# Low-Cost Biphasic DC Data Acquisition for Monitoring Cementitious Self-Sensing Materials

David P. Wamai[a,b], Austin R.J. Downey[a,c], Hasan Borke Birgin[d], Antonella D'Alessandro[d], and Filippo Ubertini[d]

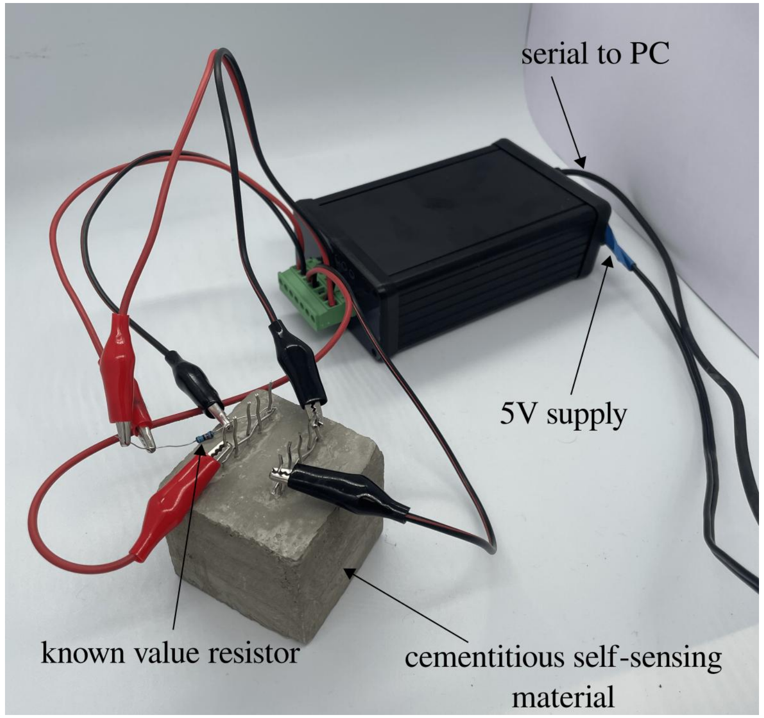
[a]Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208, USA
[b]Department of Computer Science and Engineering, University of South Carolina, Columbia, SC 29208, USA
[c]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC 29208, USA
[d]Department of Civil and Environmental Engineering, University of Perugia, Perugia, Italy

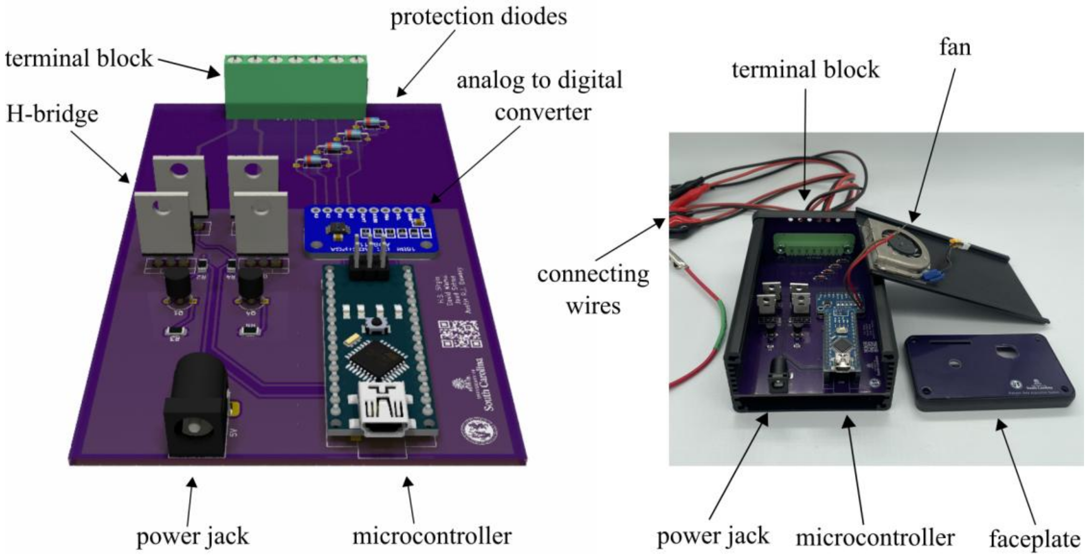
UNIVERSITY OF SOUTH CAROLINA

# General goal and outline

**Outline**

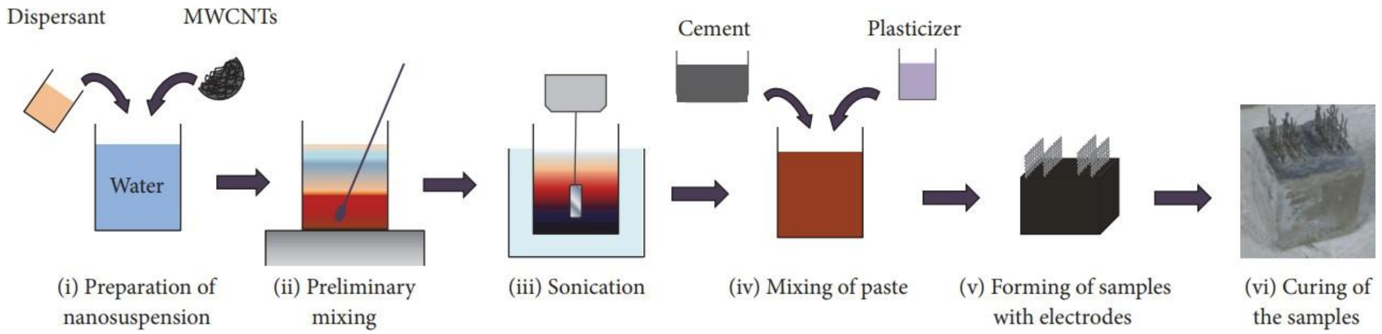
- Introduce self-sensing concrete
- Introduce the biphasic DC measurement approach
- Discuss the hardware design
- Exline an H-bridge example
- Discuss considerations  and future work



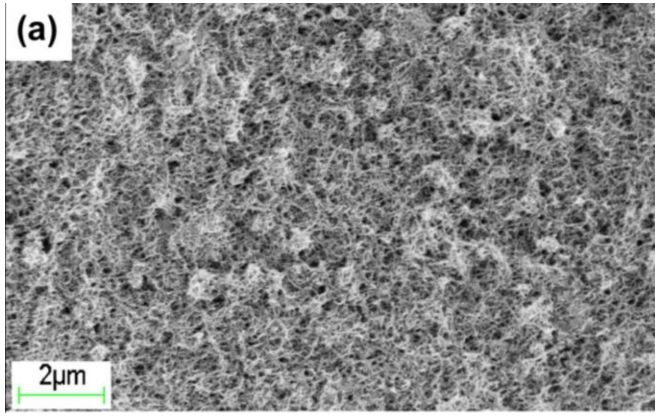



# Making Multifunctional (Self-Sensing) Concrete.

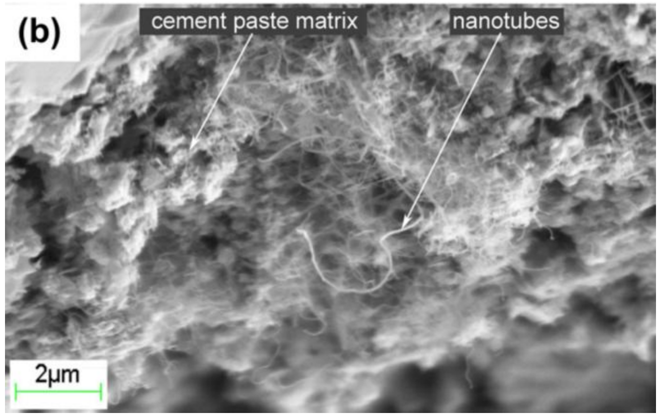
- **Conductive Fillers:** Carbon nanotubes added to cement to create electrical conductivity.
- **Mix and Cure:** Fillers uniformly dispersed, samples formed, and cured to achieve sensing properties.
- **Self-Sensing Functionality:** Changes in strain or damage alter electrical properties, allowing structural health monitoring.




Preparation process of the cement paste samples with 1% of MWCNTs




SEM image of MWCNTs-water solution magnified 50,000 times.

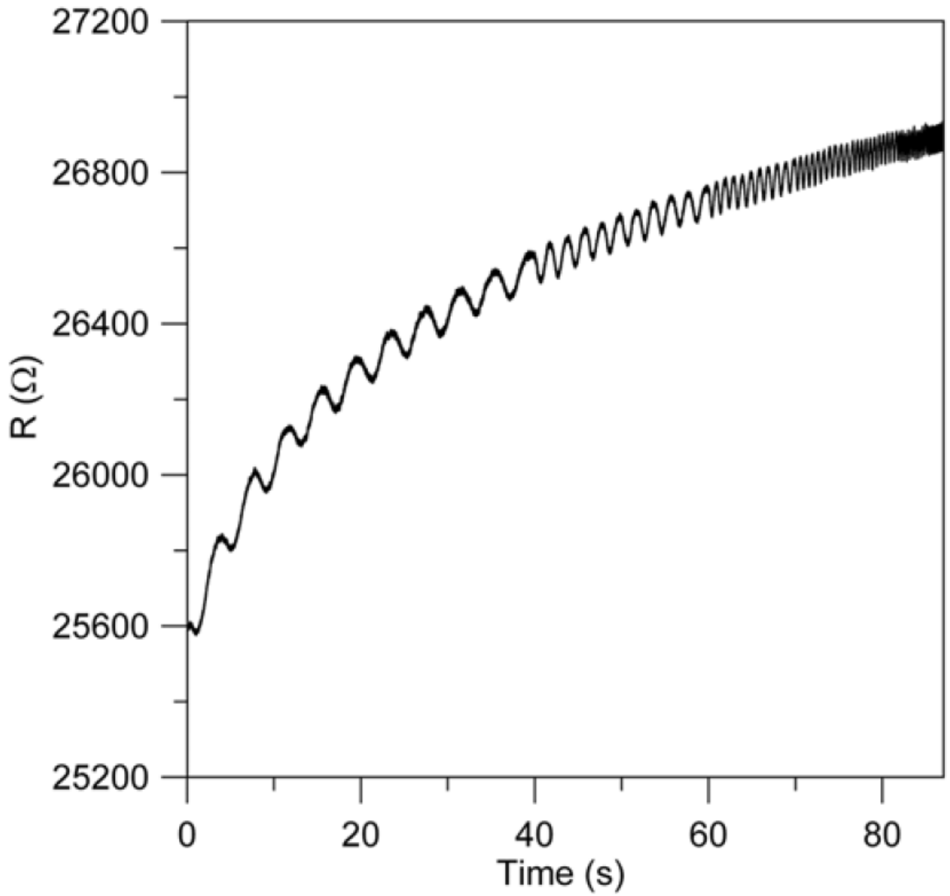



SEM image of cement paste with MWCNTs magnified 25,000 times.


D'Alessandro, Antonella, Marco Rallini, Filippo Ubertini, Annibale Luigi Materazzi, and Jose Maria Kenny. "Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications." *Cement and Concrete Composites* 65 (2016): 200-213.

