Introduction:

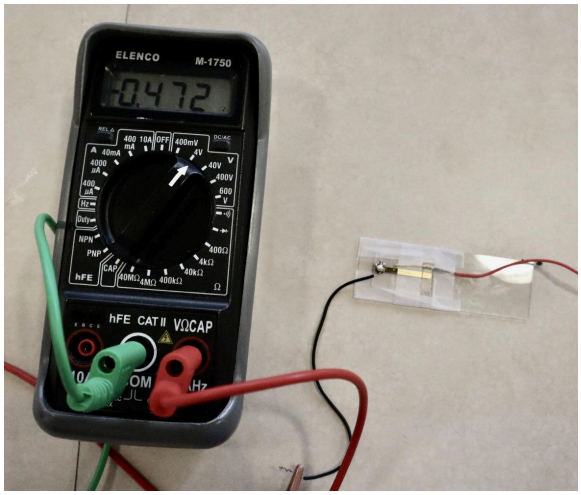
Electric Skin's first prototype is based on a device described in Nature's publication *Power Generation from Ambient Humidity using Protein Nanowires*: the Air-gen This device uses a bottom gold electrode deposited directly onto a glass slide using standard lithography, metal deposition, and lift-off process. A 0.5cm X 0.5cm surface area of nanowires that is 7um thick is then drop casted, meaning to evaporate excess H2O from the nanowires dehydrating them into place, onto this gold bottom electrode so that a portion is over the glass and a portion is over the gold electrode. A hot plate at 90°C is used to drop cast the nanowires. Bothe nanowires from Geobacter and from engineered E. coli that produce the same nanowires have been used. The nanowires are used within a week of being made and are kept in the fridge till used. The nanowires used had a concentration around ~150 µg/ml and ~200ul of liquid is dropcast into a well either etched into the glass or taped onto the surface using tape. The top electrode is a gold wire that is taped into place off to the side of the bottom electrode so the top surface of the nanowires is exposed to the air. To validate that the thickness of the nanowires was 7um thick, a SEM (scanning electron microscope) was used on the film directly. The film was prepared on a silicon wafer and was cut through to observe the cross-section directly.

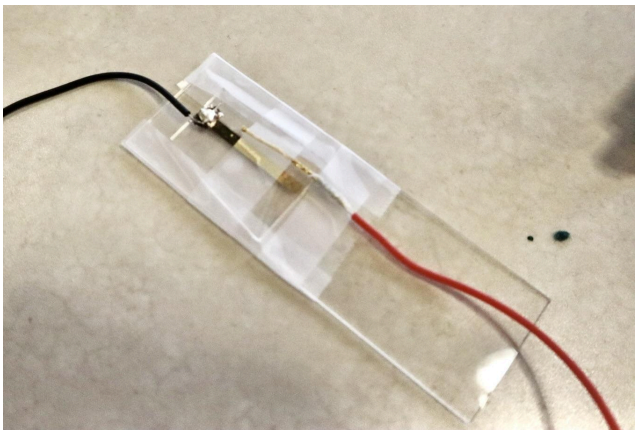
The goal of this first prototype is to replicate the amount of voltage produced by the original device found in the nature paper.

The result of the Air-gen was 0.5V of electricity at 50% humidity.

Air-gen Device specifications:

- Gold electrodes
- Fresh Nanowires from Geobacter and E. coli
- 0.5cm X 0.5cm X 7um thick
- Nanowire concentration around ~150 µg/ml and ~200ul of liquid
- Drop casting using hot plate
- Nanowires dropped off to side of bottom electrode
- Nanowires are fully exposed to air
- Thickness verified with SEM





Air-gen made by Xiaomeng Liu

Materials and Methods for Electric Skin:

Supplies for making Electric Skin first prototype:

