EECE-4710 "IoT and TinyML"

TFL Micro "Hello World" Code Walkthrough

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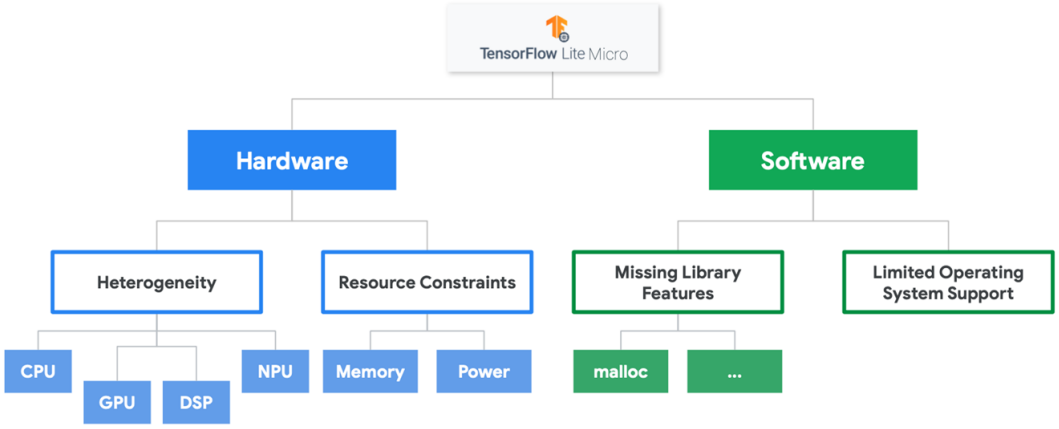
BE THE DIFFERENCE.

1

TFLite Micro - Recap

Inference at MCU level

2



3

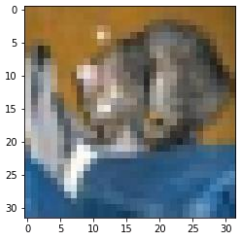
TensorFlow Lite - Recall

```
1. interpreter = tf.lite.Interpreter("/content/cifar10_quant_model.tflite")
2. interpreter.allocate_tensors()

3. set_input_tensor(interpreter, image)

4. interpreter.invoke()

5. output_details = interpreter.get_output_details()[0]
6. img_pred =np.argmax(interpreter.get_tensor(output_details['index'][0]))
```



image

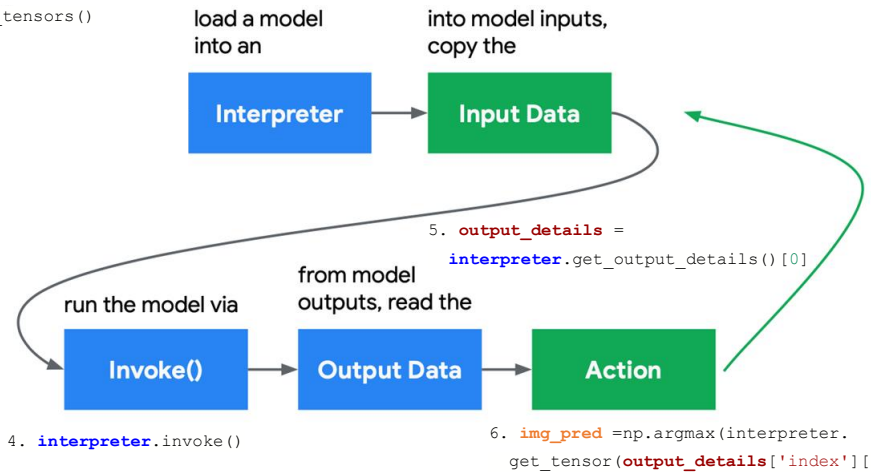
→ 3 ⇒ "CAT"

4

TensorFlow Lite - Recall

```
1. interpreter = tf.lite.Interpreter("cifar10_quant_model.tflite")
2. interpreter.allocate_tensors()
```

```
3. set_input_tensor(interpreter, image)
```



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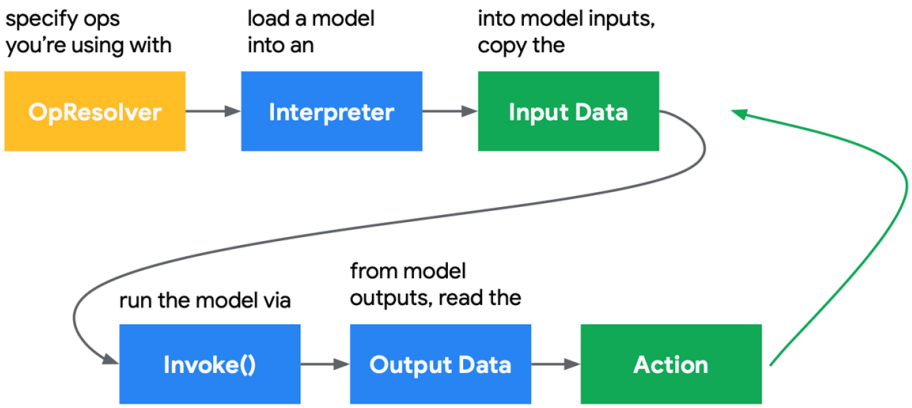
How do you use **TFL Micro**?



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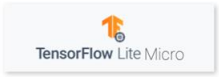
Recap: What is TensorFlow Lite Micro?



Compatible with the TensorFlow training environment.

