

1 Overview

TensorFlow Lite is an open source software library for running machine learning models on mobile and embedded devices. For more information, see www.tensorflow.org/lite.

For memory constrained devices, the library contains TensorFlow Lite for Microcontrollers. For more information, see www.tensorflow.org/lite/microcontrollers.

The MCUXpresso Software Development Kit (MCUXpresso SDK) provides a comprehensive software package with a pre-integrated TensorFlow Lite for Microcontrollers based on TensorFlow Lite 2.4.1. This document describes the steps required to download and start using the library. Additionally, the document describes the steps required to create an application for running pre-trained models.

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NOTE

The document also assumes knowledge of machine learning frameworks for model training.

2 Deployment

The eIQ TensorFlow Lite for Microcontrollers library is part of the eIQ machine learning software package, which is an optional middleware component of MCUXpresso SDK. The eIQ component is integrated into the MCUXpresso SDK Builder delivery system available on mcuxpresso.nxp.com. To include eIQ machine learning into the MCUXpresso SDK package, the eIQ middleware component is selected in the software component selector on the SDK Builder page when building a new package. See [Figure 1](#).



SDK Builder

Generate a downloadable SDK archive for use with desktop MCUXpresso Tools.

Developer Environment Settings
Selections here will impact files and examples projects included in the SDK and Generated Projects

Toolchain / IDE: All toolchains
 Host OS: Windows
 Embedded real-time operating system: Bare-Metal

Filter by Name, Category, or Descriptor Select All Unselect All

	Name	Category	Description	Dependencies
<input checked="" type="checkbox"/>	CMSIS DSP Library	CMSIS DSP Lib	CMSIS DSP Software Library	
<input type="checkbox"/>	canopen	Middleware	canopen library	
<input checked="" type="checkbox"/>	eIQ	Middleware	eIQ machine learning SDK containing: - ARM CMSIS-NN library (neural network kern... (more))	
<input type="checkbox"/>	Embedded Wizard GUI	Middleware	Embedded Wizard GUI	
<input type="checkbox"/>	emWin	Middleware	emWin graphics library	
<input type="checkbox"/>	FatFS	Middleware	FAT File System	

Figure 1. MCUXpresso SDK Builder software component selector

Once the MCUXpresso SDK package is downloaded, it can be extracted on a local machine or imported into the MCUXpresso IDE. For more information on the MCUXpresso SDK folder structure, see the Getting Started with MCUXpresso SDK User's Guide (document: [MCUXSDKGSUG](#)). The package directory structure is similar to [Figure 2](#). The eIQ TensorFlow Lite library directories are highlighted in red.