- humidity gauge (50% humidity is ideal),
- 9V battery (to test electrodes/ circuits conductivity on their own),
- 10ul pipette tips,
- 0.5 -10ul pipette,
- ruler (to measure and draw 0.5cm X 0.5cm square for drop casting),
- sharp pencil (to draw square),
- scissor (to cut tape into shape and strip top electrode wires if needed),
- scotch tape (to make wells and hold down top electrode),
- 15ml tube of Geobacter nanowires (concentration is 230ug/ml with 2ml total volume),
- silver circuit scribe pen (conductive silver and water pen for drawing circuits),
- copper tape (to use as bottom electrode),
- biomaterial (to replace glass slide),
- copper jumper wire (top electrode),
- alligator clamps (to connect multimeter to electrode without using hands),
- multimeter (to measure voltage),
- white paper (to work over for contrast in color and to draw 0.5cm X 0.5cm square as reference)
- nitrile glove (to prevent fingerprints and oils from getting on nanowires)

Notes for making device:

Always mix up the nanowire solution before use to make the solution as homogeneous as possible. This can be done by swirling the tube around or pipetting up and down. There was no vortex available (and the vortex might shear the proteins into smaller pieces).

It helps to draw the 0.5cm X 0.5cm square on a white piece of paper so you can have a reference shape that you can trace through the glass slide and the biomaterial.

The liquid nanowires have surface tension that holds them together like a water droplet would hold together. When drop casting into the well made from tape make sure to use the top of the pipet to pull the droplet to all four corners of the well so the nanowires will dry evenly in the desired shape.

Keep the Silver pen facing upside down and shake in a thrusting motion downward if it stops working. Scribble a few times to get the silver flowing. Be cautious not to let the tip of the pen be exposed to air for too long when not in use. This pen easily clogs and something better should be used.

If the top electrode is not touching the nanowires fully, the tip of the pencils eraser can be used to press it down into place.

When applying the tape to make the 0.5cm X 0.5cm square well, make sure to push down the edges of the tape that surround the square shape so no leakage of liquid nanowires can escape under the tape or between the crevice of the bottom electrode and the glass.

1st attempt:

To make this process more affordable and something you can do at home, a few methods had to be replaced. Copper tape was used as the bottom electrode instead of gold. A 0.5cm X 0.5cm sized square was directly drawn over the surface of the bottom electrode. Scotch tape was then used to create a well over the marked square. This formed the well for the nanowires to be dropped. Calculations were made based on the concentration of the nanowires at hand and it was found that ~130uL of the nanowire solution would be needed to form a 7um thick film. This was used in place of a SEM to determine expected thickness. This amount was pipetted into the well 20uL at a time. It took a long time to dry inbetween drops because there was no hot plate available. After the full 130uL was reached and the nanowires were dry a copper wire was placed on the top of the nanowires. It was taped directly over the nanowires with some space for air to flow. The multimeter showed reading that ranged from 1.5mV to 0.1mV. Humidity is slightly above 50%.

Device specifications:

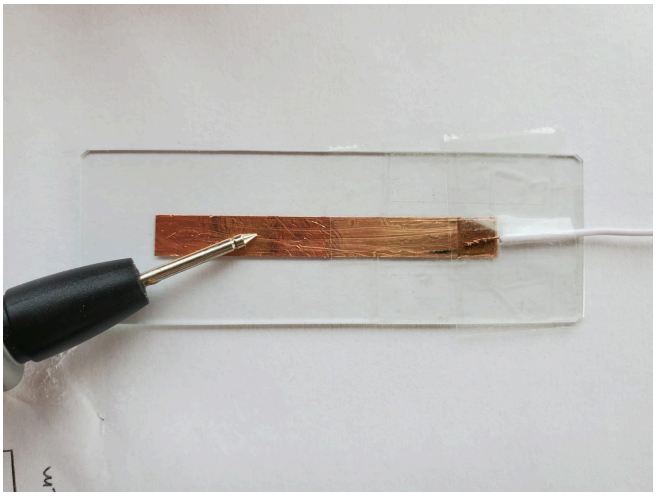
- Copper electrodes
- Old nanowires from Geobacter
- 0.5cm X 0.5cm X 7um thick
- Nanowire concentration around ~230ug/ml and ~130ul of liquid used

