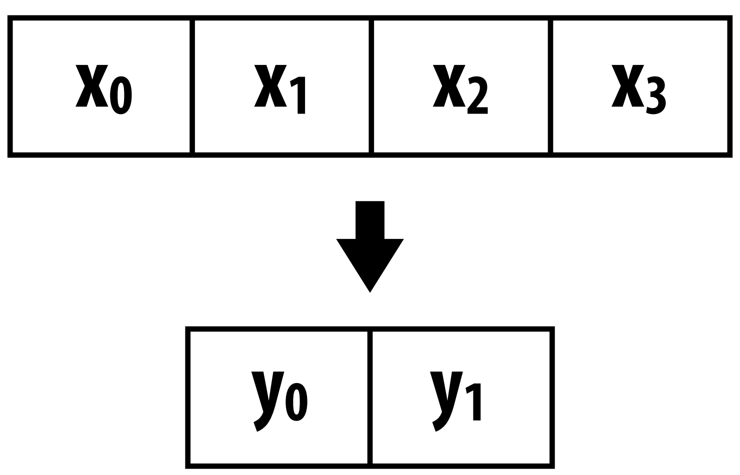
Programmable Inference Accelerator

Algorithmic improvements

- Direct convolution can be implemented efficiently in Fourier domain (convolution → element-wise multiplication)
  - Overhead: FFT to transform inputs into Fourier domain, inverse FFT to get responses back to spatial domain (NlgN)
  - Inverse transform amortized over all input channels (due to summation over inputs)

- Direct convolution using work-efficient Winograd convolutions

  1D example: consider producing two outputs of a 3-tap 1D convolution with weights: w_0 w_1 w_2



$$\begin{bmatrix} y_0 \\ y_1 \end{bmatrix} = \begin{bmatrix} x_0 & x_1 & x_2 \\ x_1 & x_2 & x_3 \end{bmatrix} \begin{bmatrix} w_0 \\ w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} m_1 + m_2 + m_3 \\ m_2 - m_3 - m_4 \end{bmatrix}$$

$$m_1 = (x_0 - x_1) w_0$$

$$m_2 = (x_1 + x_2) \frac{w_0 + w_1 + w_2}{2}$$

$$m_3 = (x_2 - x_1) \frac{w_0 - w_1 + w_2}{2}$$

$$m_4 = (x_1 - x_3) w_2$$

Filter dependent
(can be precomputed)

Winograd 1D 3-element filter:
4 multiplies
8 additions
(4 to compute m's + 4 to reduce final result)

Direct convolution: 6 multiplies, 4 adds
In 2D can notably reduce multiplications
(3x3 filter: 2.25x fewer multiples for 2x2 block of output)

Reminder: energy cost of data access

Significant fraction of energy expended moving data to processor ALUs

Operation	Energy [pJ]	Relative Cost
32 bit int ADD	0.1	1
32 bit float ADD	0.9	9
32 bit Register File	1	10
32 bit int MULT	3.1	31
32 bit float MULT	3.7	37
32 bit SRAM Cache	5	50
32 bit DRAM Memory	**640**	**6400**

Estimates for 45nm process
[Source: Mark Horowitz]

Recall: AlexNet has over 68m weights (>260MB if 4 bytes/weight)
Executing at 30fps, that's 1.3 Watts just to read the weights

Reducing network footprint

- **Large storage cost for model parameters of early DNN designs**
  - AlexNet model: ~200 MB
  - VGG-16 model: ~500 MB
  - ResNet-50: 102 MB
  - Inception-v3: 91 MB
  - In most modern DNNs, activations require more storage than weights)

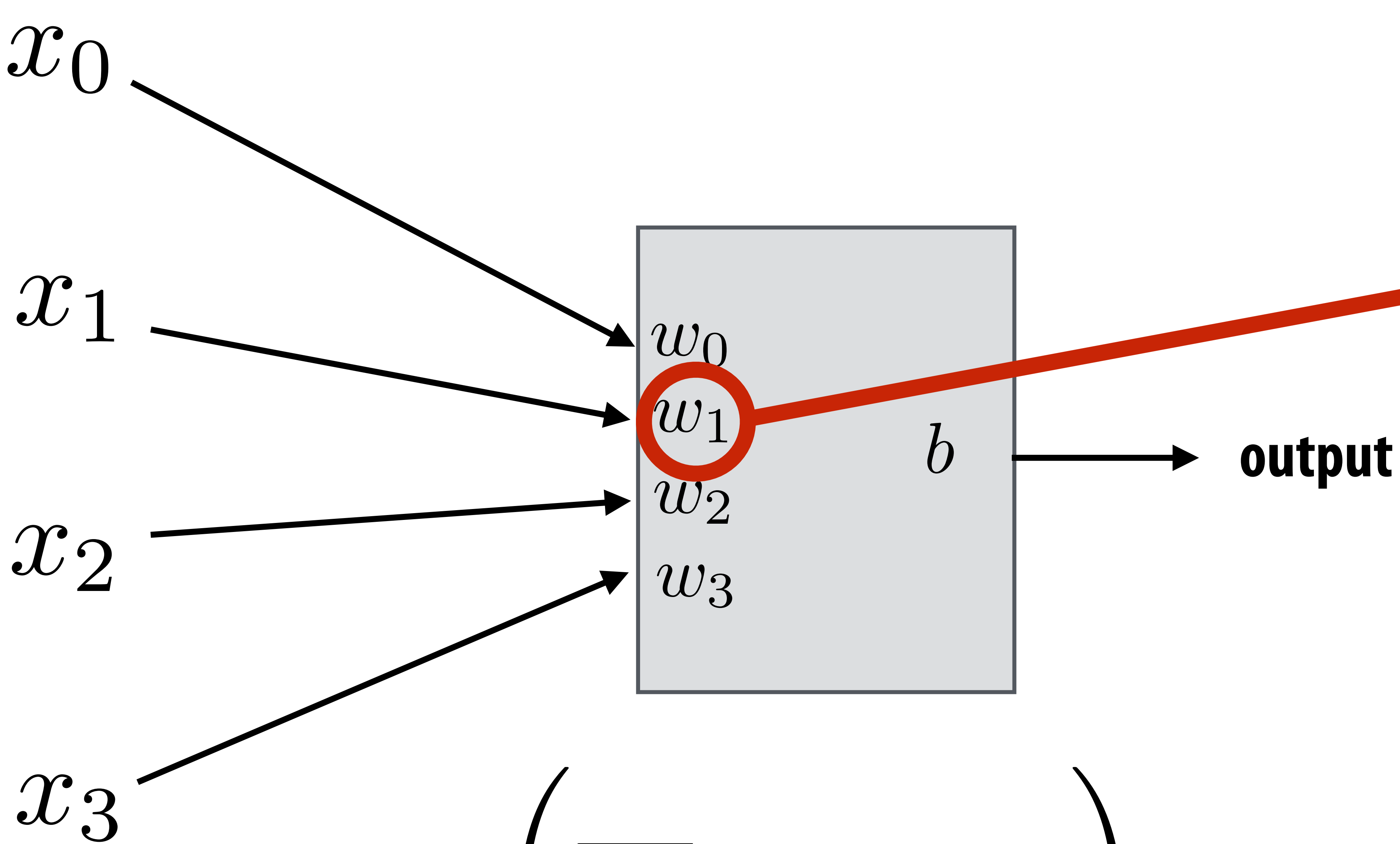
- **Footprint: cumbersome to store, download, etc.**
  - 500 MB app downloads make users unhappy!

- **Consider energy cost of 1B parameter network**
  - Running on input stream at 20 Hz
  - 640 pJ per 32-bit DRAM access
  - (20 x 1B x 640pJ) = 12.8W for DRAM access

    (more than power budget of any modern smartphone)

Is there an opportunity for compression?

“Pruning” (sparsifying) a network

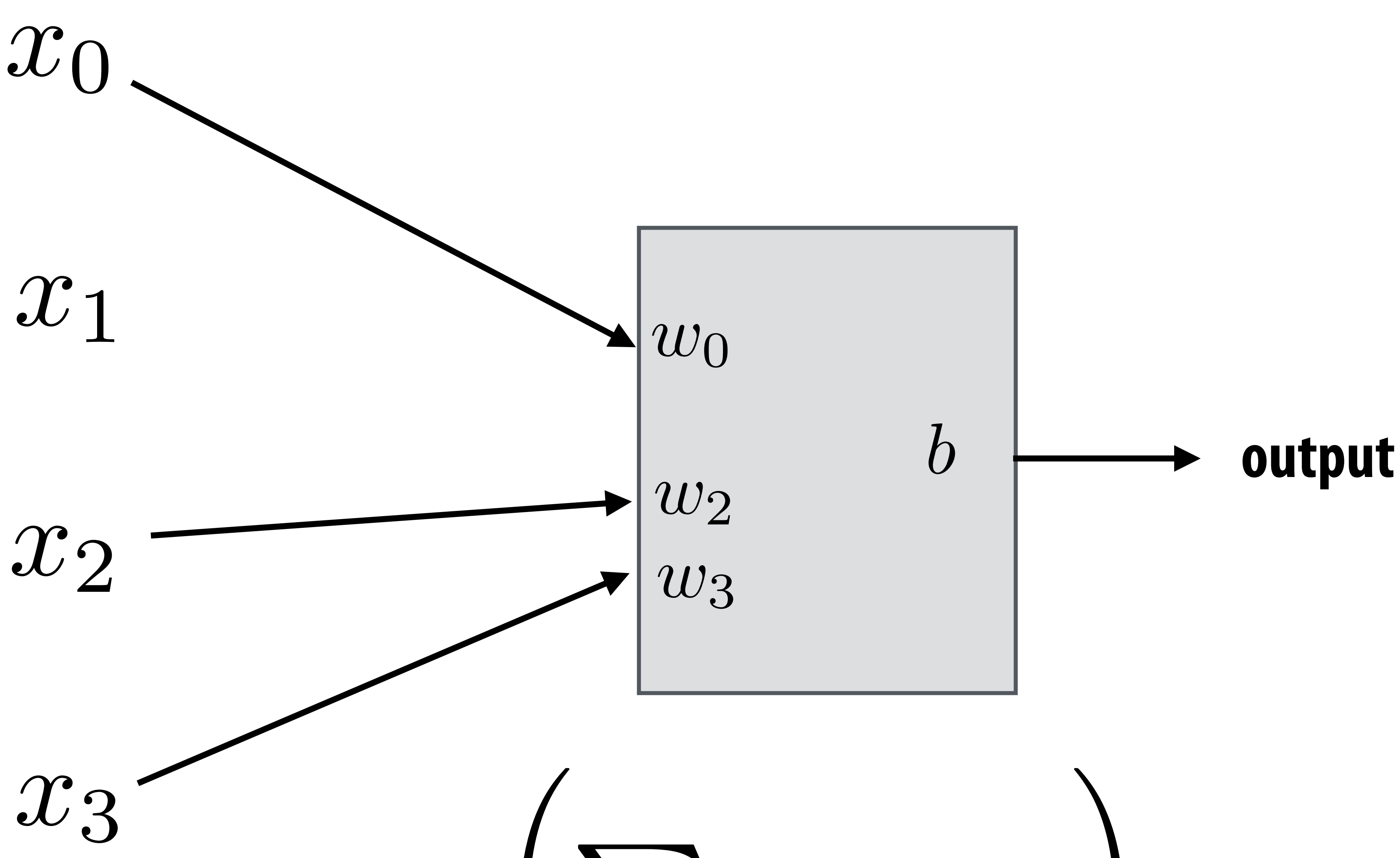


If weight is near zero, then corresponding input has little impact on output of neuron.

