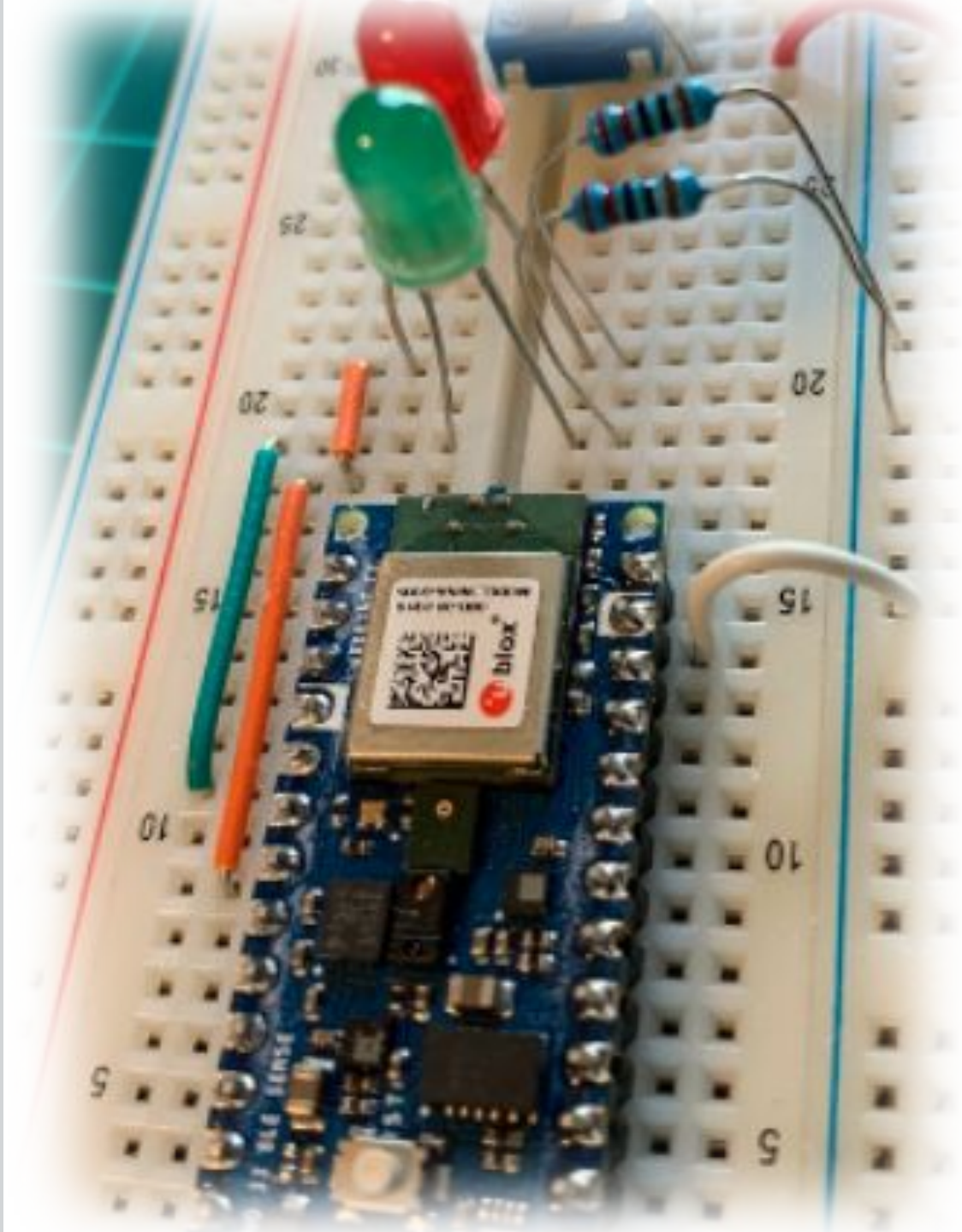
IESTI01 – TinyML

Embedded Machine Learning

19. Motion Classification

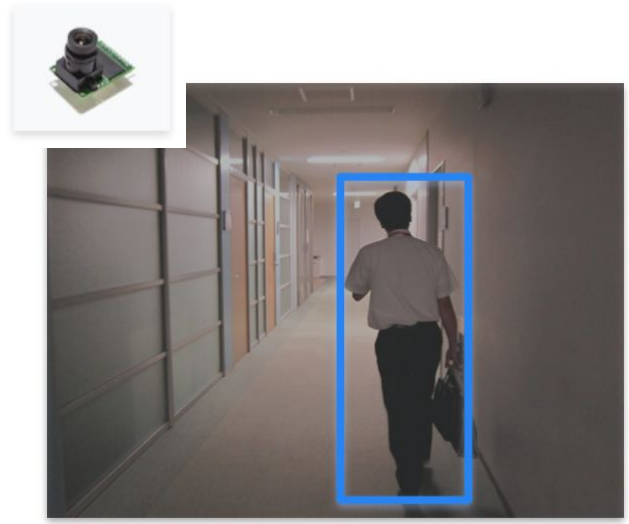


Prof. Marcelo Rovai
UNIFEI

Vibration

Sound

Vision



Vibration

Sound

Vision

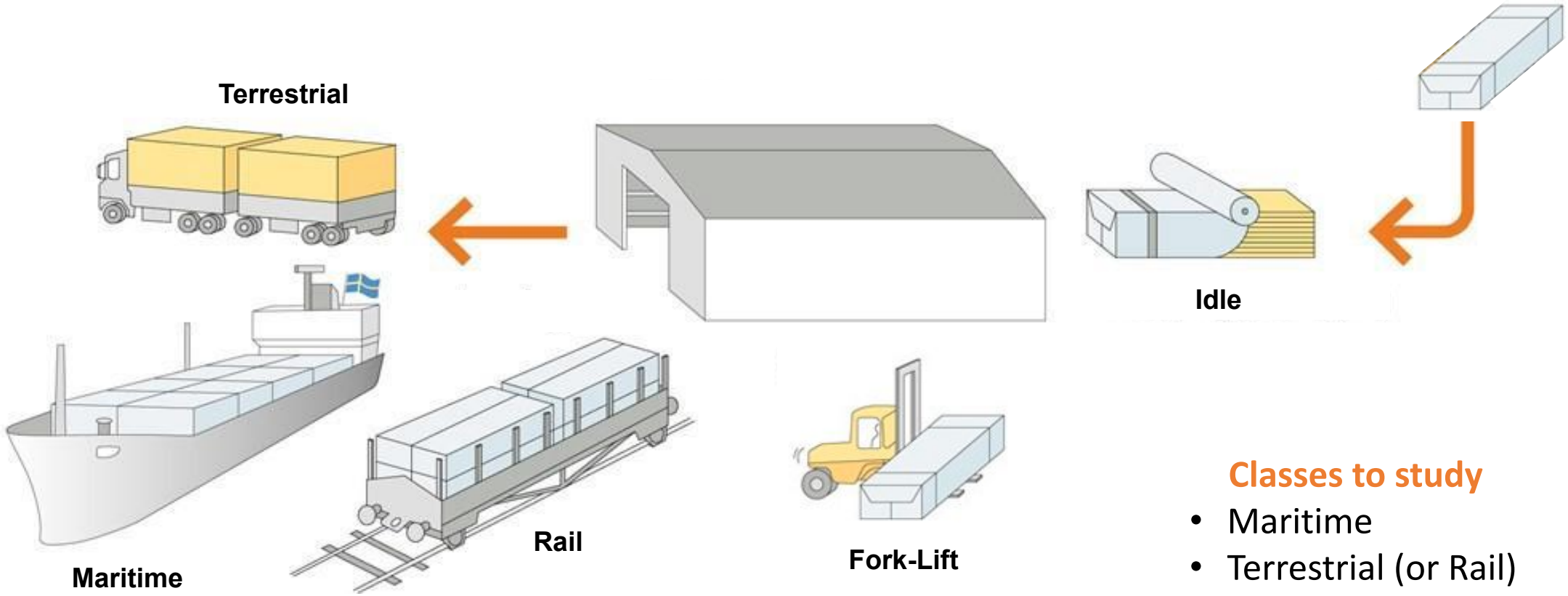
Industrial Embedded Machine Learning Demo

Daniel Situnayake, founding engineer of Edge Impulse

Introduction to Embedded ML course

Motion Classification

Case Study: Mechanical Stresses in Transport

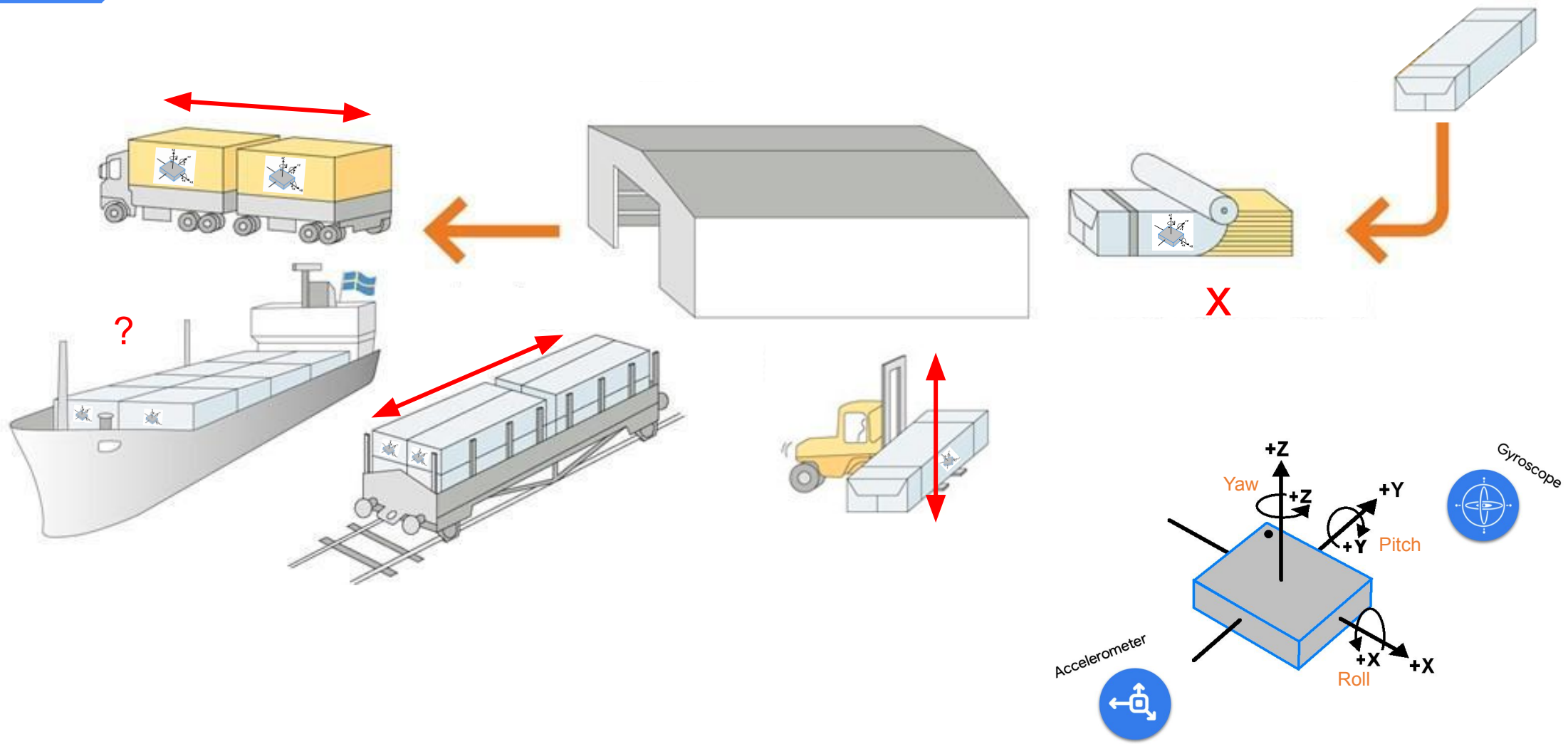


Classes to study

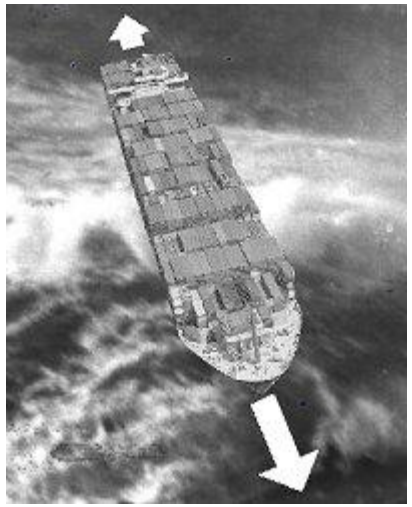
- Maritime
- Terrestrial (or Rail)
- Lift
- Idle

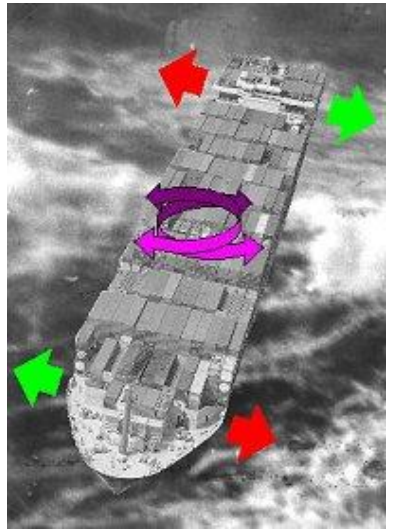
Machine Learning Workflow

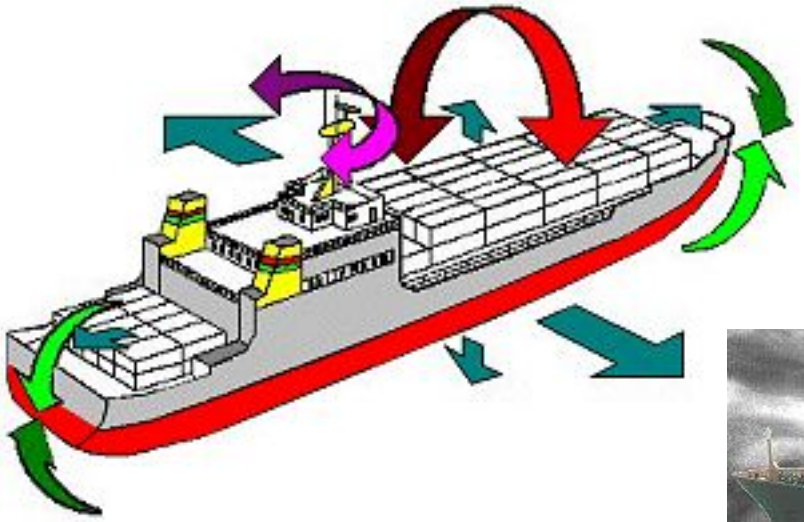
Collect Data

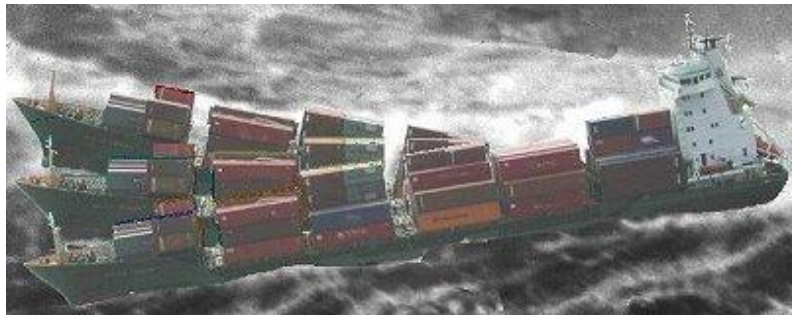


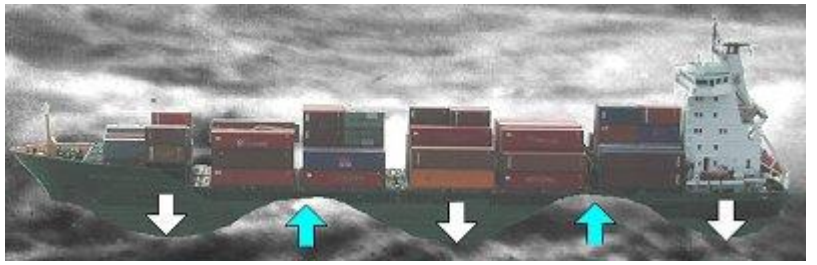
Mechanical Stresses in Maritime Transport





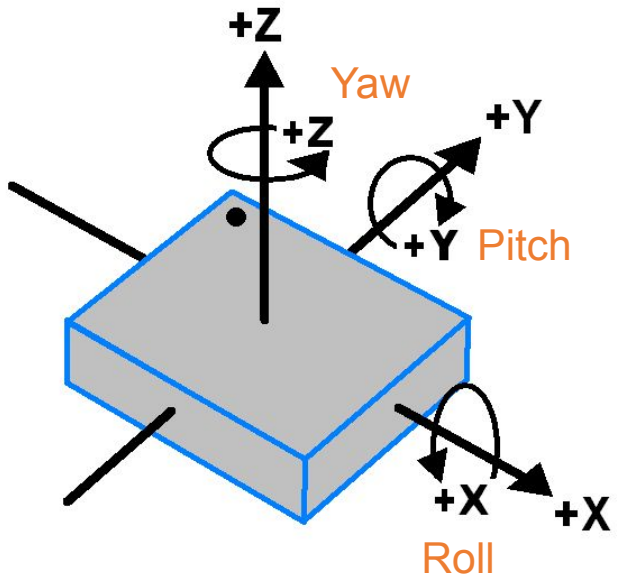


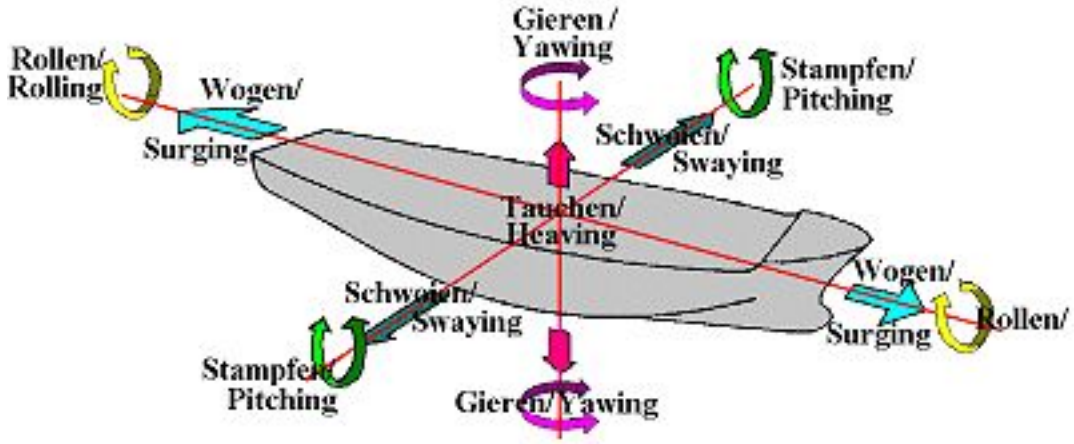




https://www.containerhandbuch.de/chb_e/stra/index.html?/chb_e/stra/stra_02_03_03.html

Mechanical Stresses in Maritime Transport





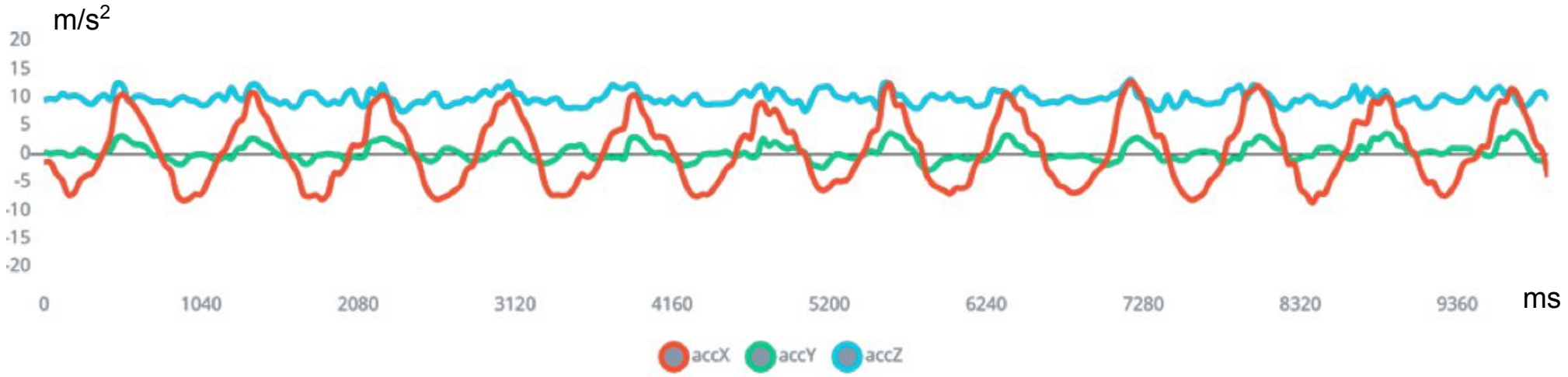
Accelerometer

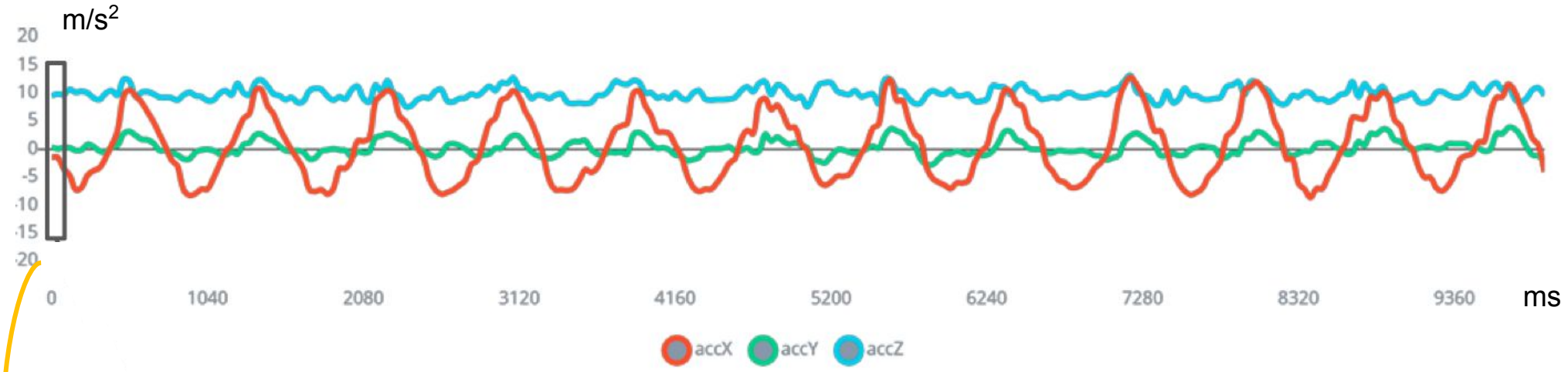
Gyroscope

	Linear motion	Rotational motion	
X	Surging is motion along the longitudinal axis.	Rolling is motion around the longitudinal axis.	Roll
Y	Swaying is motion along the transverse axis.	Pitching is motion around the transverse axis.	Pitch
Z	Heaving is motion along the vertical axis.	Yawing is motion around the vertical axis.	Yaw

