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Enabling Ultra-low Power Machine Learning at the Edge

June 26 - 28, 2023

TINY ML

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Powering Machine Learning Applications on Arm with algae

Paolo Bombelli, Research associate @ Dept. Biochemistry, University of Cambridge

Gian Marco Iodice, Machine Learning tech lead @ Arm

28/06/2023

Generating electricity from photosynthesis

Part 1

Paolo Bombelli, Research associate @ Dept. Biochemistry, University of Cambridge

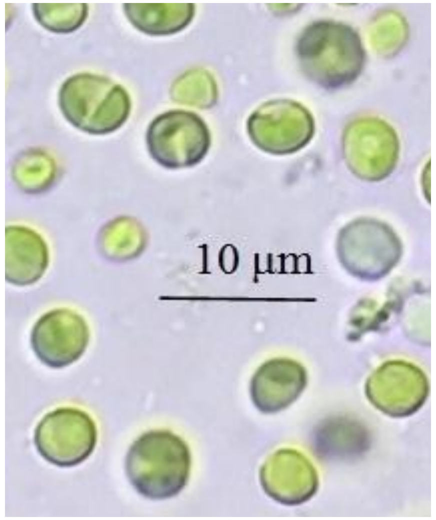
Let’s start from the beginning…

Plants:

Grow with water and sun and, for this reason, they are called autotrophic

Let’s start from the beginning…

In simple terms, algae are **aquatic plants**



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Algae:

Large group of autotrophic organisms predominantly aquatic. Algae range in size from unicellular microscopic (e.g., Chlorella, ca. 5µm) to giant multicellular (e.g., Kelp, up to 60m)

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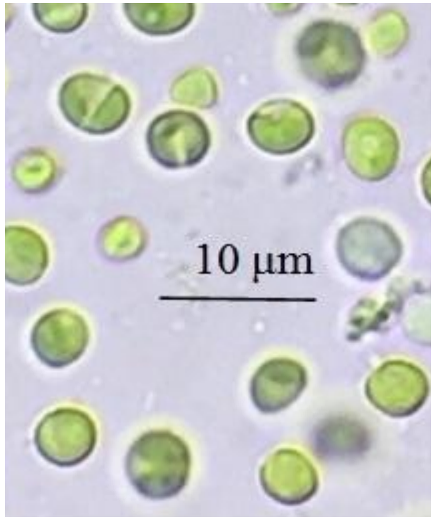
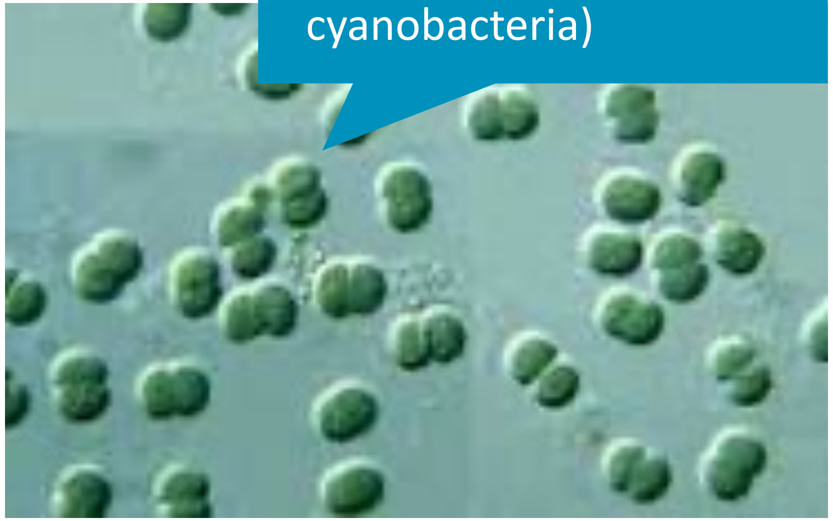
In a simple terms, they are “old” algae (algae evolved from cyanobacteria)





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Large group of autotrophic organisms predominantly aquatic. Algae range in size from unicellular microscopic (e.g., Chlorella, ca. 5µm) to giant multicellular (e.g., Kelp, up to 60m)

Cyanobacteria:

Large group of unicellular, autotrophic organisms with microscopic size (e.g., Synechocystis ca.2µm). They resemble the algae in many ways including morphology and ecological niches

