EECE-4710 “IoT and TinyML”

Person Detection Example Application

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MARQUETTE UNIVERSITY

BE THE DIFFERENCE.

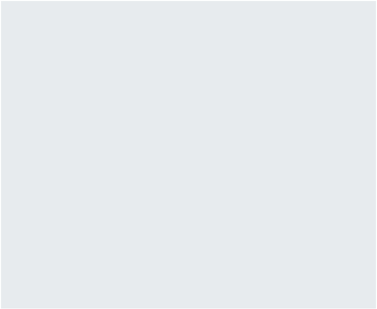
1

Person Detection

Application Architecture

2

✓



X

3

Person Detection using Transfer Learning Model

Code Walkthrough!

M:\arduino221\libraries\libraries\Arduino_TensorFlowLite\examples\person_detection\person_detection_v2.ino
(Available in the .zip file provided this week)

4

4

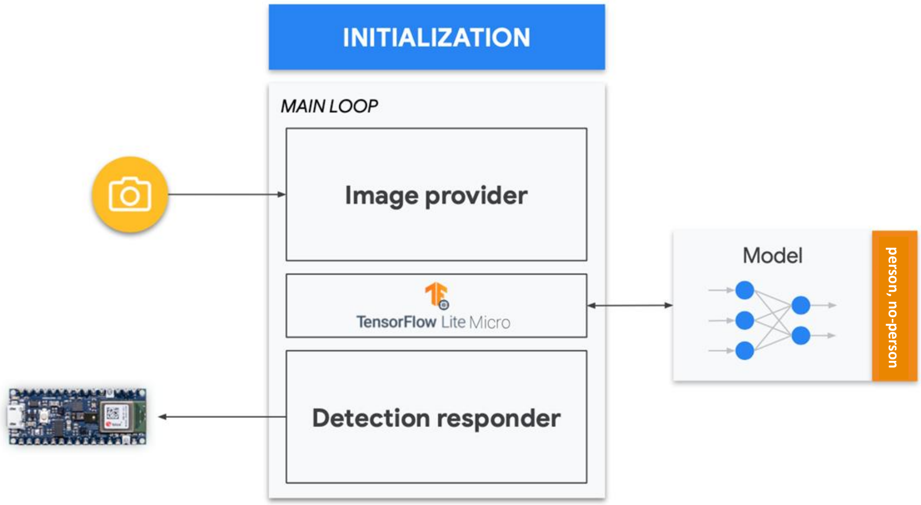
TensorFlow Lite Micro

TensorFlow Lite Micro - Paper

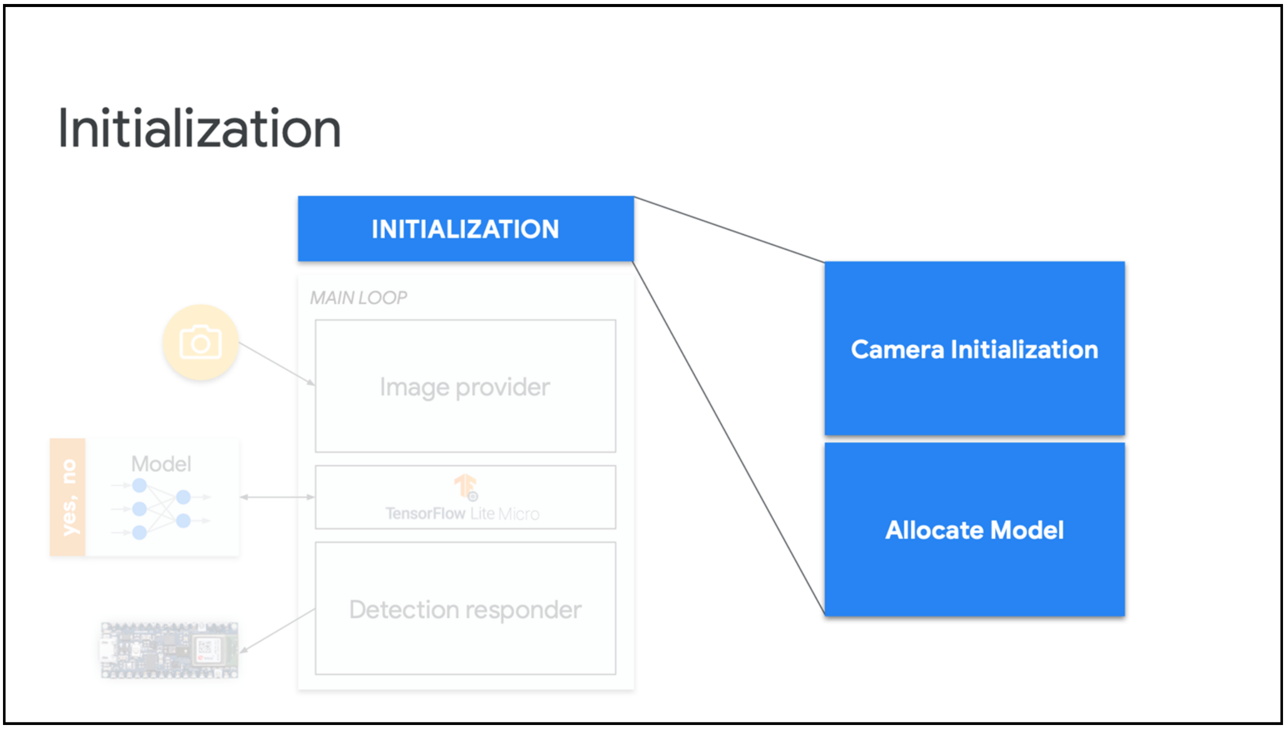
MLSys 2021: TensorFlow Lite Micro TFLM

5

Person Detection **Components**



6



Initialization

INITIALIZATION

MAIN LOOP

Image provider

Model

yes, no

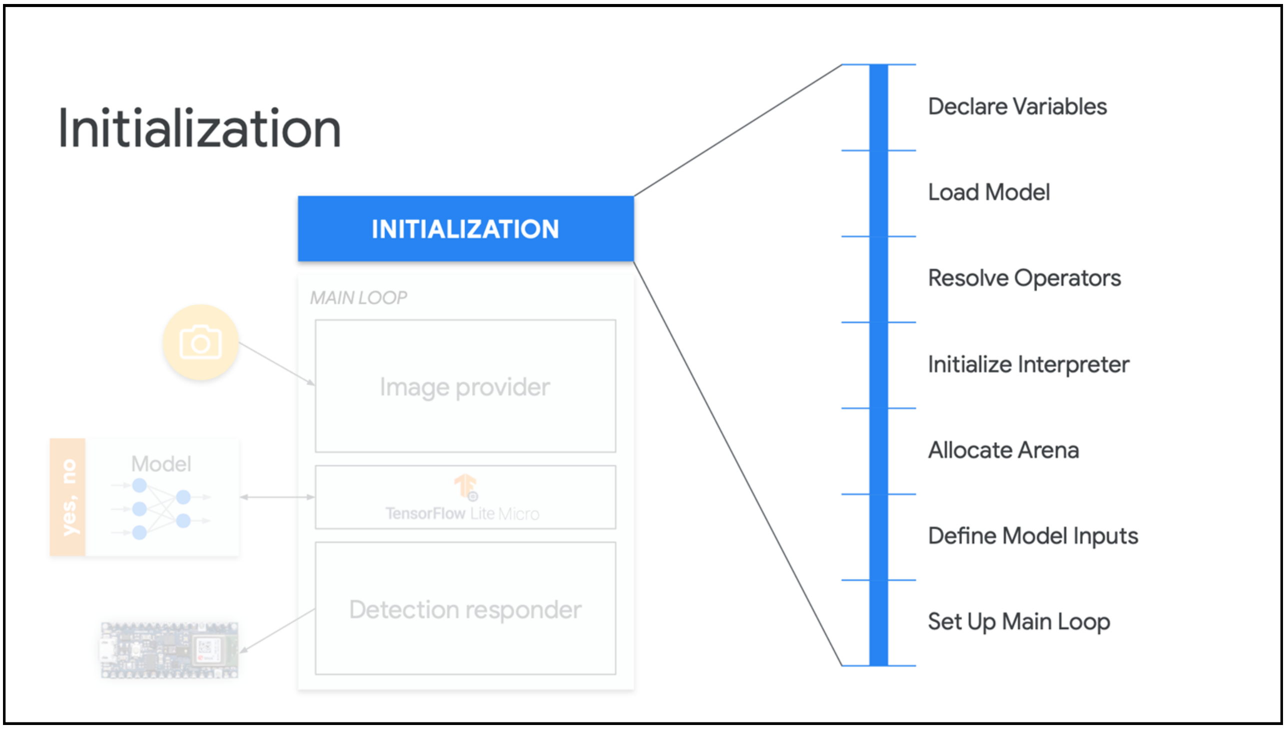
TensorFlow Lite Micro

Detection responder

Camera Initialization

Allocate Model

7



Initialization

INITIALIZATION

MAIN LOOP

Image provider

Model

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TensorFlow Lite Micro

Detection responder

Declare Variables

Load Model

Resolve Operators

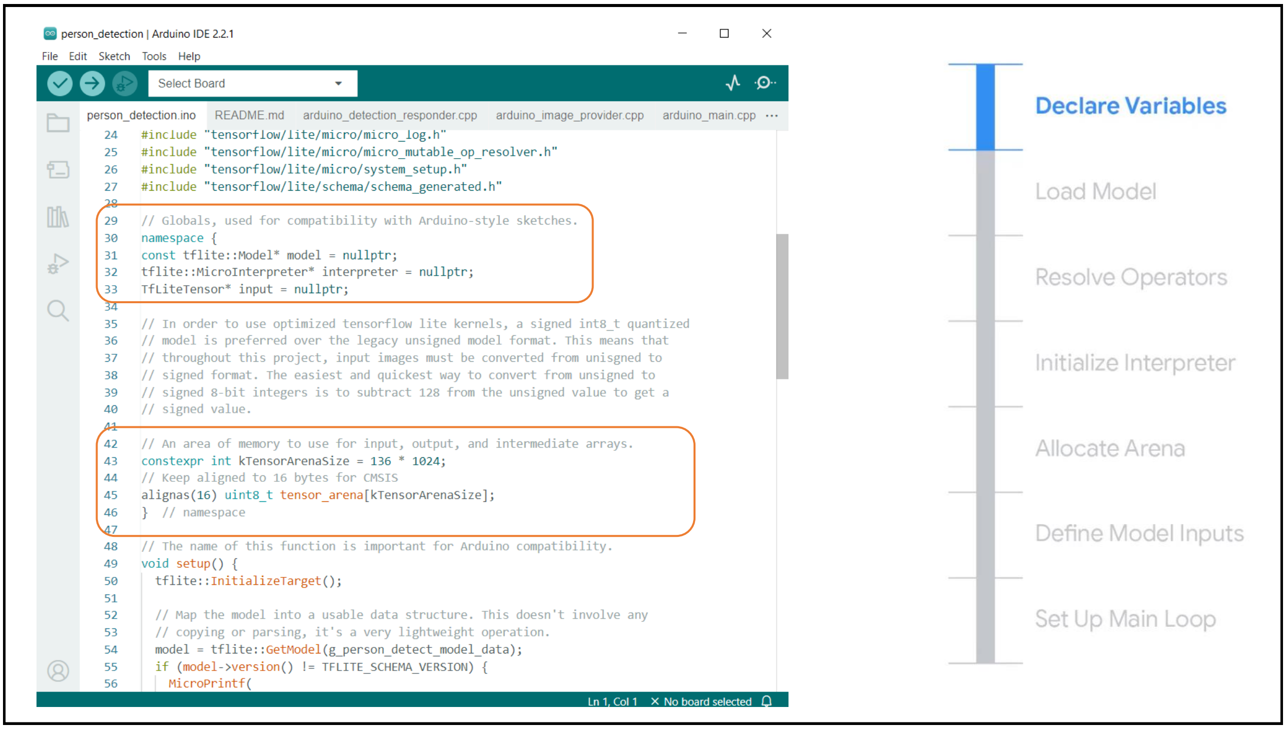
Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

