

Harvard



Yá'át'ééh 

EASI-22

Edge AI Summer  
Institute 2022

with Navajo Tech

# Our website!

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[tinyMLedu.org/EASI-22](https://tinyMLedu.org/EASI-22)

home base for **all information!**

# Workshop Agenda

Day 1

Introduction to AI and (Tiny)ML

Cloud ML

Day 2

Keyword Spotting for the Navajo Language

Mobile ML

Day 3

Bringing AI/ML from the Cloud to the Edge

Embedded ML

# Workshop Agenda

Day 1

Introduction to AI and (Tiny)ML

Cloud ML

Day 2

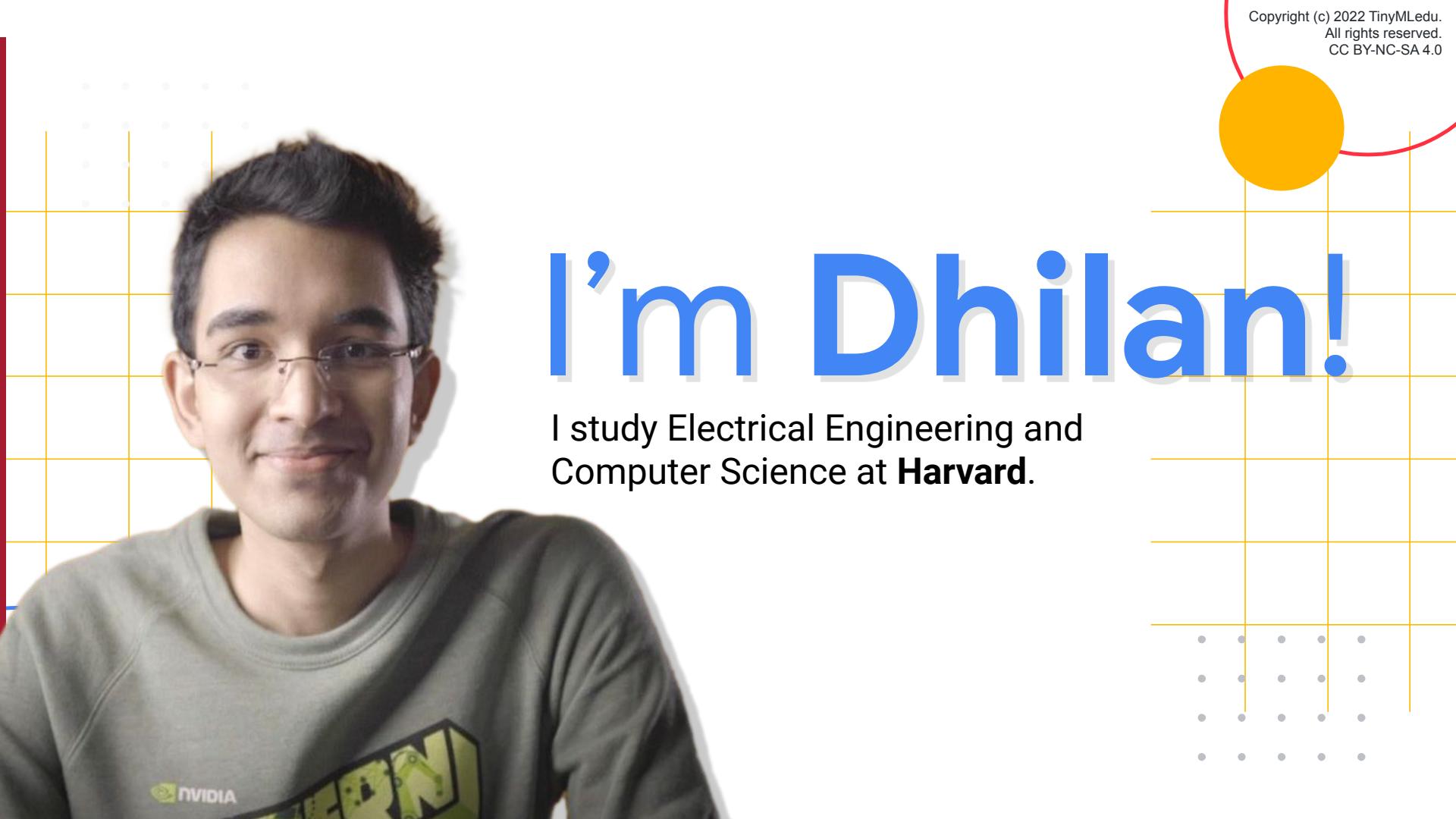
Keyword Spotting for the Navajo Language

Mobile ML

Day 3

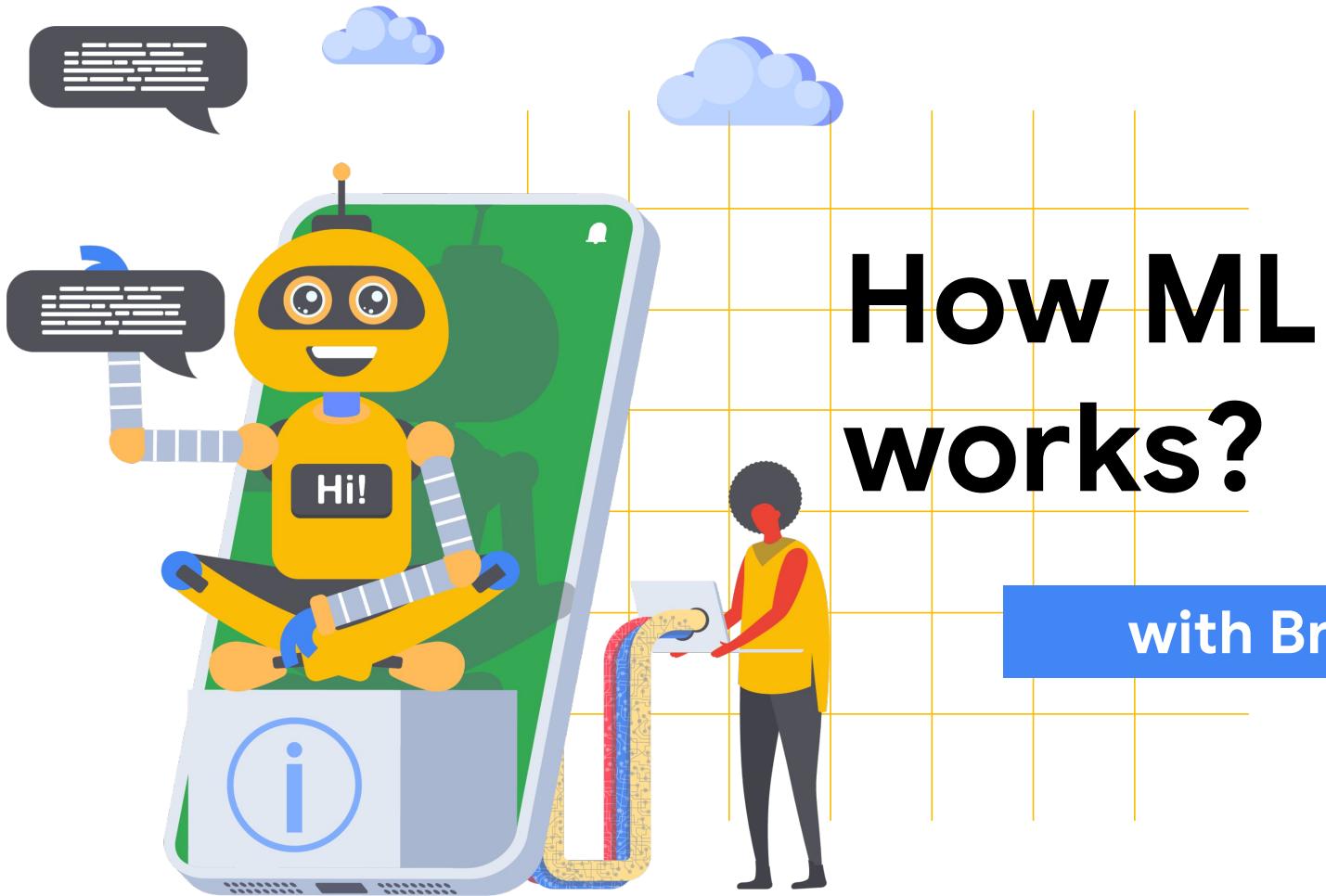
Bringing AI/ML from the Cloud to the Edge

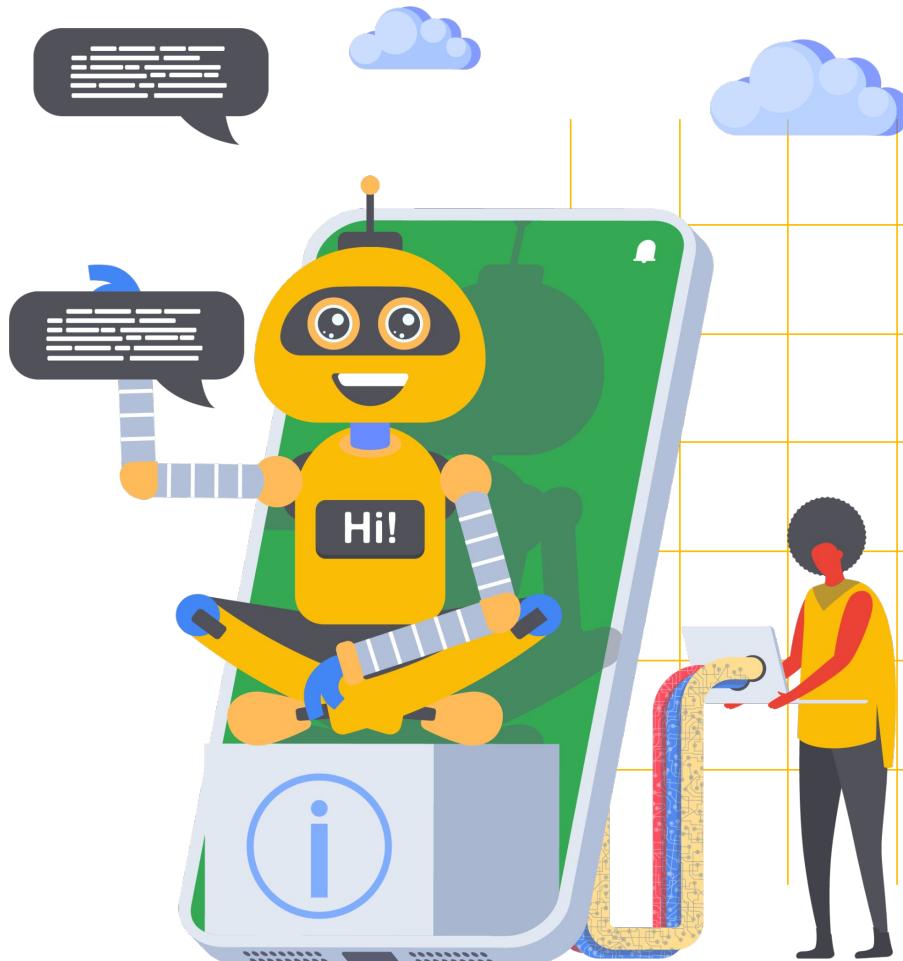
Embedded ML



# I'm Dhilan!

I study Electrical Engineering and  
Computer Science at **Harvard**.

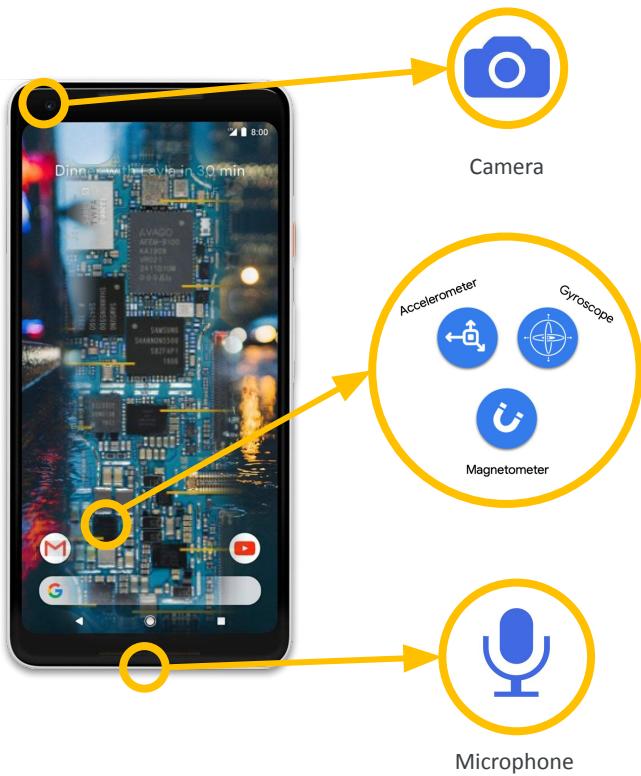




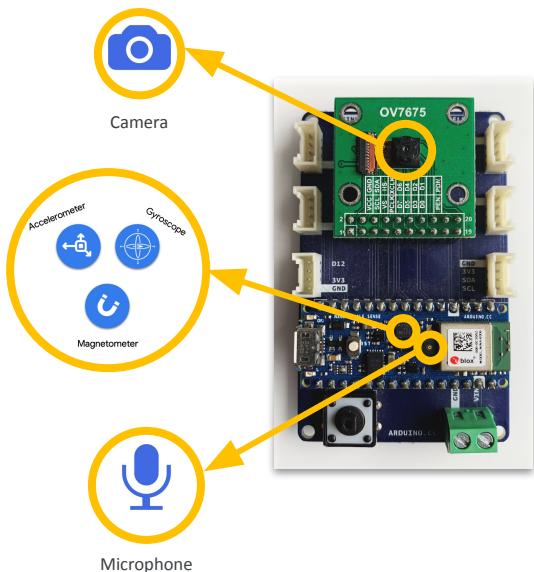
# Where ML works?

with Dhilan

# Last time: Phone



# Today: TinyML Kit



A screenshot of the Arduino Serial Monitor window titled '/dev/ttyACM0'. The window displays multiple prediction outputs. The main output is highlighted with a red box:

```
Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.)  
no: 0.00000  
noise: 0.10156  
unknown: 0.89062  
yes: 0.00781
```

Below this, there are two more prediction outputs:

```
Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.)  
no: 0.00000  
noise: 0.10156  
unknown: 0.89062  
yes: 0.00781
```

At the bottom of the monitor, the status bar shows 'Done in 6.694 seconds'.

# Today's Agenda

- Review + Why Tiny?
- Hardware Basics
- Installing and Starting the Arduino IDE
- Testing Your TinyML Kit
- Deploying KWS model onto Arduino
- Summary & Next Steps

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## Review + Why Tiny?

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# Machine Learning Workflow



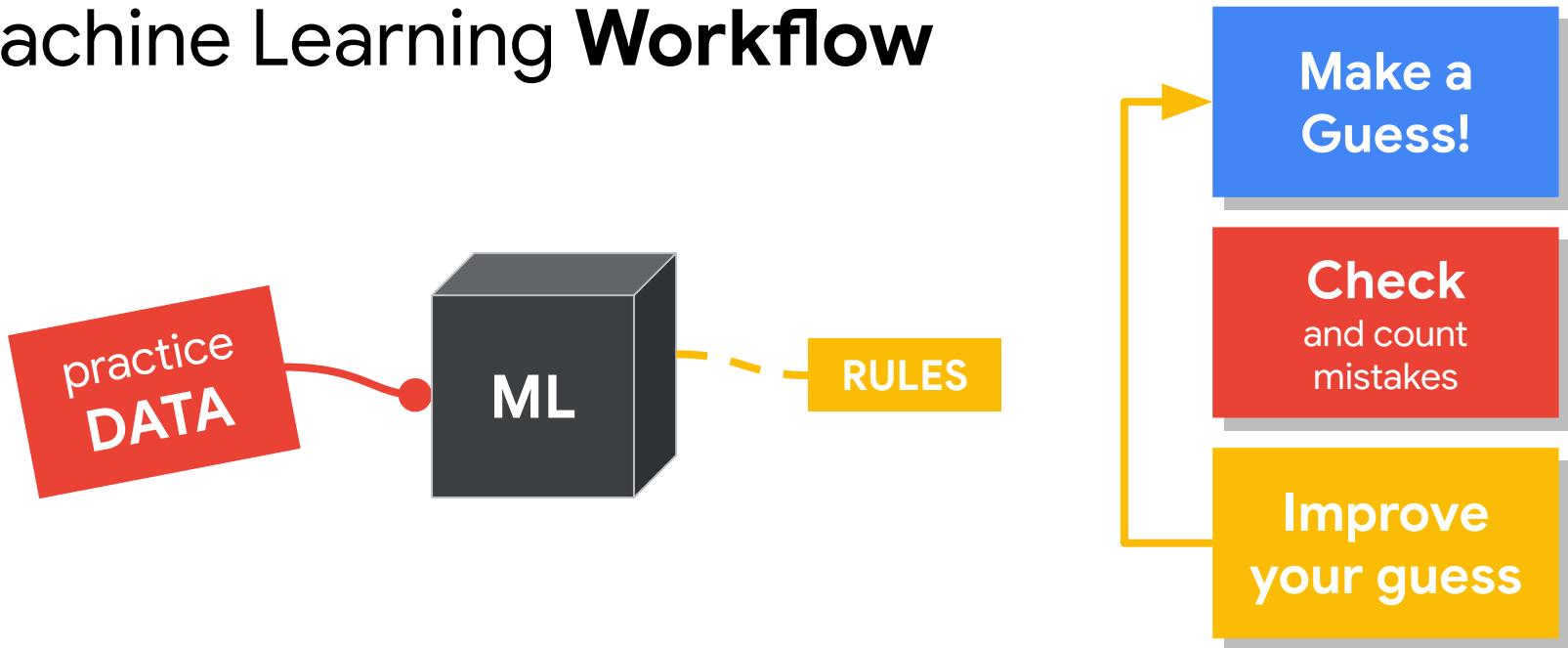
# Machine Learning Workflow



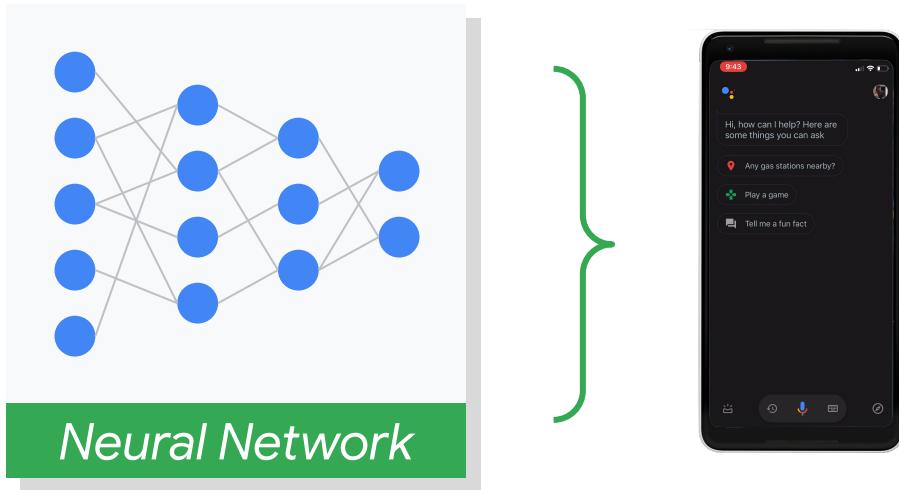
INPUTS	LABELS
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9	0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9



