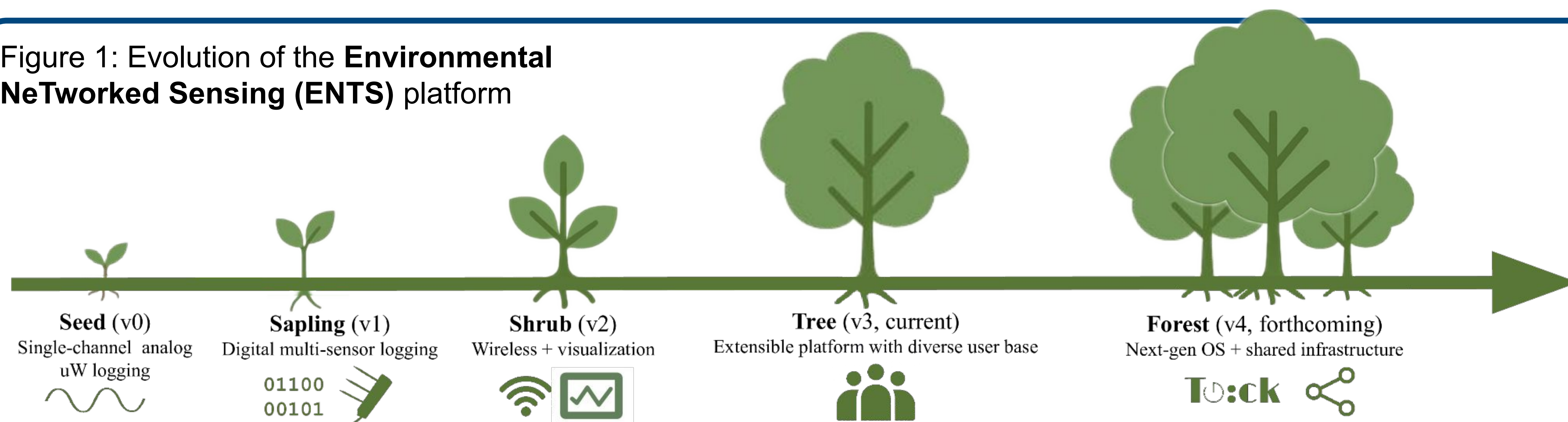


Figure 1: Evolution of the Environmental NeTworked Sensing (ENTS) platform



Failures of existing measurement systems

- Effective characterization of low-power energy sources in relation to environmental factors requires studying dozens of duplicates in a variety of isolated conditions.
- Commercial off the shelf (COTS) and research solutions are cost prohibitive, do not scale to larger experiments, and cannot facilitate in-lab to field experimentation [1,2,3].
- Many WSN platforms used to build a solution have become deprecated over time, limiting their adoption [4,5,6].

Seed (v0): Start by being good at one thing

- ENTs was initially developed to characterize the output of Microbial Fuel Cell power output.
- Seed was a naive solution to reducing the cost of measuring μ W-scale power from low-power energy sources at scale with high precision and accessibility.