- Drop casting using air drying
- Nanowires NOT dropped off to side of bottom electrode
- Nanowires NOT are fully exposed to air
- Thickness not verified besides checking voltage and using predictive math

Results:
This device created about 0.0015V to 0.001V at 50% humidity.
- Non functioning device

Discussion:
This design led to poor results. The voltage gained was between 1.5mV to 0.1mV or 0.0015V to 0.001V. Leading to the conclusion that this design must be short circuiting. The nanowires were directly dropcased over the bottom electrode and not off to the side as the original device. This means that the bottom electrode covered the entire bottom surface of the nanowires so when the top electrode was placed over the top surface of the nanowires it would inevitably touch the bottom circuit because the nanowire film is so thin. The other major difference, that was noticed after the fact, was that the top electrode was taped in two places on either side of the nanowires, but not directly over them in any way. This left the nanowires fully exposed to the air. The nanowires may not have had enough access to the humidity in the air with this first attempts because tape was applied directly over the wire over the nanowires. Air could still get in but perhaps not enough. There were a few other possibilities for why this device did not work. The nanowires used were not as fresh as the ones in the original device. The nanowires had clumped together forming visible white clumps in the solution that would not easily separate when shook or pipetted up and down. The nanowires were also not refrigerated the entire time. The expected thickness of 7um could have been a lot thinner because the nanowire solution was not homogeneous. It was also noticed that the copper seemed to have corroded, changing to a darker color.

Possible design issues:
- Short circuit
- Lack of airflow from tape over nanowires
- Used nanowires solution that was not homogenous
- Used copper instead of gold for electrodes



Multimeter reads: -00.4mV

2nd attempt:

To try and achieve the desired 0.5 volts, a second attempt was made. To solve the problem of short circuiting the device, the 0.5cm X 0.5cm square for drop casting was made off to the side of the bottom electrode so the top electrode could be placed over the glass instead of the bottom electrode. The same amount of liquid geobacter derived nanowires (130 ul) was drop casted into the well 20ul at a time and allowed to dry. To ensure enough airflow over the nanowires, the top electrode was taped on with two pieces of tape on either side of the nanowires. The top electrode was fully exposed to air over the nanowires. The voltage was measured. There was more voltage than the first attempt, but it was still low. To see if the voltage would increase if more nanowires were added, increasing the thickness of nanowires, an extra 70ul of nanowires was drop casted into the well creating a total of 200 ul of nanowires.

Device specifications:

- Copper electrodes
- Old nanowires from Geobacter
- 0.5cm X 0.5cm X 7um thick
- Nanowire concentration around ~230ug/ml and ~200ul of liquid used
- Drop casting using air drying
- Nanowires dropped off to side of bottom electrode
- Nanowires are fully exposed to air
- Thickness not verified besides checking voltage and using predictive math

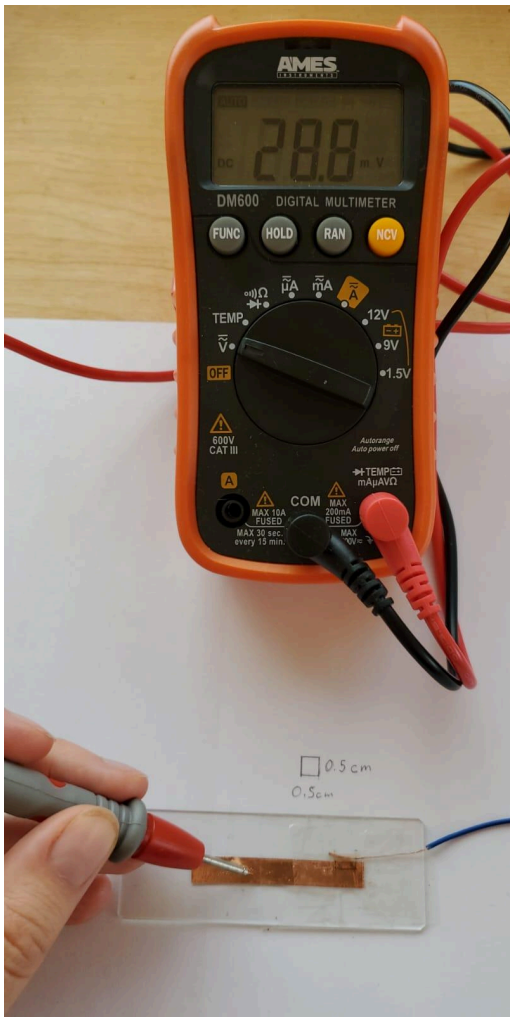
Results:
This produced a higher voltage 0.028V. The humidity was at 50%.