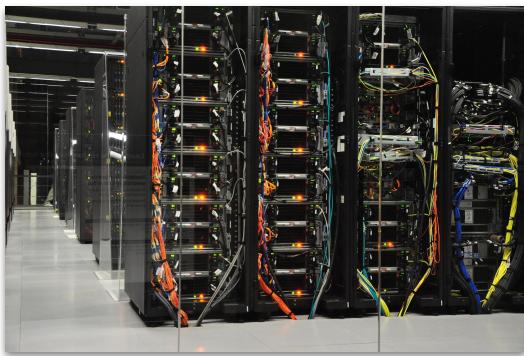
# Machine Learning Workflow



# Machine Learning Workflow



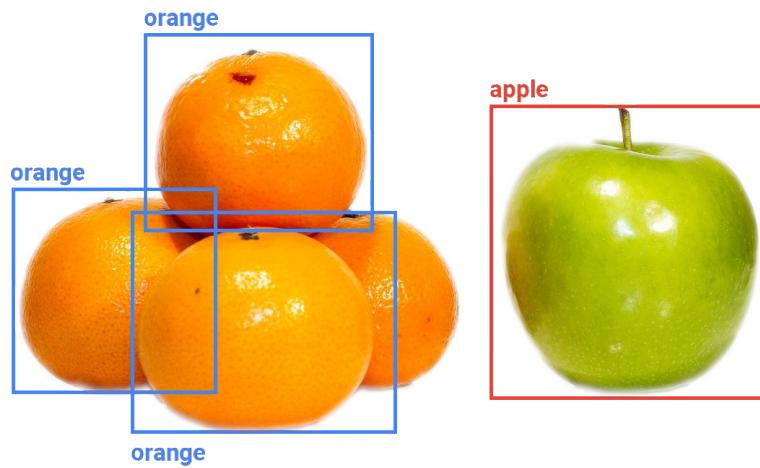
# Machine Learning Workflow



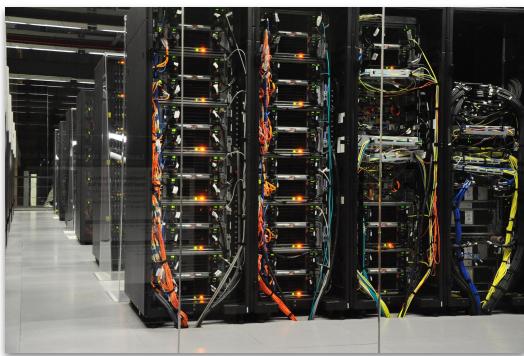
Google  
Assistant



# Machine Learning Workflow



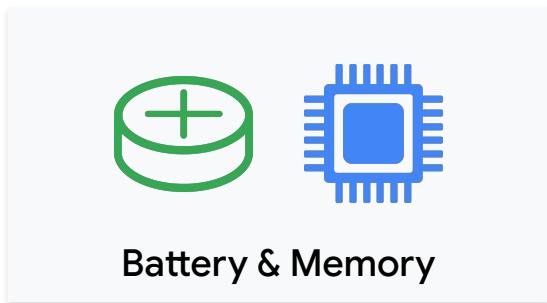
# Machine Learning Workflow



Google  
Assistant



# Machine Learning Workflow



Less memory

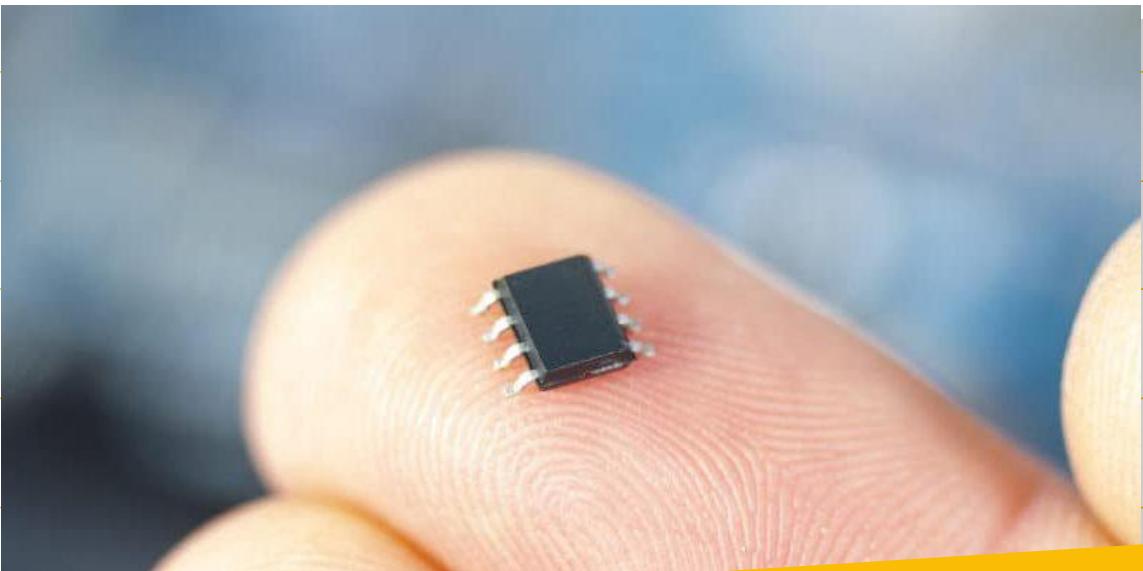
Less compute power

Only focused on *inference*



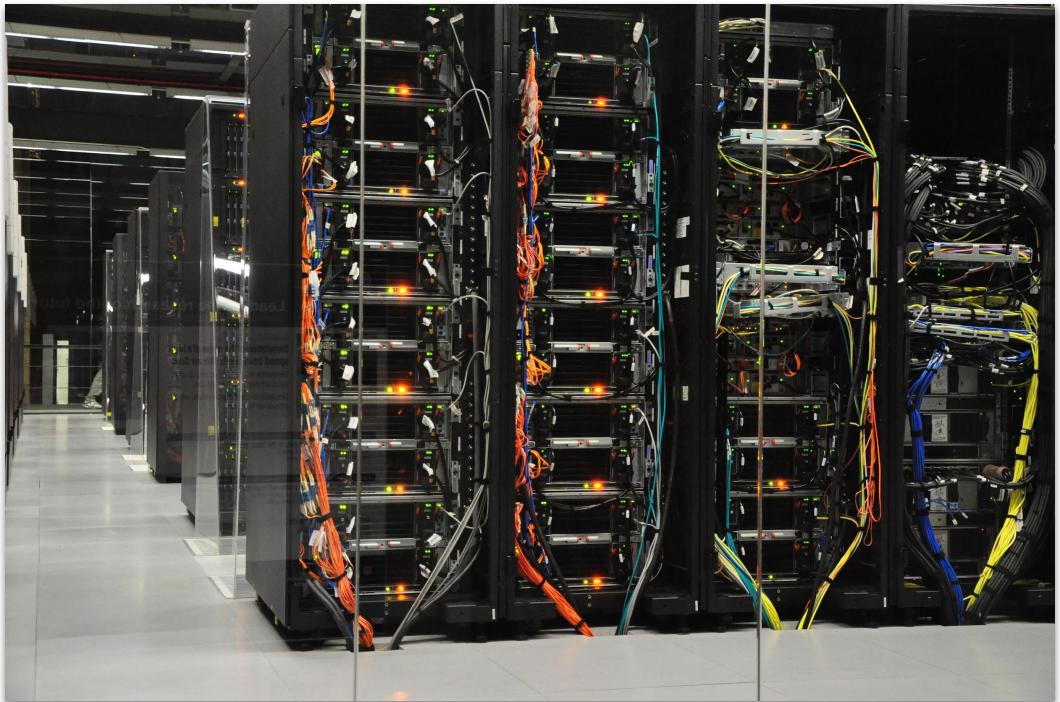
deploy

to your tiny **devices!**

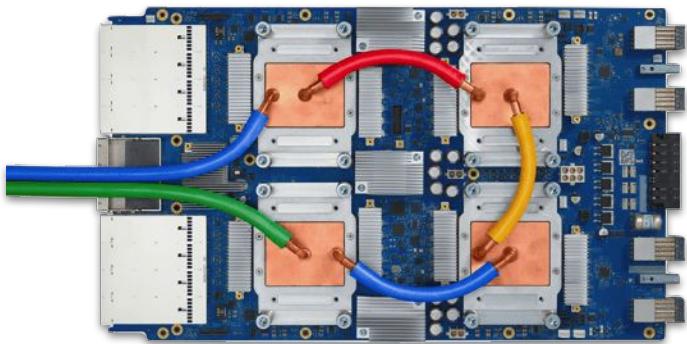


TinyML

# Datacenter



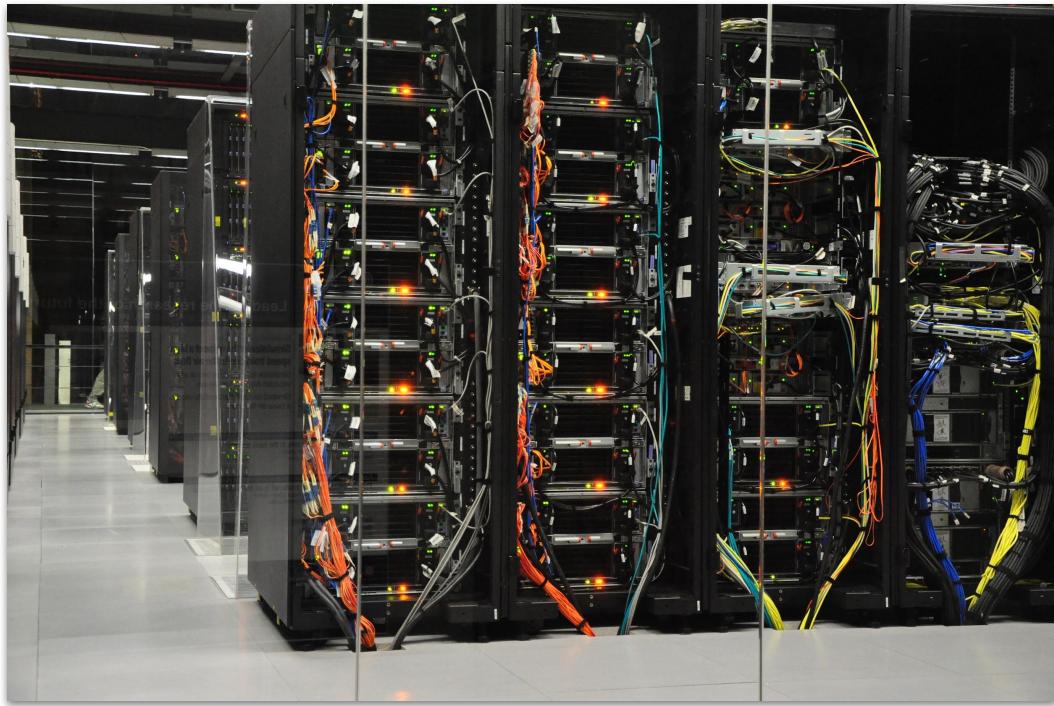
# TPUs/GPUs

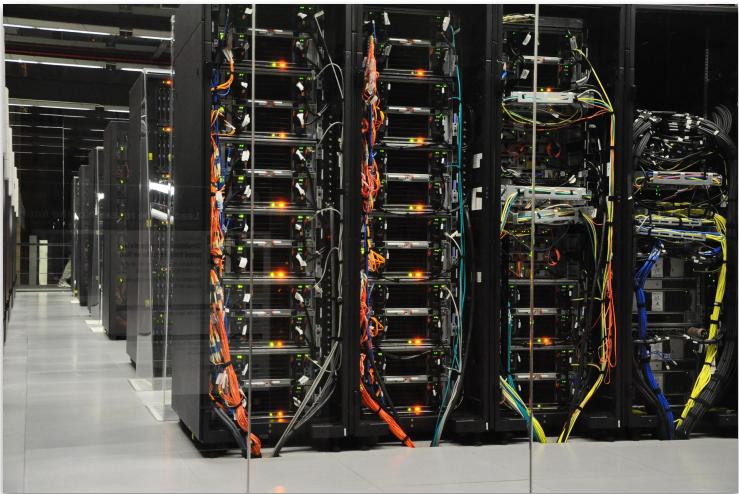


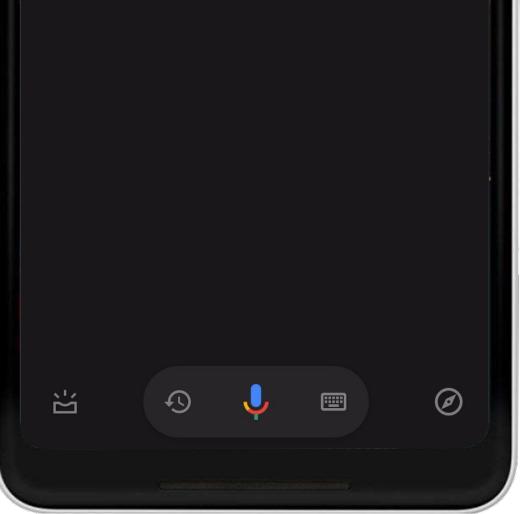
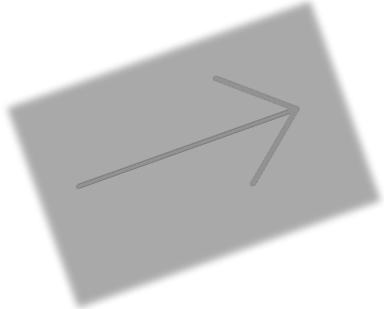


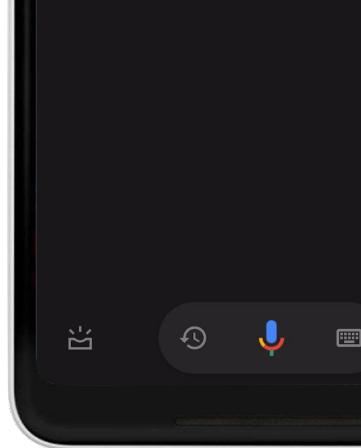
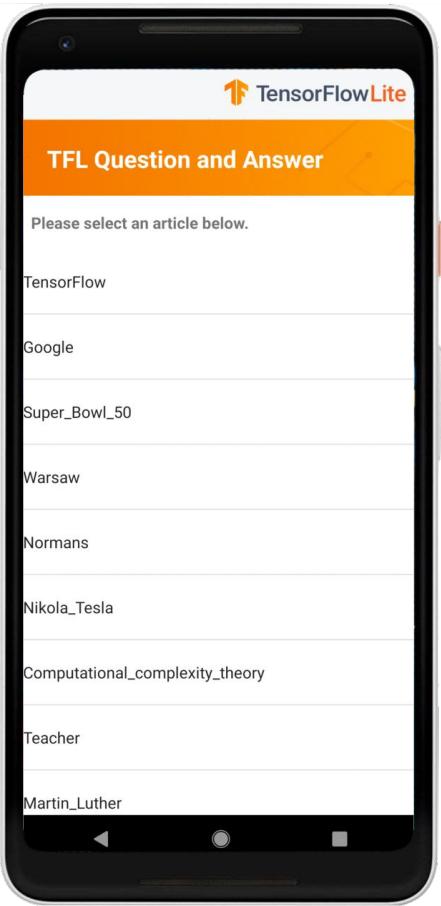
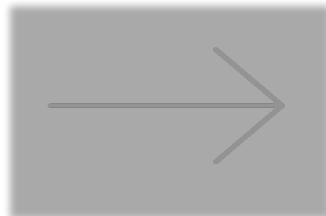
# Bigger Is Not Always Better.

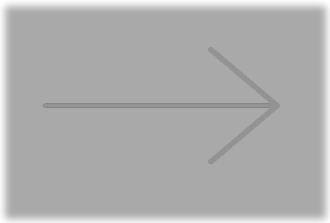
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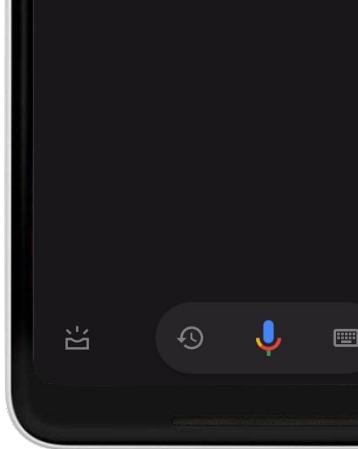


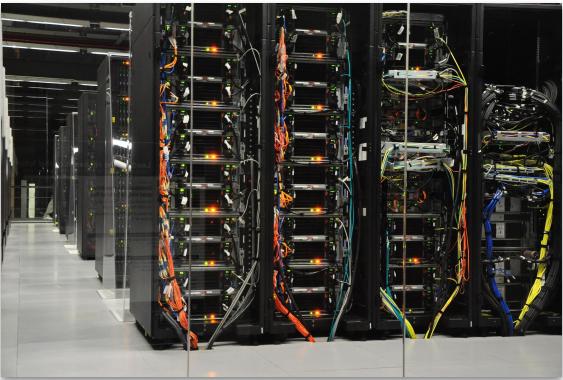
TensorFlow

### TFL Question and Answer

Please select an article below.

- TensorFlow
- Google
- Super\_Bowl\_50
- Warsaw
- Normans

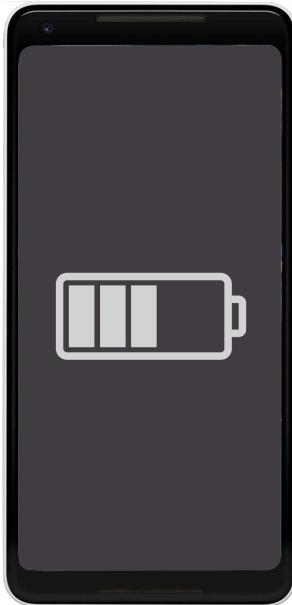
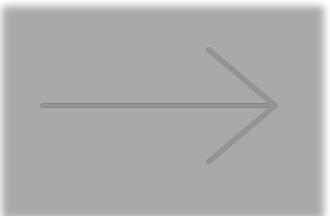
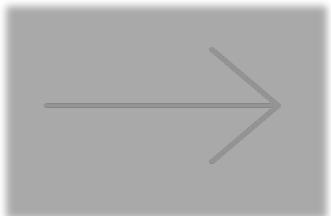


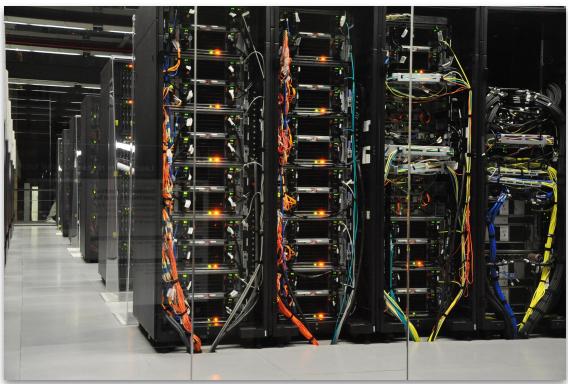


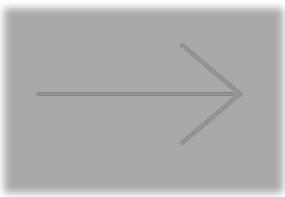
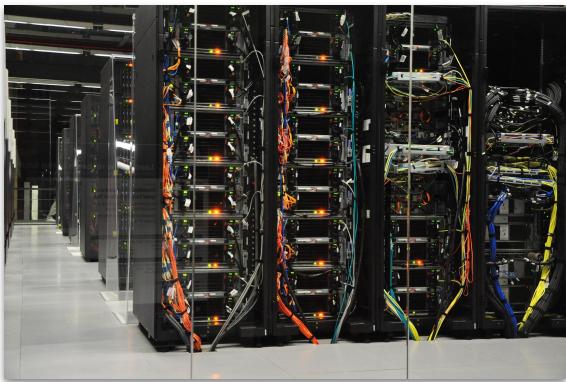
**High power**  
**High bandwidth**  
**High latency**

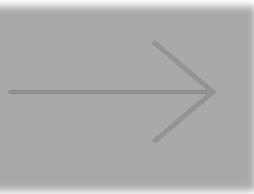
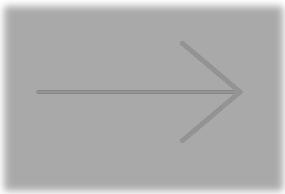
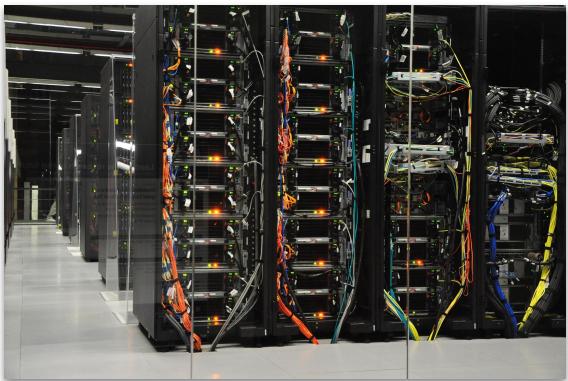


**Low power**  
**Low bandwidth**  
**Low latency**









Google Assistant



# Endpoint Devices



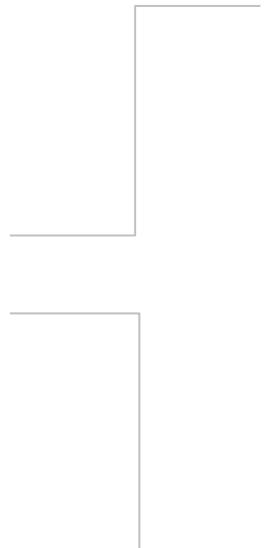
Google Assistant



# Endpoint Devices



Google Assistant



# Endpoints Have Sensors, Tons of Sensors

## Motion Sensors

Gyroscope, radar,  
magnetometer, accelerator

## Acoustic Sensors

Ultrasonic, Microphones,  
Geophones, Vibrometers

## Environmental Sensors

Temperature, Humidity,  
Pressure, IR, etc.

## Touchscreen Sensors

Capacitive, IR

## Image Sensors

Thermal, Image

## Biometric Sensors

Fingerprint, Heart rate, etc.

## Force Sensors

Pressure, Strain

## Rotation Sensors

Encoders

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Encoders

# Biometric Sensors



Non-invasive Glucose Monitoring



Fingerprint + Photoplethysmography (PPG)

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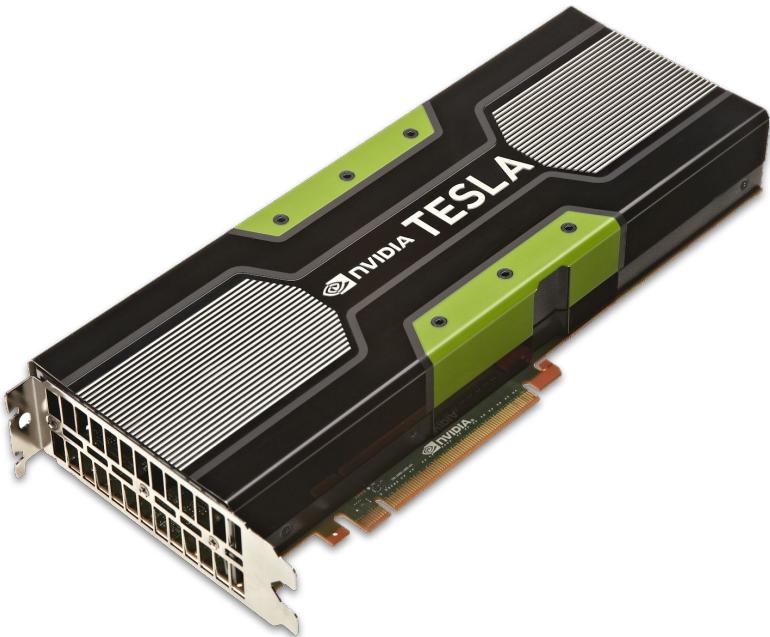
## Force Sensors

Pressure, Strain

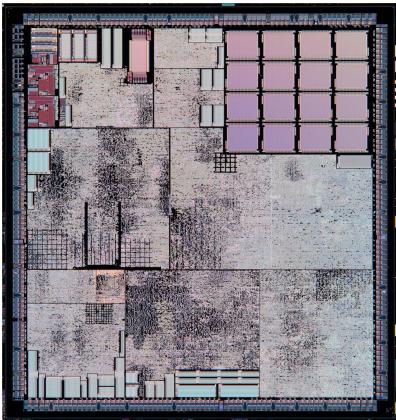
## Rotation Sensors

Encoders

# Thinking Big



# Thinking Big



# Thinking Big



# Thinking Small



# Thinking Small



# Thinking Small



**BIG**  
GPU / CPU  
 $561mm^2$



**SMALL**  
Mobile SoC  
 $83mm^2$

# Thinking Tiny



**Mobile SoC**  
 $83\text{mm}^2$



# Thinking Tiny



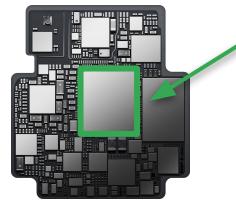
**Mobile SoC**  
 $83mm^2$



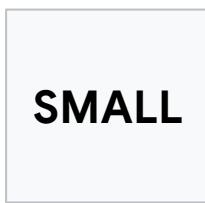
# Thinking Tiny



**Mobile SoC**  
 $83mm^2$



# Thinking Tiny



**Mobile SoC**  
 $83mm^2$



**Apple 0778**  
 $30mm^2$

# We're just getting started.

# Thinking Record-breaking

**BIG**  
GPU / CPU  
 $561\text{mm}^2$

**SMALL**

Mobile SoC  
 $83\text{mm}^2$

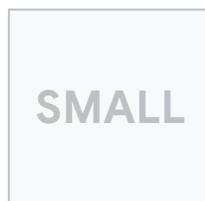
TINY

Apple 0778  
 $30\text{mm}^2$



Kinetis KL03  
 $3.2\text{mm}^2$

# Thinking Record-breaking

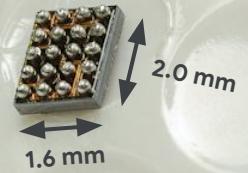


**world's smallest  
ARM-Powered MCU**

48MHz, 32KB flash, 20-pin



**Kinetis KL03**  
3.2mm<sup>2</sup>



250 Billion  
*today*

# Challenges



Latency & Bandwidth



Accuracy & Personalization



Security & Privacy



Battery & Memory



Source: Google



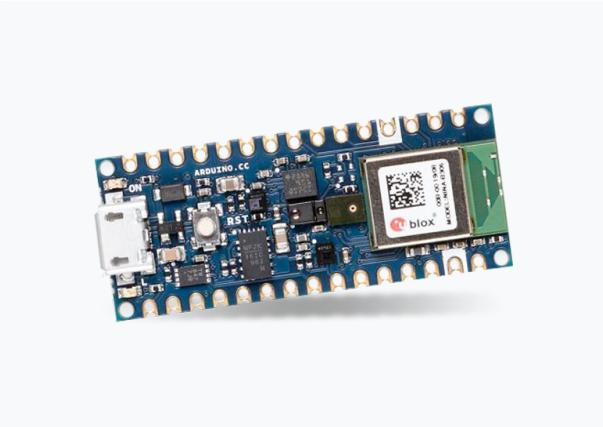
Source: Google



Less memory

Less compute power

Only focused on *inference*

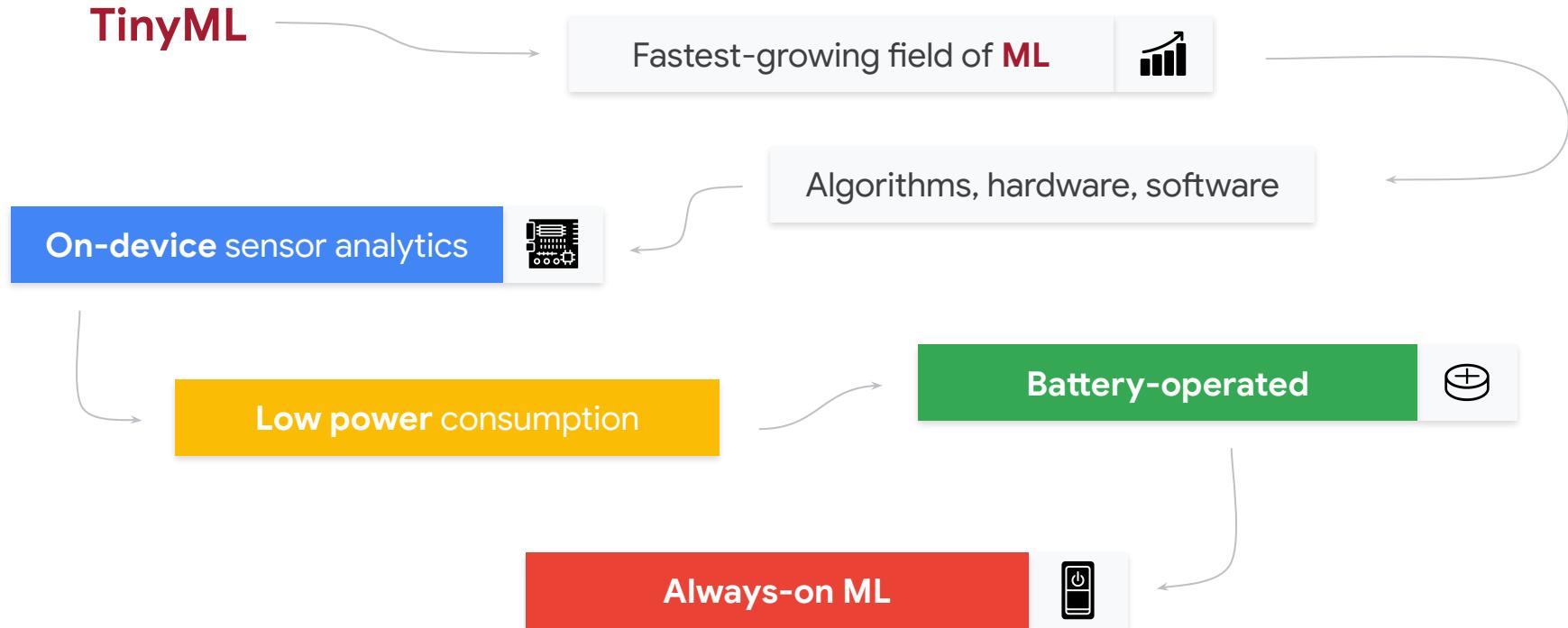


**Even less memory**

**Even less compute power**

**Also, only focused on *inference***

# What is Tiny Machine Learning (**TinyML**)?





Measuring capacity by watt-hours  
lets us compare any type of battery



**1**  
12 V car battery

$$\begin{array}{r} \text{1 battery} \\ \times (12 \text{ V} \times 50 \text{ Ah}) \\ \hline 600 \text{ Wh} \end{array}$$



**133**  
9 V batteries

$$\begin{array}{r} \text{133 batteries} \\ \times (9 \text{ V} \times .5 \text{ Ah}) \\ \hline 600 \text{ Wh} \end{array}$$



**67**  
3.6 V smartphones

$$\begin{array}{r} \text{67 smartphones} \\ \times (3.6 \text{ V} \times 2.5 \text{ Ah}) \\ \hline 600 \text{ Wh} \end{array}$$

## TYPICAL BATTERY LIFE



Data Usage

## TYPICAL BATTERY LIFE

transmit less  
data!



Data Usage

# Today's Agenda

- Review + Why Tiny?
- Hardware Basics
- Installing and Starting the Arduino IDE
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# Today's Agenda

- Review + Why Tiny?

