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ORIGINAL PAPER

Electrical characterization of the alleged bio-memristor *Physarum polycephalum*

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Abstract

This study investigates the potential of the slime mold *Physarum polycephalum* to function as a bio-memristor. In contrast to earlier reports, our experimental results did not show a significant memristive behavior. Instead, all tested slime molds exhibited elliptical I-V characteristics, attributed to their inherent capacitance. To model this behavior, we developed replacement circuits consisting solely of resistors and capacitors, which accurately reproduced the observed results. While these circuits lack memristive properties, they demonstrate potential utility as sub-circuits in analog applications, such as filters, timing circuits, and phase shift networks. Despite it not being a memristor, *P. polycephalum* may hold promise for alternative bio-electronic applications, including its use in microbial fuel cells. Our findings contribute to a deeper understanding of the electrical properties of bio-inspired systems and suggest new avenues for integrating biological components into electronic circuits.

Introduction

This paper explores the emerging field of unconventional computing, with a particular focus on slime mold-based bioelectronics. By bridging biology and electronics, we examine the convergence of distinct disciplines and address the challenges inherent in combining nature-inspired algorithms with organic engineering.

We introduce the memristor as a novel electronic component and present *Physarum polycephalum* as a model organism for investigating biological memristors. The study reviews recent advances in biological memristor research and highlights the potential of slime molds in this context. In our results, we evaluate the feasibility of slime molds as bio-memristors, comparing experimental outcomes with theoretical memristor models. Finally, we discuss discrepancies between these models and experimental findings, proposing alternative bio-electronic applications for *P. polycephalum*.

Memristors

A memristor is a non-linear electronic device characterized as a resistor with memory, as suggested by its name. It represents the fourth fundamental two-terminal circuit element, alongside the resistor (defined by a relationship between voltage and current), the inductor (flux and current), and the capacitor (charge and voltage). The memristor is uniquely defined by a relationship between flux and charge [1].

Although theoretically predicted in the early 1970s [2], it was not until 2008 that researchers at Hewlett-Packard Labs demonstrated the first operational monolithic memristor. This device was constructed by sandwiching a titanium dioxide thin film between platinum electrodes [3]. Along with providing the physical operating mechanism, the researchers

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demonstrated a pinched hysteresis loop-a tilted figure-eight pattern-that serves as the hallmark of all memristors.

Unlike conventional resistors, memristors exhibit a dynamic relationship between current (I) and voltage (V), where the resistance (R = U/I) depends on past voltages. Following the realization of the physical memristor, other two-terminal memory-based circuit elements, such as the memcapacitor and meminductor, were proposed [4]. Further developments led to the concept of memfractors, or fractional memory elements, which interpolate characteristics between memcapacitors, memristors, and meminductors [5].

Memristive devices are promising alternatives to CMOS-based logic computation, as they eliminate the need for separate storage and processing units typical of the von Neumann architecture [6–8]. Recent studies suggest that memristor-based non-von Neumann hardware could support deep neural networks, artificial intelligence, and edge computing [9–12]. Additionally, memristors have been used to construct artificial neurons, facilitating neuromorphic computing [13].

Slime mold *Physarum polycephalum*

Physarum polycephalum is easy to culture in Petri dishes and can be guided to grow specific topologies of protoplasmic tubes by strategically placing attractants (e.g., food) and repellents (e.g., salt) on the dish. This ability to influence its growth has been foundational to early studies exploring the organism's potential as a computational medium, including tasks, such as finding the shortest path to a target in a maze [14].

Our research focuses on the electrical behavior of *Physarum polycephalum*. This organism exhibits fluctuating intracellular electrical potentials, typically within a range of ± 50 mV, with oscillation periods of 50 to 200 s and amplitudes of 5 to 40 mV [15–17].

Notably, electrical current can propagate through its protoplasmic tubes, enabling the organism to function as an electronic component.