Summary of ship movement

Example: 10 seconds of accelerometer data, captured with a sample rate: 62.5 Hz





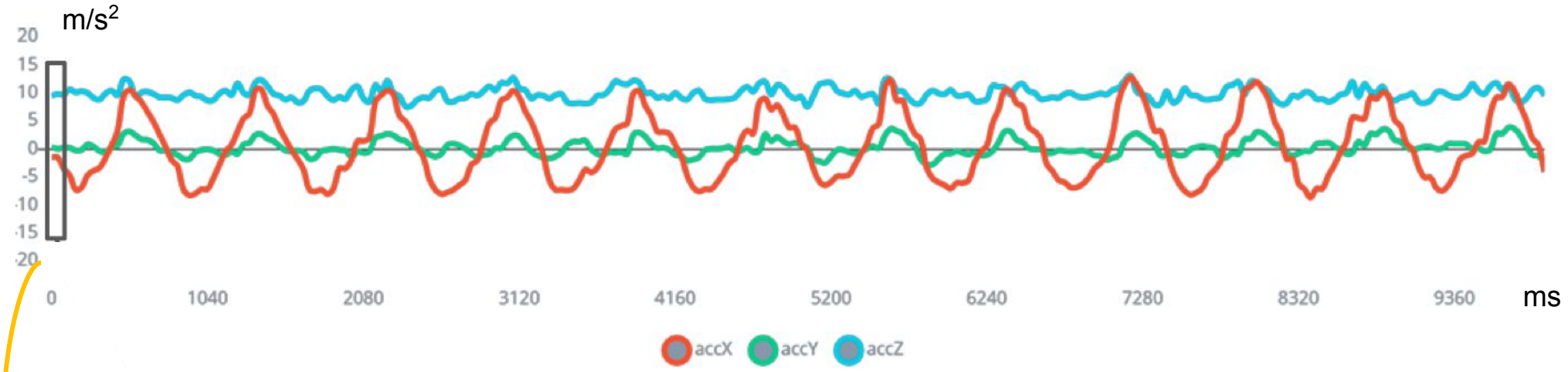
Raw Features

- accX
- accY
- accZ

Model

Classes

- Lift
- Terrestrial
- Maritime
- Iddle



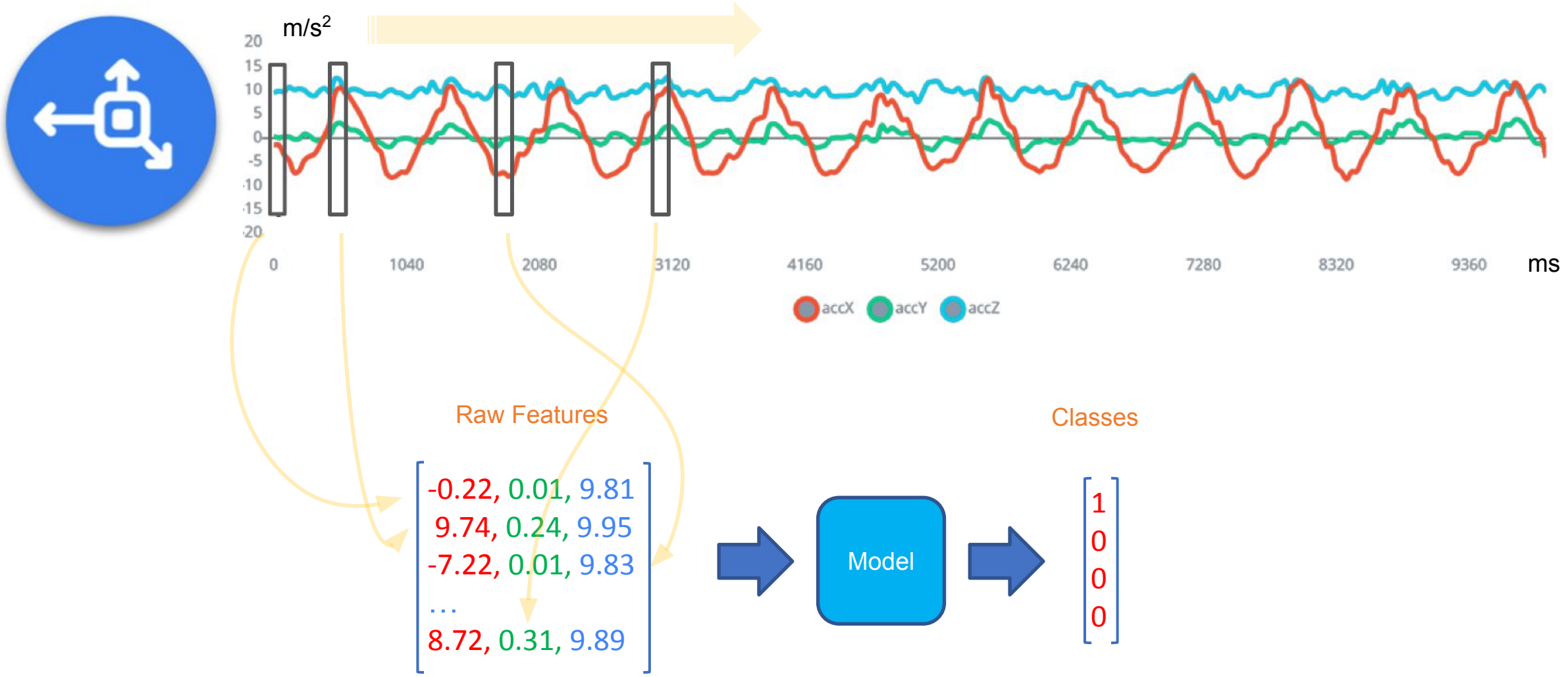
Raw Features

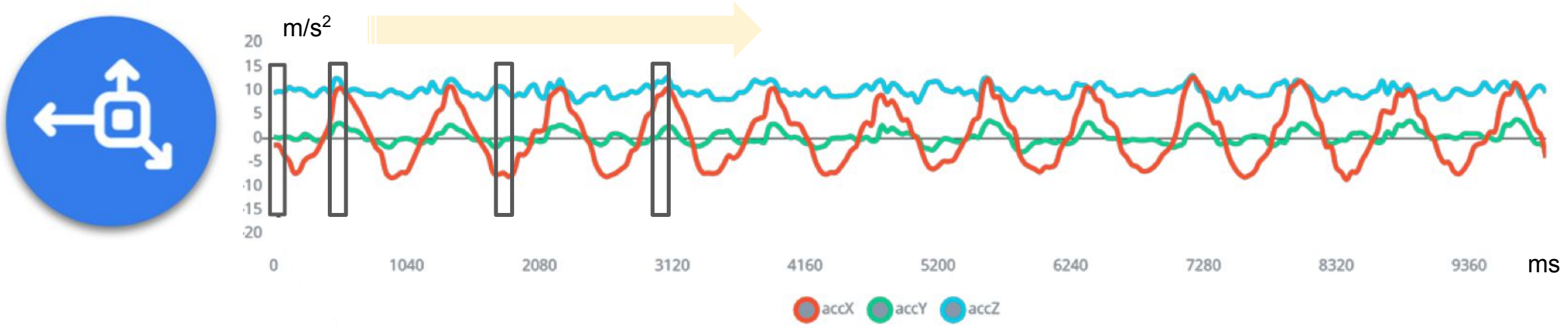
[-0.22, 0.01, 9.81]

Model

Classes

[1 0 0 0]


m/s2
20
15
10
5
0
-5
-10
-15
-20
0
1040
2080
3120
4160
5200
6240
7280
8320
9360
ms
accX
accY
accZ
Raw Features
-0.22, 0.01, 9.81
9.74, 0.24, 9.95
-7.22, 0.01, 9.83
…
8.72, 0.31, 9.89
Model
Classes
1
0
0
0



Raw Features

-0.22, 0.01, 9.81
9.74, 0.24, 9.95
-7.22, 0.01, 9.83
…
8.72, 0.31, 9.89

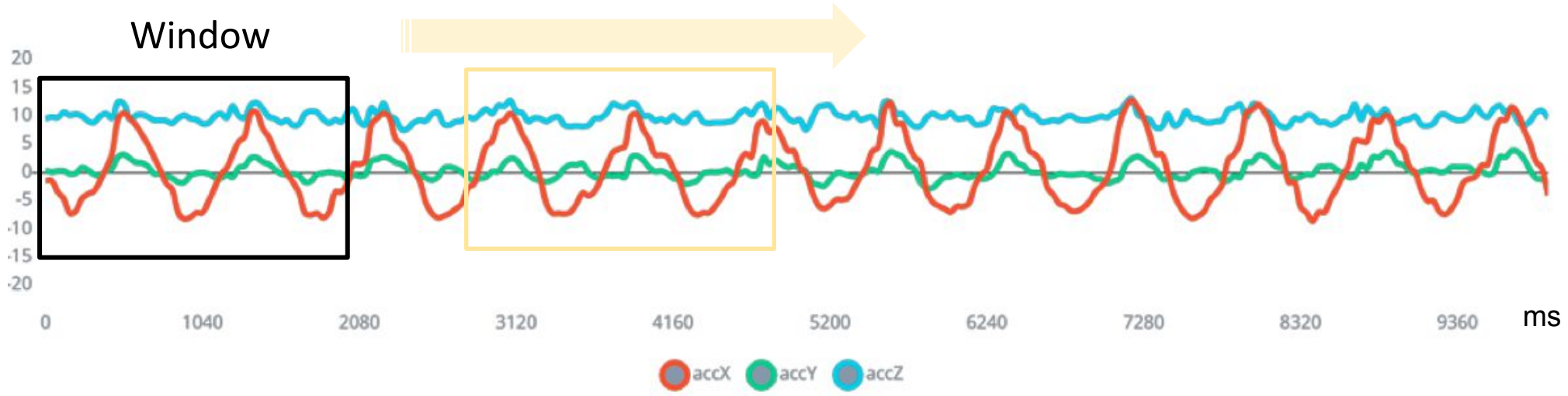
Model

Classes

? ? ? ?

Problem!

✔ Time-Series Data

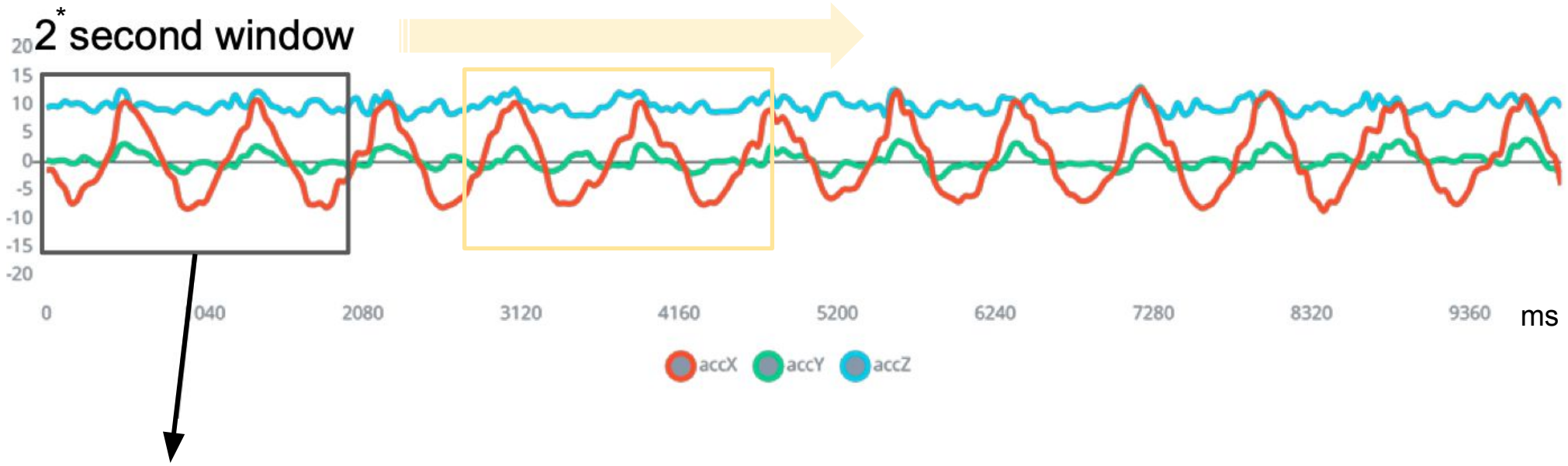

Window
20
15
10
5
0
-5
-10
-15
-20
0
1040
2080
3120
4160
5200
6240
7280
8320
9360
ms
accX
accY
accZ

Raw Features as a window

- 125** samples for each axis (62.5Hz x 2s)
- 375 total features (125 x 3 axis)

* 2 seconds is needed to capture 1 or 2 cycles of movement

** 2 seconds at sample rate of 62.5 Hz -> 125 samples



Raw Features as a window

- 125** samples for each axis
- 375 total features

Automatic Feature Extraction using DL

- Computational complexity
- Lots of training data

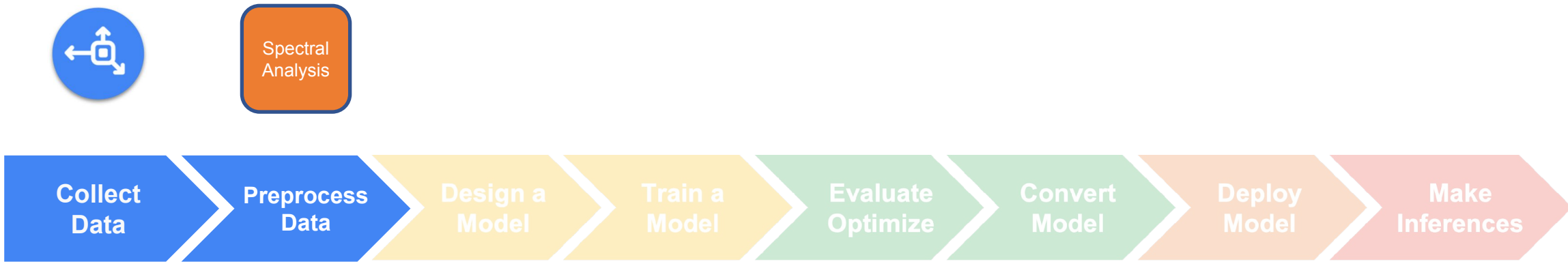
Problem!

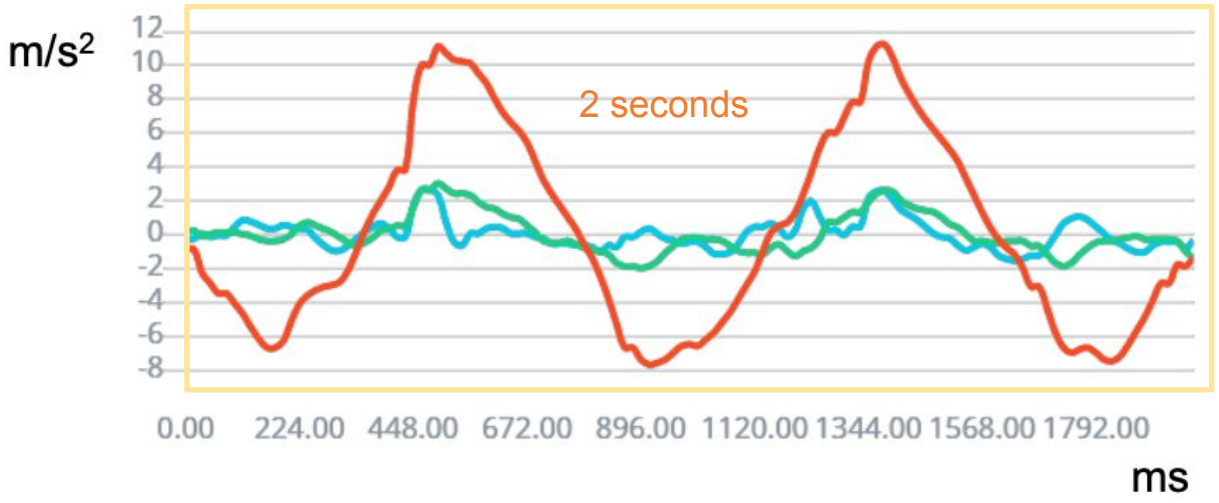
✔ More Memory

* 2 seconds is needed to capture 1 or 2 cycles of movement

** 2 seconds at sample rate of 62.5 Hz -> 125 samples

Data Pre-Processing





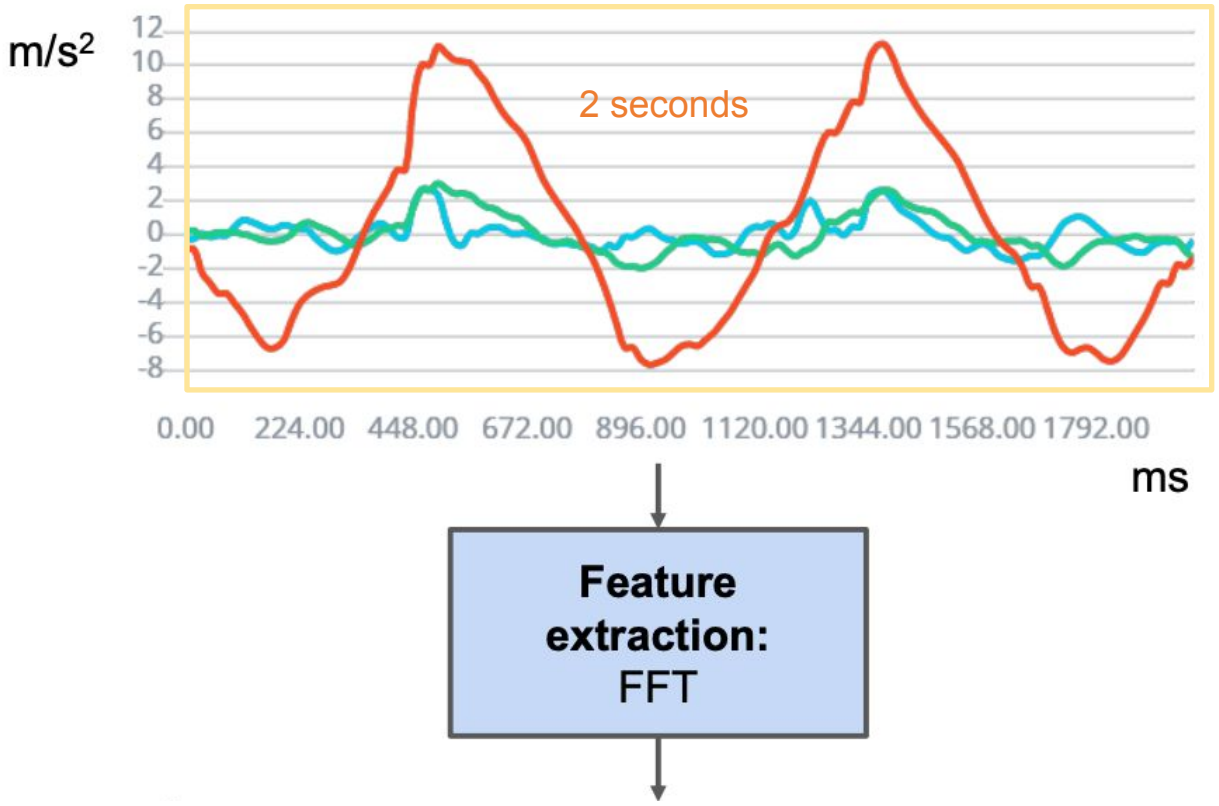
Manual Feature Extraction

3 RMS (Root Mean Square) values

- one for each axis (x, y, z)

$$x_{\mathrm{RMS}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

125

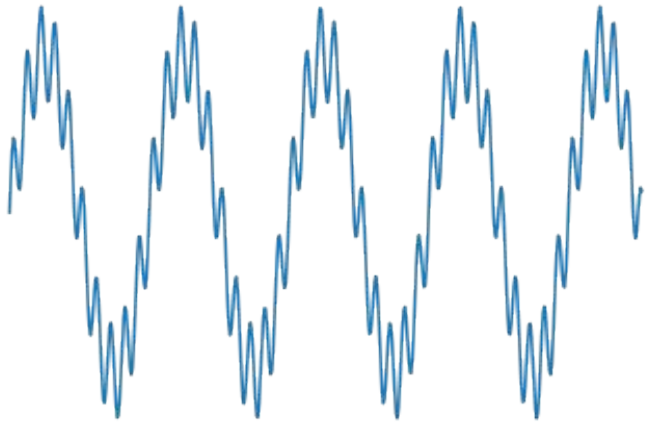


Manual Feature Extraction

3 RMS

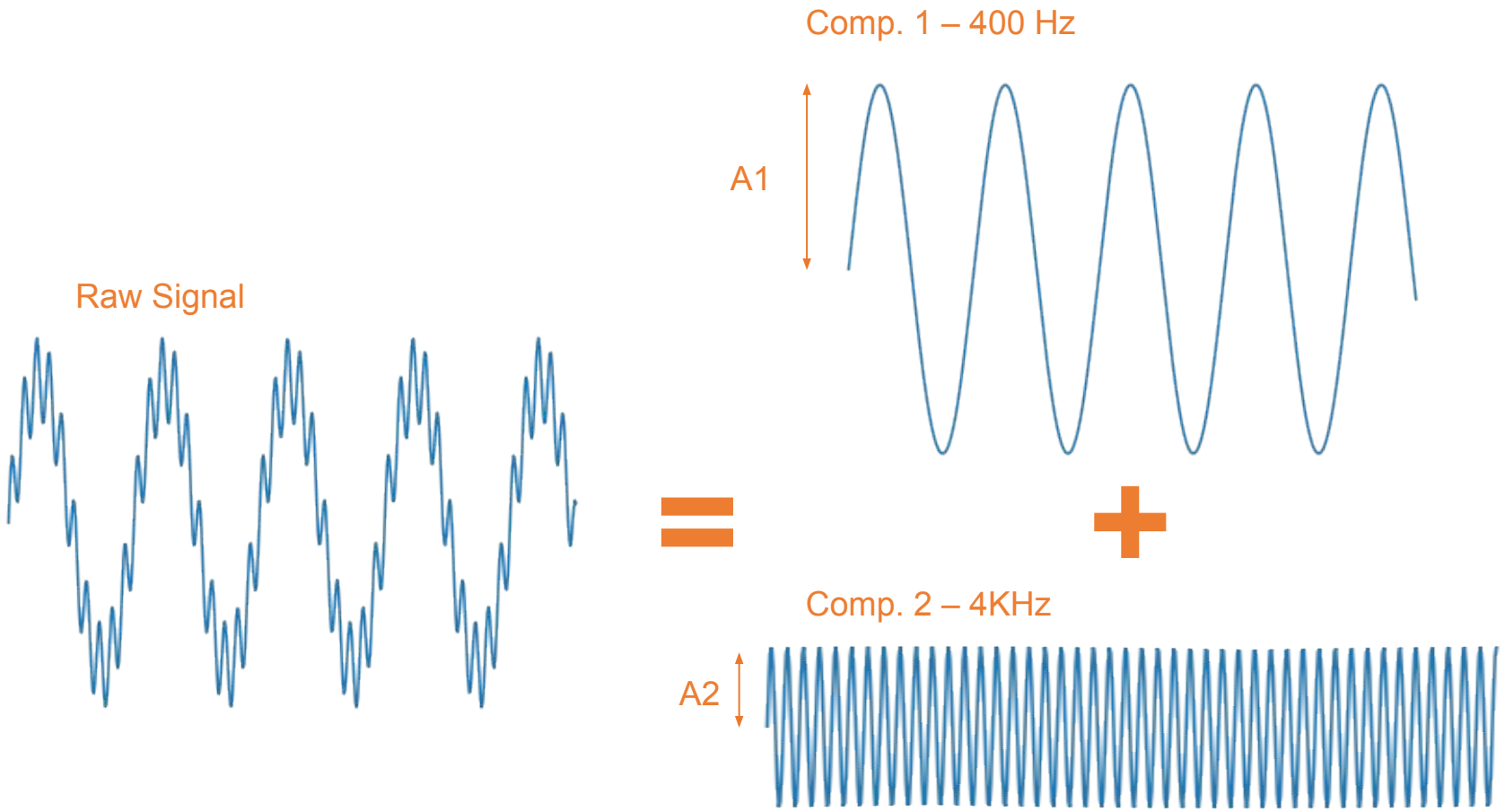
Fast Fourier Transformer (FFT)

Raw Signal

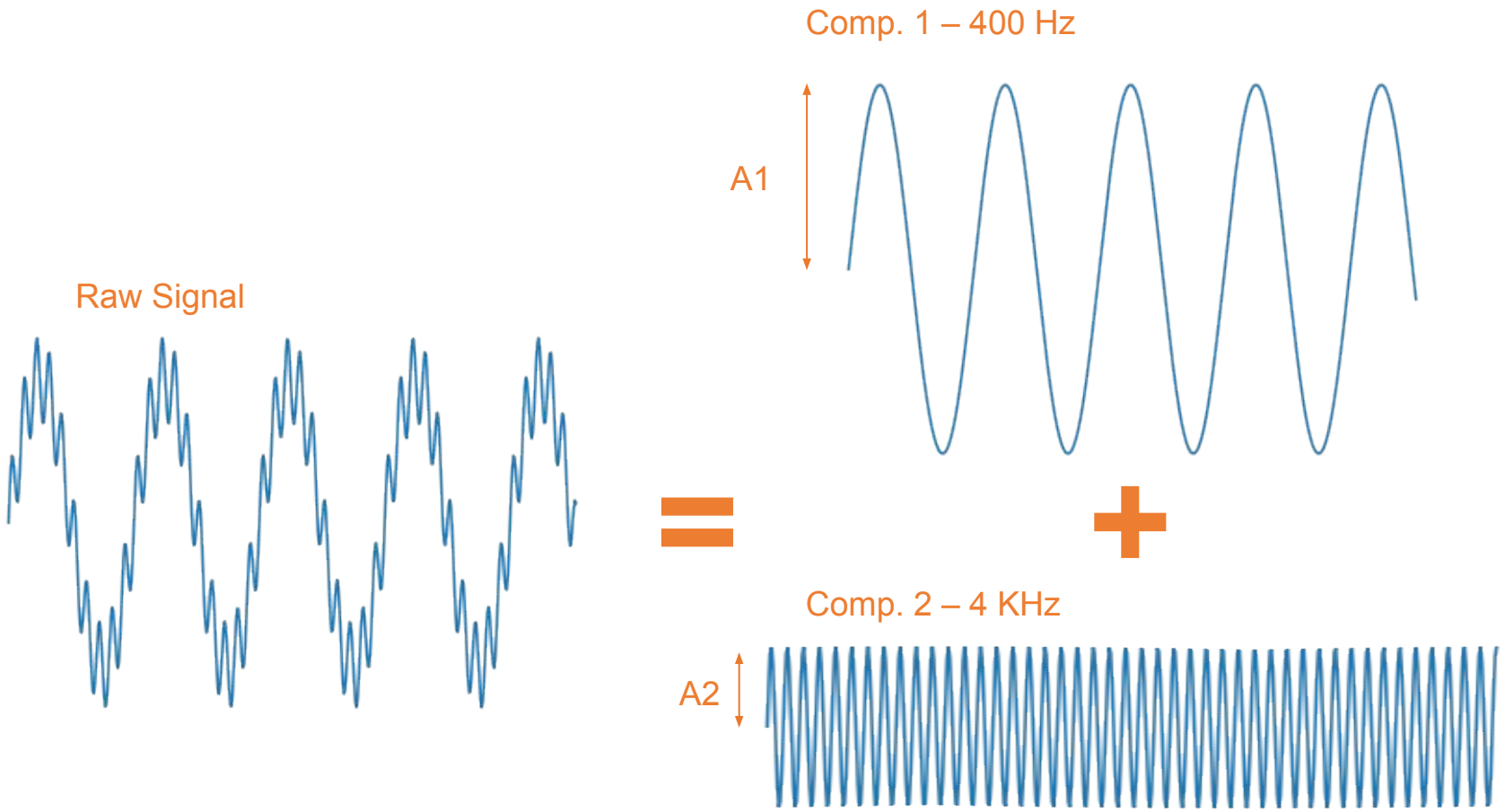


Time Domain

Fast Fourier Transformer (FFT)

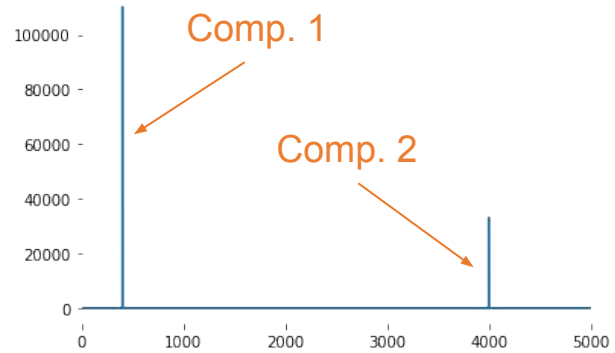


Fast Fourier Transformer (FFT)

