tinyML® Talks

Enabling Ultra-low Power Machine Learning at the Edge

“Machine Learning without batteries: the case for light-powered tinyML”

Andres Gomez - University of St. Gallen

March 3, 2022

TINY ML

www.tinyML.org

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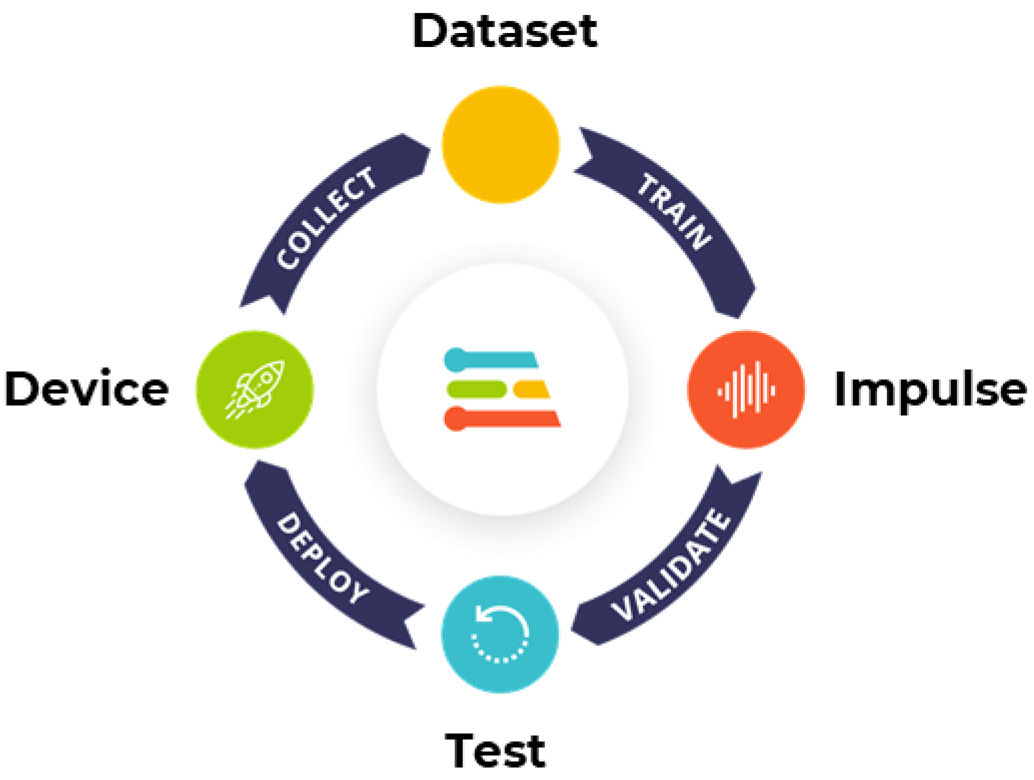
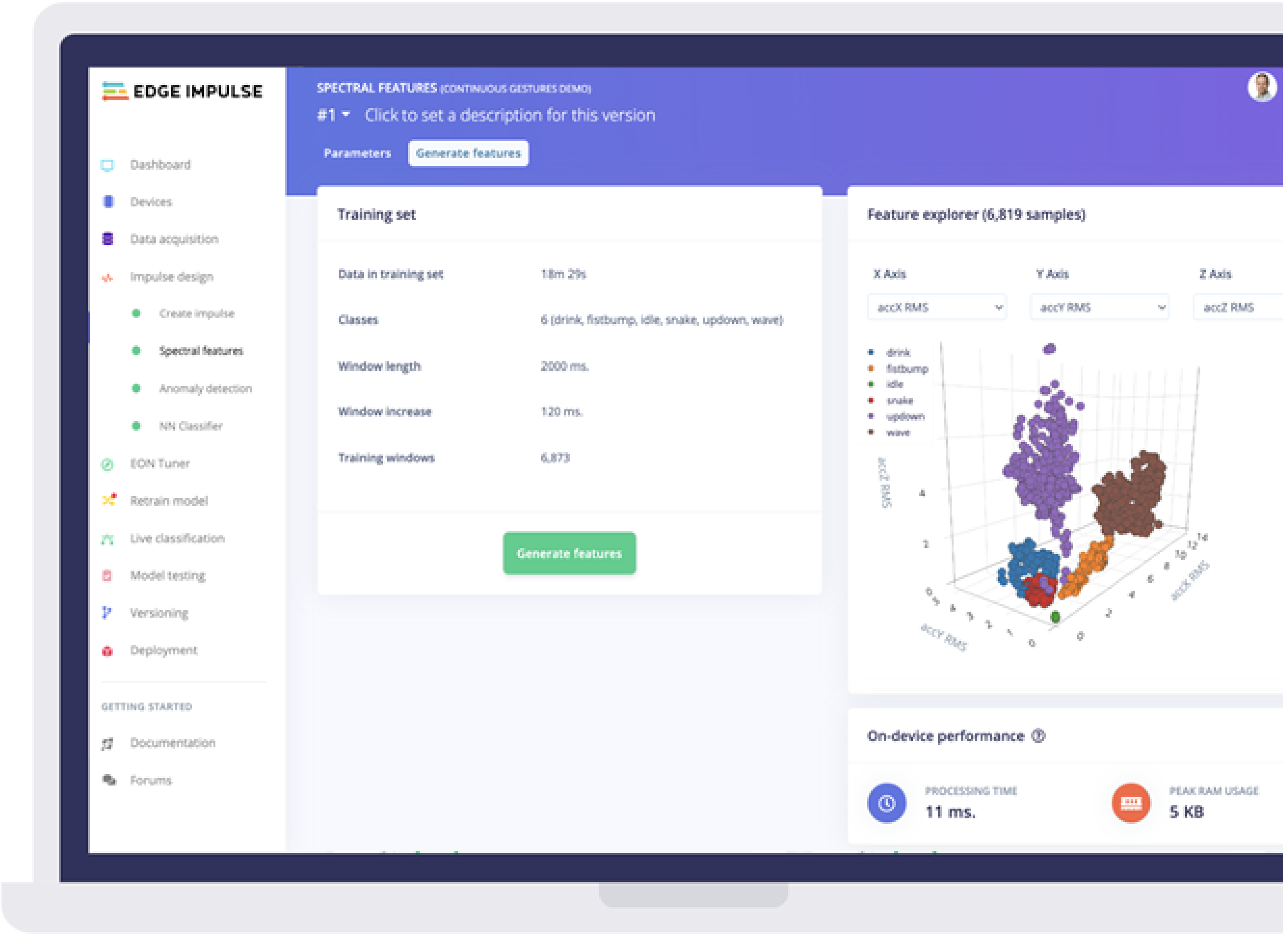
EDGE IMPULSE The leading edge ML platform



www.edgeimpulse.com



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AI research

Advancing AI research to make efficient AI ubiquitous

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Scene understanding, language understanding, behavior prediction

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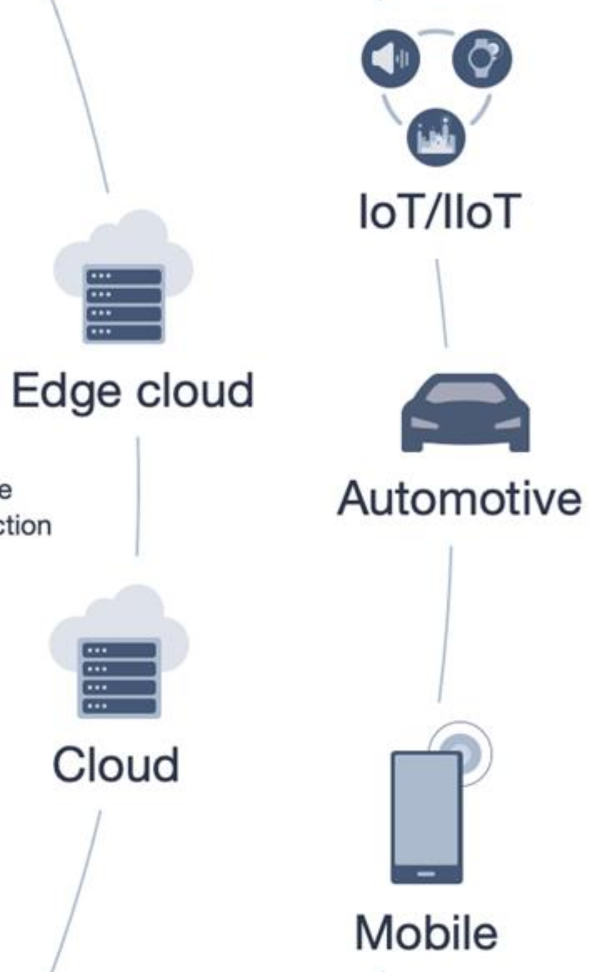

Qualcomm AI Research is an initiative of Qualcomm Technologies, Inc.

SYNTIANT

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Neural Decision Processors

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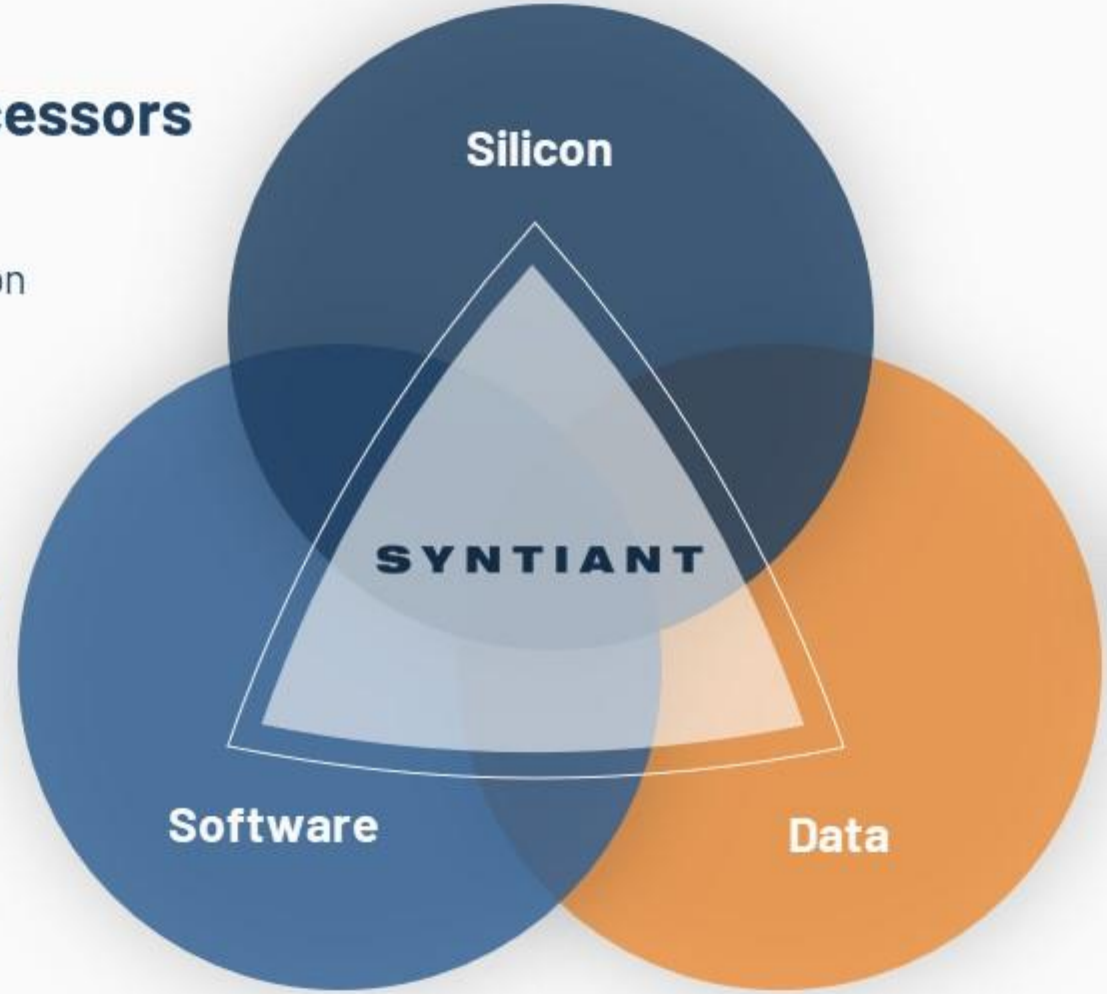

