Building a Microbial Fuel Cell

MFC Fabrication Guide for Community Oritened Eco-Transitions

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BUILDING A MICROBIAL FUEL CELL

- The information throughout this workshop comes from my past year and a half of research-creation on Microbial Fuel Cells (MFCs) which I've compiled for an open-source resource accessible to non-engineers and engineers alike.

- The research has taken explored several forms of MFCs and throughout the process my goal was to document the information to make it more accessible to artists, creators, and those outside the fields of biology and engineering.

- Most of the information was learnt with minimal prior knowledge except for a background in artistic creation with coding, electronics, and some lab experience cultivating slime molds.

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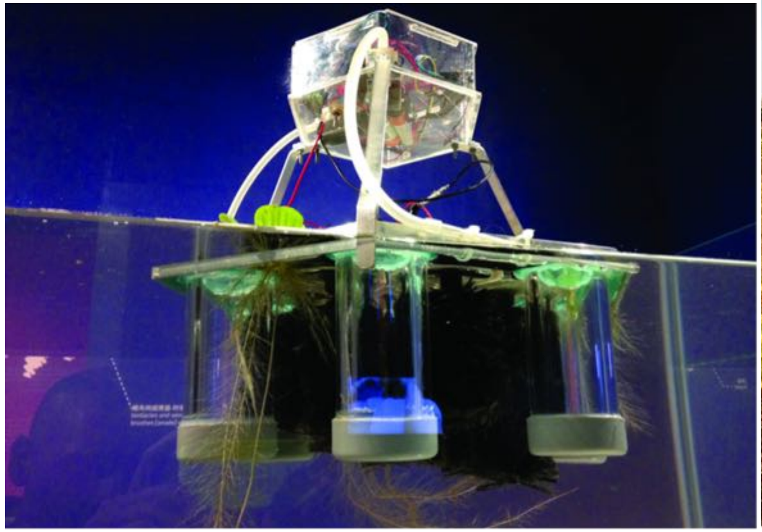
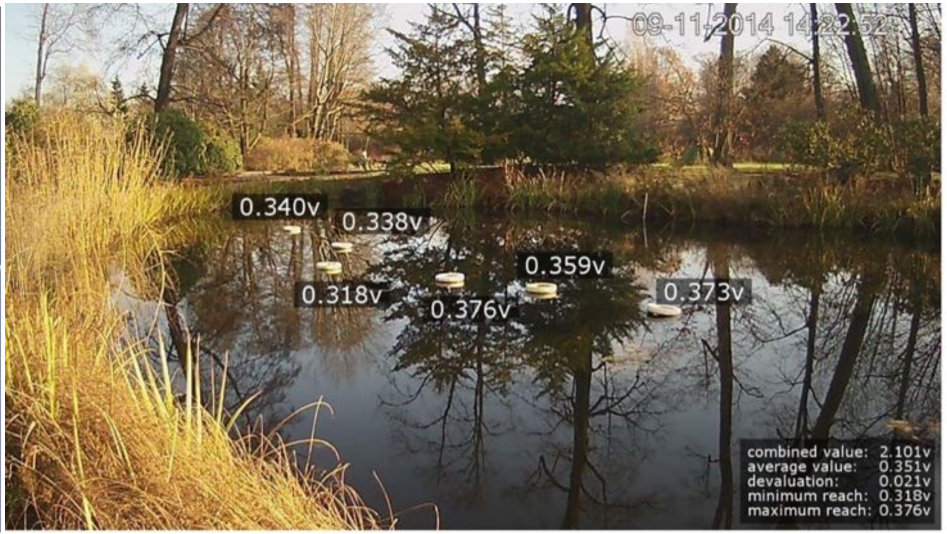
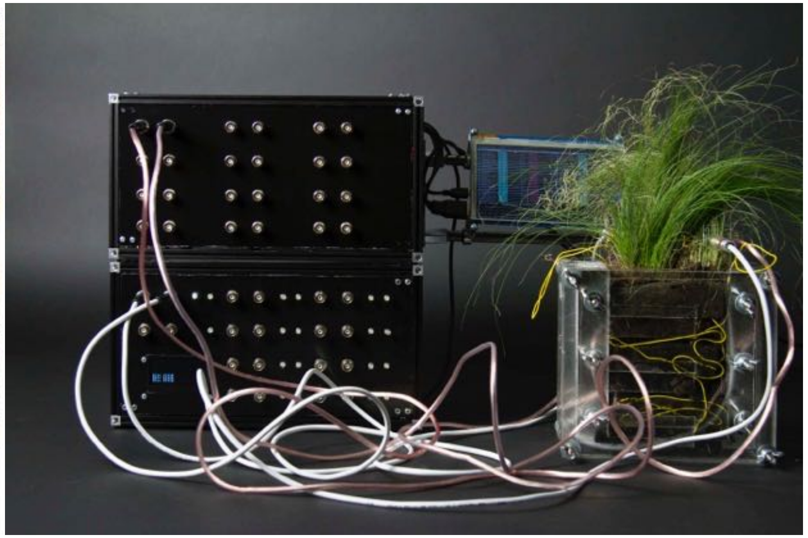


Ivan Henriques – *Caravel* (2014)

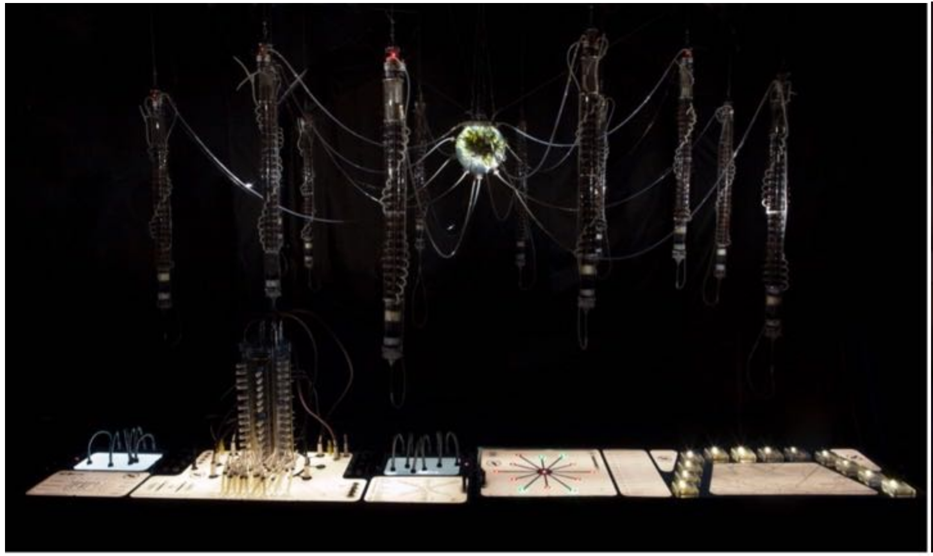


Rasa Smite & Raitis Smit - *Pond Radio (2016)*



Michael Sedbon – *Alt-C* (2018)

Fabienne Felder – *Moss FM* (2014)

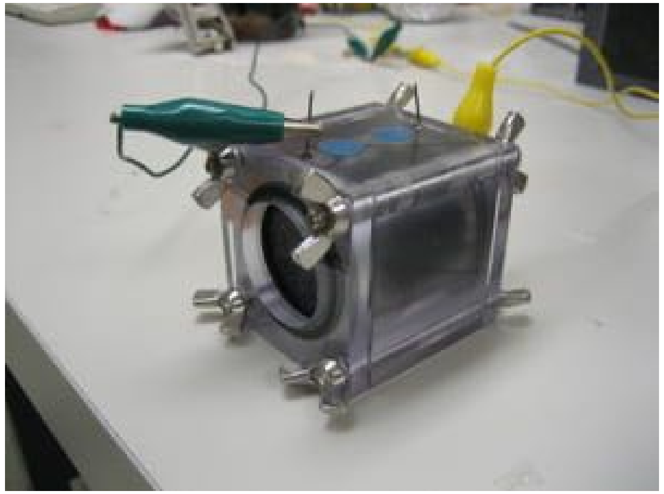


Gilberto Esparza - *Plantas Autofotosintéticas* (2013-2014)

Rasa Smite & Raitis Smit – *Biotricity (2014)*

WHAT ARE MICROBIAL FUEL CELLS?

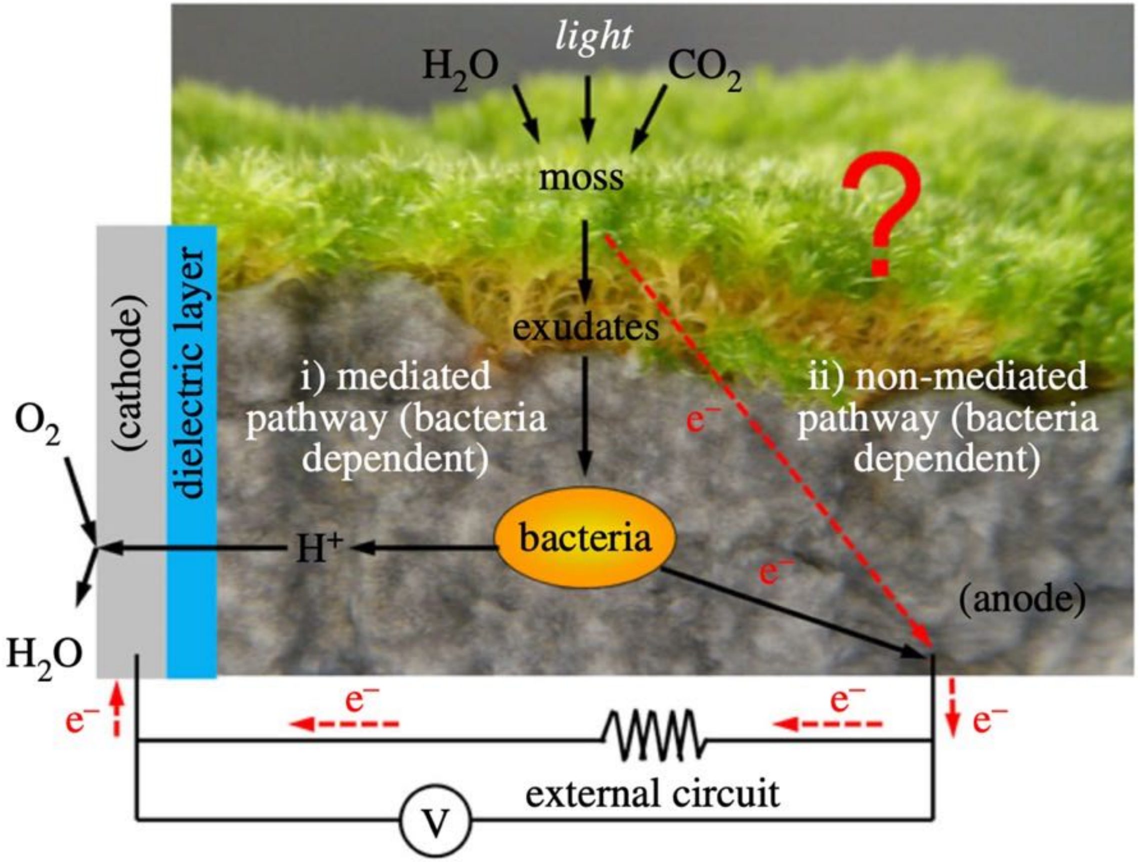
- Microbial Fuel Cells (MFCs) are *energy harvesting* devices that gather energy in the form of ions (H^+ & e^-) from the metabolic by-products of anaerobic bacteria.
- MFCs can take many forms which will be shown in the following slides
- Each MFC has two electrodes - an anion and a cation - that harvest the residual ions and pass them along an electric circuit to a series of electronics that convert the ion's ultra-low voltage power into a 'digitally' usable form for 3.3v electronic devices.



Wastewater based MFC by Logan Labs Research Group (top)
&
My bryo-MFC presented as part of the Hors Piste festival at Le Centre Pompidou. (bottom)

IONIC ENERGY

- Electricity can flow through microbial mediums because of the ions (H^+ & e^-) produced as a by-product of the microbes metabolic processes.
- A circuit is essentially the flow of ions, electrons travel from one point to the next forming an electric pathway, guided by the anodes and cathodes.
- A chemical reaction between the H^+ proton and oxygen (O_2) at the cathode pull the electron flow through the circuit.