8


person_detection | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
person_detection.ino README.md arduino_detection_responder.cpp arduino_image_provider.cpp arduino_main.cpp
Ln 1, Col 1 × No board selected

```
#include "tensorflow/lite/micro/micro_log.h"
#include "tensorflow/lite/micro/micro_mutable_op_resolver.h"
#include "tensorflow/lite/micro/system_setup.h"
#include "tensorflow/lite/schema/schema_generated.h"

// Globals, used for compatibility with Arduino-style sketches.
namespace {
const tflite::Model* model = nullptr;
tflite::MicroInterpreter* interpreter = nullptr;
TfLiteTensor* input = nullptr;

// In order to use optimized tensorflow lite kernels, a signed int8_t quantized
// model is preferred over the legacy unsigned model format. This means that
// throughout this project, input images must be converted from unisgned to
// signed format. The easiest and quickest way to convert from unsigned to
// signed 8-bit integers is to subtract 128 from the unsigned value to get a
// signed value.

// An area of memory to use for input, output, and intermediate arrays.
constexpr int kTensorArenaSize = 136 * 1024;
// Keep aligned to 16 bytes for CMSIS
alignas(16) uint8_t tensor_arena[kTensorArenaSize];
}  // namespace

// The name of this function is important for Arduino compatibility.
void setup() {
  tflite::InitializeTarget();

  // 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_person_detect_model_data);
  if (model->version() != TFLITE_SCHEMA_VERSION) {
    MicroPrintf(
```

Declare Variables

Load Model

Resolve Operators

Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

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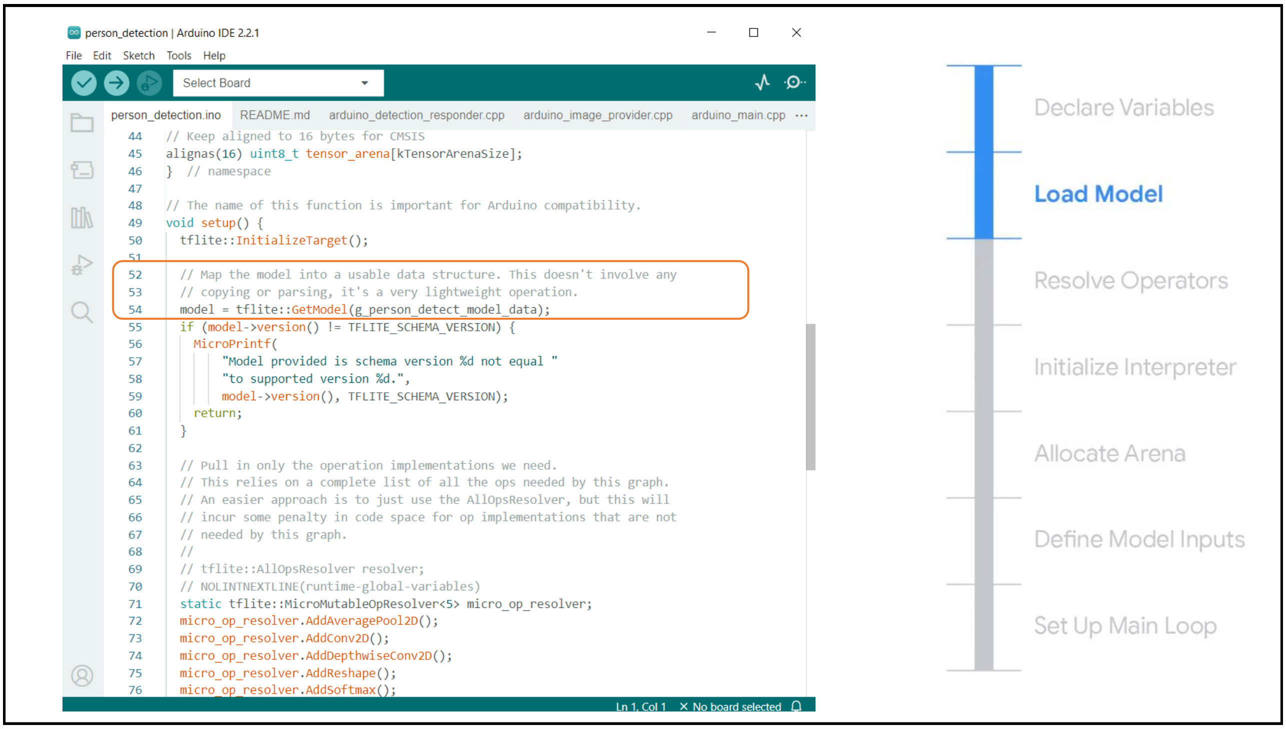
person_detection | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
person_detection.ino README.md arduino_detection_responder.cpp arduino_image_provider.cpp arduino_main.cpp
Ln 1, Col 1 × No board selected

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  tflite::InitializeTarget();

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

  // Pull in only the operation implementations we need.
  // This relies on a complete list of all the ops needed by this graph.
  // An easier approach is to just use the AllOpsResolver, but this will
  // incur some penalty in code space for op implementations that are not
  // needed by this graph.
  //
  // tflite::AllOpsResolver resolver;
  // NOLINTNEXTLINE(runtime-global-variables)
  static tflite::MicroMutableOpResolver<5> micro_op_resolver;
  micro_op_resolver.AddAveragePool2D();
  micro_op_resolver.AddConv2D();
  micro_op_resolver.AddDepthwiseConv2D();
  micro_op_resolver.AddReshape();
  micro_op_resolver.AddSoftmax();
```

Declare Variables

Load Model

Resolve Operators

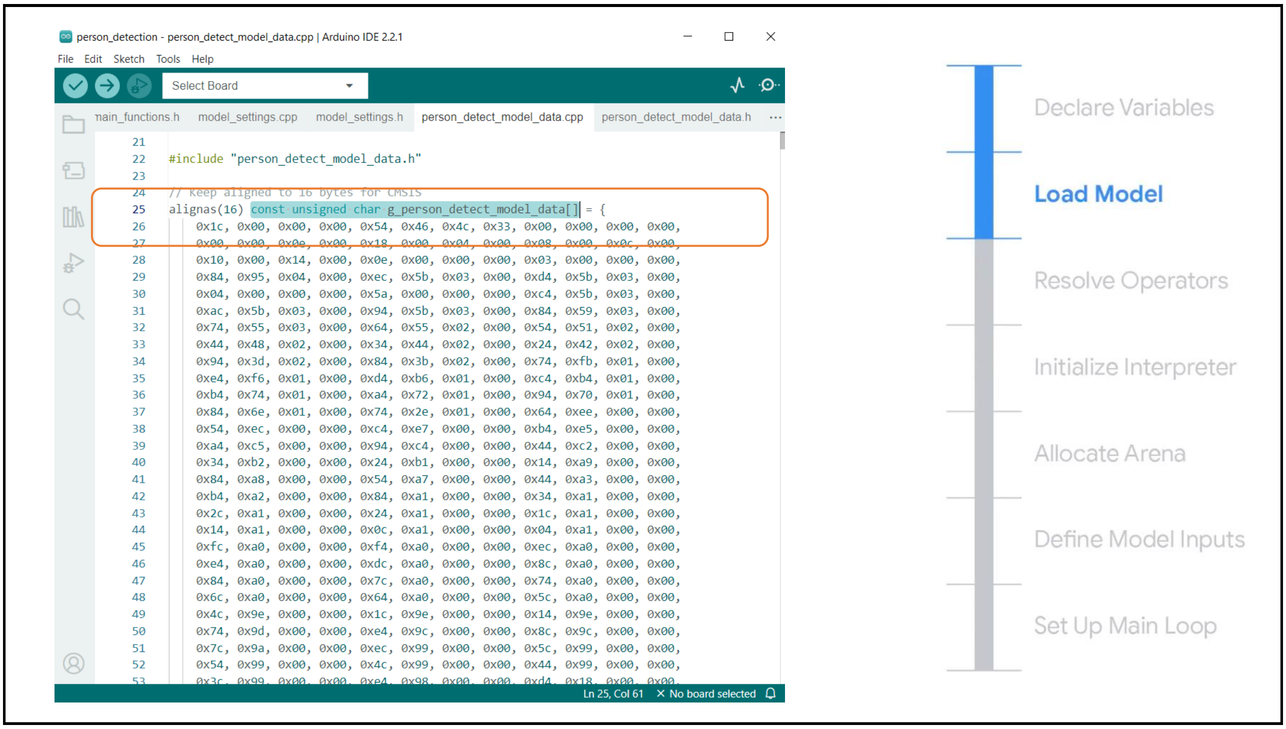
Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

10



person_detection - person_detect_model_data.cpp | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
nain_functions.h
model_settings.cpp
model_settings.h
person_detect_model_data.cpp
person_detect_model_data.h
Ln 25, Col 61 ✕ No board selected

```
#include "person_detect_model_data.h"