Researchers in unconventional computing are intrigued by the potential of *P. polycephalum* in electronics and computing, with one review listing 25 distinct applications [14]. An award-winning use of *Physarum*-based memristors was demonstrated in the field of electronic music [18, 19].

Purpose of the study

The aim of this study was to investigate the claim that slime molds exhibit memristor-like behavior, a topic of debate in the literature. For instance, Gale et al. reported testing 11 slime molds, noting that"2 exhibited good memristance curves, while the other 9 exhibited open curves"[20].

Additionally, we aim to develop a replacement circuit model to describe the electrical behavior of slime molds and explore alternative bio-electric applications for *P. polycephalum*.

Methodology

Cultivation of *P. polycephalum*

In the cultivation of *P. polycephalum* for our experiments, we initiated the process by establishing a robust stock culture in 55 mm petri dishes. Subsequently, new cultures were systematically developed in 50 ml conical centrifuge tubes. The cultures in the petri-dishes and the tubes were sealed in sterile polypropylene bags with 0.2 micron filter disc until usage. After a period of four days, in an average, the plasmodium cultures were ready for the measuring experiments. The slime molds were stored in an opaque case at room temperature.

Culture setup

To provide the necessary humidity and nutrients for growth, each tube was filled with a nutrient-free agar medium, sterilized oat flakes placed on top of it. The oat flakes were sterilized for 30 min at 120 degree Celsius in a Lacor 22 l pressure cooker. The design involved the inclusion of a 3 mm aperture positioned at the 32.5 ml markings within each centrifuge tube. This orifice functioned as a designated site for the integration of an electro-conductive collar, in parts modeled after the design of Edward Braund and Eduardo Reck Miranda [21].

Electro-conductive collar design and 3D printing

The electro-conductive collar, with an outer diameter of 4 mm and an inner diameter of 1.5 mm, was designed and 3D printed using a Prusa MK3 printer with the RepRapper Conductive PLA.

PVC tube connection setup

The experimental setup further involved the connection of two centrifuge tubes through a PVC tube with a length of 15 mm, to facilitate the growth of the slime mold through the PVC tube, connecting the two electro-conductive collars (adapters). These collars were linked to electrodes, allowing for the application of electric currents through the plasmodium, see figure 1.

Electric measurements of *P. polycephalum*

To evaluate the response of *P. polycephalum* to electric currents, we used a Rigol DG1022 function generator to

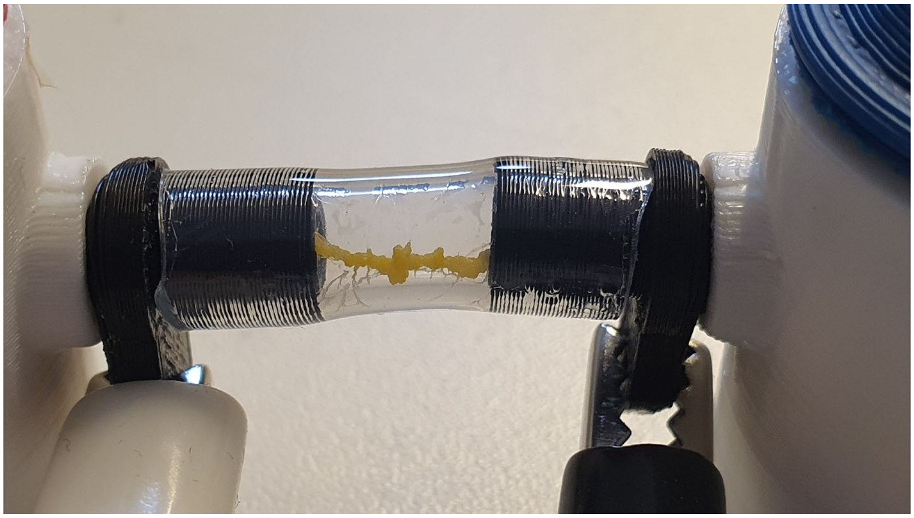


Fig. 1 The slime mold was seeded in one of the two vertical containers, with food placed in the other one. The slime grew to the other container via the horizontal transparent tube that was connected to the black conductive contacts where measurements were carried out

produce the currents under investigation. Simultaneous measurements of voltage and current were performed using the Digilent Analog Discovery 3, connected to a measuring circuit on a breadboard. Voltage values from the Rigol DG1022 were directly recorded, while current (I) was calculated using Ohm's law (I=U/R) based on the voltage drop across a series resistor with a measured value of 150 kΩ.