## Hardware Basics

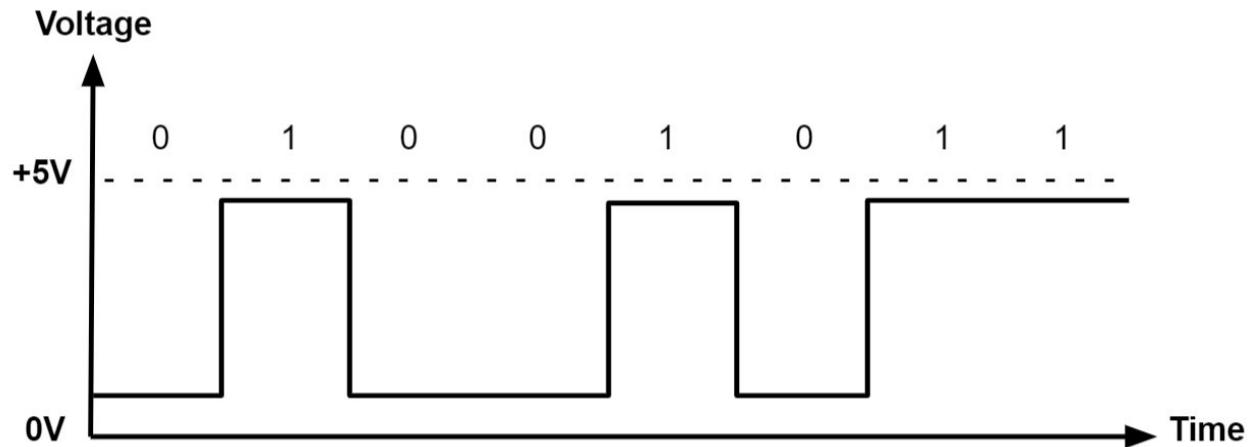
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## language of computers

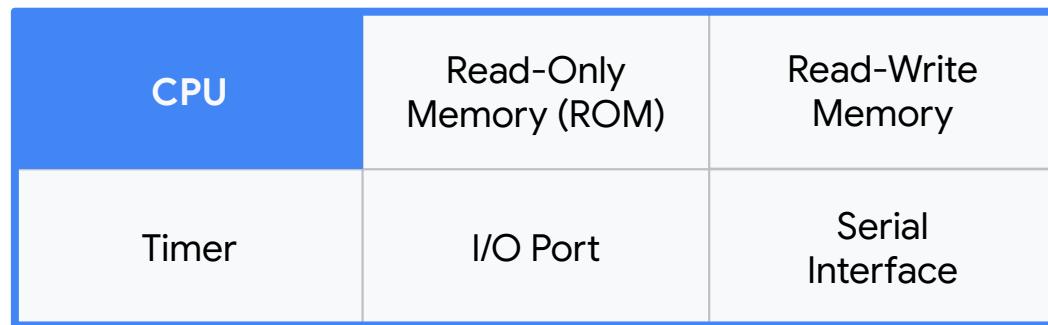
Binary	Hex	Decimal
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	8
1001	9	9
1010	A	10
1011	B	11
1100	C	12
1101	D	13
1110	E	14
1111	F	15



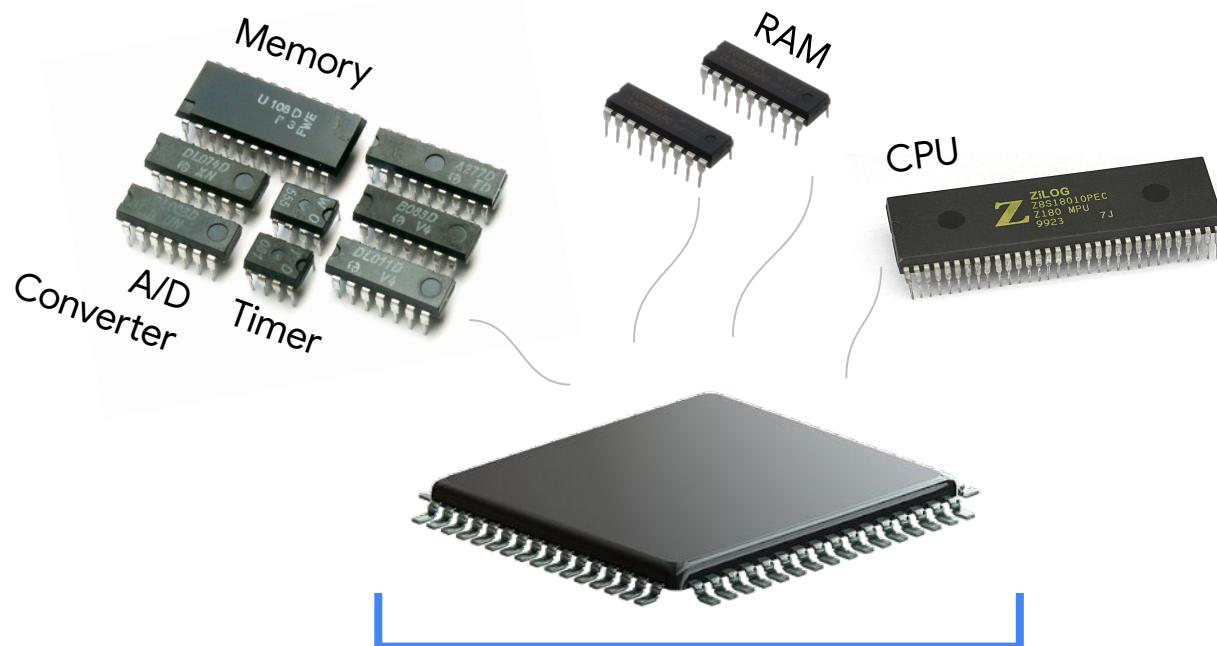




# Microcontroller



# Microcontroller: a **complete package**

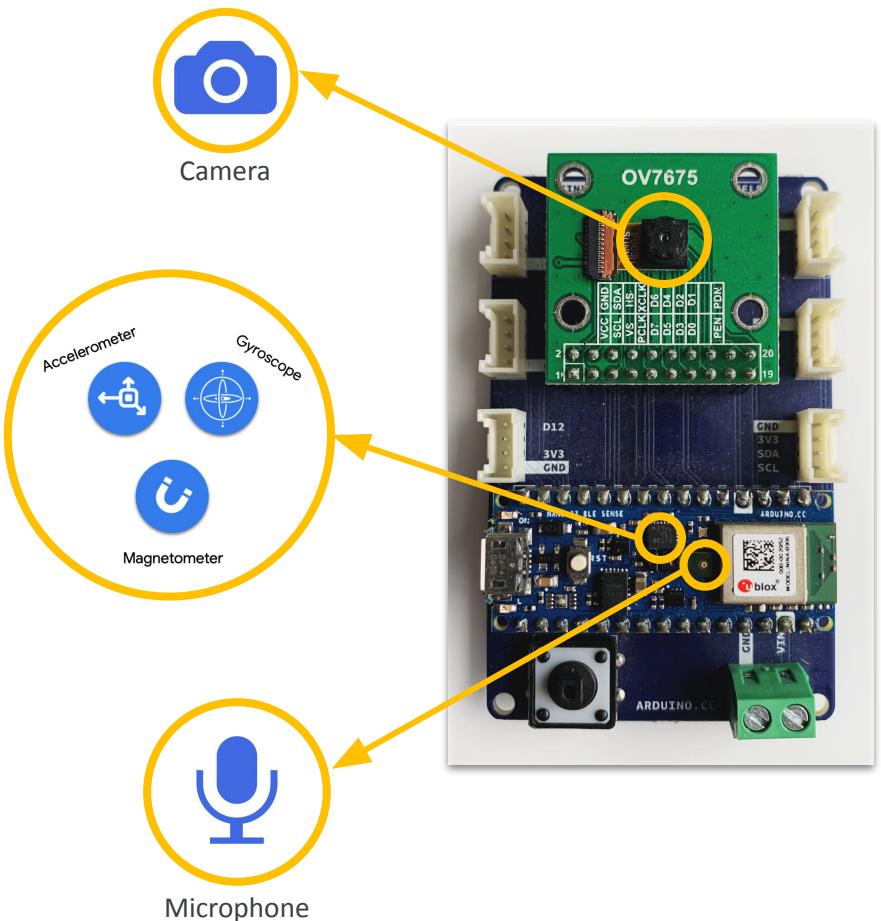


# Embedded Systems

	Board	MCU / ASIC	Clock	Memory	Sensors	Radio
	Himax WE-I Plus EVB	HX6537-A 32-bit EM9D DSP	400 MHz	2MB flash 2MB RAM	Accelerometer, Mic, Camera	None
	Arduino Nano 33 BLE Sense	32-bit nRF52840	64 MHz	1MB flash 256kB RAM	Mic, IMU, Temp, Humidity, Gesture, Pressure, Proximity, Brightness, Color	BLE
	SparkFun Edge 2	32-bit ArtemisV1	48 MHz	1MB flash 384kB RAM	Accelerometer, Mic, Camera	BLE
	Espressif EYE	32-bit ESP32-D0WD	240 MHz	4MB flash 520kB RAM	Mic, Camera	WiFi, BLE

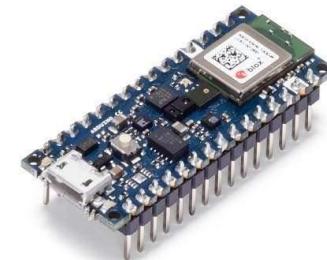
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	SparkFun Edge 2 32-bit ArtemisV1	48 MHz	1MB flash 384kB RAM	Accelerometer, Mic, Camera	BLE
	Espressif EYE 32-bit ESP32-D0WD	240 MHz	4MB flash 520kB RAM	Mic, Camera	WiFi, BLE





# Nano 33 BLE Sense (+ USB cable)



## Purpose

AI-enabled developmental **microcontroller board** with USB-A to microB cable

## Specifications

- nRF52840 MCU (ARM Cortex-M4): 3.3V, 64MHz, 1MB flash, 256 kB RAM
- Sensors on board: microphone, IMU, color, light, proximity, temperature, humidity, and more!
- BLE module with application-adjacent protocol layers (GAP, GATT) covered by **ArduinoBLE** library

# OV 7675 Camera Module



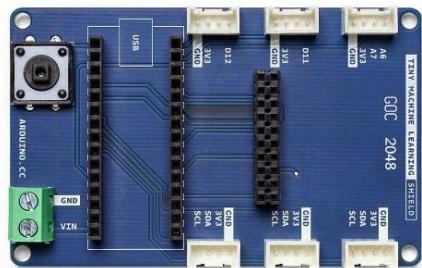
## Purpose

Breakout PCB for **tiny** camera, for use in person-detection exercises

## Specifications

- Low-voltage, 0.3 MP CMOS VGA (can step down to QVGA, QQVGA) image sensor
- Serial Camera Control Bus (SCCB) + Camera Parallel Interface (CPI) / Digital Video Port (DVP) interface
- Breaks ribbon cable out to 2x10 pin array

# Tiny Machine Learning Shield

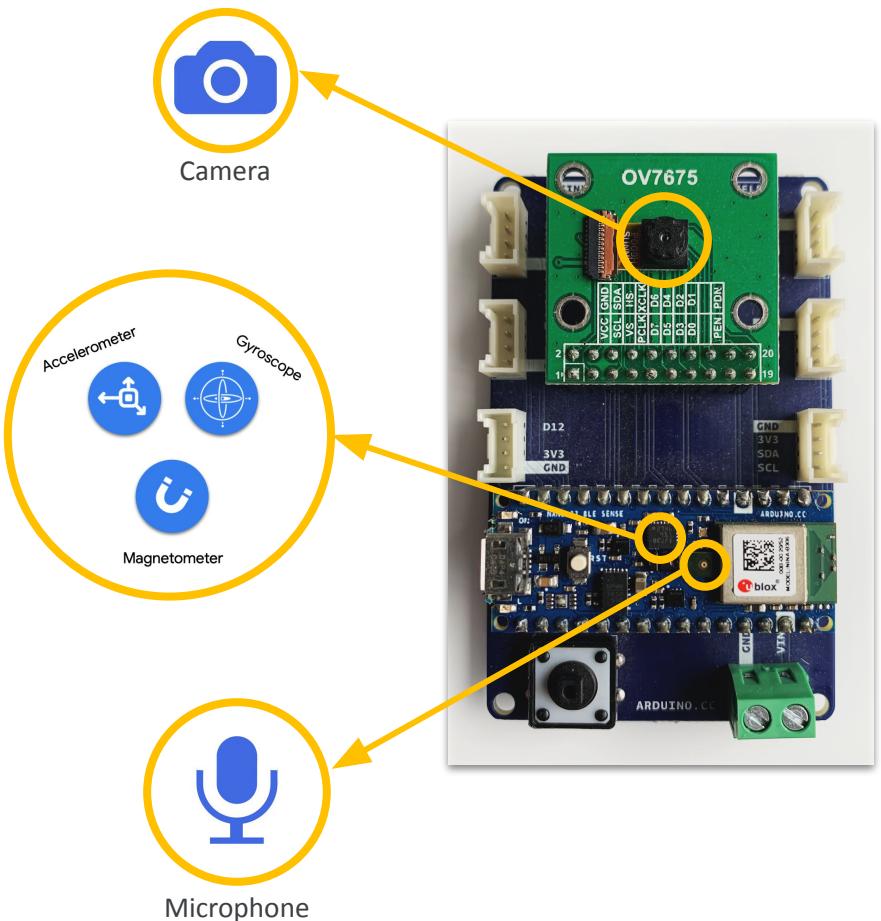


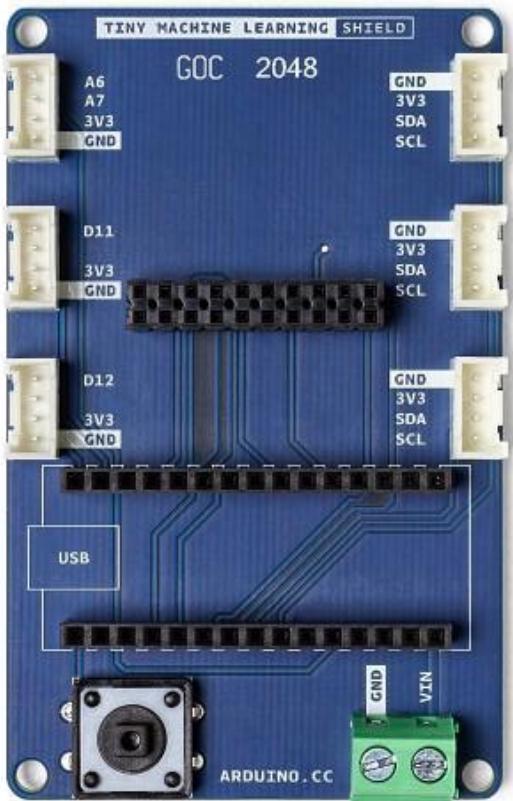
## Purpose

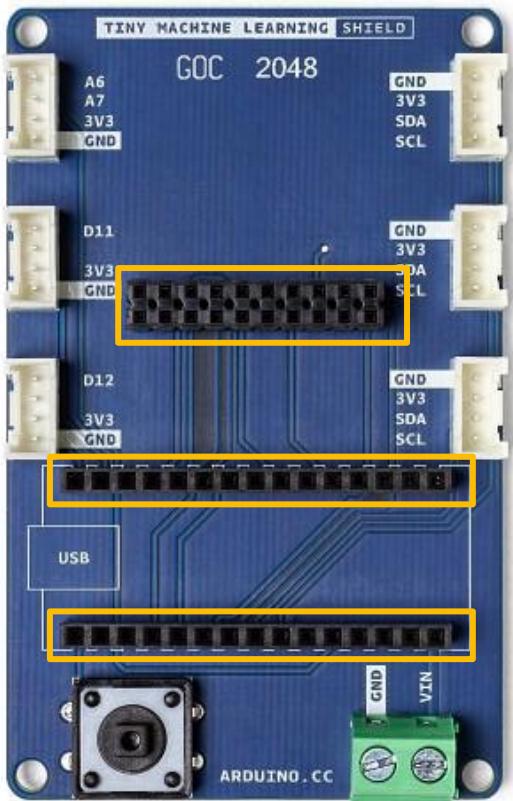
A daughter PCB designed to **breakout the I/O** from the Nano 33 BLE sense to permit easy, reliable **communication with** other local, **off-board elements**

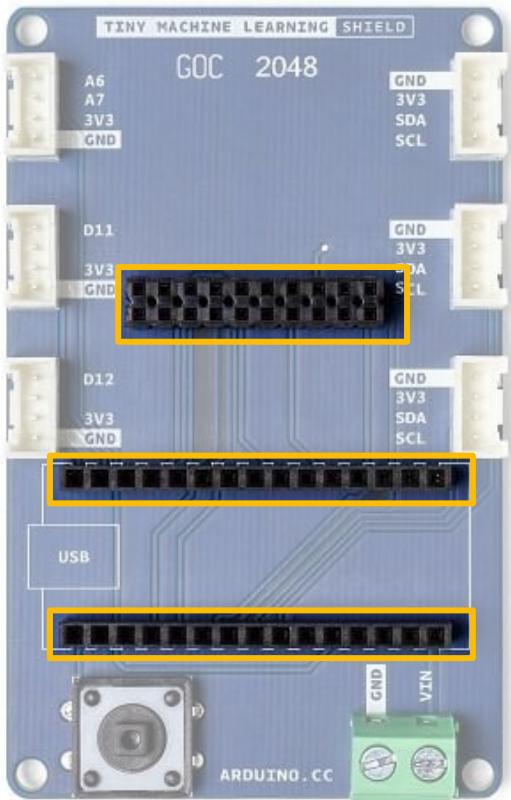
## Specifications

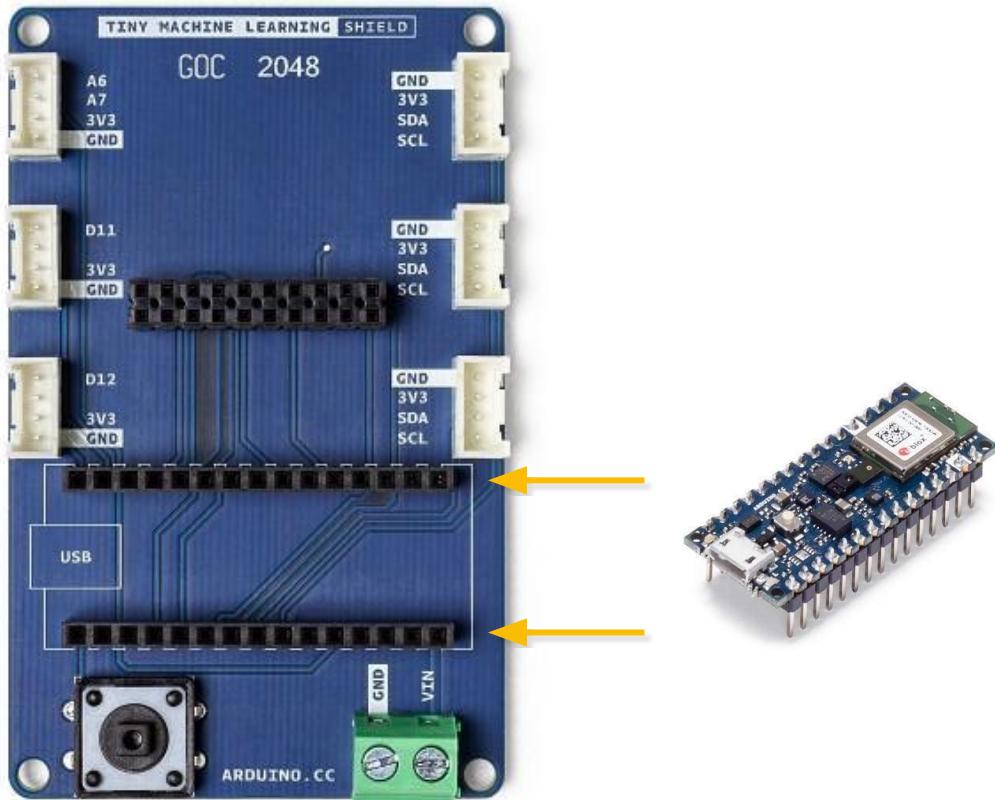
- Grove connectors (3.3V I2C and simple digital / analog - see pinouts)
- 2x10 pin array for OV7675 camera module
- Voltage input terminal block, accepts 4.5 to 21V (down regulated to 3.3V on Nano 33)

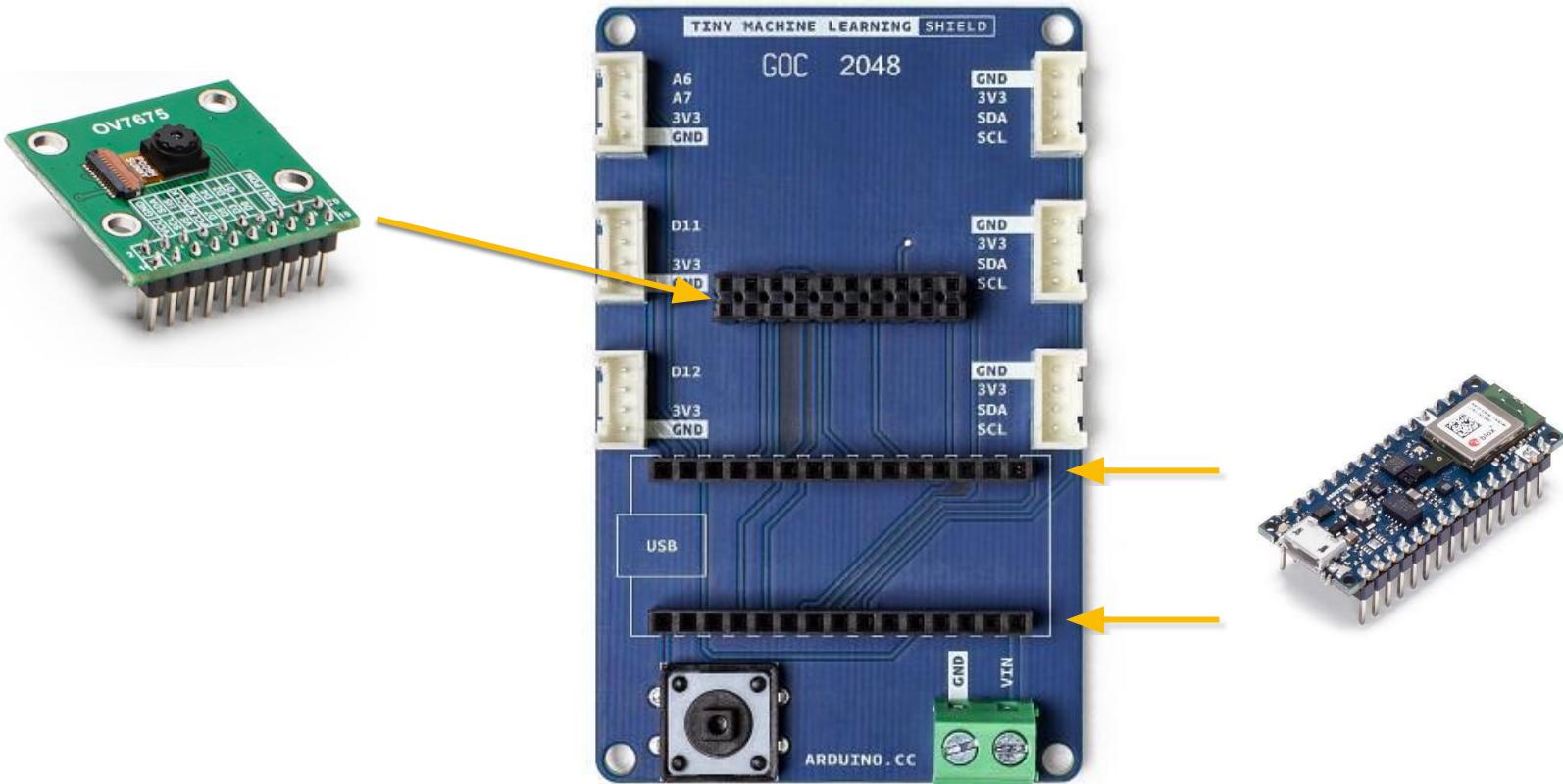


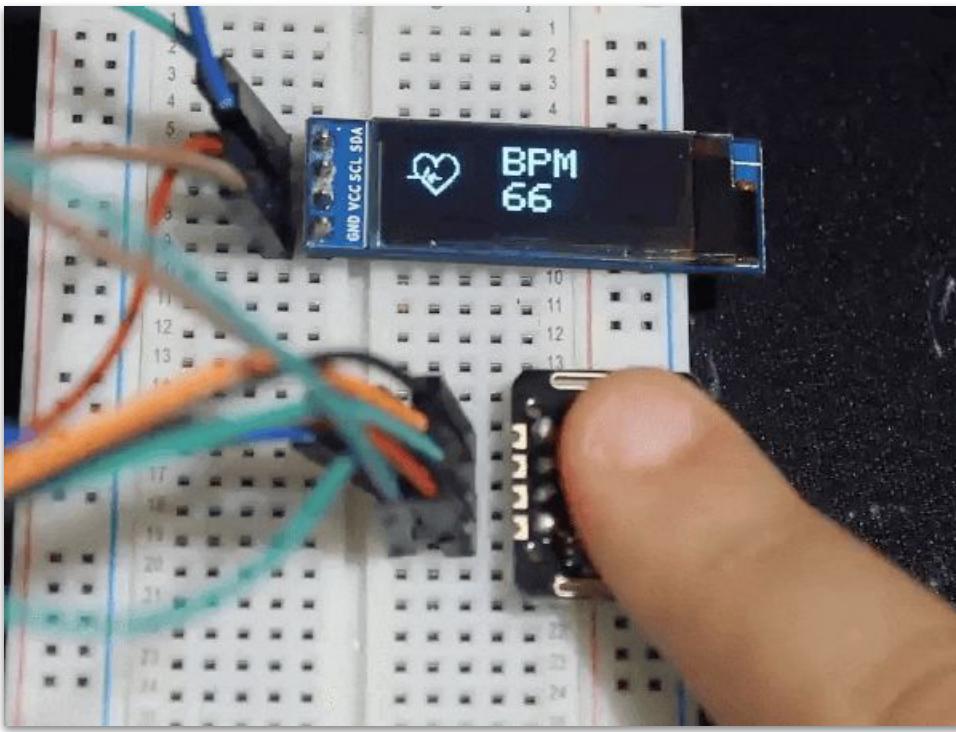














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HARDWARE

SOFTWARE

CLOUD

DO

[www.arduino.cc/en/software](http://www.arduino.cc/en/software)

# Downloads



## Arduino IDE 1.8.19

The open-source Arduino Software (IDE) makes it easy to write code and upload it to the board. This software can be used with any Arduino board.