// Keep aligned to 16 bytes for CMSIS
alignas(16) const unsigned char g_person_detect_model_data[] = {
    0x1c, 0x00, 0x00, 0x00, 0x54, 0x46, 0x4c, 0x33, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x0e, 0x00, 0x18, 0x00, 0x04, 0x00, 0x08, 0x00, 0x0c, 0x00,
    0x10, 0x00, 0x14, 0x00, 0x0e, 0x00, 0x00, 0x00, 0x03, 0x00, 0x00, 0x00,
    0x84, 0x95, 0x04, 0x00, 0xec, 0x5b, 0x03, 0x00, 0xd4, 0x5b, 0x03, 0x00,
    0x04, 0x00, 0x00, 0x00, 0x5a, 0x00, 0x00, 0x00, 0xc4, 0x5b, 0x03, 0x00,
    0xac, 0x5b, 0x03, 0x00, 0x94, 0x5b, 0x03, 0x00, 0x84, 0x59, 0x03, 0x00,
    0x74, 0x55, 0x03, 0x00, 0x64, 0x55, 0x02, 0x00, 0x54, 0x51, 0x02, 0x00,
    0x44, 0x48, 0x02, 0x00, 0x34, 0x44, 0x02, 0x00, 0x24, 0x42, 0x02, 0x00,
    0x94, 0x3d, 0x02, 0x00, 0x84, 0x3b, 0x02, 0x00, 0x74, 0xfb, 0x01, 0x00,
    0xe4, 0xf6, 0x01, 0x00, 0xd4, 0xb6, 0x01, 0x00, 0xc4, 0xb4, 0x01, 0x00,
    0xb4, 0x74, 0x01, 0x00, 0xa4, 0x72, 0x01, 0x00, 0x94, 0x70, 0x01, 0x00,
    0x84, 0x6e, 0x01, 0x00, 0x74, 0x2e, 0x01, 0x00, 0x64, 0xee, 0x00, 0x00,
    0x54, 0xec, 0x00, 0x00, 0xc4, 0xe7, 0x00, 0x00, 0xb4, 0xe5, 0x00, 0x00,
    0xa4, 0xc5, 0x00, 0x00, 0x94, 0xc4, 0x00, 0x00, 0x44, 0xc2, 0x00, 0x00,
    0x34, 0xb2, 0x00, 0x00, 0x24, 0xb1, 0x00, 0x00, 0x14, 0xa9, 0x00, 0x00,
    0x84, 0xa8, 0x00, 0x00, 0x54, 0xa7, 0x00, 0x00, 0x44, 0xa3, 0x00, 0x00,
    0xb4, 0xa2, 0x00, 0x00, 0x84, 0xa1, 0x00, 0x00, 0x34, 0xa1, 0x00, 0x00,
    0x2c, 0xa1, 0x00, 0x00, 0x24, 0xa1, 0x00, 0x00, 0x1c, 0xa1, 0x00, 0x00,
    0x14, 0xa1, 0x00, 0x00, 0x0c, 0xa1, 0x00, 0x00, 0x04, 0xa1, 0x00, 0x00,
    0xfc, 0xa0, 0x00, 0x00, 0xf4, 0xa0, 0x00, 0x00, 0xec, 0xa0, 0x00, 0x00,
    0xe4, 0xa0, 0x00, 0x00, 0xdc, 0xa0, 0x00, 0x00, 0x8c, 0xa0, 0x00, 0x00,
    0x84, 0xa0, 0x00, 0x00, 0x7c, 0xa0, 0x00, 0x00, 0x74, 0xa0, 0x00, 0x00,
    0x6c, 0xa0, 0x00, 0x00, 0x64, 0xa0, 0x00, 0x00, 0x5c, 0xa0, 0x00, 0x00,
    0x4c, 0x9e, 0x00, 0x00, 0x1c, 0x9e, 0x00, 0x00, 0x14, 0x9e, 0x00, 0x00,
    0x74, 0x9d, 0x00, 0x00, 0xe4, 0x9c, 0x00, 0x00, 0x8c, 0x9c, 0x00, 0x00,
    0x7c, 0x9a, 0x00, 0x00, 0xec, 0x99, 0x00, 0x00, 0x5c, 0x99, 0x00, 0x00,
    0x54, 0x99, 0x00, 0x00, 0x4c, 0x99, 0x00, 0x00, 0x44, 0x99, 0x00, 0x00,
    0x3c, 0x99, 0x00, 0x00, 0xe4, 0x98, 0x00, 0x00, 0xd4, 0x18, 0x00, 0x00,
```

Declare Variables

Load Model

Resolve Operators

Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

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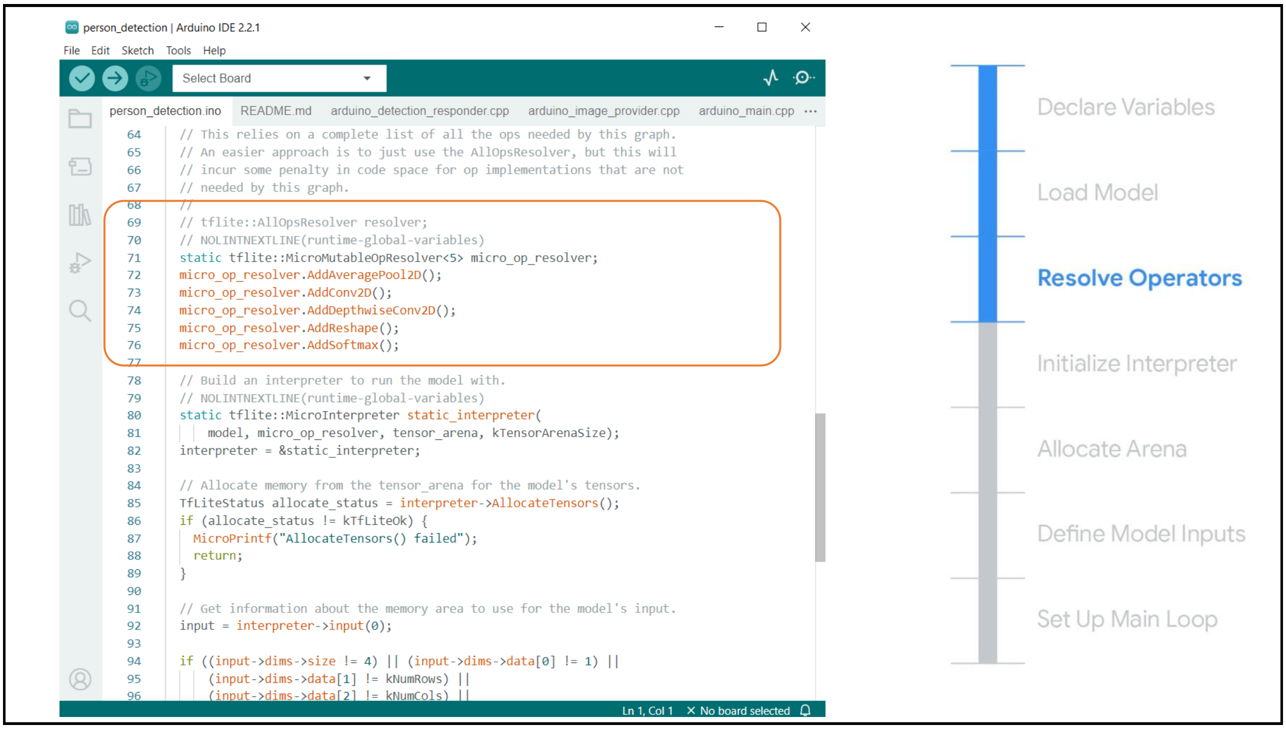


person_detection | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
person_detection.ino
README.md
arduino_detection_responder.cpp
arduino_image_provider.cpp
arduino_main.cpp
Ln 1, Col 1 ✕ No board selected

```
// This relies on a complete list of all the ops needed by this graph.
// An easier approach is to just use the AllOpsResolver, but this will
// incur some penalty in code space for op implementations that are not
// needed by this graph.
//
// tflite::AllOpsResolver resolver;
// NOLINTNEXTLINE(runtime-global-variables)
static tflite::MicroMutableOpResolver<5> micro_op_resolver;
micro_op_resolver.AddAveragePool2D();
micro_op_resolver.AddConv2D();
micro_op_resolver.AddDepthwiseConv2D();
micro_op_resolver.AddReshape();
micro_op_resolver.AddSoftmax();

// Build an interpreter to run the model with.
// NOLINTNEXTLINE(runtime-global-variables)
static tflite::MicroInterpreter static_interpreter(
    model, micro_op_resolver, tensor_arena, kTensorArenaSize);
interpreter = &static_interpreter;

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

// Get information about the memory area to use for the model's input.
input = interpreter->input(0);

if ((input->dims->size != 4) || (input->dims->data[0] != 1) ||
    (input->dims->data[1] != kNumRows) ||
    (input->dims->data[2] != kNumCols) ||
```

Declare Variables

Load Model

Resolve Operators

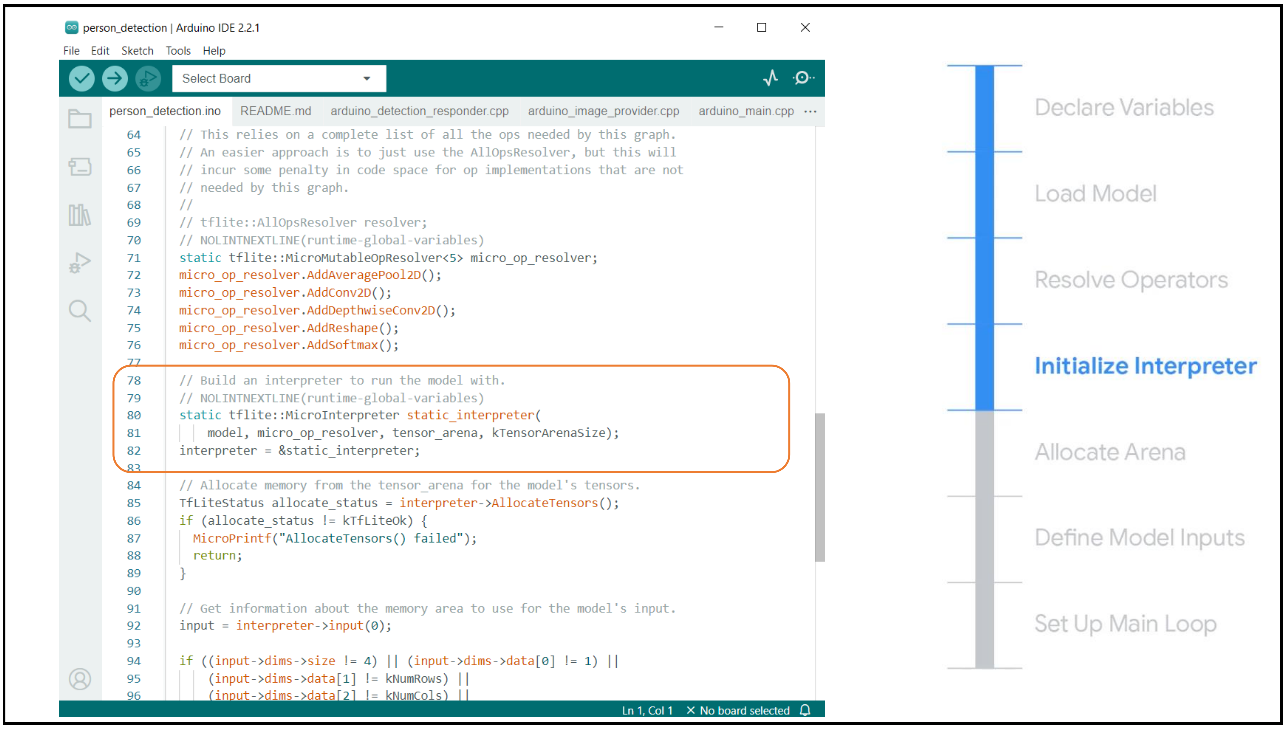
Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

12


person_detection | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
person_detection.ino
README.md
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Ln 1, Col 1
No board selected

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```

Declare Variables

Load Model

Resolve Operators

Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

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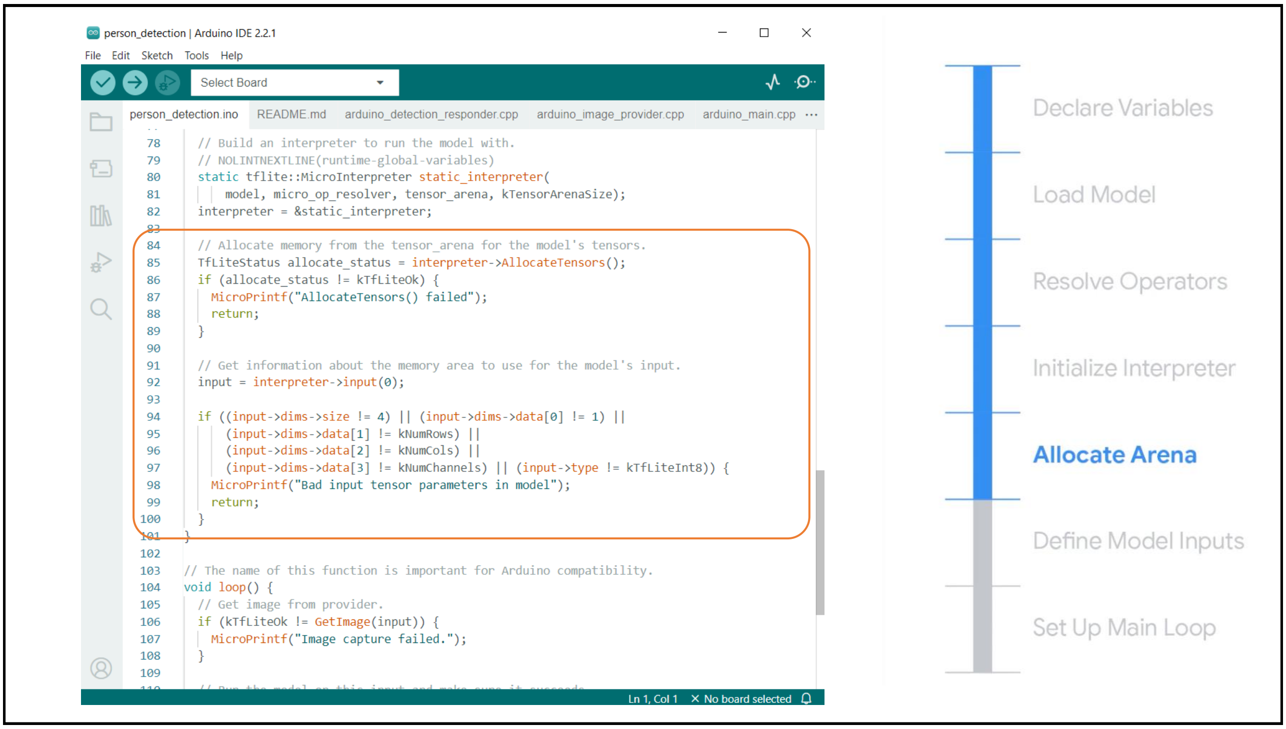
person_detection | Arduino IDE 2.2.1
File Edit Sketch Tools Help
Select Board
person_detection.ino
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arduino_image_provider.cpp
arduino_main.cpp
Ln 1, Col 1
No board selected

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  input = interpreter->input(0);

  if ((input->dims->size != 4) || (input->dims->data[0] != 1) ||
      (input->dims->data[1] != kNumRows) ||
      (input->dims->data[2] != kNumCols) ||
      (input->dims->data[3] != kNumChannels) || (input->type != kTfLiteInt8)) {
    MicroPrintf("Bad input tensor parameters in model");
    return;
  }
}

// The name of this function is important for Arduino compatibility.
void loop() {
  // Get image from provider.
  if (kTfLiteOk != GetImage(input)) {
    MicroPrintf("Image capture failed.");
  }

  // Run the model on this input and make sure it succeeds.
```