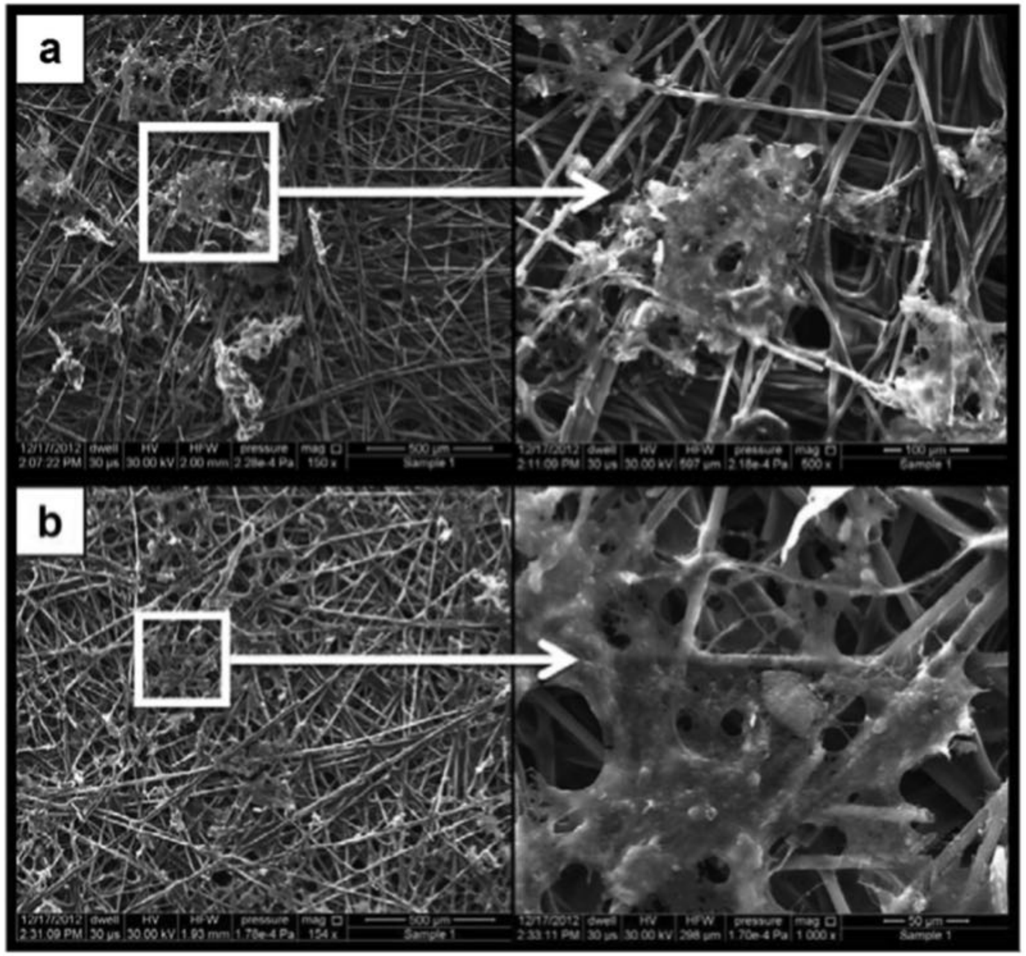
Ionic pathway of a bryo-MFC. © Bombelli, Felder, et al.

ELECTRODES

- The electrodes used in MFCs need to be porous on a microscopic scale.

- The pores allow microbes to use the electrode as a growth medium and form a biofilm which increases the overall electron flow by magnitudes, allowing us to harvest enough electrons for use in our circuit.

- Common electrodes involve carbon in a fiber, tube, or activated format. Often lab-grade electrodes use catalysts but we won't be – but more on that later.



Porous carbon electrodes after biofilm growth. © C. Santoro, et al.

THE CELL

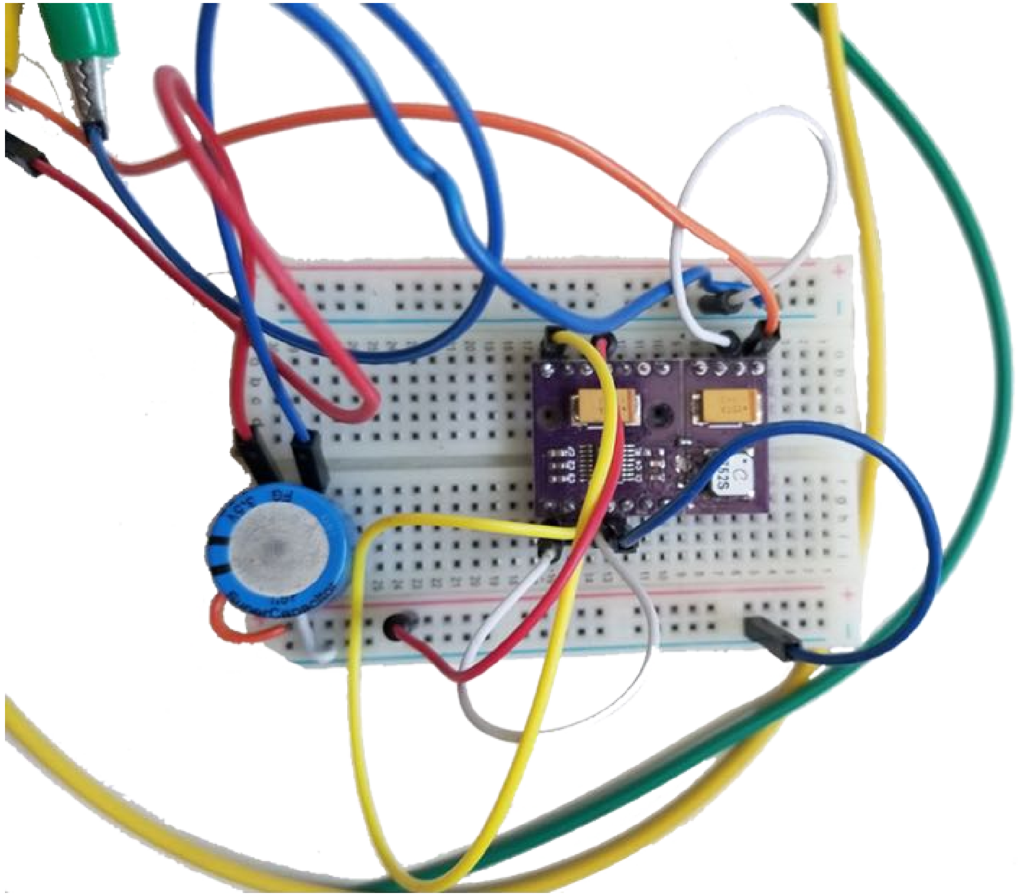
- MFCs can use either an air cathode or water-based cathode. In some examples you'll see graphite sticks in water, but this workshop will focus on air cathodes which more commonly work with plant, moss, and mud fuel cells. They are also easier to maintain outside of a lab setting.

Floating Plant-MFCs by Schievano, A., Colombo, A., Grattieri, M., et al., (2017)

THE CIRCUIT

- The energy that gets harvested from MFCs is called *ultra-low voltage energy*. It needs to be "stepped-up" or brought up from a near 1mV to 3.3V (3300mV).

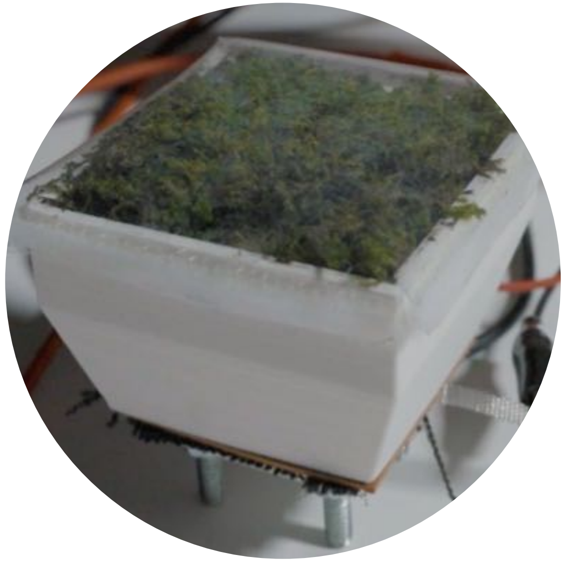
- The easiest way to do this is to buy *energy harvesting* circuits that are premade, like the LTC3108 shown right (purple PCB).



TYPES OF MFCs

Methanogenic

Plant-MFCs (PMFCs)



Bryophyte MFCs (bryo-MFCs)

Waste-Remediation MFCs

Power Flower Pot by Johann Duraffourg (left)
Mud MFC by Matthew Halpenny & Philippe Vandal (top)
Bryo-MFC by Matthew Halpenny (right)
DIY manure-dirt MFC by Lebone (bottom)

ANEROBIC MFCs

- Anerobic mud is an especially powerful MFC as the mud houses methanogens, microbes that produce methane gas and abundant ions through metabolic processes.

- Anerobic bacteria don’t require oxygen to survive and therefore can be found in anerobic ecosystems such as swamps or bogs - areas in which mud and decaying plant debris form an air-tight seal.

- Anaerobes are also found in soil near plant roots but for simplicities sake the anerobic category excludes them since soil anaerobes appear in less dense quantities than those in more anerobic environments.

Mont Tremblant National Park Wetlands

WASTEWATER MFCs

- Wastewater MFCs are cells that remediate waste through microbial metabolism while simultaneously harvest the energy produced.

- These MFCs offer wonderful future prospects of entangling microbial processes with urban systems as they act as a twofold system of purification and energy production.

- Wastewater MFCs have been proven effective at reducing toxic by-products such as Chemical Oxygen Demand (COD), heavy metals, and ammonia (NH3).

MFC wastewater treatment pilot system at Washington State University

Bryo-MFCs

- Though mosses are not the only bryophytes, bryo-MFCs largely refer to mosses. Mosses lead in bryo-MFCs due to their moisture retention and ability to grow throughout a substrate.

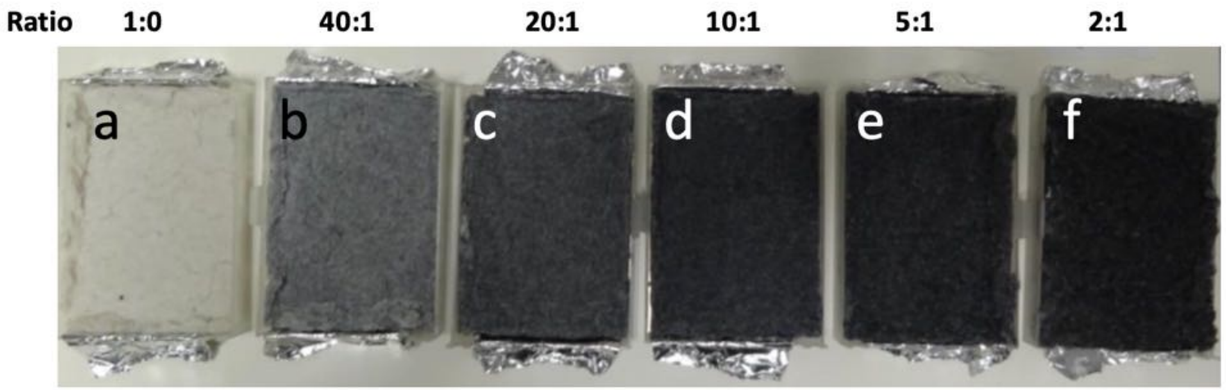
- Mosses do not have roots but rather have rhizoids. In nature they grapple onto relatively flat surfaces like rocks, micro-porous soils, and occasionally mud. They make an ideal choice for MFCs since their rhizoids are able to penetrate and sit on top of microporous electrodes and supply ions to high-surface area mediums.

- In addition to their ability to penetrate electrodes mosses and PMFCs have an advantage over mud based MFCs since they are living and hence continually supply ions under the right conditions.

