

# Quantisation

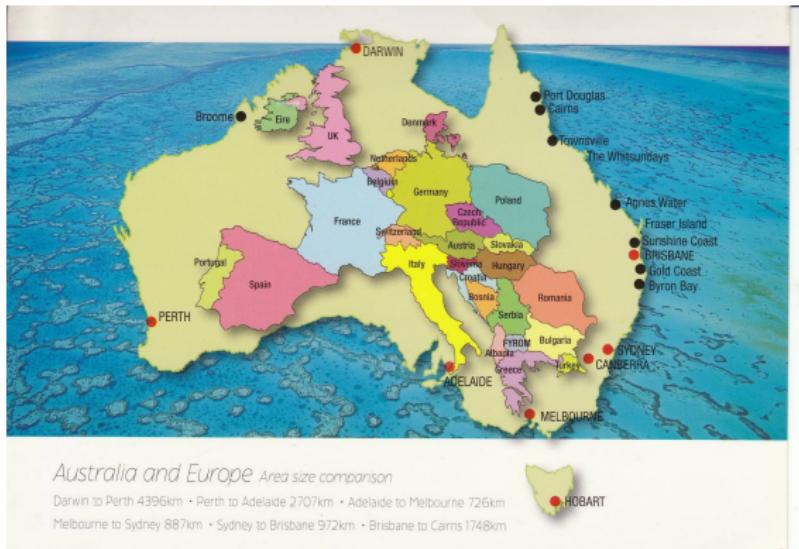
## Neural Network Optimised VLSI Accelerators

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The University of Sydney

July 2019 / NOVA Workshop

# Australia



- Australia 25M, Guangdong 100M

# Outline

## 1 Introduction

## 2 Quantised Neural Networks

Integer Quantisation

QPyTorch

## 3 Implementation

FINN: A Binarised Neural Network

SYQ: Low Precision DNN Training

## 4 Tutorial

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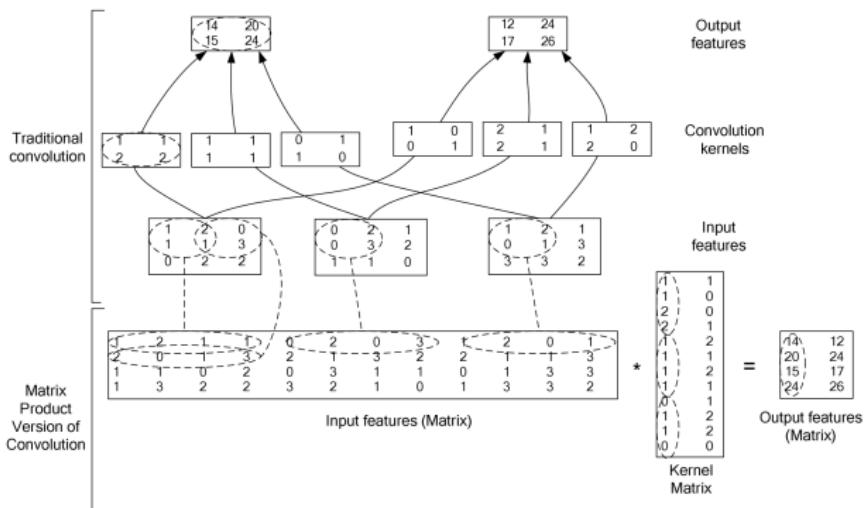
## 4 Tutorial

# Scope

- There are several degrees of freedom to explore when optimising DNN implementations
  - NN architecture (SqueezeNet, MobileNet, EfficientNet [TL19])
  - Compression (SVD, Deep Compression, Circulant [Din+17])
  - Quantization (FP16, TF-Lite, FINN, DoReFa-Net)
  - Hardware architecture
- This talk: quantisation

# Convolution Layer as MM

- Convolution layers converted to GEMM [CPS06]
- Efficient BLAS libraries can be exploited



## DNN Computation

Computational problem in DNNs is to compute a number of dot products

$$a = \sigma(\mathbf{w}^T \mathbf{x}) \quad (1)$$

where

- $\sigma$  is an element-wise nonlinear activation function
- $\mathbf{x} \in \mathbb{R}^{i.w.h}$  is the input vector
- $\mathbf{w} \in \mathbb{R}^{i.w.h}$  is the weight vector

## Arithmetic Intensity

- Computation of a DNN layer is MV multiplication
- For MV multiply is  $O(1)$ , for MM is  $O(b)$  where b is block size
- Efficient CPU/GPU implementations use batch size  $\gg 1$  (process a number of inputs together)
- For latency-critical applications (e.g. object detection for self-driving car), we want a batch size of 1
- **Make sure comparisons are at the same batch size!**

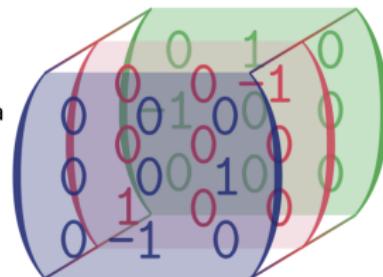
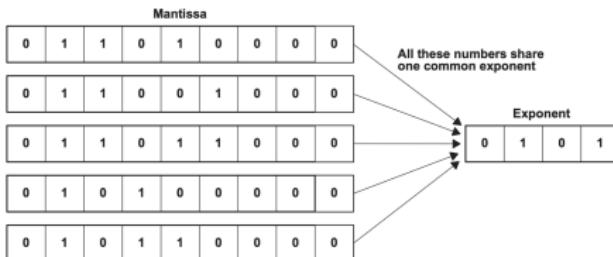
# Block Floating Point

Block floating point

Operations mostly integer

dim=-1 The whole tensor shares a single  
dim=n all elements of a dimension share a

Use  $f_x(k)$  notation



## Stochastic Rounding

- Suppose we want to round 10.4 to an integer
- Stochastic rounding

$$r(x) = \begin{cases} \lfloor x \rfloor & \text{with probability } 1 - (x - \lfloor x \rfloor) \\ \lfloor x \rfloor + 1 & \text{with probability } x - \lfloor x \rfloor \end{cases}$$

# Python Stochastic Rounding Implementation

```
import numpy as np
from timeit import timeit

# from https://medium.com/@minghz42/what-is-stochastic-rounding-b78670d0c4a
# Generates s randomly rounded values of x. The mean should be x.
def rstoc(x, s):
    r = []
    for i in range(s):
        decimal = abs(x - np.trunc(x))
        random_selector = np.random.random_sample()
        if (random_selector < decimal):
            adjustor = 1
        else:
            adjustor = 0
        if(x < 0):
            adjustor = -1 * adjustor
        r.append(np.trunc(x) + adjustor)
    return r
```

# Testing Stochastic Rounding

```
# computes elementwise relative error of elements of lists x1 and x2
def relative_error(x1, x2):
    ret = []
    for (i, r) in zip(x1, x2):
        ret.append(abs(i - r) / r)
    return ret

# For each element x of the list v, compute the mean of rstoc(x, s). Return as another list
def E_seq(v, s):
    return map(lambda x : np.mean(rstoc(x, s)), v)

spower = 7      # samples to try (execution time grows exponentially)
v = [-1.234, 0.5, 0.6789]

# this function runs
def run_rstoc():
    print("Values")
    for i in range(spower):
        print(10 ** i, list(E_seq(v, 10 ** i)))
    print("Relative Errors")
    for i in range(spower):
        print(10 ** i, list(relative_error(E_seq(v, 10 ** i), v)))
    t_rstoc = timeit(run_rstoc, number=1)
    print("Execution_time_rstoc()", t_rstoc, '\n')
```