This setup, coupled with Digilent Waveform3 software for data logging, enabled precise capture and recording of the electrical responses of *P. polycephalum*. Measurements were conducted between January 25, 2024, and April 3, 2024, totaling 310 observations across 38 distinct slime mold cultures.

In addition to experimental work, simulations of memristors were conducted using LTspice software, with data exported via the software's integrated documentation tools.

Results

We applied three different voltage levels (see [22] for details) to: (A) an LTSpice memristor simulation and (B) a slime mold. Figure 2 illustrates the results for a "typical"slime mold.

The simulated memristor produced the characteristic inclined"figure 8"hysteresis curve, pinched at the origin (0, 0) for both voltage and current. In contrast, the results for the slime molds deviated from this pattern. None of the tested slime molds exhibited a pinched hysteresis curve; instead, they displayed open ellipsoid shapes. In some cases, the ellipsoid shape had more pointed ends and appeared at a slightly different angle.

Next, we attempted to model a replacement circuit for the slime mold(s) in LTSpice to reproduce outputs similar to those shown in Figure 2. The closest match was achieved using a circuit consisting of a series capacitor and resistor, followed by a parallel capacitor and resistor. Further parametric adjustments refined this model, resulting in the replacement circuit shown in Figure 3.

It is important to note that the slime mold is not entirely passive. When connected directly to a voltmeter, it generates a measurable voltage between 20 and 40 mV, which decreases slightly over the course of the measurement.

Using the slime mold as a"pseudo-capacitor,"we integrated it into electronic circuits, such as low- and high-pass filters. In a low-pass filter, the cut-off frequency and attenuation level depend on the leading resistor. For a resistor of 5 $M\Omega$, the cut-off frequency is approximately 100 μHz, with attenuation reaching over 8 dB at 100mHz, beyond which no further attenuation is observed. An example of a high-pass filter is shown in figure 4 using a resistor of 10 $M\Omega$..

The red dotted lines in Figure 4 illustrate the phase shift observed in these specific examples, suggesting that slime molds could also be utilized in phase shift circuits.

Discussion

Slime mold does not function as a bio-memristor

Previous studies have suggested that slime molds can exhibit memristor-like behavior: functioning as passive, two-terminal electronic devices whose resistance depends on the history of applied voltage and current, resulting in a characteristic pinched hysteresis loop in their V-I curves [20, 21, 23, 24]. However, our repeated measurements indicate that, under our experimental setup, the slime mold does not behave as a (pure) memristor. None of the tested samples produced a pinched hysteresis curve.

While some experiments with slime molds yielded slightly S-shaped curves, the majority exhibited elliptical V-I characteristics when sinusoidal inputs were applied. We