Declare Variables

Load Model

Resolve Operators

Initialize Interpreter

Allocate Arena

Define Model Inputs

Set Up Main Loop

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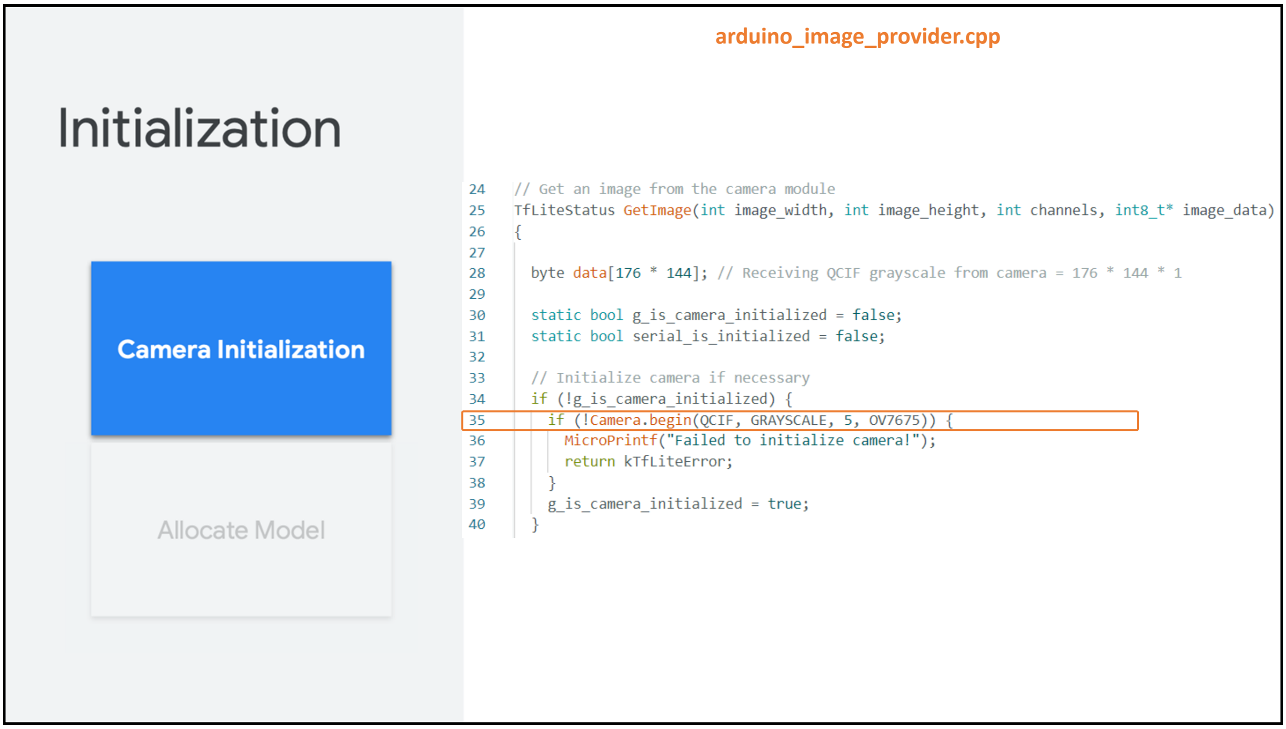

Initialization

Camera Initialization

Allocate Model

arduino_image_provider.cpp

```
// Get an image from the camera module
TfLiteStatus GetImage(int image_width, int image_height, int channels, int8_t* image_data)
{

  byte data[176 * 144]; // Receiving QCIF grayscale from camera = 176 * 144 * 1

  static bool g_is_camera_initialized = false;
  static bool serial_is_initialized = false;

  // Initialize camera if necessary
  if (!g_is_camera_initialized) {
    if (!Camera.begin(QCIF, GRAYSCALE, 5, OV7675)) {
      MicroPrintf("Failed to initialize camera!");
      return kTfLiteError;
    }
    g_is_camera_initialized = true;
  }
```

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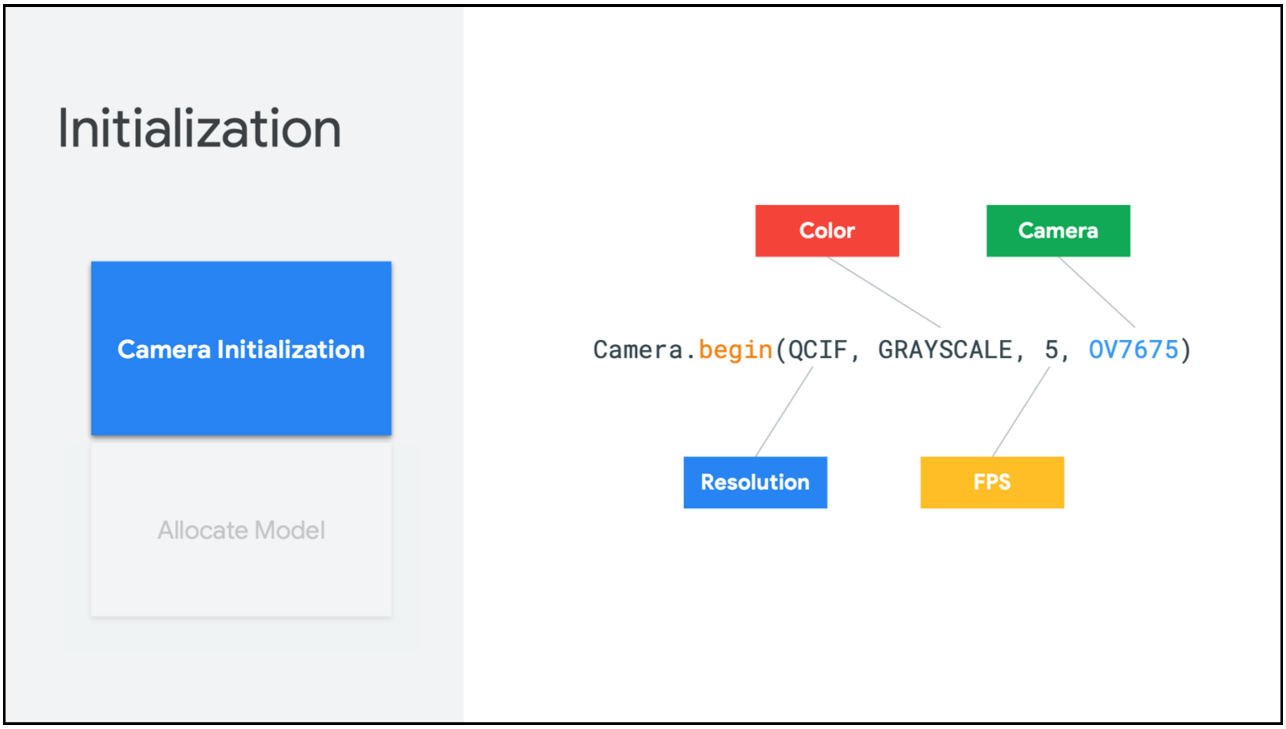

