Engineering Challenges of Deep Learning

feat. C++

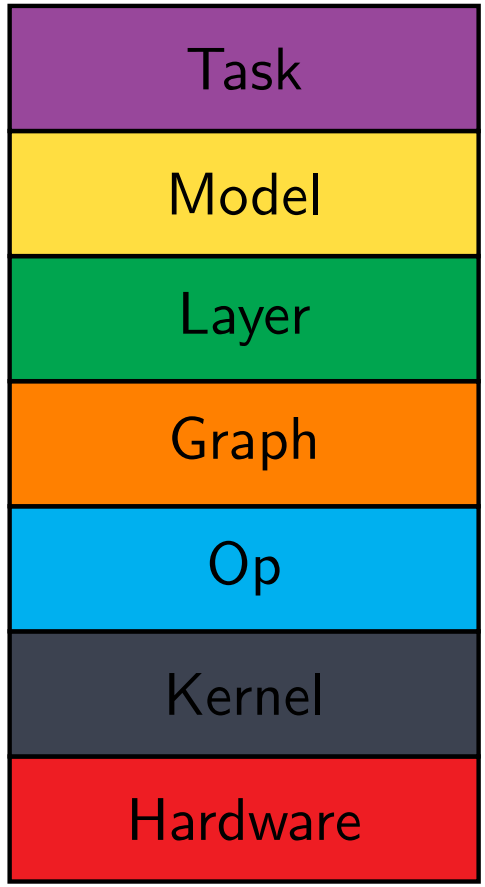
Peter Goldsborough

Facebook

November 8, 2017

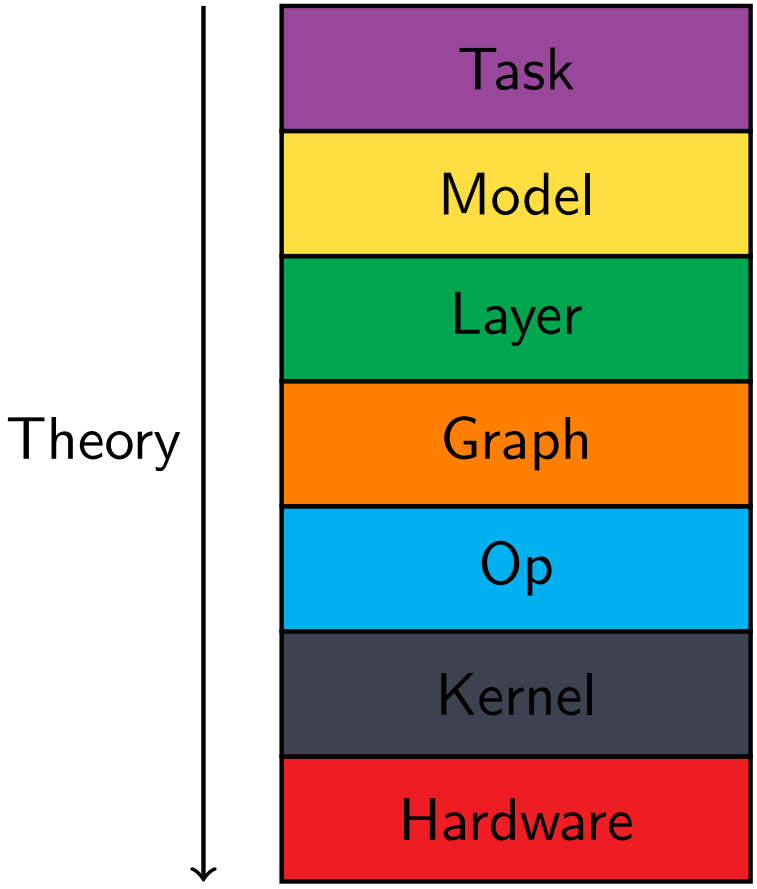
Strategy

Strategy



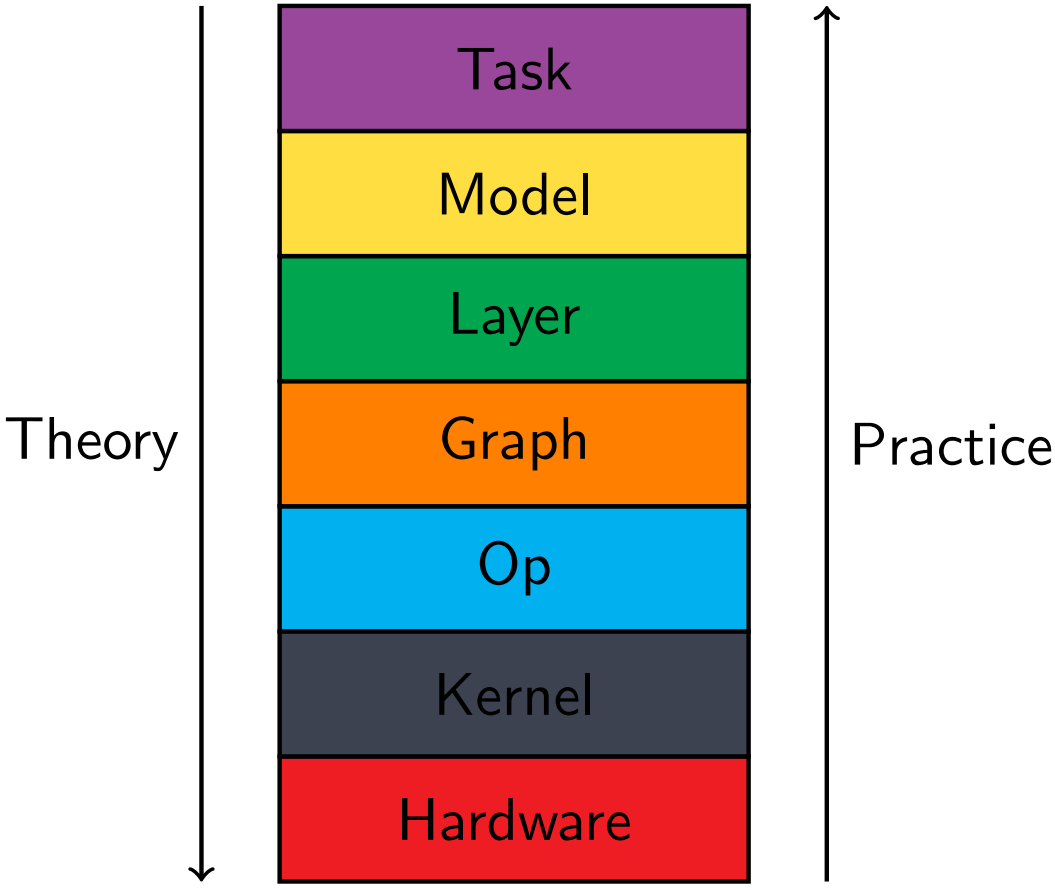
OSI Model of Machine Learning

Strategy



OSI Model of Machine Learning

Strategy



OSI Model of Machine Learning

Task Layer

Task Layer

$$f\left(\text{  }\right) = \texttt{Teapot}$$

Classification*

$\star$ Supervised

Task Layer

$$f\left(\text{  }\right) = \texttt{Teapot}$$

Classification*

$$f\left(\text{  }\right) = \text{  }$$

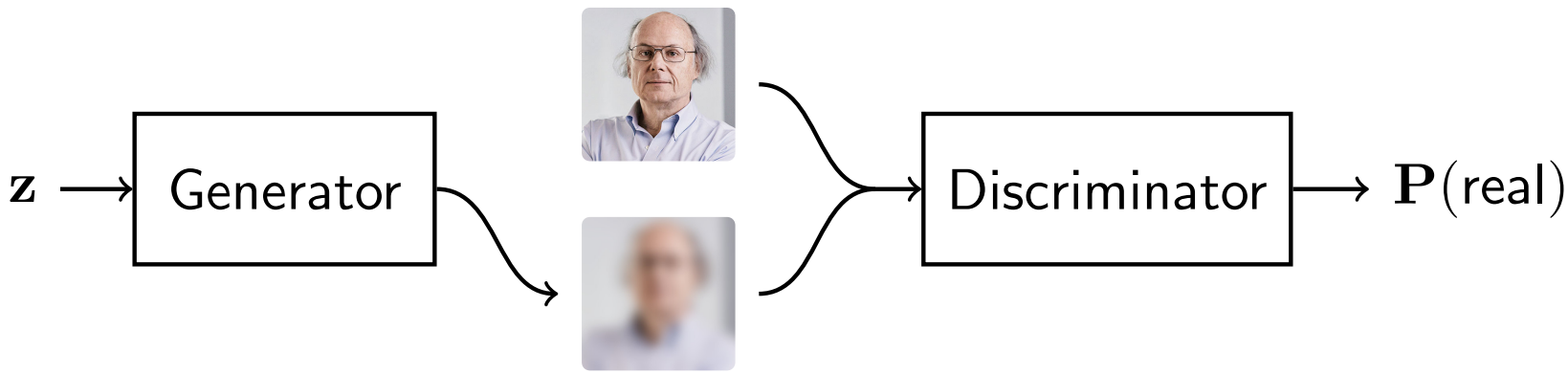
Generative†

$\star$ Supervised

$\dagger$ Unsupervised

Model Layer

Model Layer



Generative Adversarial Networks (GAN)

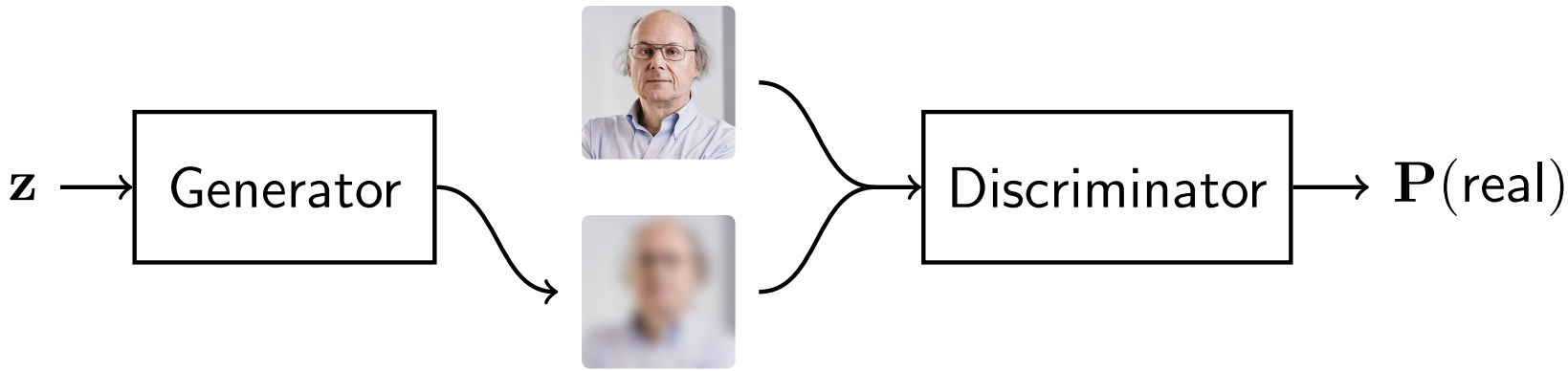
Generative Adversarial Networks

Progressive GAN: Karras et al. (2017)