$$f\left(\sum_i x_i w_i + b\right)$$

$$f(x) = max(0, x)$$

"Pruning" (sparsifying) a network



$$f\left(\sum_i x_i w_i + b\right)$$

$$f(x) = max(0, x)$$

Idea: prune connections with near zero weight

Remove entire units if all connections are pruned.

Representing "sparsified" networks

Step 1: prune low-weight links (iteratively retrain network, then prune)

- **Over 90% of weights in fully connected layers can be removed without significant loss of accuracy**
- **Store weight matrices in compressed sparse row (CSR) format**

```
Indices    1    4    9  ...
Value     1.8  0.5  2.1
```

0	1.8	0	0	0.5	0	0	0	0	1.1	...

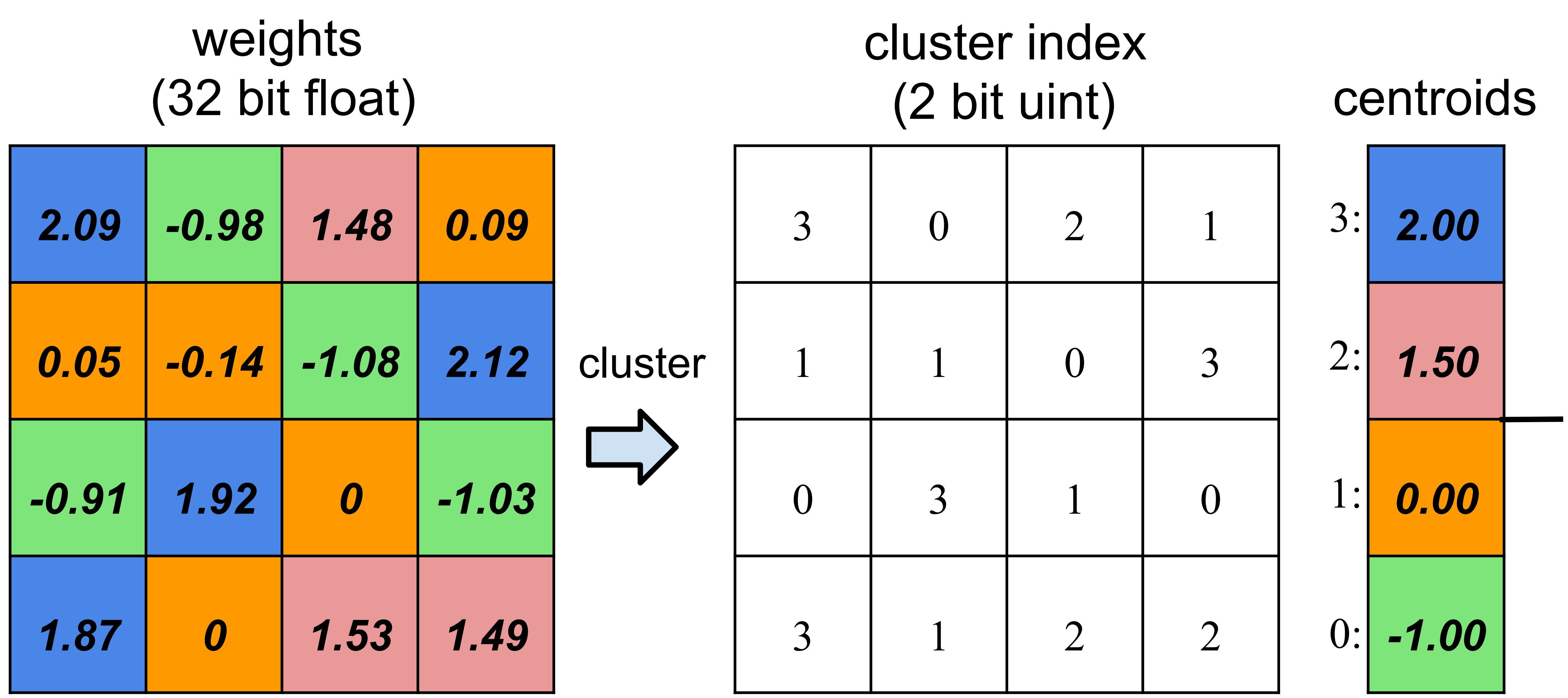
Reduce storage over head of indices by delta encoding them to fit in 8 bits

```
Indices   1    3    5  ...
Value     1.8  0.5  2.1
```

Efficiently storing the surviving connections

Step 2: Weight sharing: make surviving connections share a small set of weights

- Cluster weights via k-means clustering
- Compress weights by only storing index of assigned cluster (lg(k) bits)
- This is a form of lossy compression



Step 3: Huffman encode quantized weights and CSR indices (lossless compression)

[Han ICLR16]

VGG-16 sparsification

Large savings in fully connected layers due to combination of pruning, quantization, Huffman encoding *

Layer	#Weights	Weights% (P)	Weigh bits (P+Q)	Weight bits (P+Q+H)	Index bits (P+Q)	Index bits (P+Q+H)	Compress rate (P+Q)	Compress rate (P+Q+H)
conv1_1	2K	58%	8	6.8	5	1.7	40.0%	29.97%
conv1_2	37K	22%	8	6.5	5	2.6	9.8%	6.99%
conv2_1	74K	34%	8	5.6	5	2.4	14.3%	8.91%
conv2_2	148K	36%	8	5.9	5	2.3	14.7%	9.31%
conv3_1	295K	53%	8	4.8	5	1.8	21.7%	11.15%
conv3_2	590K	24%	8	4.6	5	2.9	9.7%	5.67%
conv3_3	590K	42%	8	4.6	5	2.2	17.0%	8.96%
conv4_1	1M	32%	8	4.6	5	2.6	13.1%	7.29%
conv4_2	2M	27%	8	4.2	5	2.9	10.9%	5.93%
conv4_3	2M	34%	8	4.4	5	2.5	14.0%	7.47%
conv5_1	2M	35%	8	4.7	5	2.5	14.3%	8.00%
conv5_2	2M	29%	8	4.6	5	2.7	11.7%	6.52%
conv5_3	2M	36%	8	4.6	5	2.3	14.8%	7.79%
fc6	103M	4%	5	3.6	5	3.5	1.6%	1.10%
fc7	17M	4%	5	4	5	4.3	1.5%	1.25%
fc8	4M	23%	5	4	5	3.4	7.1%	5.24%
Total	138M	7.5%(13×)	6.4	4.1	5	3.1	3.2% (**31**×)	2.05% (**49**×)

P = connection pruning (prune low weight connections)

Q = quantize surviving weights (using shared weights)

H = Huffman encode

ImageNet Image Classification Performance

	Top-1 Error	Top-5 Error	Model size	
VGG-16 Ref	31.50%	11.32%	552 MB	
VGG-16 Compressed	31.17%	10.91%	**11.3 MB**	49×

*** Benefits of automatic pruning apply mainly to fully connected layers, but many modern networks are dominated by costs of convolutional layers**

Compressing weights (and activations)

- Many efforts to use low precision values for DNN weights and intermediate activations
- In the extreme case: 1-bit

XNOR-Net: ImageNet Classification Using Binary Convolutional Neural Networks

Mohammad Rastegari[†], Vicente Ordonez[†], Joseph Redmon[*], Ali Farhadi[†*]

Allen Institute for AI[†], University of Washington[*]
{mohammadr,vicenteor}@allenai.org
{pjreddie,ali}@cs.washington.edu

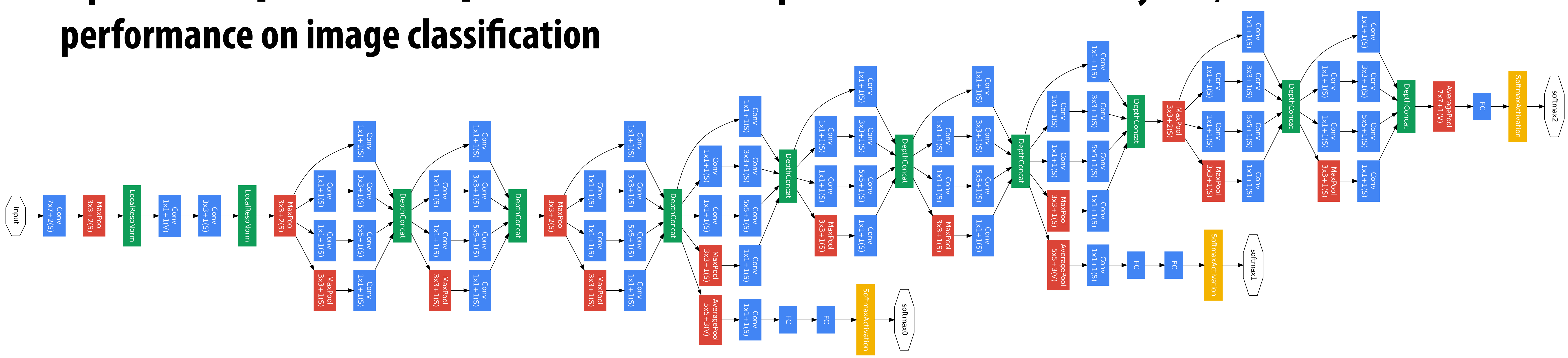
Abstract. We propose two efficient approximations to standard convolutional neural networks: Binary-Weight-Networks and XNOR-Networks. In Binary-Weight-Networks, the filters are approximated with binary values resulting in 32× memory saving. In XNOR-Networks, both the filters and the input to convolutional layers are binary. XNOR-Networks approximate convolutions using primarily binary operations. This results in 58× faster convolutional operations (in terms of number of the high precision operations) and 32× memory savings. XNOR-Nets offer the possibility of running state-of-the-art networks on CPUs (rather than GPUs) in real-time. Our binary networks are simple, accurate, efficient, and work on challenging visual tasks. We evaluate our approach on the ImageNet classification task. The classification accuracy with a Binary-Weight-Network version of AlexNet is the same as the full-precision AlexNet. We compare our method with recent network binarization methods, BinaryConnect and BinaryNets, and outperform these methods by large margins on ImageNet, more than 16% in top-1 accuracy. Our code is available at: http://allenai.org/plato/xnornet.