Built to fit on **embedded systems**:

- Very **small binary footprint**
- **No** dynamic memory allocation
- **No** dependencies on complex parts of the standard C/C++ libraries
- **No** operating system dependencies, **can run on bare metal**
- Designed to be **portable** across a wide variety of systems

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TensorFlow Lite Micro Hello World Model
Code Walkthrough!

hello_word_V2.ino

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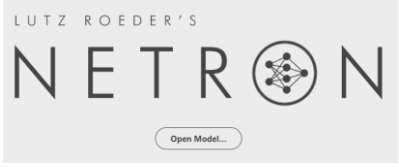
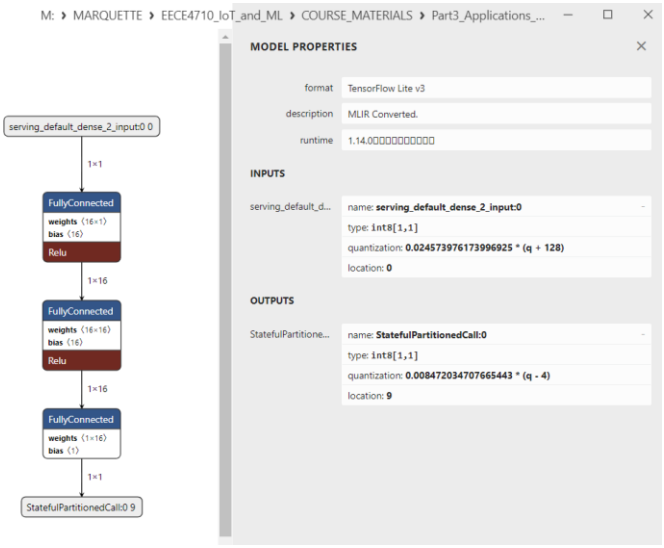
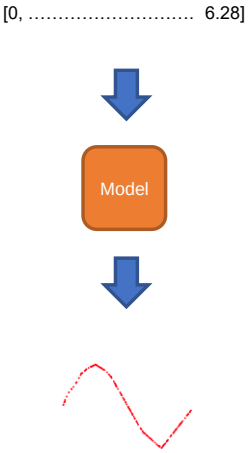
Netron

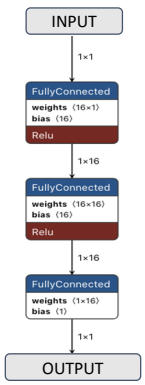
- Netron is a viewer for neural network, deep learning and machine learning models.
- Download and install it on your computer from (if you do not have it already):
  - https://github.com/lutzroeder/netron



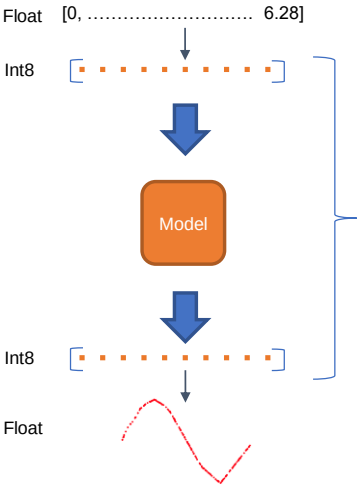


Hello World TFLM model

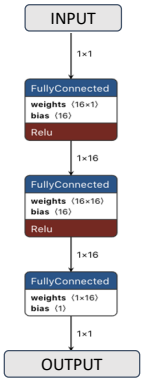




Hello World TFLM model



Model.tflite



Model.cc

```
1 !cat {MODEL_TFLITE_MICRO}
 0x02, 0x15, 0x01, 0xd1, 0x02, 0xe9, 0xee, 0x07, 0x2d, 0x18, 0xfe, 0x01,
 0x1c, 0xfa, 0x03, 0xf6, 0x0c, 0xf2, 0xed, 0xed, 0x06, 0xf2, 0xfa, 0xda,
 0x0f, 0xf1, 0x06, 0x0e, 0xee, 0xf8, 0x01, 0x0e, 0x07, 0x03, 0xf7, 0x30,
 0xf7, 0xfa, 0xf7, 0x0a, 0xd9, 0xff, 0x12, 0x02, 0xfb, 0x01, 0x14, 0xf8,
 0x07, 0xd8, 0xfd, 0x0b, 0x01, 0x1e, 0xc3, 0x10, 0x20, 0x2c, 0x0f, 0xf1,
 0x04, 0x10, 0x05, 0x2a, 0xd9, 0xf3, 0x0a, 0x00, 0xfd, 0xe0, 0xda, 0x1a,
 0xfb, 0xea, 0xfd, 0xf5, 0x0a, 0x00, 0xff, 0xe8, 0xf3, 0xe4, 0x03, 0x15,
 0x04, 0x0d, 0xff, 0xdb, 0xd9, 0x06, 0x0b, 0xda, 0xdb, 0xf9, 0x00, 0x03,
 0x0b, 0x08, 0x03, 0x03, 0x25, 0xf9, 0xd5, 0x02, 0x0e, 0x0a, 0xf1, 0xf7,
 0x09, 0x0d, 0x0c, 0xb6, 0x12, 0x08, 0x02, 0xf8, 0x04, 0x02, 0x17, 0x10,
 0x0e, 0xdf, 0x01, 0xd0, 0xff, 0x00, 0xfd, 0x0f, 0x1c, 0x02, 0x17, 0x0a,
 0x05, 0xf0, 0xfb, 0xed, 0x21, 0xfe, 0xfd, 0xec, 0xdf, 0x04, 0x03, 0xf9,
...
 0x04, 0x00, 0x00, 0x00, 0x0c, 0x00, 0x00, 0x00, 0x63, 0x6f, 0x6e, 0x76,
 0x32, 0x64, 0x5f, 0x69, 0x6e, 0x70, 0x75, 0x74, 0x00, 0x00, 0x00, 0x00,
 0x04, 0x00, 0x00, 0x00, 0x01, 0x00, 0x00, 0x00, 0x20, 0x00, 0x00, 0x00,
 0x20, 0x00, 0x00, 0x00, 0x03, 0x00, 0x00, 0x00, 0x05, 0x00, 0x00, 0x00,
 0x60, 0x00, 0x00, 0x00, 0x44, 0x00, 0x00, 0x00, 0x28, 0x00, 0x00, 0x00,
 0x14, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00, 0x00, 0xd8, 0xff, 0xff, 0xff,
 0x00, 0x00, 0x00, 0x19, 0x19, 0x00, 0x00, 0x00, 0xcc, 0xff, 0xff, 0xff,
 0x00, 0x00, 0x00, 0x09, 0x09, 0x00, 0x00, 0x00, 0x09, 0x00, 0x00, 0x00,
 0xf4, 0xff, 0xff, 0xff, 0x00, 0x00, 0x00, 0x16, 0x16, 0x00, 0x00, 0x00,
 0x0c, 0x00, 0x0c, 0x00, 0x07, 0x00, 0x00, 0x00, 0x00, 0x00, 0x08, 0x00,
 0x0c, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x11, 0x11, 0x00, 0x00, 0x00,
 0x0c, 0x00, 0x10, 0x00, 0x07, 0x00, 0x00, 0x00, 0x08, 0x00, 0x0c, 0x00,
 0x0c, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x03, 0x05, 0x00, 0x00, 0x00,
 0x03, 0x00, 0x00, 0x00
};
unsigned int g_model_len = 177232;
```