Generative Adversarial Networks

BEGAN: Berthelot et al. (2017)

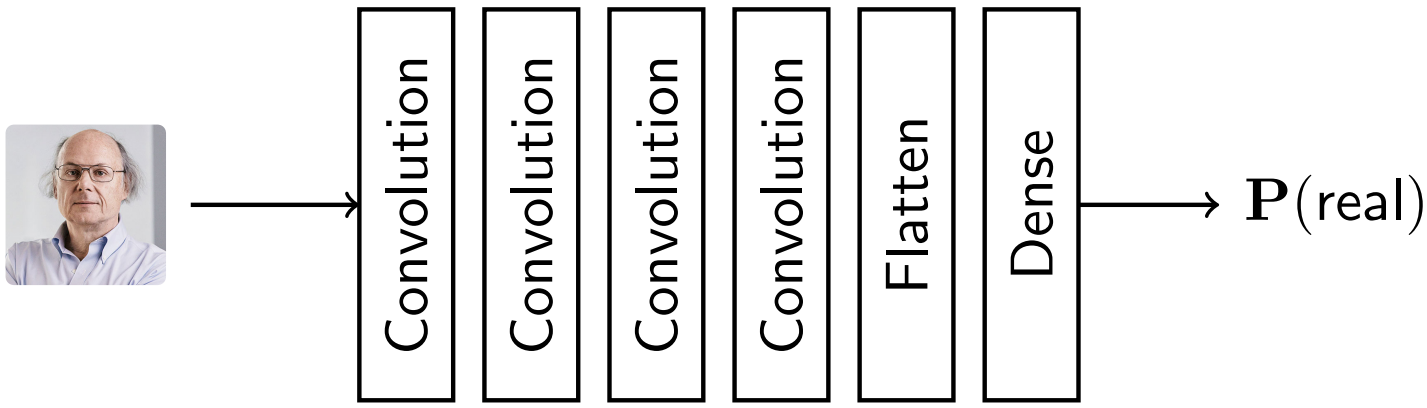
Layer Layer



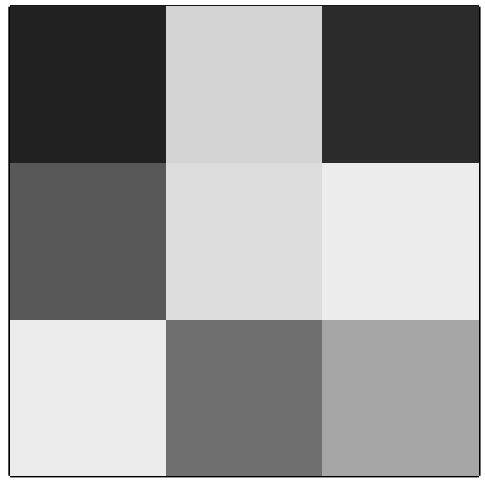
Generative Adversarial Networks (GAN)

Layer Layer

Layer Layer


Convolution
Convolution
Convolution
Convolution
Flatten
Dense
$\mathbf{P}(\text{real})$