This a great example of non-domain-specific vs. domain-specific approach to innovation

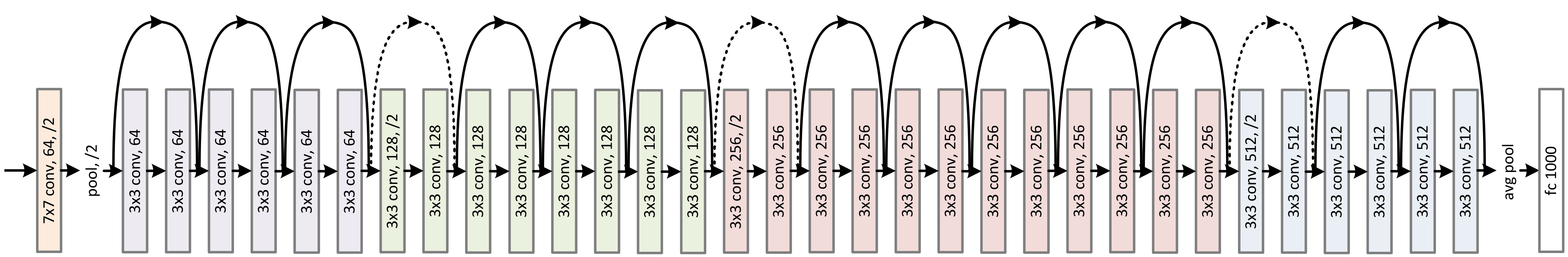
Leveraging domain-knowledge: more efficient topologies (aka better algorithm design)

- Original DNNs for image recognition where overprovisioned
  - Large filters, many filters
- Modern DNNs designs are hand-designed to be sparser

SqueezeNet: [Iandola 2017] Reduced number of parameters in AlexNet by 50x, with similar performance on image classification

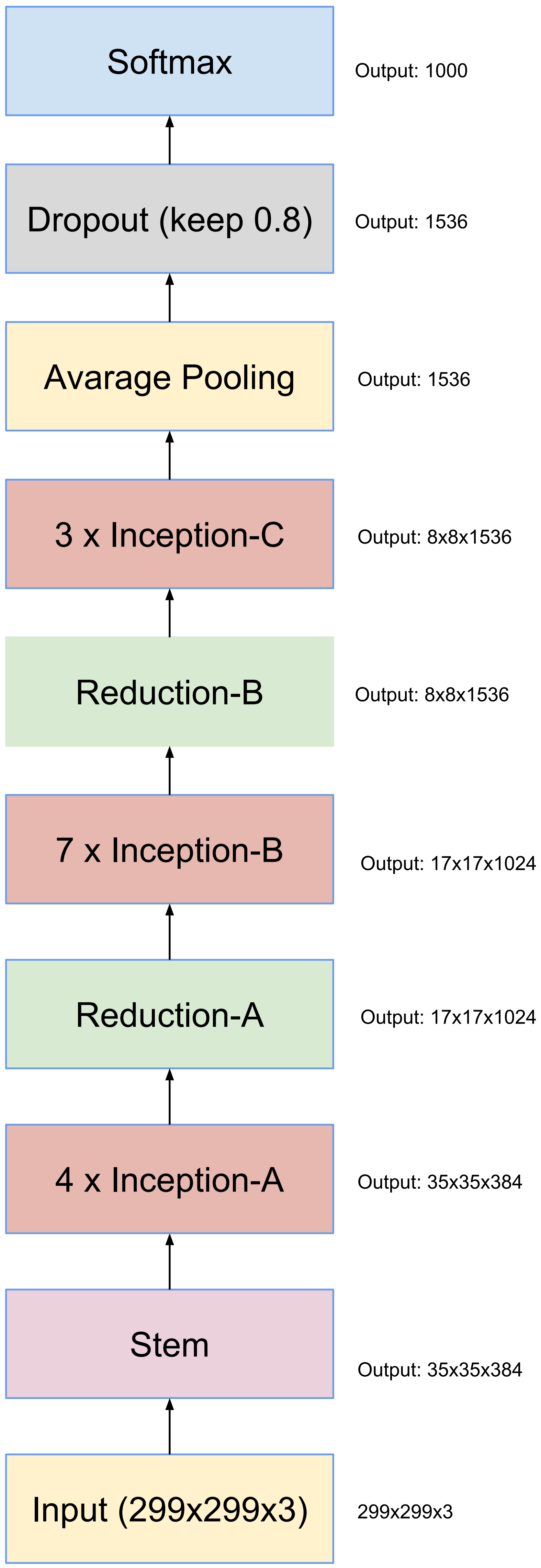


Inception v1 (GoogleLeNet) — 27 total layers, 7M parameters

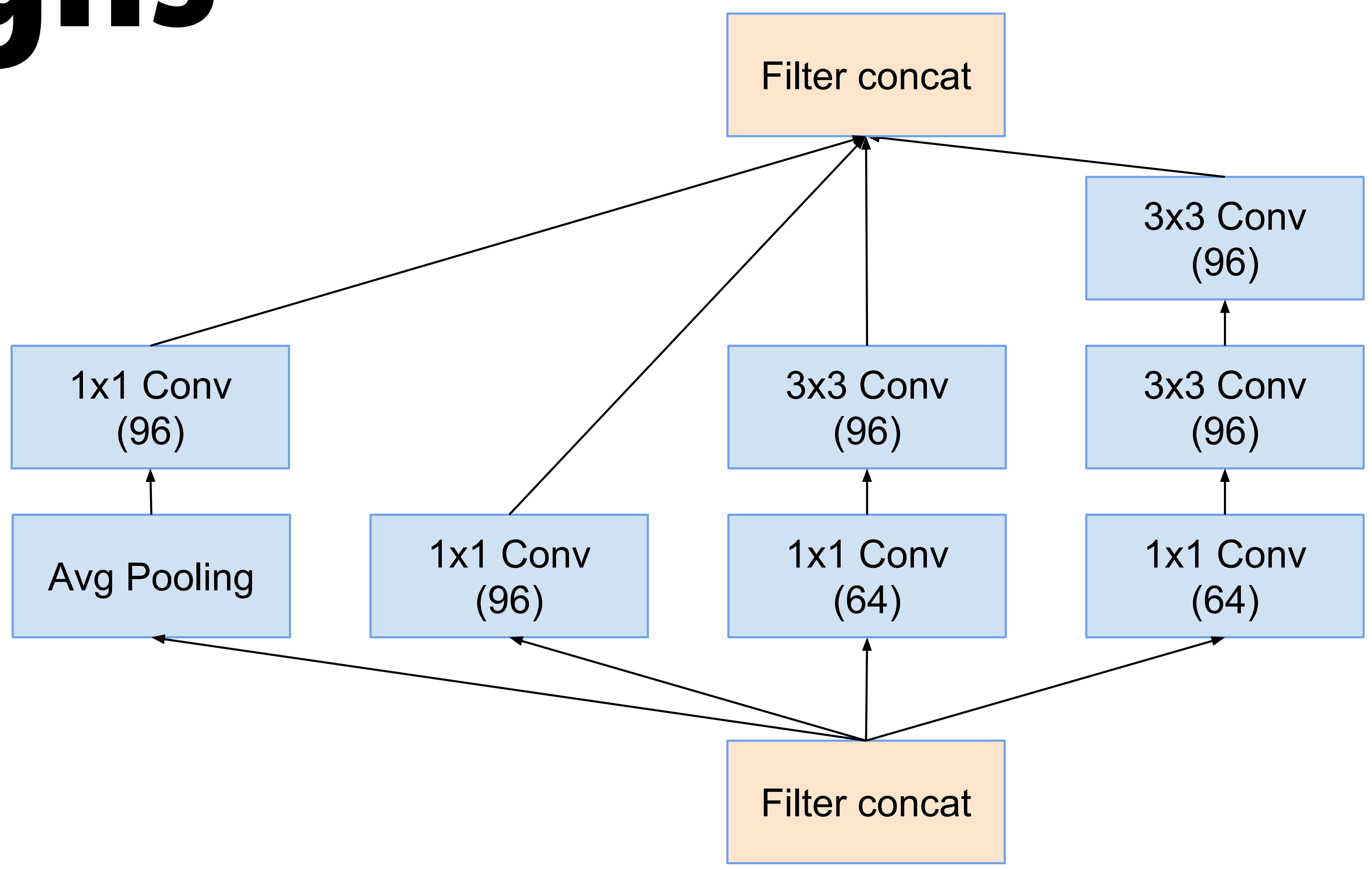


ResNet (34 layer version)