ML Training Pipeline

- Enables Production Quality Deep Learning Deployments

Data Platform

- Reduces Data Collection Time and Cost
- Increases Model Performance

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www.syntiant.com

Platinum Strategic Partners

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WE USE AI TO MAKE OTHER AI FASTER, SMALLER AND MORE POWER EFFICIENT

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- **Reduce** model optimization trial & error from weeks to days using Deeplite's **design space exploration**

- APPLY NOW **Deploy more** models to your device without sacrificing performance or battery life with our **easy-to-use software**

BECOME BETA USER **bit.ly/testdeeplite**

mobilityXlab arm AI 100 CB INSIGHTS

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KLIKA·TECH

GLOBAL IOT SOLUTIONS

Reality AI®

Add Advanced Sensing to your Product with Edge AI / TinyML

https://reality.ai info@reality.ai @SensorAI Reality AI

Pre-built Edge AI sensing modules, plus tools to build your own

Reality AI solutions

- Prebuilt sound recognition models for indoor and outdoor use cases
- Solution for industrial anomaly detection
- Pre-built automotive solution that lets cars "see with sound"

Reality AI Tools® software

- Build prototypes, then turn them into real products
- Explain ML models and relate the function to the physics
- Optimize the hardware, including sensor selection and placement

BROAD AND SCALABLE EDGE COMPUTING PORTFOLIO

Microcontrollers & Microprocessors

Arm® Core

RENESAS RA — Arm® Cortex®-M 32-bit MCUs
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Renesas Core

RENESAS RL78 — Ultra-low Energy 8 & 16-bit MCUs
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RENESAS RX — High Power Efficiently 32-bit MCUs
Motor control, Capacitive touch, Functional safety, GUI

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Winning Combinations that combine our complementary product portfolios

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Cloud Native

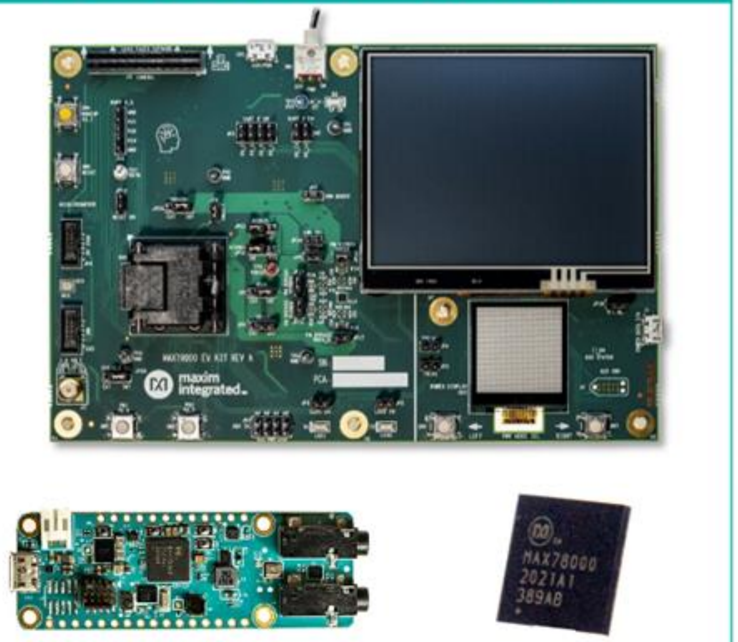
Cross-platforms working with partners in different verticals and organizations

Gold Strategic Partners

FotaHub

Maxim Integrated: Enabling Edge Intelligence

Advanced AI Acceleration IC



The new MAX78000 implements AI inferences at low energy levels, enabling complex audio and video inferencing to run on small batteries. Now the edge can see and hear like never before.

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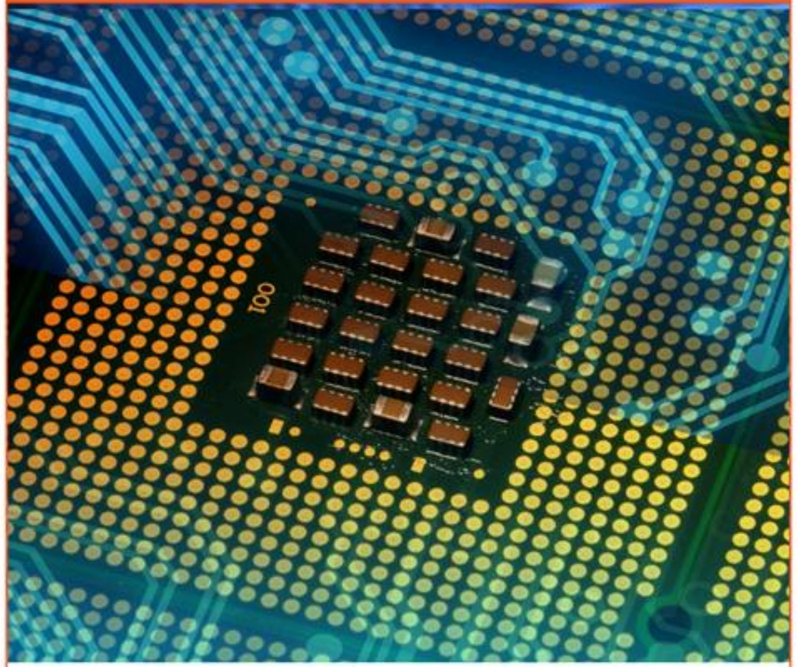
Low Power Cortex M4 Micros



Large (3MB flash + 1MB SRAM) and small (256KB flash + 96KB SRAM, 1.6mm x 1.6mm) Cortex M4 microcontrollers enable algorithms and neural networks to run at wearable power levels.

www.maximintegrated.com/microcontrollers

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- Multi-user auto-labeling of time-series data
- Code transparency and customization at each step in the pipeline

We enable the creation of production-grade smart sensor devices.

sensiml.com

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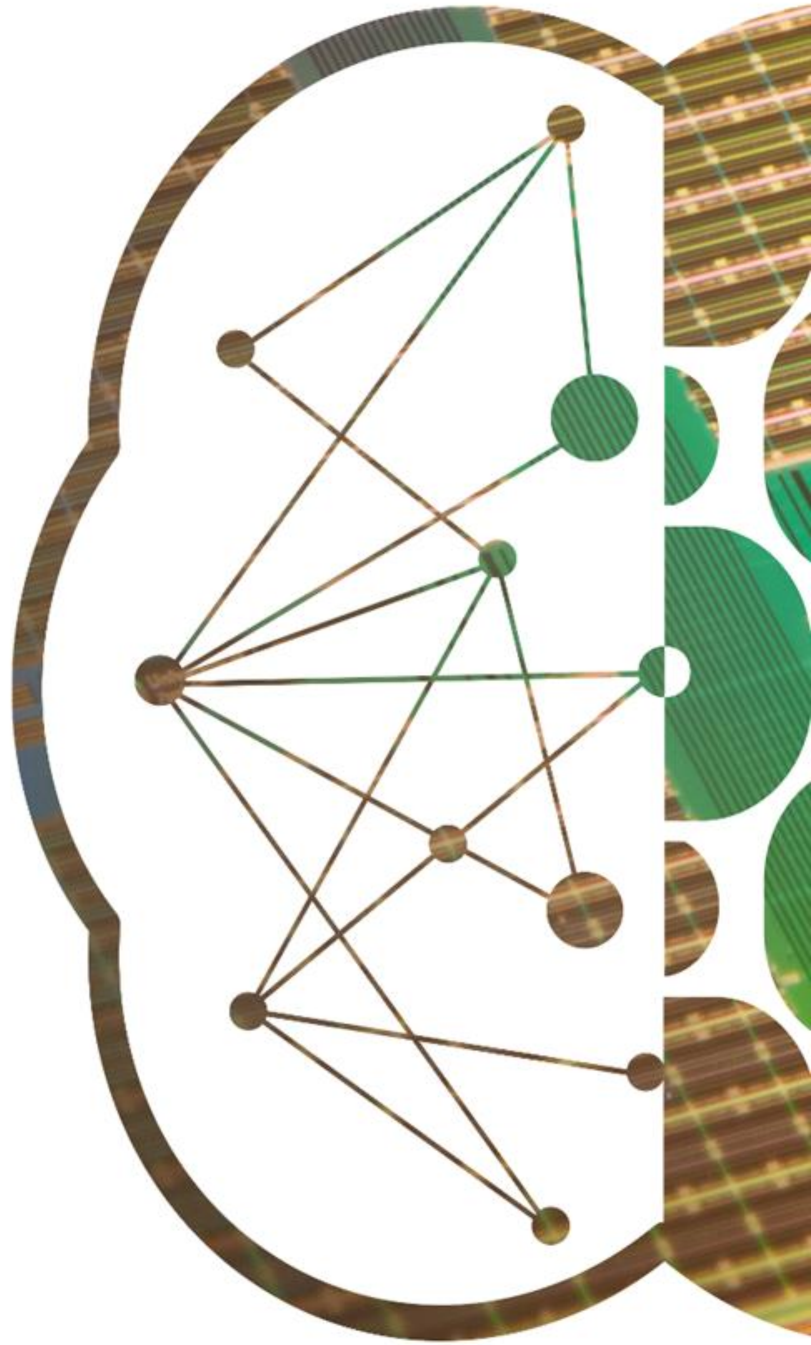
SynSense

SynSense builds **sensing and inference** hardware for **ultra-low-power** (sub-mW) **embedded, mobile and edge** devices. We design systems for **real-time always-on smart sensing**, for audio, vision, IMUs, bio-signals and more.

https://SynSense.ai



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tinyML Summit 2022

Miniature dreams can come true…

March 28-30, 2022

Hyatt Regency San Francisco Airport

https://www.tinyml.org/event/summit-2022/

*The Best Product of the Year and the Best Innovation of the Year awards are open for nominations between **November 15 and March 14.***

tinyML Research Symposium 2022

March 28, 2022

https://www.tinyml.org/event/research-symposium-2022

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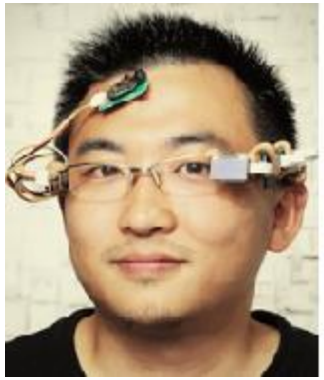
Our next tinyML Trailblazers Series

Success Stories with Eric Pan
(Founder, Seeed Studio and Chaihuo Makerspace)

LIVE ONLINE **April 6th, 2022 at 8 am PST**



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43 Groups in 34 Countries

tinyML - Enabling ultra-low Power ML at the Edge

https://www.meetup.com/tinyML-Enabling-ultra-low-Power-ML-at-the-Edge/

2.6k members
&
5.1k followers

The tinyML Community

https://www.linkedin.com/groups/13694488/

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Next tinyML Talks

Date	Presenter	Topic / Title
Tuesday, March 8	Konstantin Meshcheriakov, Solution Architect, Klika Tech	On-device model fine-tuning for industrial anomaly detection applications