Layers: Convolution



Image

Layers: Convolution

0.4	0.9	0.1
0.7	0.2	0.6
0.8	0.3	0.5

Image

Layers: Convolution

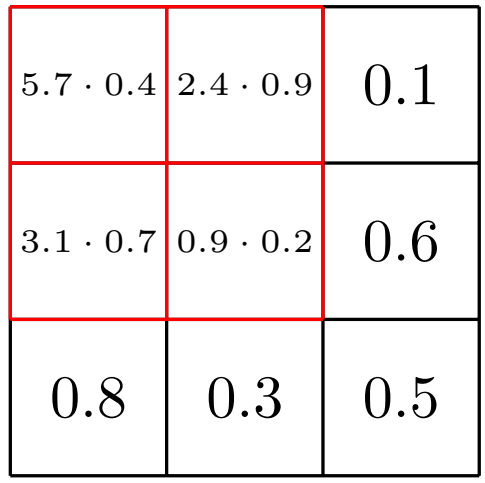
0.4	0.9	0.1
0.7	0.2	0.6
0.8	0.3	0.5

Image

5.7	2.4
3.1	0.9

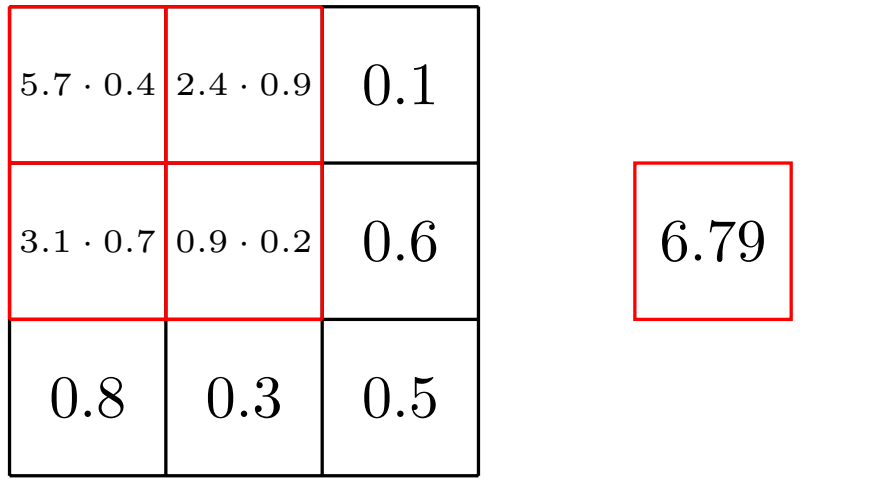
Kernel

Layers: Convolution

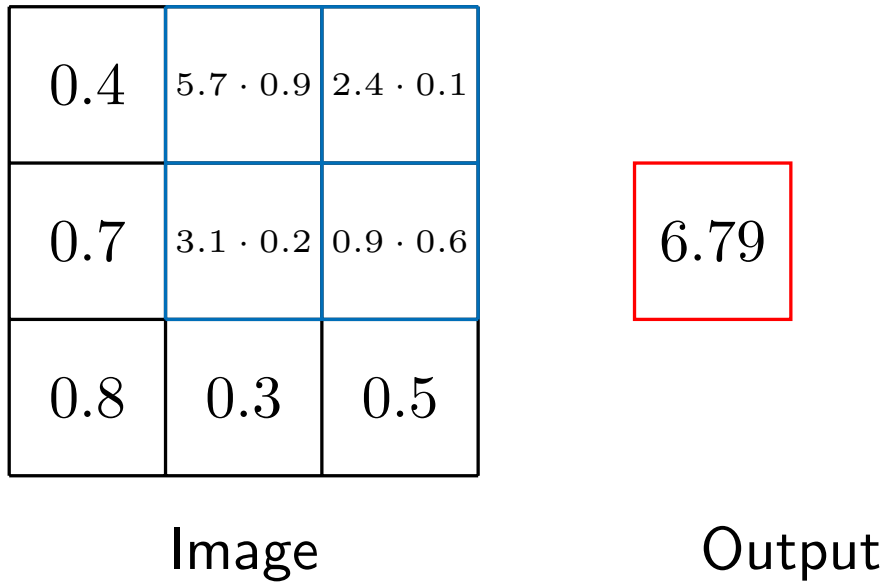


Image

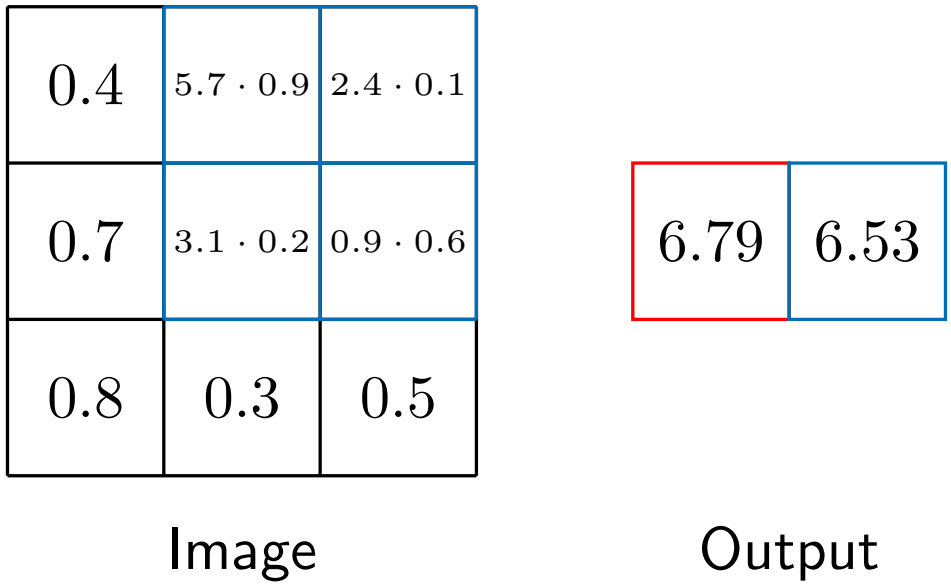
Layers: Convolution



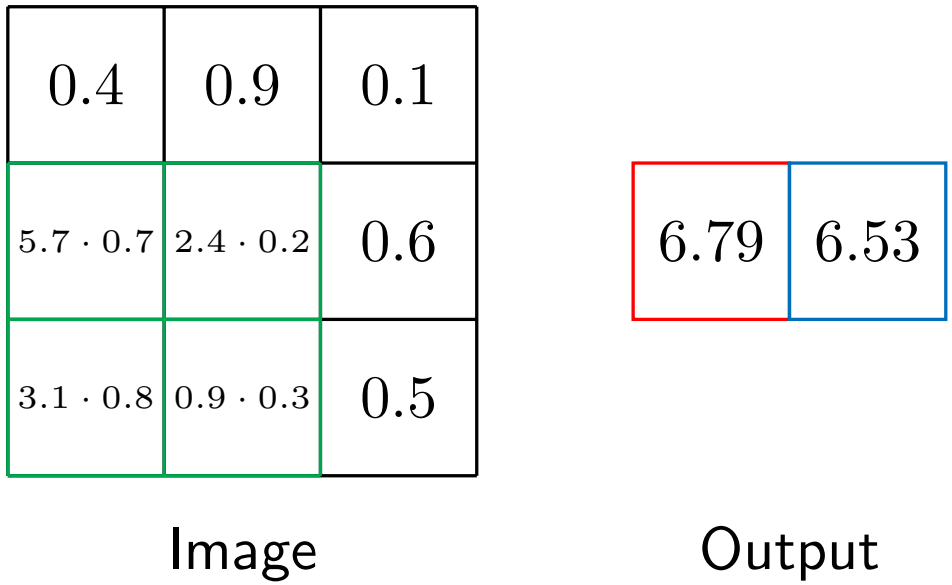
Layers: Convolution



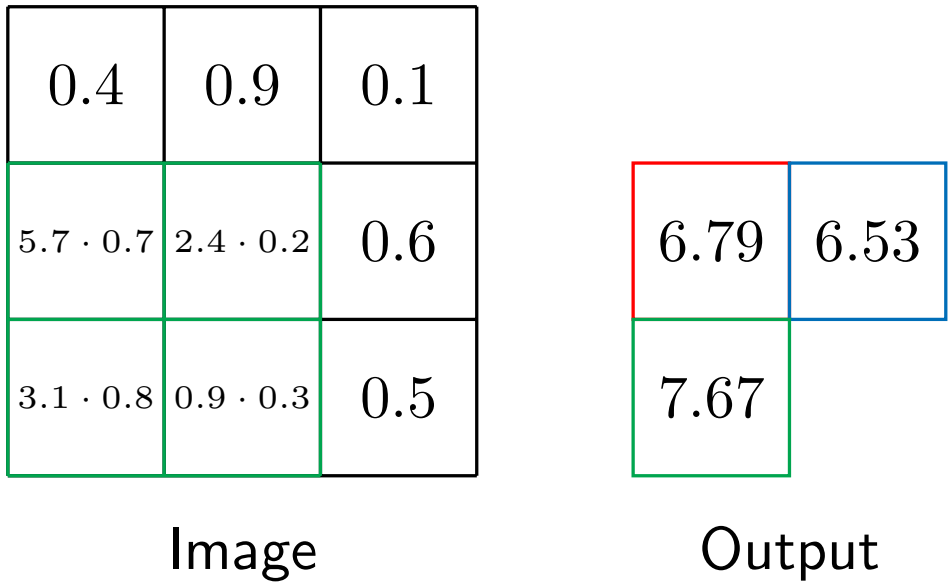
Layers: Convolution



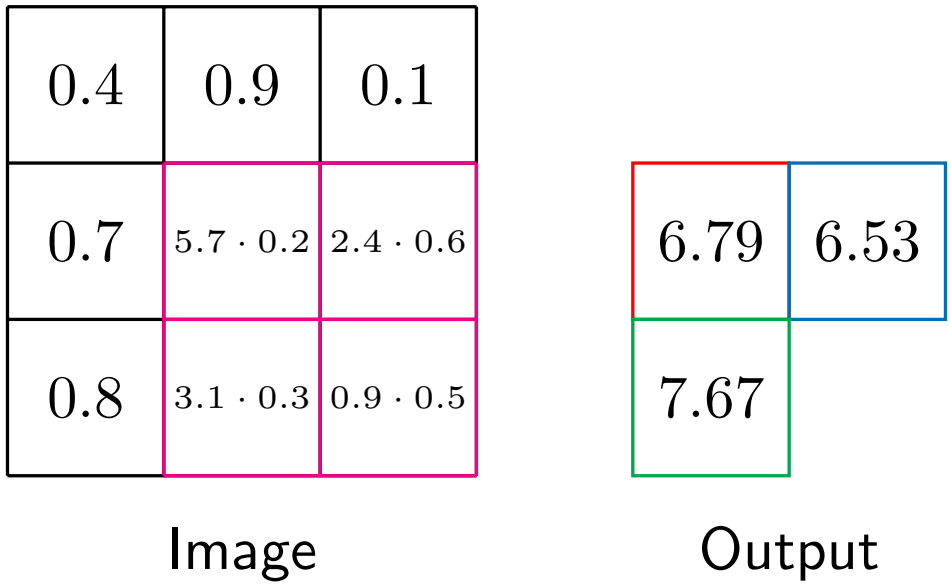
Layers: Convolution



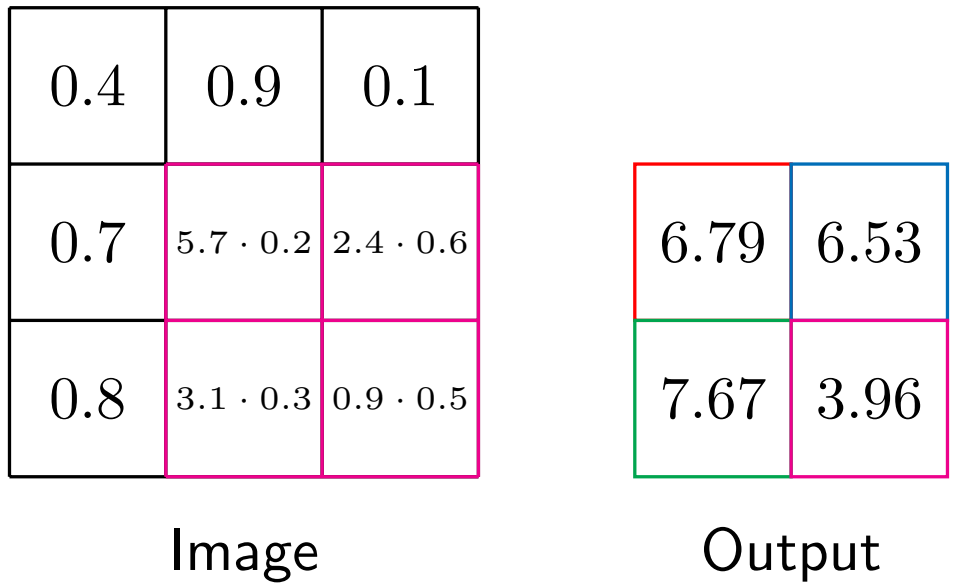
Layers: Convolution



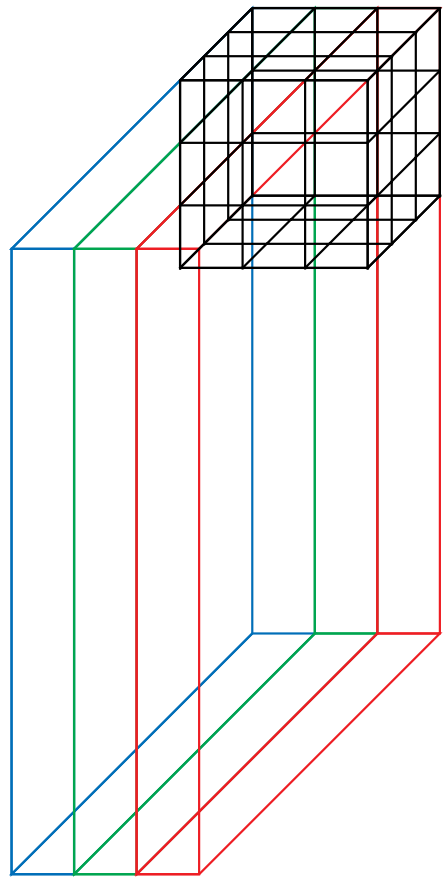
Layers: Convolution



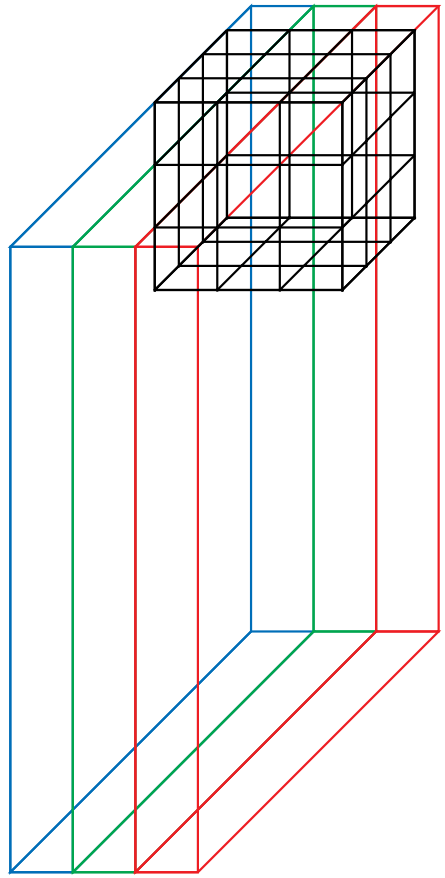