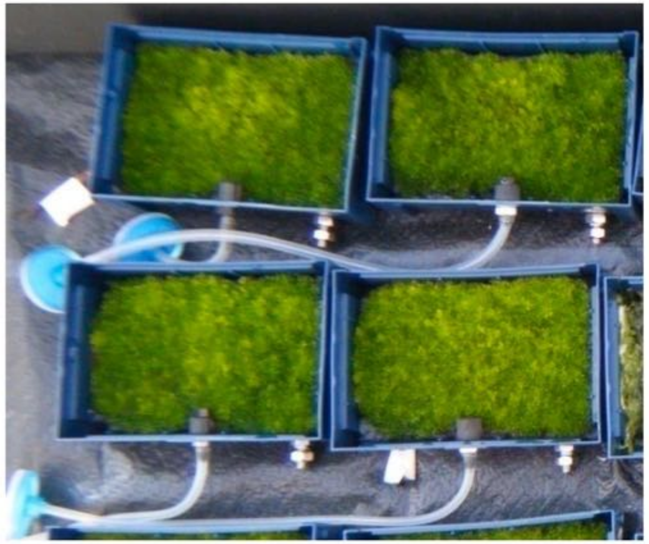
Mosses within Mont Tremblant National Park

Bryo-MFCs

- Moss rhizoids can be grown directly into electrodes by preparing carbon fiber pulp (more on this in the electrodes section) and inoculating blended moss into the medium as the team behind Moss FM did.



Carbon-based electrode mediums with varying density of carbon fiber and paper pulp



Moss FM prototypes

CRITICAL MAKING

- Why is it important to give people the ability to make things for themselves? *Through the process of making critically one can experientially learn how objects operate and processes become interwoven.*

- Without diving into a slide about societal structures I want to note that capitalism has often “de-skilled” the consumer. By this I mean industrial manufacturing was set up in a way that each worker was only given one task, one part in the bigger whole. This effectively limited competition and yielded power to those with the means of production.

- Through removing the knowledge required to build something the consumer becomes powerless in changing or replicating that technology. Open source making gives power to those outside industry, allowing the average citizen to affect change through design, art, and technology.

OPEN-SOURCE DESIGN

- During my RC I found it incredibly difficult to locate information on MFCs. Most of my research came from combing through academic article after academic article, almost all of them obfuscating information so their work could not be reproduced.

- I did find a few wonderful artists and engineers that helped me get to where I am now in my research to create an open source MFC, such as Logan Labs which I'll link to in the Resources.

- While my research is in part to provide other makers with the models I've designed, I believe it's important to also provide the tools used to design and modify these objects.

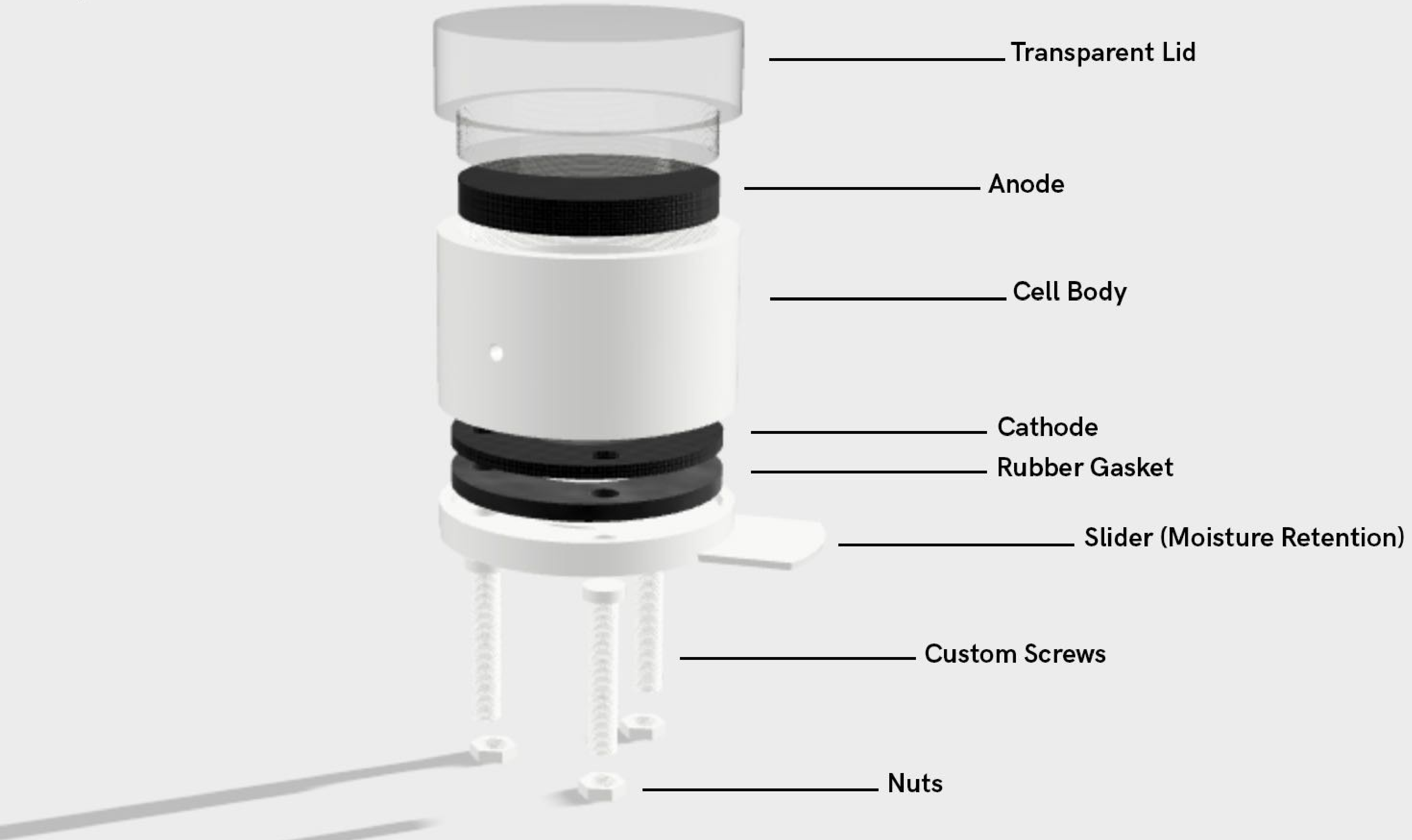
THE ROADMAP

- Each section of this workshop could easily take on its own hour-long slot. To keep the information accessible this workshop acts as more of a roadmap to navigate the creation of MFCs.

- Details will be provided with tangible examples, DIY methods, and resources for further exploration. For projects that lie outside of engineering applications, our MFCs do not need to be lab-grade efficiency found in most papers. There are many examples of more DIY accessible approaches I'll highlight here.

- Not every method will suit everyone, several steps will detail paths that can be taken determined by material availability, cost, and skill levels. This workshop aims to help you find which path is right for you and save you the long hours spent on research towards avenues that are not always publicly presented or compiled for DIY routes.

Bryo-MFC


Transparent Lid
Anode
Cell Body
Cathode
Rubber Gasket
Slider (Moisture Retention)
Custom Screws
Nuts

THE PROCESS

- We’re now moving on to the fabrication section where we’ll go over:
  - *Making the cell body.*
    - 3D printing
    - Available models.
    - Upcycling
  - *Designing and modifying your cell.*
    - CAD
  - *Making electrodes.*
    - DIY electrodes
    - Lab produced electrodes.
  - *Electronics*
    - The parts.
    - Understanding the circuit.
    - Putting it all together w/ slowness.

CELL BODY

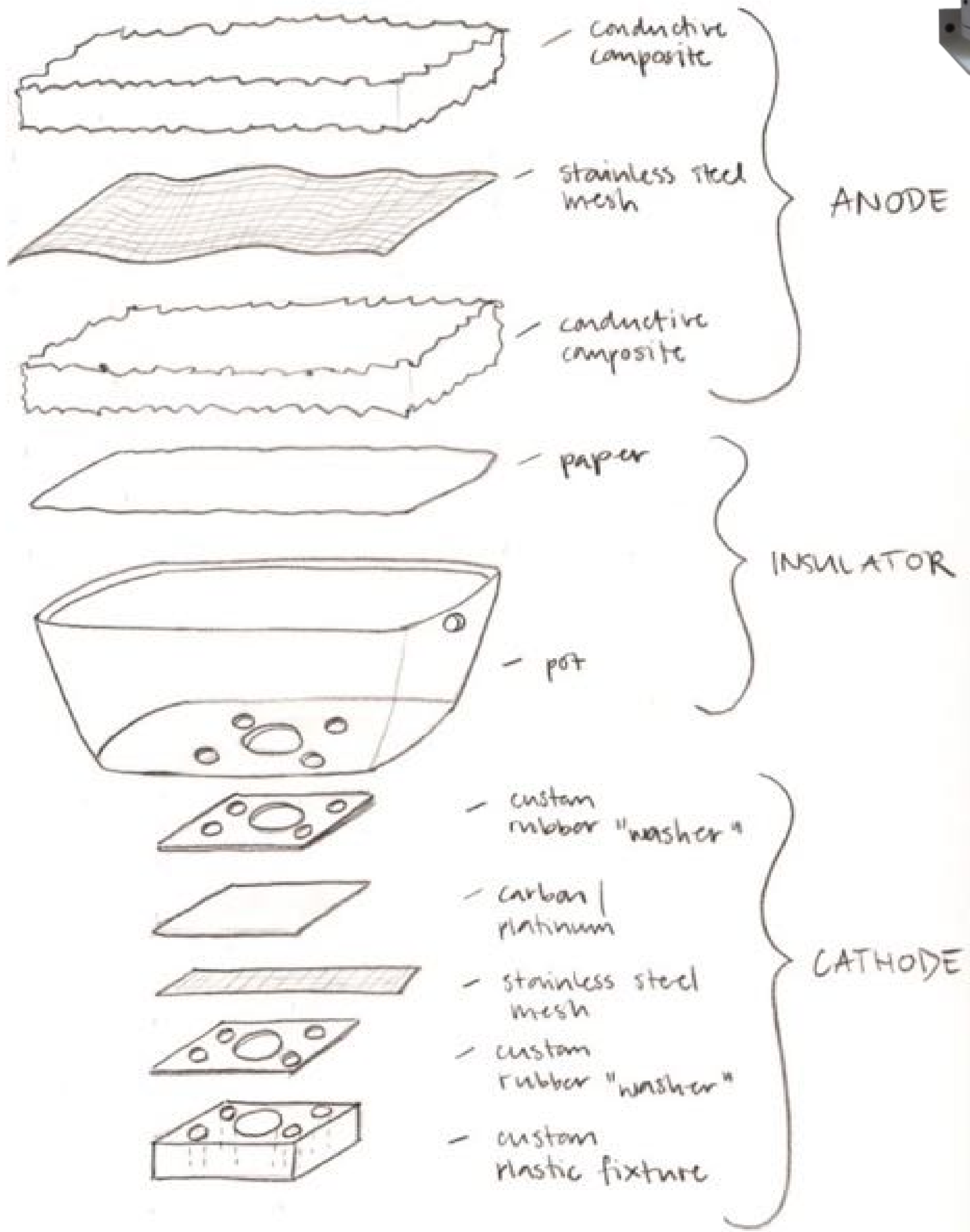
- MFCs cells vary in shape depending on their type. As we don’t want to focus on lab-grade precision our aim is a balanced body that prioritizes accessibility of materials over efficiency.

- One can either fabricate new cells with custom chapes fitting their function or upcycle plastic bottles and containers. Printing allows for custom parts that may not be readily available otherwise, such as plates, plastic screws, etc.

- Since MFCs need to retain moisture for conductivity, hydrophobic plastics /materials are a necessity.

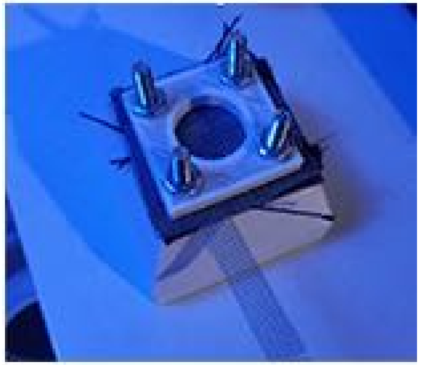
MODELLING THE CELL BODY

- The first iteration of my bryo-MFC was modelled after Felder & Bombelli's MFC design from Moss-FM.. It's a great place to start testing out MFCs.
- To recreate it I used FDM 3D printing (more on this in a few slides). One can also use resin printing but I've found the learning curve more difficult and the process more messy and slightly toxic.
- If not printed, the body of their design is easily upcycled by cutting up tupperwares, bottles, and containers. Some aspects, like the fixtures are more easily printed but not impossible via upcycling.



