

# TensorFlow 2 Support

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## Overview

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The ML models created and trained using TensorFlow 2/Keras API can be ported and executed on MAX78000. Different types of Keras models with TensorFlow sequential, functional and subclassing API are supported. The following development approach has to be used:

1. Create Keras model using supported MAX78000 TF sub-classes which reflect hardware behavior and limit operations
2. Train model and store the model graph + weights into a **saved\_model.pb** file
3. Use a Tensorflow-to-ONNX converter (**tf2onnx.convert**) to create an ONNX framework model from **saved\_model.pb**
4. Quantize ONNX model weights and feed to MAX78000 synthesis tool to generate C code
5. Compile synthesized C code, load to MAX78000 and verify it

## Setup

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1- Install NVIDIA GPU drivers CUDA 10.1, CUDA Toolkit, CUPTI and cuDNN SDK 7.6 as described in Software requirements for Tensorflow:

<https://www.tensorflow.org/install/gpu>

2- Make sure that ~/.bash\_profile includes path to CUDA and CUPTI:

```
export PATH="$PATH:/usr/local/cuda-10.1/bin"
export LD_LIBRARY_PATH="$LD_LIBRARY_PATH:/usr/local/cuda-10.1/extras/CUPTI/lib64"
```

3- To create a virtual environment please refer to section "Creating the Virtual Environment" of [1] document.

## Supported MAX78000 TensorFlow Subclasses:

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**ai85TF.py** includes a set of customized TensorFlow 2 Keras subclasses to be used by any model that is designed to run on MAX78000.

Name	Description/Keras Equivalent
Conv1D	Generic Conv1D, padding_size=0
FusedConv1D	Conv1D with activation as None, padding_size=0
FusedConv1DReLU	Conv1D with activation as 'relu', padding_size=0
FusedMaxPoolConv1D	MaxPool1D, followed by Conv1D with activation as None, padding_size=0
FusedMaxPoolConv1DReLU	MaxPool1D, followed by Conv1D with activation as 'relu', padding_size=0
FusedAvgPoolConv1D	AveragePooling1D, followed by Conv1D with activation as None, padding_size=0
FusedAvgPoolConv1DReLU	AveragePooling1D followed by Conv1D with activation as 'relu', padding_size=0
MaxPool1D	MaxPool1D
AvgPool1D	AveragePooling1D
Conv2D	Generic Conv2D, padding_size=0
FusedConv2D	Conv2D with activation as None, padding_size=0
FusedConv2DReLU	Conv2D with activation as 'relu', padding_size=0
FusedMaxPoolConv2D	MaxPool2D, followed by Conv2D with activation as None, padding_size=0
FusedMaxPoolConv2DReLU	MaxPool2D, followed by Conv2D with activation as 'relu', padding_size=0
FusedAvgPoolConv2D	AveragePooling2D, followed by Conv2D with activation as None, padding_size=0
FusedAvgPoolConv2DReLU	AveragePooling2D followed by Conv2D with activation as 'relu', padding_size=0
MaxPool2D	MaxPool2D
AvgPool2D	AveragePooling2D
FusedConv2DTranspose	Conv2DTranspose with activation as None, padding_size=0
FusedConv2DTransposeReLU	Conv2DTranspose with activation as 'relu', padding_size=0
FusedMaxPoolConv2DTranspose	MaxPool2D, followed by Conv2DTranspose with activation as 'relu', padding_size=0
FusedMaxPoolConv2DTransposeReLU	MaxPool2D, followed by Conv2DTranspose with activation as 'relu', padding_size=0

Name	Description/Keras Equivalent
FusedAvgPoolConv2DTranspose	AveragePooling2D, followed by Conv2DTranspose with activation as None, padding_size=0
FusedAvgPoolConv2DTransposeReLU	AveragePooling2D followed by Conv2DTranspose with activation as 'relu', padding_size=0
Dense	Generic Dense
FusedDense	Dense with activation as None
FusedDenseReLU	Dense with activation as 'relu'

## Limitations of supported operations:

### Conv2D:

- Kernel sizes must be 1×1 or 3×3.
- Padding can be 0, 1, or 2 (default: padding\_size = 0).
- Stride is fixed to 1. Pooling, including 1×1, can be used to achieve a stride other than 1.