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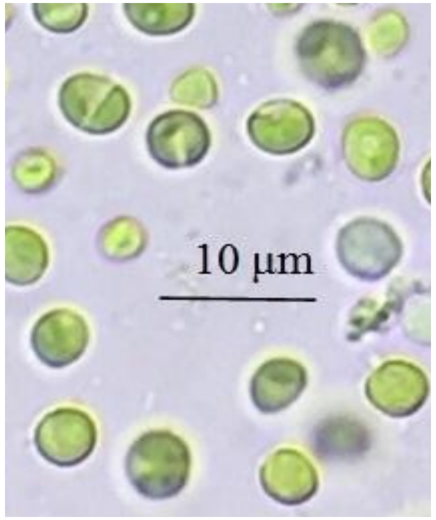
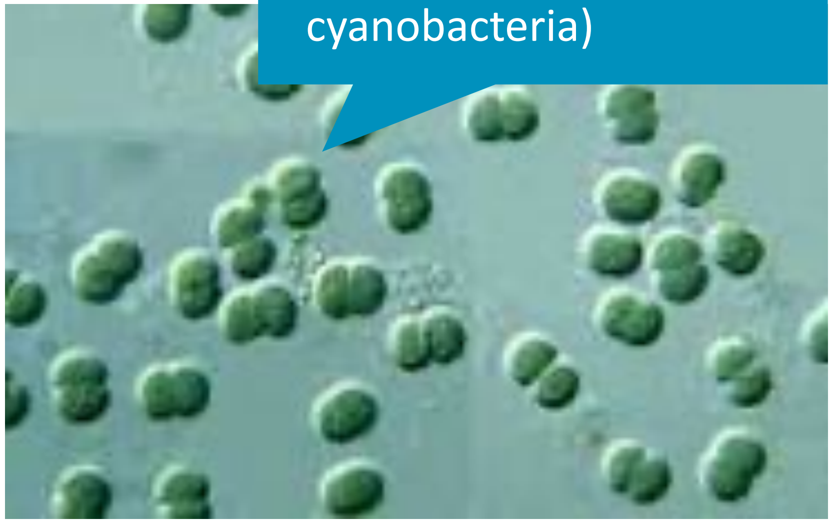




Plants:

Algae:

Cyanobacteria:

They are all able to generate electrons from water (i.e., water-photo-lysis)

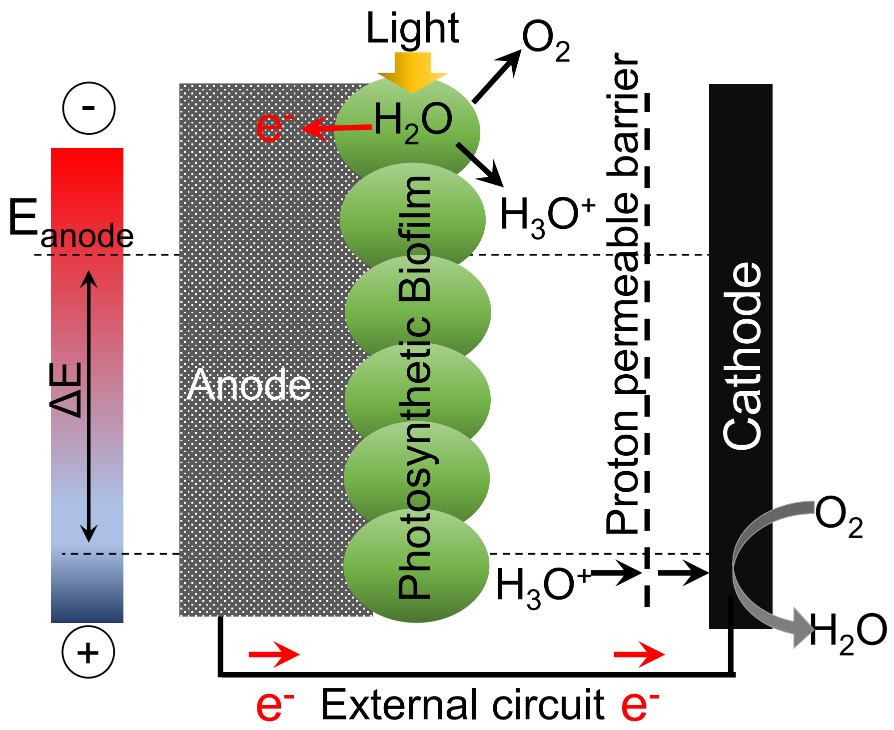
Water H_2O —Light (enzymes)→ Electrons Protons Oxygen

$$H_2O \xrightarrow[\text{(enzymes)}]{\text{Light}} e^- + H^+ + O_2$$

Can we generate electricity from photosynthesis?

Can we generate electricity from photosynthesis?

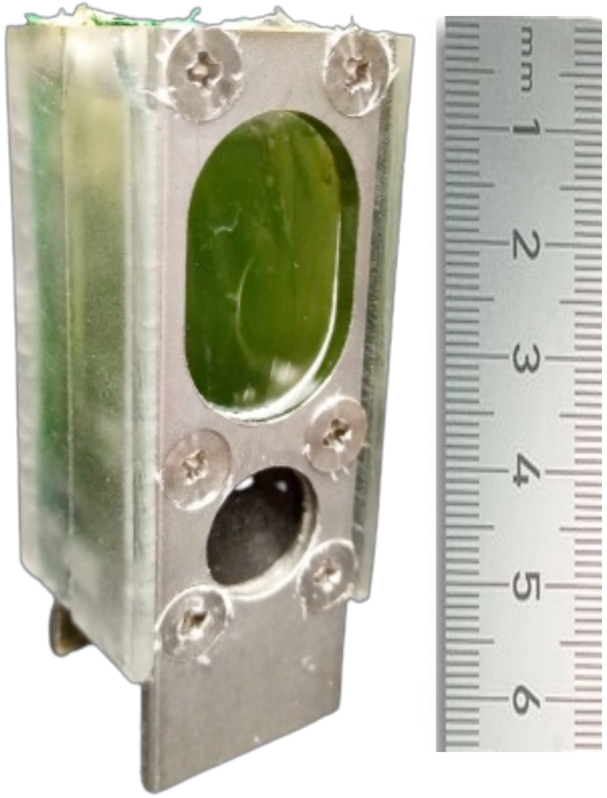
Photosynthetic microorganisms (e.g., micro-algae) are able to generate electrons that can be harvested by a suitable electrochemical setup and be used as a source of electrical current. This concept forms the basis of Bio Photo Voltaic (BPV) devices[1,2]. The main components forming a BPV are shown in the diagram below