MODELLING THE CELL BODY

- I'd also suggest Bombelli's configuration as a good first test MFC if you want to work with upcycling materials or don't want to get into printing just yet. You can even start with a Tupperware like I did.

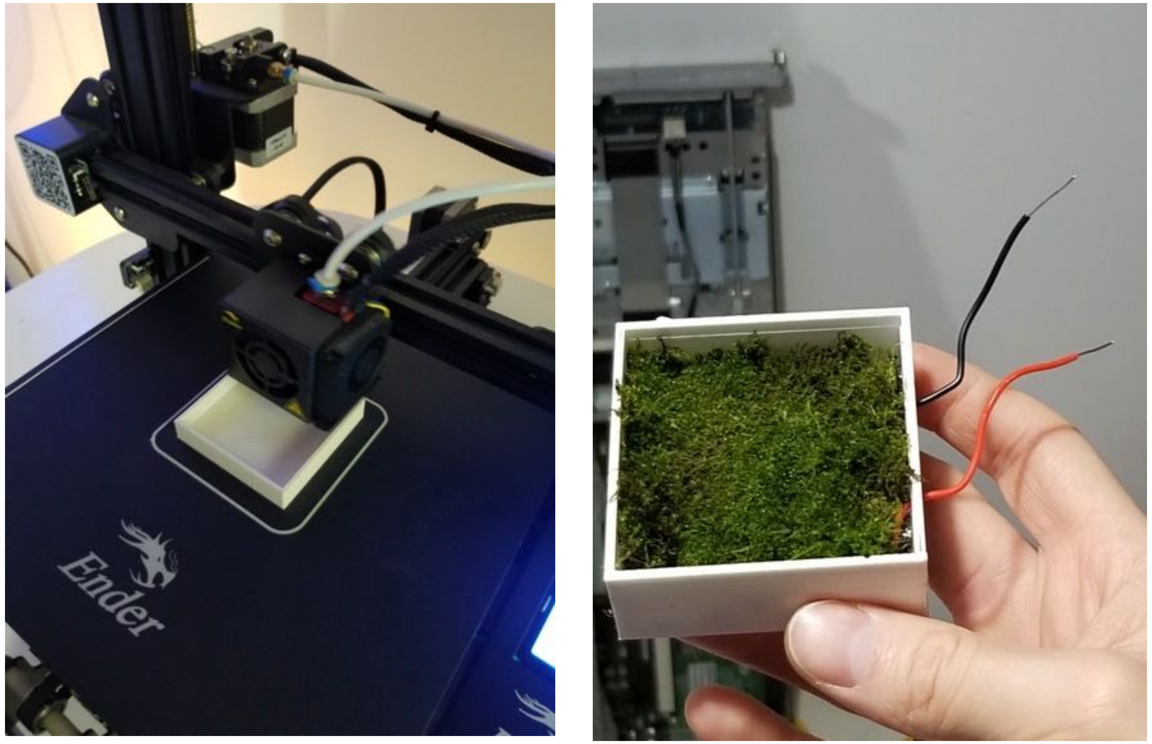


Felder's MFC (left/center), my first bryo-MFC attempt (right).

My first ever MFC attempt.

PRINTING CELLS

- Printing the cell bodies is an easy first step and gives you different options to test out.



My first 3D print with an MFC that ended up being relatively non-functioning

A full print of the open source MFC

GASKETS

- Gaskets are a critical part of each cell. Unfortunately, they can’t really be printed but luckily its easy to get a sheet or rubber or neoprene rubber.

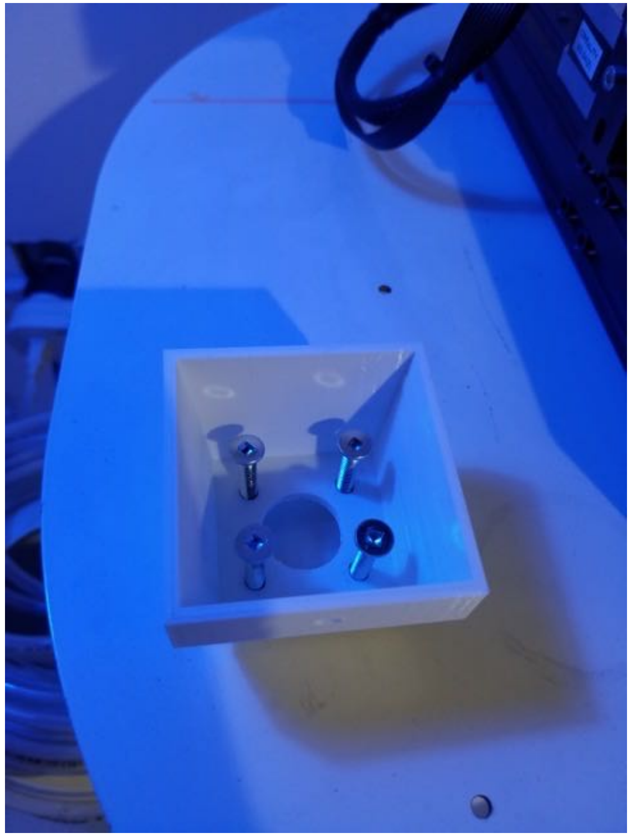
- Depending on your cell design you’ll need to cut the gasket to shape. As you can see, it’s not always the prettiest when you just use an exacto blade. I ended up purchasing a heavy-duty hole punch with adjustable sizes so I could just punch out the holes where the screws pass through.

- For cleaner cuts you can buy rotary cutters, or some makerspaces will custom laser cut rubber so all you need is a vector sketch of your gasket.

A neoprene rubber gasket cut for the open source MFC

NUTS & BOLTS

- If you're using metal screws make sure to choose ones resistant to moisture. Even galvanized steel will oxides during its early phases. It eventually stops but by then the cloth becomes saturated in zinc oxide rendering it ineffective.
- As a solution I started 3D printing screws so they were fully hydrophobic. If you do print your screws and bolts, I suggest using PLA+ filament (there's more on materials soon), which is a PLA that is more durable under stress. Regular PLA screws will most likely snap off at some point.

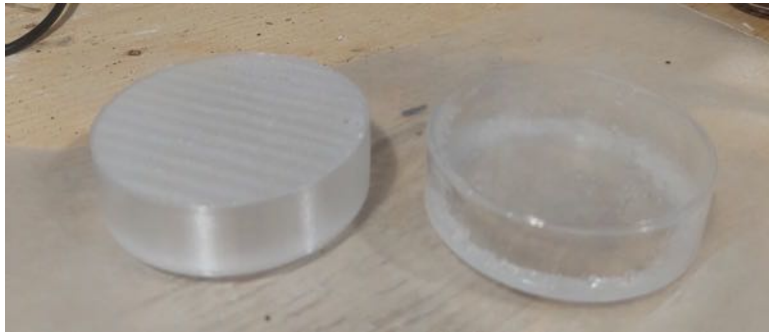


Galvanized screws (left) and PLA+ hydrophobic screws (right)

LIDS

- The open source MFC provides a screw on top (left) but it needs to printed in a translucent filament. Usually PLA isn't translucent so it can optionally be printed in PETG. The file was made so the lid's walls are one layer think for extra translucency, otherwise translucent prints become fairly opaque.

- If you want it to be transparent rather than translucent you can apply special products like XTC-3D which get rid of striations between the print layers, allowing light to pass through evenly.



Pre-treated PETG lids (top-left) and post-treated PETG lid (top-right and bottom)

LIDS (COVERS)

- You can also make an easy DIY lid to retain moisture by cutting a piece of transparent vinyl or greenhouse tarp. With this method I used adhesive Velcro to attach the vinyl to the cell body.

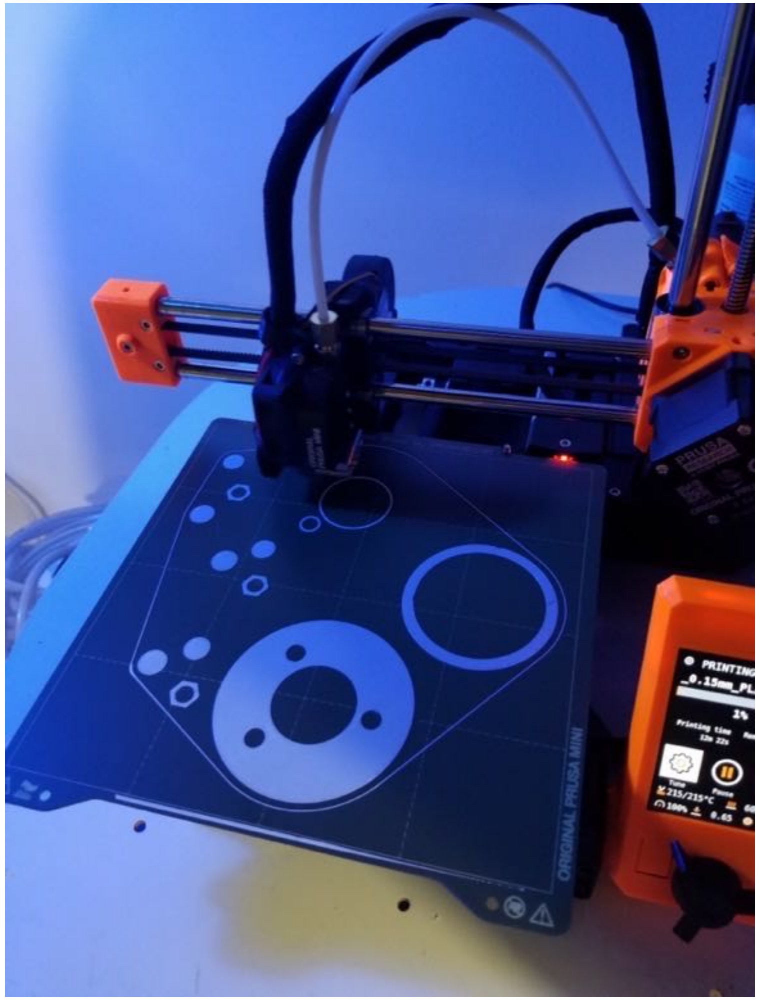
Transparent viny w/ velcro (left), MFC with vinyl cover.

3D PRINTING

- Though it is not strictly required to use 3D printing for the MFCs, I would recommend it for smaller MFCs. Some researchers had success with bucket sized MFCs, but the power output of such large cells is more difficult to pull off as someone new to MFCs as we don't have sophisticated circuits.

- Each printer comes with similar hardware, but each will have a unique learning curve. Choosing a printer depends on how much you will need to use it (print speed), the level of accuracy, and the variety of compatible materials.

- 3D printing is a great interdisciplinary shared tool since only one person needs to design the cell and they can share it with anyone who wants it.



The Prusa Mini+ in my shared research-creation space.

3D PRINTER AVAILABILITY

- The best option if you're new to 3D printing or infrequently need to print is to use 3D printers at either a maker space or local universities and libraries.

- Maker spaces are publicly open labs with fabrication equipment such as 3D printers, CNC machines, soldering equipment, etc. If you're doing research in a dense city, odds are you have one within range. To print prefabricated cells (which are included in the last section of this paper), one just needs a USB stick or SD card and a printer.

- If you already have the files, you need you can also order prints online from printing companies or contact local makers in your area and ask them for a print.

- If you want to frequently prototype new iterations for artworks or personal projects buying an entry level printer is always a great option. Depending on your budget there are a multitude of printers that fall under the 300$ bracket. Some printers cost a slight premium over budget printers but offer the user a relative ease of use, my personal favourite for ease of use are Prusa printers.