### Conv1D:

- Kernel sizes must be 1 through 9.
- Padding can be 0, 1, or 2 (default: padding\_size = 0).
- Stride is fixed to 1. Pooling, including 1, can be used to achieve a stride other than 1.

### Conv2DTranspose:

- Kernel sizes must be 3×3.
- Padding can be 0, 1, or 2 (default: padding\_size = 0).
- Stride is fixed to 2

### Pooling:

- Both max pooling and average pooling are available, with or without convolution.
- Pooling does not support padding.
- Pooling strides can be 1 through 16. For 2D pooling, the stride is the same for both dimensions.
- For 2D pooling, supported pooling kernel sizes are 1×1 through 16×16, including non-square kernels. 1D pooling supports kernels from 1 through 16. *Note: 1×1 kernels can be used when a convolution stride other than 1 is desired.*
- The number of input channels must not exceed 1024.
- The number of output channels must not exceed 1024.

For more details of MAX7800 HW related limitations please check **[1]** document.

## Training Models

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Following bash scripts are provided to download the dataset, train the model and to convert to onnx format:

```
train_cifar10.sh
train_kws20.sh
train_mnist.sh
train_cifar100.sh
train_fashionmnist.sh
train_rock.sh
```

Example: (train\_mnist.sh)

```
python train.py --epochs 100 --batch_size 256 --optimizer Adam --lr 0.001 --
model mnist_model --dataset mnist --save-sample 1
python -m tf2onnx.convert --saved-model export/mnist --opset 10 --output
export/mnist/saved_model.onnx
```

The script automatically downloads corresponding dataset and process and copy into **/data/** if needed and starts training. Training progress and results including checkpoint and a sample prediction for one test data in HWC format will be stored in log file inside **/logs/** directory. The model graph and weights are stored as **saved\_model.pb** file in log directory, as well as in **/export/** directory.

## Command-line args for Training

User can modify following training command-line parameters:

Training parameter	Description
--epochs	Number of training epochs (default: 100)
--batch_size	Training batch size (default: 32)
--optimizer	Optimizer type: Adam or SGD (default: Adam)
--lr	Initial learning rate (default: 0.0001). During training learning rate is adjusted according to schedule in model
--model	Model name
--dataset	Dataset name
--save-sample	Save input sample with specified index in <b>.npy</b> format in <b>/export/</b> folder for verification in synthesis in
--save-sample-per-class	Save one input sample for each class in <b>.npy</b> format in <b>logs</b> folder to be used for verification
--metrics	Metrics used in compiling model (default: accuracy)

Once training is complete, the model is converted to ONNX format and stored in **/export/**.

## Models

Model examples are located in **models** directory. Each model includes a Tensorflow Keras sequential model, as well as the callback function for learning rate adjustment scheduler:

```
models/cifar10_model.py
models/cifar100_model.py
models/fashionmnist_model.py
models/kws20_model.py
models/mnist_model.py
models/rock_model.py
```

## Learning rate scheduler

Each model script includes the lr scheduler callback function to be used for that model. The default schedule is ReduceLROnPlateau with following parameters:

```
lr_schedule = tf.keras.callbacks.ReduceLROnPlateau(
    monitor='val_accuracy',
    mode='max',
    factor=0.2,
    patience=3,
    verbose=1,
    min_lr=1e-5)
```

## Datasets

Dataset scripts are located in **/dataset/** directory and used to download the dataset and create a processed **.npz** dataset file (if needed) in **/data/** to be used by training script:

```
datasets/cifar10.py
datasets/cifar100.py
datasets/fashionmnist.py
datasets/kws20.py
datasets/mnist.py
datasets/rock.py
```

datasets include training, validation and test images and labels. Images are in [-128,127] range when created by dataset scripts.

In training script, they are normalized to [-0.5,0.5] and fed to the network.