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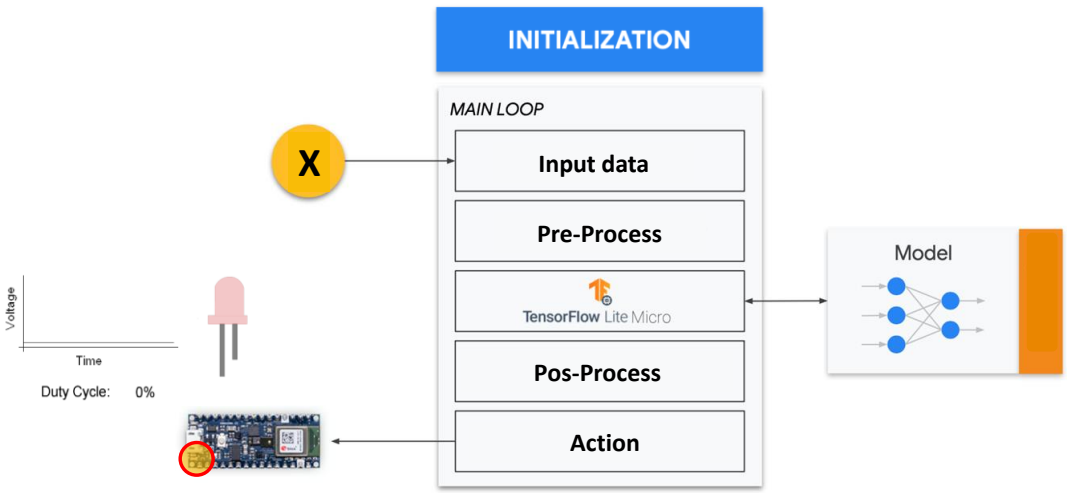
Hello World TFLM Components



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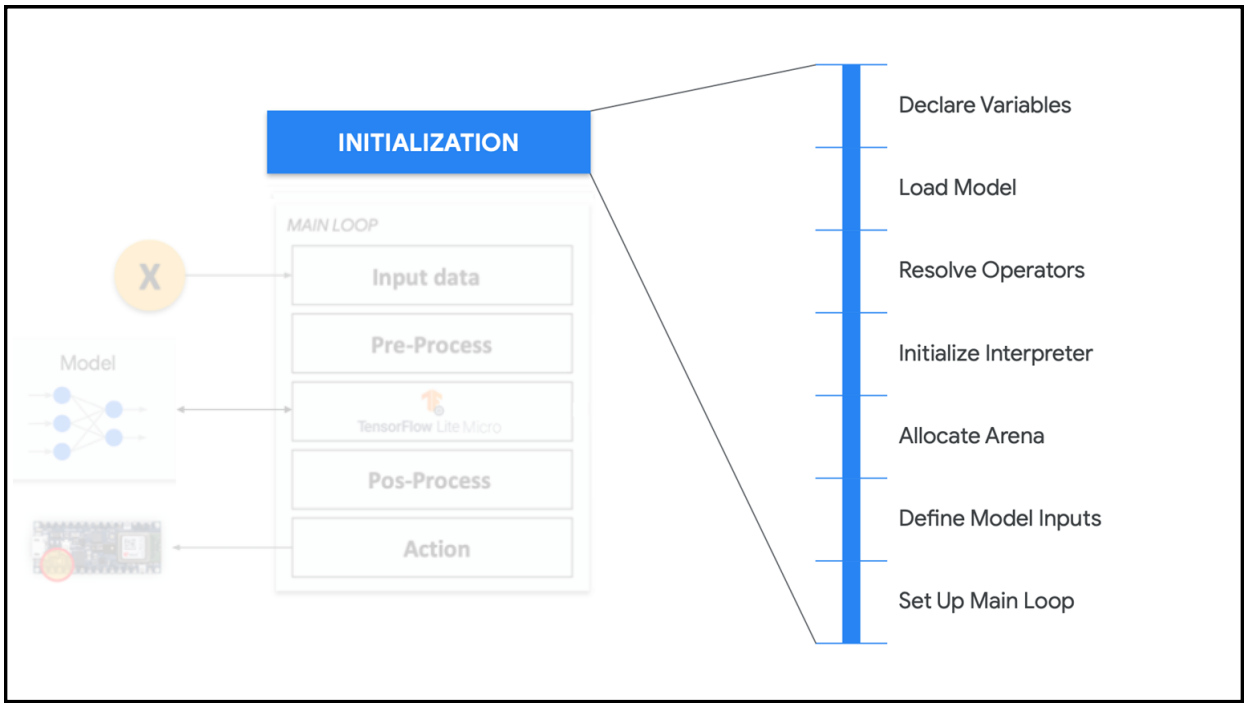
INITIALIZATION
MAIN LOOP
Input data
Pre-Process
TensorFlow Lite Micro
Pos-Process
Action
Model
Declare Variables
Load Model
Resolve Operators
Initialize Interpreter
Allocate Arena
Define Model Inputs
Set Up Main Loop

