Embedded ML (TinyML) Intro & Applications

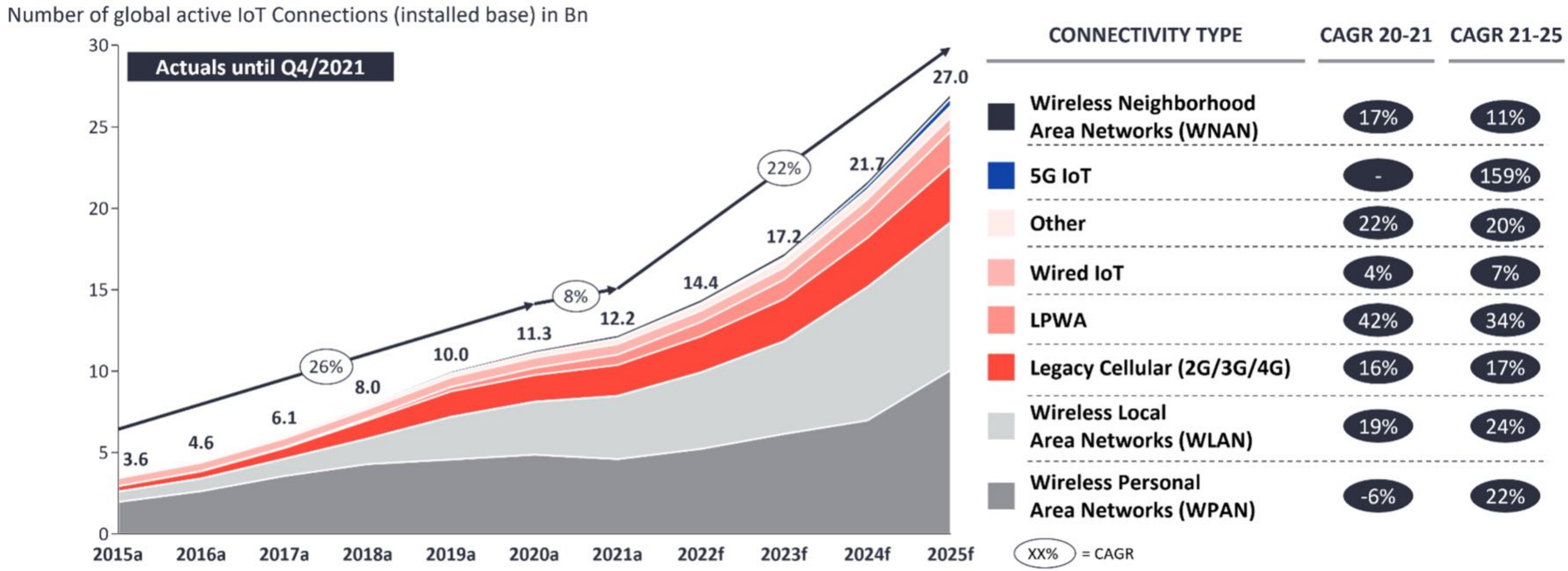
Marco Zennaro, PhD

TinyML4D Academic Network Co-Chair

TINYML4D

Internet of Things (IoT)

Global IoT Market Forecast [in billion connected IoT devices]

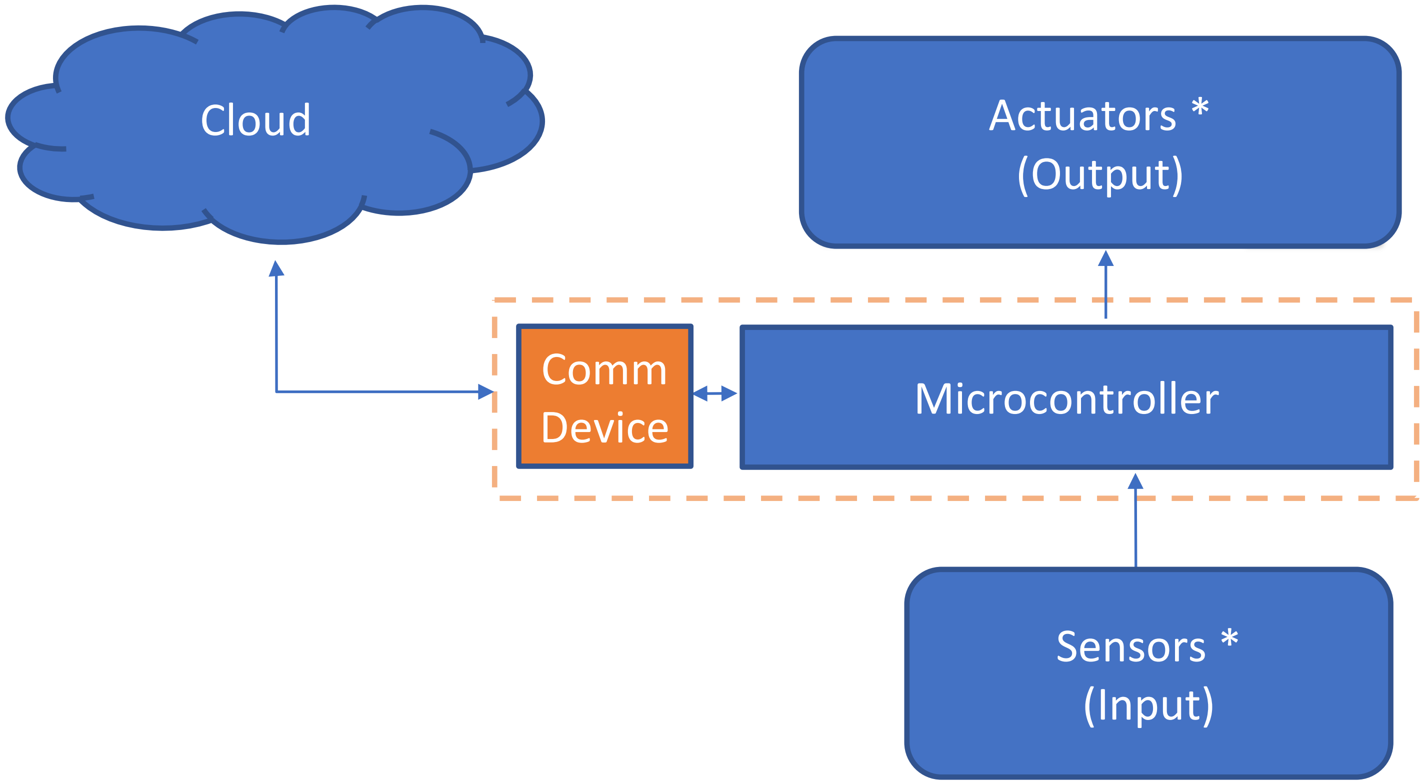


Note: IoT Connections do not include any computers, laptops, fixed phones, cellphones or tablets. Counted are active nodes/devices or gateways that concentrate the end-sensors, not every sensor/actuator. Simple one-directional communications technology not considered (e.g., RFID, NFC). Wired includes 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.

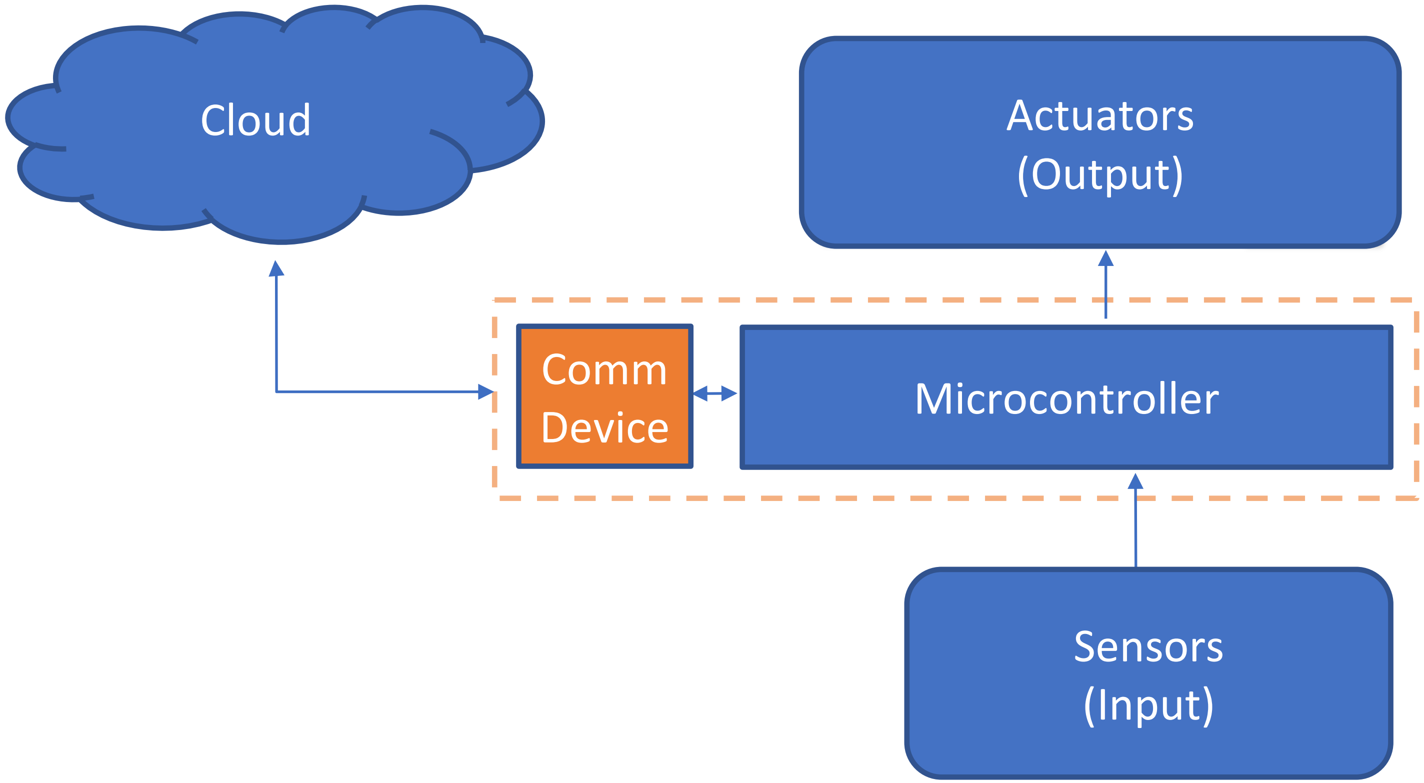
https://iot-analytics.com/number-connected-iot-devices

Typical IoT Project



*** "Things"**

Typical IoT Project



5 Quintillion

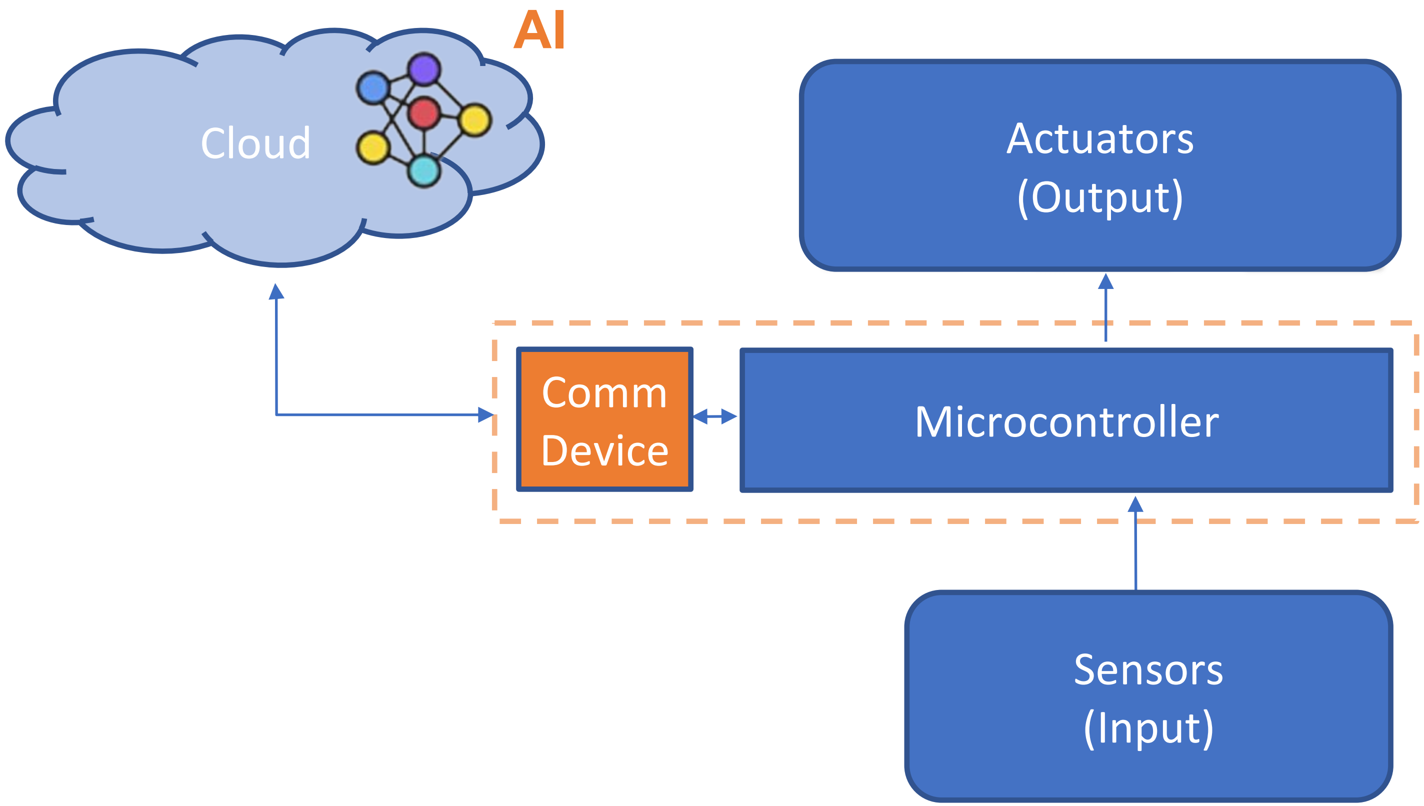
bytes of data produced every day by IoT

<1%

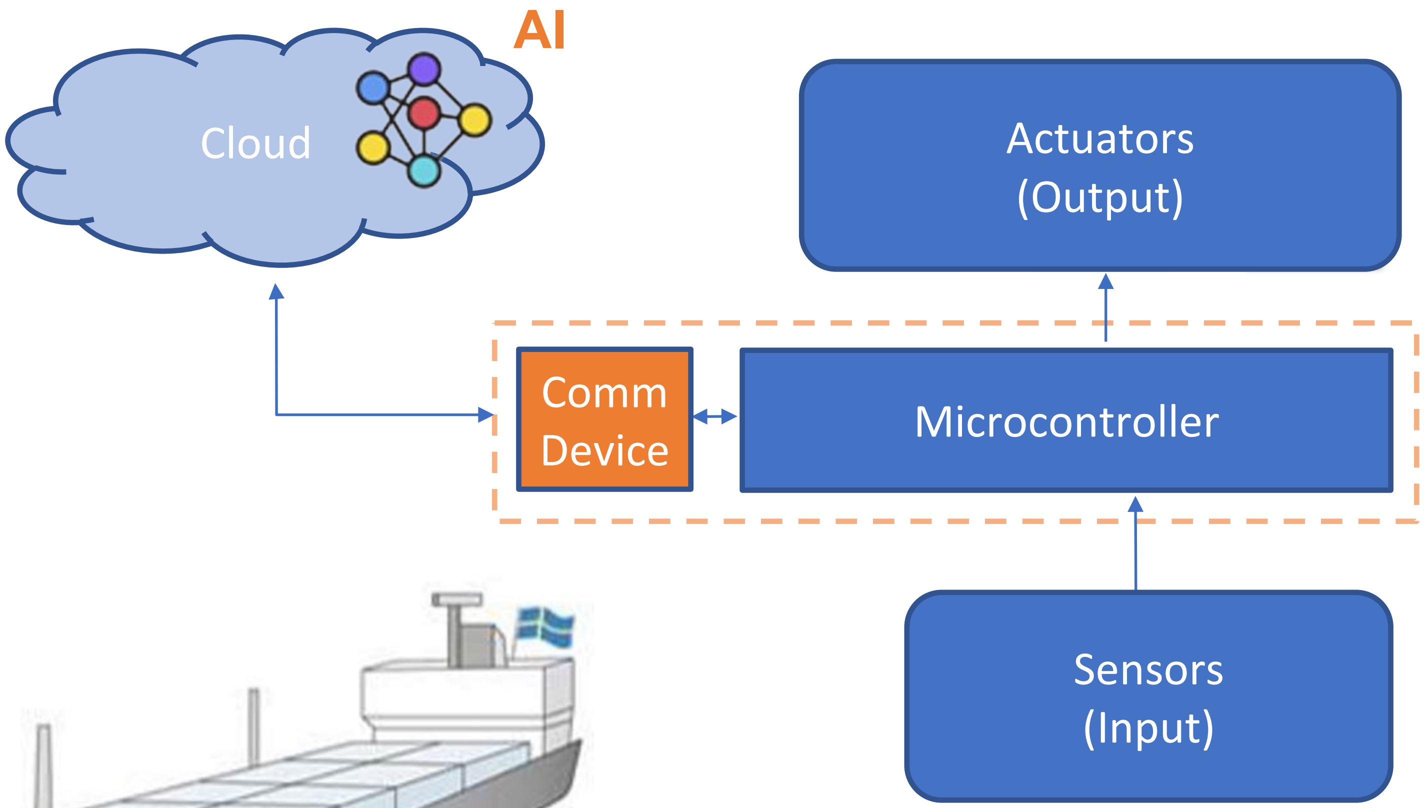
of unstructured data is analyzed or used at all

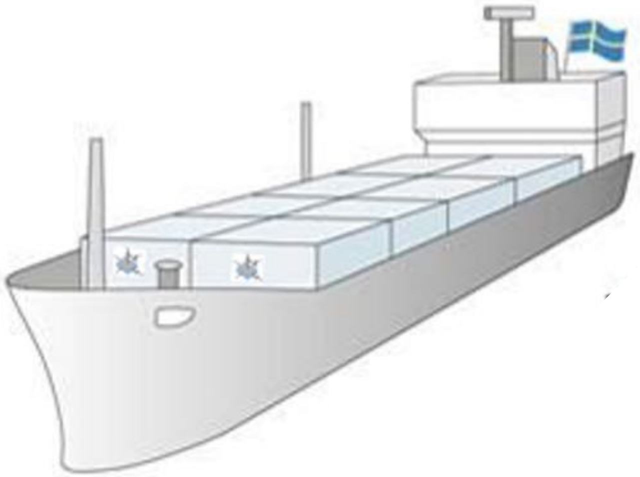
Source: Harvard Business Review, [What's Your Data Strategy?](), April 18, 2017
Cisco, [Internet of Things (IoT) Data Continues to Explode Exponentially. Who Is Using That Data and How?](), Feb 5, 2018