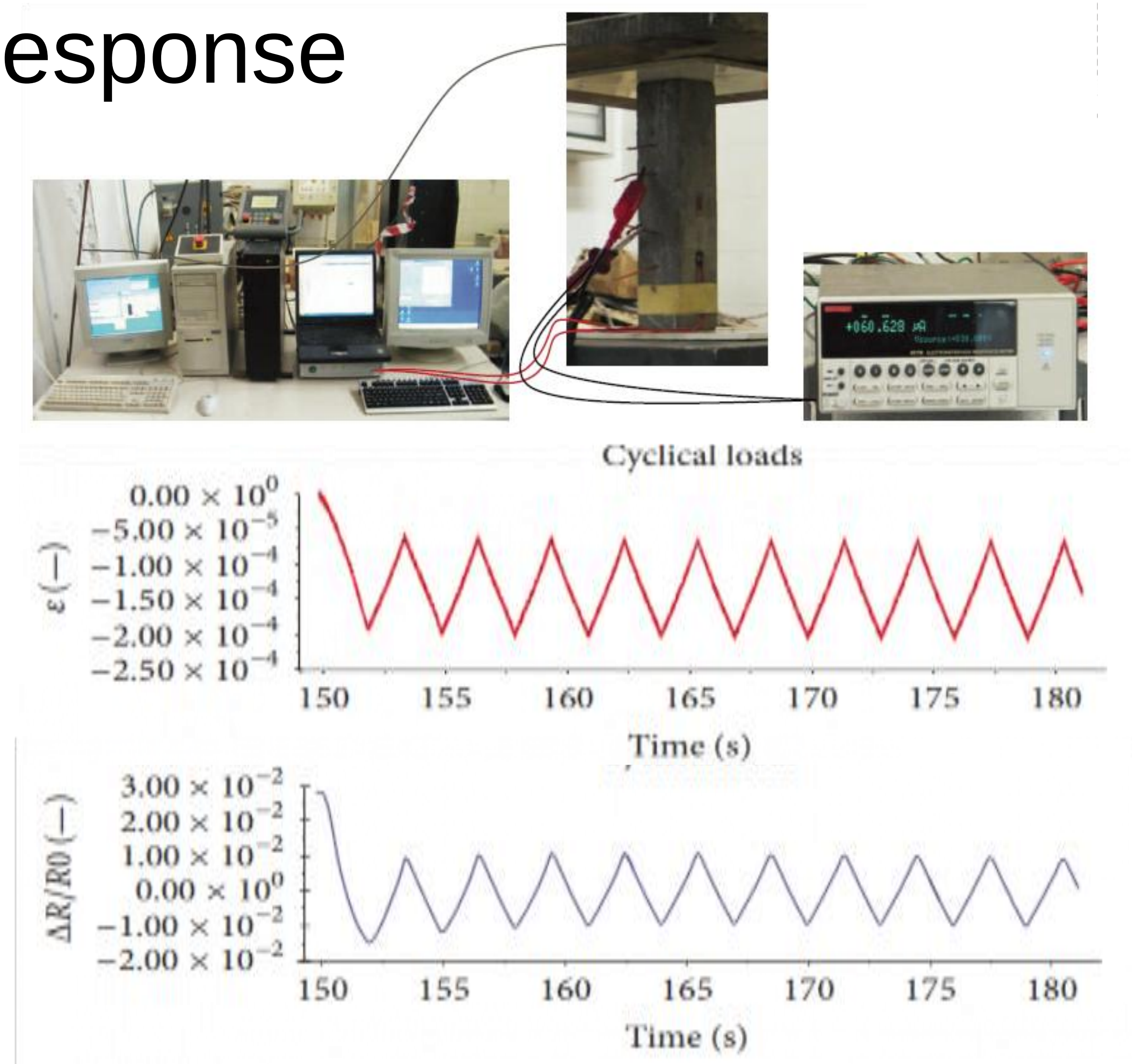
# Resistance Drift in Multifunctional Concrete

- **Challenge:** Electrical resistance drifts over time, complicating accurate long-term monitoring.
- **Possible Causes:**
  - Material polarization due to continuous DC current.
  - Changes in dielectric properties over time.
- **Traditional Solutions:**
  - Delaying measurements until drift stabilizes.
  - AC measurement techniques to reduce polarization effects.



# Dynamic Strain-Sensing Response

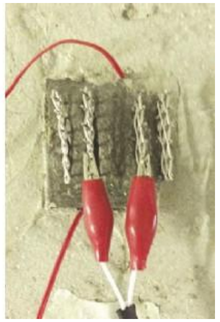
- **Minimal Drift under Dynamic Loads:** Rapid load cycling prevents polarization build-up.
- **Effective Dynamic Monitoring:** Self-sensing concrete accurately reflects applied dynamic strain.
- **Ideal for Transient Conditions:** Reliable performance when measuring short-duration, cyclical events.

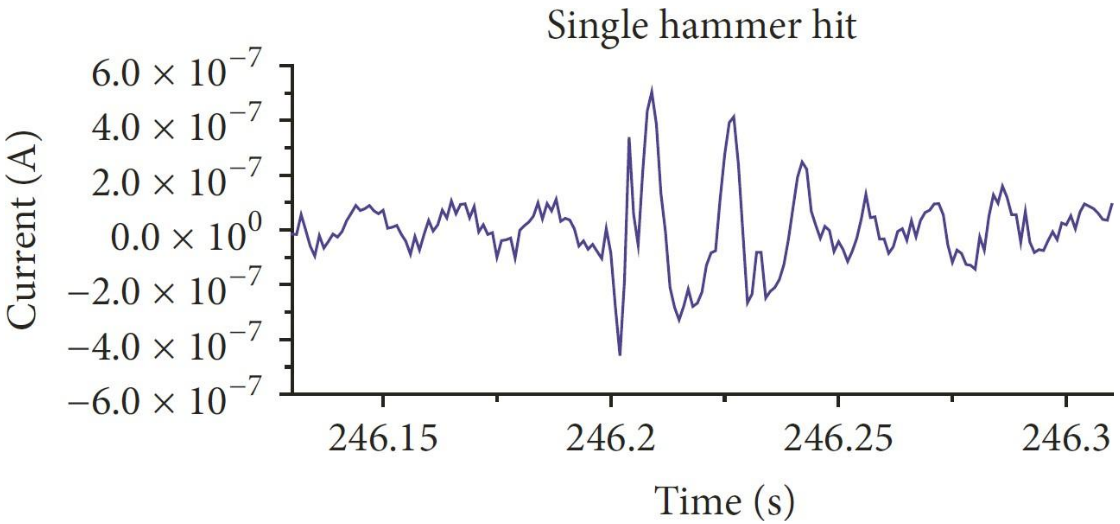



García-Macías, Enrique, Austin Downey, Antonella D'Alessandro, Rafael Castro-Triguero, Simon Laflamme, and Filippo Ubertini. "Enhanced lumped circuit model for smart nanocomposite cement-based sensors under dynamic compressive loading conditions." *Sensors and Actuators A: Physical* 260 (2017): 45-57.

# Impact Response Testing

- **Dynamic Testing Validation**
  - Single hammer hit tests demonstrate expected dynamic behavior.
  - Clear transient current response matches mechanical impact event.
- **Reliable Dynamic Measurements**
  - Self-sensing concrete accurately captures transient impact loads.
  - Measured electrical response aligns closely with mechanical excitation.



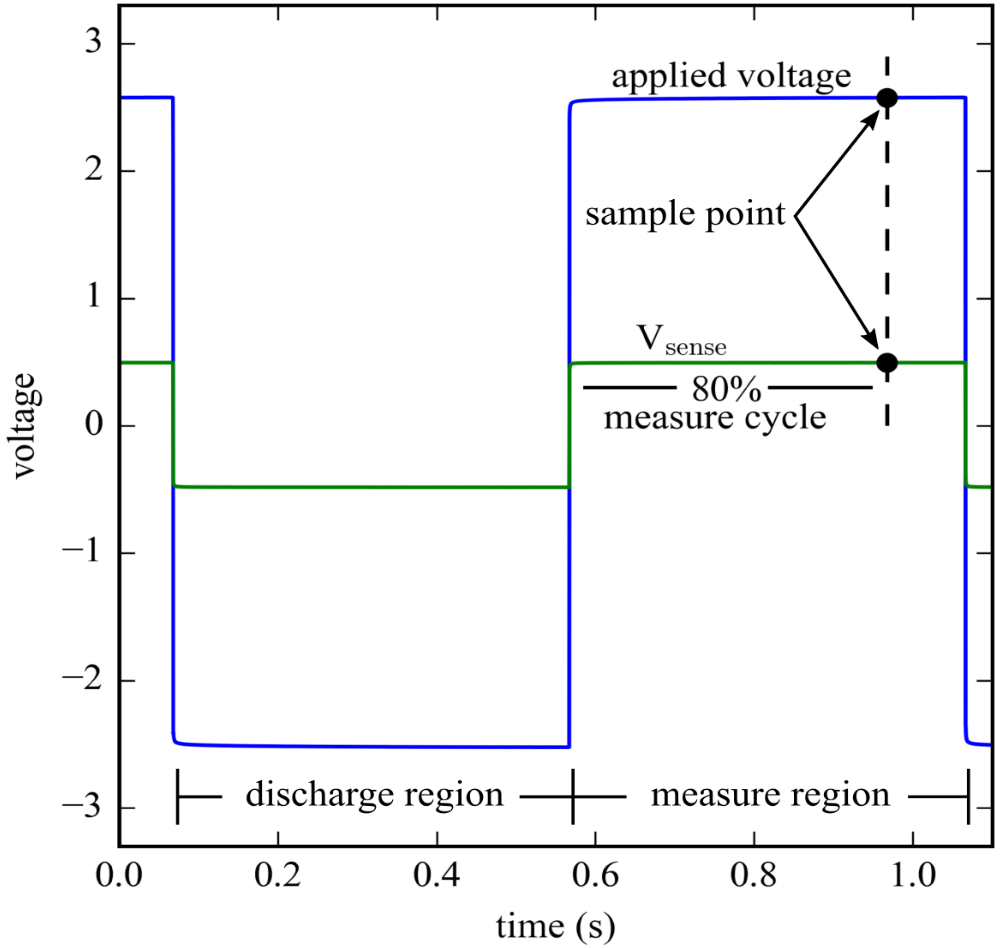



D'Alessandro, Antonella, Filippo Ubertini, Enrique García-Macías, Rafael Castro-Triguero, Austin Downey, Simon Laflamme, Andrea Meoni, and Annibale Luigi Materazzi. "Static and Dynamic Strain Monitoring of Reinforced Concrete Components through Embedded Carbon Nanotube Cement-Based Sensors." *Shock and Vibration* 2017, no. 1 (2017): 3648403.

# BIPHASIC DC MEASUREMENT APPROACH

# Biphasic DC Measurement Approach

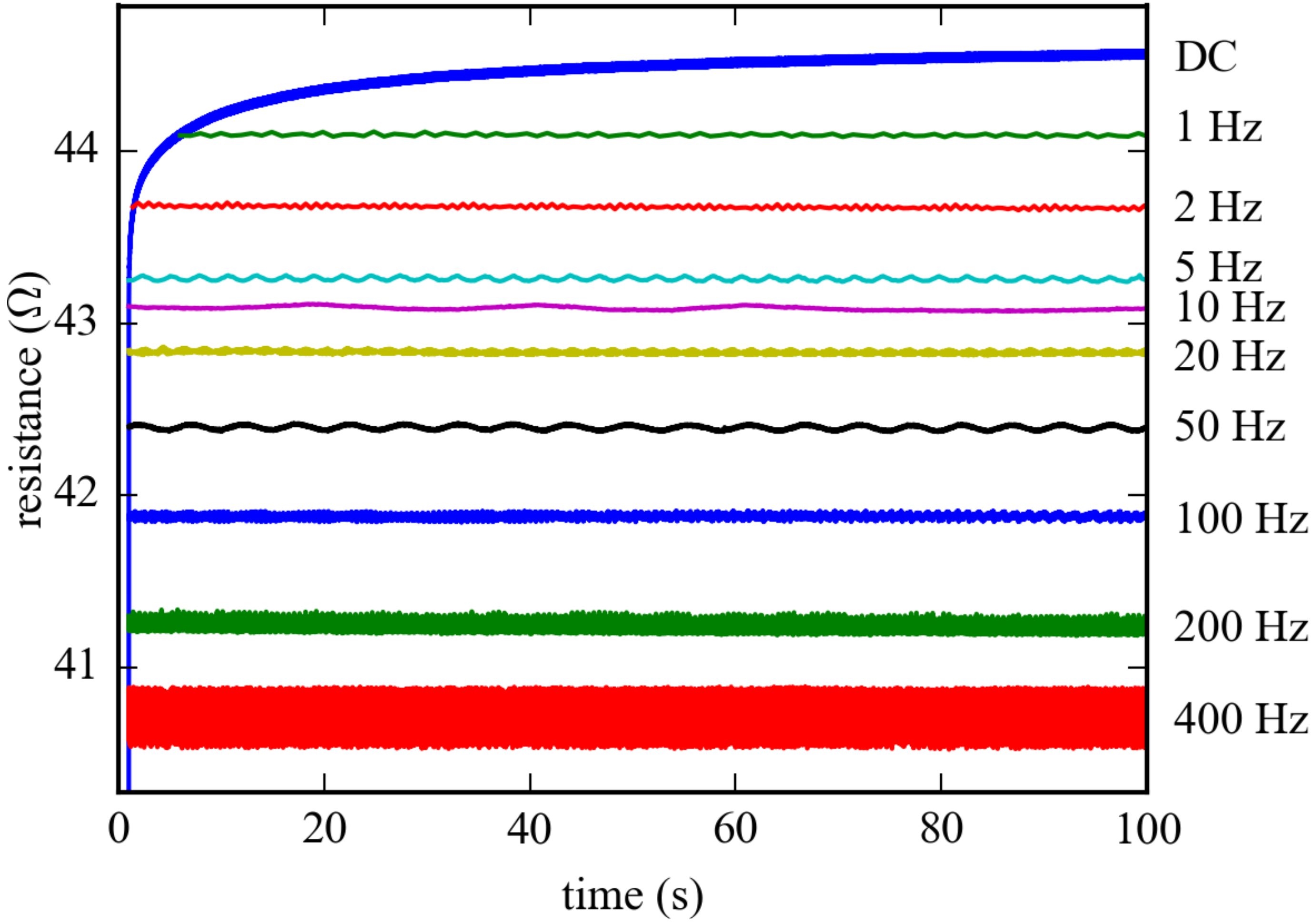
- **Uses material polarization to its advantage**
  - Alternates current direction periodically, allowing built-up polarization charges to dissipate.
- **Measure/Discharge Cycle**
  - Measurement taken at stable point (80% into positive cycle).
  - Negative cycle actively discharges material polarization.