Layers: Convolution



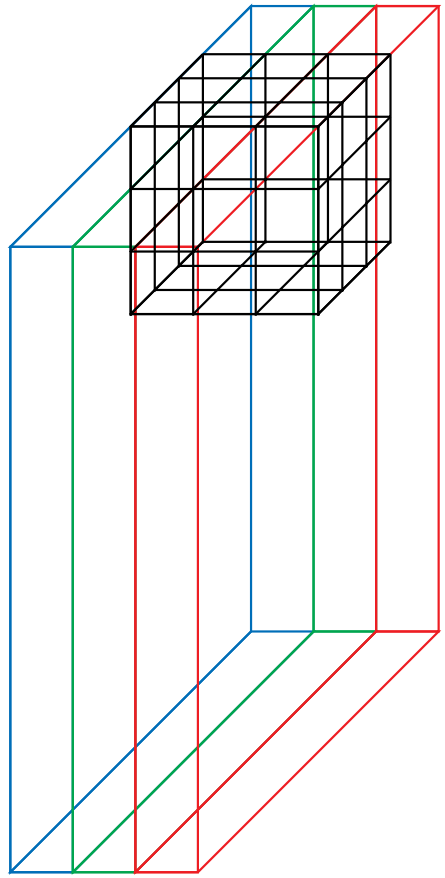
Layers: Convolution



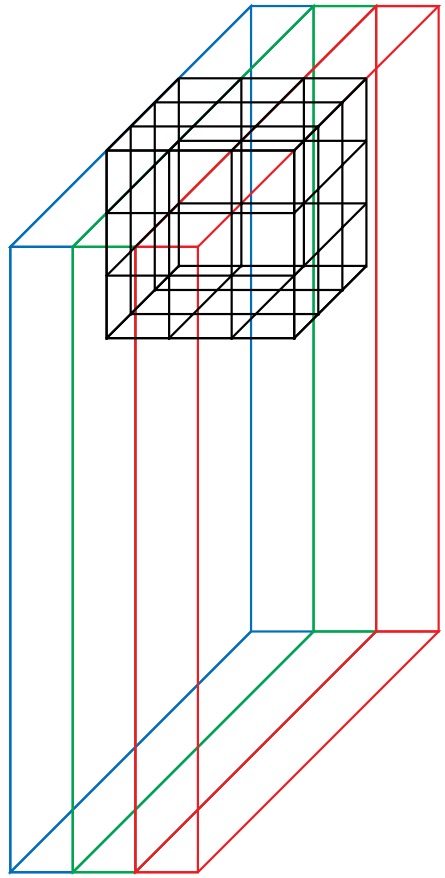
Layers: Convolution



Layers: Convolution



Layers: Convolution



Layers: Convolution

0	1	0
0	1	0
0	1	0

0	0	0
-1	1	0
0	0	0

Layers: Convolution

0	1	0
0	1	0
0	1	0

Patterns

0	0	0
-1	1	0
0	0	0

Layers: Convolution

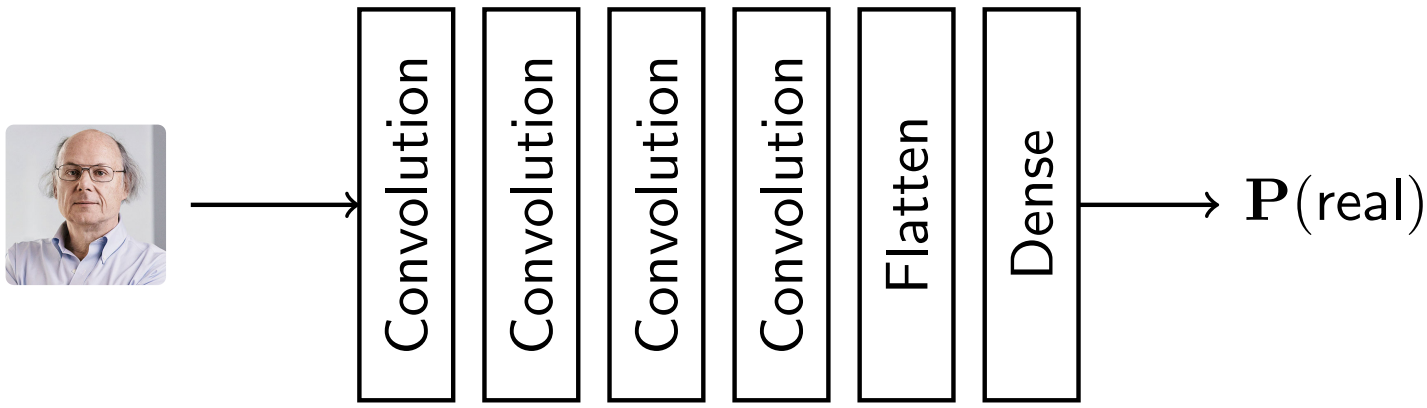
0	1	0
0	1	0
0	1	0

Patterns

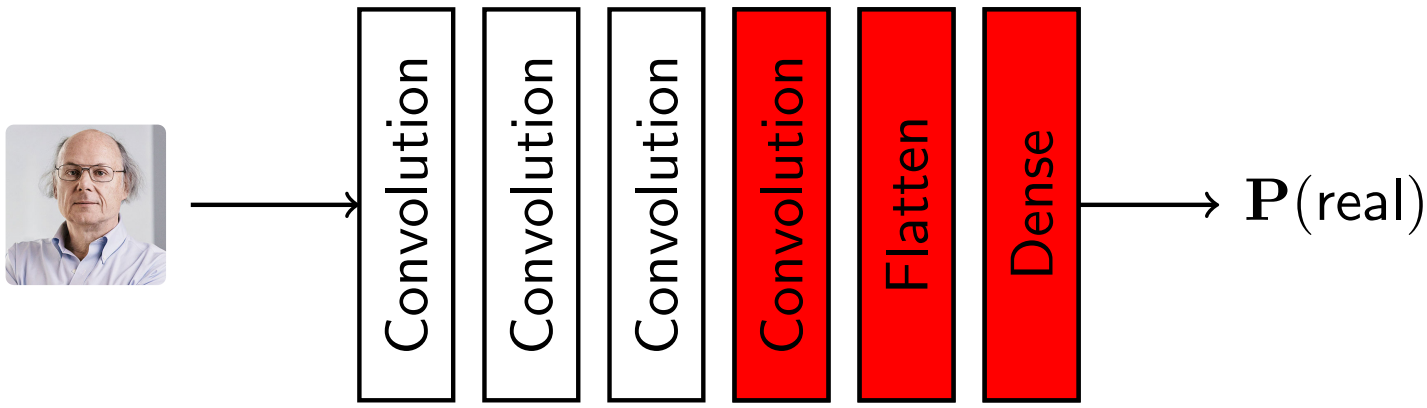
0	0	0
-1	1	0
0	0	0

Edges

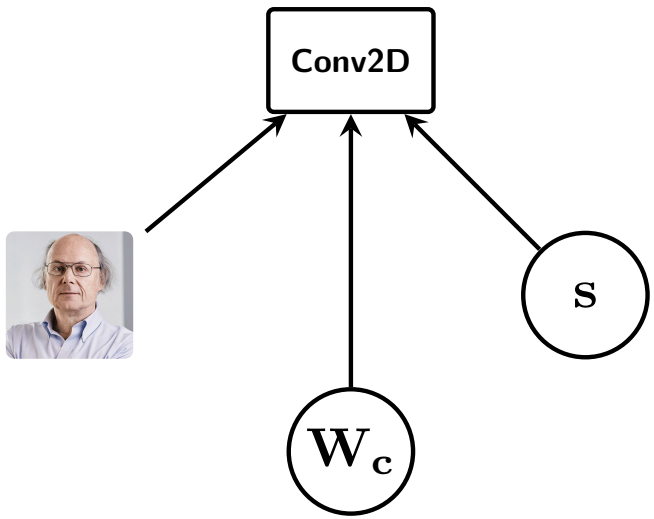
Graph Layer


Convolution
Convolution
Convolution
Convolution
Flatten
Dense
$\mathbf{P}(\text{real})$

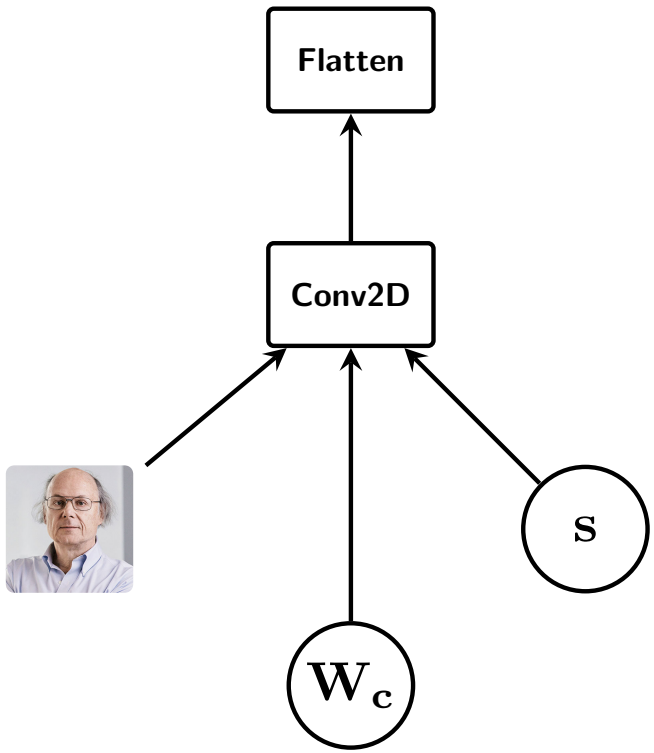
Graph Layer


Convolution
Convolution
Convolution
Convolution
Flatten
Dense
$\mathbf{P}(\text{real})$