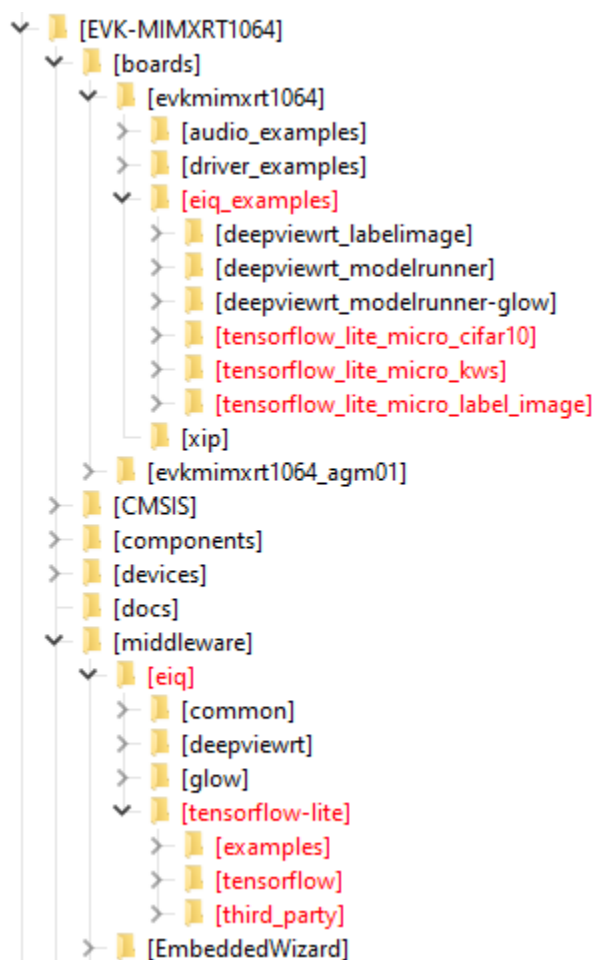


Figure 2. MCUXpresso SDK directory structure

The *boards* directory contains example application projects for supported toolchains. For the list of supported toolchains, see the *MCUXpresso SDK Release Notes*. The *middleware* directory contains the eIQ library source code and example application source code and data.

3 Example applications

The eIQ TensorFlow Lite library is provided with a set of example applications. For details, see [Table 1](#). The applications demonstrate the usage of the library in several use cases.

Table 1. List of example applications

Name	Description
tensorflow_lite_micro_adt	Anomaly detection application using an Autoencoder model. This example requires external development kit FRDM-STBC-AGM01 with sensors.
tensorflow_lite_micro_cifar10	CIFAR-10 classification of 32 × 32 RGB pixel images into 10 categories using a small Convolutional Neural Network (CNN).

Table continues on the next page...

Table 1. List of example applications (continued)

Name	Description
tensorflow_lite_micro_kws	Keyword spotting application using a neural network for word detection in pre-processed audio input.
tensorflow_lite_micro_label_image	Image recognition application using a MobileNet model architecture to classify 128 × 128 RGB pixel images into 1000 categories.

For details on how to build and run the example applications with supported toolchains, see *Getting Started with MCUXpresso SDK User's Guide* (document: [MCUXSDKGSUG](#)). When using MCUXpresso IDE, the example applications can be imported through the SDK Import Wizard as shown in [Figure 3](#).