3D PRINTING

This workshop will always be referencing FDM printing but in case you'd like to experiment with resin-based printing, the three most common types of 3D printing are:

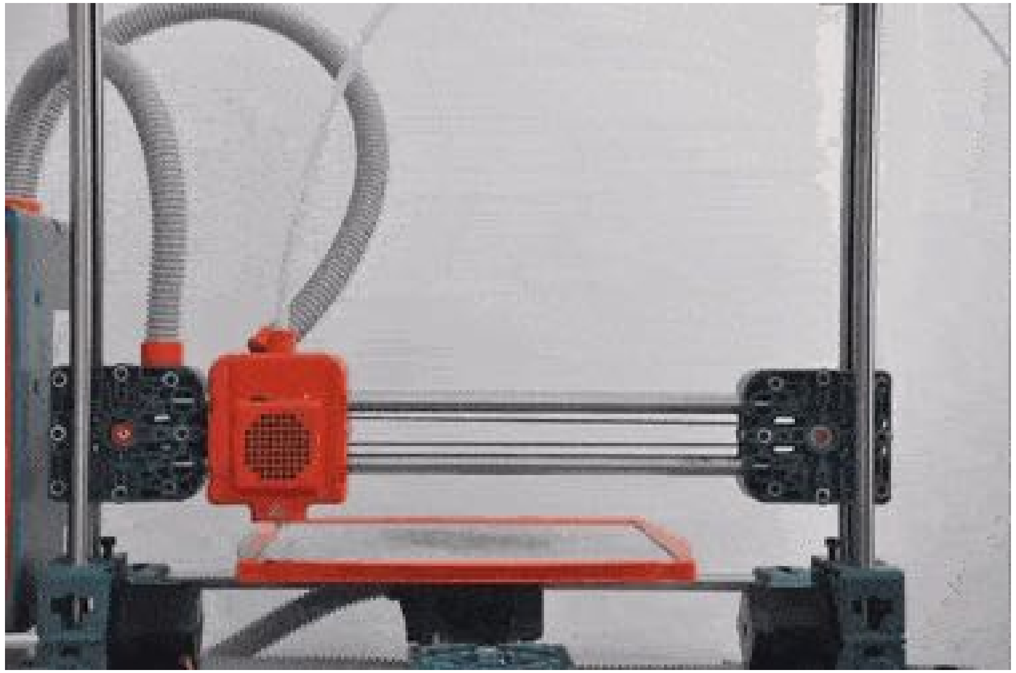
- **FDM (fused deposition modelling)**
  - Prints in horizontal layers with meltable thermoplastics. Each new layer moves up on the z-axis until finished.
- **SLA (stereolithography)**
  - Uses UV light to harden liquid resin, then pulls each horizontal layer upward out of the resin.
- **DLP (digital light processing)**
  - Similar to SLA but uses non-UV lights like LEDs.

FDM

SLA

DLP

PRINTING STYLES



FDM

Resin

PRINTING MATERIALS

- **PLA**
  - Corn-based thermoplastic that varies in composability between 70-100%. Carbon neutral if recycled properly. Has a similar variant called PLA+ that's more durable.
- **ABS**
  - Petroleum based thermoplastic that comes in pellets or filament (most machines use filament).
- **Resin**
  - Resins comes in many more varieties than thermoplastics such as elastic, flexible, castable, industrial durability, dental, transparent, etc. Some are slightly toxic to breathe and touch so more caution is needed.

PLA

ABS

Resin

3D PRINTERS BY PART

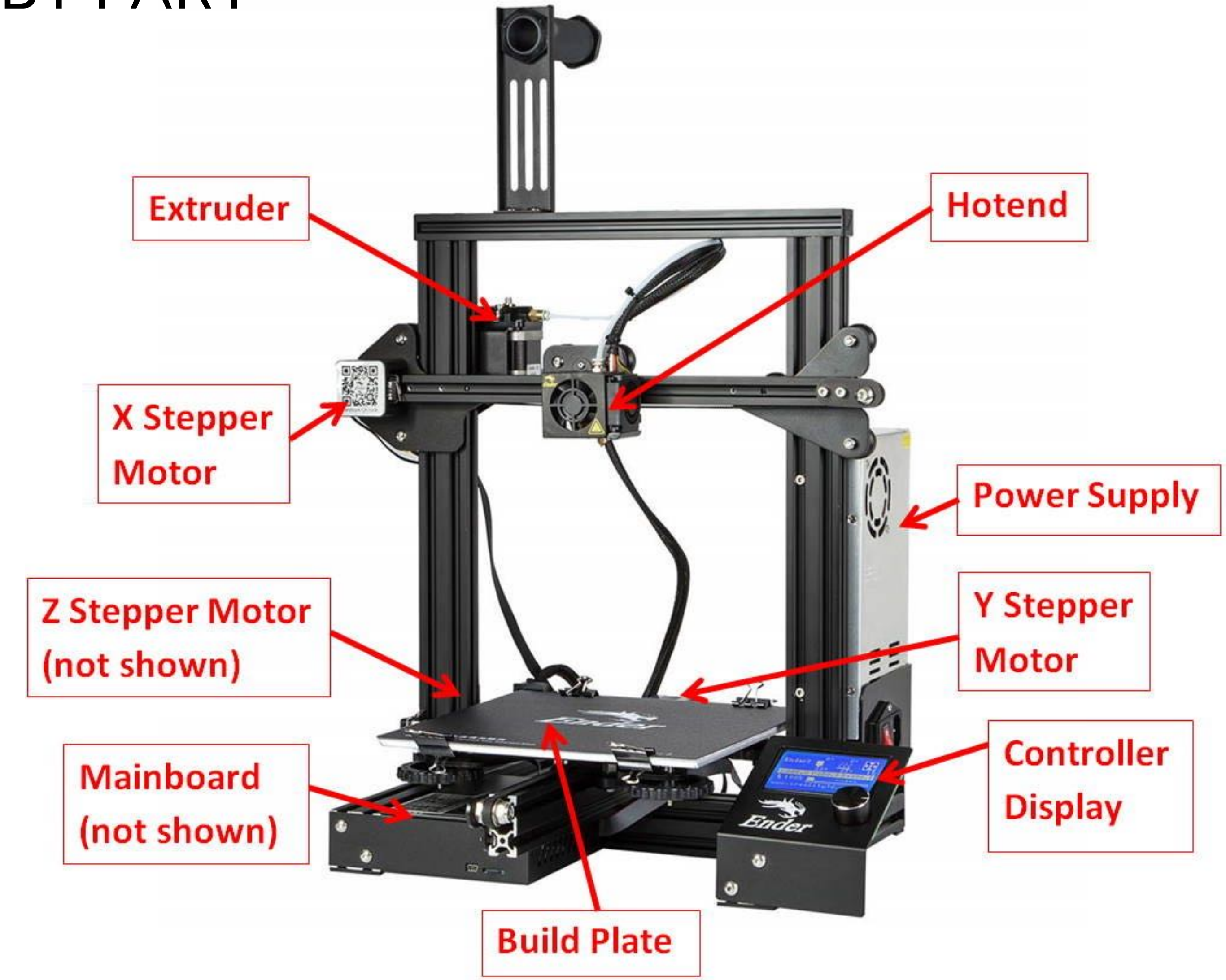


Diagram by 3DMaker Engineering

STL FILES & GCODE

- Printable 3D files usually exist as STL files which represent the 3D geometry one is trying to print but not the actual print code itself. 3D printers operate on code called gcode (standing for Gerber format code) and need to run through processing specific to the printer in use.

- To generate gcode for a specific printer we need to run the STL file through software called a Slicer. Some printers have proprietary Slicers but most printers can be used on the open source, widely compatible Cura software (by Ultimaker).

- You can find pre-made STL files on sites like *Thingiverse*, or from researchers themselves.

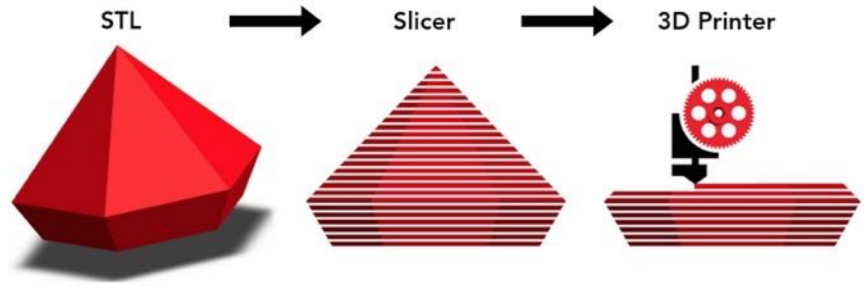
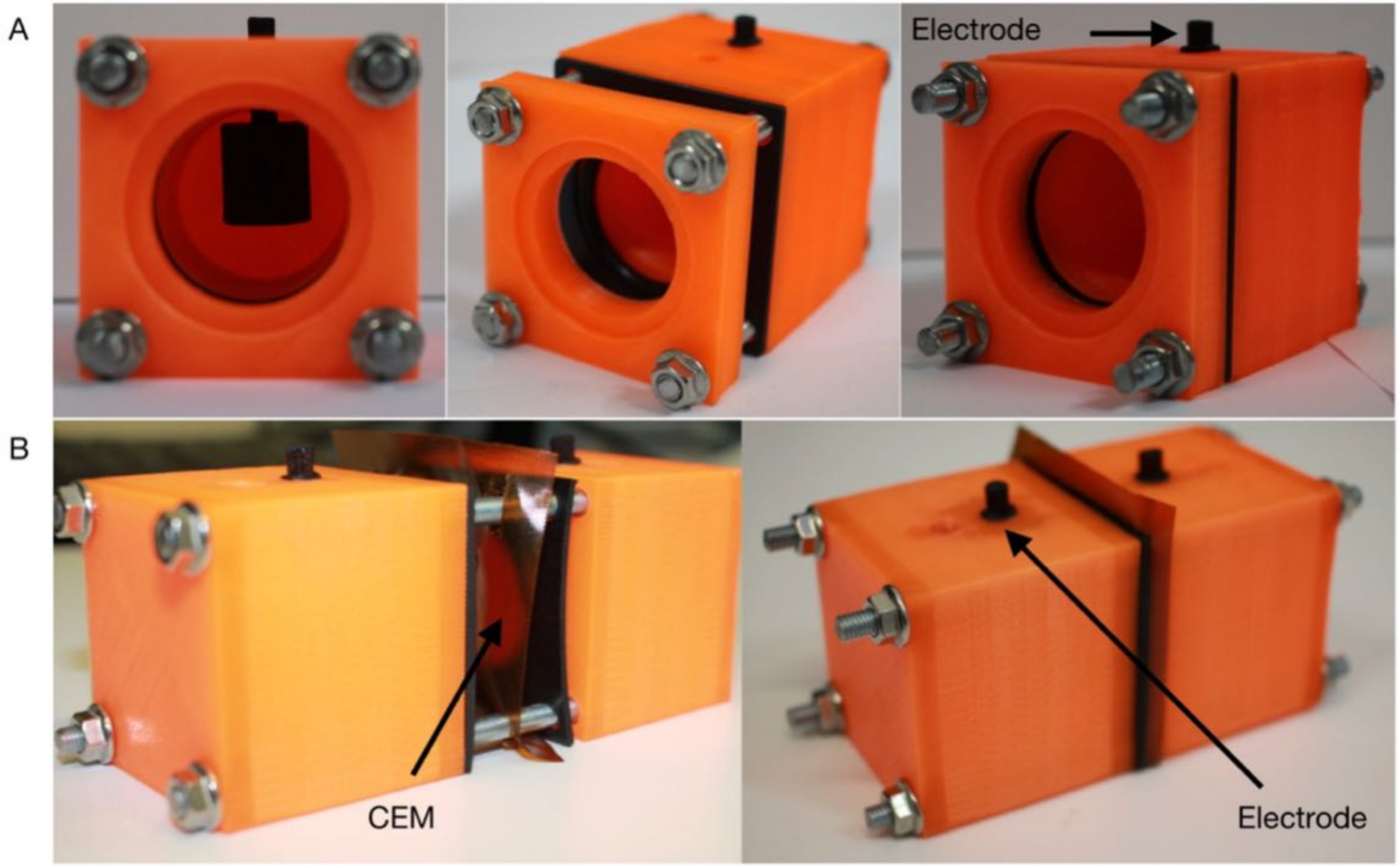
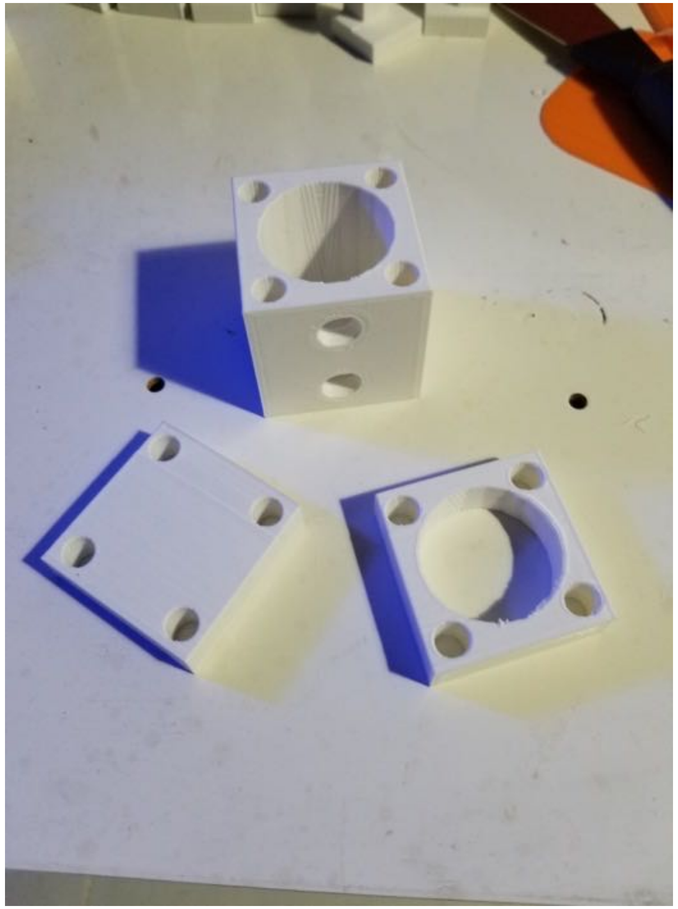