# Output Stochastic Rounding

Values

```
1 [-1.0, 0.0, 0.0]
10 [-1.2, 0.6, 0.5]
100 [-1.26, 0.44, 0.7]
1000 [-1.225, 0.511, 0.685]
10000 [-1.2389, 0.5005, 0.6842]
100000 [-1.23358, 0.50052, 0.67682]
1000000 [-1.233241, 0.500033, 0.678435]
```

Relative Errors

```
1 [-0.18962722852512154, 1.0, 0.47297098247164543]
10 [-0.10858995137763362, 0.3999999999999999, 0.11621741051701277]
100 [-0.061588330632090814, 0.020000000000000018, 0.016349977905435263]
1000 [-0.0032414910858995167, 0.040000000000000036, 0.004271615849167628]
10000 [-0.00826580226904375, 0.0052000000000000934, 0.006922963617616625]
100000 [-0.00024311183144243677, 0.001399999999999568, 0.0017970245986154057]
1000000 [-0.00020826580226900463, 0.0009320000000000439, 0.0015510384445425994]
```

Execution time `rstoc()` 25.999158156999783

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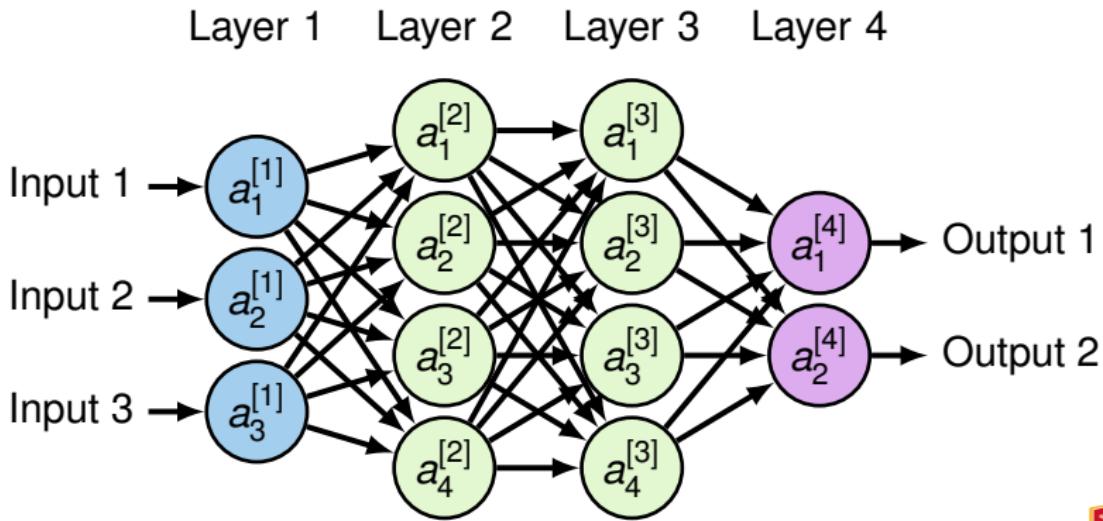
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# Backpropagation Algorithm [HH18]

- Forward Pass  $z^{[i]} = W^{[i]} a^{[i-1]}$ ,  $a^{[i]} = \sigma(z^{[i]})$
- dActivations  $\delta^{[i]} = \text{diag}(\sigma'(z^{[i]}))(W^{[i+1]})^T \delta^{[i+1]}$
- dWeights  $\Delta W^{[i]} = \delta^{[i]}(a^{[i-1]})^T$



# Backpropagation Algorithm [HH18]

```
1: function BACKPROP( $x, y$ )
2:    $a^{[1]} = x$ 
3:   for  $i = 2, \dots, L$  do                                 $\triangleright$  forward pass
4:      $z^{[i]} = W^{[i]} a^{[i-1]}$ 
5:      $a^{[i]} = \sigma(z^{[i]})$ 
6:   end for
7:    $\delta^{[L]} = diag(\sigma'(z^{[L]}))(a^{[L]} - y)$ 
8:   for  $i = L-1, \dots, 2$  do                       $\triangleright$  backward pass  $\delta$ 
9:      $\delta^{[i]} = diag(\sigma'(z^{[i]}))(W^{[i+1]})^T \delta^{[i+1]}$ 
10:    end for
11:    for  $i = L, \dots, 2$  do                       $\triangleright$  backward pass  $\Delta W$ 
12:       $\Delta W^{[i]} = \delta^{[i]}(a^{[i-1]})^T$ 
13:    end for
14:    return  $\Delta W$ 
15: end function
```

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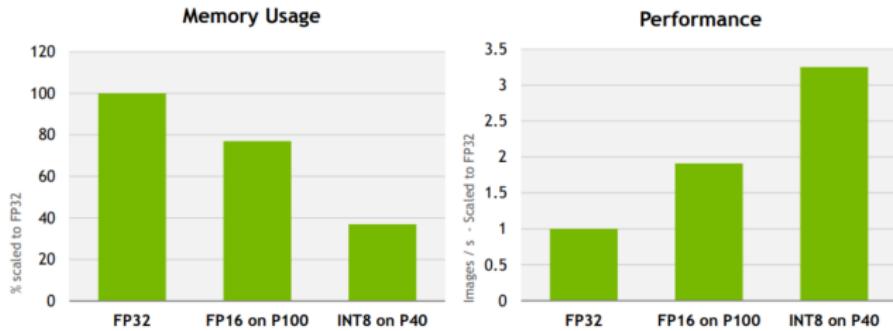
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# Role of Wordlength on Performance

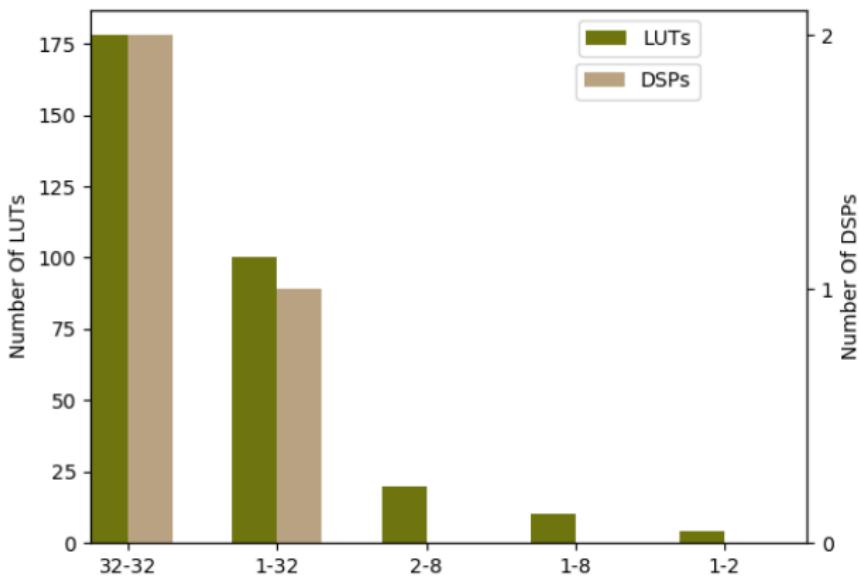
- CPU/GPU
  - Floating point performance comparable to fixed
  - Integer data types usually vectorisable hence faster
  - Nvidia offers FP64, FP32 and FP16 (> Tegra X1 and Pascal)
- FPGA
  - Datapath is flexible
  - No floating point unit so fixed point normally preferred