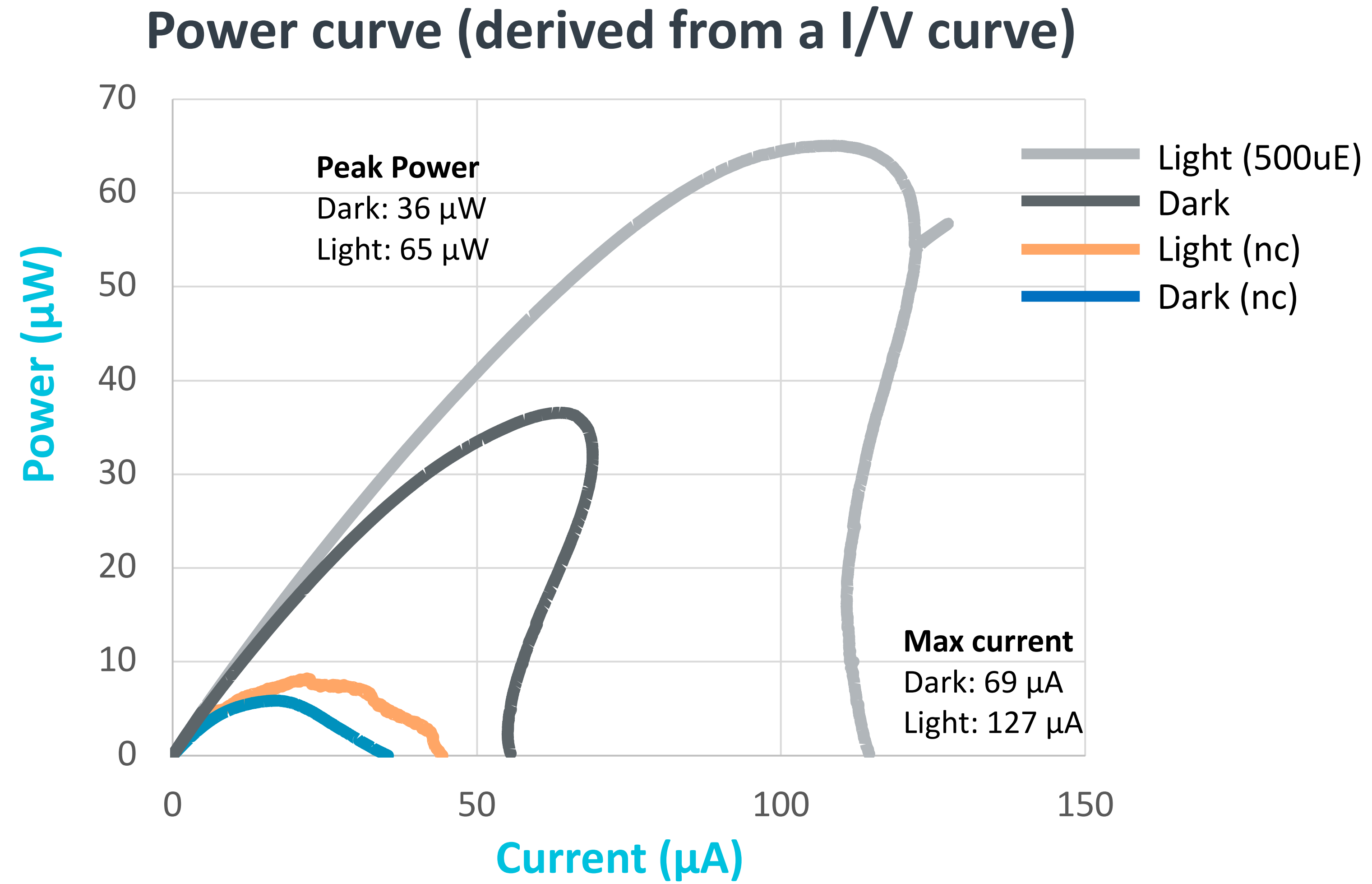
[1] McCormick *et al.*, (2015), *Energy & Environmental Science* 8 (4), 1092-1109.
[2] Howe and Bombelli (2020) Joule 4 (10), 2065-2069

How much current can we generate?

How much current can we generate?



Active volume (anode): 16.4 cm^3



Volumetric power density: dark: ~2 µW / cm^3 ; light: ~4 µW / cm^3

Bombelli *et al*. (2022) *Energy & Envtl Sci*.