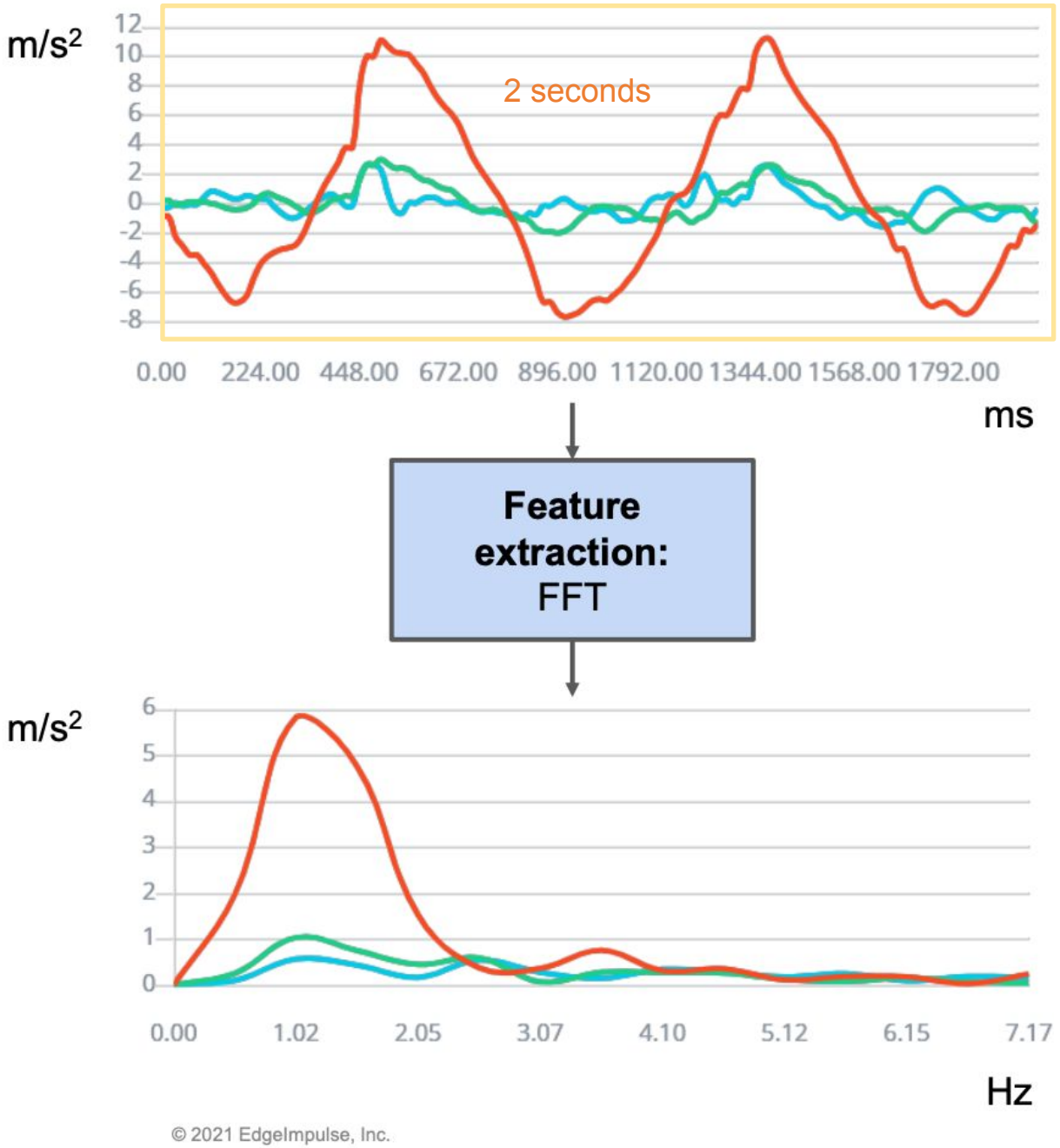


Time Domain

```
from scipy.fft import fft
yf = fft(raw signal)
plt.plot(xf, np.abs(yf));
```



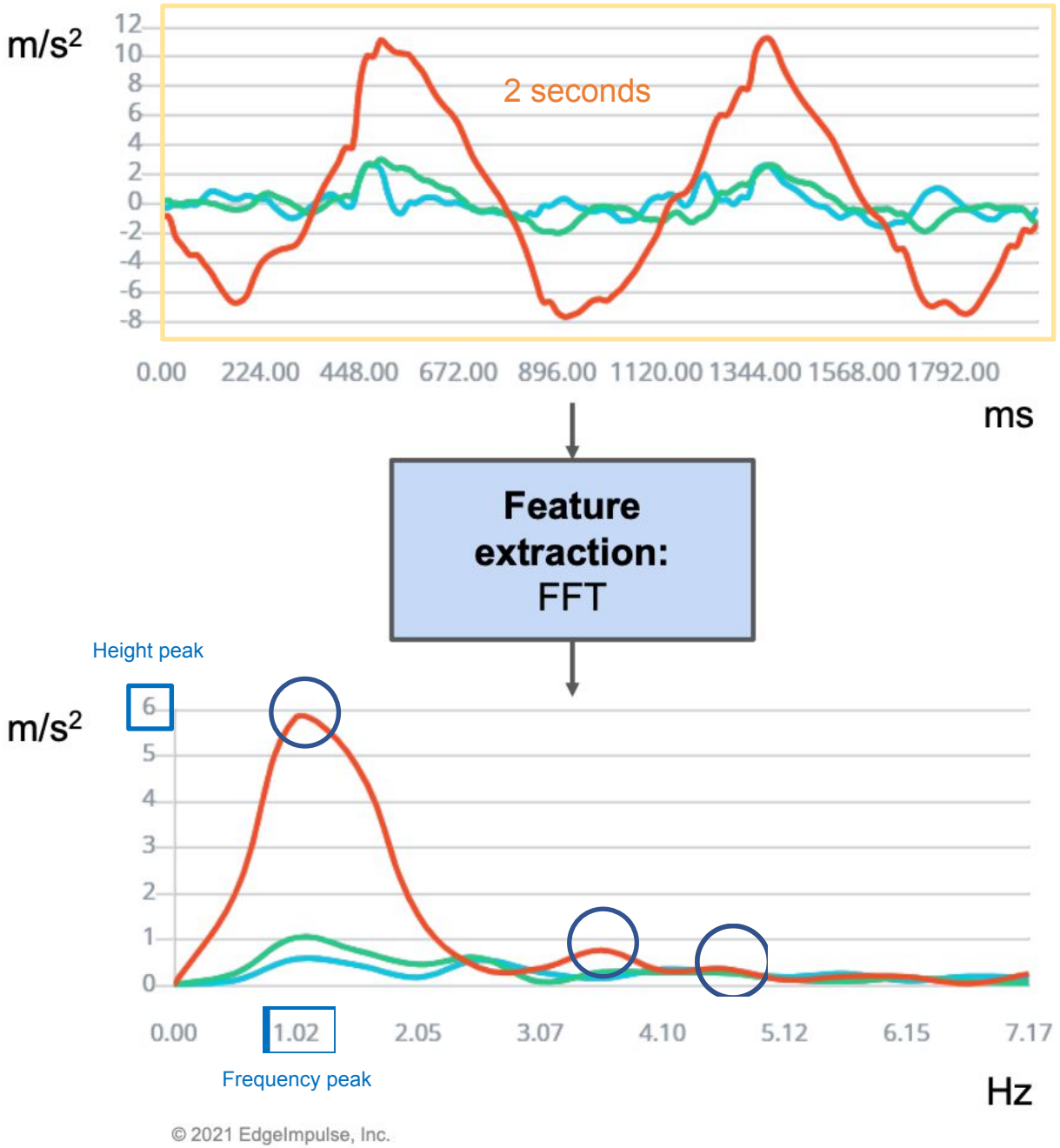
Frequency Domain



Manual Feature Extraction

3 RMS

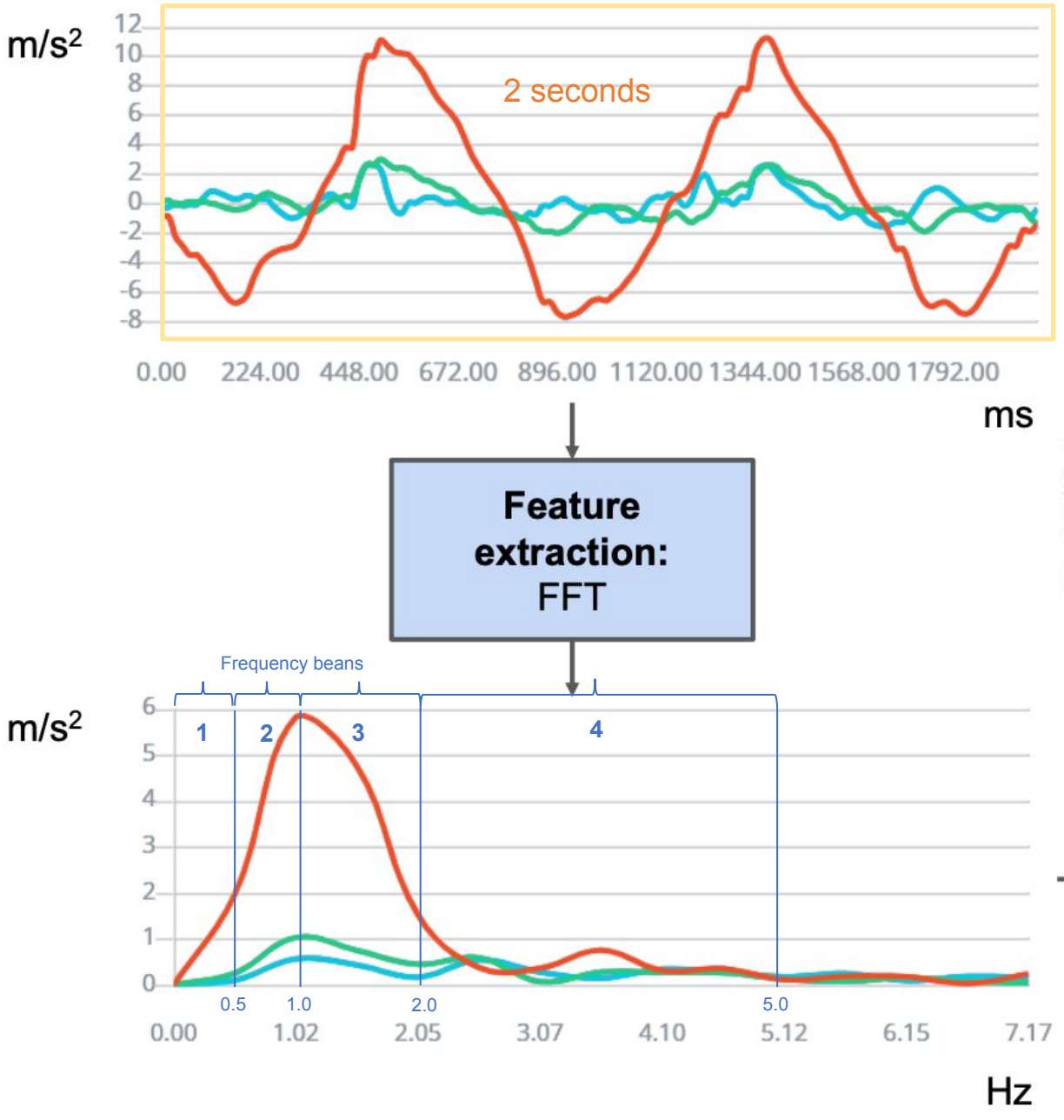
Manual Feature Extraction



3 RMS

9 Height + **9** Freq. peak values

Manual Feature Extraction



3 RMS + **9** HP + **9** FP + **12** PSD values

4 Frequency bins per axix

Feature extraction: PSD

https://blog.endaq.com/why-the-power-spectral-density-psd-is-the-gold-standard-of-vibration-analysis

Sliding Window: 80 ms

375 Raw Features

- Raw Data from sensor

Manual Feature Extraction

Spectral Analysis

11 Features

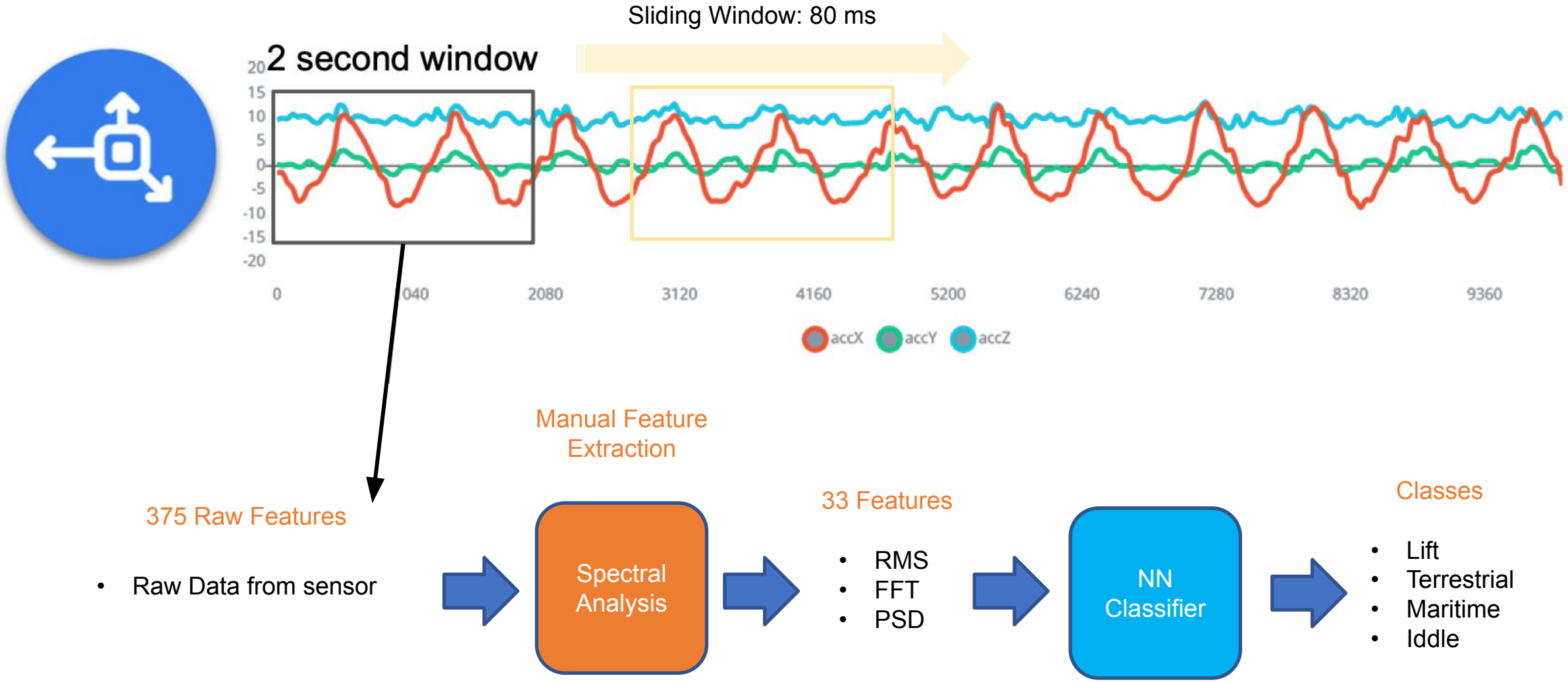
accX RMS
accX Peak
accX Peak
accX Peak
accX Peak
accX Peak
accX Spec
accX Spec
accX Spec
accX Spec

11 Features

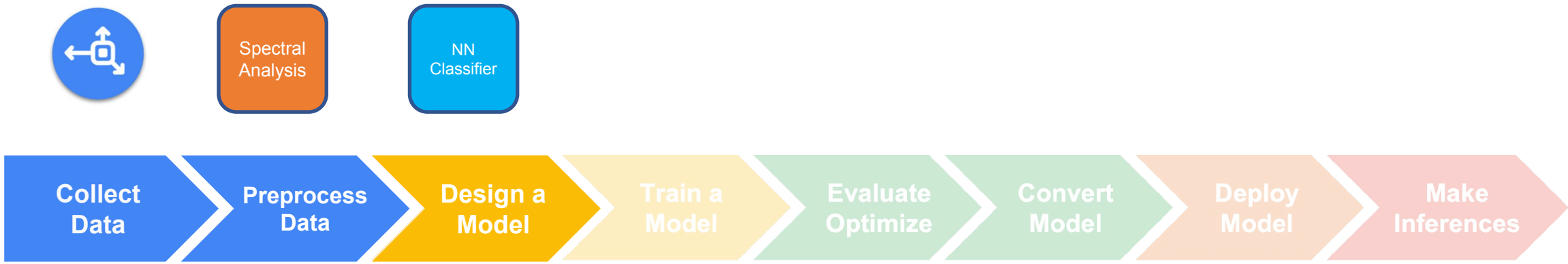
accY RMS
accY Peak
accY Peak
accY Peak
accY Peak
accY Peak
accY Spec
accY Spec
accY Spec
accY Spec

11 Features

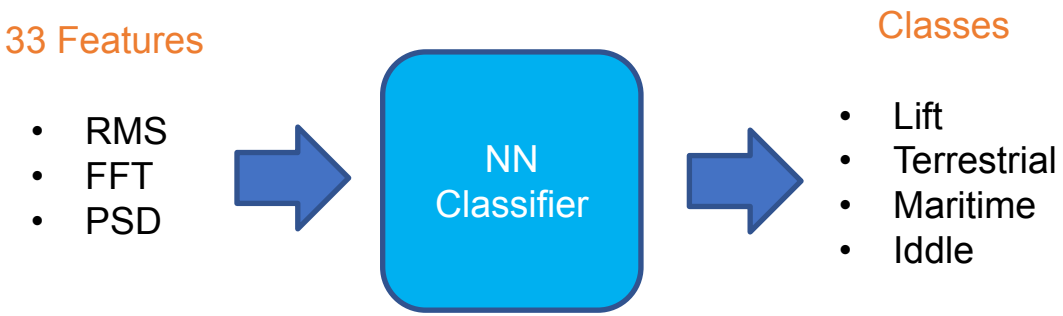
accZ RMS
accZ Peak 1 Freq
accZ Peak 1 Height
accZ Peak 2 Freq
accZ Peak 2 Height
accZ Peak 3 Freq
accZ Peak 3 Height
accZ Spectral Power 0.1 - 0.5
accZ Spectral Power 0.5 - 1.0
accZ Spectral Power 1.0 - 2.0
accZ Spectral Power 2.0 - 5.0


Sliding Window: 80 ms
2 second window
20
15
10
5
0
-5
-10
-15
-20
0
040
2080
3120
4160
5200
6240
7280
8320
9360
accX
accY
accZ
375 Raw Features
Raw Data from sensor
Manual Feature Extraction
Spectral Analysis
33 Features
RMS
FFT
PSD
NN Classifier
Classes
Lift
Terrestrial
Maritime
Iddle

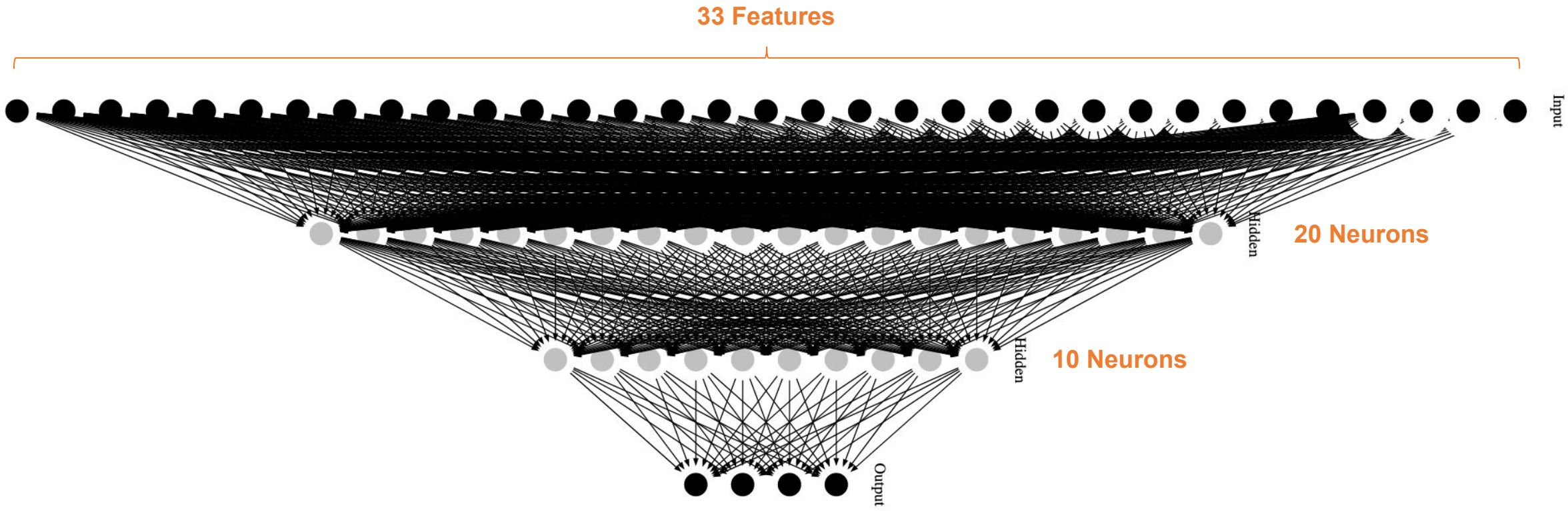
Model Design (NN Classifier)



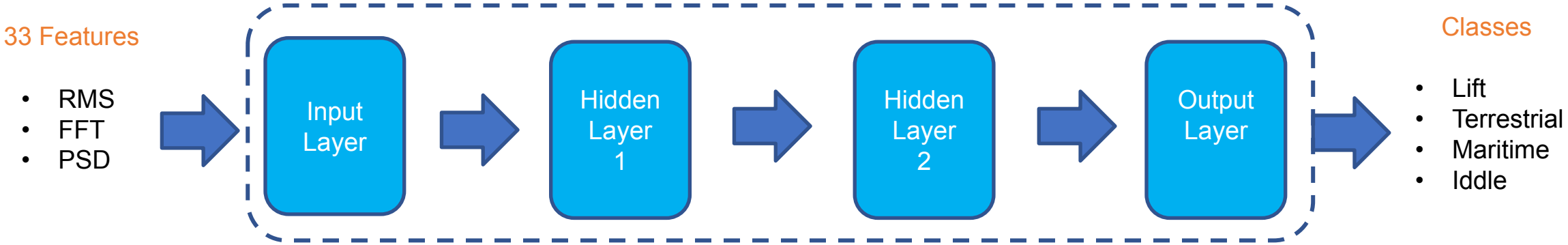
Model Design (NN Classifier)



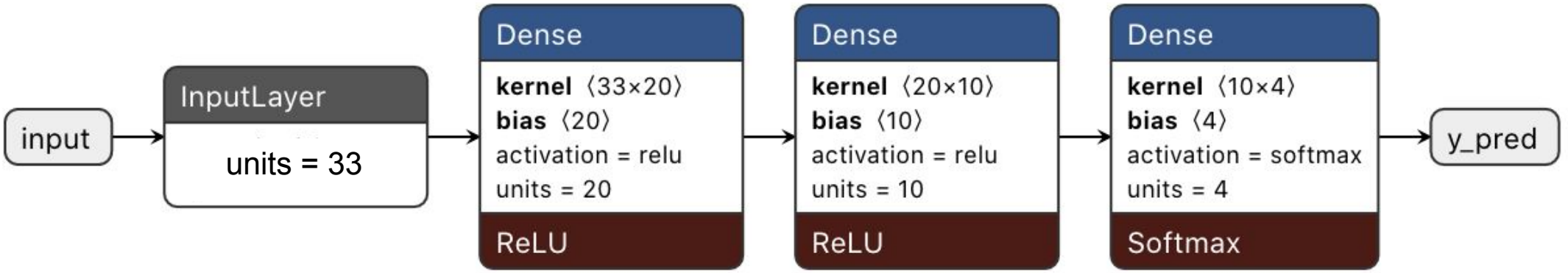
Model Design (DNN Classifier)



Model Design (DNN Classifier)

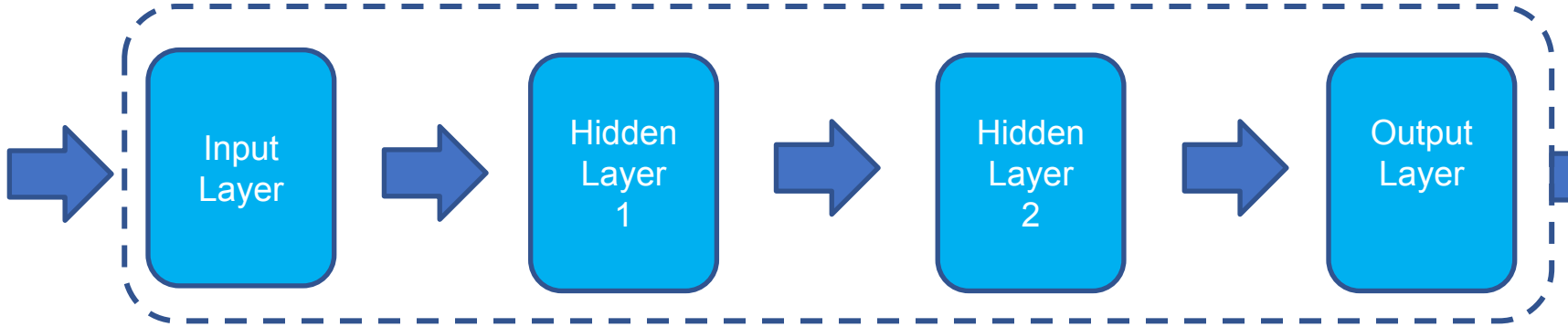


Model Design (DNN Classifier)