ResNet50 Model, Batch Size = 128, TensorRT 2.1 RC pre-release

# Role of Wordlength on Resources

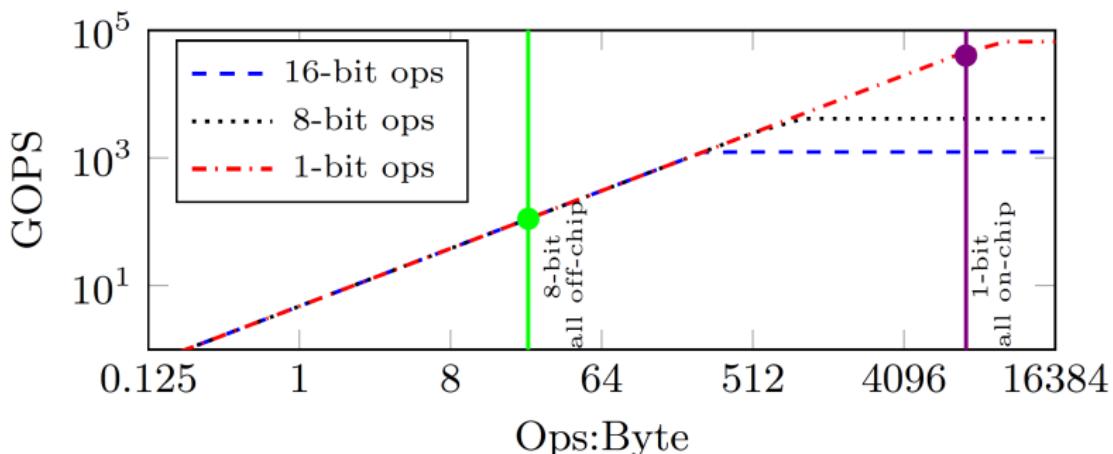
- X axis is bitwidth (weight-activation) and Y axis Number of LUTs/DSPs for MAC
- For  $k$ -bits, area is  $\mathcal{O}(k^2)$



# Roofline Model

## Roofline model for Xilinx ZU19EG

- X axis is computational intensity (ops to perform / byte fetch), Y axis is performance
- Diagonal parts show memory-bandwidth limited space
- Horizontal parts show computation limited space
- Actually this is a better metric to optimise than say GOPs/s
- **Low precision extremely advantageous for performance**



## Integer Quantization [Jac+18]

A way to map numbers  $r \in \mathbb{R}$  to unsigned integers  $q \in \mathbb{U}+$  is via an affine transformation

$$r = S(q - Z) \tag{2}$$

- $\mathbb{U}+$  is the set of unsigned W-bit integers
- $S, Z$  are the quantisation parameters
  - $S \in \mathbb{R}+$  represents a scaling constant
  - $Z \in \mathbb{U}+$  represents a zero-point

## Integer MM [Jac+18]

- $N \times N$  MM defined as

$$r_3^{(i,k)} = \sum_{j=1}^N r_1^{(i,j)} r_2^{(j,k)}, \quad (3)$$

substituting  $r = S(q - Z)$  (2) and rewriting<sup>1</sup> we get

$$q_3^{(i,k)} = Z_3 + M \left( NZ_1 Z_2 - Z_1 a_2^{(k)} - Z_2 \bar{a}_1^{(i)} + \sum_{j=1}^N q_1^{(i,j)} q_2^{(j,k)} \right) \quad (4)$$

- Multiplication with  $M = \frac{S_1 S_2}{S_3}$  is implemented in (high-precision) two's complement fixed point
- $a_2^{(k)}$  and  $\bar{a}_1^{(i)}$  together only take  $2N^2$  additions
- Sum in (4) takes  $2N^3$  and is a standard integer MAC
- CPU implementation uses uint8, accumulated as int32

---

<sup>1</sup>A good exercise is to derive Equation (4) from (3) and (2)

## Quantisation Range [Jac+18]

For each layer, quantisation parameterised by (a,b,n):

$$\text{clamp}(r; a, b) = \min(\max(x, a), b)$$

$$s(a, b, n) = \frac{b - a}{n - 1}$$

$$q(r; a, b, n) = \text{rnd}\left(\frac{\text{clamp}(r; a, b) - a}{s(a, b, n)}\right)s(a, b, n) + a \quad (5)$$

where  $r \in \mathbb{R}$  is number to be quantised,  $[a, b]$  is quantisation range,  $n$  is number of quantisation levels and  $\text{rnd}()$  rounds to nearest integer

Figure from [Jac+18] (with permission)

# Training Algorithm [Jac+18]

- 1 Create training graph of the floating-point model
- 2 Insert quantisation operations for integer computation in inference path using (5)
- 3 Train with quantised inference but floating-point backpropagation until convergence
- 4 Use weights thus obtained for low-precision inference

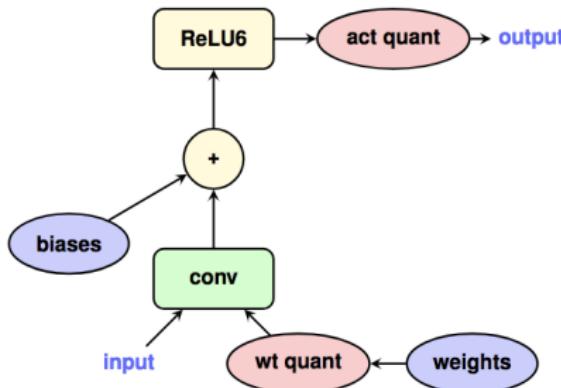


Figure from [Jac+18] (with permission)

## Accuracy vs Precision [Jac+18]

ResNet50 on ImageNet, comparison with other approaches

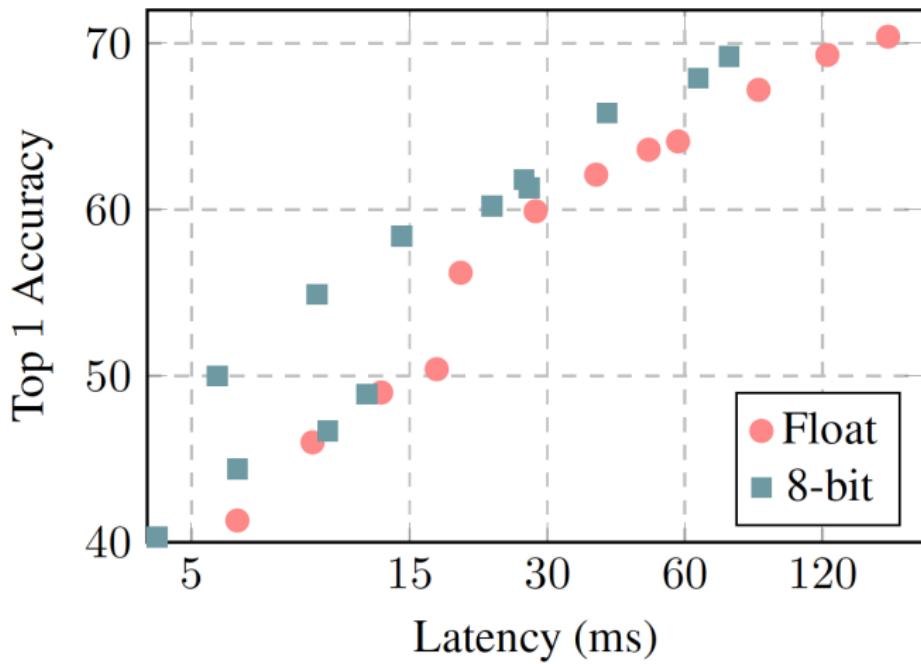
Scheme	BWN	TWN	INQ	FGQ	Ours
Weight bits	1	2	5	2	8
Activation bits	float32	float32	float32	8	8
Accuracy	68.7%	72.5%	74.8%	70.8%	74.9%

