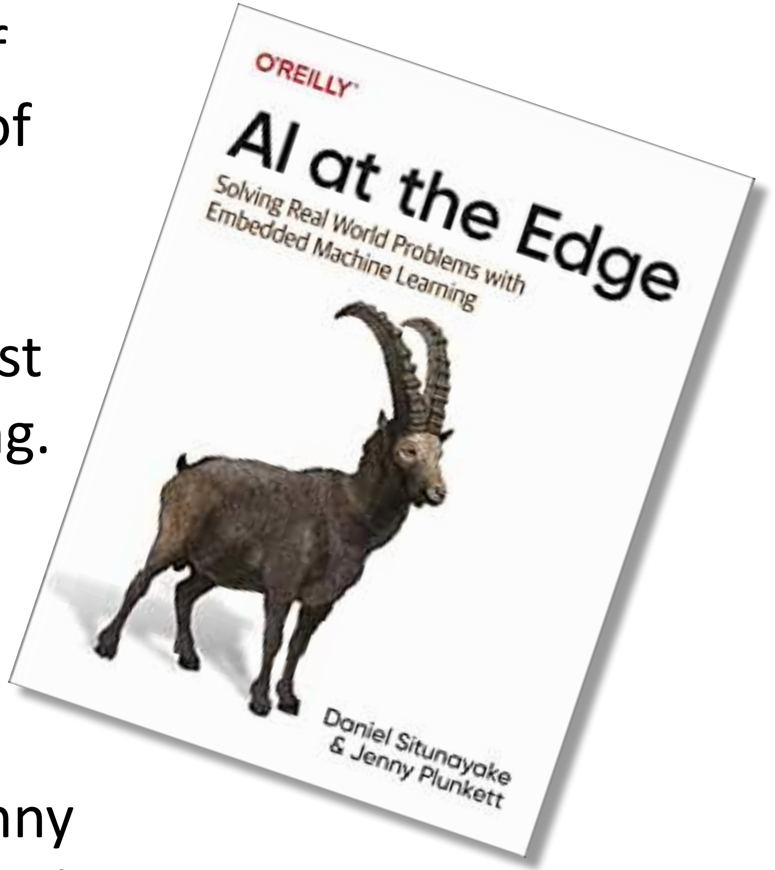
EdgeAI / TinyML

Bringing intelligence to sensors

Prof. Marcelo José Rovai
UNIFEI - Federal University of Itajubá, Brazil
TinyML4D Academic Network Co-Chair

“**Edge AI** is a truly complete technology. As a topic, it makes use of knowledge from everything from the physical properties of semiconductor electronics all the way up to the engineering of high-level architectures that span devices and the cloud. It demands expertise in the most cutting-edge approaches to artificial intelligence and machine learning along with the most venerable skills of bare-metal embedded software engineering. It makes use of the entire history of computer science and electrical engineering, laid out end to end.”



Situnayake, Daniel; Plunkett, Jenny
AI at the Edge (pp. 215-216)
O'Reilly Media

Marcelo Rovai was born in São Paulo and holds a Master's degree in Data Science from the Universidad del Desarrollo (UDD) in Chile and an MBA from IBMEC (INSPER) in Brazil. He graduated in 1982 as an Engineer from UNIFEI, Federal University of Itajubá, with a specialization from Escola Politécnica de Engenharia of São Paulo University (USP), both institutions located in Brazil.

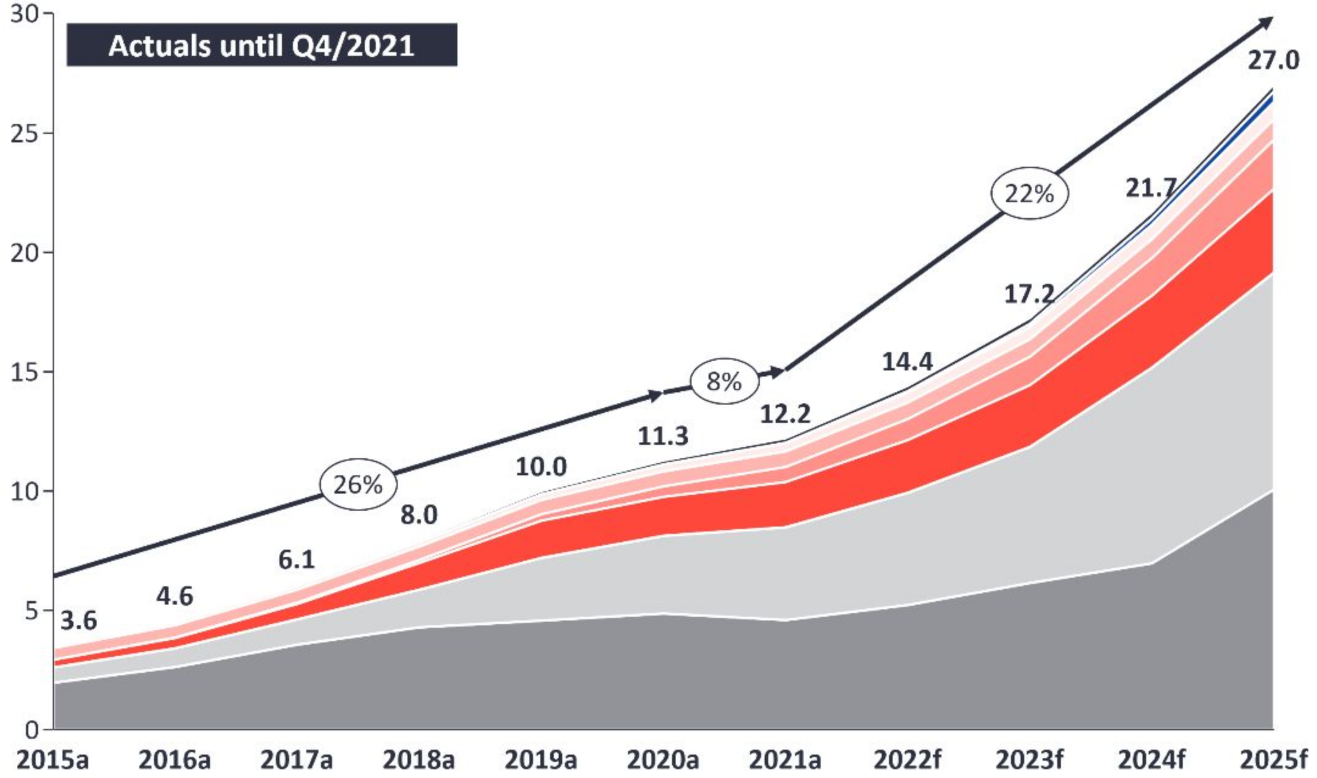
Rovai has experience as a teacher, engineer, and executive in several technology companies such as CDT/ETEP, AVIBRAS Aeroespacial, SID Informática, ATT-GIS, NCR, DELL, COMPAQ (HP), and more recently at IGT as a VP and a Senior Advisor for Latin America.

Marcelo Rovai publishes articles about electronics on websites such as MJRoBot.org, Hackster.io, Instructables.com, and Medium.com. Furthermore, he is a volunteer Professor at the UNIFEI in Brazil and a lecturer at several Congresses and Universities on IoT and TinyML. He is an active member and a Co-Chair of the TinyML4D group, an initiative to bring TinyML education to developing countries.

Internet of Things (IoT)

Global IoT Market Forecast [in billion connected IoT devices]

Number of global active IoT Connections (installed base) in Bn



CONNECTIVITY TYPE	CAGR 20-21	CAGR 21-25
Wireless Neighborhood Area Networks (WNAN)	17%	11%
5G IoT	-	159%
Other	22%	20%
Wired IoT	4%	7%
LPWA	42%	34%
Legacy Cellular (2G/3G/4G)	16%	17%
Wireless Local Area Networks (WLAN)	19%	24%
Wireless Personal Area Networks (WPAN)	-6%	22%

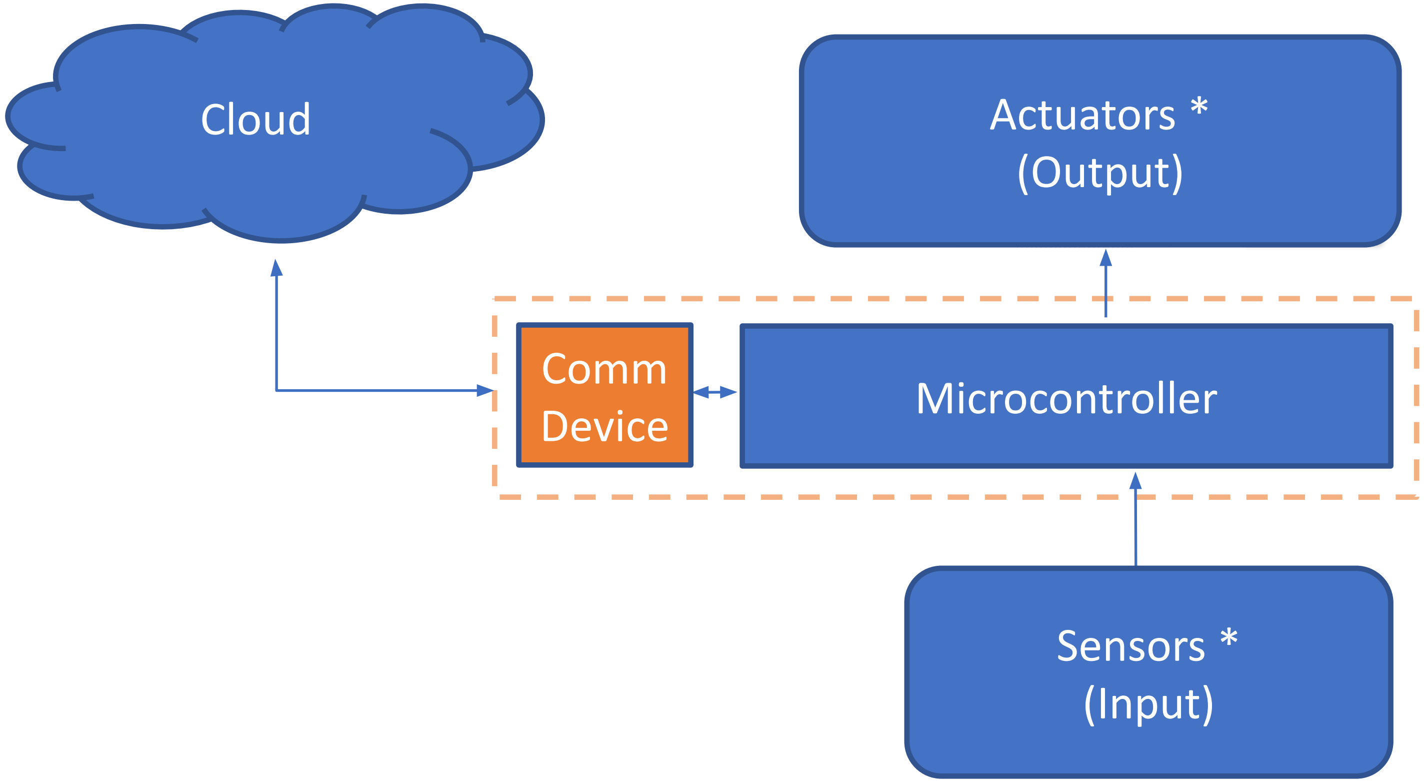
XX% = CAGR

Note: IoT Connections do not include any computers, laptops, fixed phones, cellphones or tablets. Counted are active nodes/devices or gateways that concentrate the end-sensors, not every sensor/actuator. Simple one-directional communications technology not considered (e.g., RFID, NFC). Wired includes Ethernet and Fieldbuses (e.g., connected industrial PLCs or I/O modules); Cellular includes 2G, 3G, 4G; LPWAN includes unlicensed and licensed low-power networks; WPAN includes Bluetooth, Zigbee, Z-Wave or similar; WLAN includes Wi-fi and related protocols; WNAN includes non-short range mesh, such as Wi-SUN; Other includes satellite and unclassified proprietary networks with any range.

Source: IoT Analytics Research 2022. We welcome republishing of images but ask for source citation with a link to the original post and company website.

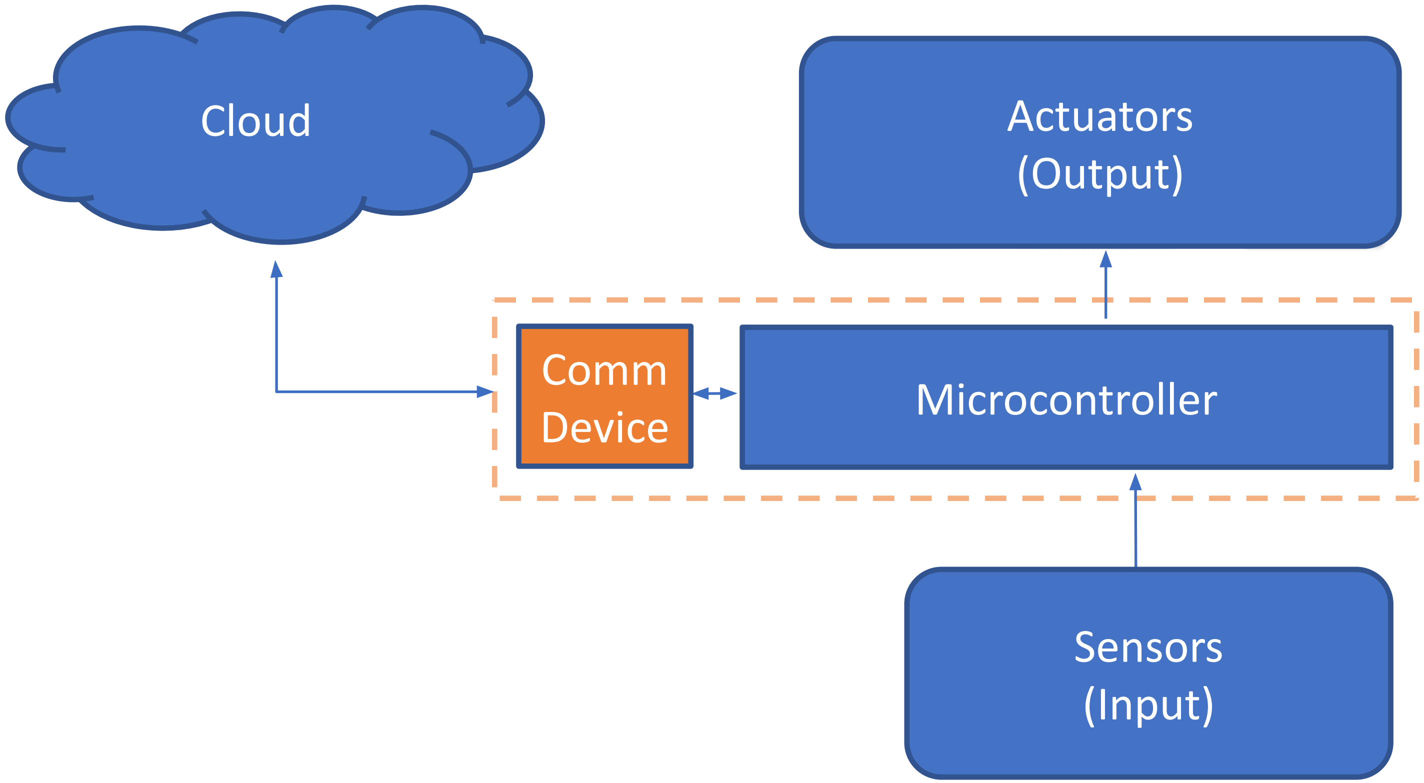
https://iot-analytics.com/number-connected-iot-devices

Typical IoT Project



*** “Things”**

Typical IoT Project



5 Quintillion

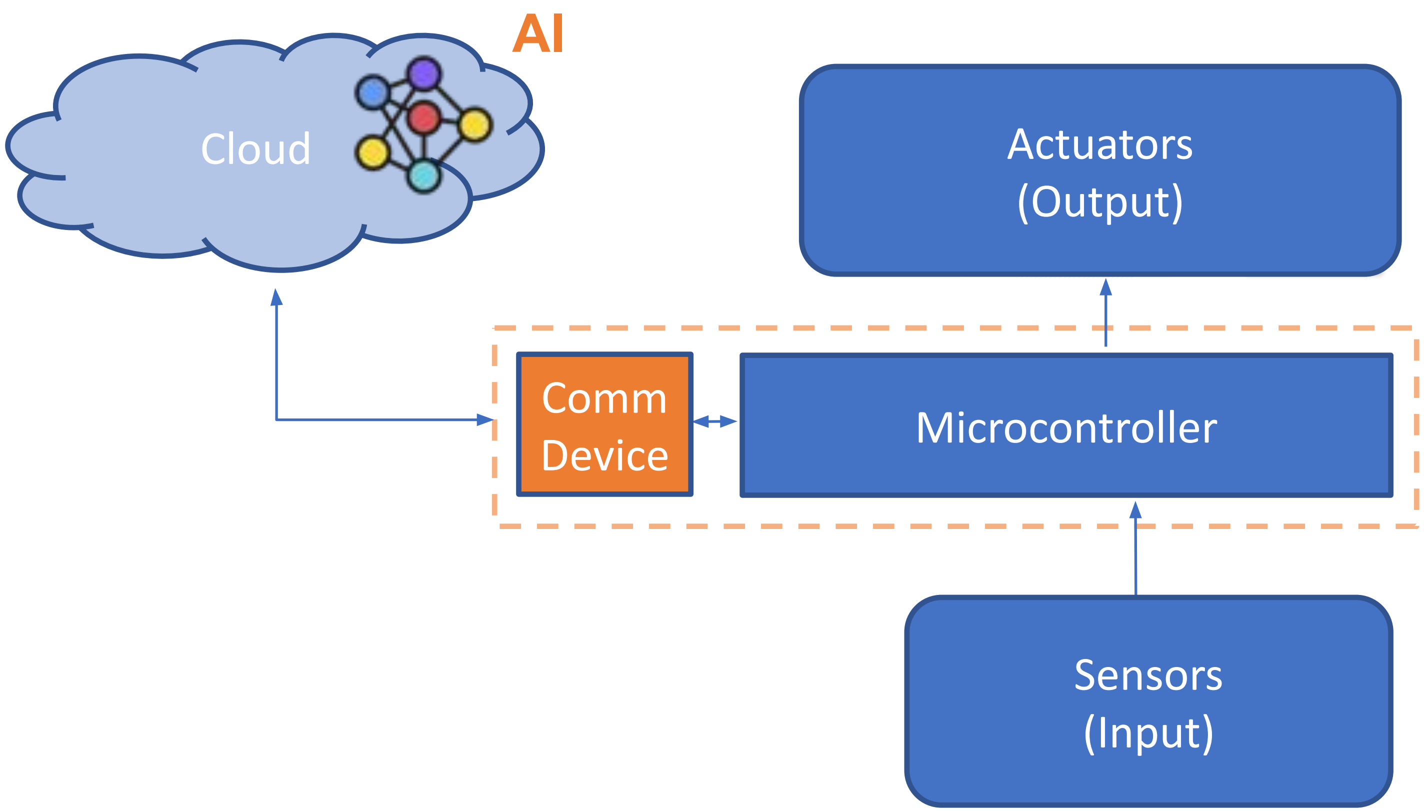
bytes of data produced every day by IoT

<1%

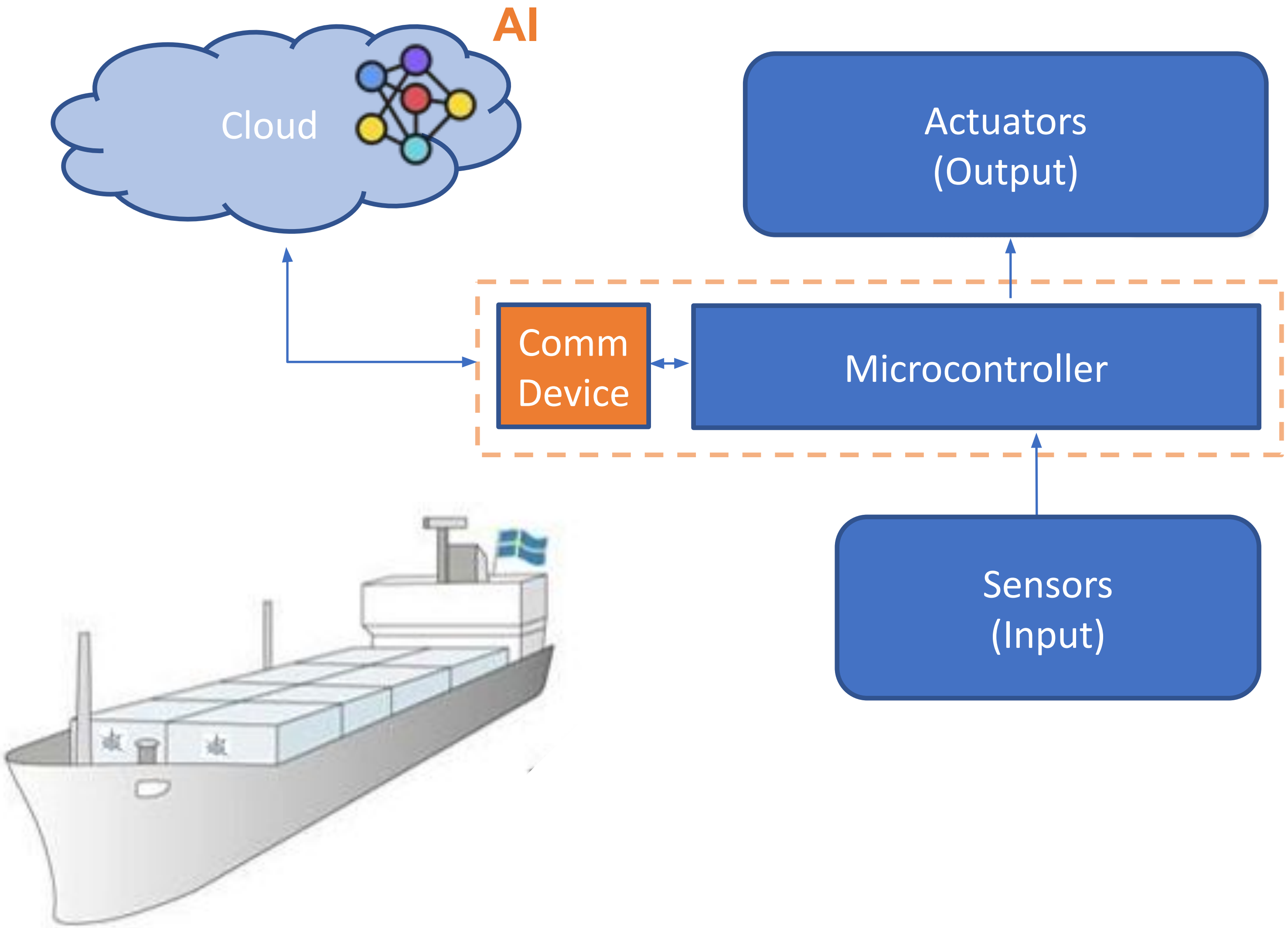
of unstructured data is analyzed or used at all

Source: Harvard Business Review, [What's Your Data Strategy?](), April 18, 2017
Cisco, [Internet of Things (IoT) Data Continues to Explode Exponentially. Who Is Using That Data and How?](), Feb 5, 2018