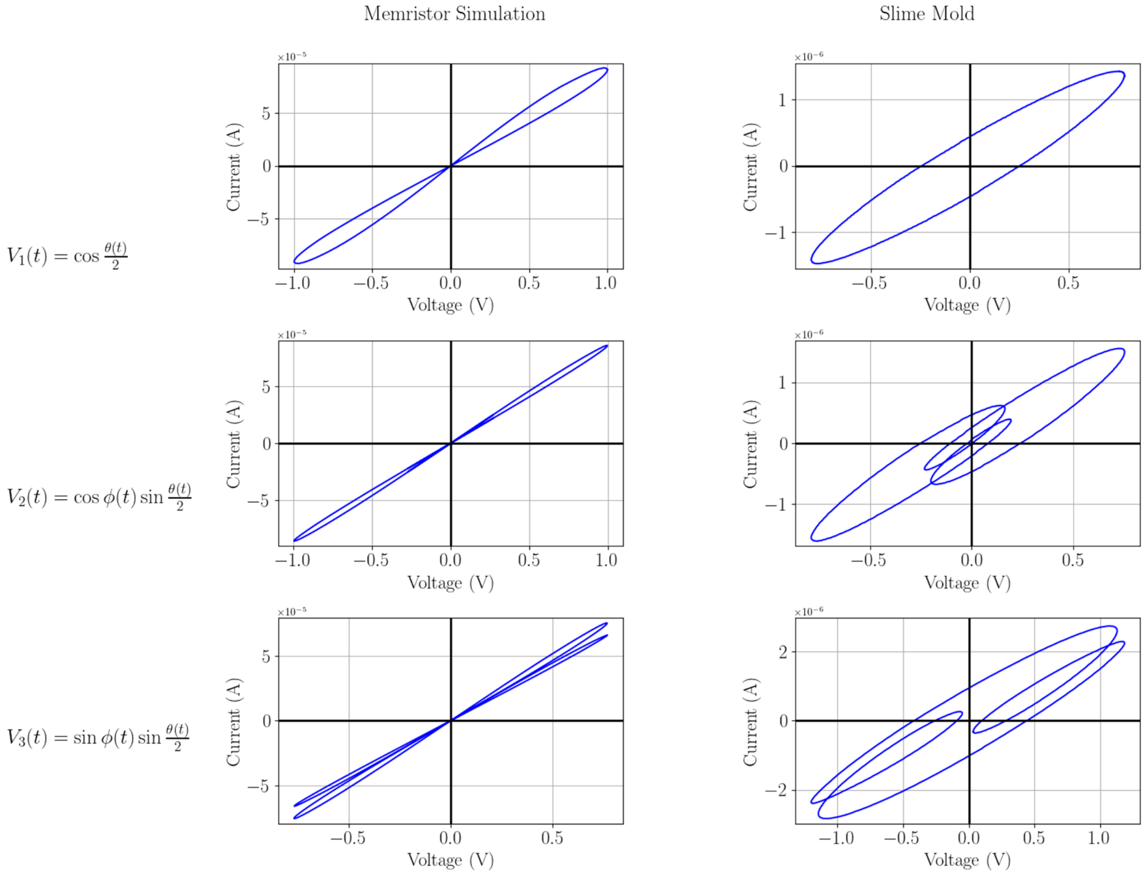
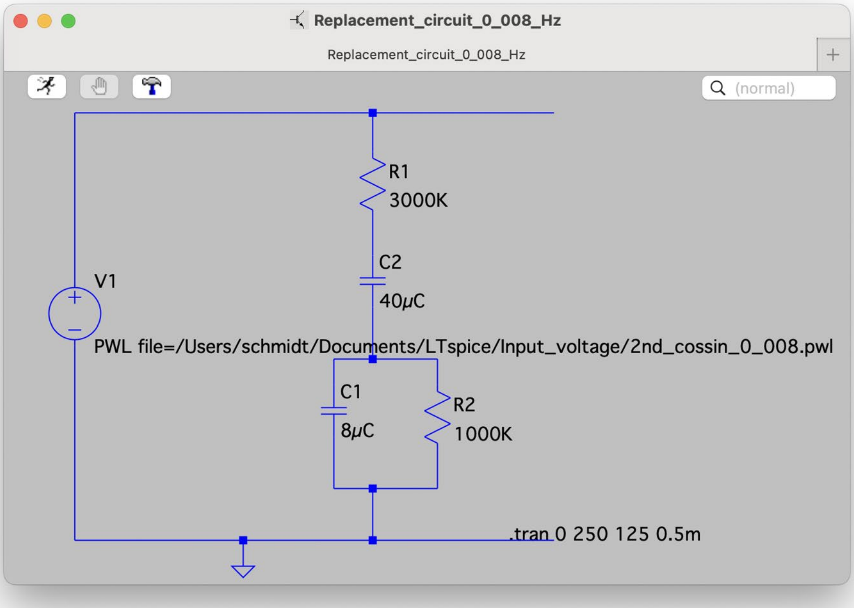