## Examples

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### MNIST model

The MNIST model is an example of Keras model with sequential API and it recognizes 28x28 images of handwritten digits from 0 to 9.

```
model = tf.keras.models.Sequential([
    tf.keras.Input(shape=(28, 28)),
    tf.keras.layers.Reshape(target_shape=(28, 28, 1)),
```

```

ai8xTF.FusedConv2DReLU(
    filters=60,
    kernel_size=3,
    strides=1,
    padding_size=1,
    use_bias=False),
ai8xTF.FusedMaxPoolConv2DReLU(
    filters=60,
    kernel_size=3,
    strides=1,
    padding_size=2,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
ai8xTF.FusedMaxPoolConv2DReLU(
    filters=56,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
ai8xTF.FusedAvgPoolConv2DReLU(
    filters=12,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
tf.keras.layers.Flatten(),
ai8xTF.FusedDense(10, wide=True, use_bias=True),
])

```

To train MNIST model execute following script:

```
$ bash train_mnist.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```

Epoch 98/100
211/211 - 2s - loss: 0.0022 - accuracy: 1.0000 - val_loss: 0.0279 -
val_accuracy: 0.9908
Epoch 99/100
211/211 - 2s - loss: 0.0022 - accuracy: 1.0000 - val_loss: 0.0279 -
val_accuracy: 0.9908
Epoch 100/100
211/211 - 2s - loss: 0.0021 - accuracy: 1.0000 - val_loss: 0.0278 -
val_accuracy: 0.9908
188/188 - 0s - loss: 0.0302 - accuracy: 0.9900
Test Accuracy: 0.9900000095367432
Confusion Matrix:
tf.Tensor(
[[619  0  1  1  0  0  1  0  2  0]
 [  0 654  0  0  0  0  0  0  0  0]
 [  0  1 569  0  0  0  0  1  0  1]

```

```
[ 0 0 2 584 0 2 0 0 1 0]
[ 1 0 0 0 572 0 0 1 0 6]
[ 1 0 0 1 0 544 2 0 3 0]
[ 2 0 1 1 1 2 572 0 1 0]
[ 0 1 3 0 1 0 0 627 0 1]
[ 1 0 2 1 1 0 0 0 580 0]
[ 0 0 0 1 7 1 0 3 1 619]], shape=(10, 10), dtype=int32)
```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "sequential"

Layer (type)	Output Shape	Param #
reshape (Reshape)	(None, 28, 28, 1)	0
fused_conv2d_re_lu (FusedConv2D)	(None, 28, 28, 60)	540
fused_max_pool_conv2d_re_lu (FusedMaxPool2D)	(None, 16, 16, 60)	32400
fused_max_pool_conv2d_re_lu (FusedMaxPool2D)	(None, 8, 8, 56)	30240
fused_avg_pool_conv2d_re_lu (FusedAvgPool2D)	(None, 4, 4, 12)	6048
flatten (Flatten)	(None, 192)	0
fused_dense (FusedDense)	(None, 10)	1930
Total params: 71,158		
Trainable params: 71,158		
Non-trainable params: 0		

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format:

```
export/mnist/saved_model.pb
export/mnist/saved_model.onnx
```

## Fashion MNIST model

This model demonstrates recognition of 10 28x28 fashion images: **T-shirt/top, trouser, pullover, dress, coat, sandal, shirt, sneaker, bag, ankle boot.**

The Fashion MNIST model is an example of Keras model with functional API:

```
# create a functional model
input_layer = tf.keras.Input(shape=(28, 28))
```

```

reshape = tf.keras.layers.Reshape(target_shape=(28, 28, 1))(input_layer)
conv1 = ai8xTF.FusedConv2DReLU(
    filters=60,
    kernel_size=3,
    strides=1,
    padding_size=1)(reshape)

conv2 = ai8xTF.FusedMaxPoolConv2DReLU(
    filters=60,
    kernel_size=3,
    strides=1,
    padding_size=2,
    pool_size=2,
    pool_strides=2)(conv1)

# dropout1= tf.keras.layers.Dropout(0.2)(conv2)

conv3 = ai8xTF.FusedMaxPoolConv2DReLU(
    filters=56,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2)(conv2)

conv4 = ai8xTF.FusedAvgPoolConv2DReLU(
    filters=12,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2)(conv3)

flat = tf.keras.layers.Flatten(input_shape=(28, 28))(conv4)

output_layer = ai8xTF.FusedDense(10, wide=True)(flat)

model = tf.keras.Model(inputs=[input_layer], outputs=[output_layer])

```

To train fashion MNIST model execute following script:

```
$ bash train_fashionmnist.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```

Epoch 97/100
211/211 - 2s - loss: 0.1520 - accuracy: 0.9490 - val_loss: 0.2439 -
val_accuracy: 0.9121
Epoch 98/100
211/211 - 2s - loss: 0.1517 - accuracy: 0.9492 - val_loss: 0.2441 -
val_accuracy: 0.9113
Epoch 99/100
211/211 - 2s - loss: 0.1515 - accuracy: 0.9491 - val_loss: 0.2440 -
val_accuracy: 0.9108
Epoch 100/100