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Declare Variables
Load Model
Resolve Operators
Initialize Interpreter
Allocate Arena
Define Model Inputs
Set Up Main Loop
#include "main_functions.h"
#include "tensorflow/lite/micro/all_ops_resolver.h"
#include "constants.h"
#include "model.h"
#include "output_handler.h"
#include "tensorflow/lite/micro/micro_error_reporter.h"
#include "tensorflow/lite/micro/micro_interpreter.h"
#include "tensorflow/lite/schema/schema_generated.h"
#include "tensorflow/lite/version.h"
// Globals, used for compatibility with Arduino-style sketches.
namespace {
tflite::ErrorReporter* error_reporter = nullptr;
const tflite::Model* model = nullptr;
tflite::MicroInterpreter* interpreter = nullptr;
TfLiteTensor* input = nullptr;
TfLiteTensor* output = nullptr;
int inference_count = 0;
constexpr int kTensorArenaSize = 2000;
uint8_t tensor_arena[kTensorArenaSize];
} // namespace

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- **Declare Variables**
- Load Model
- Resolve Operators
- Initialize Interpreter
- Allocate Arena
- Define Model Inputs
- Set Up Main Loop

```
#include "main_functions.h"

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#include "constants.h"
#include "model.h"
#include "output_handler.h"
#include "tensorflow/lite/micro/micro_error_reporter.h"
#include "tensorflow/lite/micro/micro_interpreter.h"
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#include "tensorflow/lite/version.h"

// Globals, used for compatibility with Arduino-style sketches.

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  TfLiteTensor* input = nullptr;
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constexpr int kTensorArenaSize = 2000;
uint8_t tensor_arena[kTensorArenaSize];
}  // namespace
```

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- Declare Variables
- **Load Model**
- Resolve Operators
- Initialize Interpreter
- Allocate Arena
- Define Model Inputs
- Set Up Main Loop

```
void setup() {
  // Set up logging. Google style is to avoid globals or statics because of
  // lifetime uncertainty, but since this has a trivial destructor it's okay.
  // NOLINTNEXTLINE(runtime-global-variables)
  static tflite::MicroErrorReporter micro_error_reporter;
  error_reporter = &micro_error_reporter;

  // Map the model into a usable data structure. This doesn't involve any
  // copying or parsing, it's a very lightweight operation.

  model = tflite::GetModel(g_model);

  if (model->version() != TFLITE_SCHEMA_VERSION) {
    TF_LITE_REPORT_ERROR(error_reporter,
                         "Model provided is schema version %d not equal "
                         "to supported version %d.",
                         model->version(), TFLITE_SCHEMA_VERSION);
    return;
  }

  // This pulls in all the operation implementations we need.
  // NOLINTNEXTLINE(runtime-global-variables)
  static tflite::AllOpsResolver resolver;
```

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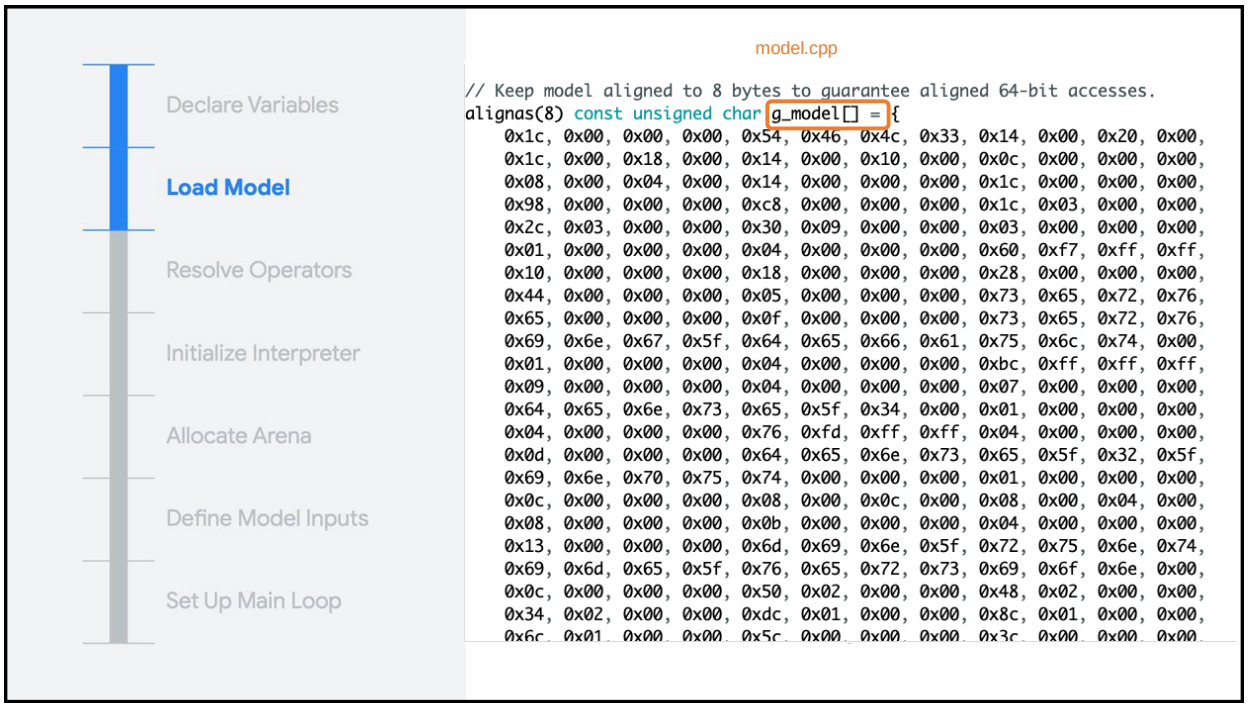

