Supplemental information for:

Evaluation of commercially-available conductive filaments for 3D printing flexible circuits on paper

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Figure S1

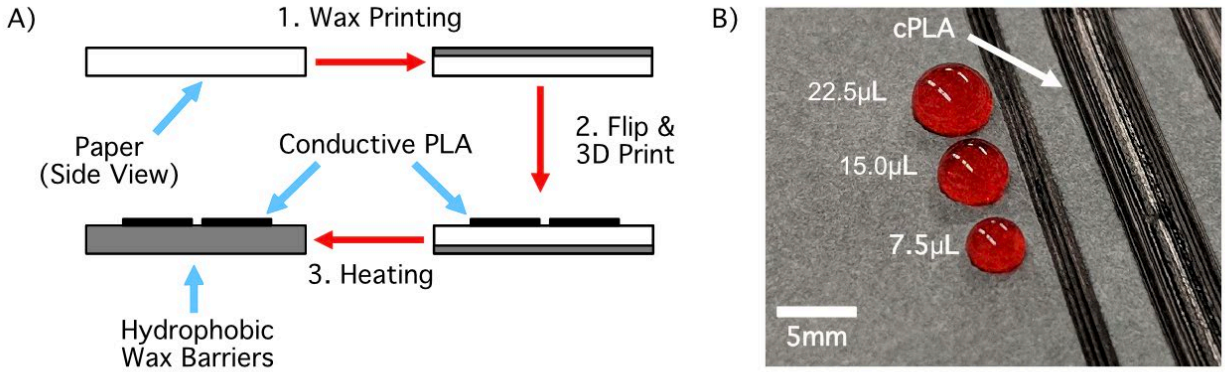

Figure S1. Making hydrophobic paper-based circuits via wax printing. A) Flowchart of the process for combining 3D printing with wax printing. Hydrophobic wax is first deposited on one side of the paper using a solid-ink printer. The paper is then flipped, and traces are 3D printed on the back of the paper. Finally, the paper is heated to reflow the wax and make the entire paper hydrophobic. B) Photograph of various sized droplets of red dye next to conductive traces on hydrophobic paper.

Figure S2

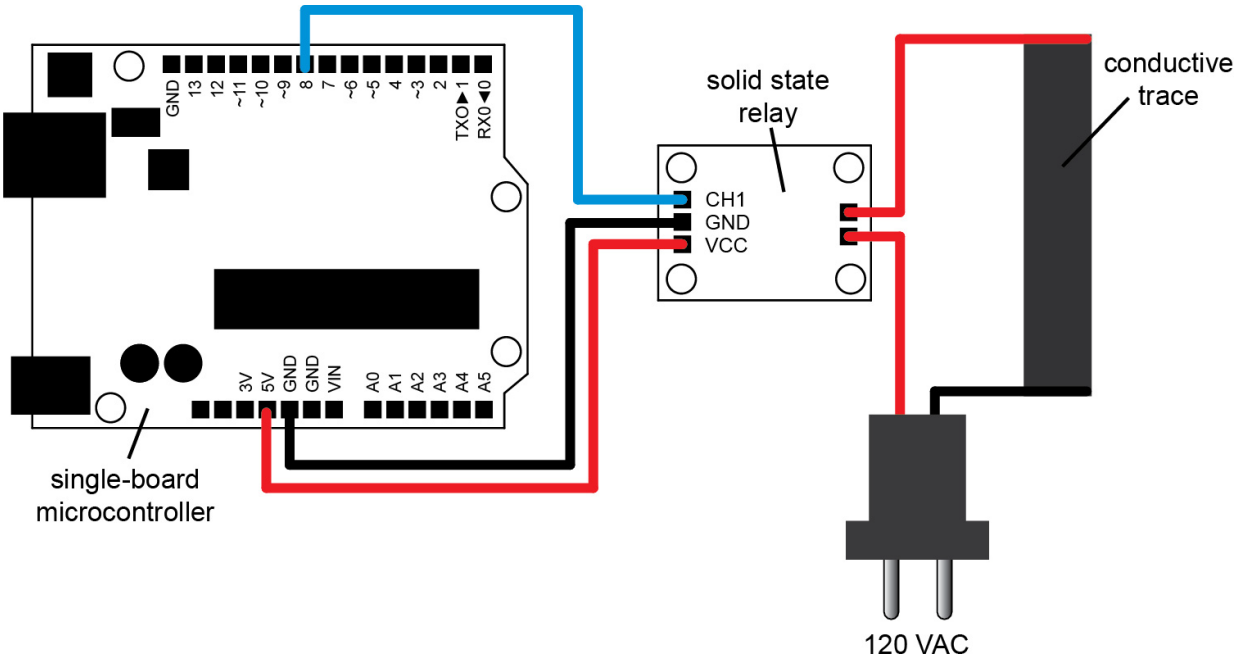

Figure S2. Schematic diagram of the circuit used to supply power to the conductive traces when they were used as resistive heaters. An 8-channel solid state relay was used for the experiments, but a single-channel solid state relay is depicted in the diagram for simplicity.