```



```

211/211 - 2s - loss: 0.1512 - accuracy: 0.9493 - val_loss: 0.2441 -
val_accuracy: 0.9107
188/188 - 0s - loss: 0.2329 - accuracy: 0.9148
Test Accuracy: 0.9148333072662354
Confusion Matrix:
tf.Tensor(
[[522   1  11  14   1   0  46   0   2   0]
 [  0 597   0  10   0   0   1   0   0   0]
 [  9   0 545   3  31   0  22   0   1   0]
 [ 15   3   2 536  17   0  13   0   1   0]
 [  0   0  24  22 546   0  33   0   2   0]
 [  0   0   0   0   0 601   1  11   4   4]
 [ 60   2  32  17  35   0 467   0   6   0]
 [  0   0   0   0   0   7   0 533   0  10]
 [  2   1   2   0   2   2   3   0 578   0]
 [  0   0   0   0   0   3   0  22   1 564]], shape=(10, 10), dtype=int32)

```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "functional\_1"

Layer (type)	Output Shape	Param #
=====		
input_1 (InputLayer)	[(None, 28, 28)]	0
reshape (Reshape)	(None, 28, 28, 1)	0
fused_conv2d_re_lu (FusedCon	(None, 28, 28, 60)	600
fused_max_pool_conv2d_re_lu	(None, 16, 16, 60)	32460
fused_max_pool_conv2d_re_lu_	(None, 8, 8, 56)	30296
fused_avg_pool_conv2d_re_lu	(None, 4, 4, 12)	6060
flatten (Flatten)	(None, 192)	0
fused_dense (FusedDense)	(None, 10)	1930
=====		
Total params: 71,346		
Trainable params: 71,346		
Non-trainable params: 0		

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format

```

export/fashionmnist/saved_model.pb
export/fashionmnist/saved_model.onnx

```

## CIFAR10 model

The CIFAR-10 dataset consists of 60000 32x32 color images in 10 classes: **plane, car, bird, cat, deer, dog, frog, horse, ship, truck**.

<https://www.cs.toronto.edu/~kriz/cifar.html>

The CIFAR10 model is an example of Keras model with sequential API:

```
model = tf.keras.models.Sequential([
    tf.keras.Input(shape=(32, 32, 3)),
    ai8xTF.FusedConv2DReLU(
        filters=60, kernel_size=3, strides=1, padding_size=1, use_bias=False),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=60,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2,
        use_bias=False),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=56,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2,
        use_bias=False),
    ai8xTF.FusedAvgPoolConv2DReLU(
        filters=12,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2,
        use_bias=False),
    tf.keras.layers.Flatten(),
    ai8xTF.FusedDense(10, wide=True, use_bias=False),
])
```

To train CIFAR10 model execute following script:

```
$ bash train_cifar10.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```
Epoch 98/100
704/704 - 5s - loss: 0.5455 - accuracy: 0.8174 - val_loss: 0.8520 -
val_accuracy: 0.7002
Epoch 99/100
704/704 - 6s - loss: 0.5443 - accuracy: 0.8179 - val_loss: 0.8533 -
val_accuracy: 0.7017
Epoch 100/100
704/704 - 6s - loss: 0.5436 - accuracy: 0.8173 - val_loss: 0.8515 -
val_accuracy: 0.7040
157/157 - 0s - loss: 0.8420 - accuracy: 0.7036
Test Accuracy: 0.7035999894142151
```

```
Confusion Matrix:
tf.Tensor(
[[356  15  21  10   6   3   3   8  31  23]
 [ 13 402   5   2   1   1   3   4  17  39]
 [ 41   3 311  32  43  36  36  13   6   6]
 [ 13   1  35 243  37 126  37  21   5   5]
 [ 16   1  22  20 335  17  26  41   4   4]
 [  3   1  27  91  26 312   9  31   1   3]
 [  7   2  31  26  33  12 367   4   1   2]
 [  9   2  20  15  36  30   3 382   3   9]
 [ 41  20   2   6   1   0   4   3 416  10]
 [ 15  47   4   6   7   5   2   5  15 394]], shape=(10, 10), dtype=int32)
```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "sequential"