Refer to the [Getting Started](#) page for Installation instructions.

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### DOWNLOAD OPTIONS

**Windows** Win 7 and newer

**Windows** ZIP file

**Windows app** Win 8.1 or 10



**Linux** 32 bits

**Linux** 64 bits

**Linux** ARM 32 bits

**Linux** ARM 64 bits

**Mac OS X** 10.10 or newer

[Release Notes](#)

[Checksums \(sha512\)](#)

HARDWARE

SOFTWARE

CLOUD

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[www.arduino.cc/en/software](http://www.arduino.cc/en/software)

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1. If you have a reliable Internet connection, you should use the [online IDE](#) (Arduino Web Editor). It will allow you to save your sketches in the cloud, having them available from any device and backed up. You will always have the most up-to-date version of the IDE without the need to install updates or community generated libraries.
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- [Windows](#)
- [Mac OS](#)
- [Linux](#)
- [Portable IDE](#) (Windows and Linux)
- [ChromeOS](#) (Arduino Create App) in the [Chrome Web Store](#)

Choose your board in the list here on the right to learn how to get started with it and how to use it on the Desktop IDE.

## Learn Arduino

- Read an [introduction](#) on what is Arduino and why you'd want to use it.
- What is the [Arduino Software \(IDE\)](#) and how do I change the default language?

Arduino IoT Cloud:

[Getting Started with Arduino IoT Cloud](#)

Instructions for our boards:

[Due](#)

[MEGA2560](#)

[MKR1000](#)

[MKR WiFi 1010](#)

[MKR FOX 1200](#)

[MKR WAN 1300](#)

[MKR WAN 1310](#)

[MKR GSM 1400](#)

[MKR NB 1500](#)

[MKR Vidor 4000](#)

[MKRZERO](#)

[Nano](#)

[NANO 33 IoT](#)

[NANO 33 BLE](#)

[NANO 33 BLE Sense](#)

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[MKR NB 1500](#)

[MKR Vidor 4000](#)

[MKRZERO](#)

[Nano](#)

[NANO 33 IoT](#)

[NANO 33 BLE](#)

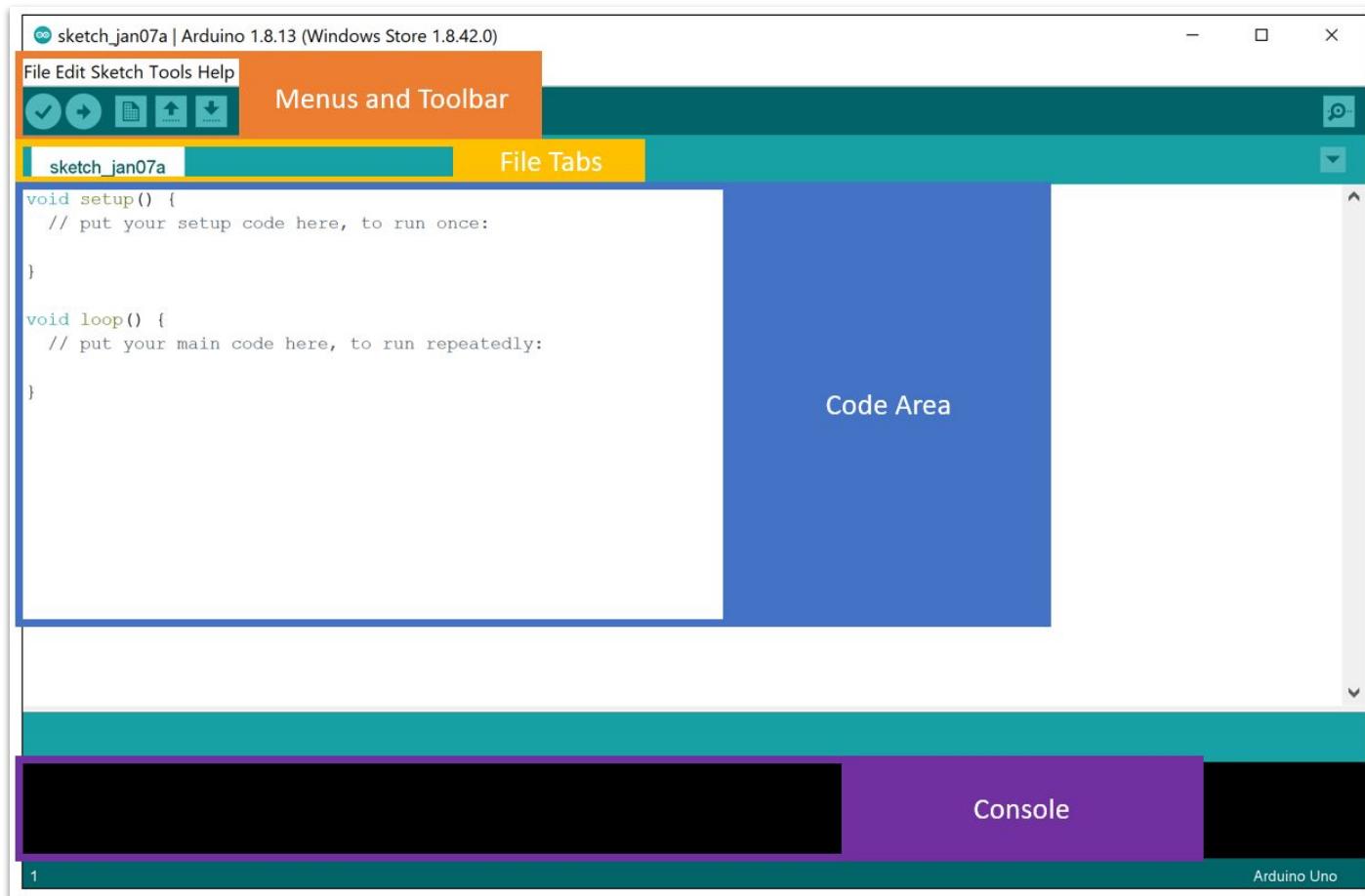
[NANO 33 BLE Sense](#)

head to Arduino's software **website**

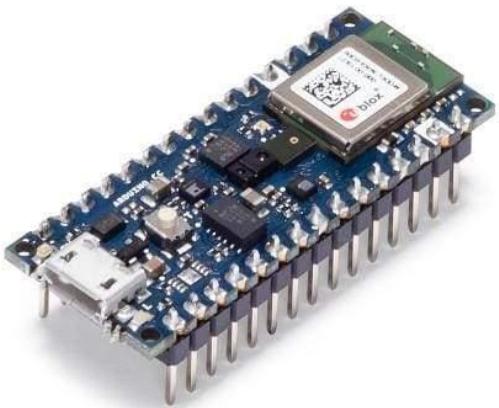
[www.arduino.cc/en/software](http://www.arduino.cc/en/software)

then **download** and **install**

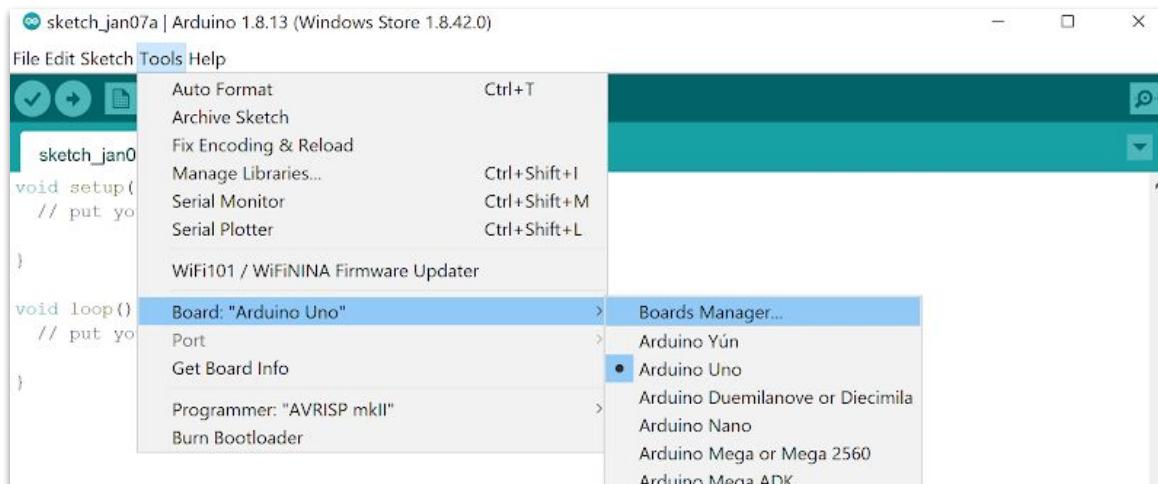
*right now!*

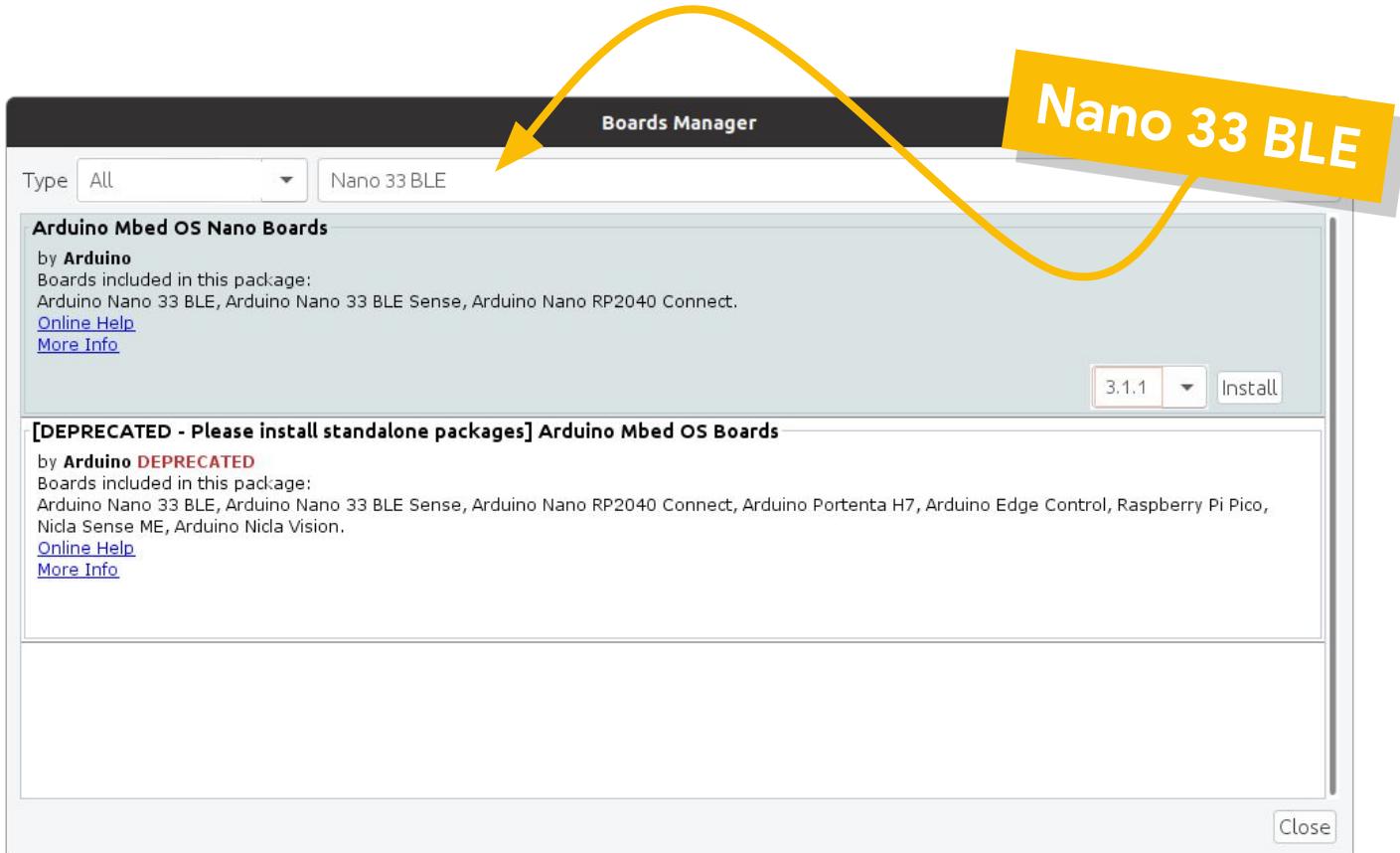


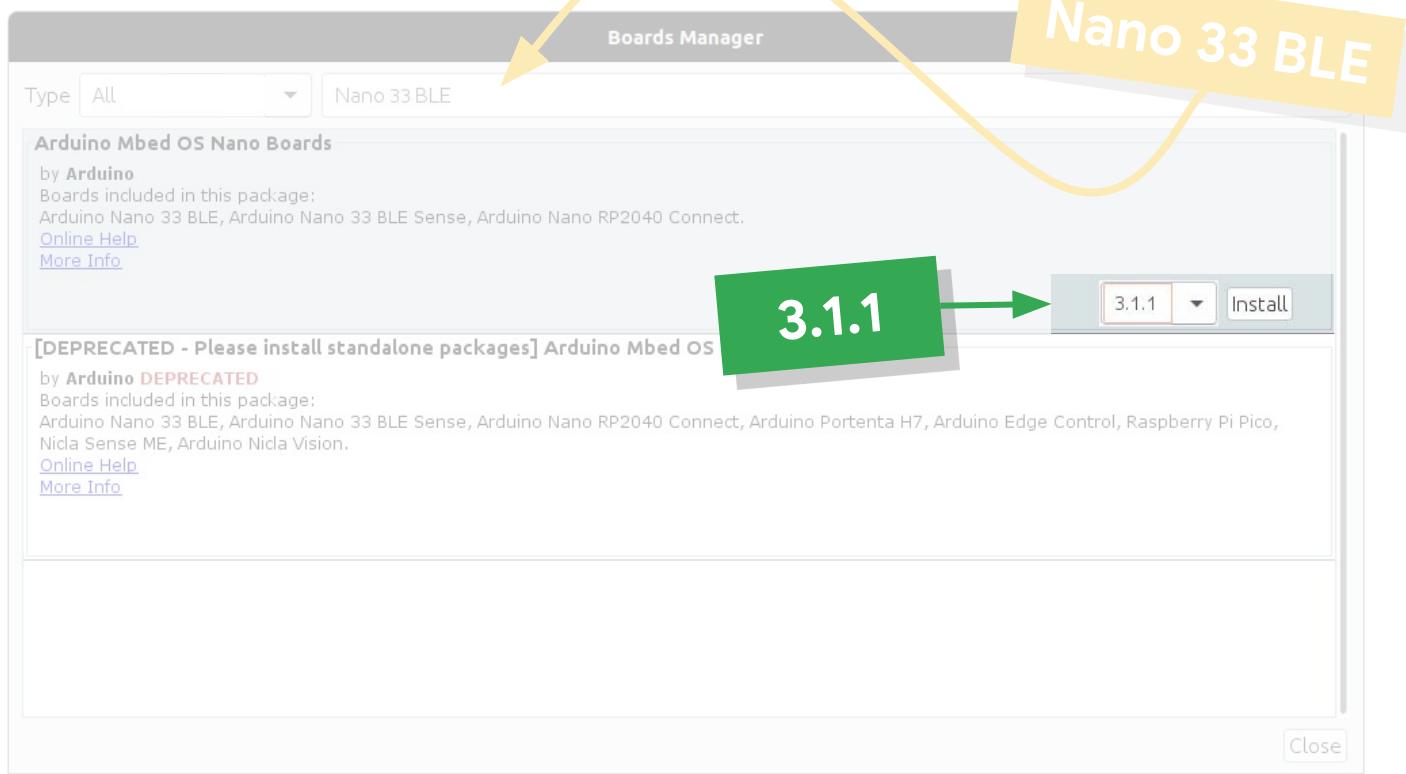
## Install Extras



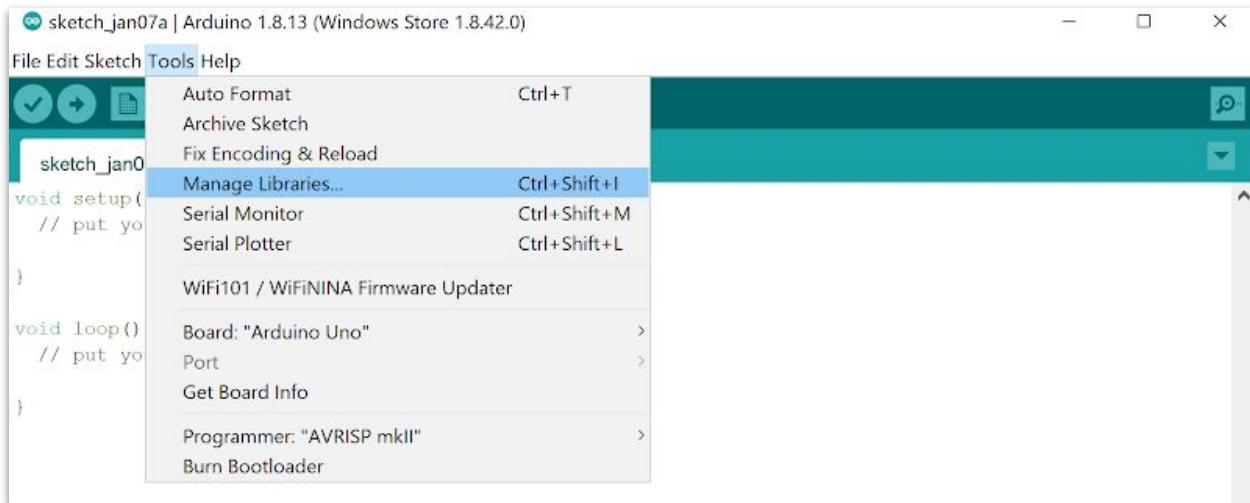
# Tools → Board → Boards Manager



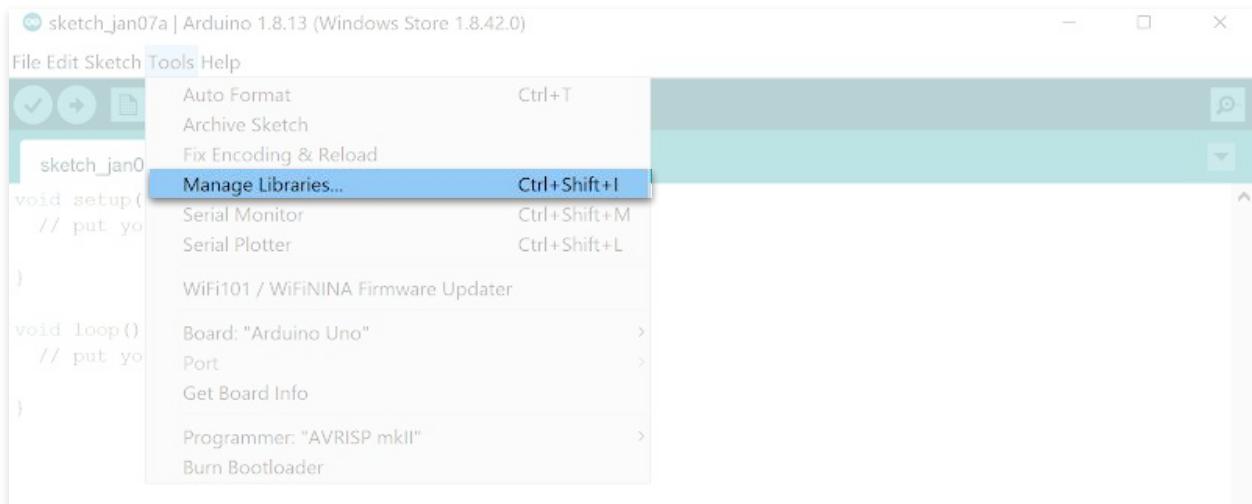




# Tools → Manage Libraries...



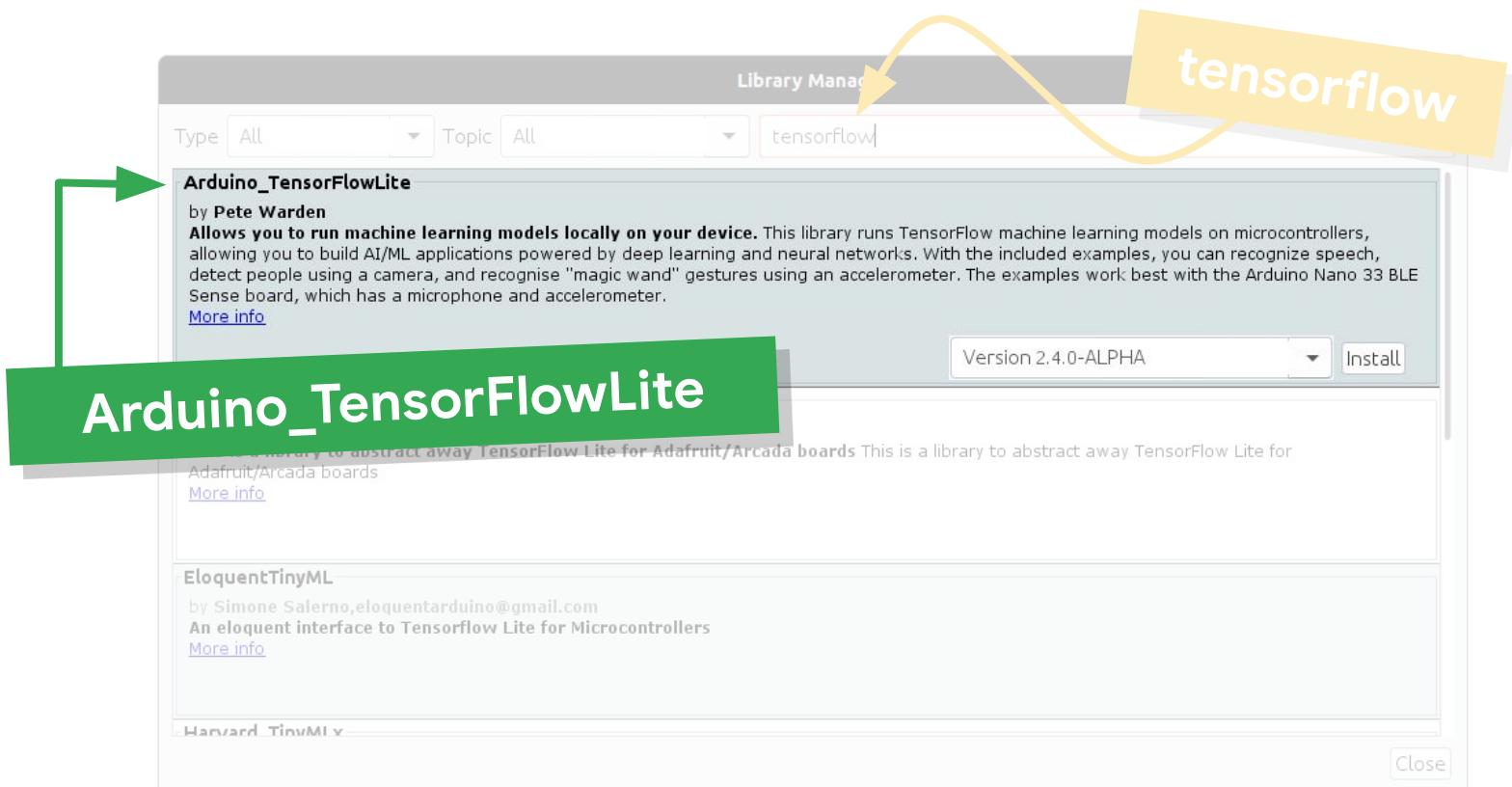
# Tools → Manage Libraries...