Downey, Austin, Antonella D'Alessandro, Filippo Ubertini, Simon Laflamme, and Randall Geiger. "Biphasic DC measurement approach for enhanced measurement stability and multi-channel sampling of self-sensing multi-functional structural materials doped with carbon-based additives." *Smart Materials and Structures* 26, no. 6 (2017): 065008.

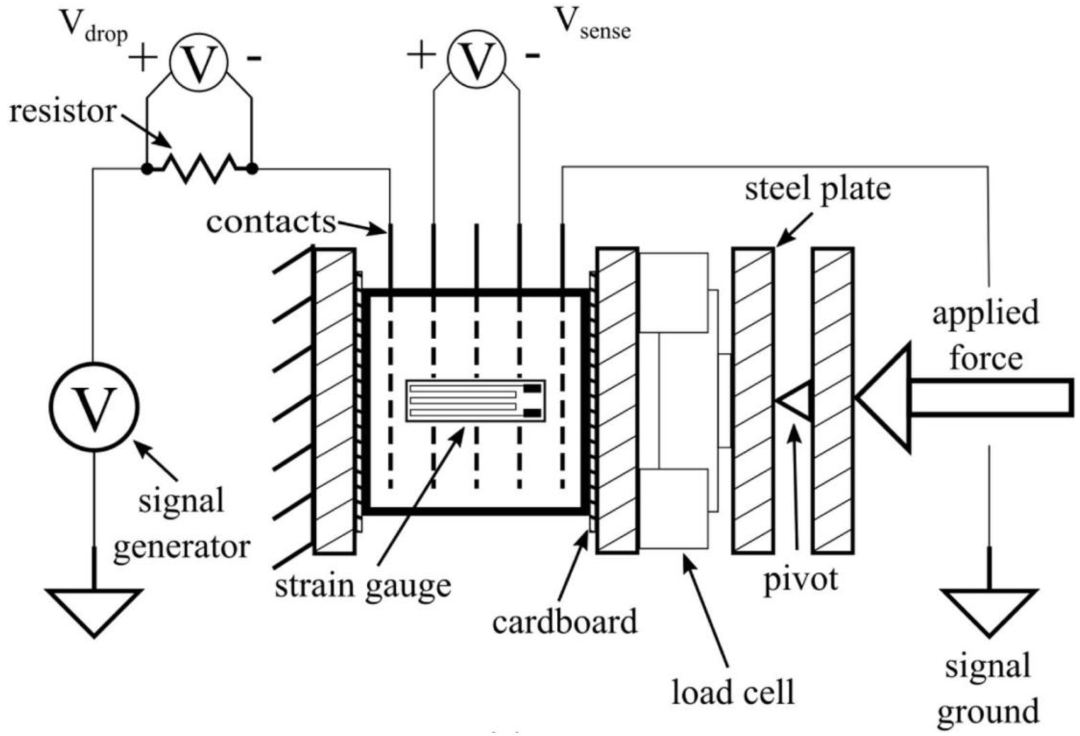
# Biphasic DC measurement approach

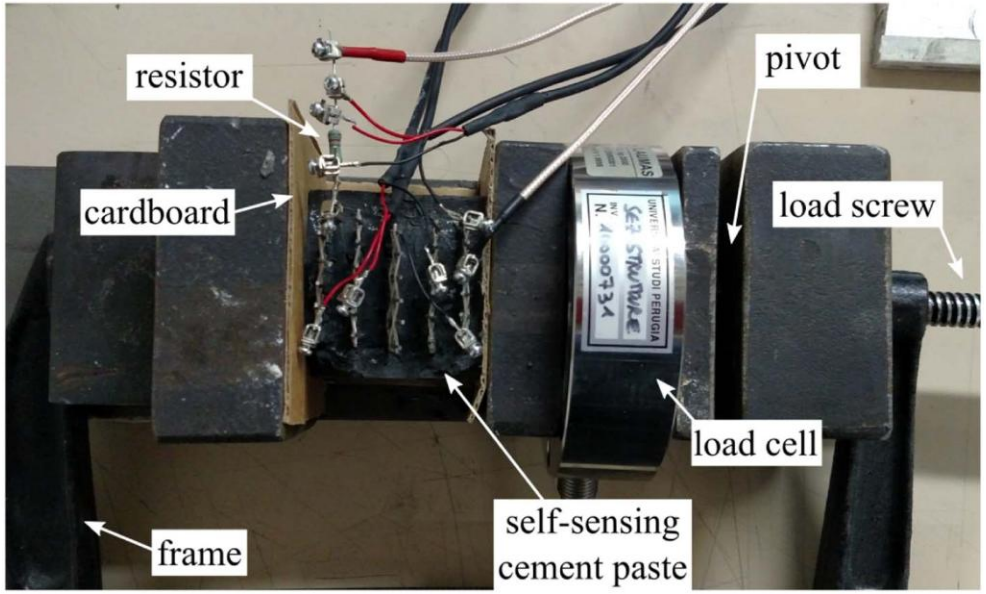
- **Proven Method:**
  - First published in 2017, widely adopted by several research groups.
  - Provides stable, drift-free measurements of self-sensing materials.
- **Open-Source Hardware:**
  - Facilitate easier replication and further innovation by the research community.



# Works in 2-Point and 4-Point Configurations

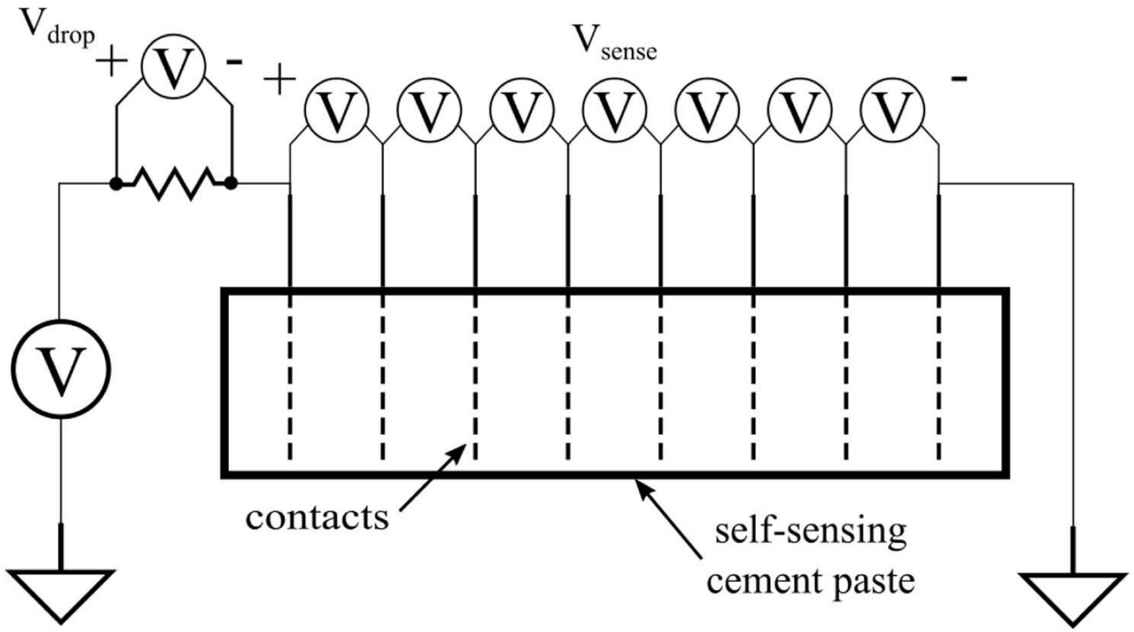
- In 2017, we validated the biphasic DC measurement method using both 2-point and 4-point configurations.



# Multichannel Measurements

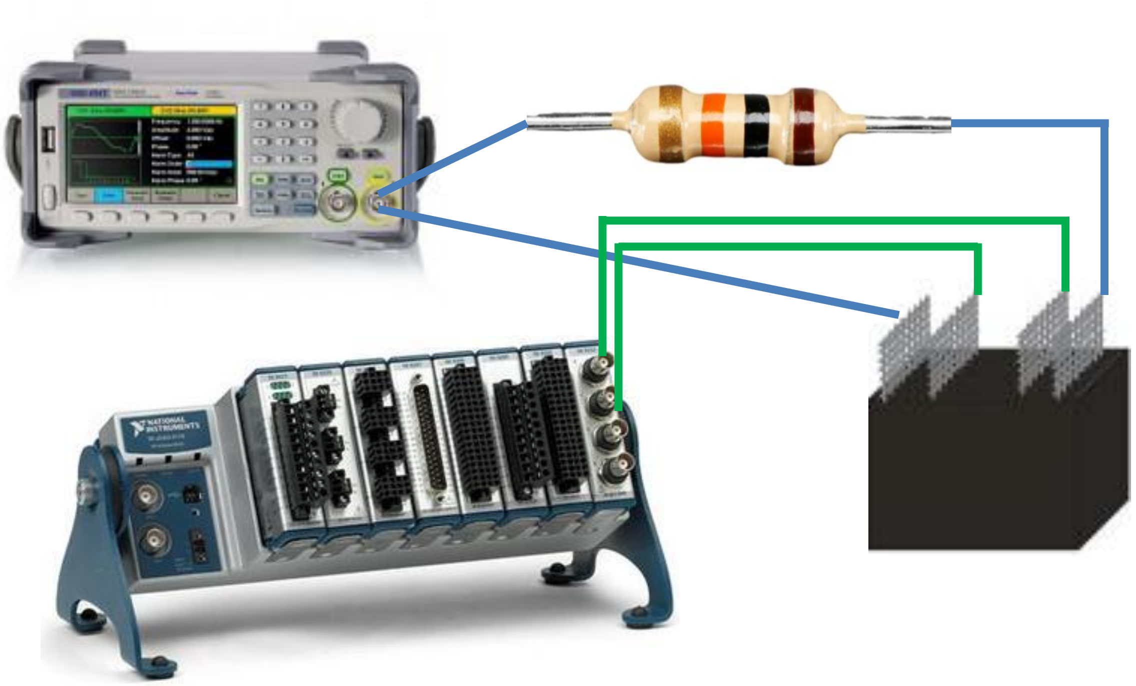
- In 2017, we demonstrated a cascading 4-point measurement system along with the biphasic approach to enable multi-channel damage detection.




# HARDWARE

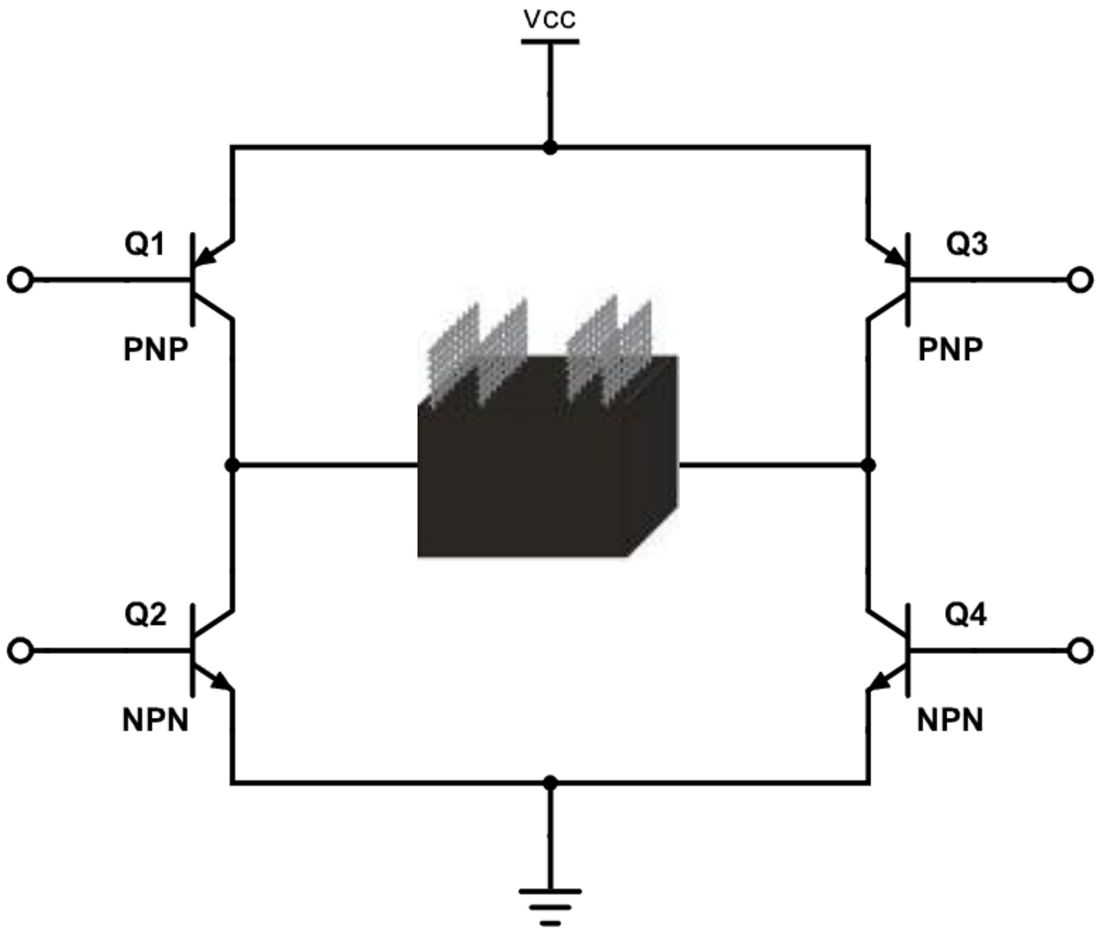
# Signal Generator Based Biphasic DC System

- **Easy to use:** straightforward connections, and standard lab equipment.
- **Reliable measurements:** accurate for initial validation.
- **Expensive:** requires costly laboratory-grade instruments.
- **Not miniaturized:** large footprint limits field or portable use.