Layer (type)	Output Shape	Param #
fused_conv2d_re_lu (FusedConv)	(None, 32, 32, 60)	1620
fused_max_pool_conv2d_re_lu	(None, 16, 16, 60)	32400
fused_max_pool_conv2d_re_lu_	(None, 8, 8, 56)	30240
fused_avg_pool_conv2d_re_lu	(None, 4, 4, 12)	6048
flatten (Flatten)	(None, 192)	0
fused_dense (FusedDense)	(None, 10)	1920
Total params: 72,228		
Trainable params: 72,228		
Non-trainable params: 0		

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format

```
export/cifar10/saved_model.pb
export/cifar10/saved_model.onnx
```

## CIFAR100 model

The CIFAR100 model classifies 100 32x32 color images from 60K dataset.

<https://www.cs.toronto.edu/~kriz/cifar.html>

The CIFAR100 model is an example of Keras model with sequential API:

```
model = tf.keras.models.Sequential([
```

```

tf.keras.Input(shape=(32, 32, 3)),
ai8xTF.FusedConv2DReLU(
    filters=60, kernel_size=3, strides=1, padding_size=1, use_bias=False),
ai8xTF.FusedMaxPoolConv2DReLU(
    filters=60,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
ai8xTF.FusedMaxPoolConv2DReLU(
    filters=56,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
ai8xTF.FusedAvgPoolConv2DReLU(
    filters=12,
    kernel_size=3,
    strides=1,
    padding_size=1,
    pool_size=2,
    pool_strides=2,
    use_bias=False),
tf.keras.layers.Flatten(),
ai8xTF.FusedDense(10, wide=True, use_bias=False),
])

```

To train CIFAR100 model execute following script:

```
$ bash train_cifar100.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```

Epoch 99/100
1407/1407 - 11s - loss: 1.1360 - accuracy: 0.7284 - val_loss: 2.8744 -
val_accuracy: 0.3305
Epoch 100/100
1407/1407 - 11s - loss: 1.1316 - accuracy: 0.7310 - val_loss: 2.8761 -
val_accuracy: 0.3283
157/157 - 0s - loss: 2.8540 - accuracy: 0.3338
Test Accuracy: 0.33379998803138733
Confusion Matrix:
tf.Tensor(
[[34  2  0 ...  0  0  0]
 [ 0 18  1 ...  0  0  0]
 [ 0  0 19 ...  1  4  0]
 ...
 [ 0  0  0 ... 11  0  0]
 [ 0  0  2 ...  1 18  0]
 [ 0  0  0 ...  1  0  8]], shape=(100, 100), dtype=int32)

```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "sequential"

Layer (type)	Output Shape	Param #
=====		
fused_conv2d_re_lu (FusedCon	(None, 32, 32, 16)	432
fused_conv2d_re_lu_1 (FusedC	(None, 32, 32, 20)	2880
fused_conv2d_re_lu_2 (FusedC	(None, 32, 32, 20)	3600
fused_conv2d_re_lu_3 (FusedC	(None, 32, 32, 20)	3600
fused_max_pool_conv2d_re_lu	(None, 16, 16, 20)	3600
fused_conv2d_re_lu_4 (FusedC	(None, 16, 16, 20)	3600
fused_conv2d_re_lu_5 (FusedC	(None, 16, 16, 44)	7920
fused_max_pool_conv2d_re_lu_	(None, 8, 8, 48)	19008
fused_conv2d_re_lu_6 (FusedC	(None, 8, 8, 48)	20736
fused_max_pool_conv2d_re_lu_	(None, 4, 4, 96)	41472
fused_max_pool_conv2d_re_lu_	(None, 2, 2, 512)	49152
fused_conv2d_re_lu_7 (FusedC	(None, 2, 2, 128)	65536
fused_max_pool_conv2d_re_lu_	(None, 1, 1, 128)	147456
conv2d_13 (Conv2D)	(None, 1, 1, 100)	12800
flatten (Flatten)	(None, 100)	0
=====		
Total params: 381,792		
Trainable params: 381,792		
Non-trainable params: 0		

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format

```
export/cifar100/saved_model.pb
export/cifar100/saved_model.onnx
```

## KWS20 model

The KWS20 model uses the 2nd version of Google speech commands dataset which consists of 35 keywords and more than 100K utterances.