Webcast start time is 8:00 am Pacific time

Please contact talks@tinyml.org if you are interested in presenting

Reminders

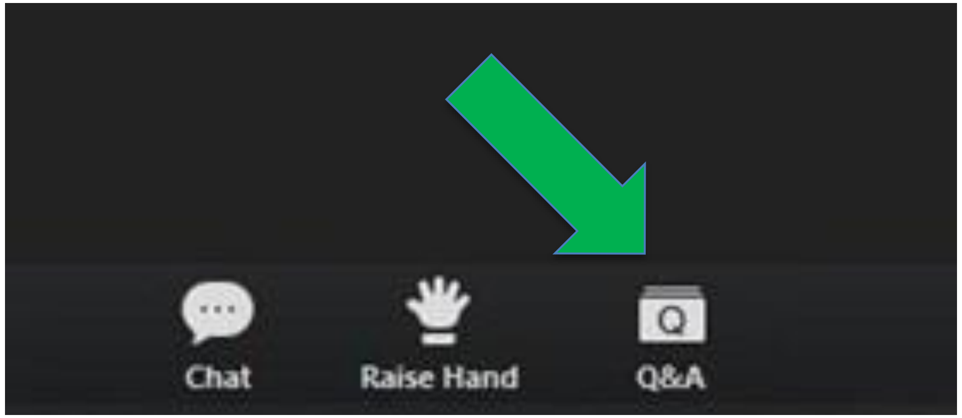
Slides & Videos will be posted tomorrow

PDF

tinyml.org/forums

youtube.com/tinyml

Please use the Q&A window for your questions



Andres Gomez

Andres Gomez received a dual degree in electronics engineering and computer engineering from the Universidad de Los Andes, Colombia, an M.Sc. degree from the ALaRI Institute (Università della Svizzera Italiana), Switzerland, and a Ph.D. from ETH Zurich, Switzerland. He has over ten years of experience with embedded systems and has worked in multiple research laboratories in Colombia, Italy, and Switzerland. More recently, he has worked as an R&D engineer at Miromico AG. He has co-authored over 30 scientific articles and has contributed to multiple open-source projects. He is currently a Postdoctoral Fellow at the University of St. Gallen, Switzerland. His current research interests include batteryless system design, the Internet of Things, and the Web of Things.

Institute of Computer Science

University of St.Gallen

Interactions

interactions.ics.unisg.ch

Machine Learning without batteries:

the case for light-powered tinyML

03.03.2022

Did you ever own one of these?

Source: GSM arena

Nokia 1110 (2004)

Average use: several days

Battery: **850 mAh**

Do you ever own one of these?

Source: GSM arena

Nokia 1110 (2004)

Average use: several days

Battery: **850 mAh**

Source: GSM arena

iPhone 13 Pro Max (2021)

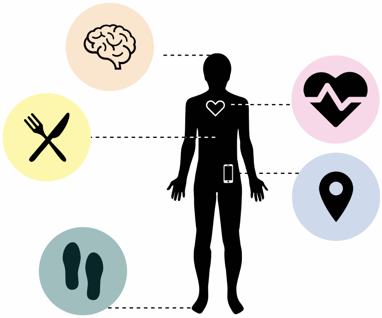
Internet use: ~12 h

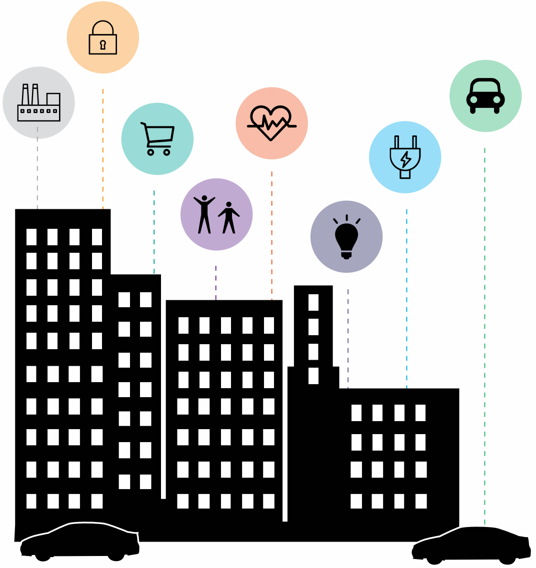
Battery: **4352 mAh**

Trend: as **functionality** increases so does the **cost**
(battery) size
environmental impact

Current Internet of Things

Making environments and devices **smarter**





People spend **90%** of their time indoors[1]

Buildings account for **28%** of CO_2 emissions[2]

Lighting and HVAC consume **64%** of energy in buildings[3]

[1] https://bit.ly/3gVWp43 [2] https://bit.ly/3sKUYe0 [3] https://bit.ly/3sQe02M

How can we improve?

Current sensing devices:

electronics

batteries

>90% of volume

~50% of cost

My research aims to **novel design paradigms:**

cost-effective	—	low-cost (organic) components
maintenance-free	—	taping into light infrastructure
environmentally friendly	—	saves energy by design

Andrés Gómez

Finished PhD studies at ETHZ in 2018

Design and Specification of Batteryless Sensing Systems

Part-time in two research institutes: 75% TIK, 75% IIS

ETH zürich

Research engineer at Miromico AG in Zurich, Switzerland (2018-2020)

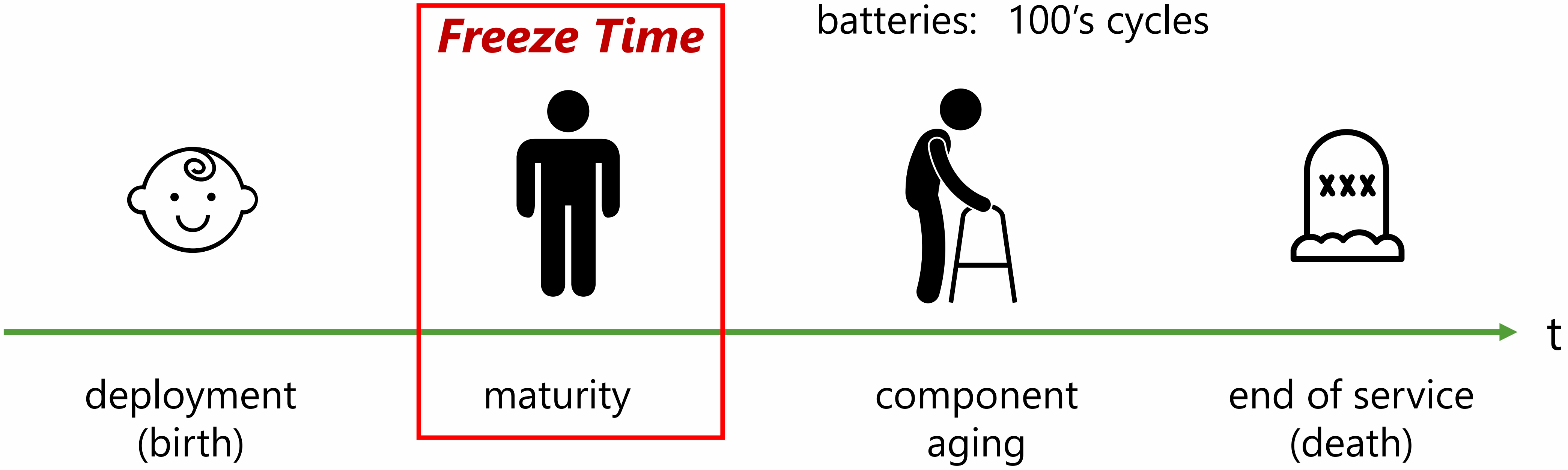
miromico

Post-doctoral fellow at University of St.Gallen since Jan. 2021

University of St.Gallen

Traditional Device Lifecycle

silicon: millennia*
solar panel: decades*
batteries: 100's cycles



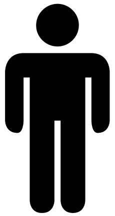
Are **long lifetimes** the *only* desirable design goal?

Predictability vs resilience

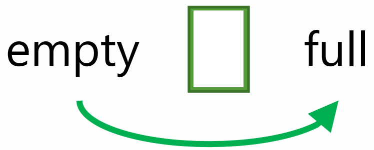
System should "live" as **long** as possible — **large** energy cycle

charging is **expensive**

Predictable
Life



System should "revive" as **quickly** as possible — **small** energy cycle



charging is **cheap**

Resilient
"Life"

A few words about energy storage

Main tradeoffs:

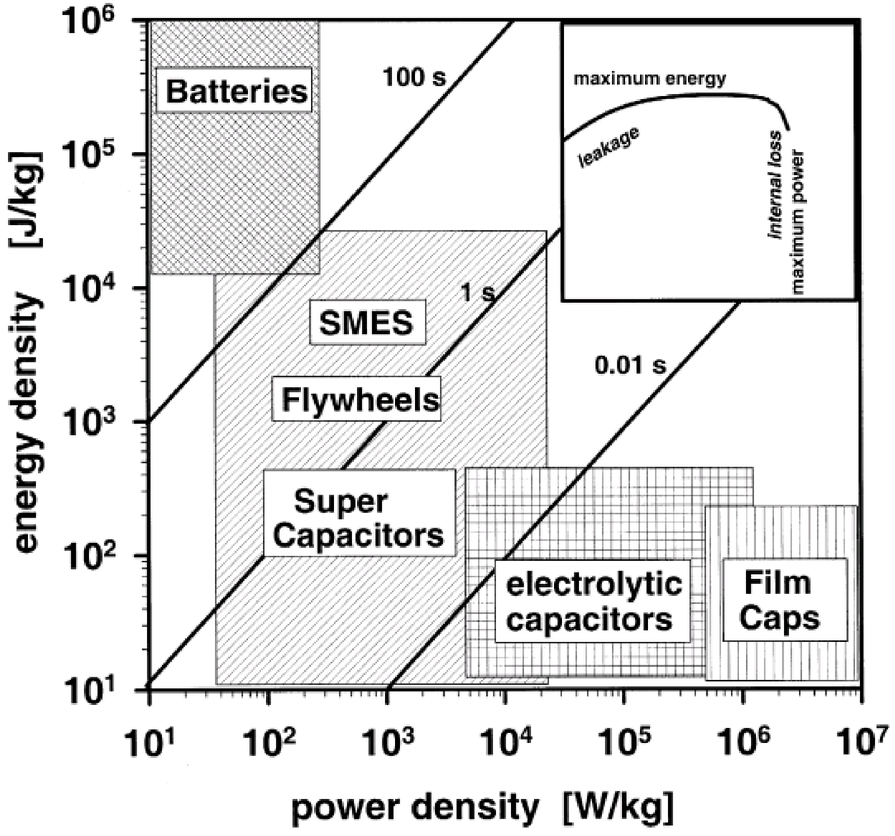
- recharge cycles
- power density
- energy density
- leakage

My objectives: **high power density**
high recharge cycles

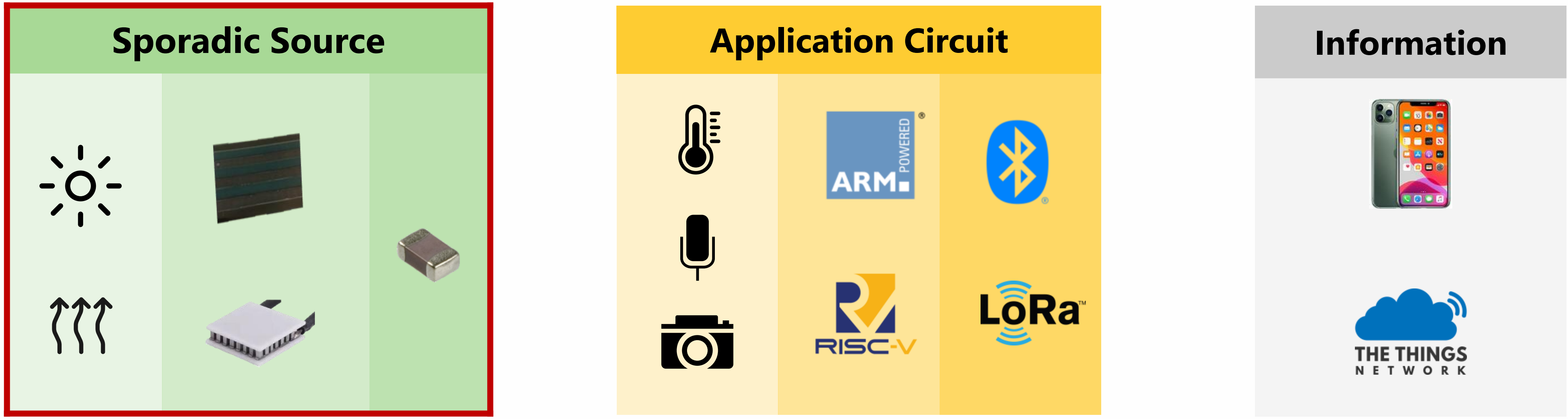
I mostly use ceramic capacitors

Ragone Plot

source: T. Christen et al.