Table 4.2: ResNet on ImageNet: Accuracy under various quantization schemes, including binary weight networks (BWN [21, 15]), ternary weight networks (TWN [21, 22]), incremental network quantization (INQ [33]) and fine-grained quantization (FGQ [26])

Figure from [Jac+18] (with permission)

# Accuracy vs Latency [Jac+18]

ImageNet classifier on Google Pixel 2 (Qualcomm Snapdragon 835 big cores)



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# PyTorch

- PyTorch is a DNN training/inference environment
- QPyTorch is an excellent quantization library for PyTorch
  - Supports floating point, fixed point and block floating point

# Headers

```
# import useful modules
import argparse
import os
import torch
import torch.nn as nn
import torch.nn.functional as F
import torchvision
import torchvision.transforms as transforms
from qtorch.quant import Quantizer
from qtorch.optim import OptimLP
from torch.optim import SGD
from qtorch import BlockFloatingPoint, FloatingPoint, FixedPoint
from tqdm import tqdm
```

# Time Execution

```
import time  
start_time = time.time()
```

# Create loaders for MNIST

```
# loading data
ds = torchvision.datasets.MNIST
path = os.path.join("./data", "MNIST")
transform_train = transforms.Compose([
    transforms.ToTensor(),
    transforms.Normalize((0.1307,), (0.3081,)))
transform_test = transforms.Compose([
    transforms.ToTensor(),
    transforms.Normalize((0.1307,), (0.3081,)))
])
train_set = ds(path, train=True, download=True, transform=transform_train)
test_set = ds(path, train=False, download=True, transform=transform_test)
loaders = {
    'train': torch.utils.data.DataLoader(
        train_set,
        batch_size=64,
        shuffle=True,
        num_workers=1,
        pin_memory=True
    ),
    'test': torch.utils.data.DataLoader(
        test_set,
        batch_size=64,
        num_workers=1,
        pin_memory=True
    )
}
```

# Define a neural network

```
class Net(nn.Module):
    def __init__(self):
        super(Net, self).__init__()
        self.conv1 = nn.Conv2d(1, 20, 5, 1)
        self.conv2 = nn.Conv2d(20, 50, 5, 1)
        self.fc1 = nn.Linear(4*4*50, 500)
        self.fc2 = nn.Linear(500, 10)

    def forward(self, x):
        x = F.relu(self.conv1(x))
        x = F.max_pool2d(x, 2, 2)
        x = F.relu(self.conv2(x))
        x = F.max_pool2d(x, 2, 2)
        x = x.view(-1, 4*4*50)
        x = F.relu(self.fc1(x))
        x = self.fc2(x)
        return F.log_softmax(x, dim=1)
```

# Create an Optimiser

```
use_cuda = False
device = torch.device("cuda" if use_cuda else "cpu")
model = Net().to(device)
optimizer = SGD(model.parameters(), lr=0.05, momentum=0.9, weight_decay=1e-4)
mxepochs = 5
```

# Train for an epoch

```
def run_epoch(loader, model, criterion, optimizer=None, phase="train"):
    assert phase in ["train", "eval"], "invalid_running_phase"
    loss_sum = 0.0
    correct = 0.0

    if phase=="train": model.train()
    elif phase=="eval": model.eval()

    ttl = 0
    with torch.autograd.set_grad_enabled(phase=="train"):
        for i, (input, target) in tqdm(enumerate(loader), total=len(loader)):
            input = input.to(device=device)
            target = target.to(device=device)
            output = model(input)
            loss = criterion(output, target)
            loss_sum += loss.cpu().item() * input.size(0)
            pred = output.data.max(1, keepdim=True)[1]
            correct += pred.eq(target.data.view_as(pred)).sum()
            ttl += input.size()[0]

            if phase=="train":
                optimizer.zero_grad()
                loss.backward()
                optimizer.step()

    correct = correct.cpu().item()
    return {
        'loss': loss_sum / float(ttl),
        'accuracy': correct / float(ttl) * 100.0,
    }
```

# Run Training

```
for epoch in range(mxepochs):
    fp_train_res = run_epoch(loaders['train'], model, F.cross_entropy,
                            optimizer=optimizer, phase="train")
    fp_test_res = run_epoch(loaders['test'], model, F.cross_entropy,
                           optimizer=optimizer, phase="eval")
    print('epoch', epoch)
    print(fp_train_res)
    print(fp_test_res)
```

# Quantized Network

- Define the network. In the definition, we insert quantization module after every convolution layer. Note that the quantization of weight, gradient, momentum, and gradient accumulator are not handled here.

```
# let's define the model we are using
class lp_Net(nn.Module):
    def __init__(self, quant=None):
        super(lp_Net, self).__init__()
        self.conv1 = nn.Conv2d(1, 20, 5, 1)
        self.conv2 = nn.Conv2d(20, 50, 5, 1)
        self.fc1 = nn.Linear(4*4*50, 500)
        self.fc2 = nn.Linear(500, 10)
        self.quant = quant()

    def forward(self, x):
        x = F.relu(self.conv1(x))
        x = self.quant(x)
        x = F.max_pool2d(x, 2, 2)
        x = self.quant(x)
        x = F.relu(self.conv2(x))
        x = self.quant(x)
        x = F.max_pool2d(x, 2, 2)
        x = self.quant(x)
        x = x.view(-1, 4*4*50)
        x = F.relu(self.fc1(x))
        x = self.quant(x)
        x = self.fc2(x)
        x = self.quant(x)
        return F.log_softmax(x, dim=1)
```