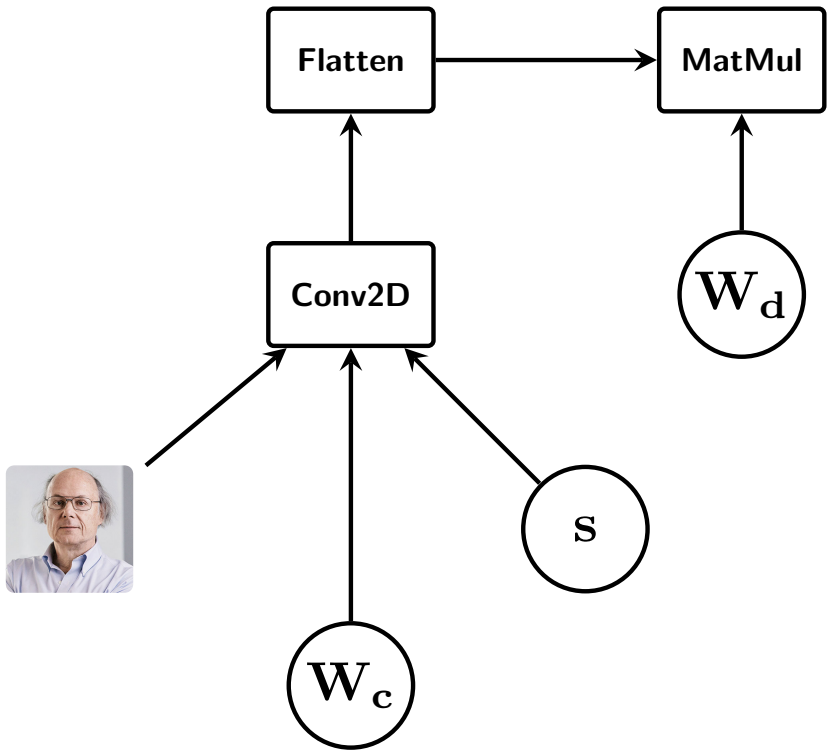
Graph Layer



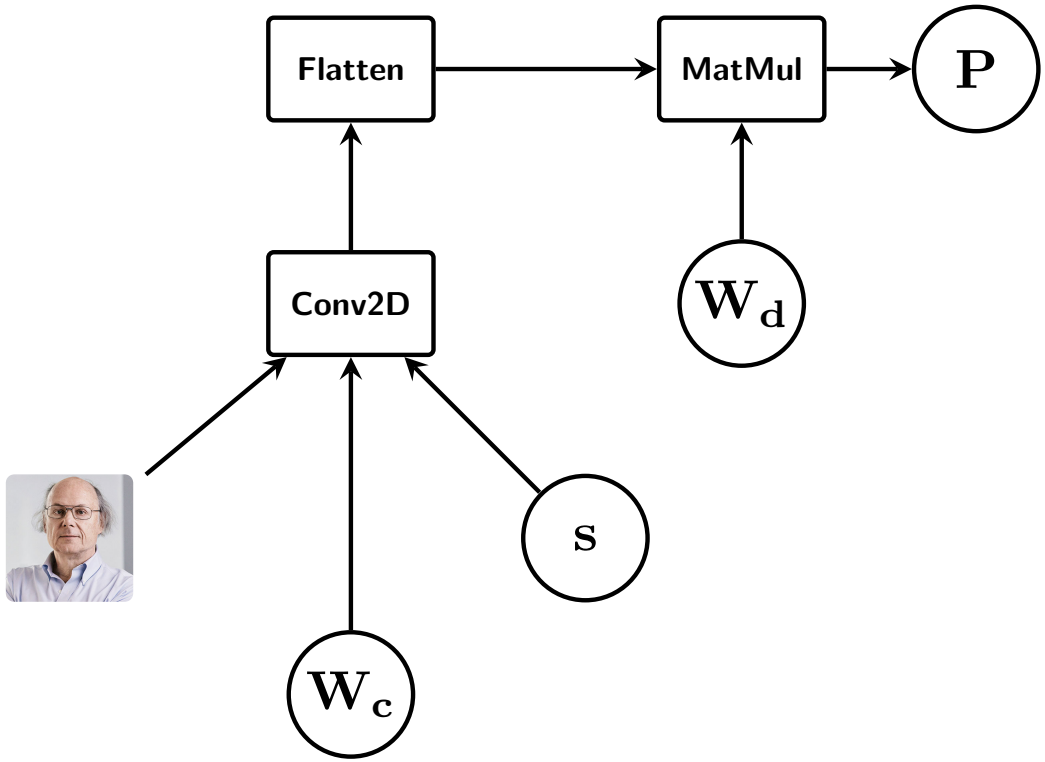
Graph Layer



Graph Layer

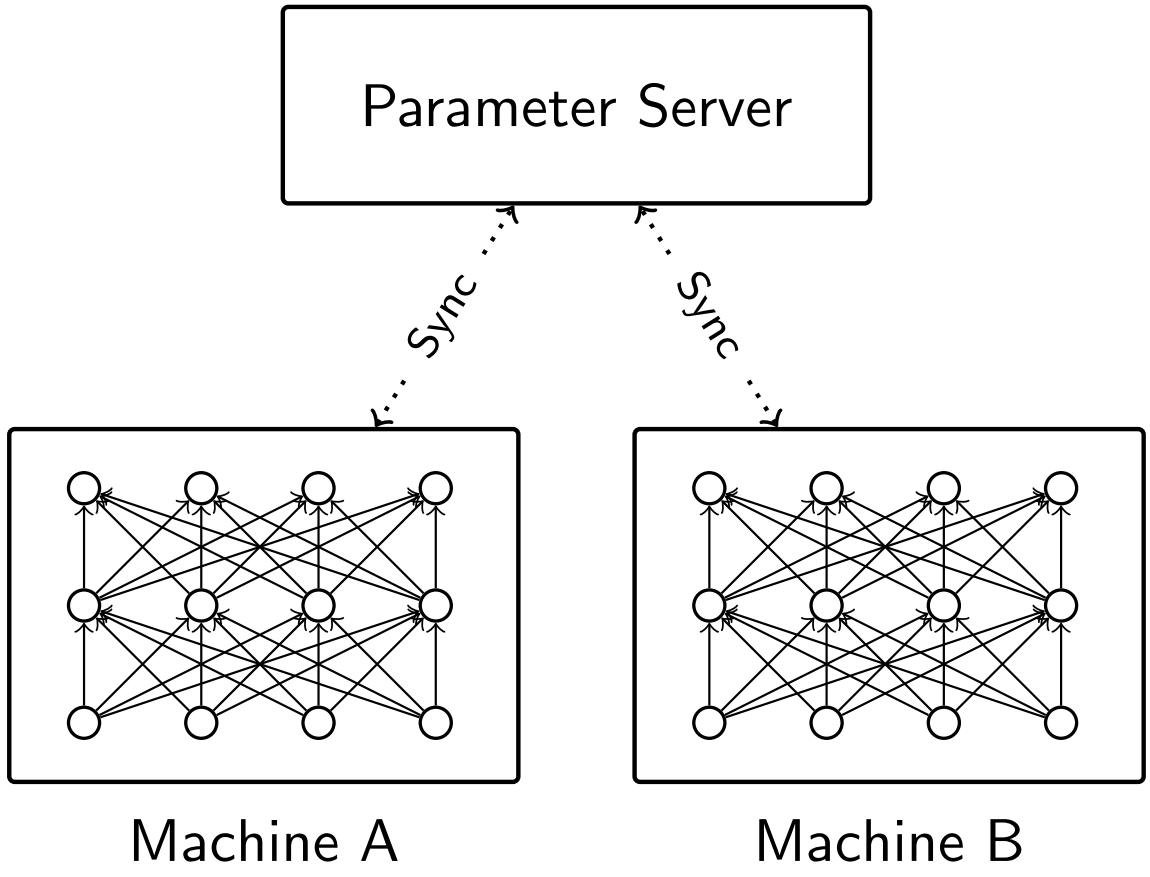


Graph Layer



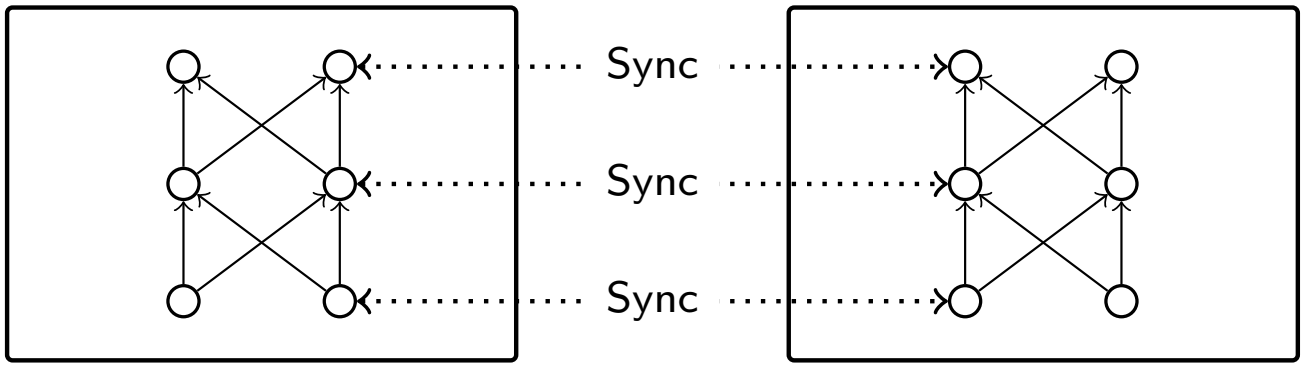
Graph Layer Parallelism

Graph Layer Parallelism



Data Parallelism

Graph Layer Parallelism



Model Parallelism

Static Graphs

Static Graphs

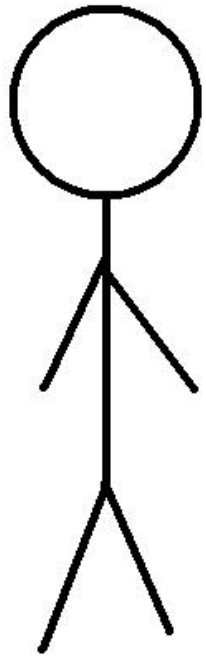
```
Matrix<6, 9> a = ...;
Matrix<6, 9> b = ...;
Matrix<16, 6> c = ...;
scalar s = 7;

d := s * a + b;
e := matmul(c, d);

x := if_clause(condition, d, e);

result := evaluate(x);
```

Dynamic Graphs

```
Matrix a = ...;
Matrix b = ...;
Matrix c = ...;
scalar s = 7;

if s > 0 {
    d := s * a + b;
} else {
    d := a - b;
}

while s > 0 {
  x = input();
  c = matmul(c, x);
}

result := c;
```

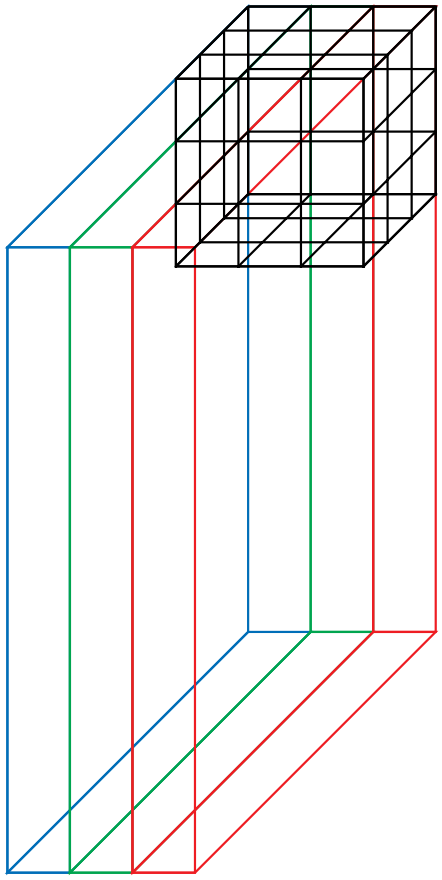
Op Layer

Op Layer

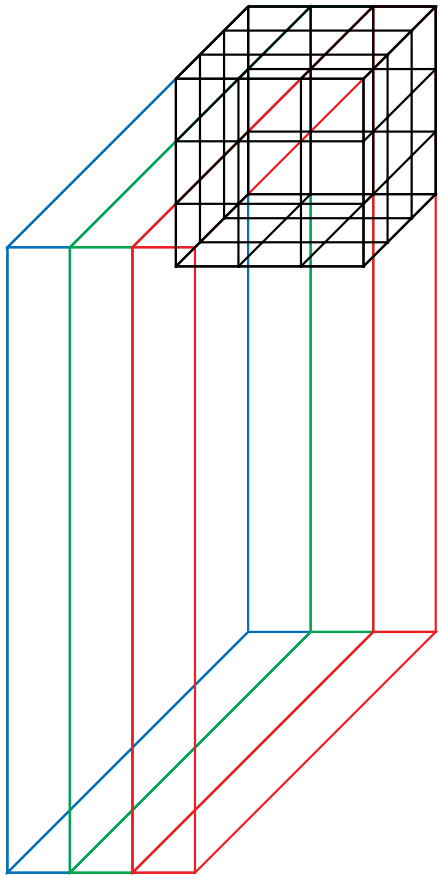


Bob

im2col

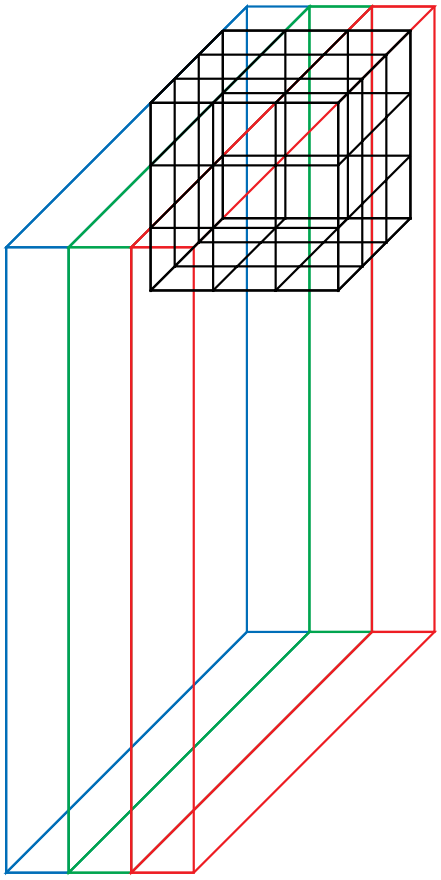


im2col



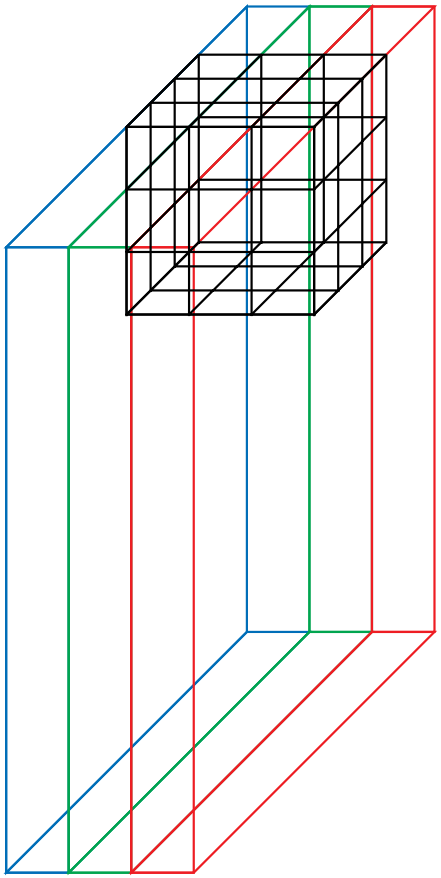
$$\boxed{x_0}\boxed{x_1}\boxed{x_2}\quad\cdots\quad\boxed{x_{24}}\boxed{x_{25}}\boxed{x_{26}}$$