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What is g_model?

- **Array of bytes**, and acts as the equivalent of a file on disk
- Holds **all** of the **information about the model**, its **operators**, their **connections**, and the trained **weights**

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- Declare Variables
- Load Model
- **Resolve Operators**
- Initialize Interpreter
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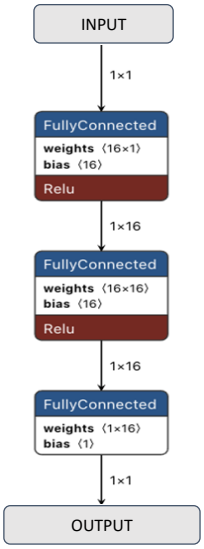

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- Declare Variables
- Load Model
- **Resolve Operators**
- Initialize Interpreter
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- Set Up Main Loop

Load ALL Ops

```
// This pulls in all the operation implementations we need.
// NOLINTNEXTLINE(runtime-global-variables)
static tflite::AllOpsResolver resolver;

// Build an interpreter to run the model with.
static tflite::MicroInterpreter static_interpreter(
    model, resolver, tensor_arena, kTensorArenaSize, error_reporter);
interpreter = &static_interpreter;

// Allocate memory from the tensor_arena for the model's tensors.
TfLiteStatus allocate_status = interpreter->AllocateTensors();
if (allocate_status != kTfLiteOk) {
  TF_LITE_REPORT_ERROR(error_reporter, "AllocateTensors() failed");
  return;
}

// Obtain pointers to the model's input and output tensors.
input = interpreter->input(0);
output = interpreter->output(0);

// Keep track of how many inferences we have performed.
inference_count = 0;
```

Used if you do not have problem with memory

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Load only the needed Ops

```
static tflite::MicroMutableOpResolver <3>
micro_op_resolver(error_reporter);
if (micro_op_resolver.AddBuiltin(
  tflite::BuiltinOperator_FULLY_CONNECTED,
  tflite::ops::micro::Register_FULLY_CONNECTED()) != kTfLiteOk)
{
  return;
}
if (micro_op_resolver.AddBuiltin(
  tflite::BuiltinOperator_FULLY_CONNECTED,
  tflite::ops::micro::Register_FULLY_CONNECTED()) != kTfLiteOk)
{
  return;
}
if (micro_op_resolver.AddBuiltin(
  tflite::BuiltinOperator_FULLY_CONNECTED,
  tflite::ops::micro::Register_FULLY_CONNECTED()) != kTfLiteOk)
{
  return;
}
```

