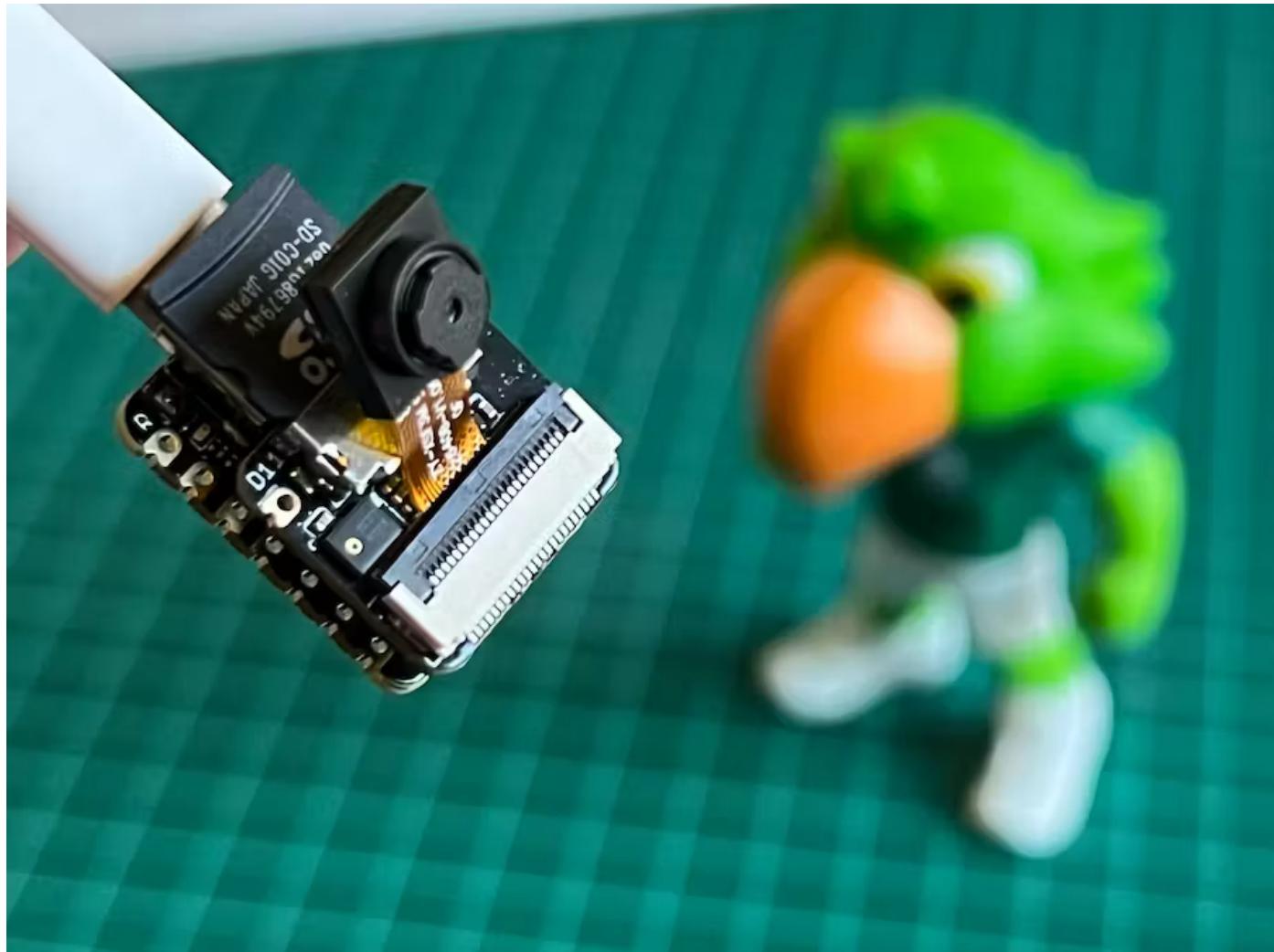


Image Classification

Explore a Computer Vision ML application on the XIAO ESP32S3 Sense: Image Classification.



MJRoBot (Marcelo Rovai)

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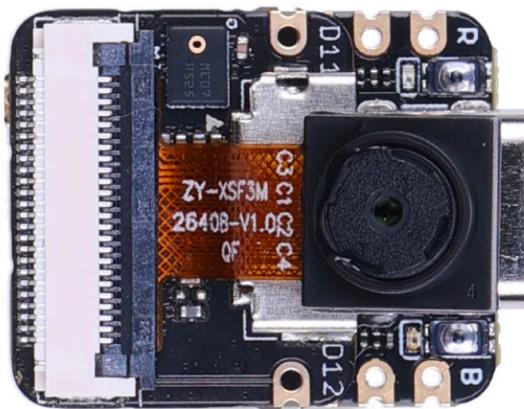
© Apache-2.0

<https://www.hackster.io/mjrobot/tinyml-made-easy-image-classification-cb42ae>

1 Things used in this project

1.1 Hardware components

[Seeed Studio Xiao ESP32S3 Sense](#) x 1



2 Software apps and online services

-  [Arduino IDE](#)
-  [Edge Impulse Studio](#)

2 Introduction

More and more, we are facing an artificial intelligence (AI) revolution where, as stated by Gartner, **Edge AI** has a very high impact potential, and **it is for now!**



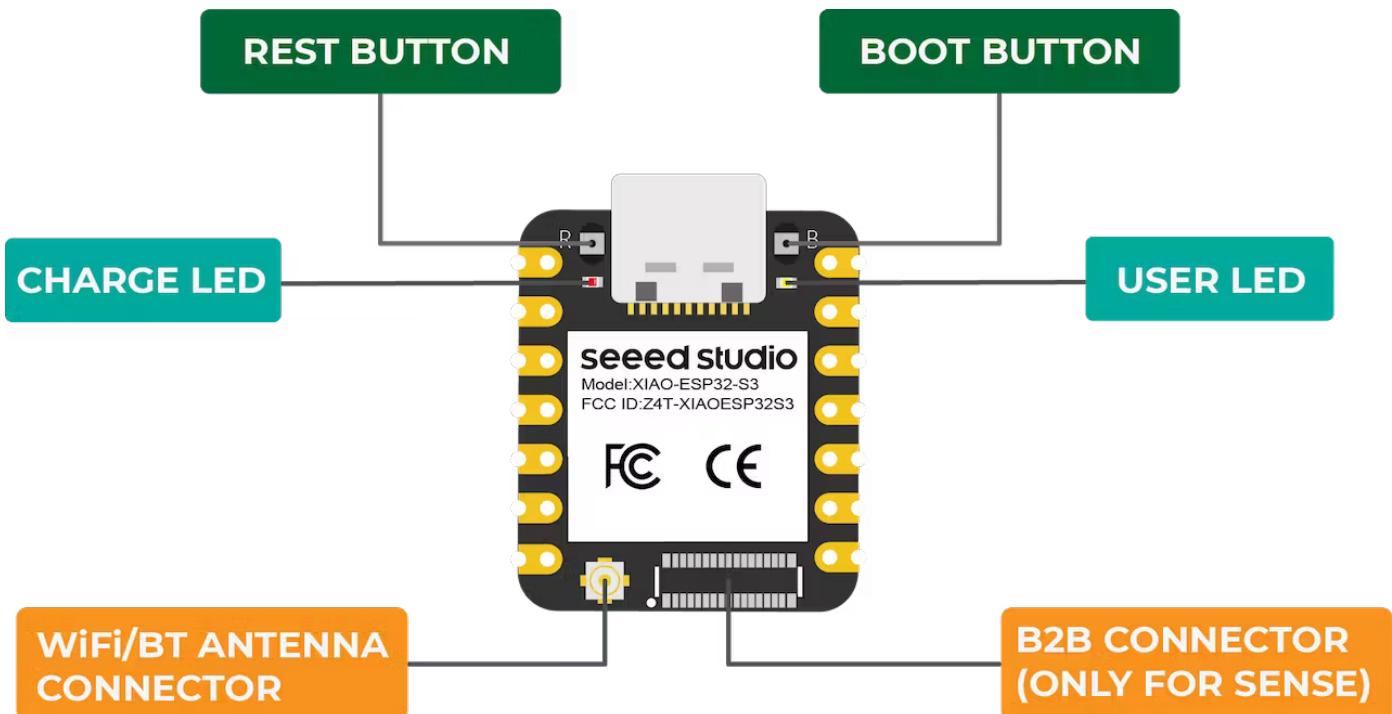
In the "bull-eye" of emerging technologies, radar is the *Edge Computer Vision*, and when we talk about Machine Learning (ML) applied to vision, the first thing that comes to mind is **Image Classification**, a kind of ML "Hello World"!

Seeed Studio released a new affordable development board, the [XIAO ESP32S3 Sense](#), which integrates a camera sensor, digital microphone, and SD card support. Combining embedded ML computing power and photography capability, this development board is a great tool to start with TinyML (intelligent voice and vision AI).

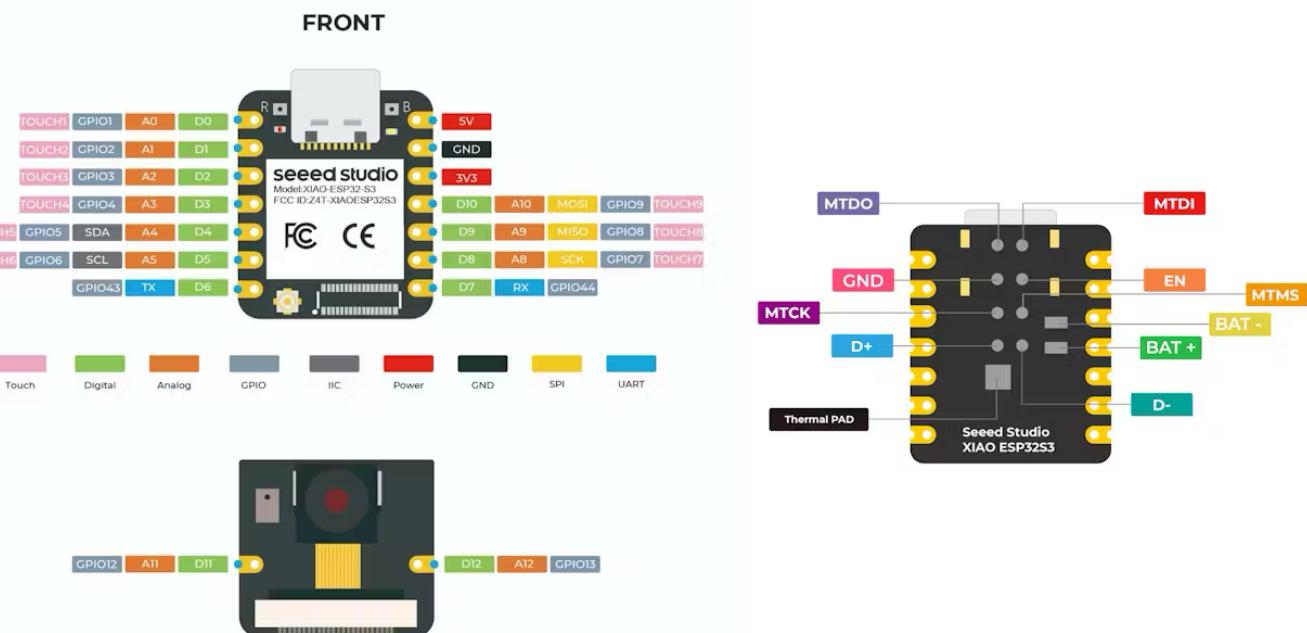


XIAO ESP32S3 Sense Main Features

- **Powerful MCU Board:** Incorporate the ESP32S3 32-bit, dual-core, Xtensa processor chip operating up to 240 MHz, mounted multiple development ports, Arduino / MicroPython supported
- **Advanced Functionality:** Detachable OV2640 camera sensor for 1600 * 1200 resolution, compatible with OV5640 camera sensor, integrating an additional digital microphone
- **Elaborate Power Design:** Lithium battery charge management capability offers four power consumption models, which allows for deep sleep mode with power consumption as low as 14µA
- **Great Memory for more Possibilities:** Offer 8MB PSRAM and 8MB FLASH, supporting SD card slot for external 32GB FAT memory
- **Outstanding RF performance:** Support 2.4GHz Wi-Fi and BLE dual wireless communication, support 100m+ remote communication when connected with U.FL antenna
- **Thumb-sized Compact Design:** 21 x 17.5mm, adopting the classic form factor of XIAO, suitable for space-limited projects like wearable devices



Below is the general board pinout:



For more details, please refer to the Seeed Studio WiKi page:

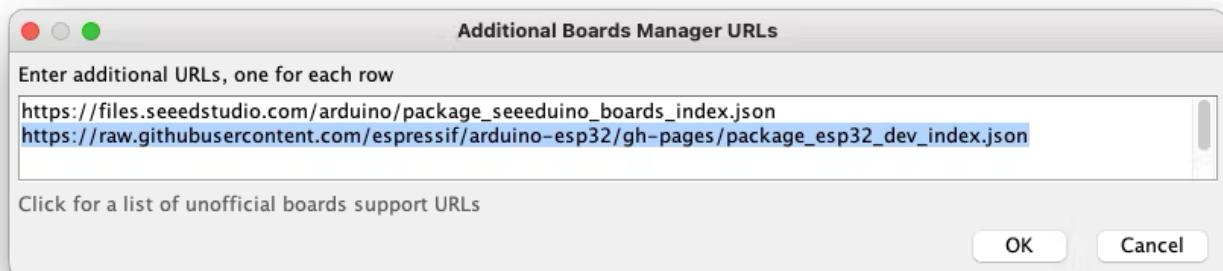
https://wiki.seeedstudio.com/xiao_esp32s3_getting_started/

3 Installing the XIAO ESP32S3 Sense on Arduino IDE

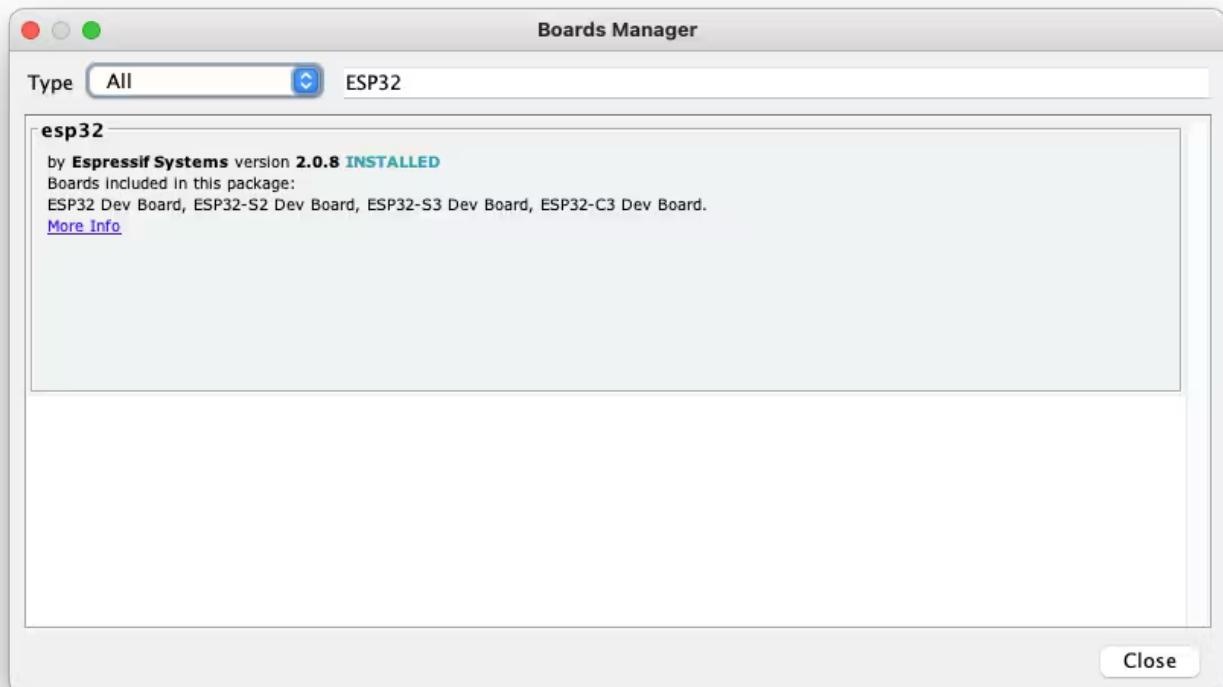
On Arduino IDE, navigate to **File > Preferences**, and fill in the URL:

https://raw.githubusercontent.com/espressif/arduino-esp32/gh-pages/package_esp32_dev_index.json

on the field ==> **Additional Boards Manager URLs**



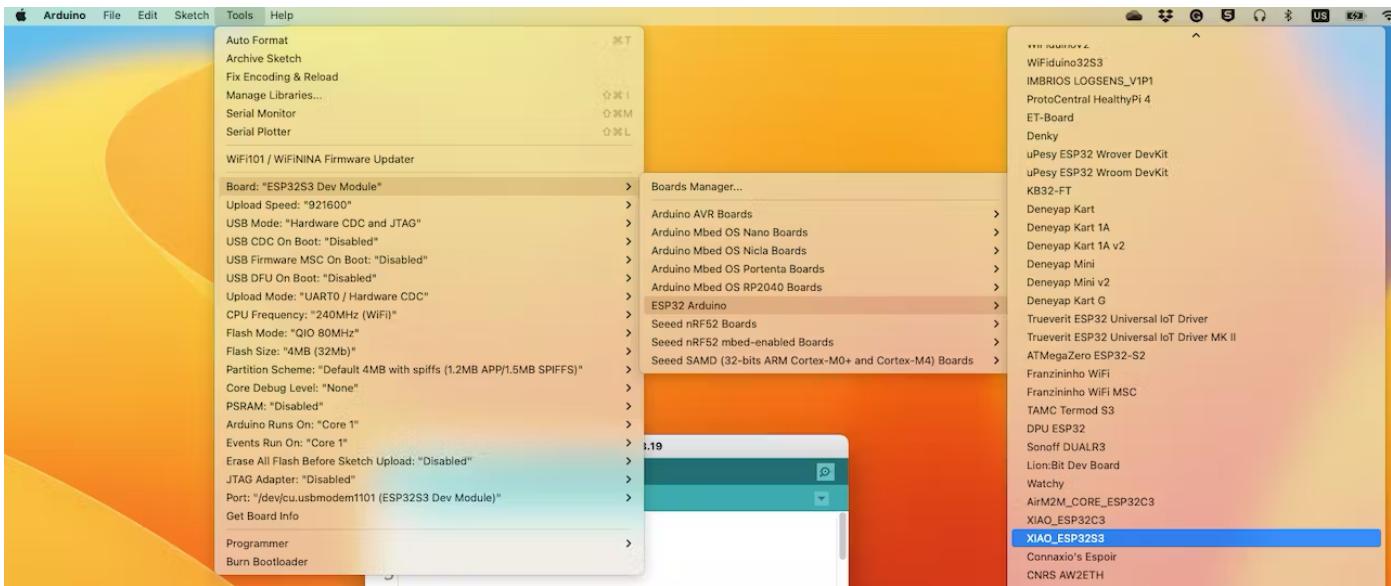
Next, open boards manager. Go to **Tools > Board > Boards Manager...** and enter with *esp32*. Select and install the most updated and stable package (avoid *alpha* versions) :



⚠ Attention

Alpha versions (for example, 3.x-alpha) do not work correctly with the XIAO and Edge Impulse. Use the last stable version (for example, 2.0.11) instead.

On **Tools**, select the Board (**XIAO ESP32S3**):



Last but not least, choose the **Port** where the ESP32S3 is connected.

That is it! The device should be OK. Let's do some tests.