Typical AIoT Project

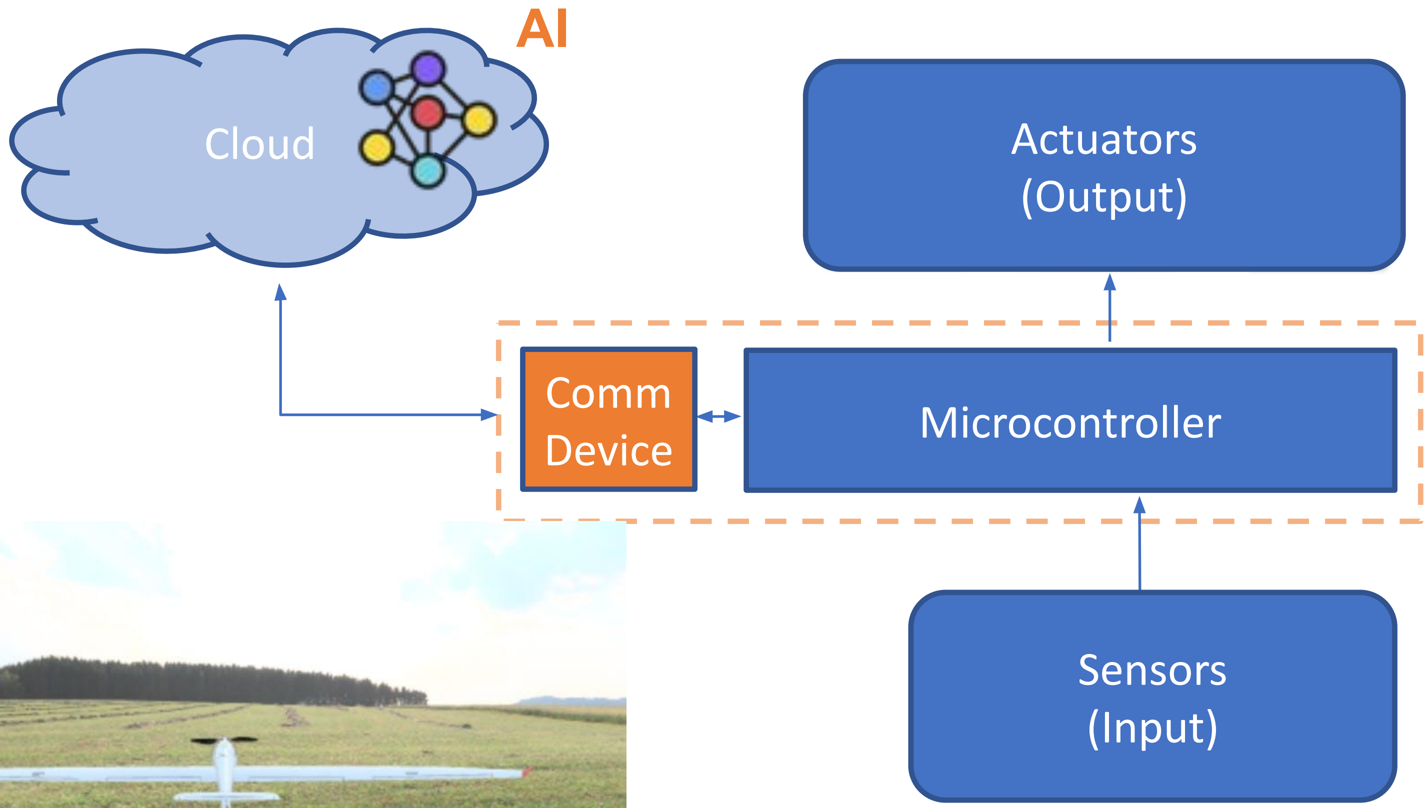


Typical AIoT Project … … Issues



Bandwidth

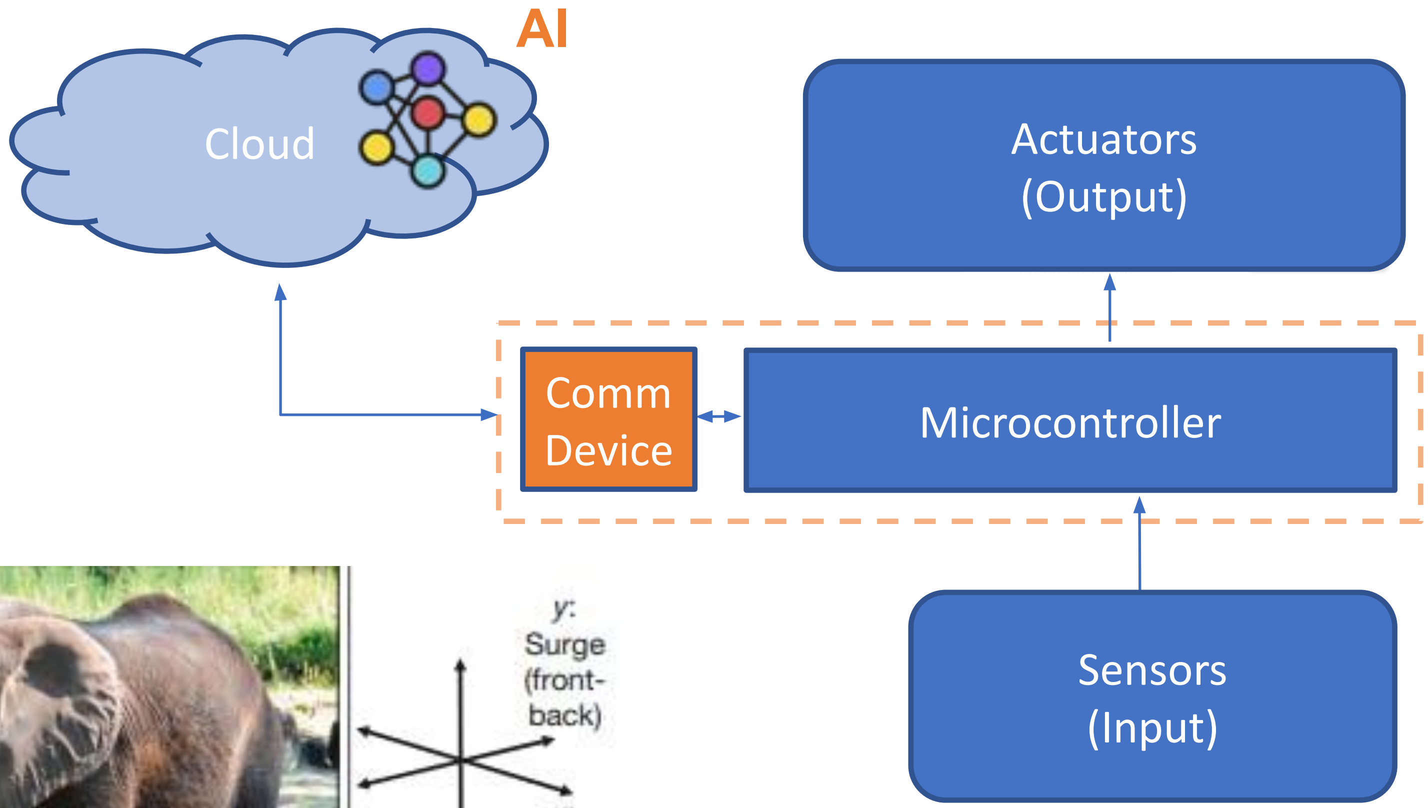
Typical AIoT Project … … Issues

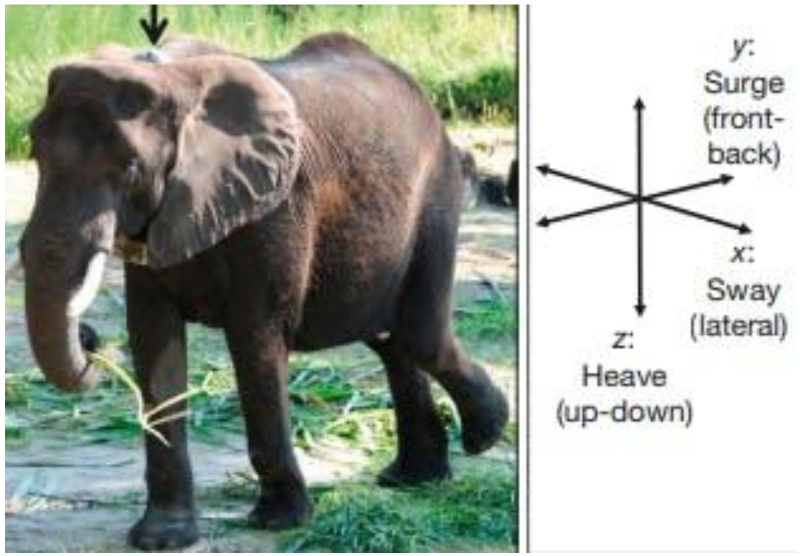


Bandwidth

Latency

Typical AIoT Project … … Issues



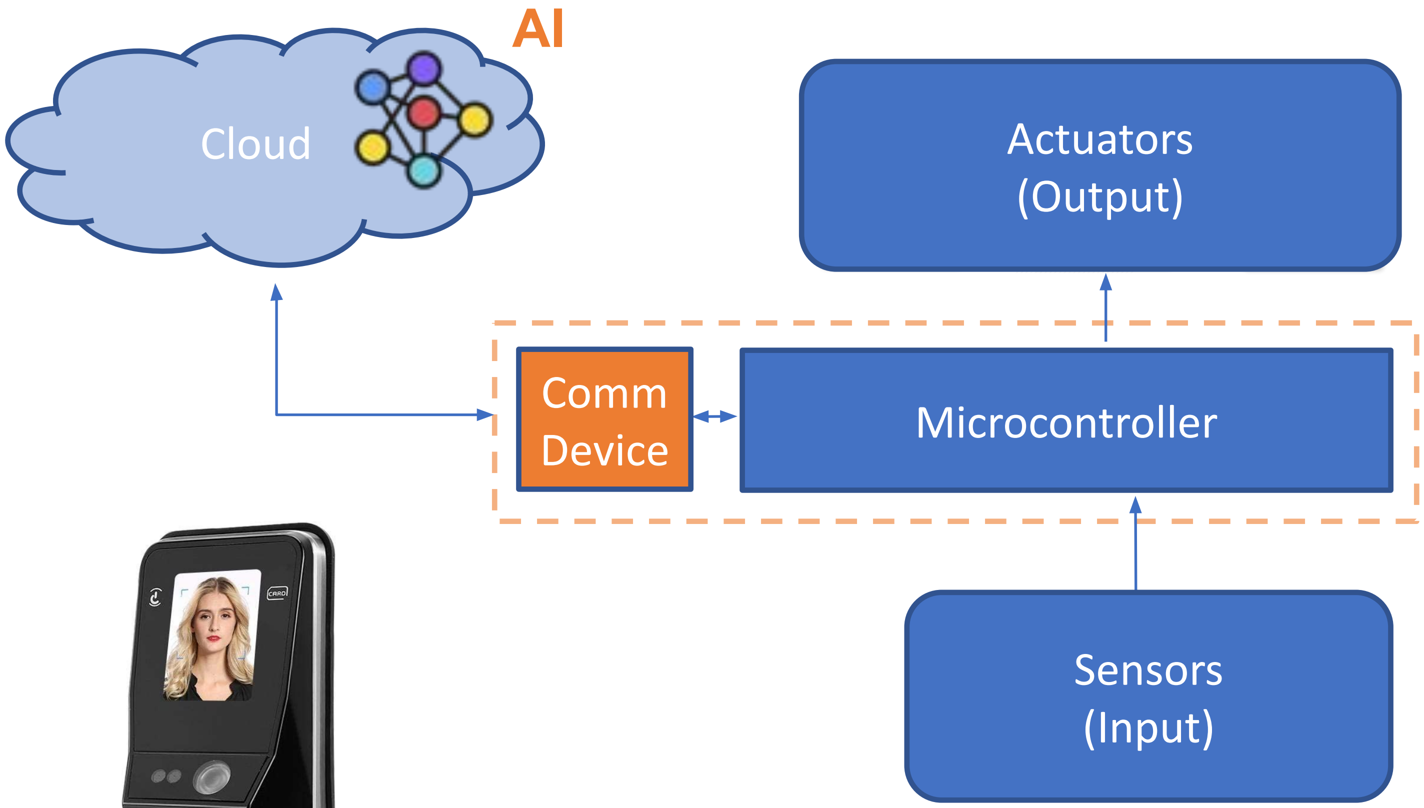


Bandwidth

Latency

Energy

Typical AIoT Project … … Issues



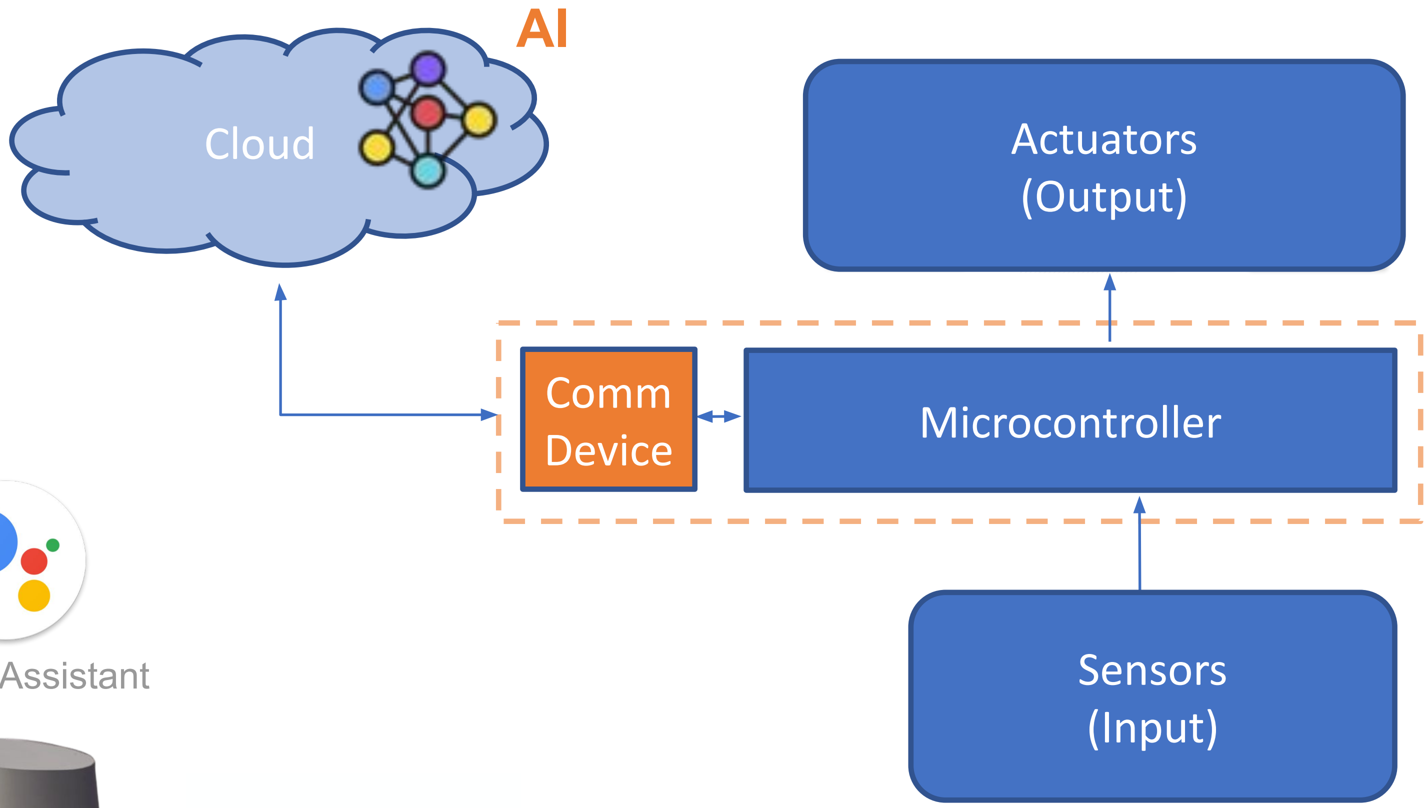
Bandwidth

Latency

Energy

Reliability

Typical AIoT Project … … Issues



Google Assistant

Bandwidth

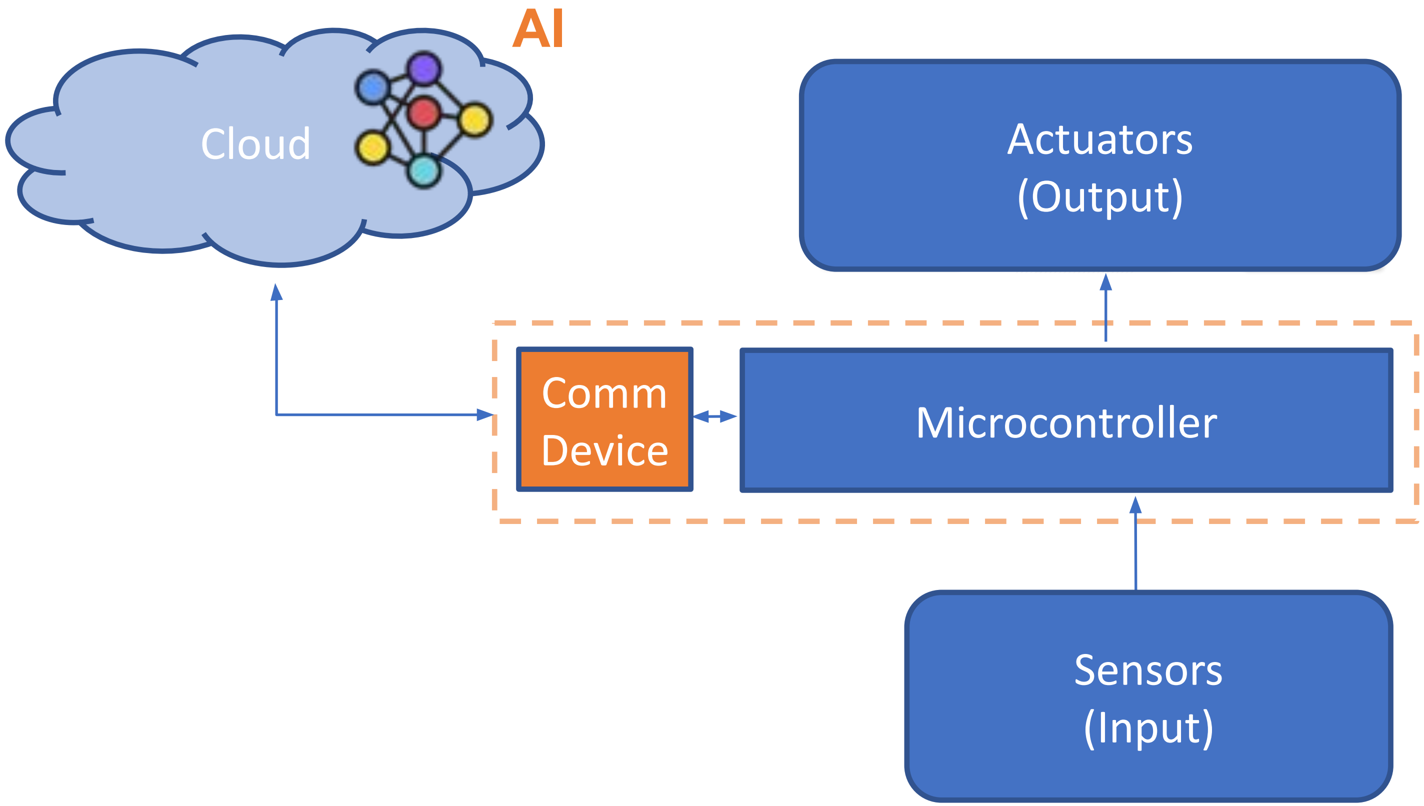
Latency

Energy

Reliability

Privacy

Typical AIoT Project … … Issues

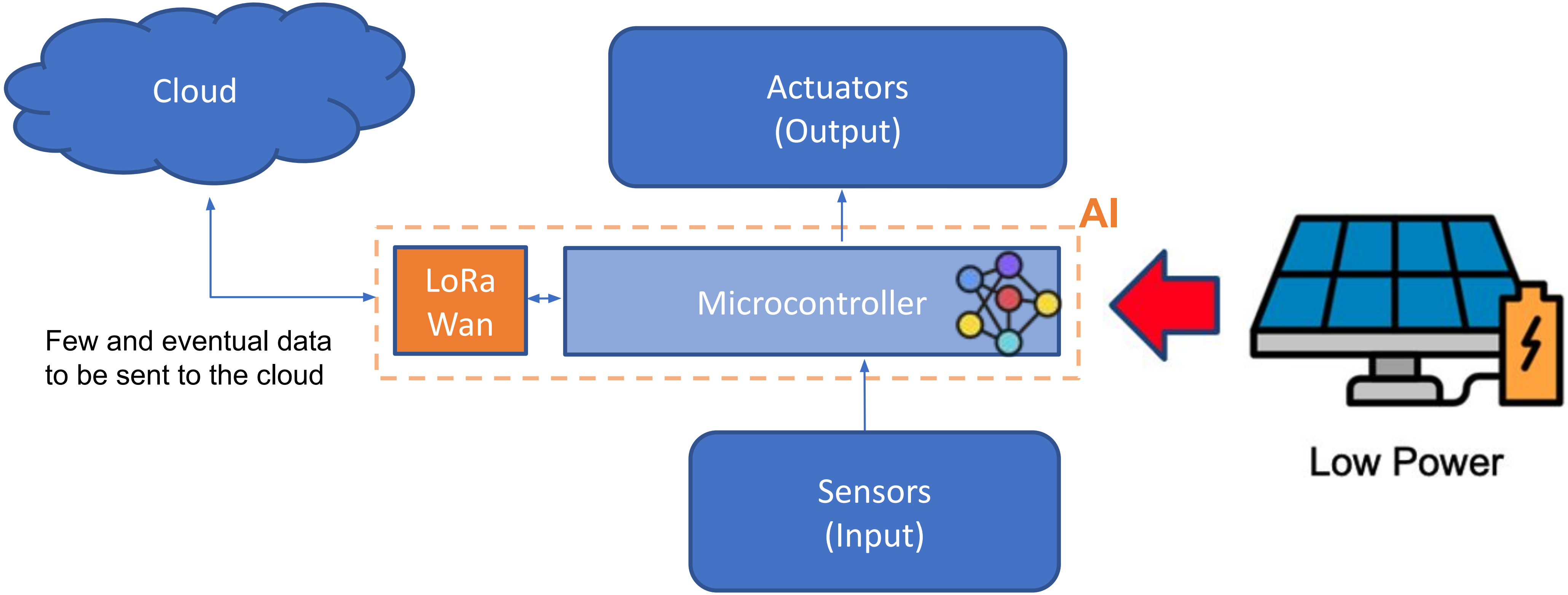


Bandwidth
Latency
Energy
Reliability
Privacy

… **Solution ?**

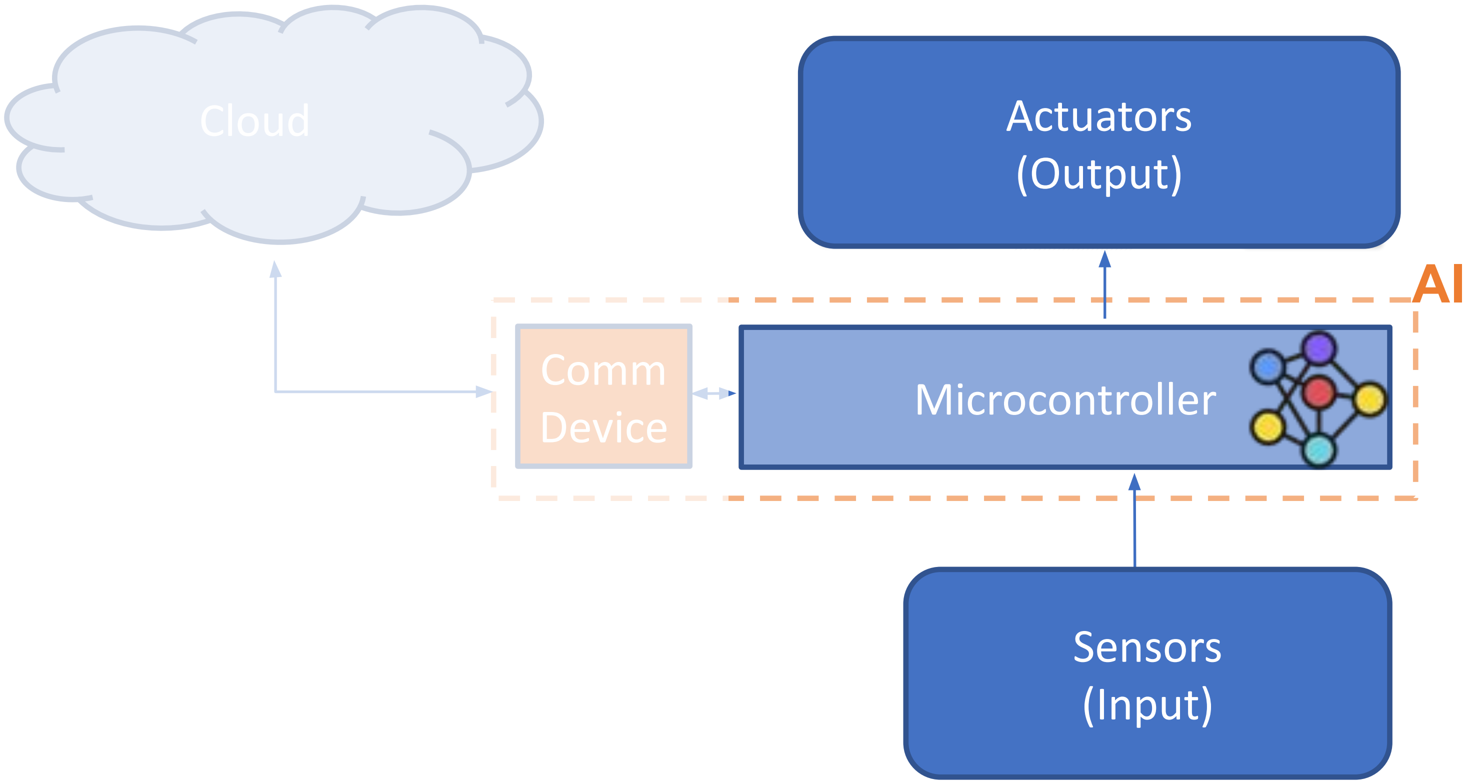
IoT 2.0 * – Edge AI/ML

* Intelligence of Things



… Solution -> ML goes close to data

When to use an Edge AI/ML approach:



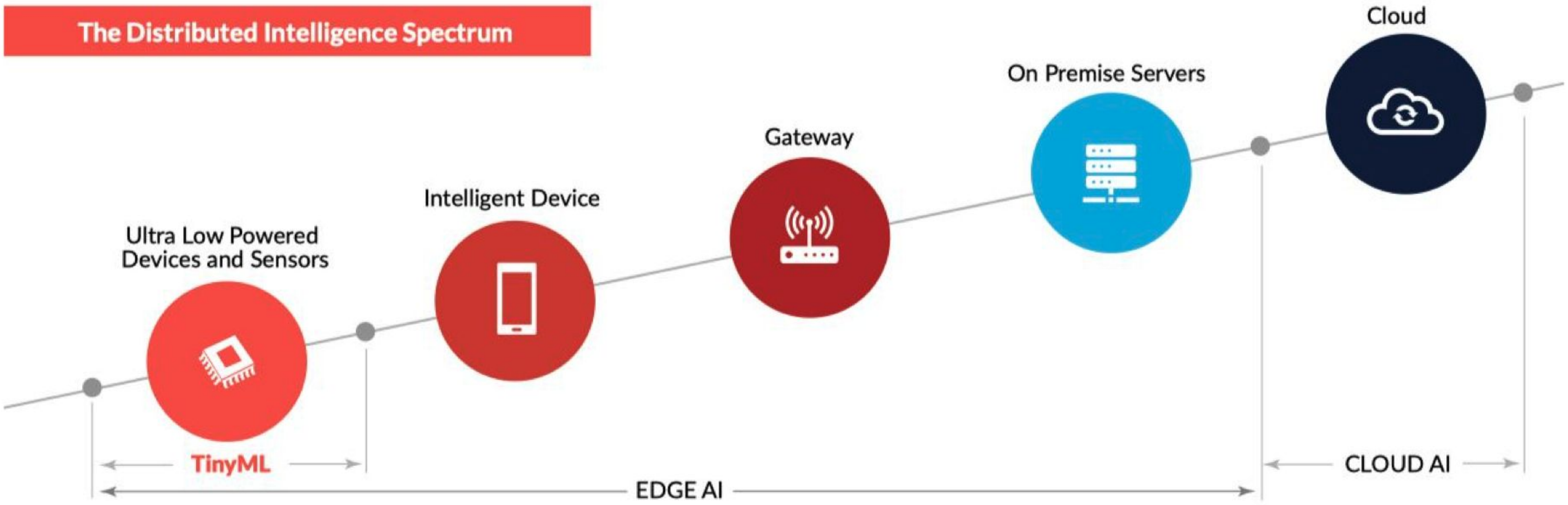
Bandwidth

Latency

Energy

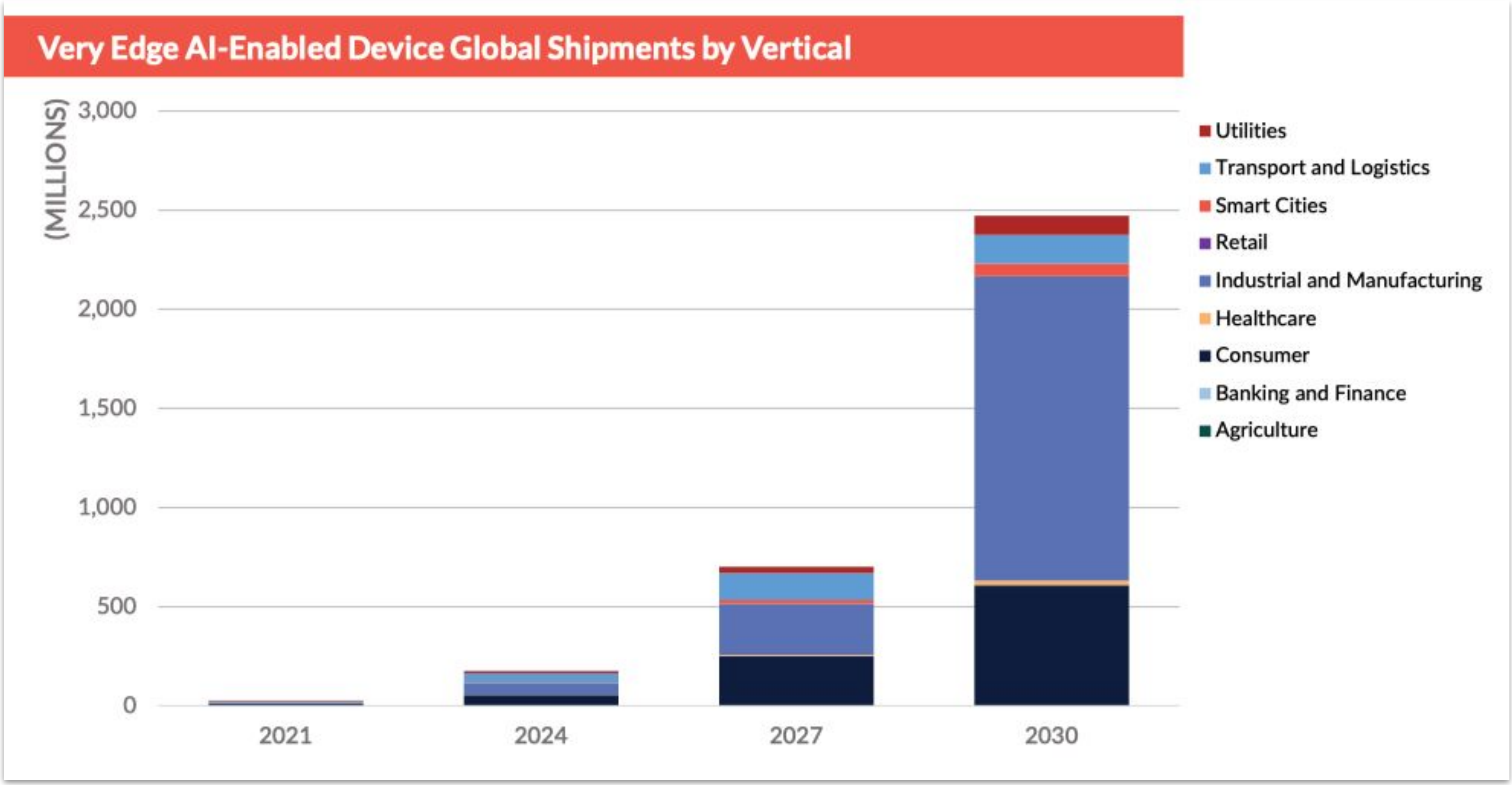
Reliability

Privacy



Source: ABI Research: TinyML

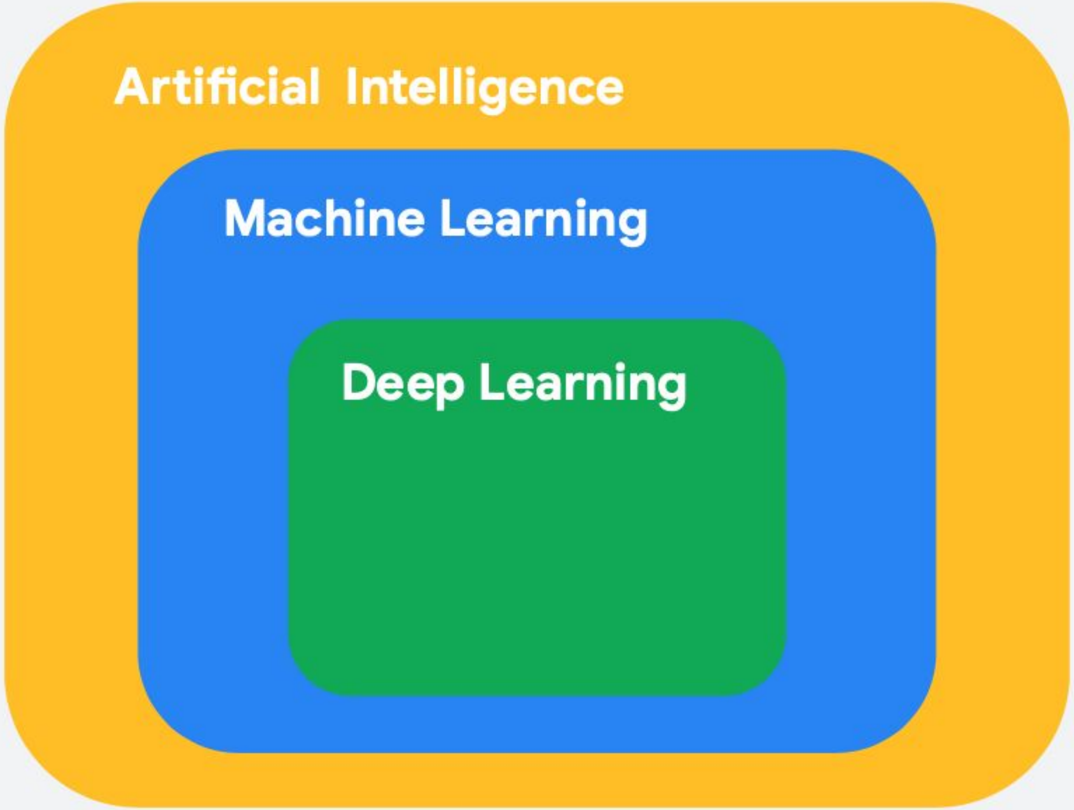
Market Forecast



Source: ABI Research: TinyML

Embedded ML (TinyML)

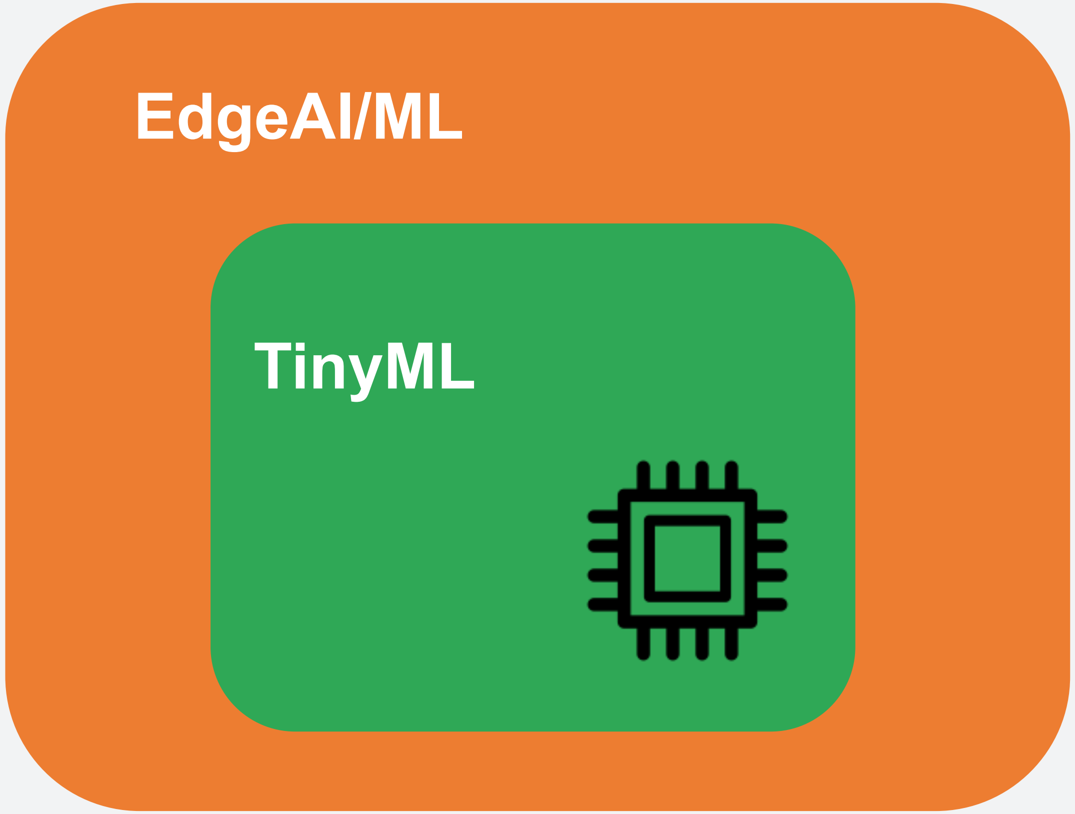
Introduction



AI: Any technique that enables computers to mimic human behavior

ML: Ability to learn without explicitly being programed

DL: Extract patterns from data using neural networks



Edge AI (or Edge ML) is the processing of Artificial Intelligence algorithms on edge, that is, on users' devices. The concept derives from **Edge Computing**, which starts from the same premise: data is stored, processed, and managed directly at the Internet of Things (IoT) endpoints.