Used if you have problem with memory

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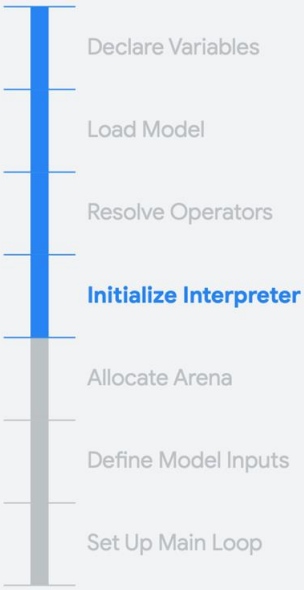


```
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static tflite::AllOpsResolver resolver;

// Build an interpreter to run the model with.
static tflite::MicroInterpreter static_interpreter(
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interpreter = &static_interpreter;

// Allocate memory from the tensor_arena for the model's tensors.
TfLiteStatus allocate_status = interpreter->AllocateTensors();
if (allocate_status != kTfLiteOk) {
  TF_LITE_REPORT_ERROR(error_reporter, "AllocateTensors() failed");
  return;
}

// Obtain pointers to the model's input and output tensors.
input = interpreter->input(0);
output = interpreter->output(0);

// Keep track of how many inferences we have performed.
inference_count = 0;
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```

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Declare Variables
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Resolve Operators
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}

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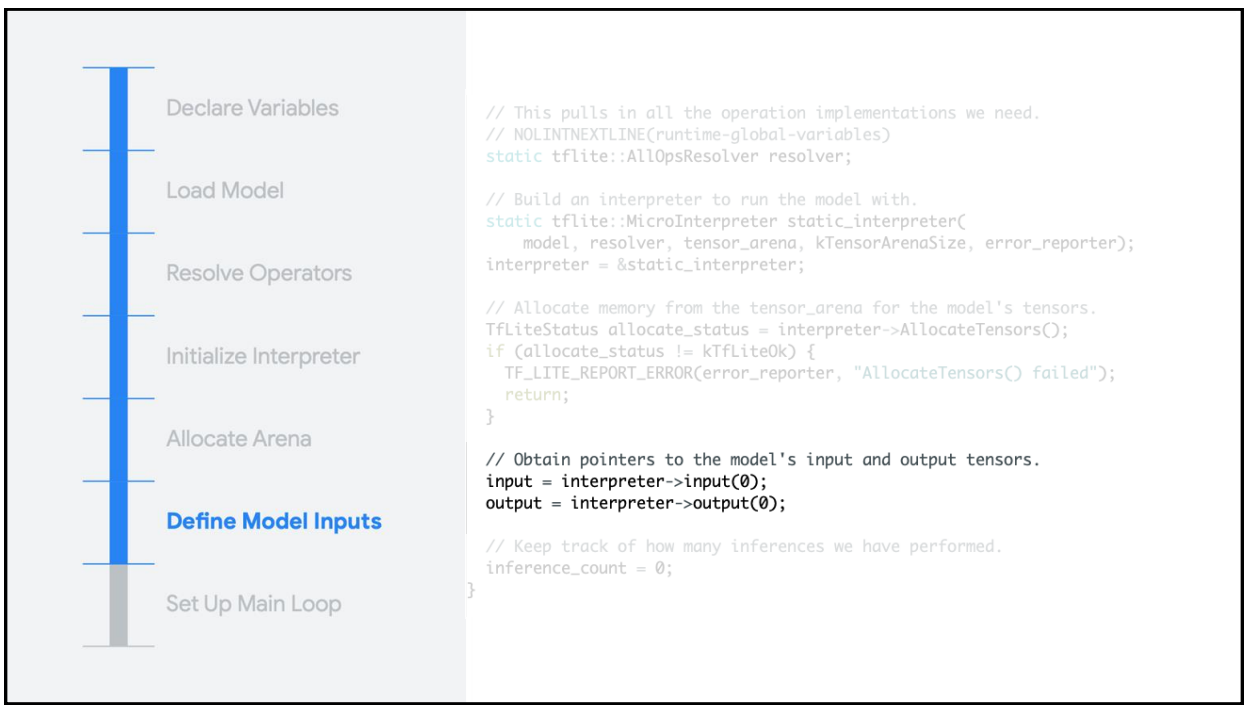
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- Declare Variables
- Load Model
- Resolve Operators
- Initialize Interpreter
- Allocate Arena
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- **Set Up Main Loop**

```
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static tflite::AllOpsResolver resolver;

// Build an interpreter to run the model with.
static tflite::MicroInterpreter static_interpreter(
    model, resolver, tensor_arena, kTensorArenaSize, error_reporter);
interpreter = &static_interpreter;

// Allocate memory from the tensor_arena for the model's tensors.
TfLiteStatus allocate_status = interpreter->AllocateTensors();
if (allocate_status != kTfLiteOk) {
  TF_LITE_REPORT_ERROR(error_reporter, "AllocateTensors() failed");
  return;
}

// Obtain pointers to the model's input and output tensors.
input = interpreter->input(0);
output = interpreter->output(0);

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inference_count = 0;
}
```

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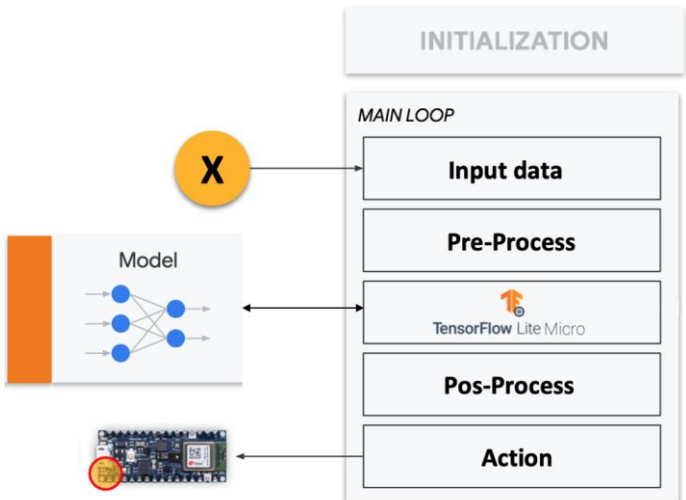

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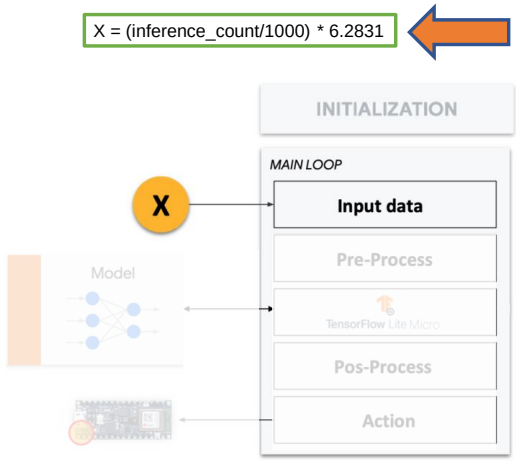


```
void loop() {
  // Calculate an x value to feed into the model. We compare the current
  // inference_count to the number of inferences per cycle to determine
  // our position within the range of possible x values the model was
  // trained on, and use this to calculate a value.
  float position = static_cast<float>(inference_count) /
                   static_cast<float>(kInferencesPerCycle);
  float x = position * kXrange;

  // Quantize the input from floating-point to integer
  int8_t x_quantized = x / input->params.scale + input->params.zero_point;
  // Place the quantized input in the model's input tensor
  input->data.int8[0] = x_quantized;