Diagram by 3DMaker Engineering

PRINTABLE FILES

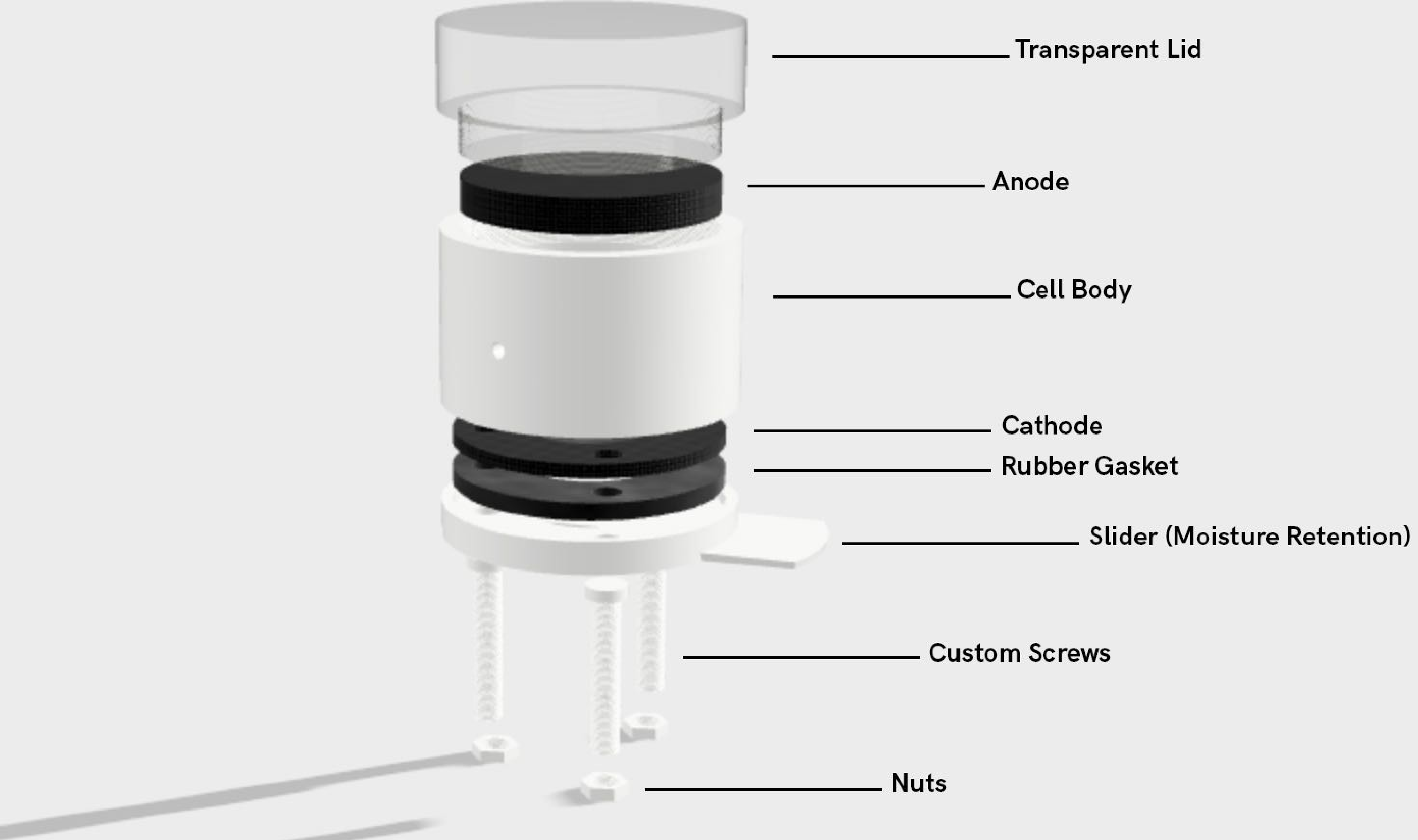


Printable waterwater MFC by researchers Janelli, Trolio, Flagiello, & Minutillo



An open-source reactor configuration

Bryo-MFC


Transparent Lid
Anode
Cell Body
Cathode
Rubber Gasket
Slider (Moisture Retention)
Custom Screws
Nuts

OPEN-SOURCE DESIGN: PT II

- Even though printable claim to exist in some research papers they are rarely actually included with the pdf. Some MFC researchers, like Logan Labs, include details on how to CNC fuel cells but often this method is expensive, inaccessible, and limited in function.
- For this reason, I've designed my own MFC and am making it an open-source and free-to-print resource. Along with the printable STL files I've included a CAD file because I believe its important to give people access to modifying the design itself to suit their needs.
- The program I'm using, Fusion 360, is free for hobbyists and makers so anyone can use it. The free version comes with some slight limitations on industrial CNC design, but we won't be dealing with that anyways.

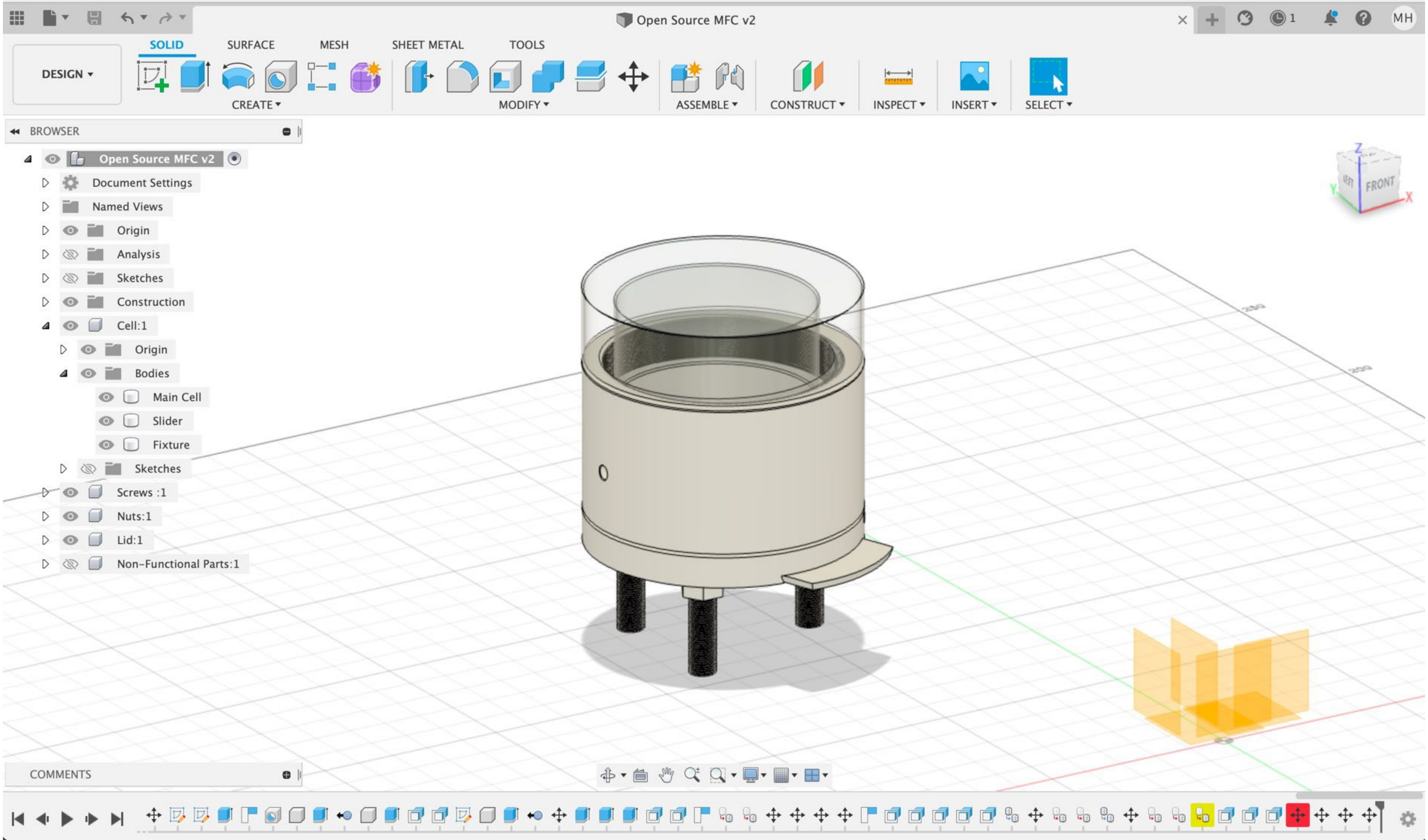
Fusion 360

CAD SOFTWARE

- I won't dive as deep into CAD (Computer Aided Design) software as it takes a bit of learning that may be too stretched for this workshop. What I will say is I had never touched CAD software before 6 months ago and after the initial learning curve I haven't looked back.

- When designing objects everyone has their own workflow, I am not specifically advocating for Fusion 360 but rather an open-source design mentality that not only provides an end object but a process.

- When designing 3D files one can use free software like Blender but software specific to modelling doesn't as easily give the user the flexibility to go back and edit parameters, like adjusting a screw width. CAD allows easier prototyping and iterative design processes so you can experience what works and doesn't work without starting from scratch each time.


Open Source MFC v2
SOLID
SURFACE
MESH
SHEET METAL
TOOLS
DESIGN
CREATE
MODIFY
ASSEMBLE
CONSTRUCT
INSPECT
INSERT
SELECT
BROWSER
Open Source MFC v2
Document Settings
Named Views
Origin
Analysis
Sketches
Construction
Cell:1
Origin
Bodies
Main Cell
Slider
Fixture
Sketches
Screws :1
Nuts:1
Lid:1
Non-Functional Parts:1
COMMENTS
FRONT
MH

ELECTRODES

- To make our electrodes we'll need very little equipment for both routes we can take, whether that be a DIY crushed carbon electrode, or buying premade carbon electrodes.