[https://storage.cloud.google.com/download.tensorflow.org/data/speech\\_commands\\_v0.02.tar.gz](https://storage.cloud.google.com/download.tensorflow.org/data/speech_commands_v0.02.tar.gz)

This model demonstrates recognition of 20 keywords: 'up', 'down', 'left', 'right', 'stop', 'go', 'yes', 'no', 'on', 'off', 'one', 'two', 'three', 'four', 'five', 'six', 'seven', 'eight', 'nine', 'zero'. The rest of keywords are placed into category as "unknown".

The KWS20 model is an example of Keras model with sequential API:

```
model = tf.keras.models.Sequential([
    # Need to specify the input shape if you want to show it in model summary
    tf.keras.Input(shape=(128, 128)),
    ai8xTF.FusedConv1DReLU(
        filters=100,
        kernel_size=1,
        strides=1,
        padding_size=0,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),
    ai8xTF.FusedConv1DReLU(
        filters=100,
        kernel_size=1,
        strides=1,
        padding_size=0,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),
    ai8xTF.FusedConv1DReLU(
        filters=50,
        kernel_size=1,
        strides=1,
        padding_size=0,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),
    ai8xTF.FusedConv1DReLU(
        filters=16,
        kernel_size=1,
        strides=1,
        padding_size=0,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),

    # Conversion 1D to 2D
    tf.keras.layers.Reshape(target_shape=(8, 16, 16)),
    ai8xTF.FusedConv2DReLU(
        filters=32,
        kernel_size=3,
        strides=1,
        padding_size=1,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),
    ai8xTF.FusedConv2DReLU(
        filters=64,
```

```

        kernel_size=3,
        strides=1,
        padding_size=1,
        kernel_regularizer=regularizer,
        activity_regularizer=activity_regularizer,
        use_bias=False),
ai8xTF.FusedConv2DReLU(
    filters=64,
    kernel_size=3,
    strides=1,
    padding_size=1,
    kernel_regularizer=regularizer,
    activity_regularizer=activity_regularizer,
    use_bias=False),
ai8xTF.FusedConv2DReLU(
    filters=30,
    kernel_size=3,
    strides=1,
    padding_size=1,
    kernel_regularizer=regularizer,
    activity_regularizer=activity_regularizer,
    use_bias=False),
ai8xTF.FusedConv2DReLU(
    filters=7,
    kernel_size=3,
    strides=1,
    padding_size=1,
    kernel_regularizer=regularizer,
    activity_regularizer=activity_regularizer,
    use_bias=False),
tf.keras.layers.Flatten(),
ai8xTF.FusedDense(
    21, wide=True,
    use_bias=False,
    kernel_regularizer=regularizer,
    activity_regularizer=activity_regularizer),
])

```

To train KWS20 model execute following script:

```
$ bash train_kws20.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```

Epoch 198/200
667/667 - 5s - loss: 0.3848 - accuracy: 0.9528 - val_loss: 0.6943 -
val_accuracy: 0.8573
Epoch 199/200
667/667 - 5s - loss: 0.3847 - accuracy: 0.9522 - val_loss: 0.7012 -
val_accuracy: 0.8545
Epoch 200/200
667/667 - 4s - loss: 0.3842 - accuracy: 0.9527 - val_loss: 0.6977 -
val_accuracy: 0.8561
319/319 - 1s - loss: 0.7320 - accuracy: 0.8514
Test Accuracy: 0.8514375686645508
Confusion Matrix:

```

```
tf.Tensor(
[[ 323  0  0  0  6  4  0  2  4 15  0  1  0  0  0
 0  0  1  0  0 17]
 [ 2 303  0  0  1 13  0 11  1  0  1  2  0  1  0
 1  1  0  8  0 34]
 [ 1  0 304  8  0  0 13  3  0  2  1  0  1  0  0
 0  0  1  3  1 23]
 [ 1  1  7 297  0  0  0  0  2  0  5  0  2  1  6
 0  0  1 14  0 21]
 [ 4  1  0  0 350  2  0  0  0  2  0  1  0  2  0
 3  8  0  0  0  9]
 [ 4 11  0  0  3 273  0 17  1  1  0  6  0  5  0
 0  0  3  1  0 46]
 [ 0  2  8  0  0  0 364  2  0  3  2  0  1  0  0
 3  0  1  0  2 15]
 [ 2 12  0  0  0 21  2 307  0  0  2  1  0  1  0
 0  0  0  7  2 30]
 [ 2  4  0  0  0  2  0  0 298 12  9  1  1  2 15
 1  0  0  2  0 12]
 [ 24  0  1  0  0  2  2  0  9 284  1  1  0  4  5
 0  0  0  0  0  7]
 [ 1  1  2  4  0  2  1  3  7  0 320  0  0  1  2
 0  0  0  7  0 33]
 [ 1  1  1  0  1  7  1  0  0  0  0 319  3  4  0
 2  3  0  1 11 18]
 [ 0  0  0  3  0  5  1  0  1  0  0  9 289  0  0
 4  3  6  1  3 32]
 [ 0  0  0  0  0  6  0  0  6  2  3  0  1 286  1
 3  0  0  0  3 48]
 [ 1  2  2 10  1  0  0  0  9  2  2  0  3  0 321
 2  1  1  3  0 26]
 [ 0  0  0  0  0  0  2  0  0  0  0  1  1  0  0
349  0  3  0  1  7]
 [ 0  6  0  0  5  0  0  0  2  0  0  6  2  1  1
 7 332  0  1  2 30]
 [ 1  0  0  0  0  2  2  0  0  0  0  2  6  0  1
 5  0 349  0  0 15]
 [ 0  2  5  9  0  3  0  7  3  0  6  0  2  0  3
 0  0  0 319  1 28]
 [ 0  1  1  0  0  1  0  1  0  0  0  7  4  1  0
 3  4  0  0 358 18]
 [ 20 32 16 12  9 32 10 21 15 14 17 10 36 37 17
 5 10  7 18 18 2332]], shape=(21, 21), dtype=int32)
```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "sequential"

Layer (type)	Output Shape	Param #
=====		
fused_conv1d_re_lu (FusedCon (None, 128, 100))		12800
fused_conv1d_re_lu_1 (FusedC (None, 128, 100))		10000
fused_conv1d_re_lu_2 (FusedC (None, 128, 50))		5000



fused_conv1d_re_lu_3 (FusedC (None, 128, 16)	800
reshape (Reshape) (None, 8, 16, 16)	0
fused_conv2d_re_lu (FusedCon (None, 8, 16, 32)	4608
fused_conv2d_re_lu_1 (FusedC (None, 8, 16, 64)	18432
fused_conv2d_re_lu_2 (FusedC (None, 8, 16, 64)	36864
fused_conv2d_re_lu_3 (FusedC (None, 8, 16, 30)	17280
fused_conv2d_re_lu_4 (FusedC (None, 8, 16, 7)	1890
flatten (Flatten) (None, 896)	0
fused_dense (FusedDense) (None, 21)	18816
=====	
Total params: 126,490	
Trainable params: 126,490	
Non-trainable params: 0	

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format

```
export/kws20/saved_model.pb
export/kws20/saved_model.onnx
```

## Rock-Paper-Scissors model

This model demonstrates recognition of images of hands playing rock, paper, scissor popular game.

[https://www.tensorflow.org/datasets/catalog/rock\\_paper\\_scissors](https://www.tensorflow.org/datasets/catalog/rock_paper_scissors)

The RPS model is an example of Keras model with sequential API:

```
IMG_SIZE = 64 # All images will be resized to 120x120
# Setup model
model = tf.keras.models.Sequential([
    tf.keras.Input(shape=(IMG_SIZE, IMG_SIZE, 3)),
    ai8xTF.FusedConv2DReLU(
        filters=15,
        kernel_size=3,
        strides=1,
        padding_size=1
    ),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=30,
        kernel_size=3,
        strides=1,
        padding_size=1,
```

```

        pool_size=2,
        pool_strides=2
    ),
    tf.keras.layers.Dropout(0.2),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=60,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2
    ),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=30,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2
    ),
    ai8xTF.FusedMaxPoolConv2DReLU(
        filters=30,
        kernel_size=3,
        strides=1,
        padding_size=1,
        pool_size=2,
        pool_strides=2
    ),
    ai8xTF.FusedConv2DReLU(
        filters=30,
        kernel_size=3,
        strides=1,
        padding_size=1
    ),
    tf.keras.layers.Flatten(),
    tf.keras.layers.Dropout(0.2),
    ai8xTF.FusedDense(3, wide=True)
])