TinyML is a subset of EdgeML, where sensors are generating data with ultra-low power consumption (batteries), so that we can ultimately deploy machine learning continuously ("always on devices")

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

TinyML

Fastest-growing field of **ML**

22

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

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

23

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

On-device sensor analytics

24

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

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

On-device sensor analytics

Low power consumption

25

What is Tiny Machine Learning (TinyML)?

TinyML

- Fastest-growing field of **ML**
- Algorithms, hardware, software
- **On-device** sensor analytics
- **Low power** consumption
- **Battery-operated**

26

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of ML

Algorithms, hardware, software

On-device sensor analytics

Low power consumption

Battery-operated

Always-on ML

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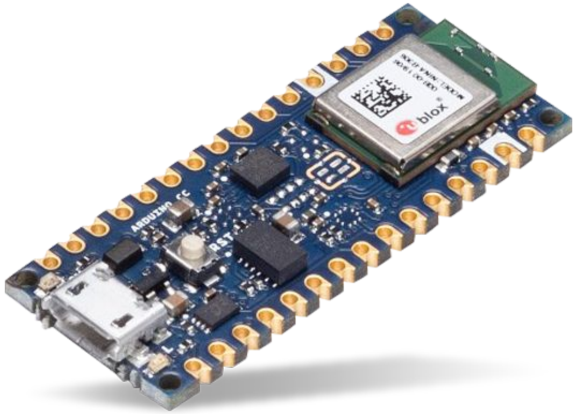
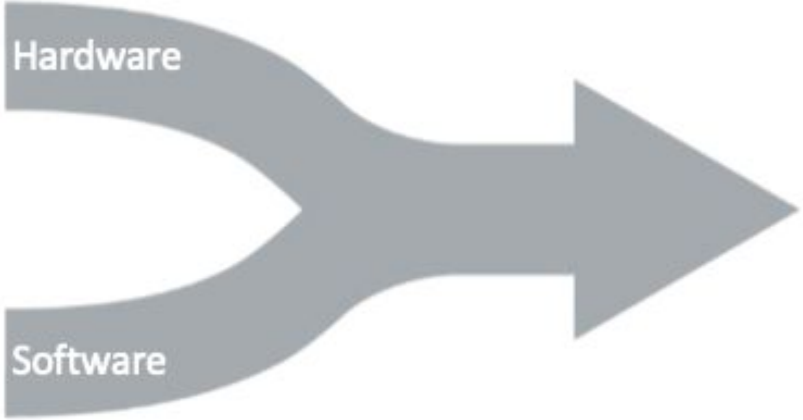
What Makes TinyML ?

TinyML

What Makes TinyML ?

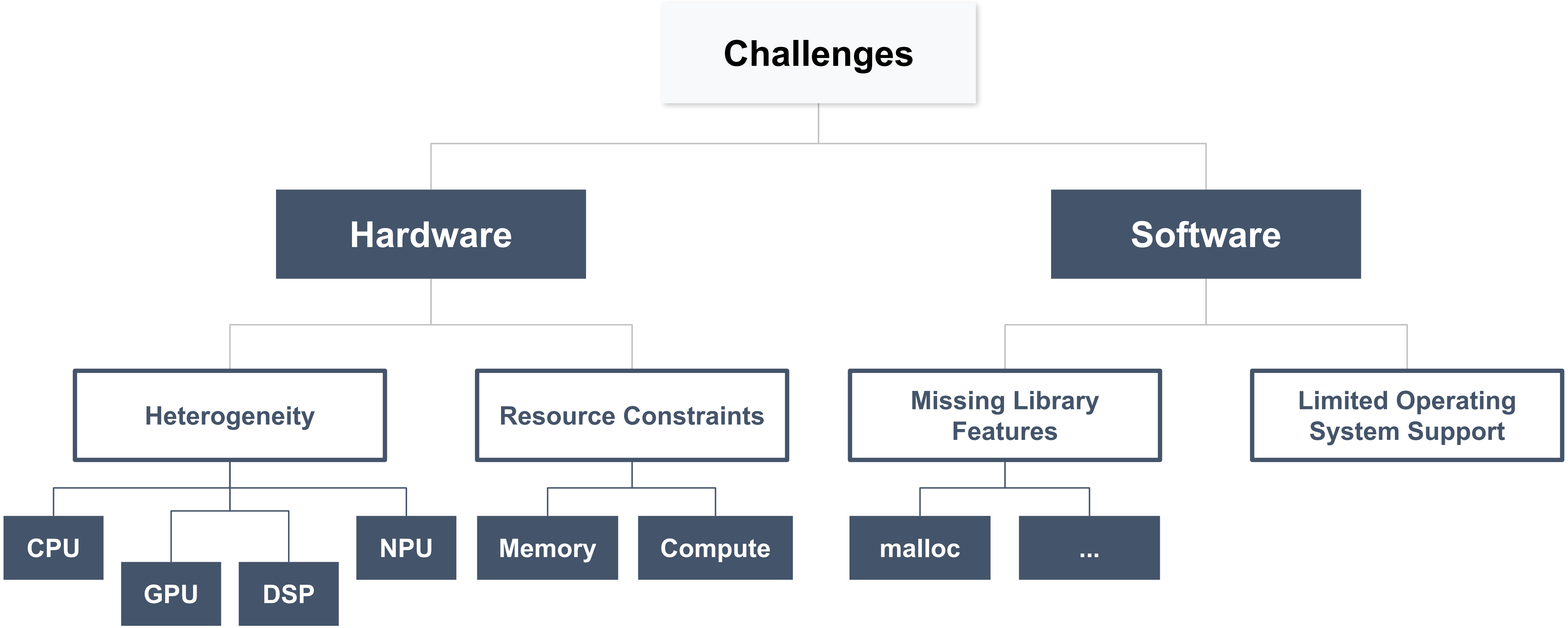


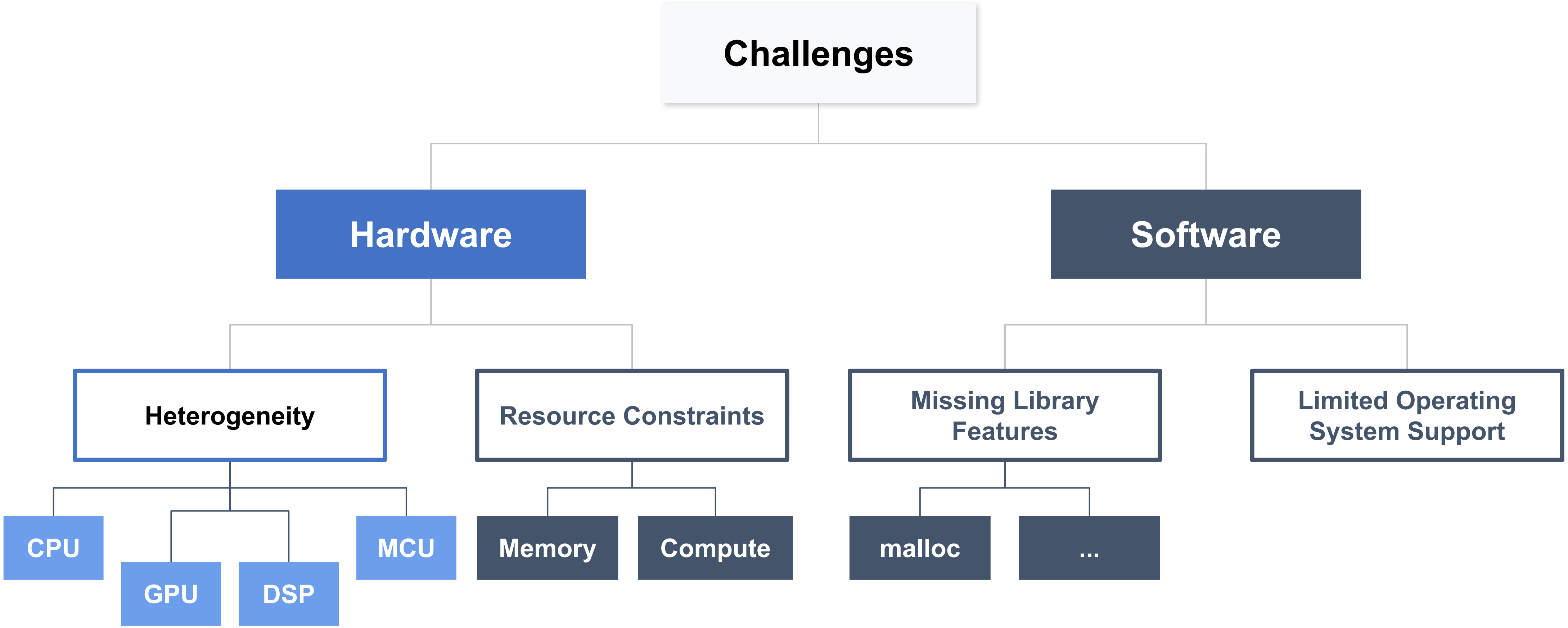
TensorFlow Lite



TinyML

TinyML Challenges


Challenges
Hardware
Software
Heterogeneity
Resource Constraints
Missing Library Features
Limited Operating System Support
CPU
GPU
DSP
NPU
Memory
Compute
malloc
...



Challenges
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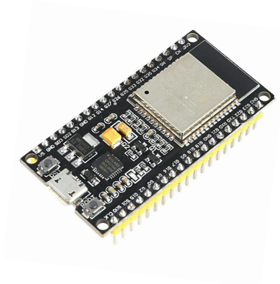
malloc
...

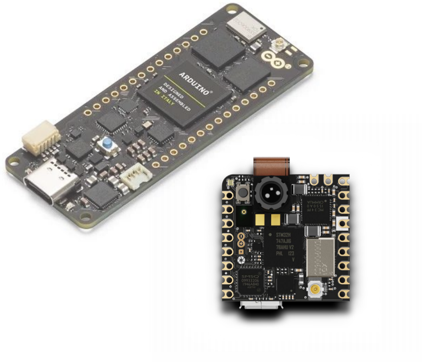
250 Billion

MCUs today

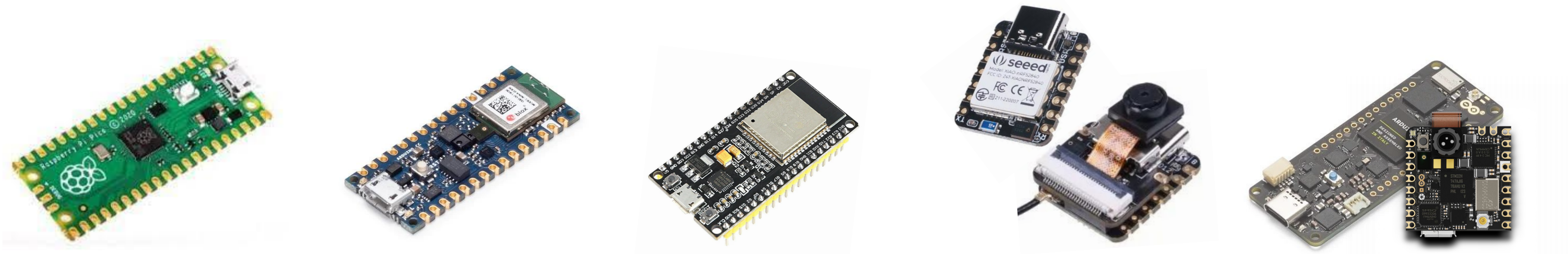
33

Hardware



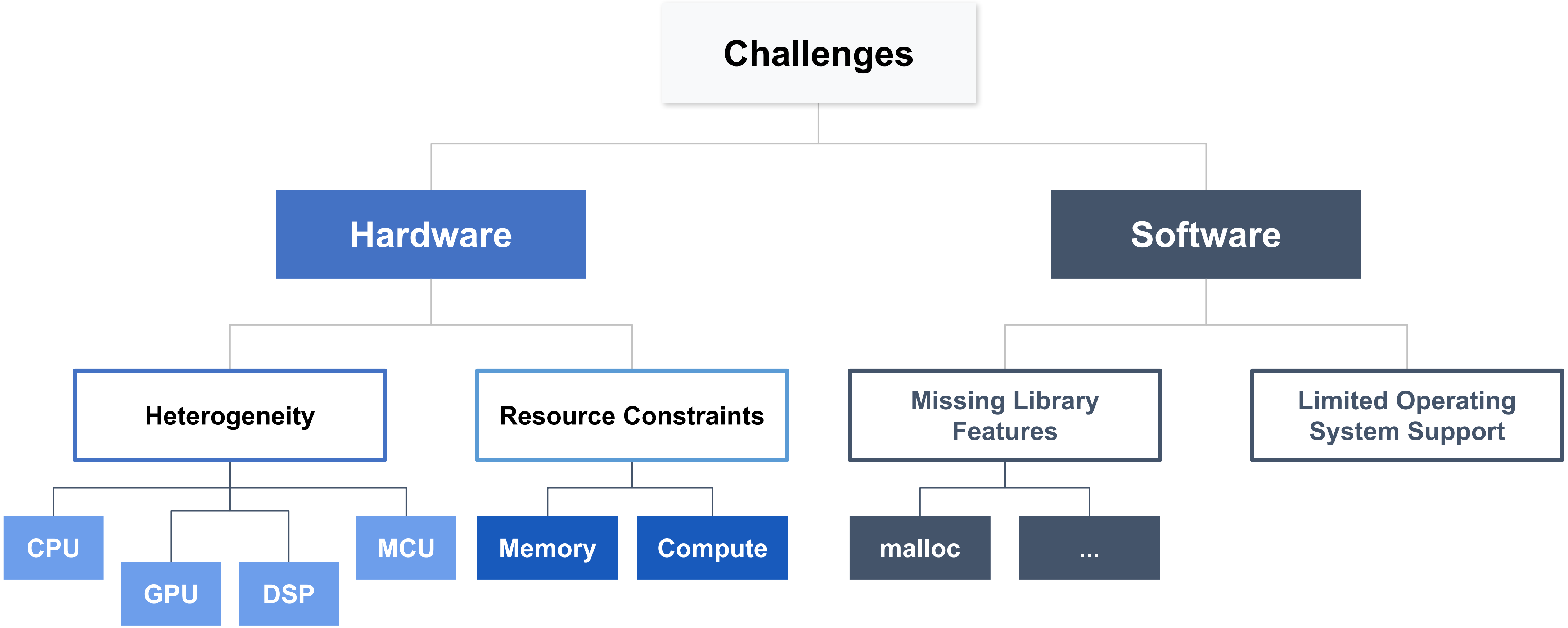


Hardware



	Raspberry Pico (W)	Arduino Nano Sense	ESP 32	Seeed XIAO Sense / ESP32S3	Arduino Pro
32Bits CPU	Dual-core Arm Cortex-M0+	Arm Cortex-M4F	Xtensa LX6 Dual Core	Arm Cortex-M4F (BLE) Xtensa LX7 Dual Core	Dual Core Arm Cortex M7/M4
CLOCK	133MHz	64MHz	240MHz	64 / 240MHz	480/240MHz
RAM	264KB	256KB	520KB (part available)	256KB / 8MB	1MB
ROM	2MB	1MB	2MB	2MB / 8MB	2MB
Radio	(Yes for W)	BLE	BLE/WiFi	BLE / WiFi (ESP32S3)	BLE/WiFi
Sensors	No	Yes	No	Yes (Sense)	Yes (Nicla)
Bat. Power Manag.	No	No	No	Yes	Yes
Price	$	$$$	$	$$	$$$$$

https://media.digikey.com/Resources/Maker/the-original-guide-to-boards-2022.pdf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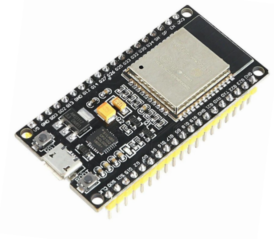
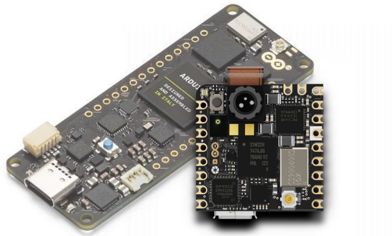
malloc
...

Hardware







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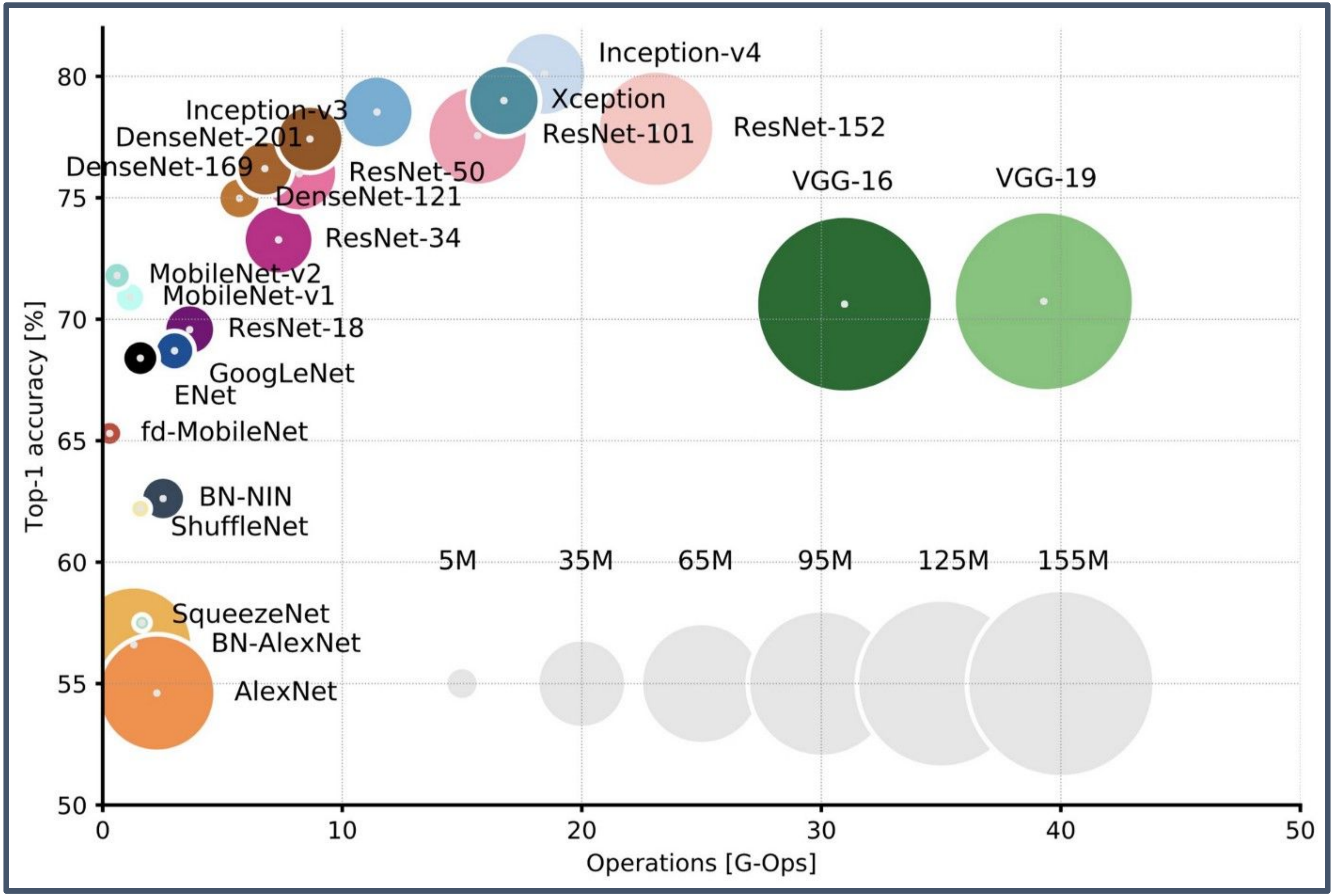
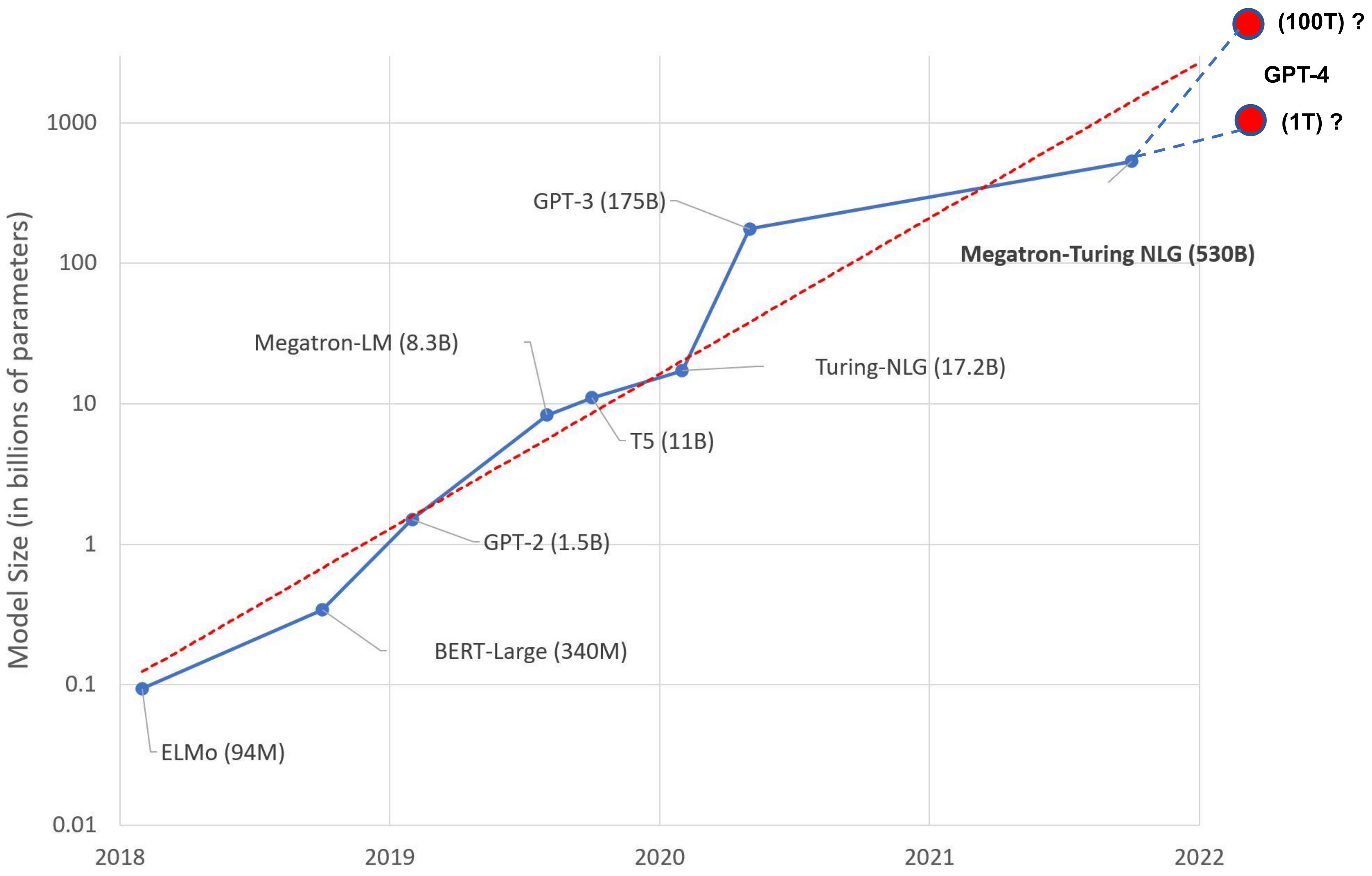
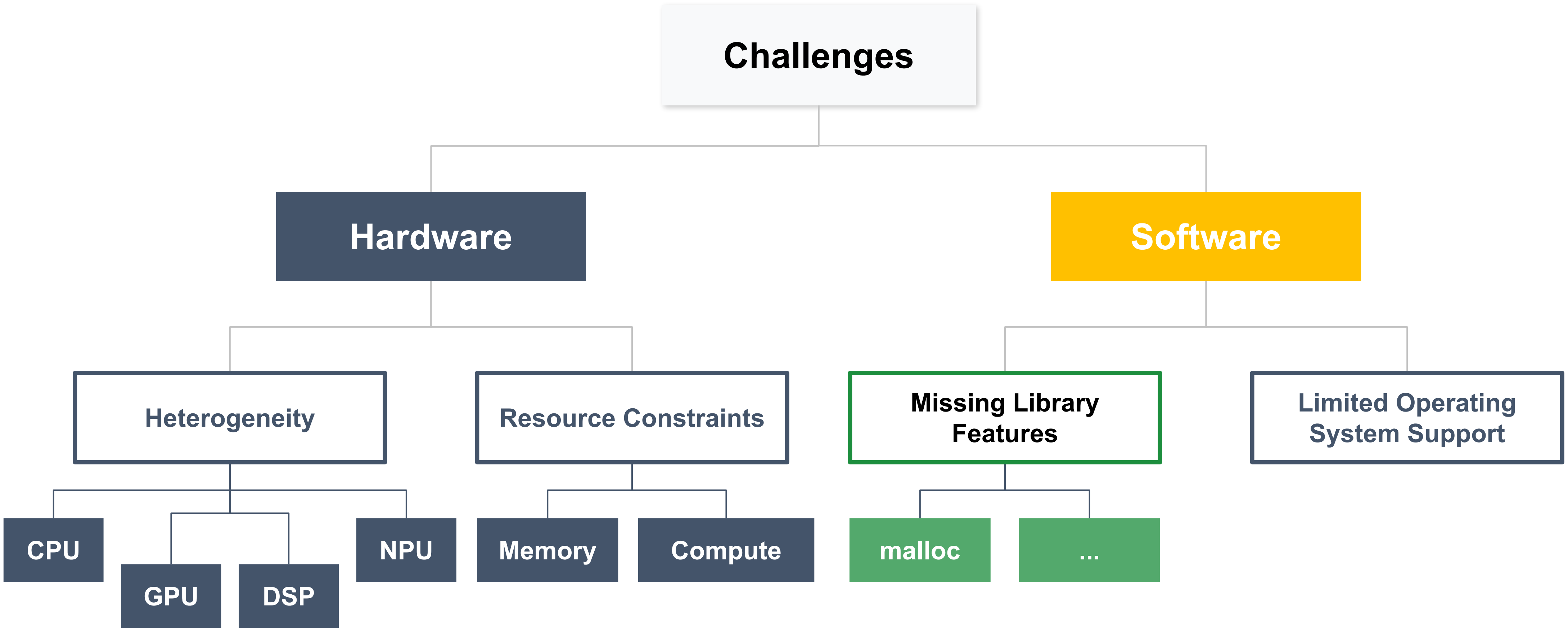
https://media.digikey.com/Resources/Maker/the-original-guide-to-boards-2022.pdf

https://arxiv.org/pdf/1910.01108.pdf
https://towardsdatascience.com/neural-network-architectures-156e5bad51ba





https://huggingface.co/blog/large-language-models https://arxiv.org/abs/2303.08774


Challenges
Hardware
Software
Heterogeneity
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malloc
...