Typical AIoT Project



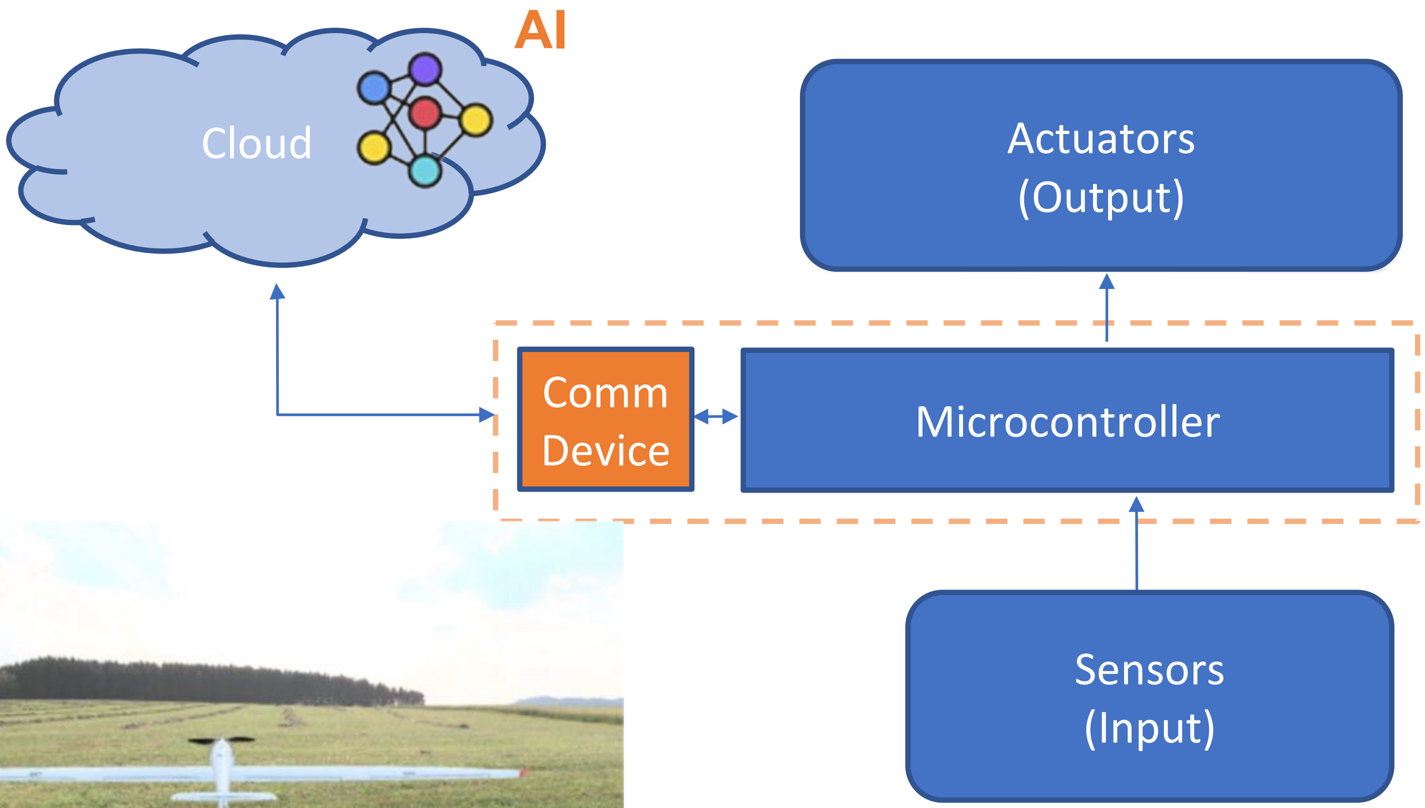
Typical AIoT Project … … Issues





Bandwidth

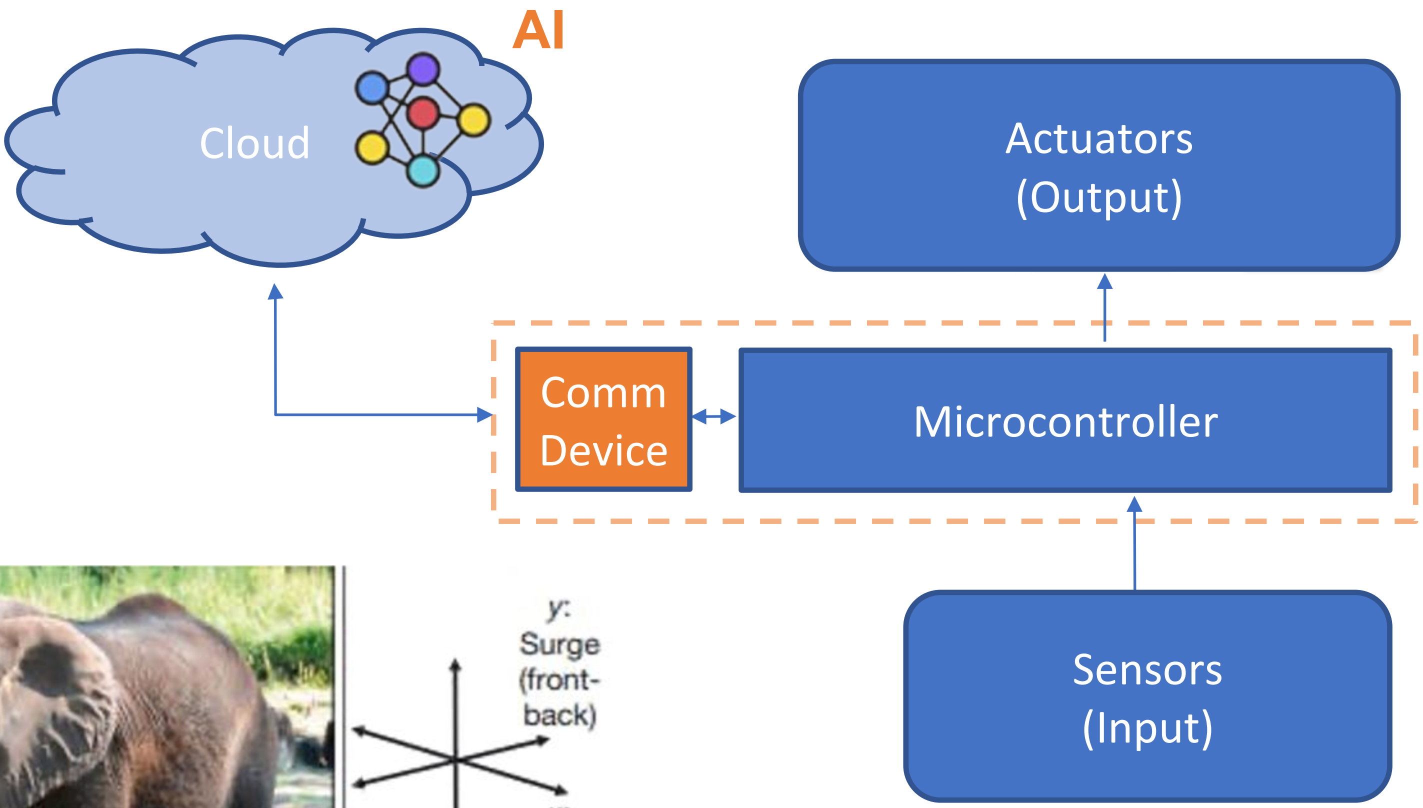
Typical AIoT Project … … Issues

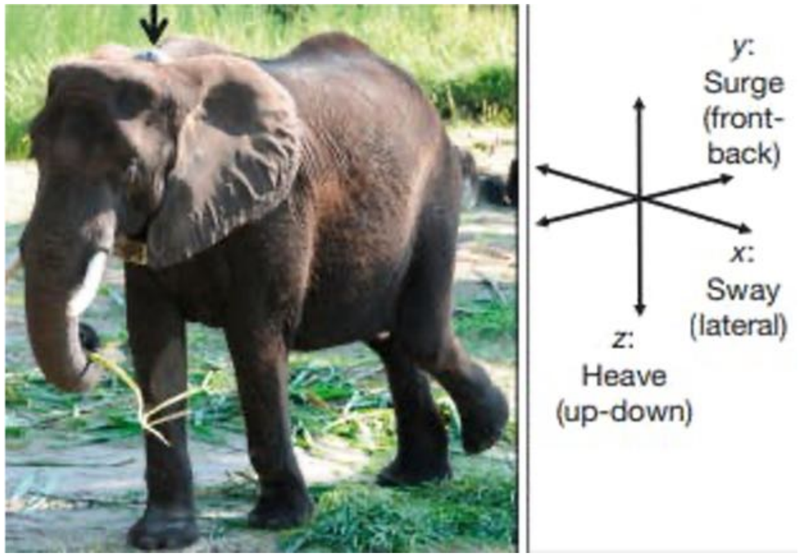


Bandwidth

Latency

Typical AIoT Project … … Issues



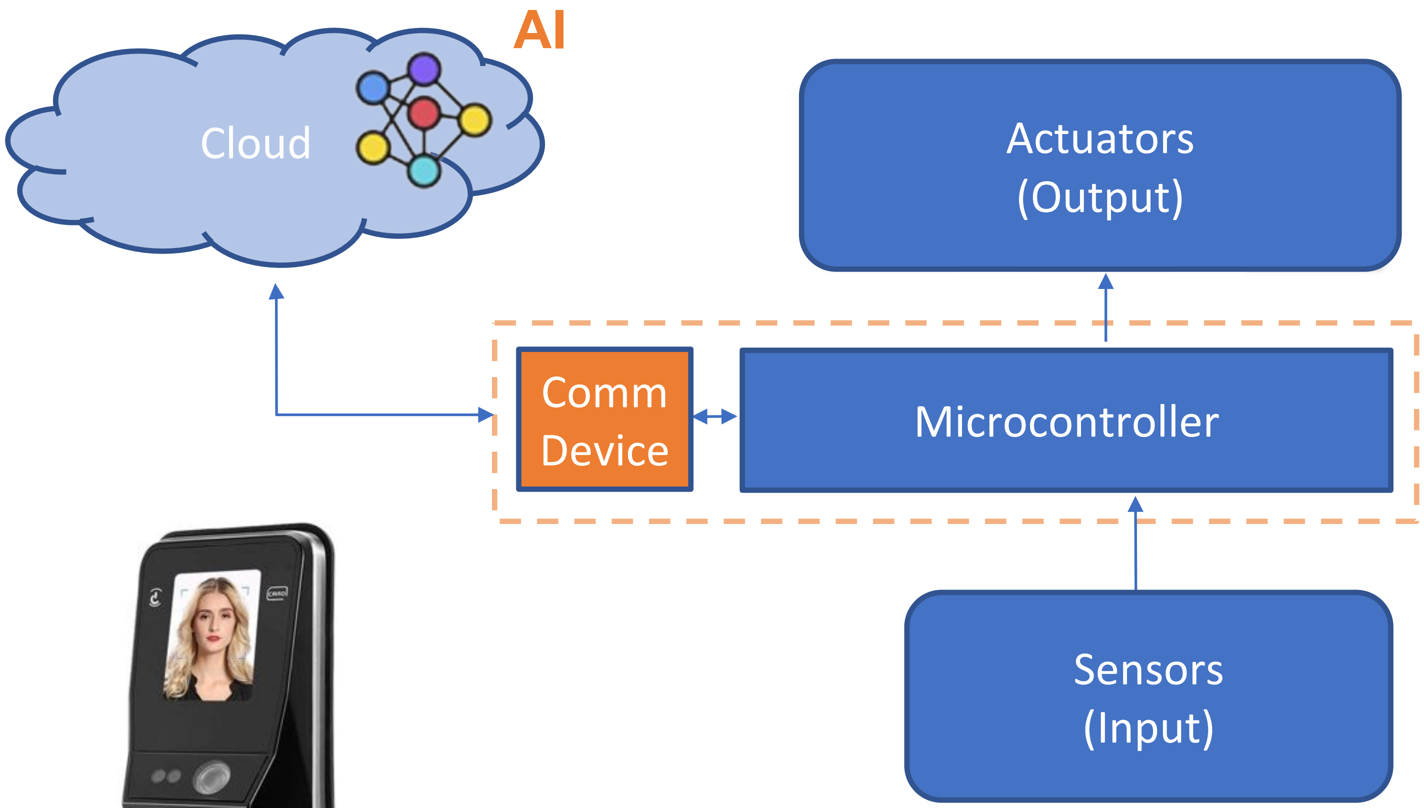


Bandwidth

Latency

Energy

Typical AIoT Project …



… Issues

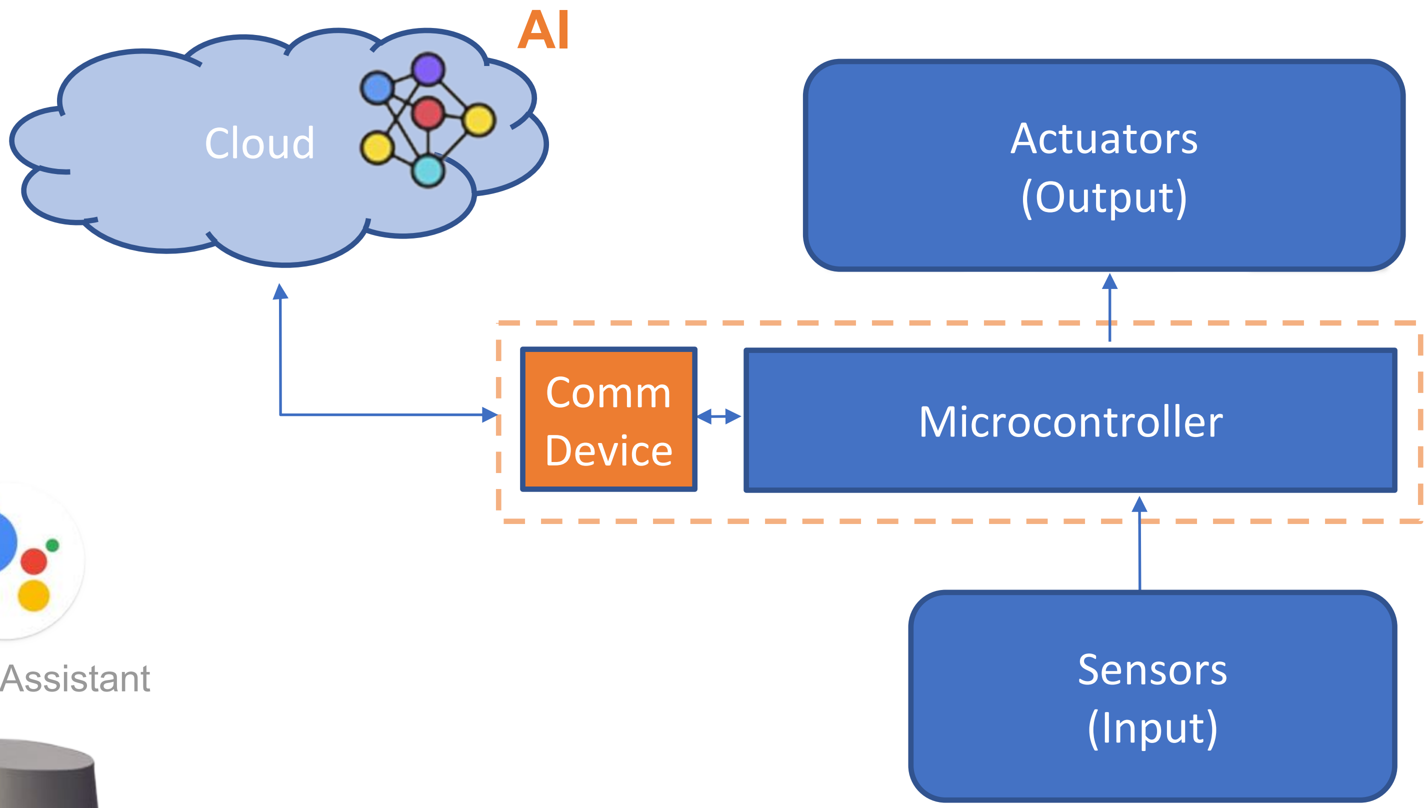
Bandwidth

Latency

Energy

Reliability

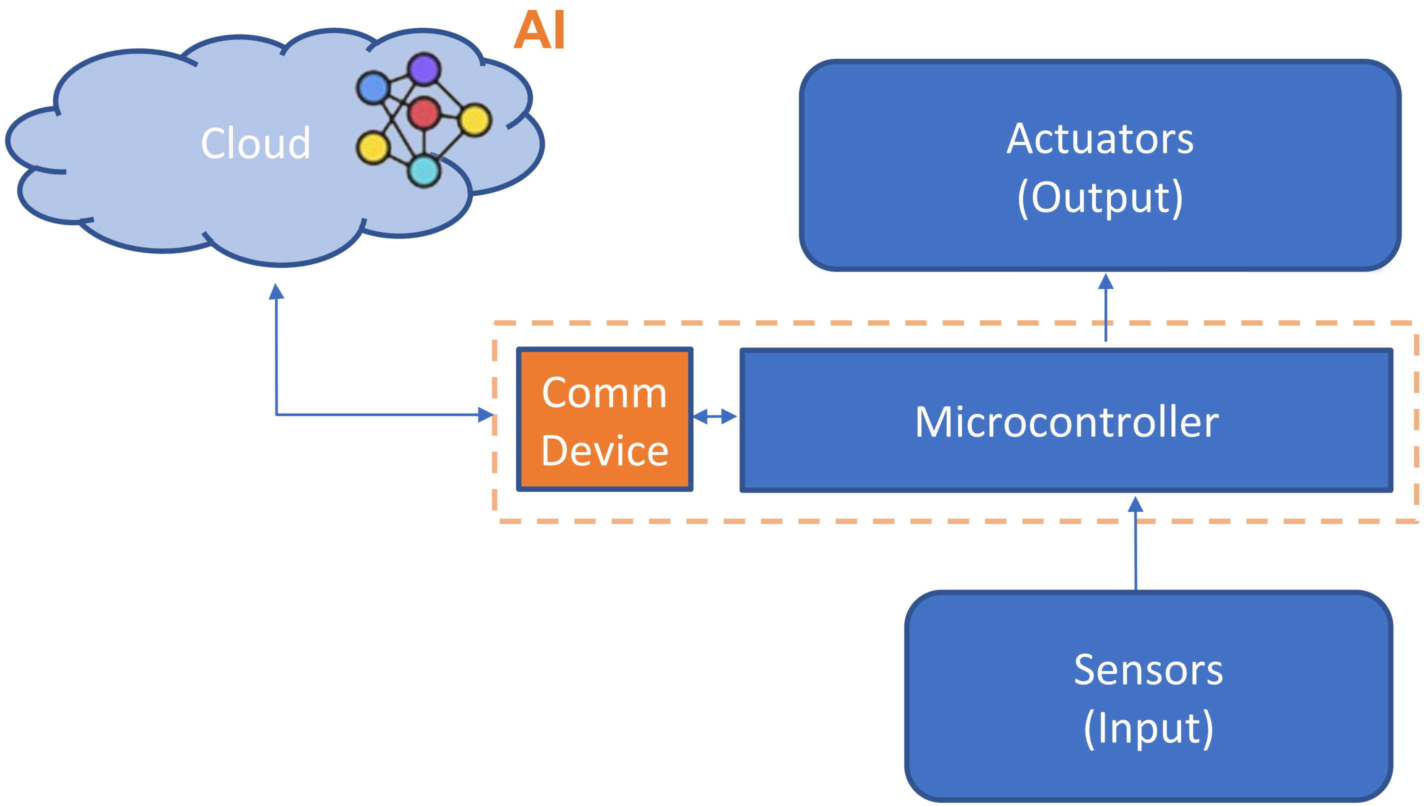
Typical AIoT Project … … Issues



Google Assistant

- Bandwidth
- Latency
- Energy
- Reliability
- **Privacy**

Typical AIoT Project …



… Issues

Bandwidth

Latency

Energy

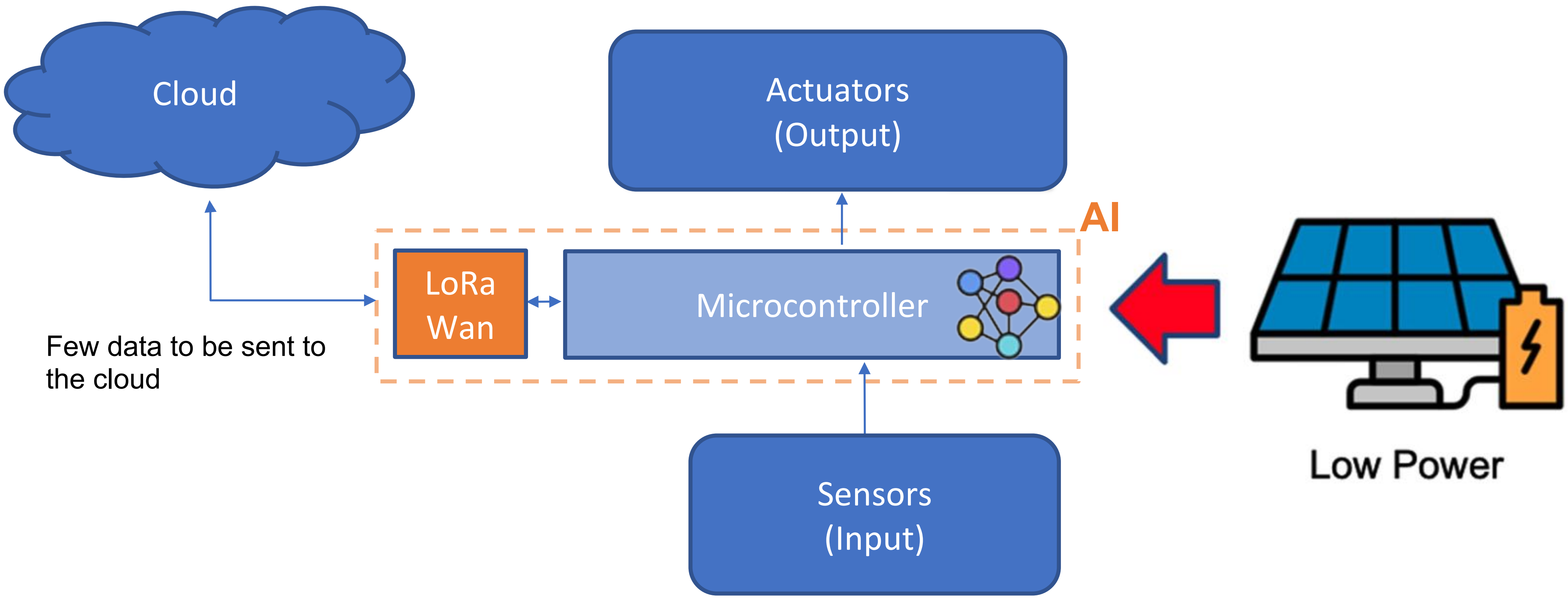
Reliability

Privacy

… Solution ?

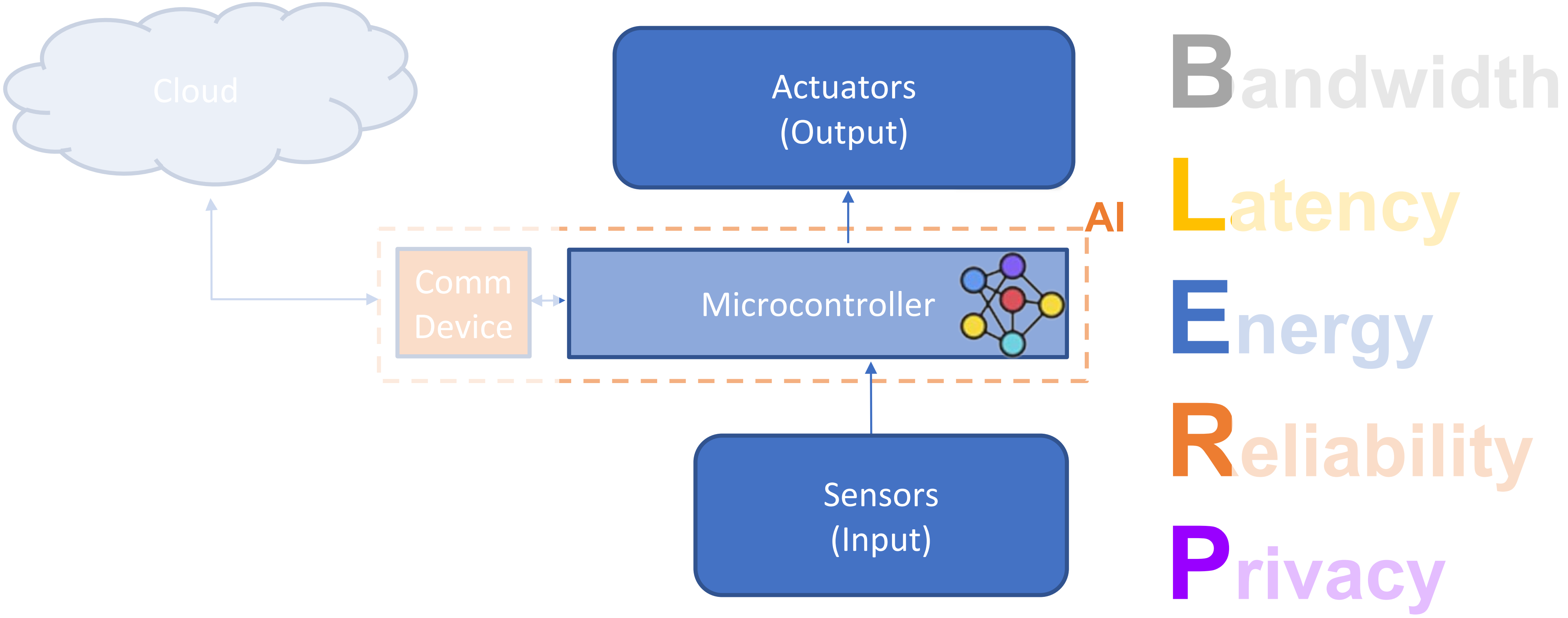
IoT 2.0 * – Edge AI/ML

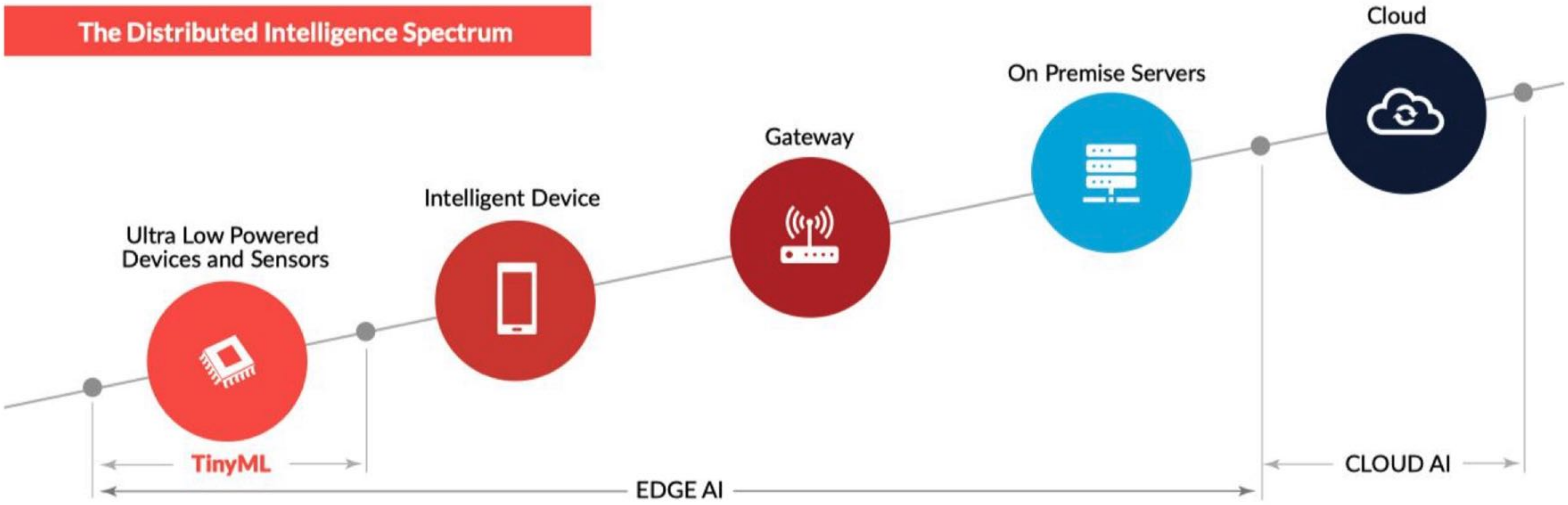
* Intelligence of Things



… Solution -> ML goes close to data

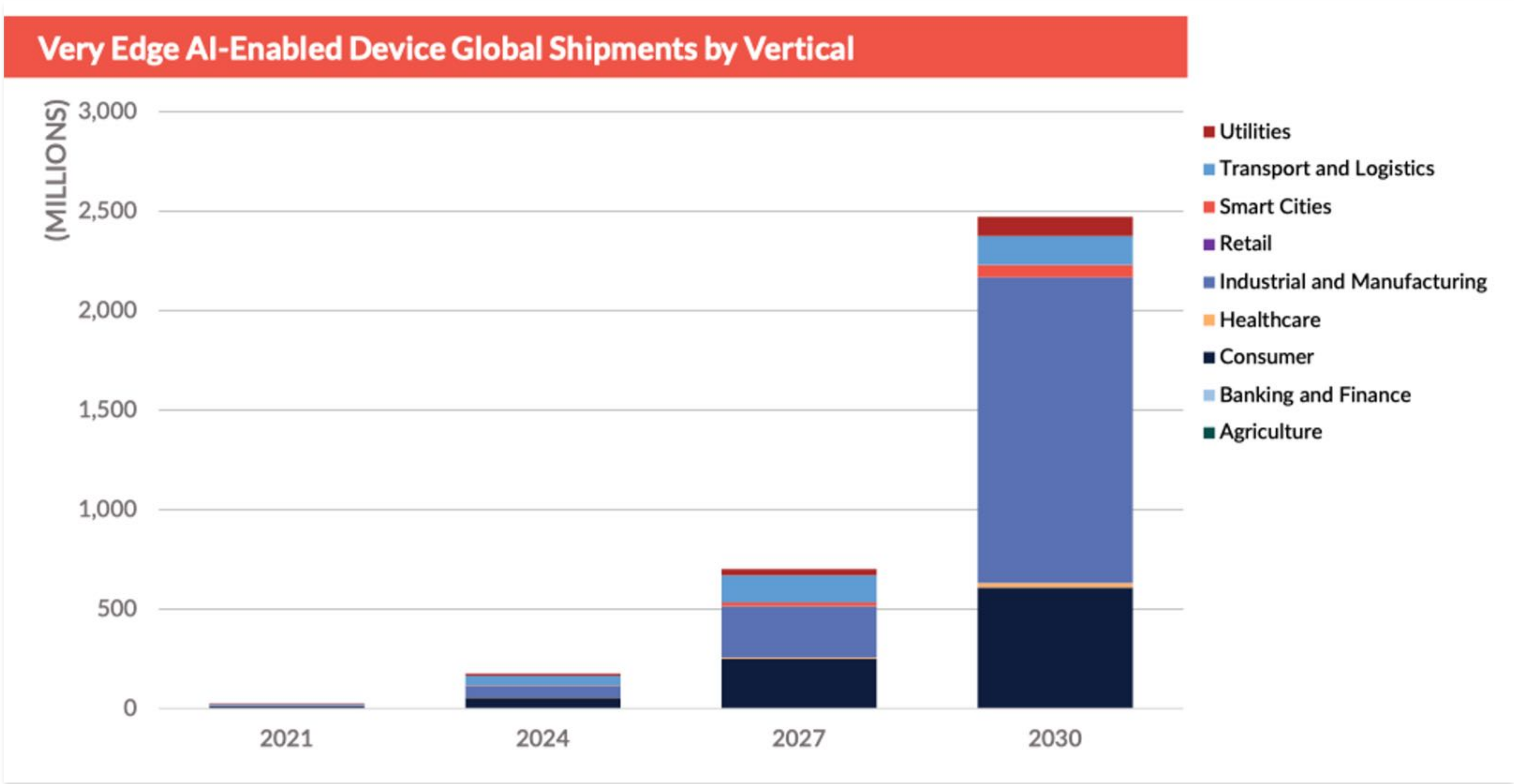
When to use an Edge AI/ML approach:





Source: ABI Research: TinyML

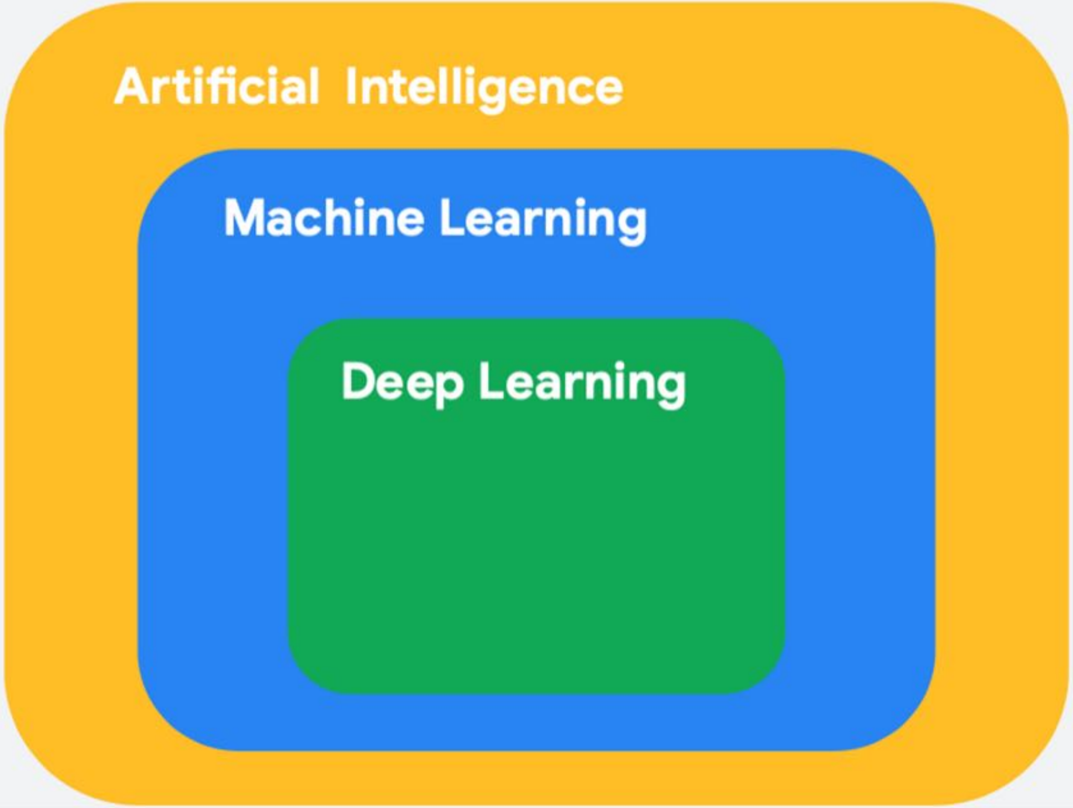
Market Forecast



Source: ABI Research: TinyML

Embedded ML (TinyML)

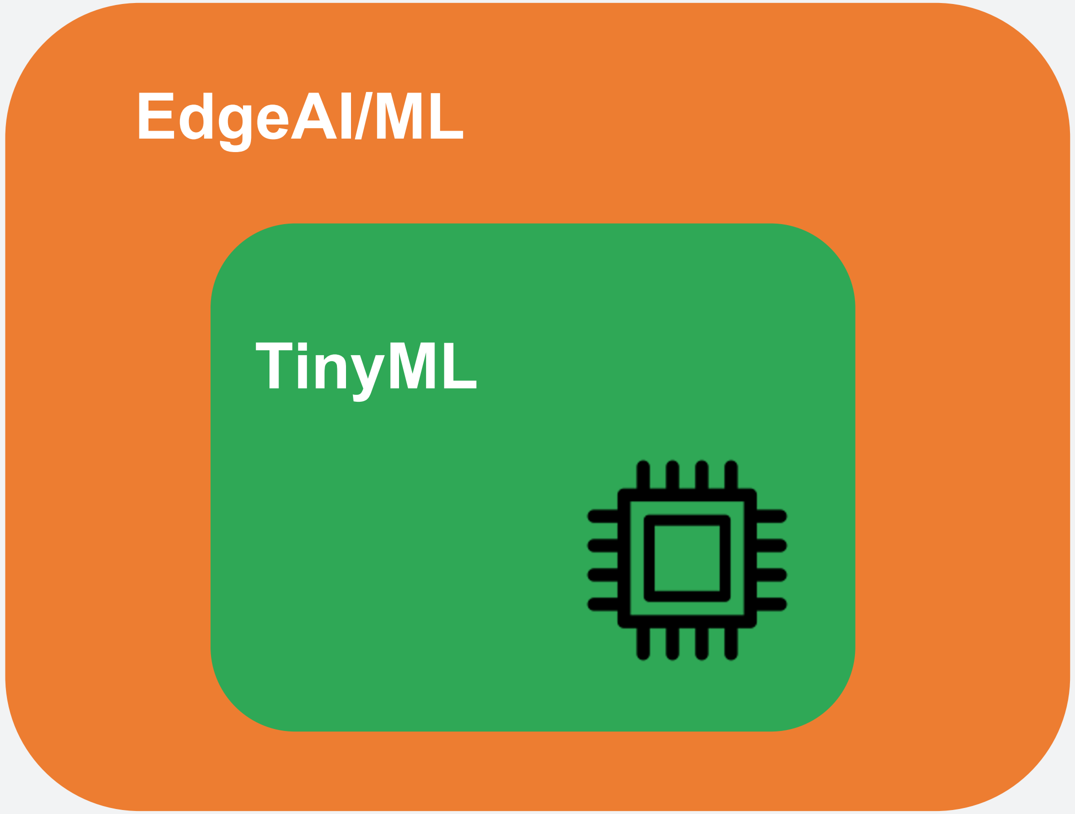
Introduction



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**

20

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

21

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

On-device sensor analytics

22

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of ML

Algorithms, hardware, software

On-device sensor analytics

Low power consumption

23

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of **ML**

Algorithms, hardware, software

On-device sensor analytics

Low power consumption

Battery-operated

24

What is Tiny Machine Learning (TinyML)?

TinyML

Fastest-growing field of ML

Algorithms, hardware, software

On-device sensor analytics

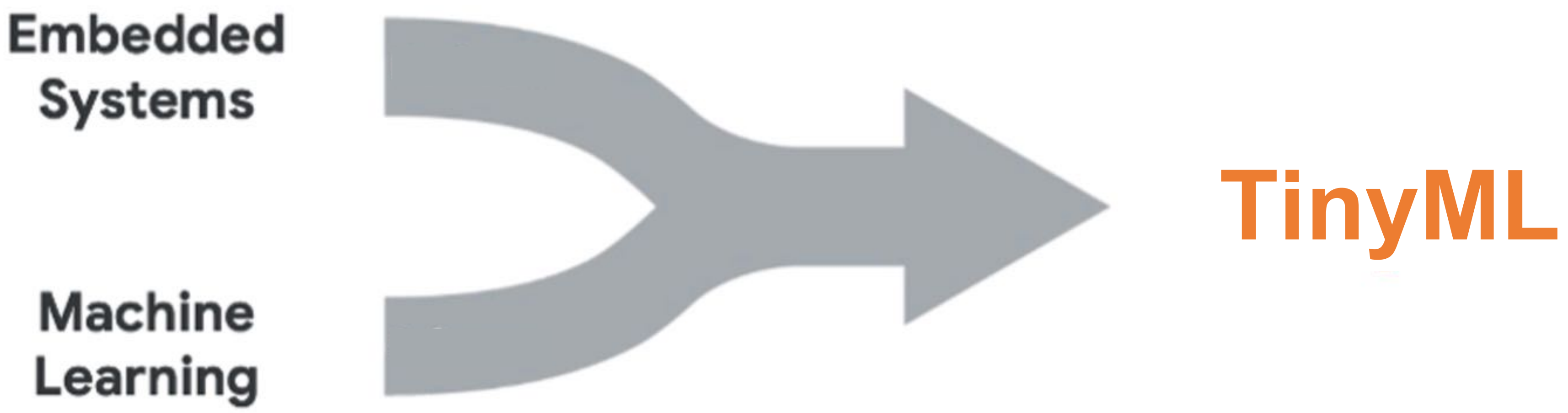
Low power consumption

Battery-operated

Always-on ML

25

What Makes **TinyML** ?

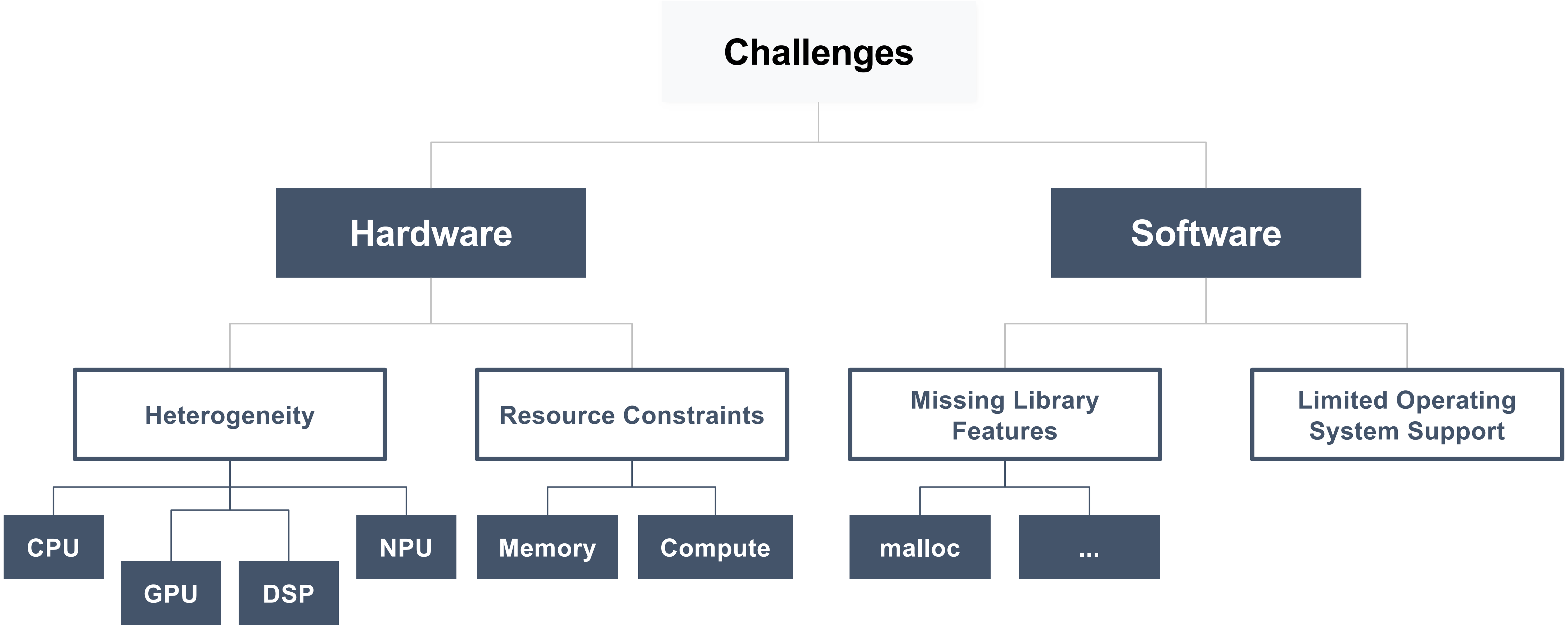


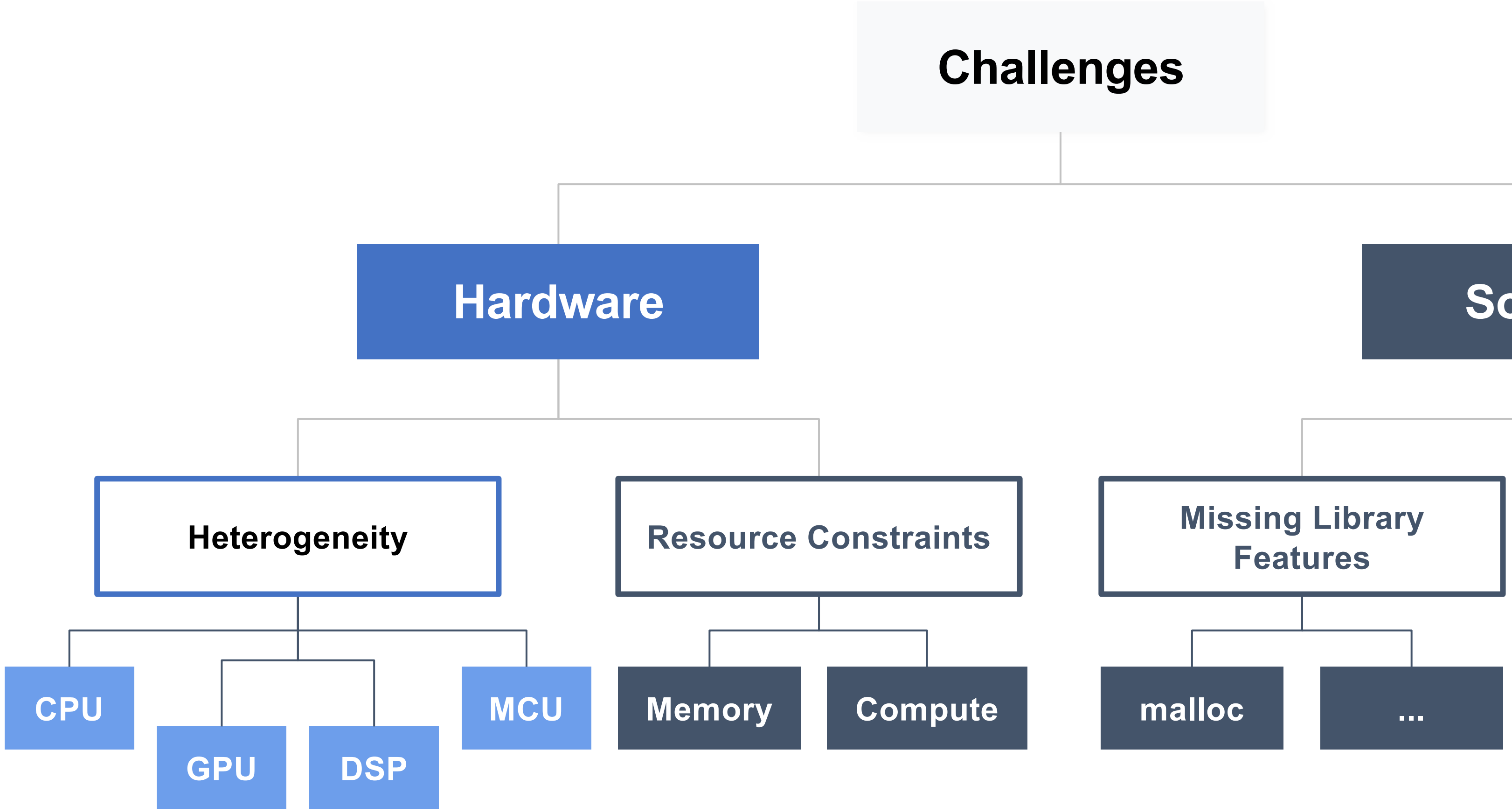
What Makes TinyML ?

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
...

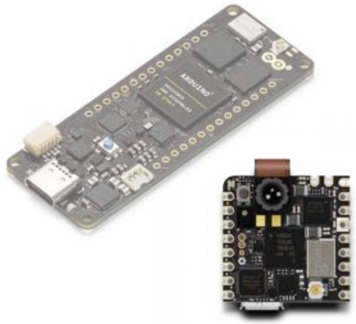

Challenges
Hardware
Software
Heterogeneity
Resource Constraints
Missing Library Features
Limited Operating System Support
CPU
GPU
DSP
MCU
Memory
Compute
malloc
...

250 Billion

MCUs today

31

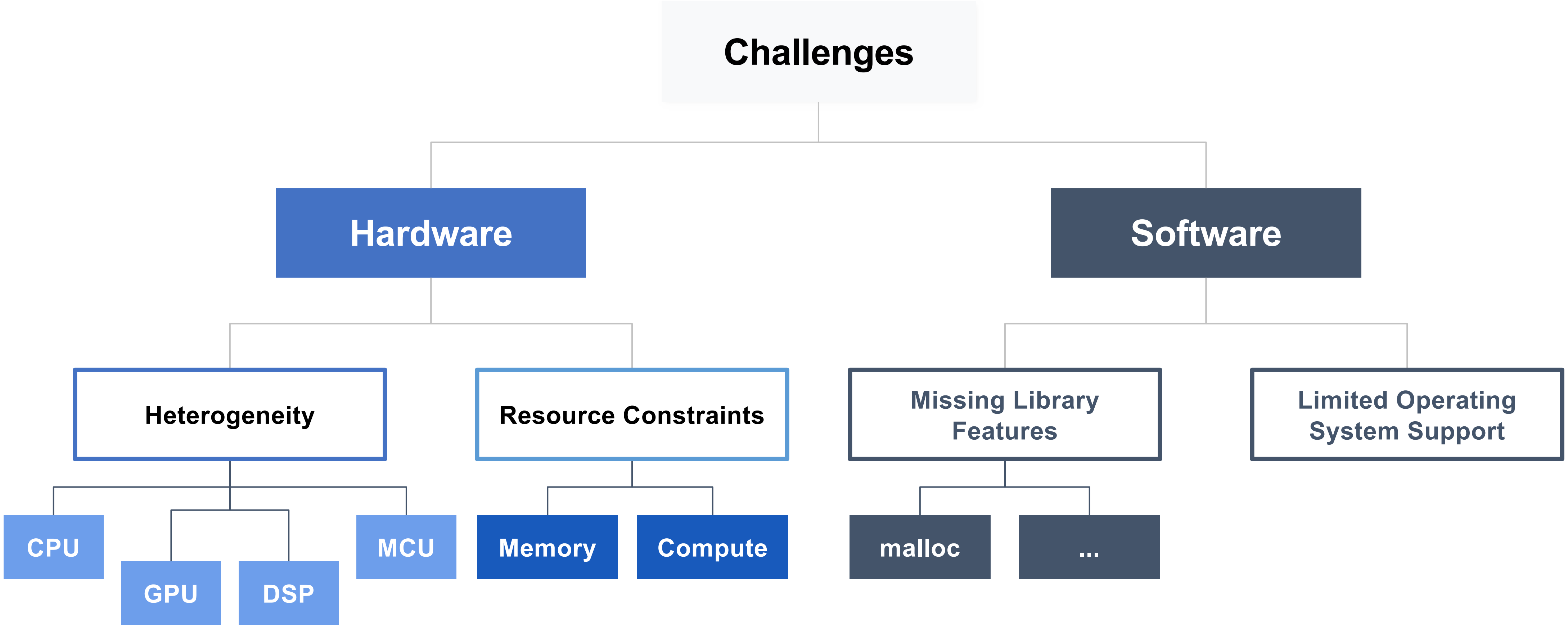
Hardware



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	$	$$$	$	$$	$$$$$

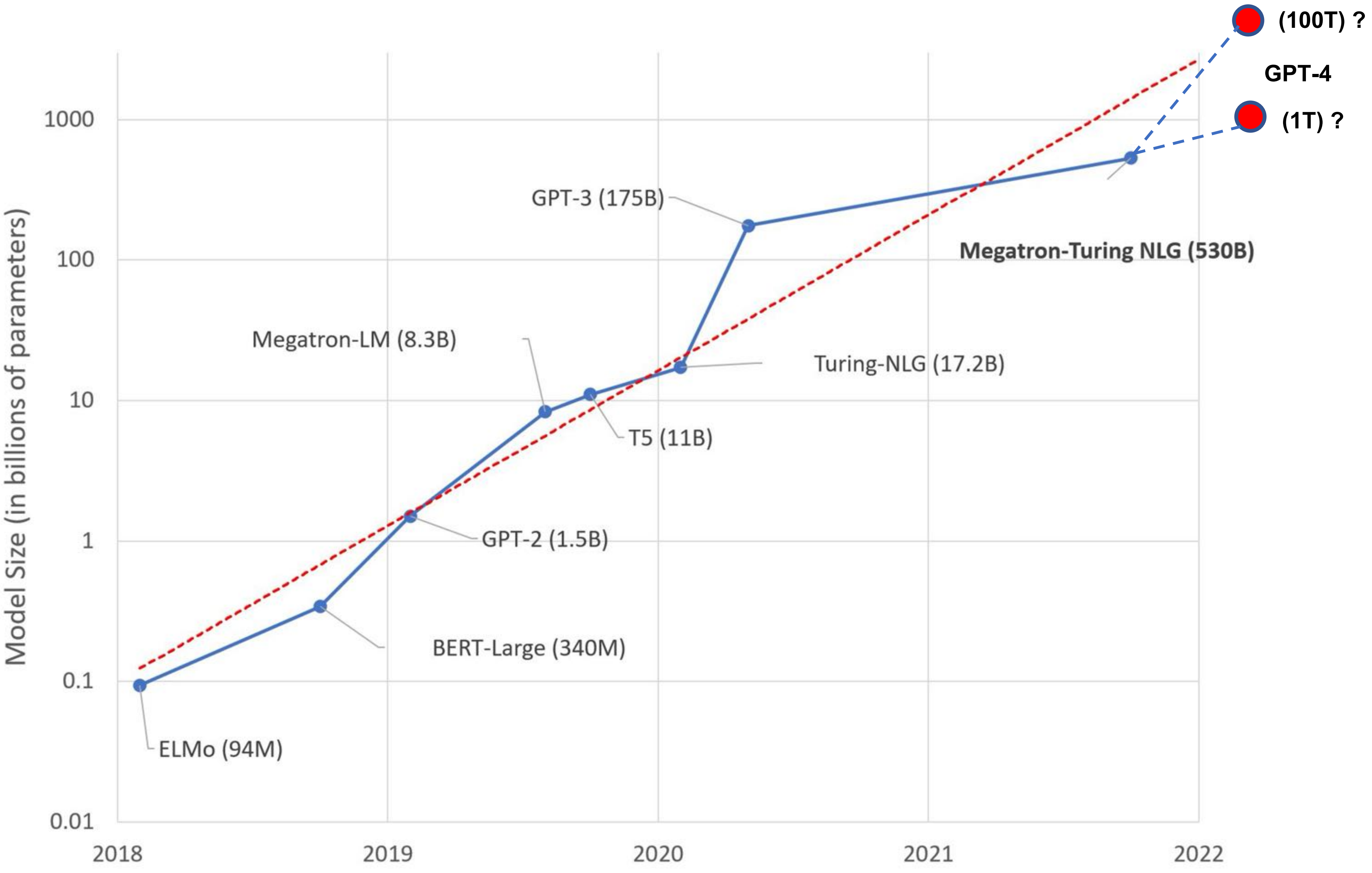
https://media.digikey.com/Resources/Maker/the-original-guide-to-boards-2022.pdf