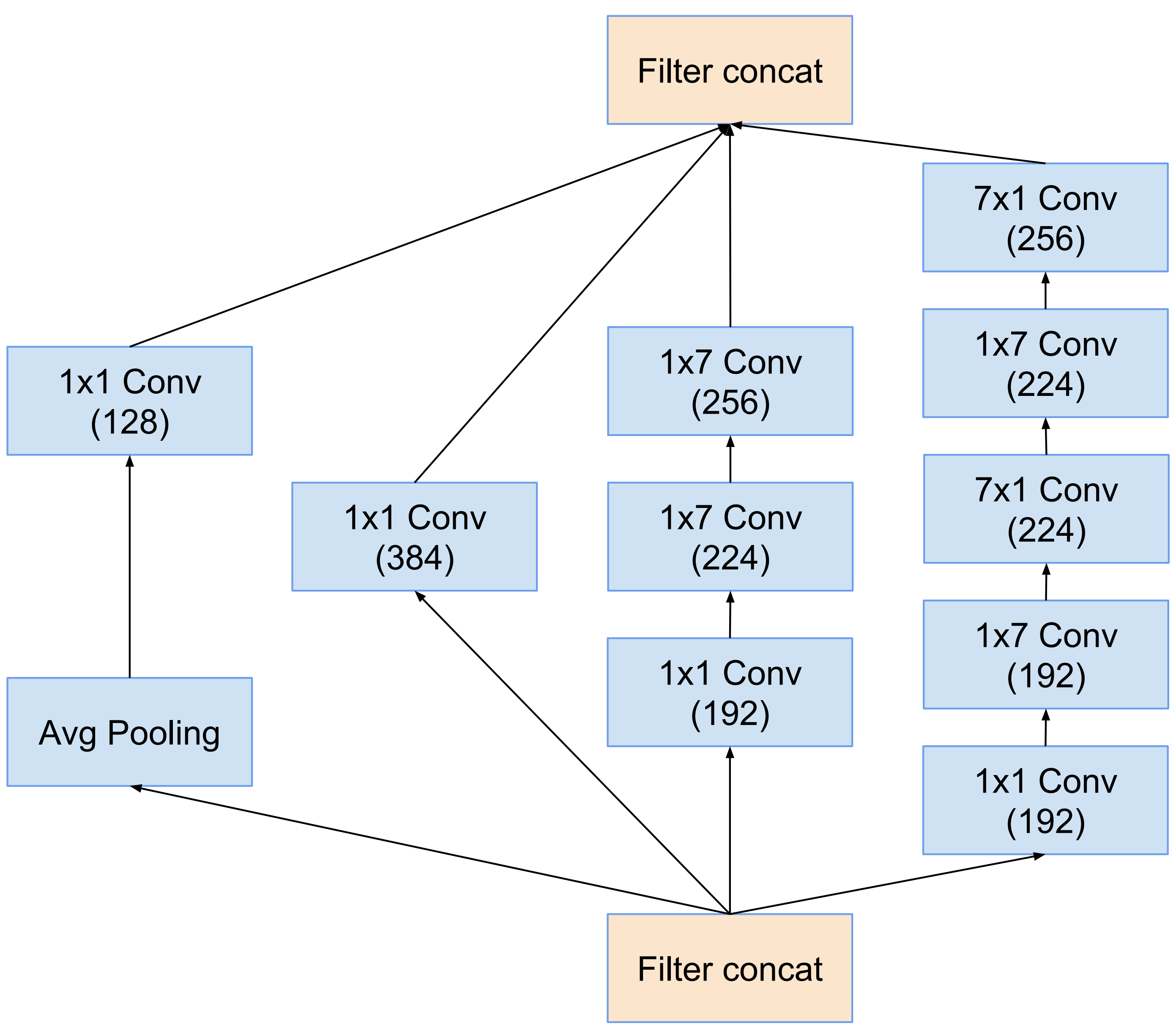
Modular network designs



Inception v4

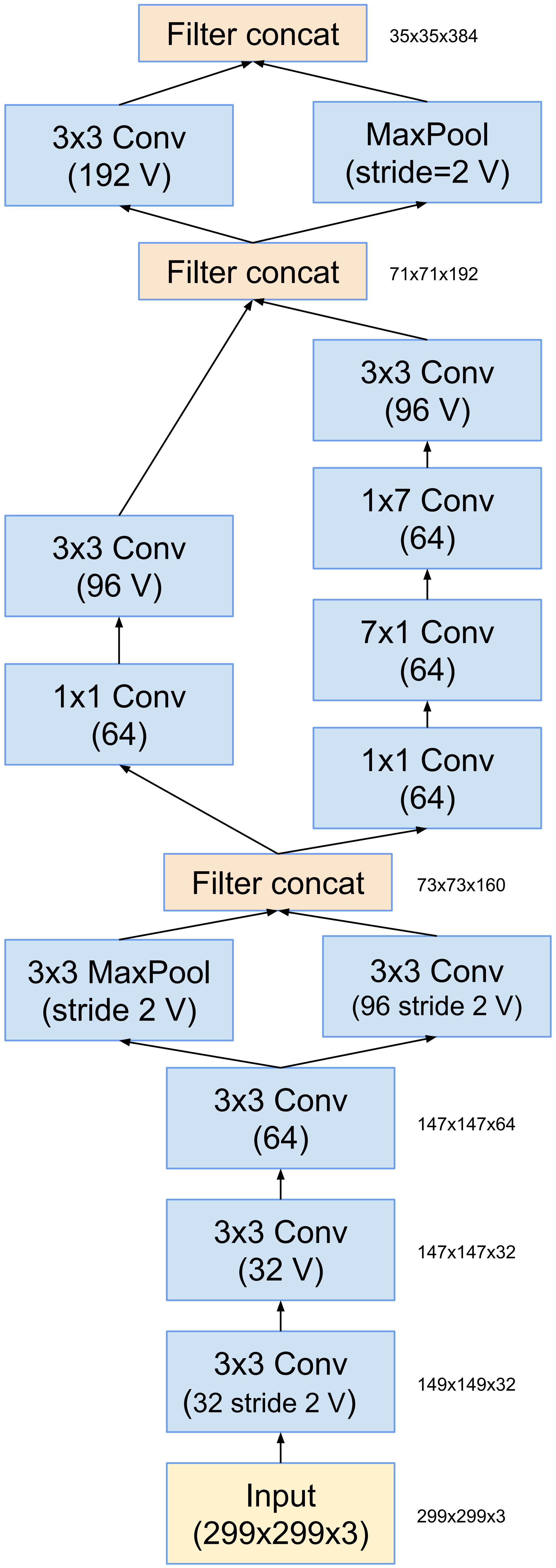


A block

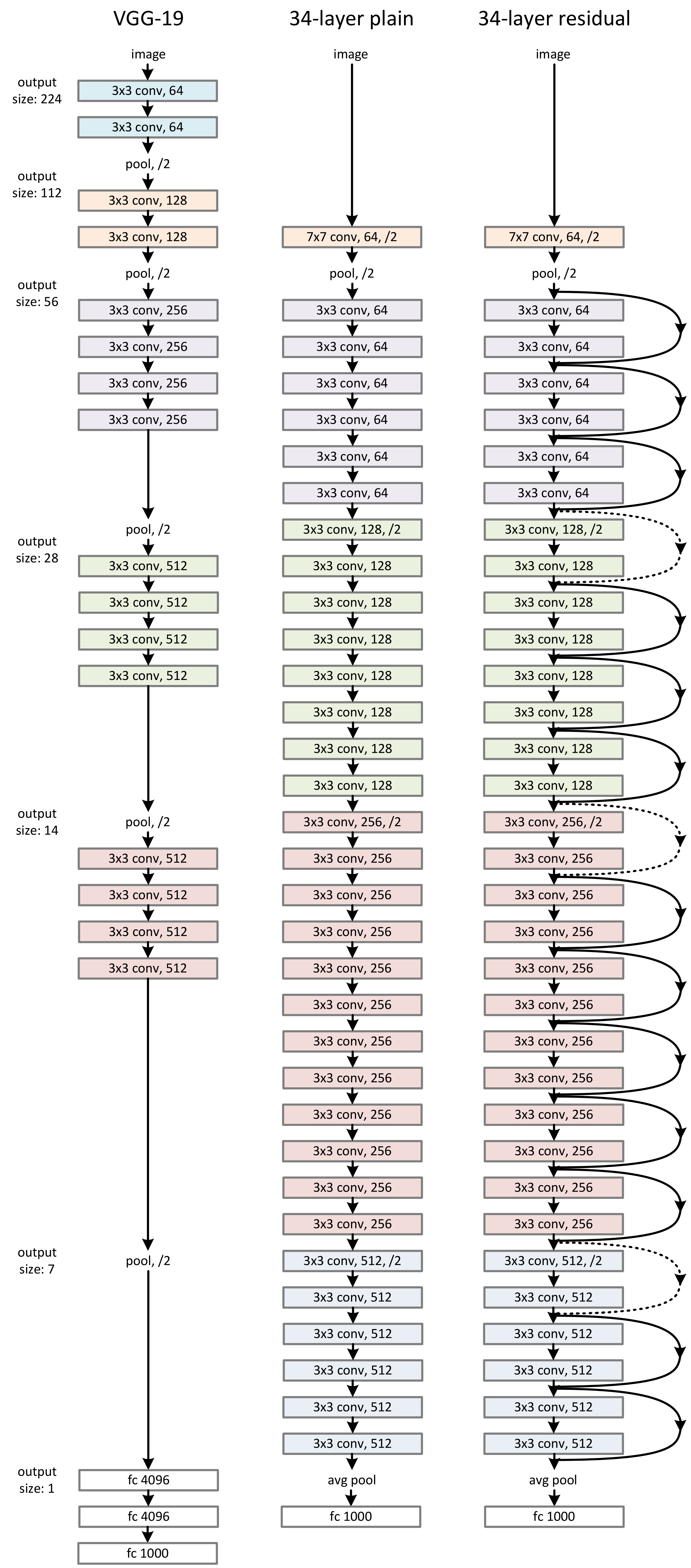


B block

Inception stem



ResNet