Energy-Driven Design



Sporadic Source	Application Circuit	Information
Inexpensive	***Sporadically Powered*** ∃t (P(t) = 0)	***Non-Deterministic*** ***possibly correlated****

Key Feature Environment sporadically supplies energy

Objective minimize wake-up time (~1 sec)

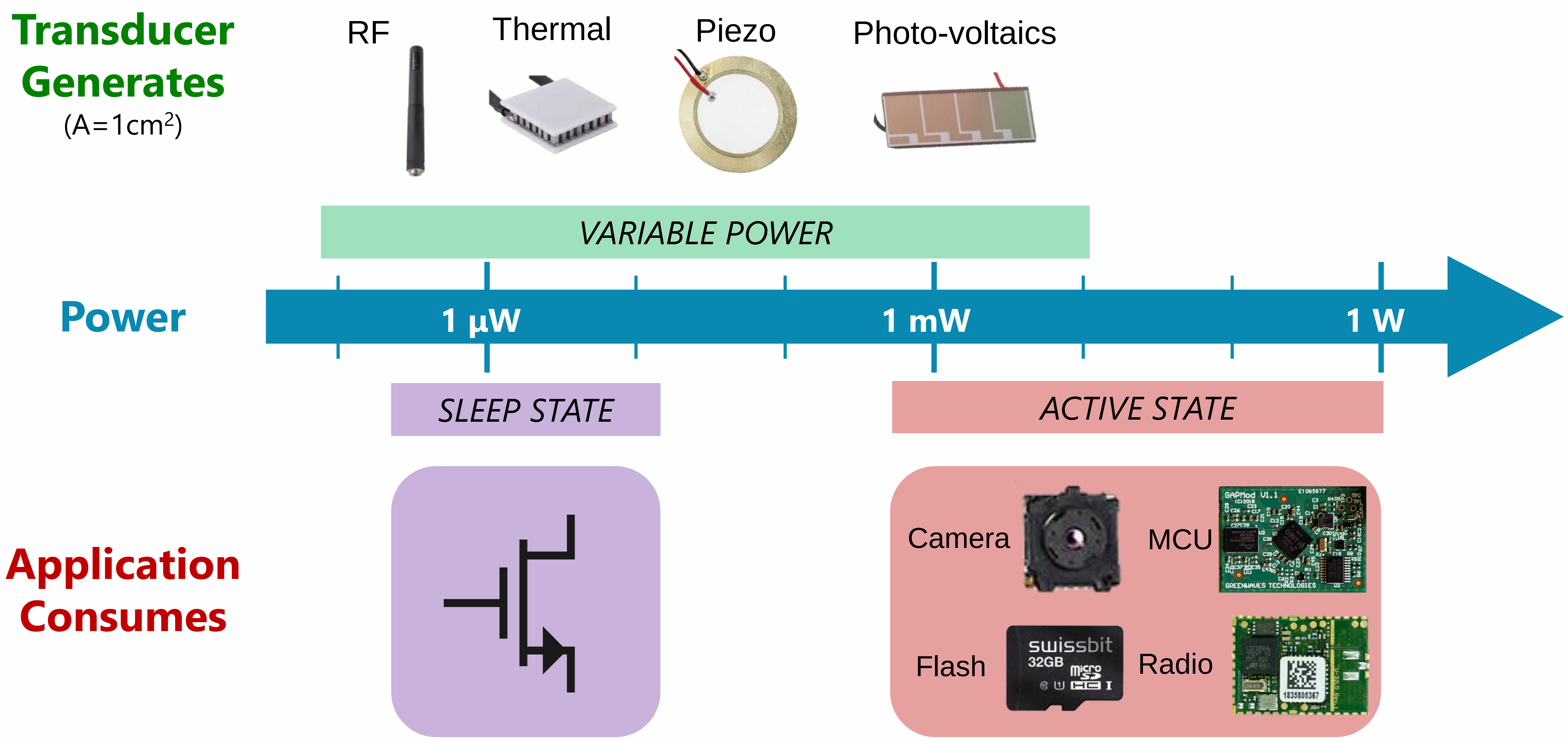
Energy Harvesting

Sporadic Source

Application Circuit

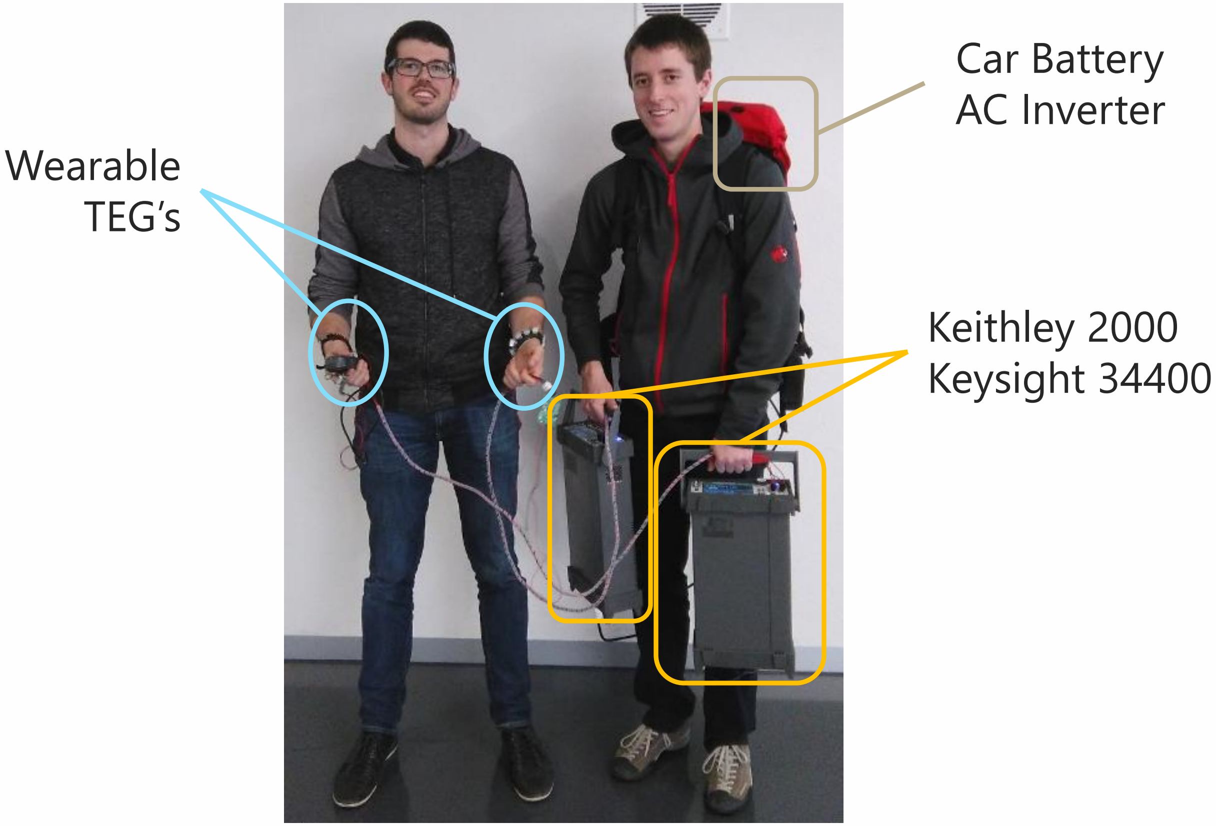
ML Model

The Great Power Imbalance



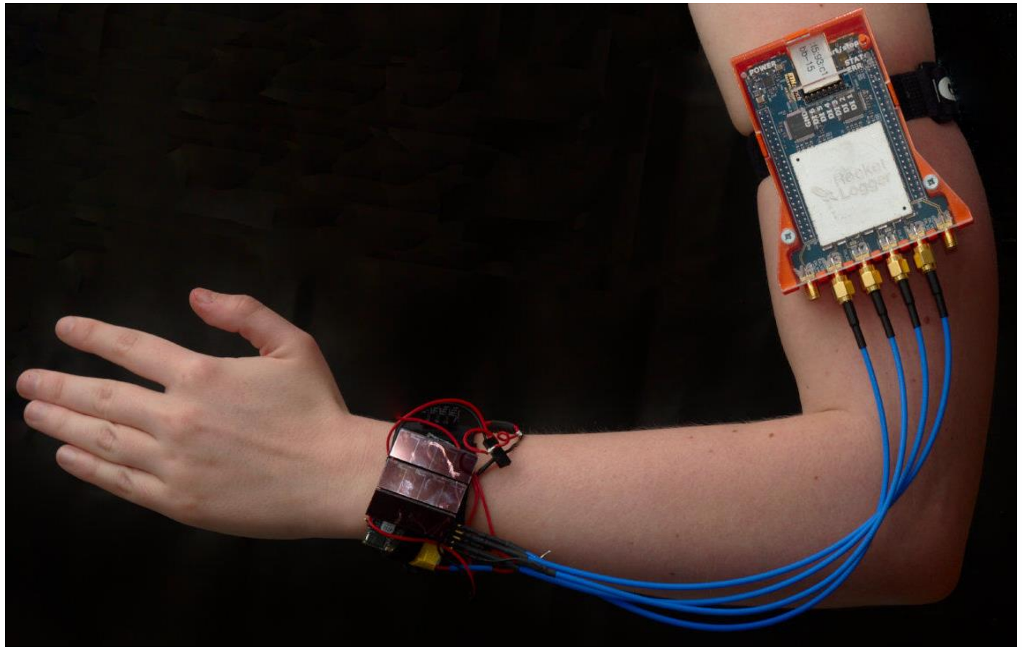
Understanding Environmental Energy

Accurate, in-situ measurements are challenging!



Understanding Environmental Energy

We designed the RocketLogger to facilitate this



2 high accuracy I channels
4 high accuracy V channels
6 digital channels

Open-Source Project:

https://rocketlogger.ethz.ch/

Used by researchers in:

How Much Energy Is Available Indoors?