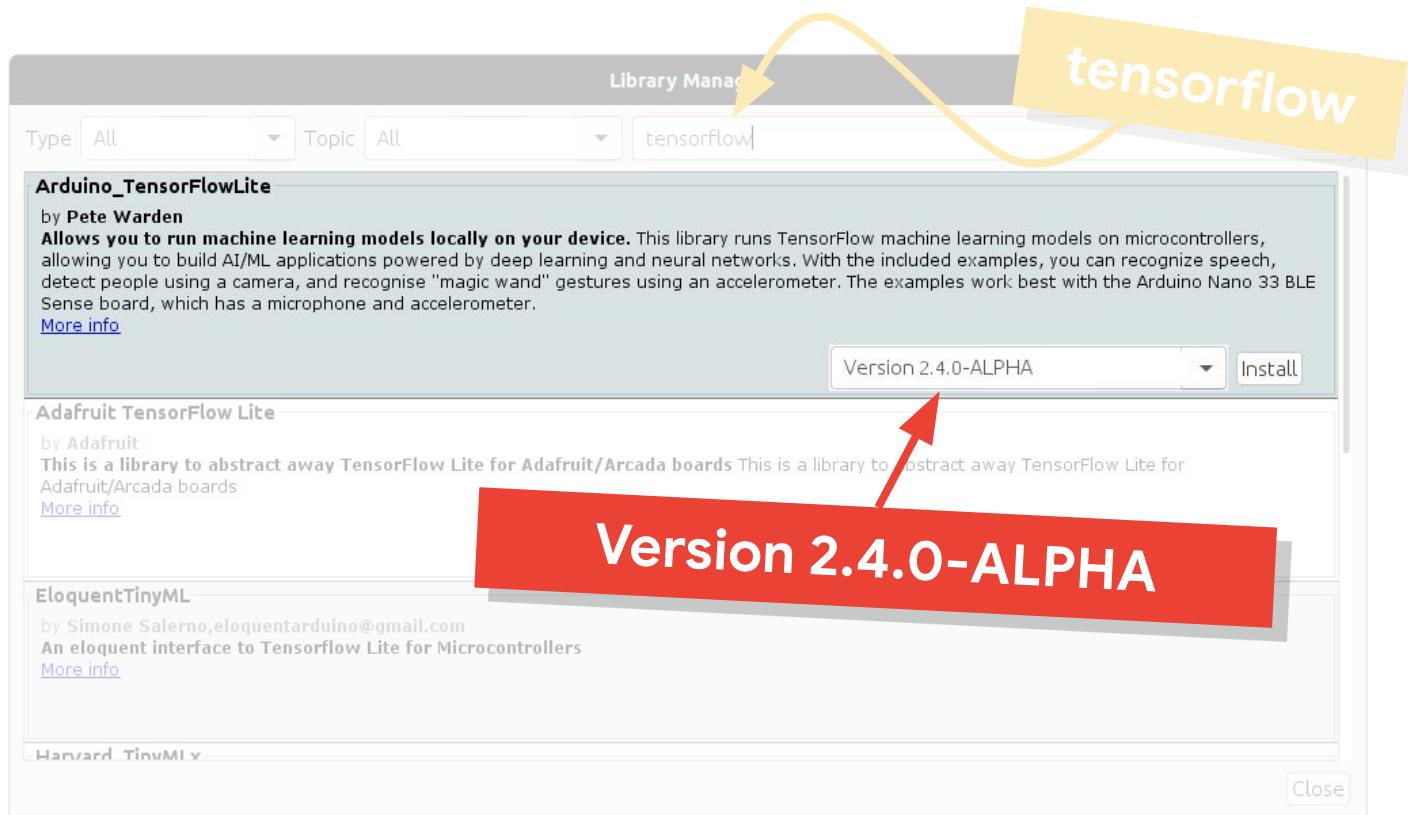


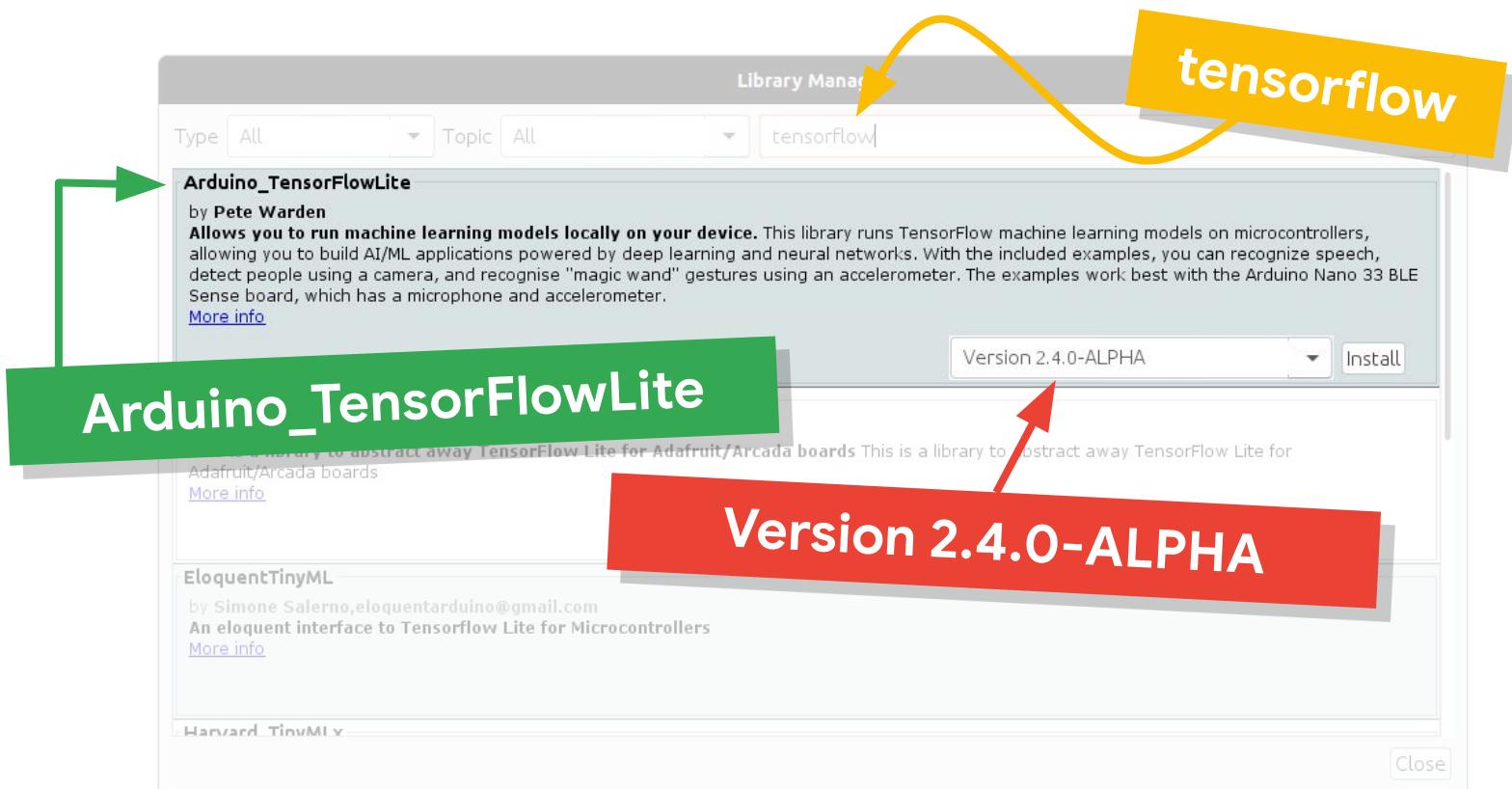
The screenshot shows the Arduino Library Manager interface. At the top, there is a search bar with the text "tensorflow". A yellow arrow points from a large yellow banner with the word "tensorflow" on it towards the search bar. Below the search bar, there are two dropdown menus: "Type All" and "Topic All". The main content area displays three library entries:

- Arduino\_TensorFlowLite** by Pete Warden. Description: Allows you to run machine learning models locally on your device. This library runs TensorFlow machine learning models on microcontrollers, allowing you to build AI/ML applications powered by deep learning and neural networks. With the included examples, you can recognize speech, detect people using a camera, and recognise "magic wand" gestures using an accelerometer. The examples work best with the Arduino Nano 33 BLE Sense board, which has a microphone and accelerometer. [More info](#). Version: 2.4.0-ALPHA. [Install](#).
- Adafruit TensorFlow Lite** by Adafruit. Description: This is a library to abstract away TensorFlow Lite for Adafruit/Arcada boards. This is a library to abstract away TensorFlow Lite for Adafruit/Arcada boards. [More info](#).
- EloquentTinyML** by Simone Salerno, eloquentarduino@gmail.com. Description: An eloquent interface to Tensorflow Lite for Microcontrollers. [More info](#).

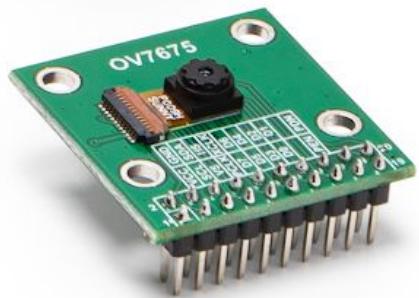
At the bottom left, there is a small logo for Harvard TinyML. On the right side of the bottom bar, there is a "Close" button.

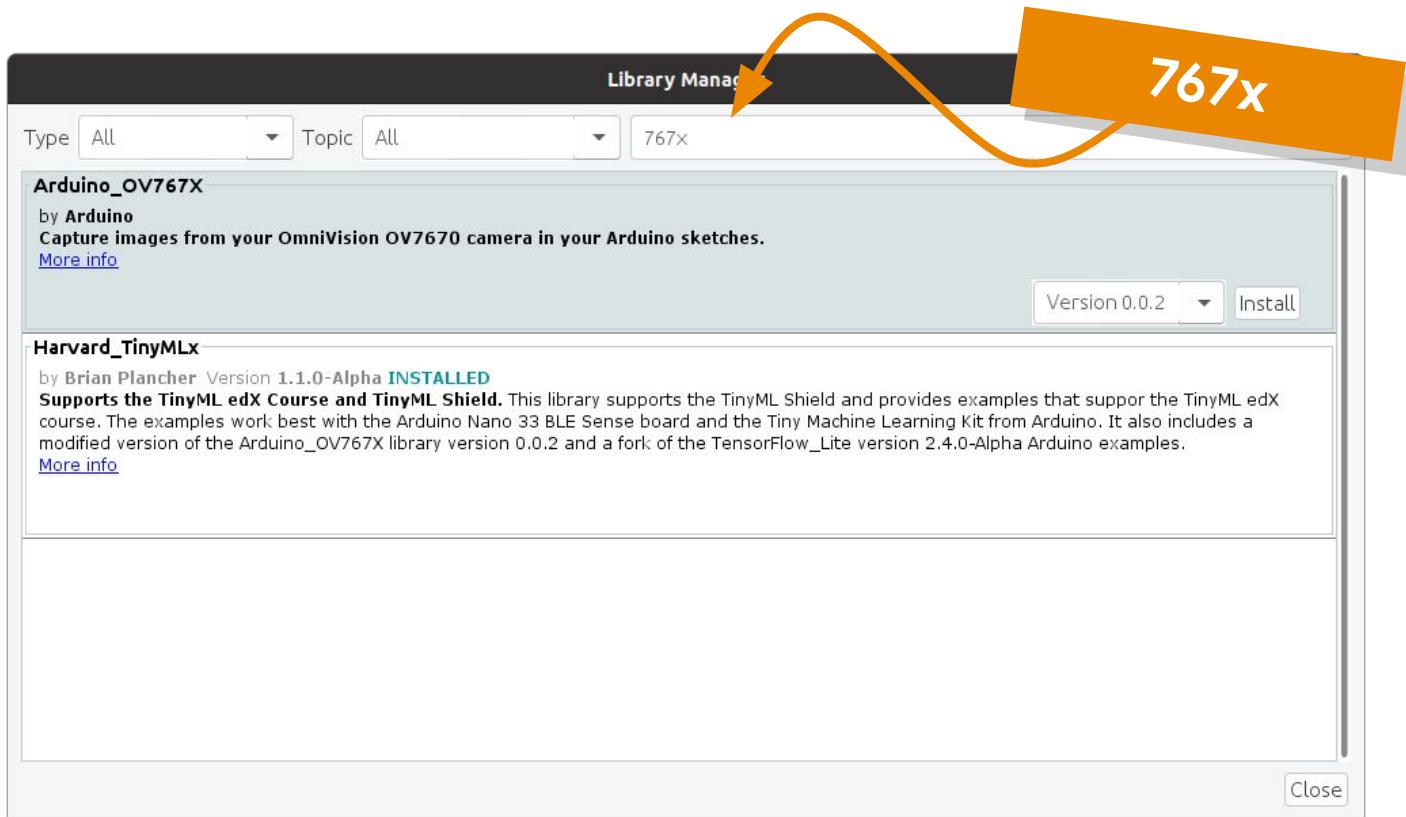




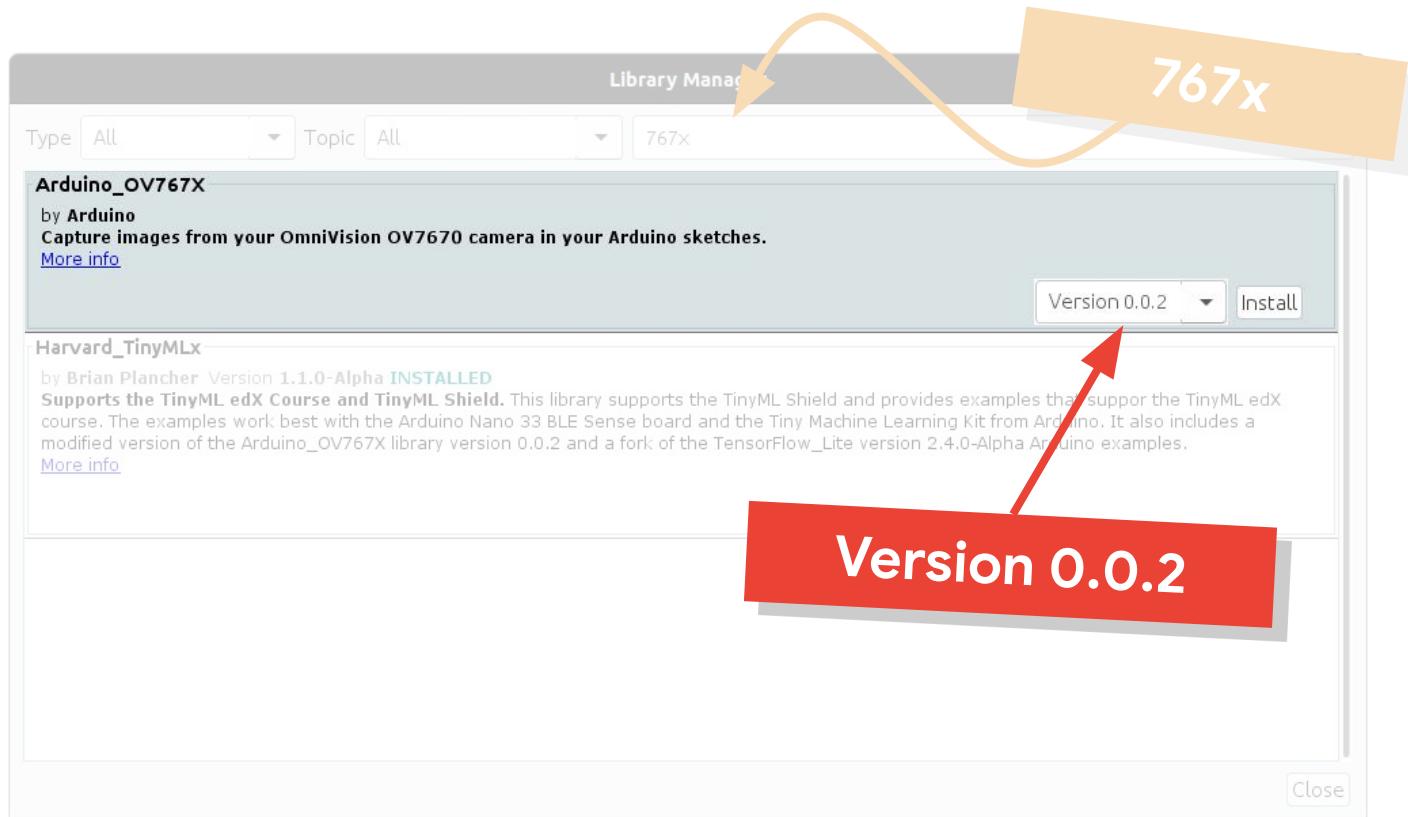


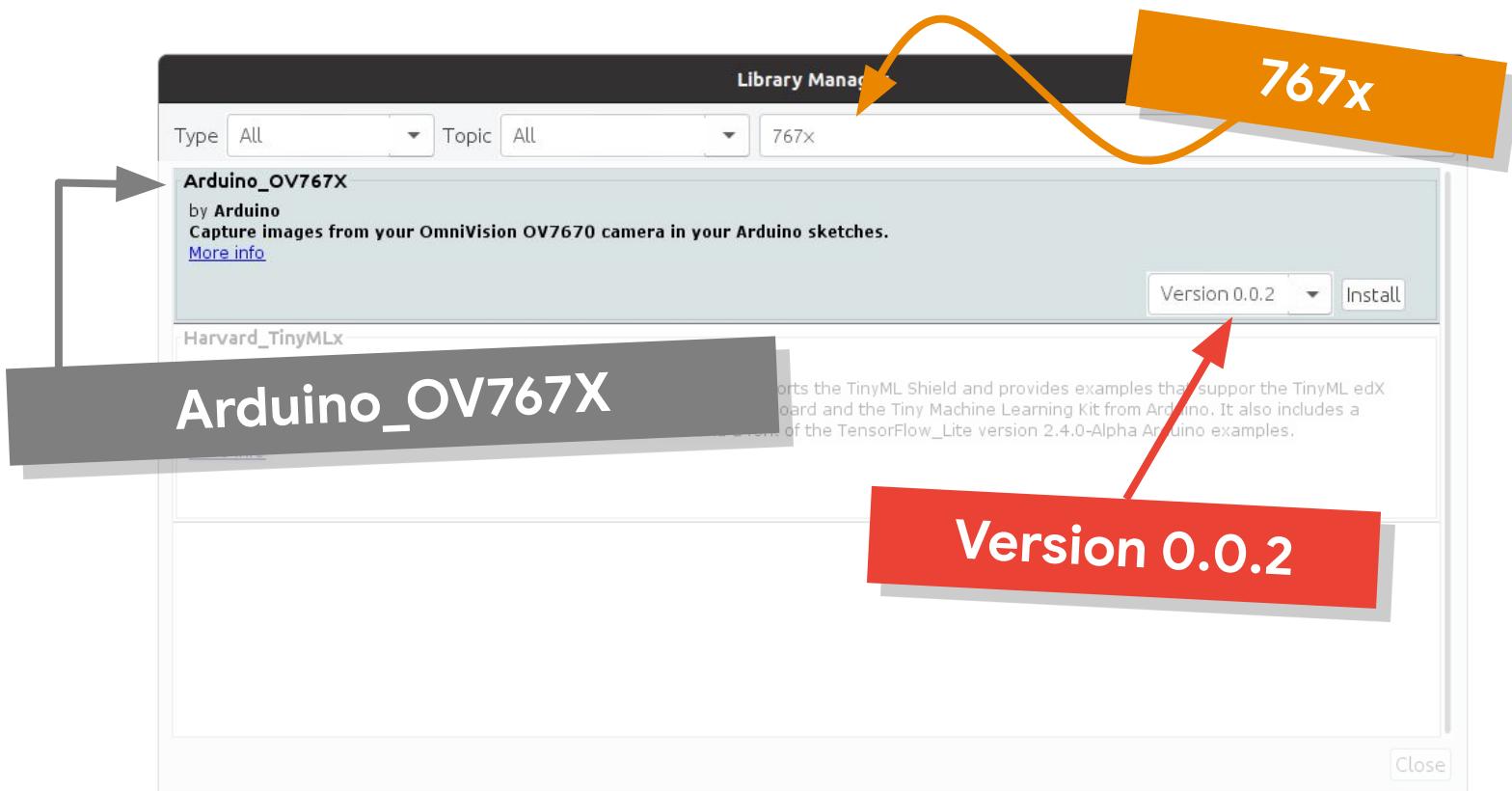
## Install Extras





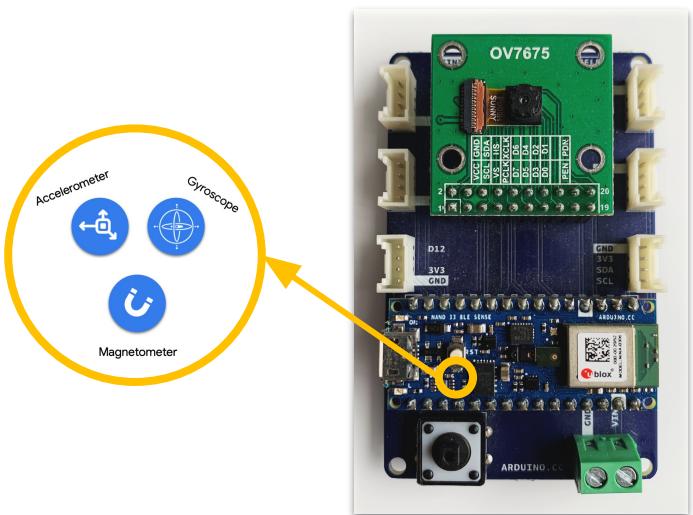


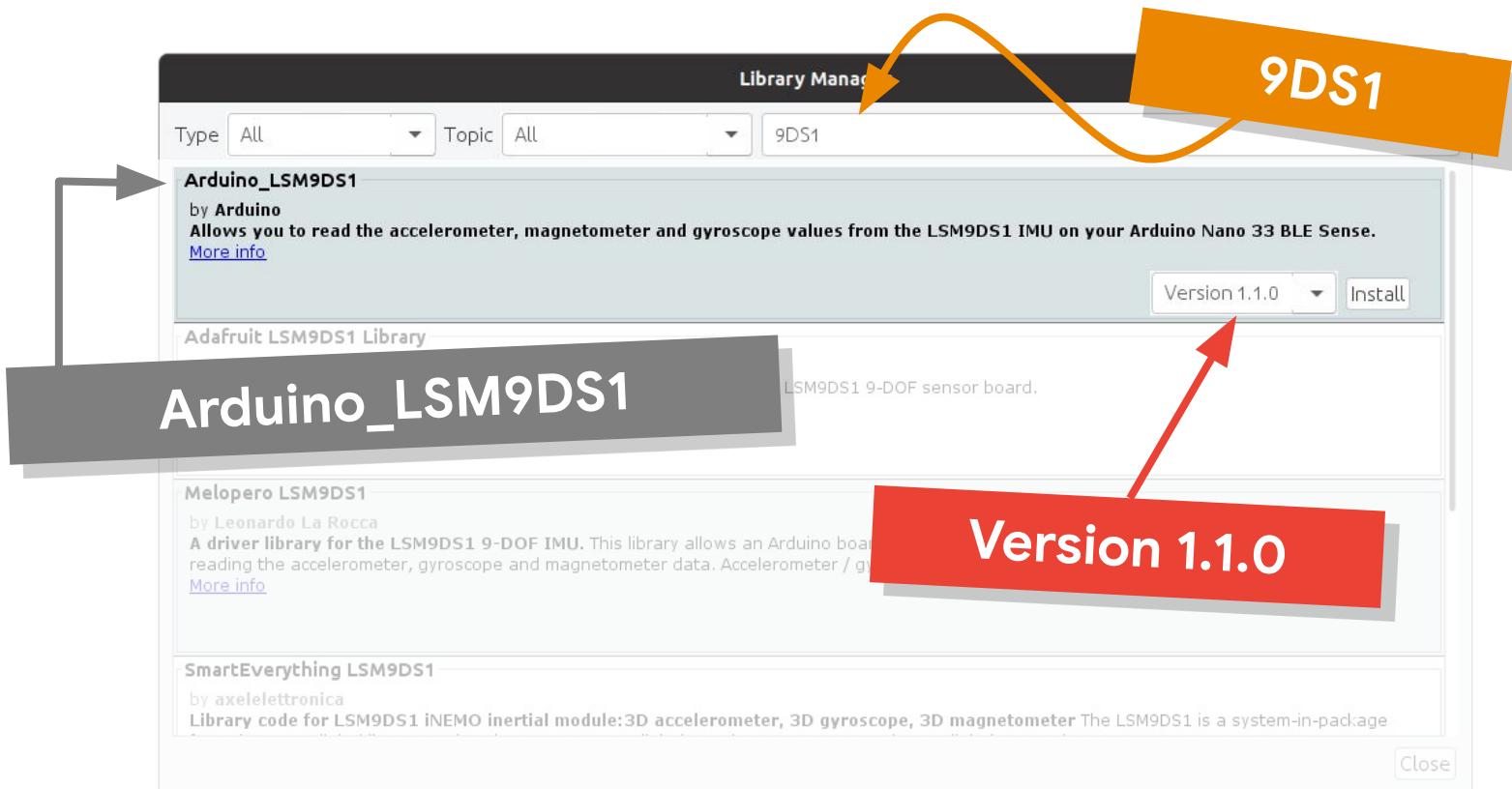




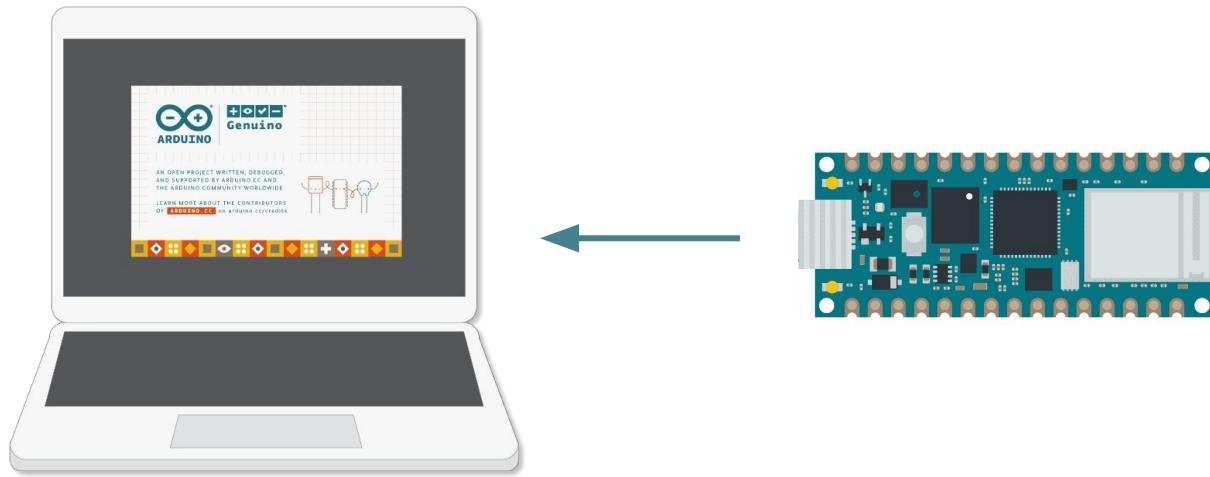


# Install Extras





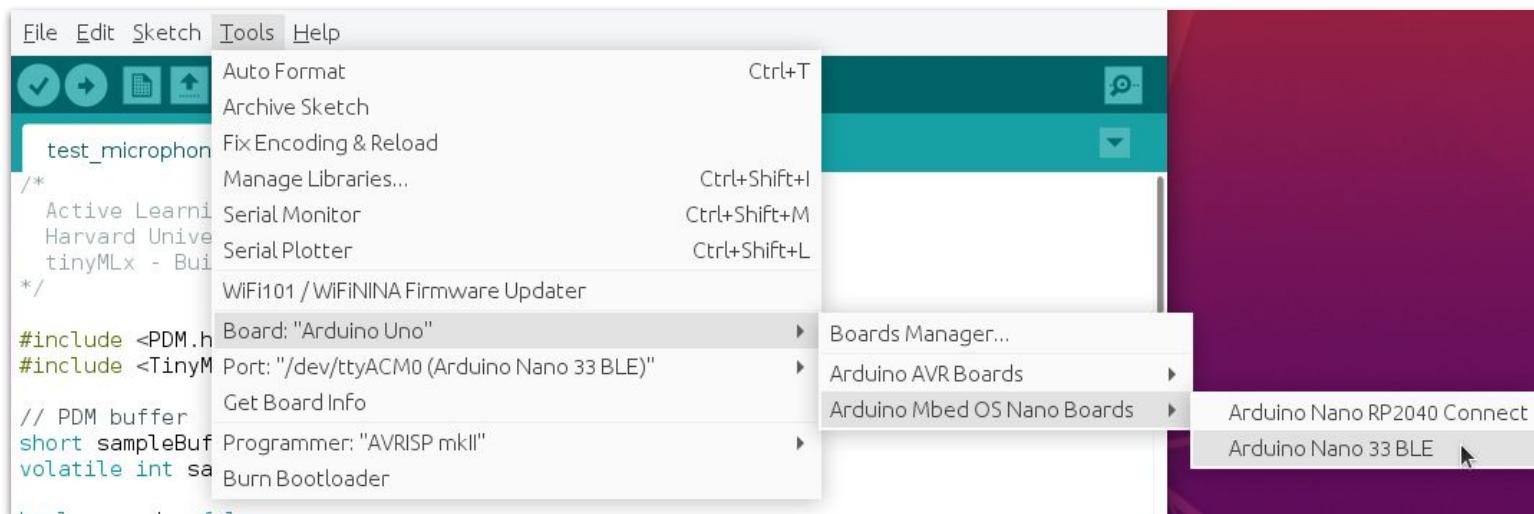




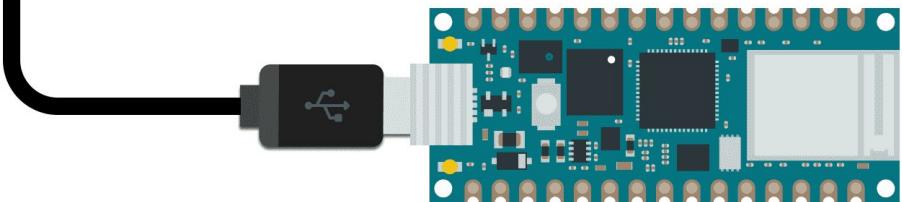
Tools → Board: “[something]”