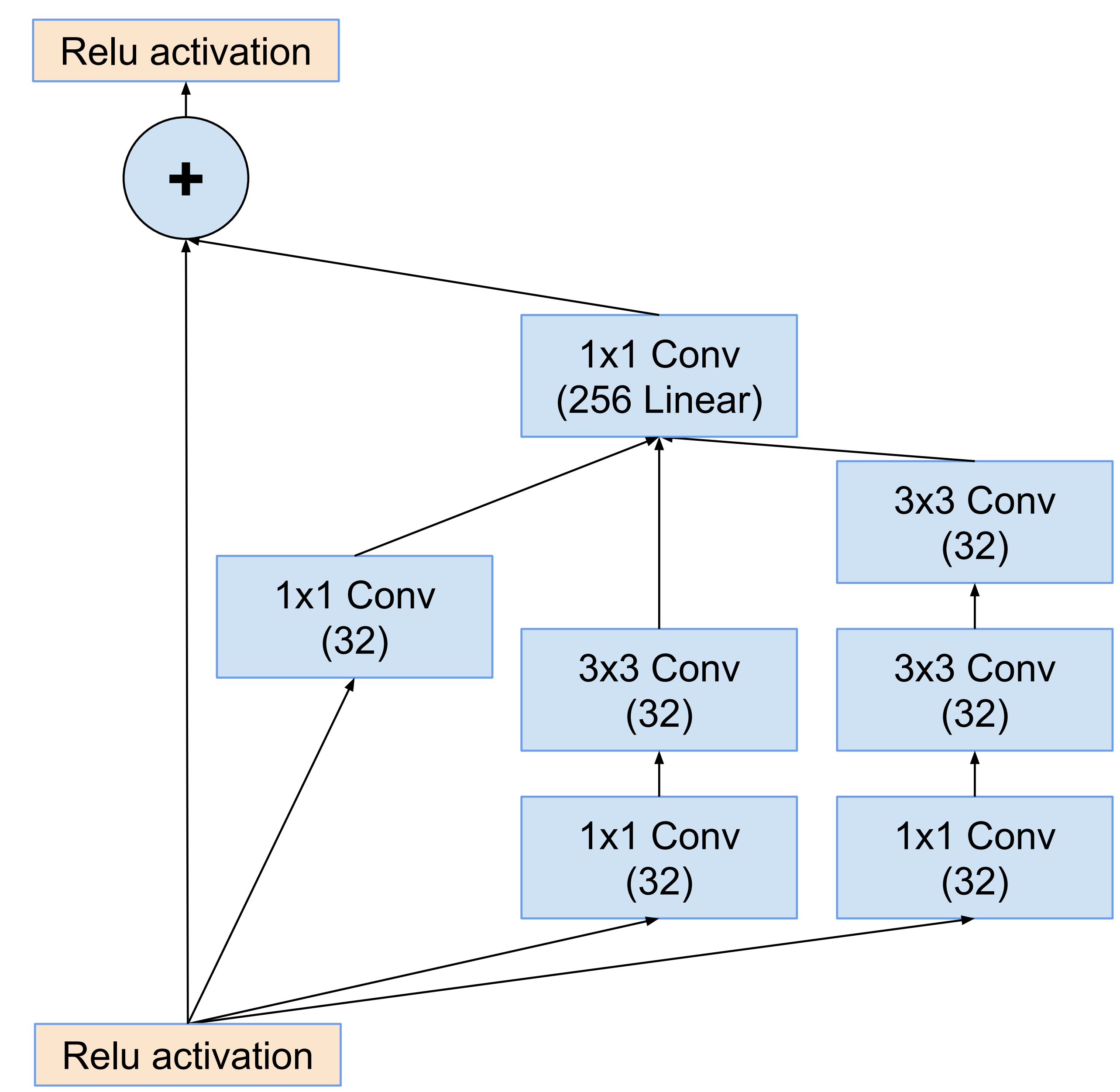
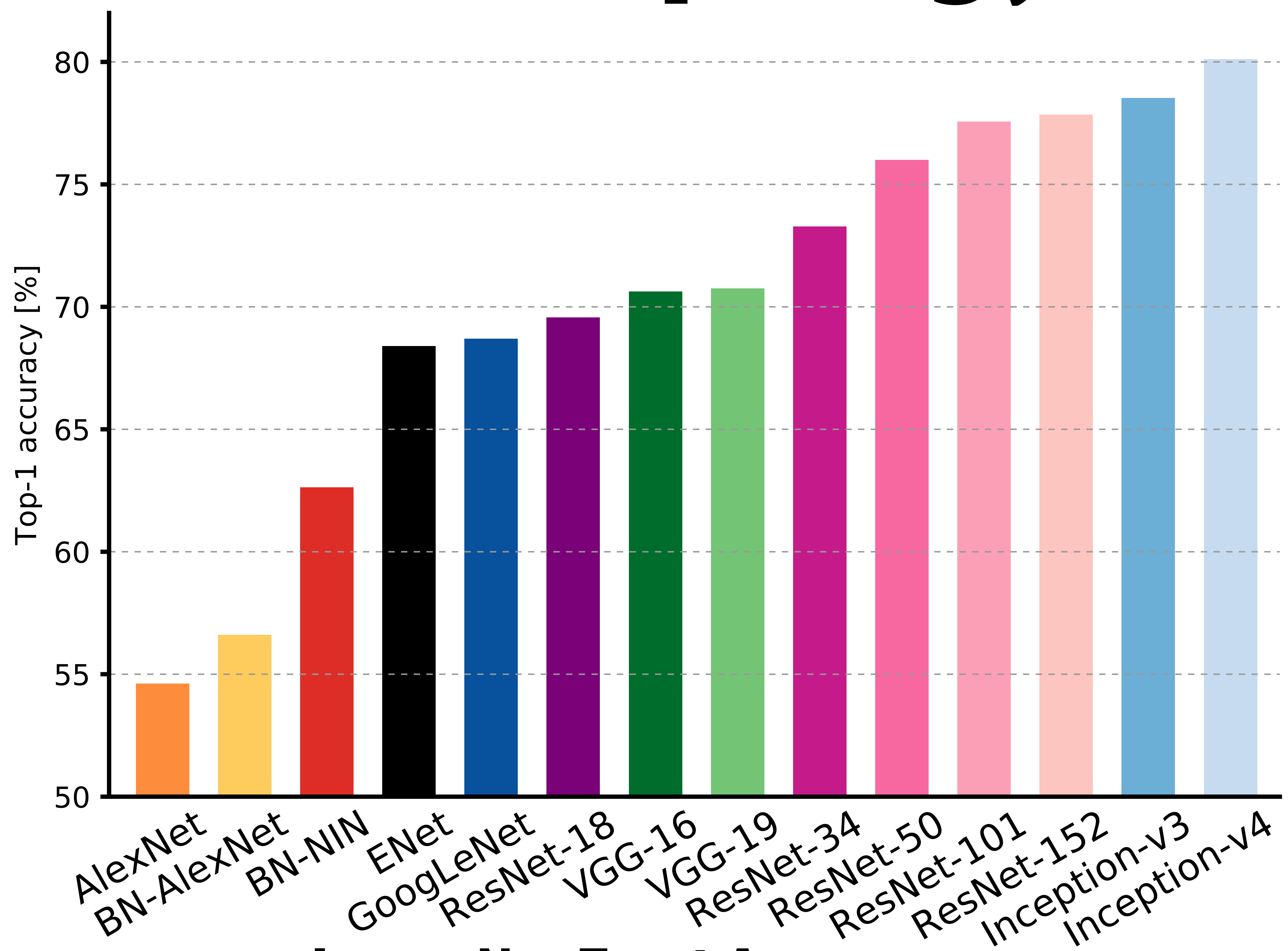
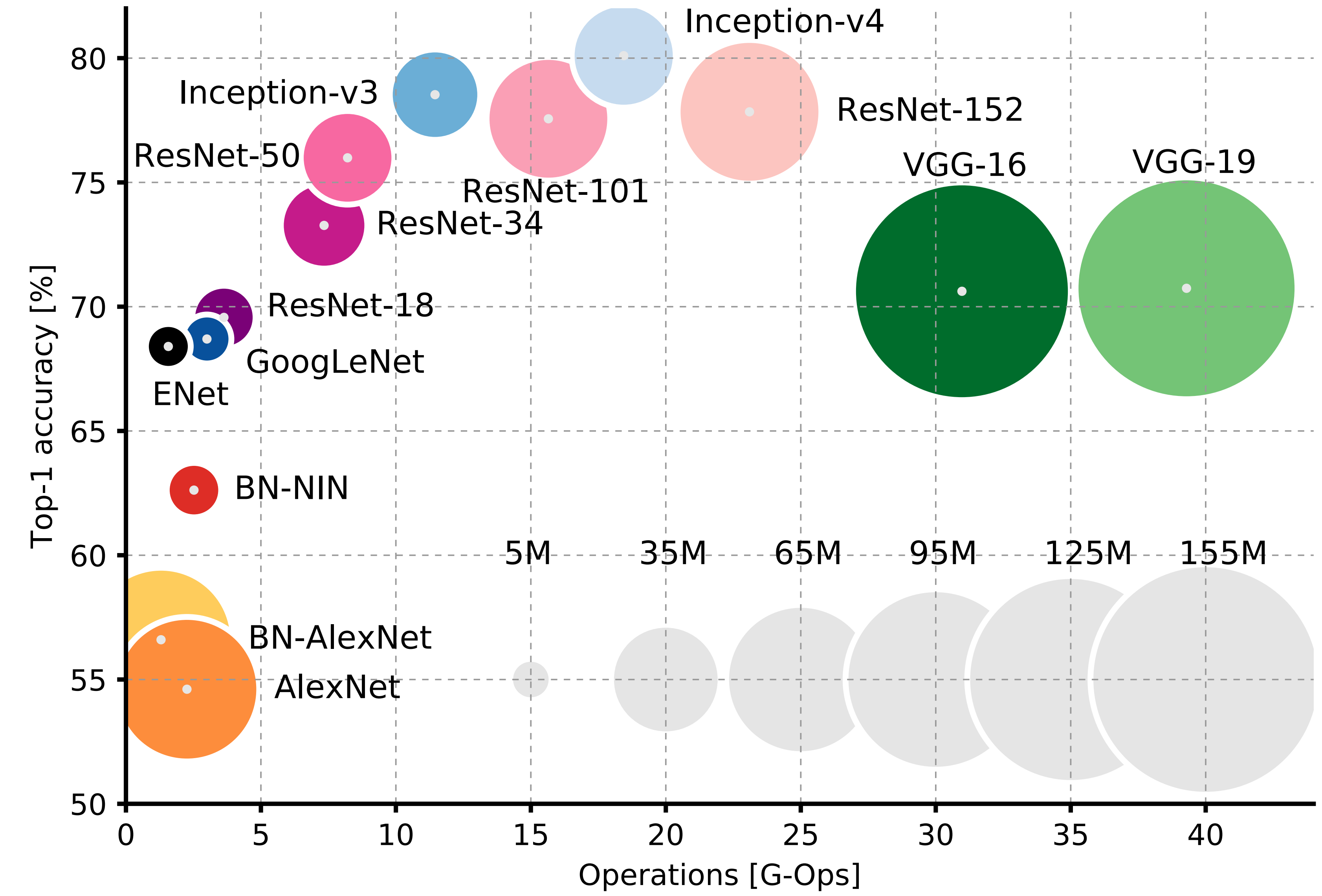


Figure 10. The schema for 35 × 35 grid (Inception-ResNet-A) module of Inception-ResNet-v1 network.