BPV’s domain of application

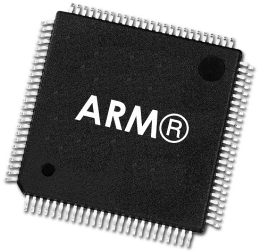
BPV's domain of application

– Power Consumption +

Micro and small electronic devices

Small domestic appliances

Large domestic appliances and industrial electric devices








μWs mWs Ws kW kWs

Powered by disposable and/or removable batteries

Powered by built-in butteries charged through the national grid

Powered by national grid

BPV's domain of application

– Power Consumption +

BPV's application today	BPV's application tomorrow
Micro and small electronic devices	Small domestic appliances

Large domestic appliances and industrial electric devices

µWs — mWs — Ws — kW — kWs

Powered by disposable and/or removable batteries

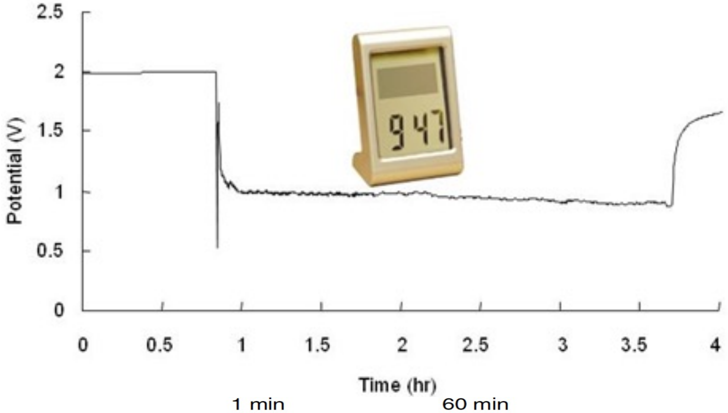
Powered by built-in butteries charged through the national grid

Powered by national grid

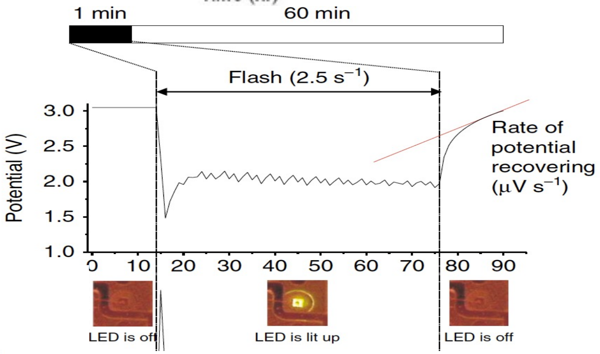
Example of electronic devices powered using a BPV

Example of electronic devices powered using a BPV

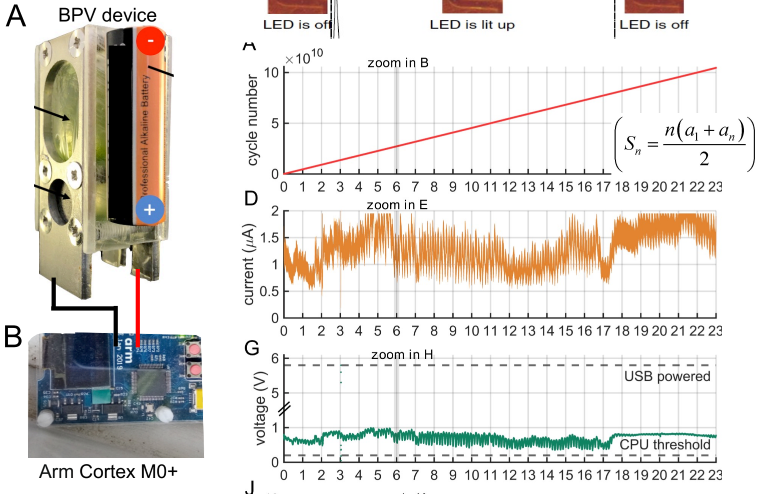
Power a digital clock

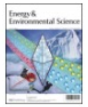


Power an intermittent LED from digitally printed cyanobacteria



Power an Arm Cortex-M0+ for > 6 months, in a domestic environment under ambient light





From the journal:
Energy & Environmental Science

Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system†

Alistair J. McCormick,*[a] Paolo Bombelli,[b] Amanda M. Scott,[b] Alexander J. Philips,[b] Alison G. Smith,[c] Adrian C. Fisher[b] and Christopher J. Howe[a]

nature communications

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Article | Open Access | Published: 06 November 2017

Electricity generation from digitally printed cyanobacteria

Marin Sawa, Andrea Fantuzzi, Paolo Bombelli, Christopher J. Howe, Klaus Hellgardt & Peter J. Nixon