  // Run inference, and report any error
  TfLiteStatus invoke_status = interpreter->Invoke();
  if (invoke_status != kTfLiteOk) {
    TF_LITE_REPORT_ERROR(error_reporter, "Invoke failed on x: %f\n",
                         static_cast<double>(x));
    return;
  }
  // Obtain the quantized output from model's output tensor
  int8_t y_quantized = output->data.int8[0];
  // Dequantize the output from integer to floating-point
  float y = (y_quantized - output->params.zero_point) * output->params.scale;

  // Output the results. A custom HandleOutput function can be implemented
  // for each supported hardware target.
  HandleOutput(error_reporter, x, y);

  // Increment the inference_counter, and reset it if we have reached
  // the total number per cycle
  inference_count += 1;
  if (inference_count >= kInferencesPerCycle) inference_count = 0;
}
```

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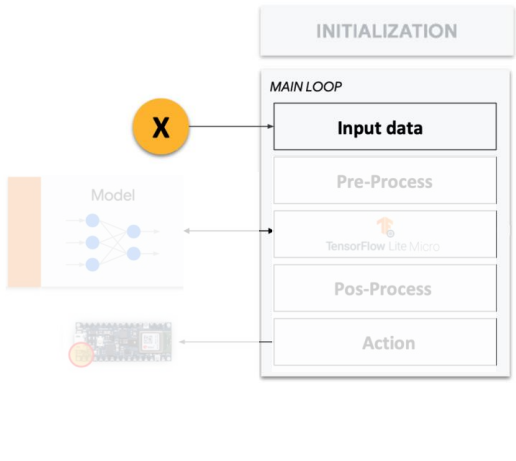

arduino_constants.cpp

```
#include "constants.h"

// This is tuned so that a full cycle takes ~4 seconds on an Arduino MKRZERO.
const int kInferencesPerCycle = 1000;
```

constants.h

```
#ifndef TENSORFLOW_LITE_MICRO_EXAMPLES_HELLO_WORLD_CONSTANTS_H_
#define TENSORFLOW_LITE_MICRO_EXAMPLES_HELLO_WORLD_CONSTANTS_H_

// This constant represents the range of x values our model was trained on,
// which is from 0 to (2 * Pi). We approximate Pi to avoid requiring additional
// libraries
const float kXrange = 2.f * 3.14159265359f;

// This constant determines the number of inferences to perform across the range
// of x values defined above. Since each inference takes time, the higher this
// number, the more time it will take to run through the entire range. The value
// of this constant can be tuned so that one full cycle takes a desired amount
// of time. Since different devices take different amounts of time to perform
// inference, this value should be defined per-device.
extern const int kInferencesPerCycle;

#endif  // TENSORFLOW_LITE_MICRO_EXAMPLES_HELLO_WORLD_CONSTANTS_H_
```

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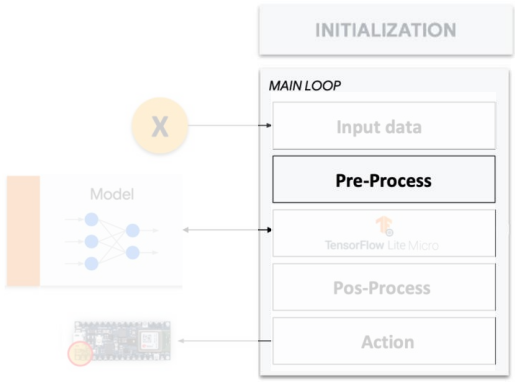


```
void loop() {
  // Calculate an x value to feed into the model. We compare the current
  // inference_count to the number of inferences per cycle to determine
  // our position within the range of possible x values the model was
  // trained on, and use this to calculate a value.
  float position = static_cast<float>(inference_count) /
                   static_cast<float>(kInferencesPerCycle);
  float x = position * kXrange;

  // Quantize the input from floating-point to integer
  int8_t x_quantized = x / input->params.scale + input->params.zero_point;
  // Place the quantized input in the model's input tensor
  input->data.int8[0] = x_quantized;

  // Run inference, and report any error
  TfLiteStatus invoke_status = interpreter->Invoke();
  if (invoke_status != kTfLiteOk) {
    TF_LITE_REPORT_ERROR(error_reporter, "Invoke failed on x: %f\n",
                         static_cast<double>(x));
    return;
  }
  // Obtain the quantized output from model's output tensor
  int8_t y_quantized = output->data.int8[0];
  // Dequantize the output from integer to floating-point
  float y = (y_quantized - output->params.zero_point) * output->params.scale;

  // Output the results. A custom HandleOutput function can be implemented
  // for each supported hardware target.
  HandleOutput(error_reporter, x, y);