4 Testing the board with BLINK

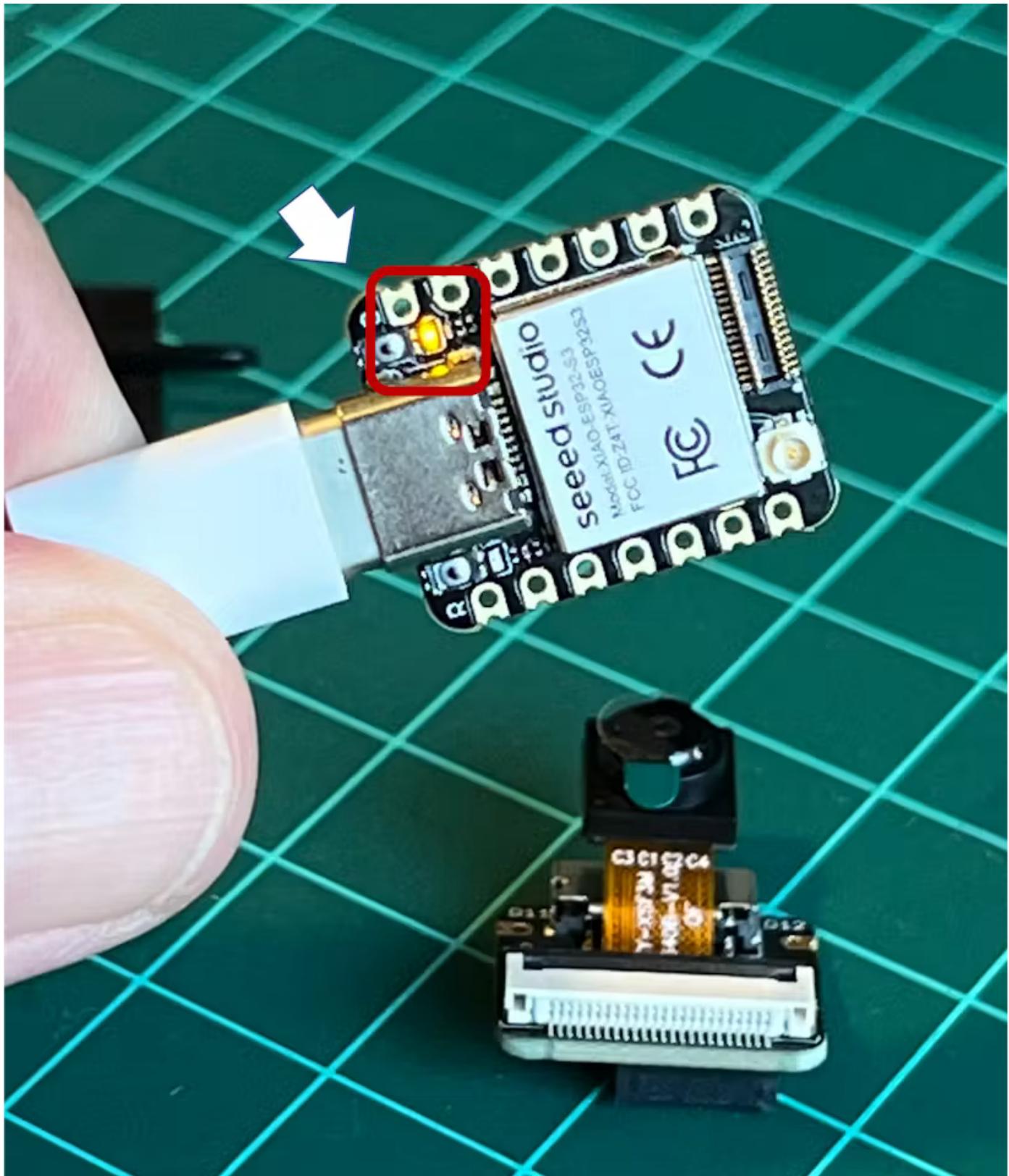
The XIAO ESP32S3 Sense has a built-in LED that is connected to GPIO21. So, you can run the blink sketch as it is (using the `LED_BUILTIN` Arduino constant) or by changing the Blink sketch accordingly:

```
#define LED_BUILTIN 21

void setup() {
    pinMode(LED_BUILTIN, OUTPUT); // Set the pin as output
}

// Remember that the pin work with inverted logic
// LOW to Turn on and HIGH to turn off
void loop() {
    digitalWrite(LED_BUILTIN, LOW); //Turn on
    delay (1000); //Wait 1 sec
    digitalWrite(LED_BUILTIN, HIGH); //Turn off
    delay (1000); //Wait 1 sec
}
```

Note that the pins work with inverted logic: LOW to Turn on and HIGH to turn off.



5 Connecting Sense module (Expansion Board)

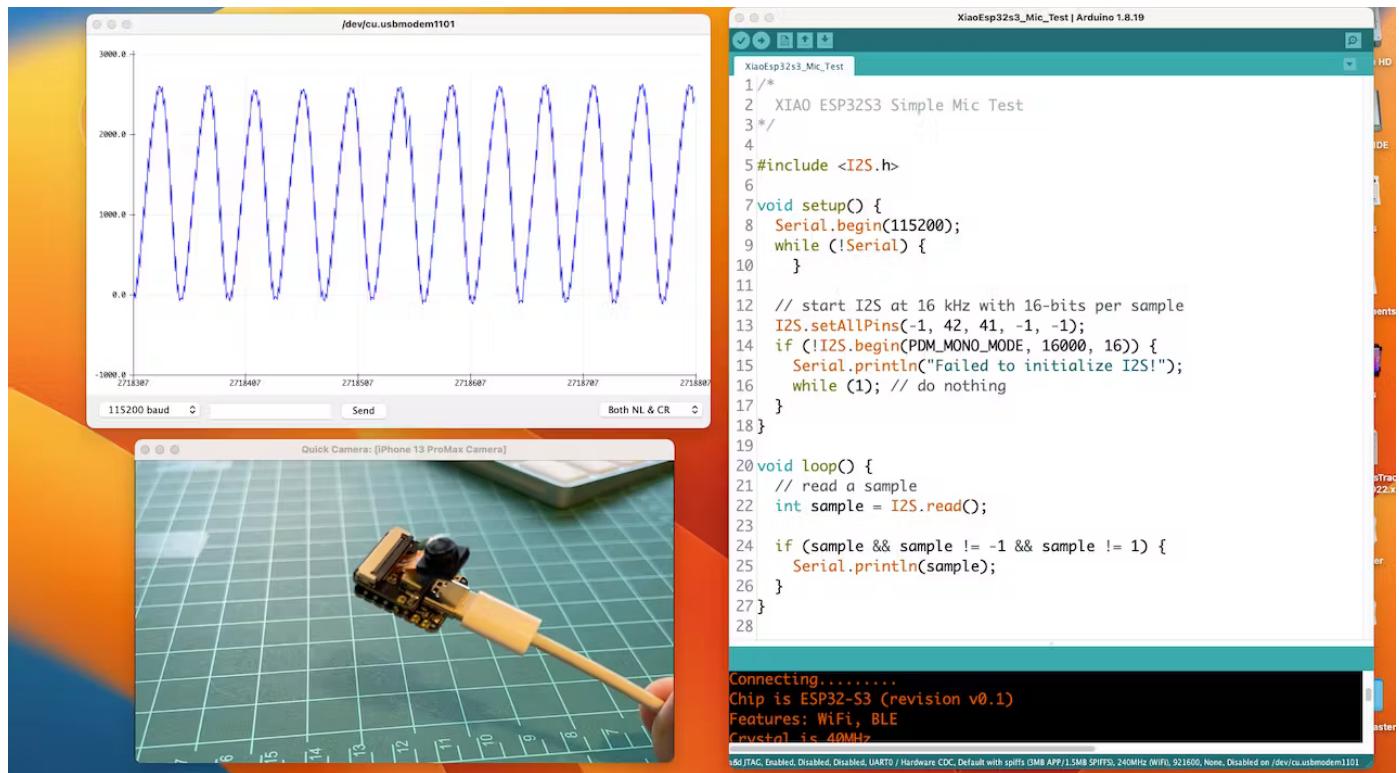
When purchased, the expansion board is separated from the main board, but installing the expansion board is very simple. You need to align the connector on the expansion board with the B2B connector on the XIAO ESP32S3, press it hard, and when you hear a "click," the installation is complete.



As commented in the introduction, the expansion board, or the "sense" part of the device, has a 1600x1200 OV2640 camera, an SD card slot, and a digital microphone.

6 Microphone Test

Let's start with sound detection. Go to the [GitHub project](#) and download the sketch: [XIAOEsp2s3_Mic_Test](#) and run it on the Arduino IDE:



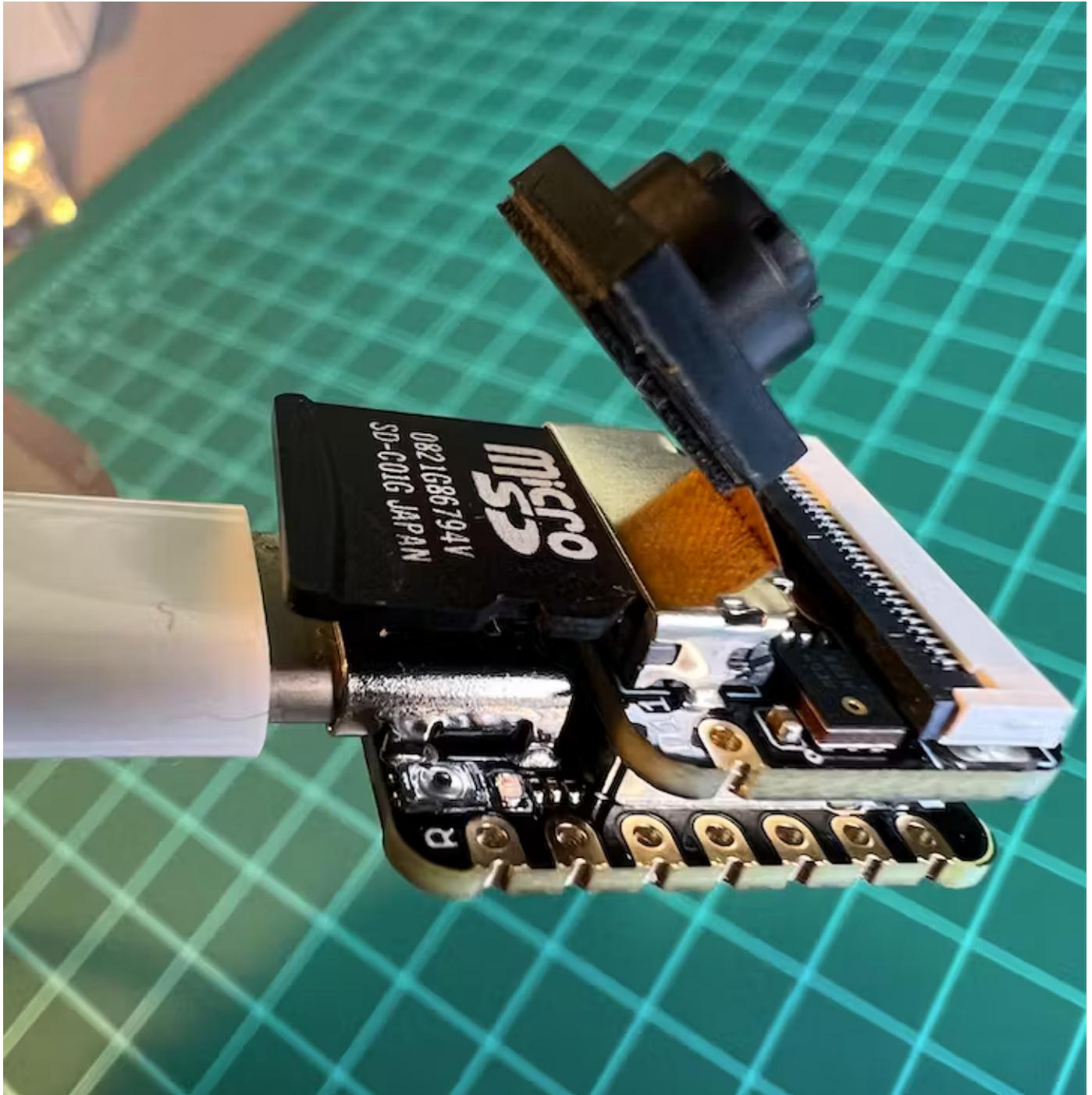
When producing sound, you can verify it on the Serial Plotter.

Save recorded sound (.wav audio files) to a microSD card.

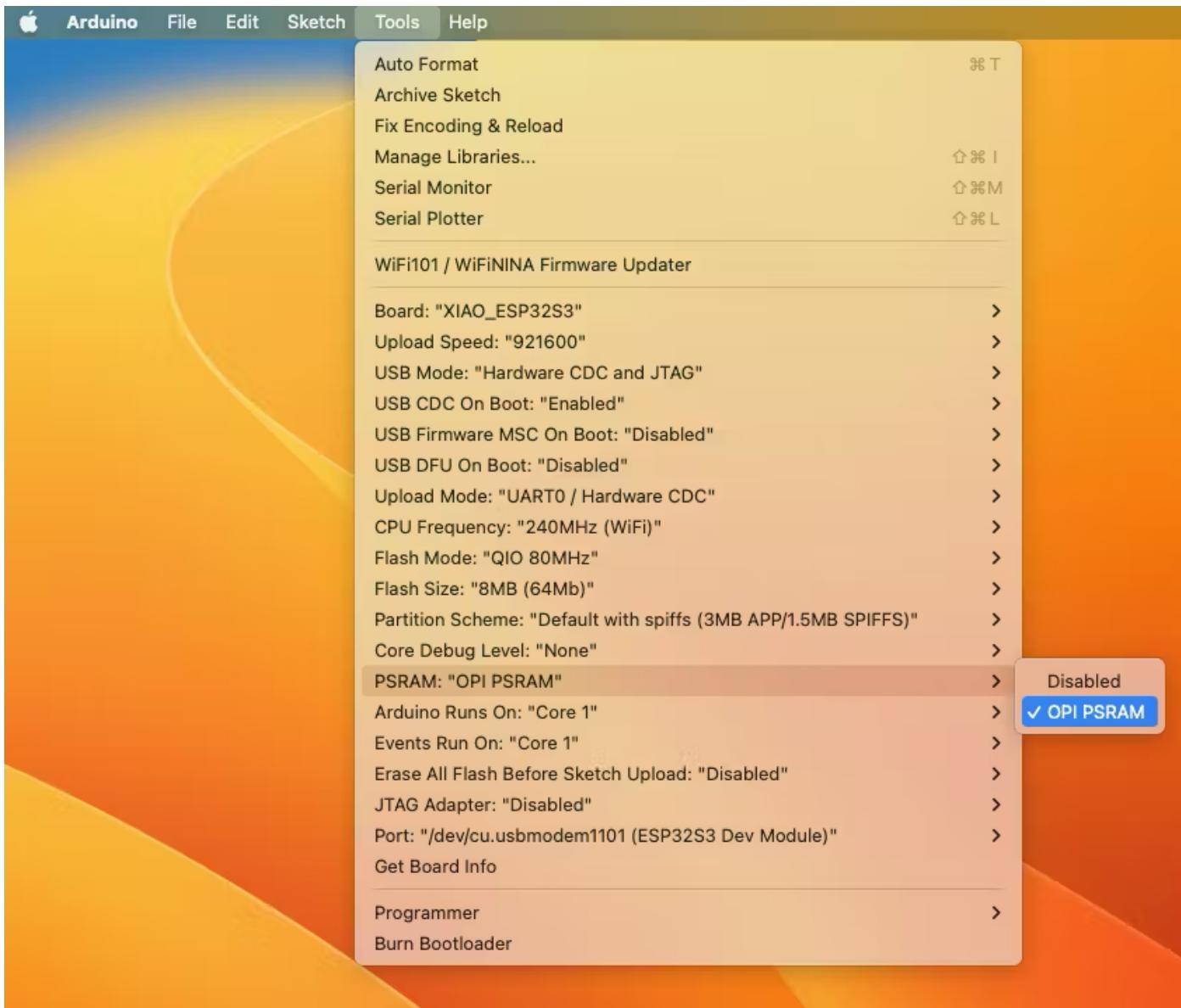
Now, the onboard SD Card reader can save .wav audio files. For that, we need to habilitate the XIAO PSRAM.

ESP32-S3 has only a few hundred kilobytes of internal RAM on the MCU chip. It can be insufficient for some purposes so that ESP32-S3 can use up to 16 MB of external PSRAM (Psuedostatic RAM) connected with the SPI flash chip. The external memory is incorporated in the memory map and, with certain restrictions, is usable in the same way as internal data RAM.

For a start, Insert the SD Card on the XIAO as shown in the photo below (the SD Card should be formatted to **FAT32**).



- Download the sketch [Wav_Record](#), which you can find on GitHub.
- To execute the code (Wav Record), it is necessary to use the PSRAM function of the ESP-32 chip, so turn it on before uploading.: Tools>PSRAM: "OPI PSRAM">OPI PSRAM



- Run the code `Wav_Record.ino`
- This program is executed only once after the user **turns on the serial monitor**, recording for 20 seconds and saving the recording file to a microSD card as "arduino_rec.wav."
- When the "." is output every 1 second in the serial monitor, the program execution is finished, and you can play the recorded sound file with the help of a card reader.

A screenshot of a Mac OS X terminal window titled "/dev/cu.usbmodem1101". The window contains the following text:

```
.....Ready to start recording ...
Buffer: 667064 bytes
Record 640000 bytes
Writing to the file ...
The recording is over.
.....
```

At the bottom of the window, there are several configuration options:

- Autoscroll Show timestamp
- Both NL & CR ↴ ↵
- 115200 baud ↴ ↵
- Clear output

The sound quality is excellent!

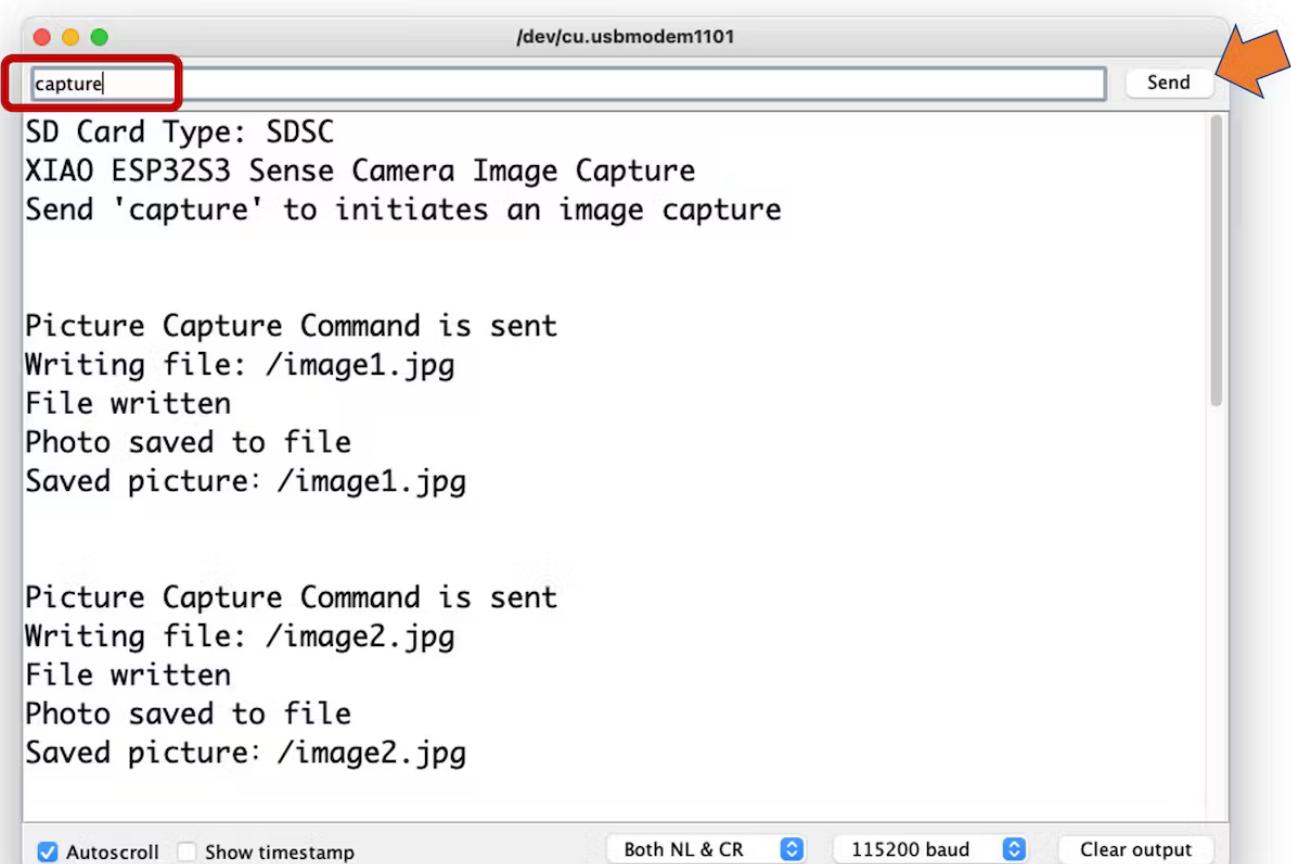
The explanation of how the code works is beyond the scope of this tutorial, but you can find an excellent description on the [wiki](#) page.