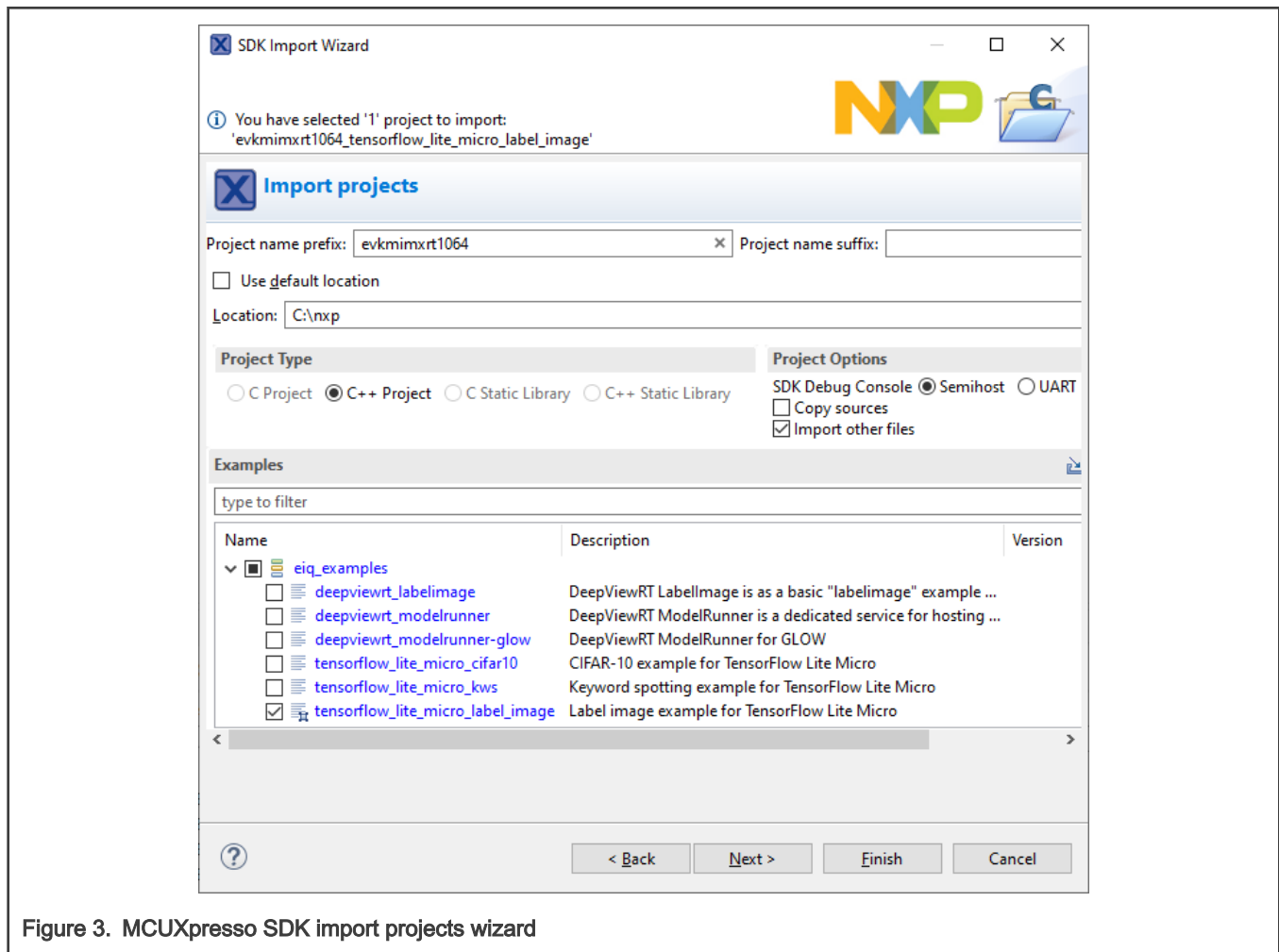


Figure 3. MCUXpresso SDK import projects wizard

After building the example application and downloading it to the target, the execution stops in the *main* function. When the execution resumes, an output message displays on the connected terminal. For example, [Figure 4](#) shows the output of the `tensorflow_lite_micro_label_image` example application printed to the MCUXpresso IDE Console window when semihosting debug console is selected in the SDK Import Wizard.

```

evkbimxrt1050_tensorflow_lite_micro_label_image LinkServer Release [C/C++ (NXP Semiconductors) MCU Application]
[MCUXpresso Semihosting Telnet console for 'evkbimxrt1050_tensorflow_lite_micro_label_image

Label image object recognition example using a TensorFlow Lite Micro model.
Detection threshold: 23%
Expected category: stopwatch
Model: mobilenet_v1_0.25_128_quant_int8

Static data processing:
-----
Inference time: 89 ms
Detected: stopwatch (87%)
-----

Camera data processing:
Data for inference are ready
-----
Inference time: 88 ms
Detected: No label detected (0%)
-----

```

Figure 4. PuTTY console window

4 Comparison

The TensorFlow Lite library since version 2.3 provides an alternative implementation optimized for microcontrollers with low memory capacity called TensorFlow Lite for Microcontrollers (or TensorFlow Lite Micro). In comparison to TensorFlow Lite, the Micro version uses static memory allocation, has no dependencies on standard C or C++ libraries and contains implementations of operation kernels optimized for ARM Cortex-M architecture using ARM's CMSIS-NN library. The following table contains a comparison of supported operations by both libraries.

Table 2. Supported operations

TensorFlow Lite operations	Supported by TensorFlow Lite for Microcontrollers
ABS	Yes
ADD	Yes
ADD_N	No
ARG_MAX	Yes
ARG_MIN	Yes
AUDIO_SPECTROGRAM	No
AVERAGE_POOL_2D	Yes
BATCH_MATMUL	No
BATCH_TO_SPACE_ND	No
BIDIRECTIONAL_SEQUENCE_LSTM	No
BIDIRECTIONAL_SEQUENCE_RNN	No
CAST	No
CEIL	Yes
CONCATENATION	Yes

Table continues on the next page...