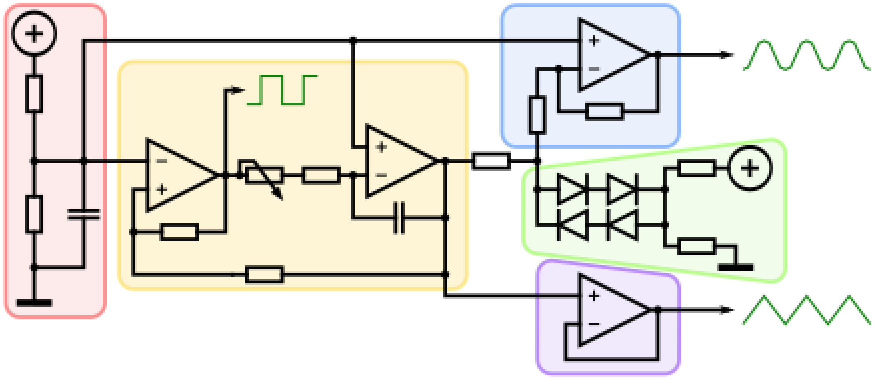
# H-Bridge Configuration

- We selected an H-Bridge configuration to implement the Biphasic DC approach, allowing easy reversal of current direction through the sensing material.
- An H-Bridge is an electronic circuit composed of four transistors arranged in an "H" shape. It enables the voltage applied across a load (such as our sensing material) to be reversed easily, simply by activating different transistor pairs.

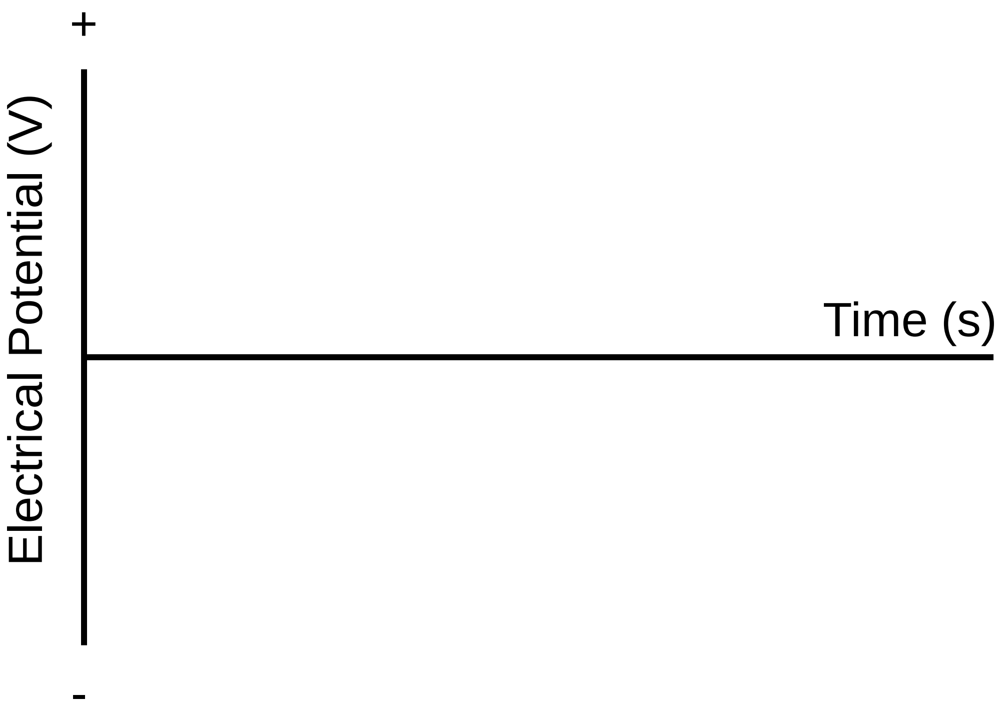


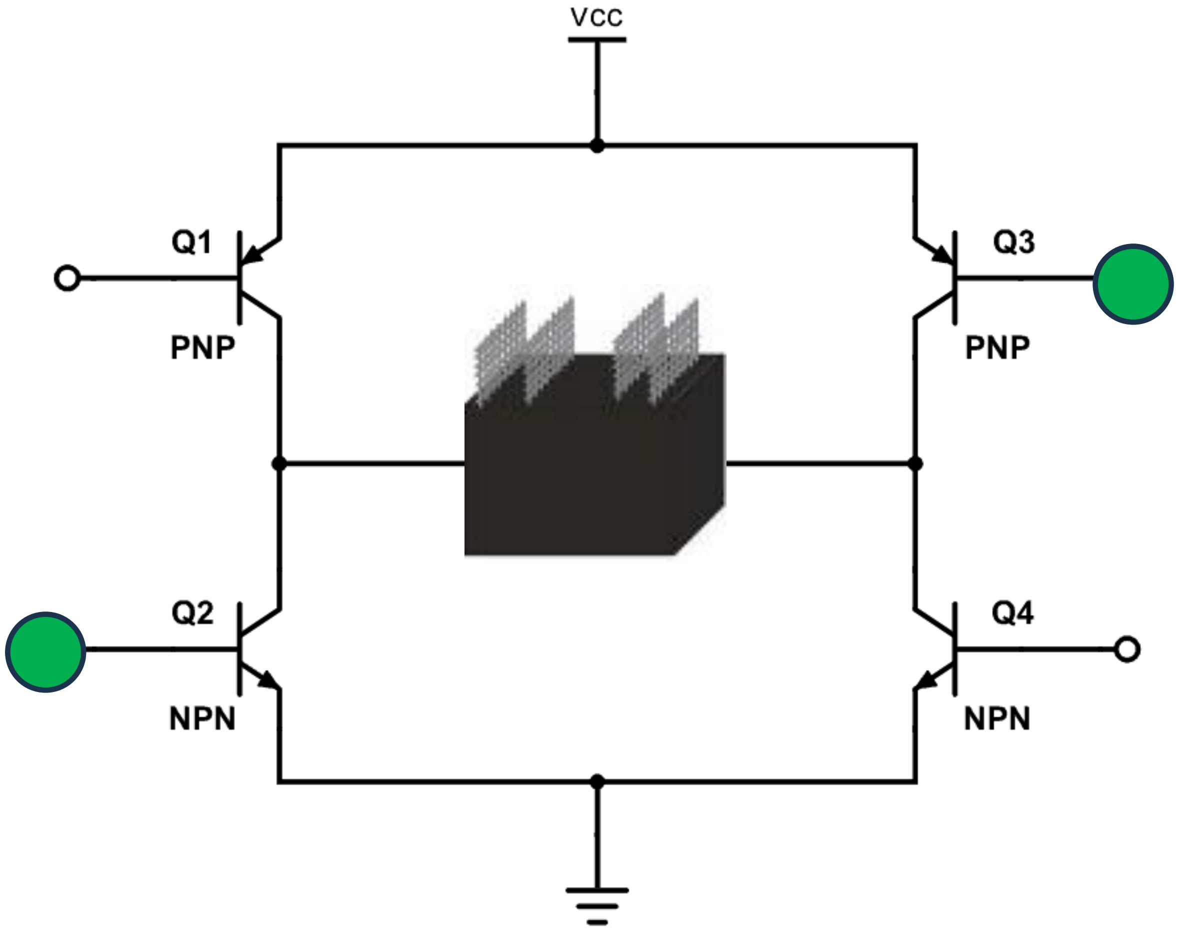
# Why Choose a H Bridge Over a Traditional Signal Generator Circuit?

- Traditional Op-Amp Circuit:
  - Requires ±5V (rail-to-rail) dual power supply.
  - Additional complexity and components for negative voltage generation.
- H Bridge Implementation:
  - Operates from a single-voltage source.
  - Eliminates the need for dual power rails (+5V and -5V).
- Trade-Off: Component Complexity vs. Efficiency
  - H Bridge Circuit: Uses 4 MOSFETs, slightly more complex.
  - Traditional Circuit: Single amplifier but more complex power stage.
- Expected Benefits of H Bridge Approach
  - Potential increase in efficiency and stability.
  - Reduced system-level complexity by removing additional power supply circuitry.
  - Components are easy to source on low-cost modules.