Nature Communications 8, Article number: 1327 (2017) | Cite this article

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

PAPER

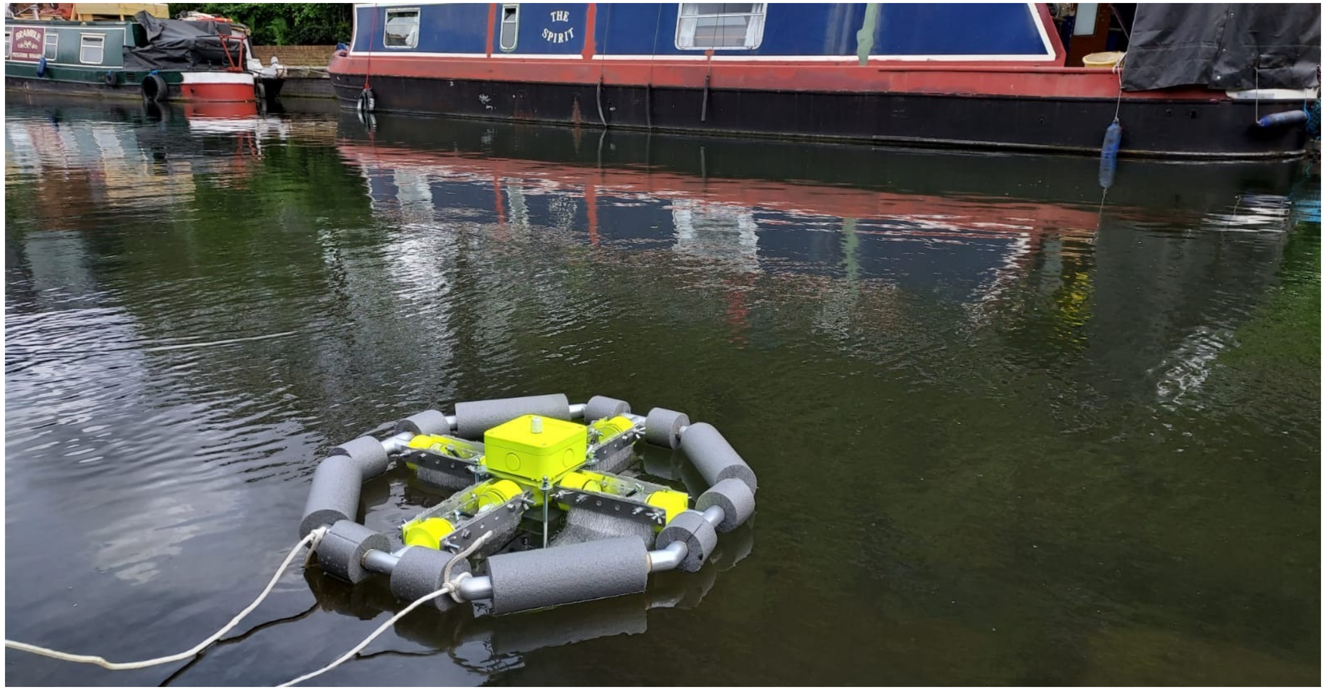
Check for updates

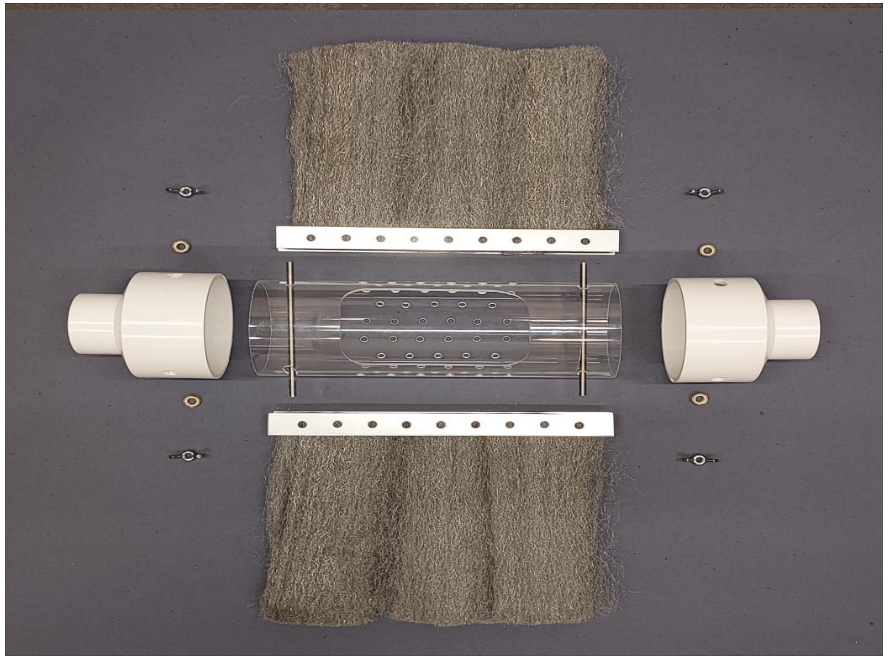
Cite this: *Energy Environ. Sci.*, 2022, 15, 2529

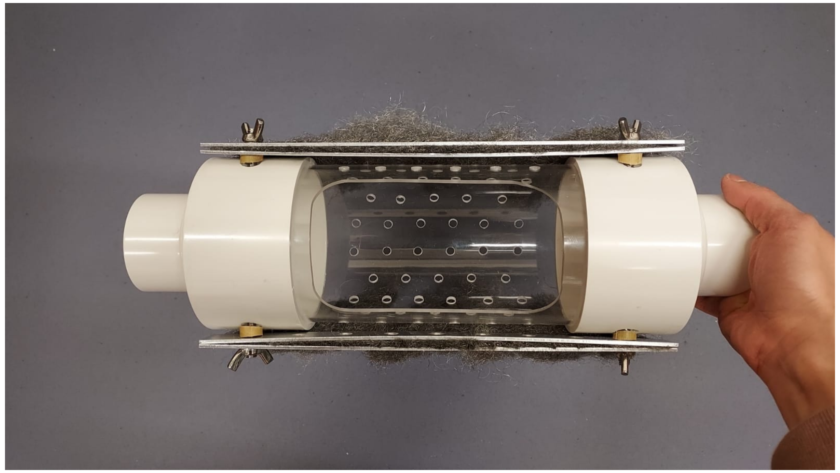
Powering a microprocessor by photosynthesis†