  // Increment the inference_counter, and reset it if we have reached
  // the total number per cycle
  inference_count += 1;
  if (inference_count >= kInferencesPerCycle) inference_count = 0;
}
```

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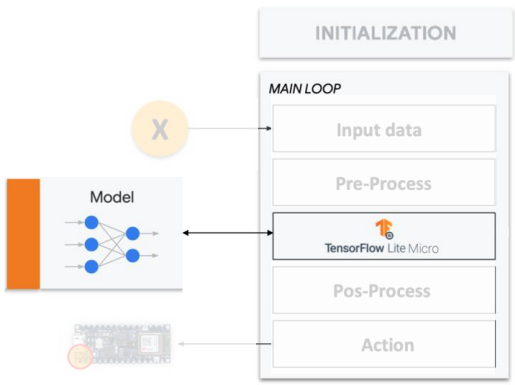


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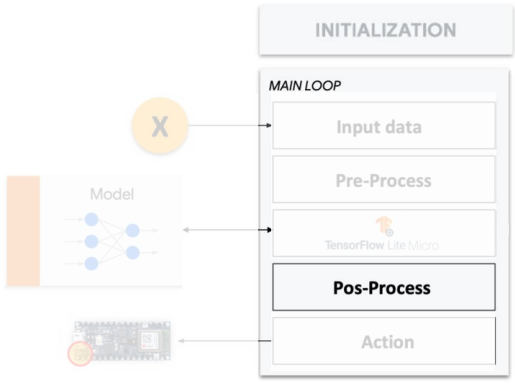


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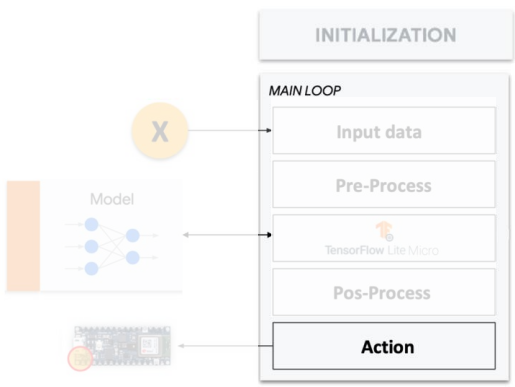


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  // inference_count to the number of inferences per cycle to determine
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```

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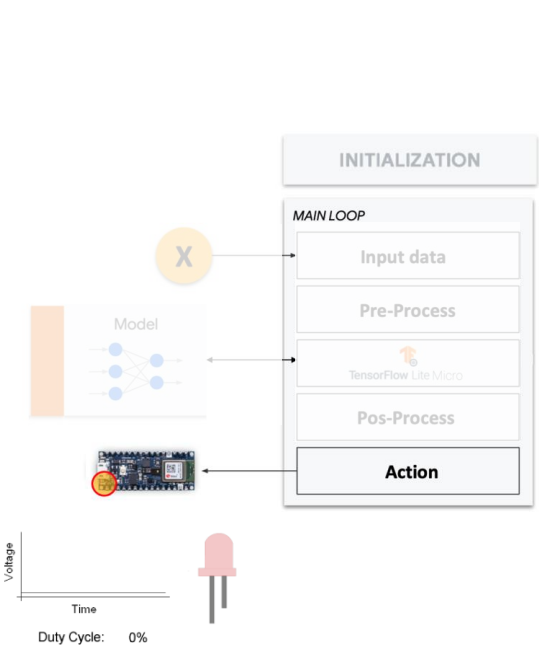

arduino_output_handler.cpp

```
#include "output_handler.h"

#include "Arduino.h"
#include "constants.h"

// The pin of the Arduino's built-in LED
int led = LED_BUILTIN;

// Track whether the function has run at least once
bool initialized = false;

// Animates a dot across the screen to represent the current x and y values
void HandleOutput(tflite::ErrorReporter* error_reporter, float x_value,
                  float y_value) {
  // Do this only once
  if (!initialized) {
    // Set the LED pin to output
    pinMode(led, OUTPUT);
    initialized = true;
  }

  // Calculate the brightness of the LED such that y=-1 is fully off
  // and y=1 is fully on. The LED's brightness can range from 0-255.
  int brightness = (int)(127.5f * (y_value + 1));

  // Set the brightness of the LED. If the specified pin does not support PWM,
  // this will result in the LED being on when y > 127, off otherwise.
  analogWrite(led, brightness);

  // Log the current brightness value for display in the Arduino plotter
  TF_LITE_REPORT_ERROR(error_reporter, "%d\n", brightness);
}
```

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- A previous edition of this course was developed in collaboration with Dr. Susan C. Schneider of Marquette University.
- We are very grateful and thank all the following professors, researchers, and practitioners for jump-starting courses on TinyML and for sharing their teaching materials:

- Prof. Marcelo Rovai - TinyML - Machine Learning for Embedding Devices, UNIFEI
  - https://github.com/Mjrovai/UNIFEI-IESTI01-TinyML-2022.1
- Prof. Vijay Janapa Reddi - CS249r: Tiny Machine Learning, Applied Machine Learning on Embedded IoT Devices, Harvard
  - https://sites.google.com/g.harvard.edu/tinyml/home
- Prof. Rahul Mangharam – ESE3600: Tiny Machine Learning, Univ. of Pennsylvania
  - https://tinyml.seas.upenn.edu/#
- Prof. Brian Plancher - Harvard CS249r: Tiny Machine Learning (TinyML), Barnard College, Columbia University
  - https://a2r-lab.org/courses/cs249r_tinyml/

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References

- Additional references from where information and other teaching materials were gathered include:

- Applications & Deploy textbook: “TinyML” by Pete Warden, Daniel Situnayake
  - https://www.oreilly.com/library/view/tinyml/9781492052036/
- Deploy textbook “TinyML Cookbook” by Gian Marco Iodice
  - https://github.com/PacktPublishing/TinyML-Cookbook
- Jason Brownlee
  - https://machinelearningmastery.com/
- TinyMLedu
  - https://tinyml.seas.harvard.edu/
- Professional Certificate in Tiny Machine Learning (TinyML) – edX/Harvard
  - https://www.edx.org/professional-certificate/harvardx-tiny-machine-learning
- Introduction to Embedded Machine Learning - Coursera/Edge Impulse
  - https://www.coursera.org/learn/introduction-to-embedded-machine-learning
- Computer Vision with Embedded Machine Learning - Coursera/Edge Impulse
  - https://www.coursera.org/learn/computer-vision-with-embedded-machine-learning

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