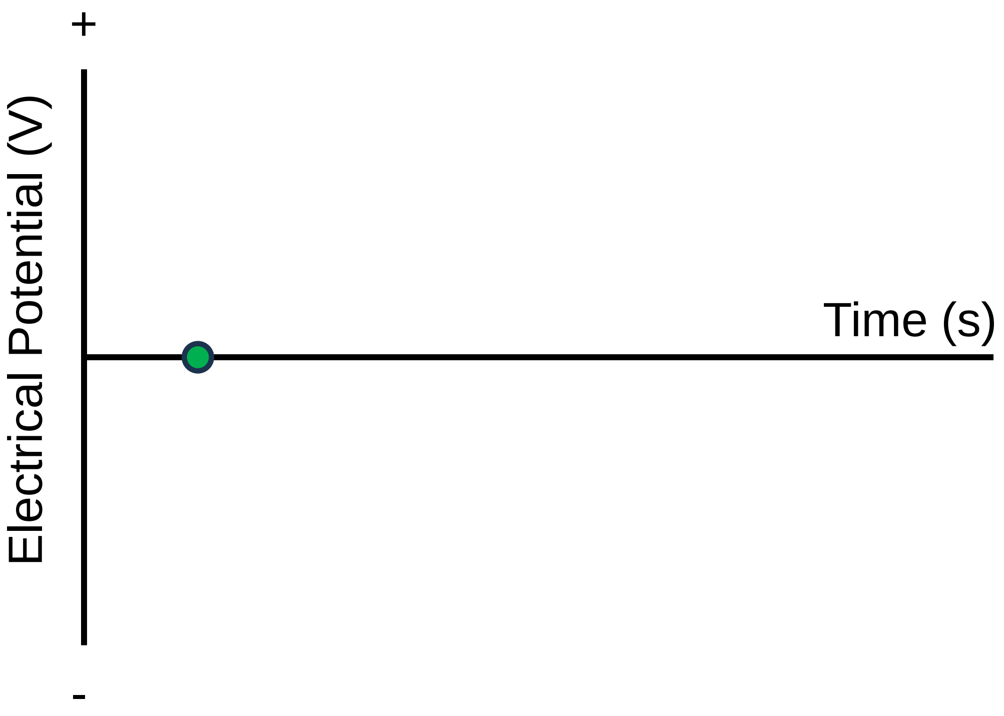


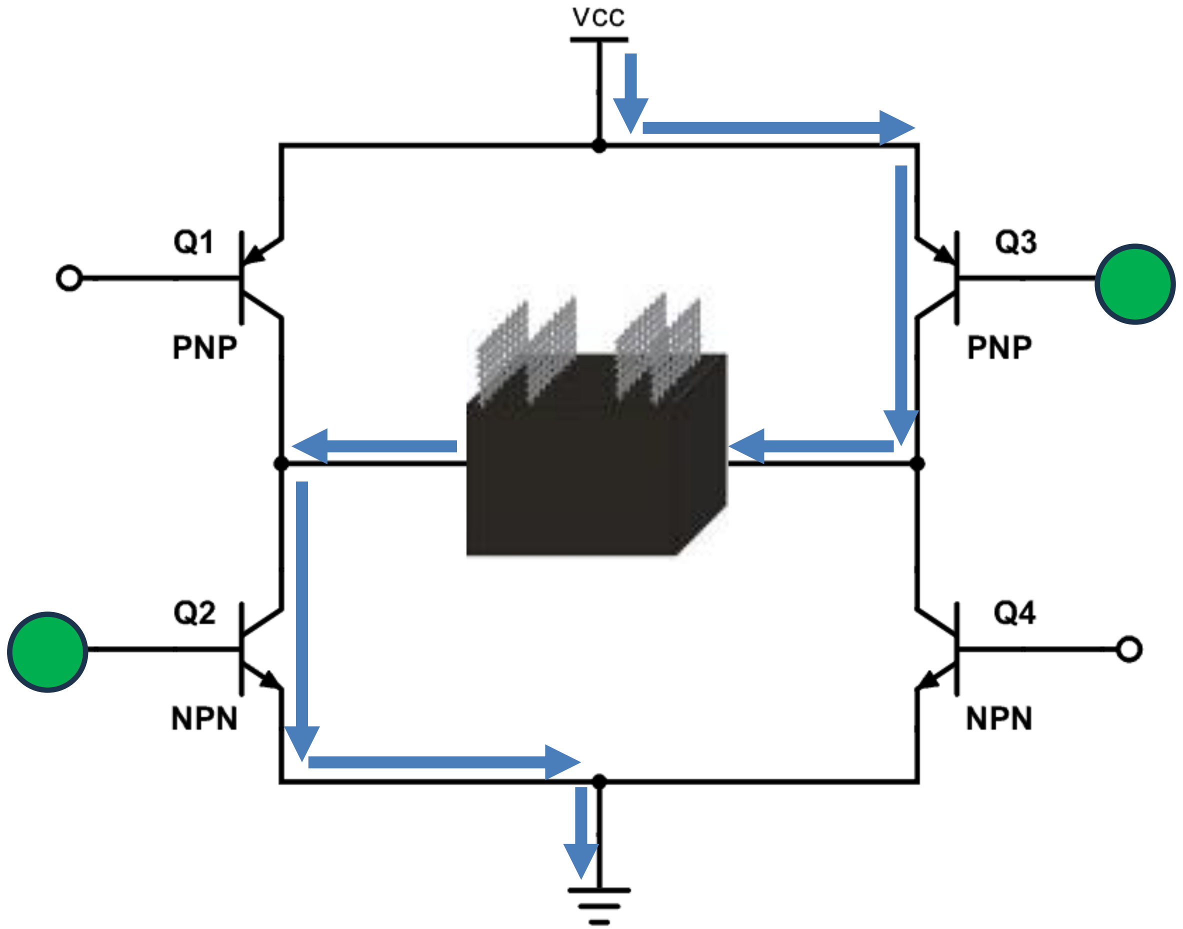
# MOSFET Initialization



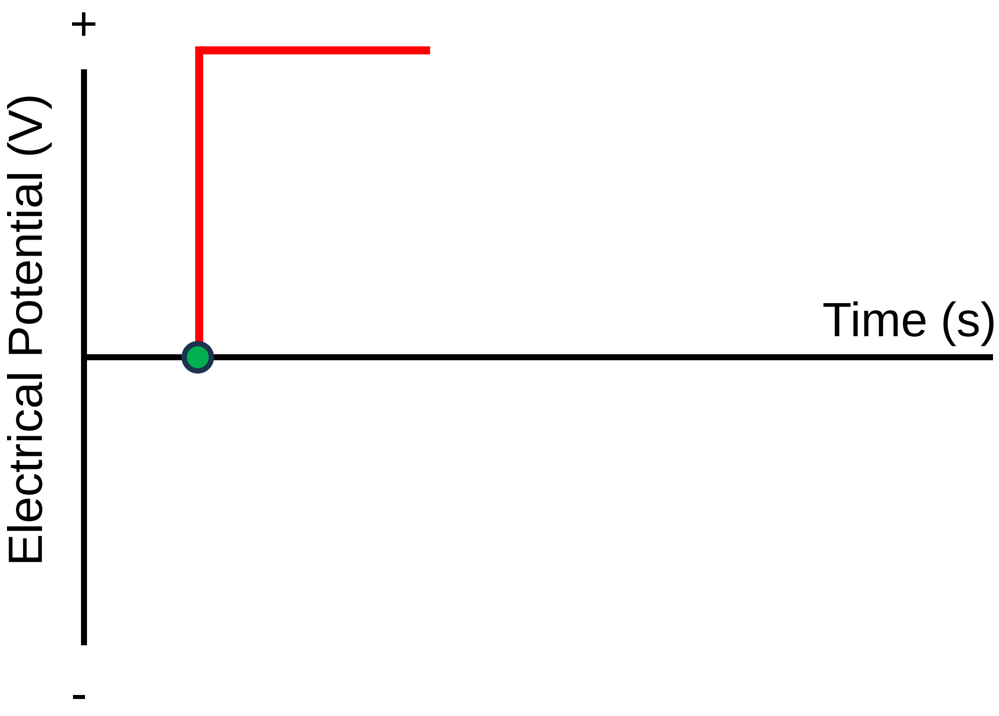



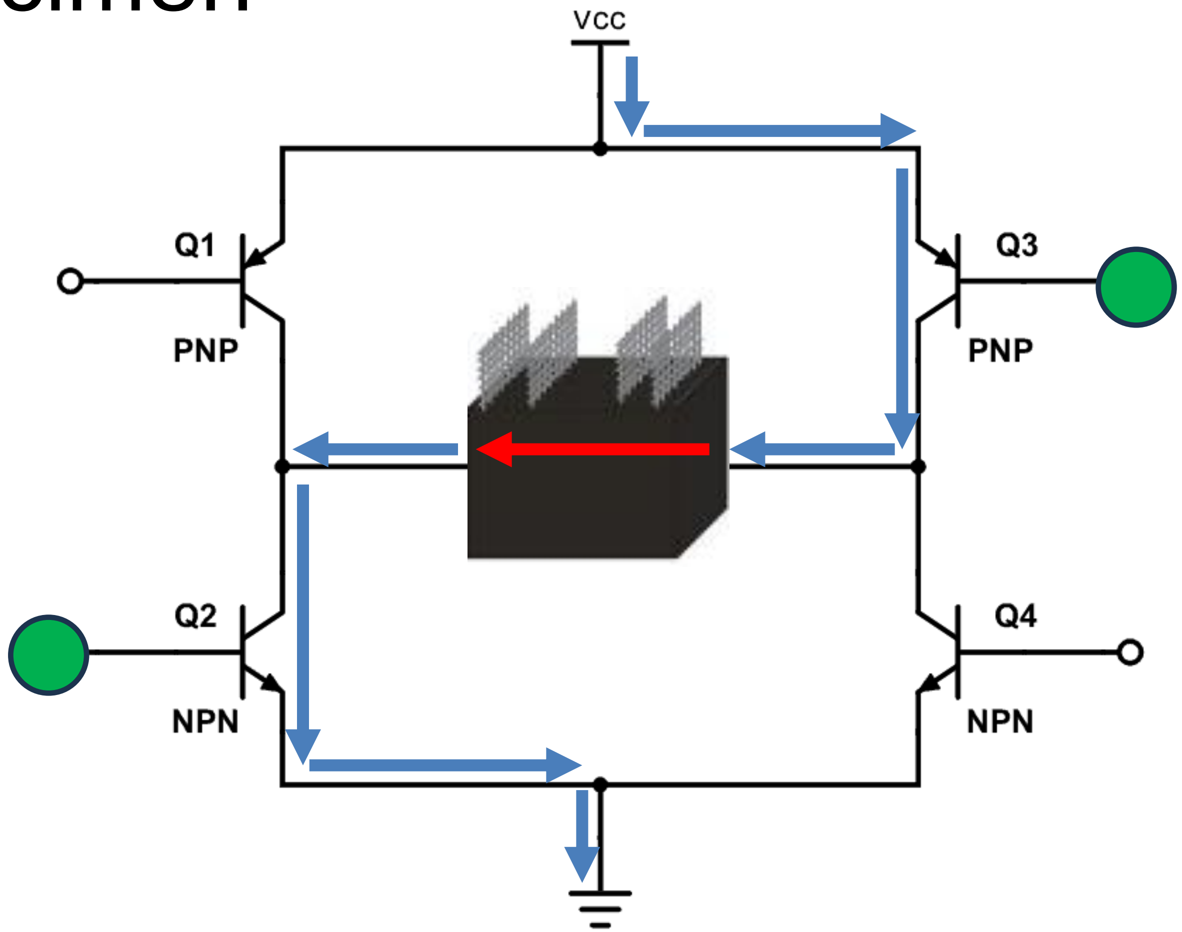
# Current Flow in Circuit



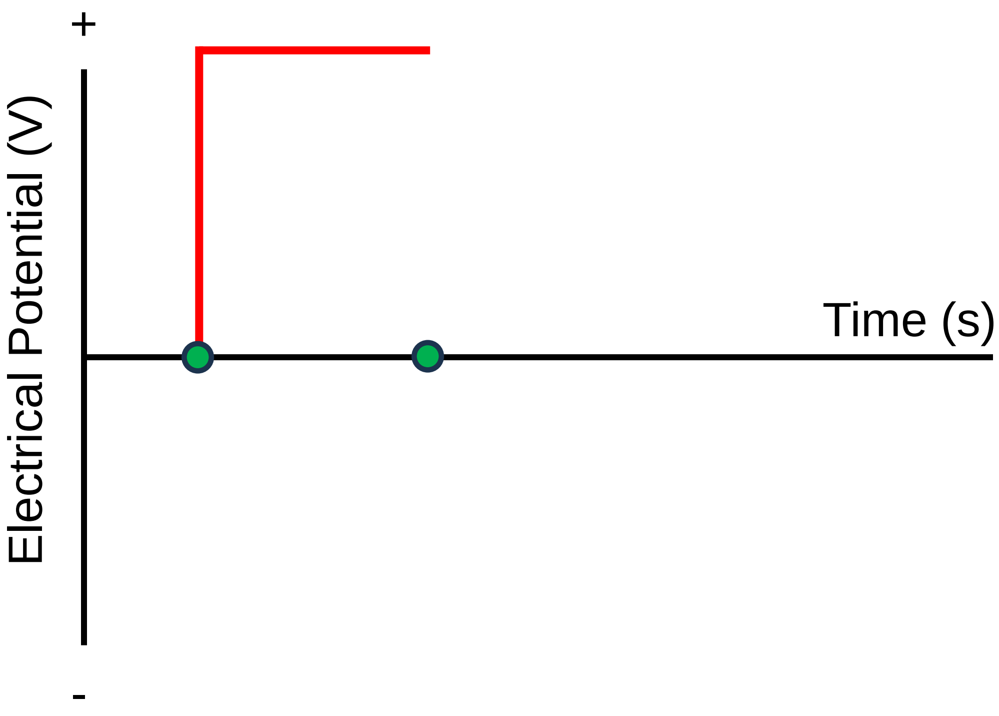



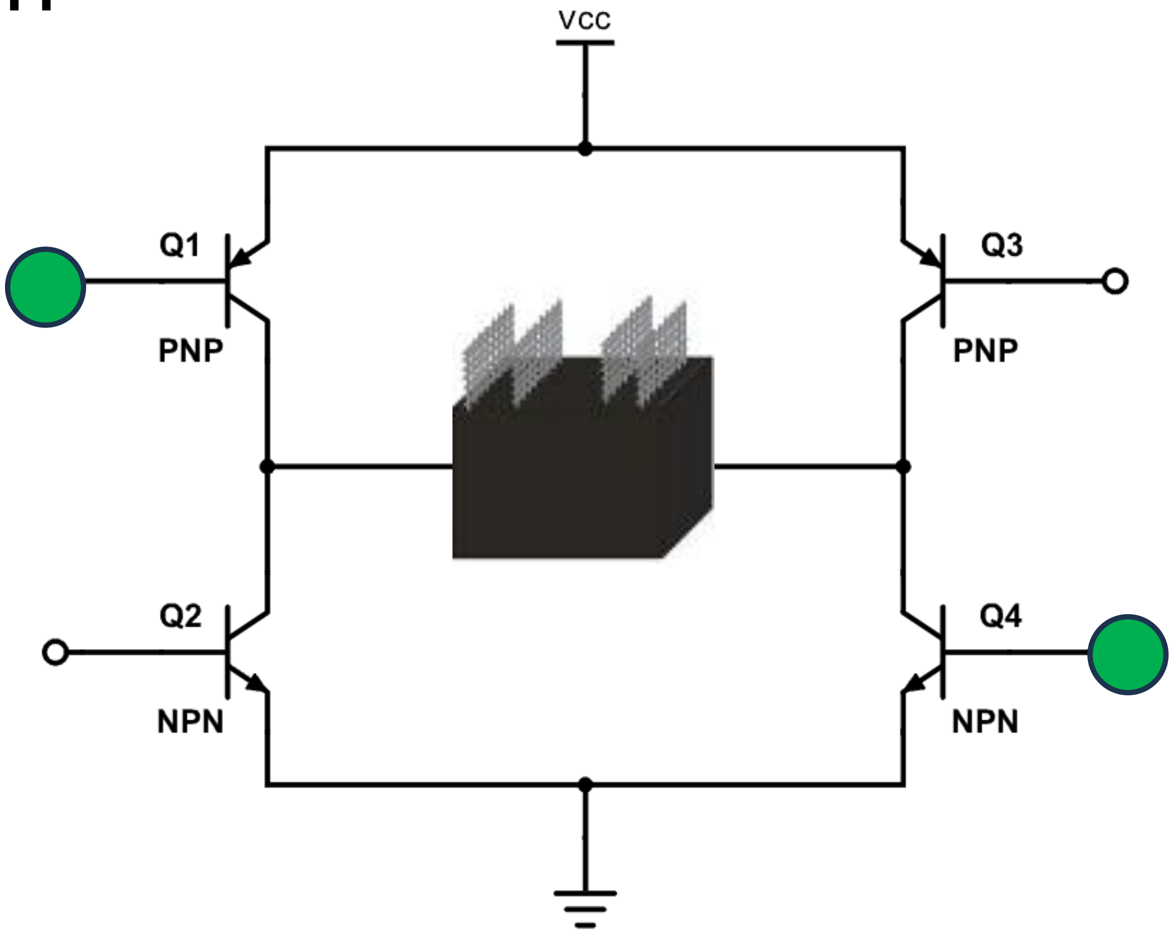