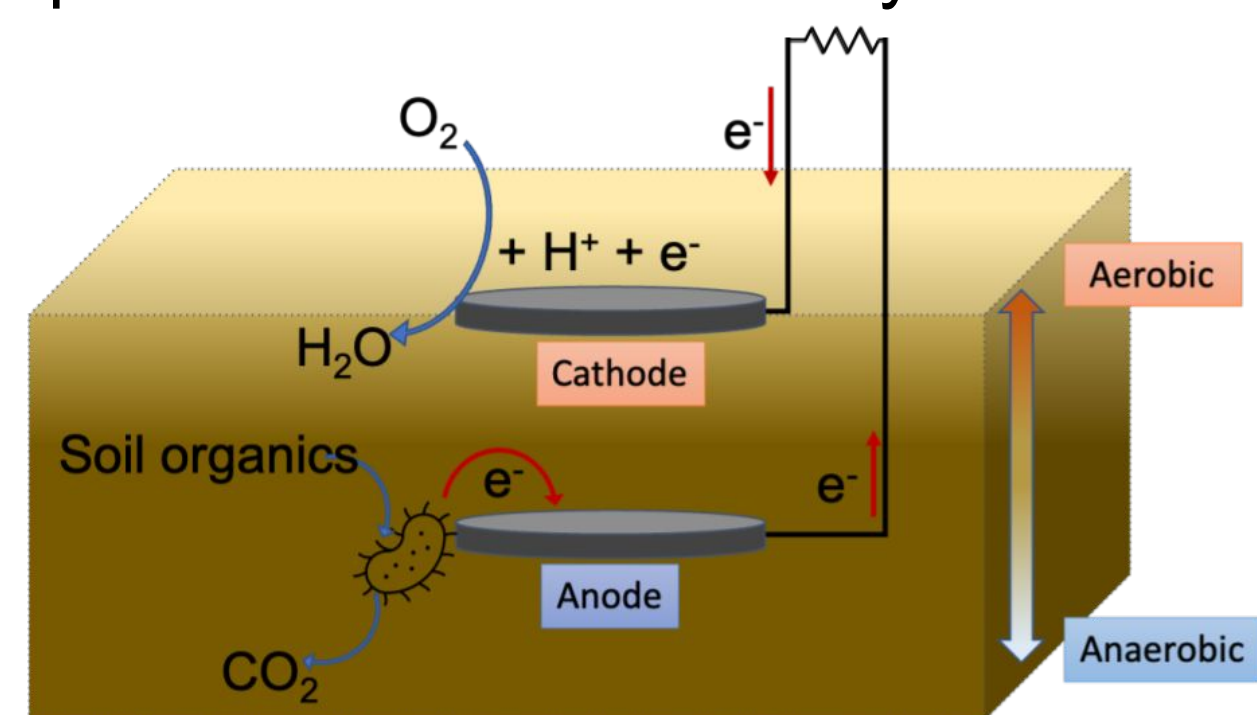


Figure 2: Typical soil MFC structure.

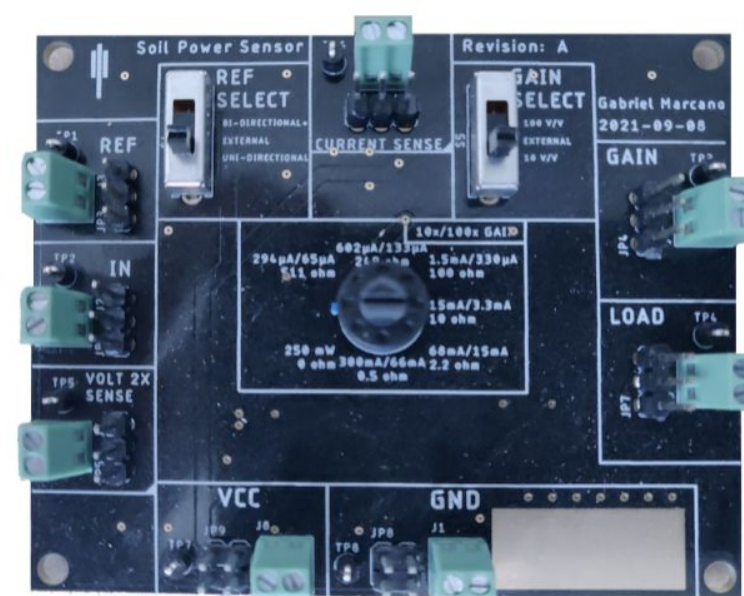


Figure 3: Seed v0 design focusing on large-scale low-power analog measurements.

Sapling (v1): Usability for in-field experiments

- In the Sapling stage, we improved ENTs' usability by expanding its analog and digital sensing capabilities to support the lab-to-field transition.
- Through collaborations, we gained insight on the need to focus on providing extensibility rather than modularity in order to meet the needs of novel experiments.