Figure S3

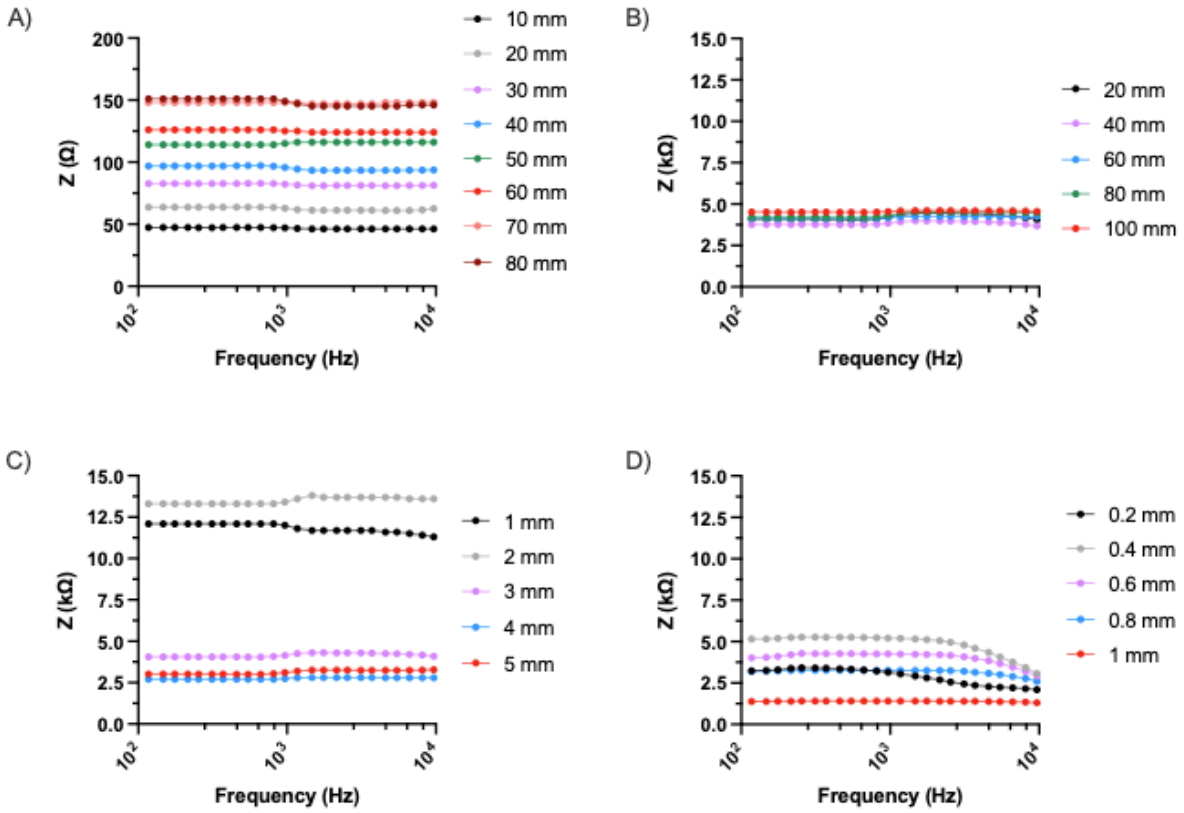

Figure S3. Characterization of Electrifi and BuMat traces printed on Whatman Grade 3 Chr paper. A) Effect of Electrifi trace length on impedance. All traces were 3-mm wide and 0.6-mm high. B) Effect of BuMat trace length on impedance. All traces were 3-mm wide and 0.6-mm high. C) Effect of BuMat trace width on impedance. All traces were 30-mm long and 0.6-mm high. C) Effect of BuMat trace height on impedance. All traces were 30-mm long and 3-mm wide. The effects of width and height on the impedance of Electrifi traces were not characterized due to the difficulty of printing the material and subsequent poor print quality.