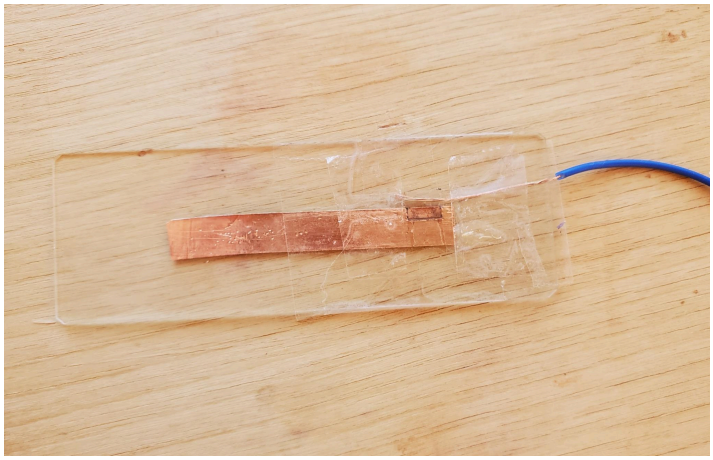
- Low functioning device

Discussion:
The produced voltage of 0.028V is a sign that the device is working, but it is not working optimally at the desired 0.5 volts. The device was no longer short circuiting and the nanowires were fully exposed to the air. More nanowires could have been added to see if the thickness of the nanowires was the problem, but it seemed more wise to try a second variation of the device design first before wasting the limited supply of nanowires on hand. Besides the thickness of the nanowires being a potential problem there are other things that could still be causing problems. The nanowires used are still older than the ones used in the original device. There was corrosion on the bottom copper electrode where the nanowires were dropped. The liquid nanowires could have slipped between the crack of the copper electrode and glass that was being sealed by the tape. This seal could have been broken, allowing the nanowires to move outside of the 0.5cm X 0.5cm square. This would dramatically change the thickness of the nanowires. The bottom copper electrode is made by using a piece of copper adhesive tape. It is thin, but maybe not thin enough to keep a proper seal between the tape and glass.

Possible design issues:

- Nanowires film is too thin
- Nanowires are too old
- Corrosion of copper electrode
- Nanowires could have slipped between the cracks of bottom electrode tape and glass





Multimeter reads: 28.8mV

<u>3rd attempt:</u>

To again try and achieve the desired 0.5V described in the Nature paper, a 3rd attempt was made at making the device. This time some of the materials used would be changed besides the nanowires because there was no new source at this time. The design idea is the same. There is a bottom electrode with a 0.5cm X 0.5cm X 7um film of nanowires that were drop casted into place off to the side of the bottom electrode, with a final top electrode placed off the the side of the top electrode to prevent short circuiting. About 200ul of nanowires were used for drop casting into the 0.5cm X 0.5cm taped well. The difference was the type of bottom electrode used and the material that the nanowires are being dropped onto. Instead of using copper tape as the bottom electrode that was corroding, a silver circuit scribe pen was used to draw a silver bottom electrode over a biomaterial made from alginate and chitosan. This is one of the materials that could be used in a fully biodegradable prototype.