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

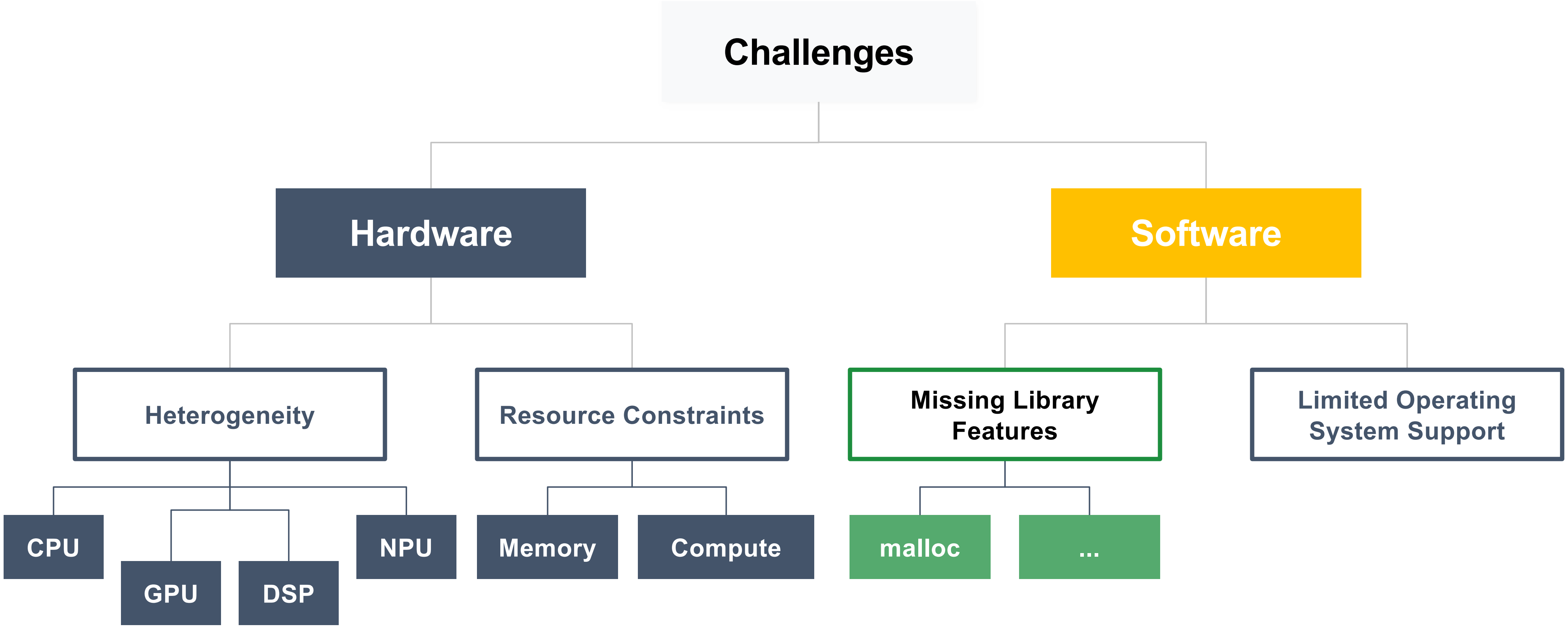
Hardware

	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



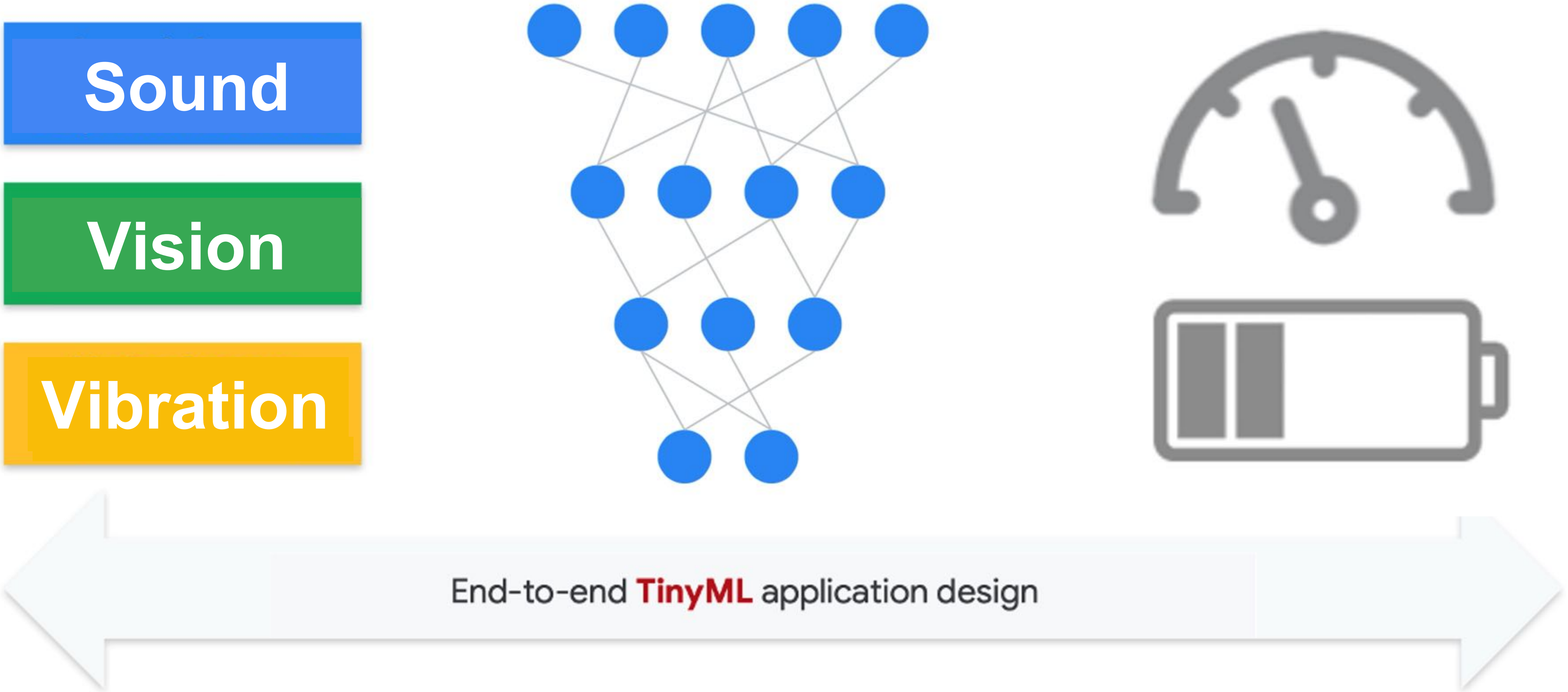
https://huggingface.co/blog/large-language-models https://arxiv.org/abs/2303.08774


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

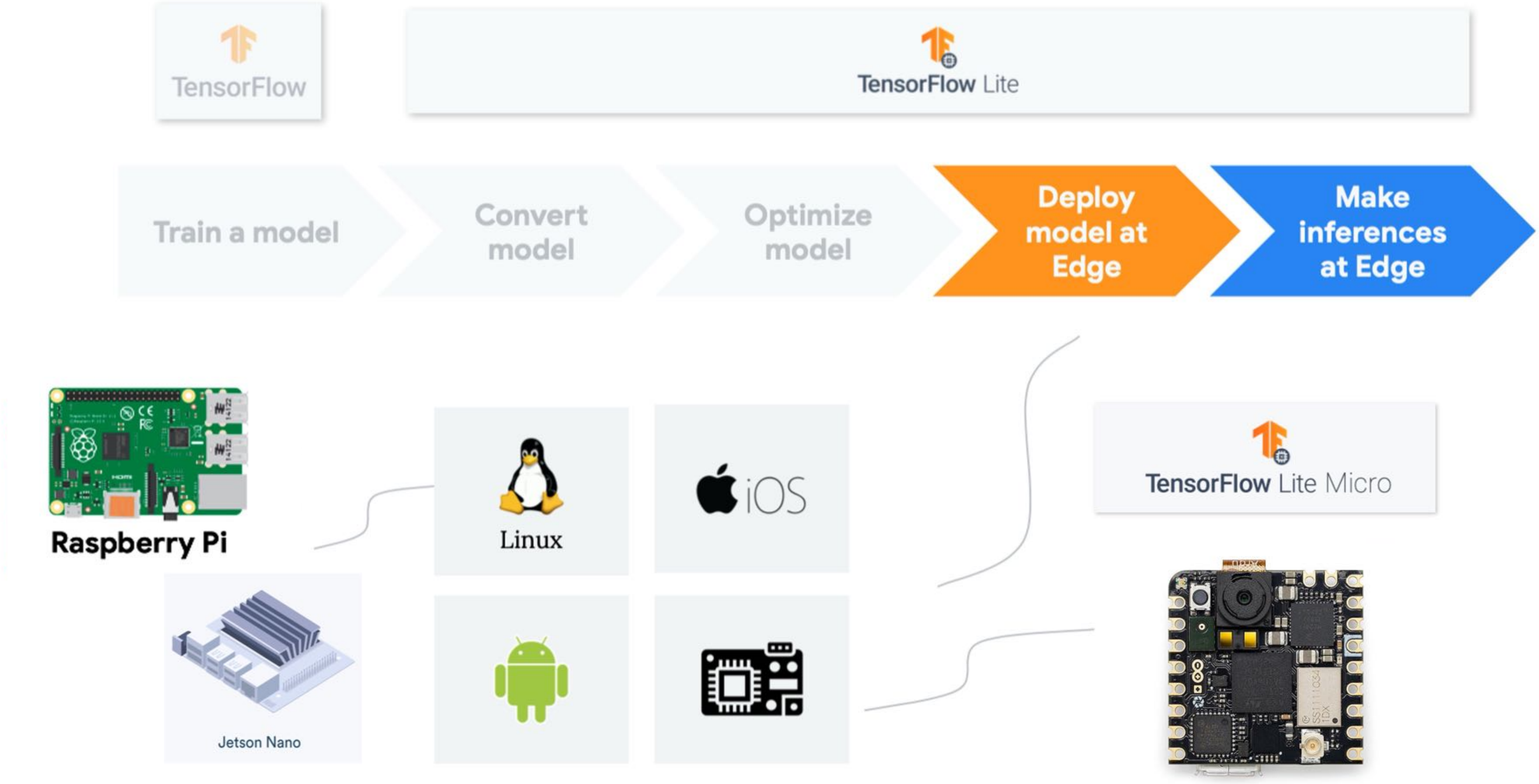
Datasets Preprocessing

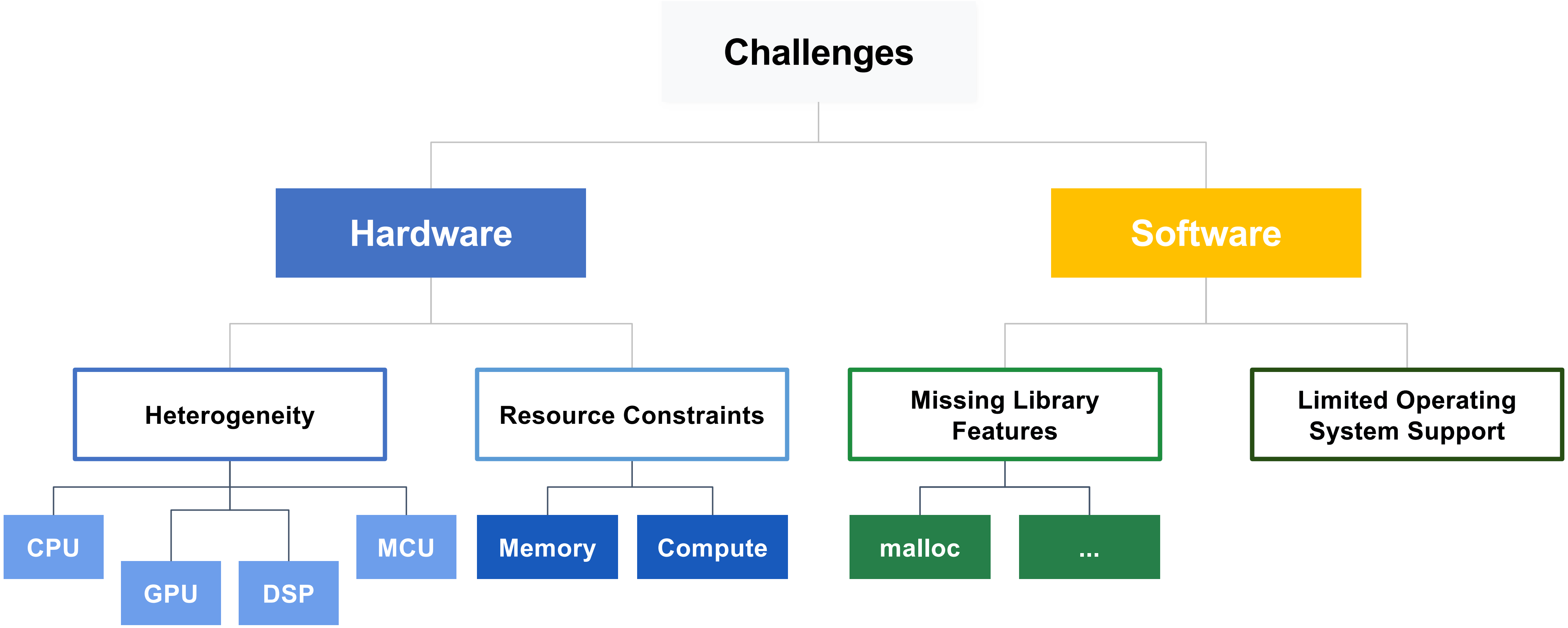
Quantization Pruning

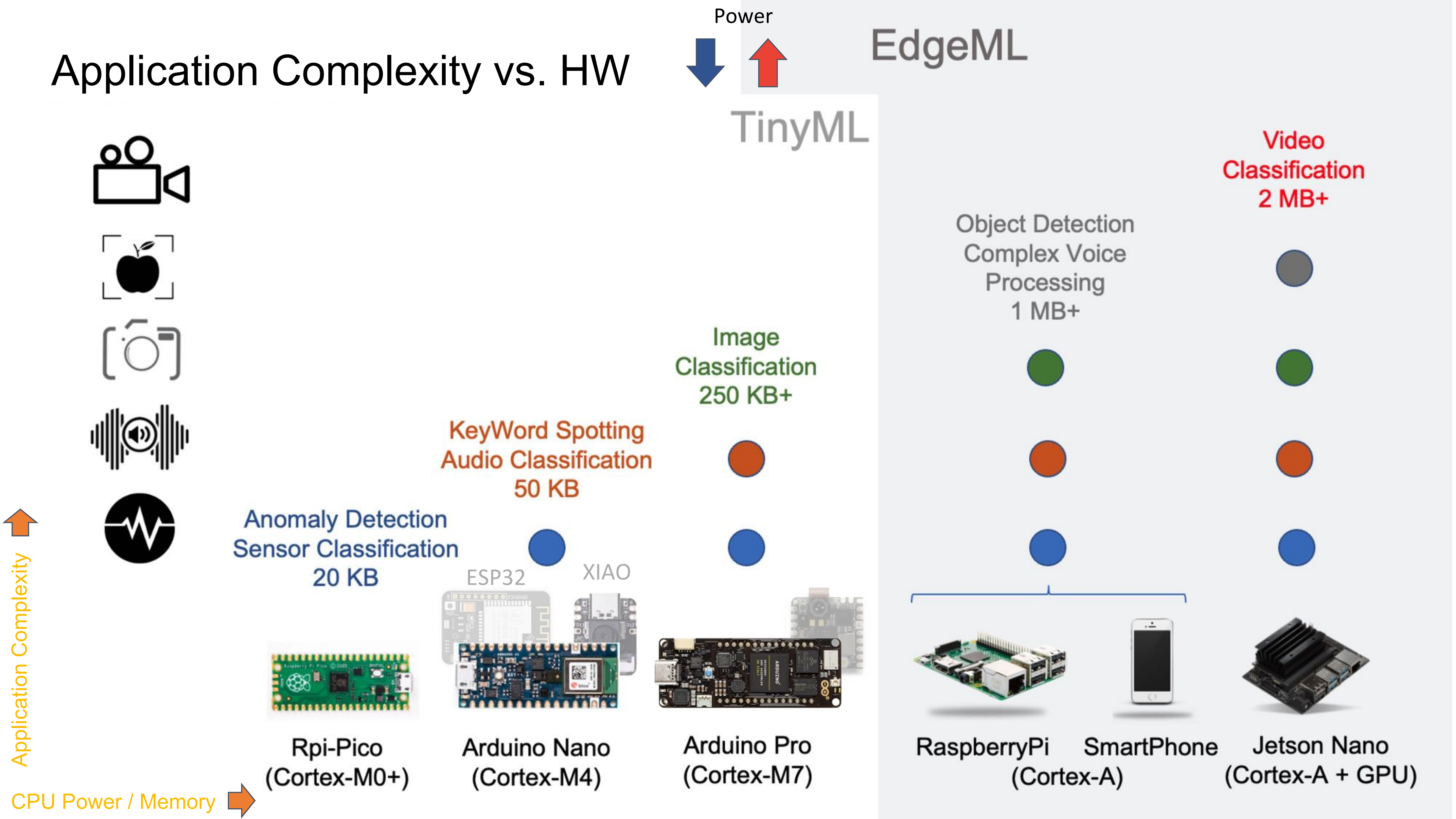
Resource constraints



Software

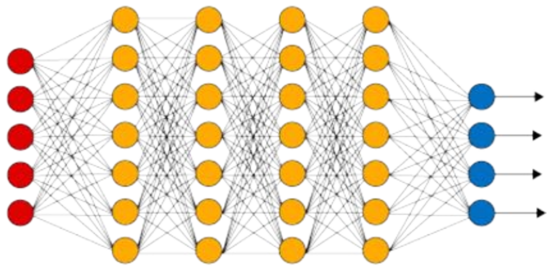

TensorFlow
TensorFlow Lite
Train a model
Convert model
Optimize model
Deploy model at Edge
Make inferences at Edge
Raspberry Pi
Linux
iOS
TensorFlow Lite Micro
Jetson Nano

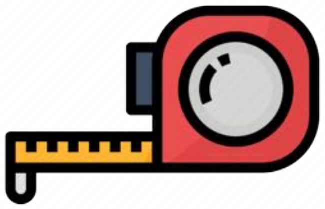

Challenges
Hardware
Software
Heterogeneity
Resource Constraints
Missing Library Features
Limited Operating System Support
CPU
GPU
DSP
MCU
Memory
Compute
malloc
...


Application Complexity vs. HW
Power
EdgeML
TinyML
Video Classification 2 MB+
Object Detection Complex Voice Processing 1 MB+
Image Classification 250 KB+
KeyWord Spotting Audio Classification 50 KB
Anomaly Detection Sensor Classification 20 KB
ESP32
XIAO
Rpi-Pico (Cortex-M0+)
Arduino Nano (Cortex-M4)
Arduino Pro (Cortex-M7)
RaspberryPi
SmartPhone
(Cortex-A)
Jetson Nano (Cortex-A + GPU)
Application Complexity
CPU Power / Memory

How to Train a ML Model?

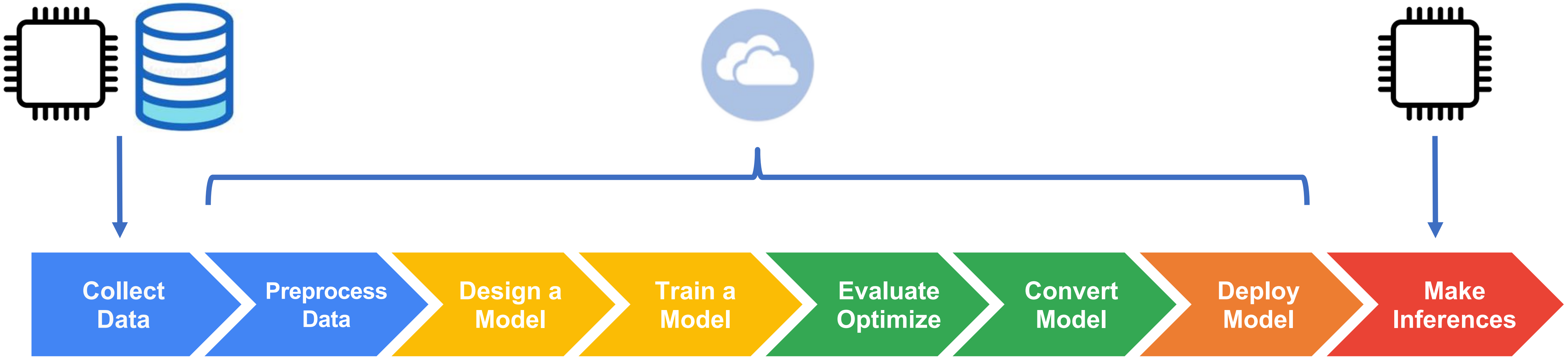
Machine Learning Workflow ("What")



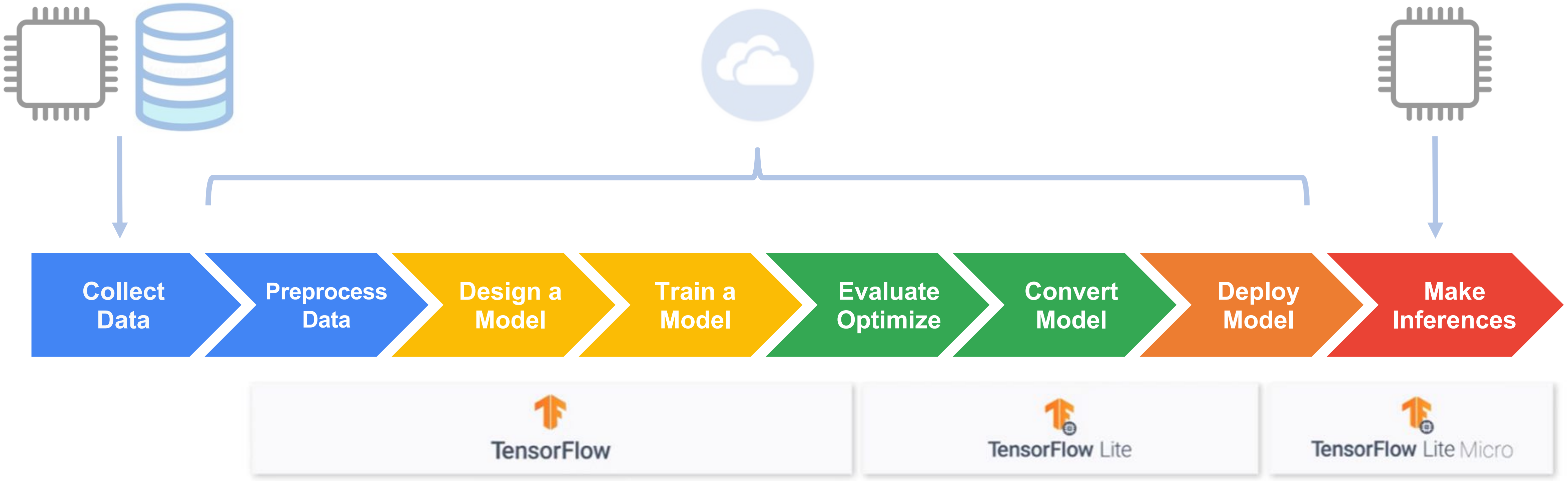


- Collect Data
- Preprocess Data
- Design a Model
- Train a Model
- Evaluate Optimize
- Convert Model
- Deploy Model
- Make Inferences

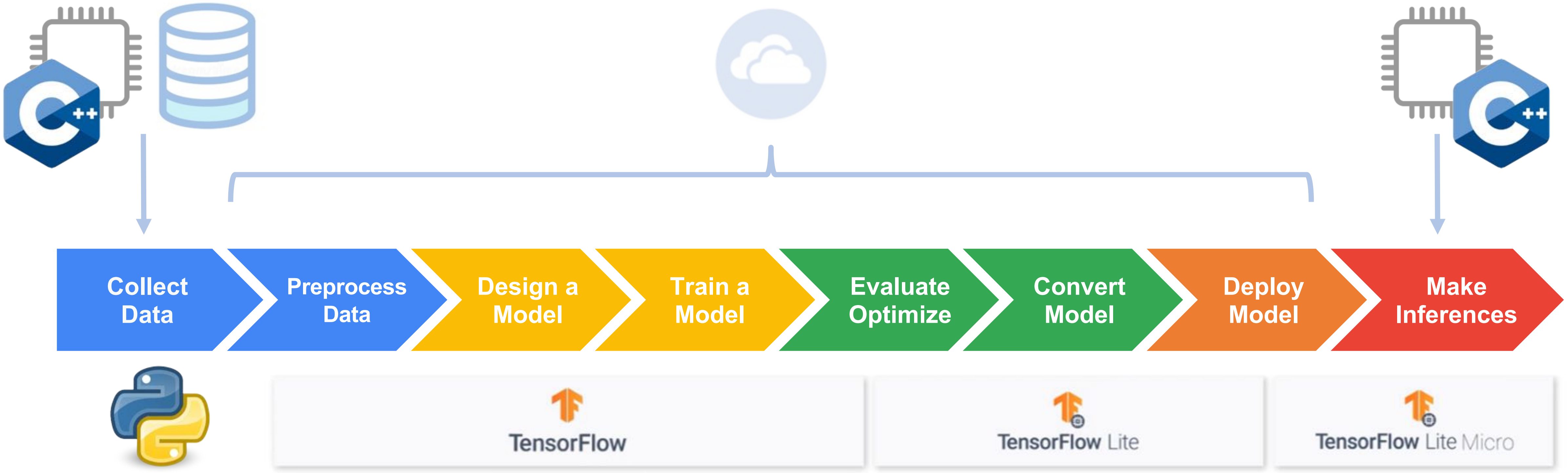
Machine Learning Workflow ("Where")



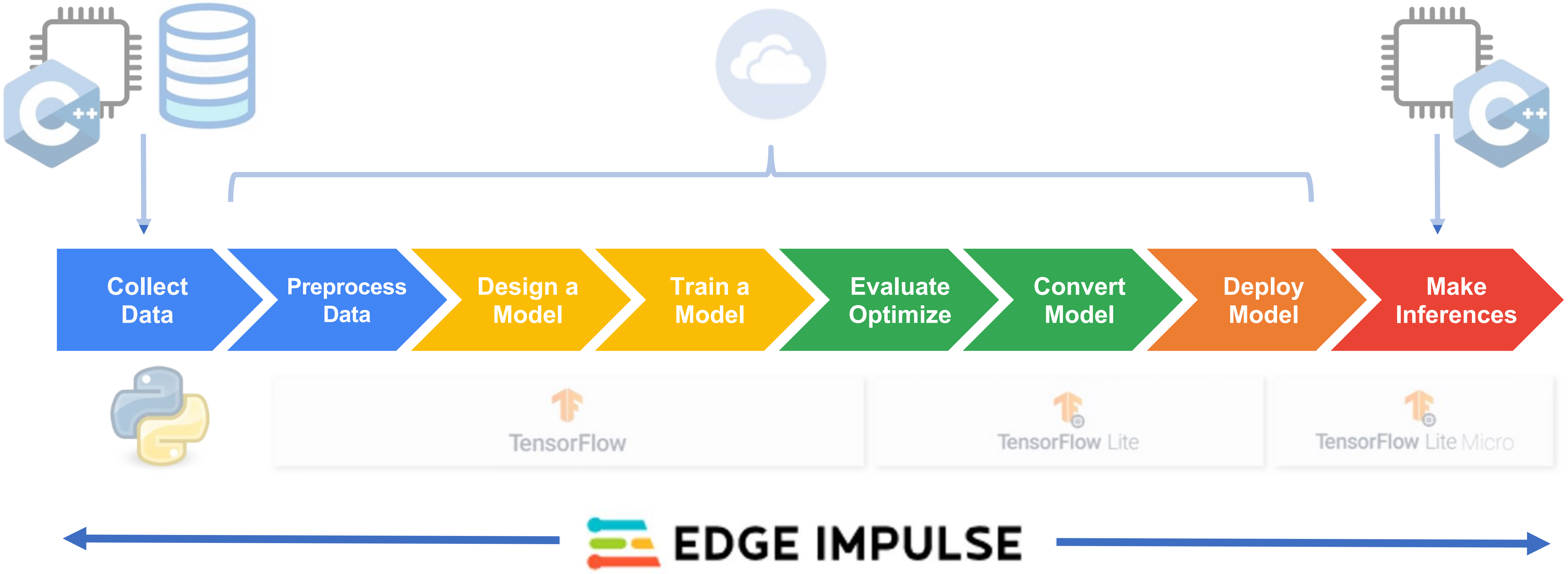
Machine Learning Workflow ("How")