# Quantization Types

- First we define a low and high precision format and give each part of the forward and backward passes a precision

```
# define two floating point formats
lowp = FixedPoint(wl=8, fl=7)
highp = FloatingPoint(exp=8, man=7) # this is bfloat16

# define quantization functions
weight_quant = Quantizer(forward_number=lowp, backward_number=None,
                         forward_rounding="nearest", backward_rounding="nearest")
grad_quant = Quantizer(forward_number=lowp, backward_number=None,
                       forward_rounding="nearest", backward_rounding="stochastic")
momentum_quant = Quantizer(forward_number=highp, backward_number=None,
                           forward_rounding="nearest", backward_rounding="stochastic")
acc_quant = Quantizer(forward_number=highp, backward_number=None,
                      forward_rounding="nearest", backward_rounding="nearest")

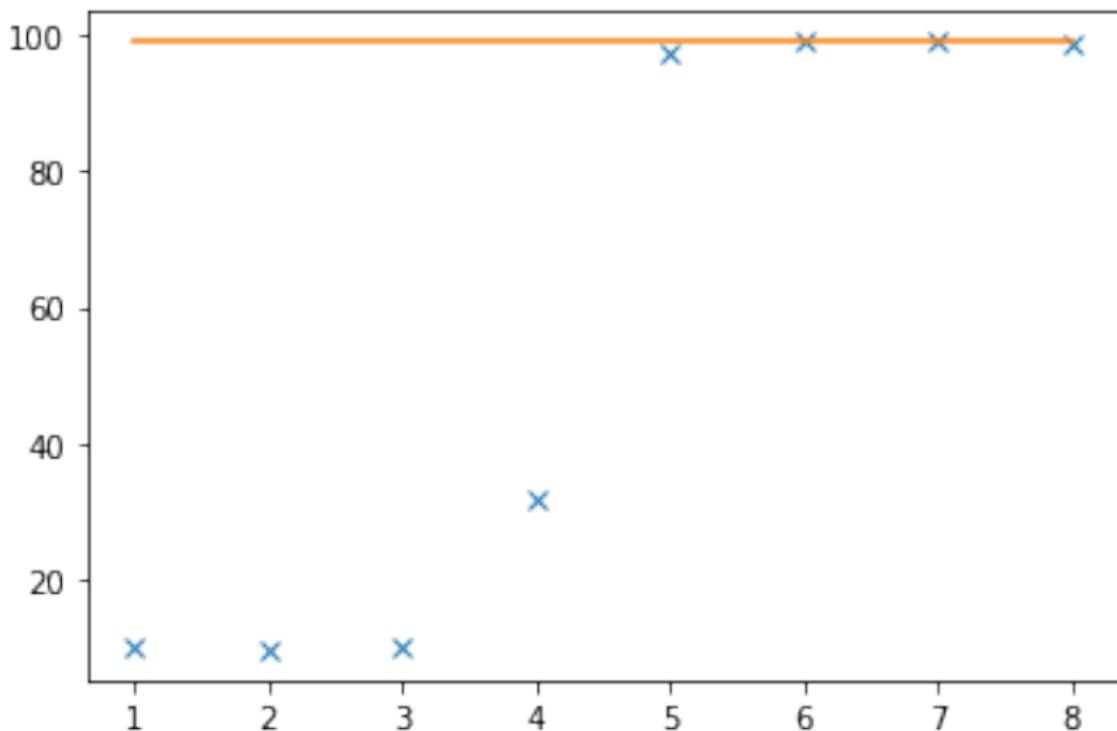
# define a lambda function so that the Quantizer module can be duplicated easily
act_error_quant = lambda : Quantizer(forward_number=lowp, backward_number=lowp,
                                      forward_rounding="nearest", backward_rounding="nearest")
```

# Quantized Training

- A low precision optimiser that uses the previously defined types

```
use_cuda = False
device = torch.device("cuda" if use_cuda else "cpu")
model = lp_Net(act_error_quant).to(device)
optimizer = SGD(model.parameters(), lr=0.05, momentum=0.9, weight_decay=1e-4)
lp_optimizer = OptimLP(optimizer,
                      weight_quant=weight_quant,
                      grad_quant=grad_quant,
                      momentum_quant=momentum_quant,
                      acc_quant=acc_quant
)
for epoch in range(mxepochs):
    train_res = run_epoch(loaders['train'], model, F.cross_entropy,
                          optimizer=lp_optimizer, phase="train")
    test_res = run_epoch(loaders['test'], model, F.cross_entropy,
                         optimizer=lp_optimizer, phase="eval")
    print('epoch', epoch)
    print(train_res)
    print(test_res)
```

# Result



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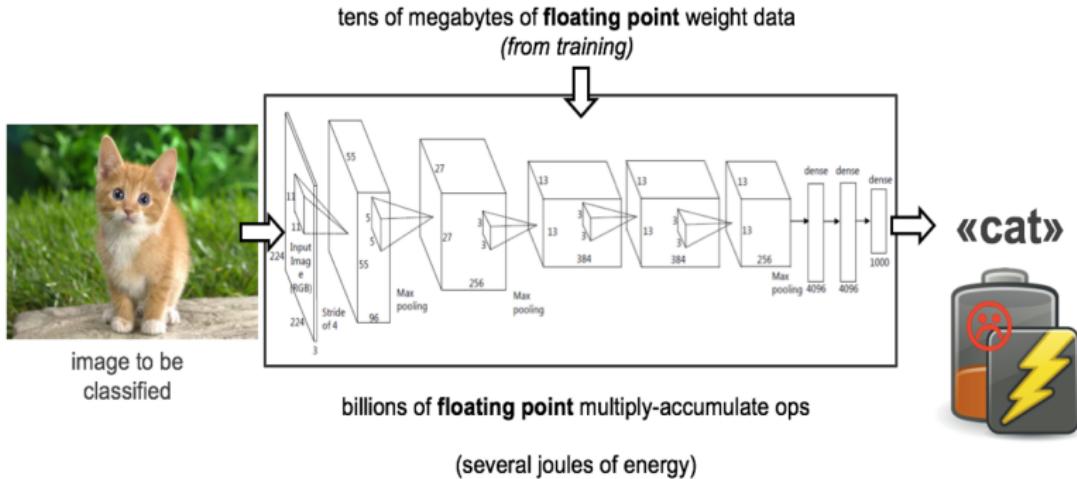
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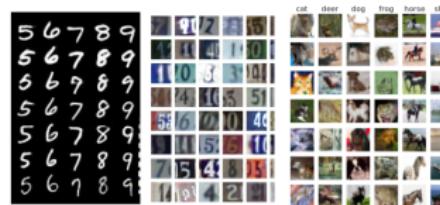
# Inference with Convolutional Neural Networks

Slides from Yaman Umuroglu et. al., "FINN: A framework for fast, scalable binarized neural network inference," FPGA'17



# Binarized Neural Networks

- › The extreme case of quantization
  - Permit only two values: +1 and -1
  - Binary weights, binary activations
  - Trained from scratch, not truncated FP
  
- › Courbariaux and Hubara et al. (NIPS 2016)
  - Competitive results on three smaller benchmarks
  - Open source training flow
  - Standard “deep learning” layers
    - Convolutions, max pooling, batch norm, fully connected...



	MNIST	SVHN	CIFAR-10
Binary weights & activations	0.96%	2.53%	10.15%
FP weights & activations	0.94%	1.69%	7.62%
BNN accuracy loss	-0.2%	-0.84%	-2.53%

*% classification error (lower is better)*

# Advantages of BNNs

## Vivado HLS estimates on Xilinx UltraScale+ MPSoC ZU19EG

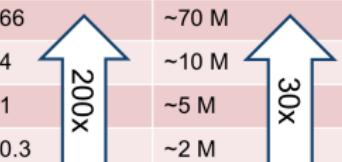
### › Much smaller datapaths

- Multiply becomes XNOR, addition becomes popcount
- No DSPs needed, everything in LUTs
- Lower cost per op = more ops every cycle

### › Much smaller weights

- Large networks can fit entirely into on-chip memory (OCM)
- More bandwidth, less energy compared to off-chip

Precision	Peak TOPS	On-chip weights
1b	~66	~70 M
8b	~4	~10 M
16b	~1	~5 M
32b	~0.3	~2 M