→ Arduino Mbed OS Nano Boards

→ Arduino Nano 33 BLE



MICRO USB CABLE



**PLUG IN via MicroUSB**

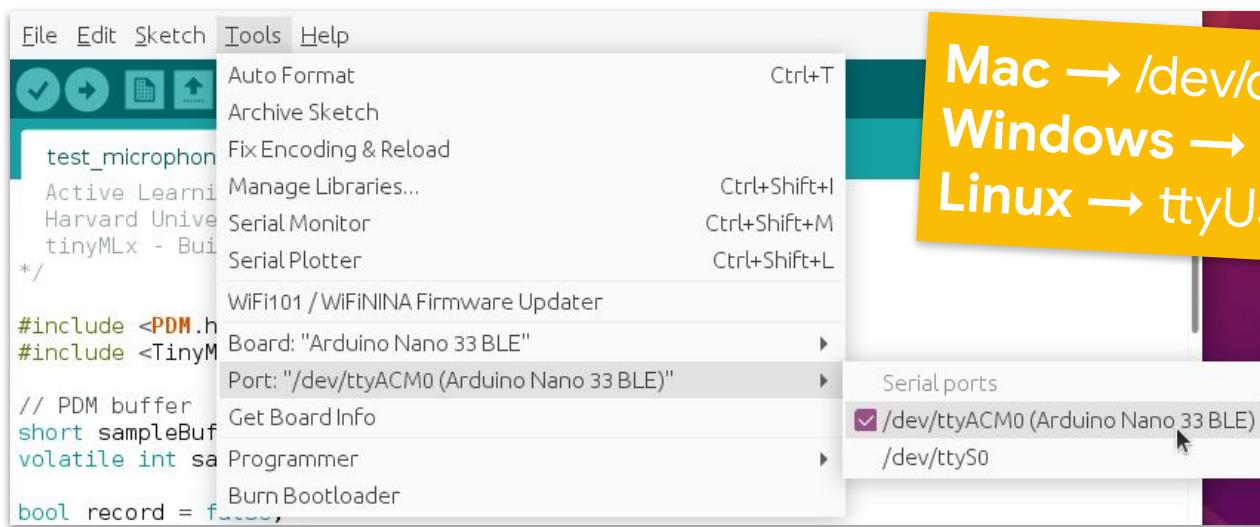
to your computer

*right now!*

set board and port for later

Tools → Port: “[???] (Arduino Nano 33 BLE)”

→ <??> (Arduino Nano 33 BLE)



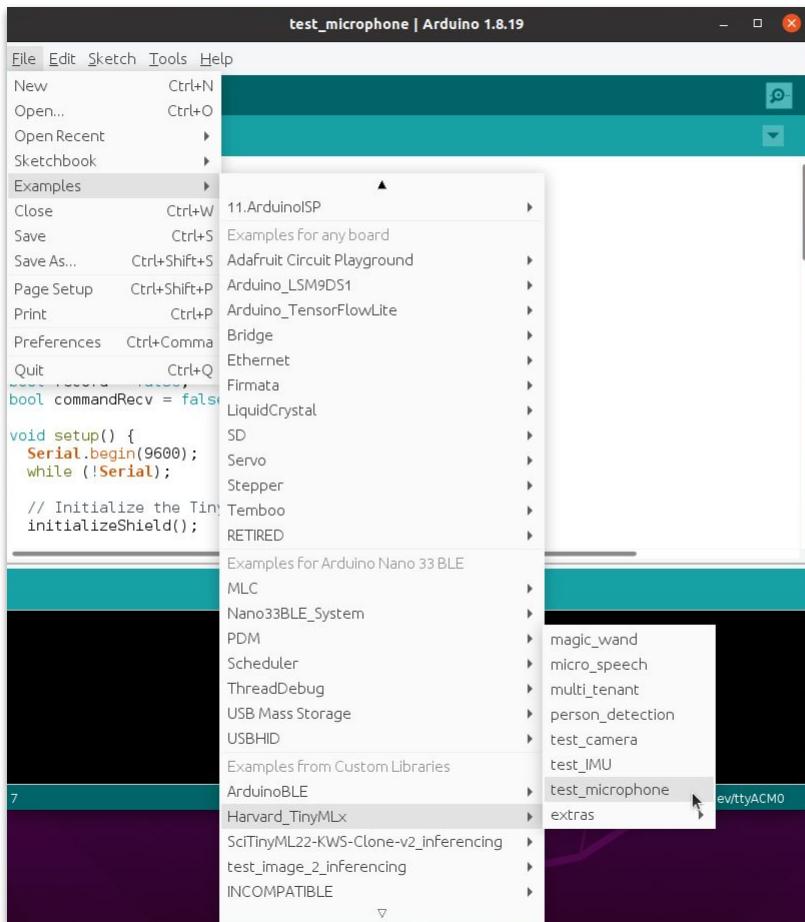
Mac → /dev/cu.usbmodem<#>  
Windows → COM<#>  
Linux → ttyUSB<#> or ttyACM<#>

# Today's Agenda

- Review + Why Tiny?
- Hardware Basics
- Installing and Starting the Arduino IDE

## Testing Your TinyML Kit

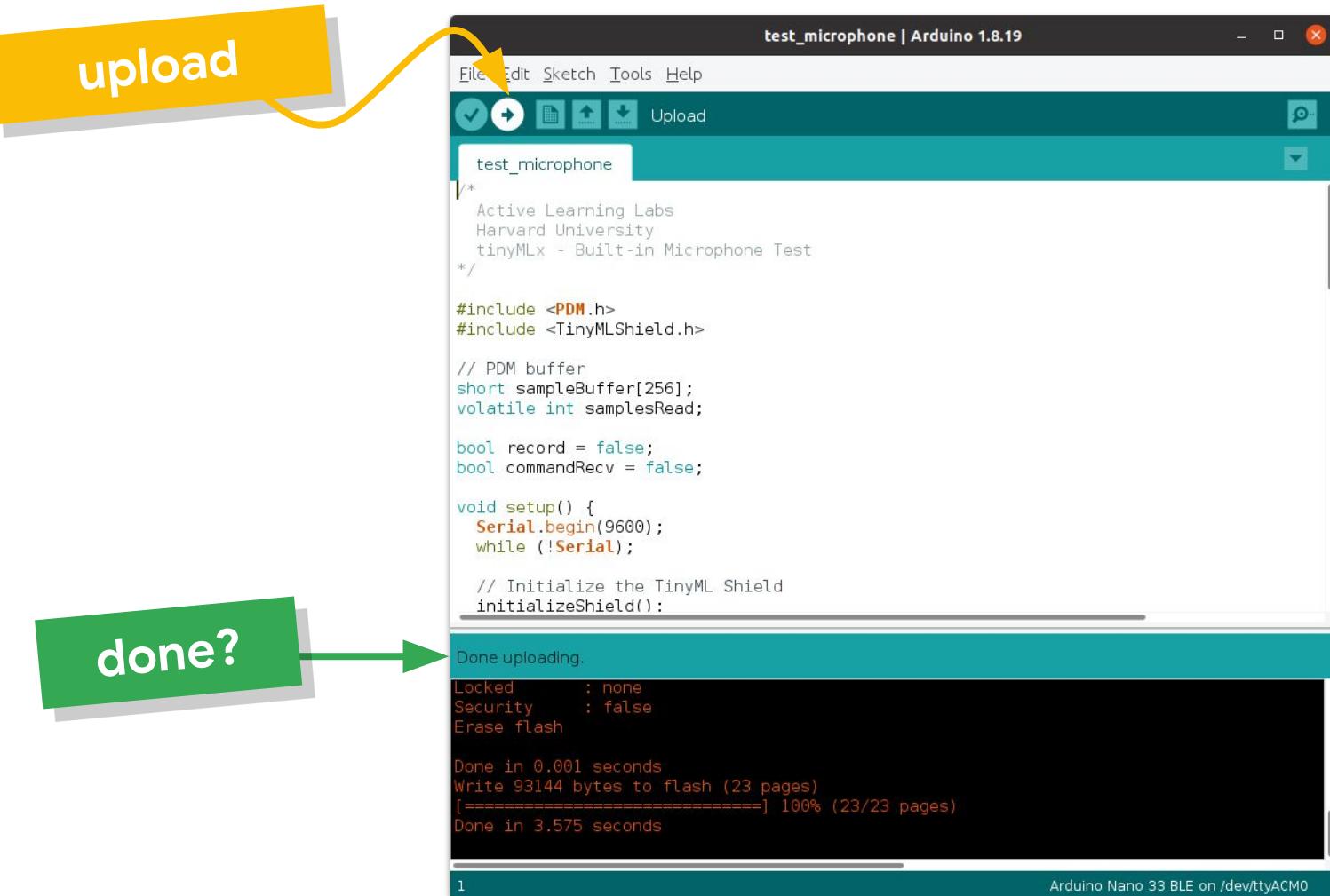
- Deploying KWS model onto Arduino
- Summary & Next Steps



File → Examples

→ Harvard\_TinyMLx

→ test\_microphone



An error occurred while uploading the sketch

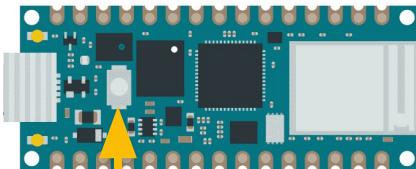
```
/home/plancher/Arduino/libraries/test_image_2_inferencing/src/edge-impulse-sdk/CMSIS/NN/Source/PoolingFunctions/arm_pool_q7_hw0.cpp: In function 'void arm_pool_q7_hw0(  
    uint32_t* __SIMD32(pCnt)++ = __QADD16(vo2, in);  
  
/home/plancher/Arduino/libraries/test_image_2_inferencing/src/edge-impulse-sdk/tensorflow/lite/core/api/op_resolver.cpp: In function  
/home/plancher/Arduino/libraries/test_image_2_inferencing/src/edge-impulse-sdk/tensorflow/lite/core/api/op_resolver.cpp:34:20:  
    builtin_code < BuiltinOperator_MIN) {  
    ~~~~~~^~~~~~
```

Sketch uses 224024 bytes (22%) of program storage space. Maximum is 983040 bytes.

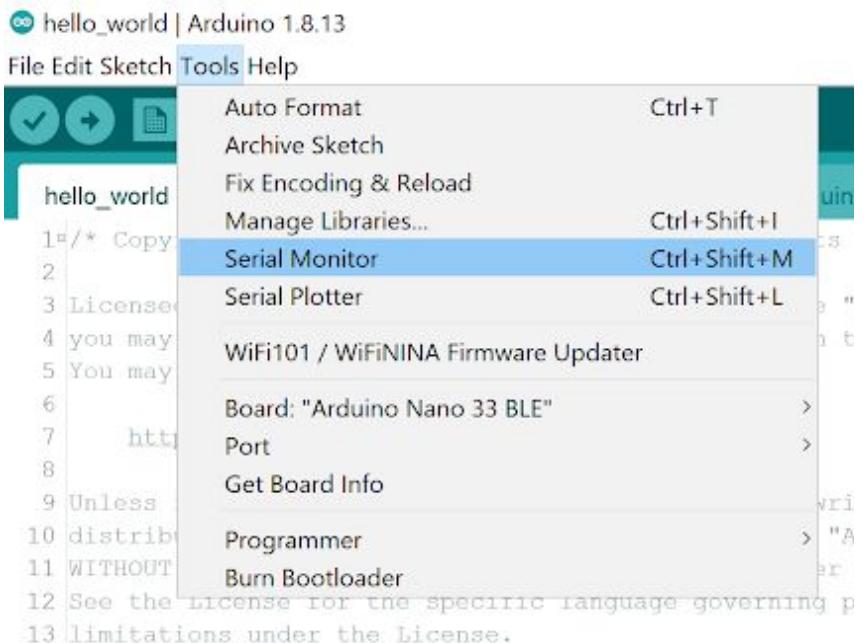
Global variables use 58672 bytes (22%) of dynamic memory, leaving 203472 bytes for local variables. Maximum is 262144 bytes.  
An error occurred while uploading the sketch

Device unsupported

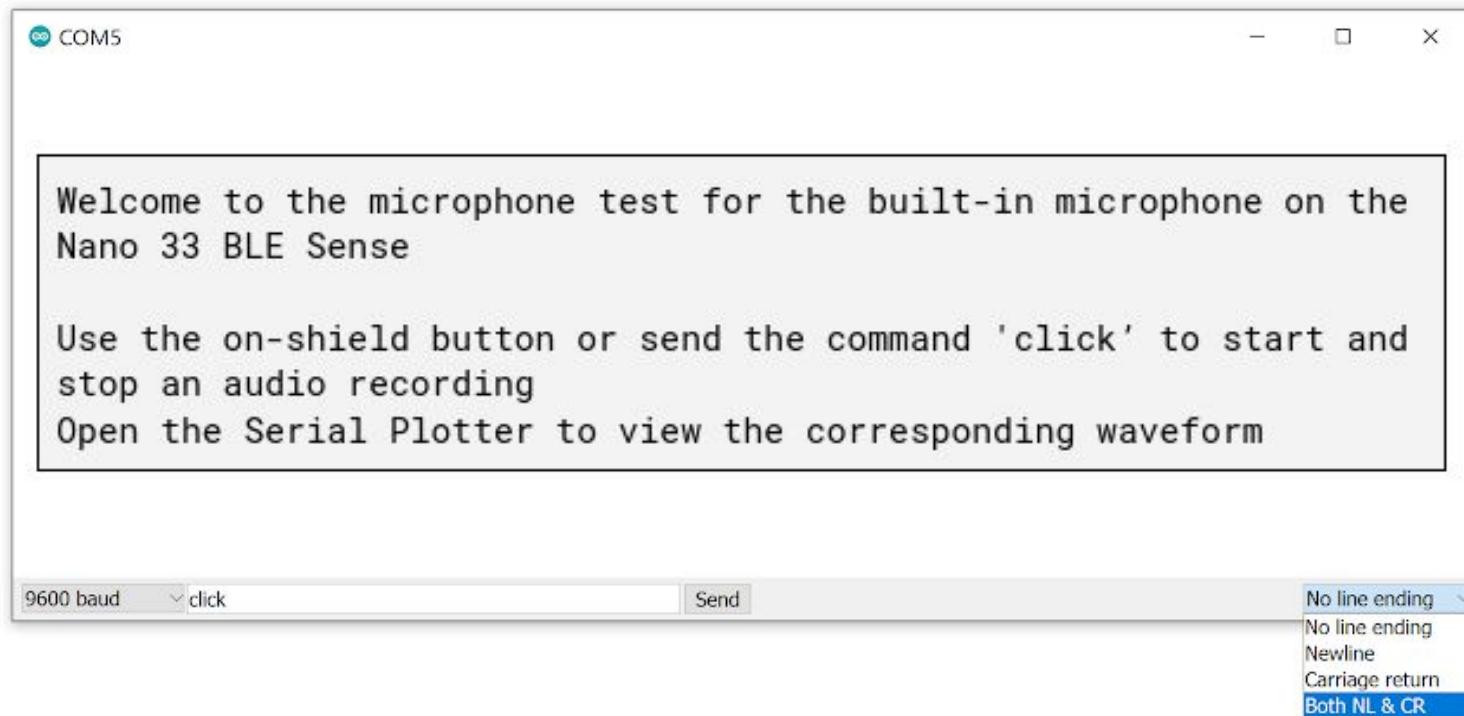
Double Tap Reset for  
Bootloader Mode!



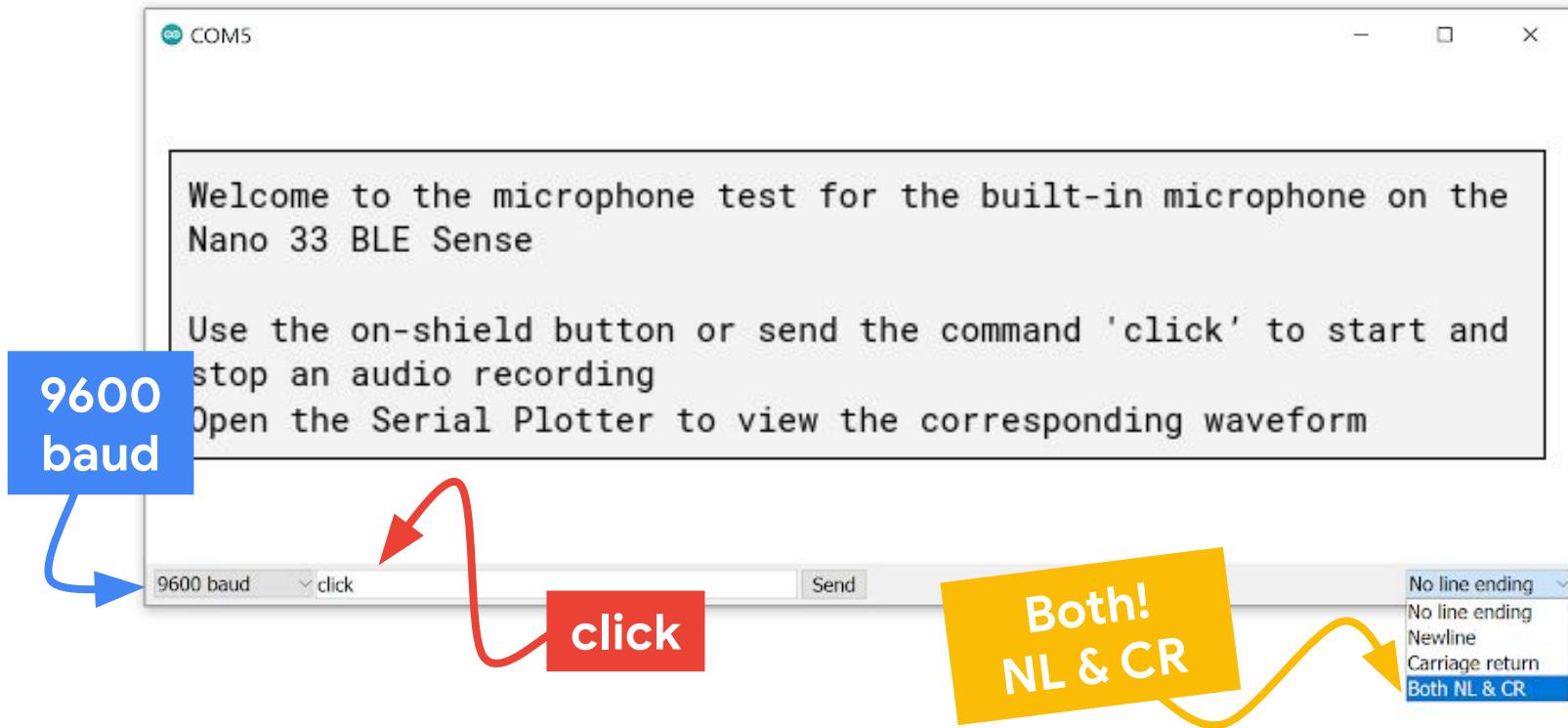
# Tools → Serial Monitor



## Tools → Serial Monitor



## Tools → Serial Monitor



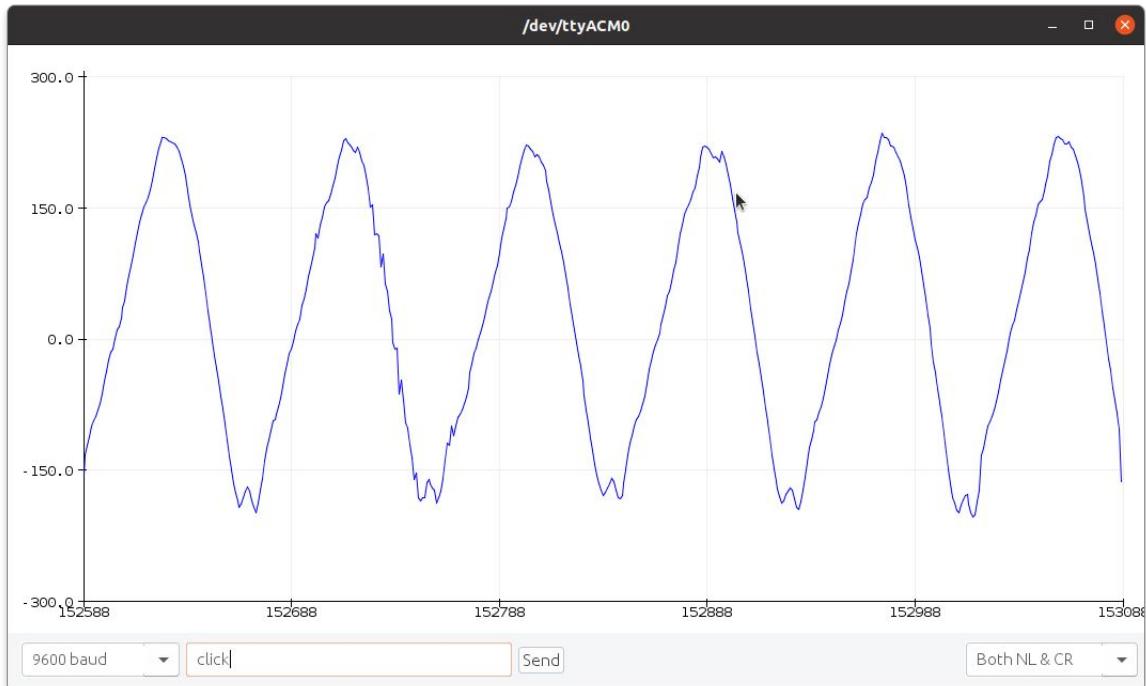
## Tools → Serial Monitor



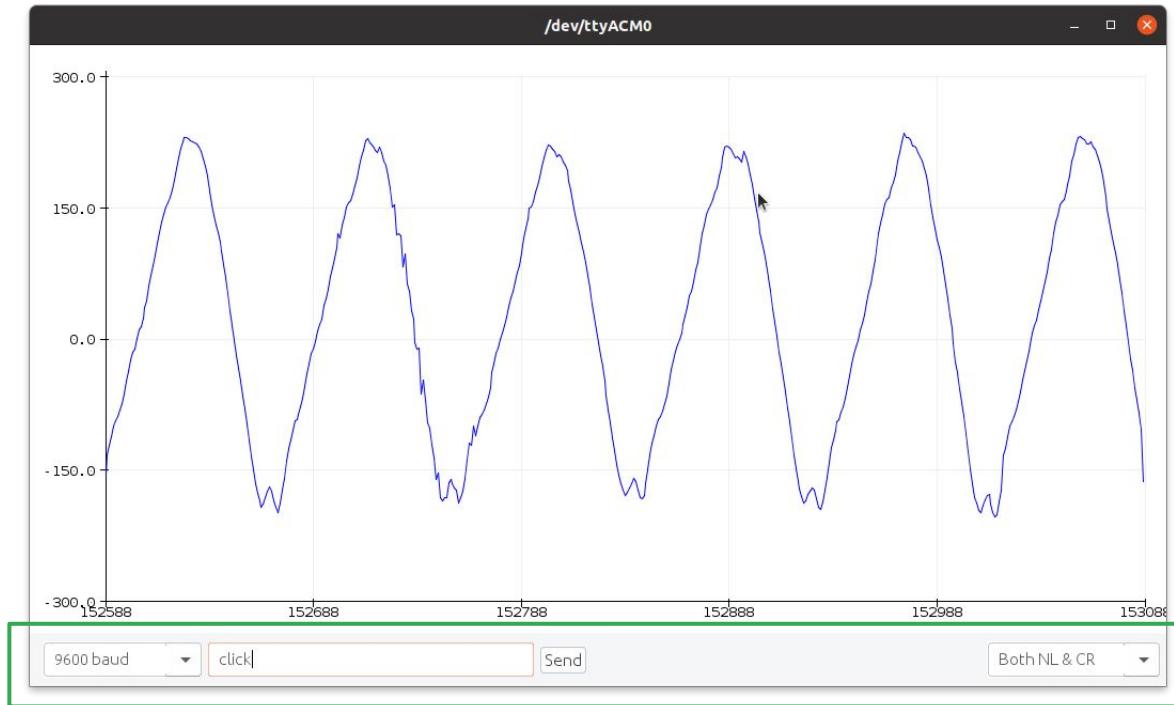
## Tools → Serial Monitor



## Tools → *Serial Plotter*



## Tools → *Serial Plotter*



How clean of a  
wave can you get?