Initialization

Camera Initialization

Allocate Model

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Camera.begin(QCIF, GRAYSCALE, 5, OV7675)
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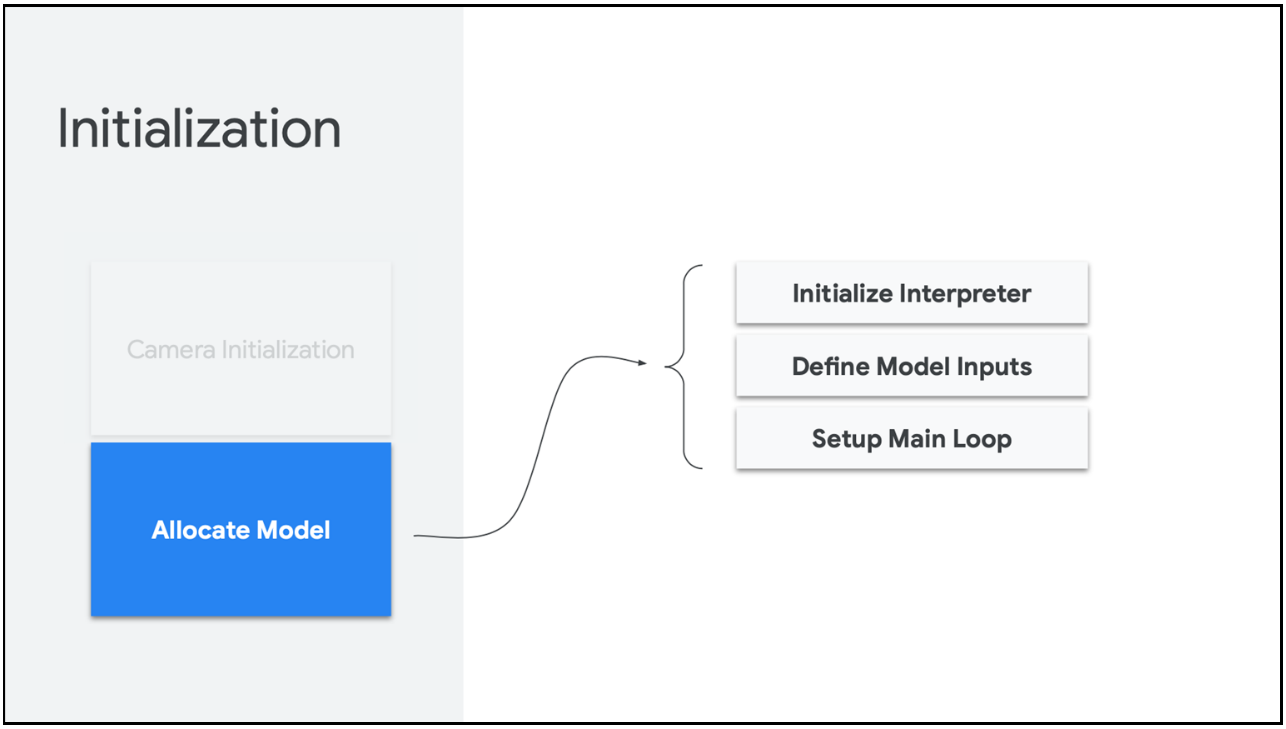
16



Initialization

Camera Initialization

Allocate Model

Initialize Interpreter

Define Model Inputs

Setup Main Loop

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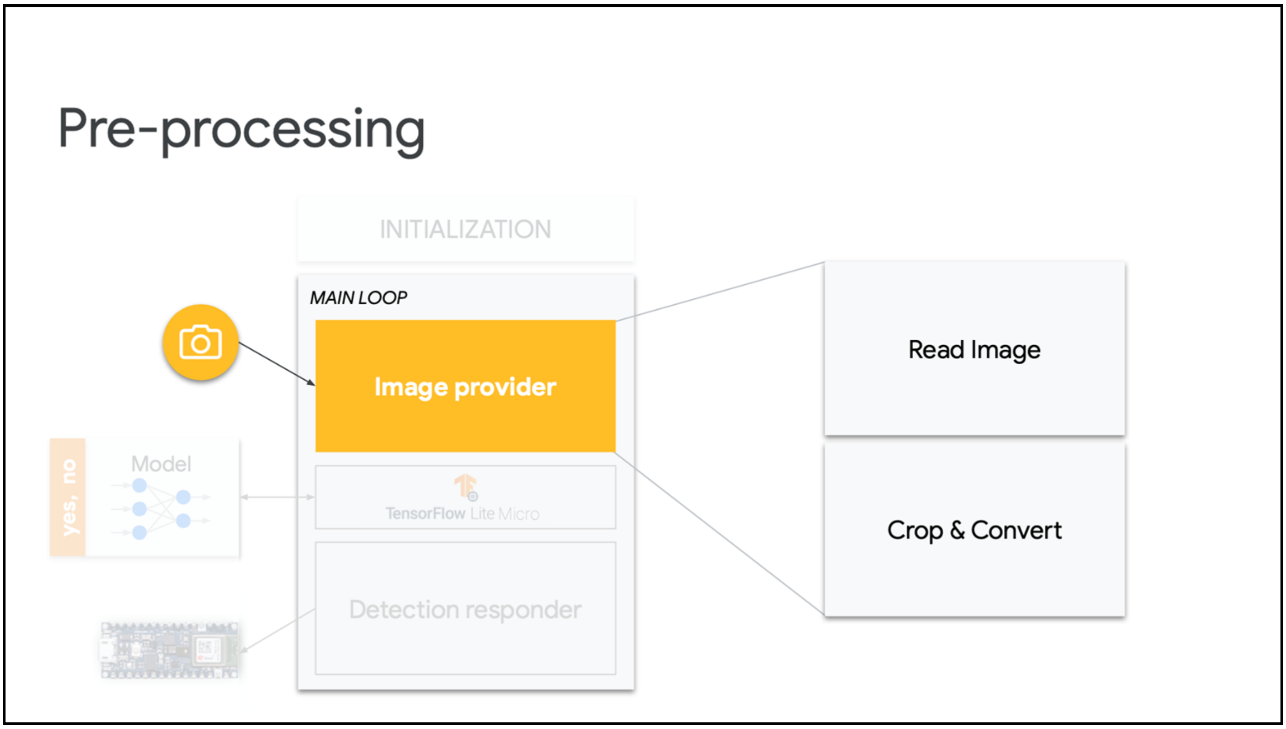

Pre-processing

INITIALIZATION

MAIN LOOP

Image provider

TensorFlow Lite Micro

Detection responder

yes, no

Model

Read Image

Crop & Convert

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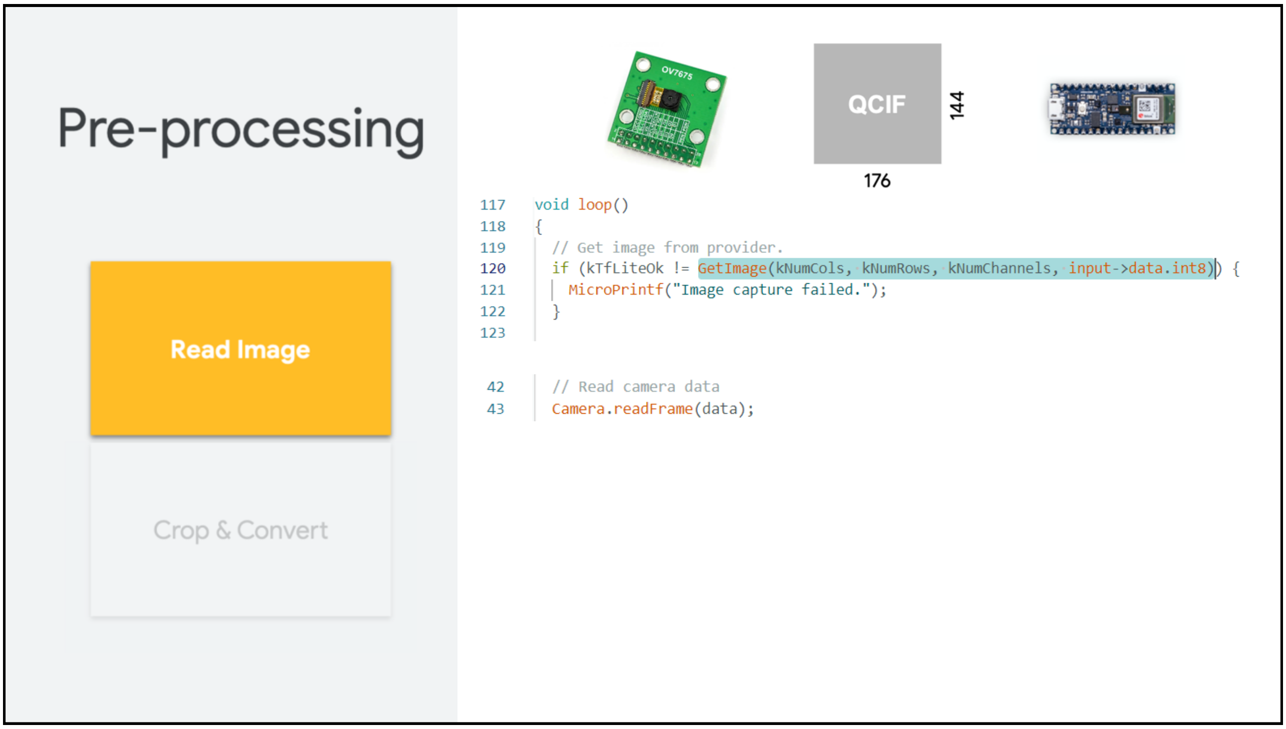

Pre-processing

Read Image

Crop & Convert

```
void loop()
{
  // Get image from provider.
  if (kTfLiteOk != GetImage(kNumCols, kNumRows, kNumChannels, input->data.int8)) {
    MicroPrintf("Image capture failed.");
  }

```

```
  // Read camera data
  Camera.readFrame(data);
```

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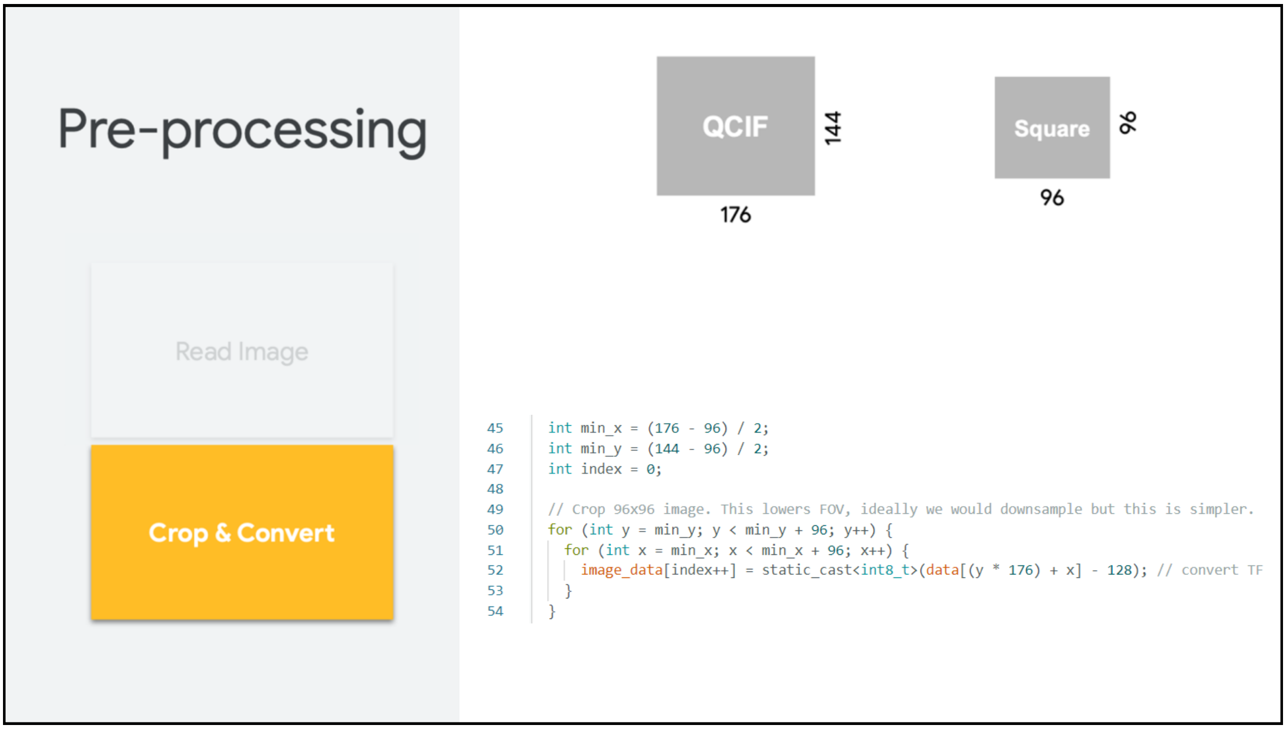