Table 2. Supported operations (continued)

TensorFlow Lite operations	Supported by TensorFlow Lite for Microcontrollers
CONV_2D	Yes
COS	Yes
DENSIFY	No
DEPTH_TO_SPACE	No
DEPTHWISE_CONV_2D	Yes
DEQUANTIZE	Yes
DETECTION_POSTPROCESS	No
DIV	No
ELU	No
EMBEDDING_LOOKUP	No
EMBEDDING_LOOKUP_SPARSE	No
EQUAL	Yes
EXP	No
EXPAND_DIMS	No
FAKE_QUANT	No
FILL	No
FLOOR	Yes
FLOOR_DIV	No
FLOOR_MOD	No
FULLY_CONNECTED	Yes
GATHER	No
GATHER_ND	No
GREATER	Yes
GREATER_EQUAL	Yes
HARD_SWISH	Yes
HASHTABLE_LOOKUP	No
IF	No
L2_NORMALIZATION	Yes
L2_POOL_2D	No
LEAKY_RELU	No
LESS	Yes
LESS_EQUAL	Yes

Table continues on the next page...

Table 2. Supported operations (continued)

TensorFlow Lite operations	Supported by TensorFlow Lite for Microcontrollers
LOCAL_RESPONSE_NORMALIZATION	No
LOG	Yes
LOG_SOFTMAX	No
LOGICAL_AND	Yes
LOGICAL_NOT	Yes
LOGICAL_OR	Yes
LOGISTIC	Yes
LSH_PROJECTION	No
LSTM	No
MATRIX_DIAG	No
MATRIX_SET_DIAG	No
MAX_POOL_2D	Yes
MAXIMUM	Yes
MEAN	Yes
MFCC	No
MINIMUM	Yes
MIRROR_PAD	No
MUL	Yes
NEG	Yes
NON_MAX_SUPPRESSION_V4	No
NON_MAX_SUPPRESSION_V5	No
NOT_EQUAL	Yes
NUMERIC_VERIFY	No
ONE_HOT	No
PACK	Yes
PAD	Yes
PADV2	Yes
POW	No
PRELU	Yes
QUANTIZE	Yes
RANGE	No
RANK	No

Table continues on the next page...

Table 2. Supported operations (continued)

TensorFlow Lite operations	Supported by TensorFlow Lite for Microcontrollers
REDUCE_ANY	No
REDUCE_MAX	Yes
REDUCE_MIN	No
REDUCE_PROD	No
RELU	Yes
RELU_N1_TO_1	No
RELU6	Yes
RESHAPE	Yes
RESIZE_BILINEAR	No
RESIZE_NEAREST_NEIGHBOR	Yes
REVERSE_SEQUENCE	No
REVERSE_V2	No
RNN	No
ROUND	Yes
RSQRT	Yes
SCATTER_ND	No
SEGMENT_SUM	No
SELECT	No
SELECT_V2	No
SHAPE	Yes
SIN	Yes
SKIP_GRAM	No
SLICE	No
SOFTMAX	Yes
SPACE_TO_BATCH_ND	No
SPACE_TO_DEPTH	No
SPARSE_TO_DENSE	No
SPLIT	Yes
SPLIT_V	Yes
SQRT	Yes
SQUARE	Yes
SQUARED_DIFFERENCE	No

Table continues on the next page...

Table 2. Supported operations (continued)

TensorFlow Lite operations	Supported by TensorFlow Lite for Microcontrollers
SQUEEZE	No
STRIDED_SLICE	Yes
SUB	Yes
SUM	No
SVDF	Yes
TANH	Yes
TILE	No
TOPK_V2	No
TRANSPOSE	No
TRANSPOSE_CONV	No
UNIDIRECTIONAL_SEQUENCE_LSTM	No
UNIDIRECTIONAL_SEQUENCE_RNN	No
UNIQUE	No
UNPACK	Yes
WHERE	No
WHILE	No
ZEROS_LIKE	No

5 Converting a model

TensorFlow contains a conversion tool and a Python API for converting TensorFlow models stored in the Protocol Buffers format (.pb) or similar alternatives to TensorFlow Lite models stored in the FlatBuffers format (.tflite). Therefore, to convert a model to the TensorFlow Lite format, the user must first install TensorFlow. For more information, see www.tensorflow.org/lite/convert.