Sensors

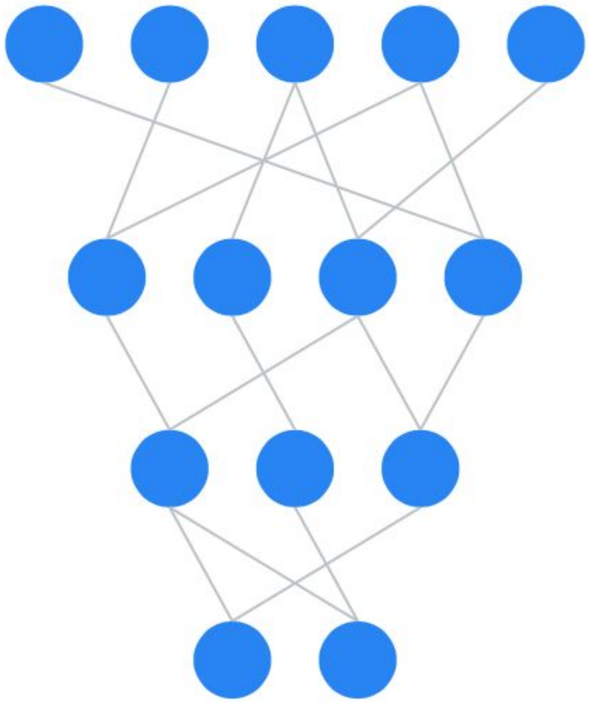
Models

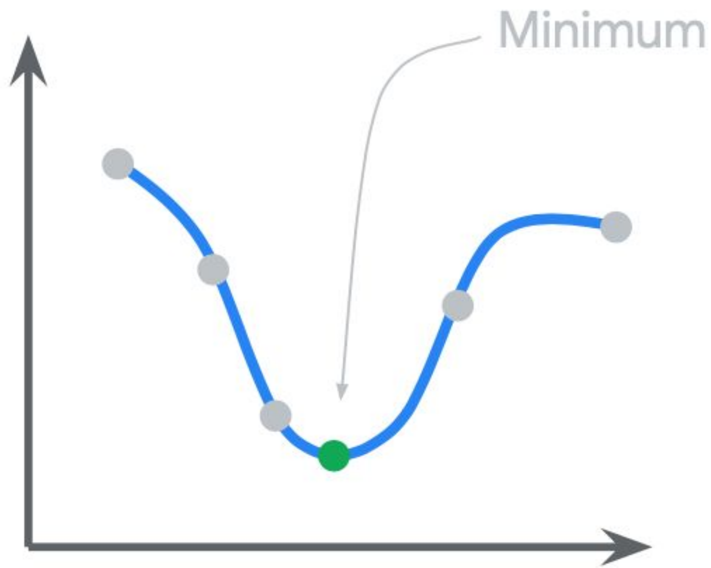
Metrics

Acoustic Sensors
Ultrasonic, **Microphones**, Geophones, Vibrometers

Image Sensors
Thermal, **Image**

Motion Sensors
Gyroscope, Radar, **Accelerometer**





End-to-end **TinyML** application design

Datasets
Preprocessing

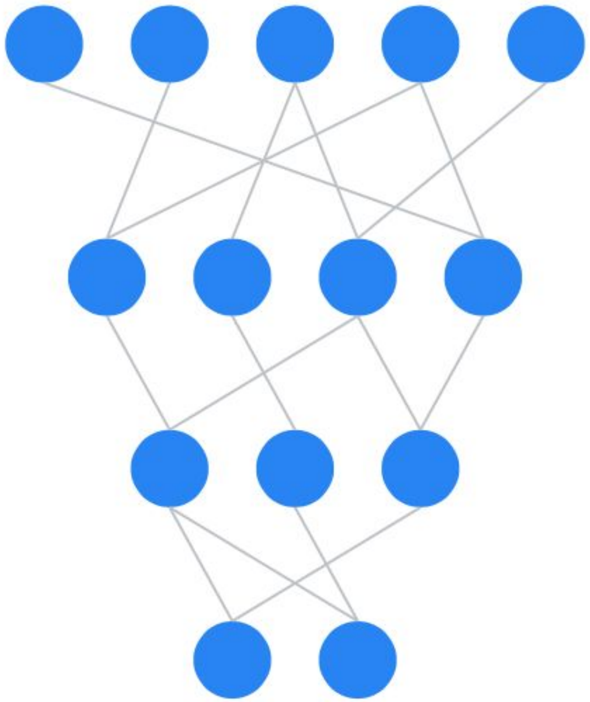
Quantization
Pruning

Resource
constraints

Sound

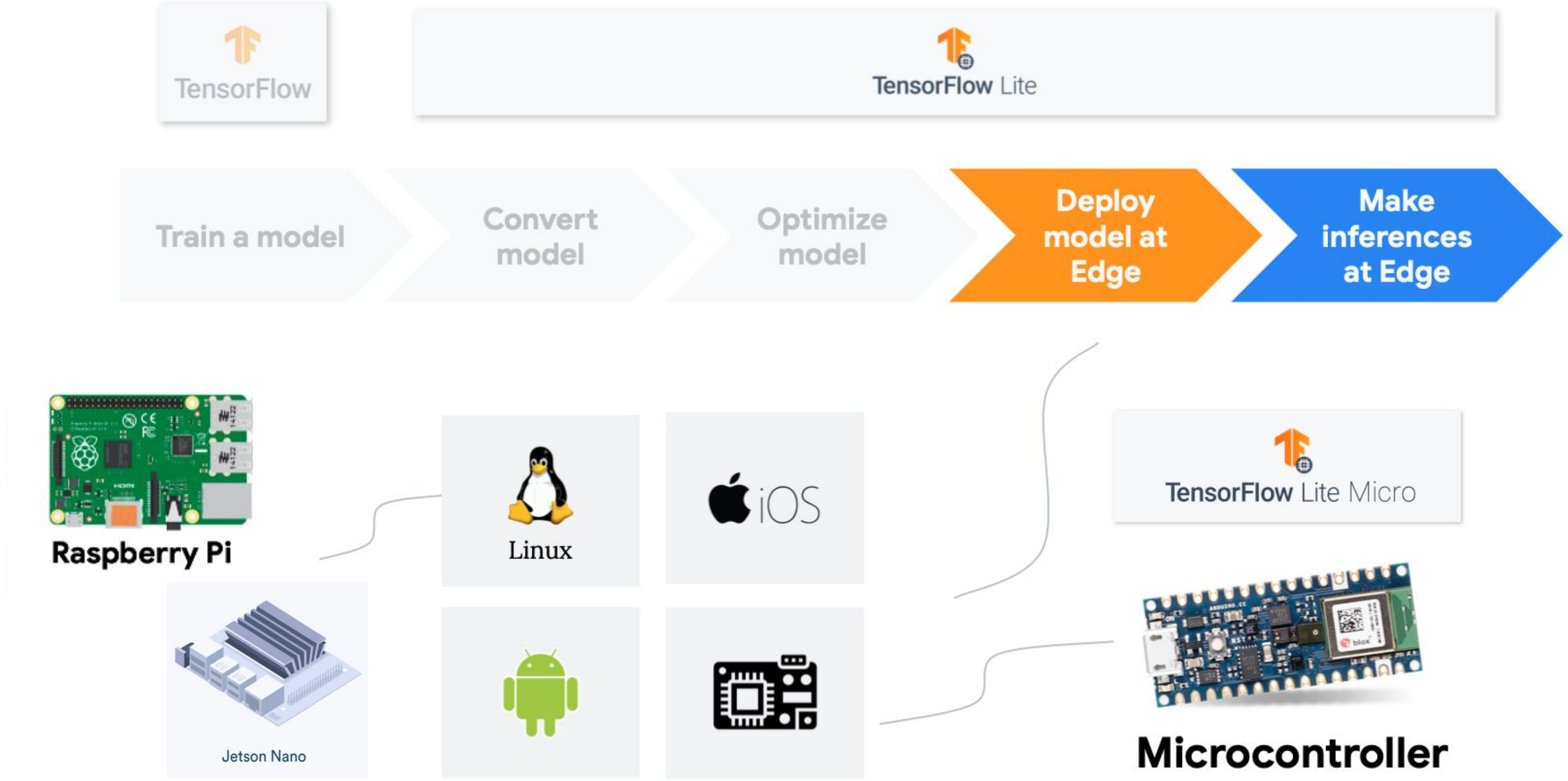
Vision

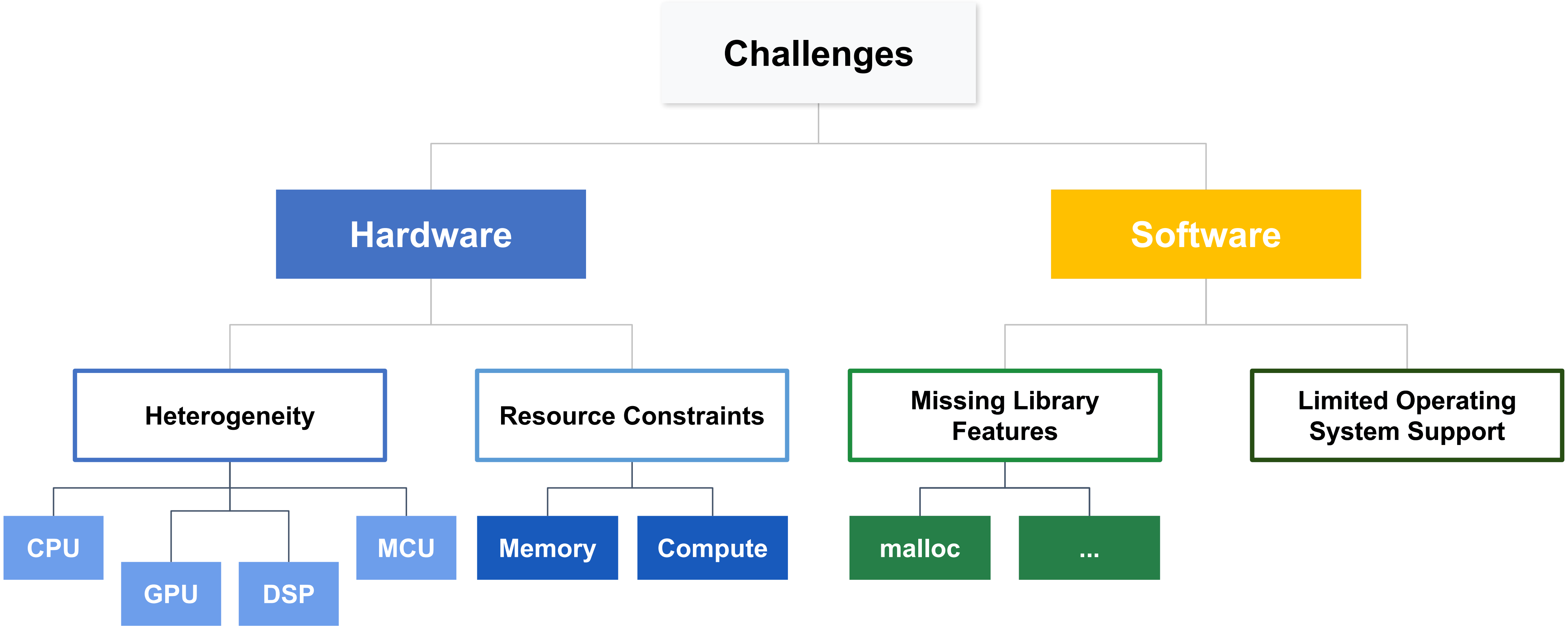
Vibration



End-to-end **TinyML** application design

Software


TensorFlow
TensorFlow Lite
Train a model
Convert model
Optimize model
Deploy model at Edge
Make inferences at Edge
Raspberry Pi
Jetson Nano
Linux
iOS
TensorFlow Lite Micro
Microcontroller


Challenges
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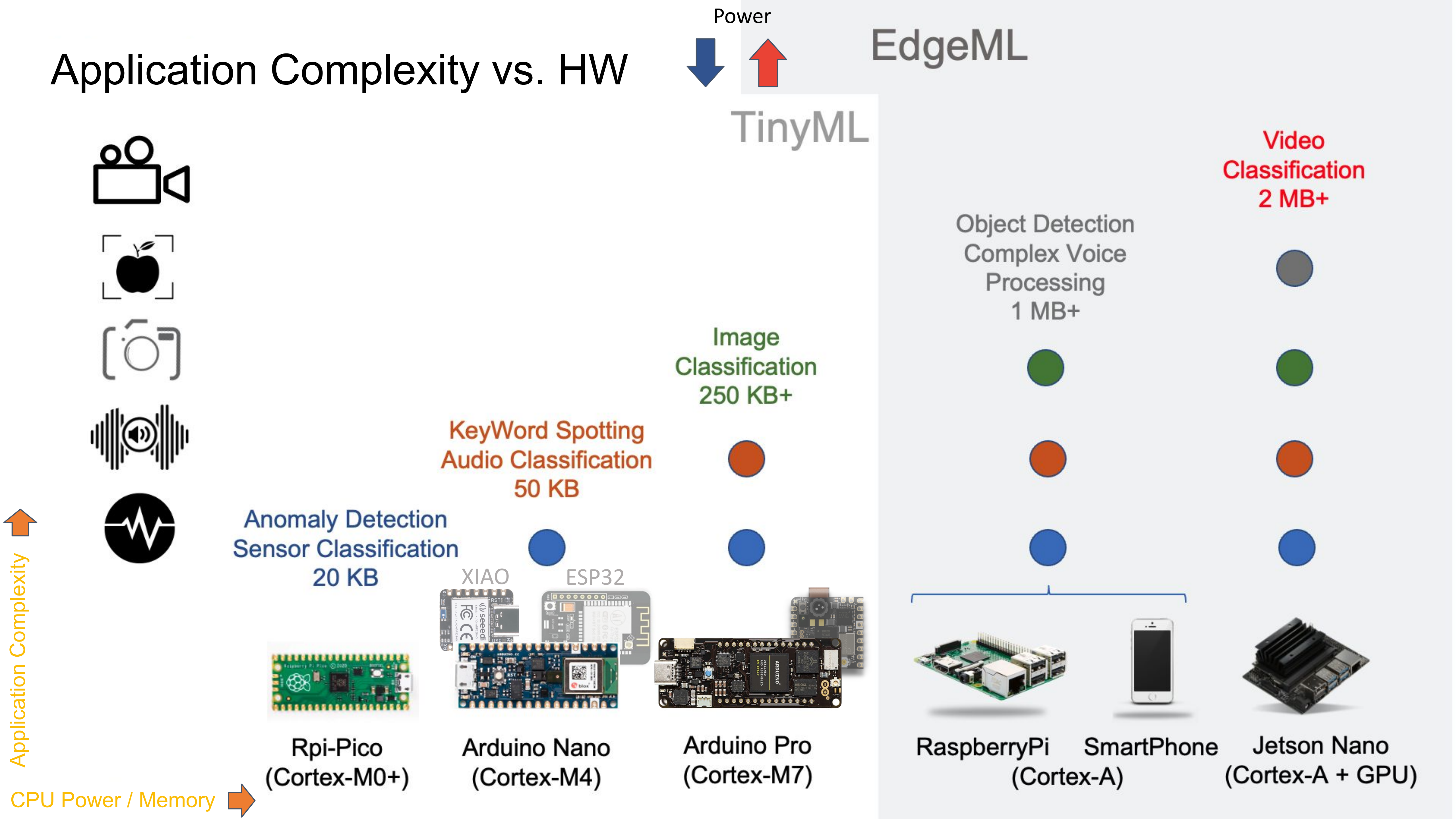
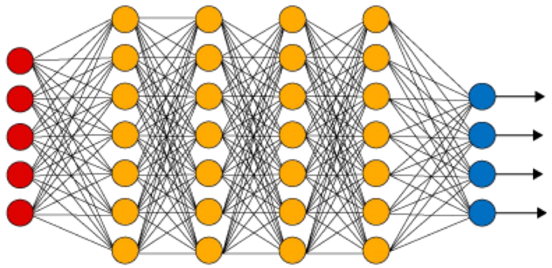
...

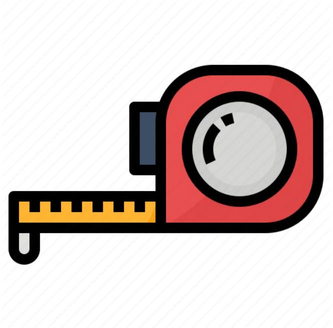
Application Complexity vs. HW



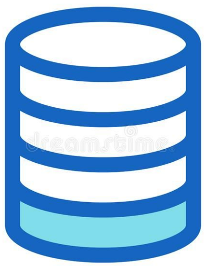
How to Train a ML Model?

Machine Learning Workflow ("What")

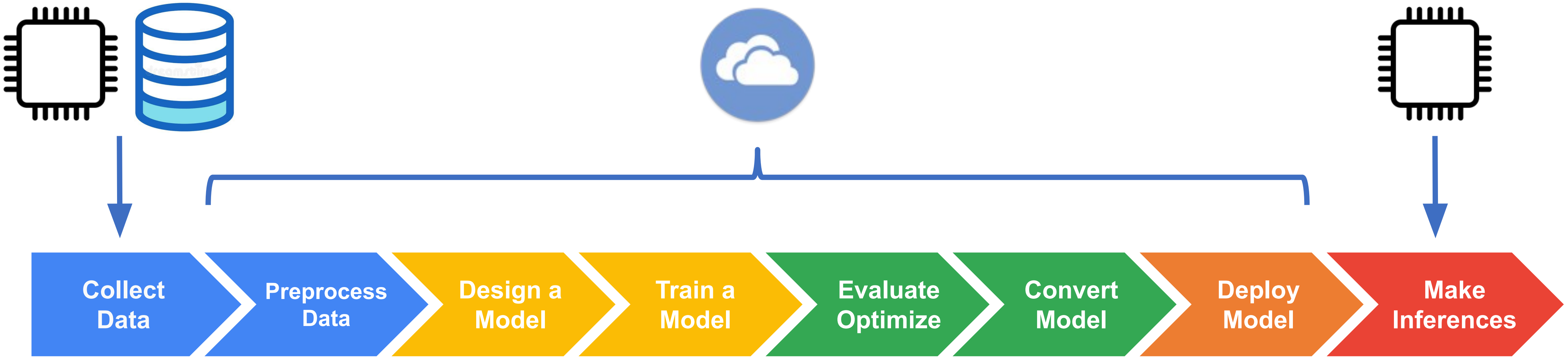




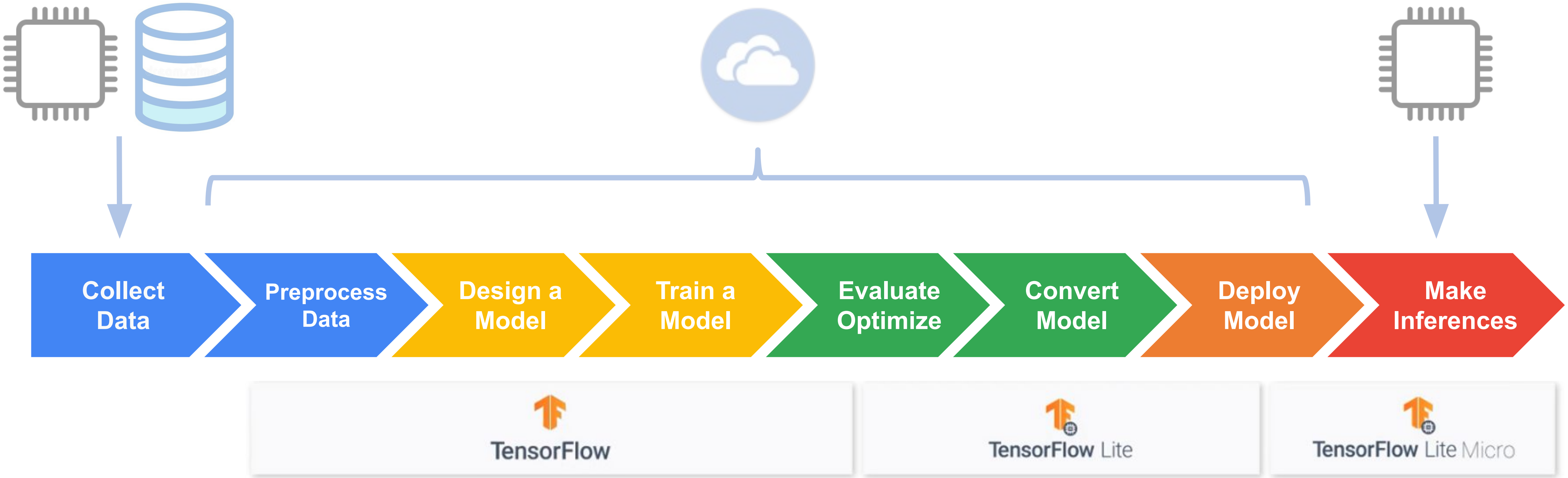
Collect Data → Preprocess Data → Design a Model → Train a Model → Evaluate Optimize → Convert Model → Deploy Model → Make Inferences



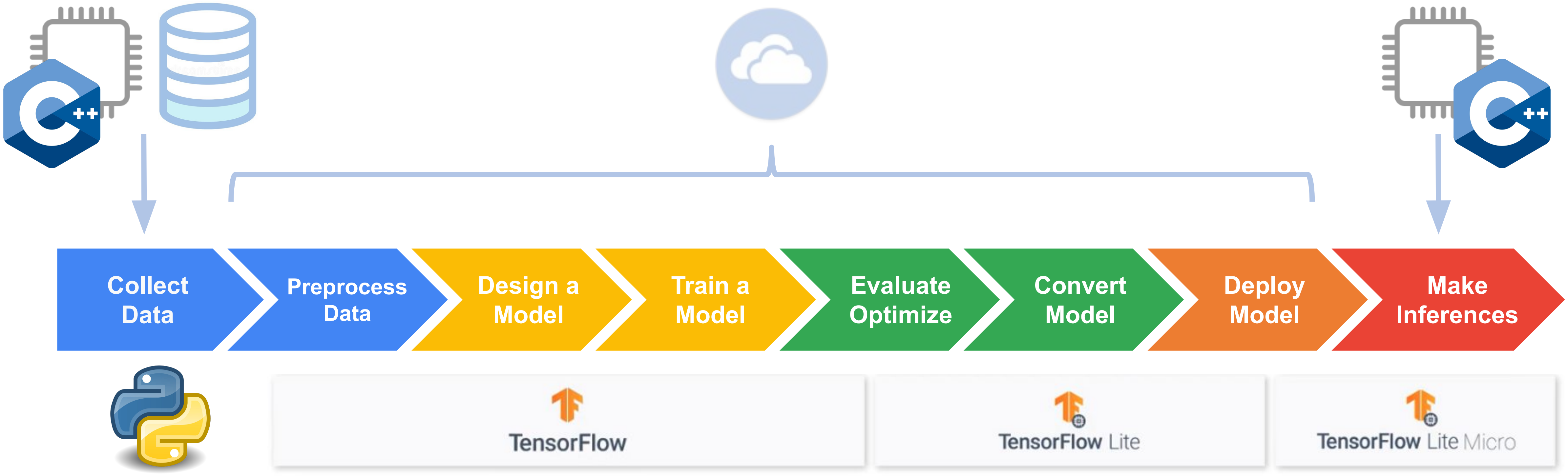
Machine Learning Workflow ("Where")



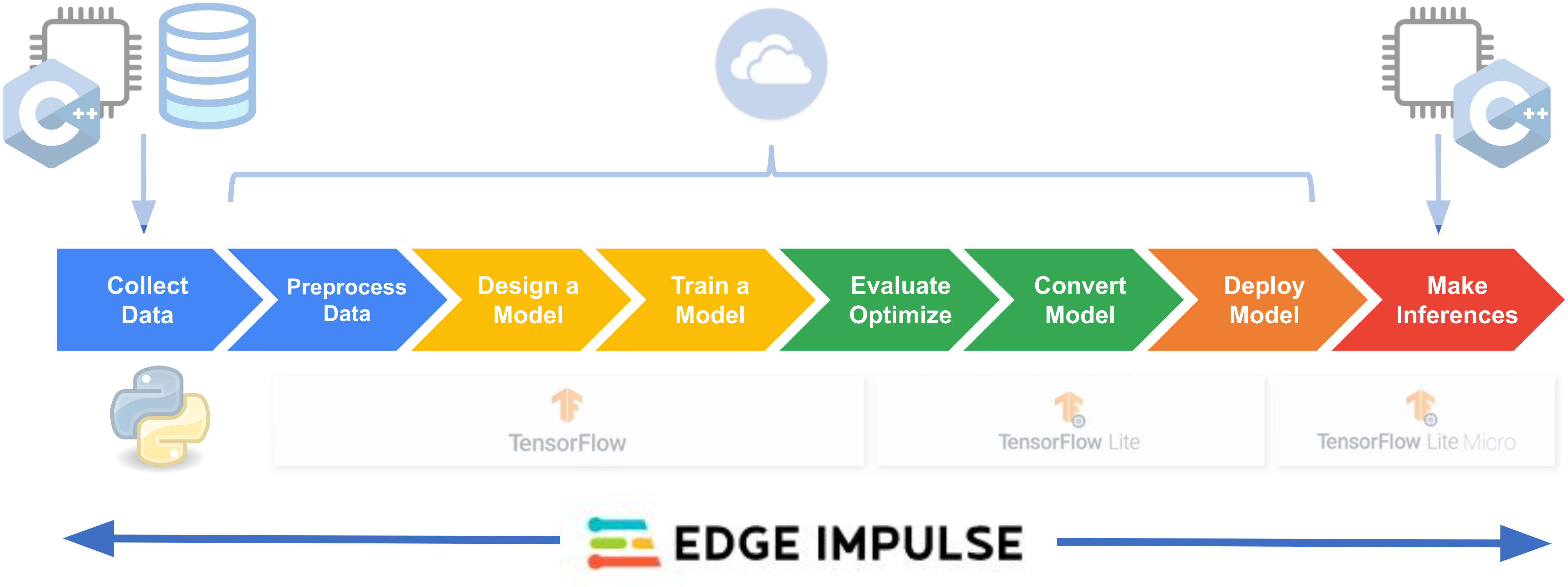
Machine Learning Workflow ("How")

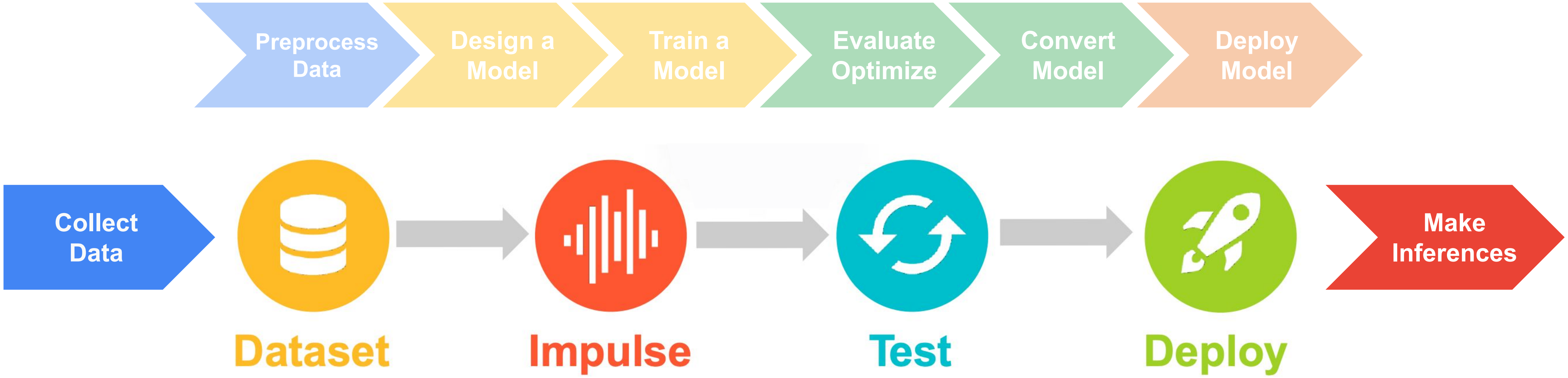


Machine Learning Workflow ("How")