Pre-processing

Read Image

Crop & Convert

```
int min_x = (176 - 96) / 2;
int min_y = (144 - 96) / 2;
int index = 0;

// Crop 96x96 image. This lowers FOV, ideally we would downsample but this is simpler.
for (int y = min_y; y < min_y + 96; y++) {
  for (int x = min_x; x < min_x + 96; x++) {
    image_data[index++] = static_cast<int8_t>(data[(y * 176) + x] - 128); // convert TF
  }
}
```

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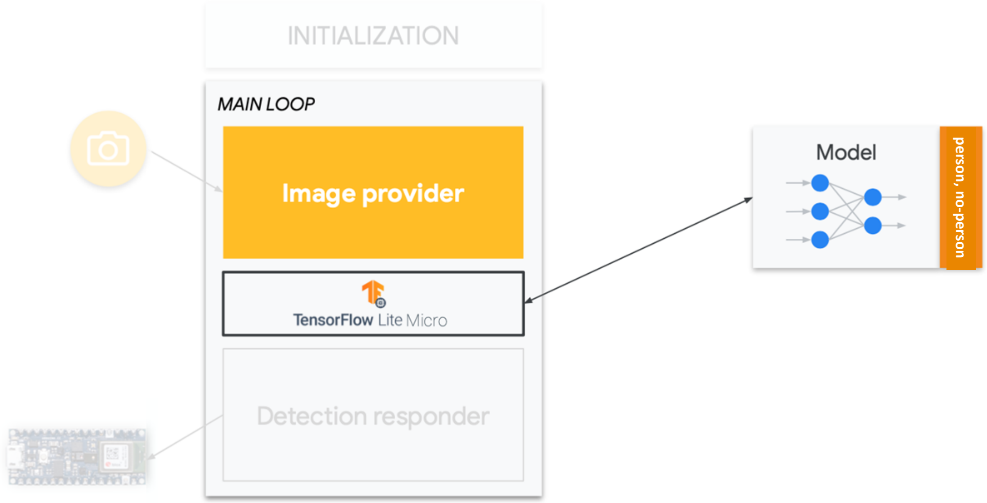
Interpreter + Model



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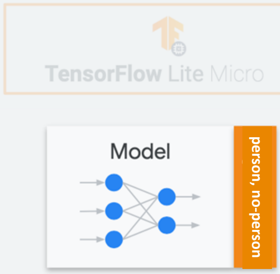
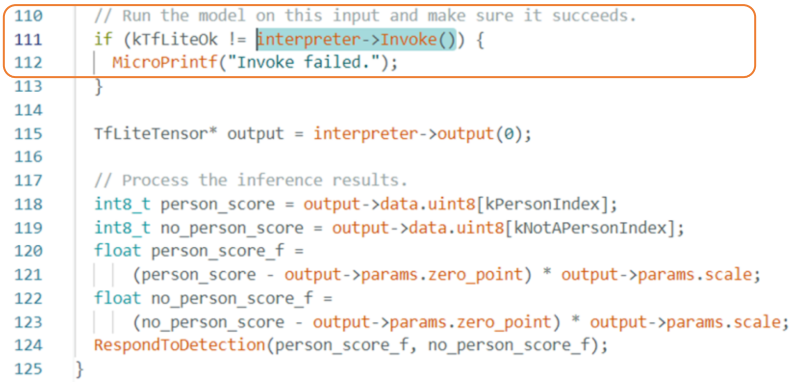
Interpreter + Model





```
    // Run the model on this input and make sure it succeeds.
    if (kTfLiteOk != interpreter->Invoke()) {
      MicroPrintf("Invoke failed.");
    }

    TfLiteTensor* output = interpreter->output(0);

    // Process the inference results.
    int8_t person_score = output->data.uint8[kPersonIndex];
    int8_t no_person_score = output->data.uint8[kNotAPersonIndex];
    float person_score_f =
        (person_score - output->params.zero_point) * output->params.scale;
    float no_person_score_f =
        (no_person_score - output->params.zero_point) * output->params.scale;
    RespondToDetection(person_score_f, no_person_score_f);
  }
```

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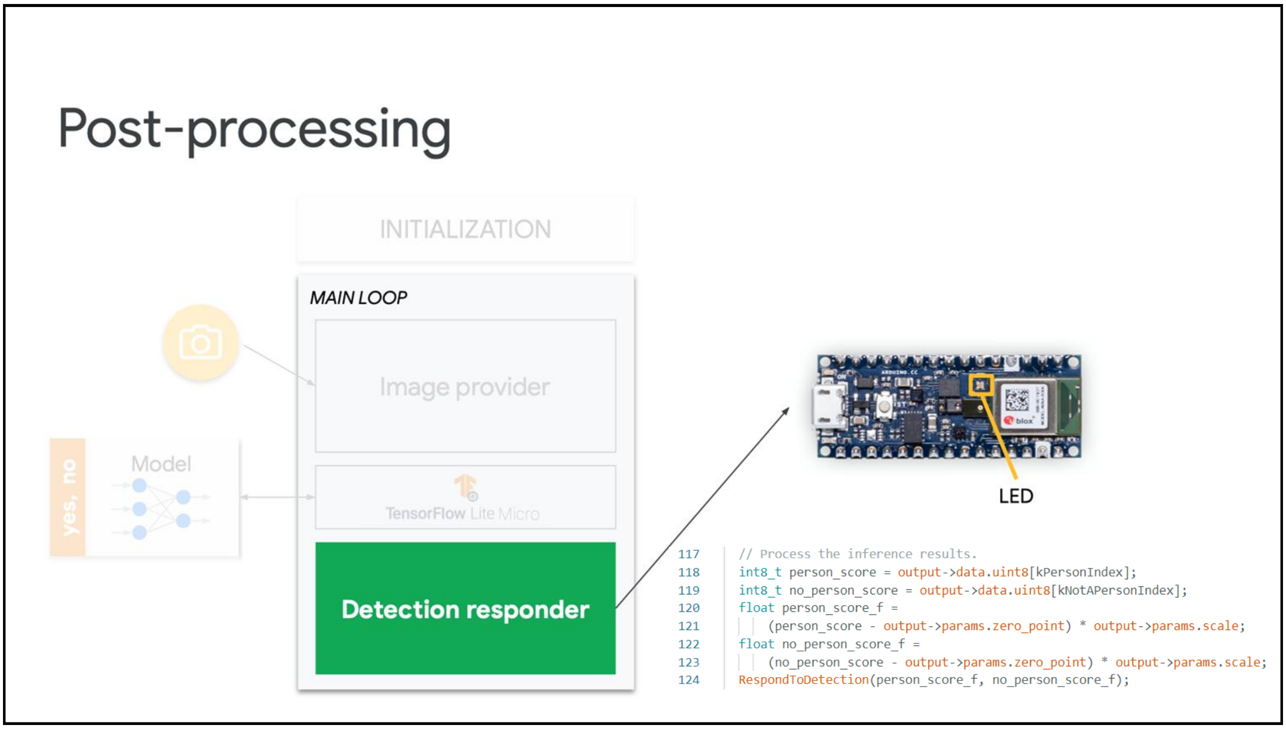

Post-processing

```
// Process the inference results.
int8_t person_score = output->data.uint8[kPersonIndex];
int8_t no_person_score = output->data.uint8[kNotAPersonIndex];
float person_score_f =
    (person_score - output->params.zero_point) * output->params.scale;
float no_person_score_f =
    (no_person_score - output->params.zero_point) * output->params.scale;
RespondToDetection(person_score_f, no_person_score_f);
```

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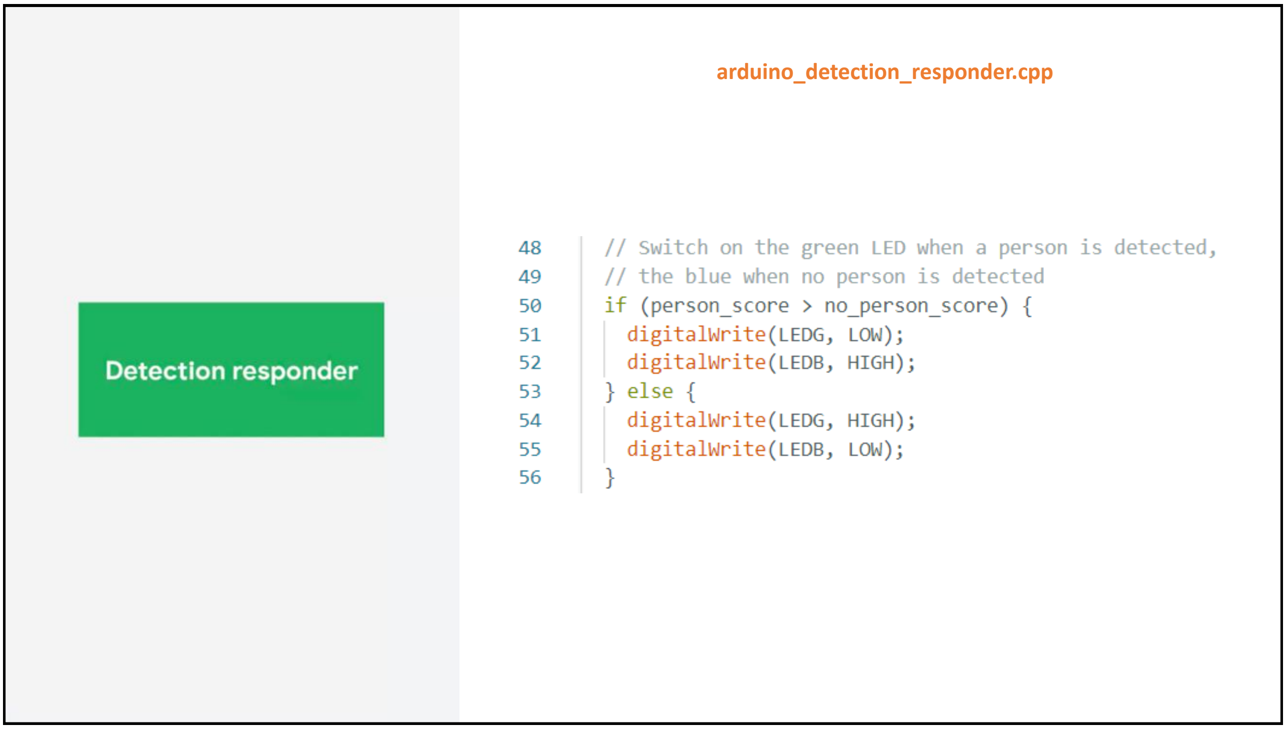