Device specifications:

- Silver circuit scribe as bottom electrode
- Biomaterial as drop casting surface
- Old nanowires from Geobacter

- 0.5cm X 0.5cm X 7um thick
- Nanowire concentration around ~230ug/ml and ~200ul of liquid used
- Drop casting using air drying
- Nanowires dropped off to side of bottom electrode
- Nanowires are fully exposed to air
- Thickness not verified besides checking voltage and using predictive math

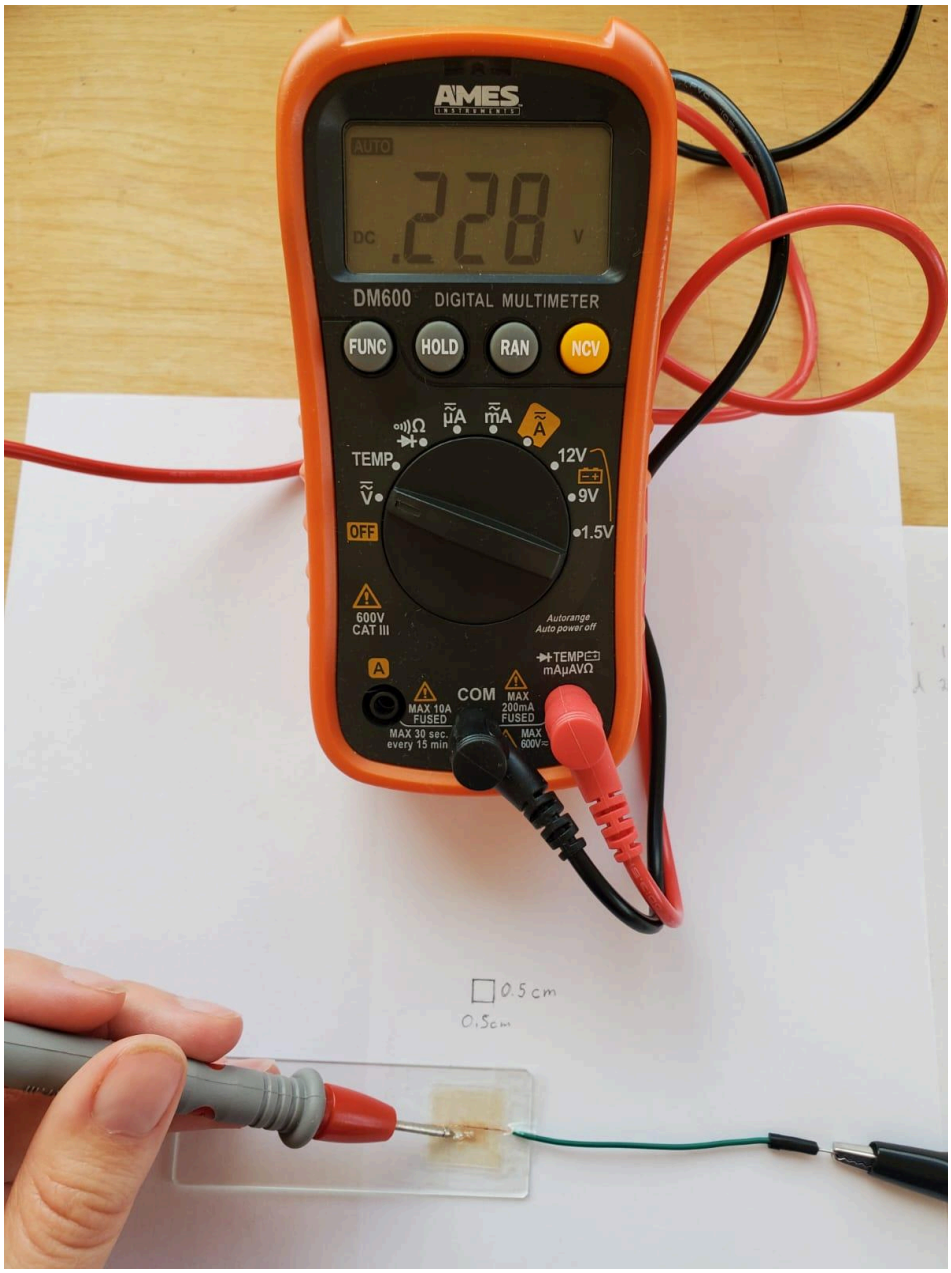
Results:
This produced a reasonable result of 0.228V at 50% humidity.