7 Testing the Camera

To test the camera, you should download the folder [take_photos_command](#) from GitHub. The folder contains the sketch (.ino) and two .h files with camera details.

- Run the code: `take_photos_command.ino`. Open the Serial Monitor and send the command `capture` to capture and save the image on the SD Card:

Verify that `[Both NL & CR]` is selected on Serial Monitor.



The screenshot shows the Arduino Serial Monitor window. The title bar reads `/dev/cu.usbmodem1101`. In the top-left text input field, the word `capture` is typed and highlighted with a red rectangle. In the top-right corner, there is a `Send` button with an orange arrow pointing towards it. The main text area displays two sets of output logs for image captures:

```
SD Card Type: SDSC
XIAO ESP32S3 Sense Camera Image Capture
Send 'capture' to initiates an image capture

Picture Capture Command is sent
Writing file: /image1.jpg
File written
Photo saved to file
Saved picture: /image1.jpg

Picture Capture Command is sent
Writing file: /image2.jpg
File written
Photo saved to file
Saved picture: /image2.jpg
```

At the bottom of the window, there are several configuration buttons: `Autoscroll` (checked), `Show timestamp` (unchecked), `Both NL & CR` (selected), `115200 baud` (selected), and `Clear output`.

Here is an example of a taken photo:

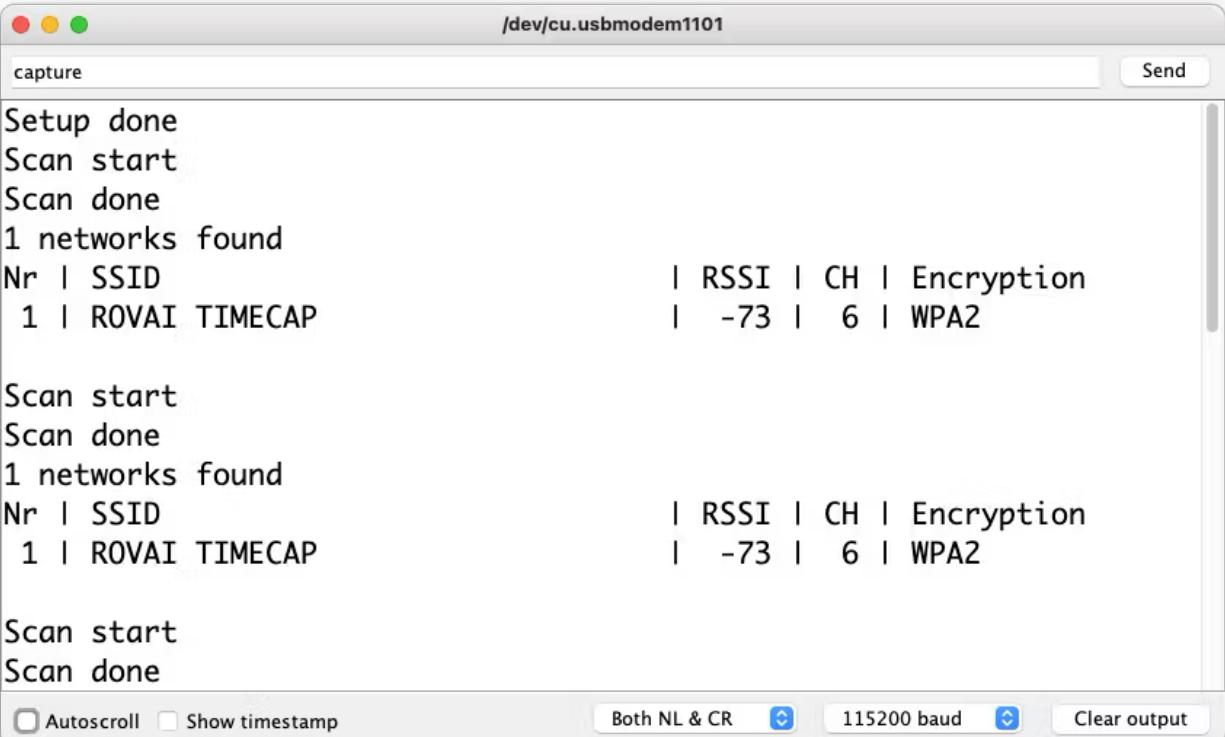


8 Testing WiFi

One of the differentiators of the XIAO ESP32S3 is its WiFi capability. So, let's test its radio, scanning the wifi networks around it. You can do it by running one of the code examples on the board.

Go to Arduino IDE Examples and look for **WiFi ==> WiFiScan**

On the Serial monitor, you should see the wifi networks (SSIDs and RSSIs) in the range of your device. Here is what I got in the lab:



The screenshot shows the Arduino Serial Monitor window titled "capture" connected to "/dev/cu.usbmodem1101". The window displays the output of a WiFi scan. The text in the window is as follows:

```
Setup done
Scan start
Scan done
1 networks found
Nr | SSID | RSSI | CH | Encryption
1 | ROVAI TIMECAP | -73 | 6 | WPA2

Scan start
Scan done
1 networks found
Nr | SSID | RSSI | CH | Encryption
1 | ROVAI TIMECAP | -73 | 6 | WPA2

Scan start
Scan done
```

At the bottom of the window, there are several configuration options: "Autoscroll" (unchecked), "Show timestamp" (unchecked), "Both NL & CR" (selected), "115200 baud" (selected), and "Clear output".

Simple WiFi Server (Turning LED ON/OFF)

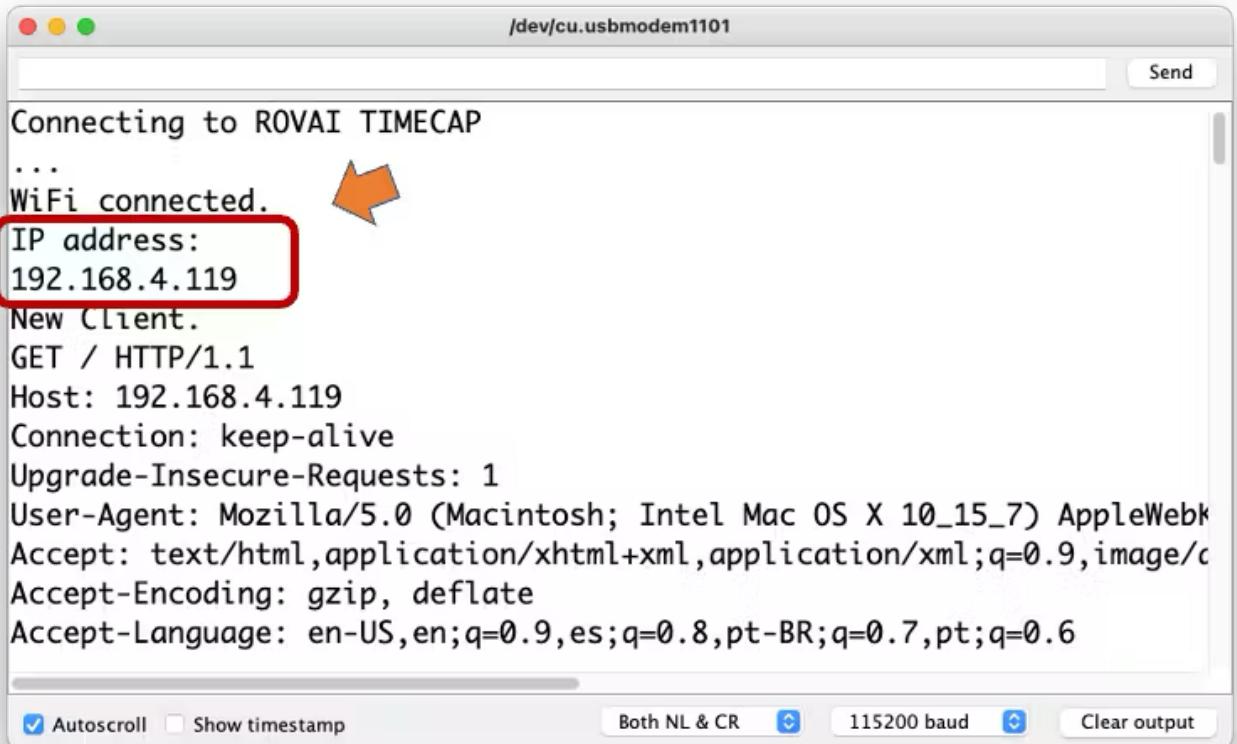
Let's test the device's capability to behave as a WiFi Server. We will host a simple page on the device that sends commands to turn the XIAO built-in LED ON and OFF.

Like before, go to GitHub to download the folder with the sketch [SimpleWiFiServer](#).

Before running the sketch, you should enter your network credentials:

```
const char* ssid      = "Your credentials here";
const char* password = "Your credentials here";
```

You can monitor how your server is working with the Serial Monitor.



```
Connecting to ROVAI TIMECAP
...
WiFi connected.
IP address:
192.168.4.119
New Client.
GET / HTTP/1.1
Host: 192.168.4.119
Connection: keep-alive
Upgrade-Insecure-Requests: 1
User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/605.1.15 (KHTML, like Gecko) Version/12.0.3 Safari/605.1.15
Accept: text/html,application/xhtml+xml,application/xml;q=0.9,image/c
Accept-Encoding: gzip, deflate
Accept-Language: en-US,en;q=0.9,es;q=0.8,pt-BR;q=0.7,pt;q=0.6
```

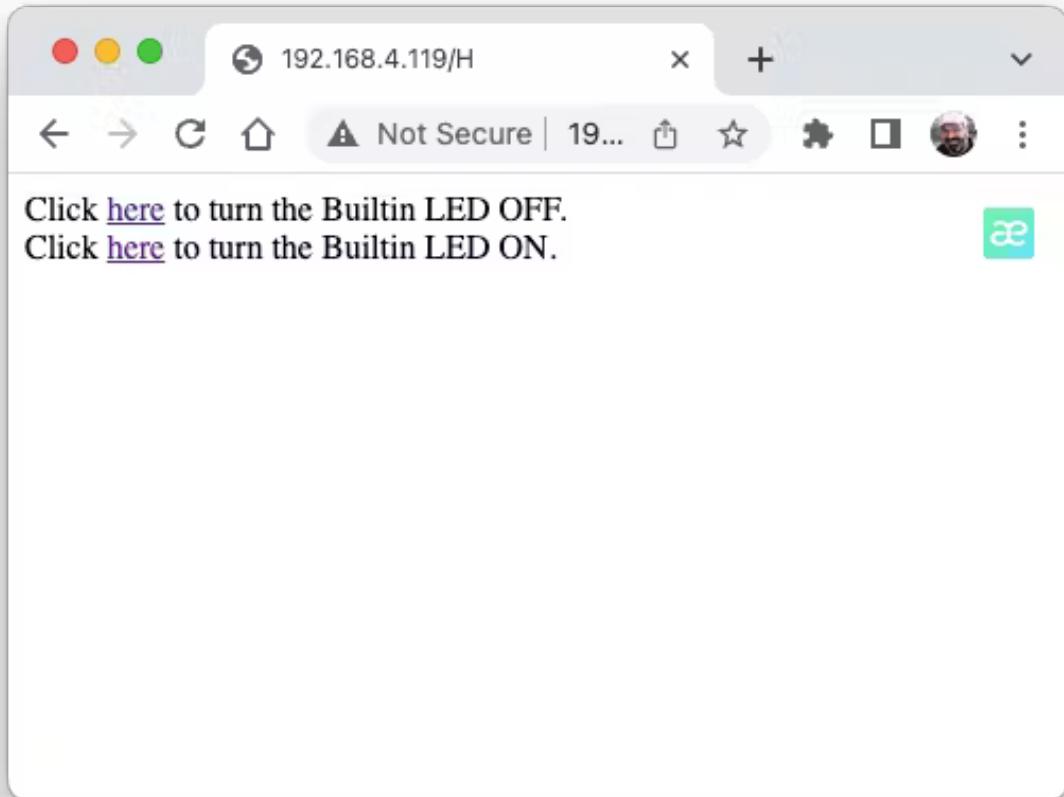
Autoscroll Show timestamp

Both NL & CR

115200 baud

Clear output

Take the IP address and enter it on your browser:



You will see a page with links that can turn the built-in LED of your XIAO ON and OFF.

Streaming video to Web

Now that you know that you can send commands from the webpage to your device, let's do the reverse. Let's take the image captured by the camera and stream it to a webpage:

Download from GitHub the [folder](#) that contains the code: XIAO-ESP32S3-Streaming_Video.ino.

Remember that the folder contains the.ino file and a couple of .h files necessary to handle the camera.

Enter your credentials and run the sketch. On the Serial monitor, you can find the page address to enter in your browser:

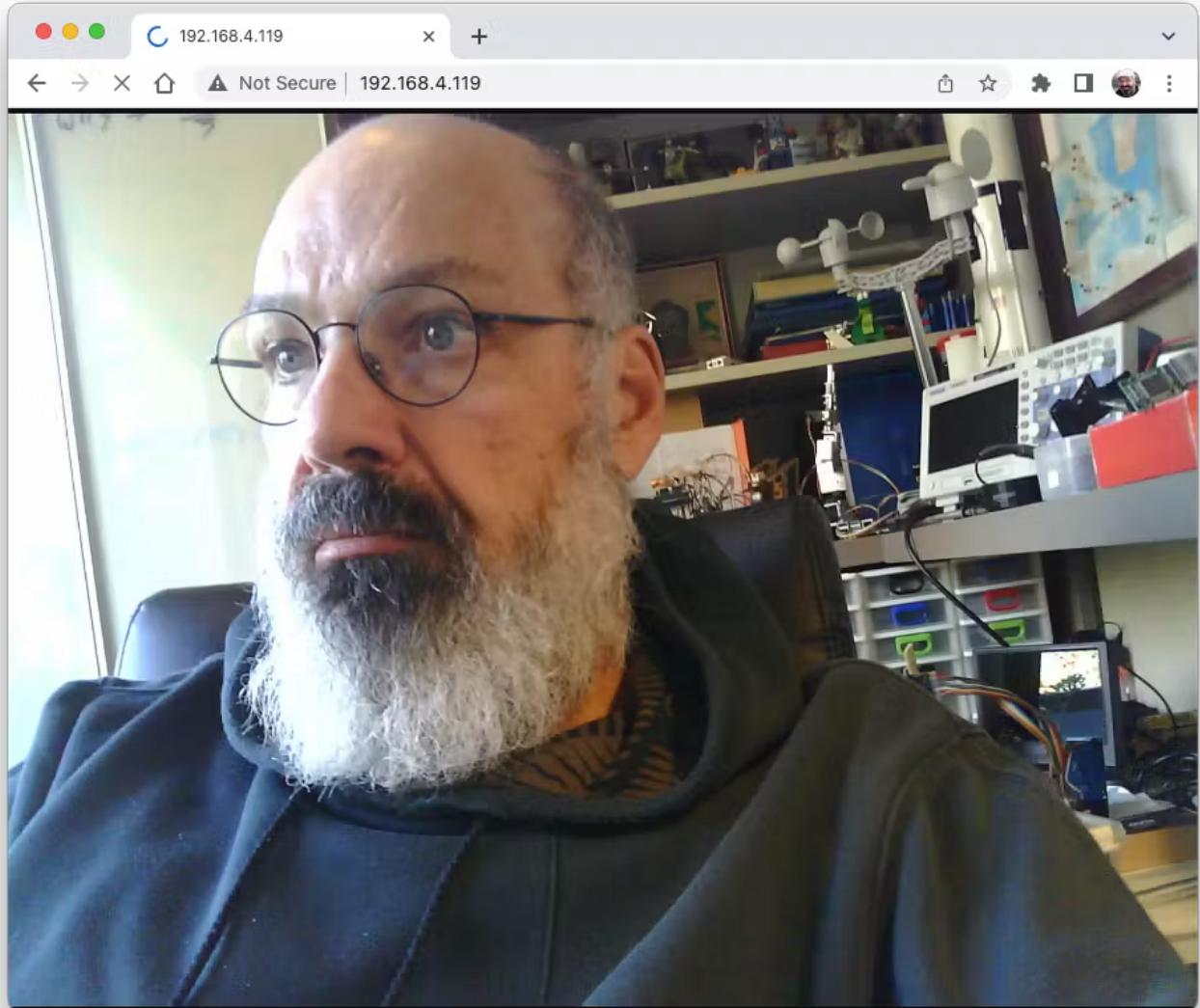


A screenshot of a Mac OS X terminal window titled "/dev/cu.usbmodem1101". The window contains the following text:

```
...
WiFi connected
Camera Stream Ready! Go to: http://192.168.4.119
```

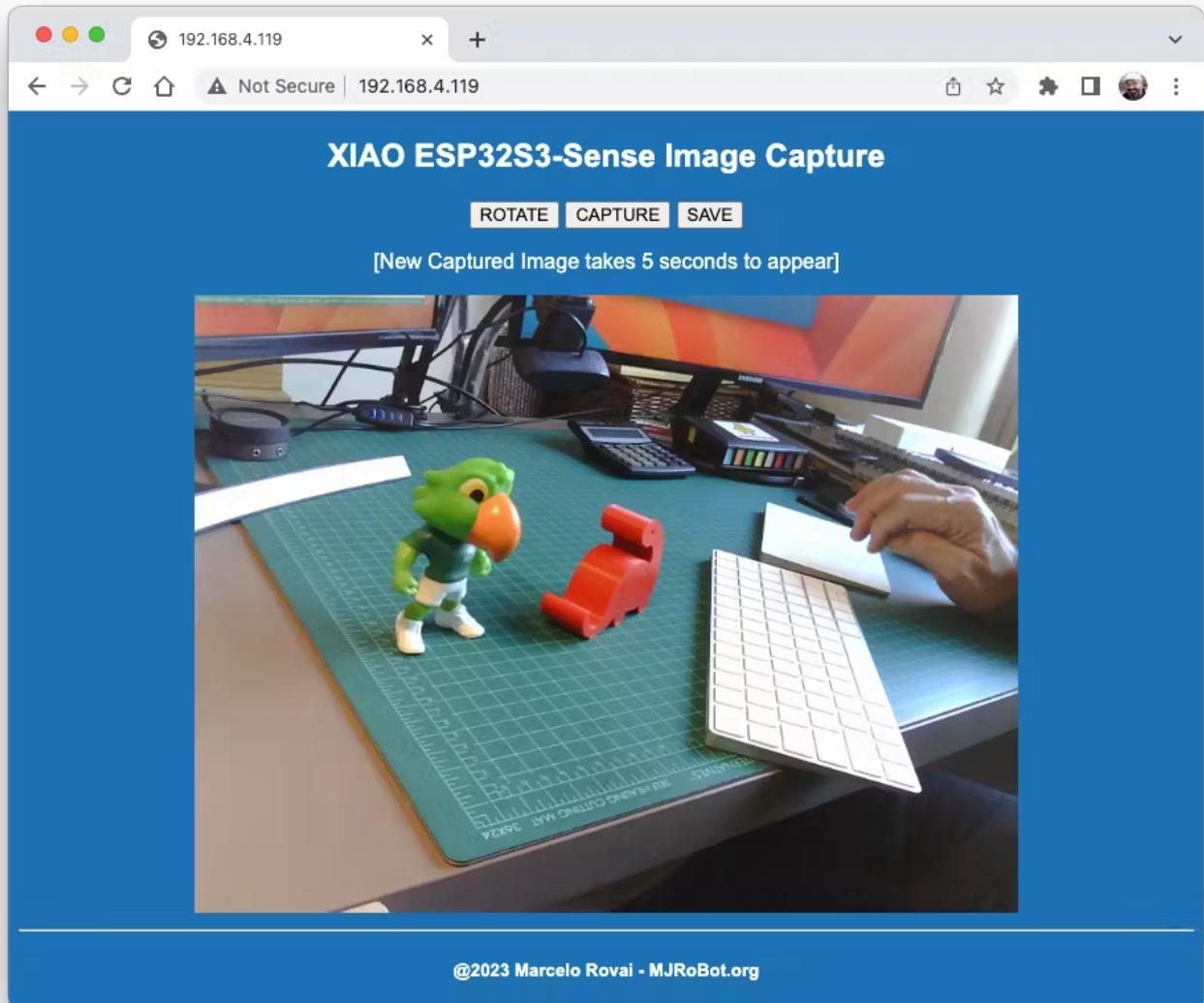
The terminal has a standard OS X look with red, yellow, and green close buttons at the top left. A "Send" button is located in the top right corner. At the bottom, there are several configuration options: "Autoscroll" (checked), "Show timestamp" (unchecked), "Both NL & CR" (selected), "115200 baud" (selected), and a "Clear output" button.