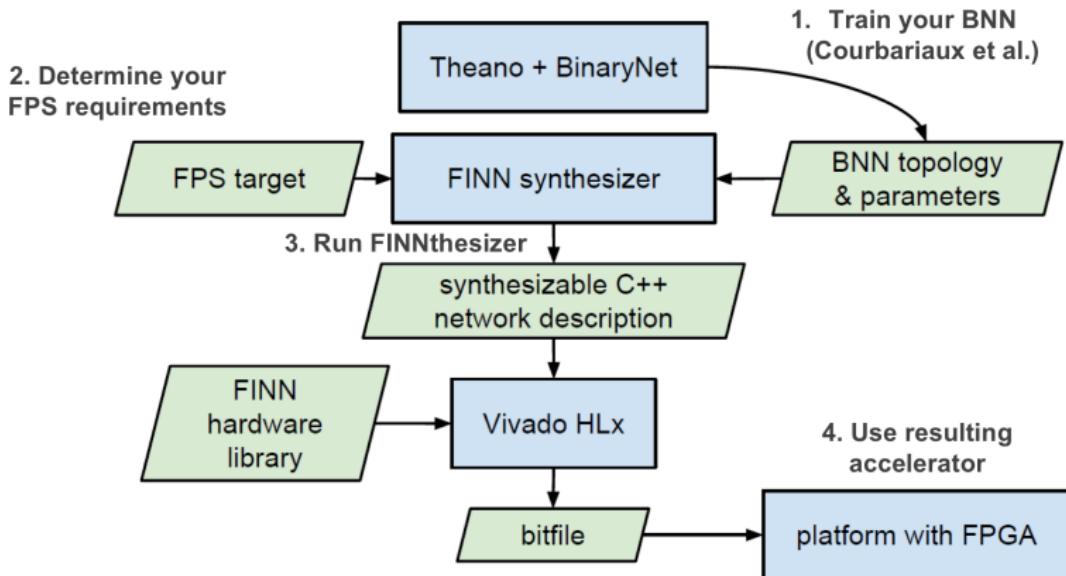
The table compares the precision, peak TOPS, and on-chip weight requirements for different data types. As precision increases from 1b to 32b, both TOPS and on-chip weight decrease significantly. Two blue arrows point upwards from the 16b and 32b rows to the Peak TOPS and On-chip weights columns, respectively, highlighting the performance and resource efficiency gains.

### › fast inference with large BNNs

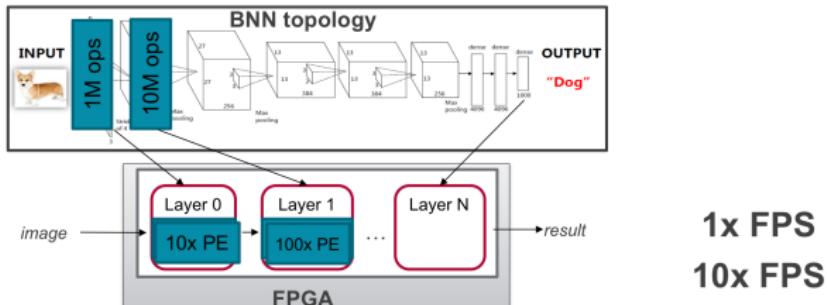
## Design Flow

- One size does not fit all - Generate tailored hardware for network and use-case
- Stay on-chip - Higher energy efficiency and bandwidth
- Support portability and rapid exploration - Vivado HLS (High-Level Synthesis)
- Simplify with BNN-specific optimizations - Exploit compile time optimizations to simplify hardware, e.g. batchnorm and activation => thresholding

# Design Flow



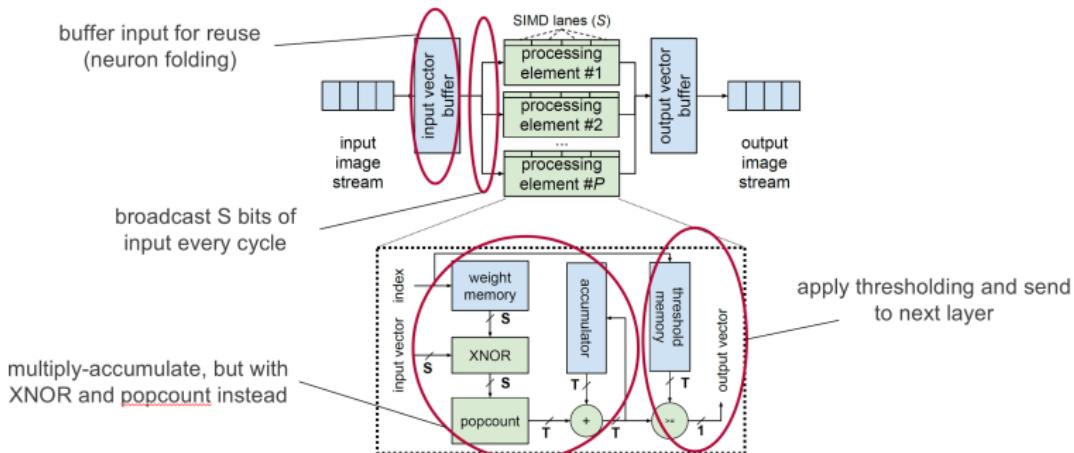
# Heterogeneous Streaming Architecture



- One hardware layer per BNN layer, parameters built into bitstream
  - Both inter- and intra-layer parallelism
- Heterogeneous: Avoid “one-size-fits-all” penalties
  - Allocate compute resources according to FPS and network requirements
- Streaming: Maximize throughput, minimize latency
  - Overlapping computation and communication, batch size = 1

# Matrix-Vector Threshold Unit (MVTU)

- Core computational element of FINN, tiled matrix-vector multiply
- Computes a  $(P)$  row  $\times (S)$  column chunk of matrix every cycle, per-layer configurable tile size

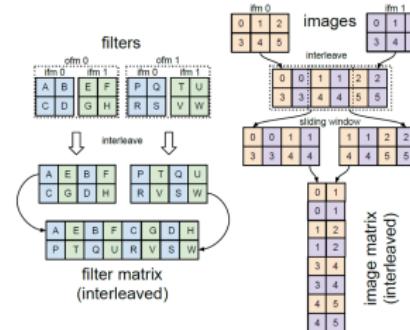
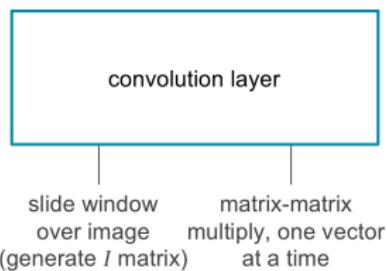


# Convolutional Layers

## ► Lower convolutions to matrix-matrix multiplication, $W \cdot I$

- $W$  : filter matrix (generated offline)
- $I$ : image matrix (generated on-the-fly)

## ► Two components:



# Performance

FINN

Prior Work

	Accuracy	FPS	Power (chip)	Power (wall)	kFPS / Watt (chip)	kFPS / Watt (wall)	Precision
MNIST, SFC-max	95.8%	12.3 M	7.3 W	21.2 W	1693	583	1
MNIST, LFC-max	98.4%	1.5 M	8.8 W	22.6 W	177	269	1
CIFAR-10, CNV-max	80.1%	21.9 k	3.6 W	11.7 W	6	2	1
SVHN, CNV-max	94.9%	21.9 k	3.6 W	11.7 W	6	2	1
MNIST, Alemdar et al.	97.8%	255.1 k	0.3 W	-	806	-	2
CIFAR-10, TrueNorth	83.4%	1.2 k	0.2 W	-	6	-	1
SVHN, TrueNorth	96.7%	2.5 k	0.3 W	-	10	-	1

Max accuracy loss: ~3%

10 – 100x better performance

CIFAR-10/SVHN energy efficiency comparable to TrueNorth ASIC

# Outline

## 1 Introduction

## 2 Quantised Neural Networks

Integer Quantisation

QPyTorch

## 3 Implementation

FINN: A Binarised Neural Network

SYQ: Low Precision DNN Training

## 4 Tutorial

## Symmetric Quantisation (SYQ) [Far+18]

- To compute quantised weights from FP weights

$$\mathbf{Q}_I = \text{sign}(\mathbf{W}_I) \odot \mathbf{M}_I \quad (6)$$

with,

$$M_{I,i,j} = \begin{cases} 1 & \text{if } |W_{I,i,j}| \geq \eta_I \\ 0 & \text{if } -\eta_I < W_{I,i,j} < \eta_I \end{cases} \quad (7)$$

$$\text{sign}(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ -1 & \text{otherwise} \end{cases} \quad (8)$$

where  $\mathbf{M}$  represents a masking matrix,  $\eta$  is the quantization threshold hyperparameter (0 for binarised)