- Reasonably functioning device

Discussion:
This device is working the best out of all of the other attempts. A voltage of 0.228V is the closest to the desired 0.5 volts. This voltage gives high confidence that the nanowires really do produce voltage from the humidity in the air as the Nature paper states. In the paper it shows that 0.2V is produced by less than 3um thick film. Leading to the conclusion that the nanowires used are old and have possibly fallen out of solution making the mixture less homogenous and the resulting thickness of the film less predictable by measuring out volume. There is still room for improvement in the design as well. The silver bottom electrode would not have stuck to the glass like it did the biomateria. It does not stick to the biomaterial that well either and can be easily pulled off by accident with the tape. There is no adhesive in the silver circuit scribe pen solution that could bind it to the bottom materials. Silver is more conductive than copper and this may be increasing the voltage that is read by the multimeter. The silver also does not seem to corrode from the nanowire solution. There is no change in color. The silver pen also creates a thinner material to drop cast over and there does not seem to be the same dip or lip that must be sealed by the tape like the copper created from its inherent thickness. It does not appear that any nanowire solution seeped between the seam of the bottom electrode, tape, and biomaterial. It is unclear how well the nanowire has stuck to the biomaterial. They have been left undisturbed as much as possible with only the contact from the top electrode. The way the top electrode is adhered to the nanowires could also be improved or the top electrode itself could be made from a different material. The tip of an eraser had to be used to press the top electrode into place a number of times to stay in good contact with the nanowires. This is still a finicky device. No further improvement can be made till new nanowires are made and there are new materials to experiment with as bottom electrodes, top electrodes, materials to drop cast with, and materials to form well are found or made.

Possible design issues:

- Using old nanowires that have fallen out of solution
- Not having a thick enough layer of nanowires
- Not having good consistent contact between nanowires and top electrode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AUTO
DC .228 V
DM600 DIGITAL MULTIMETER
FUNC
HOLD
RAN
NCV
TEMP
12V
9V
1.5V
OFF
600V CAT III
Autorange Auto power off
TEMP mAμAVΩ
COM
MAX 10A FUSED
MAX 30 sec. every 15 min
MAX 200mA FUSED
MAX 600V
0.5cm
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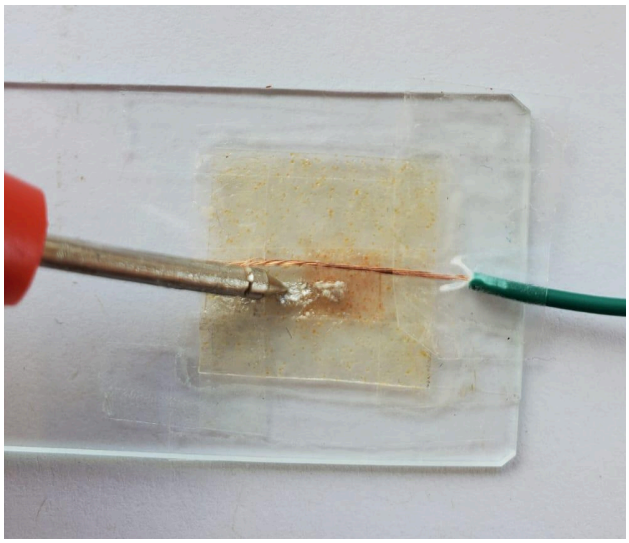

Multimeter reads: 0.228V