Measurement campaign @ ETH Zurich

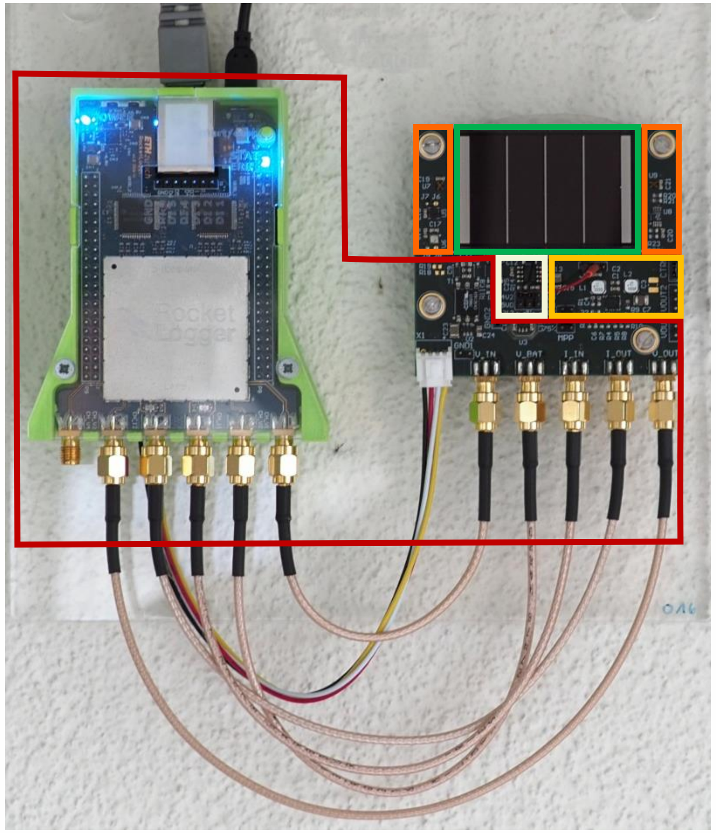
Started July 2017 with 6 indoor stations

Ambient & Electrical data:

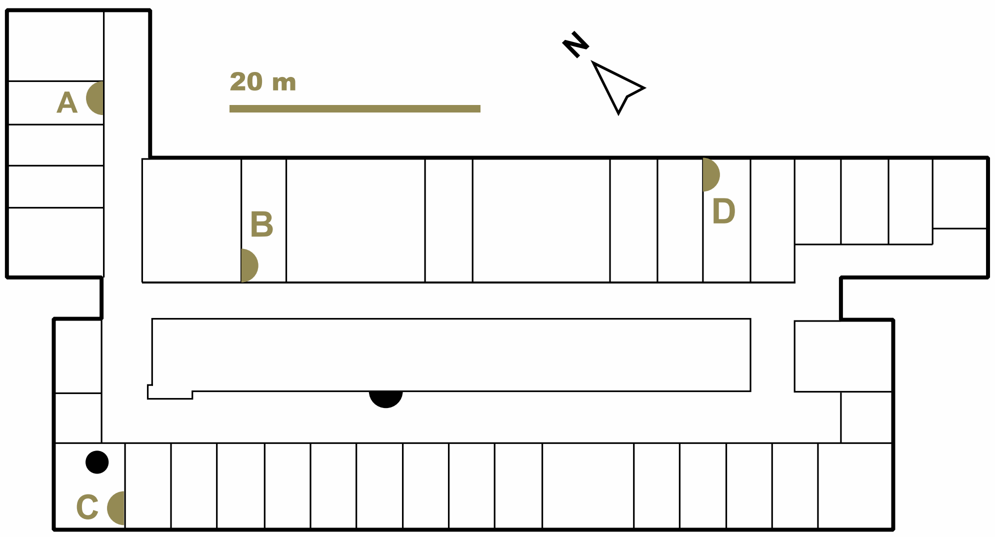
- Illuminance @ 1 Hz
- Harvested power @ 10 Hz
- 25 billion data points (139 GB of data)

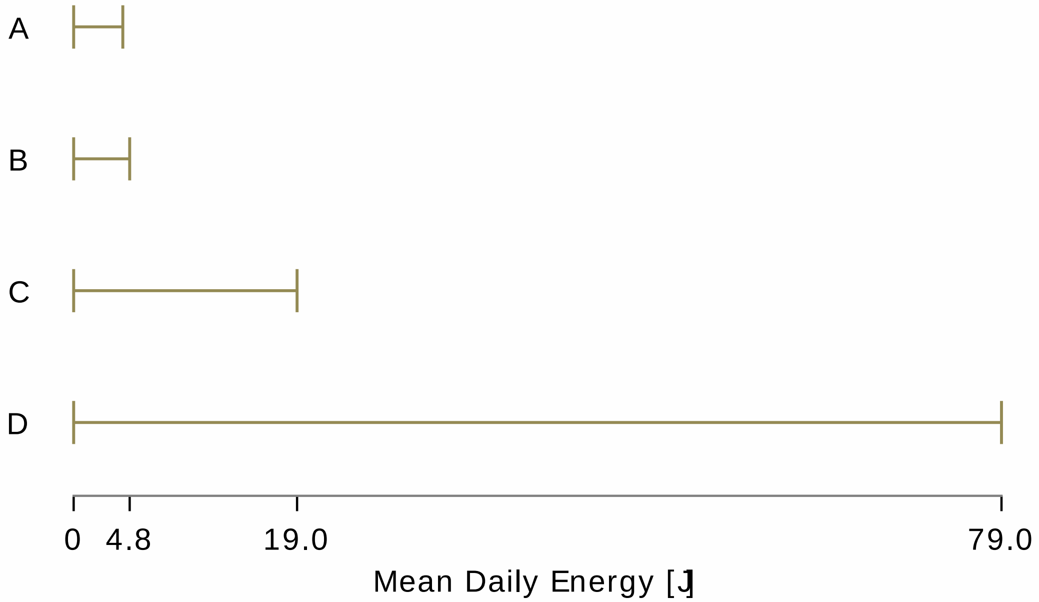
Publicly available data set:

DOI 10.5281/zenodo.3363925



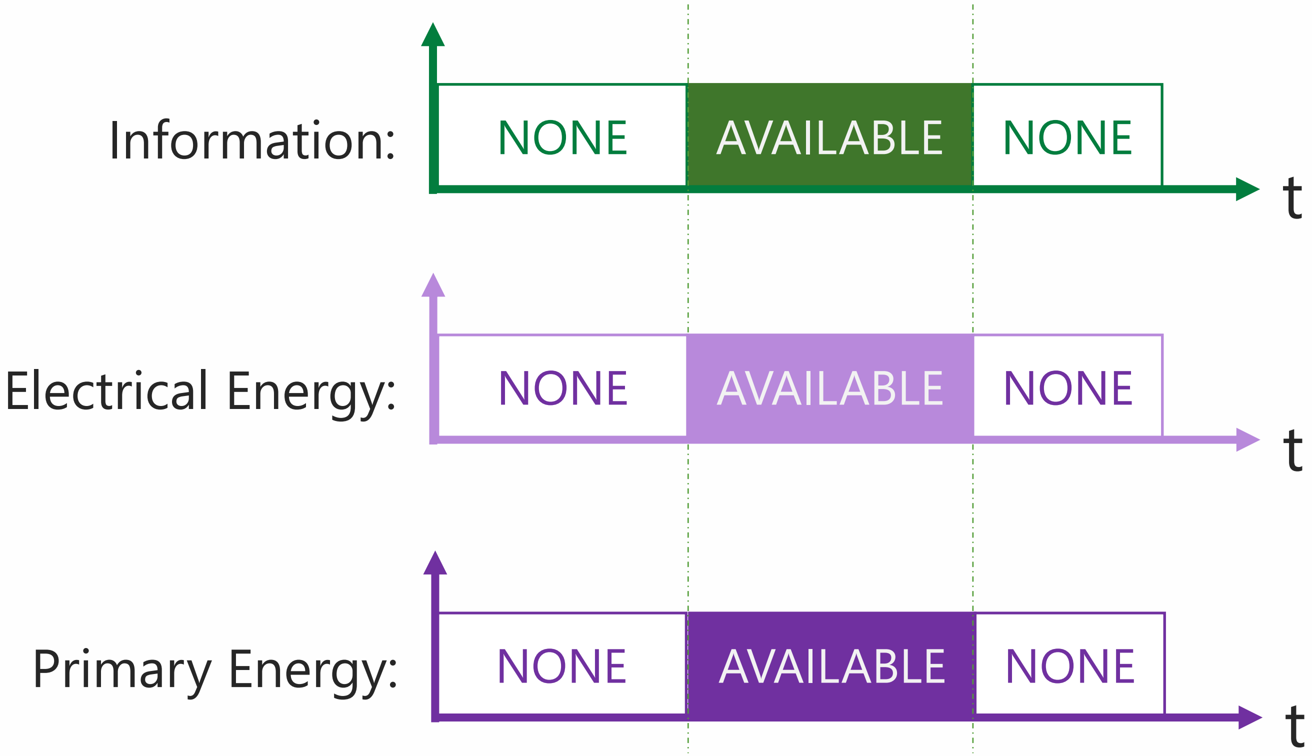
Daily Harvested Energy Distribution (2+ years)

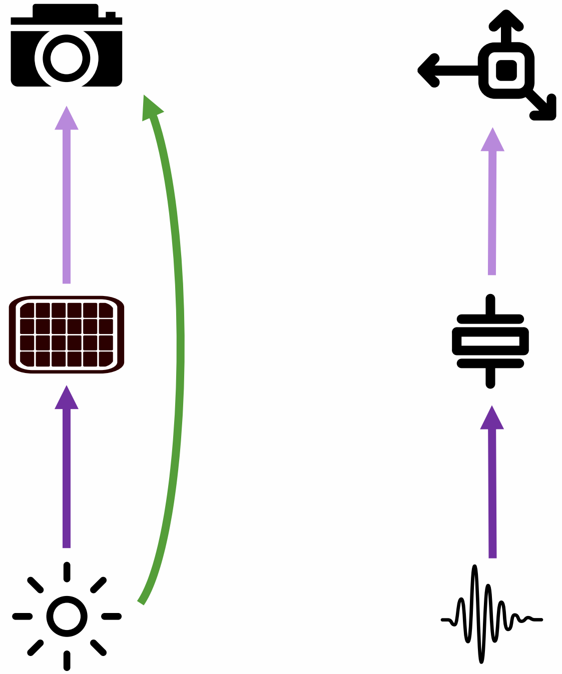




High energy variability with many variables: geography, architecture, human activity, etc

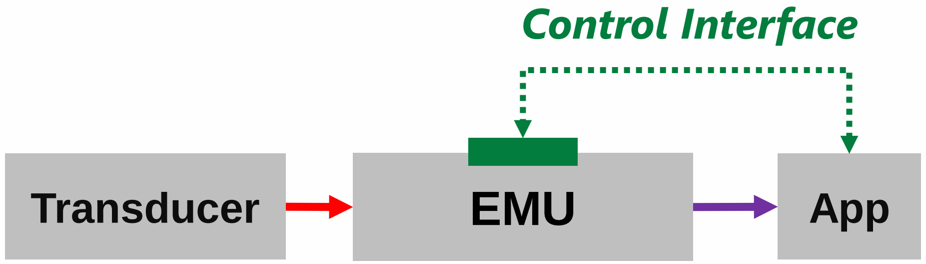
When are Energy-Driven Systems Optimal?





human activity
correlates with light

Energy Management Unit (EMU)