Detection responder

arduino_detection_responder.cpp

```
// Switch on the green LED when a person is detected,
// the blue when no person is detected
if (person_score > no_person_score) {
  digitalWrite(LEDG, LOW);
  digitalWrite(LEDB, HIGH);
} else {
  digitalWrite(LEDG, HIGH);
  digitalWrite(LEDB, LOW);
}
```

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Person Detection (Optional)

Multi-Tenancy

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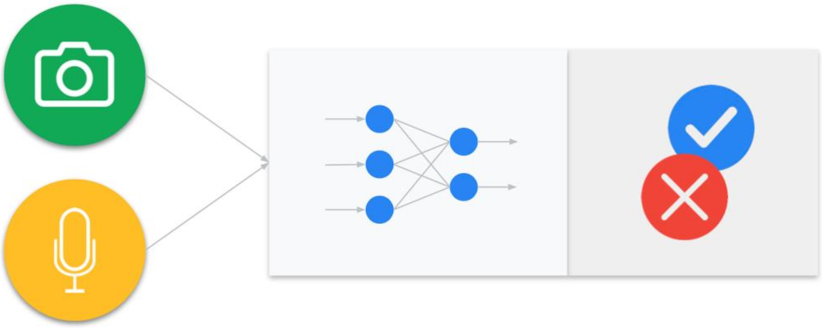
25

MultiModal



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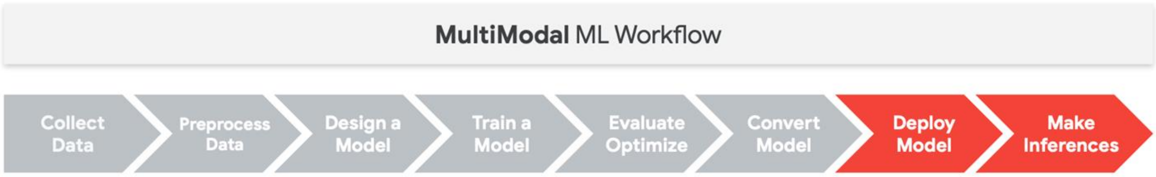

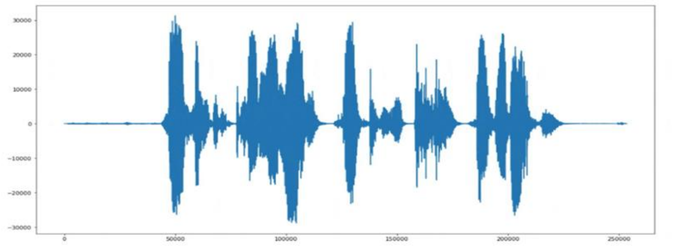

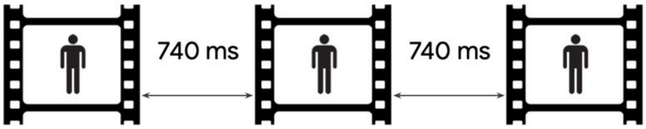

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Example Person Detection Application

- Contact-free elevator control that enforces mask wearing
- Requires both **keyword spotting** and **mask detection**

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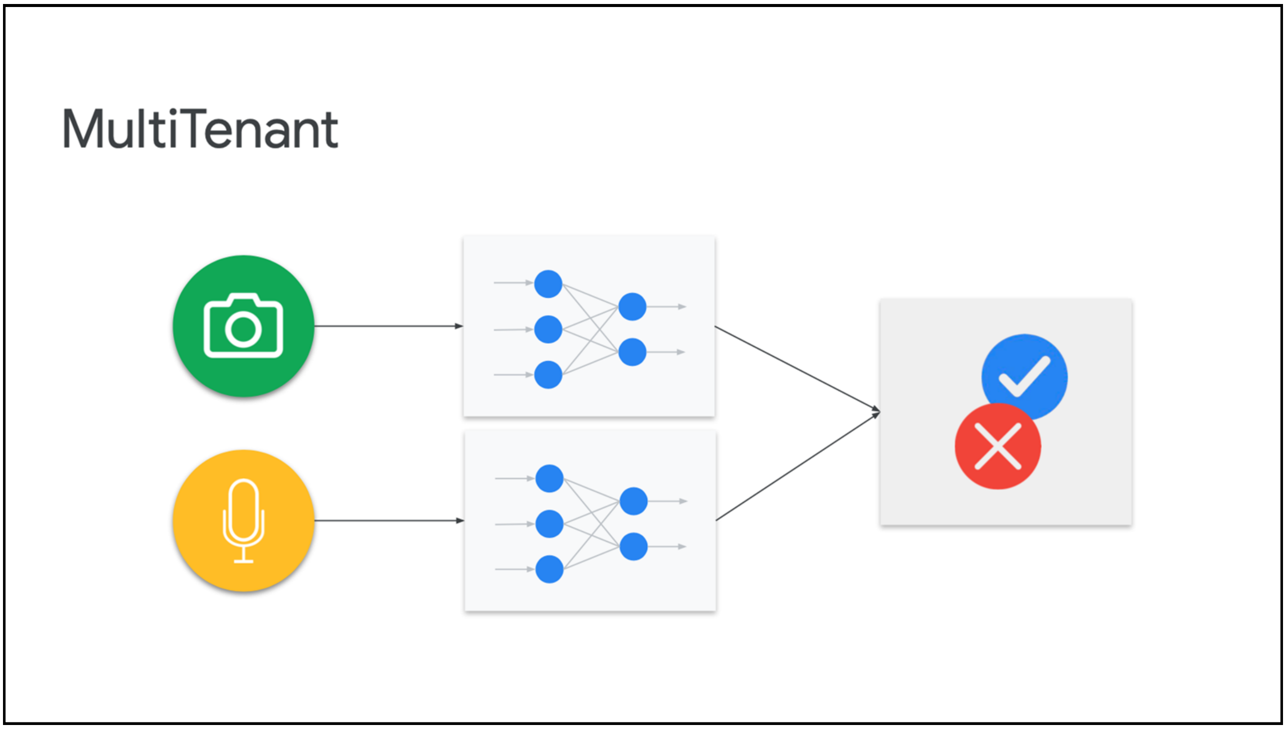
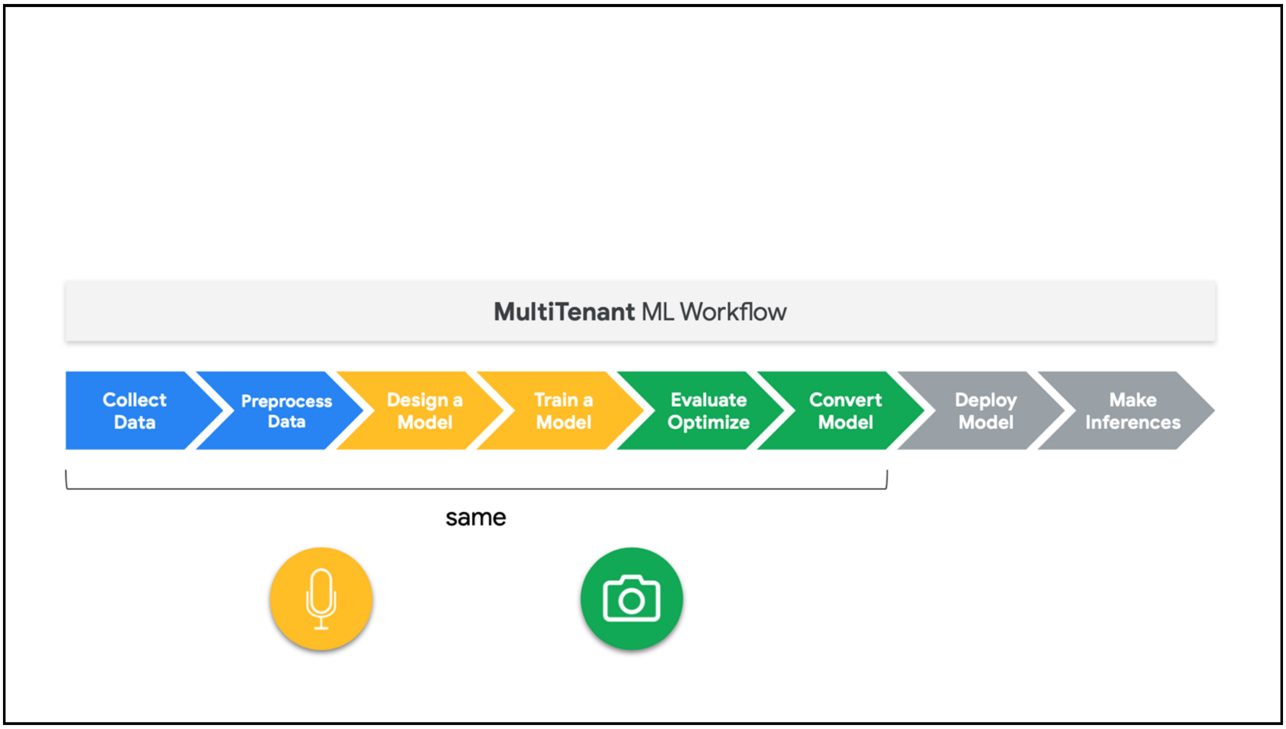