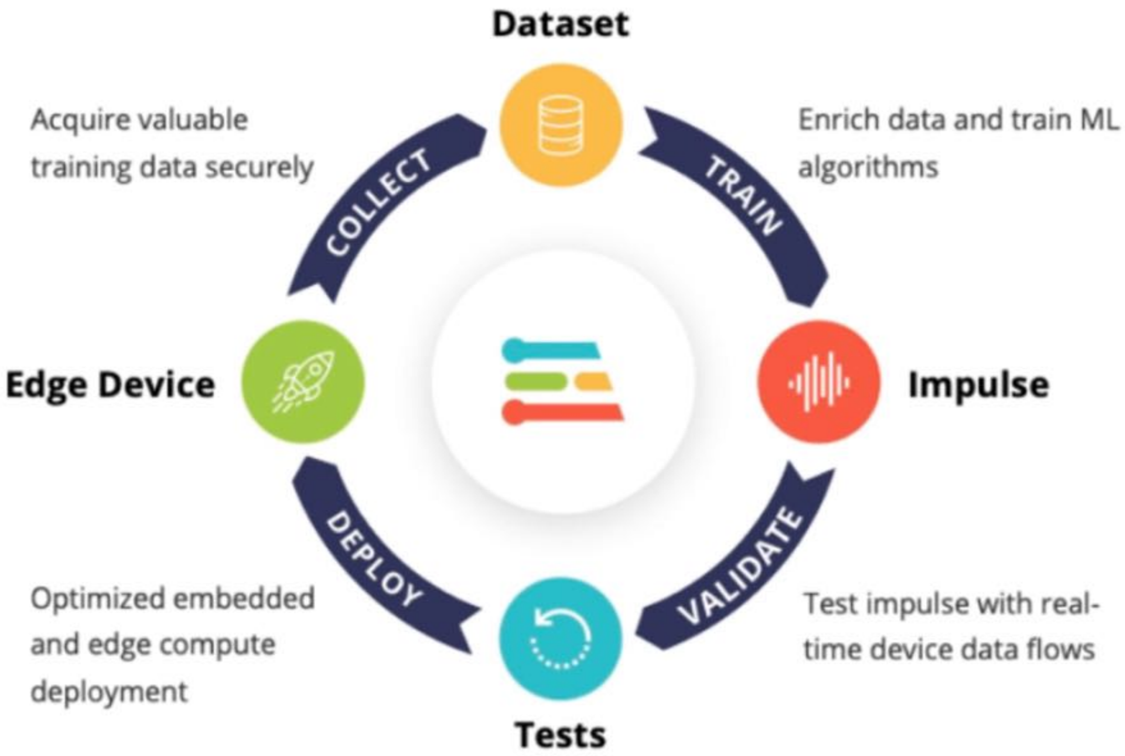
Machine Learning Workflow ("How")

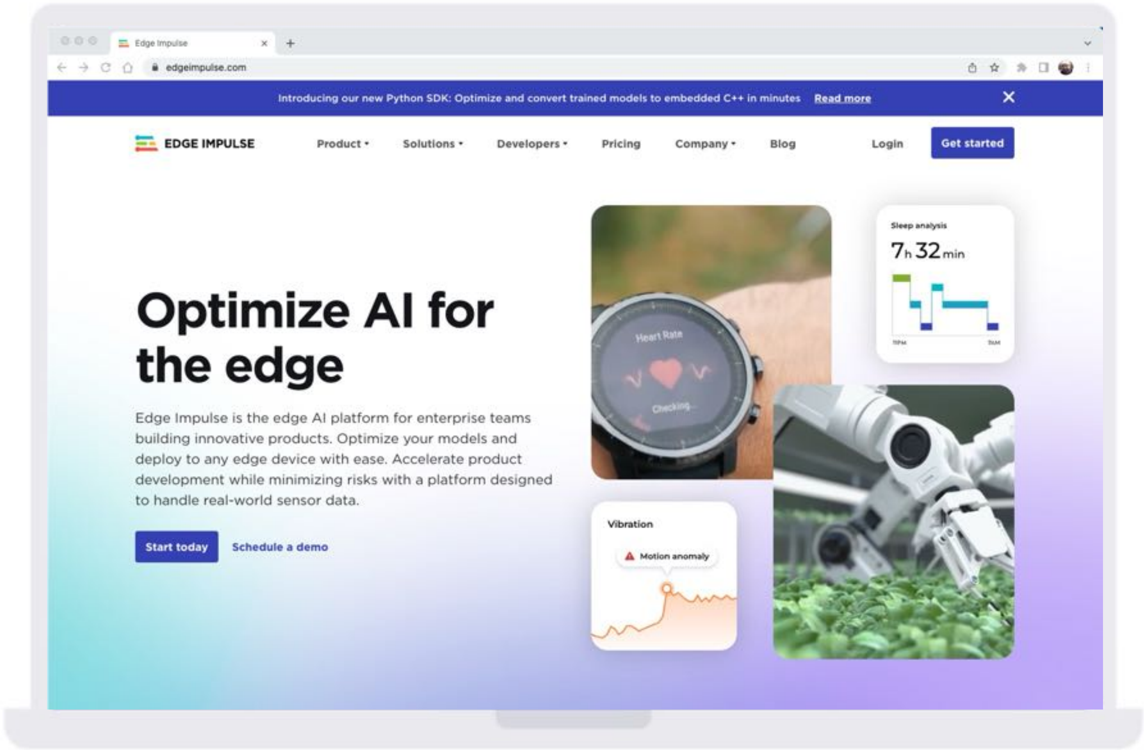


Machine Learning Workflow ("How")



EI Studio - Embedded ML platform ("AutoML")



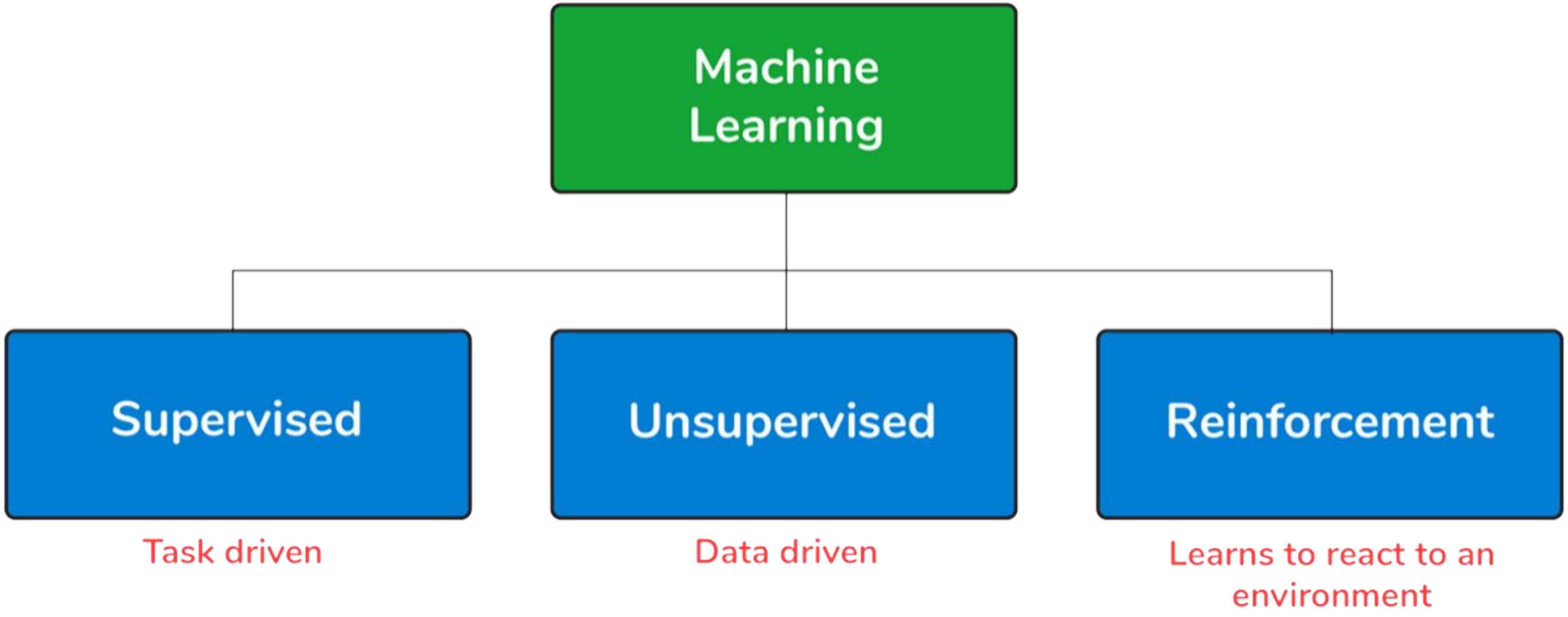


Learn more at http://edgeimpulse.com

[2023 SciTinyML Workshop - Edge Impulse Overview by Shawn Hymel]

TinyML Applications

Examples



- Regression
- Classification
- Object Detection

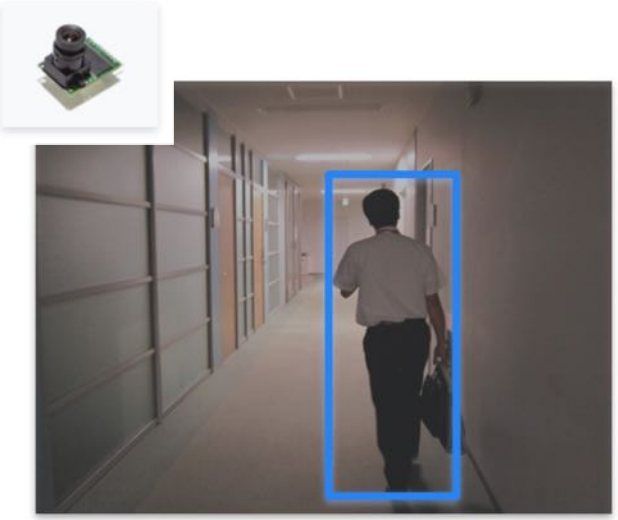
- Anomaly Detection

- Autonomous Navigation

Sound

Vibration

Vision



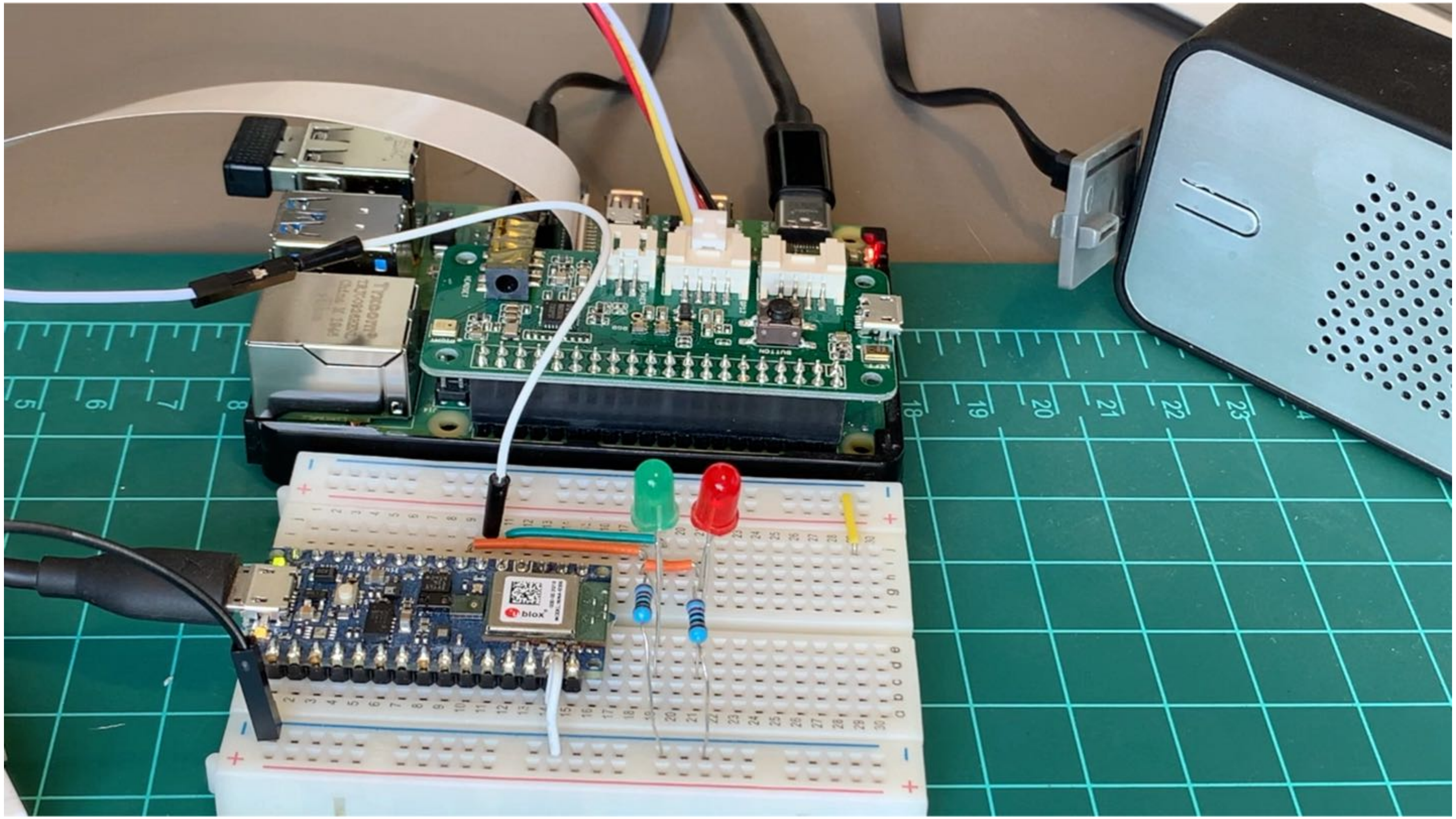
Sound

Vibration

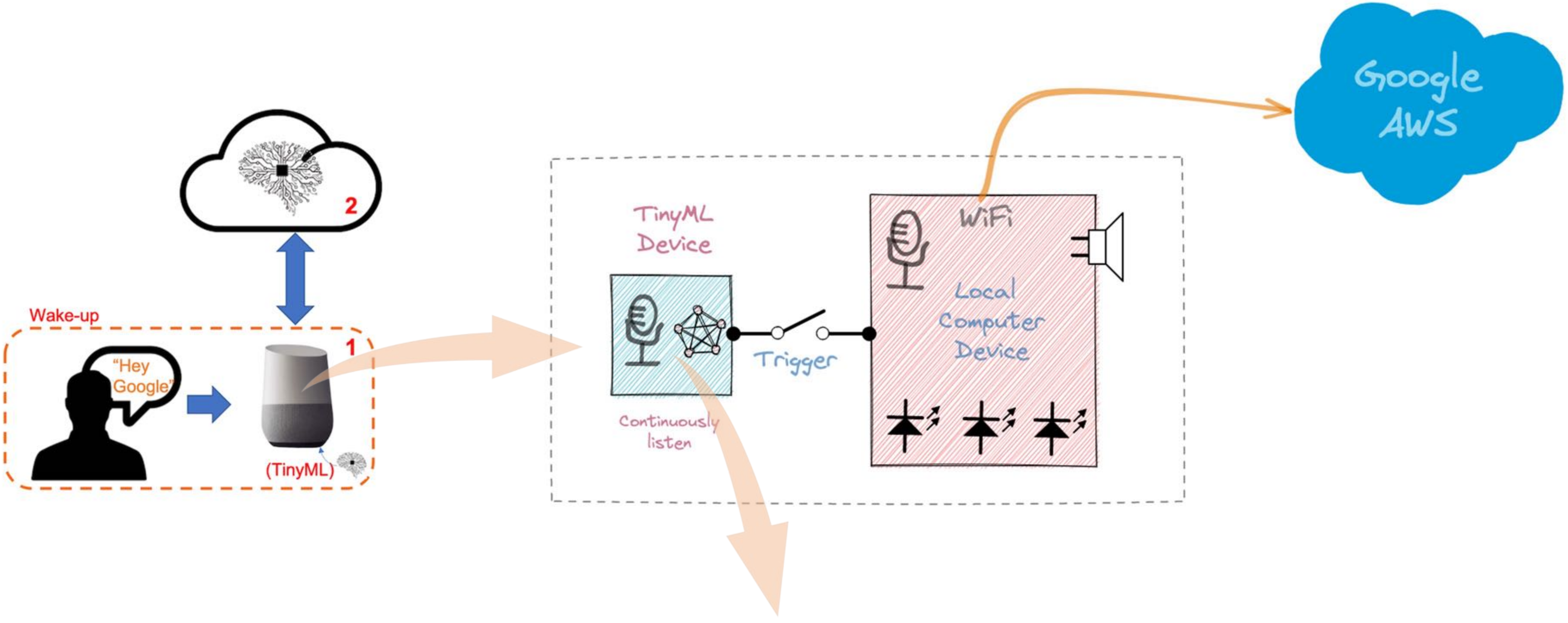
Vision

Personal Assistant

Personal Assistant

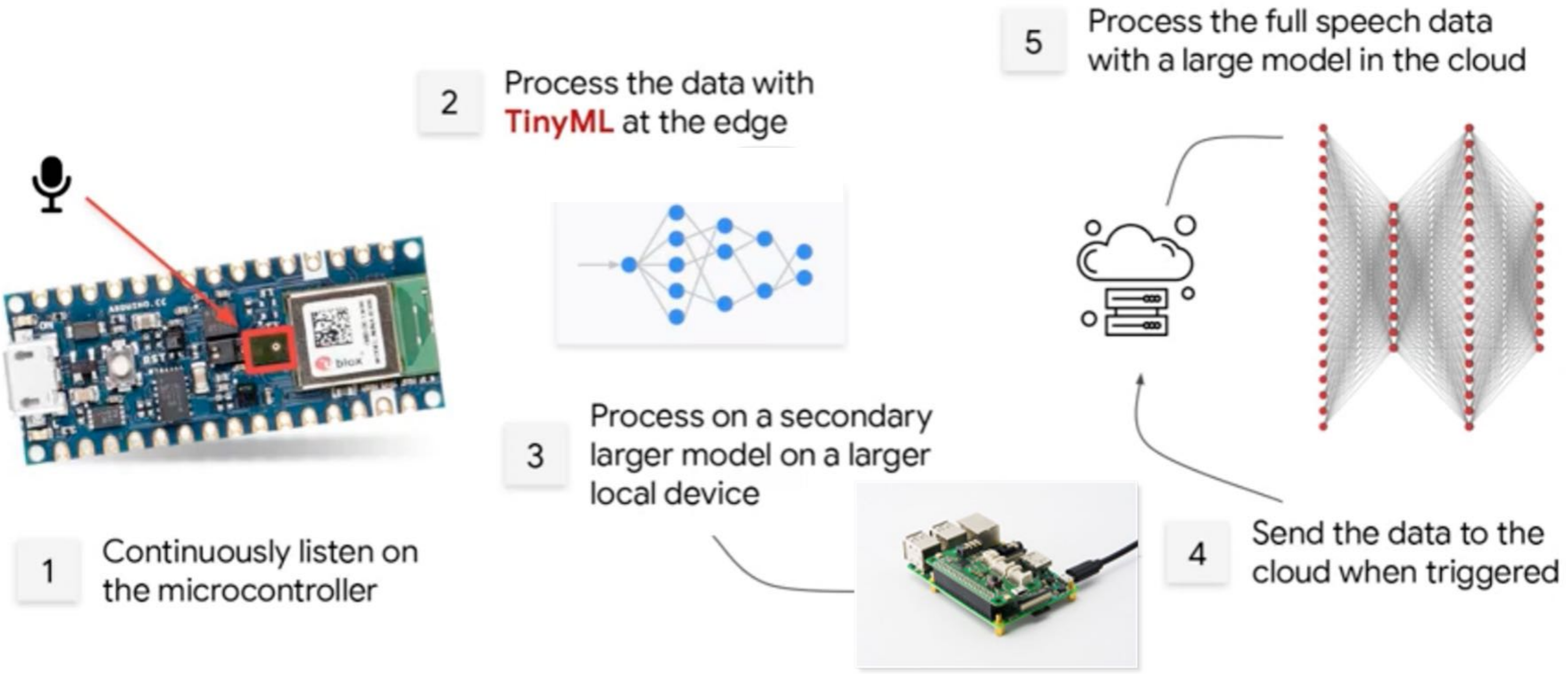


Personal Assistant

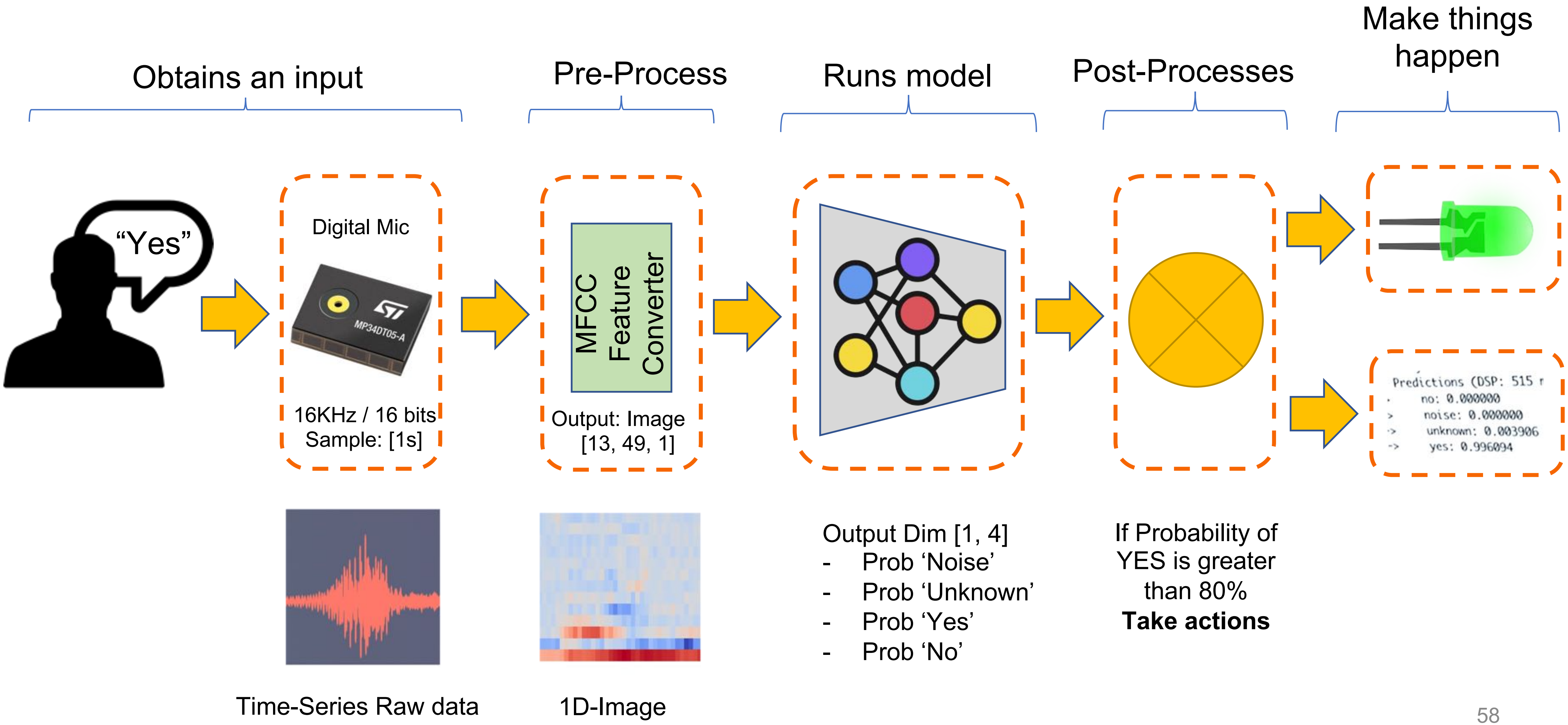


KWS

“Cascade” Detection: multi-stage model



KeyWord Spotting (KWS) - Inference



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

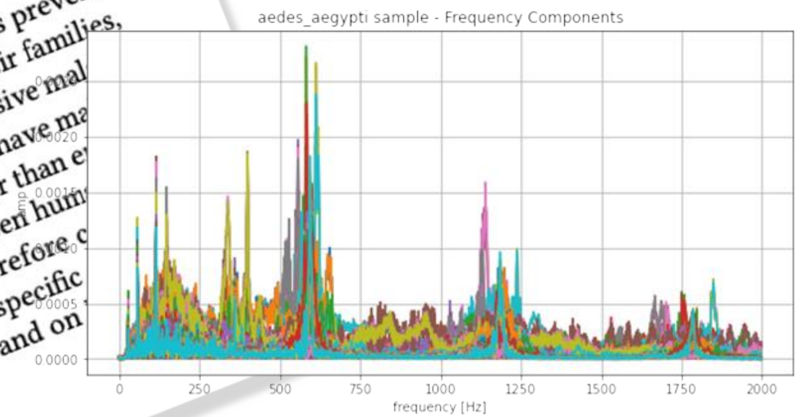
ABSTRACT

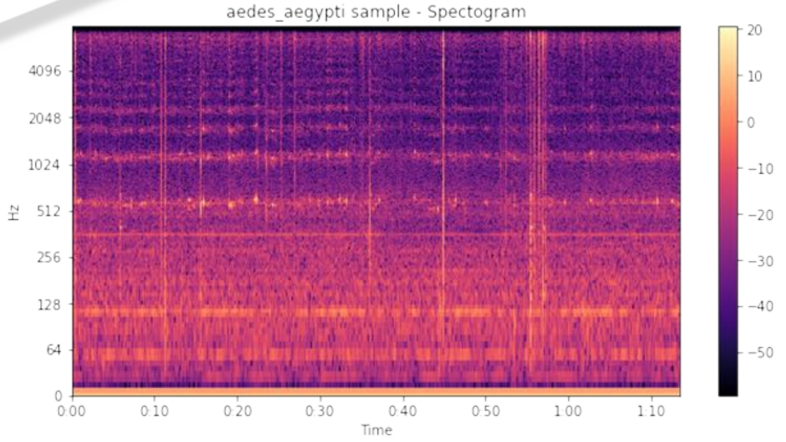
Every year more than one billion people are infected and more than one million people die from vector-borne diseases including malaria, dengue, zika and chikungunya. Mosquitoes are the best known disease vector and are geographically spread worldwide. It is important to raise awareness of mosquito proliferation 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

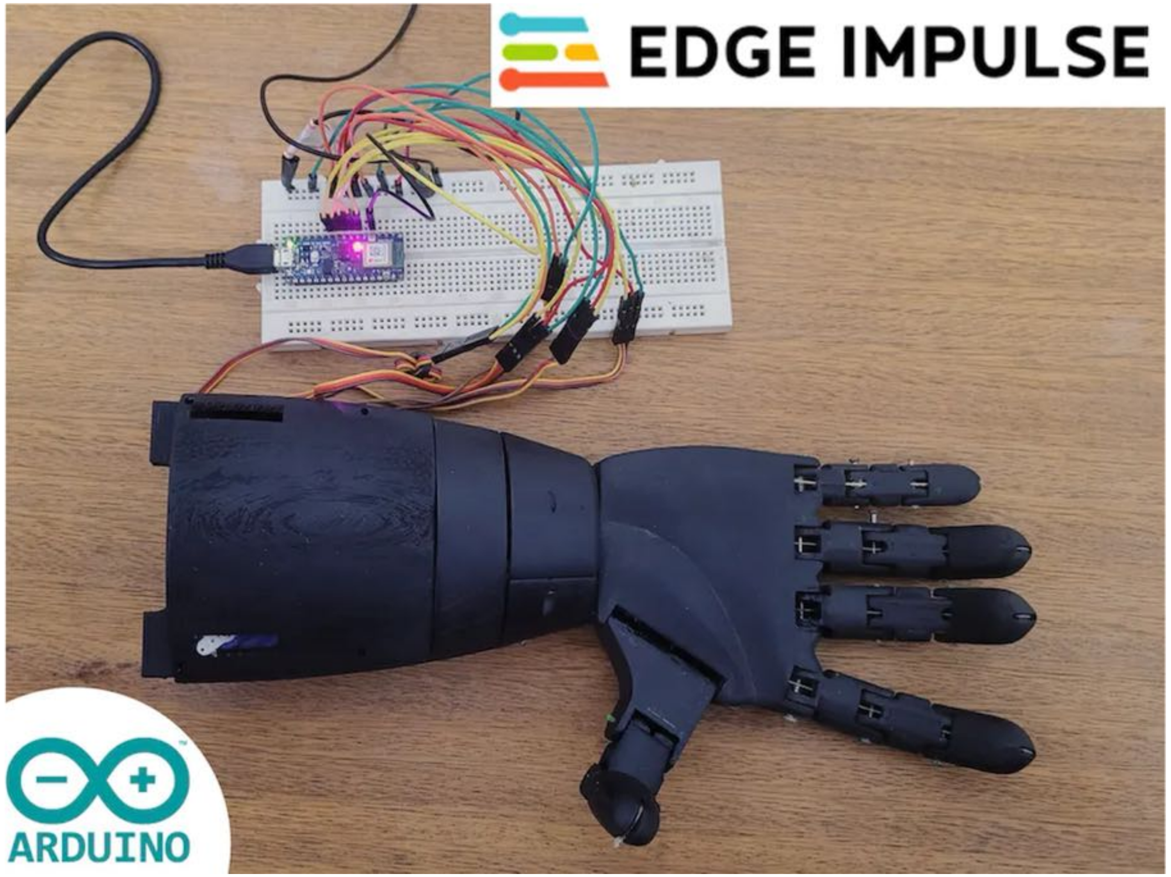
Countries affected by malaria turn to control rather than e tion. Vector control means decreasing contact between hum disease carriers on an area-by-area basis. It is therefore c be able to detect the presence of mosquitoes in a specific paper presents an approach based on TinyML and on embedded devices.