P_{in} = 5 μW

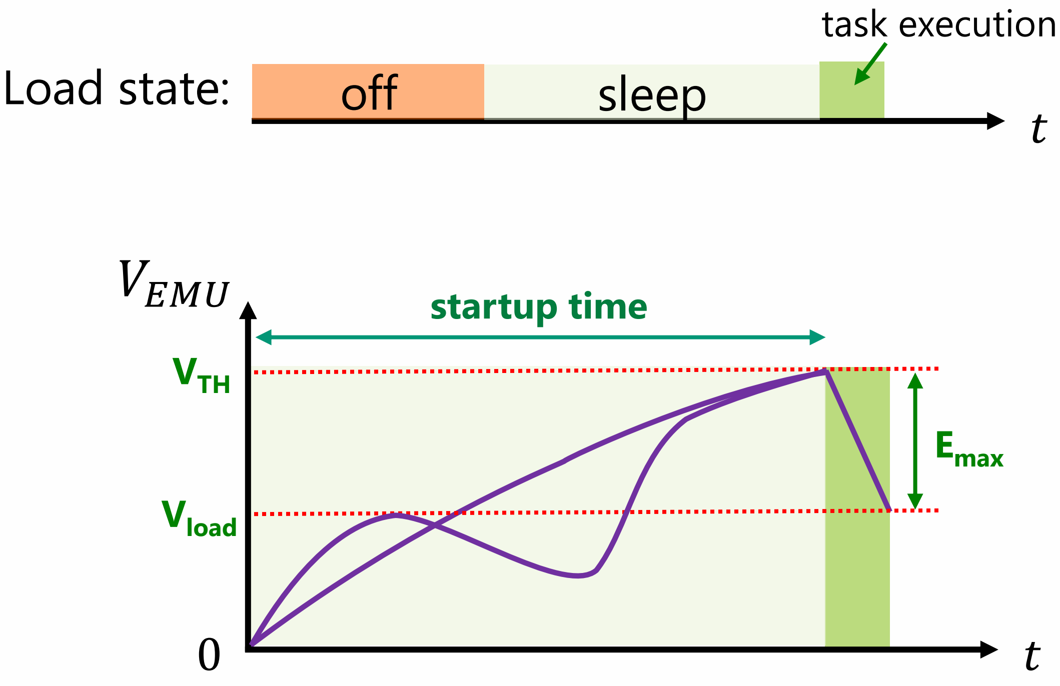
P_{app} = 100 mW

Source/Load have **decoupled** voltage and current

Energy input/output simultaneously optimized

Optimizing $C, \Delta V^2$ minimizes startup time

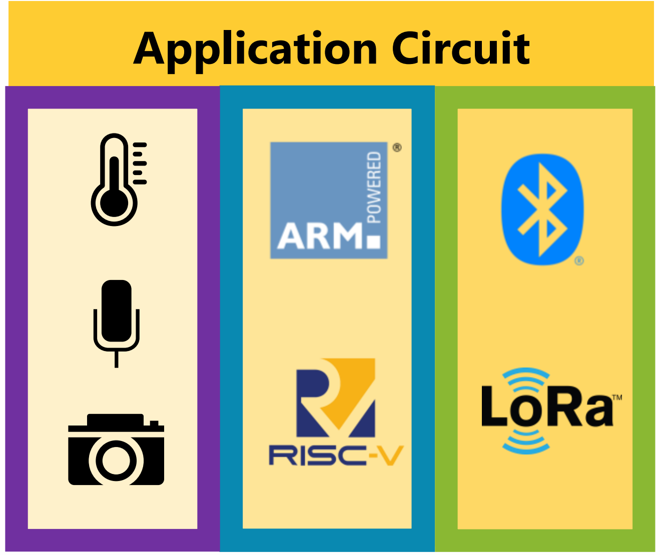
Transient behavior:



System's energy efficiency: $\eta_{sys} \leq$ **0.9**

Intermittent Operation

Energy-driven systems must be compatible with power cycling



Sensors:

Digital sensors are easy to turn on and turn off

Transcievers:

Easy to stop with asynch. comm.

Digital computation:

If small enough, no need to interrupt process

Reliable Execution

Sporadic Source

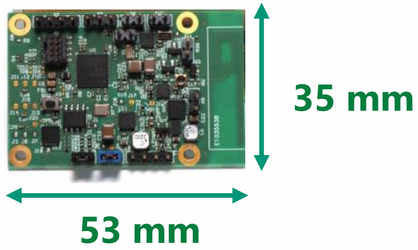
Application Circuit

ML Model

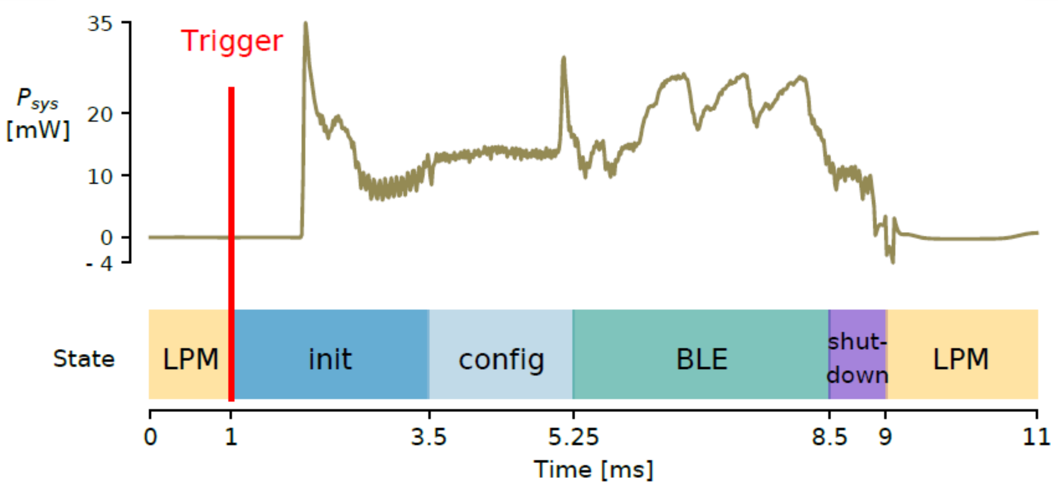
Atomic Task Execution

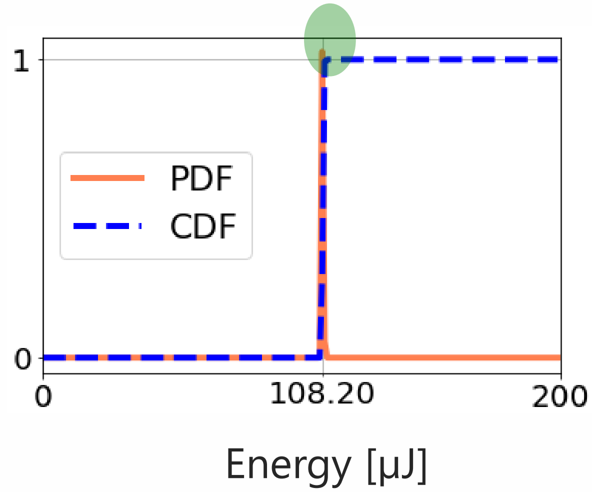
BLE Ambient Sensor

CC2650-based Platform



Power Trace for a single activation





"Batteryless" Limit

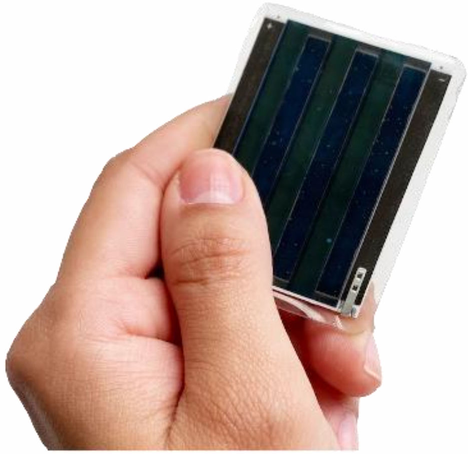
Q_{max} = 109 [μJ]

- **Reliable Operation**
- **Min. Startup Time**

In **indoor** Environments:

> 28K activations per day
> 3 pkt/s (for 8 hours)

Privacy-Enabled Edge Devices



Without Light: Full power down

impossible to gather data

With Lights: System powers up quickly

Gathers, processes and transmits data

miroCard is **powerful and private**:

It can process sensor data streams

and users can disable it by covering it

Open Source HW/SW

https://mirocard.swiss/

2021 HiPEAC
Tech Transfer Award

ML on the MiroCard

Light-Powered
Batteryless

User Agency
Controlled exposure

Sensors
Temperature, Humidity, & Acceleration

Bluetooth Low Energy
Data Transmission

Machine Learning
Local processing capability

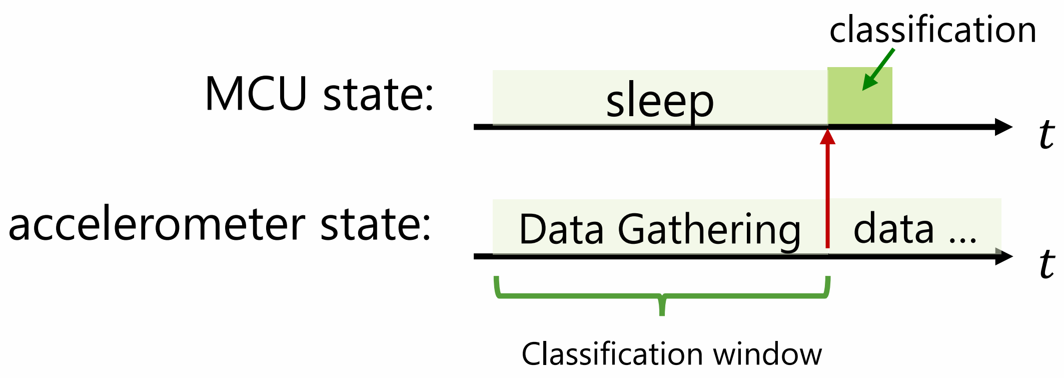
Can we do gesture detection on miroCards?

We need long time series of data

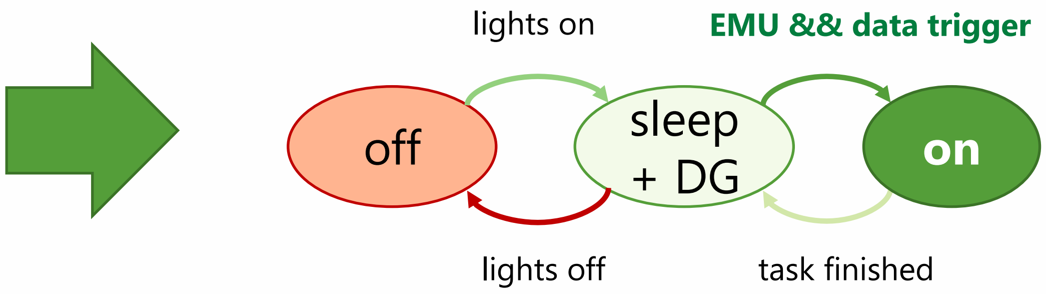
We are adding a data requirement to batteryless processing

Data streaming applications

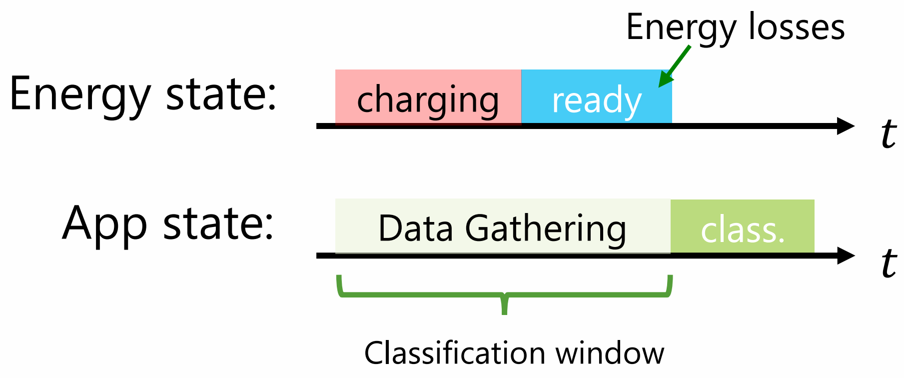
Traditional classification behavior:



Batteryless data classification:



Energy + data dependency may lead to **inefficiencies**



Gesture Detection

Sporadic Source

Application Circuit

ML Model

Data Set Acquisition

Training Data

12 Participants

Label Distribution		
Random	22 583	33.2%
Up-Down	22 357	32.8%
Sideways	23 096	33.9%
Total	68 036	100%

Set Distribution		
Training	32 865	48.3%
Validation	14 085	20.7%
Testing	21086	31%
Total	68 036	100%

ML model:

inf XL

Simple C-code

- Additions
- 8- & 16-bits integers

Low memory usage

Adaptable & Reusable

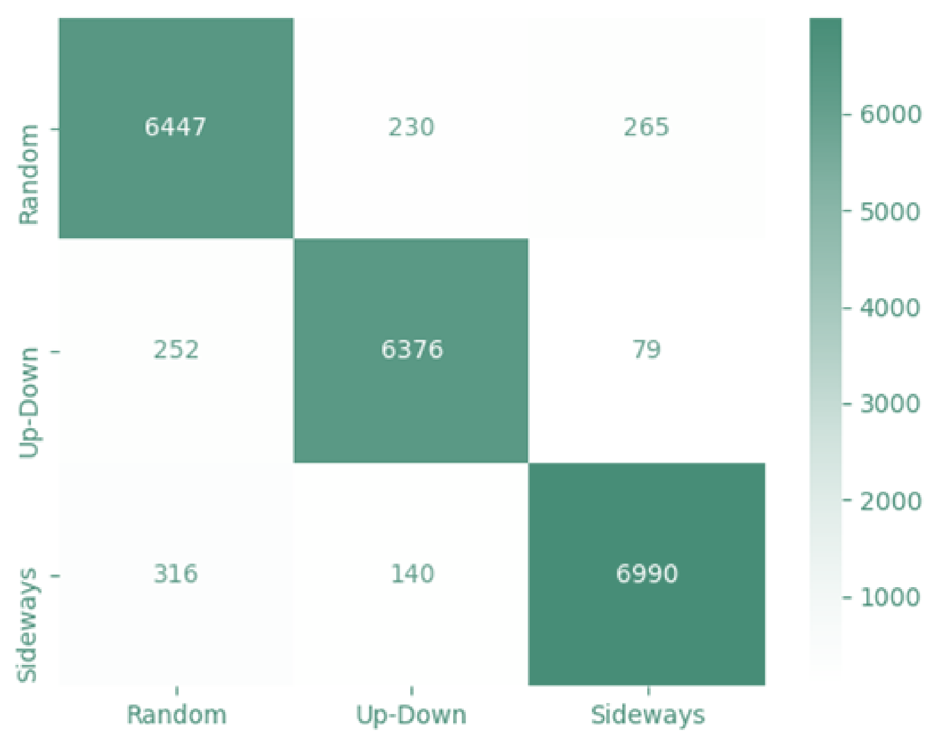
- Easy to embed in OS

Low energy consumption

- Minimal increase in additional energy demand

Trained Model Results

Confusion Matrix

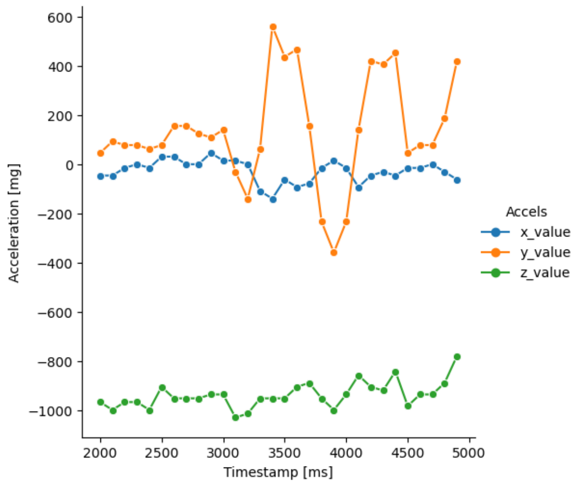


Model Evaluation

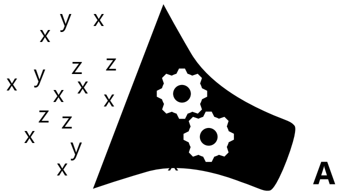
Labels	Precision	Recall	F1-score	Sample Size
Rand	0.92	0.93	0.92	6 933
Updown	0.95	0.95	0.95	6 707
side	0.95	0.94	0.95	7 446
Accuracy			0.94	21 086
Macro avg	0.94	0.94	0.94	21 086

Windowed-Data Classification

Data Exploration



Data Processing



Data Labelling

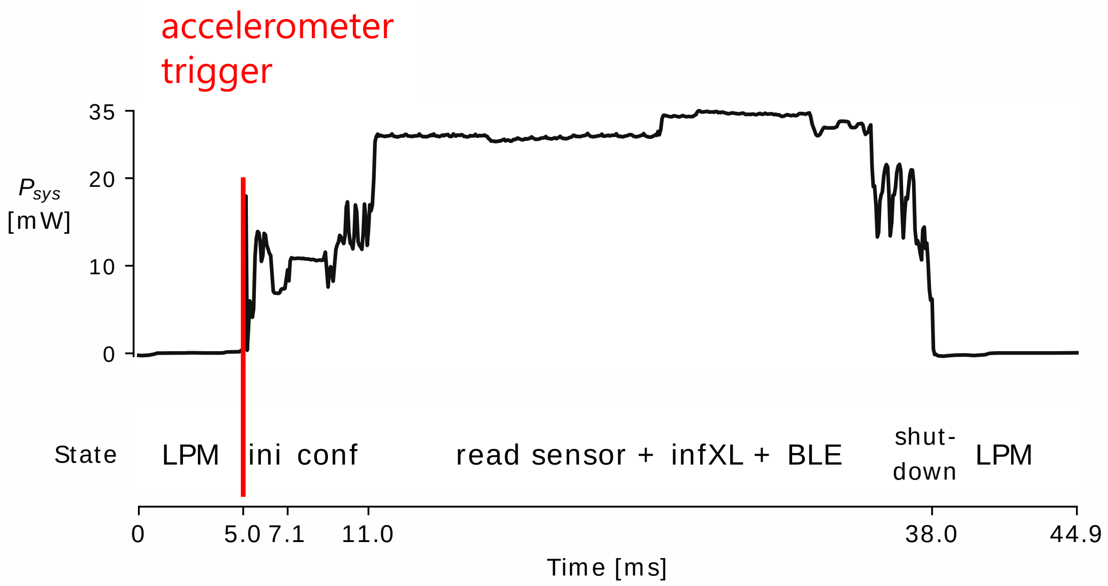

[0]: Random


[1]: Up-Down


[2]: Sideways

Embedded Implementation

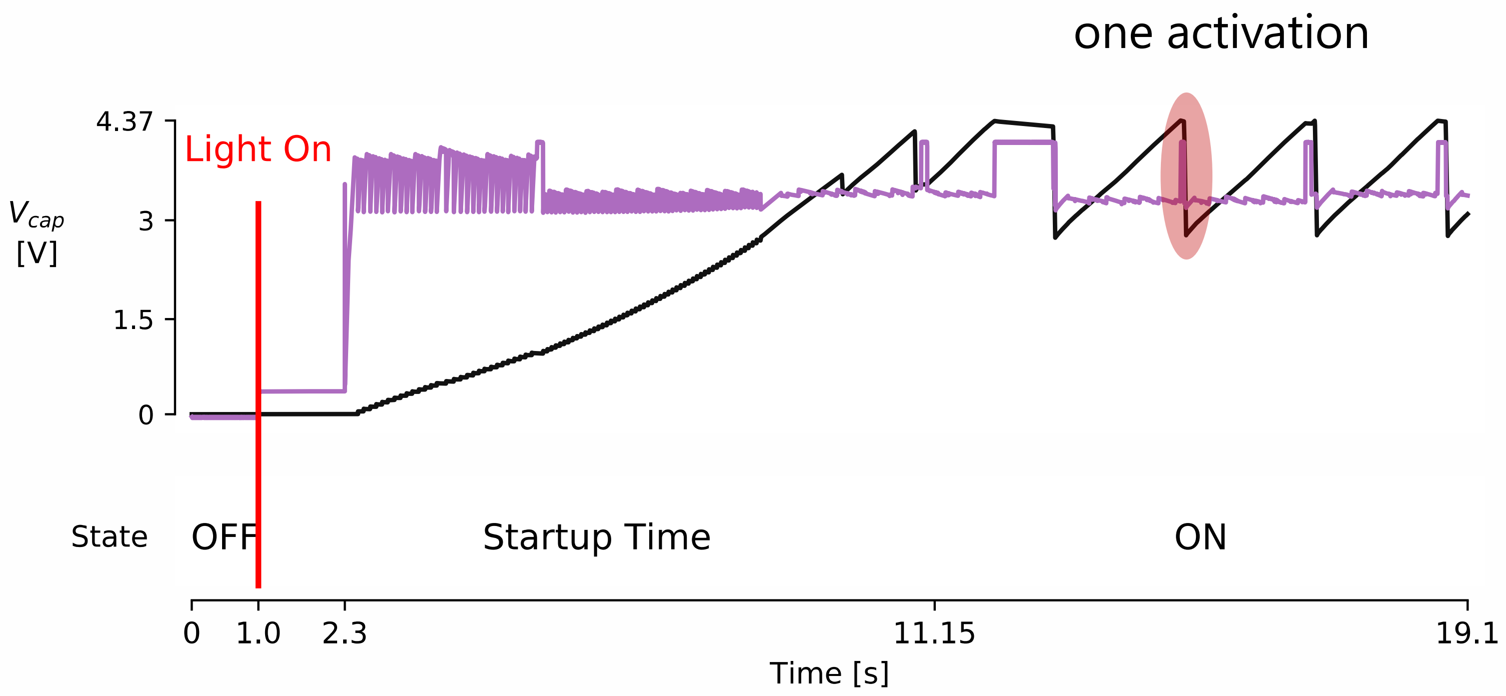
Application's power trace:



RocketLogger Measurements		
	Average	**Standard Deviation**
Execution Time	32.7 ms	0.4 ms
Energy @ 2.5V	728.01 uJ	0.8 uJ
$\mathbf{P_{sleep+dg}}$	65 uW	-