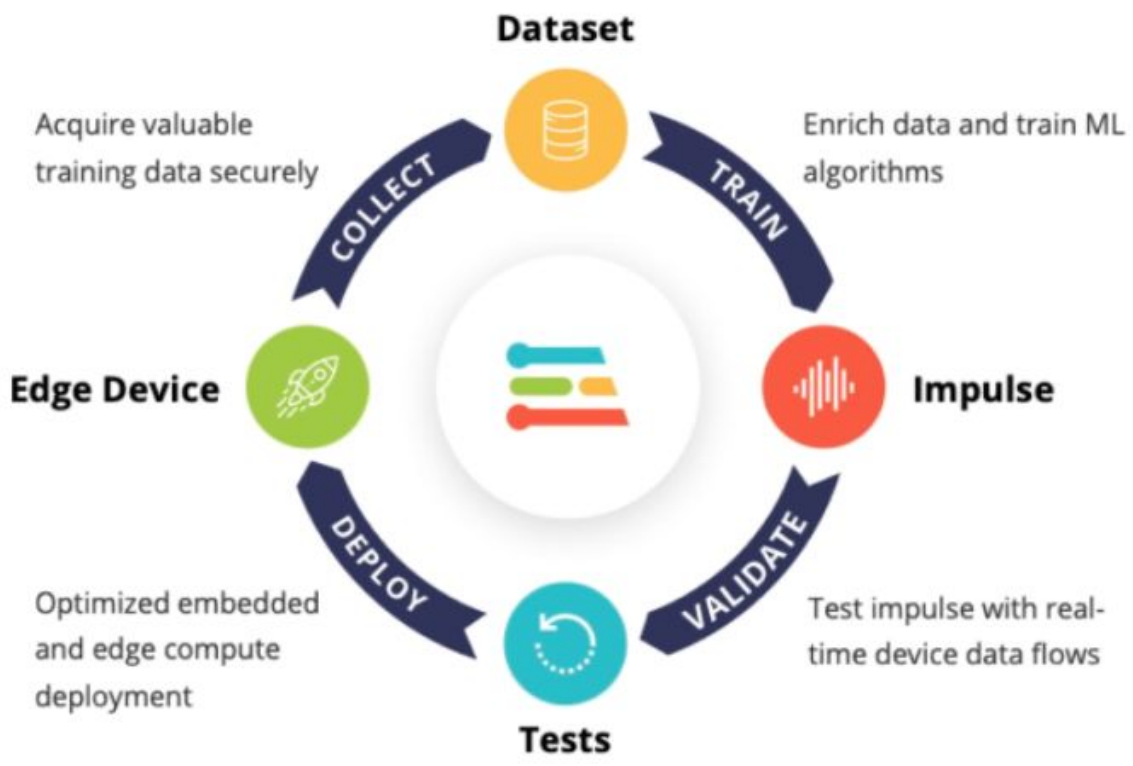


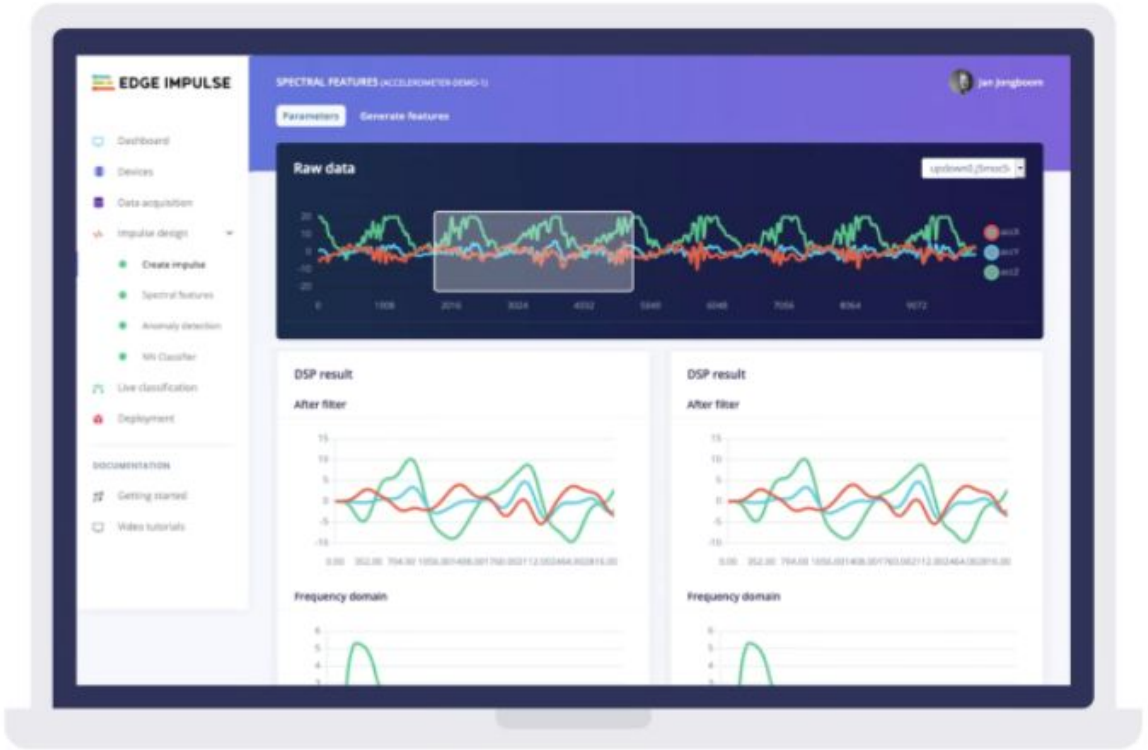
Machine Learning Workflow (“How”)




Preprocess Data
Design a Model
Train a Model
Evaluate Optimize
Convert Model
Deploy Model
Collect Data
Dataset
Impulse
Test
Deploy
Make Inferences

EI Studio - Embedded ML platform ("AutoML")

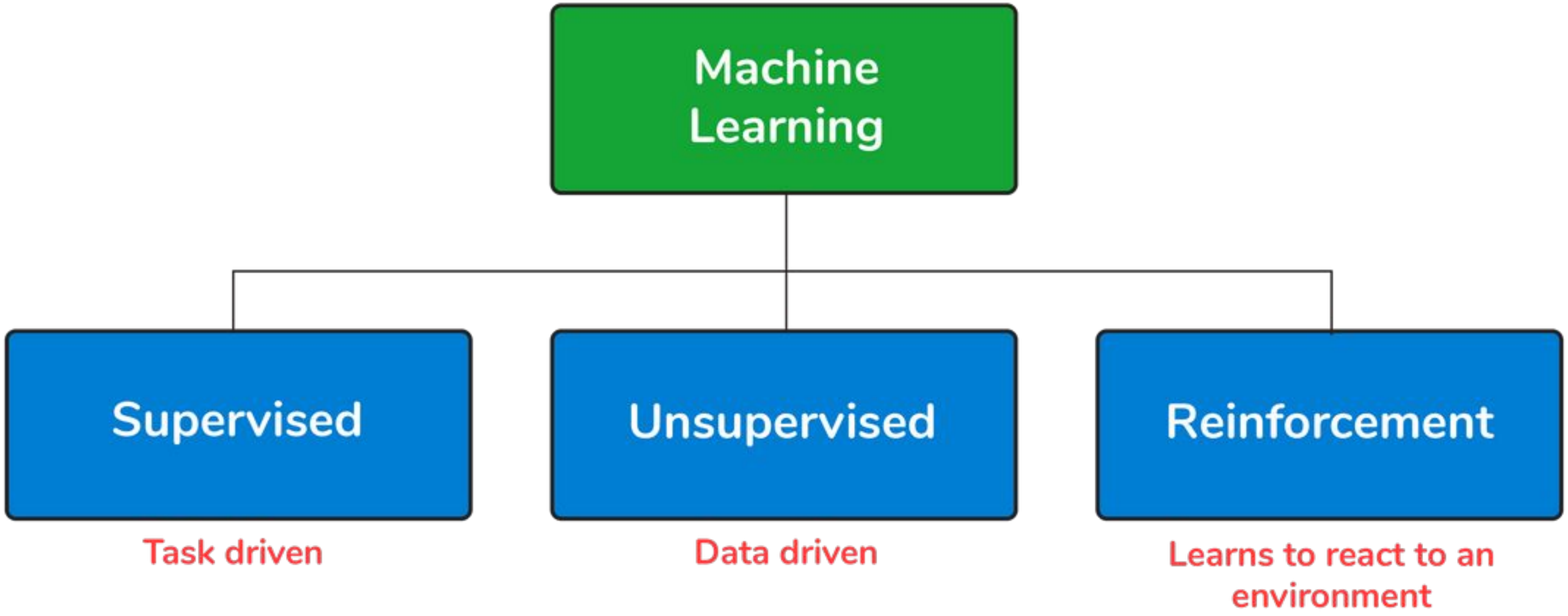




Learn more at http://edgeimpulse.com

TinyML Application

Examples



- Regression
- Classification
- Object Detection

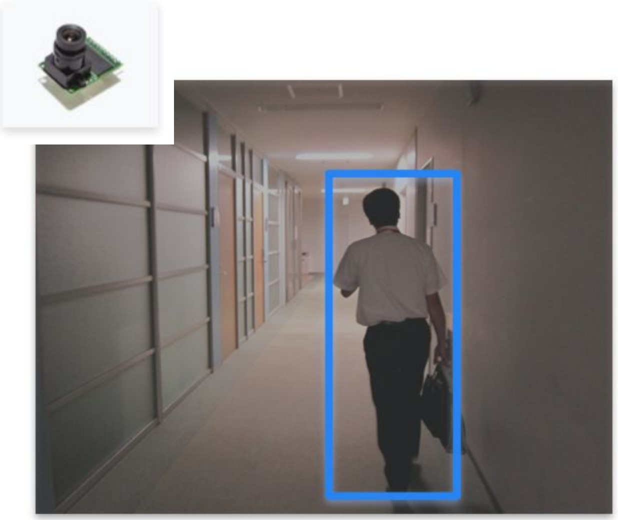
- Anomaly Detection

- Autonomous Navigation

Sound

Vibration

Vision

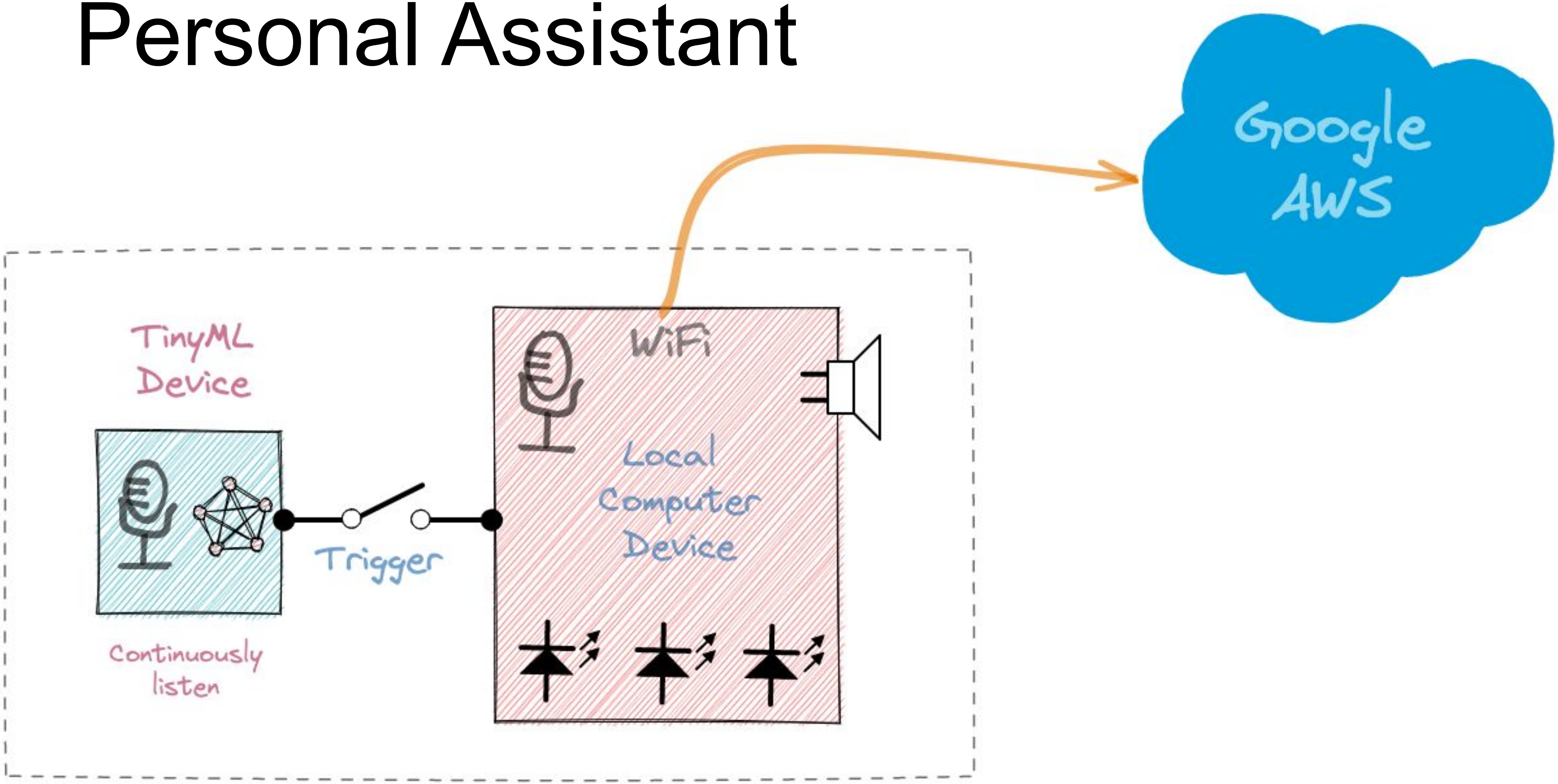


Sound

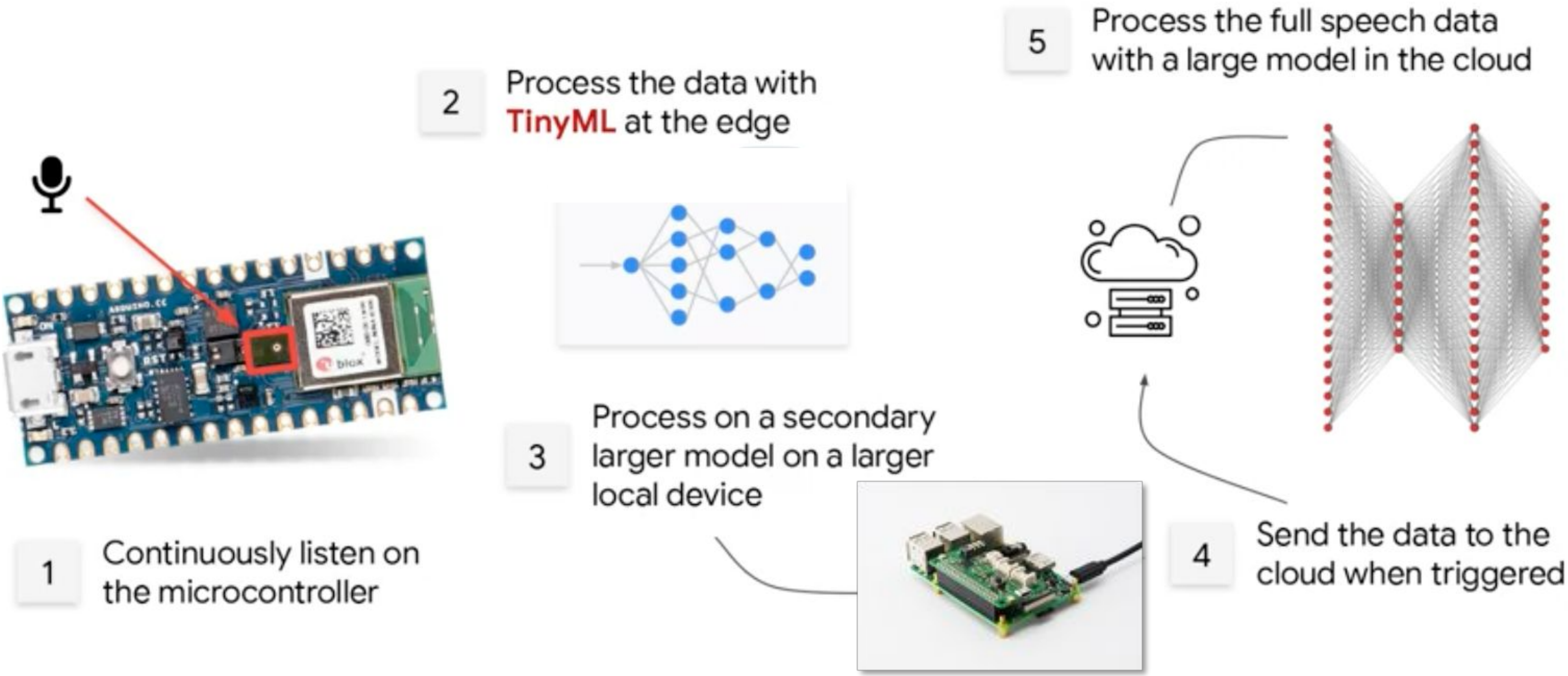
Vibration

Vision

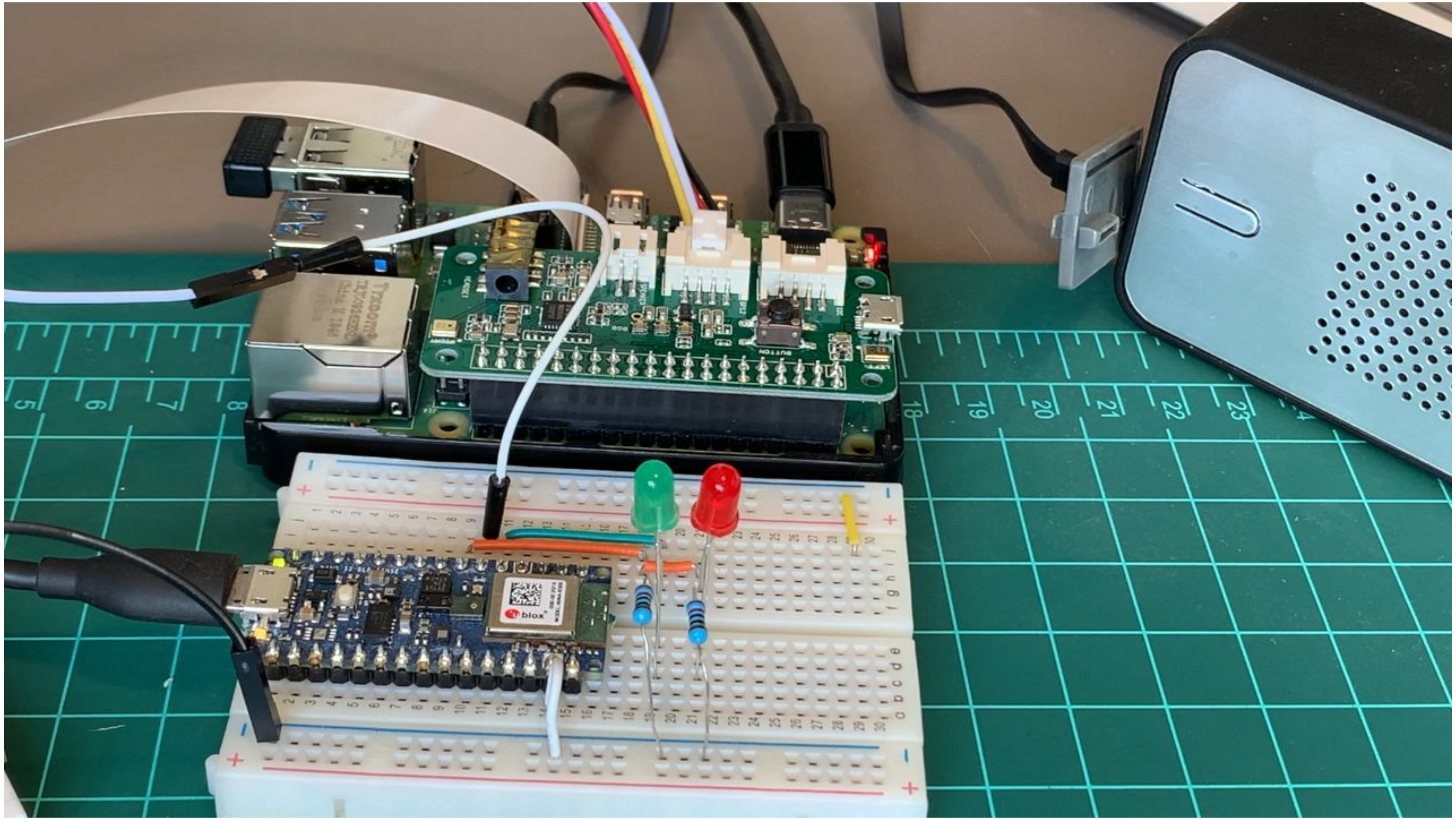
Personal Assistant



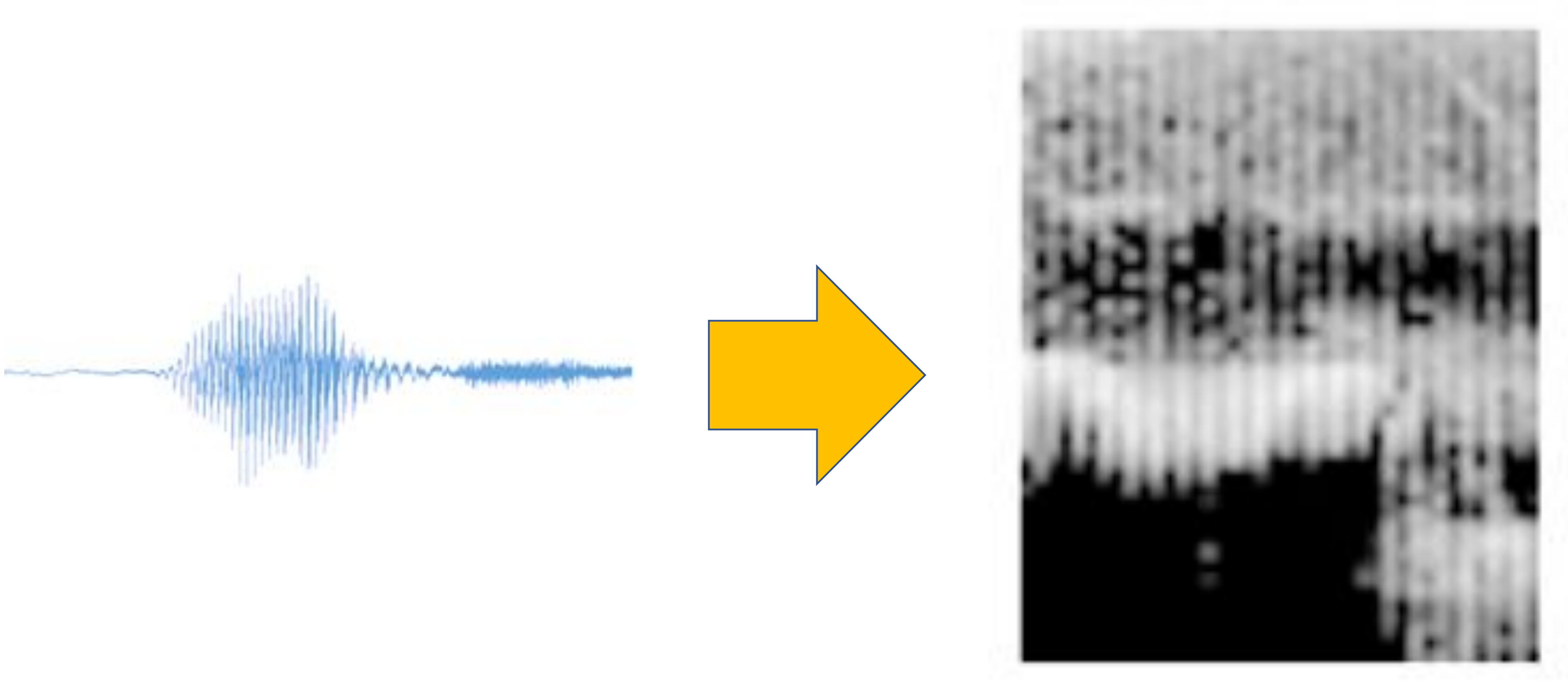
“Cascade” Detection: multi-stage model



KeyWord Spotting (KWS)



https://mjrobot.org/2021/01/27/building-an-intelligent-voice-assistant-from-scratch/



Sound

Image

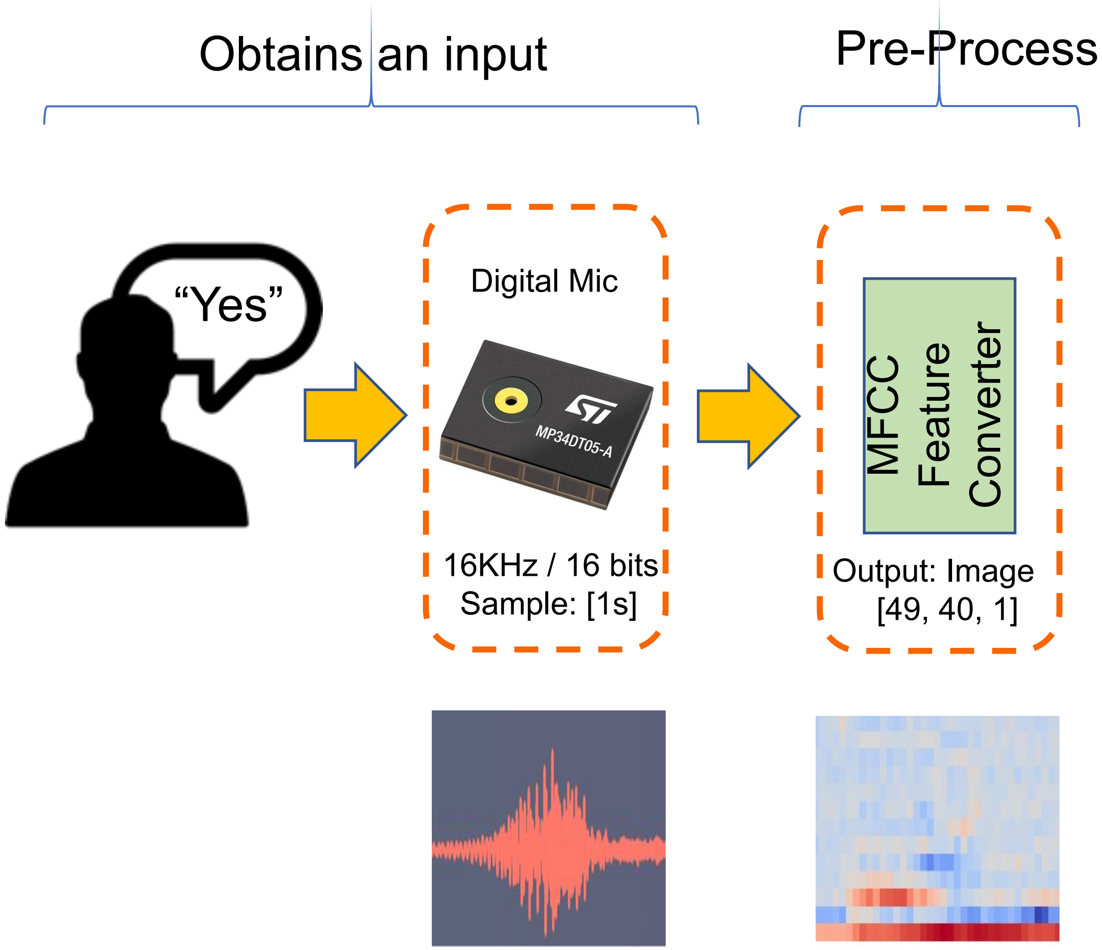
KeyWord Spotting (KWS) - **Inference**

Obtains an input

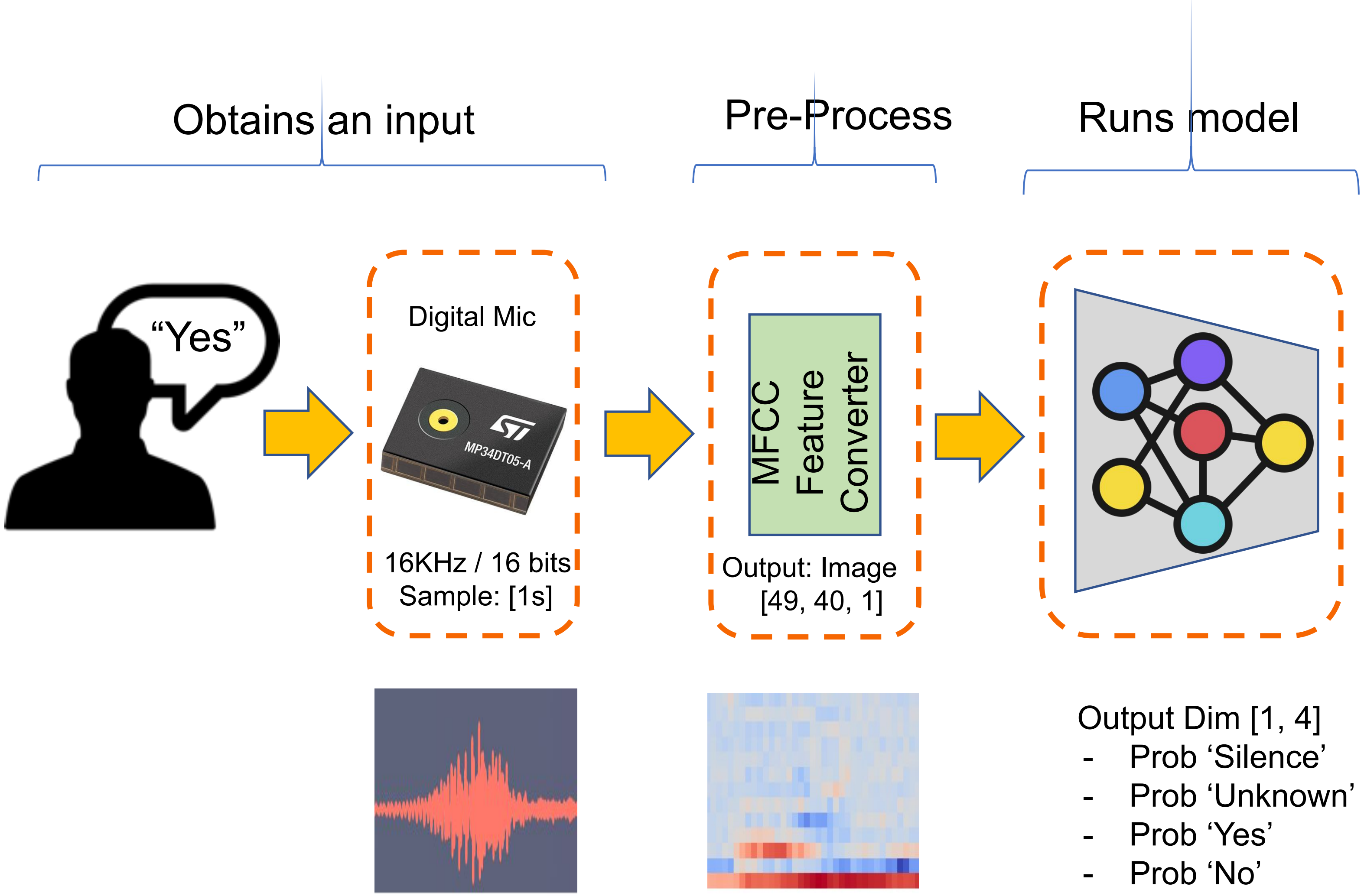
Digital Mic

16KHz / 16 bits
Sample: [1s]