- Open source implementation

<https://github.com/julianfaraone/SYQ>

## Scaling Factors

- To recover the dynamic range of each layer

$$\mathbf{Q}_I = \alpha_I \text{sign}(\mathbf{W}_I) \odot \mathbf{M}_I \quad (9)$$

- Further accuracy by using a vector  $\alpha_I$  for fine-grained scaling
- However, to ensure hardware amenability we need ordered scaling

## Scaling Factors ctd..

$$w = \begin{bmatrix} 0.8 & 0.2 & 0.1 & -0.4 \\ -0.4 & -0.2 & 0.1 & 0.9 \\ 0.3 & -0.4 & 0.2 & 0.4 \end{bmatrix}$$

$$\Rightarrow sign(w) = \begin{bmatrix} 1.0 & 1.0 & 1.0 & -1.0 \\ -1.0 & -1.0 & 1.0 & 1.0 \\ 1.0 & -1.0 & 1.0 & 1.0 \end{bmatrix}$$

- total quantization error = 7.6

## Scaling Factors ctd..

$$w = \begin{bmatrix} 0.8 & 0.2 & 0.1 & -0.4 \\ -0.4 & -0.2 & 0.1 & 0.9 \\ 0.3 & -0.4 & 0.2 & 0.4 \end{bmatrix}$$

$$\alpha = \|w\| = 0.37$$

$$\Rightarrow \alpha * sign(w) = \begin{bmatrix} 0.37 & 0.37 & 0.37 & -0.37 \\ -0.37 & -0.37 & 0.37 & 0.37 \\ 0.37 & -0.37 & 0.37 & 0.37 \end{bmatrix}$$

- total quantization error = 2.2

## Scaling Factors ctd..

$$w = \begin{bmatrix} 0.8 & 0.2 & 0.1 & -0.4 \\ -0.4 & -0.2 & 0.1 & 0.9 \\ 0.3 & -0.4 & 0.2 & 0.4 \end{bmatrix}$$

$$\alpha = \begin{bmatrix} \|w_1\| \\ \|w_2\| \\ \|w_3\| \end{bmatrix} = \begin{bmatrix} 0.375 \\ 0.4 \\ 0.325 \end{bmatrix}$$

$$\Rightarrow \alpha * sign(w) = \begin{bmatrix} 0.375 & 0.375 & 0.375 & -0.375 \\ -0.4 & -0.4 & 0.4 & 0.4 \\ 0.325 & -0.325 & 0.325 & 0.325 \end{bmatrix}$$

- total quantization error = 1.925

## Symmetric Quantisation (SYQ) [Far+18]

- Make approximation  $W_I \approx \alpha_I Q_I$ ,  $Q_I \in \mathcal{C}$
- $\mathcal{C}$  is the codebook,  $\mathcal{C} \in \{C_1, C_2, \dots\}$  e.g.  $\mathcal{C} = \{-1, +1\}$  for binary,  $\mathcal{C} = \{-1, 0, +1\}$  for ternary
- A diagonal matrix  $\alpha_I$  is defined by the vector  $\alpha_I = [\alpha_I^1, \dots, \alpha_I^m]$ :

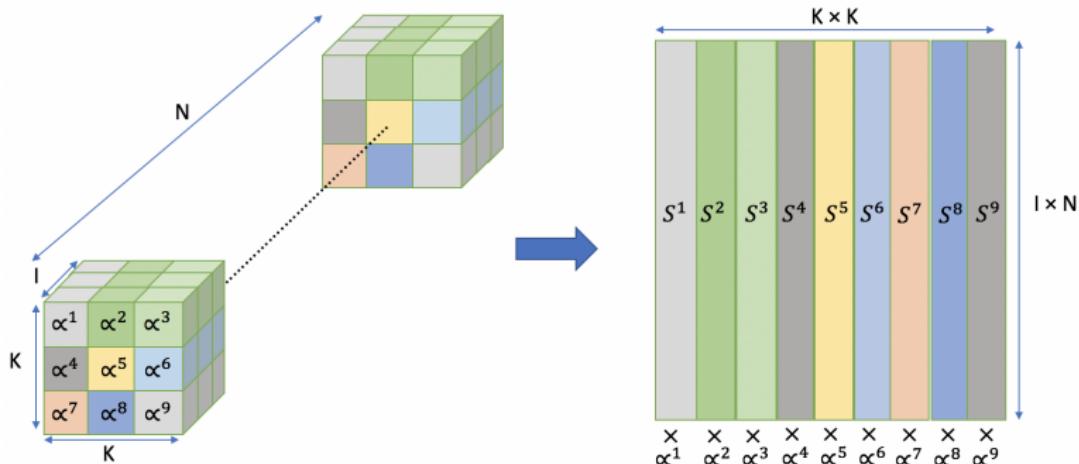
$$\alpha = \text{diag}(\alpha) := \begin{bmatrix} \alpha^1 & 0 & .. & 0 & 0 \\ 0 & \alpha^2 & .. & : & 0 \\ : & : & .. & \alpha^{m-1} & : \\ 0 & 0 & .. & 0 & \alpha^m \end{bmatrix}$$

- Train by solving

$$\alpha_I^* = \operatorname{argmin}_{\alpha} E(\alpha, \mathbf{Q}) \quad \text{s.t.} \quad \alpha \geq 0, \quad Q_{I,i,j} \in \mathcal{C}$$

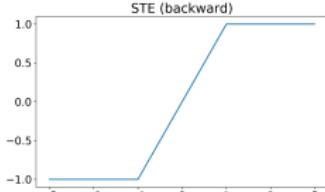
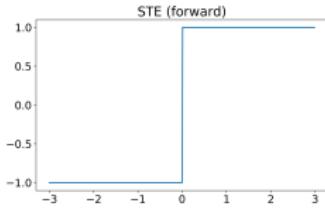
# Subgroups

- Finer-grained quantisation improves weight approximation
- Pixel-wise shown, layer-wise has similar accuracy



# Dealing with Non-differentiable Functions

- Recall (6)  $\mathbf{Q}_I = \text{sign}(\mathbf{W}_I) \odot \mathbf{M}_I$
- This step function has a derivative which is zero everywhere: *vanishing gradients* problem
- Address via a straight through estimator (STE)
- Consider  $q = \text{sign}(r)$  and  $g_r \approx \frac{\partial C}{\partial q}$  then  $\frac{\partial C}{\partial r} \approx g_q \mathbf{1}_{|r| \leq 1}$



## SYQ Forward

- Quantise the inference step

**Initialize:** Set subgrouping granularity for  $S_I^i$  and set  $\alpha_{I_0}^i$ .

**Inputs:** Minibatch of inputs & targets ( $I, Y$ ), Error function  $E(Y, \hat{Y})$ , current weights  $W_t$  and learning rate,  $\gamma_t$

**Outputs:** Updated  $W_{t+1}$ ,  $\alpha_{t+1}$  and  $\gamma_{t+1}$

### **SYQ Forward:**

**for**  $I=2$  to  $L-1$  **do**

$Q_I = sign(W_I) \odot M_I$  **with**  $\eta$

**for**  $i$ th subgroup in  $I$ th layer **do**

            Apply  $\alpha_I^i$  to  $S_I^i$

**end for**

**end for**

$\hat{Y} = \text{SYQForward}(I, Y, Q_I, \alpha_I)$

## SYQ Backward

- Do the backprop step with FP32 weights
- Compute  $\mathbf{W}$  and  $\alpha$

### **SYQ Backward:**

$\frac{\partial \hat{E}}{\partial \mathbf{Q}_I} = \text{WeightBackward}(\mathbf{Q}_I, \alpha_I, \frac{\partial \hat{E}}{\partial \hat{Y}})$