```

To train RPS model execute following script:

```
$ bash train_rock.sh
```

Training progress, accuracy results and confusion table are reported and stored in log file.

```

Epoch 98/100
79/79 - 0s - loss: 6.1023e-05 - accuracy: 1.0000 - val_loss: 0.3391 -
val_accuracy: 0.9140
Epoch 99/100
79/79 - 1s - loss: 5.7724e-05 - accuracy: 1.0000 - val_loss: 0.3437 -
val_accuracy: 0.9140
Epoch 100/100
79/79 - 0s - loss: 6.5221e-05 - accuracy: 1.0000 - val_loss: 0.3369 -
val_accuracy: 0.9140
6/6 - 0s - loss: 0.3191 - accuracy: 0.9140
Test Accuracy: 0.9139785170555115
Confusion Matrix:
tf.Tensor(
[[61  0  0]
 [ 8 47  8]
 [ 0  0 62]], shape=(3, 3), dtype=int32)

```

At end of training a summary of the model is reported and model graph/weights are stored as **saved\_model.pb** file

Model: "sequential"

Layer (type)	Output Shape	Param #
=====		
fused_conv2d_re_lu (FusedCon	(None, 64, 64, 15)	420
fused_max_pool_conv2d_re_lu	(None, 32, 32, 30)	4080
dropout (Dropout)	(None, 32, 32, 30)	0
fused_max_pool_conv2d_re_lu_	(None, 16, 16, 60)	16260
fused_max_pool_conv2d_re_lu_	(None, 8, 8, 30)	16230
fused_max_pool_conv2d_re_lu_	(None, 4, 4, 30)	8130
fused_conv2d_re_lu_1 (FusedC	(None, 4, 4, 30)	8130
flatten (Flatten)	(None, 480)	0
dropout_1 (Dropout)	(None, 480)	0
fused_dense (FusedDense)	(None, 3)	1443
=====		
Total params: 54,693		
Trainable params: 54,693		
Non-trainable params: 0		

*Note: Empty class may be included as part of subclasses in the sequential model. However, it is not needed and skipped in serialization.*

Additionally, the model is converted to ONNX format

```
export/rock/saved_model.pb  
export/rock/saved_model.onnx
```

## Post-training model quantization

To quantize weights execute following script (MNIST example):

```
$ bash quantize_mnist.sh
```

The MNIST ONNX model with quantized weights is stored in **/export/mnist/** directory.

Alternatively, the user can quantize all model examples by running bash script:

```
$ bash quantize_ALL.sh
```

## Model evaluation

After quantization the model can be evaluated and compared with unquantized model (MNIST example):

```
$ bash evaluate_mnist.sh
```

Alternatively, the user can evaluate all model examples by running bash script:

```
$ bash evaluate_ALL.sh
```

## MAX78000 synthesis

To quantize TensorFlow model and synthesize MAX78000 C source code from ONNX file execute the following command (MNIST example):

```
$ (ai8x-synthesis) ./ai8xize.py --verbose -L --top-level cnn --test-dir  
tensorflow --prefix tf-mnist --checkpoint-file ../ai8x-  
training/TensorFlow/export/mnist/saved_model.onnx --config-file  
./networks/mnist-chw-ai85-tf.yaml --sample-input ../ai8x-  
training/TensorFlow/export/mnist/sampled_data.npy --device MAX78000 --compact-data  
--mexpress --embedded-code --scale 1.0 --softmax --display-checkpoint $@
```

It requires three input files:

**/ai8x-training/TensorFlow/export/mnist/saved\_model.onnx** - ONNX presentation of TensorFlow model

**/ai8x-synthesis/networks/mnist-chw-ai85-tf.yaml** - YAML description of the model

**/ai8x-training/TensorFlow/export/mnist/sampled\_data.npy** - input data sample file

Other used options are described in section "Network Loader (AI8Xize)" of **[1]**

Generated C code is stored in **/ai8x-synthesis/tensorflow/tf-mnist/** directory.

To generate MAX78000 C source code for all TensorFlow examples execute following script:

```
$ (ai8x-synthesis) bash gen-tf-demos-max78000.sh
```

## References

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[1] ai8x-training/README.md