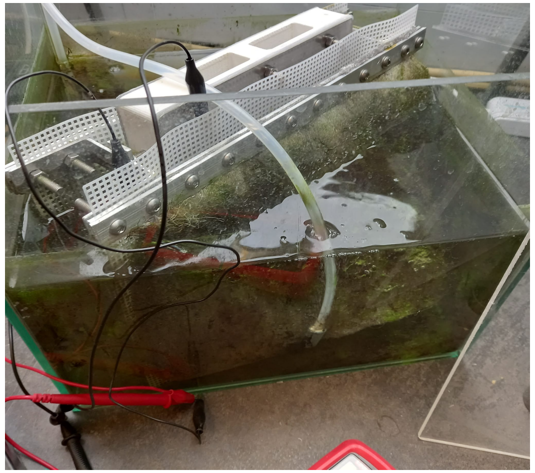
P. Bombelli,‡[ab] A. Savanth,‡[c] A. Scarampi,‡[a] S. J. L. Rowden,‡[a] D. H. Green,[d] A. Erbe,[e] E. Årstøl,[f] I. Jevremovic,[e] M. F. Hohmann-Marriott,[fg] S. P. Trasatti,[b] E. Ozer*[c] and C. J. Howe*[a]

The next step: floating-BPV for powering a tinyML application









Designing an Arm-based microcontroller board from scratch

Part 2

Gian Marco Iodice, Tech lead for ML @ Arm

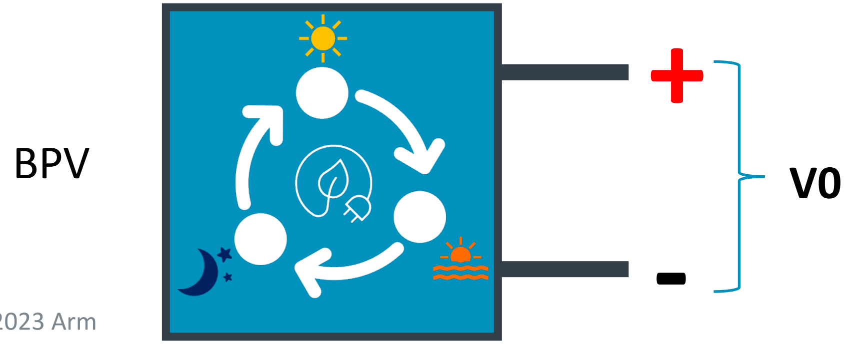
Sustainable technology for thriving and healthier communities

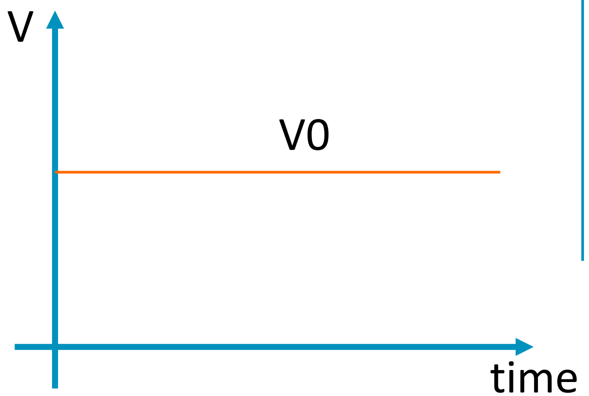
When we see big environmental problems, we may instinctively feel that the solution has to be just as big…

-Todd Myers

When powering tinyML with algae

- Monitoring environment through many sensors
- Rural areas where a small amount of power might be beneficial to power environmental sensors.
- Provide continuous electricity for longer than traditional batteries
  - It can last years!





Goal

Demonstrating that people, regardless of their expertise, has the power to address environmental challenges using today's technology in a sustainable and affordable manner.