Use the following steps:

1. On Linux® OS (Ubuntu 16.04 or later (64-bit)):
 - a. Install Python using the command:


```
sudo apt-get install python3
```
 - b. Install TensorFlow with Python *pip* package manager: `pip3 install --user tensorflow==2.4.1`
2. On macOS® (10.12.6 (Sierra) or later (64-bit)):
 - a. Install Python (version 3.7.x) using an installer downloaded from www.python.org/downloads/mac-osx.
 - b. Install TensorFlow with Python *pip* package manager from the command line:


```
pip3 install --user tensorflow==2.4.1
```
 - c. Update the system path to include the user's Library/Python/3.7/bin directory: `export PATH="$HOME/Library/Python/3.7/bin:$PATH"`
3. On Windows® OS (Windows OS 7 or later (64-bit)):
 - a. Install Python (version 3.7.x) using an installer downloaded from <https://www.python.org/downloads/windows>.

- b. Update the Microsoft Visual C++ Redistributable for Visual Studio 2015, 2017 and 2019 to the latest version available at <https://support.microsoft.com/en-us/help/2977003/the-latest-supported-visual-c-downloads>.
- c. Install TensorFlow with Python pip package manager: `pip install --user tensorflow==2.4.1`

NOTE

Detailed instructions on how to install TensorFlow can be found at www.tensorflow.org/install. The page also contains a list of all supported platforms and alternative installation methods.

NOTE

It is out of the document scope to describe the process of creating and training a model. To learn how to obtain a trained model, see the tutorials and reference manuals of machine learning frameworks. For more information, see <https://www.tensorflow.org/tutorials/images/cnn>.

The following command in [Converting a model performing floating-point inference](#) converts a trained model stored in the *mobilenet_v1_0.25_128_frozen.pb* file (from the package available at download.tensorflow.org/models/mobilenet_v1_2018_08_02/mobilenet_v1_0.25_128.tgz) to a TensorFlow Lite model file *mobilenet_v1_0.25_128.tflite* performing floating-point inference. The *input* and *MobilenetV1/Predictions/Reshape_1* parameter values are the input and output node names.

Converting a model performing floating-point inference

```
tflite_convert \
--output_file=mobilenet_v1_0.25_128.tflite \
--graph_def_file=mobilenet_v1_0.25_128_frozen.pb \
--input_arrays=input \
--output_arrays=MobilenetV1/Predictions/Reshape_1 \
--enable_v1_converter
```

The description of the parameters can be displayed by running *tflite_convert -help*.

The names of the input and output nodes can be retrieved from a model visualizer like <https://lutzroeder.github.io/netron/>, for example. By clicking the first node in the displayed graph, its name is shown in the properties panel. This is typically the input node. Similarly, by clicking the last node, the name of the output node can be retrieved.

NOTE

TensorFlow Lite supports only a subset of TensorFlow operations. During the conversion process, some of those operations might be deleted or fused. Since the set of TensorFlow Lite operations is smaller than TensorFlow's, not every model is convertible. If the original TensorFlow model uses an operation not supported by TensorFlow Lite, the converter reports it as an error. For more information, see the guide at https://www.tensorflow.org/lite/guide/ops_compatibility.

5.1 Quantization

Quantization is a technique to reduce the model size while maintaining only small degradation of the model precision. Typically, quantization reduces the number of bits associated with weights and activations from 32-bit floating-point values to 8-bits. This yields a 4x reduction in model size. Furthermore, processors with fixed-point SIMD instructions can leverage these for faster computations.

Probably the best way to perform model quantization is [quantization-aware training](#). The model can be afterward converted using the converter, which is compatible with models quantized by TensorFlow. Alternatively, a model can be quantized [post-training](#) using per-channel quantization. The Python script shown in [Quantizing and converting a model](#) quantizes and converts the floating point model from *mobilenet_v1_0.25_128_frozen.pb* (from the package available at download.tensorflow.org/models/mobilenet_v1_2018_08_02/mobilenet_v1_0.25_128.tgz) to a TensorFlow Lite model *mobilenet_v1_0.25_128_quant_int8.tflite*. The input and output node names can be retrieved using a model visualizer

like [Netron](#). The quantization is performed using images from the training dataset, which the script expects to be stored in the `dataset` directory.