Open the page on your browser (wait a few seconds to start the streaming). That's it.



Streamlining what your camera is "seen" can be important when you position it to capture a dataset for an ML project (for example, using the code "take_photos_commands.ino").

Of course, we can do both things simultaneously: show what the camera sees on the page and send a command to capture and save the image on the SD card. For that, you can use the code Camera_HTTP_Server_STA, which can be downloaded from GitHub.



The program will do the following tasks:

- Set the camera to JPEG output mode.
- Create a web page (for example ==> <http://192.168.4.119/>). The correct address will be displayed on the Serial Monitor.
- If server.on ("/capture", HTTP_GET, serverCapture), the program takes a photo and sends it to the Web.
- It is possible to rotate the image on webPage using the button [ROTATE]
- The command [CAPTURE] only will preview the image on the webpage, showing its size on the Serial Monitor
- The [SAVE] command will save an image on the SD Card and show the image on the browser.
- Saved images will follow a sequential naming (image1.jpg, image2.jpg).

```
...
WiFi connected..!
Got IP: 192.168.4.119
HTTP server started
Capturing Image for view only
The picture has a size of 143360 bytes
Saving Image to SD Card
Photo saved to file
Saved picture: /image1.jpg

Saving Image to SD Card
Photo saved to file
Saved picture: /image2.jpg
```

Autoscroll Show timestamp Both NL & CR 115200 baud Clear output

This program can be used for an image dataset capture with an Image Classification project.

Inspect the code; it will be easier to understand how the camera works. This code was developed based on the great Rui Santos Tutorial [ESP32-CAM Take Photo and Display in Web Server](#), which I invite all of you to visit.

Using the CameraWebServer

In the Arduino IDE, go to `File > Examples > ESP32 > Camera`, and select `CameraWebServer`

You also should comment on all cameras' models, except the XIAO model pins:

```
#define CAMERA_MODEL_XIAO_ESP32S3 // Has PSRAM
```

And do not forget the `Tools` to enable the PSRAM.

Enter your wifi credentials and upload the code to the device:

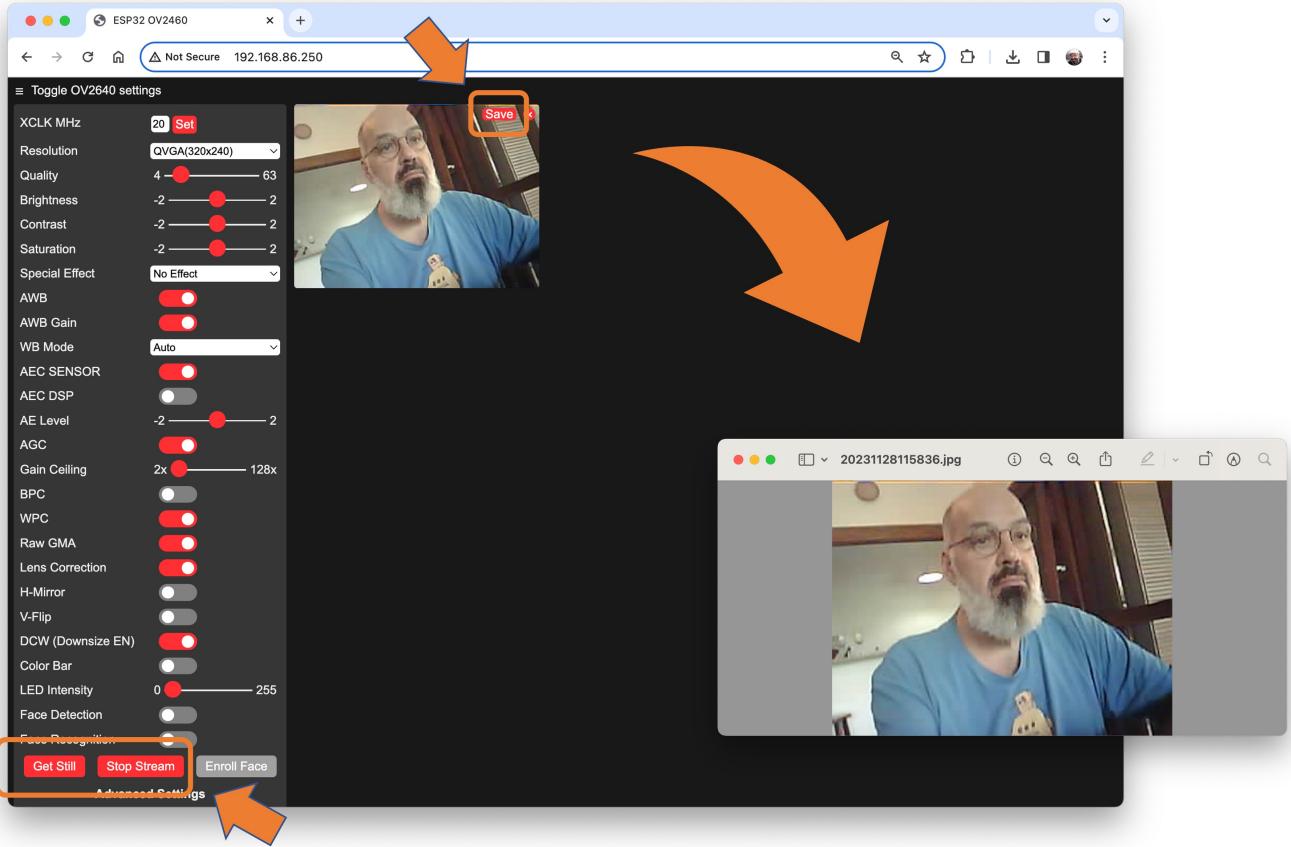
```
CameraWebServer | Arduino 1.8.19
CameraWebServer $ app_httpd.cpp camera_index.h camera_pins.h
12
13 // =====
14 // Select camera model
15 // =====
16 //#define CAMERA_MODEL_WROVER_KIT // Has PSRAM
17 //#define CAMERA_MODEL_ESP_EYE // Has PSRAM
18 //#define CAMERA_MODEL_ESP32S3_EYE // Has PSRAM
19 //#define CAMERA_MODEL_M5STACK_PSRAM // Has PSRAM
20 //#define CAMERA_MODEL_M5STACK_V2_PSRAM // M5Camera version B Has PSRAM
21 //#define CAMERA_MODEL_M5STACK_WIDE // Has PSRAM
22 //#define CAMERA_MODEL_M5STACK_ESP32CAM // No PSRAM
23 //#define CAMERA_MODEL_M5STACK_UNITCAM // No PSRAM
24 //#define CAMERA_MODEL_AI_THINKER // Has PSRAM
25 //#define CAMERA_MODEL_TTC0_T_JOURNAL // No PSRAM
26 #define CAMERA_MODEL_XIAO_ESP32S3 // Has PSRAM
27 // `` Espressif internal boards ''
28 //#define CAMERA_MODEL_ESP32_CAM_BOARD
29 //#define CAMERA_MODEL_ESP32S2_CAM_BOARD
30 //#define CAMERA_MODEL_ESP32S3_CAM_LCD
31 //#define CAMERA_MODEL_DFRobot_FireBeetle2_ESP32S3 // Has PSRAM
32 //#define CAMERA_MODEL_DFRobot_Romeo_ESP32S3 // Has PSRAM
33 #include "camera_pins.h"
34
35 // =====
36 // Enter your WiFi credentials
37 // =====
38 const char* ssid = "*****";
39 const char* password = "*****";
```

CDC and JTAG, Enabled, Disabled, UART0 / Hardware CDC, Default with spiffs (3MB APP/1.5MB SPIFFS), 240MHz (WiFi), 921600, None, Disabled on /dev/cu.usbmodem101

If the code is executed correctly, you should see the address on the Serial Monitor:

```
WiFi connected
[ 1946][I][app_httpd.cpp:1361] startCameraServer(): Starting web server on port: '80'
[ 1948][I][app_httpd.cpp:13791 startCameraServer(): Starting stream server on port: '81'
Camera Ready! Use 'http://192.168.86.250' to connect
```

Copy the address on your browser and wait for the page to be uploaded. Select the camera resolution (for example, QVGA) and select [START STREAM]. Wait for a few seconds/minutes, depending on your connection. You can save an image on your computer download area using the [Save] button.



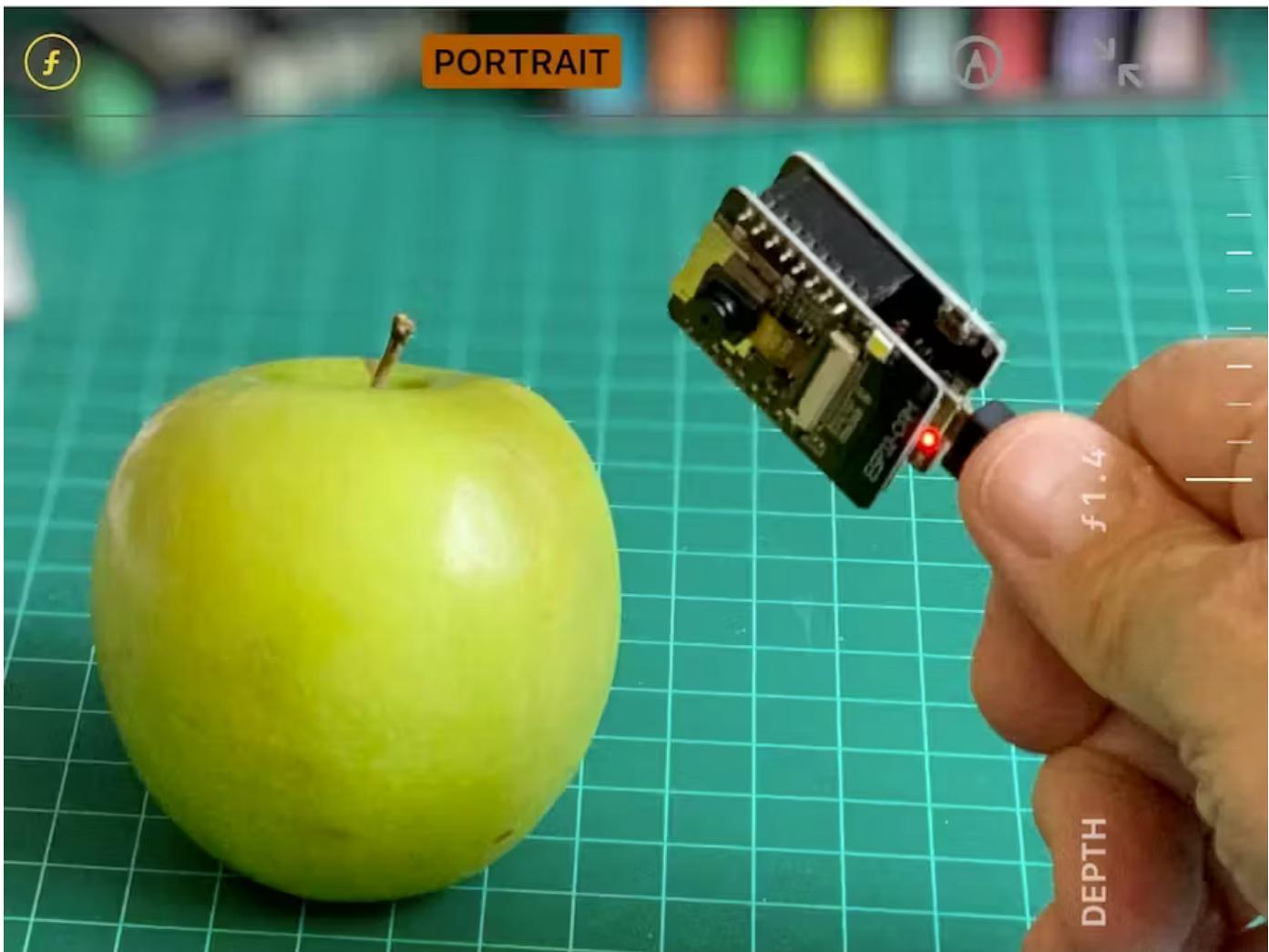
That's it! You can save the images directly on your computer to be used on projects.

9 Fruits versus Veggies - A TinyML Image Classification Project



Now that we have an embedded camera running, it is time to try image classification. For comparative motive, we will replicate the same image classification project developed to be used with an old ESP2-CAM:

[ESP32-CAM: TinyML Image Classification - Fruits vs Veggies](#)



The whole idea of our project will be to train a model and proceed with inference on the XIAO ESP32S3 Sense. For training, we should find some data (**in fact, tons of data!**).

But first of all, we need a goal! What do we want to classify?

With TinyML, a set of techniques associated with machine learning inference on embedded devices, we should limit the classification to three or four categories due to limitations (mainly memory). We will differentiate **apples** from **bananas** and **potatoes** (you can try other categories).

So, let's find a specific dataset that includes images from those categories. Kaggle is a good start:

<https://www.kaggle.com/kritikseth/fruit-and-vegetable-image-recognition>

This dataset contains images of the following food items:

- **Fruits** - banana, apple, pear, grapes, orange, kiwi, watermelon, pomegranate, pineapple, mango.
- **Vegetables** - cucumber, carrot, capsicum, onion, potato, lemon, tomato, radish, beetroot, cabbage, lettuce, spinach, soybean, cauliflower, bell pepper, chili pepper, turnip, corn, sweetcorn, sweet potato, paprika, jalepeño, ginger, garlic, peas, eggplant.

Each category is split into the **train** (100 images), **test** (10 images), and **validation** (10 images).

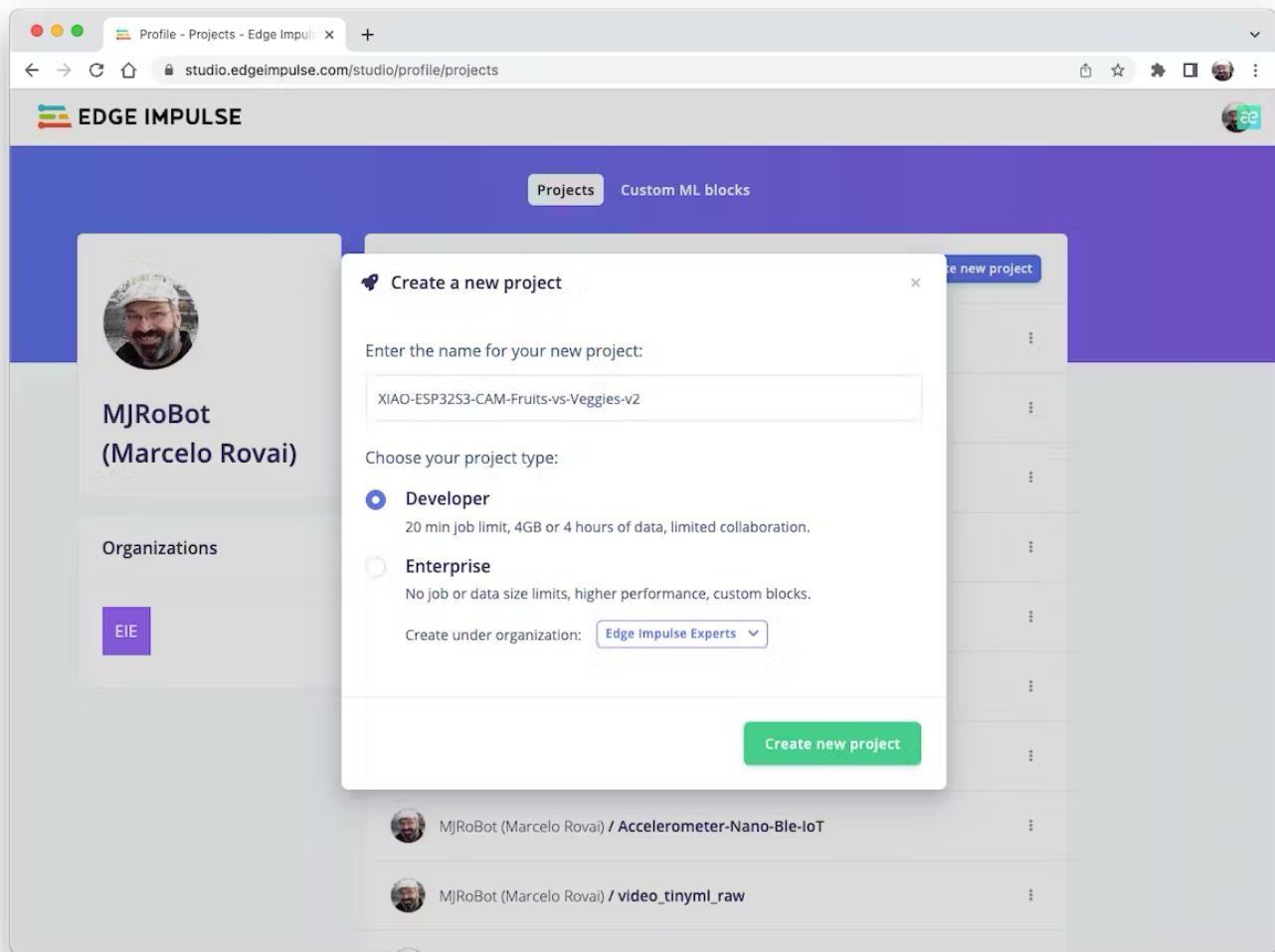
- Download the dataset from the Kaggle website to your computer.

Optional, you can add some fresh photos of bananas, apples, and potatoes from your home kitchen, using, for example, the codes discussed in the last section.

10 Training the model with Edge Impulse Studio

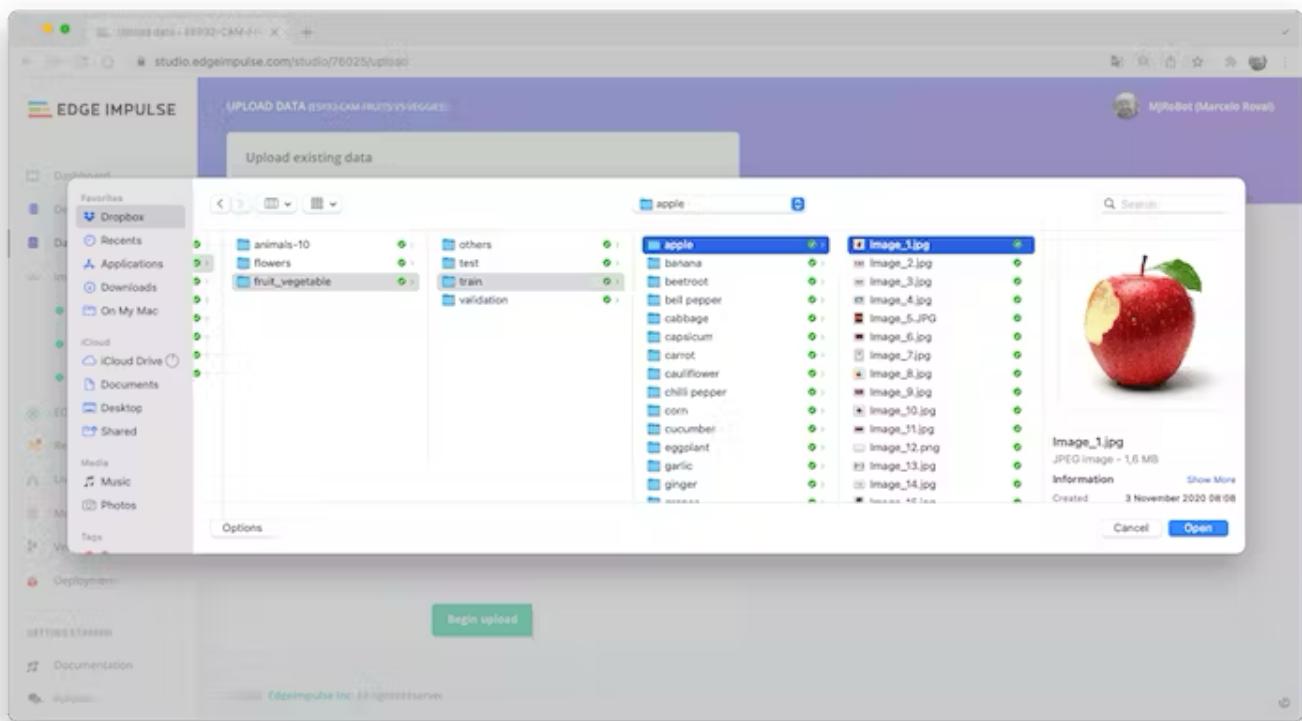
We will use the Edge Impulse Studio to train our model. As you know, [Edge Impulse](#) is a leading development platform for machine learning on edge devices.