Figure S4

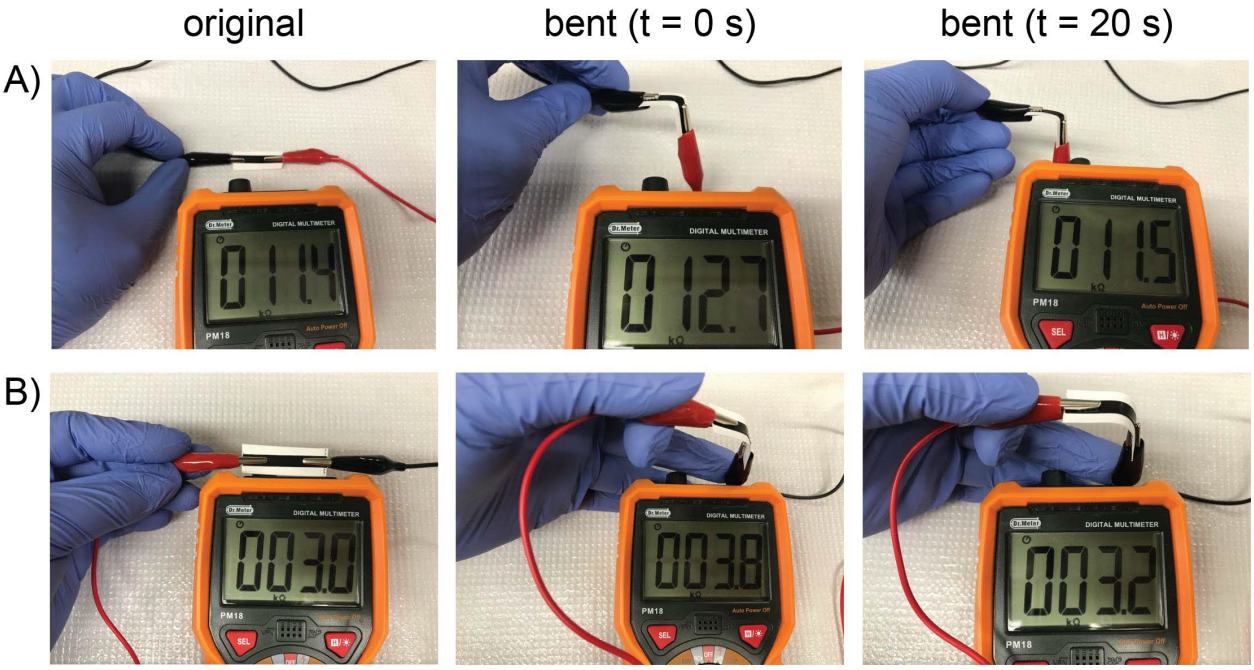

Figure S4. Photographs depicting the effect of bending two different traces (A and B) on their electrical resistance. The resistance of the traces increased significantely upon bending the traces to a 90° angle, but then equilibrated within ~20 s to a value that was close to the original resistance. Similar results were obtianed for 10 traces with different dimensions. All traces were printed using Protopasta on Whatman Grade 3 Chr paper.

Figure S5

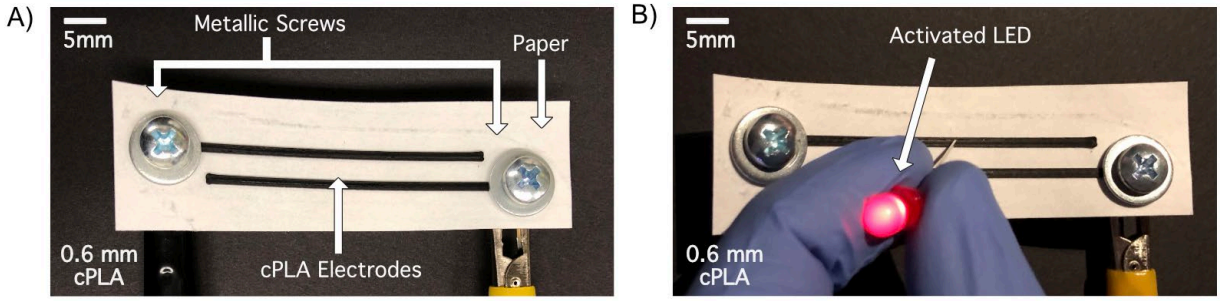

Figure S5. Photographs of screw terminal interfaces with 3D printed Protopasta traces (A), and an activated LED to demonstrate the functionality of this interfacing modality (B).