arm

How

By powering the first ML application with algae on an Arm-based microcontroller

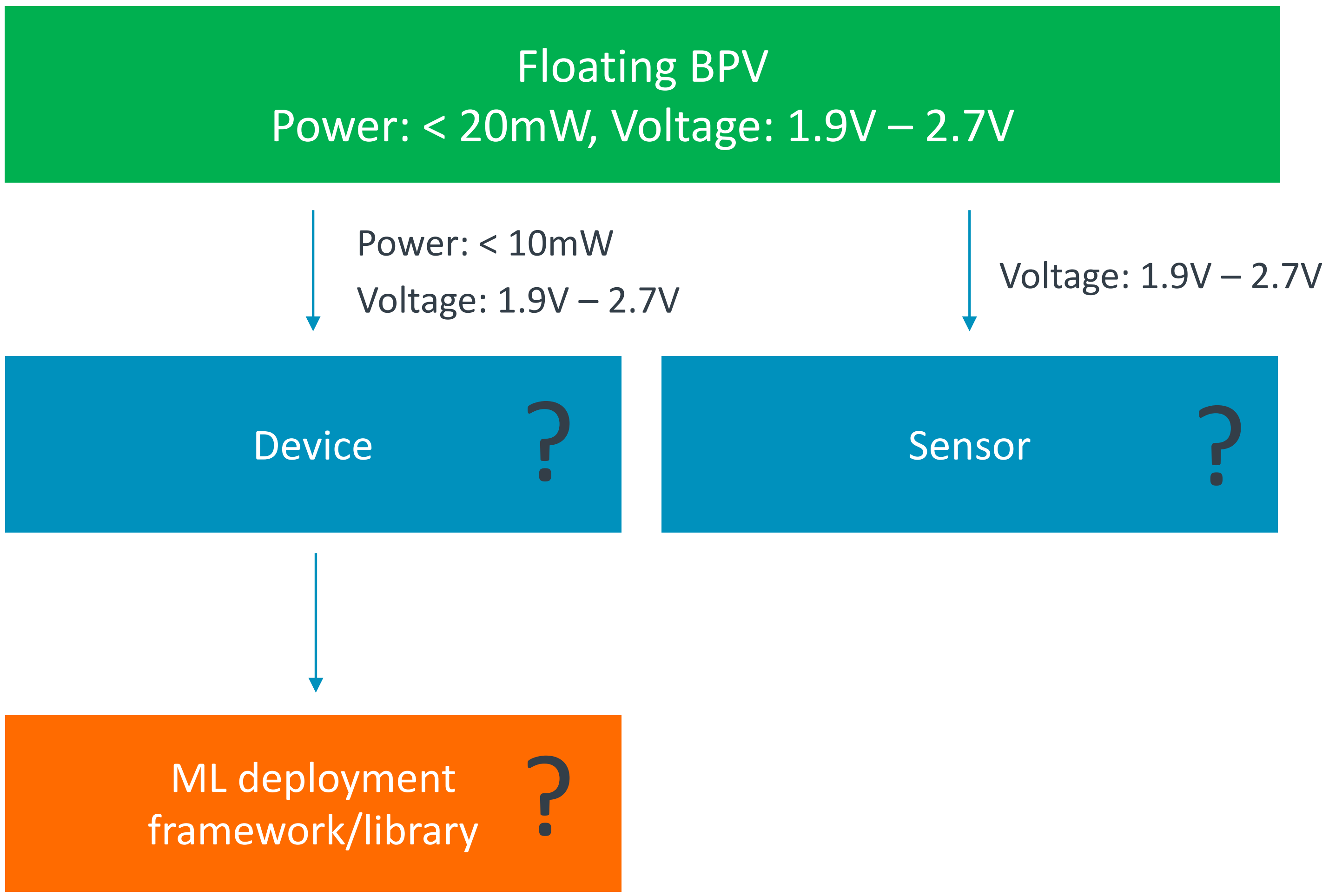
Project

Monitoring weather conditions and water quality with tinyML in the river Thames (London) using native algae of the river.

Ingredients for a tinyML application

The battery defines the power and voltage constraints

The device selection has implication on the ML framework adoption



Device selection considerations

- When aiming for a user-friendly development experience, microcontrollers are typically the preferred option.

- The microcontroller must be low-power (less than 10mW) and operating with voltages between 1.9V – 2.7V
  - No floating-point hardware acceleration
  - Small program (32 Kbytes) and data memory (8 Kbytes)
  - Low CPU clock frequency (16 MHz)
  - Only a few external HW components should be used. Mainly sensors.
  - Voltage regulator has to be very efficient

Today's microcontroller challenges

- Many microcontroller development boards do not operate with voltage below 3.3V
  - Most platforms operates with input voltages between 3.3 – 5V

- Therefore, we may need to build a custom board to target the specific voltage requirements
  - Nowadays, it can be very easy and fun developing a custom board with a microcontroller, thanks to detailed datasheets and plenty of free supporting online material
  - For prototyping, consider microcontroller that are easy to solder and can fit into breadboards
    - For example, SO8N or DIP footprint

Sensor selection considerations

- The sensors must be low-power (a few mW) and operating with voltages between 1.9V – 2.7V

- Some suitable sensors are:
  - IMU
  - Temperature/humidity
  - Optical flow
  - Light
  - Pressure
  - Gas
  - Turbidity

Today's sensor challenges

- Many sensor modules do not operate with a voltage below 3.3V
- We may need to design a board from scratch. This may reduce the number of options for easy prototyping

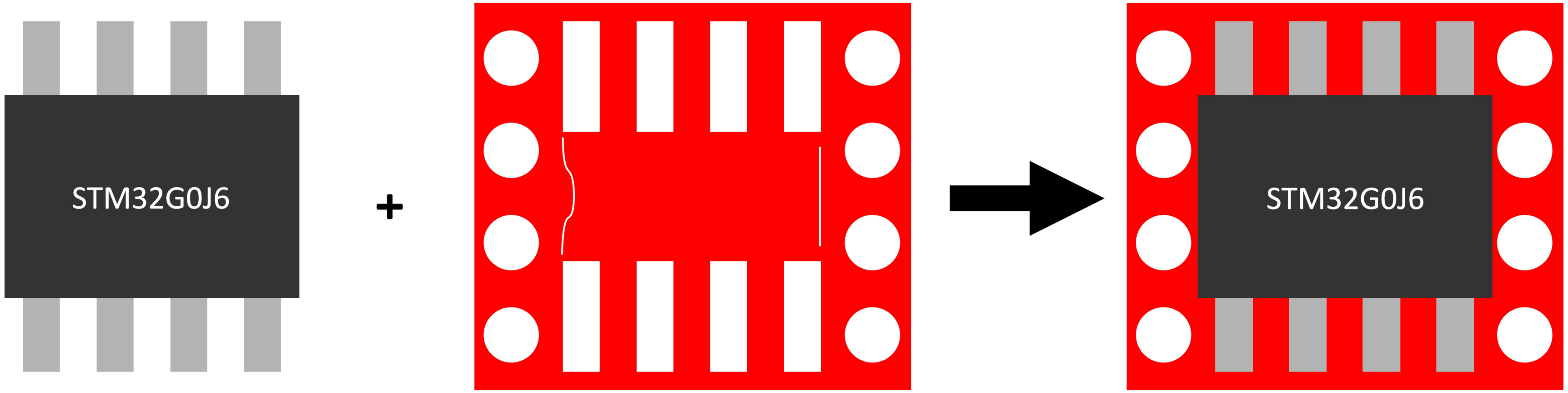
ML deployment framework/library selection considerations