Enter your account credentials (or create a free account) at Edge Impulse. Next, create a new project:



Data Acquisition

Next, on the UPLOAD DATA section, upload from your computer the files from chosen categories:



It would be best if you now had your training dataset split into three classes of data:

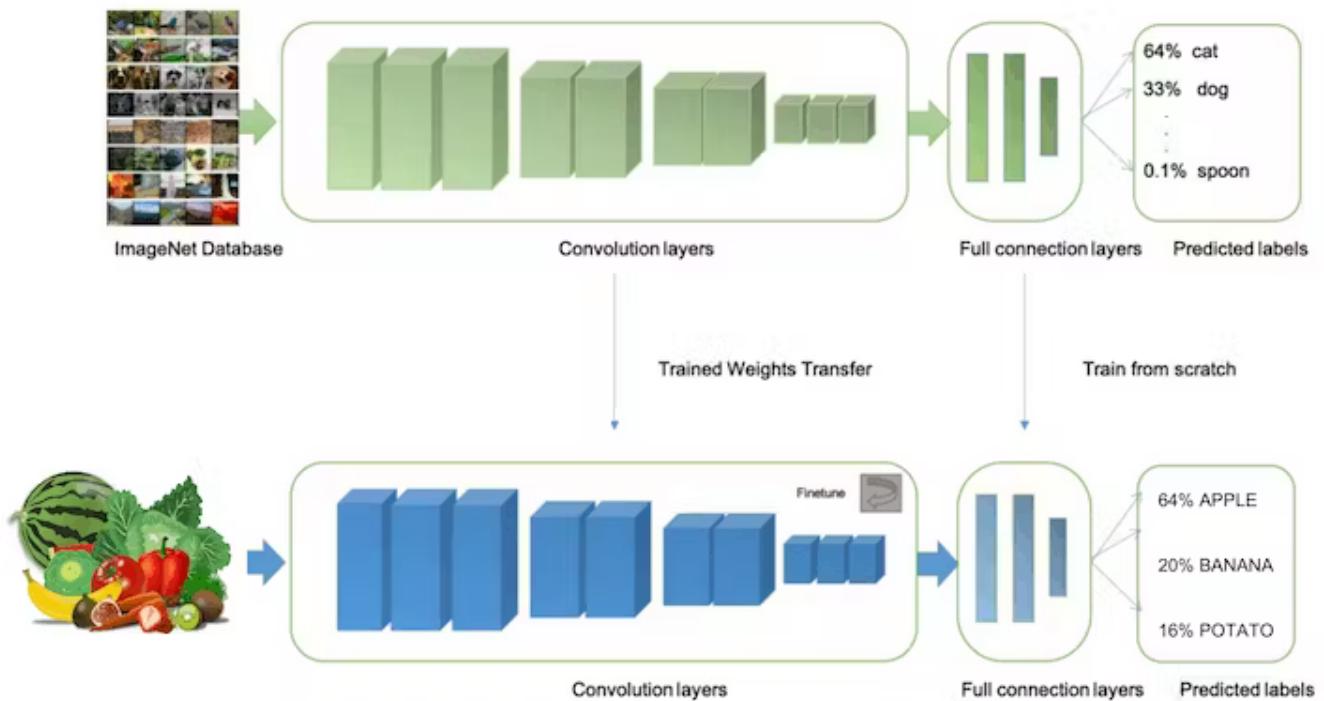
| SAMPLE NAME | LABEL | ADDED | LENGTH |
|------------------------|--------|-----------------------|--------|
| Image_89.jpg.2p4ed0vt | banana | jan 12 2022, 15:45... | |
| Image_91.jpg.2p4ed1po | banana | jan 12 2022, 15:45... | |
| Image_88.png.2p4ecv5e | banana | jan 12 2022, 15:45... | |
| Image_92.jpg.2p4ecus5 | banana | jan 12 2022, 15:45... | |
| Image_100.jpg.2p4ectpi | banana | jan 12 2022, 15:45... | |
| Image_90.jpg.2p4ecinc | banana | jan 12 2022, 15:45... | |
| Image_98.jpg.2p4ecrad6 | banana | jan 12 2022, 15:45... | |
| Image_83.png.2p4ecr56 | banana | jan 12 2022, 15:45... | |
| Image_84.jpg.2p4ecr6e | banana | jan 12 2022, 15:45... | |
| Image_79.jpg.2p4eccq9q | banana | jan 12 2022, 15:45... | |
| Image_86.jpg.2p4ecqsh | banana | jan 12 2022, 15:45... | |
| Image_85.jpg.2p4ecqcsc | banana | jan 12 2022, 15:45... | |

You can upload extra data for further model testing or split the training data. I will leave it as it is to use the most data possible.

Impulse Design

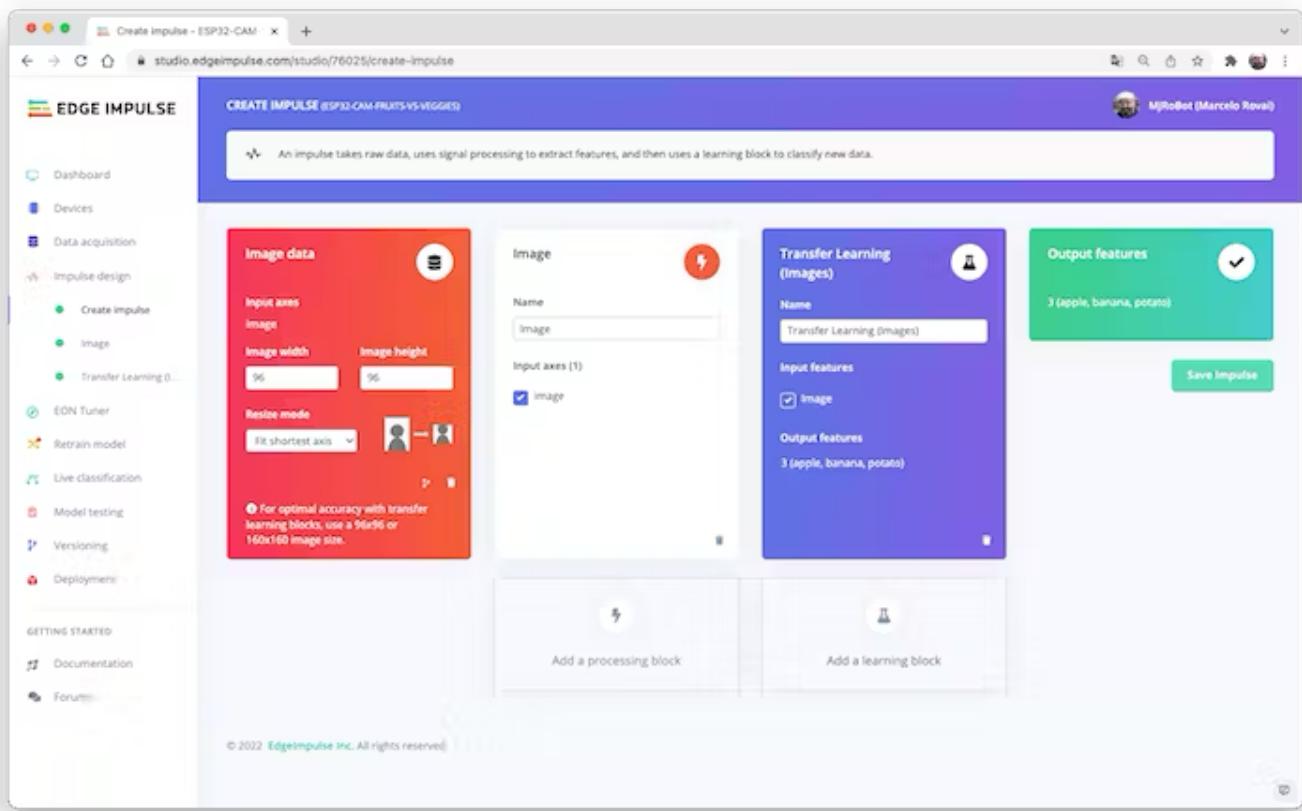
An impulse takes raw data (in this case, images), extracts features (resize pictures), and then uses a learning block to classify new data.

Classifying images is the most common use of deep learning, but much data should be used to accomplish this task. We have around 90 images for each category. Is this number enough? Not at all! We will need thousands of images to "teach or model" to differentiate an apple from a banana. But, we can solve this issue by re-training a previously trained model with thousands of images. We call this technique "Transfer Learning" (TL).



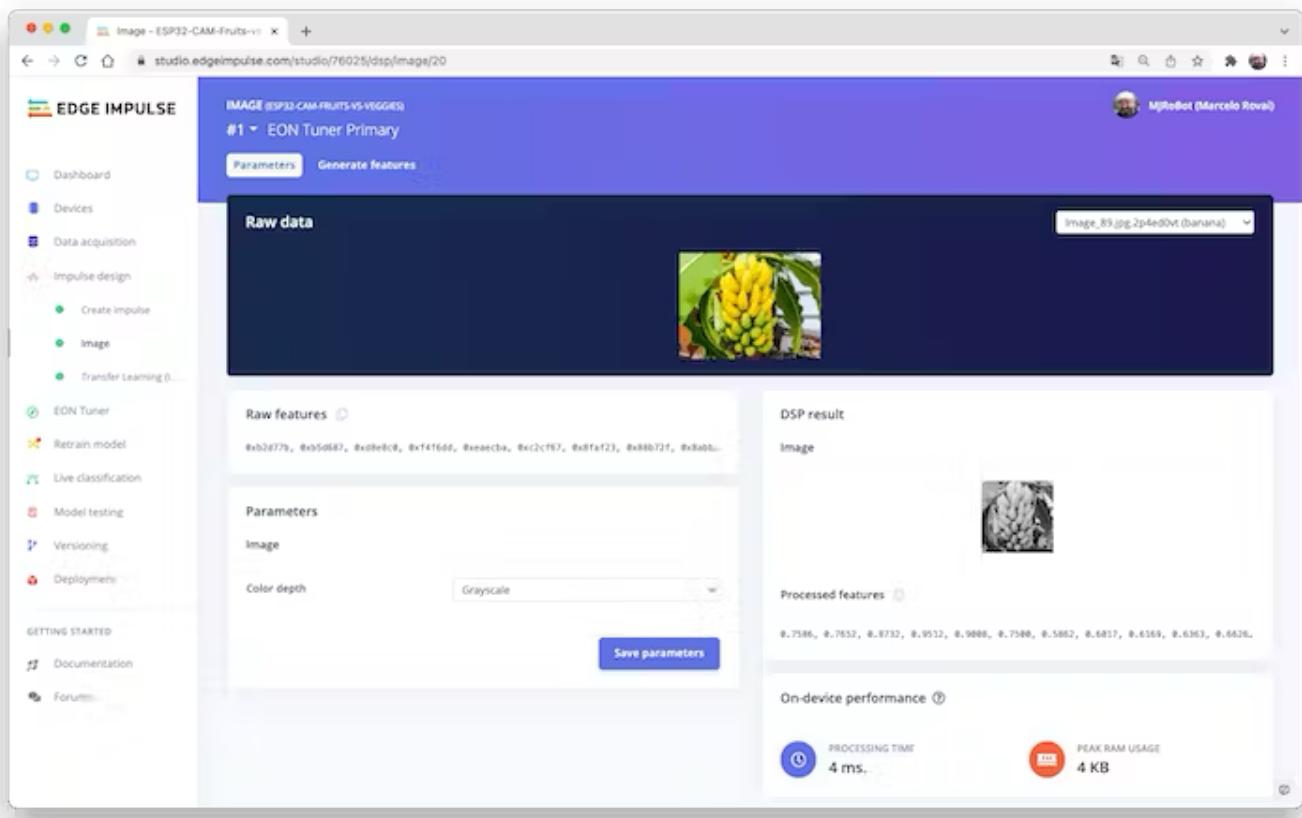
With TL, we can fine-tune a pre-trained image classification model on our data, performing well even with relatively small image datasets (our case).

So, starting from the raw images, we will resize them (96x96) pixels and feed them to our Transfer Learning block:



Pre-processing (Feature generation)

Besides resizing the images, we can change them to Grayscale or keep the actual RGB color depth. Let's start selecting `Grayscale`. Doing that, each one of our data samples will have dimension 9, 216 features (96x96x1). Keeping RGB, this dimension would be three times bigger. Working with Grayscale helps to reduce the amount of final memory needed for inference.



Do not forget to `[Save parameters]`." This will generate the features to be used in training.

Training (Transfer Learning & Data Augmentation)

In 2007, Google introduced [MobileNetV1](#), a family of general-purpose computer vision neural networks designed with mobile devices in mind to support classification, detection, and more. MobileNets are small, low-latency, low-power models parameterized to meet the resource constraints of various use cases.

Although the base MobileNet architecture is already tiny and has low latency, many times, a specific use case or application may require the model to be smaller and faster. MobileNet introduces a straightforward parameter α (alpha) called width multiplier to construct these smaller, less computationally expensive models. The role of the width multiplier α is to thin a network uniformly at each layer.

Edge Impulse Studio has available MobileNet V1 (96x96 images) and V2 (96x96 and 160x160 images), with several different α values (from 0.05 to 1.0). For example, you will get the highest accuracy with V2, 160x160 images, and $\alpha=1.0$. Of course, there is a trade-off. The higher the accuracy, the more memory (around 1.3M RAM and 2.6M ROM) will be needed to run the model, implying more latency.

The smaller footprint will be obtained at another extreme with **MobileNet V1** and $\alpha=0.10$ (around 53.2K RAM and 101K ROM).

When we first published this project to be running on an ESP32-CAM, we stayed at the lower side of possibilities, which guaranteed the inference with small latency but not with high accuracy. For this first pass, we will keep this model design (**MobileNet V1** and $\alpha=0.10$).

Another necessary technique to use with deep learning is **data augmentation**. Data augmentation is a method that can help improve the accuracy of machine learning models, creating additional artificial data. A data augmentation system makes small, random changes to your training data during the training process (such as flipping, cropping, or rotating the images).

Under the hood, here you can see how Edge Impulse implements a data Augmentation policy on your data:

```
# Implements the data augmentation policy
def augment_image(image, label):
    # Flips the image randomly
    image = tf.image.random_flip_left_right(image)

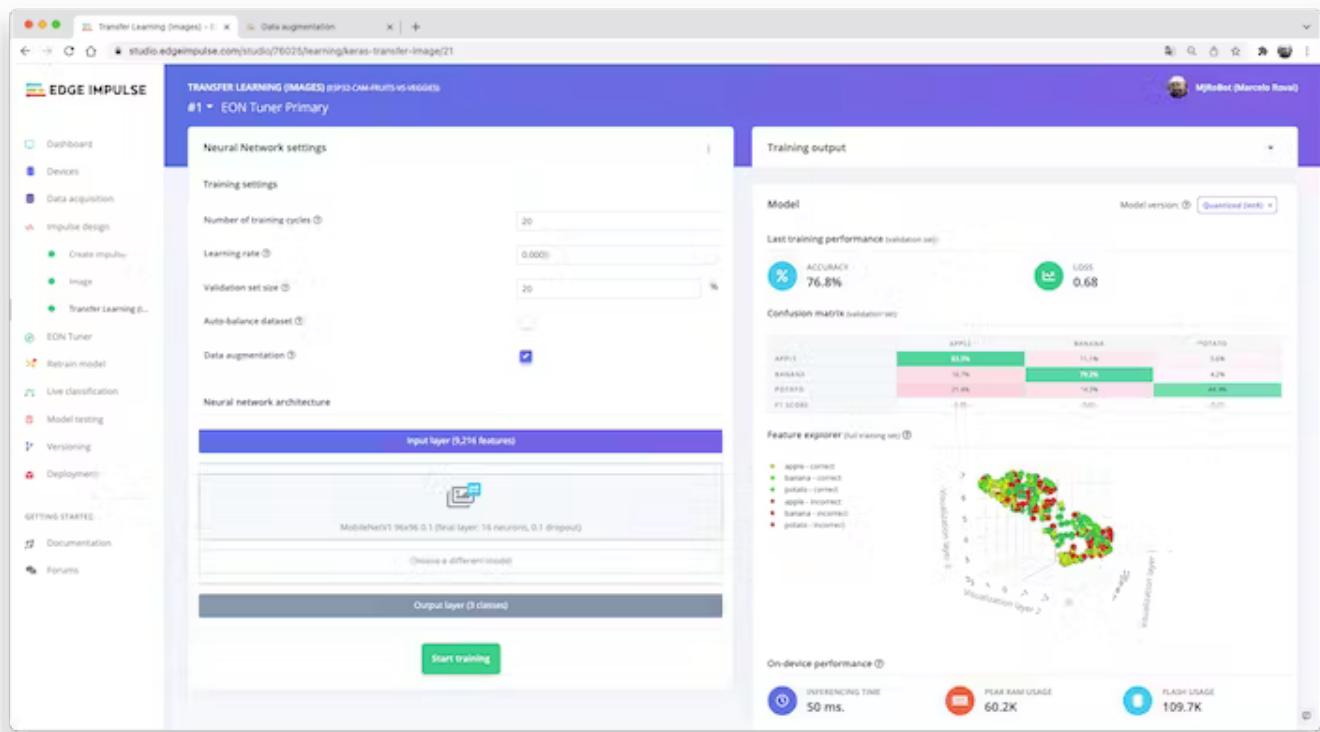
    # Increase the image size, then randomly crop it down to
    # the original dimensions
    resize_factor = random.uniform(1, 1.2)
    new_height = math.floor(resize_factor * INPUT_SHAPE[0])
    new_width = math.floor(resize_factor * INPUT_SHAPE[1])
    image = tf.image.resize_with_crop_or_pad(image, new_height, new_width)
    image = tf.image.random_crop(image, size=INPUT_SHAPE)

    # Vary the brightness of the image
    image = tf.image.random_brightness(image, max_delta=0.2)

    return image, label
```

Exposure to these variations during training can help prevent your model from taking shortcuts by "memorizing" superficial clues in your training data, meaning it may better reflect the deep underlying patterns in your dataset.