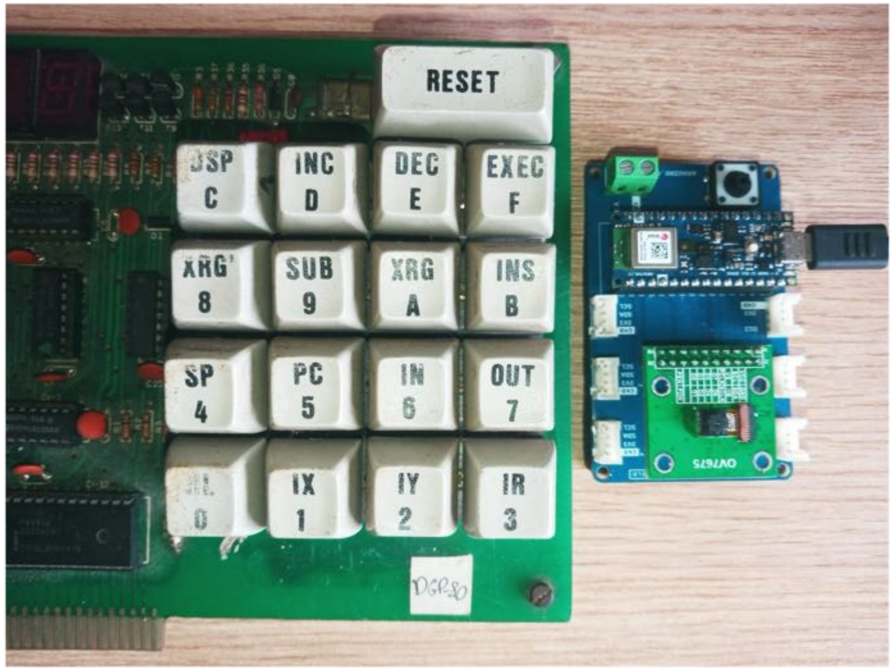
https://www.edgeimpulse.com/blog/the-world-is-all-abuzz-about-tinyml

Bionic Hand Voice Commands Module

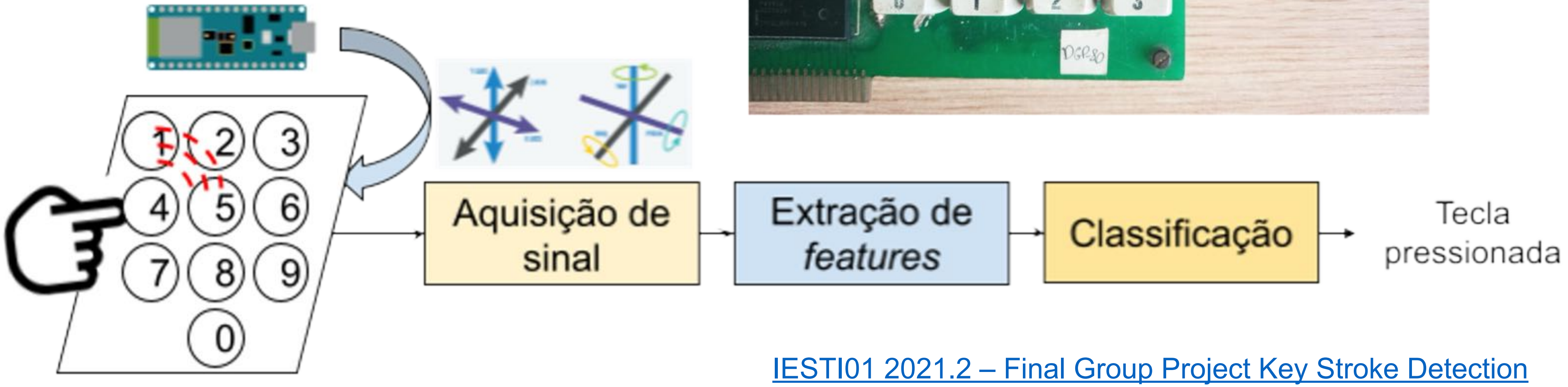


https://www.hackster.io/ex-machina/bionic-hand-voice-commands-module-w-edge-impulse-arduino-aa97e3

Keystroke **Sound** Detection



Renam Castro
Professor IFESP



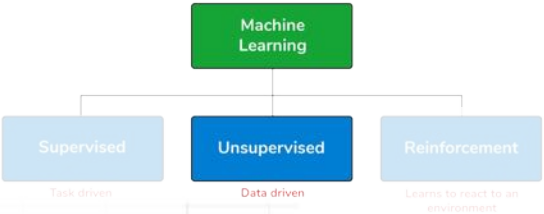
[IESTI01 2021.2 – Final Group Project Key Stroke Detection]

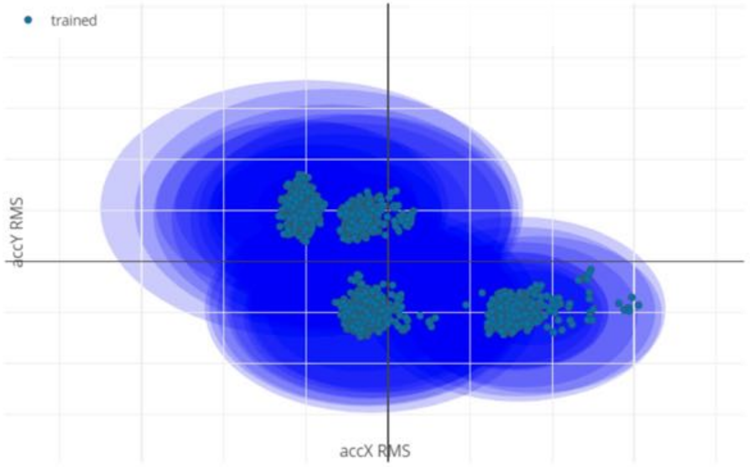
Sound

Vibration

Vision

Industrial – Anomaly Detection



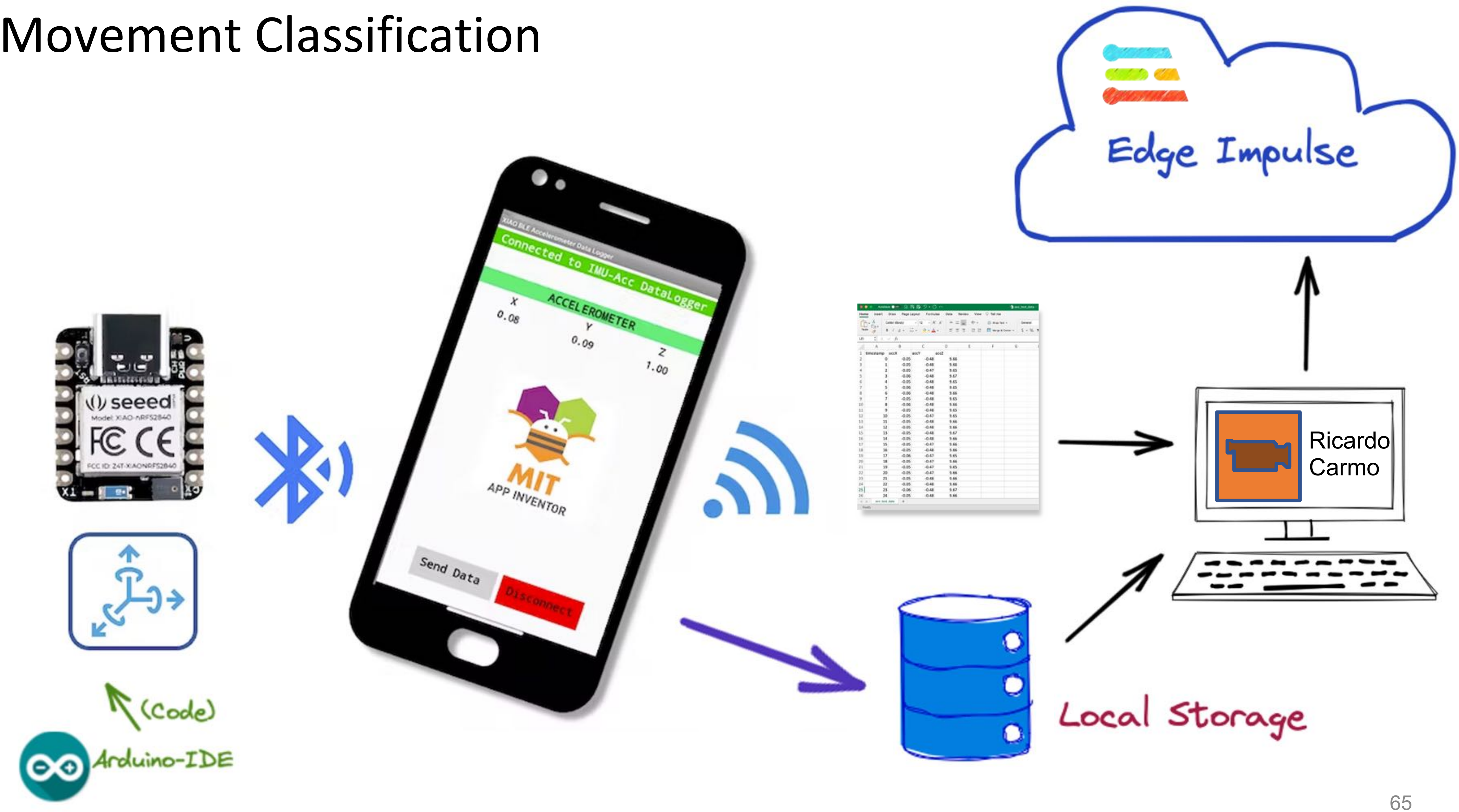


[IESTI01 2021.2 - Final Group Project: Bearing Failure Detection]

Movement Classification

CNPq UNIFEI

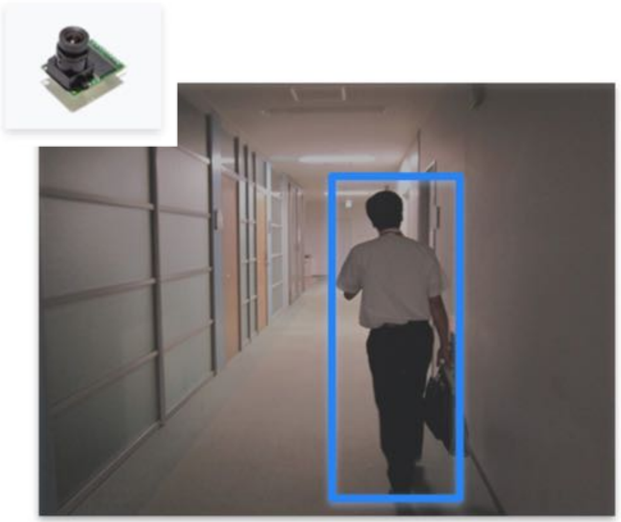
Movement Classification



Sound

Vibration

Vision



Computer Vision Main Types

Image Classification

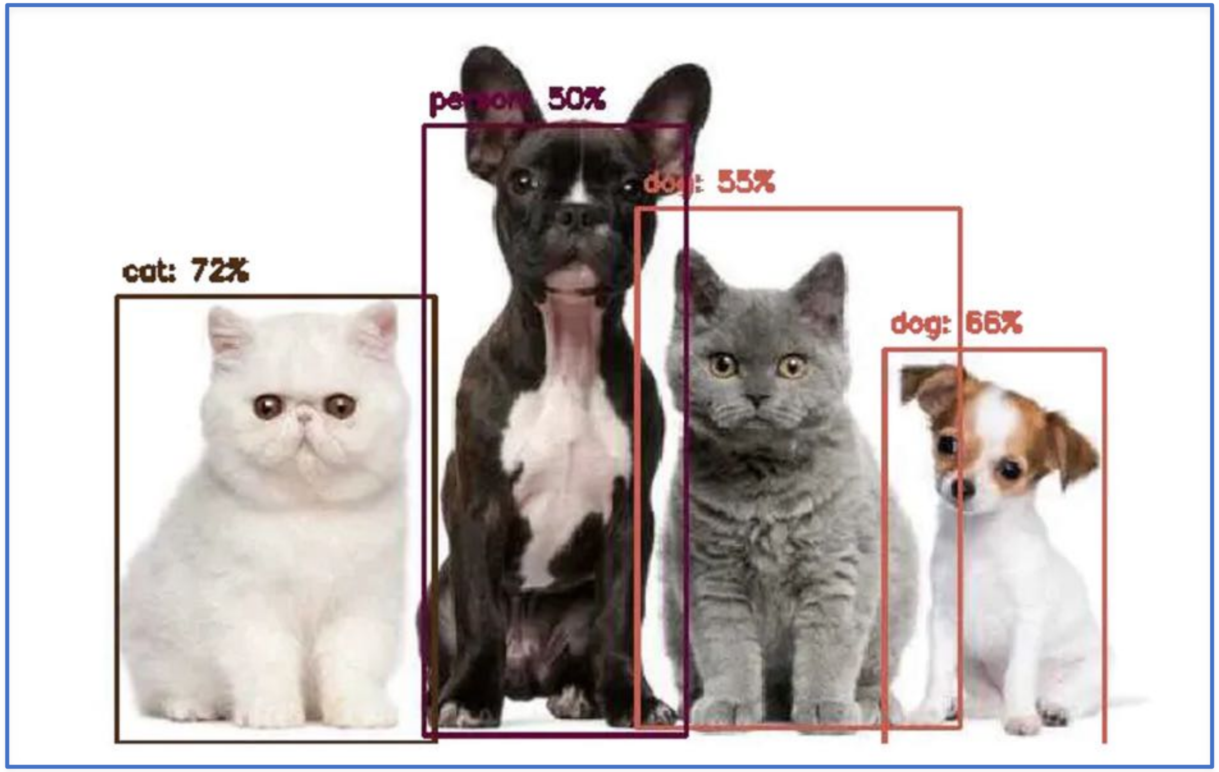
(**Multi-Class** Classification)

Cat: 70%

Dog: 80%

Object Detection

Multi-Label Classification + Object **Localization**



Computer Vision Main Types

Image Classification

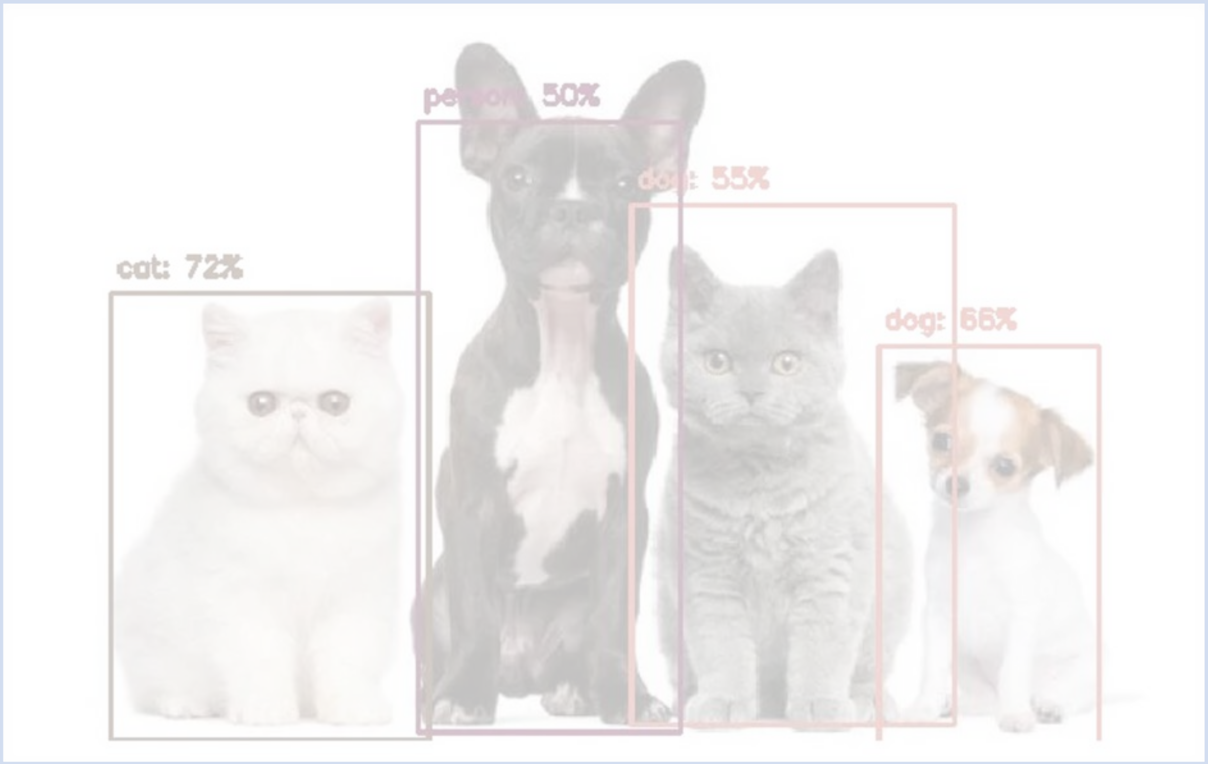
(**Multi-Class** Classification)

Cat: 70%

Dog: 80%

Object Detection

Multi-Label Classification + Object **Localization**



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

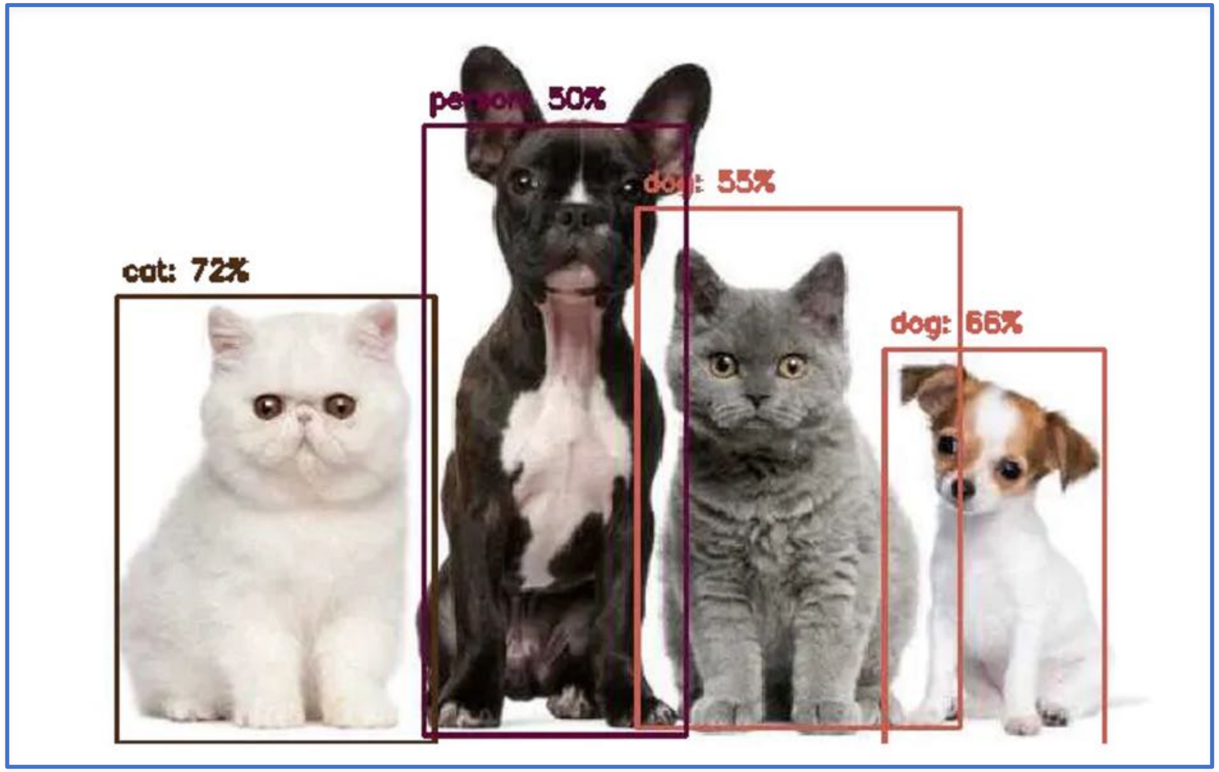
(**Multi-Class** Classification)