33 Features

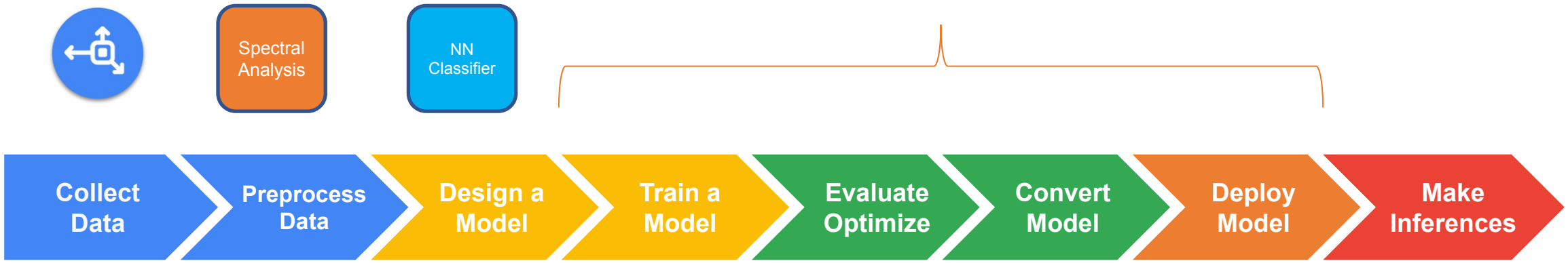
- RMS
- FFT
- PSD



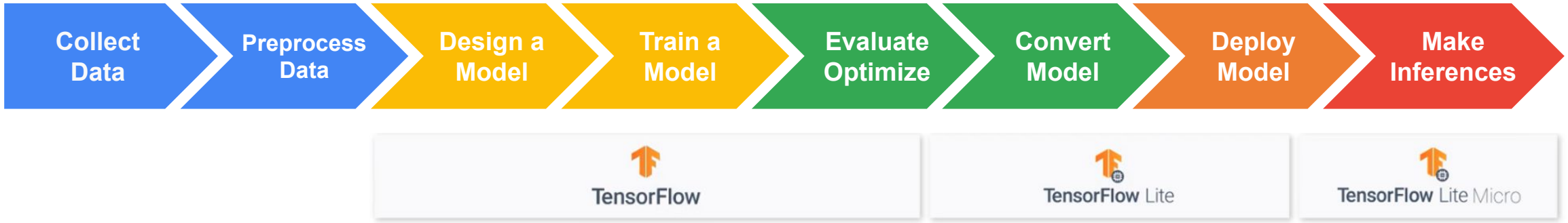
Classes

- Lift
- Terrestrial
- Maritime
- Iddle

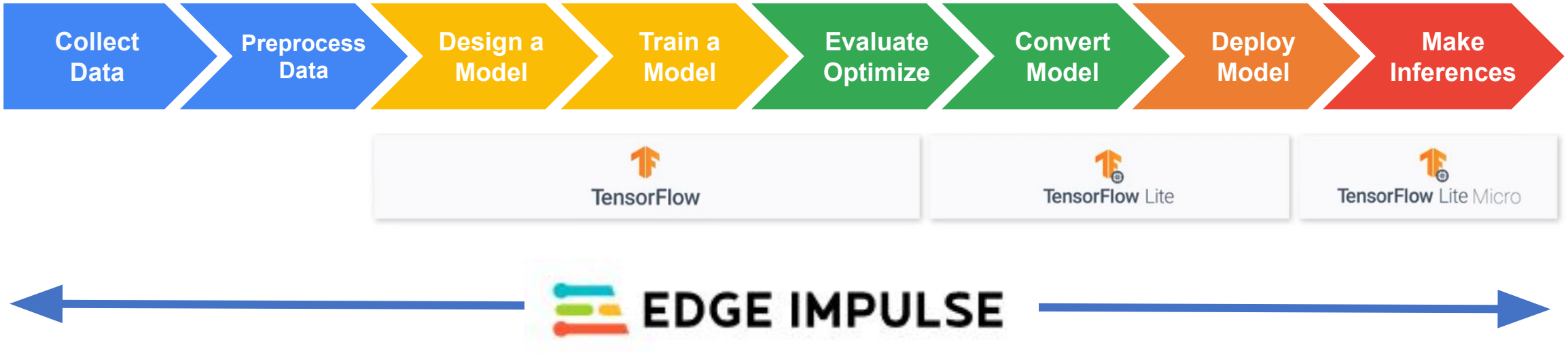
Train, Evaluate, Convert, Deploy the Model



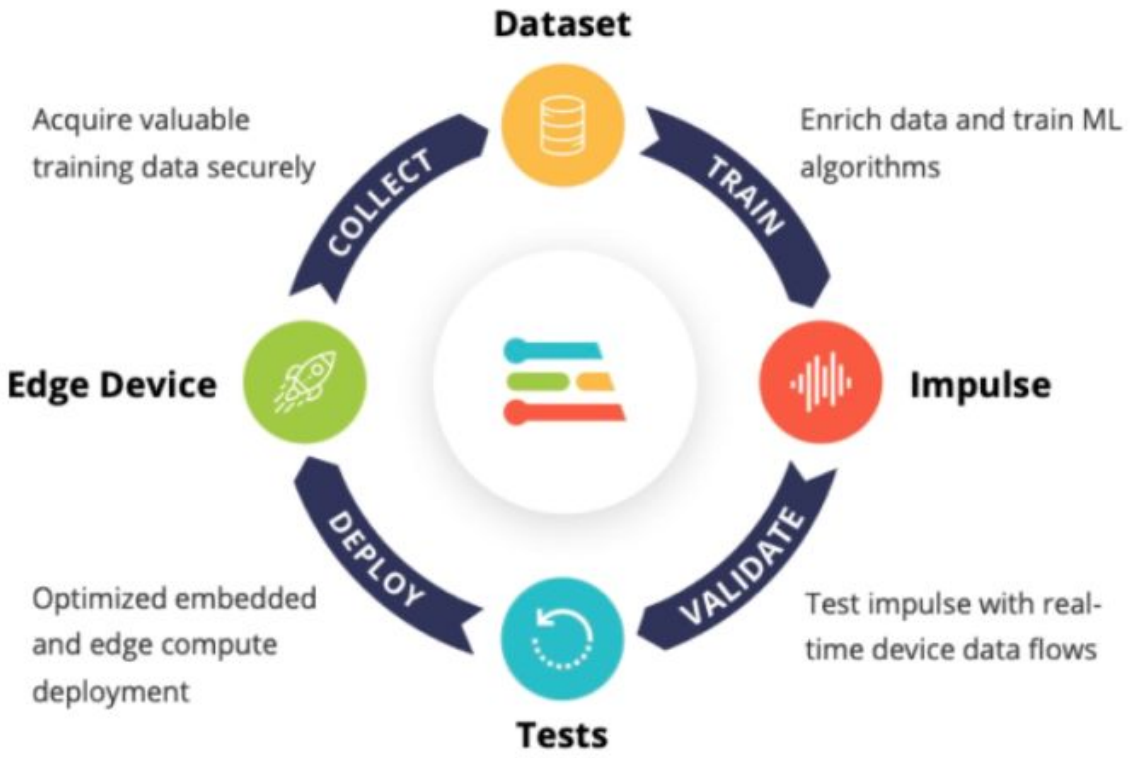
Train, Evaluate, Convert, Deploy the Model

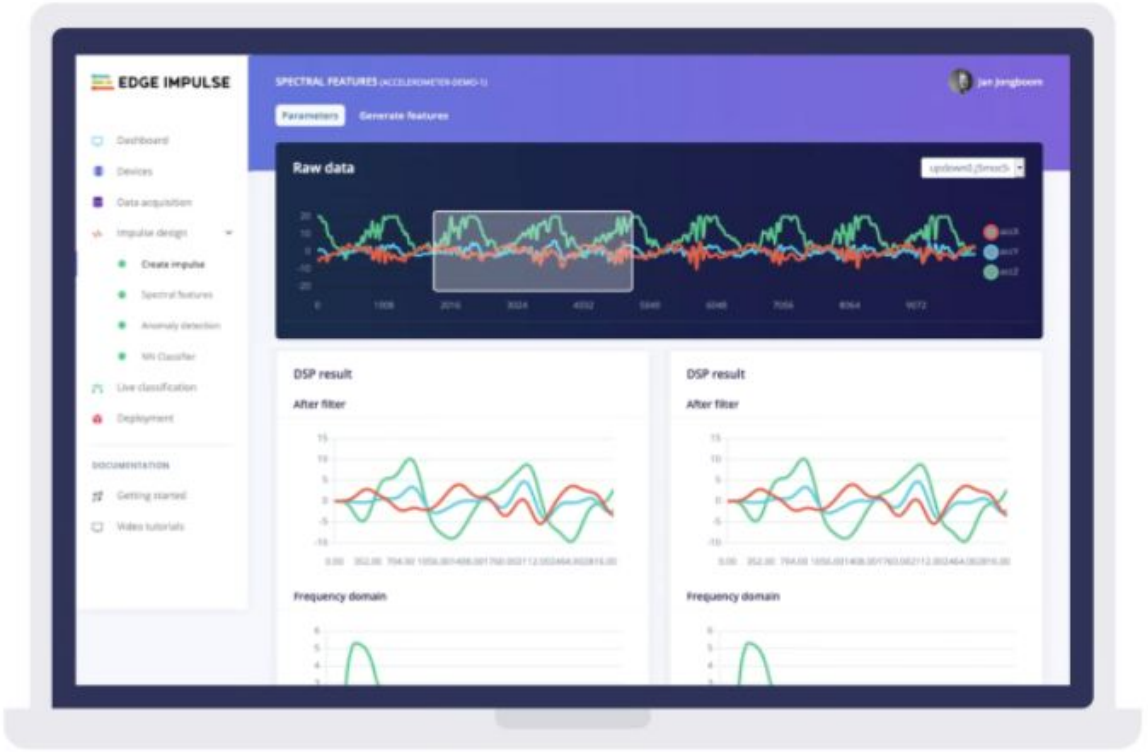


Machine Learning Workflow

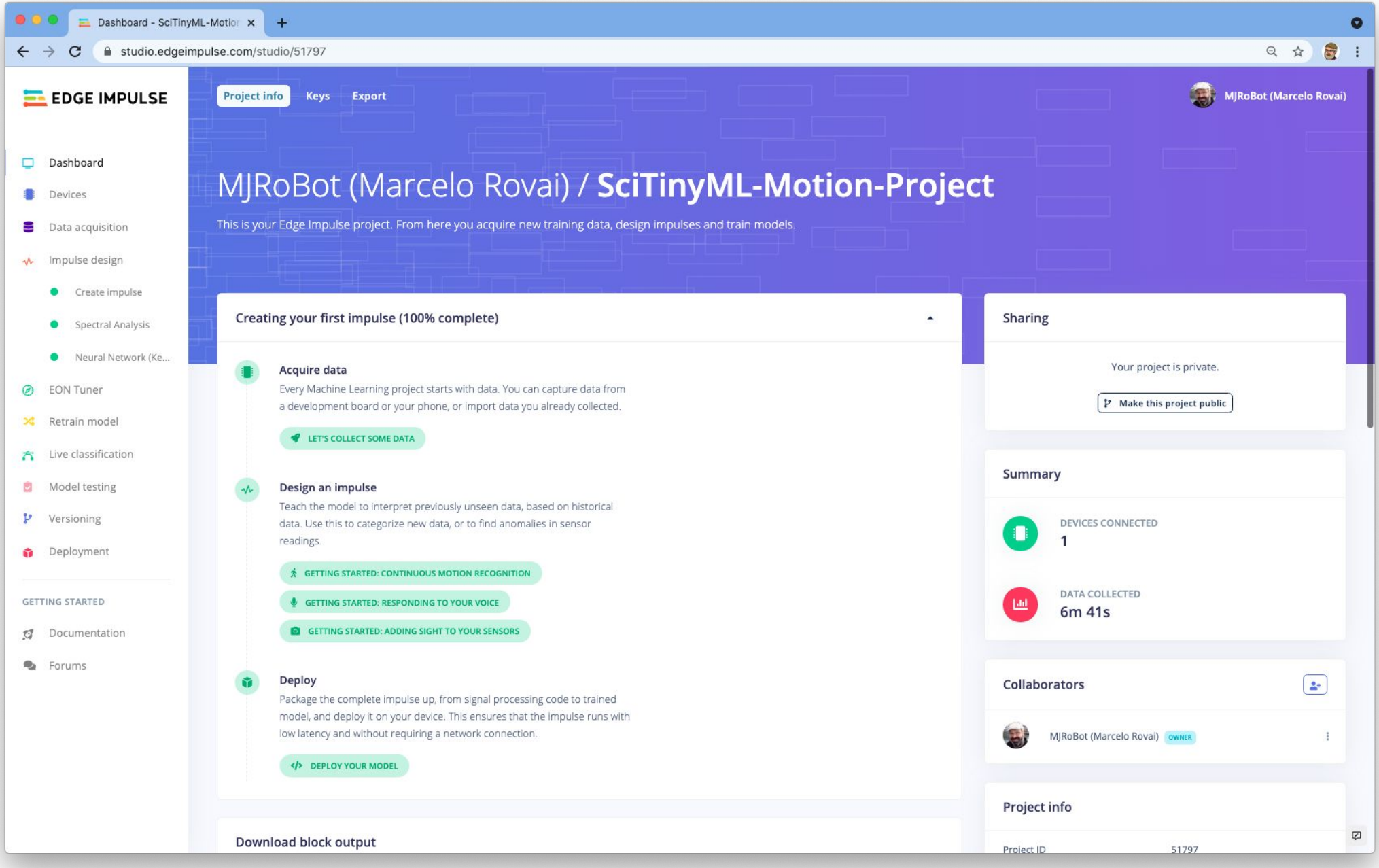


EI Studio - Embedded ML platform

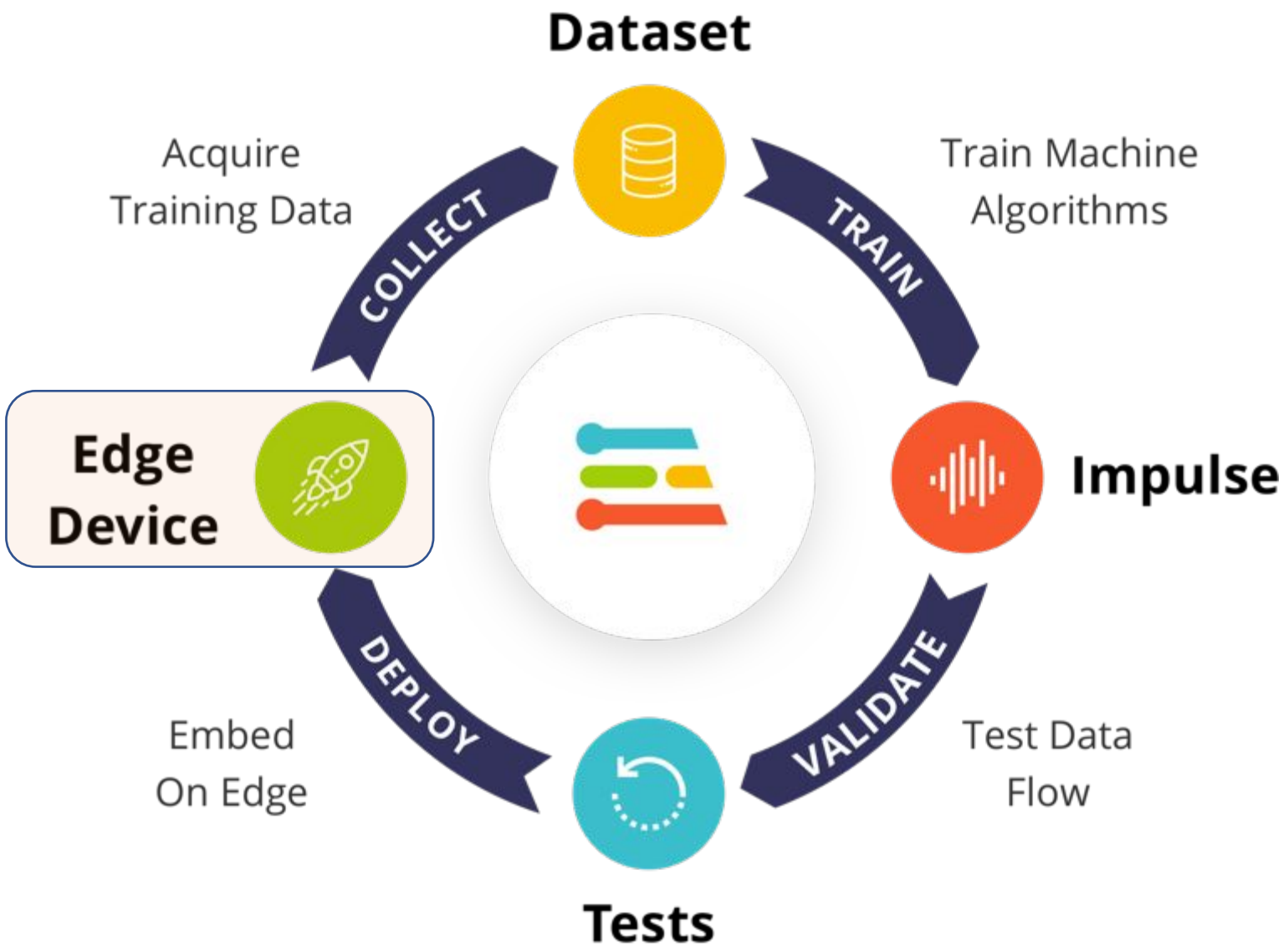




Learn more at http://edgeimpulse.com

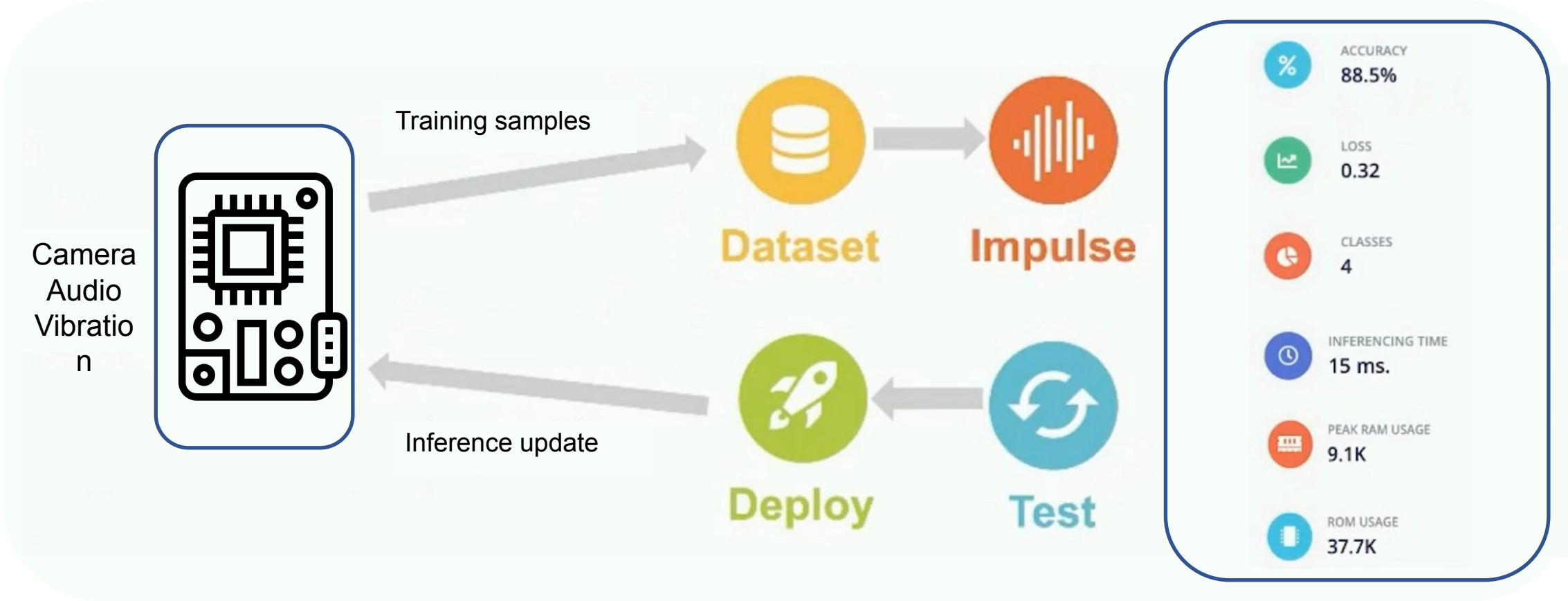


https://studio.edgeimpulse.com/public/51963/latest

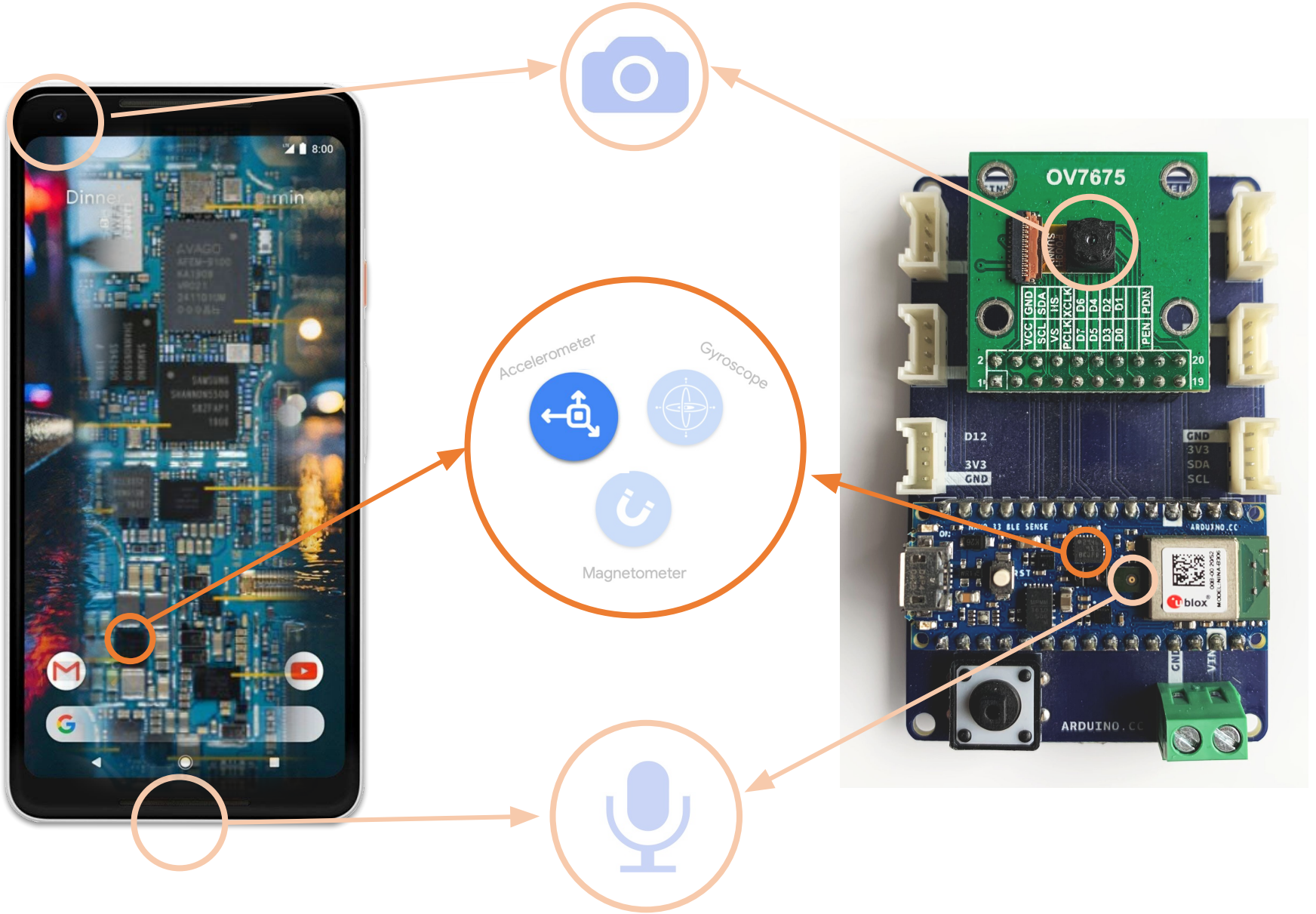


- Pre-Processing Data
- Design a Model
- Train a Model

Data-driven engineering



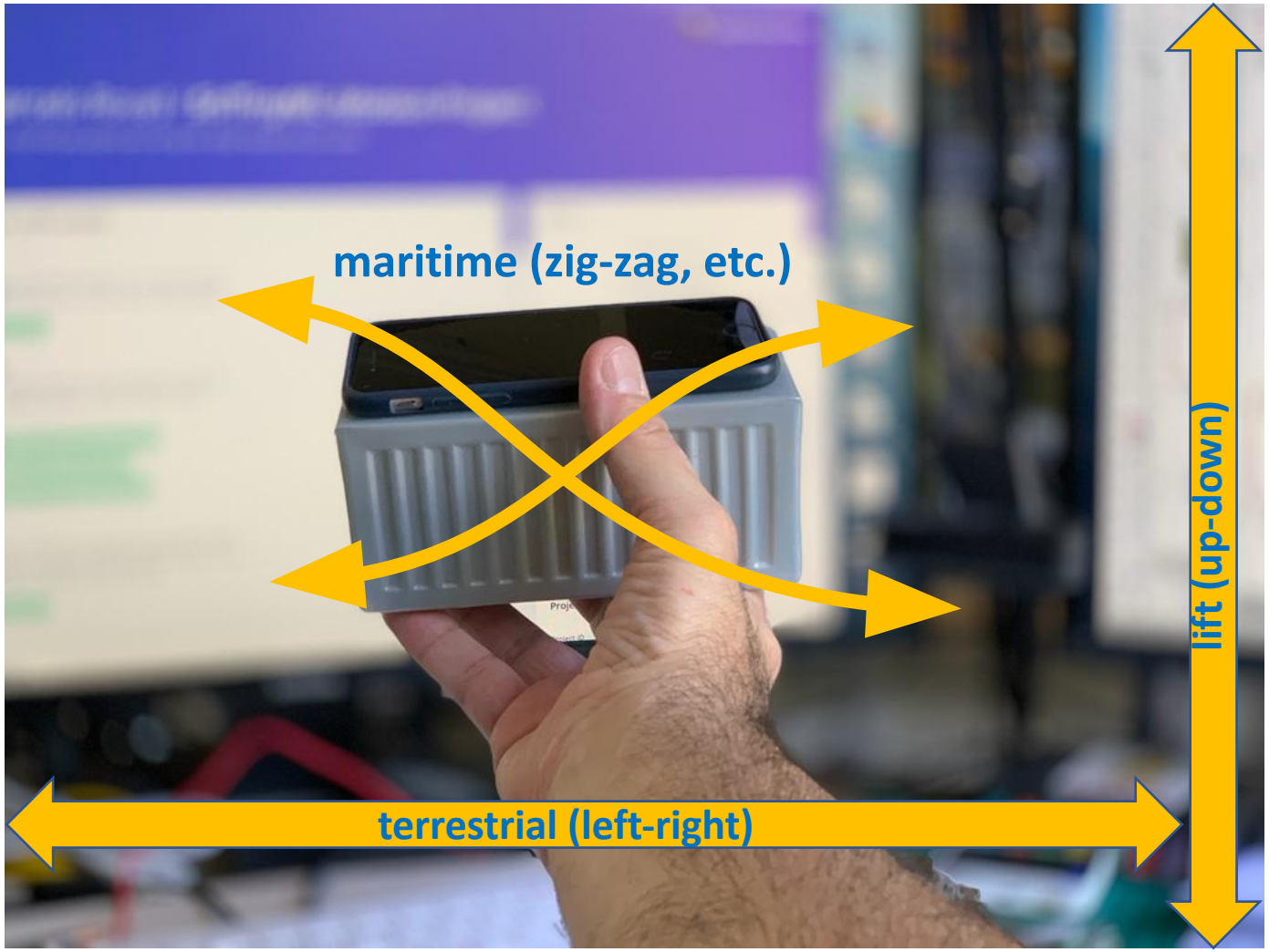
Sensor - IMU (Inertial Measurement Unit)