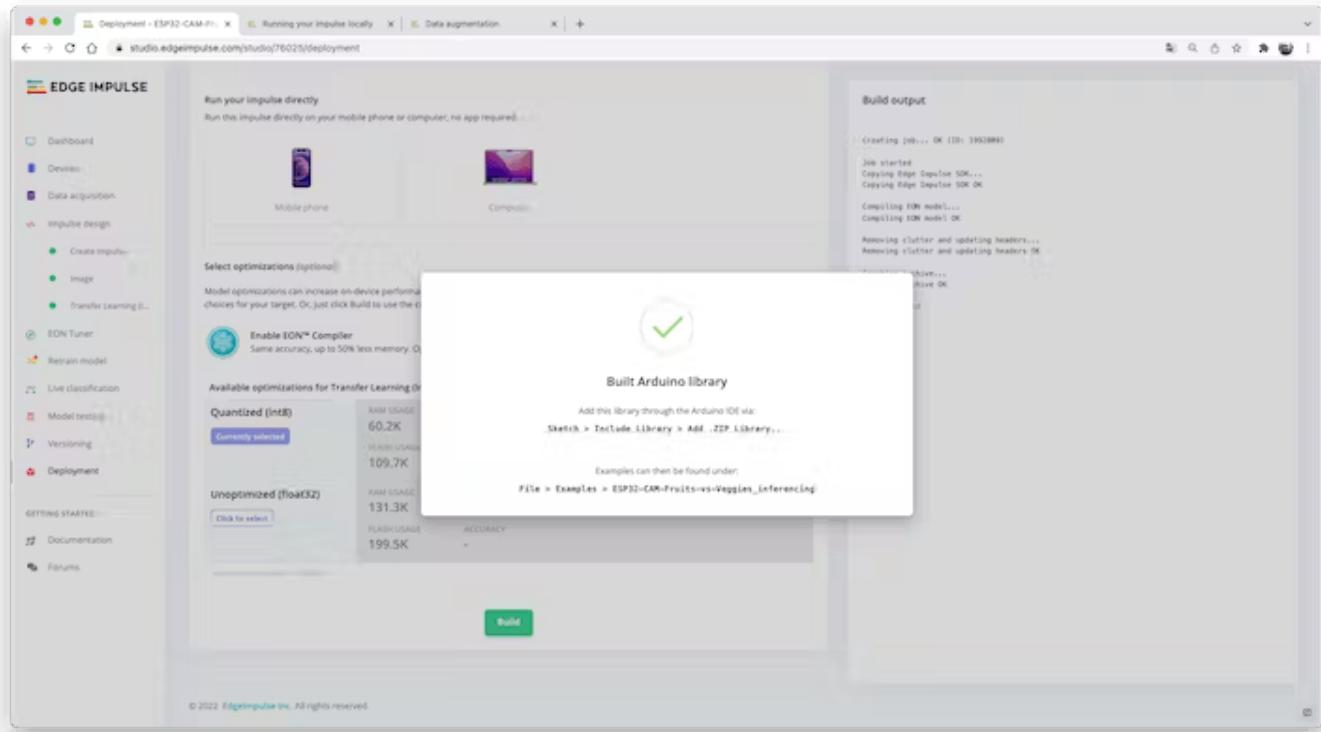
The final layer of our model will have 16 neurons with a 10% dropout for overfitting prevention. Here is the Training output:



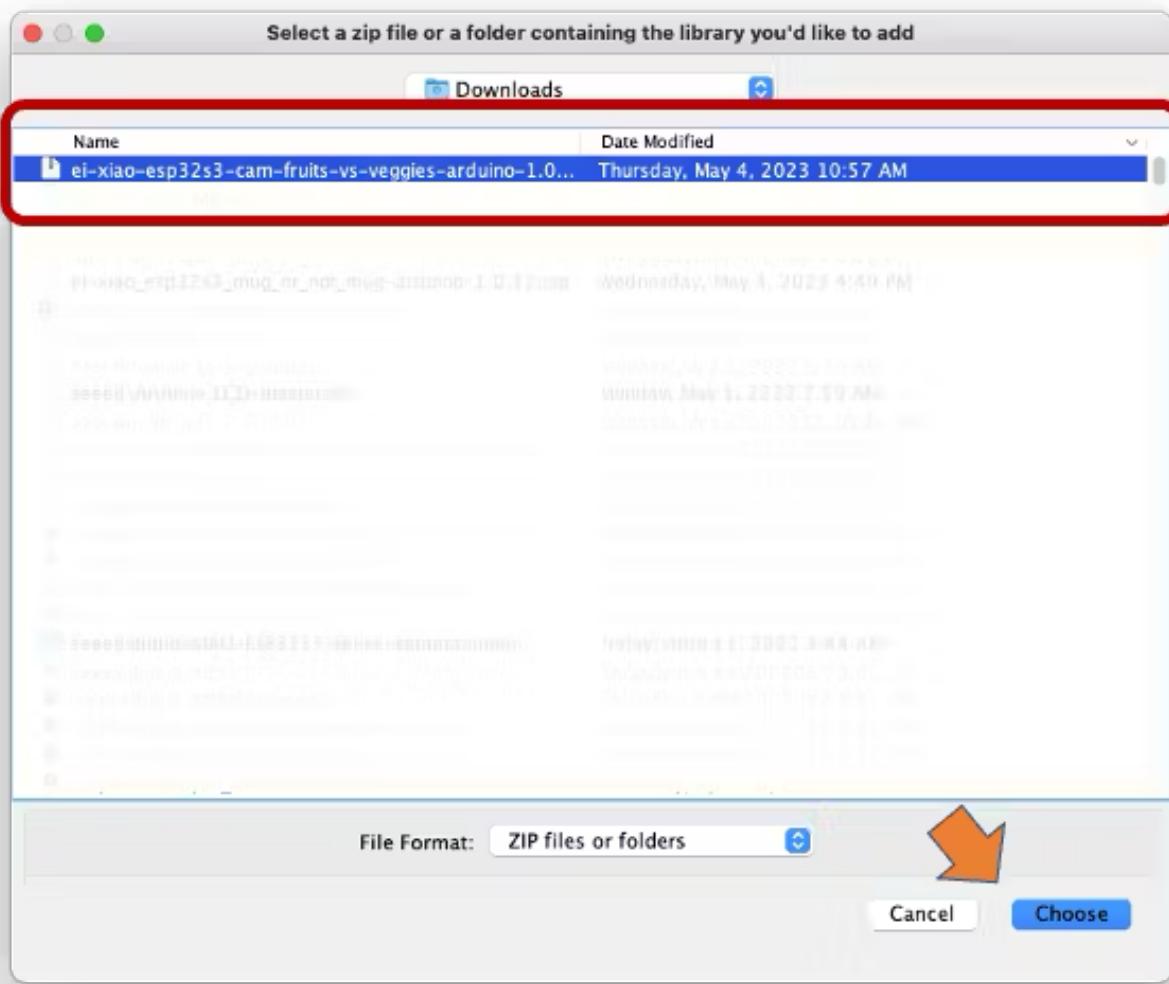
The result could be better. The model reached around 77% accuracy, but the amount of RAM expected to be used during the inference is relatively tiny (about 60 KBytes), which is very good.

Deployment

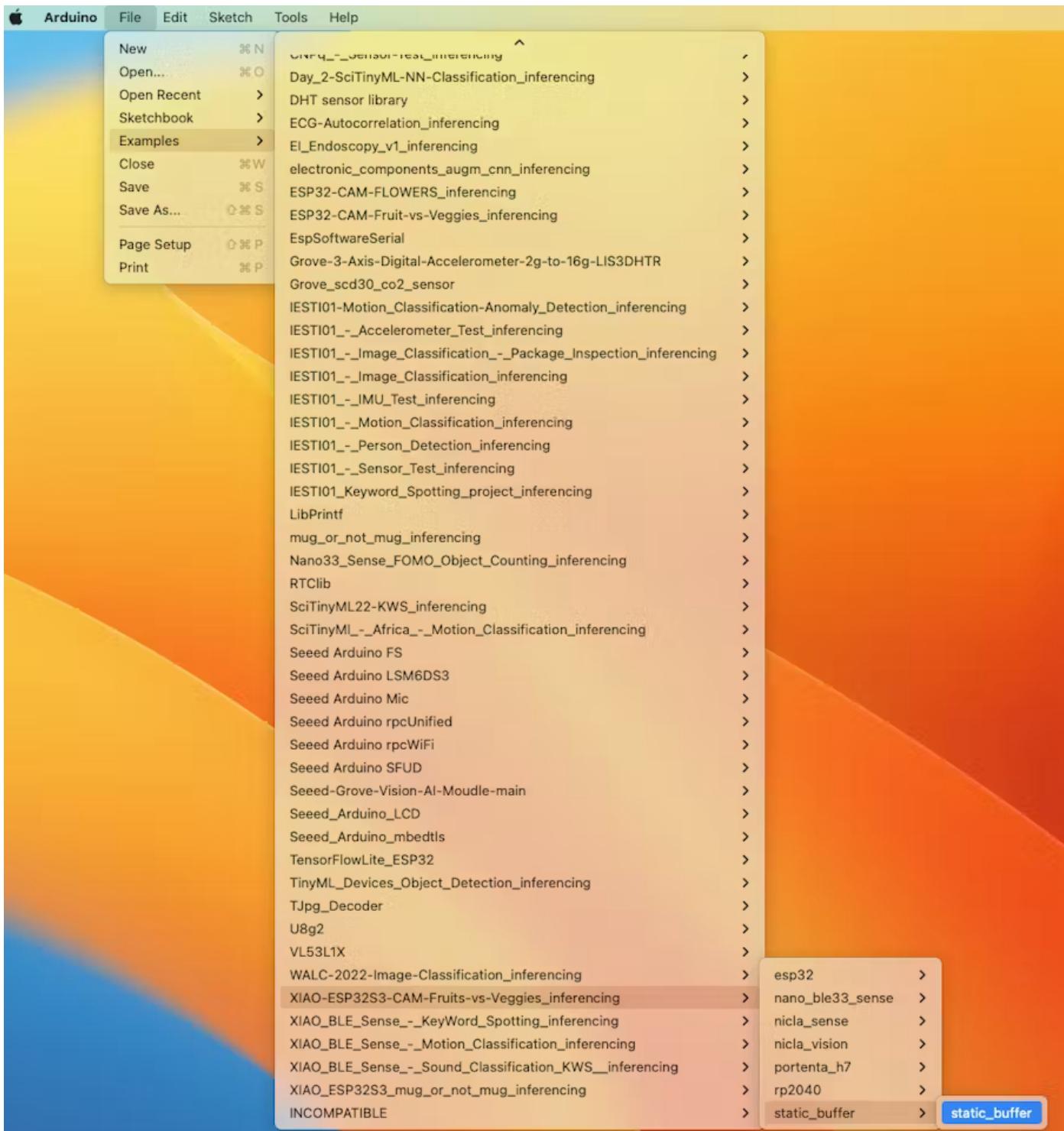
The trained model will be deployed as a .zip Arduino library:



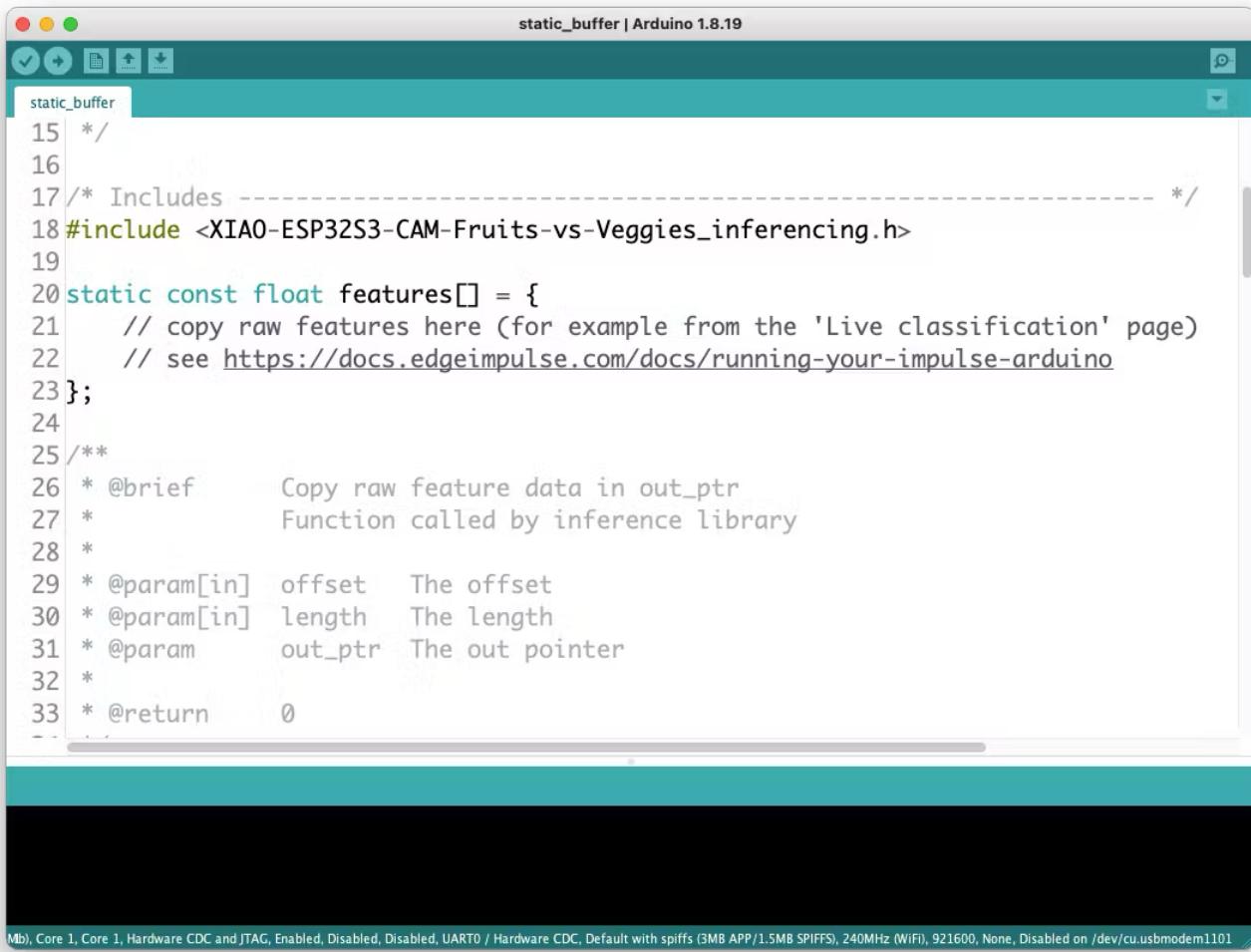
Open your Arduino IDE, and under **Sketch**, go to **Include Library** and **add.ZIP Library**. Please select the file you download from Edge Impulse Studio, and that's it!



Under the **Examples** tab on Arduino IDE, you should find a sketch code under your project name.



Open the Static Buffer example:



The screenshot shows the Arduino IDE interface with a teal header bar. The title bar reads "static_buffer | Arduino 1.8.19". Below the header is a toolbar with icons for file operations like Open, Save, and Print. The main area is a code editor with the following content:

```
static_buffer
15 */
16
17 /* Includes -----
18 #include <XIAO-ESP32S3-CAM-Fruits-vs-Veggies_inferencing.h>
19
20 static const float features[] = {
21     // copy raw features here (for example from the 'Live classification' page)
22     // see https://docs.edgeimpulse.com/docs/running-your-impulse-arduino
23 };
24
25 /**
26 * @brief      Copy raw feature data in out_ptr
27 *             Function called by inference library
28 *
29 * @param[in]  offset    The offset
30 * @param[in]  length   The length
31 * @param      out_ptr   The out pointer
32 *
33 * @return     0
--
```

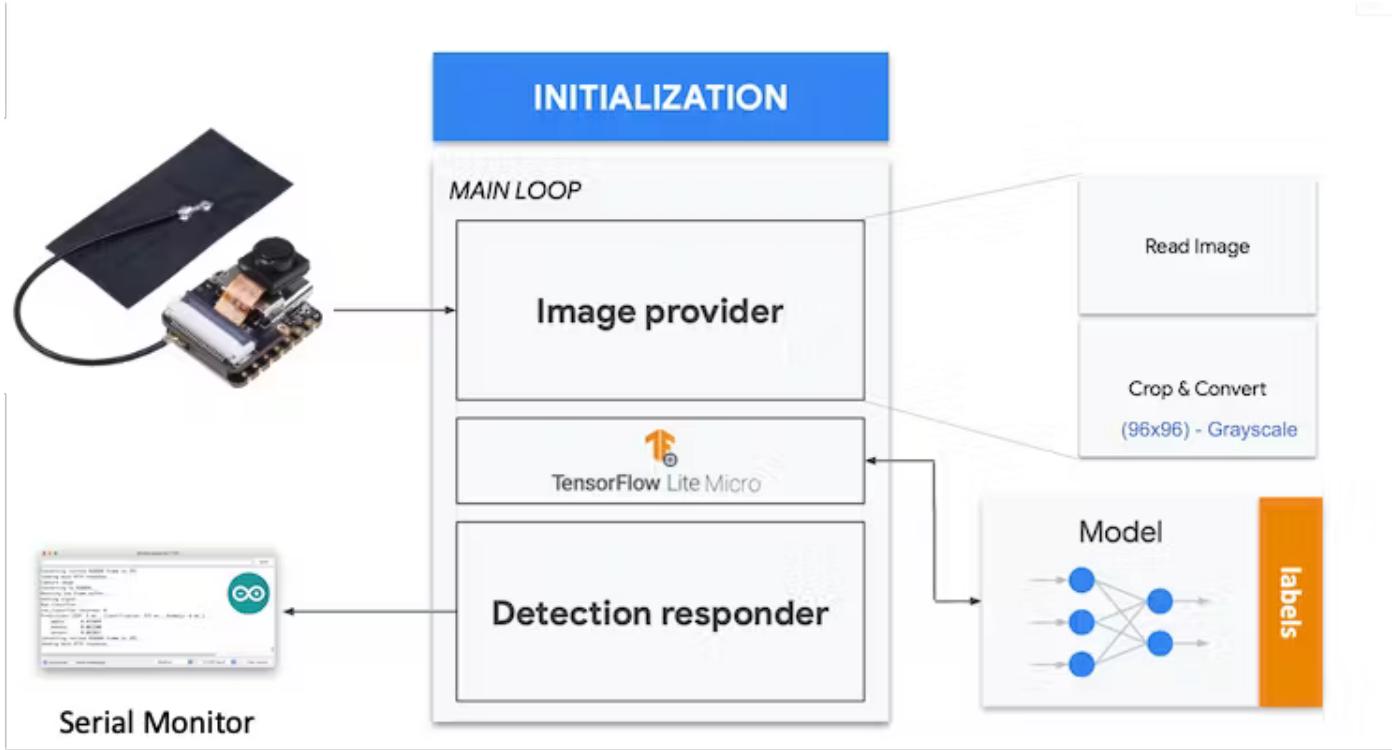
At the bottom of the code editor, there is a status bar with the text "Mb), Core 1, Core 1, Hardware CDC and JTAG, Enabled, Disabled, UART0 / Hardware CDC, Default with spiffs (3MB APP/1.5MB SPIFFS), 240MHz (WiFi), 921600, None, Disabled on /dev/cu.usbmodem1101".

You can see that the first line of code is exactly the calling of a library with all the necessary stuff for running inference on your device.

```
#include <XIAO-ESP32S3-CAM-Fruits-vs-Veggies_inferencing.h>
```

Of course, this is a generic code (a "template") that only gets one sample of raw data (stored on the variable: `features = {}`) and runs the classifier, doing the inference. The result is shown on the Serial Monitor.

We should get the sample (image) from the camera and pre-process it (resizing to 96x96, converting to grayscale, and flattening it). This will be the input tensor of our model. The output tensor will be a vector with three values (labels), showing the probabilities of each one of the classes.



Returning to your project (Tab Image), copy one of the Raw Data Sample:

XIAO-ESP32S3-CAM-Fruits-v2

studio.edgeimpulse.com/studio/221775/dsp/image/20

MJRoBot (Marcelo Rovai) / XIAO-ESP32S3-CAM-Fruits-vs-Veggies-v2

EDGE IMPULSE

#1 ▾ EON Tuner Primary

Parameters Generate features

Raw data

Show: All labels Image_89.jpg.2p4ed0vt (b.

Copy 9216 features to clipboard

Raw features

DSP result

Image

Parameters

Image

Color depth Grayscale

Processed features

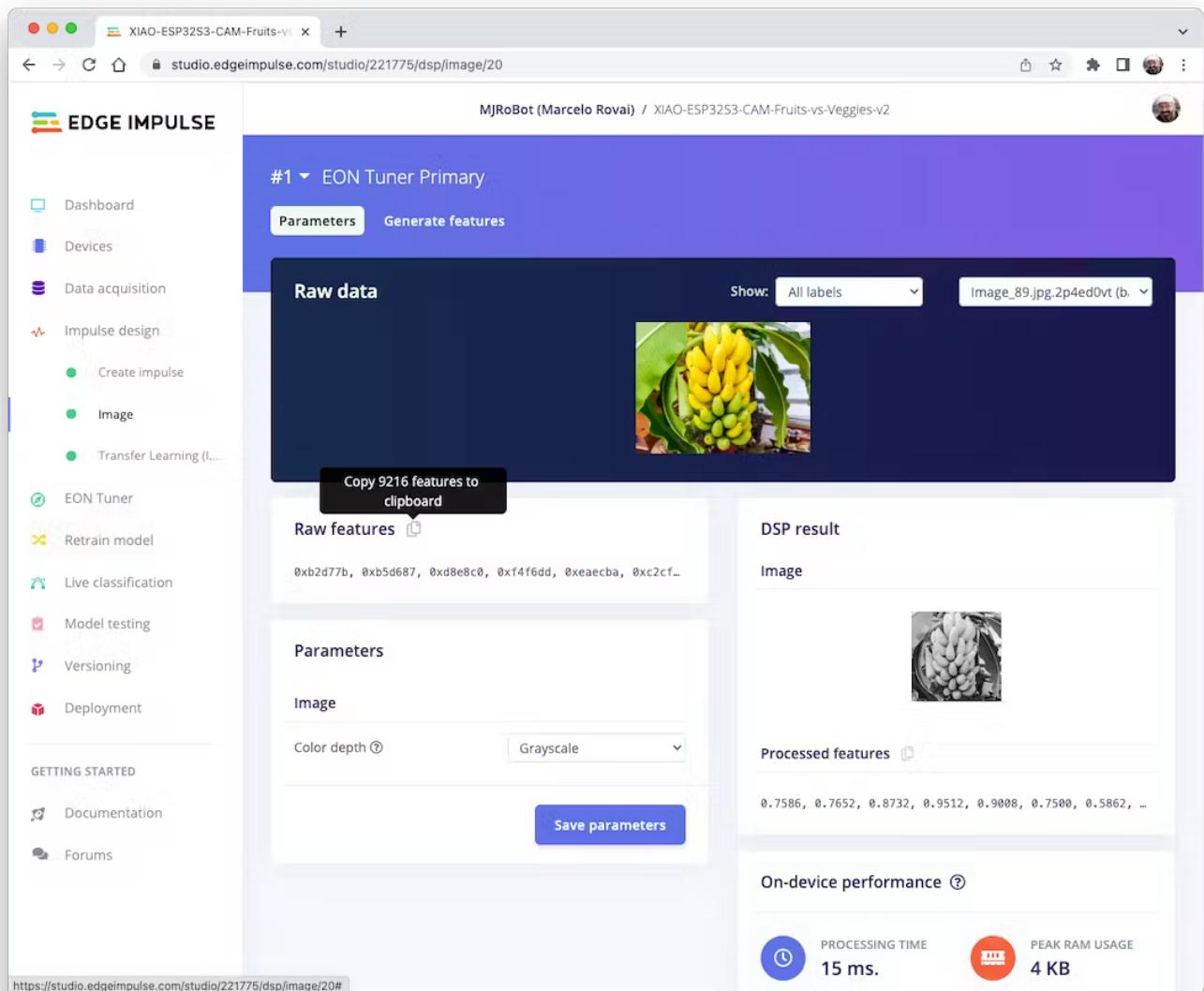
Save parameters

On-device performance

PROCESSING TIME  15 ms.