- It depends on:
  - The target device (microcontroller?)
  - The features of the target device (on-board memory)
- There are many great tools (and often free and/or open source) for microcontrollers.
  - However, we should consider the feasibility of fitting the ML model onto the chosen microcontroller.
  - Frameworks with ahead-of-time (AOT) capabilities may be preferred to reduce program memory usage.
    - The model should NOT be loaded at runtime

Our solution

~£1.7 single unit or **~£0.5** on large order

~£0.9 single unit



~£2.6 single unit

STM32G031J6 MCU

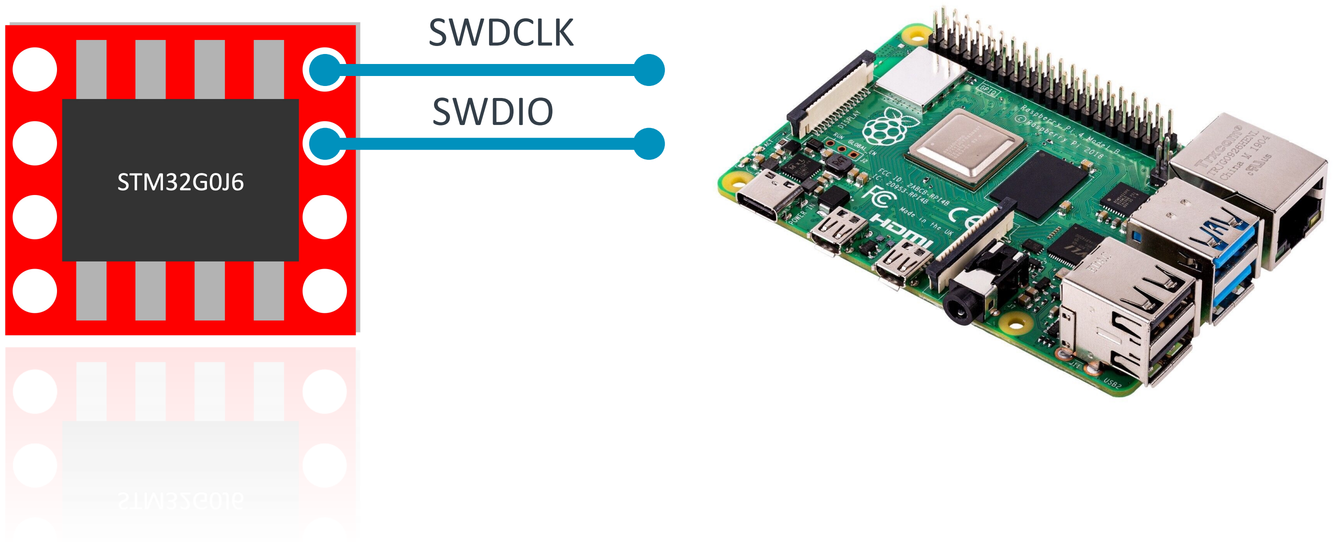
SparkFun SOIC to DIP adapter

Feature	
CPU	Arm Cortex-M0+ @16 MHz
Operating voltage - Power	2 - 3.6V - 93uA/MHz
FLASH - SRAM	32 Kbytes – 8 KBytes
Peripherals	I2C, SPI, UART, USART, Timers, DMA, RTC, ADC, PWM

Programming and debugging with SWD on Raspberry Pi

Target

Host + debugger probe



Serial Wire Debug (SWD):

Arm interface for flashing and debugging an Arm-based microcontroller with only two wires (**SWDCLK** and **SWDIO**)

- We can use the SWD IO pins on Raspberry Pi to communicate with the microcontroller
- Raspberry Pi can be used as a standard computer for programming the microcontroller.

Designing and deploying the first ML model powered by algae!

- As first model powered by algae, we have considered the sine wave model.
  - This model represents the “Hello, World” for the tinyML community.
  - We express our deepest gratitude to Pete Warden and Daniel Situnayake for their contribution.
- The model was trained and quantized (8-bit) directly in Google Colaboratory
- The tinyML application was written in C++
  - The application has been compiled and uploaded from the Raspberry Pi
- The model has been accelerated on the microcontroller using CMSIS-NN

Stats	Values
Model params	3 Fully Connected layers with a total of 321 params
Program memory	9.7 Kbytes
SRAM	2.1 Kbytes
Current consumption	1.8 mA

State of the project and some pics!

Floating BPV design and implementation	In progress
Prototyping a microcontroller board with less than £5	✓
Evaluate power consumption for running the sine wave model	✓
Evaluate application life	✗

Phase 1

Expand the microcontroller board with low-power sensors for water monitoring	✗
Design a tinyML model for weather/water monitoring	✗

Phase 2

Natural Artificial Intelligence of Things (NAIoT)

28/06/2023 @ tinyML EMEA
First use of this acronym

…it's time to think small

-Todd Myers

Acknowledgments

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Howe's lab

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Thank You
Danke
Gracias
Grazie
谢谢
ありがとう
Asante
Merci
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Kiitos
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