Motion Classification

Transportation Classes

- **lift** (up-down)
- **terrestrial** (left-right)
- **maritime** (zig-zag, etc.)
- **idle**



Motion Classification

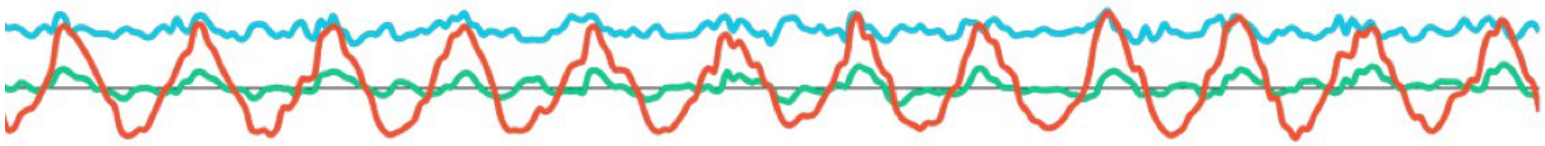
Transportation Classes

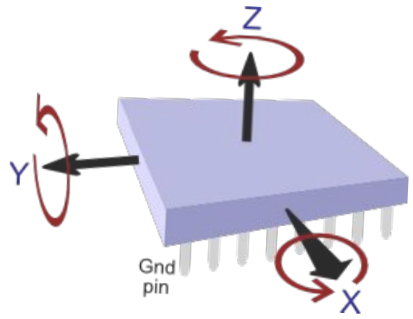
- **lift** (up-down)
- **terrestrial** (left-right)
- **maritime** (zig-zag, etc.)
- **idle**

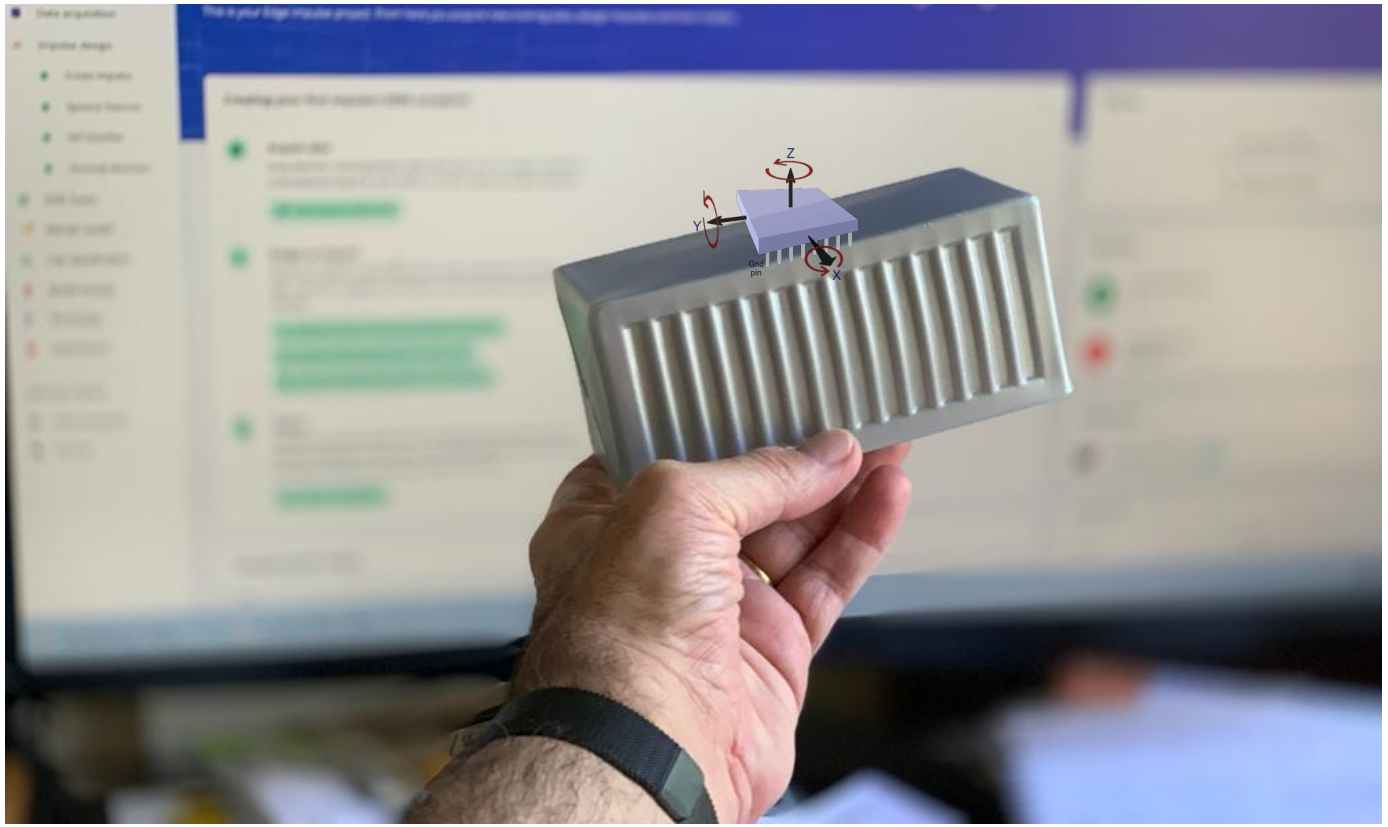
Motion Classification

Transportation Classes

- **lift** (up-down)
- **terrestrial** (left-right)
- **maritime** (zig-zag, etc.)
- **idle**



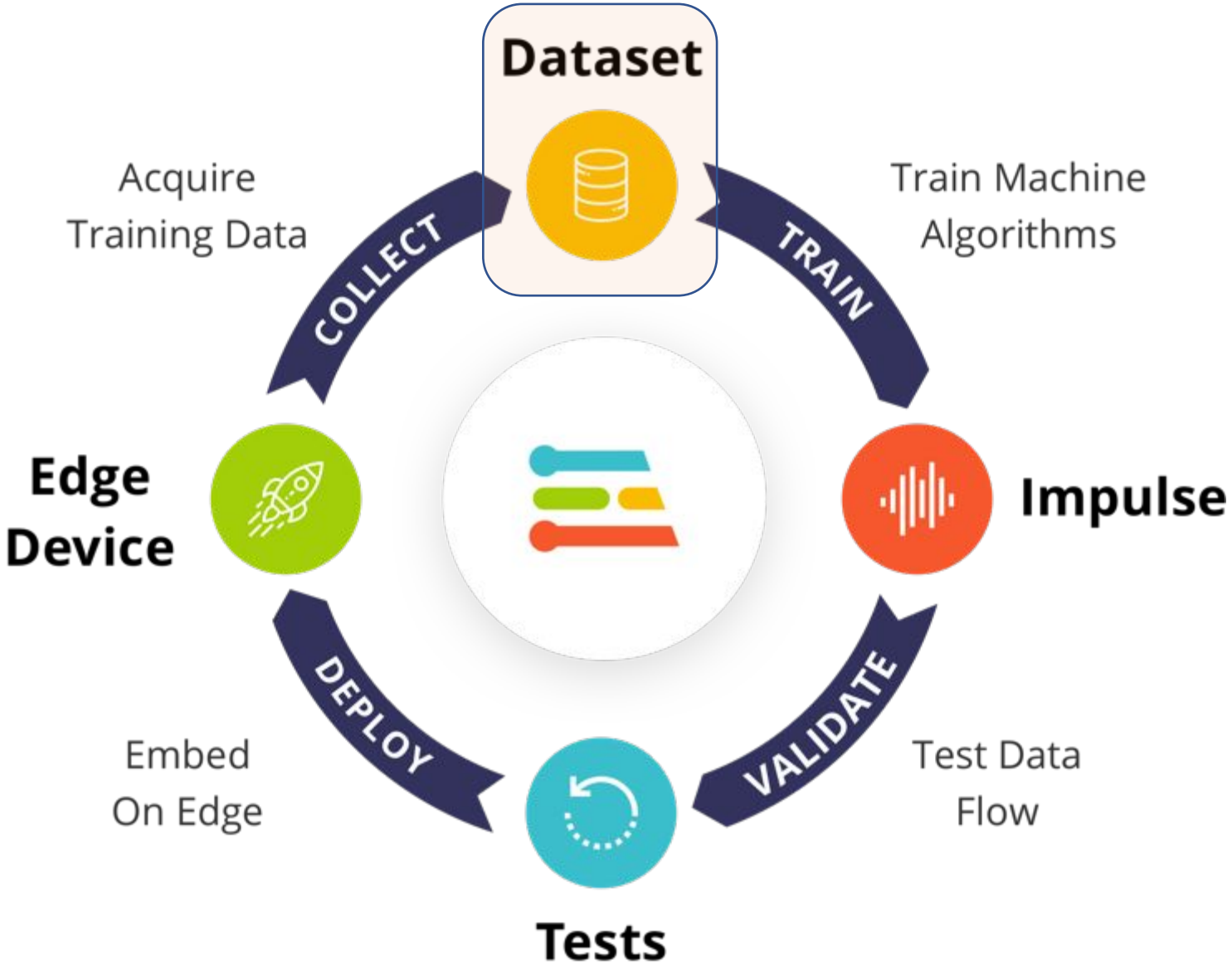




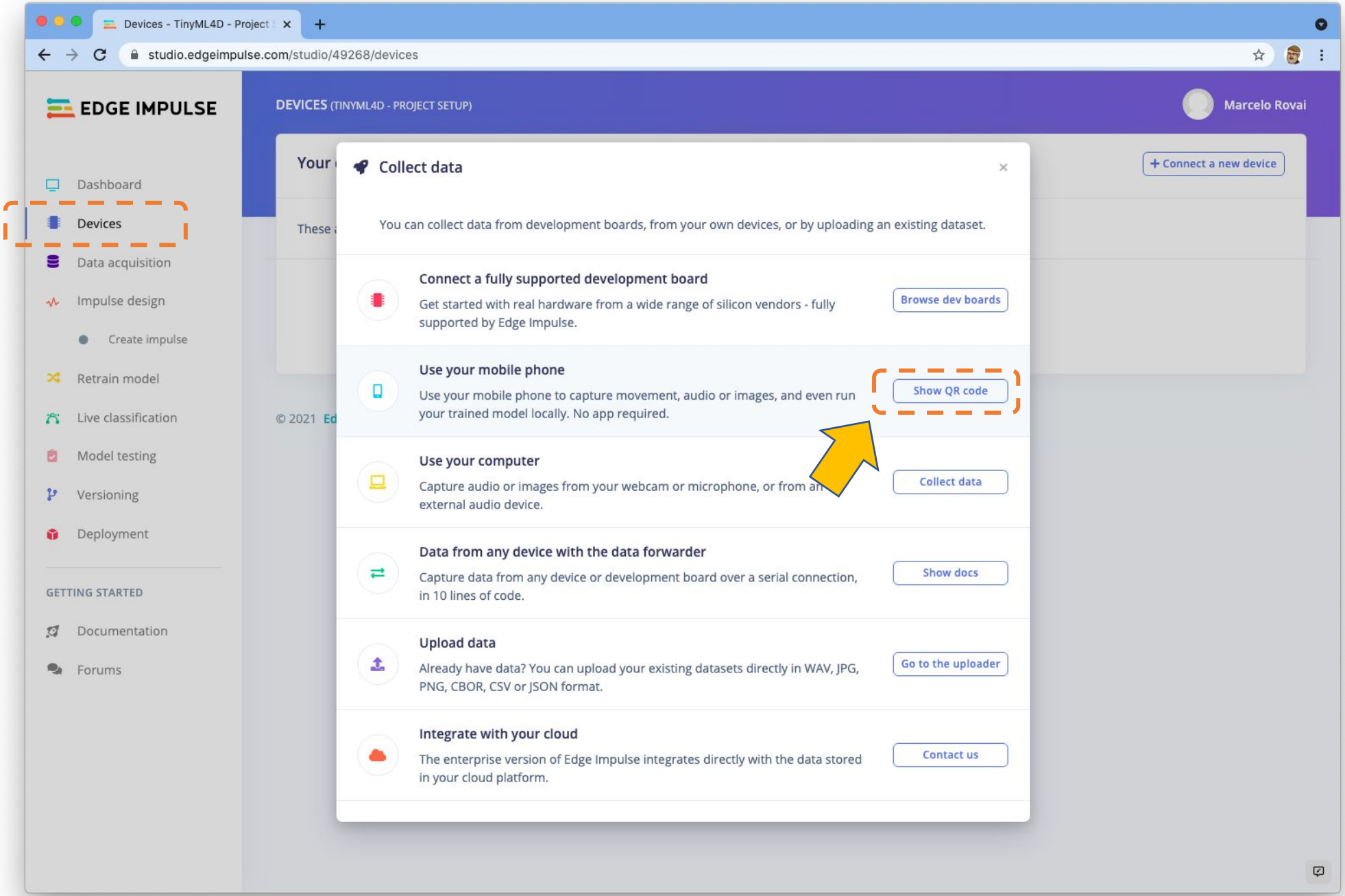
Data: collect & test using accelerometer as sensor

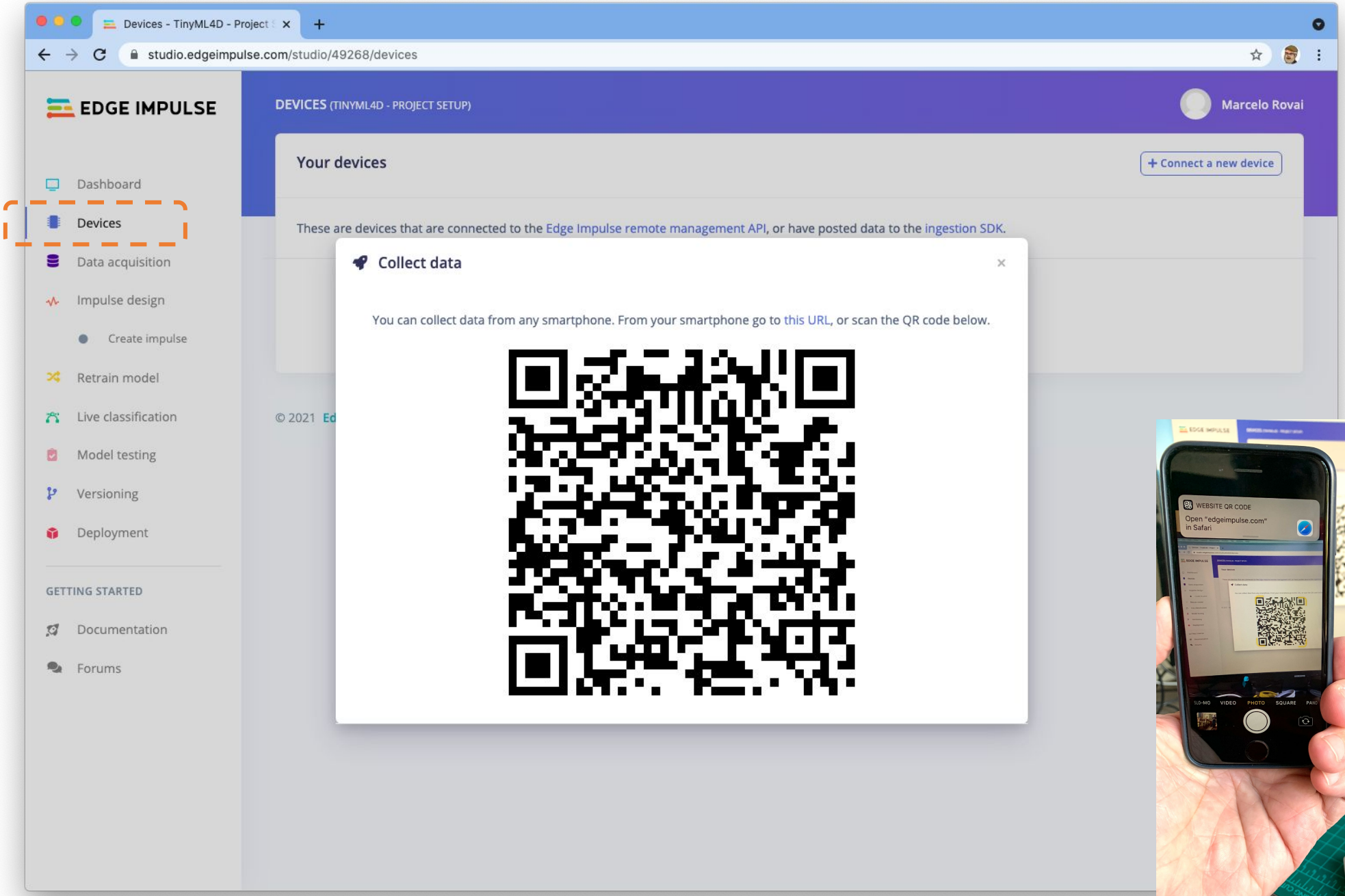
Dataset Collection

Using Smart-Phone

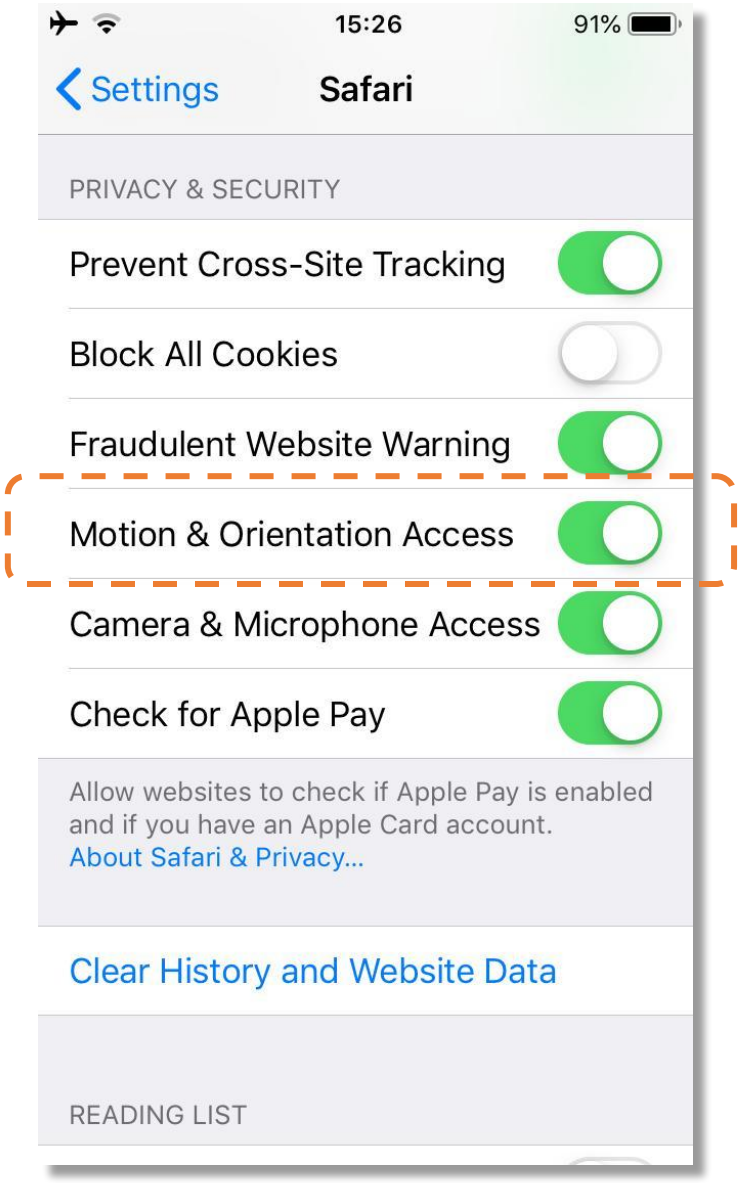


- Pre-Processing Data
- Design a Model
- Train a Model

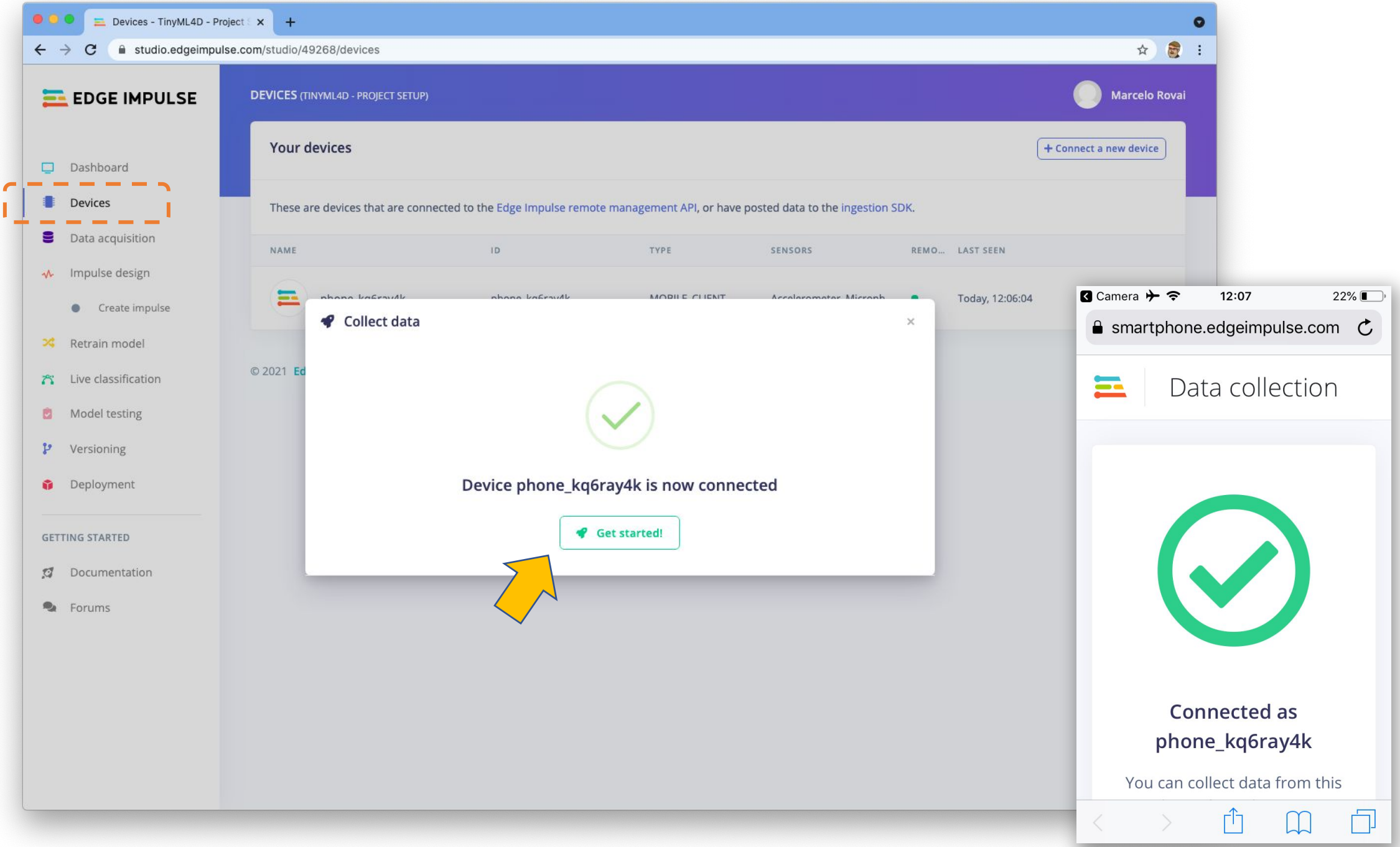

Devices - TinyML4D - Project
studio.edgeimpulse.com/studio/49268/devices
EDGE IMPULSE
DEVICES (TINYML4D - PROJECT SETUP)
Marcelo Rovai
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
+ Connect a new device
Collect data
You can collect data from development boards, from your own devices, or by uploading an existing dataset.
Connect a fully supported development board
Get started with real hardware from a wide range of silicon vendors - fully supported by Edge Impulse.
Browse dev boards
Use your mobile phone
Use your mobile phone to capture movement, audio or images, and even run your trained model locally. No app required.
Show QR code
Use your computer
Capture audio or images from your webcam or microphone, or from an external audio device.
Collect data
Data from any device with the data forwarder
Capture data from any device or development board over a serial connection, in 10 lines of code.
Show docs
Upload data
Already have data? You can upload your existing datasets directly in WAV, JPG, PNG, CBOR, CSV or JSON format.
Go to the uploader
Integrate with your cloud
The enterprise version of Edge Impulse integrates directly with the data stored in your cloud platform.
Contact us