PEAK RAM USAGE  4 KB

<https://studio.edgeimpulse.com/studio/221775/dsp/image/20#>



9,216 features will be copied to the clipboard. This is the input tensor (a flattened image of 96x96x1), in this case, bananas. Paste this Input tensor on `features[] = {0xb2d77b, 0xb5d687, 0xd8e8c0, 0xeaecba, 0xc2cf67, ...}`

The screenshot shows the Arduino IDE interface with a teal header bar. The title bar reads "static_buffer | Arduino 1.8.19". Below the header is a toolbar with icons for file operations like Open, Save, and Upload. The main area is a code editor with the following content:

```
static_buffer §
16
17 /* Includes -----
18 #include <XIAO-ESP32S3-CAM-Fruits-vs-Veggies_inferencing.h>
19
20 static const float features[] = {
21     0xb2d77b, 0xb5d687, 0xd8e8c0, 0xf4f6dd, 0xeaecba, 0xc2cf67, 0x8faf23, 0x88b72f
22 };
23
24 /**
25 * @brief   Contains feature vectors for fruit and vegetable inference
26 */
```

At the bottom of the screen, there is a status bar with the text "MB, Core 1, Core 1, Hardware CDC and JTAG, Enabled, Disabled, UART0 / Hardware CDC, Default with spiffs (3MB APP/1.5MB SPIFFS), 240MHz (WiFi), 921600, None, Disabled on /dev/cu.usbmodem1101".

Edge Impulse included the [library ESP NN](#) in its SDK, which contains optimized NN (Neural Network) functions for various Espressif chips, including the ESP32S3 (running at Arduino IDE).

When running the inference, you should get the highest score for "banana."

The screenshot shows the Serial Monitor window with a light gray background. The title bar says "/dev/cu.usbmodem1101". The main area displays the output of the Edge Impulse standalone inferencing (Arduino) code. It shows three sets of predictions for the categories apple, banana, and potato. The scores are identical across all three runs.

```
Edge Impulse standalone inferencing (Arduino)
run_classifier returned: 0
Timing: DSP 4 ms, inference 317 ms, anomaly 0 ms
Predictions:
apple: 0.16406
banana: 0.73047
potato: 0.10547
Edge Impulse standalone inferencing (Arduino)
run_classifier returned: 0
Timing: DSP 4 ms, inference 317 ms, anomaly 0 ms
Predictions:
apple: 0.16406
banana: 0.73047
potato: 0.10547
Edge Impulse standalone inferencing (Arduino)
```

At the bottom of the window, there are several control buttons: "Autoscroll" (unchecked), "Show timestamp" (unchecked), "Both NL & CR" (selected), "115200 baud" (selected), and "Clear output".

Great news! Our device handles an inference, discovering that the input image is a banana. Also, note that the inference time was around 317ms, resulting in a maximum of 3 fps if you tried to classify images from a video. It is a better result than the ESP32 CAM (525ms of latency).

Now, we should incorporate the camera and classify images in real time.

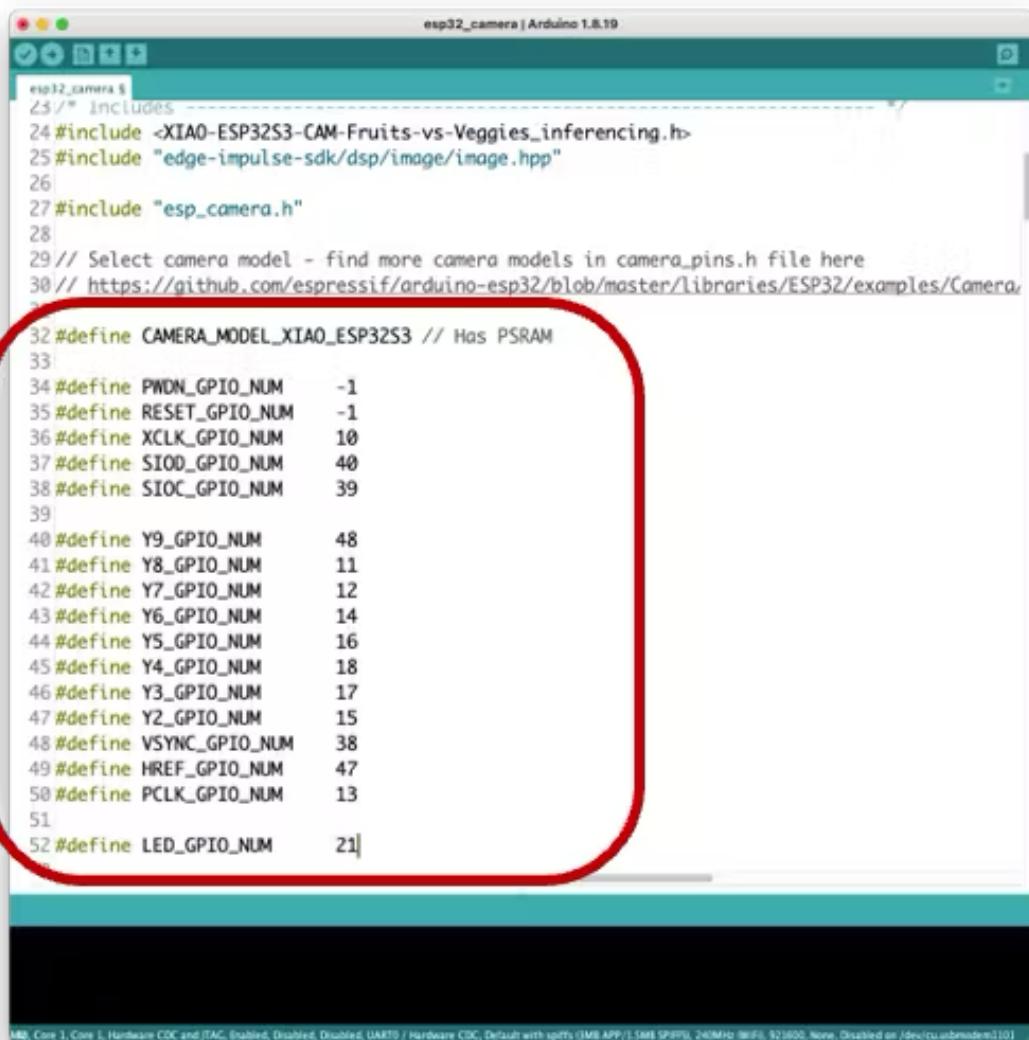
Go to the Arduino IDE Examples and download from your project the sketch esp32_camera:



You should change lines 32 to 75, which define the camera model and pins, using the data related to our model. Copy and paste the below lines, replacing the lines 32-75:

```
#define PWDN_GPIO_NUM      -1
#define RESET_GPIO_NUM     -1
#define XCLK_GPIO_NUM       10
#define SIOD_GPIO_NUM       40
#define SIOC_GPIO_NUM       39
#define Y9_GPIO_NUM         48
#define Y8_GPIO_NUM         11
#define Y7_GPIO_NUM         12
#define Y6_GPIO_NUM         14
#define Y5_GPIO_NUM         16
#define Y4_GPIO_NUM         18
#define Y3_GPIO_NUM         17
#define Y2_GPIO_NUM         15
#define VSYNC_GPIO_NUM      38
#define HREF_GPIO_NUM       47
#define PCLK_GPIO_NUM       13
```

Here you can see the resulting code:



```
esp32_camera.ino
1 // This sketch uses the XIAO-ESP32S3-CAM-Fruits-vs-Veggies_inferencing.h header file
2 // which includes the edge-impulse-sdk/dsp/image/image.hpp header file
3 // Select camera model - find more camera models in camera_pins.h file here
4 // https://github.com/espressif/arduino-esp32/blob/master/libraries/ESP32/examples/Camera/
5
6 #define CAMERA_MODEL_XIAO_ESP32S3 // Has PSRAM
7
8 #define PDN_GPIO_NUM      -1
9 #define RESET_GPIO_NUM   -1
10 #define XCLK_GPIO_NUM     10
11 #define SIOD_GPIO_NUM    40
12 #define SIOC_GPIO_NUM    39
13
14 #define Y9_GPIO_NUM       48
15 #define Y8_GPIO_NUM       11
16 #define Y7_GPIO_NUM       12
17 #define Y6_GPIO_NUM       14
18 #define Y5_GPIO_NUM       16
19 #define Y4_GPIO_NUM       18
20 #define Y3_GPIO_NUM       17
21 #define Y2_GPIO_NUM       15
22 #define VSYNC_GPIO_NUM    38
23 #define HREF_GPIO_NUM     47
24 #define PCLK_GPIO_NUM     13
25
26 #define LED_GPIO_NUM      21
```

The modified sketch can be downloaded from GitHub: [xiao_esp32s3_camera](https://github.com/adafruit/xiao_esp32s3_camera).

Note that you can optionally keep the pins as a .h file as we did in previous sections.

Upload the code to your XIAO ESP32S3 Sense, and you should be OK to start classifying your fruits and vegetables! You can check the result on Serial Monitor.

11 Testing the Model (Inference)



Getting a photo with the camera, the classification result will appear on the Serial Monitor:

```
banana: 0.90234
potato: 0.03906
Predictions (DSP: 4 ms., Classification: 318 ms., Anomaly: 0 ms.):
apple: 0.03906
banana: 0.93359
potato: 0.02734
Predictions (DSP: 4 ms., Classification: 317 ms., Anomaly: 0 ms.):
apple: 0.05469
banana: 0.90625
potato: 0.03906
Predictions (DSP: 4 ms., Classification: 318 ms., Anomaly: 0 ms.):
apple: 0.04297
banana: 0.92578
potato: 0.03125
```

Autoscroll Show timestamp Both NL & CR 115200 baud Clear output

Other tests:

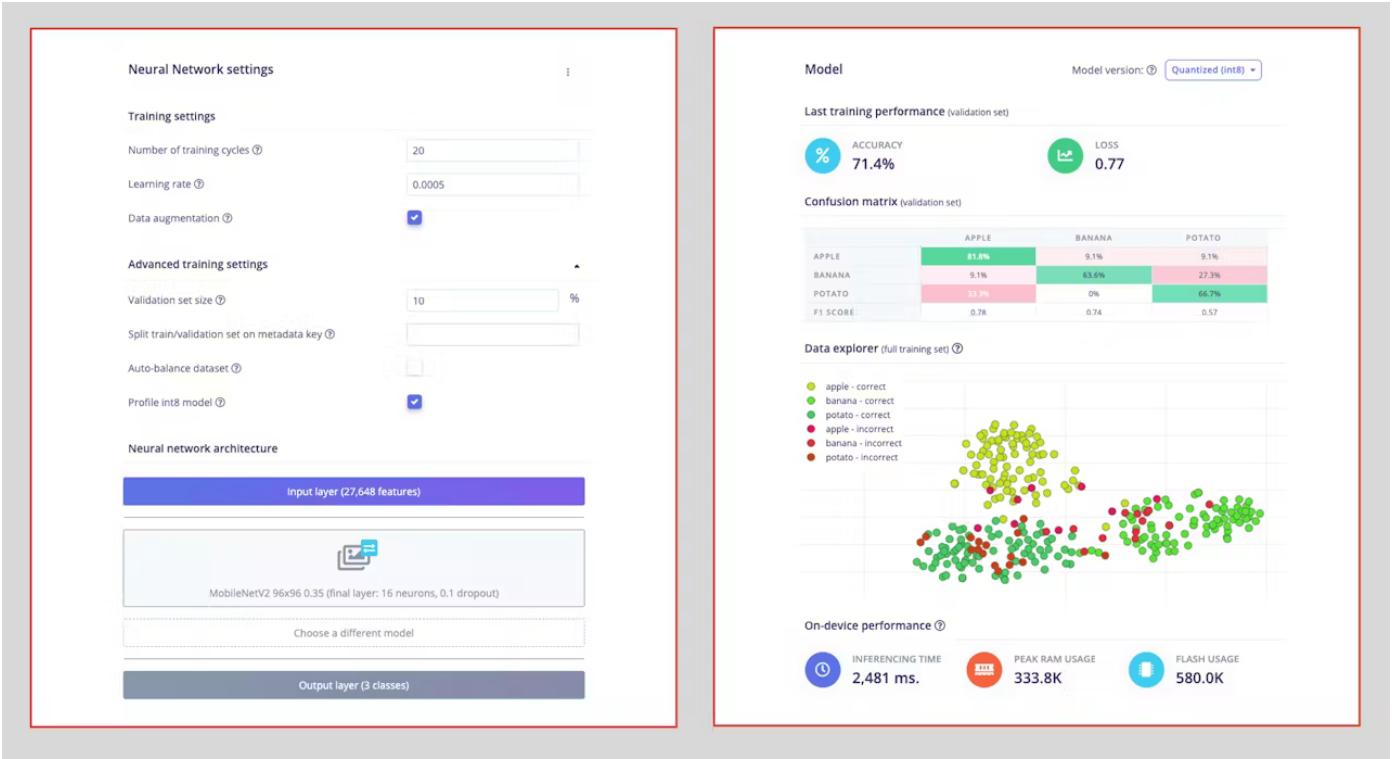
```
banana: 0.14844
potato: 0.12891
Predictions (DSP: 4 ms., Classification: 318 ms., Anomaly: 0 ms.):
apple: 0.78906
banana: 0.06641
potato: 0.14453
Predictions (DSP: 4 ms., Classification: 317 ms., Anomaly: 0 ms.):
apple: 0.71484
banana: 0.06641
potato: 0.21875
Predictions (DSP: 4 ms., Classification: 318 ms., Anomaly: 0 ms.):
apple: 0.79297
banana: 0.05469
potato: 0.14844
```

Autoscroll Show timestamp Both NL & CR 115200 baud Clear output



12 Testing with a Bigger Model

Now, let's go to the other side of the model size. Let's select a MobilenetV2 96x96 0.35, having as input RGB images.



Even with a bigger model, the accuracy could be better, and the amount of memory necessary to run the model increases five times, with latency increasing seven times.

Note that the performance here is estimated with a smaller device, the ESP-EYE. The actual inference with the ESP32S3 should be better.

To improve our model, we will need to train more images.

Even though our model did not improve accuracy, let's test whether the XIAO can handle such a bigger model. We will do a simple inference test with the Static Buffer sketch.

Let's redeploy the model. If the EON Compiler is enabled when you generate the library, the total memory needed for inference should be reduced, but it does not influence accuracy.

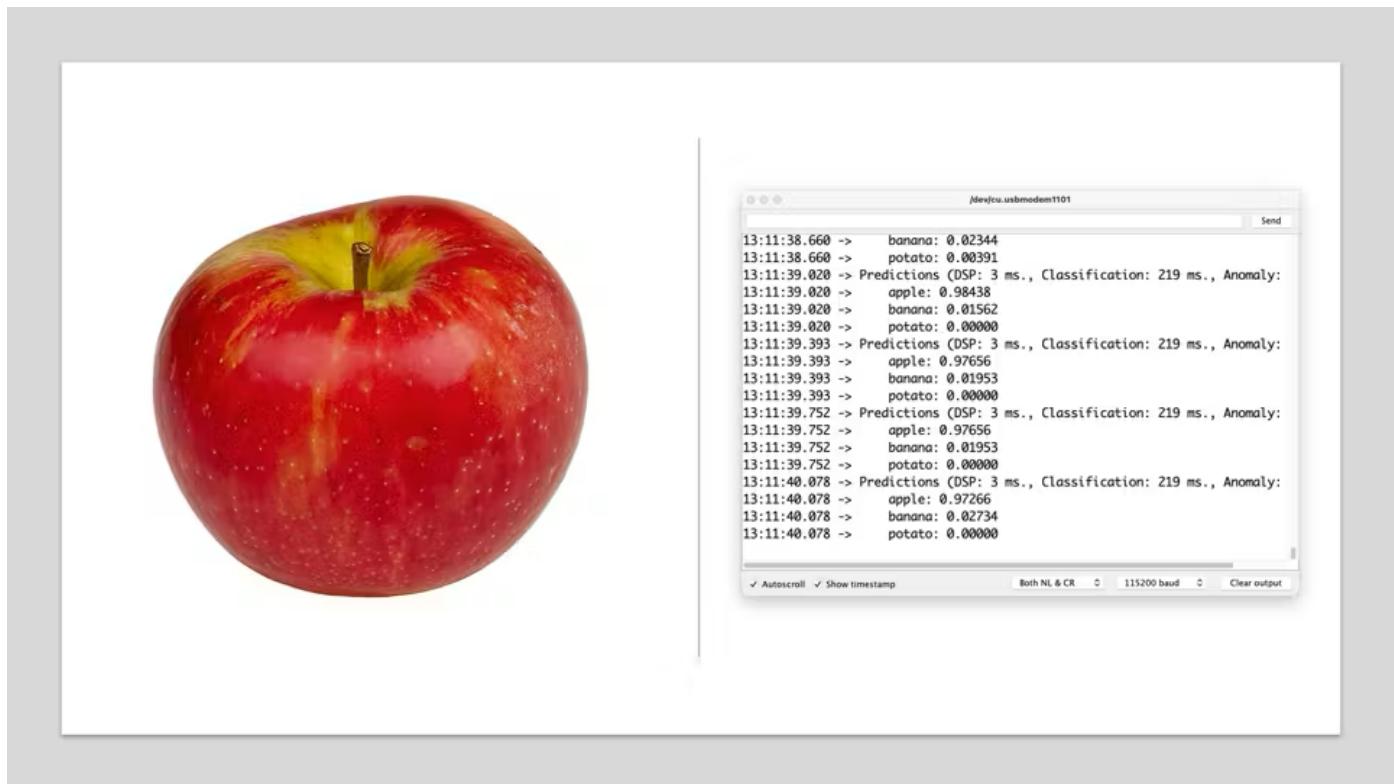
⚠️ Attention - The Xiao ESP32S3 with PSRAM enabled has enough memory to run the inference, even in a bigger model. Keep the EON Compiler **NOT ENABLED**.