Fig. 2 Current–voltage characteristic of the memristor simulation and the slime mold for different input signals

Fig. 3 Final slime mold replacement circuit containing only resistors and capacitors



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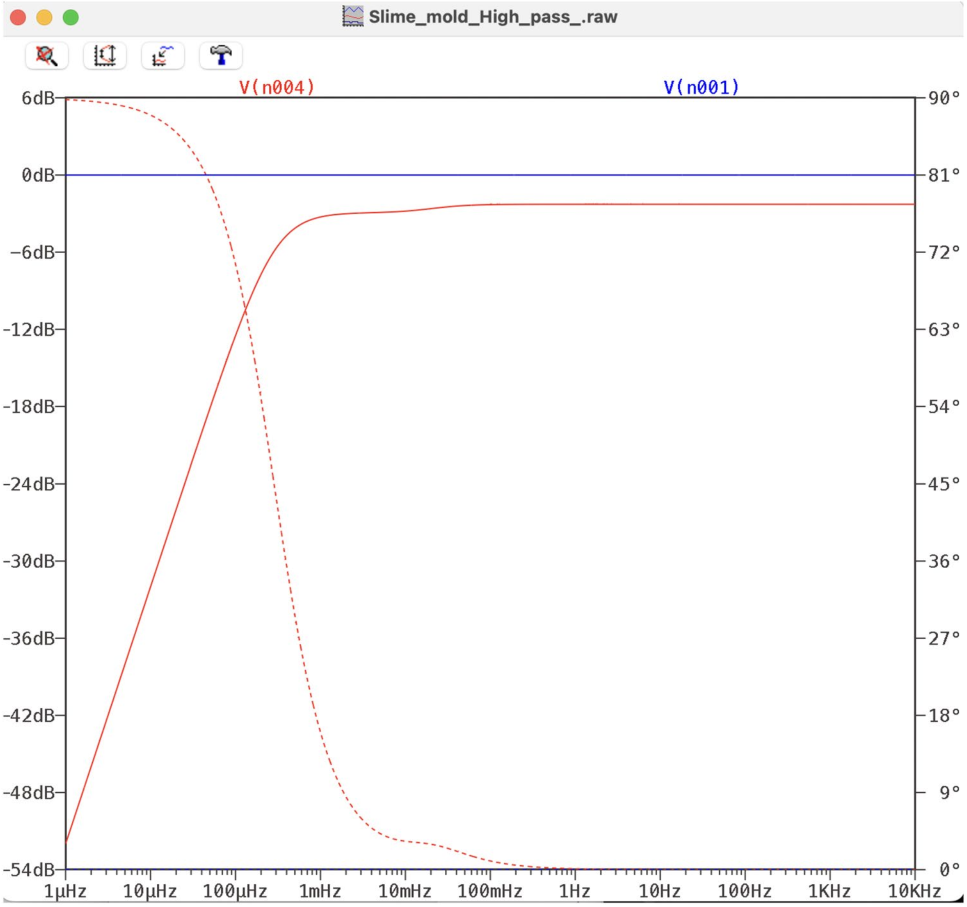

Fig. 4 The Bode diagram of the high-pass (like) filter shows an attenuation (red line) below a cut-off frequency of about 0.4 mHz. The same circuit also acts as a Phase Shift Circuit with a maximum shift of 90° at 1μHz down to 0° at 1 Hz (red dotted line)

attribute this elliptical behavior to capacitance created by the cell membrane and the internal cell fluids, which act as electrolytes.