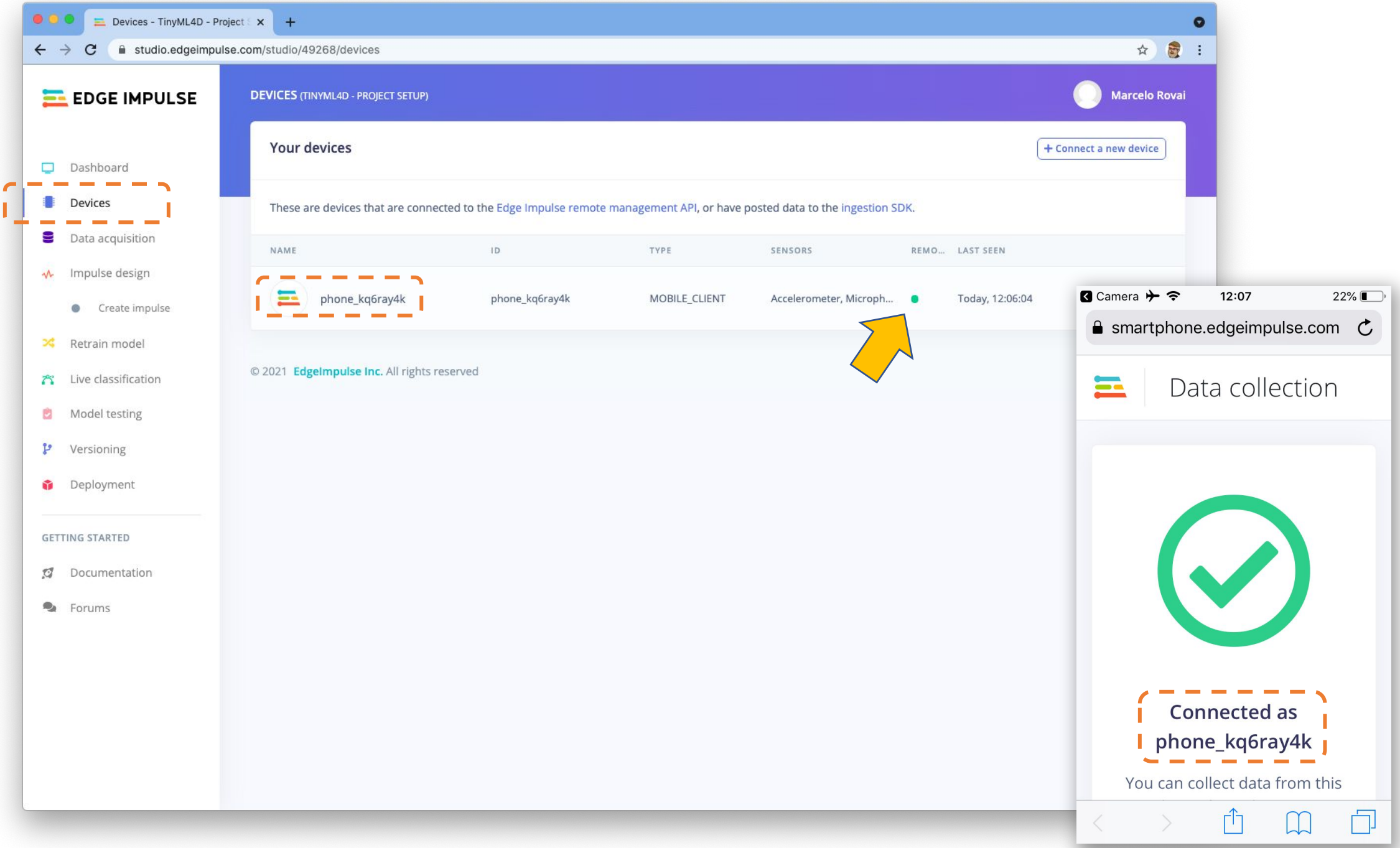

Devices - TinyML4D - Project
studio.edgeimpulse.com/studio/49268/devices
EDGE IMPULSE
DEVICES (TINYML4D - PROJECT SETUP)
Marcelo Rovai
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Your devices
+ Connect a new device
These are devices that are connected to the Edge Impulse remote management API, or have posted data to the ingestion SDK.
Collect data
You can collect data from any smartphone. From your smartphone go to this URL, or scan the QR code below.
© 2021 Ed

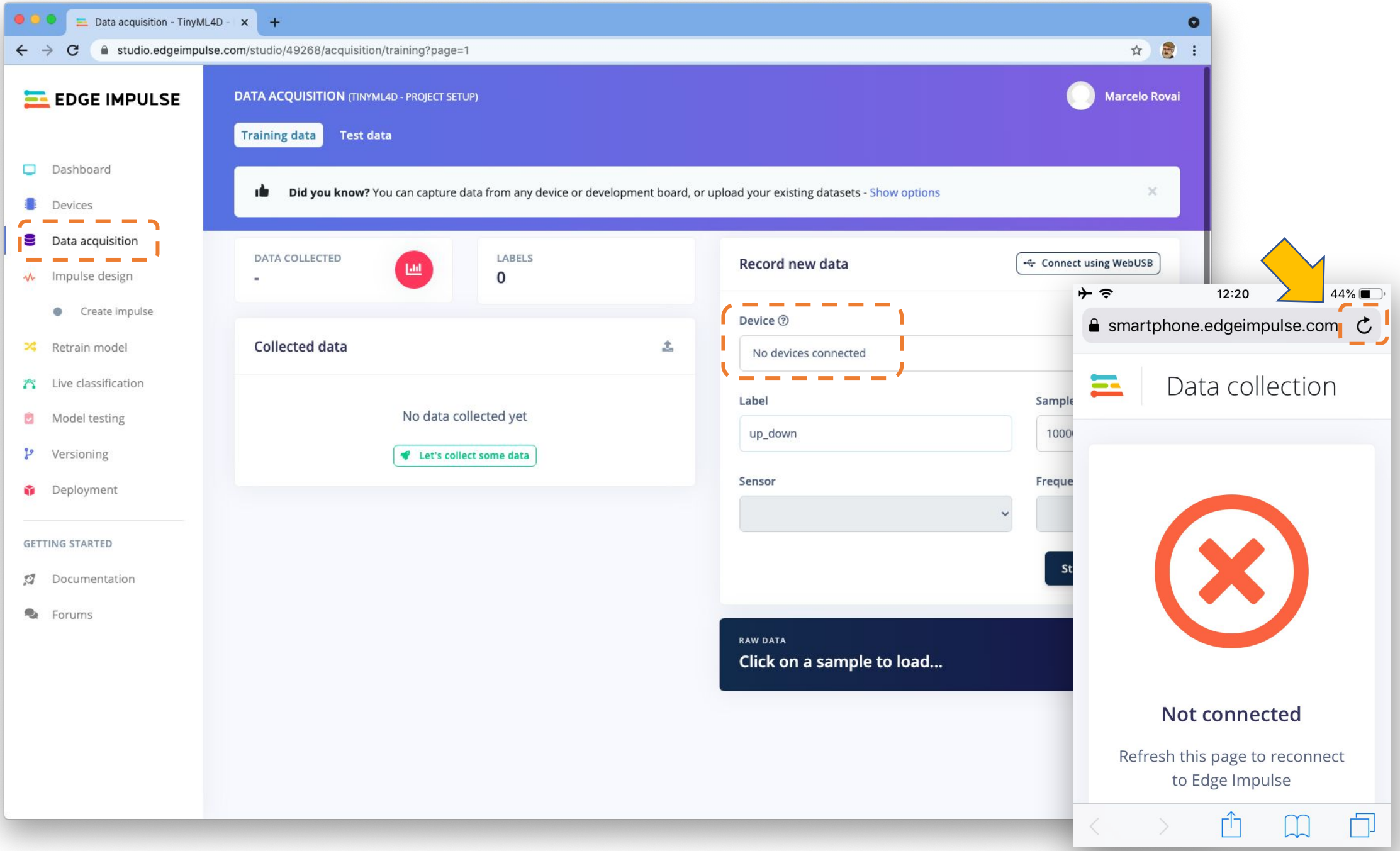

WEBSITE QR CODE
Open "edgeimpulse.com" in Safari



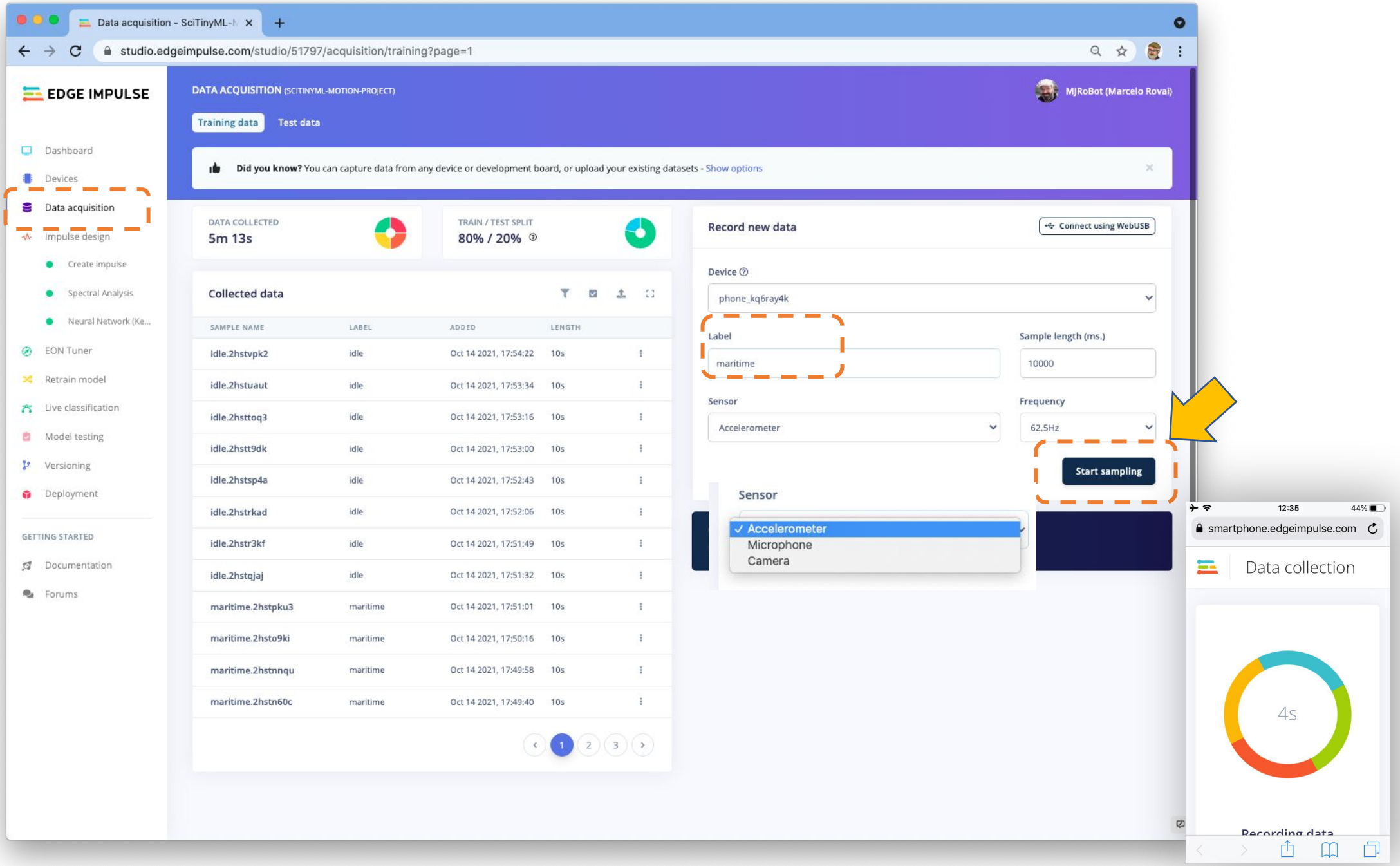
Depending on your mobile OS version and/or your Browser, could be necessary to give access to device IMU sensor


Devices - TinyML4D - Project
studio.edgeimpulse.com/studio/49268/devices
EDGE IMPULSE
DEVICES (TINYML4D - PROJECT SETUP)
Marcelo Rovai
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Your devices
+ Connect a new device
These are devices that are connected to the Edge Impulse remote management API, or have posted data to the ingestion SDK.
NAME
ID
TYPE
SENSORS
REMO...
LAST SEEN
Today, 12:06:04
© 2021
Collect data
Device phone_kq6ray4k is now connected
Get started!
Camera
12:07
22%
smartphone.edgeimpulse.com
Data collection
Connected as
phone_kq6ray4k
You can collect data from this

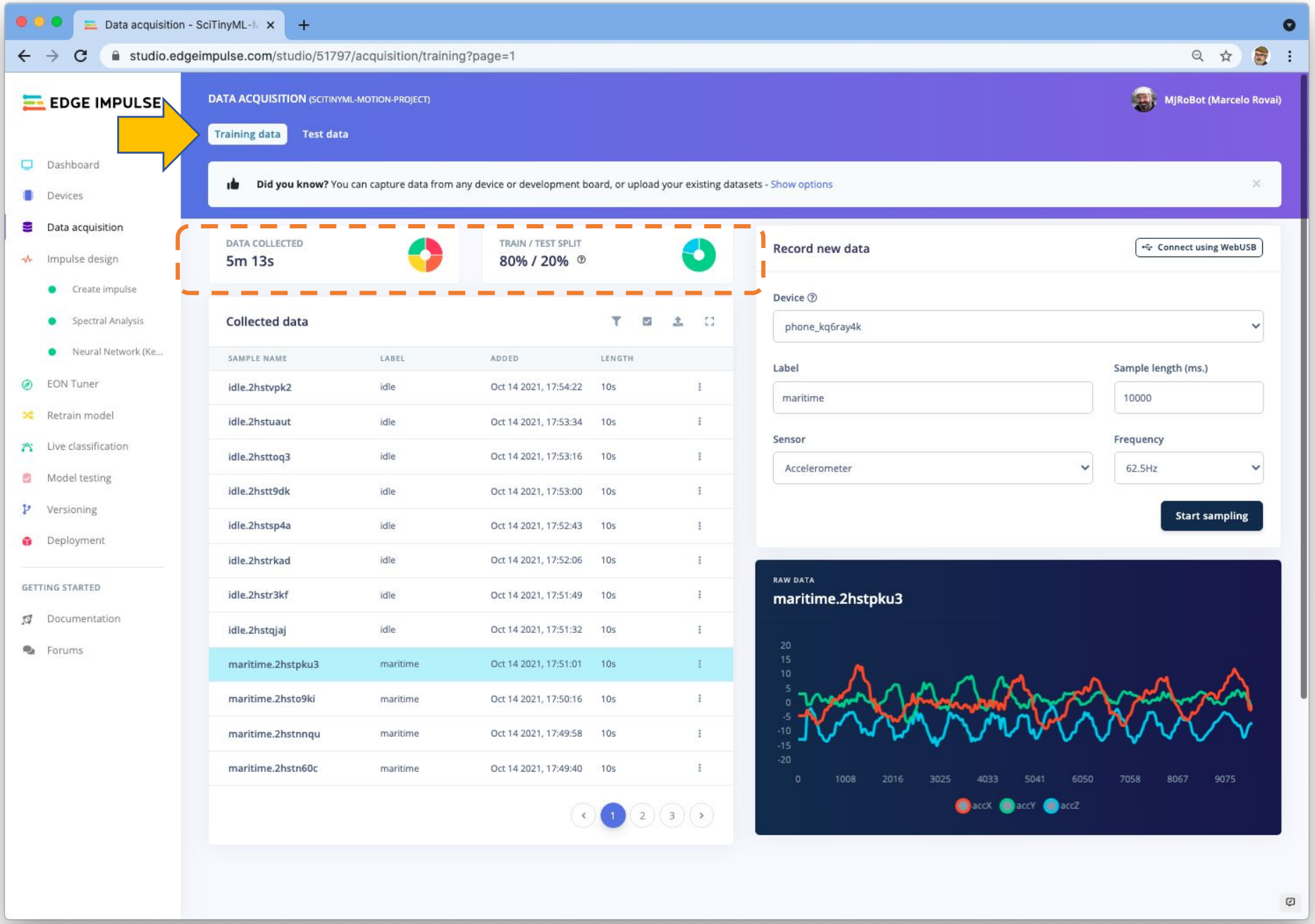

Devices - TinyML4D - Project
studio.edgeimpulse.com/studio/49268/devices
EDGE IMPULSE
DEVICES (TINYML4D - PROJECT SETUP)
Marcelo Rovai
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Your devices
+ Connect a new device
These are devices that are connected to the Edge Impulse remote management API, or have posted data to the ingestion SDK.
NAME
ID
TYPE
SENSORS
REMO...
LAST SEEN
phone_kq6ray4k
phone_kq6ray4k
MOBILE_CLIENT
Accelerometer, Microph...
Today, 12:06:04
© 2021 EdgeImpulse Inc. All rights reserved
Camera
12:07
22%
smartphone.edgeimpulse.com
Data collection
Connected as
phone_kq6ray4k
You can collect data from this


Data acquisition - TinyML4D -
studio.edgeimpulse.com/studio/49268/acquisition/training?page=1
EDGE IMPULSE
DATA ACQUISITION (TINYML4D - PROJECT SETUP)
Marcelo Rovai
Training data
Test data
Did you know? You can capture data from any device or development board, or upload your existing datasets - Show options
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
DATA COLLECTED
-
LABELS
0
Collected data
No data collected yet
Let's collect some data
Record new data
Connect using WebUSB
Device
No devices connected
Label
up_down
Sensor
RAW DATA
Click on a sample to load...
12:20
44%
smartphone.edgeimpulse.com
Data collection
Not connected
Refresh this page to reconnect to Edge Impulse