MultiTenant

29



MultiTenant ML Workflow

Collect Data

Preprocess Data

Design a Model

Train a Model

Evaluate Optimize

Convert Model

Deploy Model

Make Inferences

same

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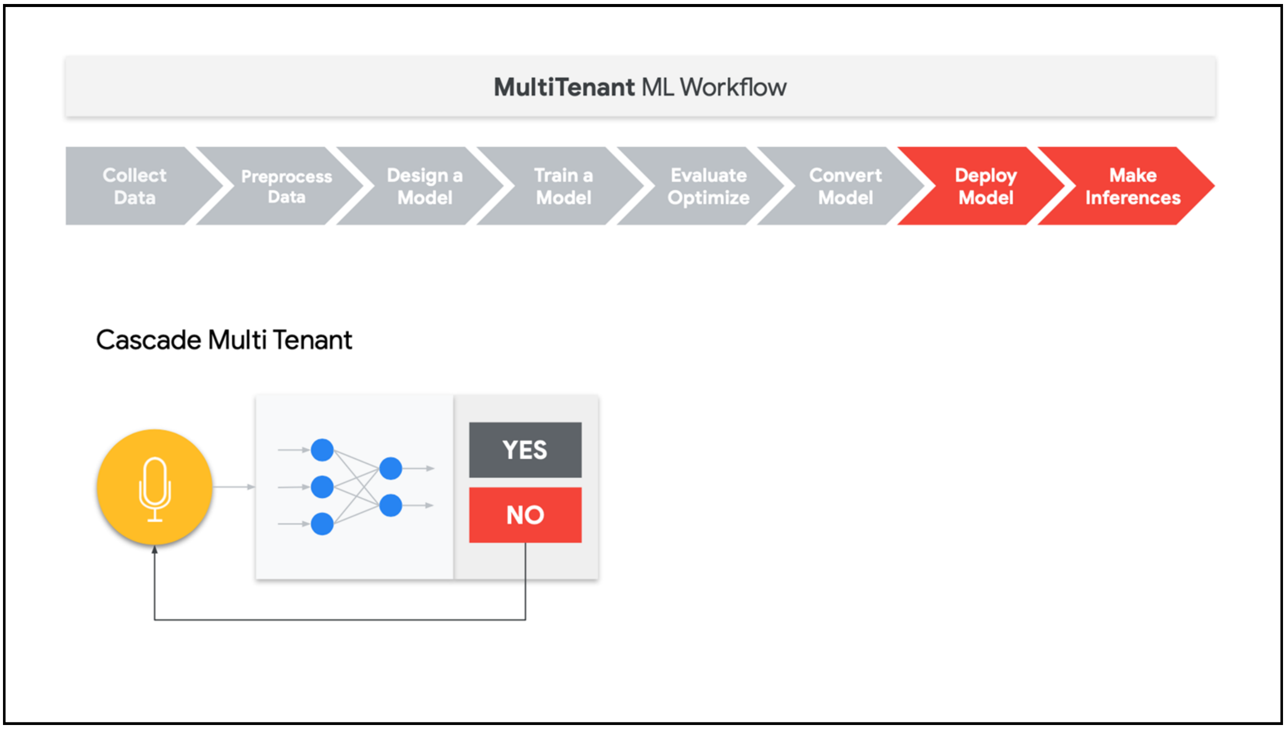
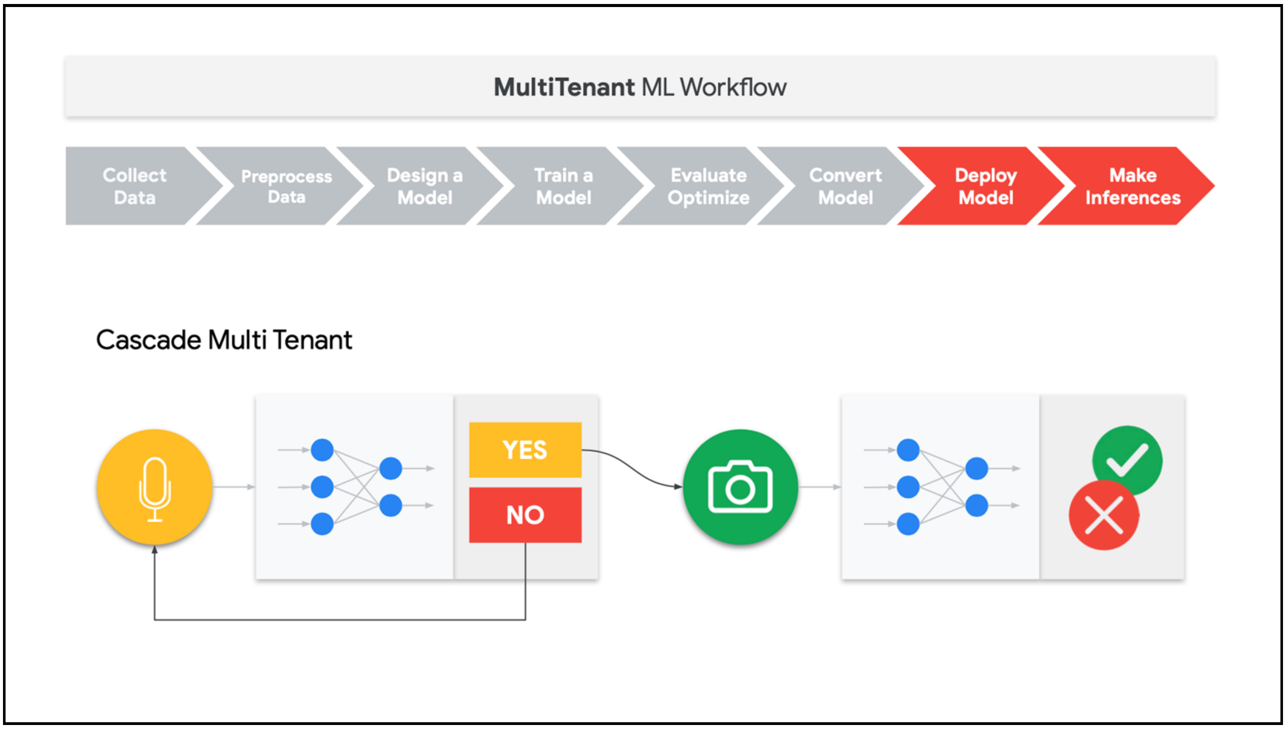


MultiTenant ML Workflow

Collect Data → Preprocess Data → Design a Model → Train a Model → Evaluate Optimize → Convert Model → Deploy Model → Make Inferences

Cascade Multi Tenant

31

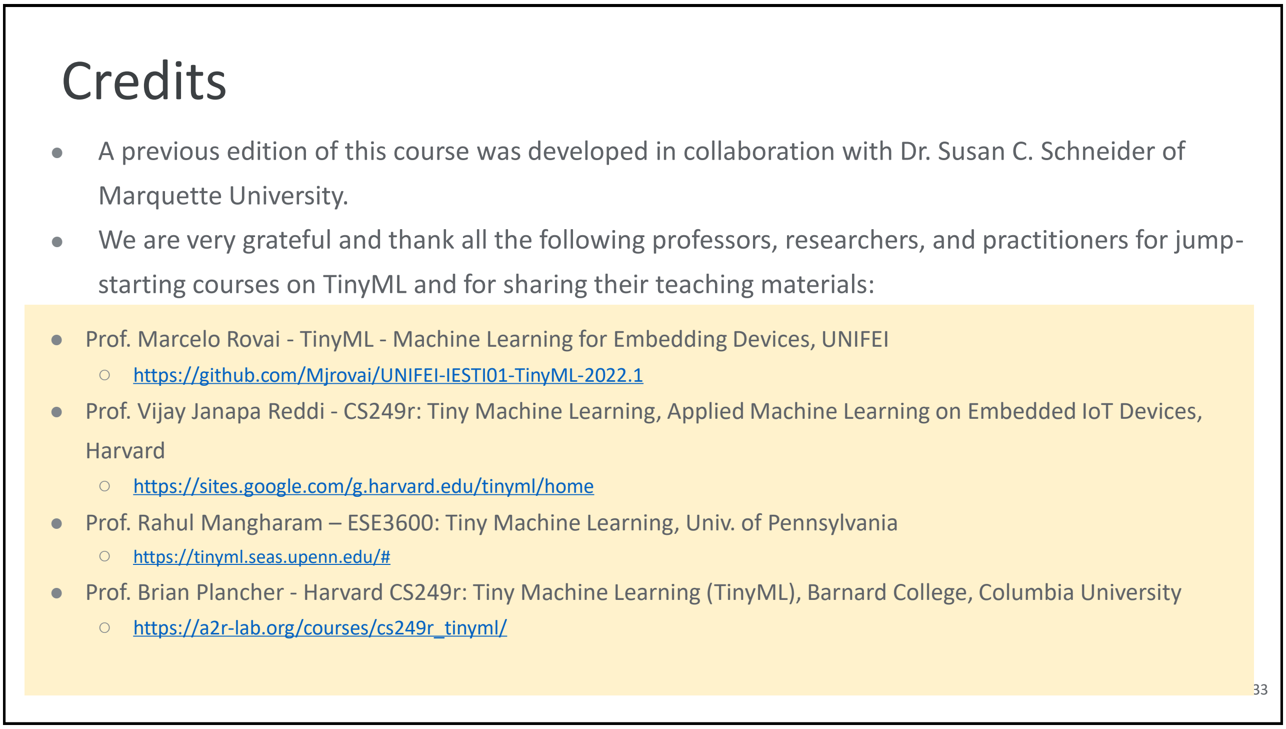


MultiTenant ML Workflow

Collect Data → Preprocess Data → Design a Model → Train a Model → Evaluate Optimize → Convert Model → Deploy Model → Make Inferences

Cascade Multi Tenant

32



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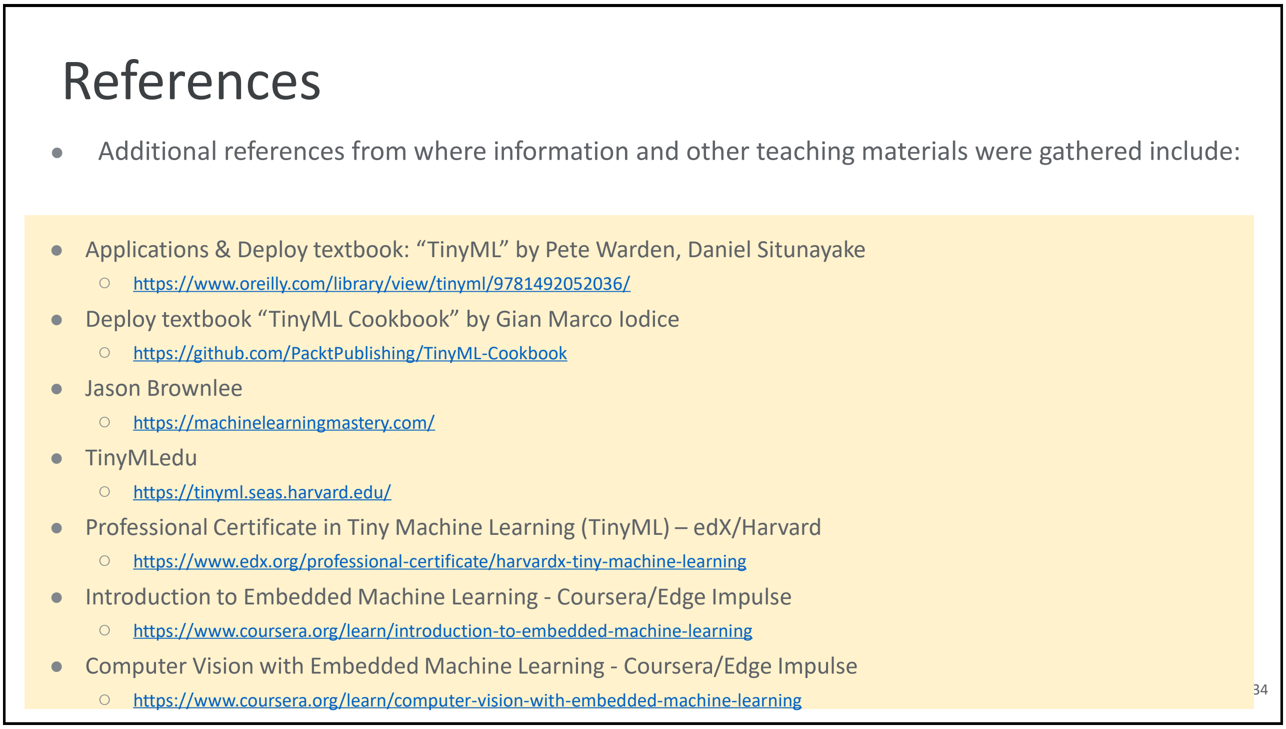
  - https://github.com/Mjrovai/UNIFEI-IESTI01-TinyML-2022.1
- Prof. Vijay Janapa Reddi - CS249r: Tiny Machine Learning, Applied Machine Learning on Embedded IoT Devices, Harvard
  - https://sites.google.com/g.harvard.edu/tinyml/home
- Prof. Rahul Mangharam – ESE3600: Tiny Machine Learning, Univ. of Pennsylvania
  - 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/



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
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  - https://www.coursera.org/learn/introduction-to-embedded-machine-learning
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