# Current Flow Across Specimen



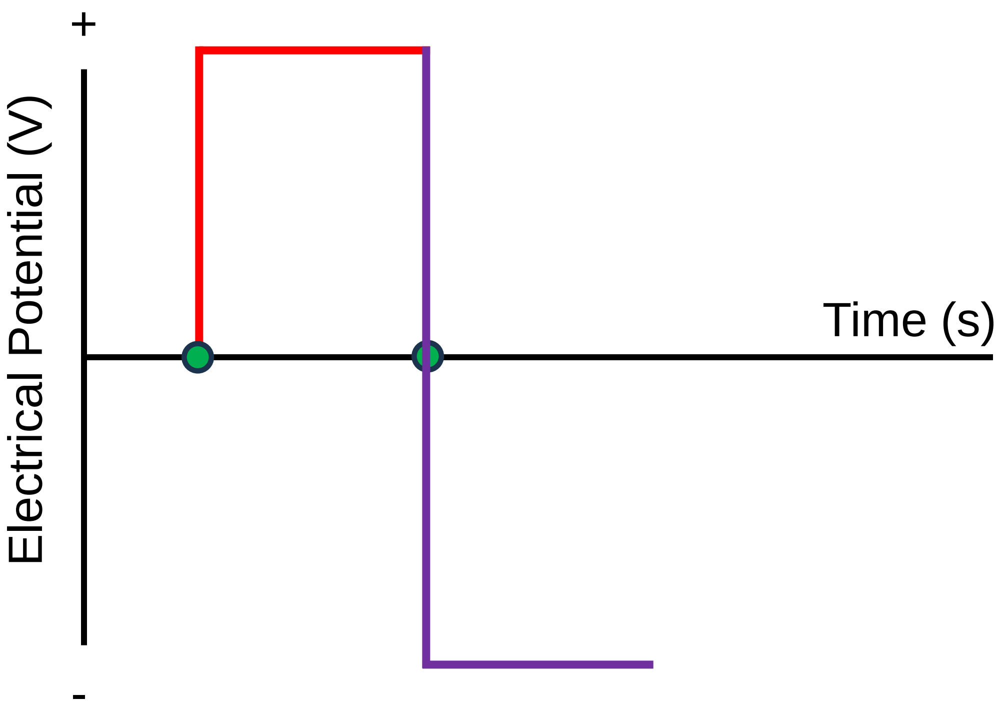



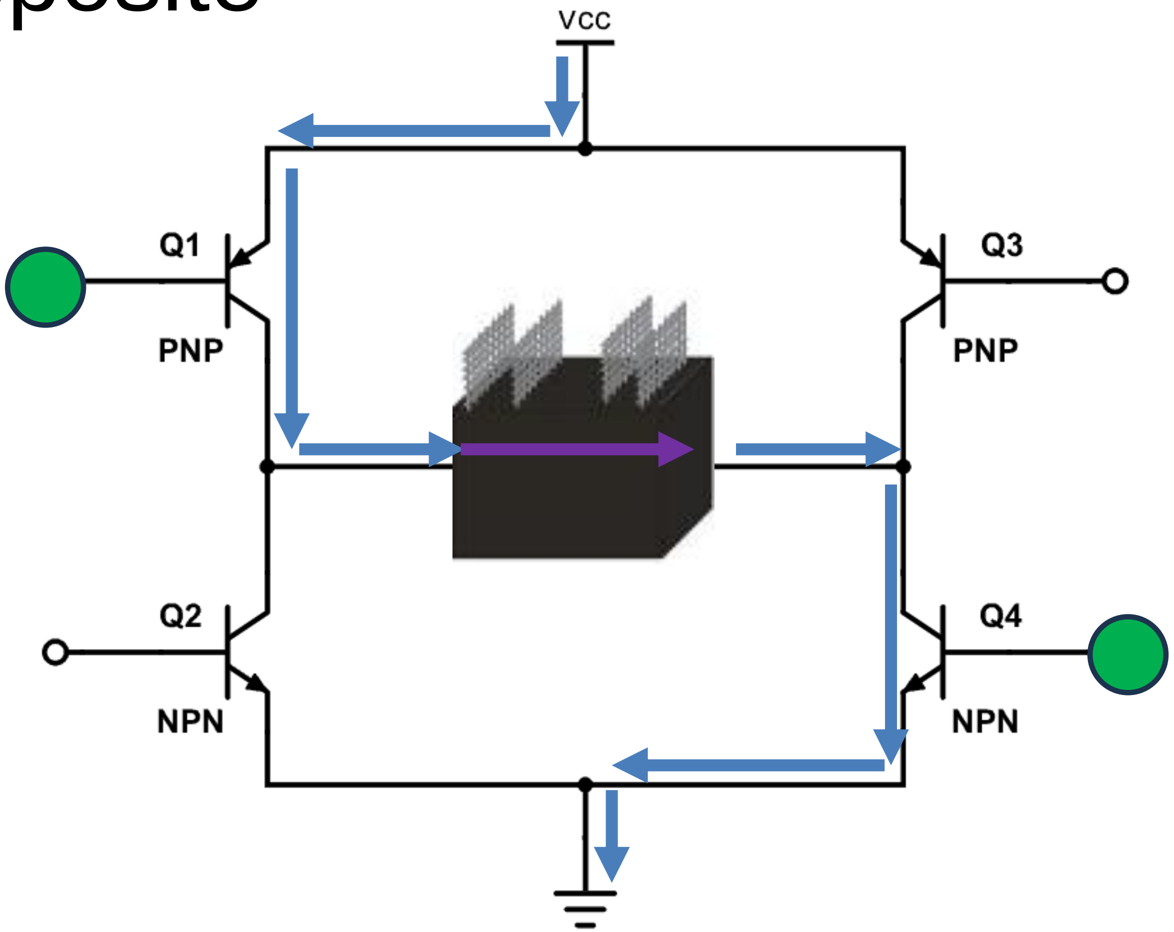
# Opposite Path Initialization



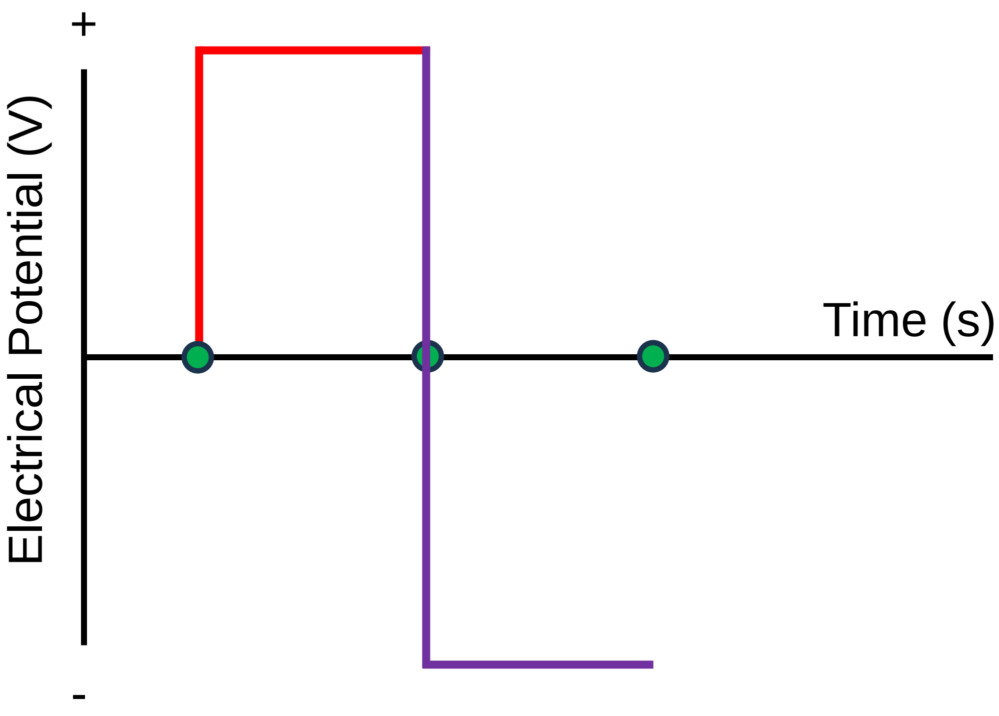



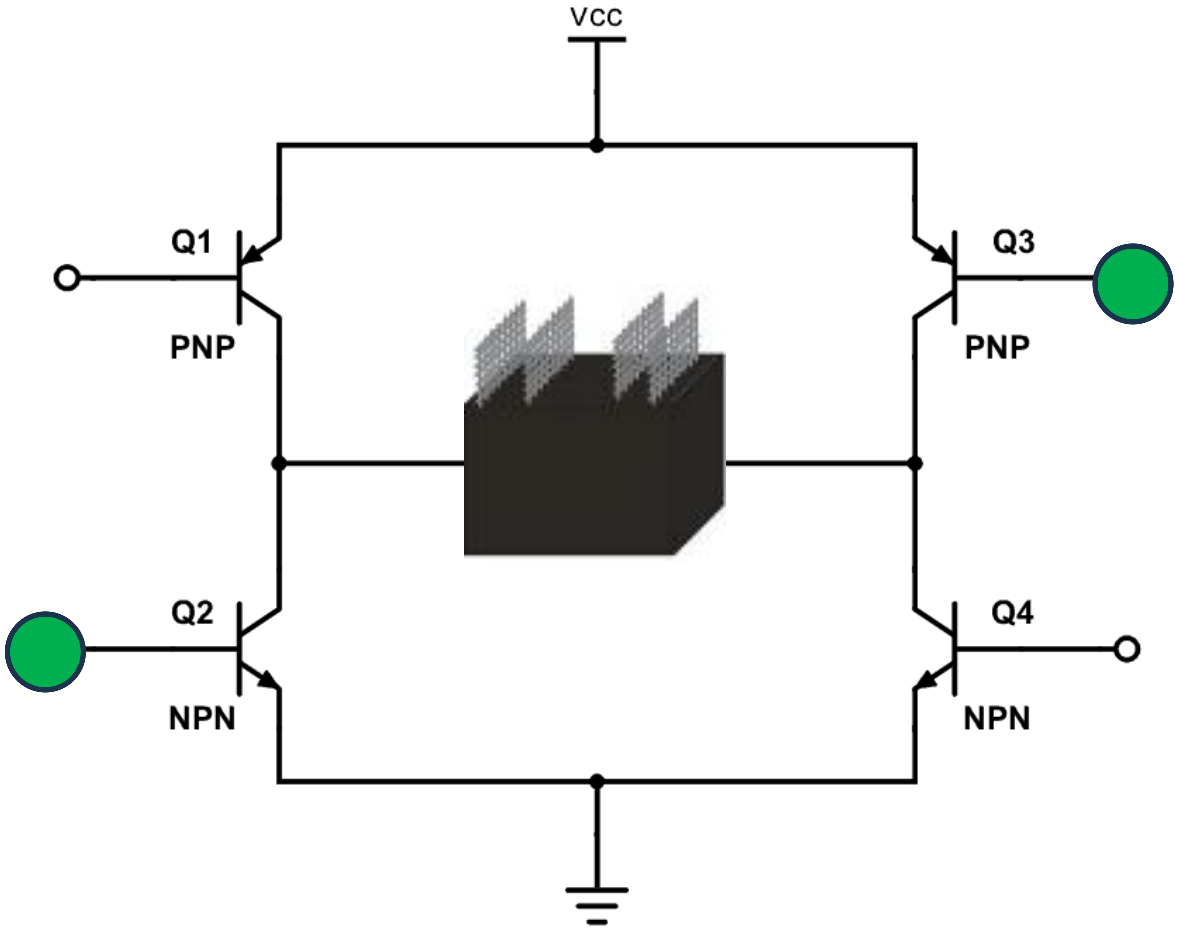
# Current Flow Through Opposite



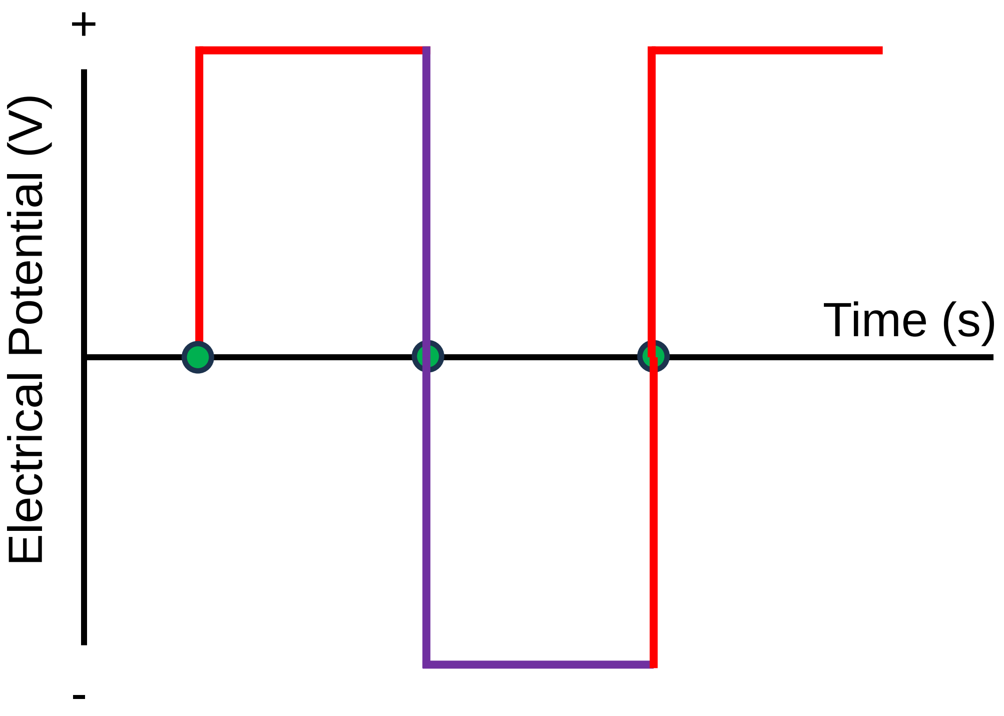



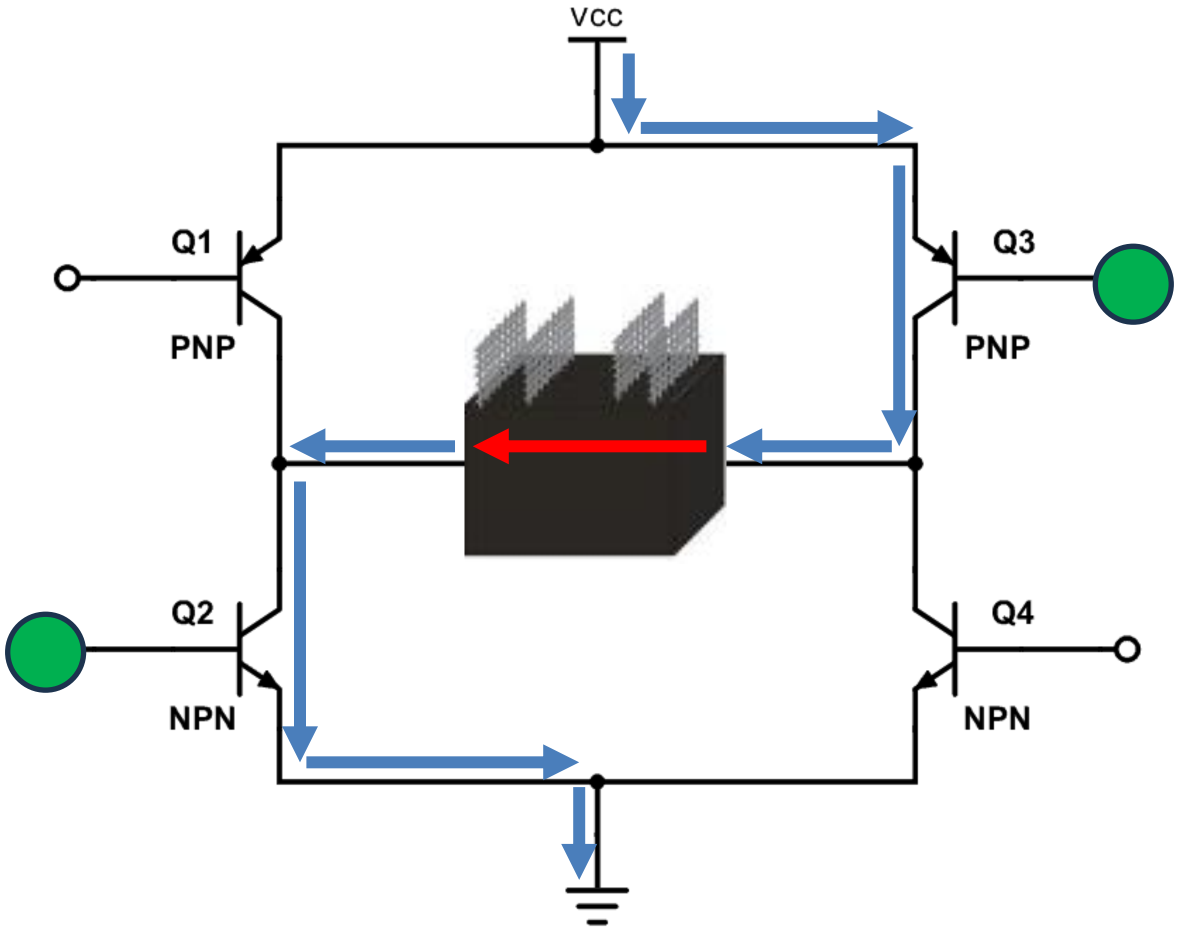