im2col



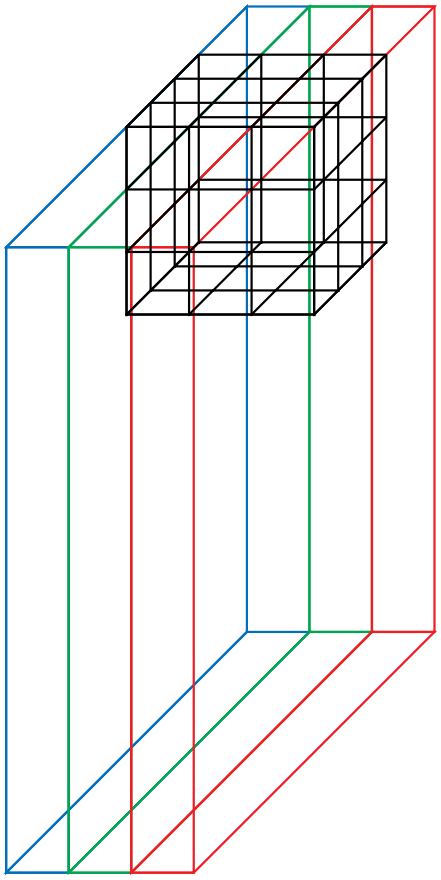
x_0	x_1	x_2	$\cdots$	x_{24}	x_{25}	x_{26}
x_0	x_1	x_2	$\cdots$	x_{24}	x_{25}	x_{26}

im2col



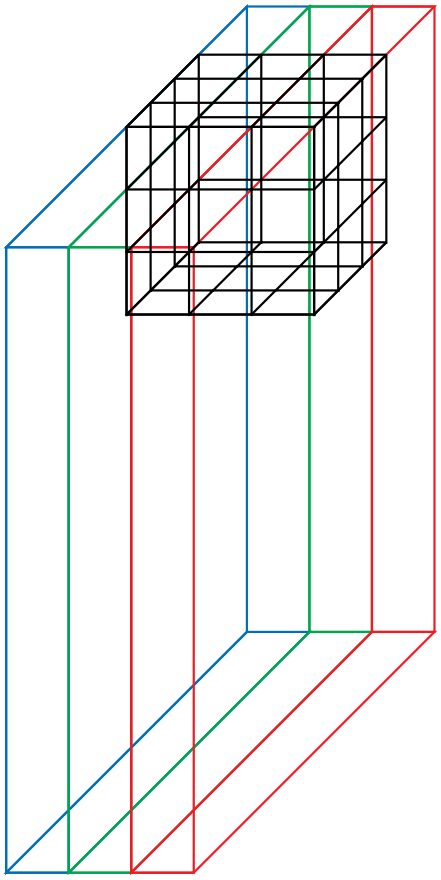
$$\begin{array}{|c|c|c|c|c|c|}
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
\end{array}$$

im2col



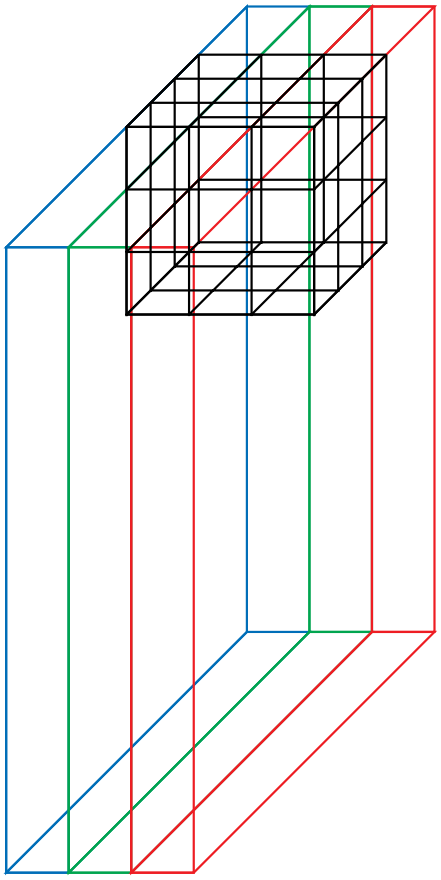
$$
\begin{array}{|c|c|c|c|c|c|}
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\hline
\end{array}
$$

im2col



$$
\begin{array}{ccc|c|ccc|c}
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_0 \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_1 \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_2 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_{24} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_{25} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} & k_{26}
\end{array}
$$

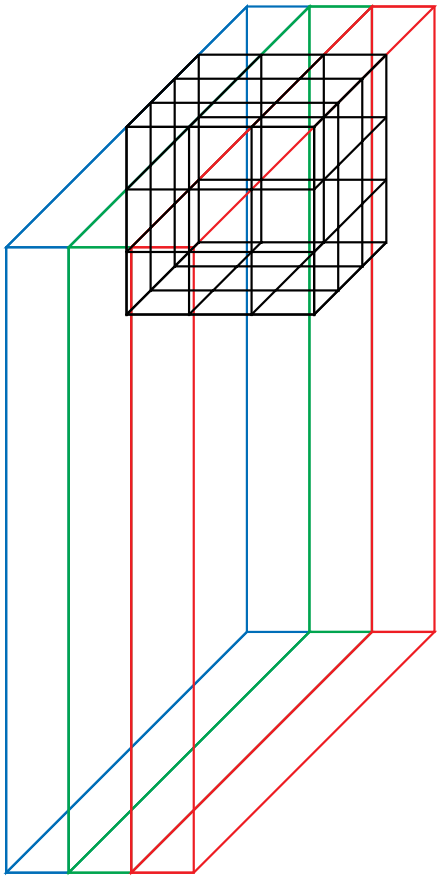
im2col



$$
\begin{array}{|c|c|c|}\hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline \end{array}
\cdots
\begin{array}{|c|c|c|}\hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline \end{array}
\qquad
\begin{array}{|c|c|}\hline k_0 & k_0 \\ \hline k_1 & k_1 \\ \hline k_2 & k_2 \\ \hline \end{array}
$$

$$
\begin{array}{|c|c|c|}\hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline \end{array}
\cdots
\begin{array}{|c|c|c|}\hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline \end{array}
\qquad
\begin{array}{|c|c|}\hline k_{24} & k_{24} \\ \hline k_{25} & k_{25} \\ \hline k_{26} & k_{26} \\ \hline \end{array}
$$

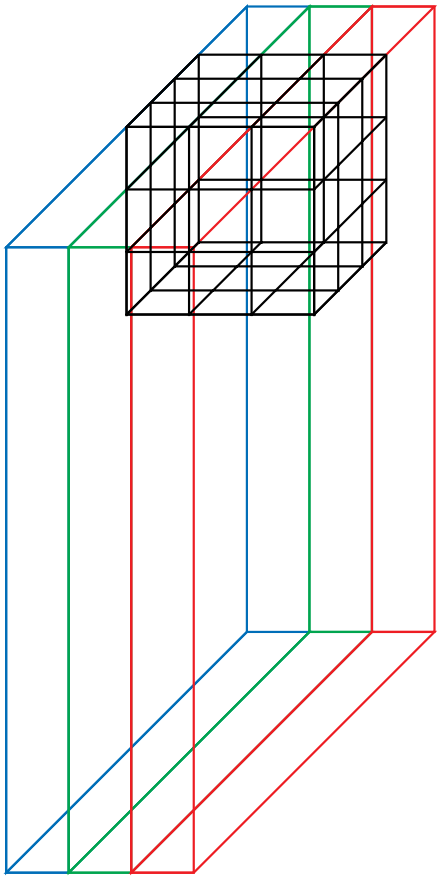
im2col



$$
\begin{array}{|c|c|c|}\hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline \end{array}
\cdots
\begin{array}{|c|c|c|}\hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline \end{array}
\qquad
\begin{array}{|c|c|c|}\hline k_0 & k_0 & k_0 \\ \hline k_1 & k_1 & k_1 \\ \hline k_2 & k_2 & k_2 \\ \hline \end{array}
$$

$$
\begin{array}{|c|c|c|}\hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline x_0 & x_1 & x_2 \\ \hline \end{array}
\cdots
\begin{array}{|c|c|c|}\hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline x_{24} & x_{25} & x_{26} \\ \hline \end{array}
\qquad
\begin{array}{|c|c|c|}\hline k_{24} & k_{24} & k_{24} \\ \hline k_{25} & k_{25} & k_{25} \\ \hline k_{26} & k_{26} & k_{26} \\ \hline \end{array}
$$