Cat: 70%

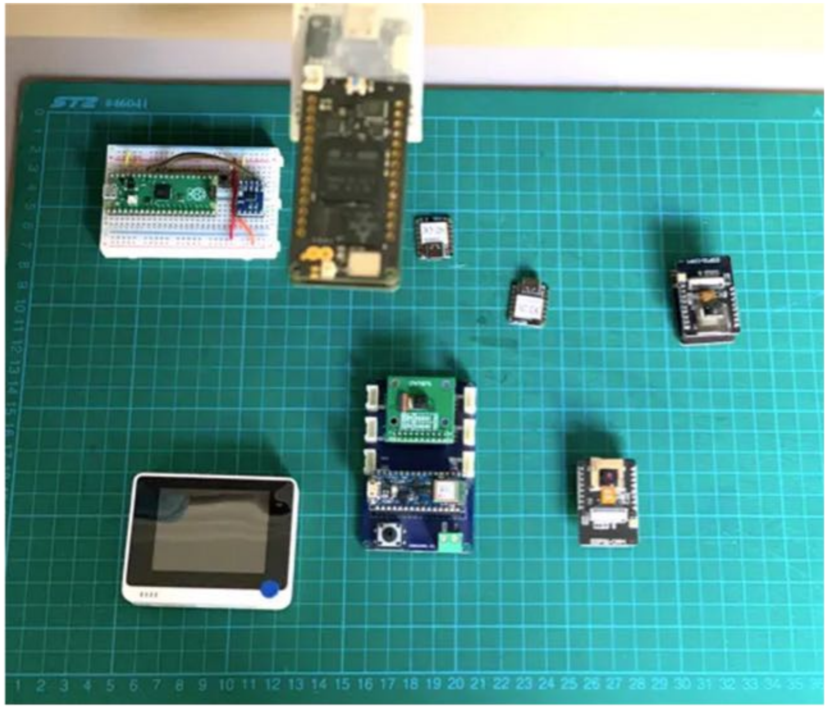
Dog: 80%

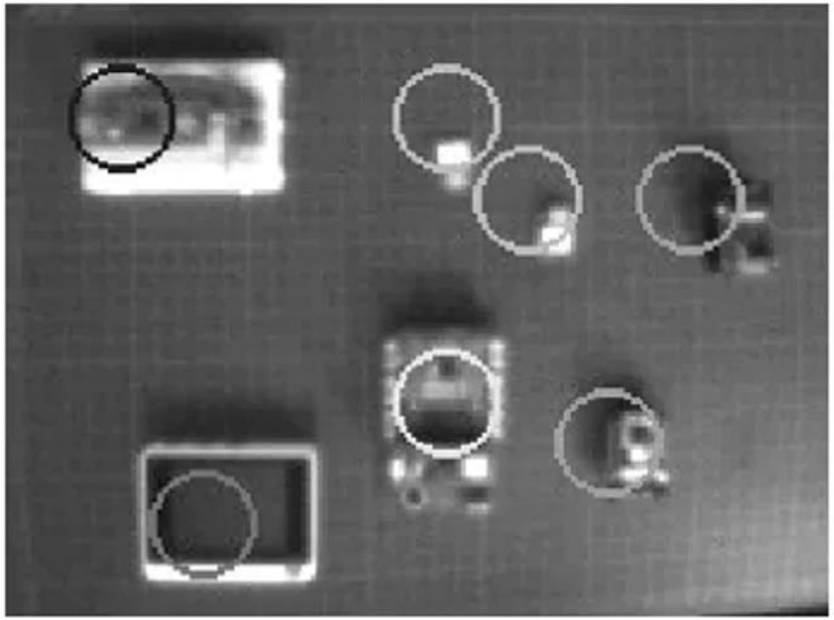
Object Detection

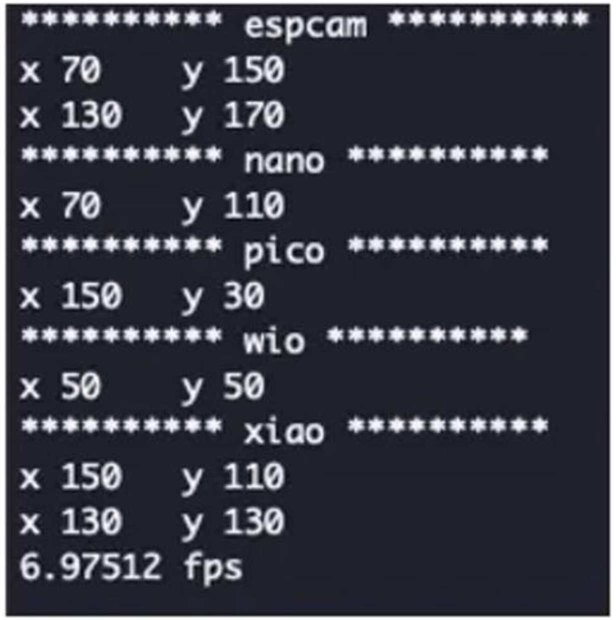
Multi-Label Classification + Object **Localization**



Detecting Objects using TinyML (FOMO)

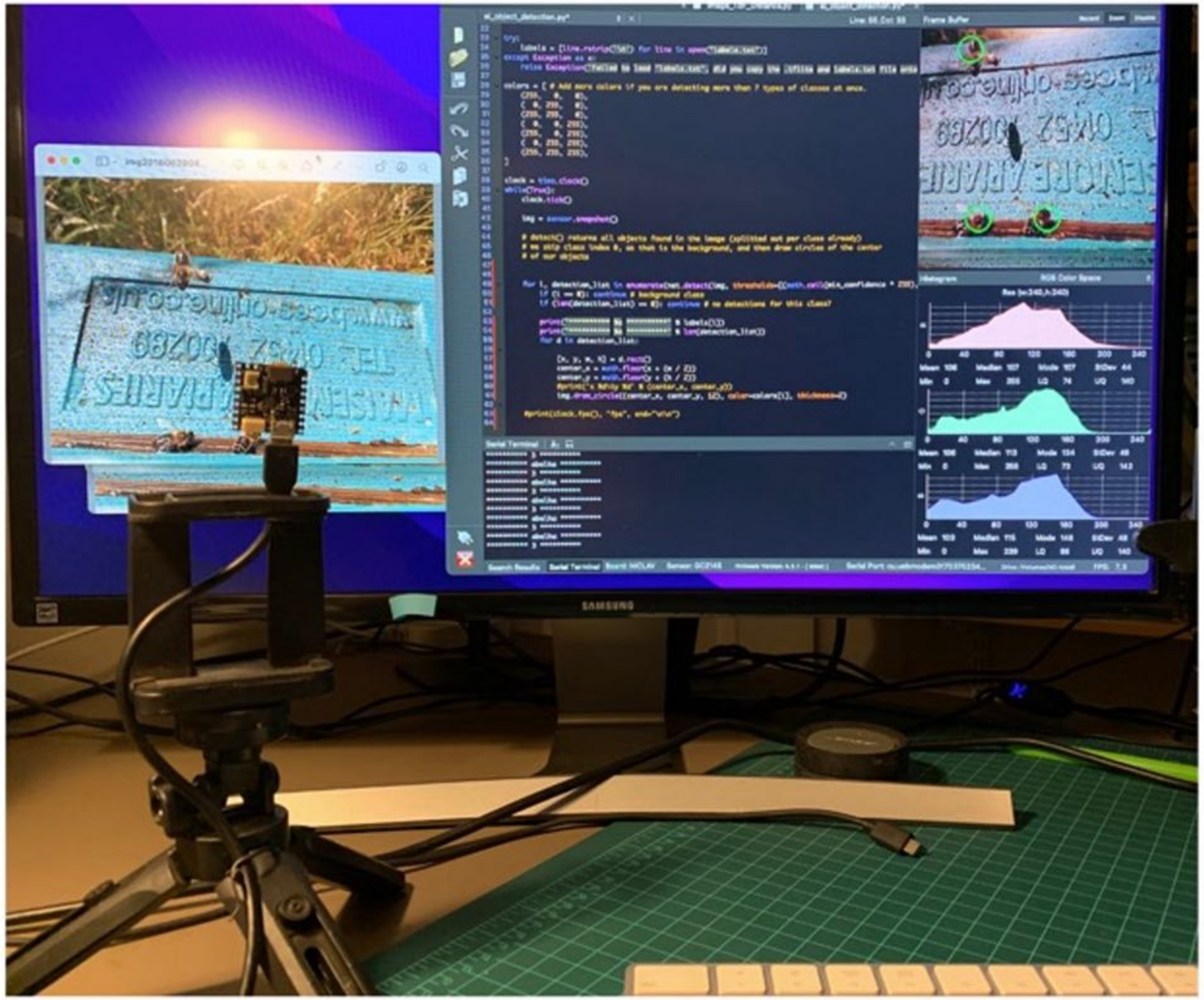






[EdgeAI made simple - Exploring Image Processing (Object Detection) on microcontrollers with Arduino Portenta, Edge Impulse FOMO, and OpenMV]

Detecting Objects using TinyML (FOMO)

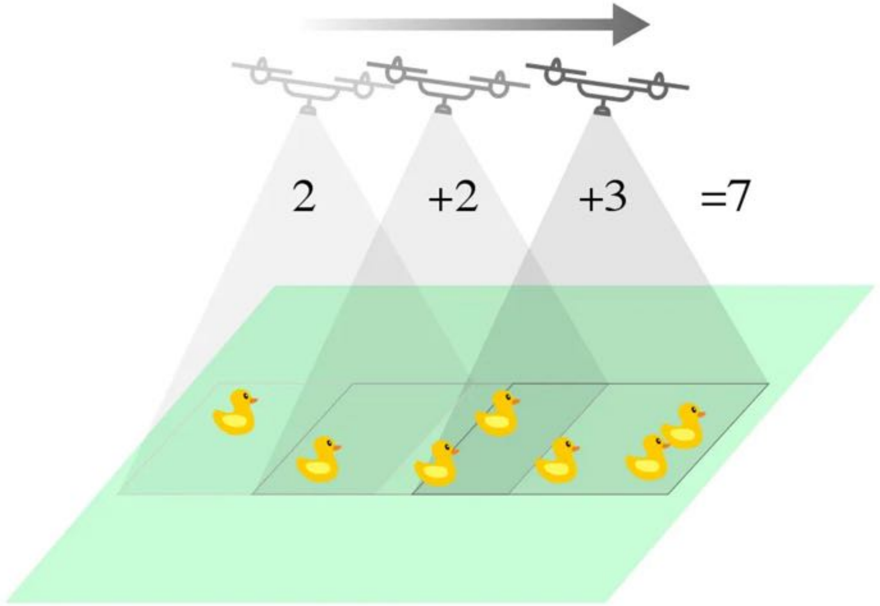


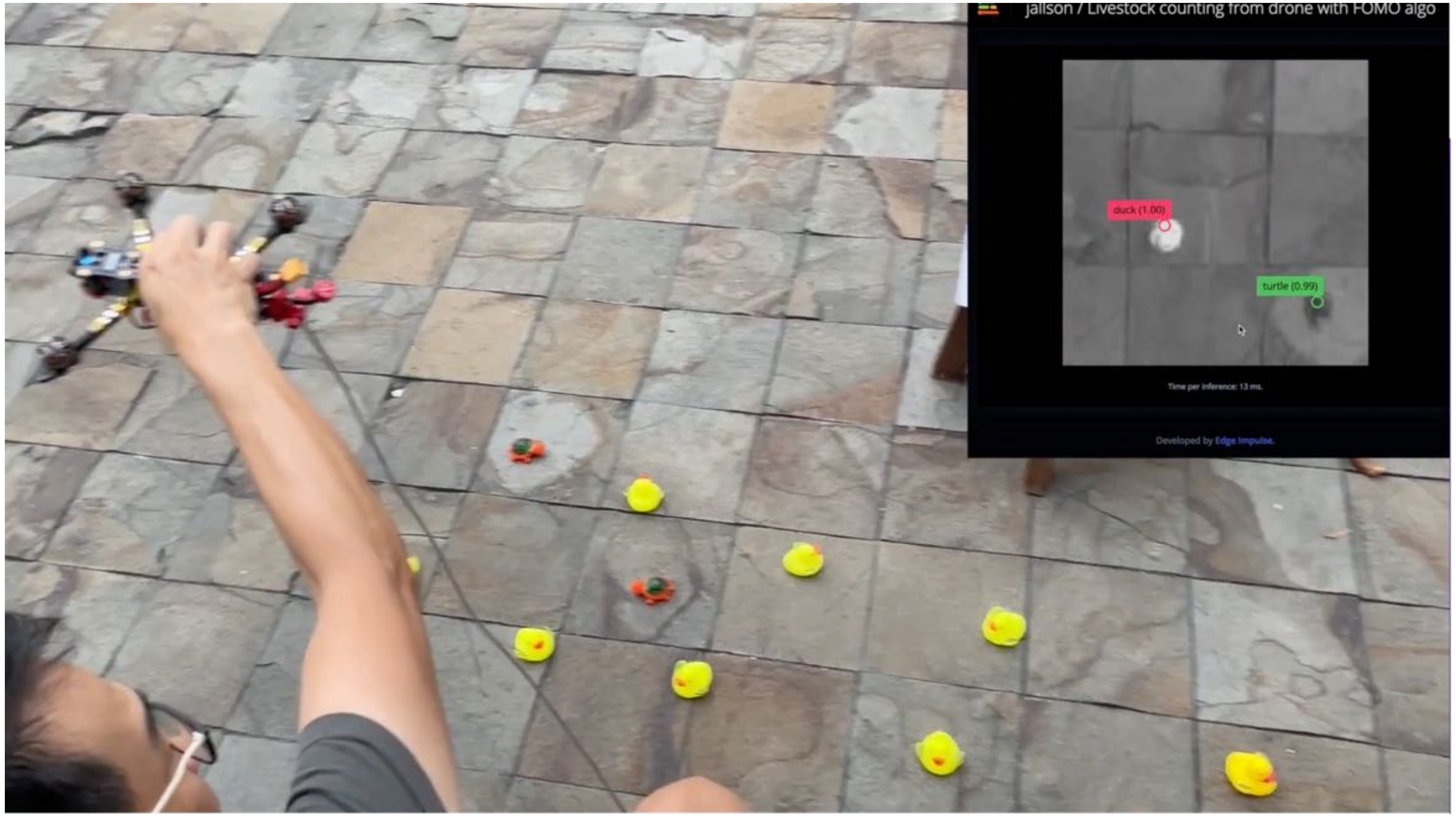
OpenMV

MicroPython

EDGE IMPULSE

Livestock / Wildlife Counting from Drone with FOMO





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

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]

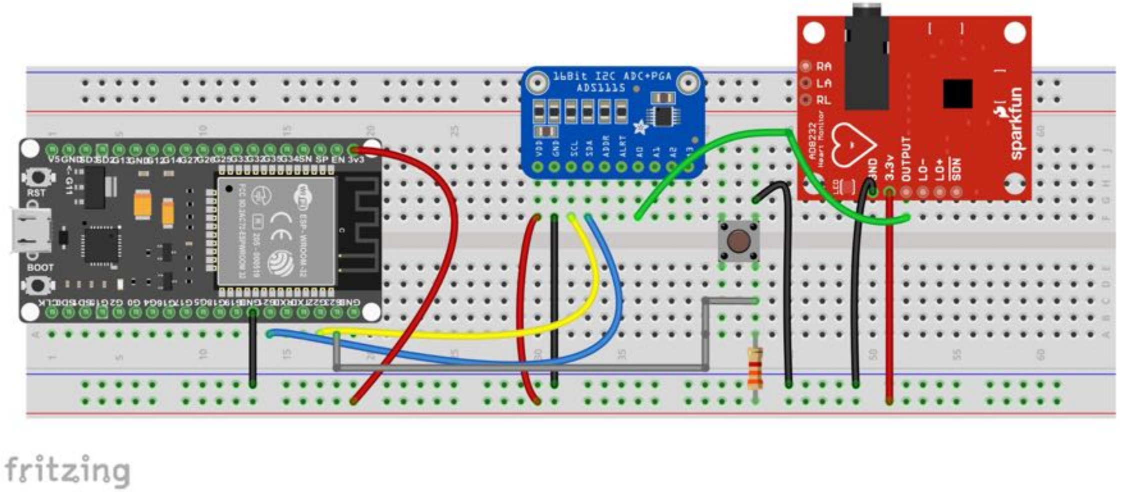
Vibration

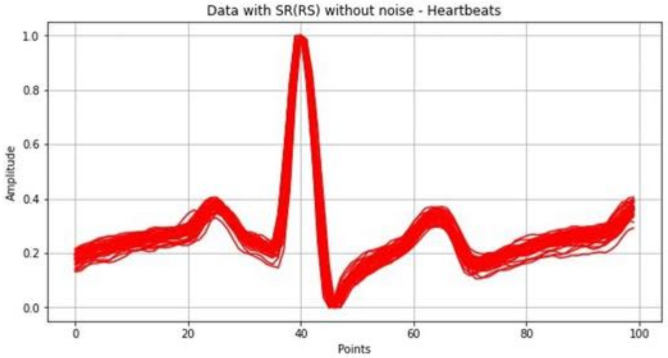
- Motion Recognition with RPi Pico [Doc]
- Gesture Recognition with Wio Terminal [Doc]
- Anomaly Detection with XIAO BLE Sense [Doc]

Other Sensors / MCUs / Models

Examples

AD8232 - Single Lead Heart Rate Monitor

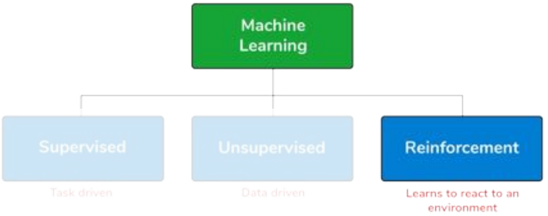




Guilherme Silva
Engenheiro - UNIFEI

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

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

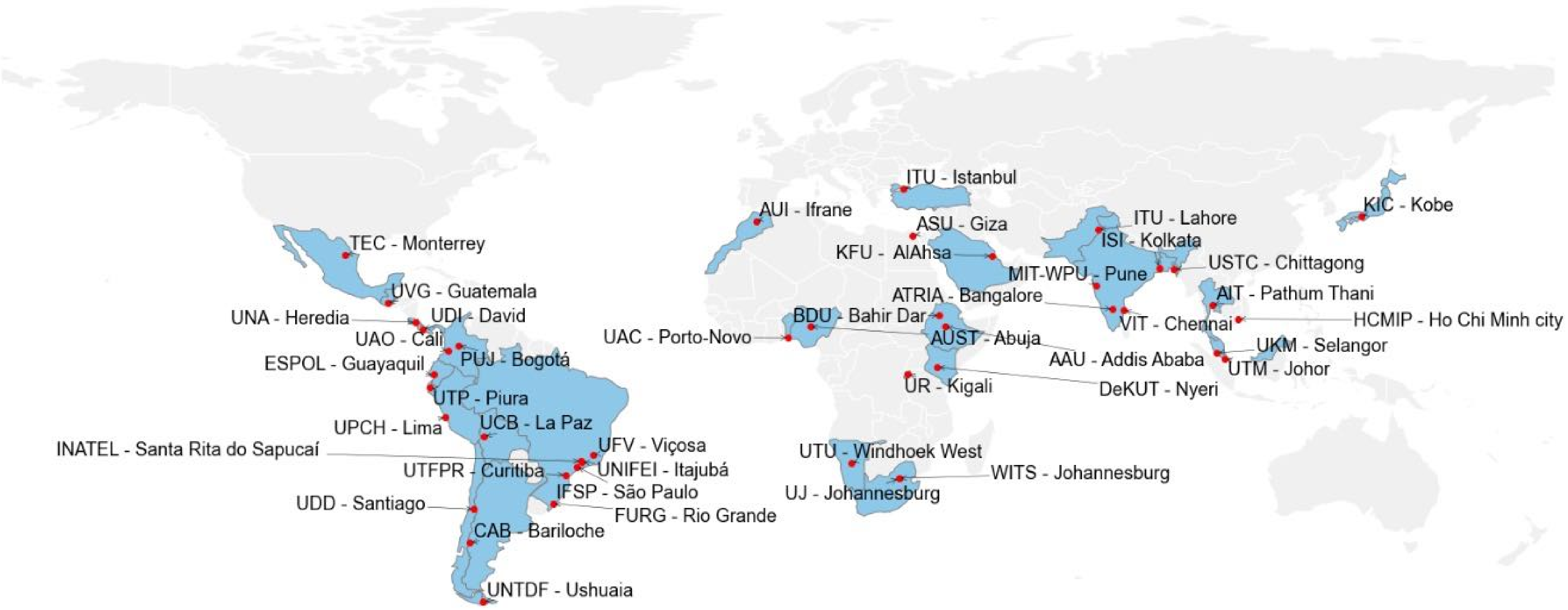
https://arxiv.org/abs/1909.11236

https://youtu.be/wmVKbX7MOnU

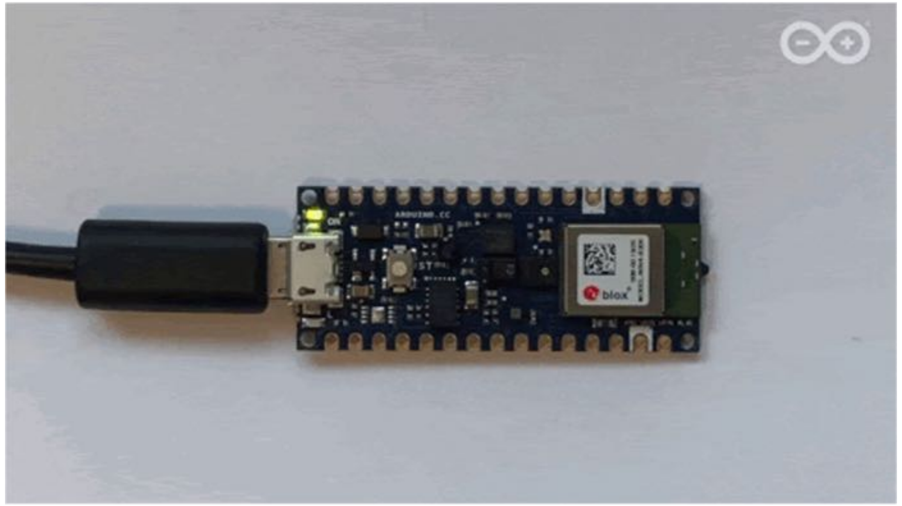
TinyML Academic Network

Widening access to applied machine learning by establishing best practices in education.

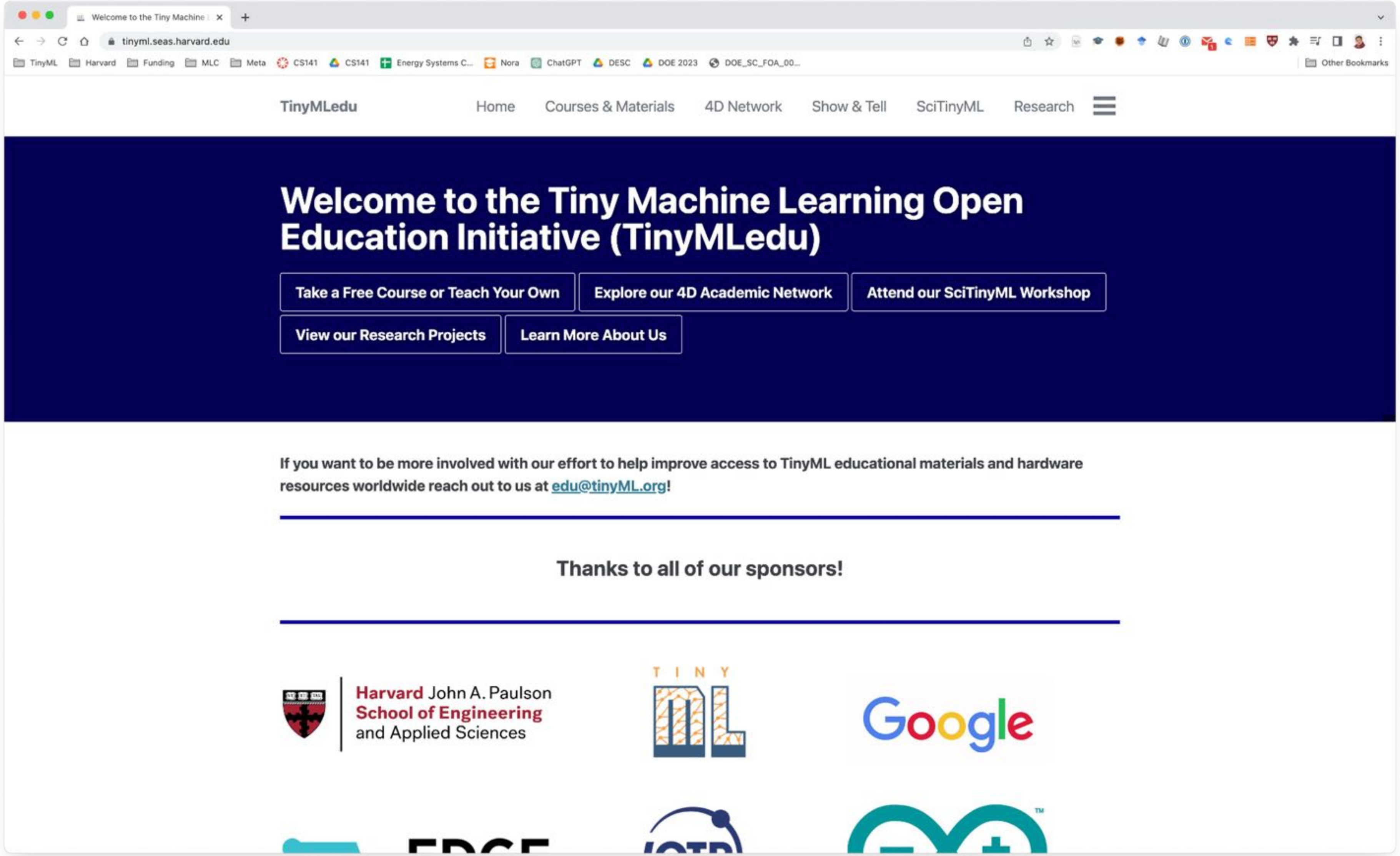
TinyML4D Academic Network - March 2023



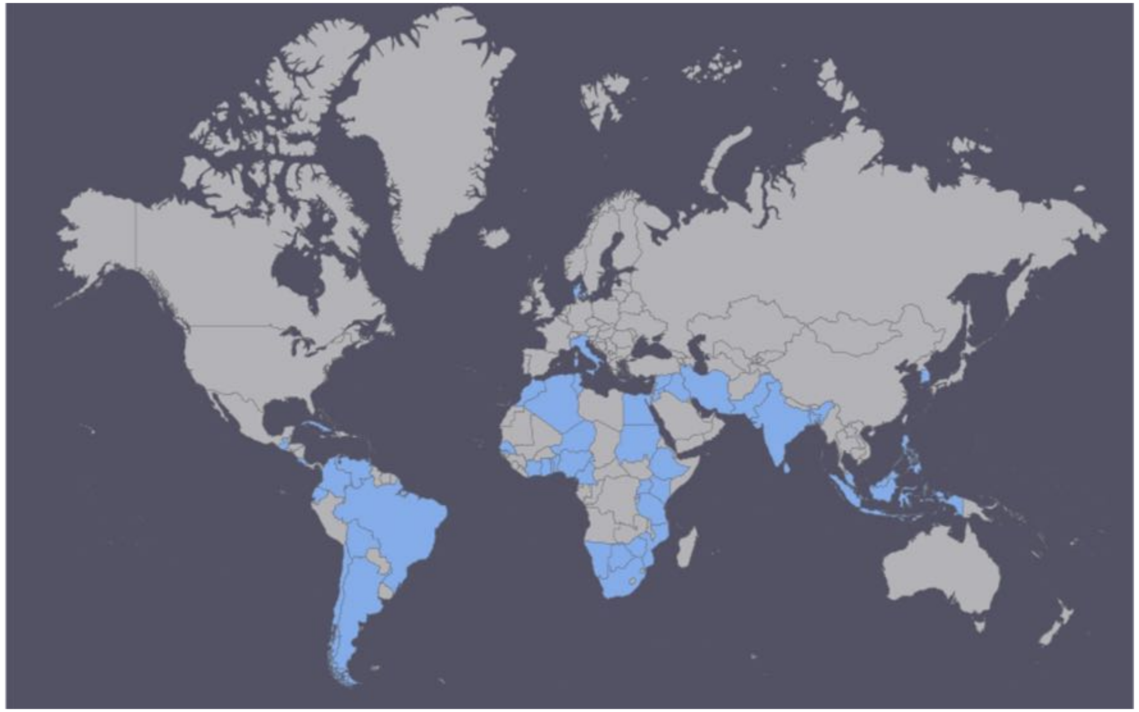

TINY MACHINE
LEARNING KIT
ARDUINO
in partnership with:
edX
TensorFlow
OV7675



tinymledu.org



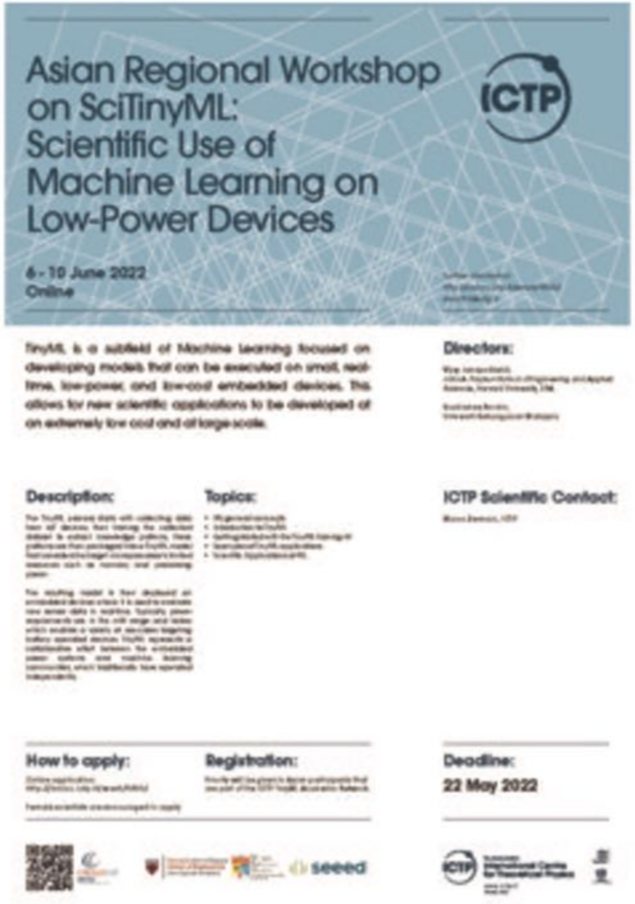
2021 activities



210 participants from 48 countries

2022 activities

187 participants
29 African countries



100 participants
8 Asian countries

183 participants
17 LatAm countries

April 2023 ICTP virtual workshop

Workshop on Scientific Use of Machine Learning on Low-Power Devices: Applications and Advanced Topics

ICTP

17 - 21 April 2023
An ICTP Virtual Meeting
Trieste, Italy

Further information:
http://indico.ictp.it/event/10166/
smr3832@ictp.it

TinyML is a subfield of Machine Learning focused on developing models that can be executed on small, real-time, low-power, and low-cost embedded devices. This allows for new scientific applications to be developed at an extremely low cost and at large scale.