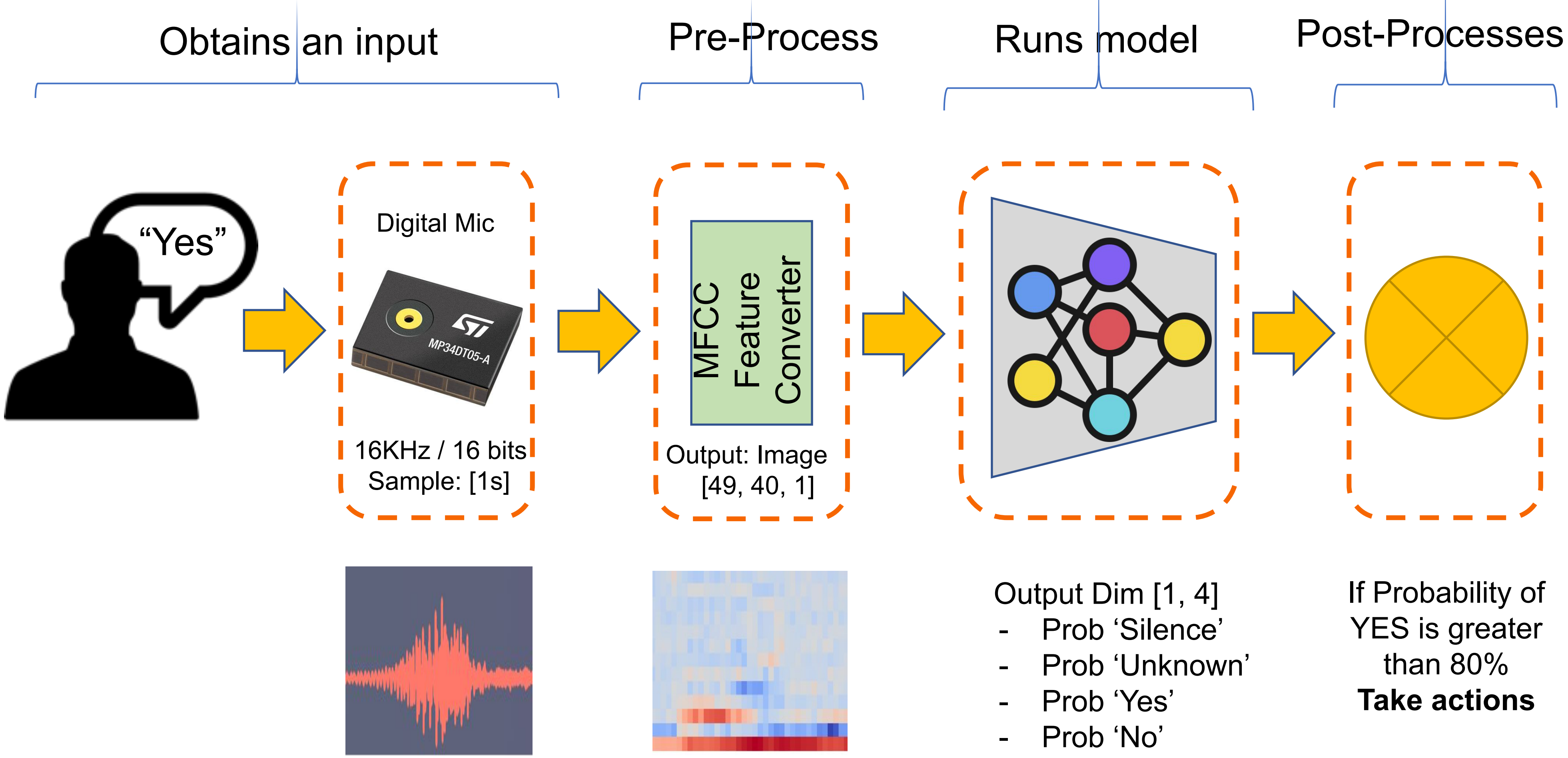
KeyWord Spotting (KWS) - **Inference**



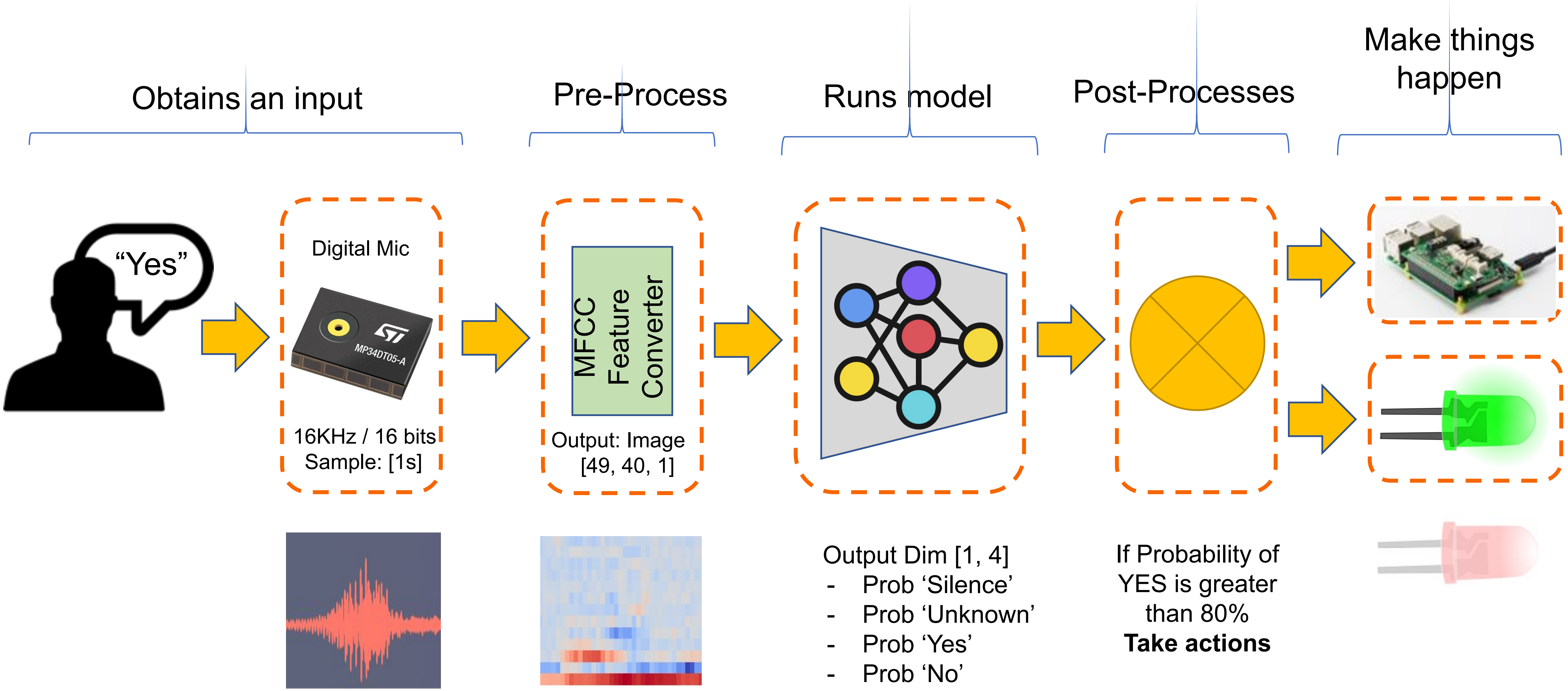
KeyWord Spotting (KWS) - **Inference**



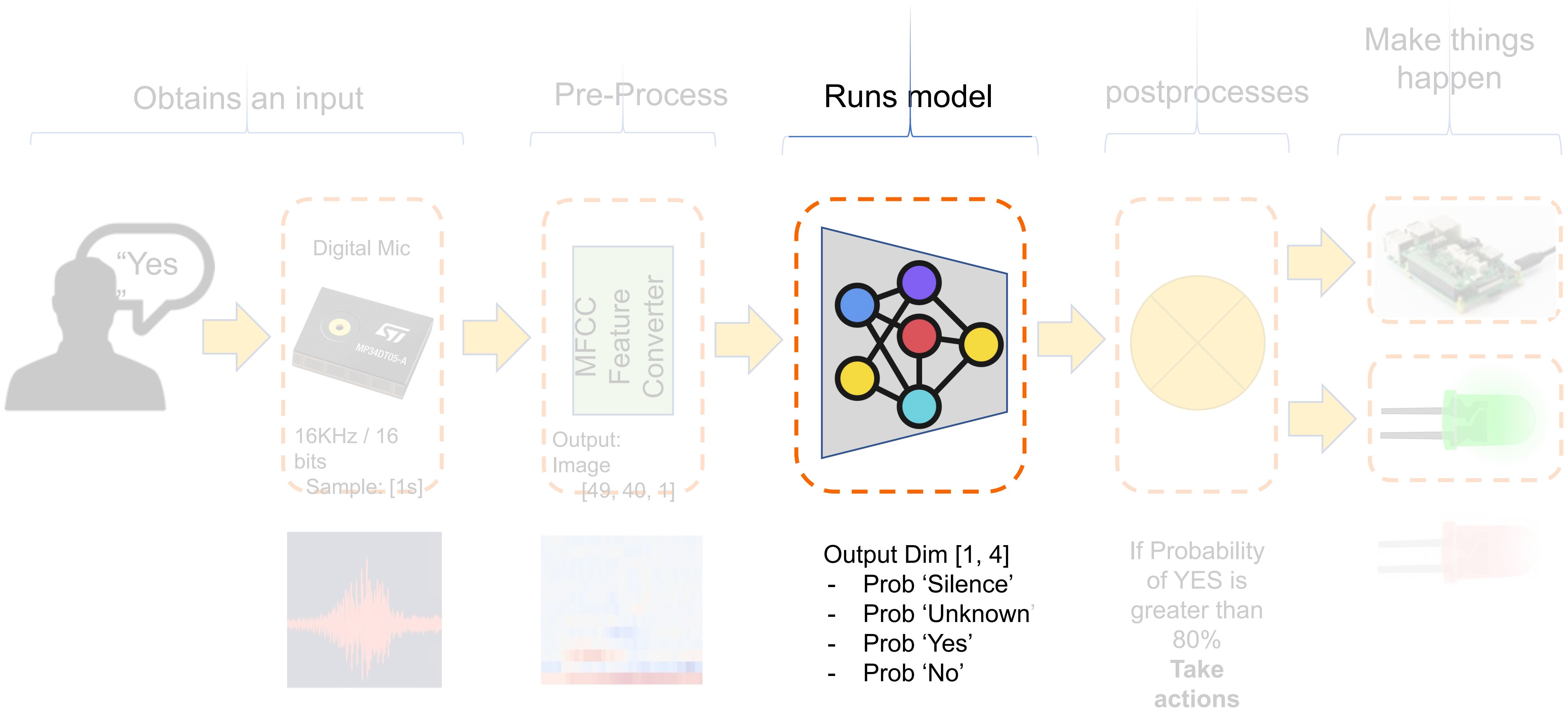
KeyWord Spotting (KWS) - **Inference**



KeyWord Spotting (KWS) - **Inference**



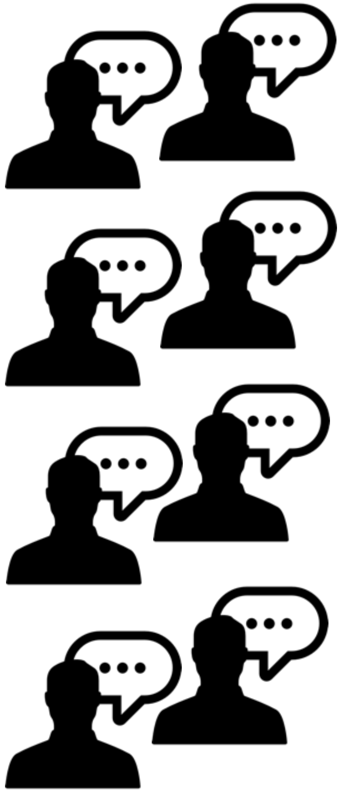
KeyWord Spotting (KWS) - Model



KeyWord Spotting (KWS) – **Create Model (Training)**

Obtains data

Pre-Process

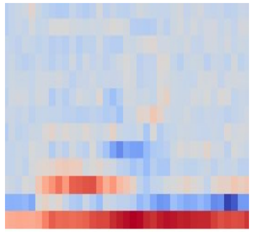


Digital Mic

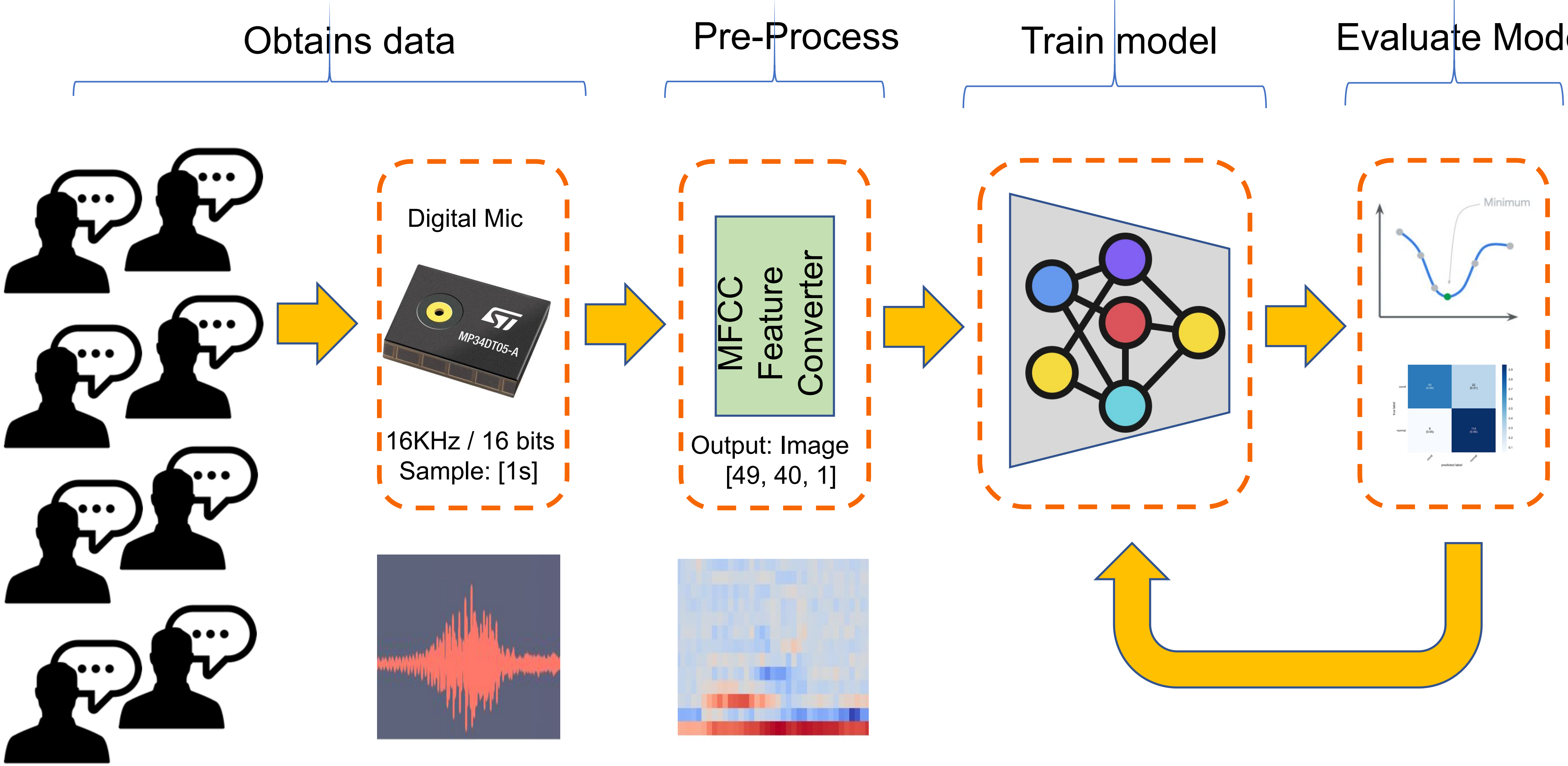
16KHz / 16 bits
Sample: [1s]

MFCC Feature Converter

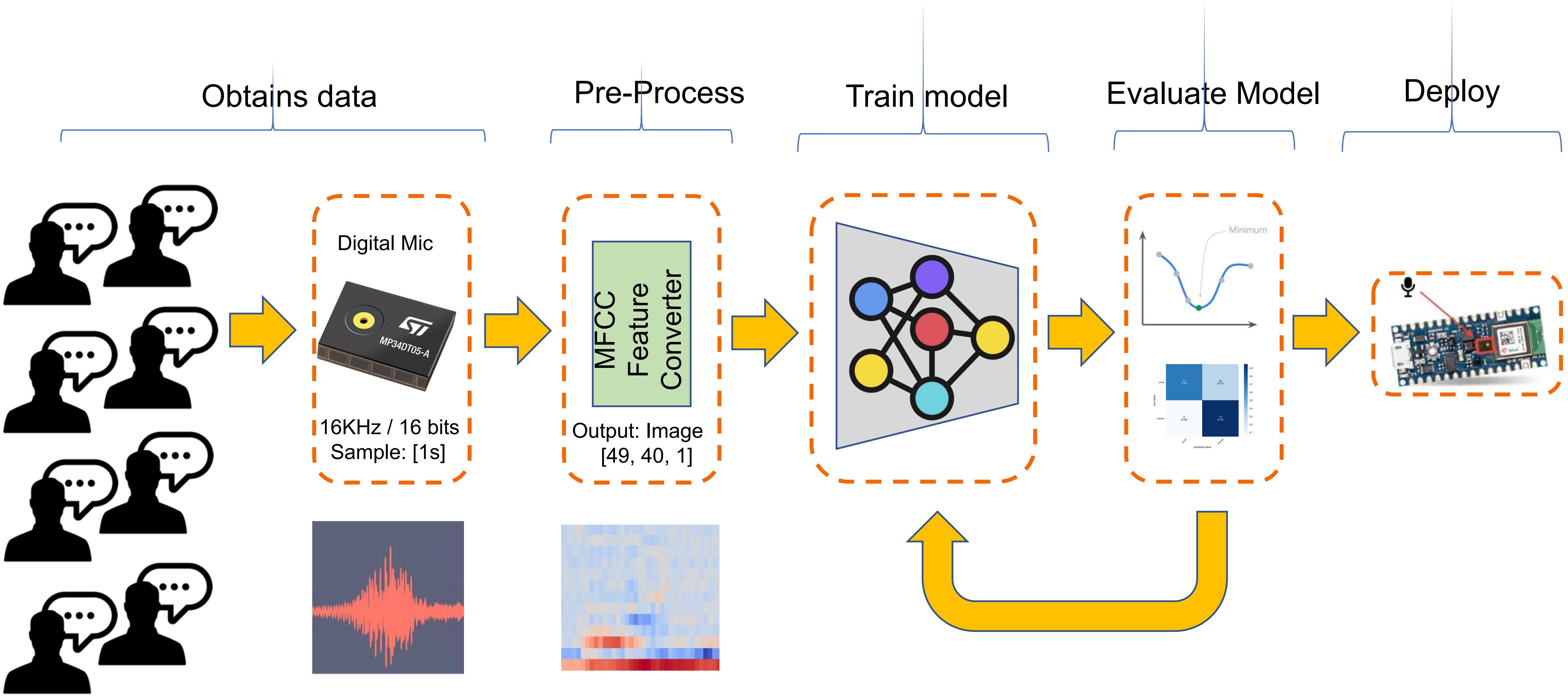
Output: Image
[49, 40, 1]



KeyWord Spotting (KWS) – **Create Model (Training)**



KeyWord Spotting (KWS) – Create Model (Training)



Classifying mosquito wingbeat sound using TinyML

Moez Altayeb
University of Khartoum, Sudan
ICTP, Trieste, Italy
mohedahmed@hotmail.com

Marcelo Rovai
Universidade Federal de Itajubá
Itajubá, Brazil
rovai@unifei.edu.br

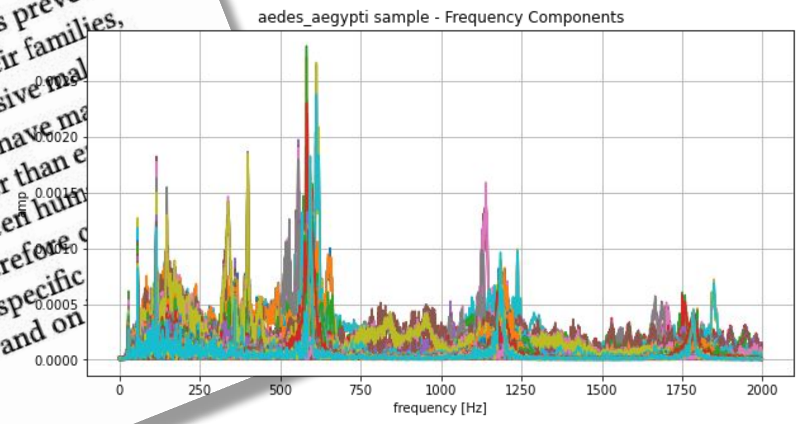
Marco Zennaro
ICTP
Trieste, Italy
mzennaro@ictp.it

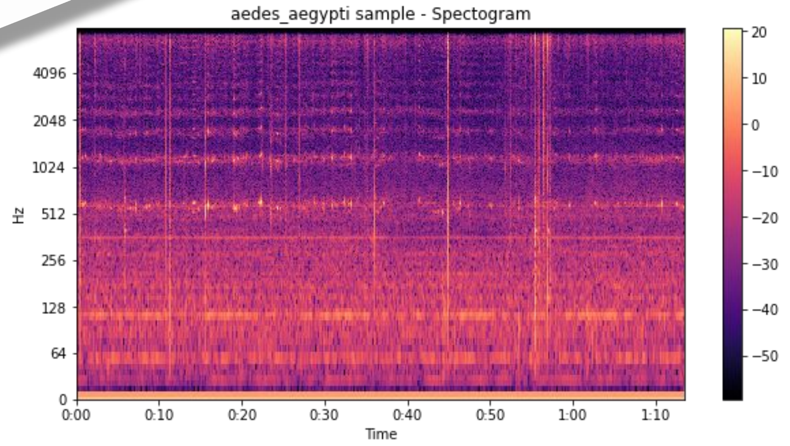
ABSTRACT

Every year more than one billion people are infected and more than one million people die from vector-borne diseases including malaria, dengue, zika and chikungunya. Mosquitoes are the best known disease vector and are geographically spread worldwide. It is important to raise awareness of mosquito proliferation by monitoring their incidence, especially in poor regions. Acoustic detection of mosquitoes has been studied for long and ML can be used to automatically identify mosquito species by their wingbeat. We present a prototype solution based on an openly available dataset, on the Edge Impulse platform and on three commercially-available TinyML devices. The proposed solution is low-power, low-cost and can run without human intervention in resource-constrained areas. This insect monitoring system can reach a global scale.

affected. People from poor communities with little access to health care and clean water sources are also at risk. Although anti-malarial drugs exist, there's currently no malaria vaccine.

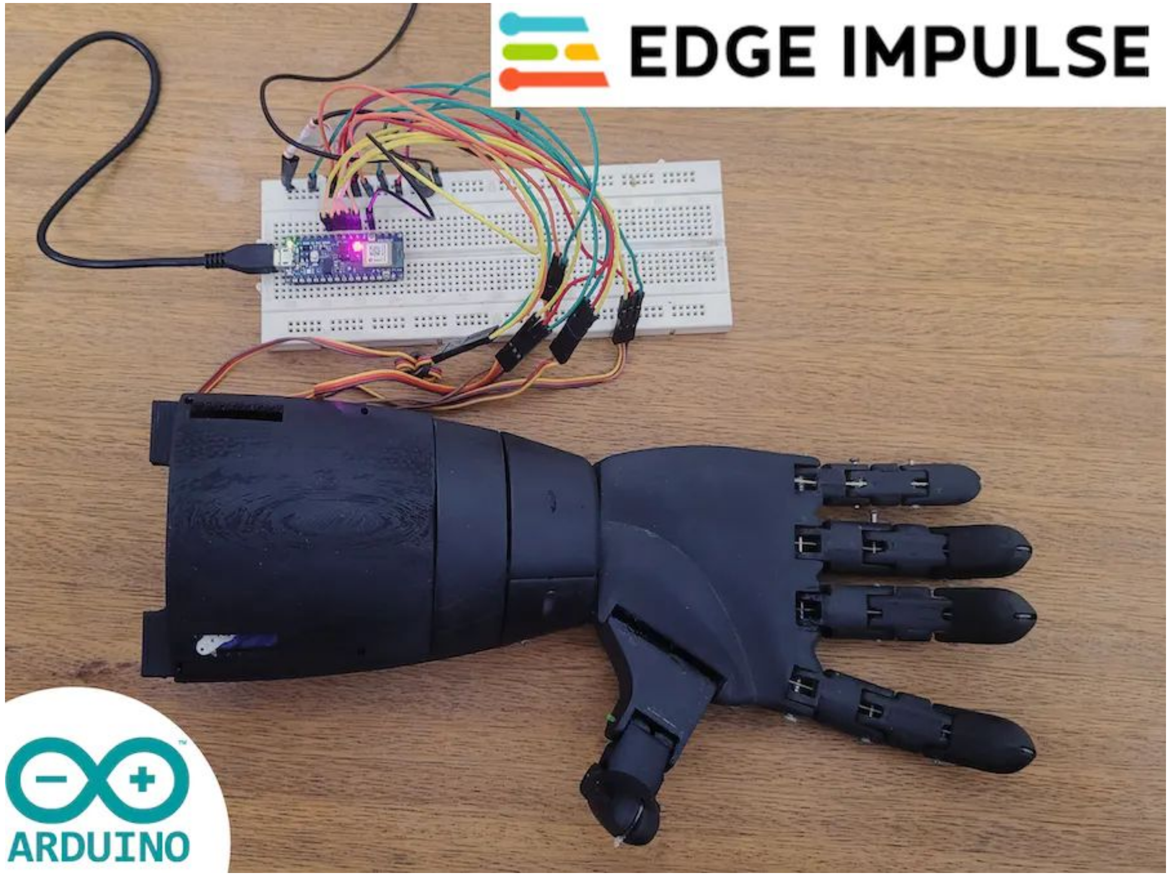
Vector-borne diseases also exacerbate poverty. Illness prevent people from working and supporting themselves and their families, impeding economic development. Countries with intensive mal
have much lower income levels than those that don't have ma
Countries affected by malaria turn to control rather than e
tion. Vector control means decreasing contact between hum
disease carriers on an area-by-area basis. It is therefore c
be able to detect the presence of mosquitoes in a specific
paper presents an approach based on TinyML and on
embedded devices.