Improvements: Microcontroller, onboard storage, expanded sensing capabilities

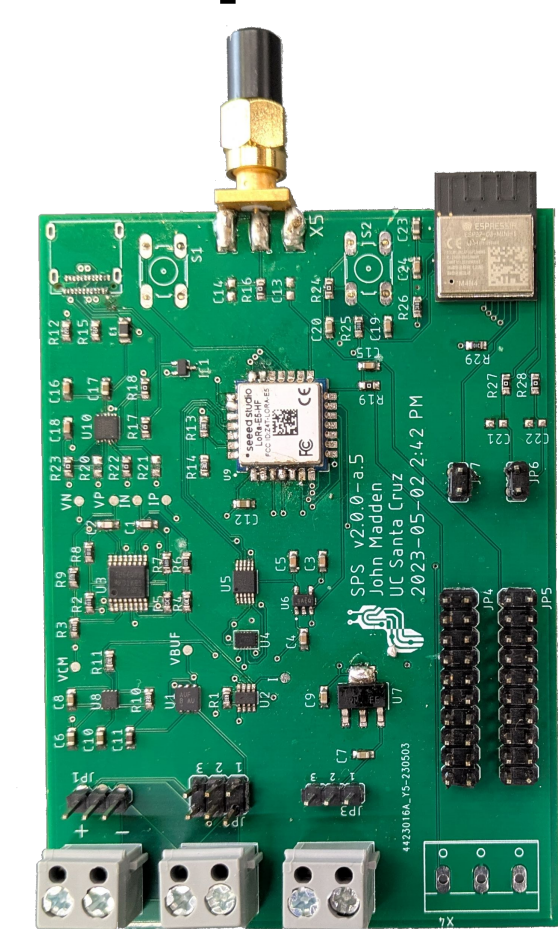


Figure 4: Sapling v1 design with onboard wireless communication and non-volatile memory for in-field experiments.

Shrub (v2): Extensibility for longevity

- ENTs grew into Shrub (v2) by focusing on **longevity through extensibility**.
- We learned extending the capabilities of a system is easier than fitting into an existing framework.
- ENTs was extended to support biomimetic leaf wetness sensing for disease mitigation.

Improvements: LoRaWAN, 802.11 WiFi, basic power visualization, SDI-12



Figure 5: Deploying bio-mimetic leaf wetness sensor in the field

Tree (v3): Co-design informs growth

- A successful wireless sensor networks **requires collaboration** with potential users across disciplines.
- Such collaboration informs meaningful design decisions for real-world uses cases.
- In Tree (v3) we branched out to environmental scientists studying the power output from prickly pear cacti to collect field data.

Improvements: Waterproof enclosure, arbitrary sensor measurements, I2C, battery and solar charging



Figure 6: Outdoor deployment of ENTs to monitor prickly pear cacti power output.

Principles for WSNs

1. **Design for breadth:** ENTs is over provisioned with extra sensor channels, dual communication for long and short distances, and generous power headroom. This allows for rapid prototyping without the need for hardware modifications.
2. **Prioritize extensibility over modularity:** Modularity offers a fixed set of interchangeable parts, making it difficult to expand beyond the original use case. ENTs ensures capabilities can be continually added through our extensible design.
3. **Co-design and outreach:** The longevity of ENTs is ensured through long term relationships between developers and domain scientists. We accomplish this through proactive outreach, maintaining high quality documentation, and fostering collaborative communities