# Switching Again



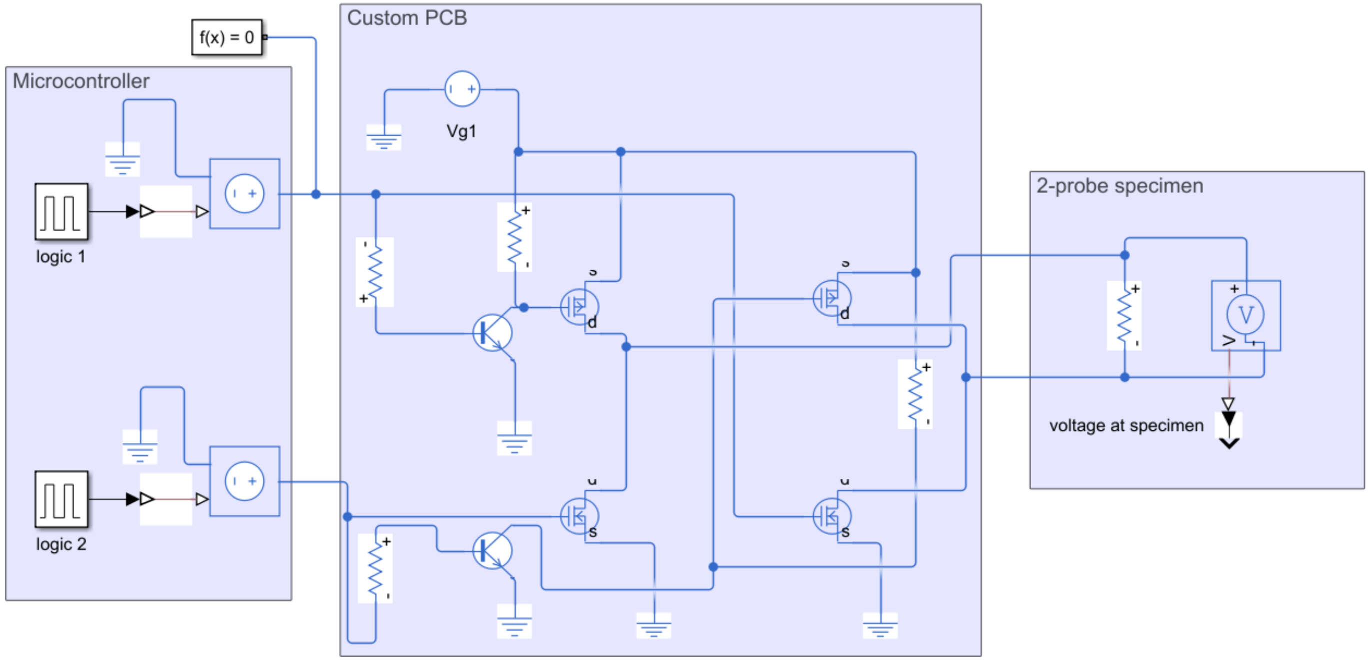
# The Process Continoues



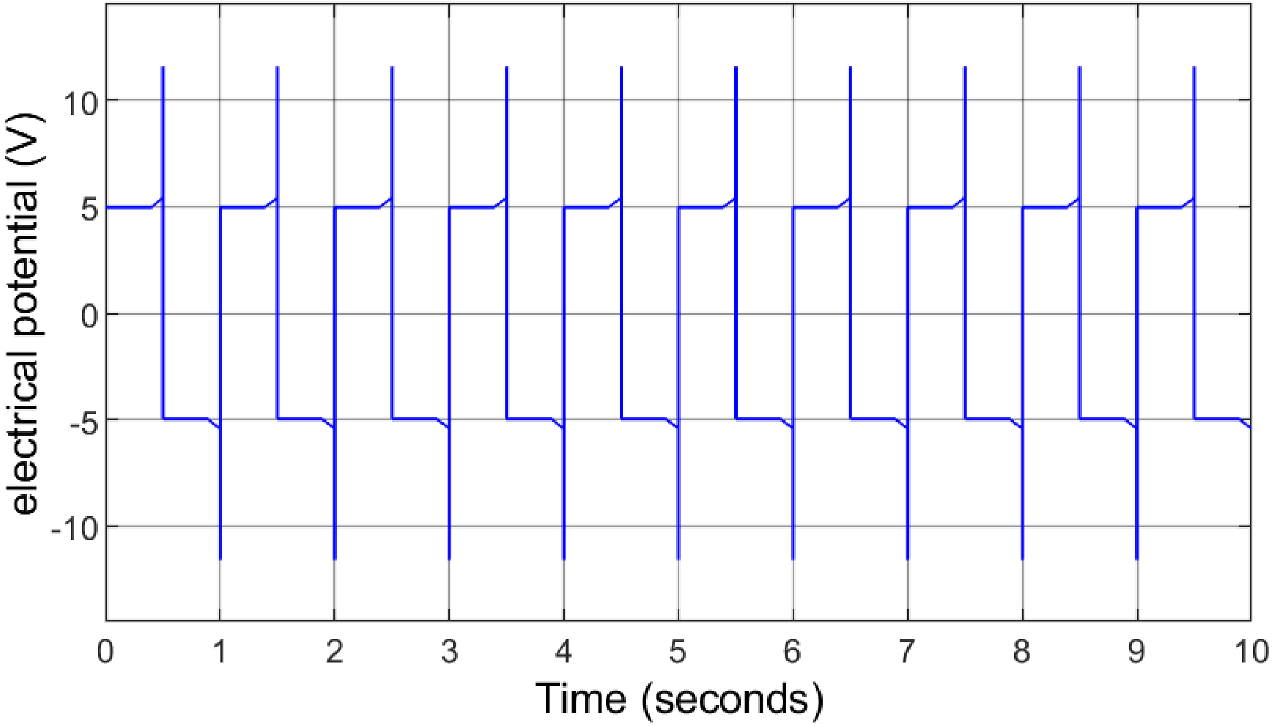
# Simscape Simulation

- Simulated using transistor-based H-bridge to alternate current direction.
- Two-probe sensing setup captures voltage across self-sensing material.