# Today's Agenda

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## Deploying KWS model onto Arduino

- Summary & Next Steps



- [Dashboard](#)
- [Devices](#)
- [Data acquisition](#)
- [Impulse design
  - \[Create impulse\]\(#\)
  - \[Image\]\(#\)
  - \[Transfer learning\]\(#\)](#)
- [EON Tuner](#)
- [Retrain model](#)
- [Live classification](#)
- [Model testing](#)
- [Versioning](#)
- [Deployment](#)

- [GETTING STARTED](#)
- [Documentation](#)
- [Forums](#)

## DEPLOYMENT (TEST IMAGE 2)

### Deploy your impulse

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.](#)

#### Create library

Turn your impulse into optimized source code that you can run on any device.



C++ library



Arduino library



Cube.MX CMSIS-PACK



WebAssembly



TensorRT library



OpenMV library

#### Build firmware

Get a ready-to-go binary for your development board that includes your impulse.



Arduino Nano 33 BLE Sense  
Arduino Dev Board Compatible



Arduino Portenta H7  
Arduino Dev Board Compatible



Himax WE-I Plus  
Arduino Dev Board Compatible



- [Dashboard](#)
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#### GETTING STARTED

- [Documentation](#)
- [Forums](#)



Computer



Mobile phone

#### Select optimizations (optional)

Model optimizations can increase on-device performance but may reduce accuracy. Click below to analyze optimizations and see the recommended choices for your target. Or, just click Build to use the currently selected options.



##### Enable EON™ Compiler

Same accuracy, up to 50% less memory. Open source.



#### Available optimizations for Transfer learning

##### Quantized (int8)

Currently selected

RAM USAGE

66.1K

LATENCY

58 ms

FLASH USAGE

108.1K

ACCURACY

-

Analyze optimizations

##### Unoptimized (float32)

Click to select

RAM USAGE

155.6K

LATENCY

43 ms

FLASH USAGE

193.8K

ACCURACY

-

Estimate for Arduino Portenta H7 (Cortex-M7 480MHz)

Build



- Dashboard
- Devices
- Data acquisition
- Impulse design
  - Create impulse
  - Image
  - Transfer learning
- EON Tuner
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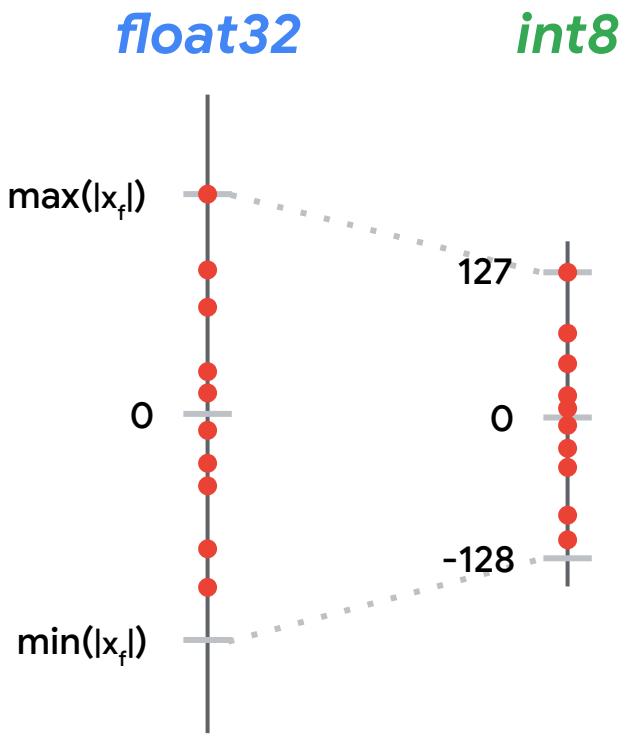
# Quantization

**Reduces the precision** of numbers used in a model which results in:

- **smaller** model size
- **faster** computation

# Reducing the Precision

4 bytes per  
model  
parameter



1 byte per  
model  
parameter

# Tradeoff

	Floating-point Baseline	After Quantization	Accuracy Drop
<b>MobileNet v1 1.0 224</b>	71.03%	69.57%	▼1.46%
<b>MobileNet v2 1.0 224</b>	70.77%	70.20%	▼0.57%
<b>Resnet v1 50</b>	76.30%	75.95%	▼0.35%

# float32

**Model** Model version: ⓘ Unoptimized (float32) ▾

**Last training performance** (validation set)

ACCURACY 100.0%	LOSS 0.25
--------------------	--------------

**Confusion matrix** (validation set)

	CAR	TRUCK
CAR	100%	0%
TRUCK	0%	100%
F1 SCORE	1.00	1.00

**Feature explorer** (full training set) ⓘ

- car - correct
- truck - correct
- car - incorrect
- truck - incorrect

**On-device performance** ⓘ

INFERENCING TIME 43 ms.	PEAK RAM USAGE 155.6K	FLASH USAGE 193.8K
----------------------------	--------------------------	-----------------------

# int8

**Model** Model version: ⓘ Quantized (int8) ▾

**Last training performance** (validation set)

ACCURACY 70.0%	LOSS 0.33
-------------------	--------------

**Confusion matrix** (validation set)

	CAR	TRUCK
CAR	60%	40%
TRUCK	20%	80%
F1 SCORE	0.67	0.73

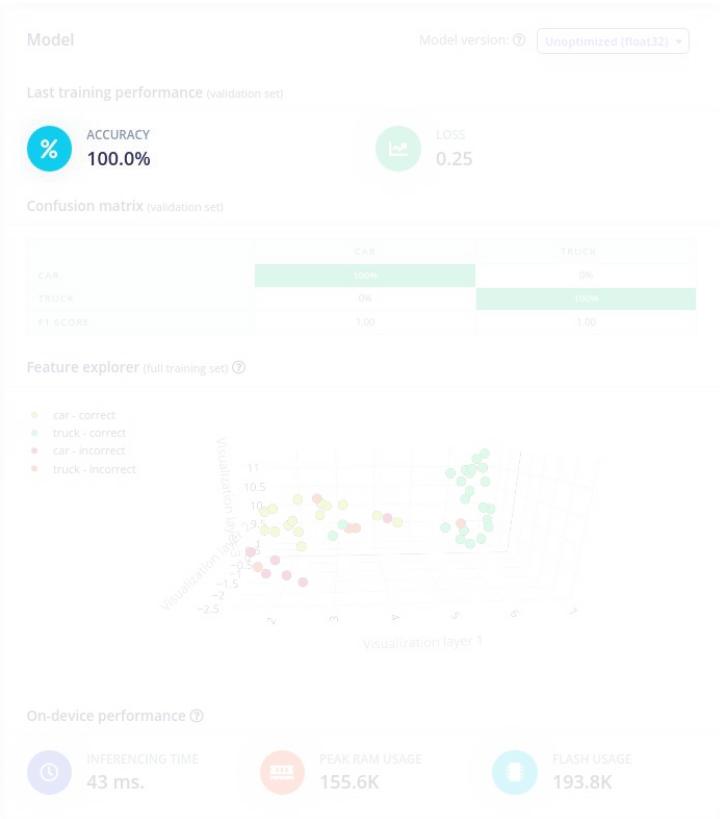
**Feature explorer** (full training set) ⓘ

- car - correct
- truck - correct
- car - incorrect
- truck - incorrect

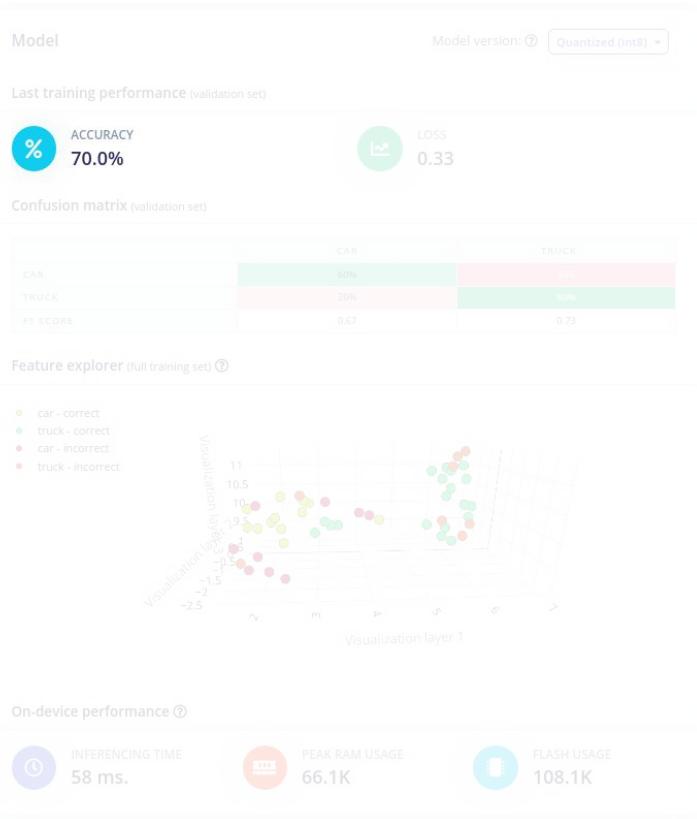
**On-device performance** ⓘ

INFERENCING TIME 58 ms.	PEAK RAM USAGE 66.1K	FLASH USAGE 108.1K
----------------------------	-------------------------	-----------------------

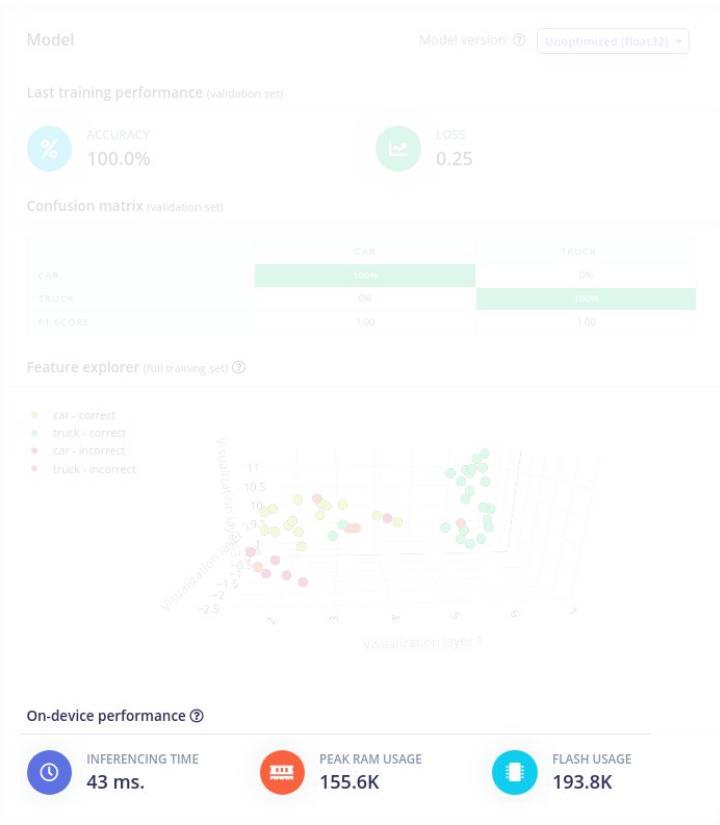
# float32



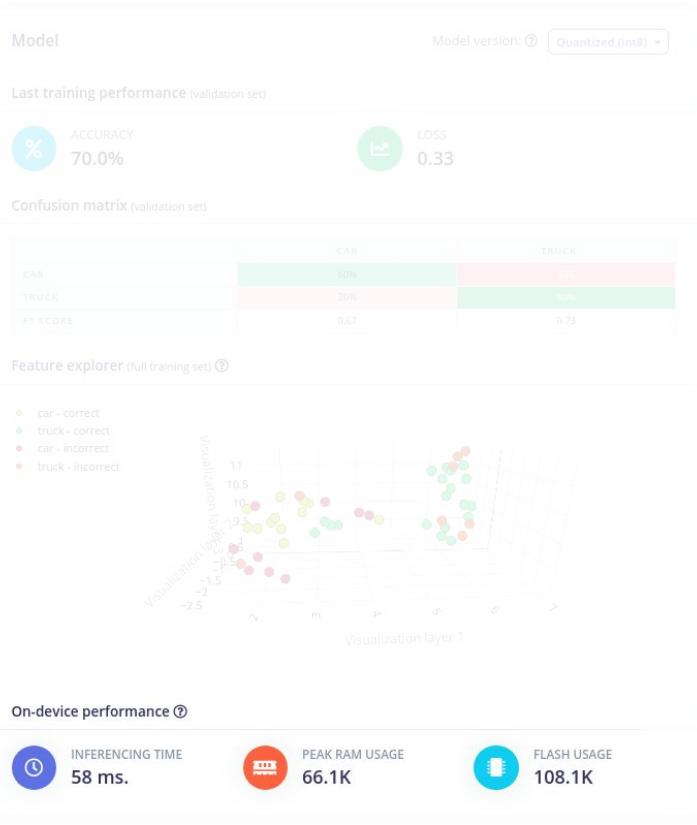
# int8



# float32



# int8



ions and see the recommended choices for your target. Or, just click Build to use the currently selected

Writing templates...  
Writing templates OK



## Built Arduino library

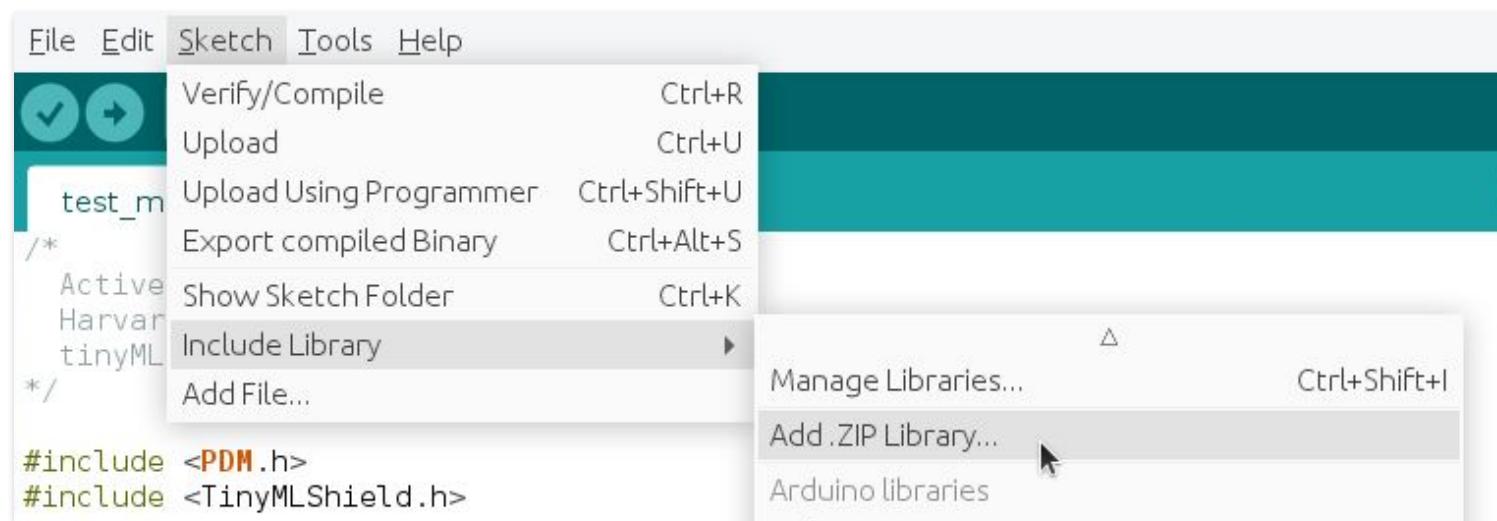
Add this library through the Arduino IDE via:

**Sketch > Include Library > Add .ZIP Library...**

Examples can then be found under:

**File > Examples > YOUR\_PROJECT\_NAME**

# Sketch → Include Library → Add .ZIP Library



ions and see the recommended choices for your target. Or, just click Build to use the currently selected

Writing templates...  
Writing templates OK



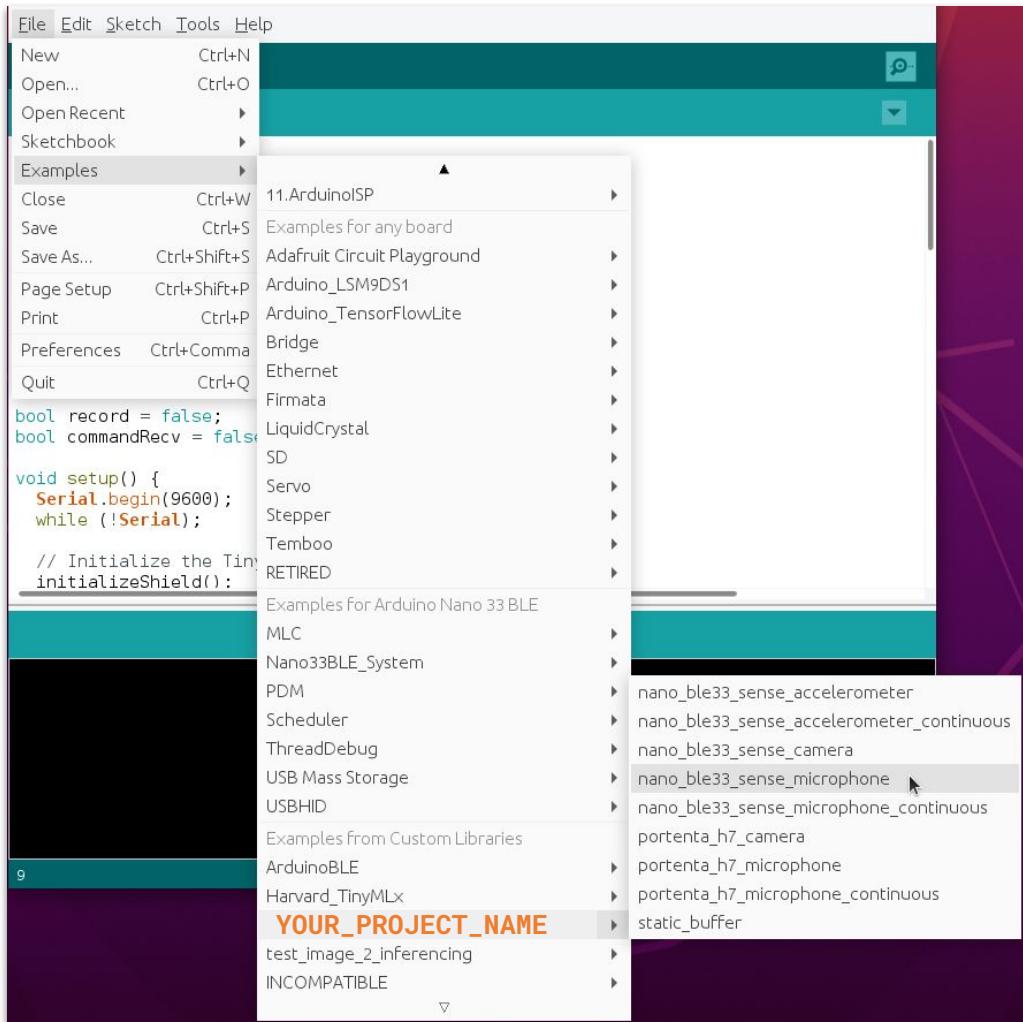
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Add this library through the Arduino IDE via:

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File → Examples →  
YOUR\_PROJECT\_NAME →  
nano\_ble33\_sense\_microphone



The screenshot shows the Arduino IDE interface with the title bar "nano\_ble33\_sense\_microphone | Arduino 1.8.19". The menu bar includes File, Edit, Sketch, Tools, and Help. Below the menu is a toolbar with icons for save, upload, and refresh. The main code editor window displays the sketch "nano\_ble33\_sense\_microphone" which includes the Edge Impulse license and copyright information. The status bar at the bottom shows "1" and "Arduino Nano 33 BLE on /dev/ttyACM0". A green callout box on the left contains the text "done?" with a green arrow pointing towards the status bar.

```
/*
 * Edge Impulse Arduino examples
 * Copyright (c) 2021 EdgeImpulse Inc.
 *
 * Permission is hereby granted, free of charge, to any person obtaining
 * a copy of this software and associated documentation files (the "Software"),
 * to deal in the Software without restriction, including without limitation
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 * MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT.
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 * CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT,
 * TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE
 * SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.
 */

```

Done uploading.

```
Locked      : none
Security    : false
Erase flash

Done in 0.000 seconds
Write 173792 bytes to flash (43 pages)
[=====] 100% (43/43 pages)
Done in 6.694 seconds
```

1 Arduino Nano 33 BLE on /dev/ttyACM0

An error occurred while uploading the sketch

```
/home/plancher/Arduino/libraries/test_image_2_inferencing/src/edge-impulse-sdk/CMSIS/NN/Source/PoolingFunctions/arm_pool_q7_hw0.c: In function '_SIMD32(pCnt)++ = _QADD16(vo2, in);'  
^  
/home/plancher/Arduino/libraries/test_image_2_inferencing/src/edge-impulse-sdk/tensorflow/lite/core/api/op_resolver.cpp: In function '_builtin_code < BuiltinOperator_MIN) {'  
~~~~~^~~~~~  
~~~~~^~~~~~
```

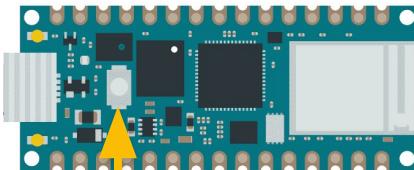
Sketch uses 224024 bytes (22%) of program storage space. Maximum is 983040 bytes.

Global variables use 58672 bytes (22%) of dynamic memory, leaving 203472 bytes for local variables. Maximum is 262144 bytes.

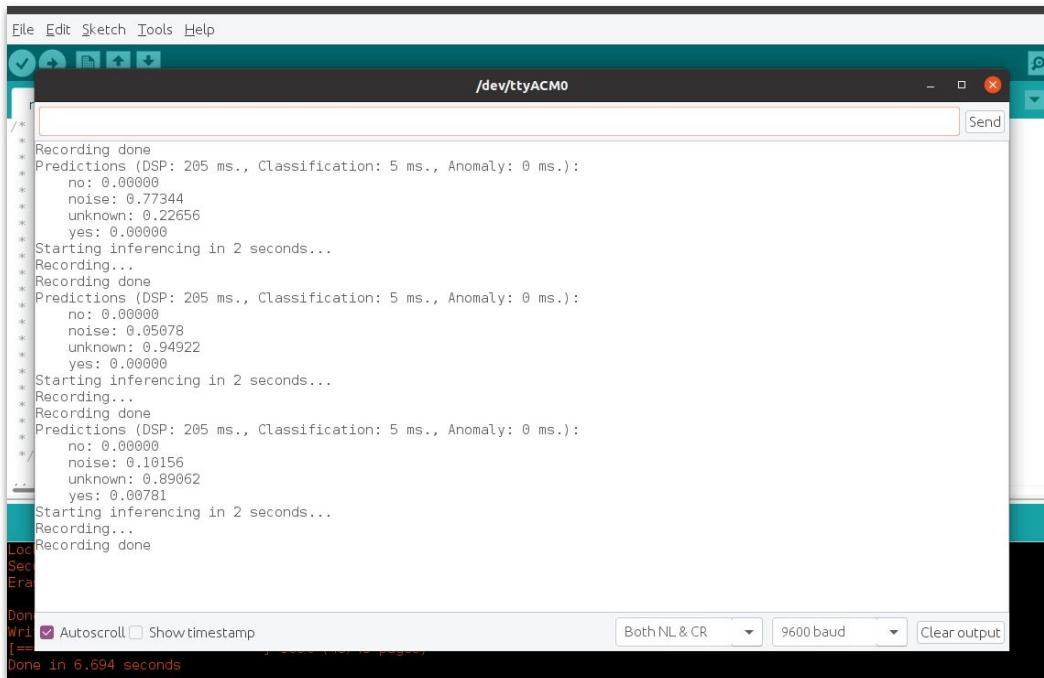
An error occurred while uploading the sketch

Device unsupported

Double Tap Reset for  
Bootloader Mode!



# Tools → Serial Monitor



File Edit Sketch Tools Help



/dev/ttyACM0

```
/*
* Recording done
* Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.):
*   no: 0.00000
*   noise: 0.77344
*   unknown: 0.22656
*/
```

Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.)  
no: 0.00000  
noise: 0.10156  
unknown: 0.89062  
yes: 0.00781

```
/*
* Predictions (DSP: 205 ms., Classification:
```

```
  no: 0.00000
  noise: 0.10156
  unknown: 0.89062
  yes: 0.00781
```

Starting inferencing in 2 seconds...