Collect Data



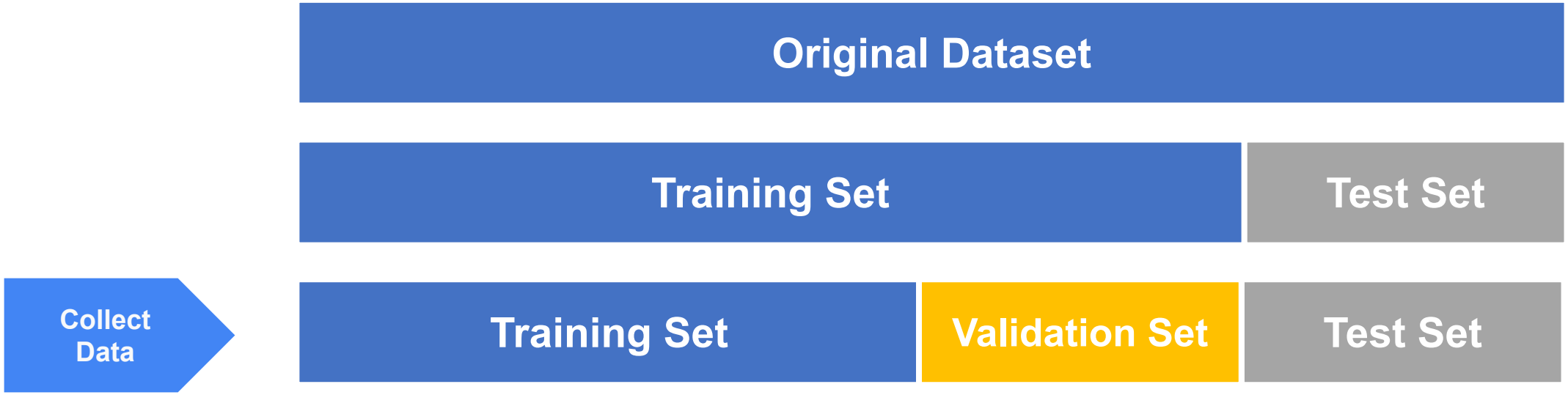
Collect Data

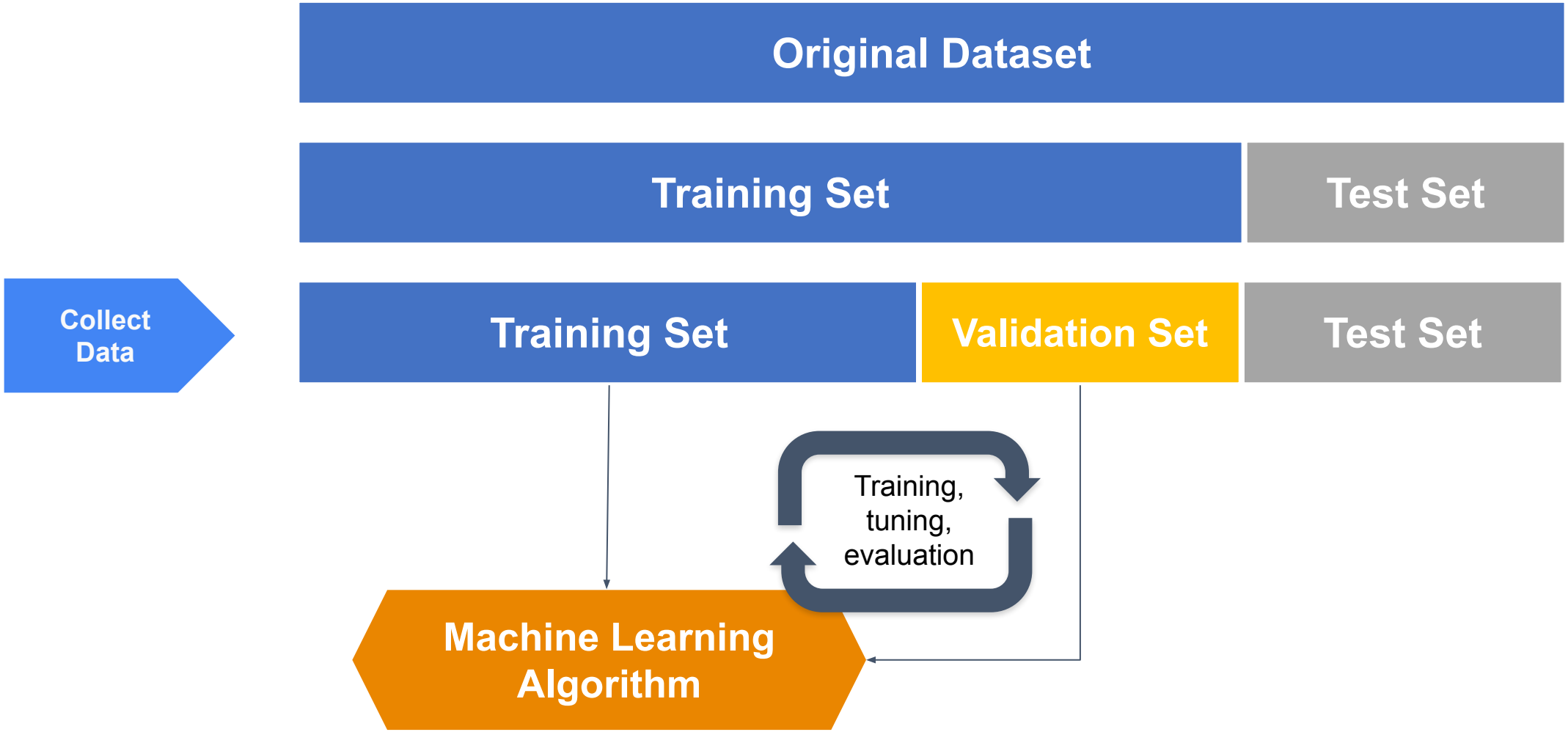


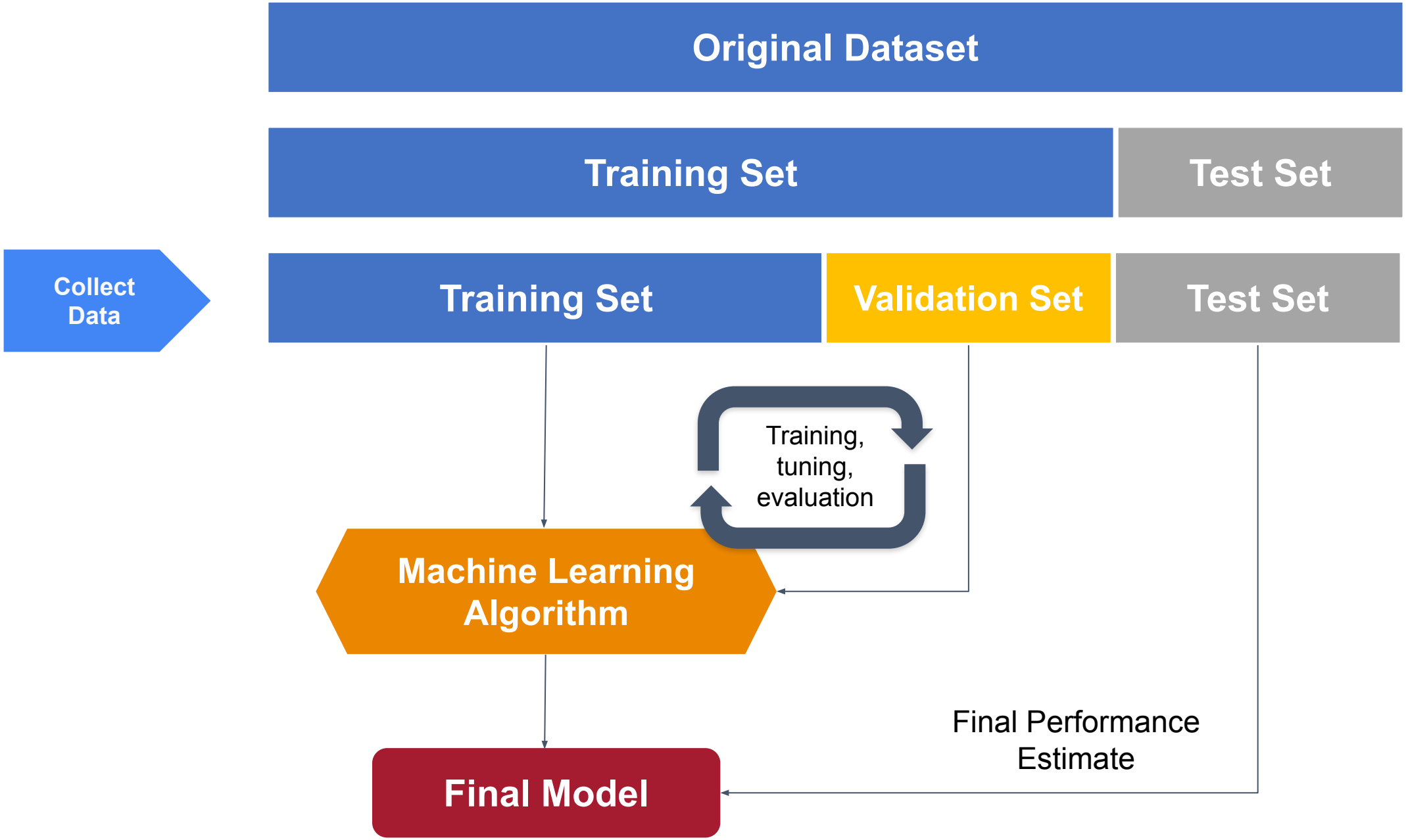
Collect Data

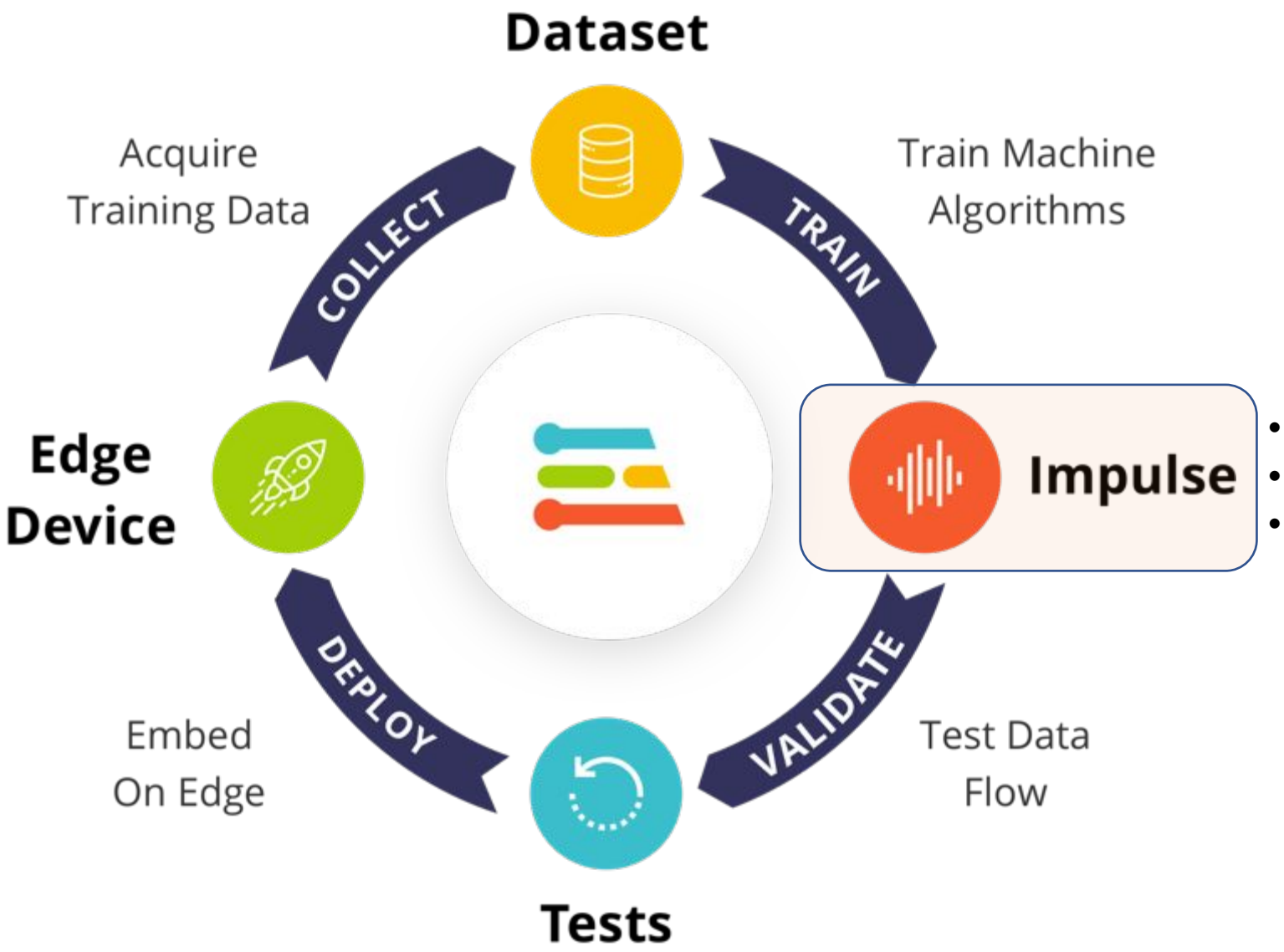
Original Dataset


Original Dataset
Collect Data
Training Set
Test Set

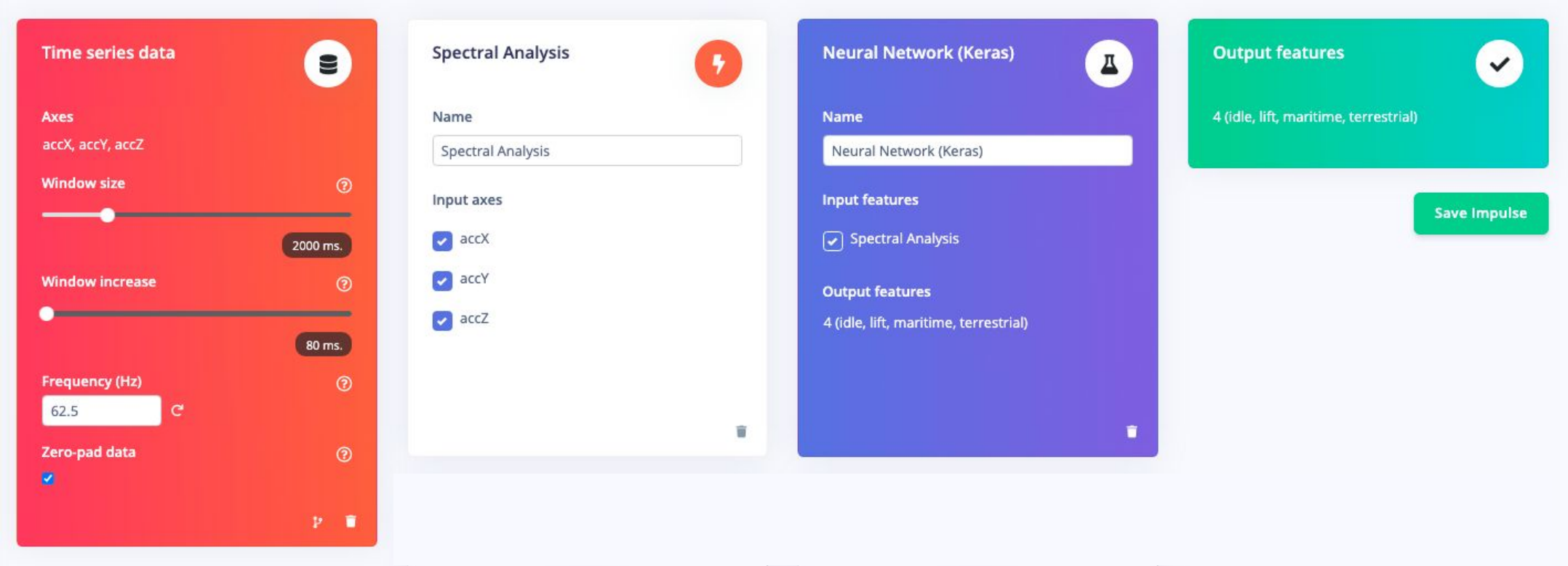

Original Dataset
Training Set
Test Set
Collect Data
Training Set
Validation Set
Test Set

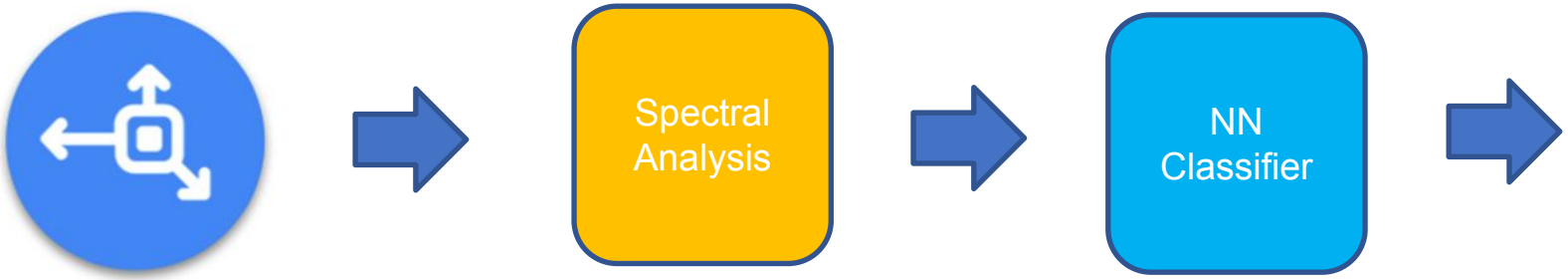

Original Dataset
Training Set
Test Set
Collect Data
Training Set
Validation Set
Test Set
Training, tuning, evaluation
Machine Learning Algorithm


Original Dataset
Training Set
Test Set
Collect Data
Training Set
Validation Set
Test Set
Training, tuning, evaluation
Machine Learning Algorithm
Final Performance Estimate
Final Model



- Pre-Processing Data
- Design a Model
- Train a Model

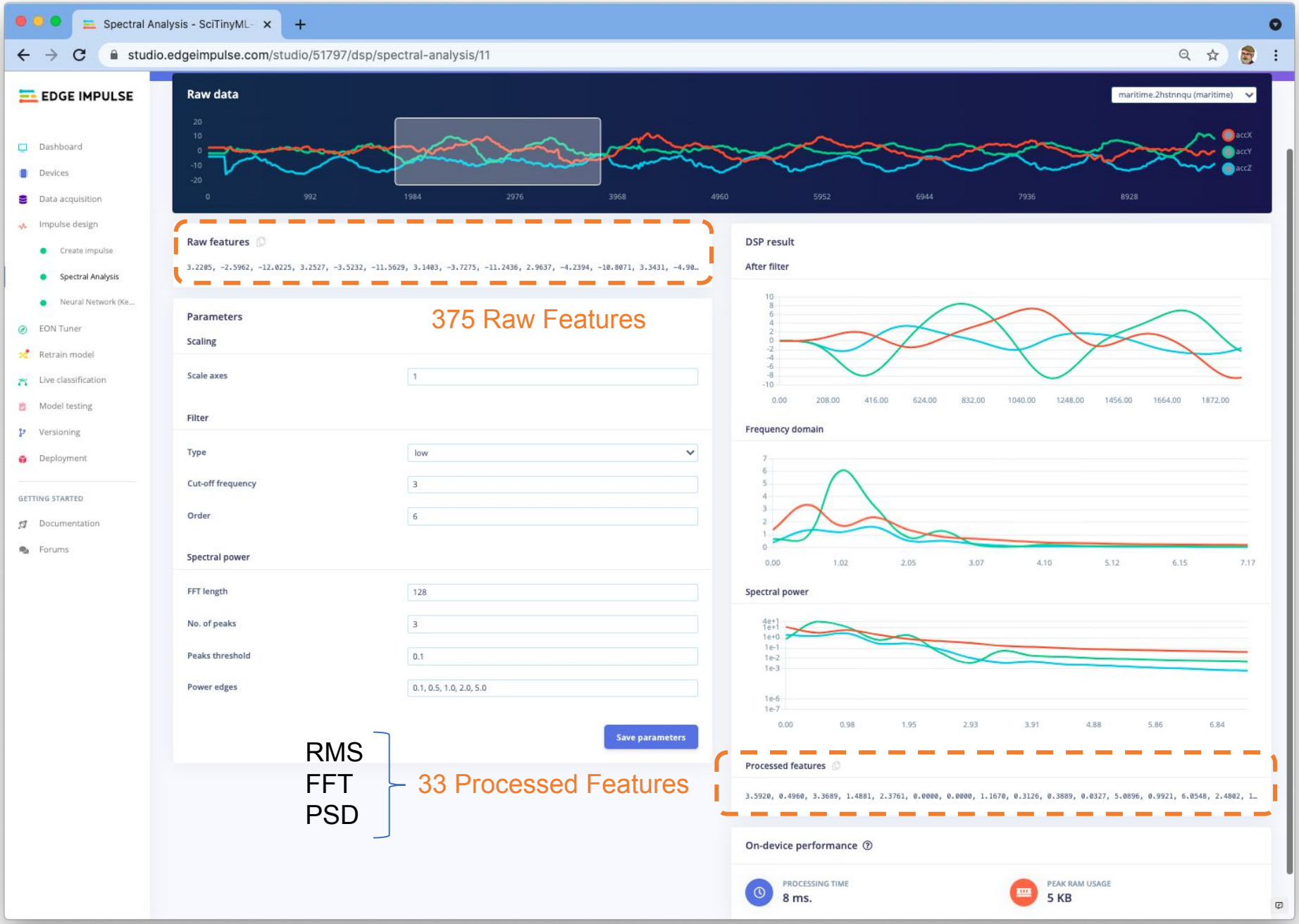




Classes

- Lift
- Terrestrial
- Maritime
- Iddle

Preprocess Data



Preprocess Data

Spectral Analysis - SciTinyML

studio.edgeimpulse.com/studio/51797/dsp/spectral-analysis/11/generate-features

EDGE IMPULSE

- Dashboard
- Devices
- Data acquisition
- Impulse design
  - Create impulse
  - Spectral Analysis
  - Neural Network (Ke...
- EON Tuner
- Retrain model
- Live classification
- Model testing
- Versioning
- Deployment

GETTING STARTED

- Documentation
- Forums

SPECTRAL ANALYSIS (SCITINYML-MOTION-PROJECT)

#1 EON Tuner Primary

Parameters | Generate features

MJRoBot (Marcelo Rovai)

Training set

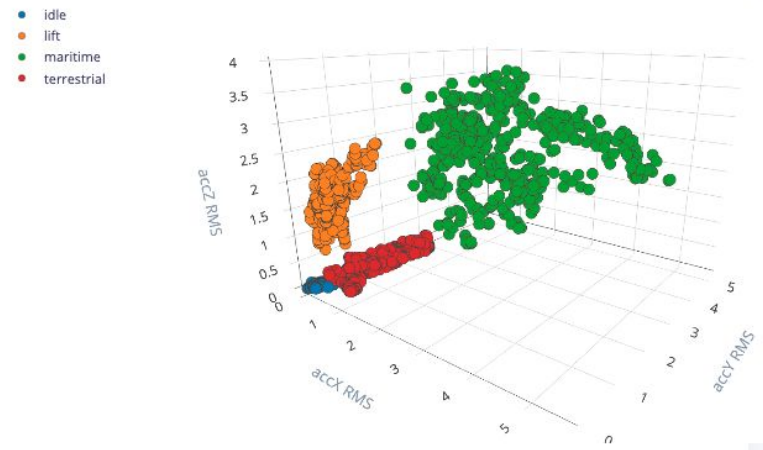
Data in training set	5m 22s
Classes	4 (idle, lift, maritime, terrestrial)
Window length	2000 ms.
Window increase	80 ms.
Training windows	3,230

Generate features

- ✓ accX RMS
- accX Peak 1 Freq
- accX Peak 1 Height
- accX Peak 2 Freq
- accX Peak 2 Height
- accX Peak 3 Freq
- accX Peak 3 Height
- accX Spectral Power 0.1 - 0.5
- accX Spectral Power 0.5 - 1.0
- accX Spectral Power 1.0 - 2.0
- accX Spectral Power 2.0 - 5.0
- accY RMS
- accY Peak 1 Freq
- accY Peak 1 Height
- accY Peak 2 Freq
- accY Peak 2 Height
- accY Peak 3 Freq
- accY Peak 3 Height
- accY Spectral Power 0.1 - 0.5
- accY Spectral Power 0.5 - 1.0
- accY Spectral Power 1.0 - 2.0
- accY Spectral Power 2.0 - 5.0
- accZ RMS
- accZ Peak 1 Freq
- accZ Peak 1 Height
- accZ Peak 2 Freq
- accZ Peak 2 Height
- accZ Peak 3 Freq
- accZ Peak 3 Height
- accZ Spectral Power 0.1 - 0.5
- accZ Spectral Power 0.5 - 1.0
- accZ Spectral Power 1.0 - 2.0
- accZ Spectral Power 2.0 - 5.0

Feature explorer (3,132 samples)

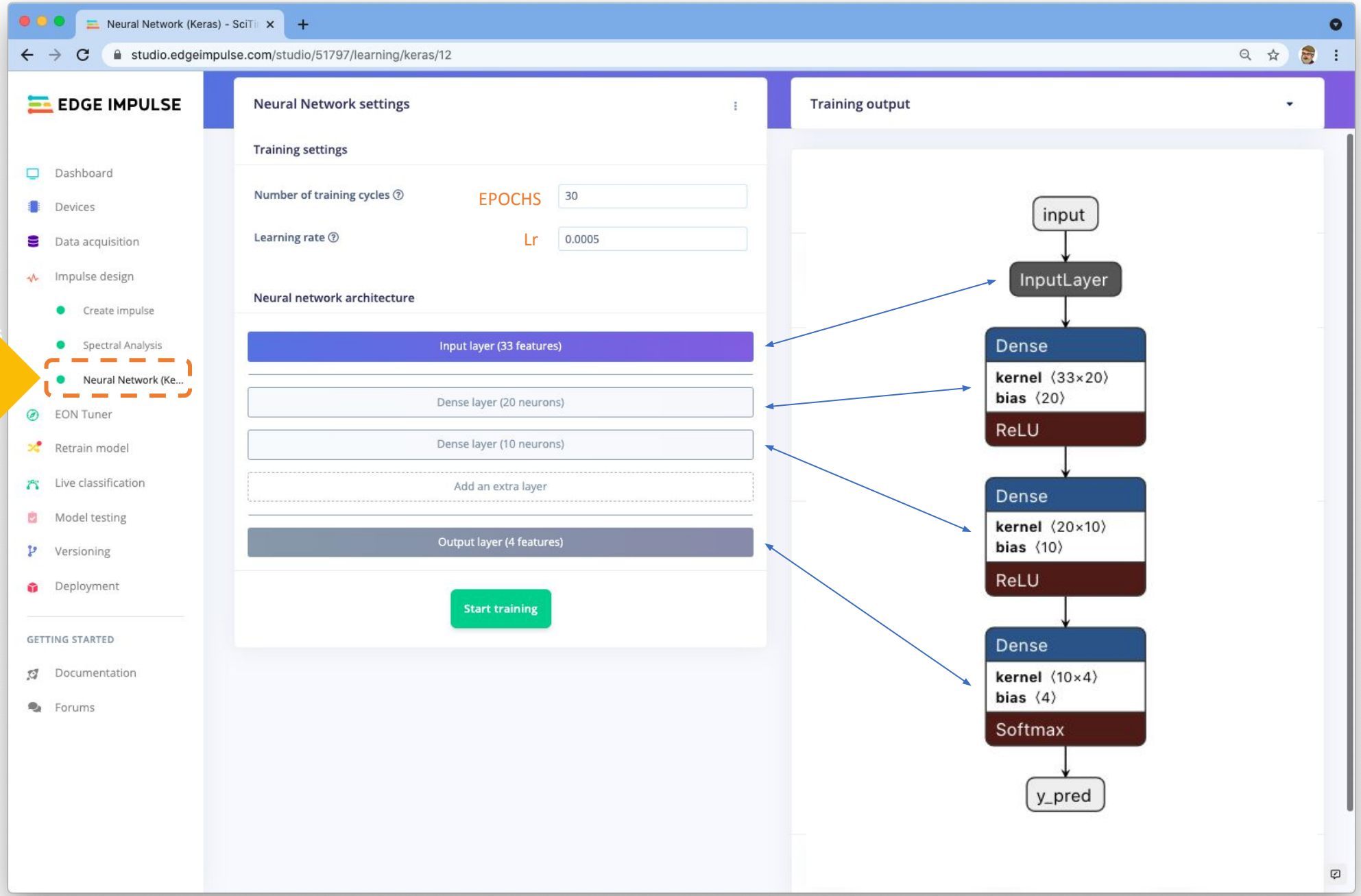
X Axis: accX RMS | Y Axis: accY RMS | Z Axis: accZ RMS



On-device performance

PROCESSING TIME
8 ms.

PEAK RAM USAGE
5 KB



Design a Model

Train a Model

Neural Network (Keras) - SciTi

studio.edgeimpulse.com/studio/51797/learning/keras/12

EDGE IMPULSE

- Dashboard
- Devices
- Data acquisition
- Impulse design
  - Create impulse
  - Spectral Analysis
  - Neural Network (Ke...
- EON Tuner
- Retrain model
- Live classification
- Model testing
- Versioning
- Deployment

GETTING STARTED

- Documentation
- Forums

Neural Network settings

Training settings

Number of training cycles — EPOCHS: 30

Learning rate — Lr: 0.0005

Neural network architecture

Input layer (33 features)

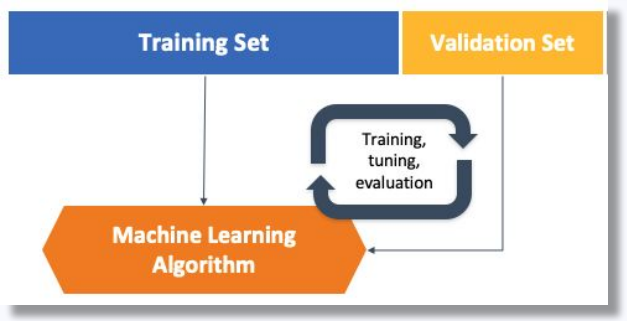
Dense layer (20 neurons)

Dense layer (10 neurons)

Add an extra layer

Output layer (4 features)

Start training



Training output

Model

Model version: Quantized (int8)

Last training performance (validation set)

ACCURACY 99.7%

LOSS 0.01

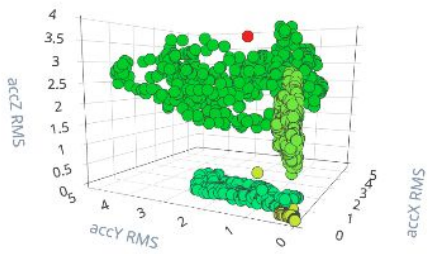
Confusion matrix (validation set)

	IDLE	LIFT	MARITIME	TERRESTRIAL
IDLE	100%	0%	0%	0%
LIFT	0%	100%	0%	0%
MARITIME	0%	0.6%	99.4%	0%
TERRESTRIAL	0.6%	0%	0%	99.4%
F1 SCORE	1.00	1.00	1.00	1.00

Feature explorer (full training set)

accX RMS | accY RMS | accZ RMS

- idle - correct
- lift - correct
- maritime - correct
- terrestrial - correct
- maritime - incorrect
- terrestrial - incorrect



On-device performance

INFERENCING TIME 1 ms.

PEAK RAM USAGE 1.7K

FLASH USAGE 19.0K

Evaluate
Optimize

Neural Network (Keras) - SciTi

studio.edgeimpulse.com/studio/51797/learning/keras/12

EDGE IMPULSE

- Dashboard
- Devices
- Data acquisition
- Impulse design
  - Create impulse
  - Spectral Analysis
  - Neural Network (Ke...
- EON Tuner
- Retrain model
- Live classification
- Model testing
- Versioning
- Deployment

GETTING STARTED

- Documentation
- Forums

Neural Network settings

Training settings

Number of training cycles: 30

Learning rate: 0.0005

Neural network architecture

Input layer (33 features)

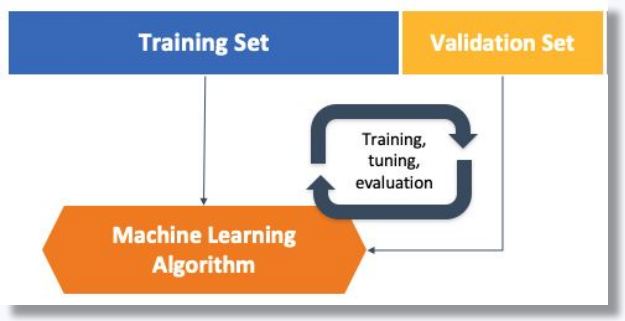
Dense layer (20 neurons)

Dense layer (10 neurons)

Add an extra layer

Output layer (4 features)

Start training



Training output

Model

Model version: Quantized (int8)

Last training performance (validation set)

ACCURACY 99.7%

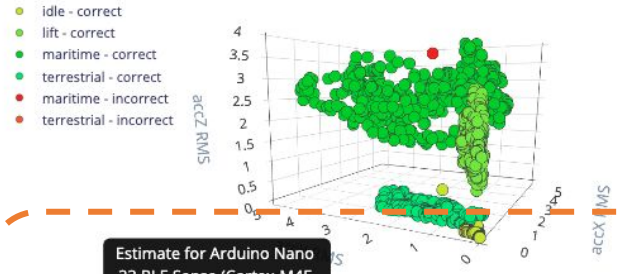
LOSS 0.01

Confusion matrix (validation set)

	IDLE	LIFT	MARITIME	TERRESTRIAL
IDLE	100%	0%	0%	0%
LIFT	0%	100%	0%	0%
MARITIME	0%	0.6%	99.4%	0%
TERRESTRIAL	0.6%	0%	0%	99.4%
F1 SCORE	1.00	1.00	1.00	1.00

Feature explorer (full training set)

accX RMS | accY RMS | accZ RMS



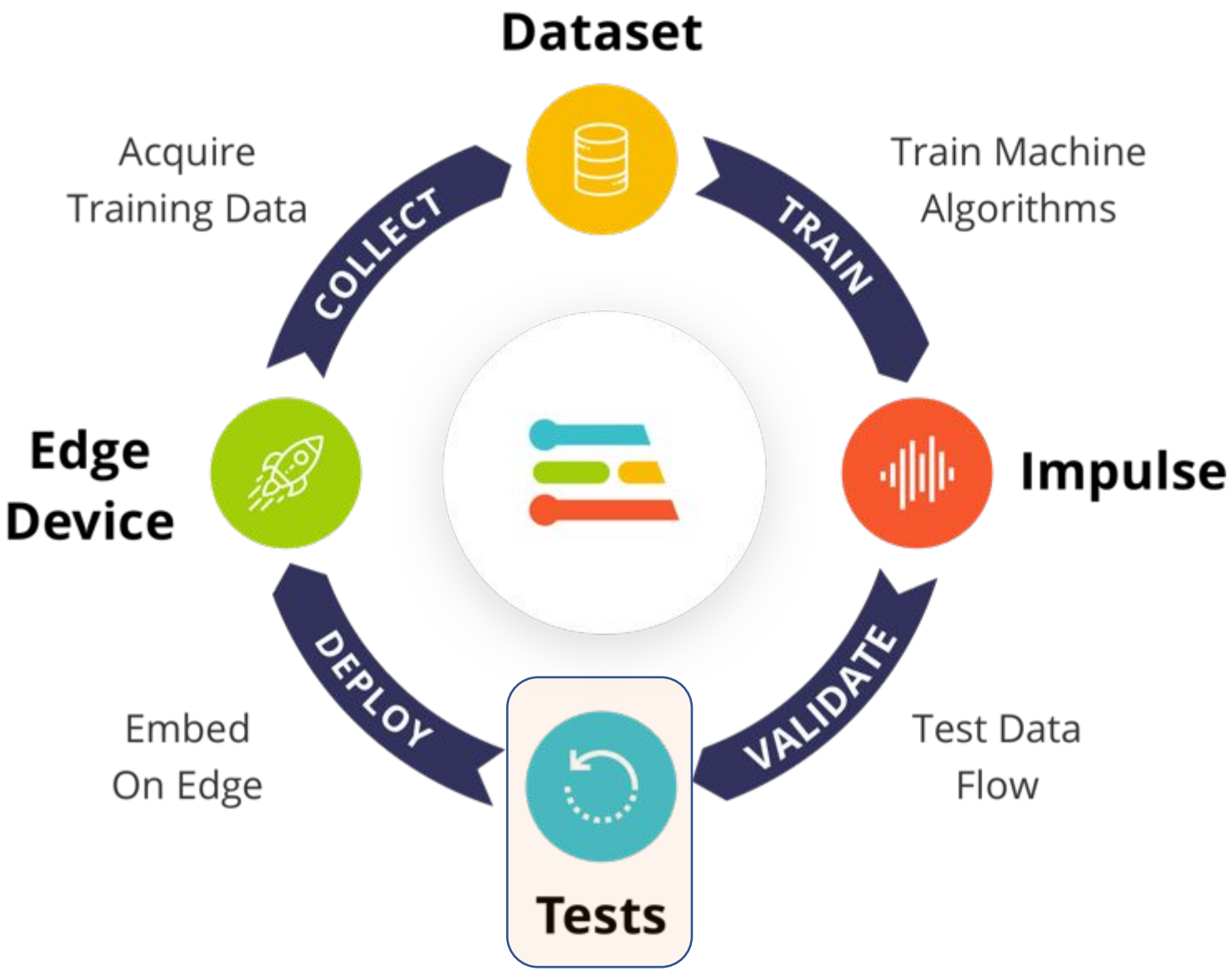
Estimate for Arduino Nano 33 BLE Sense (Cortex-M4F 64MHz), compiled with Edge Impulse EON™ compiler

On-device performance

INFERENCING TIME 1 ms.