Quantizing and converting a model

```
import os
import numpy as np
from PIL import Image
import tensorflow as tf

input_mean = 127.5
input_std = 127.5

converter = tf.compat.v1.lite.TFLiteConverter.from_frozen_graph(
    'mobilenet_v1_0.25_128_frozen.pb',          # TensorFlow model file
    ['input'],                                  # input node names
    ['MobilenetV1/Predictions/Reshape_1'],      # output node names
    input_shapes={'input': (1, 128, 128, 3)}) # input tensor dimensions

converter.optimizations = [tf.lite.Optimize.DEFAULT]
converter.target_spec.supported_ops = [tf.lite.OpsSet.TFLITE_BUILTINS_INT8]
converter.inference_input_type = tf.int8
converter.inference_output_type = tf.float32

def representative_dataset_gen():
    images = []
    for image in os.listdir('dataset'):
        image = os.path.join('dataset', image)
        if os.path.isfile(image):
            image = np.array(Image.open(image).resize((128, 128)))
            image = (image - input_mean) / input_std
            image = image.astype(np.float32)
            image = image.reshape((1, 128, 128, 3))
            images.append(image)
    for image in images:
        yield [image]

converter.representative_dataset = representative_dataset_gen
tflite_quant_model = converter.convert()
with open('mobilenet_v1_0.25_128_quant_int8.tflite', 'wb') as f:
    f.write(tflite_quant_model)
```

6 Running an inference

After converting the model to the TensorFlow Lite format, it is converted into a C language array to include it in the application source code. The `xxd` utility can be used for this purpose (distributed with the *Vim* editor for many platforms on <https://www.vim.org/>) as shown in [Converting a model to a C language header file](#). The utility converts a TensorFlow Lite model into a C header file with an array definition containing the binary image of the model and a variable containing the data size.

Converting a model to a C language header file

```
xxd -i mobilenet_v1_0.25_128_quant.tflite > mobilenet_v1_0.25_128_quant_model.h
```

After the header file is generated, the type of the array is changed from `unsigned char` to `const char` to match the library API input parameters and the default array name can be changed to a more convenient one. The user must align the buffer to at least 64-bit boundary (the size of a double precision floating-point number) to avoid misaligned memory access. The alignment can be

achieved by using the `__ALIGNED(16)` macro from the `cmsis_compiler.h` header file (available in the MCUXpresso SDK) in the array declaration before the data assignment.

The easiest way to create an application with the proper configuration is to copy and modify an existing example application. To learn where to find the example applications and how to build them, see the [Example applications](#).

Running an inference using TensorFlow Lite for Microcontrollers involves several steps (shown for quantized model with signed 8-bit values as input and 32-floating point values as output):

1. Include the necessary eIQ TensorFlow Lite Micro library header files and the converted model.

Including header files

```
#include "tensorflow/lite/micro/micro_error_reporter.h"
#include "tensorflow/lite/micro/micro_interpreter.h"
#include "tensorflow/lite/micro/all_ops_resolver.h"
#include "tensorflow/lite/version.h"

#include "mobilenet_v1_0.25_128_quant_model.h"
```

2. Allocate a static memory buffer for input and output tensors and intermediate arrays. Load the FlatBuffer model image (assuming the `mobilenet_v1_0.25_128_quant_model.h` file generated in [Converting a model to a C language header file](#) defines an array named `mobilenet_model` and a size variable named `mobilenet_model_len`), build the interpreter object and allocate memory for tensors.