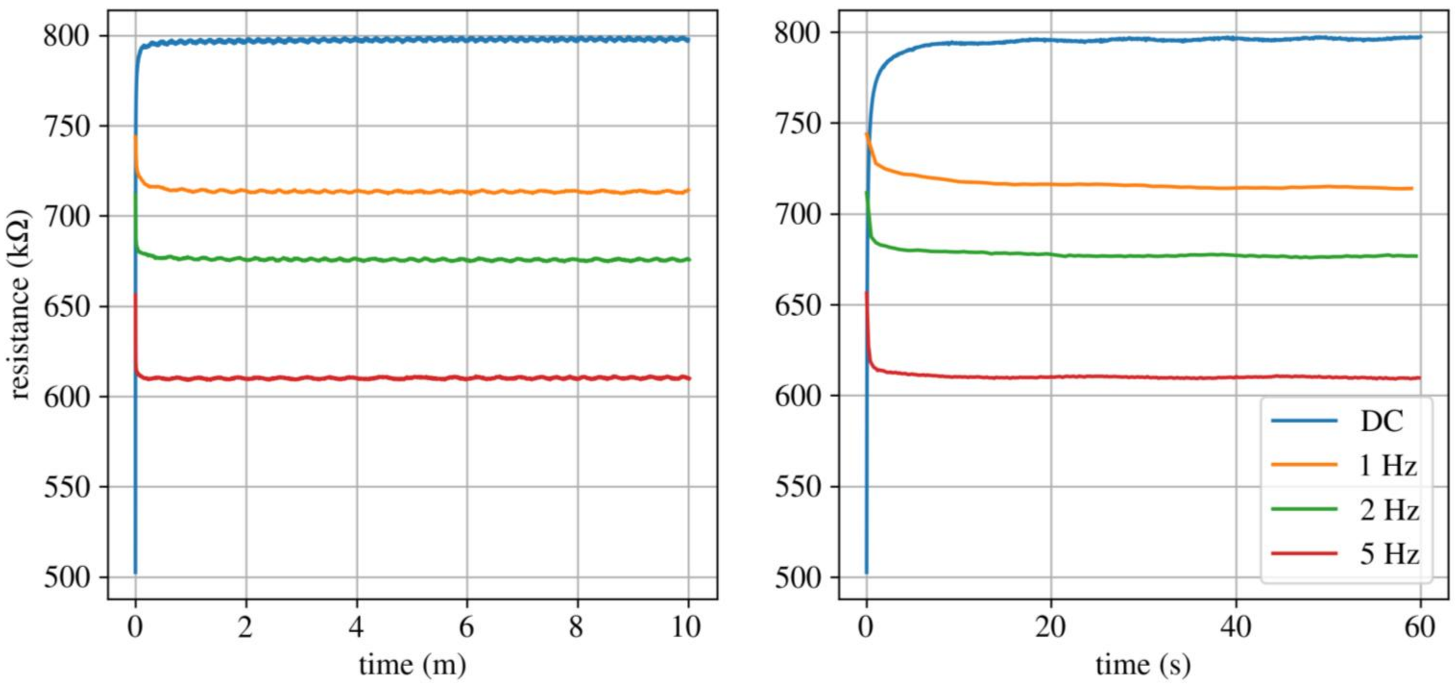
# Simscape Results

- Simulation validated stable voltage/resistance outputs without observable drift.
- Demonstrates feasibility for real-world structural health monitoring (SHM) applications.



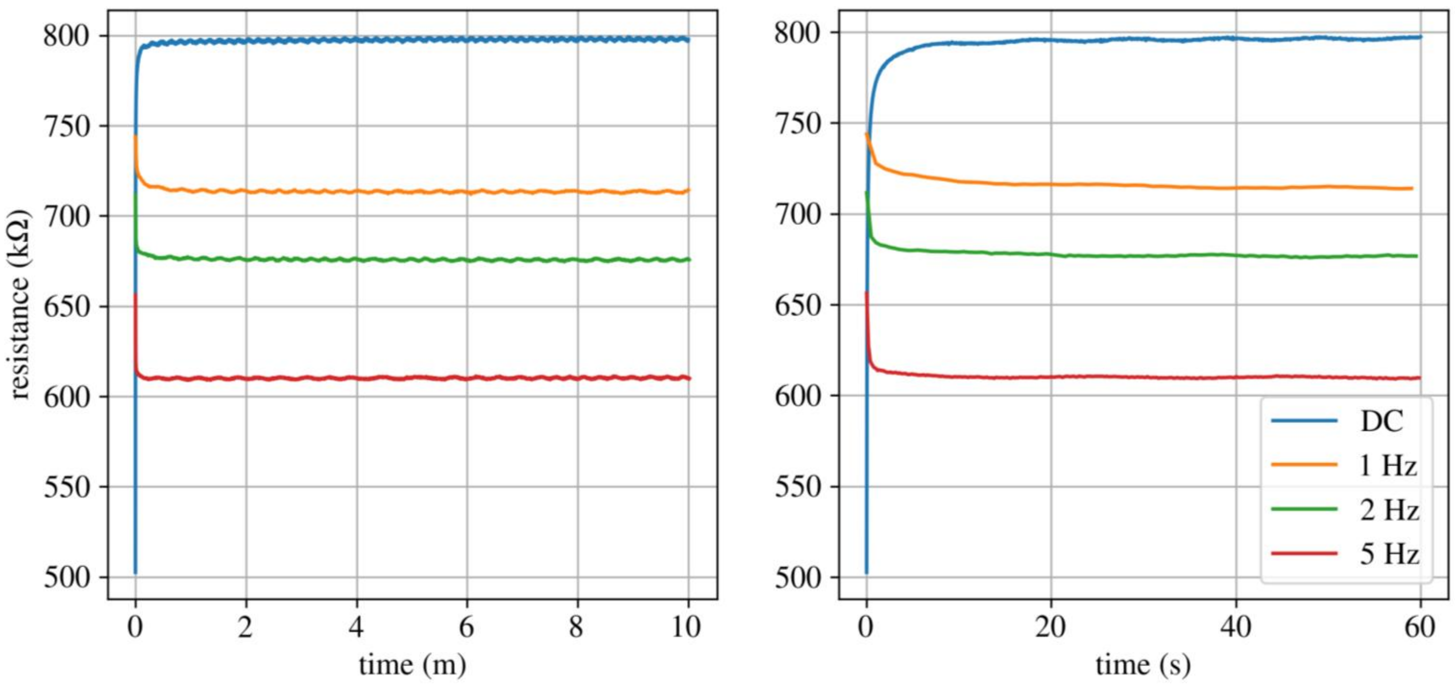
# Experimental Results

- Result of acquisition performed with a 220 kΩ self-sensing material show:
- Good results over a minute of test
- No drift in the long term
- No surprises



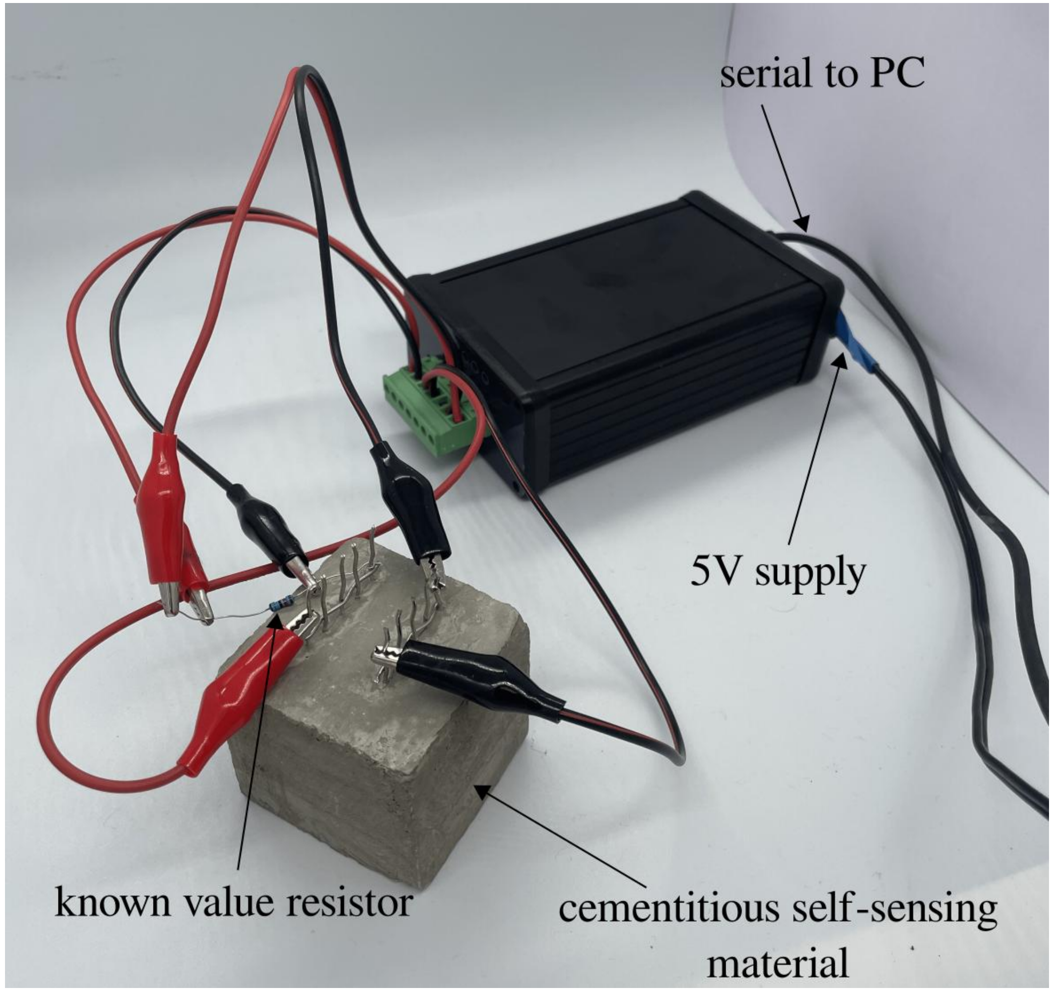
# Experimental Results

- Result of acquisition performed with a 220 kΩ self-sensing material show:
- Good results over a minute of test
- No drift in the long term
- No surprises



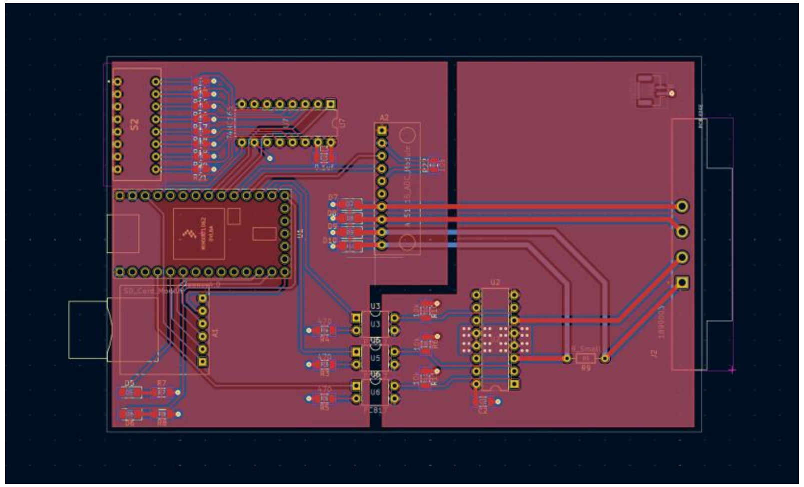
# Hardware Consideration

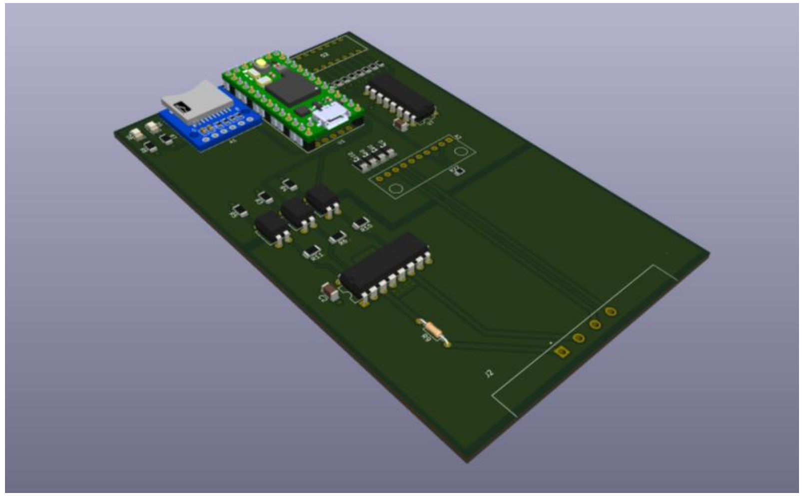
- **Frequency Limitation (5 Hz):** Currently limited to ~5 Hz measurement cycles due to microcontroller processing speed.
- **Switching Noise Management:** Stable operation, but switching noise demands careful upfront circuit design.
- **Material Range Validation:** Further research is required to verify the accuracy of materials with significantly different resistances.



# Usability improvements in the Next Version

- **Integrated SD Card Storage:** Allows easy and reliable onboard data logging.
- **Full Floating Bridge:** Provides superior noise rejection and improved measurement accuracy.
- **Easier Assembly:** Designed for straightforward soldering and rapid assembly.
- **Programmable Reference Resistors:** Enables flexible, software-controlled adjustment of measurement range.





# Acknowledgements

MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

National Science Foundation

The authors from the University of Perugia would like to gratefully acknowledge the support of the Italian Ministry of University and Research (MUR) via the FIS2021 Advanced Grant “SMS-SAFEST - Smart Masonry enabling SAFEty-assessing Structures after earthquakes” (FIS00001797). This work is also partly supported by the National Science Foundation through Grant numbers 1956071, 2152896, and 2237696. The views and conclusions contained within this document are those of the authors and should not be interpreted as representing the official policies of the National Science Foundation or the U.S. Government. Their support is gratefully acknowledged.

# THANKS!

## Hardware Design

https://github.com/ARTS-Laboratory/Biphasic-data-acquisition-system

Austin R.J. Downey
Email: austindowney@sc.edu
Github: austindowney
Department of Mechanical Engineering
University of South Carolina