Configure your deployment

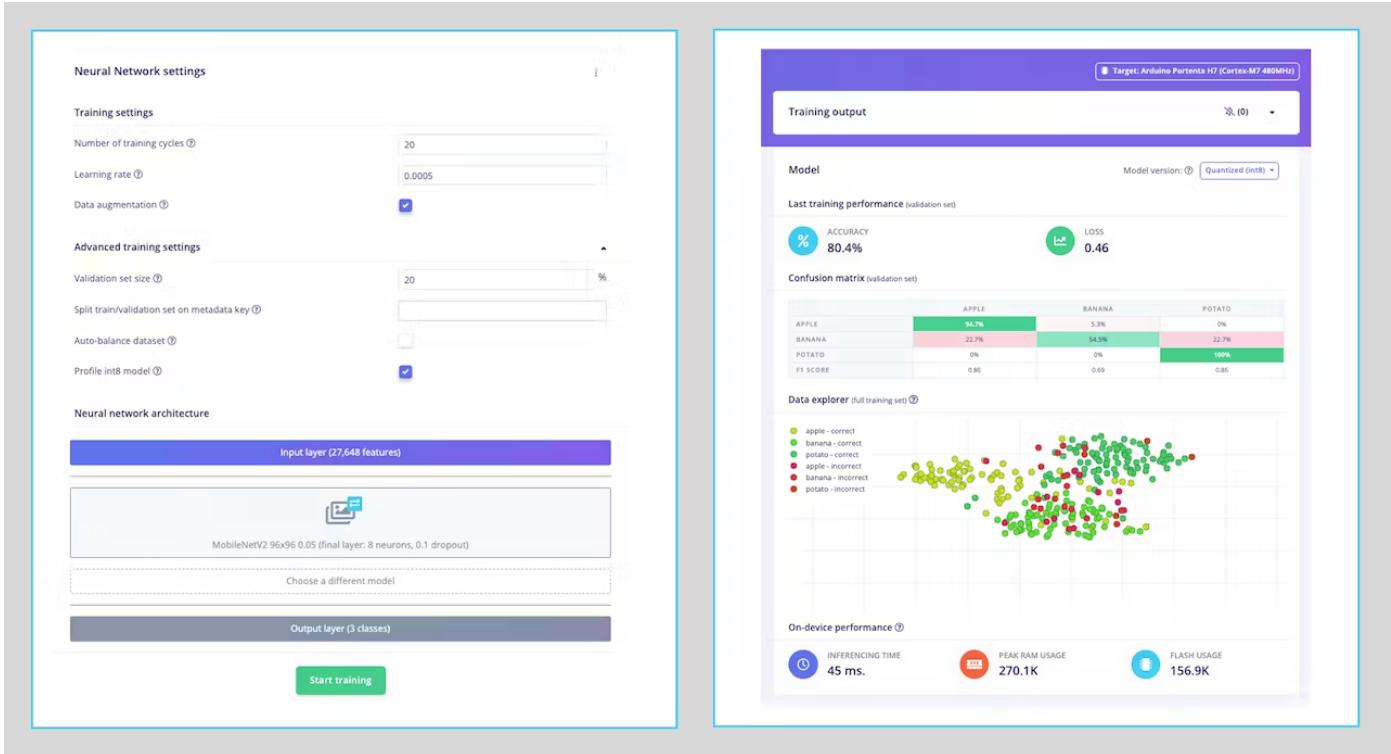
You can deploy your impulse to any device. This makes the model run without an internet connection, minimizes latency, and runs with minimal power consumption. [Read more.](#)

The screenshot shows the Edge Impulse Studio interface. On the left, there's a search bar for 'Arduino library' and a sidebar with options like Dashboard, Devices, Data acquisition, Impulse design, EON Tuner, Retrain model, Live classification, Model testing, Versioning, and Deployment. Under 'Deployment', there's a section for 'SELECTED DEPLOYMENT' labeled 'Arduino library'. Below it, 'MODEL OPTIMIZATIONS' mention that optimizations can increase on-device performance but may reduce accuracy. A button 'Enable EON™ Compiler' is highlighted with an orange box. Two tables compare 'Quantized (int8)' and 'Unoptimized (float32)' models across Latency, RAM, Flash, and Accuracy. A 'Run model testing' button is present. On the right, the 'Configure your deployment' panel shows a success message: 'Built Arduino library' with a green checkmark. It also includes a note to add the library to the Arduino IDE via Sketch > Include Library > Add ZIP Library... and provides examples for File > Examples > XIAO-ESP32S3-CNN-Fruit-vs-Veggies-ESP-NW_Inference. The 'Build output' panel shows a log of the build process, and a download link for 'en-xiao-esp32s3-...-zip' is highlighted with an orange box.

Doing an inference with MobilinetV2 96x96 0.35, having as input RGB images, the latency was 219ms, which is great for such a bigger model.



For the test, I trained the model again, using the smallest version of MobileNet V2, with an alpha of 0.05. Interesting that the result in accuracy was higher.



Note that the estimated latency for an Arduino Portenta (or Nicla), running with a clock of 480MHz is 45ms.

Deploying the model, I got an inference of only 135ms, remembering that the XIAO runs with half of the clock used by the Portenta/Nicla (240MHz):

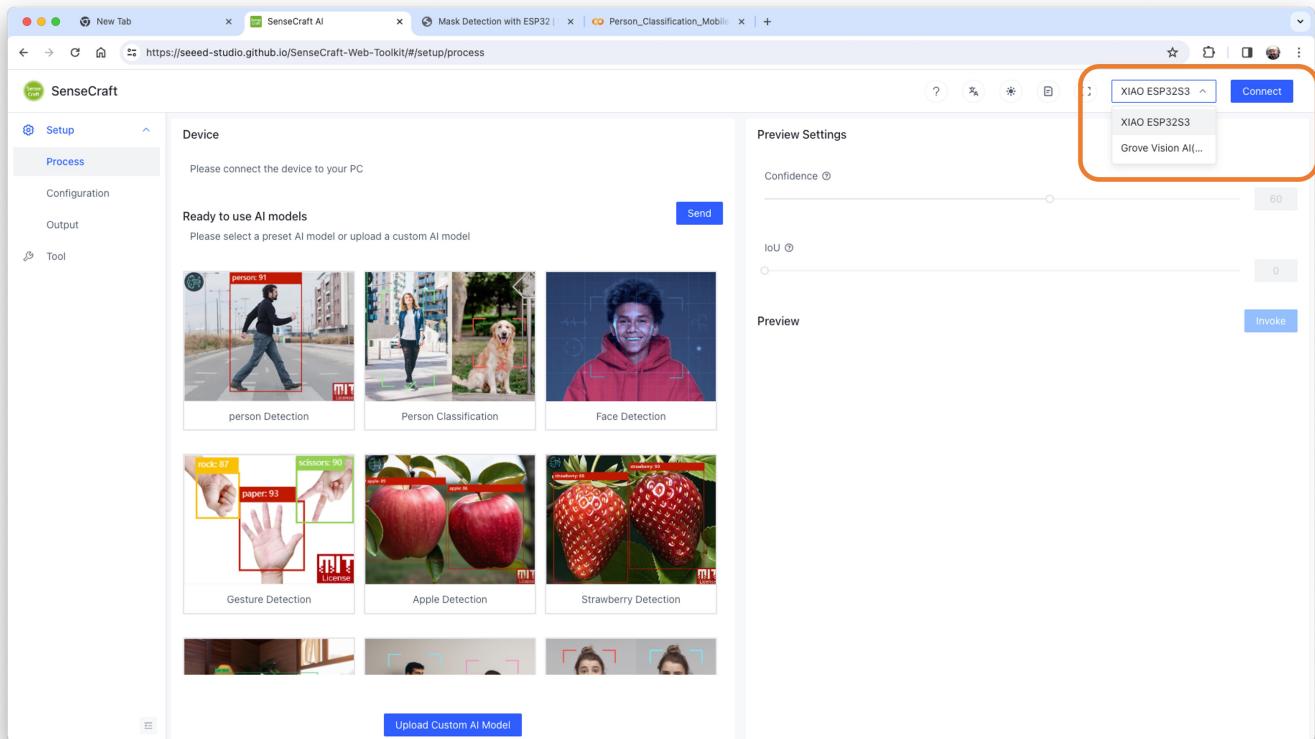
```
10:44:47.849 -> banana: 0.01953
10:44:47.849 -> potato: 0.12891
10:44:48.103 -> Predictions (DSP: 3 ms., Classification: 135 ms., Anomaly: 0 ms.):
10:44:48.103 -> apple: 0.86328
10:44:48.103 -> banana: 0.03906
10:44:48.103 -> potato: 0.10156
10:44:48.356 -> Predictions (DSP: 3 ms., Classification: 135 ms., Anomaly: 0 ms.):
10:44:48.356 -> apple: 0.90234
10:44:48.356 -> banana: 0.02344
10:44:48.356 -> potato: 0.07422
10:44:48.612 -> Predictions (DSP: 3 ms., Classification: 135 ms., Anomaly: 0 ms.):
10:44:48.612 -> apple: 0.91797
10:44:48.612 -> banana: 0.02344
10:44:48.612 -> potato: 0.05859
10:44:48.861 -> Predictions (DSP: 3 ms., Classification: 135 ms., Anomaly: 0 ms.):
10:44:48.861 -> apple: 0.88281
10:44:48.861 -> banana: 0.03516
10:44:48.861 -> potato: 0.08203
10:44:49.114 -> Predictions (DSP: 3 ms., Classification: 135 ms., Anomaly: 0 ms.):
```

13 Running inference on the SenseCraft-Web-Toolkit

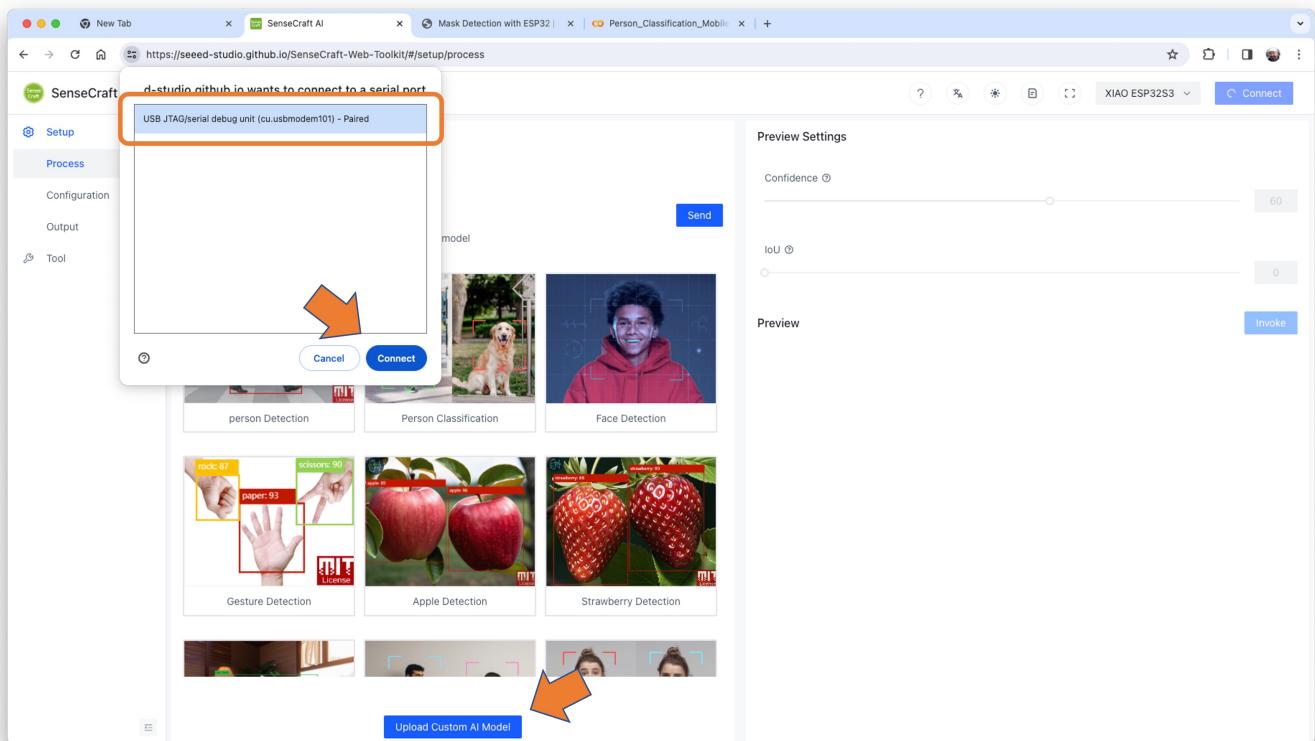
One significant limitation of viewing inference on Arduino IDE is that we can not see what the camera focuses on. A good alternative is the **SenseCraft-Web-Toolkit**, a visual model deployment tool provided by [SSCMA](#) (Seeed SenseCraft Model Assistant). This tool allows you to deploy models to various platforms easily through simple operations. The tool offers a user-friendly interface and does not require any coding.

Follow the following steps to start the SenseCraft-Web-Toolkit:

1. Open the [SenseCraft-Web-Toolkit website](#).
2. Connect the XIAO to your computer:
 - Having the XIAO connected, select it as below:



- Select the device/Port and press [Connect] :



You can try several Computer Vision models previously uploaded by Seeed Studio. Try them and have fun!

In our case, we will use the blue button at the bottom of the page: [\[Upload Custom AI Model\]](#).

But first, we must download from Edge Impulse Studio our **quantized .tflite** model.

3. Go to your project at Edge Impulse Studio, or clone this one:

- [XIAO-ESP32S3-CAM-Fruits-vs-Veggies-v1-ESP-NN](#)

4. On the `Dashboard`, download the model ("block output"): `Transfer learning model - TensorFlow Lite (int8 quantized)`.

EDGE IMPULSE

Download block output

| TITLE | TYPE | SIZE |
|-------------------------|----------------------------------|-------------|
| Image training data | NPY file | 279 windows |
| Image training labels | NPY file | 279 windows |
| Image testing data | NPY file | 15 windows |
| Image testing labels | NPY file | 15 windows |
| Transfer learning model | TensorFlow Lite (float32) | 245 KB |
| Transfer learning model | TensorFlow Lite (int8 quantized) | 171 KB |
| Transfer learning model | TensorFlow SavedModel | 314 KB |
| Transfer learning model | Keras h5 model | 248 KB |

Collaborators (1/4)

MJRobot (Marcelo Rovai) OWNER

Summary

DEVICES CONNECTED 0

DATA COLLECTED 294 items

Project info

5. On SenseCraft-Web-Toolkit, use the blue button at the bottom of the page: [Upload Custom AI Model]. A window will pop up. Enter the Model file that you downloaded to your computer from Edge Impulse Studio, choose a Model Name, and enter with labels (ID: Object):

SenseCraft

Setup

Process

Configuration

Output

Tool

Custom AI Model

Model Name: Fruits_vs_Veggies: Img Classification

Model File: fruits-vs-veggies-v1-esp-nn-transfer-l...

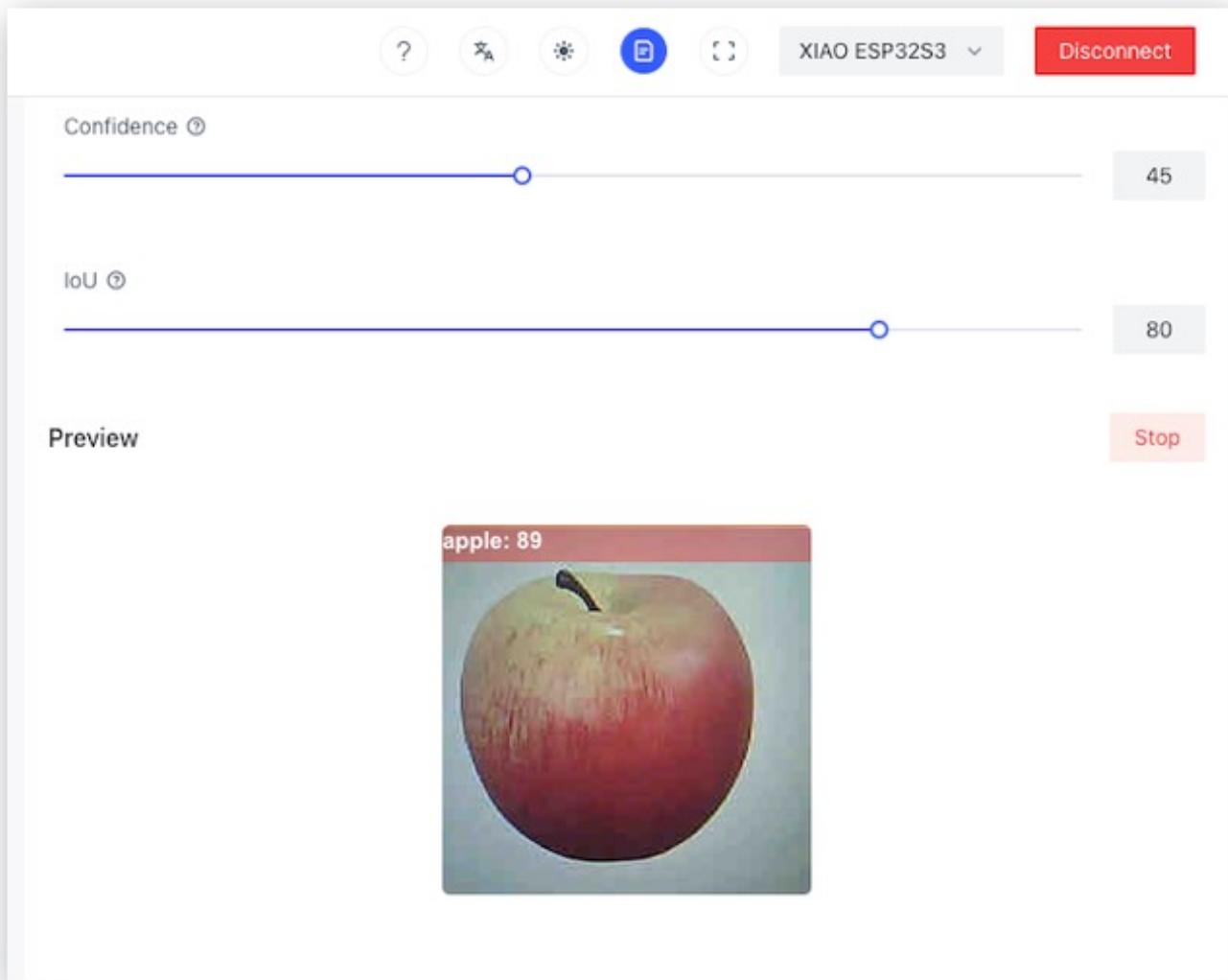
ID:Object: Apple X 1banana X 2potato X

Cancel Send Model

Upload Custom AI Model

Note that you should use the labels trained on EI Studio, entering them in alphabetic order (in our case: apple, banana, potato).

After a few seconds (or minutes), the model will be uploaded to your device, and the camera image will appear in real-time on the Preview Sector:



The Classification result will be at the top of the image. You can also select the Confidence of your inference cursor `confidence`.

Clicking on the top button (Device Log), you can open a Serial Monitor to follow the inference, the same that we have done with the Arduino IDE:

The screenshot shows the SenseCraft AI web interface. On the left, there's a sidebar with 'Setup', 'Process', 'Configuration', 'Output', and 'Tool' tabs. The 'Process' tab is active, displaying a logger window with a red circle around it. The logger output is as follows:

```

Logger
classes: [[77,0]]
perf: {"preprocess":3,"inference":106,"postprocess":1}
classes: [[91,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[81,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[81,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[78,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[85,0]]
perf: {"preprocess":3,"inference":107,"postprocess":0}
classes: [[76,0]]
perf: {"preprocess":3,"inference":107,"postprocess":0}
classes: [[78,0]]
perf: {"preprocess":3,"inference":107,"postprocess":0}
classes: [[81,0]]
perf: {"preprocess":3,"inference":107,"postprocess":0}
classes: [[82,0]]
perf: {"preprocess":3,"inference":107,"postprocess":0}
classes: [[86,0]]
perf: {"preprocess":3,"inference":106,"postprocess":1}
classes: [[83,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[87,0]]
perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[89,0]]

```

To the right of the logger is a 'Confidence' slider set to 45 and an 'IoU' slider set to 80. Below these are 'Preview' and 'Stop' buttons. The preview window shows an image of an apple with the text 'apple: 89' above it.

On Device Log, you will get information as:

```

perf: {"preprocess":4,"inference":106,"postprocess":0}
classes: [[89,0]]

```

- Preprocess time (image capture and Crop): 4ms;
- Inference time (model latency): 106ms,
- Postprocess time (display of the image and inclusion of data): 0ms.
- Output tensor (classes), for example: [[89,0]]; where 0 is Apple (and 1 is banana and 2 is potato)

Here are other screenshots:



14 Conclusion

The XIAO ESP32S3 Sense is very flexible, inexpensive, and easy to program. The project proves the potential of TinyML. Memory is not an issue; the device can handle many post-processing tasks, including communication.

You will find the last version of the codes on the GitHub repository: [XIAO-ESP32S3-Sense](#).