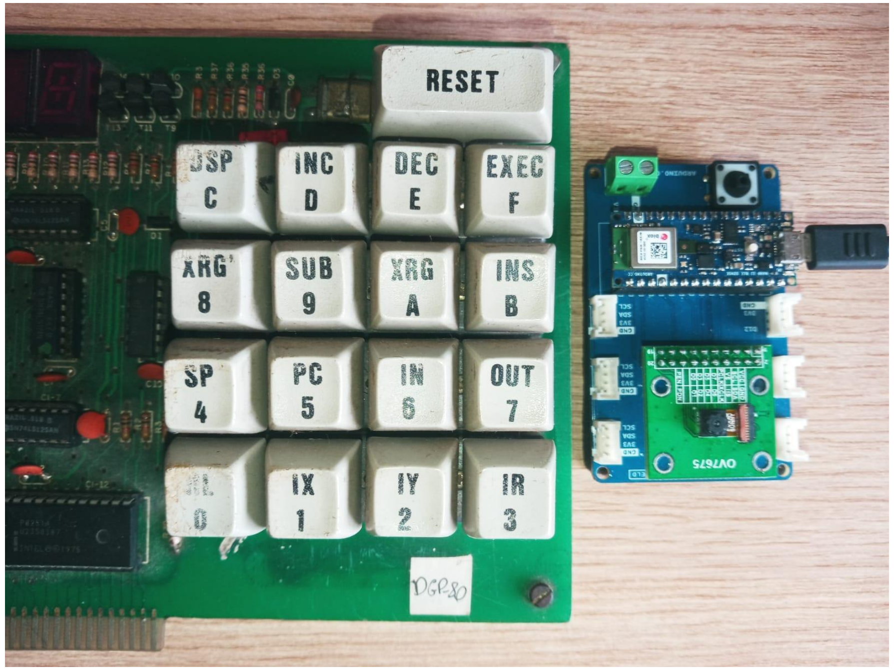
https://www.edgeimpulse.com/blog/the-world-is-all-abuzz-about-tinyml

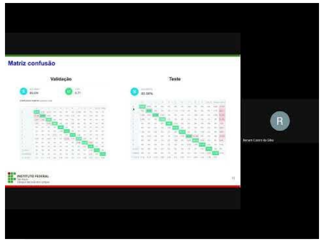
Bionic Hand Voice Commands Module



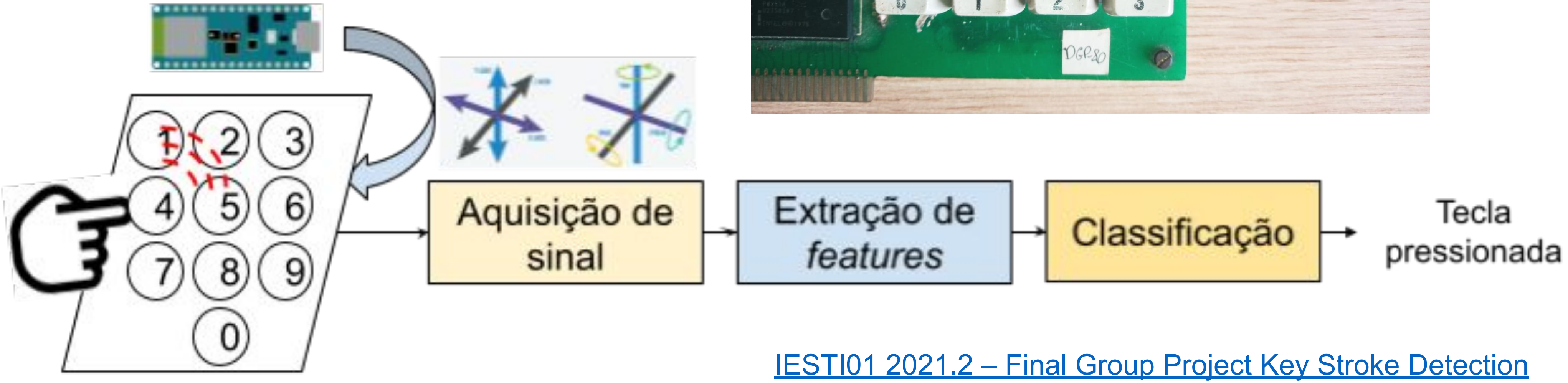
https://www.hackster.io/ex-machina/bionic-hand-voice-commands-module-w-edge-impulse-arduino-aa97e3

Keystroke **Sound** Detection





Renam Castro
Professor IFESP



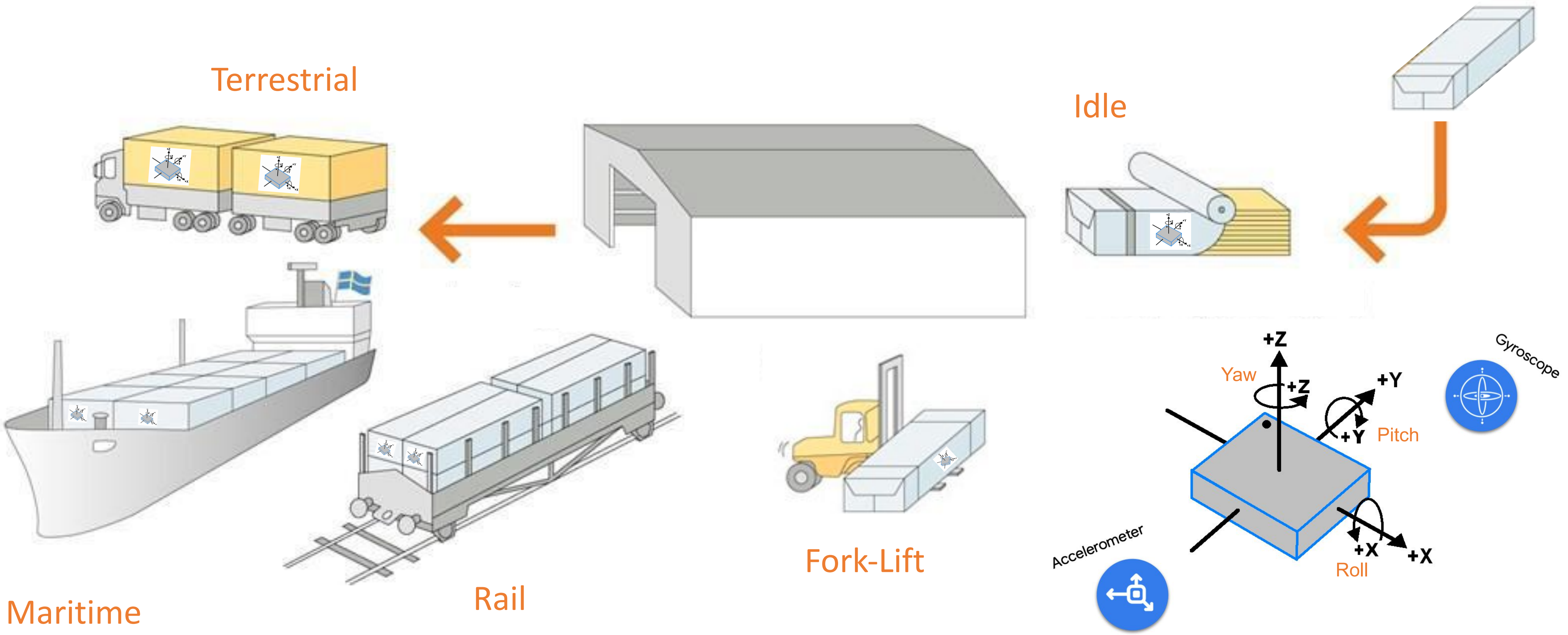
[IESTI01 2021.2 – Final Group Project Key Stroke Detection]()

Sound

Vibration

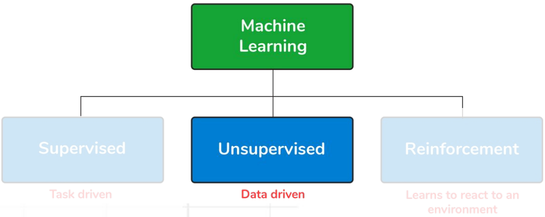
Vision

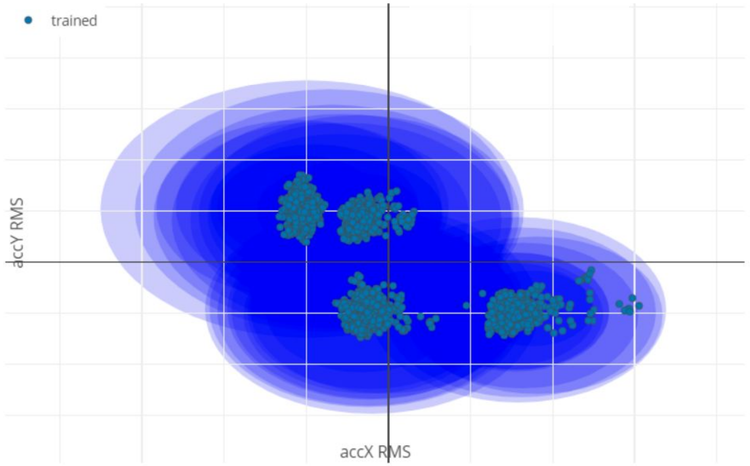
Mechanical Stresses in Transport

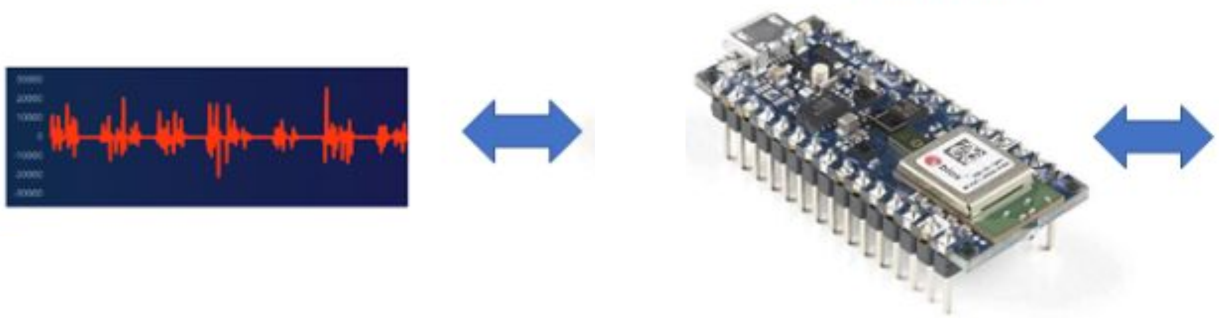


[ICTP SciTyniML 21 - Hands on Embedded ML - Motion/Anomaly Detection and Scientific Applications]

Industrial – Anomaly Detection







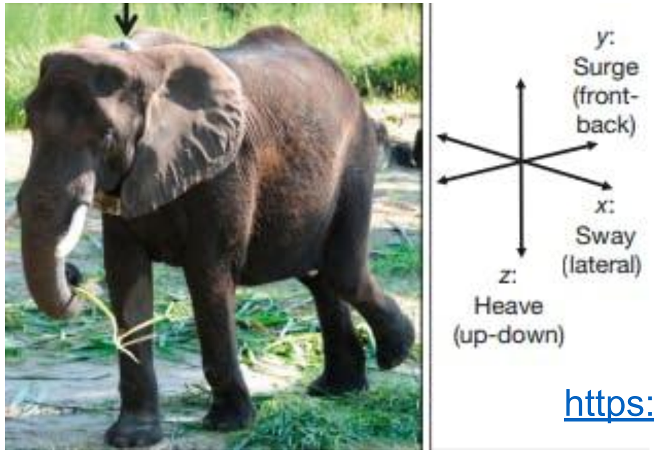
[IESTI01 2021.2 - Final Group Project: Bearing Failure Detection]

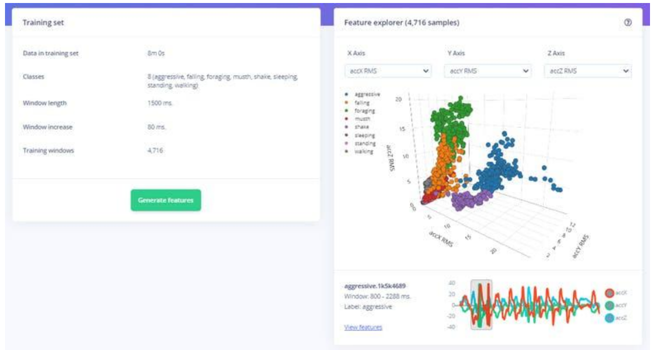
Predict and classify common Elephant behavior

Aggressive

Standing

Sleeping



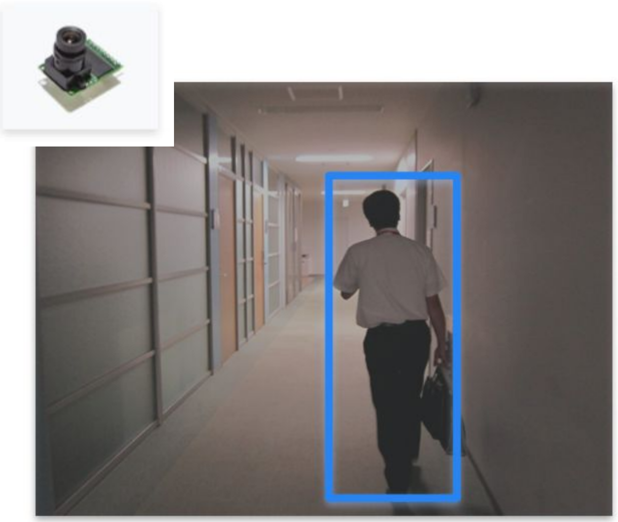


https://www.hackster.io/dhruvsheth_/eletect-tinyml-and-iot-based-smart-wildlife-tracker-c03e5a

Sound

Vibration

Vision



Computer Vision Main Types

Image Classification

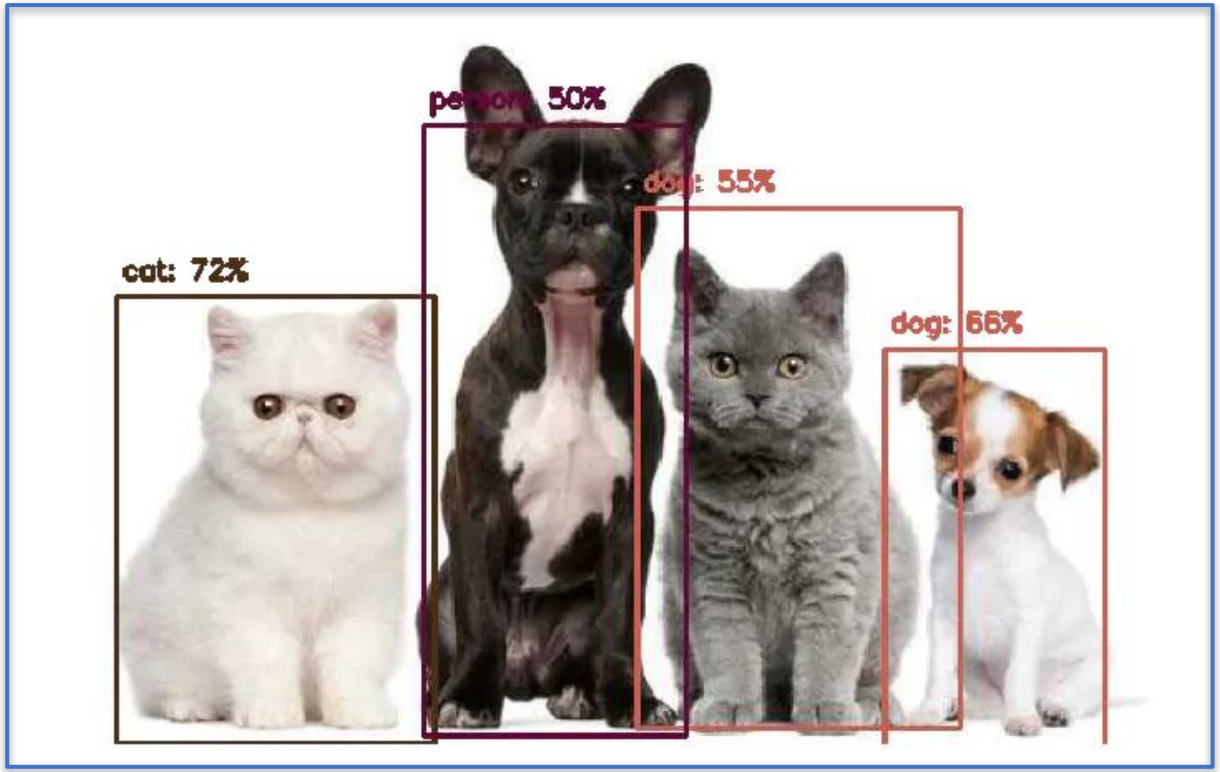
(**Multi-Class** Classification)

Cat: 70%

Dog: 80%

Object Detection

Multi-Label Classification + Object **Localization**



Computer Vision Main Types

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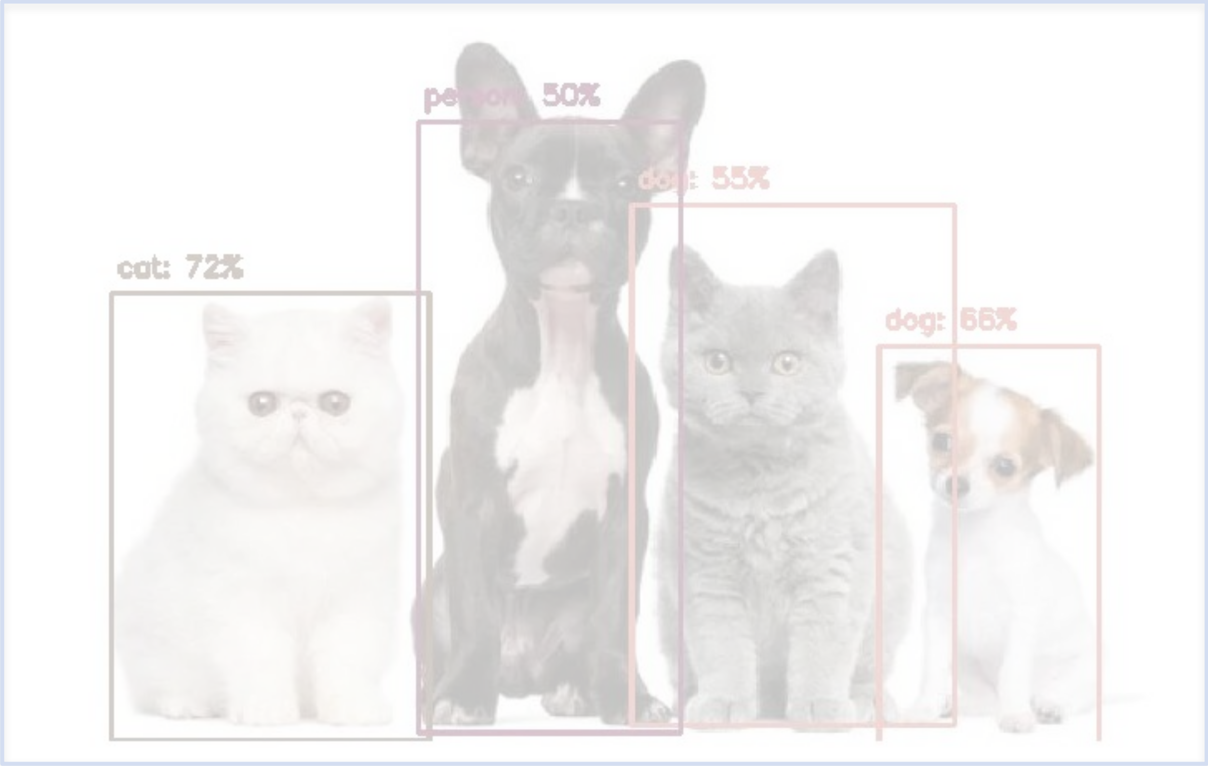

Forest Fire Detection

TinyML Aerial Forest Fire Detection

IESTI01 - Forest Fire Detection – Proof of Concept

Coffee Disease Classification

João Vitor Yukio Bordin Yamashita
Graduando em Engenharia Eletrônica pela UNIFEI

https://www.hackster.io/Yukio/coffee-disease-classification-with-ml-b0a3fc

Computer Vision Main Types

Image Classification
(**Multi-Class** Classification)

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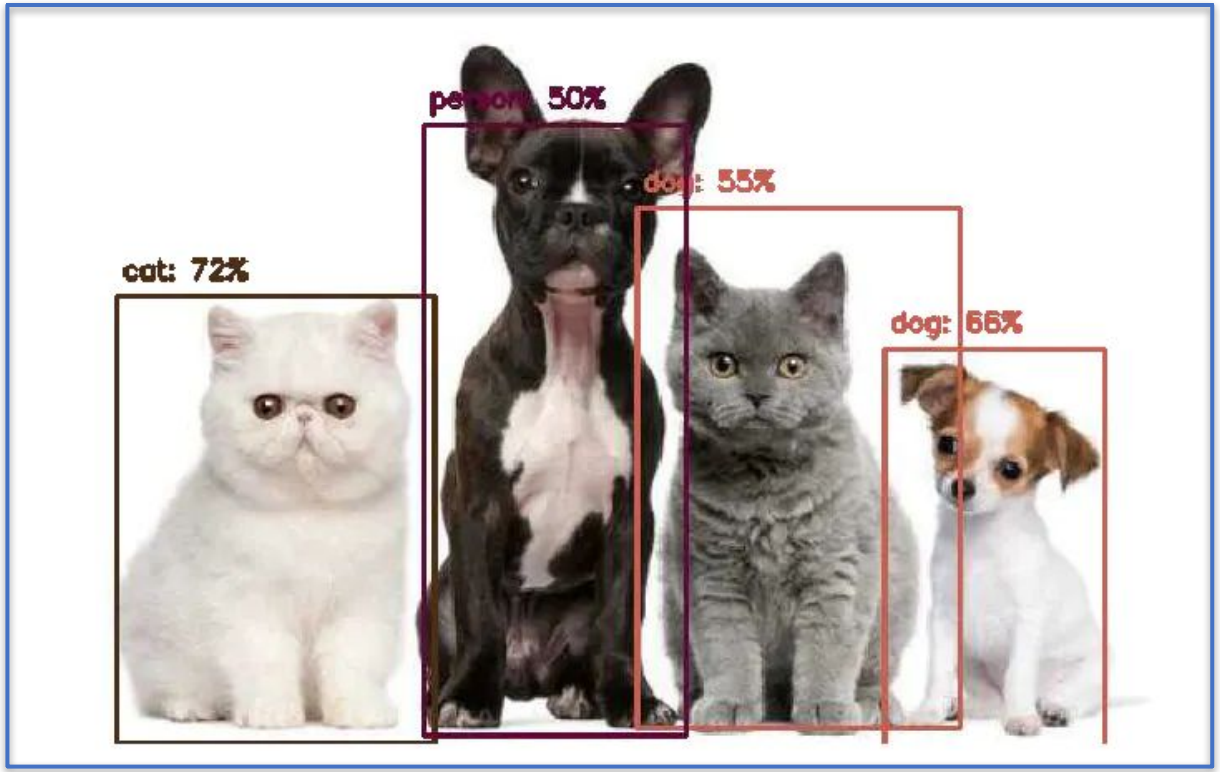
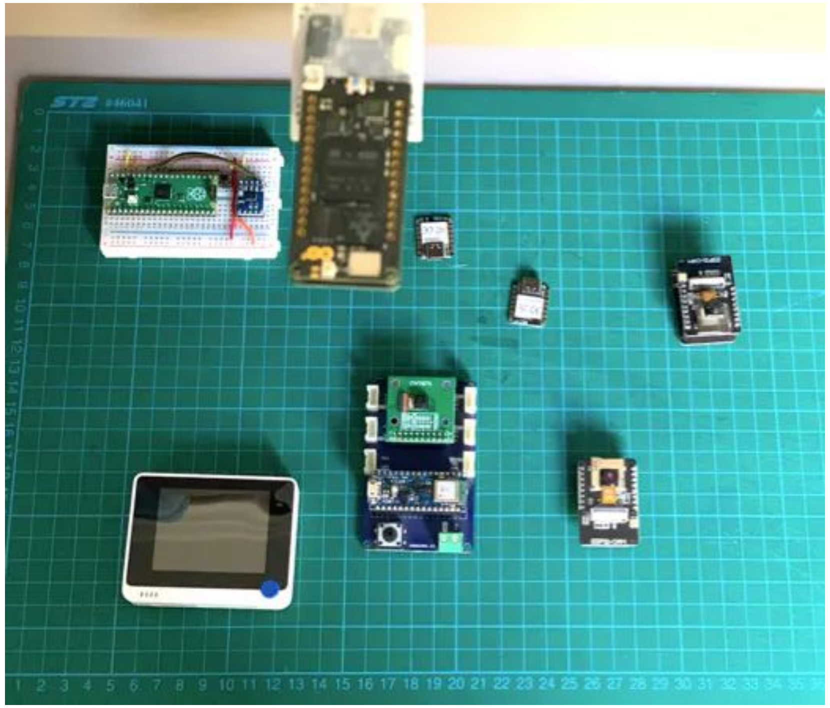
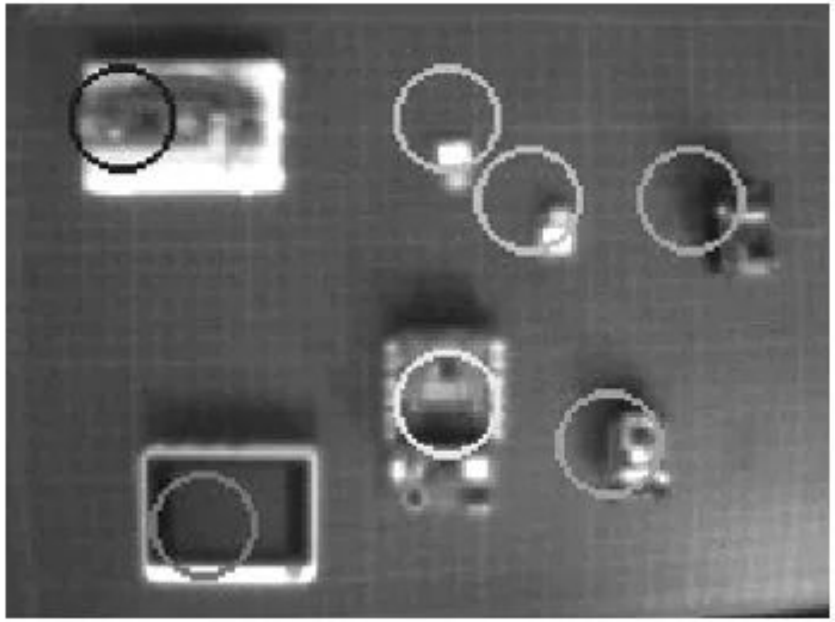
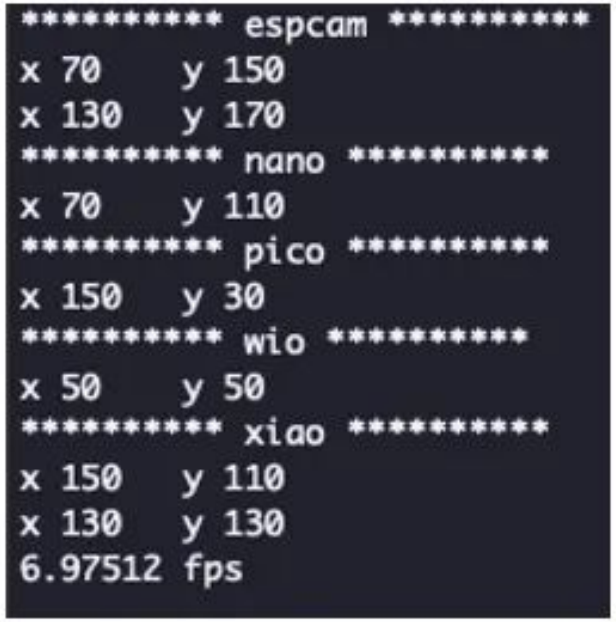
Object Detection
Multi-Label Classification + Object **Localization**



Detecting Objects using TinyML (FOMO)

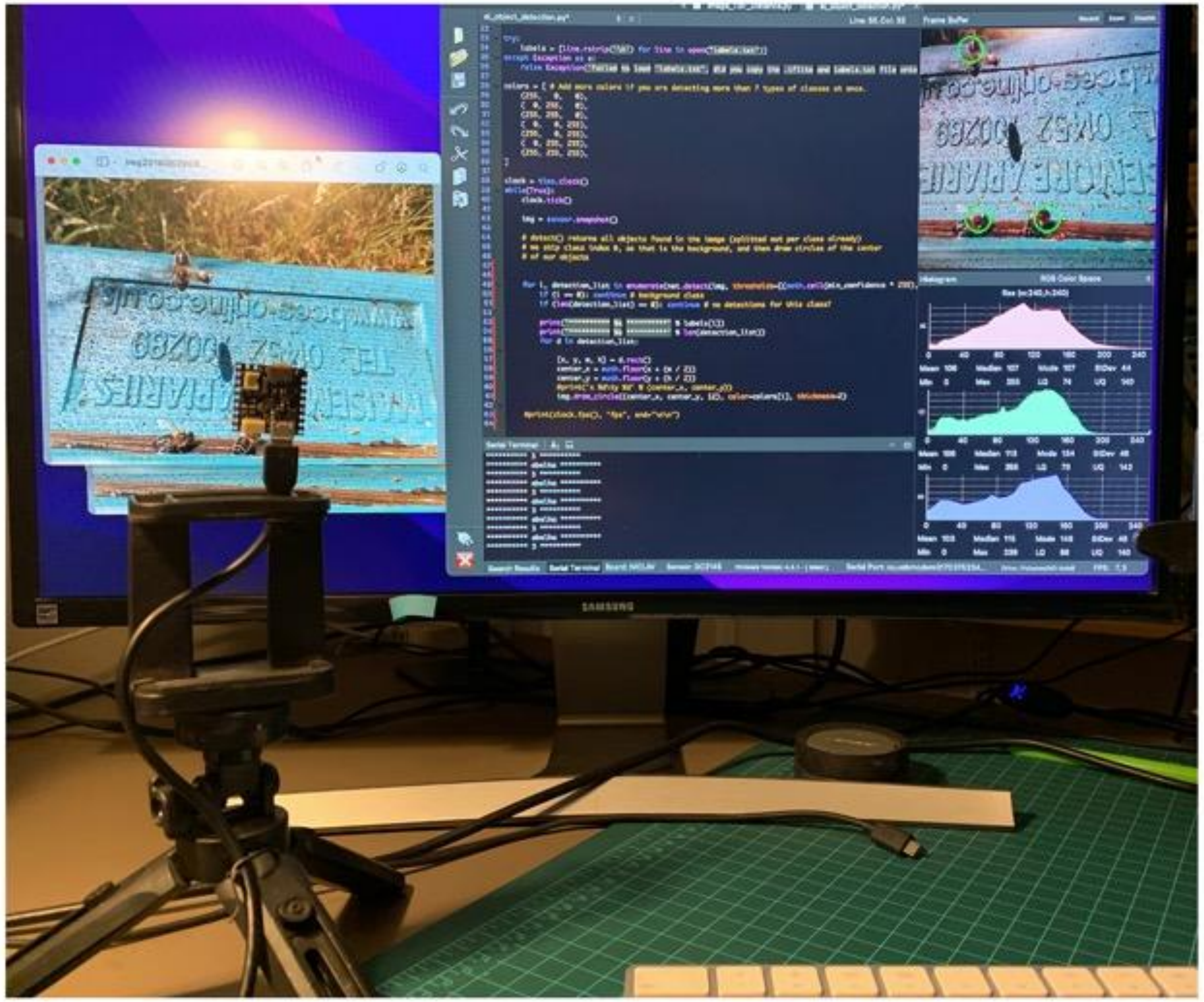


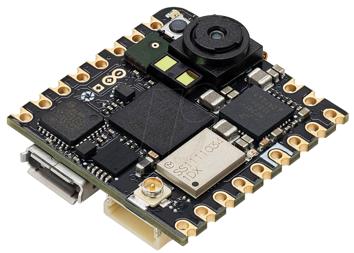




[EdgeAI made simple - Exploring Image Processing (Object Detection) on microcontrollers with Arduino Portenta, Edge Impulse FOMO, and OpenMV]