Loading the FlatBuffer model

```
constexpr int kTensorArenaSize = 1024 * 1024;
static uint8_t tensorArena[kTensorArenaSize];

const tflite::Model* model = tflite::GetModel(mobilenet_model);
// TODO: Report an error if model->version() != TFLITE_SCHEMA_VERSION

static tflite::AllOpsResolver microOpResolver;
static tflite::MicroErrorReporter microErrorReporter;
static tflite::MicroInterpreter interpreter(model,
    microOpResolver, tensorArena, kTensorArenaSize,
    microErrorReporter);

interpreter->AllocateTensors();
// TODO: Check return value for kTfLiteOk
```

3. Fill-in the input data into the input tensor. For example, if a speech recognition model, image data from a camera or audio data from a microphone. The dimensions of the input data must be the same as the dimensions of the input tensor. These dimensions were specified when the model was created.

Filling-in input data

```
// Get access to the input tensor data
TfLiteTensor* inputTensor = interpreter->input(0);

// Copy the input tensor data from an application buffer
for (int i = 0; i < inputTensor->bytes; i++)
    inputTensor->data.int8[i] = input_data[i];
```

4. Run the inference and read the output data from the output tensor. The dimensions of the output data must be the same as the dimensions of the output tensor. These dimensions were specified when the model was created.

Running inference and reading output data

```
// Run the inference
interpreter->Invoke();
// TODO: Check the return value for TfLiteOk

// Get access to the output tensor data
TfLiteTensor* outputTensor = interpreter->output(0);

// Copy the output tensor data to an application buffer
for (int i = 0; i < outputTensor->bytes / sizeof(float32); i++)
    output_data[i] = outputTensor->data.f[i];
```

7 Code size optimization

Typically, models do not use all the operators that are available in TensorFlow Lite. However, because of the default operator registration mechanism used in the library, the toolchain linker is not able to remove the code of unused operators. In order to reduce code size, it is possible to only register the specific operators used by a model. To determine which operators are used by a particular model, a model visualizer tool like Netron can be used. Then a mutable operator resolver object can be created that only registers the operators that are used by the model being inferred.

7.1 Register all operators

Use the `tflite::AllOpsResolver` object class, which is later passed to the `tflite::MicroInterpreter` object. Make sure to include the `tensorflow/lite/micro/all_ops_resolver.h` header file.

Register all available operators in TensorFlow Lite Micro

```
#include "tensorflow/lite/micro/all_ops_resolver.h"

tflite::AllOpsResolver microOpResolver;

static tflite::MicroInterpreter interpreter(
    model, microOpResolver, tensorArena, kTensorArenaSize, microErrorReporter);
```

7.2 Register only used operators

Use the `tflite::MicroMutableOpResolver` object template, which is later passed to the `tflite::MicroInterpreter` object. Depending on the list of used operators, the result should be similar to [Register only used operators in TensorFlow Lite Micro](#). Make sure to update the `MicroMutableOpResolver` template parameter to reflect the number of operators that need to be registered.

Register only used operators in TensorFlow Lite Micro

```
#include "tensorflow/lite/micro/kernels/micro_ops.h"
#include "tensorflow/lite/micro/micro_mutable_op_resolver.h"

tflite::MicroMutableOpResolver<6> microOpResolver;
microOpResolver.AddAveragePool2D();
microOpResolver.AddConv2D();
microOpResolver.AddDepthwiseConv2D();
microOpResolver.AddDequantize();
microOpResolver.AddReshape();
microOpResolver.AddSoftmax();
```

```
static tf::MicroInterpreter interpreter(  
    model, microOpResolver, tensorArena, kTensorArenaSize, microErrorReporter);
```

8 Note about the source code in the document

Example code shown in this document has the following copyright and BSD-3-Clause license:

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9 Revision history

[Table 3](#) summarizes the changes done to this document since the initial release.

Table 3. Revision history

Revision number	Date	Substantive changes
0	12/2019	Initial release
1	04/2020	Updated to TensorFlow Lite 2.1
2	17 December 2020	Updated TensorFlow Lite to version 2.3.0 with TensorFlow Lite for Microcontrollers
3	10 July 2021	Removed TensorFlow Lite in favor of TensorFlow Lite for Microcontrollers. Updated TensorFlow Lite for Microcontrollers to version 2.4.1.

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