Fabrication of Elbonian MFCs. © Superaccu OÜ

ELECTRODE MATERIALS

Graphite felt

Carbon paper

Activated charcoal

Grafoil

Carbon fiber brush

Graphene

ELECTRODES

- The most efficient electrodes are carbon-based felts, graphene, and platinum coated carbon cloth. These materials need to be purchased from a lab and can be quite expensive. For a more DIY approach one can make electrodes out of stainless-steel mesh and activated charcoal. The stainless-steel mesh is generally used in gardening applications but is perfect for our purposes because it is fine, rust-resistant, and conductive

- Activated charcoal comes in many forms, or *allotropes*, some are more electrically conductive than others. Generally, unprocessed carbon has a low conductive potential until its converted into one of its many end products. Graphite is fairly conductive while graphene is very conductive. One of the reasons we add steel to our electrodes is to help pass electrons more efficiently to our circuit. The carbon we're using acts like an electron sponge and the steel pulls out the water.

DIY Mortar & Pestle Method

- The most DIY version of electrodes we can make are ones made of stainless-steel mesh and activated charcoal.
- Microbes won't grow on stainless-steel, so we need to cover the mesh with charcoal. stain-less steel is preferred over other metals since it will need to be waterproof. The charcoal you buy at the aquarium store comes in small pellets, in order to increase the surface area for electron flow we need to get it as fine as possible.
- An easy way to do this is with a mortar and pestle, a less accessible but more efficient DIY method is to use a hydraulic pump to crush the carbon.

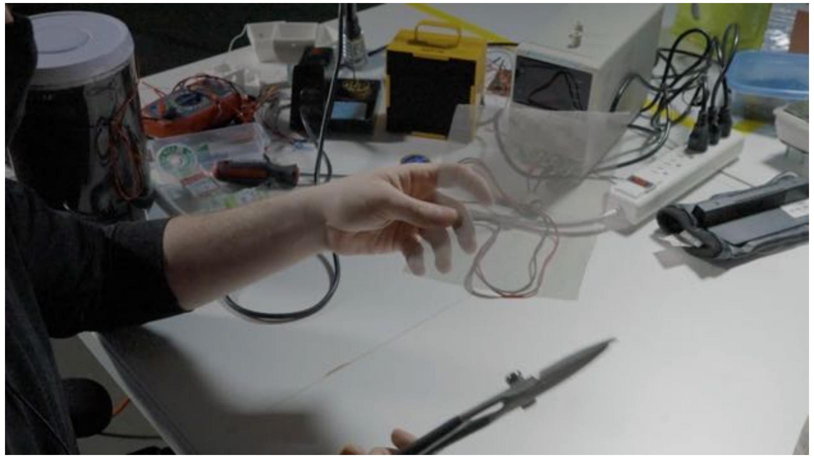
Photos by Guillaume Pascale for Hors Piste.

DIY Mortar & Pestle Method

- Once the charcoal is powder-like we need to bind it to the stainless-steel electrode. The electrode can be cut in whatever shape your cell is. I recommend tin snips to cut it but a variety of cutting tools, like wire cutters, can be used. A good pair of work gloves is also recommended as the steel can be quite sharp when cut.

- We can bind the charcoal to the electrode using epoxy. Since the charcoal consists of varied tiny bits, they will form a conductive shell touching the steel. Before the next step we should add in some wiring to bring power outside the cell. Place the wire within some epoxy and make sure its wrapped around some steel.

- For the charcoal to dry in a compact shape we need to apply pressure. If we don't have a hydraulic pump available (car owners may) we can use c-clamps.



Photos by Guillaume Pascale for Hors Piste.

DIY Mortar & Pestle Method

- For the charcoal to dry in a compact shape we need to apply pressure. If we don't have a hydraulic pump available (car owners may) we can use c-clamps.
- Leave the electrode in the clamp for 20-60 minutes, the longer the better since were dealing with so many tiny bits of charcoal. Check the wire, if its not secure or not conductive (not touching the steel) you can try to add a soldered joint to it.
- If its conductive it's working and you're ready to set it in your cell! In this example it's going in an anaerobic mud MFC.

Photos by Guillaume Pascale for Hors Piste.

DIY Mortar & Pestle Method

USING LAB-GRADE ELECTRODES

- Even though making DIY electrodes and upcycling materials is always a great option, there's no shame in buying pre-made.
- It's often difficult to find vendors, here in Canada I use the US based company *Fuel Cell Store*. Even though its not illegal to ship these electrodes globally they often carry a hefty import and shipping cost since they're specialty items.
- One big advantage of lab-grade electrodes is they're very helpful when you're building your first few MFCs. It reduces the chance your DIY electrode isn't built correctly and since lab-grade electrodes will always be more efficient and easier to work with it helps get things running before experimenting with more DIY methods.

CARBON CLOTH & FELT

- The two materials you'll want to start with are carbon cloth and carbon felt.
  - The felt provides a fluffy, conductive growing medium for your microbes or rhizoids.
  - The cloth often comes with a platinum catalyst aiding reactions at your cathode.

- There are a few methods for turning cloth and felt into usable electrodes, the first is one I found during my research: the cloth and felt can be attached to stainless steel mesh as we did with the mortar and pestle method.

- The second method involves using stainless steel thread instead of mesh.

Graphite felt

Carbon paper

Mesh Method

- The mesh method was used in my earlier bryo-MFC prototypes. It's a great method if you have the mesh on hand – gardeners might - or can easily grab some from a hardware store.

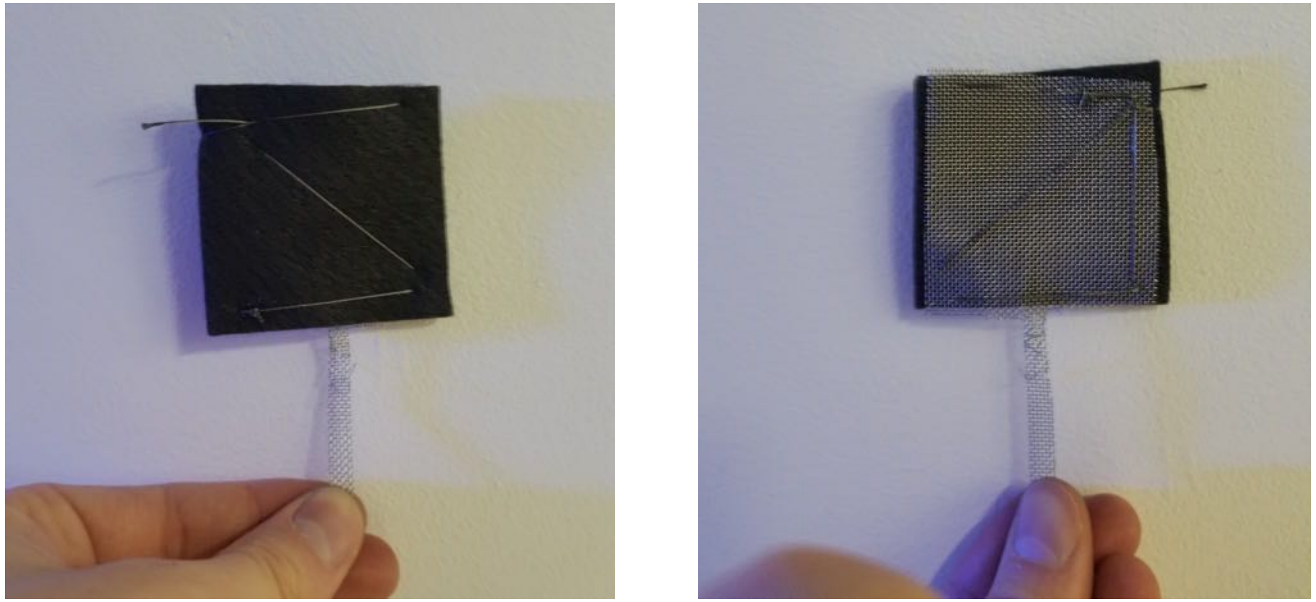
- It involves compressing a stainless-steel mesh and a carbon cloth electrode at the exposed cathode site (air hole).

- The mesh method works best if you can apply a lot of force between your fixture, so a good washer is recommended.

My second bryo-MFC design.

Mesh-Thread Combination

- Often if I'm using the mesh method I'll stitch in some thread for extra contact between the mesh and felt/paper.
- The mesh method is useful if you prefer using alligator clips as the strip of exposed stainless-steel is easy to clip on to.



Thread/mesh anodes

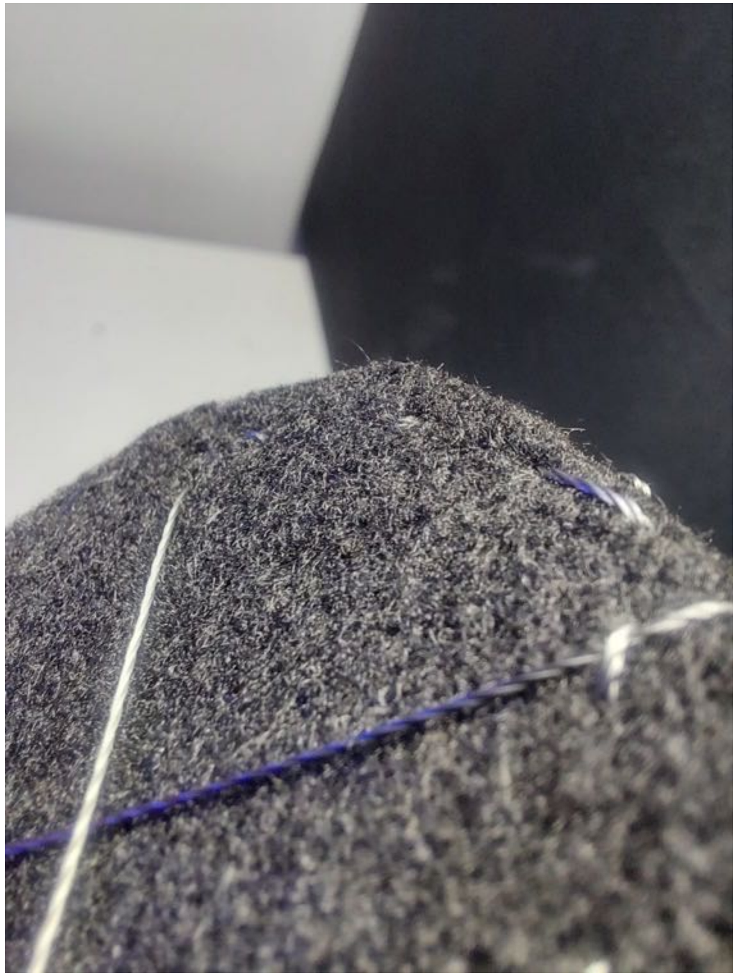
Thread Method

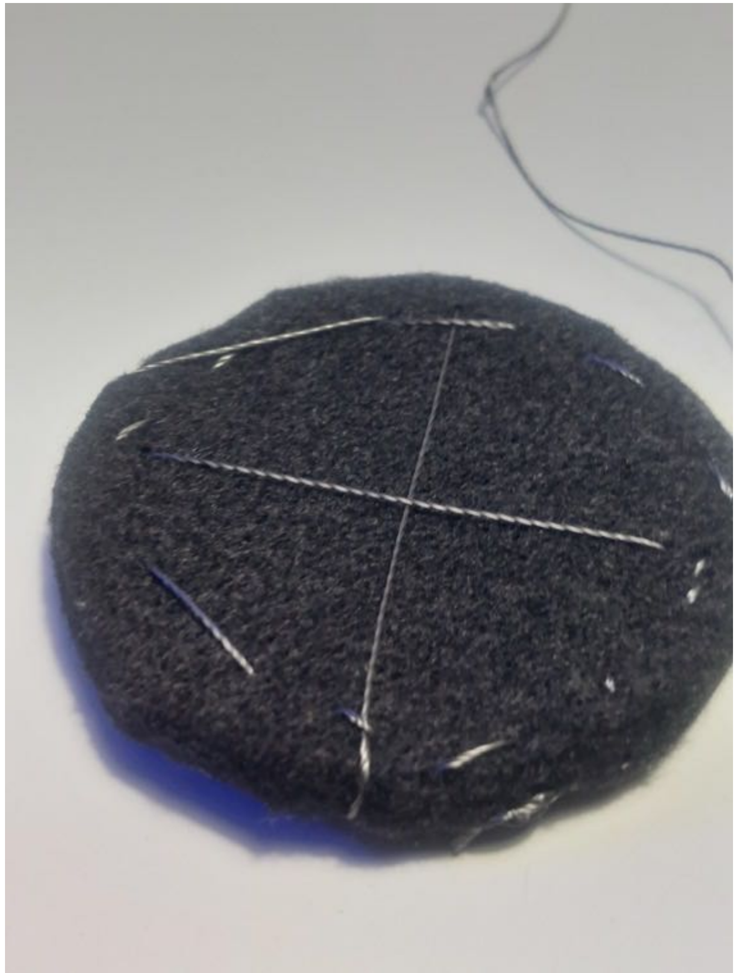
- You can purchase conductive thread from most electronics providers, I first bought mine from *Adafruit*. I personally find the thread much easier to work with as you can avoid some scratches from the stainless-steel mesh.