Our results consistently showed elliptical V-I relationships across all datasets. While some measurements exhibited a slight saddle, indicative of minor non-linear behavior and possible memfractance, none demonstrated the characteristic pinched hysteresis loop of a memristor. This absence suggests only weak or no memristive behavior under the conditions we tested.

Why do our findings differ from those reported in the literature? First, the reported memristive effects do not appear universally across all experiments. For example, Gale et al. [25] stated:"*Of the eleven samples in batch 1, two exhibited good memristance curves (i.e., pinched hysteresis), while the other nine exhibited open curves*."Additionally,"*For batch 2, which were measured at a larger voltage range* (*between*±*100 and* ± *250mV*), *eight out of eight samples showed good memristive curves*."

Similarly, Braund and Miranda [21] observed a combination of pinched and open curves, depending on factors, such as electrode distance, slime mold tube length, and specific measurement parameters. Unlike our approach, they applied stepwise voltage changes with amplitudes between ±250 and ±500 mV and time steps of 0.5, 1, 2, and 2.5 s using a Keithley 617 Programmable Electrometer. They averaged their measurements across these steps. We also tested stepwise voltage increments but did not observe pinched curves.

Another key difference is that Braund and Miranda seemingly relied on the first voltage cycle, which always begins at the 0–0 origin. In contrast, we omitted the first cycle in our analysis, as the capacitance remains uncharged at the start.

Our findings, which are based on what we believe to be the largest experimental dataset on measuring memristance in slime molds, do not align with previous reports of pinched hysteresis curves. Whether future experiments validate earlier findings or support our results remains to be seen.

Slime mold as a component in electrical circuits

The replacement circuit we developed (see figure 3), supplemented by an additional 20 mV voltage source that gradually diminishes, provides a reasonable first-approximation model of the slime mold's behavior, excluding the nonlinear"saddles."While these circuits do not exhibit memristive properties, they may still serve as useful sub-circuits in various applications.

For instance, this configuration could be incorporated into circuits, such as a Low-Pass or High-Pass Filter, or a Voltage Divider with Frequency Dependence, which operates similarly to the Low-Pass Filter. Another potential use is within a Phase Shift Network. Beyond these, the slime mold could be applied in circuits like an RC Integrator Circuit, RC Differentiator Circuit, RC Time Constant Circuit, or a Snubber Circuit.

Additionally, previous research has demonstrated that slime molds can enhance the performance of microbial fuel cells when used on the cathode side [26]. These and other bio-electric applications suggest promising future directions for deploying slime molds in bio-electronic systems, even though they do not exhibit memristive behavior.

Conclusion

The potential for bio-inspired materials, such as slime molds, to exhibit memristive behavior is of considerable interest due to their natural adaptability and self-organizing properties. However, the biological component *Physarum polycephalum*, previously reported to show memristive characteristics, was found in our experiments to lack significant memristive properties, likely due to its inherent capacitance.

Our findings demonstrated that the electrical behavior of slime molds could be effectively modeled using replacement circuits composed solely of resistors and capacitors. While some samples displayed slight non-linearity when exceeding specific voltage thresholds, none exhibited clear characteristics of a memristor or memcapacitor.

Despite this, the RC replacement network is versatile and may serve as a sub-circuit in various analog applications, including high- and low-pass filters, timing circuits, signal processing units, and phase shift networks. While slime molds are unsuitable for designing memristor base circuits, they may still hold promise as bio-electronic components for diverse applications.

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Author contributions G.S. and U.R. cultivated and prepared the slime mold samples. M.S., G.S. and U.R. carried out the electronic measurements on the slime molds, M.S., and G.S did the LTSpice simulations. M.S. and G.S. wrote the draft(s) of this manuscript, Z.S. and E.M. provided feedback and improvements to the draft. E.M. provided specifications on how to cultivate the slime mold and design the electronic measurement set up.

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Data availability The datasets generated and analyzed during the current study can be made available on reasonable request.

Declarations

Conflict of interest Authors have no conflict of interest.

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