$\frac{\partial \hat{E}}{\partial \alpha_I} = \text{ScalarBackward}(\frac{\partial \hat{E}}{\partial \mathbf{Q}_I}, \alpha_I, \frac{\partial \hat{E}}{\partial \hat{Y}})$

$\mathbf{W}_{t+1} = \text{UpdateWeights}(\mathbf{W}_t, \frac{\partial \hat{E}}{\partial \mathbf{Q}_I}, \gamma)$

$\alpha_{t+1} = \text{UpdateScalars}(\alpha_t, \frac{\partial \hat{E}}{\partial \alpha_I}, \gamma)$

$\gamma_{t+1} = \text{UpdateLearningRate}(\gamma_t, t)$

## Results for 8-bit activations

<b>Model</b>		<b>Bin</b>	<b>Tern</b>	<b>FP32</b>	<b>Reference</b>
AlexNet	Top-1	<b>56.6</b>	<b>58.1</b>	56.6	57.1
	Top-5	<b>79.4</b>	<b>80.8</b>	80.2	80.2
VGG	Top-1	<b>66.2</b>	<b>68.7</b>	69.4	-
	Top-5	<b>87.0</b>	<b>88.5</b>	89.1	-
ResNet-18	Top-1	<b>62.9</b>	<b>67.7</b>	69.1	69.6
	Top-5	<b>84.6</b>	<b>87.8</b>	89.0	89.2
ResNet-34	Top-1	<b>67.0</b>	<b>70.8</b>	71.3	73.3
	Top-5	<b>87.6</b>	<b>89.8</b>	89.1	91.3
ResNet-50	Top-1	<b>70.6</b>	<b>72.3</b>	76.0	76.0
	Top-5	<b>89.6</b>	<b>90.9</b>	93.0	93.0

- Our ResNet and AlexNet reference results are obtained from <https://github.com/facebook/fb.resnet.torch> and <https://github.com/BVLC/caffe>

## Alexnet Comparison

<b>Model</b>	<b>Weights</b>	<b>Act.</b>	<b>Top-1</b>	<b>Top-5</b>
DoReFa-Net [Zho+16]	1	2	49.8	-
QNN [Hub+16]	1	2	51.0	73.7
HWGQ [Cai+17]	1	2	52.7	76.3
<b>SYQ</b>	<b>1</b>	<b>2</b>	<b>55.2</b>	<b>78.4</b>
DoReFa-Net [Zho+16]	1	4	53.0	-
<b>SYQ</b>	<b>1</b>	<b>4</b>	<b>56.2</b>	<b>79.4</b>
BWN [Ras+16]	1	32	56.8	79.4
<b>SYQ</b>	<b>1</b>	<b>8</b>	<b>56.6</b>	<b>79.4</b>
<b>SYQ</b>	<b>2</b>	<b>2</b>	<b>55.7</b>	<b>79.1</b>
FGQ [Mel+17]	2	8	49.04	-
TTQ [Zhu+16]	2	32	57.5	79.7
<b>SYQ</b>	<b>2</b>	<b>8</b>	<b>58.1</b>	<b>80.8</b>

# Summary

- Reducing precision
  - Significantly reduce computational costs in DNNs
  - Data may now fit entirely on chip, avoiding external memory accesses
  - Computations greatly simplified
  - Key dimension for optimisation in CPU/GPU/FPGA implementations
- Convolutional layer can be computed as a MM
- Still an active research topic

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## 4 Tutorial

# Installation

- To load:

```
docker load -i nova-quant-docker.tar
```

- To run:

```
docker run -it -p8888:8888 \
pytorch-jupyter-docker_jupytertorch:latest bash
```

- Then:

```
git clone https://github.com/phwl/nova-quant
cd nova-quant
jupyter notebook --allow-root --no-browser --ip='*'
```

- On your browser:

```
http://127.0.0.1:8888/?token=1b14e...
```

## Questions

- 1 Follow the instructions in the following jupyter notebooks to complete the tutorial.
- 2 sround.ipynb an implementation of stochastic rounding (slide 10).
- 3 Read the QPyTorch Functionality Overview at  
[https://github.com/Tiiiger/QPyTorch/blob/master/examples/tutorial/Functionality\\_Overview.ipynb](https://github.com/Tiiiger/QPyTorch/blob/master/examples/tutorial/Functionality_Overview.ipynb)
- 4 mnist.ipynb training of a low-precision MNIST inference network.

## References I

- [TL19] Mingxing Tan et al. “EfficientNet: Rethinking Model Scaling for Convolutional Neural Networks”. In: *arXiv e-prints*, arXiv:1905.11946 (May 2019), arXiv:1905.11946. arXiv: 1905.11946 [cs.LG].
- [Din+17] Caiwen Ding et al. “CirCNN: Accelerating and Compressing Deep Neural Networks Using Block-circulant Weight Matrices”. In: *Proceedings of the 50th Annual IEEE/ACM International Symposium on Microarchitecture*. MICRO-50 '17. Cambridge, Massachusetts: ACM, 2017, pp. 395–408. ISBN: 978-1-4503-4952-9. DOI: 10.1145/3123939.3124552. URL: <http://doi.acm.org/10.1145/3123939.3124552>.

## References II

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## References III

- [Jac+18] Benoit Jacob et al. “Quantization and Training of Neural Networks for Efficient Integer-Arithmetic-Only Inference”. In: *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. June 2018.
- [Far+18] Julian Faraone et al. “SYQ: Learning Symmetric Quantization For Efficient Deep Neural Networks”. In: *Proc. Computer Vision and Pattern Recognition (CVPR)*. Utah, US, June 2018.
- [Zho+16] Shuchang Zhou et al. “DoReFa-Net: Training Low Bitwidth Convolutional Neural Networks with Low Bitwidth Gradients”. In: *CoRR* abs/1606.06160 (2016). URL:  
<http://arxiv.org/abs/1606.06160>.

## References IV

- [Hub+16] Itay Hubara et al. “Quantized Neural Networks: Training Neural Networks with Low Precision Weights and Activations”. In: *CoRR* abs/1609.07061 (2016). arXiv: 1609.07061. URL: <http://arxiv.org/abs/1609.07061>.
- [Cai+17] Zhaowei Cai et al. “Deep Learning with Low Precision by Half-wave Gaussian Quantization”. In: *CoRR* abs/1702.00953 (2017). arXiv: 1702.00953. URL: <http://arxiv.org/abs/1702.00953>.
- [Ras+16] Mohammad Rastegari et al. “XNOR-Net: ImageNet Classification Using Binary Convolutional Neural Networks”. In: *CoRR* abs/1603.05279 (2016). URL: <http://arxiv.org/abs/1603.05279>.

## References V

- [Mel+17] Naveen Mellemudi et al. “Ternary Neural Networks with Fine-Grained Quantization”. In: *CoRR* abs/1705.01462 (2017). URL: <http://arxiv.org/abs/1705.01462>.
- [Zhu+16] Chenzhuo Zhu et al. “Trained Ternary Quantization”. In: *CoRR* abs/1612.01064 (2016). URL: <http://arxiv.org/abs/1612.01064>.