Effect of topology innovation



ImageNet Top 1 Accuracy



Flops cost (area of circle is # params)

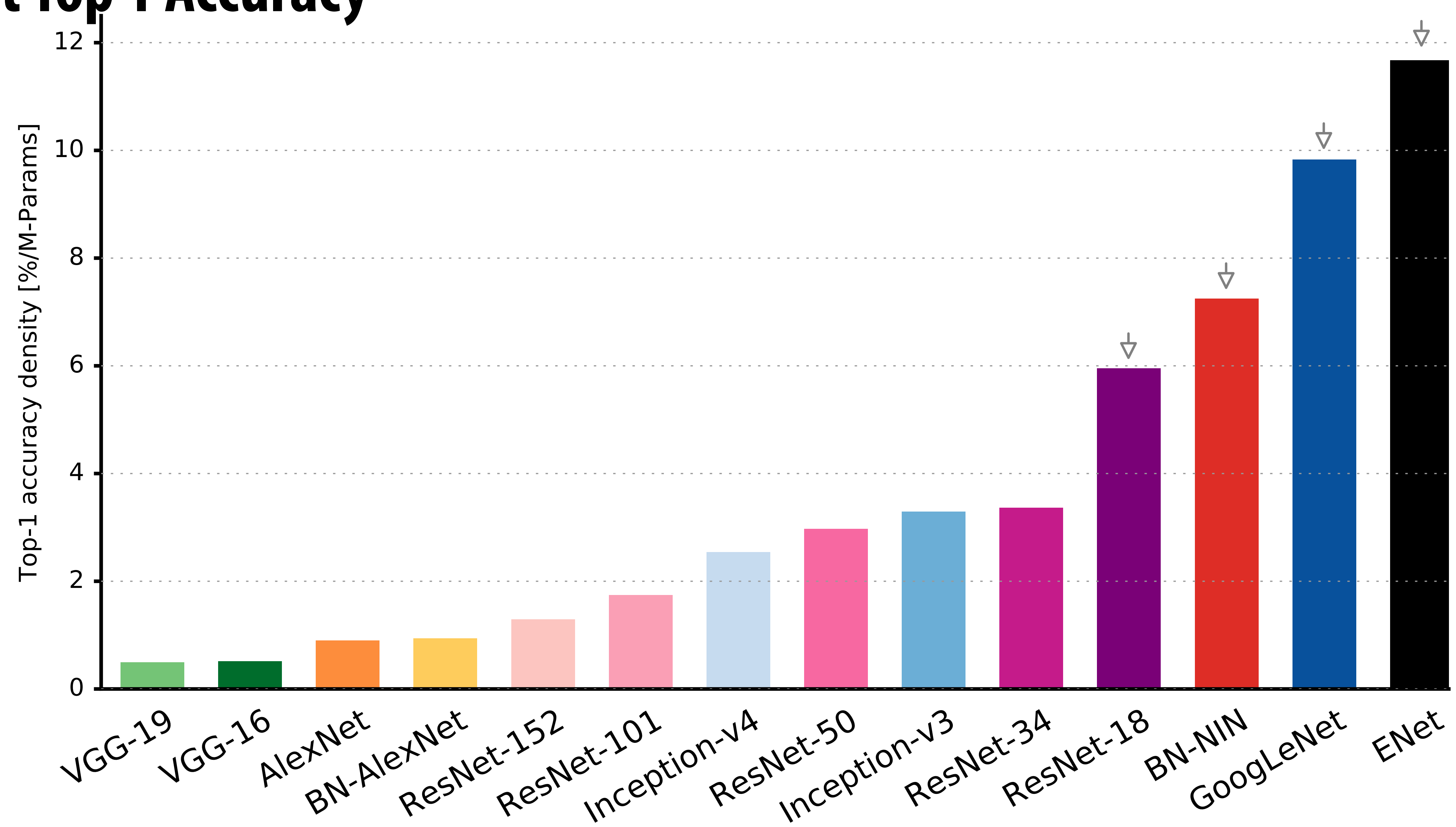


Figure credit: Canziani et al 2017

Accuracy (points) per flop

Improving accuracy/cost (image classification)

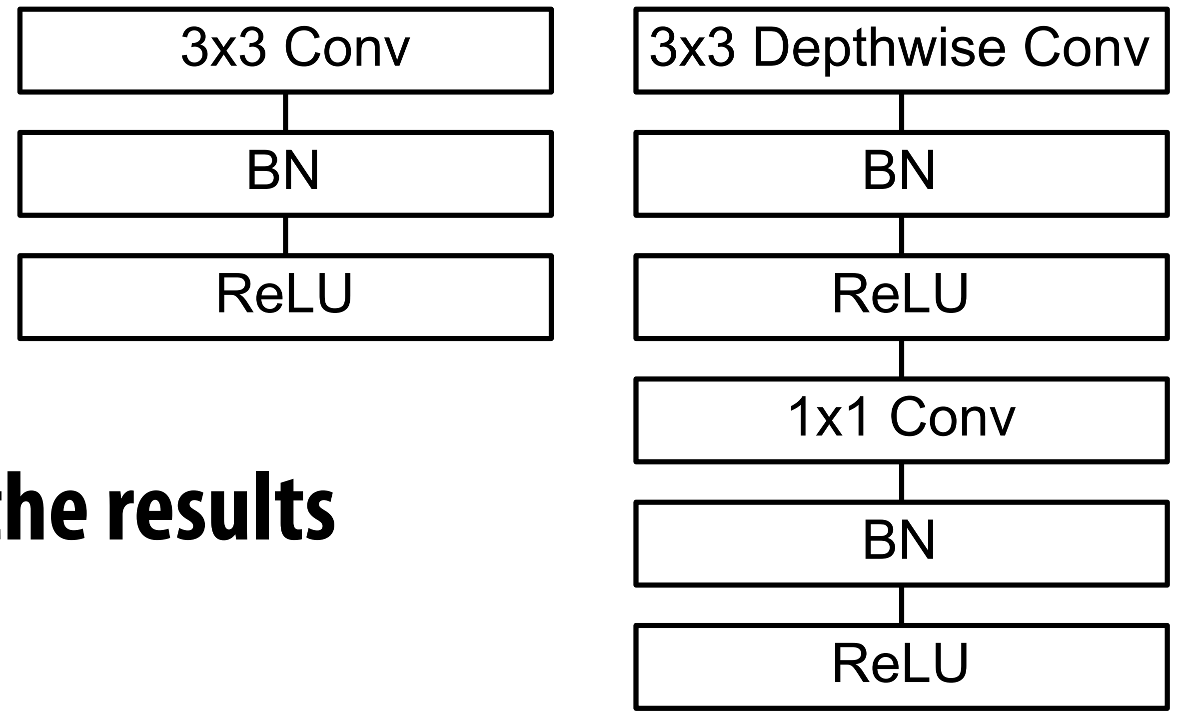
2014 → 2017 ~ 25x improvement in cost at similar accuracy

	ImageNet Top-1 Accuracy	Num Params	Cost/image (MADDs)	
VGG-16	71.5%	138M	15B	[2014]
GoogleNet	70%	6.8M	1.5B	[2015]
ResNet-18	73% *	11.7M	1.8B	[2016]
MobileNet-224	70.5%	4.2M	0.6B	[2017]

* 10-crop results (ResNet 1-crop results are similar to other DNNs in this table)

MobileNet

[Howard et al. 2017]



Factor NUM_FILTERS 3x3xNUM_CHANNELS convolutions into:
- **NUM_CHANNELS 3x3x1 convolutions for each input channel**
- **And NUM_FILTERS 1x1xNUM_CHANNELS convolutions to combine the results**

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Type / Stride	Filter Shape	Input Size
Conv / s2	$3 \times 3 \times 3 \times 32$	$224 \times 224 \times 3$
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Conv / s1	$1 \times 1 \times 64 \times 128$	$56 \times 56 \times 64$
Conv dw / s1	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 128$	$56 \times 56 \times 128$
Conv dw / s2	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 256$	$28 \times 28 \times 128$
Conv dw / s1	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 256$	$28 \times 28 \times 256$
Conv dw / s2	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 512$	$14 \times 14 \times 256$
$5\times$ Conv dw / s1	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
Conv / s1	$1 \times 1 \times 512 \times 512$	$14 \times 14 \times 512$
Conv dw / s2	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
Conv / s1	$1 \times 1 \times 512 \times 1024$	$7 \times 7 \times 512$
Conv dw / s2	$3 \times 3 \times 1024$ dw	$7 \times 7 \times 1024$
Conv / s1	$1 \times 1 \times 1024 \times 1024$	$7 \times 7 \times 1024$
Avg Pool / s1	Pool 7×7	$7 \times 7 \times 1024$
FC / s1	1024×1000	$1 \times 1 \times 1024$
Softmax / s1	Classifier	$1 \times 1 \times 1000$

Image classification (ImageNet)
Comparison to Common DNNs

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
1.0 MobileNet-224	70.6%	569	4.2
GoogleNet	69.8%	1550	6.8
VGG 16	71.5%	15300	138

Image classification (ImageNet)
Comparison to Other Compressed DNNs

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
0.50 MobileNet-160	60.2%	76	1.32
Squeezenet	57.5%	1700	1.25
AlexNet	57.2%	720	60