PEAK RAM USAGE 1.7K

FLASH USAGE 19.0K



- Pre-Processing Data
- Design a Model
- Train a Model

Evaluate
Optimize

Model testing - SciTinyML-Mot

studio.edgeimpulse.com/studio/51797/validation

EDGE IMPULSE

- Dashboard
- Devices
- Data acquisition
- Impulse design
  - Create impulse
  - Spectral Analysis
  - Neural Network (Ke...
- EON Tuner
- Retrain model
- Live classification
- Model testing
- Versioning
- Deployment

GETTING STARTED

- Documentation
- Forums

MODEL TESTING (SCITINYML-MOTION-PROJECT)

MJRoBot (Marcelo Rovai)

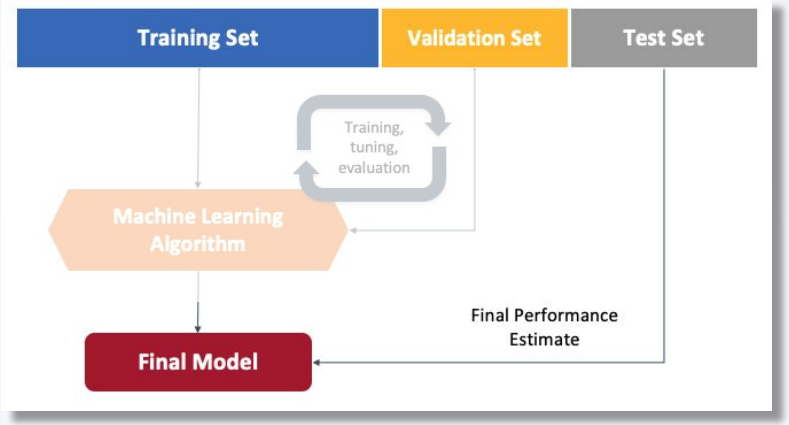
This lists all test data. You can manage this data through Data acquisition.

Test data

Classify all

Set the 'expected outcome' for each sample to the desired outcome to automatically score the impulse.

SAMPLE NAME	EXPECTED OUTCO...	LENGTH	ACCURACY	RESULT
testing.2hvf...	testing	10s		
terrestrial.2...	terrestrial	10s	100%	98 terrestrial
terrestrial.2...	terrestrial	10s	100%	98 terrestrial
lift .2hssi1t6	lift	10s	100%	98 lift
lift .2hst8tvj	lift	10s	100%	98 lift



Model testing output

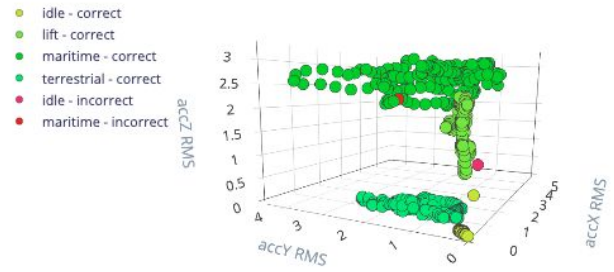
Model testing results

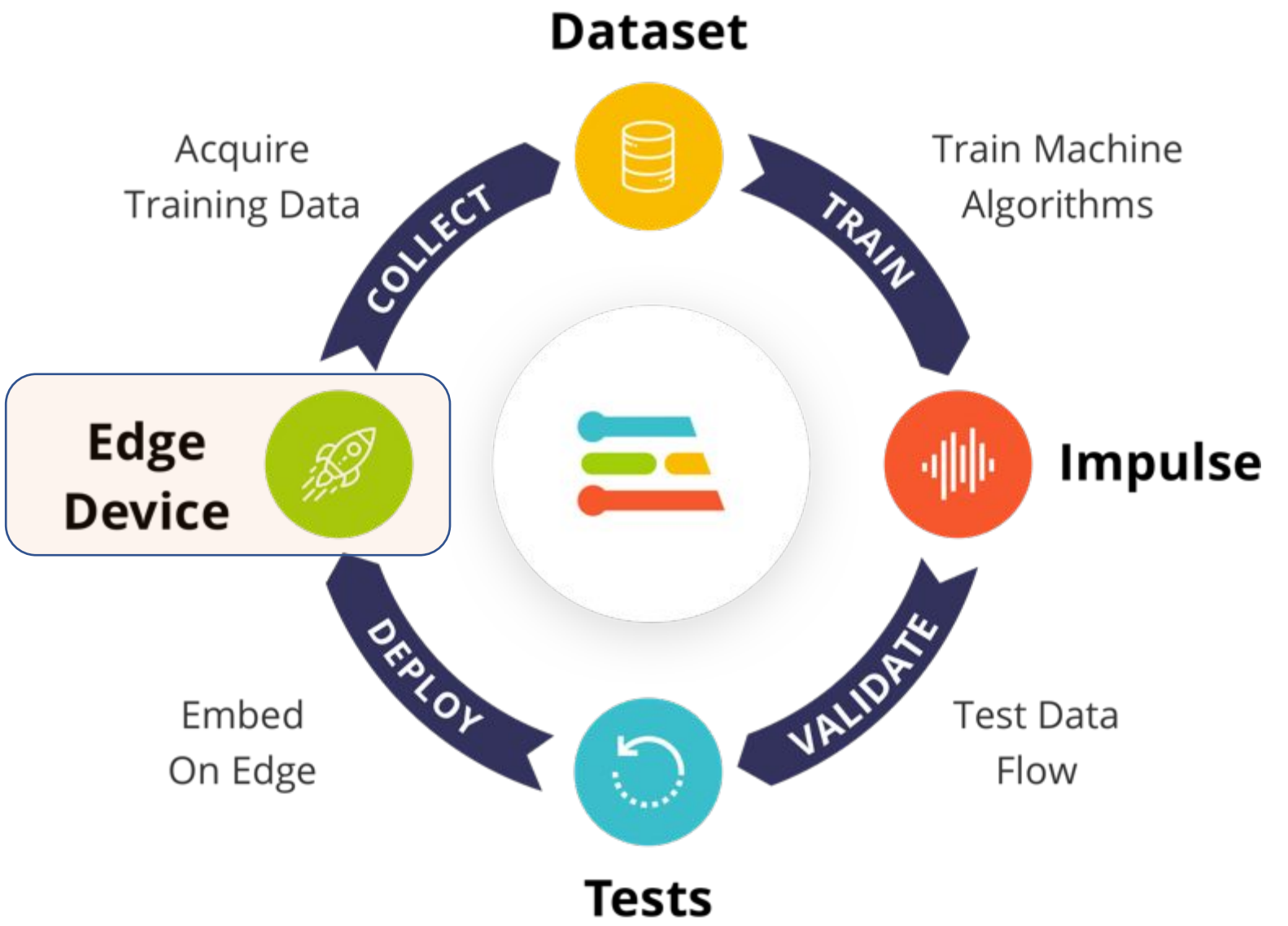
ACCURACY
99.74%

	IDLE	LIFT	MARITIME	TERRESTRIAL	UNCERTAIN
IDLE	99.5%	0.5%	0%	0%	0%
LIFT	0%	100%	0%	0%	0%
MARITIME	0%	0%	99.5%	0%	0.5%
TERRESTRIAL	0%	0%	0%	100%	0%
F1 SCORE	1.00	1.00	1.00	1.00	

Feature explorer

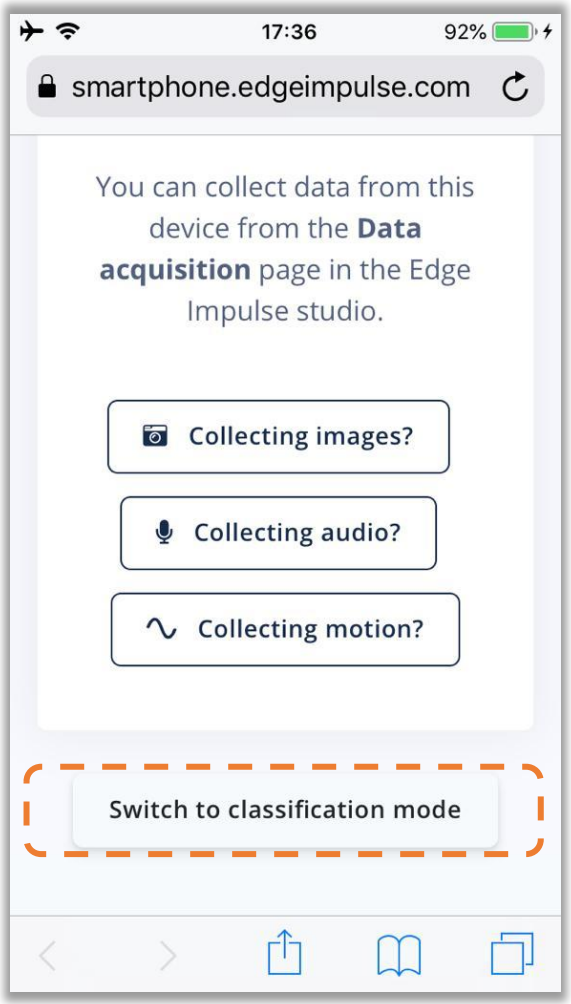
accX RMS | accY RMS | accZ RMS

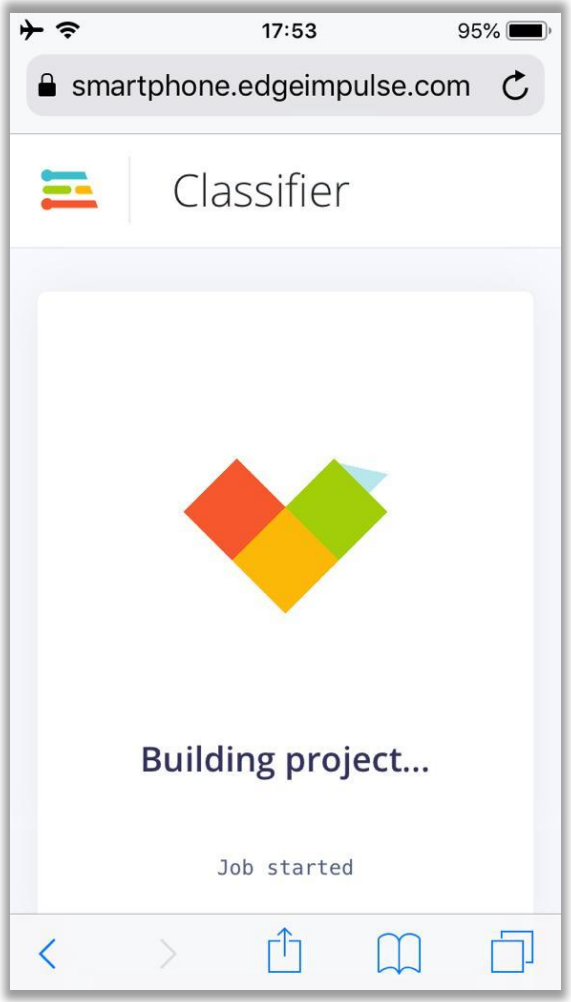




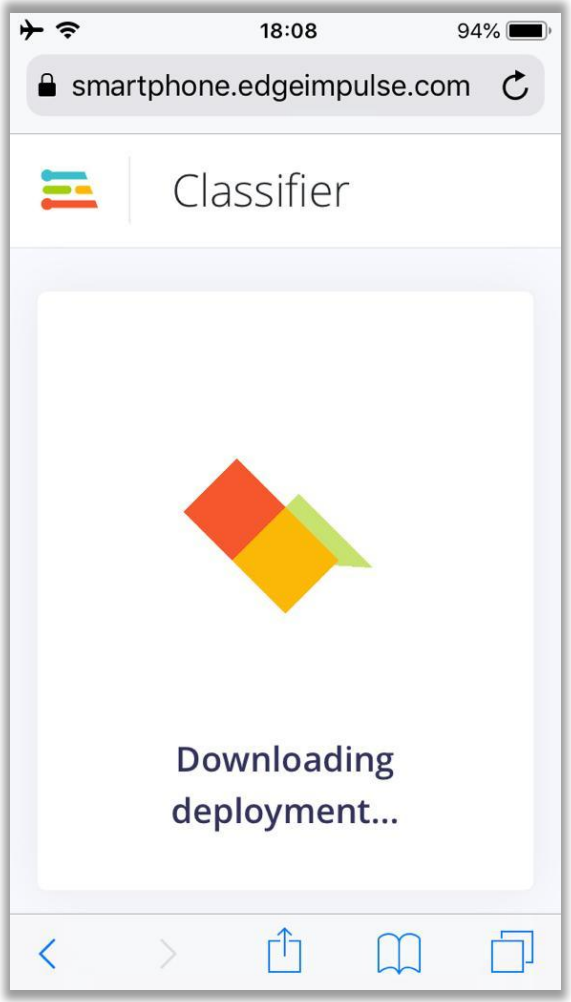
- Pre-Processing Data
- Design a Model
- Train a Model

Convert Model

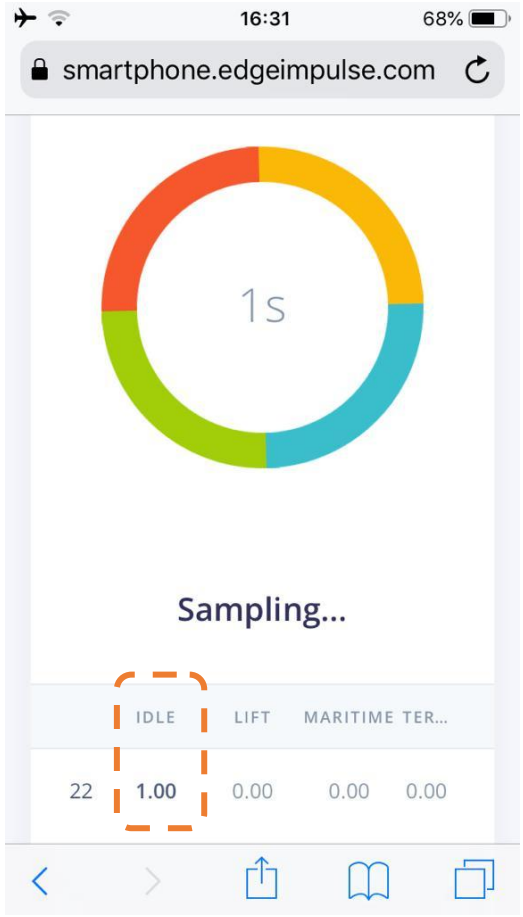


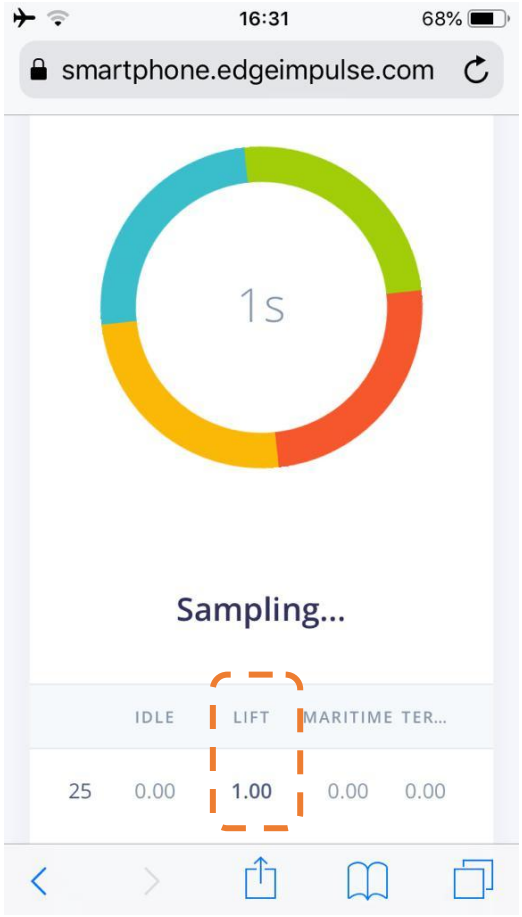


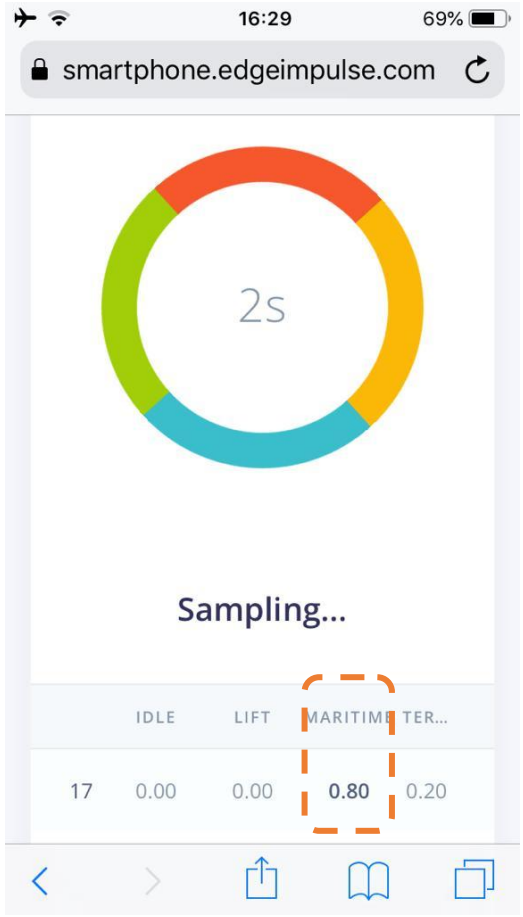
Deploy Model

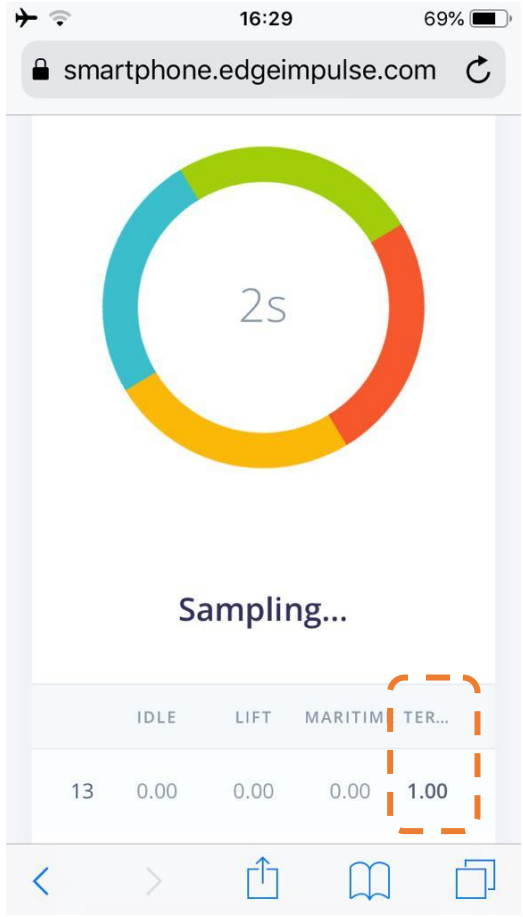


Make Inferences



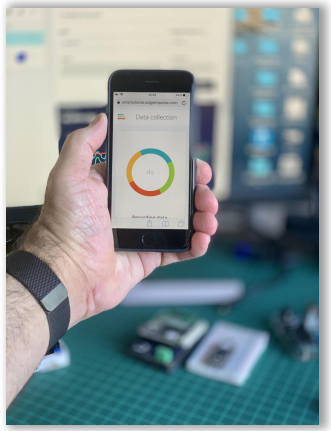


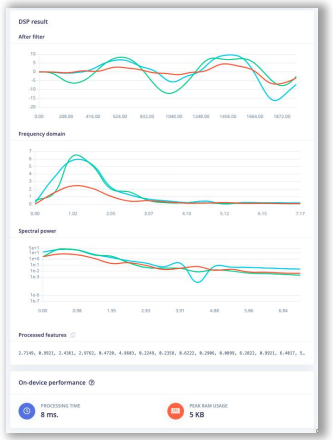


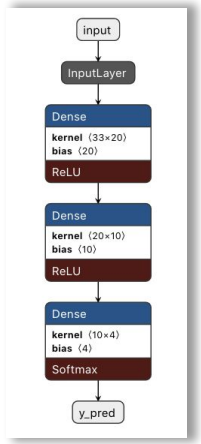


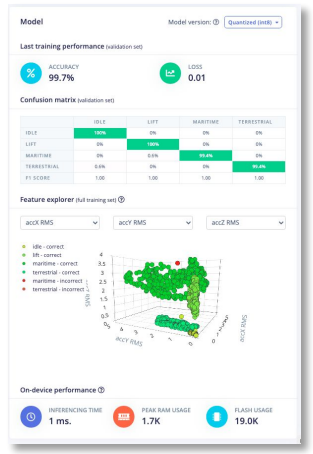
Motion Classification - Summary

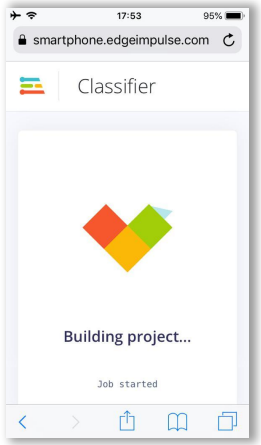
Collect Data → Preprocess Data → Design a Model → Train a Model → Evaluate Optimize → Convert Model → Deploy Model → Make Inferences

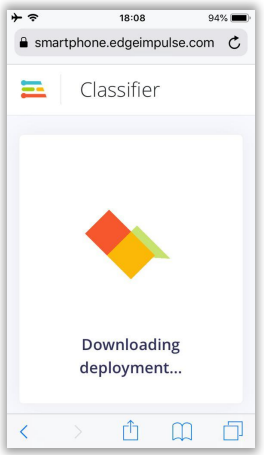


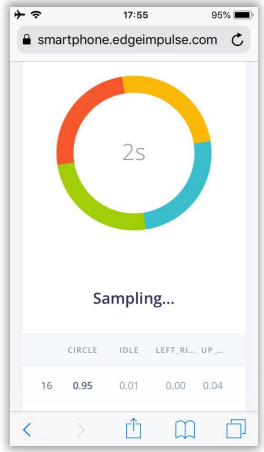






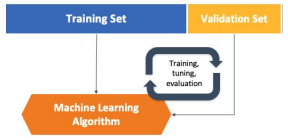


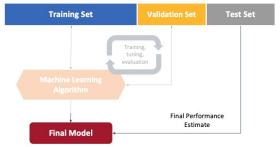




Spectral Analysis

NN Classifier





Reading Material

Main references

- Harvard School of Engineering and Applied Sciences - CS249r: Tiny Machine Learning
- 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
- Fundamentals textbook: “Deep Learning with Python” by François Chollet
- Applications & Deploy textbook: “TinyML” by Pete Warden, Daniel Situnayake
- Deploy textbook “TinyML Cookbook” by Gian Marco Iodice

I want to thank Shawn Hymel and Edge Impulse, Pete Warden and Laurence Moroney from Google, Professor Vijay Janapa Reddi and Brian Plancher from Harvard, and the rest of the TinyMLedu team for preparing the excellent material on TinyML that is the basis of this course at UNIFEI.

The IESTI01 course is part of the **TinyML4D**, an initiative to make TinyML education available to everyone globally.

Thanks

UNIFEI