Detecting Objects using TinyML (FOMO)





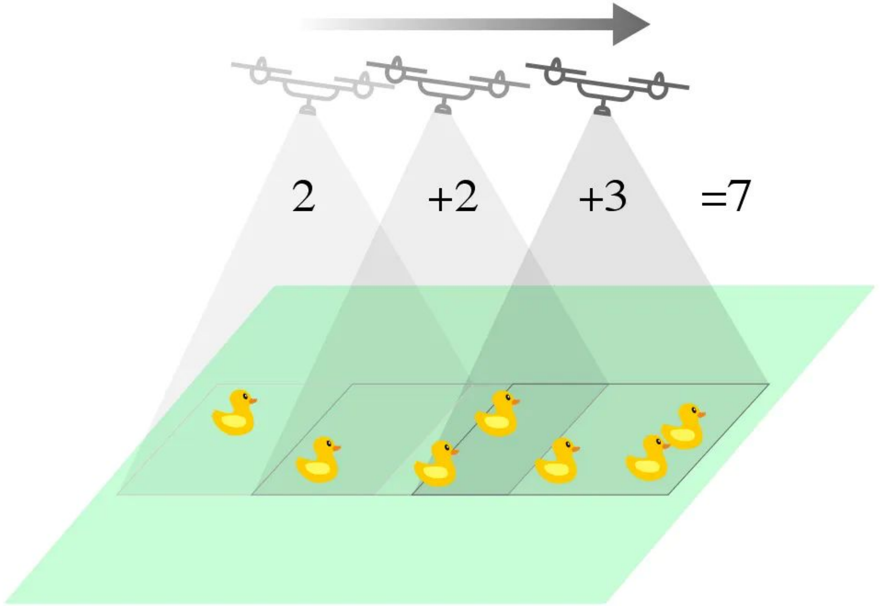
OpenMV

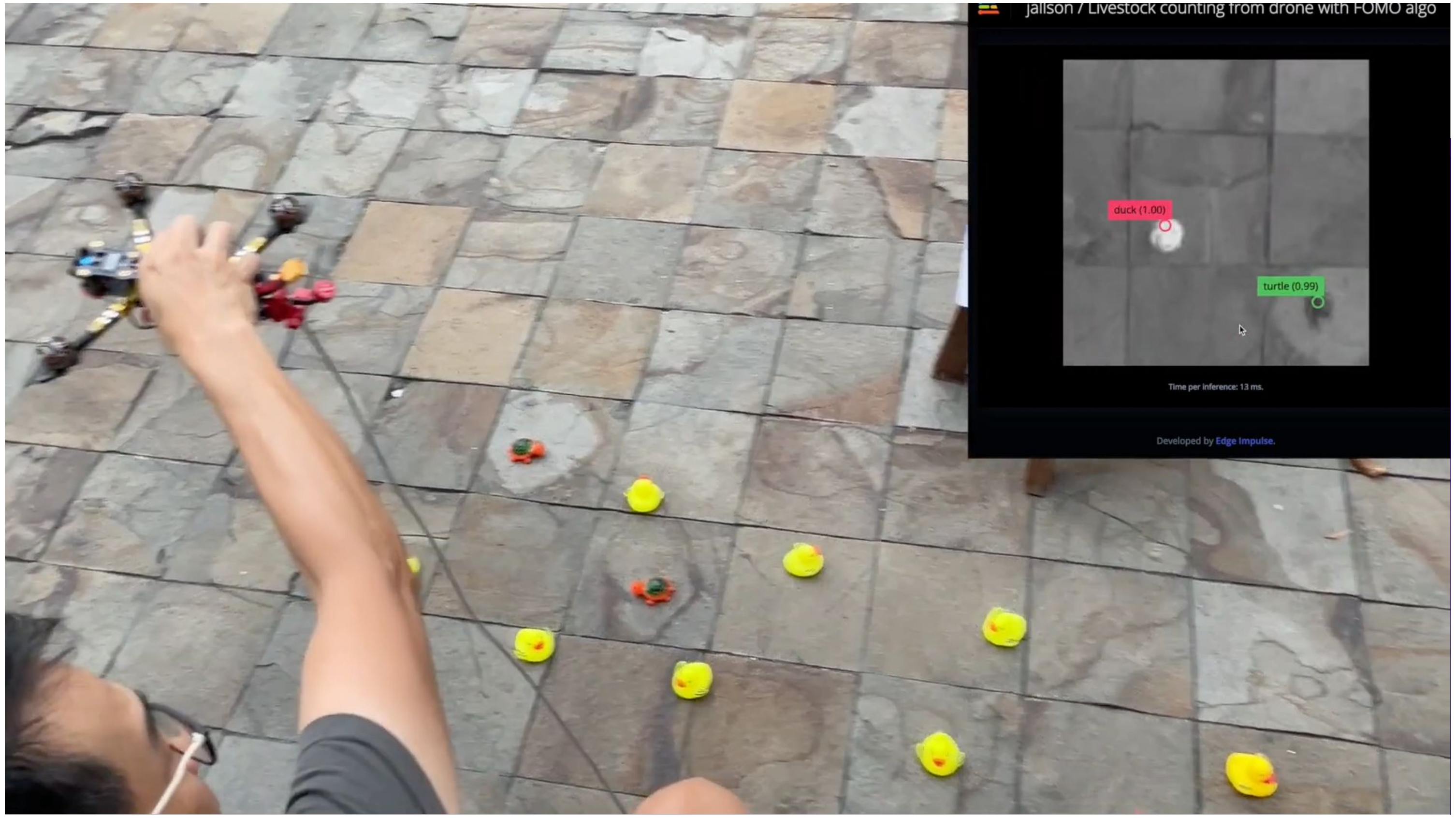
MicroPython

EDGE IMPULSE

https://youtu.be/MYuc3QISquw

Livestock / Wildlife Counting from Drone with FOMO



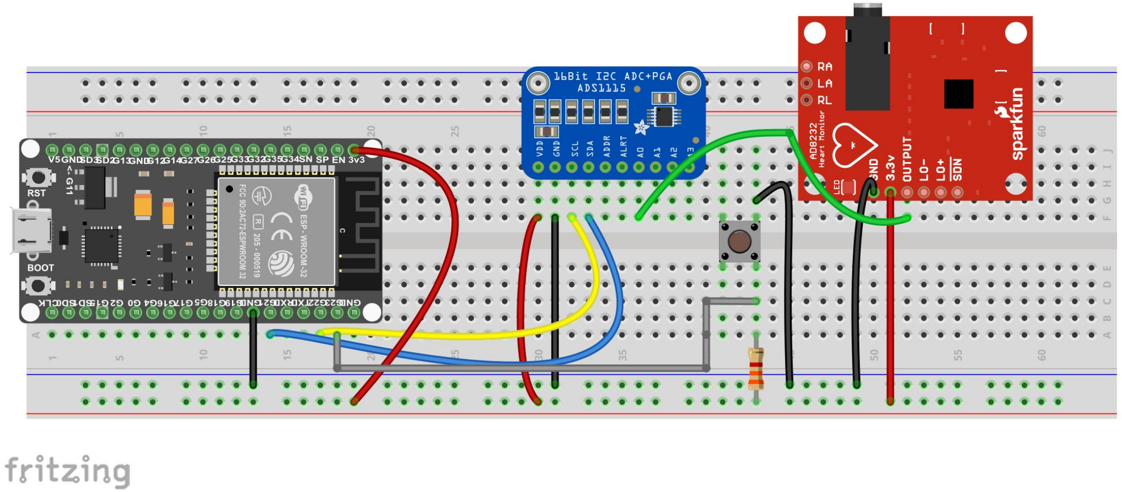


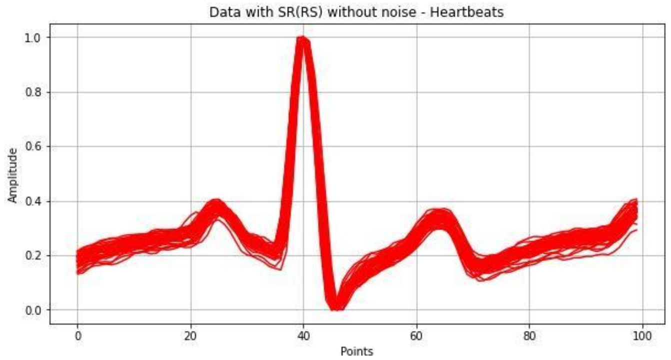
https://www.hackster.io/jallsonsuryo/livestock-wildlife-counting-from-drone-with-fomo-algorithm-a2f734

Other Sensors / MCUs / Models

Examples

AD8232 - Single Lead Heart Rate Monitor





Guilherme Silva
Engenheiro - UNIFEI

[Atrial Fibrillation Detection on ECG using TinyML
Silva et al. UNIFEI 2021]

Other TinyML / MCUs Project Examples

Vision

- Image Classification with ESP32-CAM [Doc]
- Image Classification with Portenta H7 [Doc]
- Object Detection with Portenta H7 [Doc]

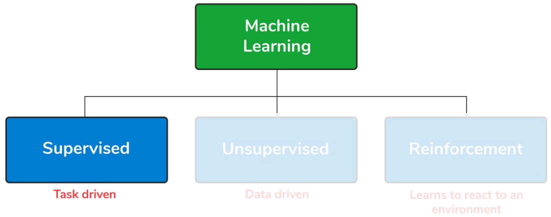
Sound

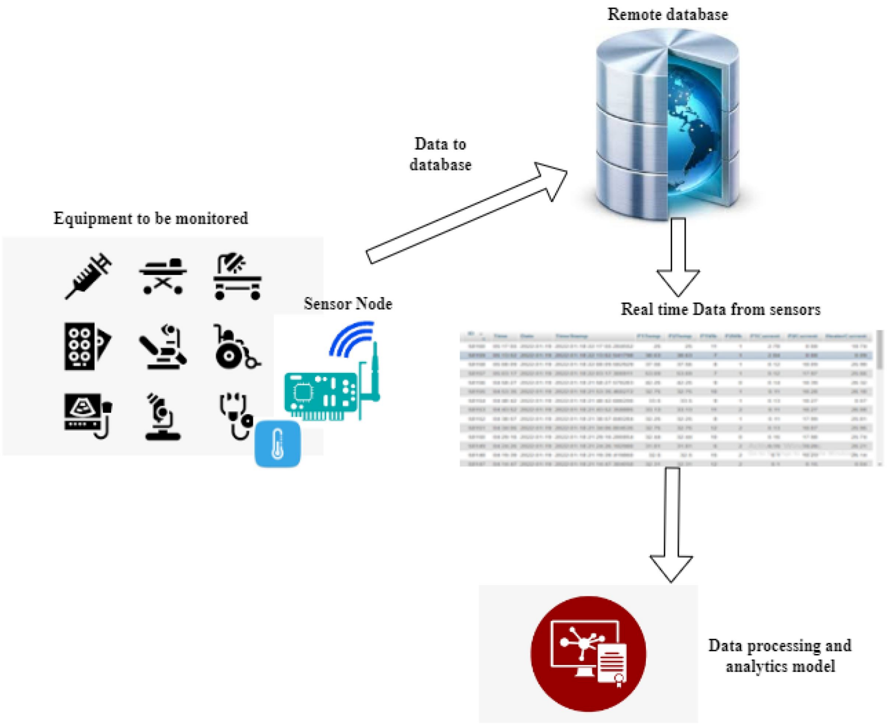
- Listening Temperature with Nano 33 [Doc]
- COPD Detection with Nano 33 [Doc]
- Sound Classification with XIAO BLE Sense [Doc]

Vibration

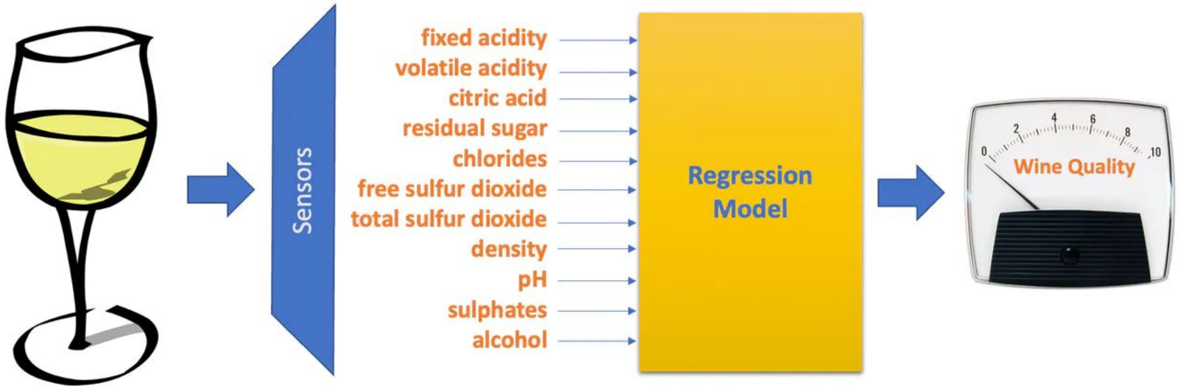
- Motion Recognition with RPi Pico [Doc]
- Gesture Recognition with Wio Terminal [Doc]
- Anomaly Detection with XIAO BLE Sense [Doc]

Regression on TinyML





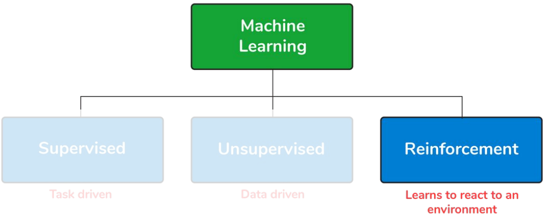
Sensor fusion



[On-Device IoT-Based Predictive Maintenance Analytics Model: Comparing TinyLSTM and TinyModel from Edge Impulse]

[TinyML Made Easy: Exploring Regression - White Wine Quality]

Reinforcement on TinyML



Deep Reinforcement Learning for Autonomous Source Seeking on a Nano Drone

Bardienus P. Duisterhof[1,3] Srivatsan Krishnan[1] Jonathan J. Cruz[1] Colby R. Banbury[1] William Fu[1]

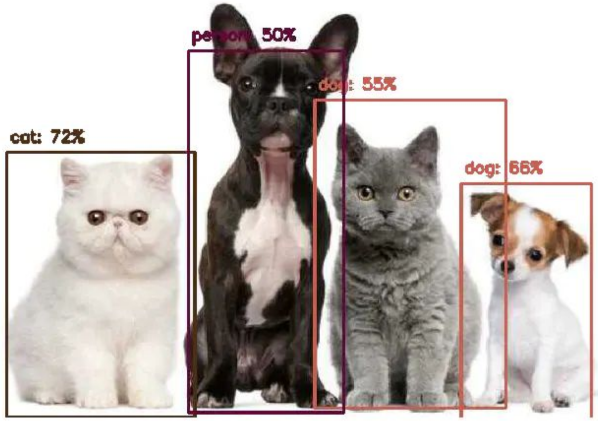
Aleksandra Faust[2] Guido C. H. E. de Croon[3] Vijay Janapa Reddi[1,4]

[1]Harvard University, [2]Robotics at Google, [3]Delft University of Technology, [4]The University of Texas at Austin

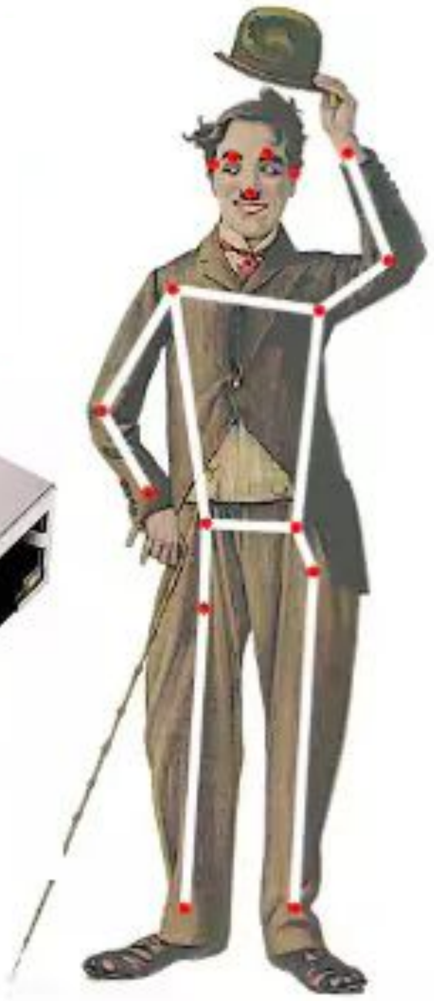
https://arxiv.org/abs/1909.11236

https://youtu.be/wmVKbX7MOnU

Exploring AI at the edge (Computer Vision)



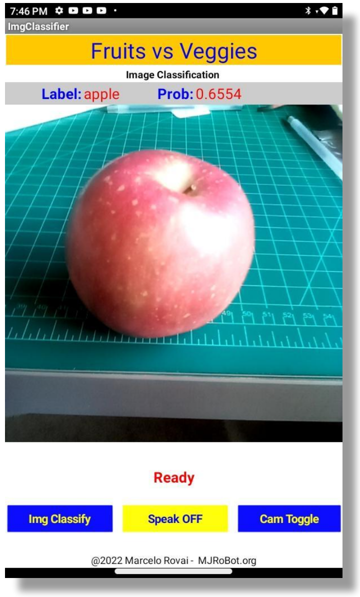
TensorFlow Lite

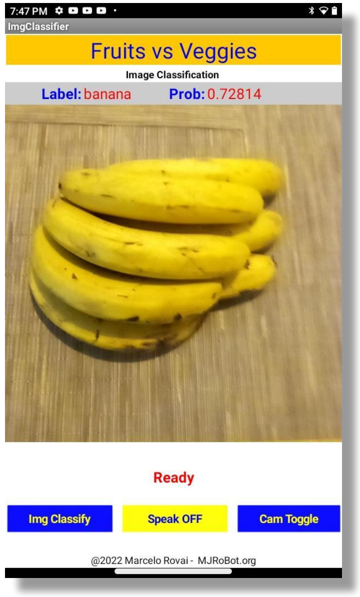


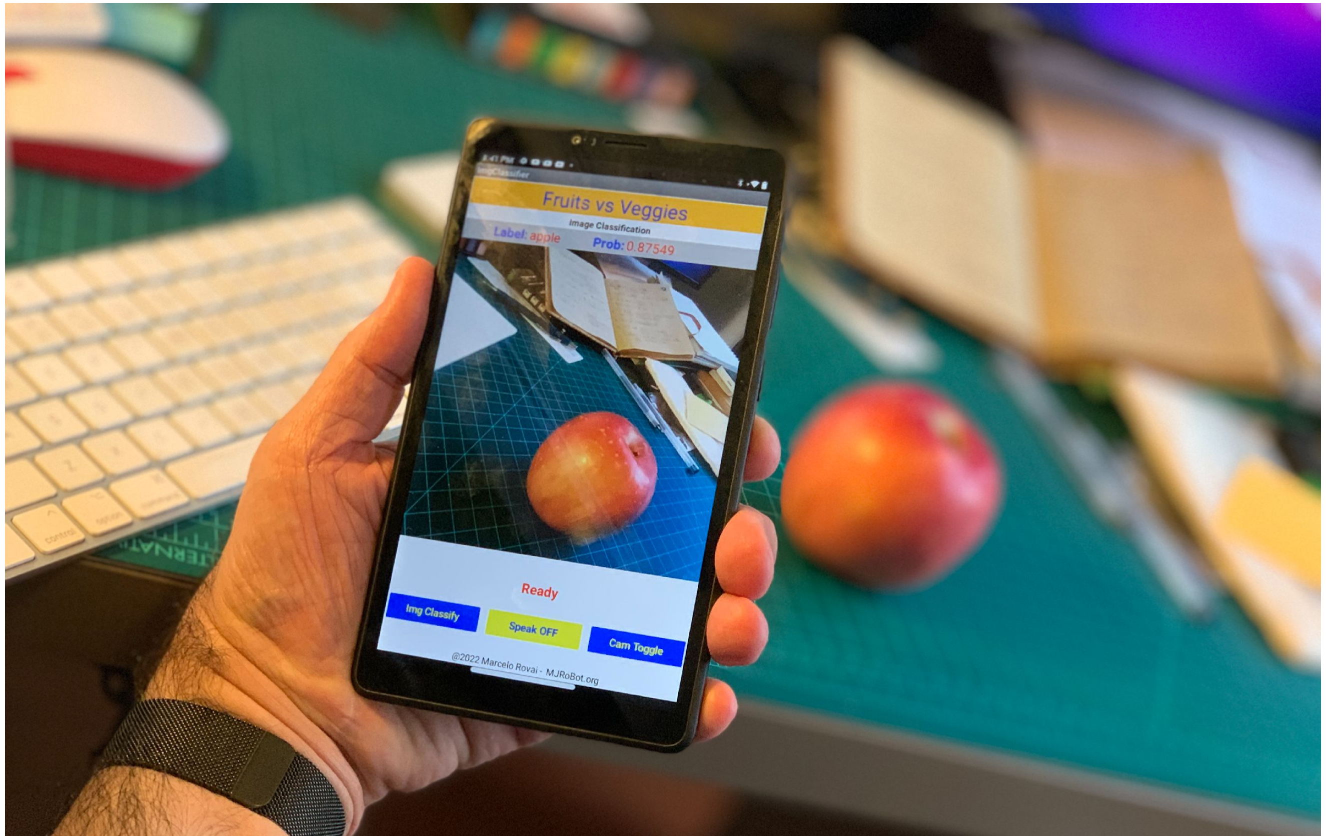
[Exploring AI at the Edge!]

Classifying Images using Smartphones

AI WITH APP INVENTOR







https://www.hackster.io/mjrobot/app-inventor-edgeml-image-classification-fruit-vs-veggies-b671da

Projects by Students (UNIFEI – IESTI01)

- **Sound:**
  - Earthquake detection
  - Covid Detection (cough)
  - Key Detection
  - Pulmonary Disease
  - Snore Detection
  - Bionic Hand Control

- **Other Sensors:**
  - Bionic Hand – Finger Detection
  - Electric Charges
  - ECG – Fibrial Atrilation detection

- **Image:**
  - Mask Detection
  - Forest Fire Detection
  - Helmet Detection
  - Water Consumption (hydrometer)
  - Sign Language
  - Coffee Disease Classification
  - Bee Counting

- **Vibration:**
  - Personal Trainer
  - Bearing – Anomaly Detection

UNIFEI IESTI01 2021.1 – Final Projects UNIFEI IESTI01 2021.2 – Final Projects UNIFEI IESTI01 2022.1 – Final Projects

TinyML4D **Show & Tell** Presentations

Date	**Thread**	**Video**
March 30th, 2023	Thread here when ready	Video here when ready
Feb 23rd, 2023	thread here	Video here when ready
January 26th, 2023	thread here 17	https://youtu.be/-0xRZ-5UYUc 9
December 1st, 2022	thread here 2	https://youtu.be/e49pkjnIMIQ 8
October 27th, 2022	thread here 2	https://youtu.be/s8_hKpOWUwY 1

TinymML4D Academic Network Show and Tell Main Index.

The TinyML4D Academic Network Students should use this form to sign up for the latest presentations.
https://forms.gle/ic52HZMqVv4pBrkP7 2

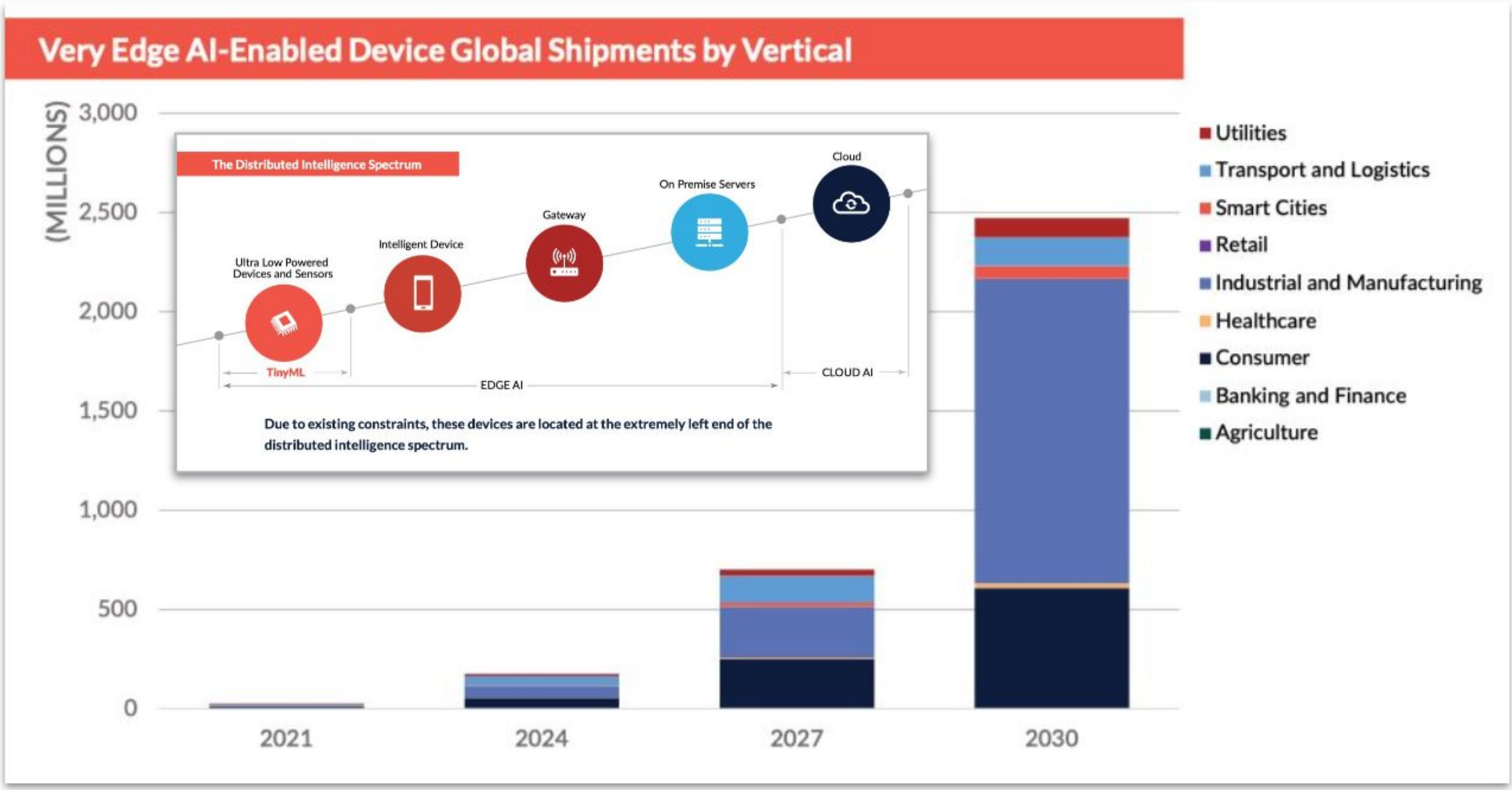
The Show and Tell are typically held at 2 pm UTC on the last Thursday of each month and will take place in this Zoom room.
https://zoom.us/j/95229860797 1
Meeting ID: 952 2986 0797
Passcode: 141278

To learn more about **Edge AI**

- IESTI01 TinyML - Machine Learning for Embedding Devices (Videos: Pt)
- WALC 22 – Applied AI - TinyML (Videos in Spanish)
- Professional Certificate in Tiny Machine Learning (TinyML) – edX/Harvard
- Introduction to Embedded Machine Learning - Coursera/Edge Impulse
- Computer Vision with Embedded Machine Learning - Coursera/Edge Impulse
- "Deep Learning with Python" book by François Chollet
- "TinyML" book by Pete Warden, Daniel Situnayake
- "TinyML Cookbook" by Gian Marco Iodice
- "AI at the Edge" book by Daniel Situnayake, Jenny Plunkett

The Future of the EdgeAI

Massive Potential for Impact



Source: ABI Research: TinyML

Edge AI has a **very high** impact potential, and it is for **now**!

Conclusion

The Future of ML is Tiny and Bright

***Vijay Janapa Reddi**, Ph. D. | Associate Professor |*
John A. Paulson School of Engineering and Applied Sciences | Harvard University |

Thanks

UNIFEI