Value of improving DNN topology

- Increasing overall accuracy on a task (often primary goal of CV/ML papers)
- Increasing accuracy/unit cost
- What is cost of evaluating DNN?
  - Number of ops (often measured in multiply adds)
  - Bandwidth!
    - Loading model weights + loading/storing intermediate activations
    - Careful! Certain layers are bandwidth bound, e.g., batch norm

Depthwise separable convolutions add additional batch norm operations to network (after each step of depthwise conv layer)

Input: Values of x over a mini-batch: $\mathcal{B} = \{x_{1\ldots m}\}$;
Parameters to be learned: γ, β

Output: $\{y_i = \mathrm{BN}_{\gamma,\beta}(x_i)\}$

$$\mu_{\mathcal{B}} \leftarrow \frac{1}{m}\sum_{i=1}^{m} x_i \qquad \text{// mini-batch mean}$$

$$\sigma_{\mathcal{B}}^2 \leftarrow \frac{1}{m}\sum_{i=1}^{m}(x_i - \mu_{\mathcal{B}})^2 \qquad \text{// mini-batch variance}$$

$$\widehat{x}_i \leftarrow \frac{x_i - \mu_{\mathcal{B}}}{\sqrt{\sigma_{\mathcal{B}}^2 + \epsilon}} \qquad \text{// normalize}$$

$$y_i \leftarrow \gamma\widehat{x}_i + \beta \equiv \mathrm{BN}_{\gamma,\beta}(x_i) \qquad \text{// scale and shift}$$

Implication: number of ops can be a poor predictor of run time of network (too small to utilize processor, bandwidth bound, etc.)!

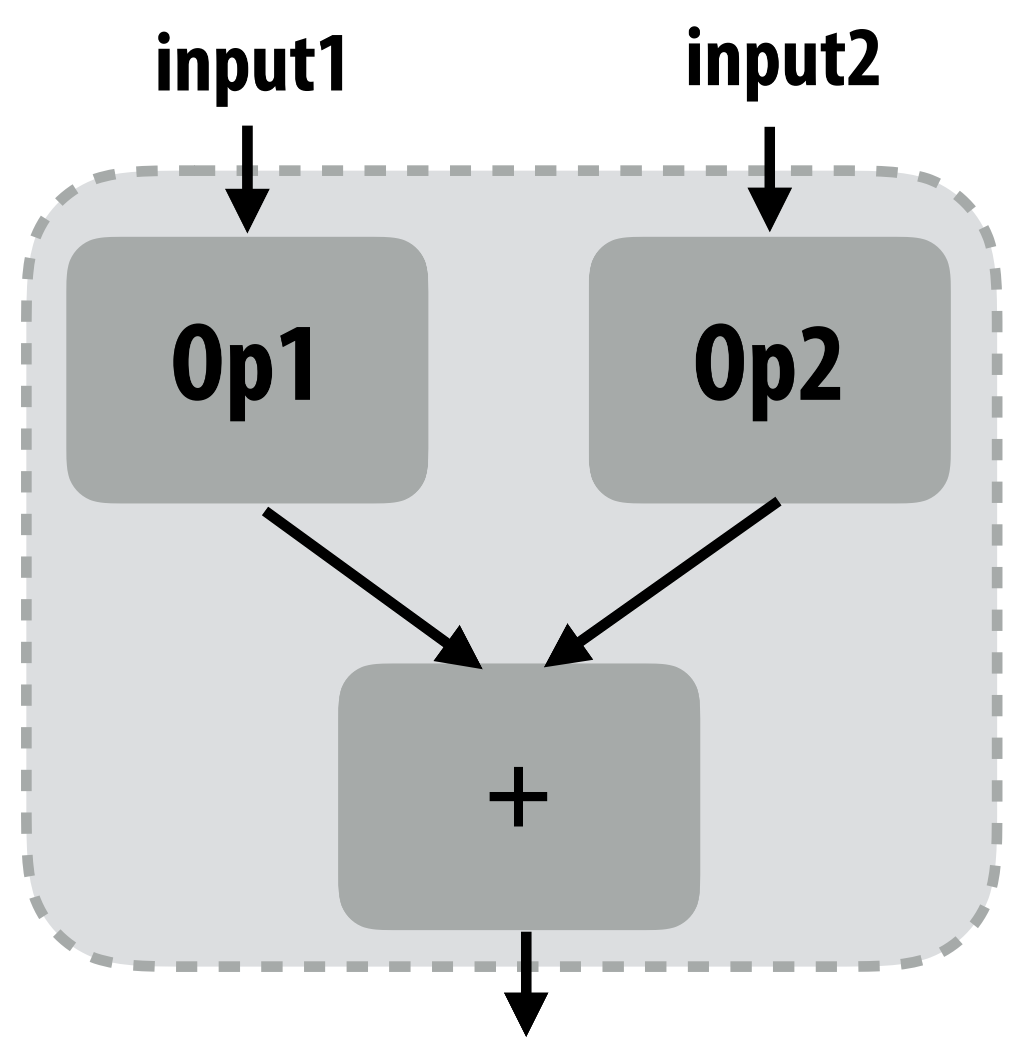
Model optimization techniques

- Manually designing better models
  - Common parameters: depth of network, width of filters, number of filters per layer, convolutional stride, etc.
- Good scheduling of performance-critical operations (layers)
  - Loop blocking/tiling, fusion
  - Typically optimized manually by humans (but significant research efforts to automate scheduling)
- Compressing models
  - Lower bit precision
  - Automatic sparsification/pruning
- Automatically discovering efficient model topologies (architecture search)

DNN architecture search

- Learn an efficient DNN topology along with associated weights
- Example: progressive neural architecture search [Liu et al. 18]

"Block" = (input1, input2, op1, op2)



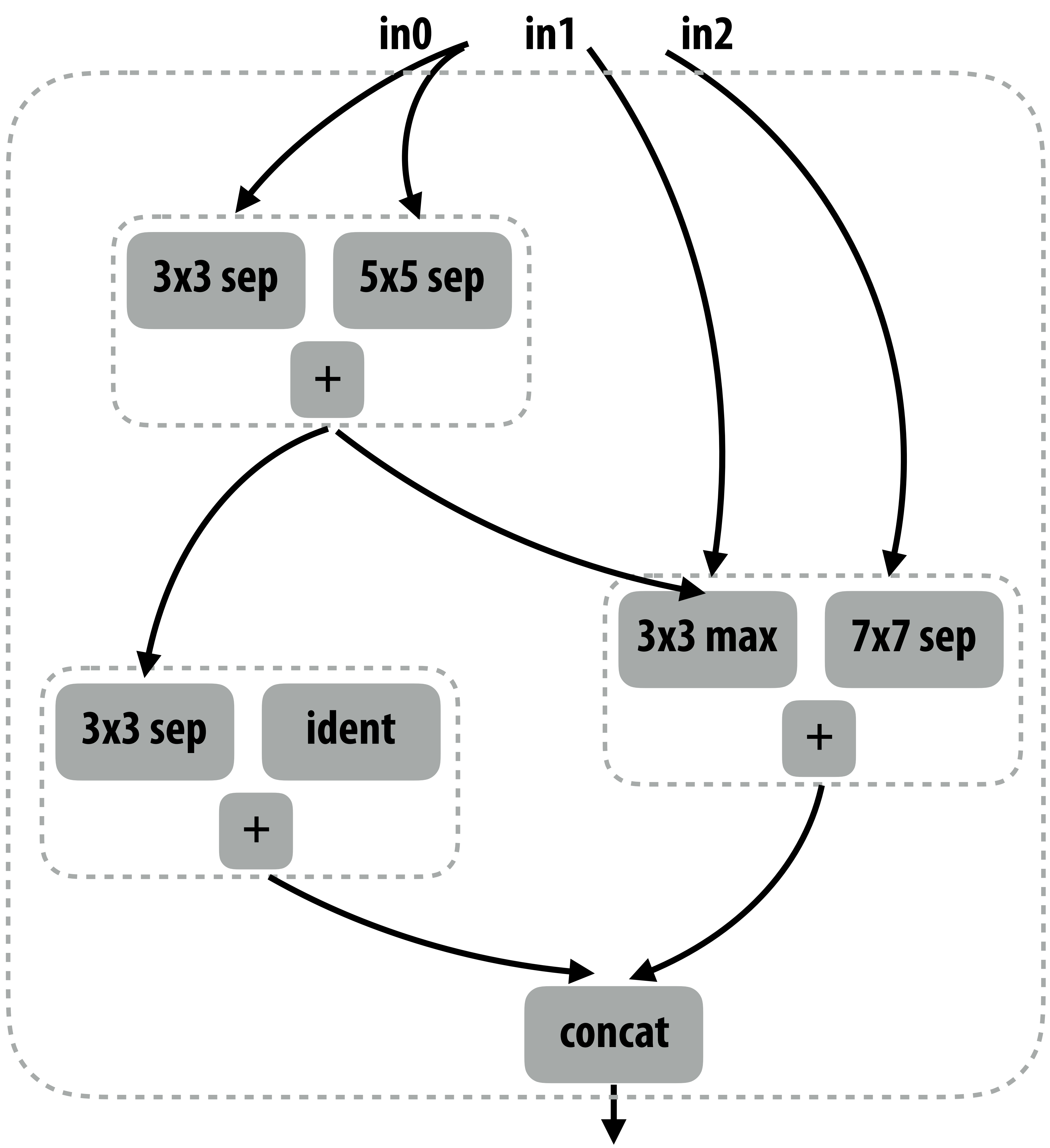
Eight possible operations:

3x3 depthwise-separable conv	identity
5x5 depthwise-separable conv	3x3 average pool
7x7 depthwise-separable conv	3x3 max pool
1x7 followed by 7x1 conv	3x3 dilated conv