Figure S6

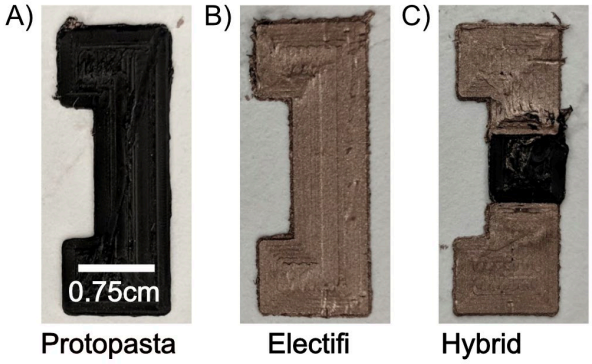

Figure S6. Hybrid conductive traces containing both Electrifi (higher conductivity) and Protopasta (lower conductivity) elements. A) Protopast trace. B) Electrifi trace. C) Hybrid trace. The Protopasta center could serve as a resistor.

Figure S7

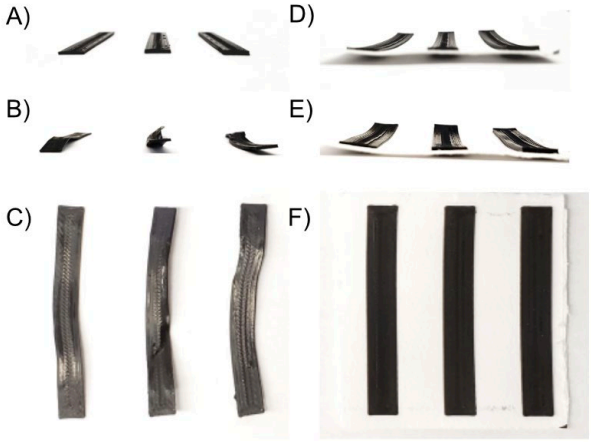

Figure S7. Effect of heating freestanding and paper-based Protopasta traces. A-C) Freestanding Protopasta traces before (A) and after (B and C) being heated to ~100 °C (21% duty cycle). D-F) Protopasta traces printed on paper before (D) and after (E and F) being heated to ~100 °C (21% duty cycle).

Tables S1. Summary of commercially-available conductive filaments. The first three filaments were used in this study. The remaining filaments were not tested but since they are all made from similar polymers and materials, we expect that these other filaments could also be 3D printed on paper.

Conductive filament	Polymer	Conductive material	Cost ($/g)	Resistivity (Ω·cm)	References
Protoplant Protopasta	PLA	graphite	0.10	15	1-4
Multi 3D Electrifi	polyester	copper	1.80	0.006	1-3, 5
BuMat	ABS	graphite	0.05	N/A	6, 7
Amolen	PLA	N/A	0.11	1.42	1, 2, 8
3dk 3dkonductive	PLA	carbon black	0.17	24	1, 2, 9
Jaycar	PLA	graphene	0.06	6	1, 2, 10
G6 Materials BlackMagic3D	PLA	graphene	1.00	0.6	1-3, 11
3D Printer Pro	ABS	carbon fiber	0.10	N/A	12

References

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(2) All3DP https://all3dp.com/2/conductive-filament-brands-compared/ (accessed Feb 21, 2022)

(3) Flowers, P. F.; Reyes, C.; Ye, S.; Kim, M. J.; Wiley, B. J. 3D Printing Electronic Components and Circuits with Conductive Thermoplastic Filament. *Addit. Manuf.* **2020**, *18* (2017), 156–163. https://doi.org/10.1016/j.addma.2017.10.002.

(4) Protoplant https://www.proto-pasta.com/collections/conductive/products/conductive-pla (accessed Feb 21, 2022)

(5) Multi3D https://www.multi3dllc.com/product/electrifi/ (accessed Feb 21, 2022)

(6) BuMat https://www.bumatusa.com/ (accessed Feb 21, 2022)

(7) Amazon https://www.amazon.ca/BuMat-Conductive-Filament-2-2-Pound-Printing/dp/B00O5WY8HU (accessed Feb 21, 2022)

(8) Amolen https://amolen.com/ (accessed Feb 21, 2022)

(9) 3dk https://3dk.berlin/en/special/169-3dkonductive.html (accessed Feb 21, 2022)

(10) Jaycar https://www.jaycar.com.au/ (accessed Feb 21, 2022)

(11) Palenzuela, C. L. M.; Novotny, F.; Krupicka, P.; Sofer, Z.; Pumera, M. 3D-Printed Graphene/Polylactic Acid Electrodes Promise High Sensitivity in Electroanalysis. *Anal. Chem.* **2018**, *90* (9), 5753–5757. https://doi.org/10.1021/acs.analchem.8b00083.

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