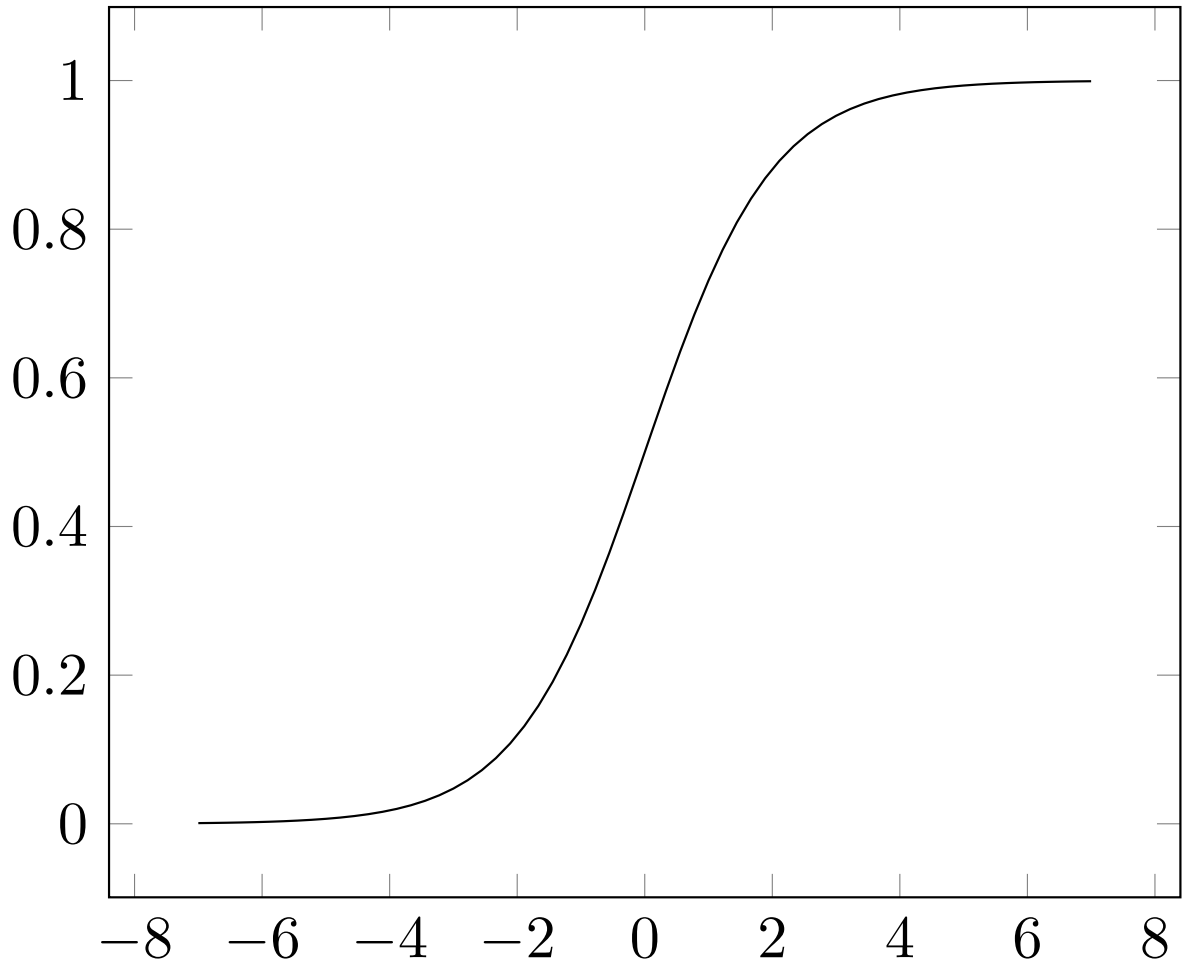
im2col



$$
\begin{bmatrix}
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26} \\
x_0 & x_1 & x_2 & \cdots & x_{24} & x_{25} & x_{26}
\end{bmatrix}
\times
\begin{bmatrix}
k_0 & k_0 & k_0 \\
k_1 & k_1 & k_1 \\
k_2 & k_2 & k_2 \\
\vdots & \vdots & \vdots \\
k_{24} & k_{24} & k_{24} \\
k_{25} & k_{25} & k_{25} \\
k_{26} & k_{26} & k_{26}
\end{bmatrix}
$$

Kernel Layer

Kernel Layer



Sigmoid Activation Function

Kernel Layer

Kernel Layer

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

Forward Pass

Kernel Layer

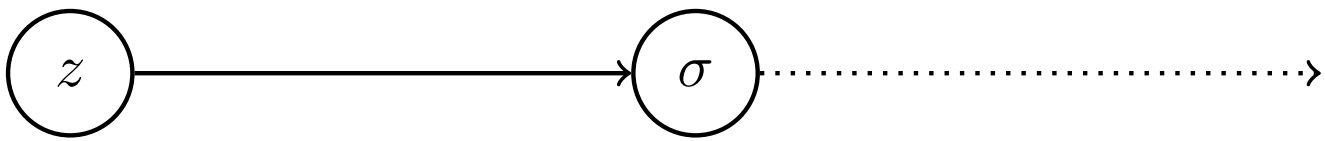
$$\sigma(z) = \frac{1}{1+e^{-z}}$$

Forward Pass

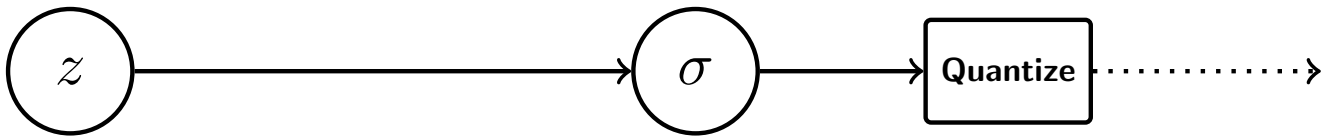
$$\sigma'(z) = \sigma(z)(1 - \sigma(z))$$

Backward Pass

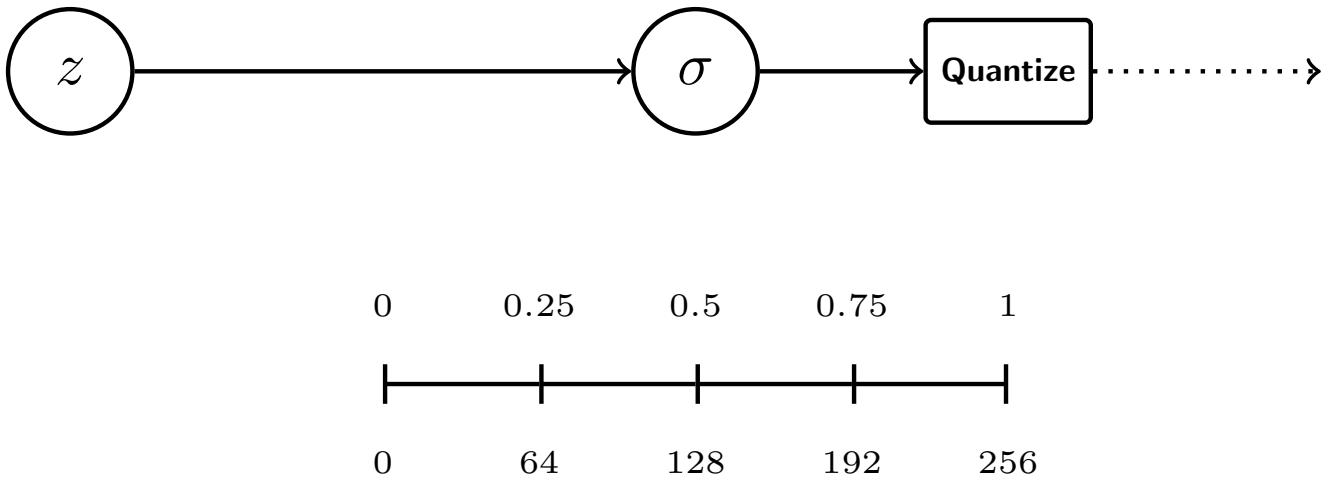
Quantization



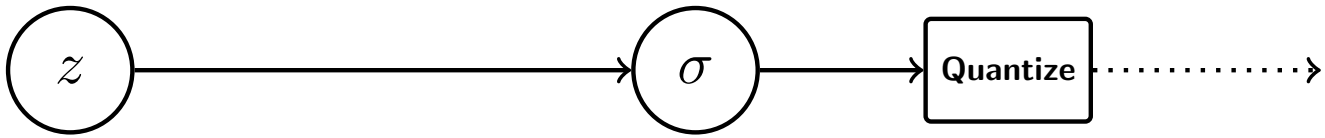
Quantization

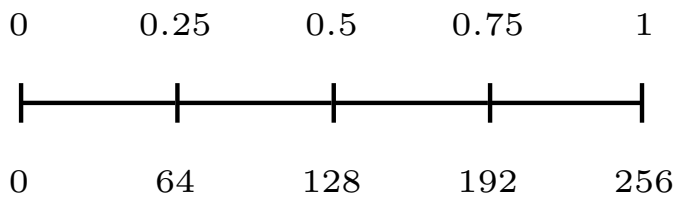


Quantization



Quantization





`github.com/google/gemmlowp`

Hardware Layer

Hardware Layer

CPU

Hardware Layer

CPU

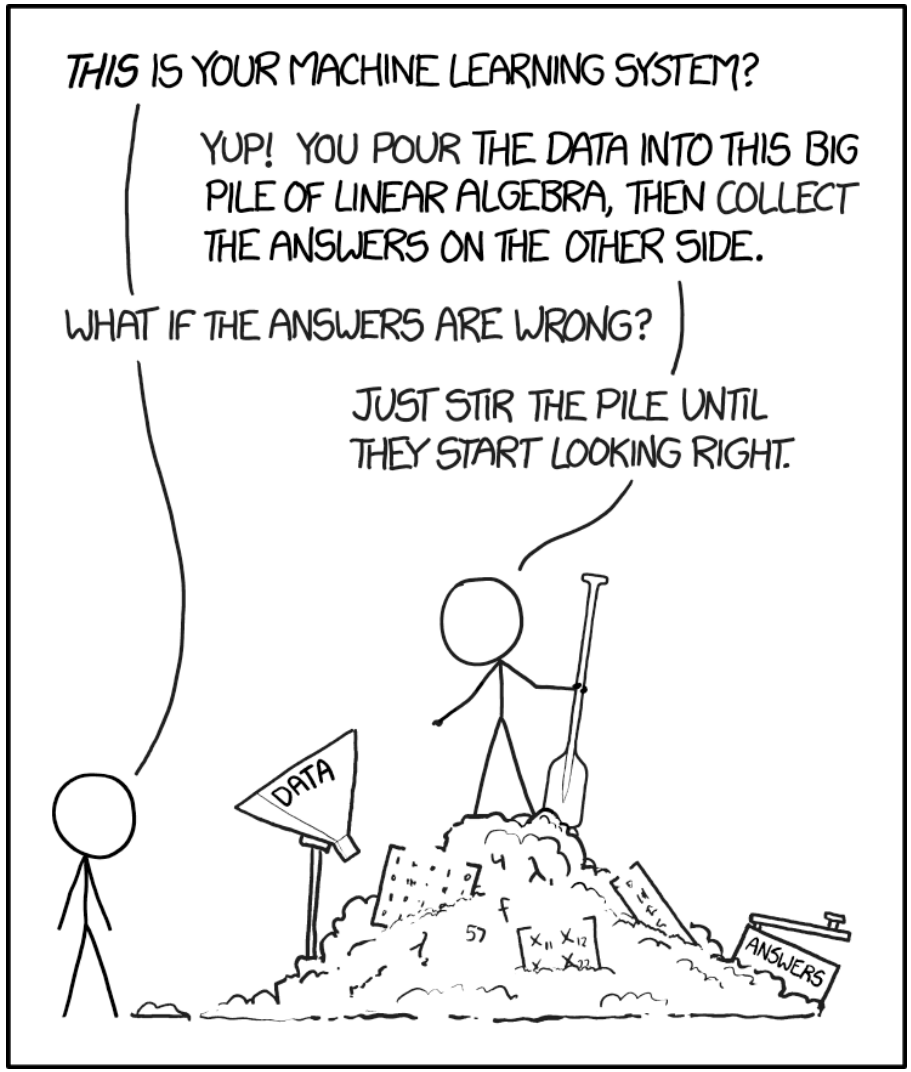
GPU

Hardware Layer

CPU

GPU

ASIC


THIS IS YOUR MACHINE LEARNING SYSTEM?
YUP! YOU POUR THE DATA INTO THIS BIG PILE OF LINEAR ALGEBRA, THEN COLLECT THE ANSWERS ON THE OTHER SIDE.
WHAT IF THE ANSWERS ARE WRONG?
JUST STIR THE PILE UNTIL THEY START LOOKING RIGHT.
DATA
ANSWERS