Recording...

Recording done

Loc

Sec

Era

Don

Wri

Autoscroll  Show timestamp

[==

Done in 6.694 seconds

Confidence that the audio  
is one of the choices (0-1 scale)

Both NL & CR

9600 baud

Clear output

# Today's Agenda

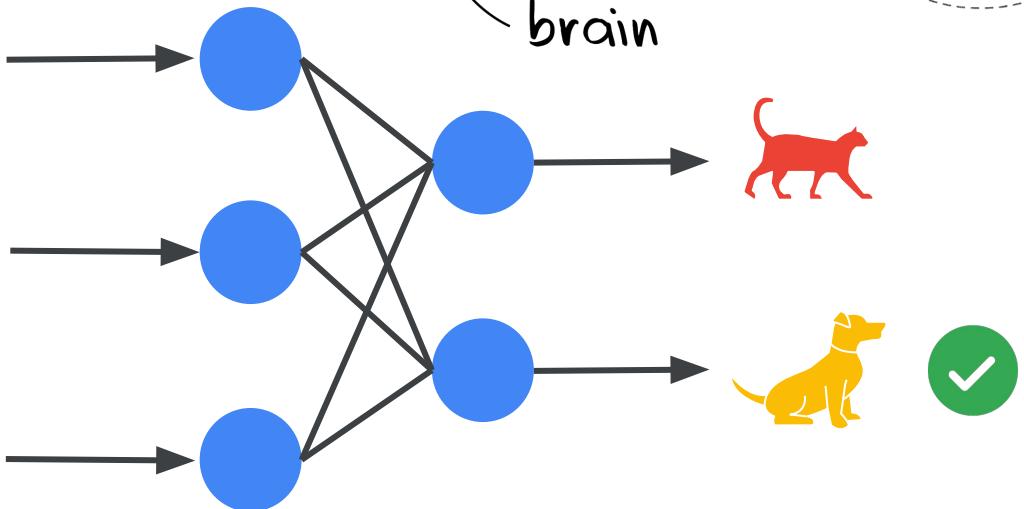
- Review + Why Tiny?
- Hardware Basics
- Installing and Starting the Arduino IDE
- Testing Your TinyML Kit
- Deploying KWS model onto Arduino

## Summary & Next Steps

# Machine Learning



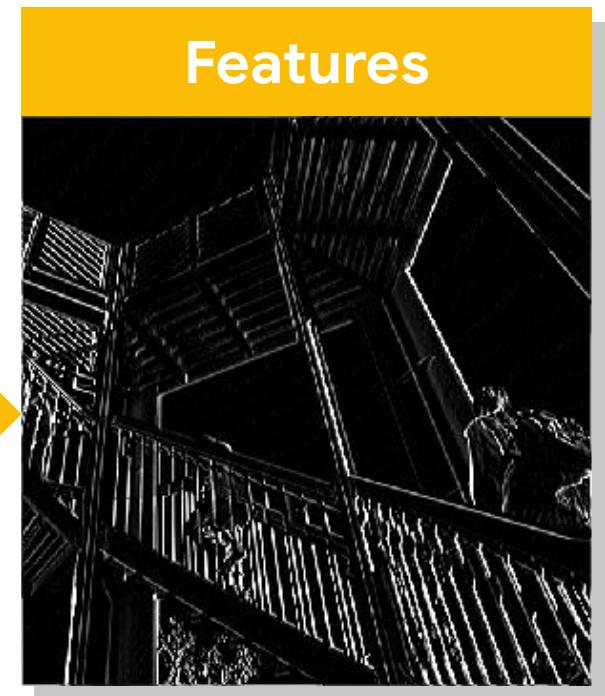
# Deep Learning with Neural Networks



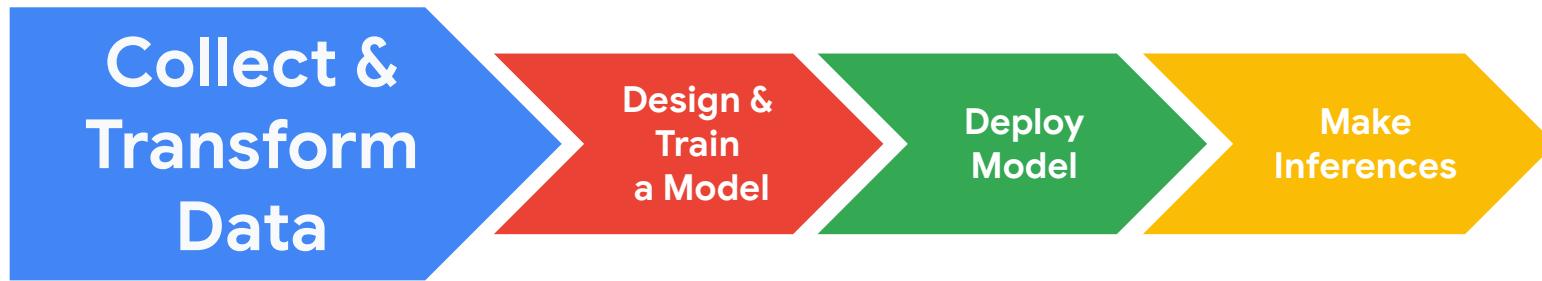
# Features can be found with **Convolutions**



-1	0	1
-2	0	2
-1	0	1

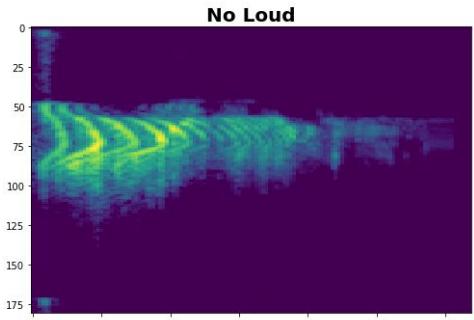
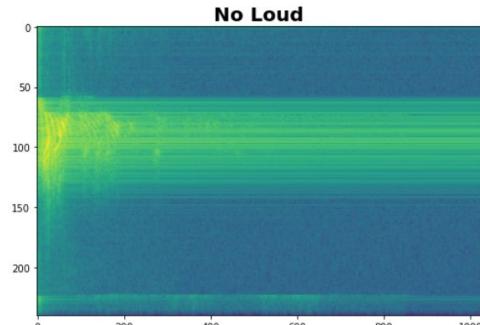
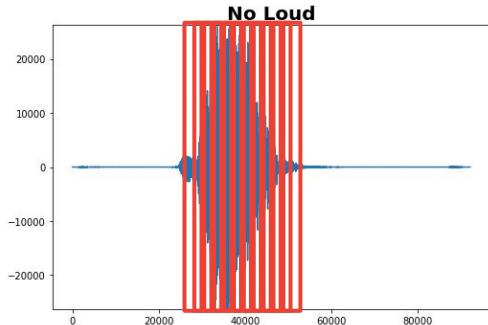
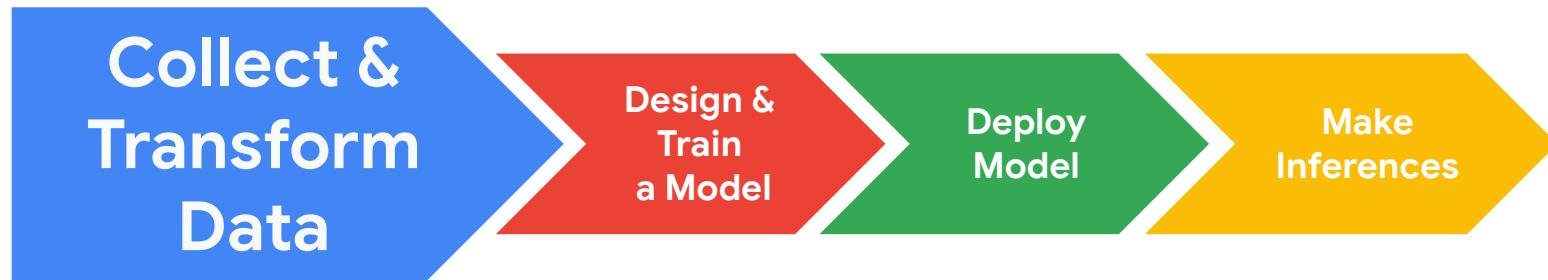


# The (Tiny) Machine Learning Workflow

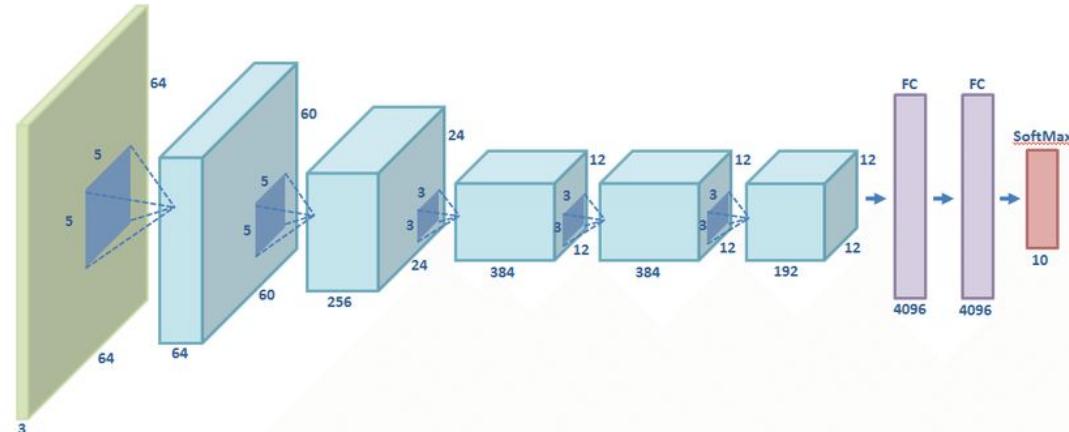
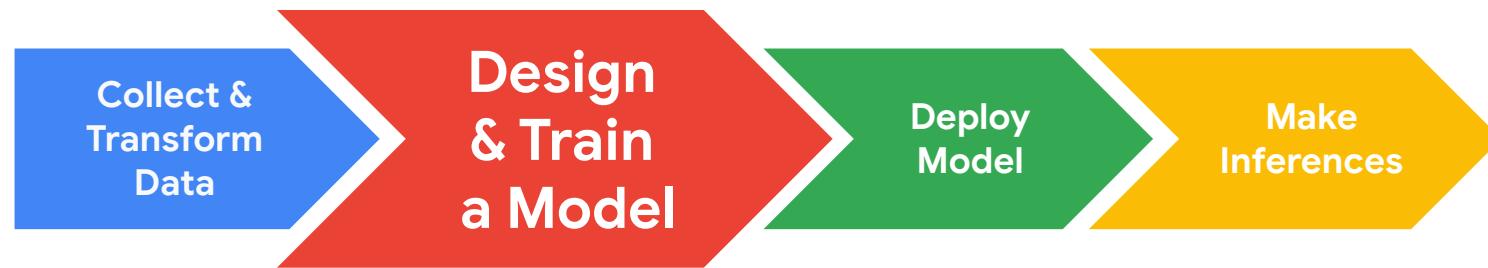


ML is *everywhere* → collect **GOOD** data **RESPONSIBLY**

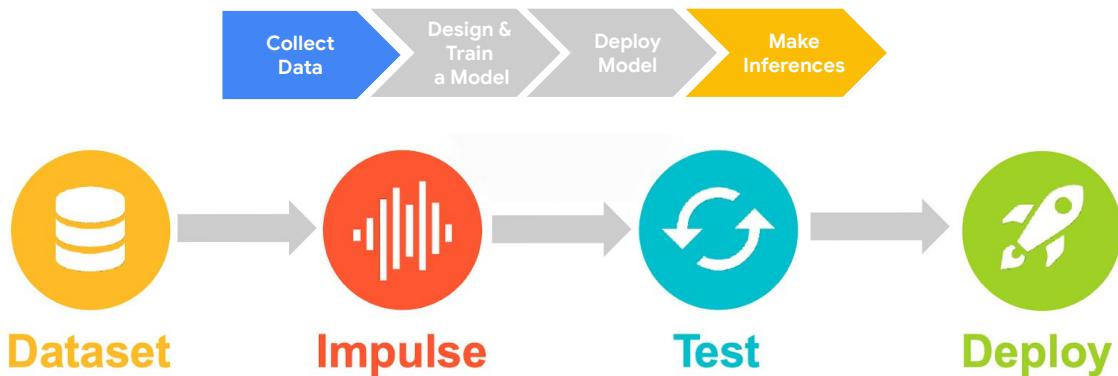
# The (Tiny) Machine Learning Workflow



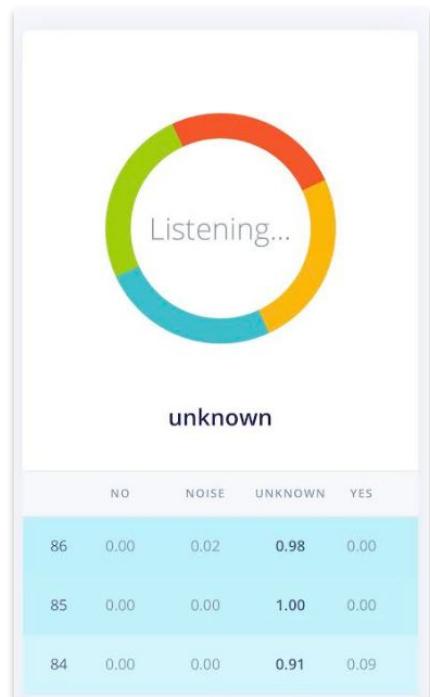
# The (Tiny) Machine Learning Workflow



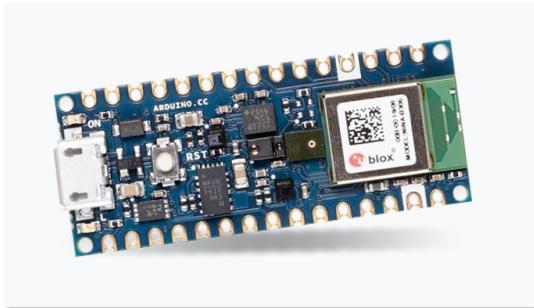
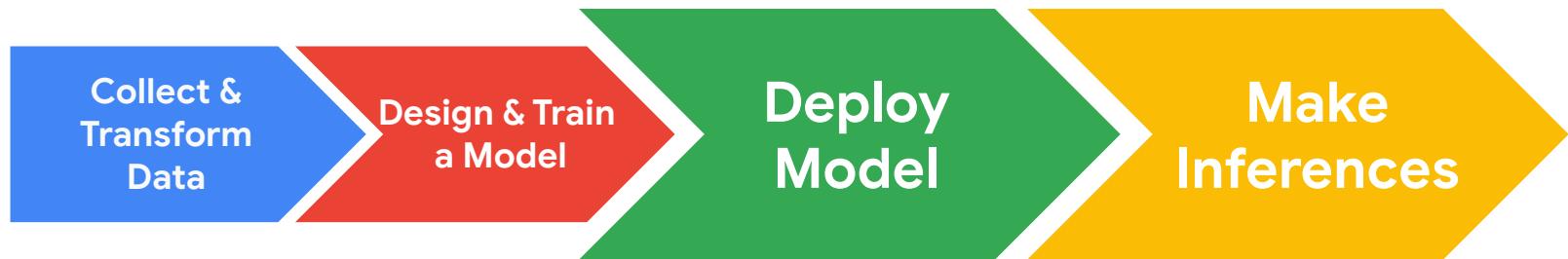
# The (Tiny) Machine Learning Workflow



Edge Impulse Simplifies  
Training and Deployment



# The (Tiny) Machine Learning Workflow



Even less memory

Even less compute power

Also, only focused on *inference*

File Edit Sketch Tools Help



/dev/ttyACM0

```
/*
* Recording done
* Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.):
*   no: 0.00000
*   noise: 0.77344
*   unknown: 0.22656
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Predictions (DSP: 205 ms., Classification: 5 ms., Anomaly: 0 ms.)  
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[==

Done in 6.694 seconds

Confidence that the audio  
is one of the choices (0-1 scale)

Both NL & CR

9600 baud

Clear output

# Workshop Agenda

Day 1

Introduction to AI and (Tiny)ML

Cloud ML

Day 2

Keyword Spotting for the Navajo Language

Mobile ML

Day 3

Bringing AI/ML from the Cloud to the Edge

Embedded ML

# Workshop Agenda

Day 1

Introduction to AI and (Tiny)ML

Cloud ML

Day 2

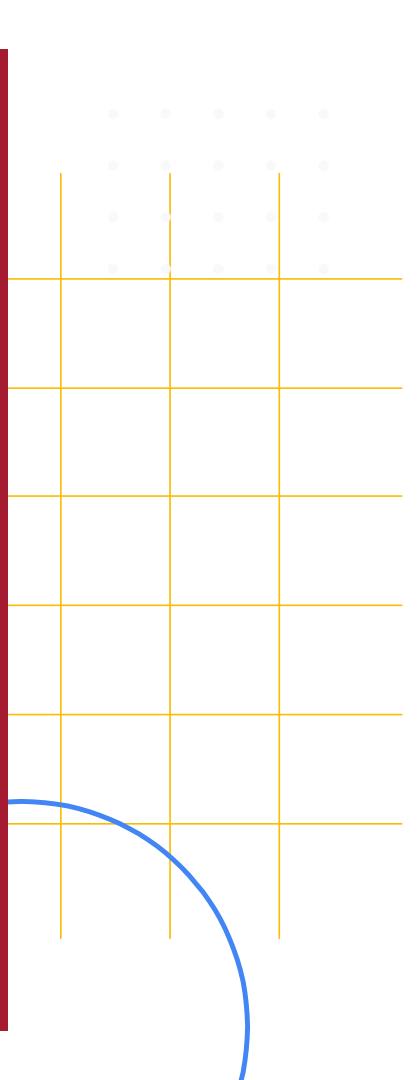
Keyword Spotting for the Navajo Language

Mobile ML

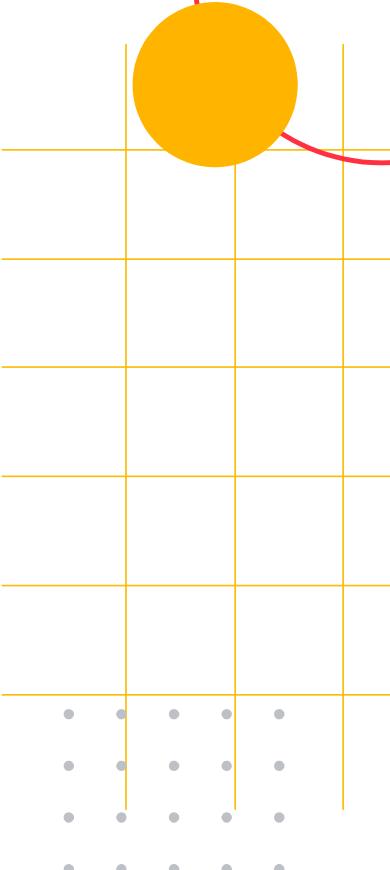
Day 3

Bringing AI/ML from the Cloud to the Edge

Embedded ML



Practice with more  
machine learning!



Experiments with Google

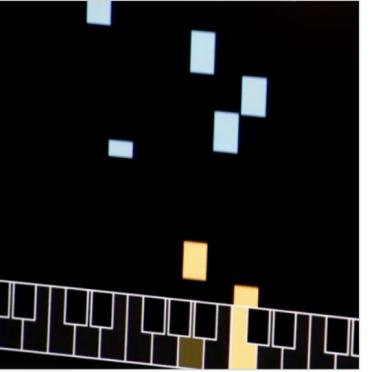
Collections Experiments Search SUBMIT EXPERIMENT

### AI + MUSIC



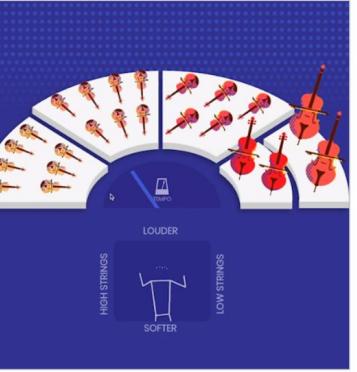
**FREDDIEMETER**  
by Google Research, Google Creative Lab, YouTube Music

An AI-powered singing challenge that rates how closely your singing matches the voice



**AI DUET**  
by Yotam Mann

A piano that responds to you.



**SEMI-CONDUCTOR**  
by Google Creative Lab

Conduct your own orchestra in the browser by moving your arms

[experiments.withgoogle.com](https://experiments.withgoogle.com)

# Teachable Machine

**Train a computer to recognize your  
own images, sounds, & poses.**

A fast, easy way to create machine learning models for  
your sites, apps, and more – no expertise or coding  
required.

Snap

Clap

Get Started

mlo p5.js Coral Node.js TensorFlow.js

teachablemachine.withgoogle.com

# Classification result

**Summary**

Name	helloworld.jan5.wav.1ncrr7qm.s17
Expected outcome	helloworld
CATEGORY	COUNT
helloworld	0
noise	0
unknown	1
uncertain	0

**Detailed result**  Show only unknowns

TIMESTAMP	HELLOWORLD	NOISE	UNKNOWN
0	0.36	0.01	0.62

**Raw DATA**  
**helloworld.jan5.wav.1ncrr7qm.s17**



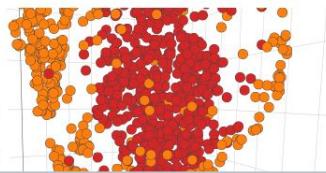
Raw features [?](#)  
37, 34, 42, 36, 14, 1, -3, -9, -7, -10, -20, -29, -26, -21, -23, --

**MFCC (1,649 samples)** [?](#)

X Axis Y Axis Z Axis

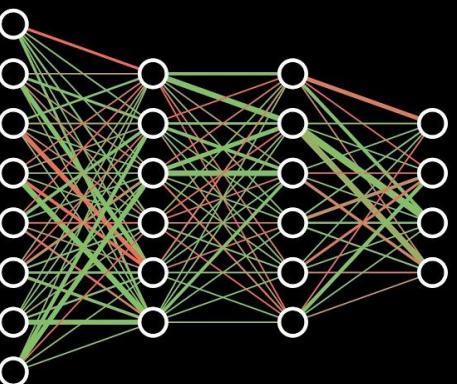
Visualization layer [?](#) Visualization layer [?](#) Visualization layer [?](#)

- helloworld
- noise
- unknown
- classification 0



edgeimpulse.com

# Neural Networks



From the  
ground up

3Blue1Brown

# Introduction to TensorFlow for Artificial Intelligence, Machine Learning, and Deep Learning

★★★★★ 4.7 15,457 ratings |  96%



Laurence Moroney

Enroll for Free

Starts Jun 24

Financial aid available

coursera

Browse > Data Science > Machine Learning

# Introduction to Embedded Machine Learning

★★★★★ 4.8 335 ratings • 83 reviews

 Shawn Hymel +1 more instructor

**Enroll for Free**  
Starts Jun 16

Financial aid available

18,297 already enrolled

Offered By

 **EDGE IMPULSE**



EDGE IMPULSE arm ARDUINO

**coursera**

# The Future of ML is Tiny and Bright



Professional Certificate in  
Tiny Machine Learning (TinyML)

I'm interested

## Courses in this program



HarvardX's Tiny Machine Learning (TinyML) Professional Certificate



Fundamentals of TinyML



Applications of TinyML



Deploying TinyML

edx.org



## Explore projects

Trending ▾

All difficulties ▾

Featured ▾

Any type ▾

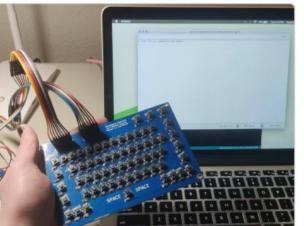


### Getting Started with the Raspberry Pi Pico

Arduino "having11" Guy

15

2.5K



### 64-Key Prototyping Keyboard Matrix for Arduino

Cameron Coward

19

6.8K



### ML-Based Bird and Squirrel Detector (Raspberry Pi and AWS)

Mike Sadowski

31

5.3K



### Self-Playing Melodica

touchmysound

30

3.9K

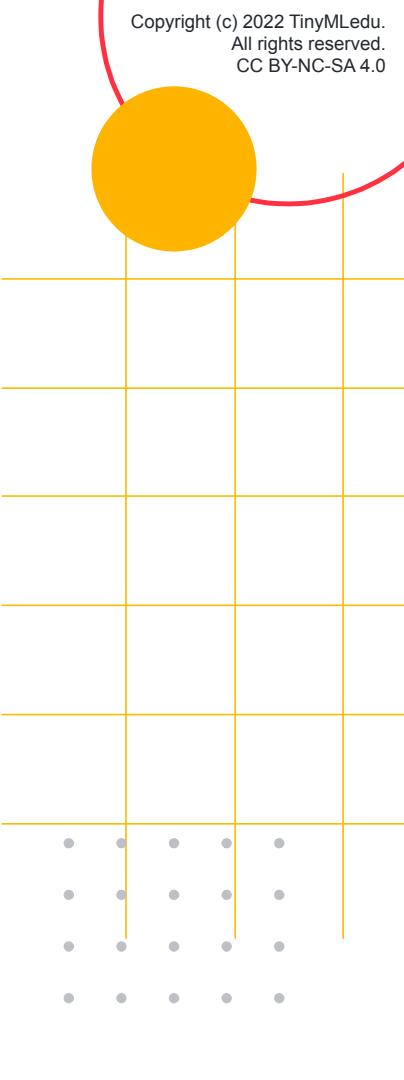
hackster.io

# Our website!

---

[tinyMLEdu.org/EASI-22](https://tinyMLEdu.org/EASI-22)

home base for **all information!**



# survey!

[bit.ly/EASI22-Post](https://bit.ly/EASI22-Post)

help us make this workshop **better!**

# Our team!



with help from **many more**



hágoónee' 🙌

thank you and **keep exploring with ML**