Directors:
B. PLANCHER, Barnard College, USA
V. J. REDDI, Harvard University, USA
M. ROVAI, Federal University of Itajubá, Brazil

Description:
TinyML represents a collaborative effort between the embedded power systems and Machine Learning communities, which traditionally have operated independently.

TinyML has a significant role to play in achieving the SDGs and facilitating scientific research in areas such as environmental monitoring, physics of complex systems and energy management.

The TinyML process starts with collecting data from IoT devices, then training the collected dataset to extract knowledge patterns; these patterns are then packaged into a TinyML model that considers the target microprocessor's limited resources such as memory, processing power, and energy.

Through hands-on examples, this workshop will focus on both introductory and advanced topics in TinyML to pave the way to the development of real-world applications.

Topics:
- Introduction to TinyML
- Getting Started with the TinyML Kit
- Examples of TinyML Applications
- The TinyML Development Workflow
- Scientific Applications of ML
- Recent Research and Advanced Topics in TinyML

Local Organiser:
M. ZENNARO, ICTP, Italy

How to apply:
Online application:
http://indico.ictp.it/event/10166/

Female scientists are encouraged to apply.

Registration:
There is no registration fee.

Deadline:
7 April 2023

BARNARD
Harvard John A. Paulson School of Engineering and Applied Sciences
UNIFEI
ICTP International Centre for Theoretical Physics
www.ictp.it

SciTinyML

Scientific Use of Machine Learning on Low-Power Devices

TinyMLedu

Home
Schedule April 17-21
Call for Show and Tell Talks
Team

Updated: 2/23
by @plancherb1

Day	Date	Topics	Speakers and Materials
Day 1	Monday	**Introduction to (tiny)ML** *10:00 AM* Workshop Opening and Schedule *10:30 AM* Keynote *11:15 AM* Introduction to Machine Learning *12:15 PM* Introduction to Embedded ML *12:55 PM* Day Closing	Marco Zennaro of ICTP Diego Mendez Chaves of Pontificia Universidad Javeriana Robert Thas John of Versus
Day 2	Tuesday	**Hands-on Introduction to TinyML** *10:00 AM* Day Opening *10:05 AM* Edge Impulse Overview and New Features *10:40 AM* Hands-on Motion Classification and Anomaly Detection *12:10 PM* AI Ethics: Avoiding Bias *12:55 PM* Day Closing	Marco Zennaro of ICTP Shawn Hymel of Edge Impulse José Antonio Bagur Nájera of Universidad del Valle de Guatemala Viola Schiaffonati and Manuel Roveri of Politecnico di Milano
Day 3	Wednesday	**Expanding Your Options and Devices** *10:00 AM* Day Opening *10:05 AM* Leveraging Other Microcontrollers and Sensors *11:00 AM* WebUSB and FOMO *11:30 AM* Adding IoT to a Project with Blues Wireless *11:55 AM* Industry 5.0 with Jetson Nano *12:25 PM* MLOps: Scaling Deployments *12:55 PM* Day Closing	Marco Zennaro of ICTP Marcelo Rovai of Federal University of Itajuba - UNIFEI Jeremy Ellis of School District 75 Mission Peter Ing of TFG (The Foschini Group) Marcelo Pias of Federal University of Rio Grande - FURG Colby Banbury of Harvard University
Day 4	Thursday	**TinyML Show and Tell** *10:00 AM* Day Opening *10:05 AM* Selected Show and Tell Talks *12:55 PM* Day Closing	Brian Plancher of Barnard College, Columbia University
Day 5	Friday	**Advanced Scientific TinyML** *10:00 AM* Day Opening *10:05 AM* Scientific Applications of TinyML 1 *10:50 AM* TinyML and Sustainability *11:20 AM* TinyML and Robotics *11:50 AM* Scientific Applications of TinyML 2 *12:55 PM* Workshop Closing and Future Events	Marco Zennaro of ICTP Matthew Stewart of Harvard University Bardienus Duisterhof of Carnegie Mellon University - CMU

Local/Relevant Applications

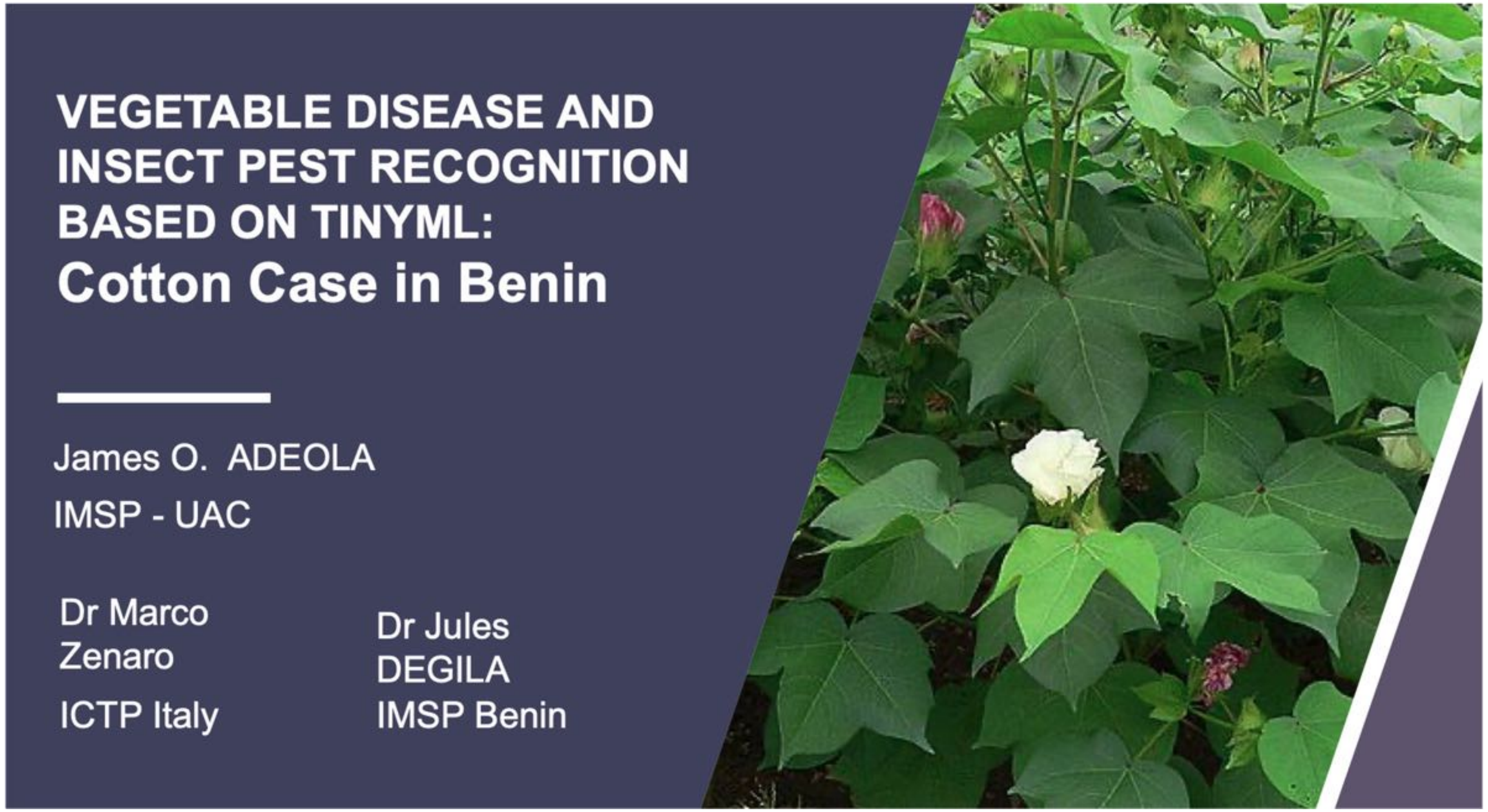
Timothy Kudzanayi Kuhamba

Thanx Marisa[a*], Munyaradzi Munochiveyi[a*], Wadzanai Julius Zondai[a*], Ramson Munyaradzi Nyamukondiwa[a] , Isheanesu Newengo[b]

Case Study Zimbabwe

A DEEP LEARNING BASED APPROACH FOR FOOT AND MOUTH DISEASE DETECTION

Local/Relevant Applications

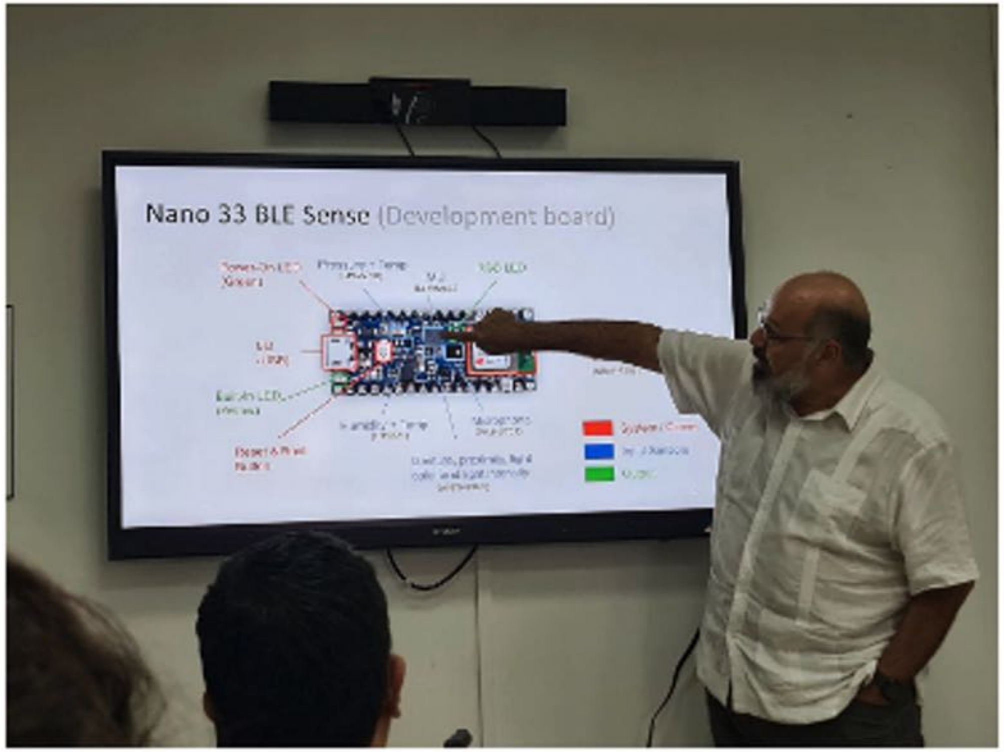


Local/Relevant Applications

Outreach activities

Solomon from Ethiopia

Marcelo Rovai at WALC 22 - UdI, Panama



- 5 days Workshop
- 46 remote and 16 in site participants from Latin America

TinyML Academic Network @ UN 2022

Science-Policy Brief for the Multistakeholder Forum on Science, Technology and Innovation for the SDGs, May 2022

TinyML: Applied AI for Development

Marco Zennaro (ICTP/UNESCO), Brian Plancher (Harvard University), Vijay Janapa Reddi (Harvard University)

Abstract

Artificial intelligence (AI) will likely be an instrumental part of progress towards the United Nations' Sustainable Development Goals (SDGs). However, its adoption and impact are limited by the immense power consumption, strong connectivity requirements and high costs of cloud-based deployments. TinyML is a new technology that allows machine learning (ML) models to run on low-cost, low-power microcontrollers, circumventing many of these issues. We believe that TinyML has a significant role to play in achieving the SDGs and facilitating scientific research in areas such as environmental monitoring, physics of complex systems and energy management. To broaden access and participation and increase the impact of this new technology, we present an initiative that is creating and supporting a global network of academic institutions working on TinyML in developing countries. We suggest the development of additional open educational resources, South–South academic collaboration and pilot projects of at-scale TinyML solutions aimed at addressing the SDGs.

Challenges with Machine Learning in Developing Countries

Machine learning has a huge potential to tackle societal issues in diverse fields that include agriculture, conservation and healthcare. A recent study [1] highlights the influence of AI on all aspects of

main energy consumer component of an embedded system.

3. **Privacy:** Applications that send data from the point of collection to the cloud may leak private information as data must be transmitted over the internet.

TinyML Academic Network @ UN 2023

Bridging the Digital Divide: the Promising Impact of TinyML for Developing Countries

Marco Zennaro (ICTP/UNESCO), Brian Plancher (Barnard College, Columbia University), Vijay Janapa Reddi (Harvard University)

Abstract

The rise of TinyML has opened up new opportunities for the development of smart, low-power devices in resource-constrained environments. This technology has particular relevance for developing countries, where access to energy and computing resources is often limited. In light of this, a network of 40 universities has been established over the past two years with the goal of promoting the use of TinyML in developing regions. The members of this network have taught courses at their home institutions and have completed their first research projects covering topics ranging from the diagnosis of respiratory diseases in Rwanda to assistive technology development in Brazil, bee population monitoring in Kenya and estimating the lifespan of the date palm fruit in Saudi Arabia. These initial projects demonstrate the potential

Papers published

Mihigo, Irene Niyonambaza, et al. "On-Device IoT-Based Predictive Maintenance Analytics Model: Comparing TinyLSTM and TinyModel from Edge Impulse." Sensors 22.14 (2022): 5174.

Altayeb, Moez, Marco Zennaro, and Marcelo Rovai. "Classifying mosquito wingbeat sound using TinyML." Proceedings of the 2022 ACM Conference on Information Technology for Social Good. 2022.

Bamoumen, Hatim, et al. "How TinyML Can be Leveraged to Solve Environmental Problems: A Survey." 2022 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies (3ICT). IEEE, 2022.

Avellaneda, Diego, Diego Mendez, and Giancarlo Fortino. "A TinyML Deep Learning Approach for Indoor Tracking of Assets." Sensors 23.3 (2023): 1542.

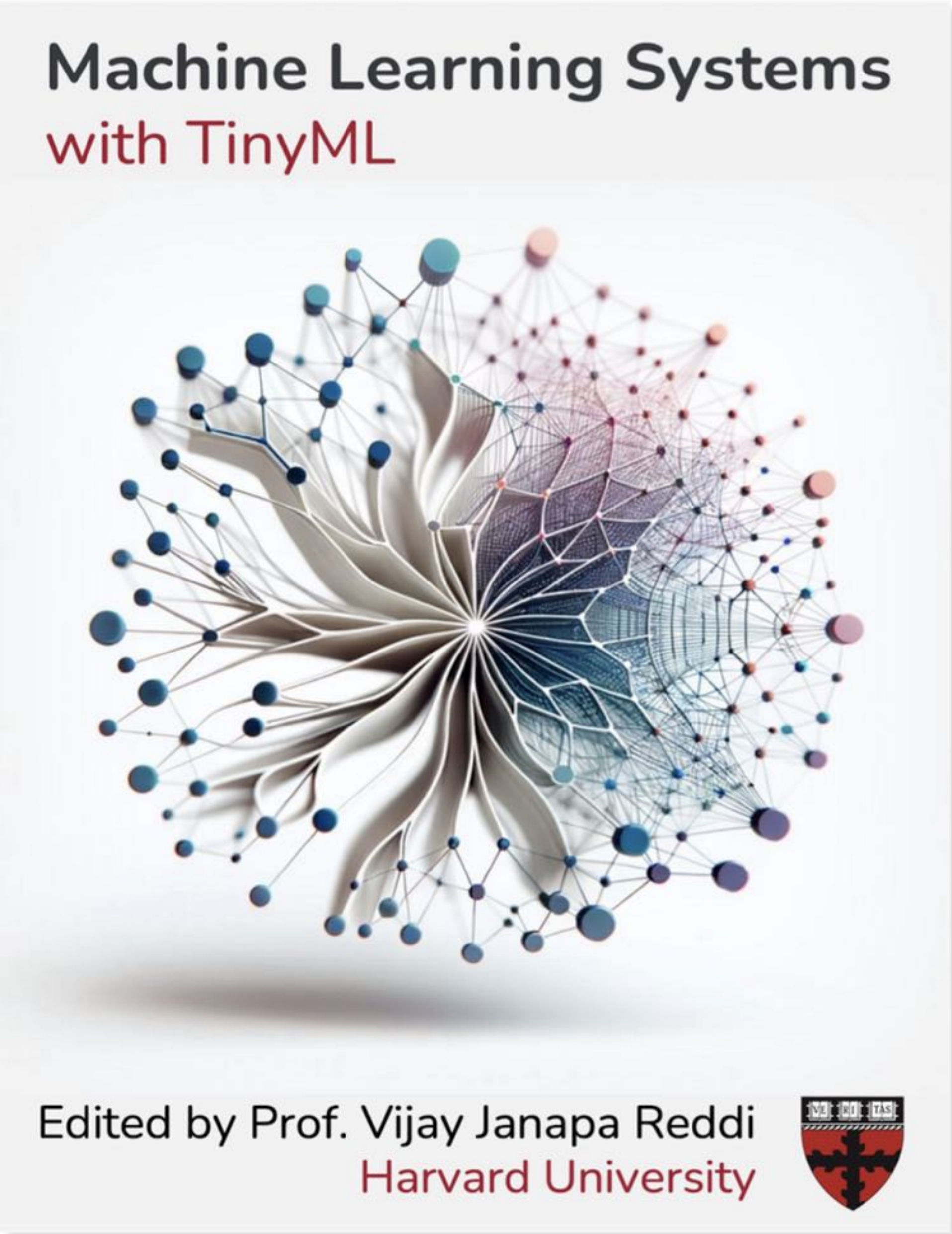
Papers published

Avellenada, Diego, Diego Mendez, and Giancarlo Fortino. "BLE-based Indoor Positioning Platform Utilizing Edge Tiny Machine Learning." 2022 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech). IEEE, 2022.

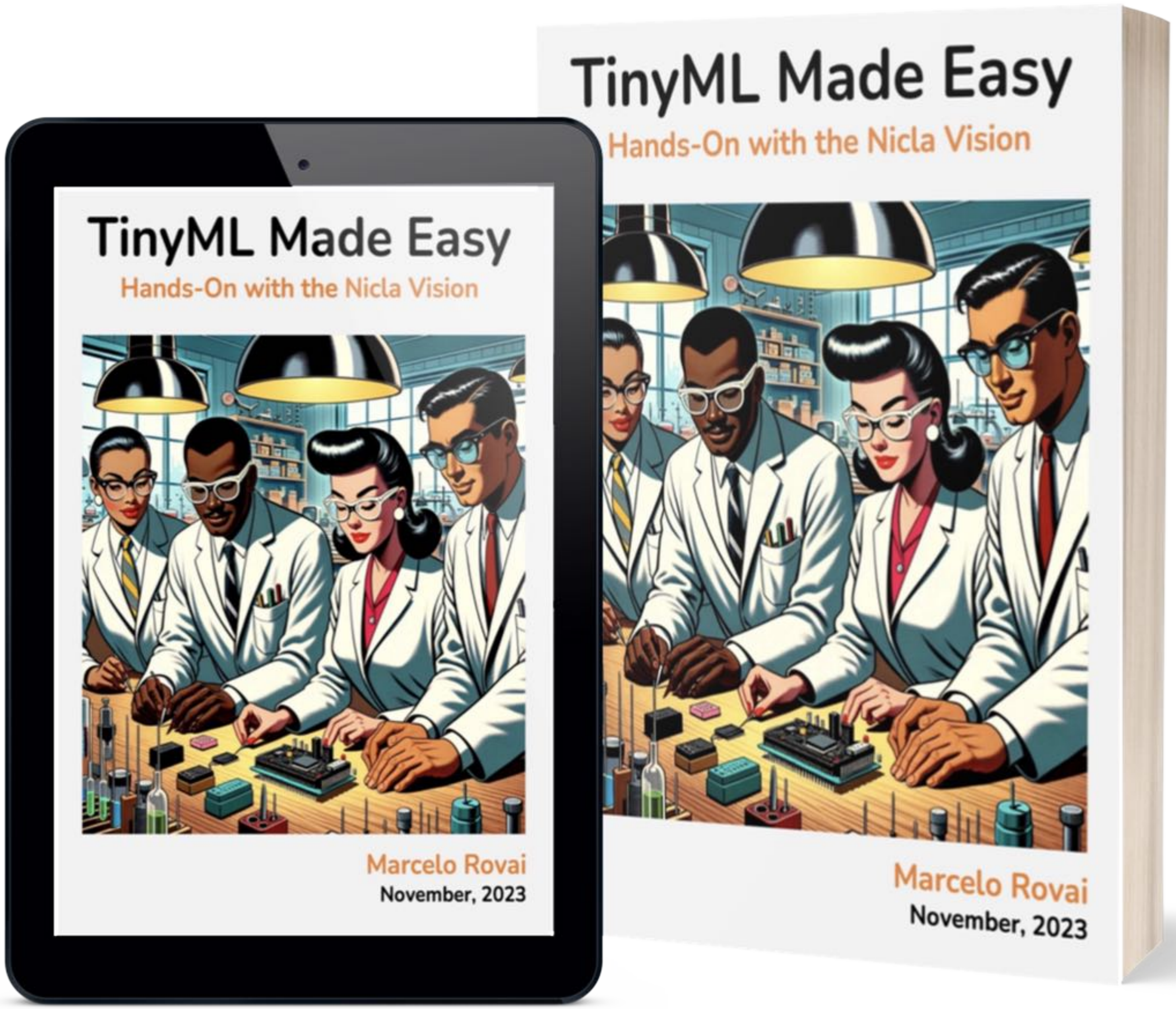
Plancher, Brian, and Vijay Janapa Reddi. "TinyMLedu: The tiny machine learning open education initiative." Proceedings of the 53rd ACM Technical Symposium on Computer Science Education V. 2. 2022.

G. Silva, M.D. Lima, J.A.F. Filho and M.J. Rovai " "Atrial Fibrillation and Sinus Rhythm detection using TinyML (Embedded Machine Learning). “IX Latin American Congress on Biomedical Engineering” and “XXVIII Brazilian Congress on Biomedical Engineering”

João Vitor Yamashita et al.. "Coffee disease classification at the edge using deep learning". Smart Agricultural Technology Volume 4, August 2023, 100183



https://github.com/harvard-edge/cs249r_book



https://github.com/Mjrovai/TinyML_Made_Easy_NiclaV_eBook

Thanks

TINYML4D