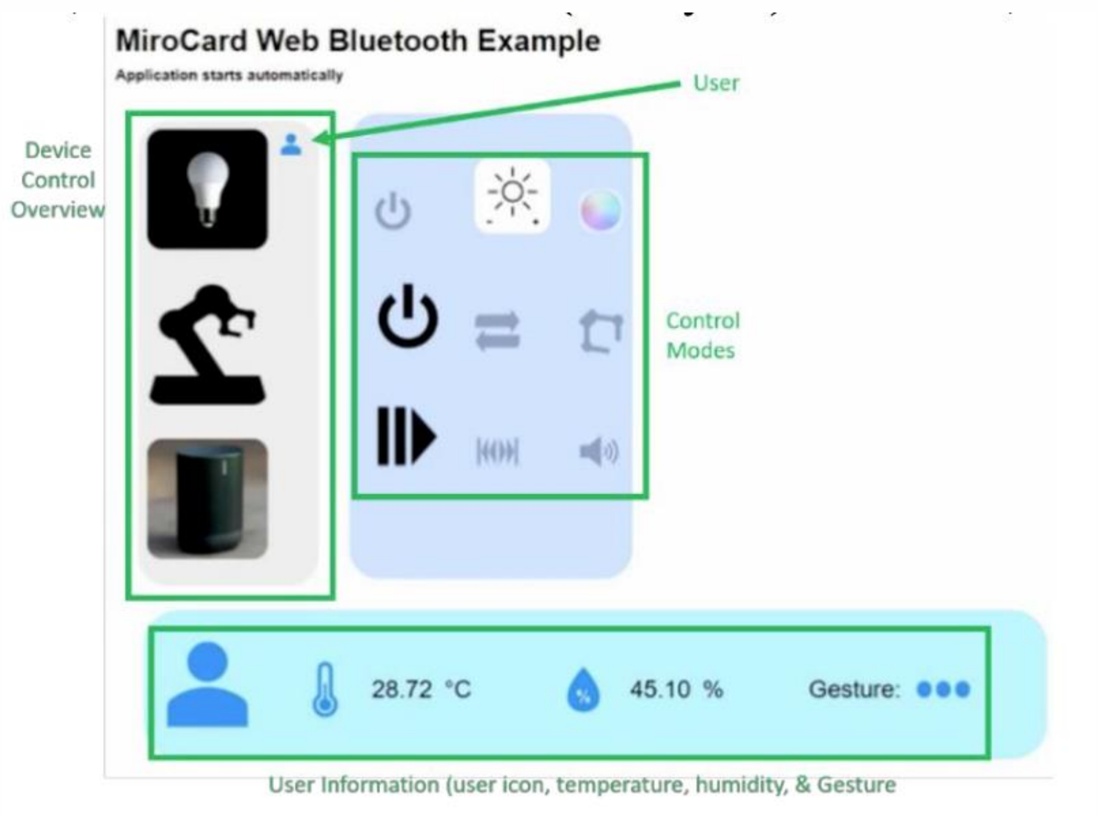
Fast Cold-Start

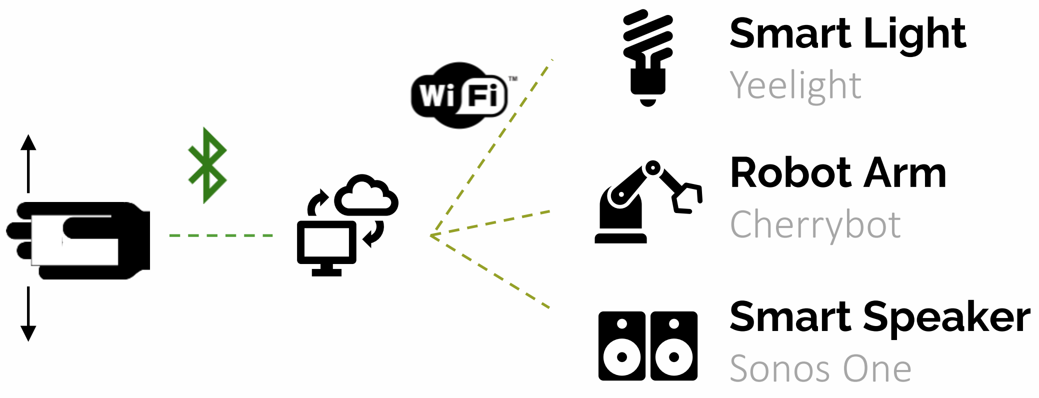
Cold-start lasts only 10.15 seconds when exposed to a constant 900 lux environment



Demo

Accelerometer-controlled interactions



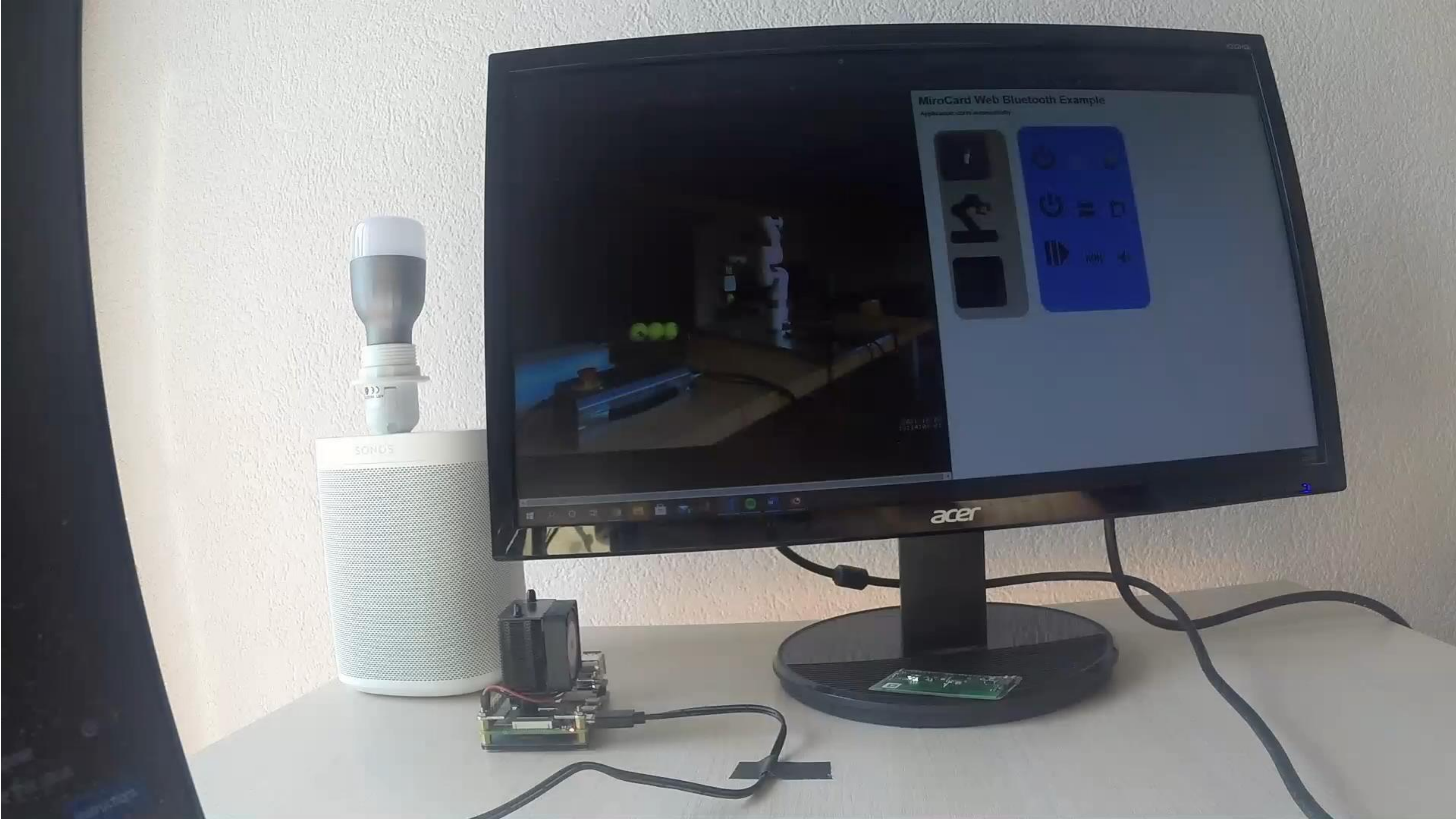


Actions:

Change light color, intensity

Control robot arm movements

Change song, volume


MiroCard Web Bluetooth Example
SONOS
acer

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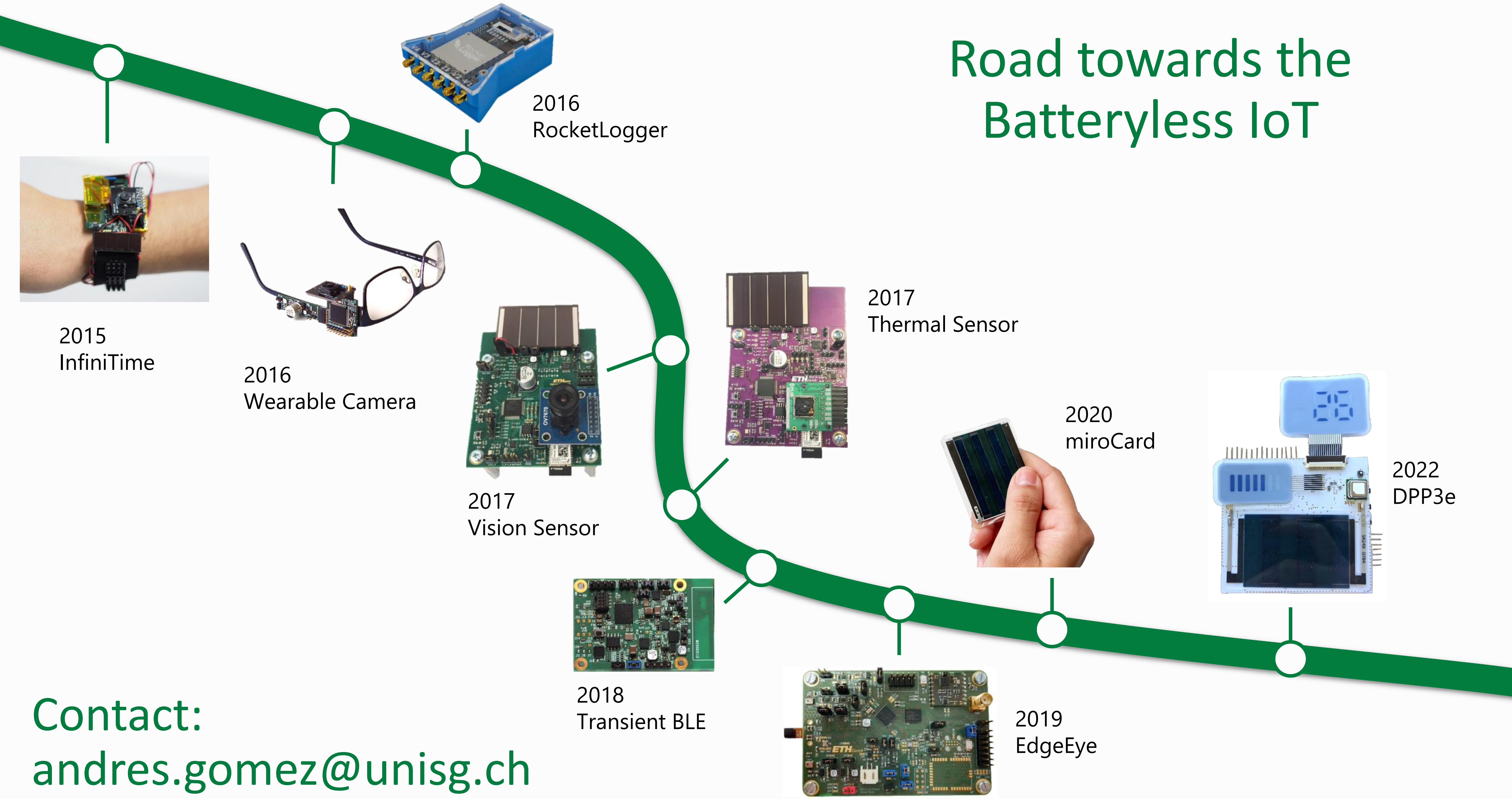
Among **many others …**



Road towards the Batteryless IoT
2015
InfiniTime
2016
Wearable Camera
2016
RocketLogger
2017
Vision Sensor
2017
Thermal Sensor
2018
Transient BLE
2019
EdgeEye
2020
miroCard
2022
DPP3e
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