System Overview

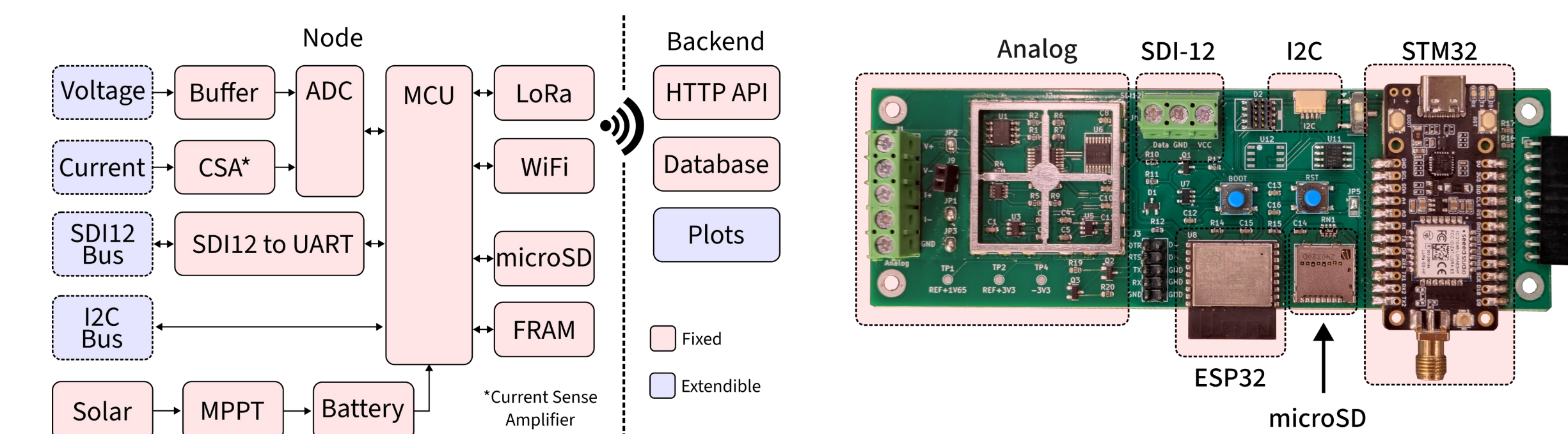


Figure 7: ENTs system diagram.

Figure 8: ENTs v3 board hardware.

- **Approachable and extensible:** ENTs allows domain experts to leverage the benefits of wireless sensor networks without needing a background in embedded systems.
- **End-to-end:** Provide a customizable and complete solution which encompasses a physical enclosure, electronics hardware, embedded firmware, database, and web-based visualization platform.
- **Affordable:** Comparable feature-wise to COTS solutions while maintaining a reasonable production cost. (50 USD)
- **Longevity:** ENTs is designed with open source engagement in mind to keep ongoing development user-focused.

Capabilities:

- **MCU:** STM32WLE5, ESP32-C3
- **Communication:** LoRaWAN, WiFi
- **Sensing:** I2C, SDI12, Analog interface
- 1 Mbyte onboard storage
- Waterproof enclosure
- User configuration
- Data visualization website

	ENTS
Size	116 × 67 mm
Price per channel	50 USD
General	
Idle	15 mW
Logging	50 mW
Channels	1
Sampling Rate	1000 SPS
Voltage	
Range	±2 V
Resolution	100 μ V
Accuracy	5.81 ± 15.5 μ V
Leakage Current	4 nA
Noise Floor	5.04 μ Vrms
Current	
Range	±0.8 mA
Resolution	119.2 pA
Accuracy	83.0 nA ± 658 nA
Burden Voltage	0.33 mV
Noise Floor	1.53 nA

Figure 9: ENTs v3 capabilities.



Figure 10: Voltage data from the visualization dashboard.

Open Source Contributions

To date, ENTs has:

- Participated in Google Summer of Code since 2022.
- Involved 7 undergraduate students in the development of the project.
- Designed and taught a student led course preparing undergraduates for contributing to open source projects and research.

Forest (v4): Future Works

- Migrating ENTs to TockOS for robustness and extensibility with secure principles [7].
- *In progress:* Additional applications in irrigation for agriculture.



GitHub Paper Link

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