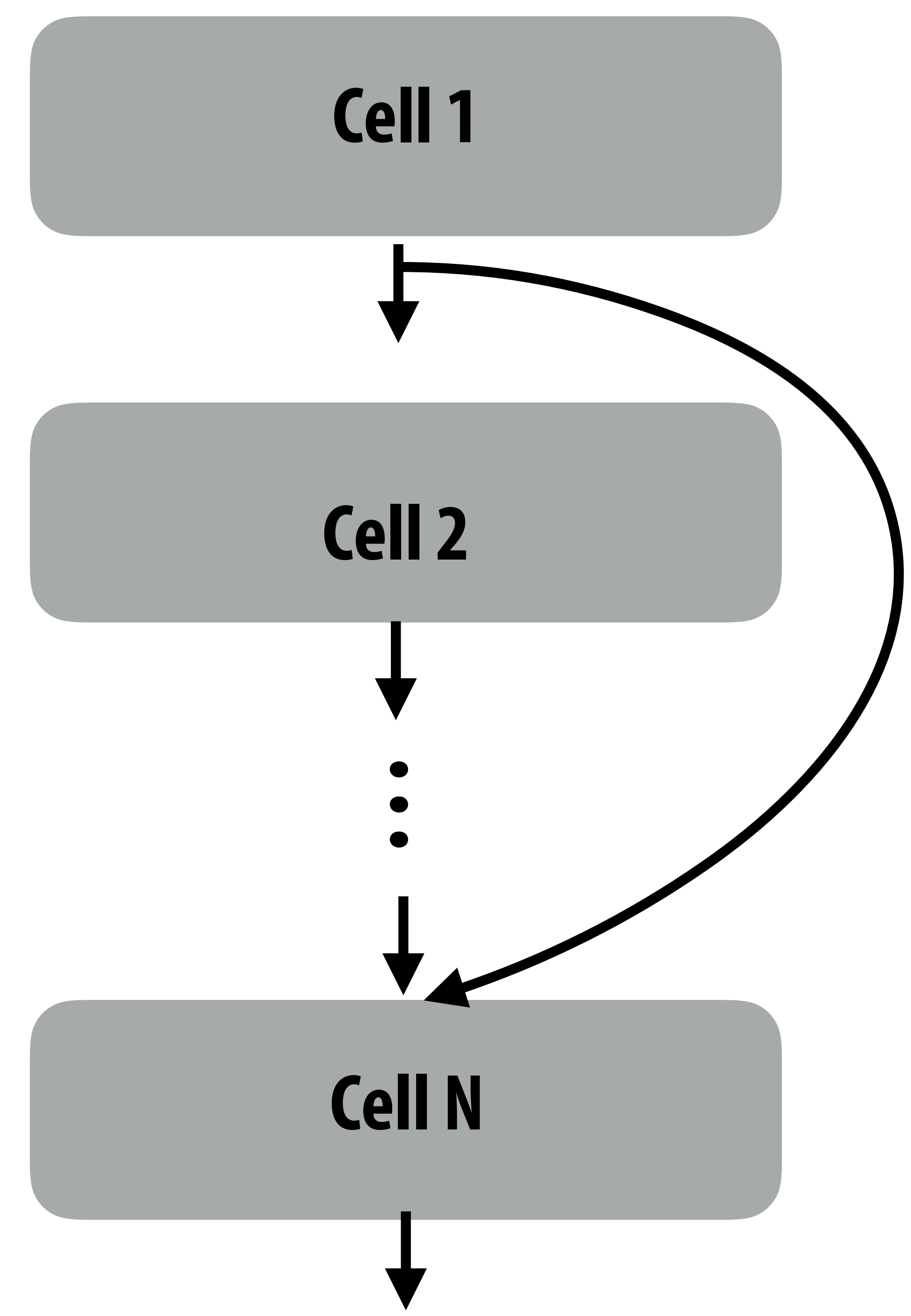
Architecture search space

[Liu et al. 18]

Cells are DAGs of *B* blocks



DNNs are sequences of *N* cells



Cells have one output, can receive input from all prior cells

Progressive neural architecture search

- Parameters:
  - N = number of cells in DNN
  - B = max blocks per cell

- Let S be the set of 1-block cells (8 choices)
- train N-cell DNNs using cells given by s in S
- keep *k* best performing cells on test set
- for i=2 to B:
  - for each s in S, add new cells to S by adding additional block to s (many possible ways to add new block)
  - train N-cell DNNs for all cells in S
  - keep *k* best performing cells on test set

Progressive neural architecture search results

- Automatic search was able to find model architectures that yielded similar/ better accuracy to hand designed models (and comparable costs)

Model	Params	Mult-Adds	Top-1	Top-5
MobileNet-224 [14]	4.2M	569M	70.6	89.5
ShuffleNet (2x) [37]	5M	524M	70.9	89.8
NASNet-A ($N = 4$, $F = 44$) [41]	5.3M	564M	74.0	91.6
AmoebaNet-B ($N = 3$, $F = 62$) [27]	5.3M	555M	74.0	91.5
AmoebaNet-A ($N = 4$, $F = 50$) [27]	5.1M	555M	74.5	92.0
AmoebaNet-C ($N = 4$, $F = 50$) [27]	6.4M	570M	75.7	92.4
PNASNet-5 ($N = 3$, $F = 54$)	5.1M	588M	74.2	91.9

- Forms of architecture search implemented by Cloud-based ML hosting services (user provides training data, service searches for good model)

Google Cloud
Cloud AutoML BETA

Why might a GPU be a good platform for DNN evaluation?

Deep neural networks on GPUs

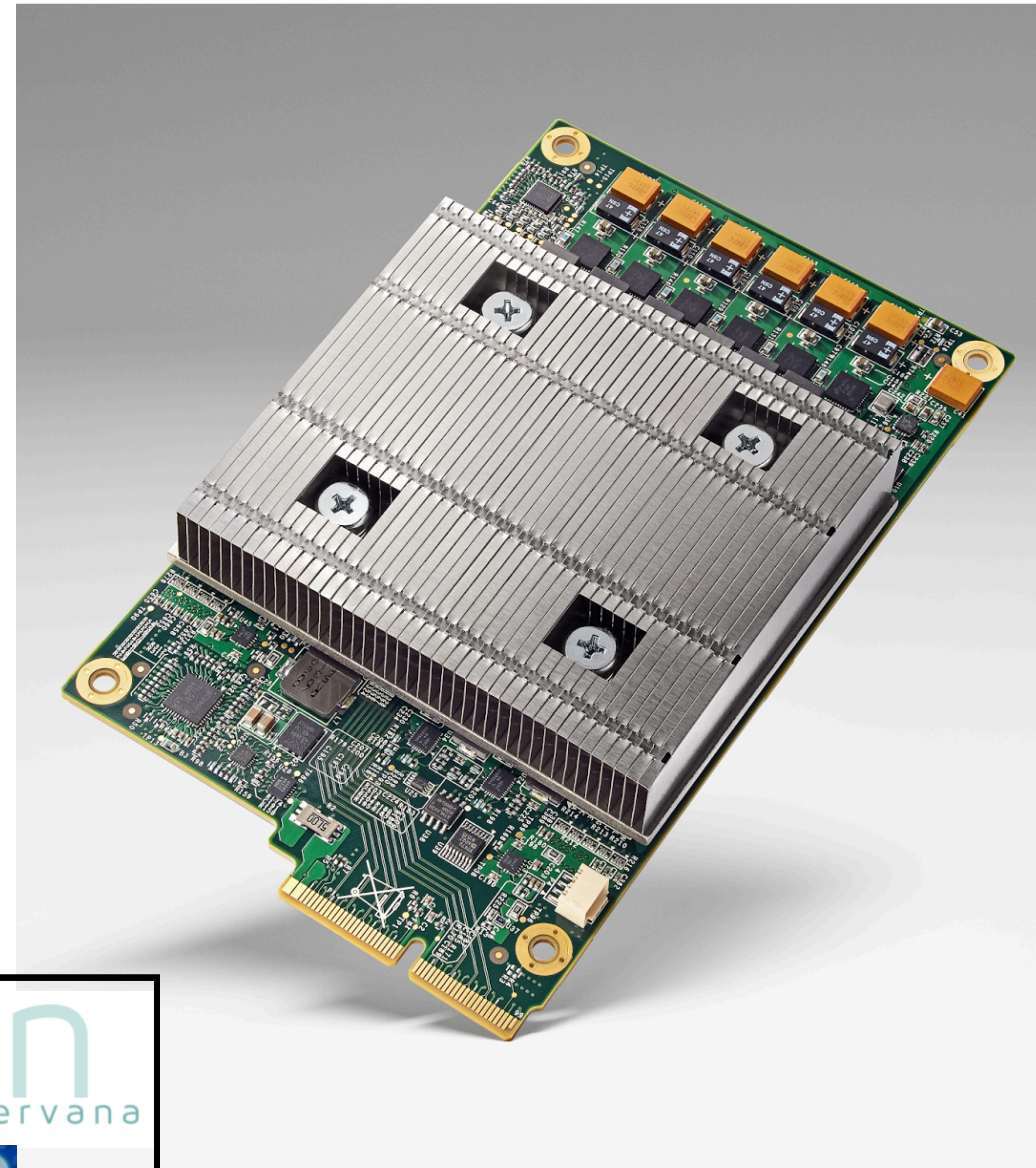
- **Many high-performance DNN implementations target GPUs**
  - High arithmetic intensity computations (computational characteristics similar to dense matrix-matrix multiplication)
  - Benefit from flop-rich architectures
  - Highly-optimized library of kernels exist for GPUs (cuDNN)
    - Most CPU-based implementations use basic matrix-multiplication-based formulation (good implementations could run faster!)

Facebook's Big Sur

Why might a GPU be a sub-optimal platform for DNN evaluation?

Increasing efficiency through specialization

Example: Google's Tensor Processing Unit (TPU)
Accelerates deep learning operations in Google datacenter



Intel has announced
Lake Crest ML accelerator
(formerly called Nervana)

Summary: efficiently evaluating deep nets

- Workload characteristics
  - Convlayers: high arithmetic intensity, significant portion of cost when evaluating DNNs for computer vision
  - Similar data access patterns to dense-matrix multiplication (exploiting temporal reuse is key), but implementation as matrix-matrix multiplication is sub-optimal

- Significant interest in reducing size of networks for both training and evaluation

- Algorithmic techniques (better model architectures) are responsible for huge speedups in recent years
  - Expect increasing use of automated model search techniques

- Model innovation complemented and extended by much ongoing work on efficient mapping of key layers to CPUs/GPUs and on custom hardware for evaluation
  - Specialized hardware is a topic of a coming lecture