Hardware: GPU

Titan X

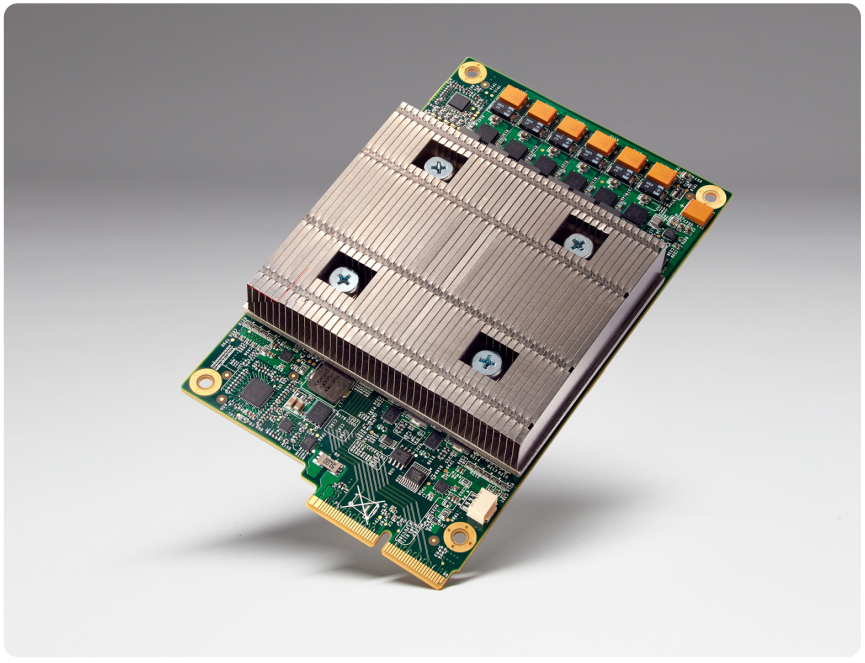
- 3840 cores
- 12GB on-chip memory
- 547.7GB/s bandwidth
- 12 TFLOPS

Hardware: Big Basin

Big Basin

- 8 NVIDIA Tesla P100 GPUs
- NVLink (3x faster than PCIe)
- 16 GB RAM
- 10.6 TFLOPS/GPU
- Reduced Precision Computing

Hardware: TPU

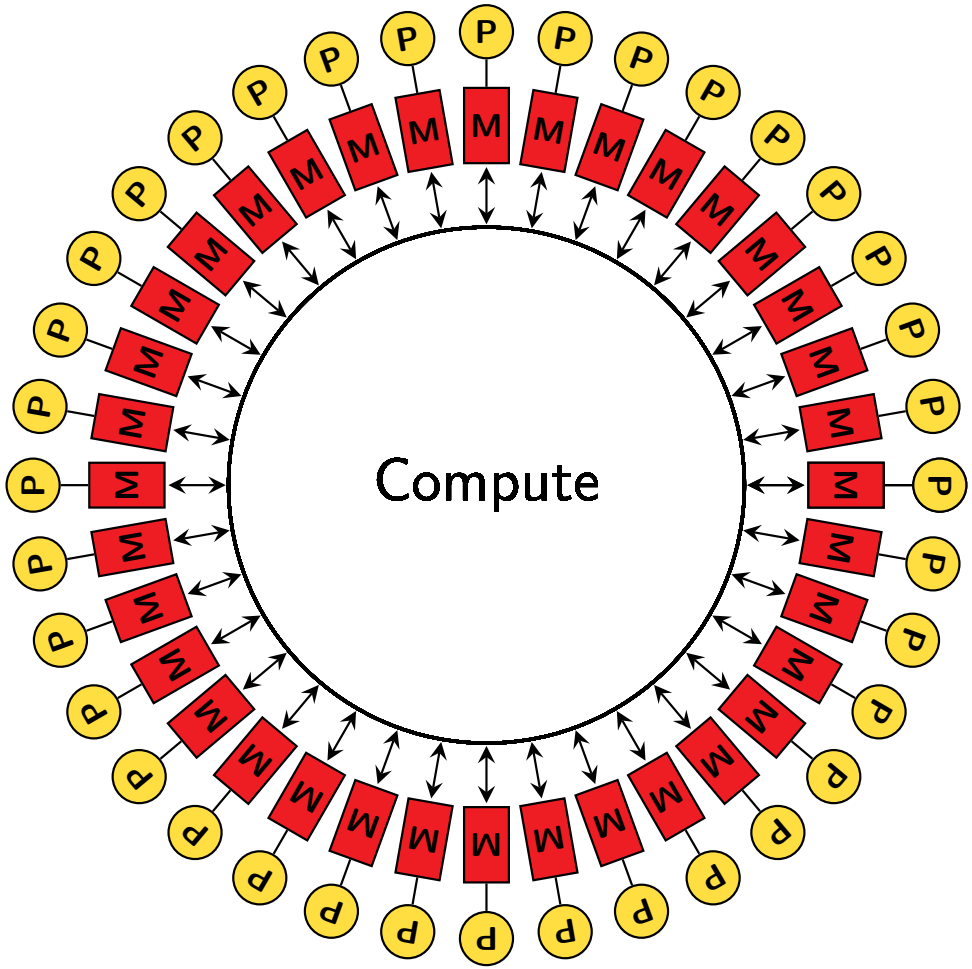


TPU

- *Coprocessor*
- 92 TOPS for 8-bit int
- 42 TFLOPS (TPU2)
- 24 MB Memory

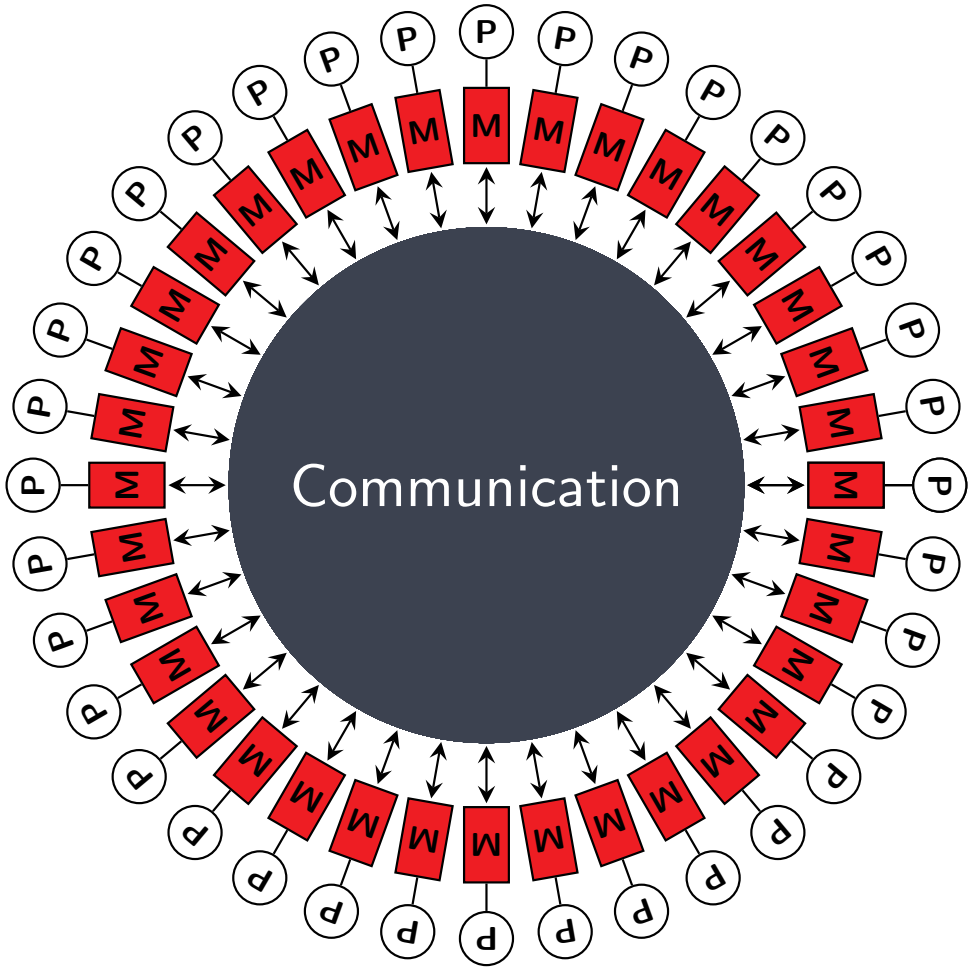
Hardware: IPU

Hardware: IPU



Bulk Synchronous Parallelism

Hardware: IPU



Bulk Synchronous Parallelism

Hardware: IPU

- Startup from Bristol (UK)
- Graphcore *Colossus*
- TBR later this year
- >1000 Processors/Chip
- Mixed Precision Arithmetic
- 2x – 200x faster than GPUs

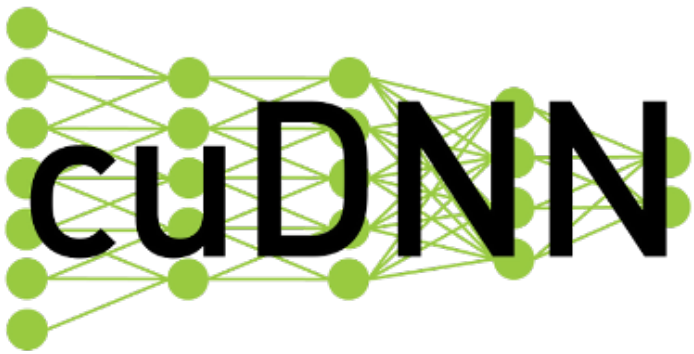
Graphcore

Kernel Layer

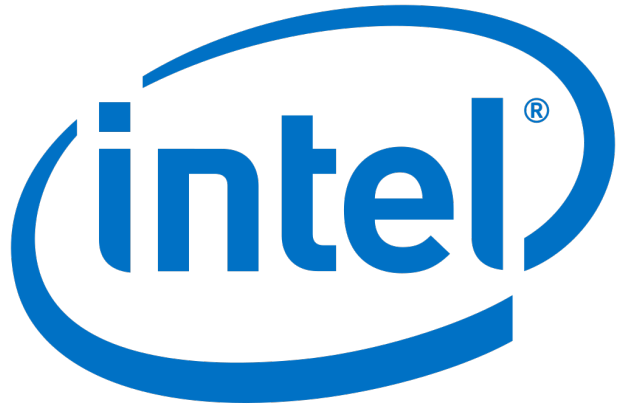
Kernel Layer

cuDNN/cuBLAS

Kernel Layer



cuDNN/cuBLAS



MKL

Demo: Convolution with cuDNN

`github.com/peter-can-talk/meeting-cpp-2017`

Demo: Custom TensorFlow Op

Graph Layer

Graph Layer: TensorFlow

- Google (2015)
- Static Graphs*
- GPUs ✓
- Distributed ✓
- C++ API ✗
- Very "Deployable"
- Often Too Low-Level

* Dynamic with *TF Eager* (Oct. 2017)

Graph Layer: PyTorch/Caffe2

- Facebook (2016)
- Dynamic Graphs
- For Research
- GPUs ✓
- Distributed ✓
- Pure Python

- Facebook (2017)
- Static Graphs
- For Deployment
- GPUs ✓
- Distributed ✓
- C++ API ✓

Graph Layer: MXNet

- Community, then Amazon
- Apache Incubator
- Highly Modular
- GPUs ✓
- Distributed ✓
- Python, R, Scala, Julia, C++ ✓

Graph Layer: Dlib

- No Corporate Backing
- Mature and Reliable
- Pure C++ ✓
- GPUs ✓
- Distributed ✗

Demo: MXNet Classifier

Demo: Dlib Classifier

Q & A

github.com/peter-can-talk/meeting-cpp-2017