- The thread can be stitched through the felt and the cloth easily as they themselves are fibers. Arguably the thread makes more contact with the carbon medium as its woven throughout rather than making contact at a few points.

2 ply stainless-steel thread

Thread Method: Examples

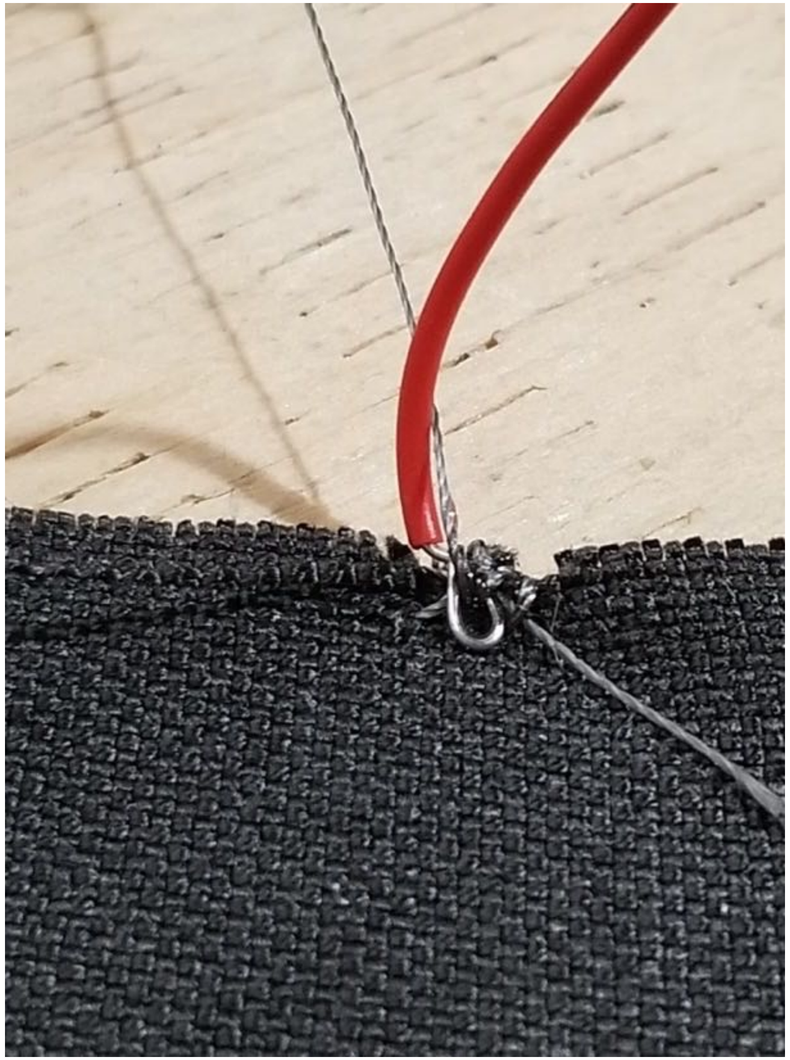




Thread Method: Sealing

- If you choose to use wires with the thread, or attach anything to the thread, you need to double knot your thread and apply a simple sealant.

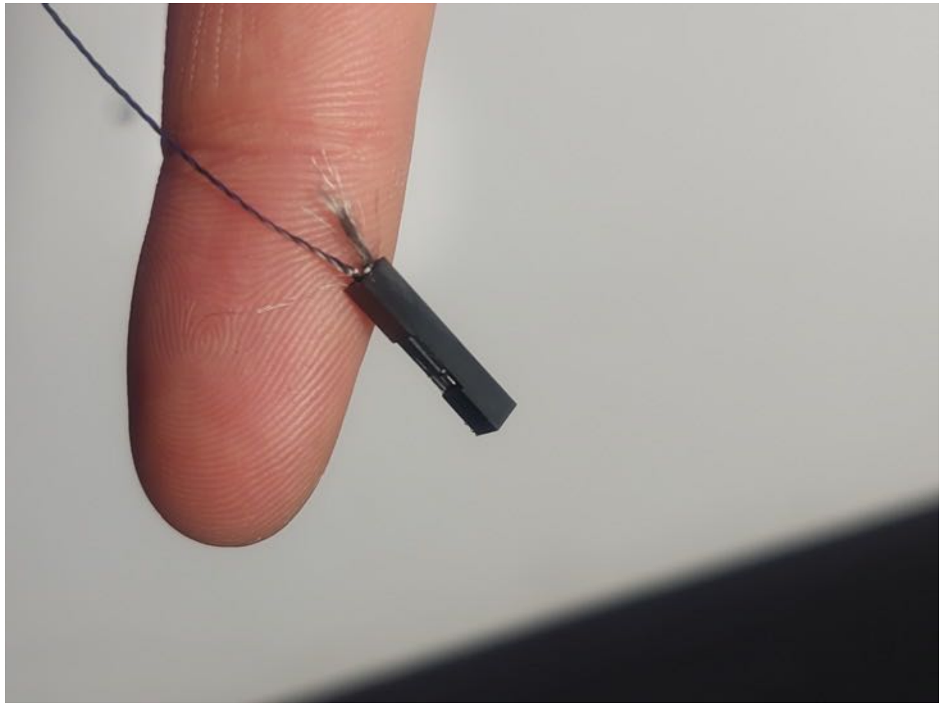
- If you don't seal the knot, it will eventually undo itself. The easiest solution is to dab some transparent nail polish on the knot.



A sealed, knotted conductive thread / wire connection

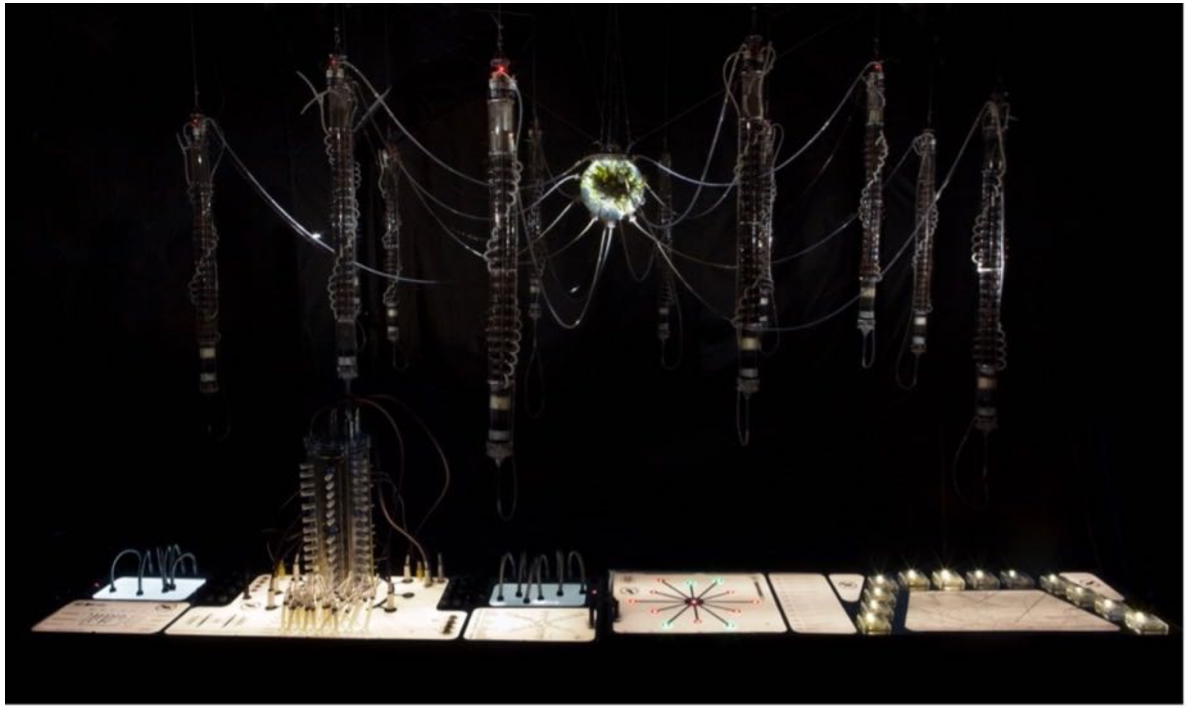
Thread Method: Crimping

- If you have the tools available to crimp connectors, I've found that crimping a Dupont connector to the thread makes the MFC easily connected and disconnected while prototyping.
- The Dupont connectors also make it easier to chain together MFCs which will most likely be needed in most scenarios.
- I have yet to experiment with silver wires that connect between the Dupont connectors of the MFCs but I believe its extra conductivity would help the cells.



Dupont connector crimped onto the stainless-steel thread.

CONNECTING MFCS



ELECTRONICS

- The electronics portion of the workshop is likely the most difficult. How the electronics are formatted depends on the microcontroller used and hence the coding also is dependent on what you choose out of the options I'll be laying out.

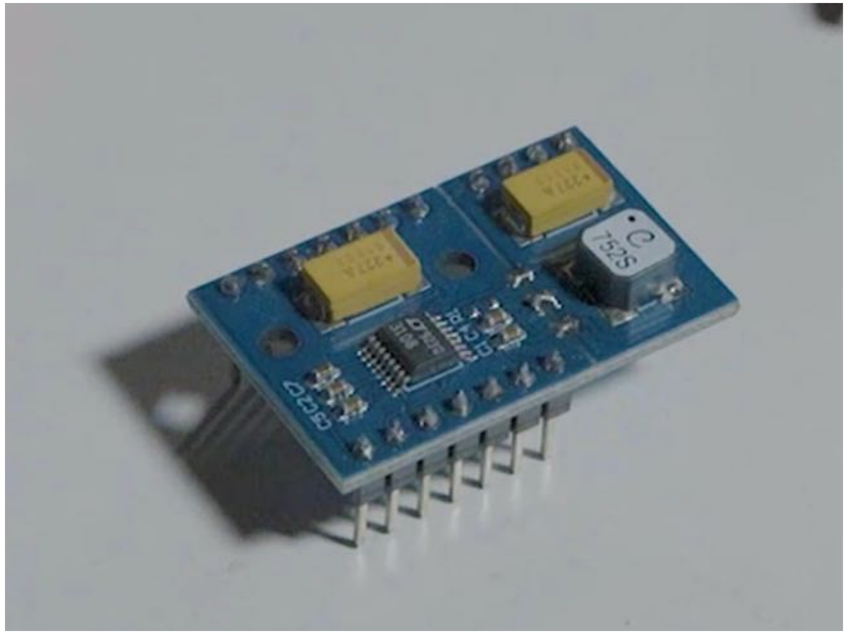
- A few prefabricated boards exist but even they do not come complete. Each board is missing certain components depending on their usage.

- Unfortunately, in all my research I have yet to find a ready-made circuit for MFCs. This is in part due to researchers creating custom boards without revealing their schematics and in part due to the publicly available boards being produced intentionally general, so they apply to more applications.

ENERGY HARVESTING

- The boards we have available fall under the category of *energy harvesting*. This means many of them can be configured for ultra-low voltage energy harvesting from sources like Peltier cells (heat differentials), piezos (kinetic energy and wind), and solar.

- MFCs also qualify as energy harvesters and the boards can be adapted for use with the cells. I've found a myriad of confusing options and arrangements so for this workshop I'll focus on the nearly complete board the *LTC3108-1*.



The LTC3108-1

POWER MANAGEMENT CIRCUITS

- Most energy harvesting devices can power themselves on at energy levels as low as 20mv. Most modern electronics require at least 3300mv at a specific amperage to maintain power. The circuits that convert this energy are called *power management circuits*, or *PMCs*.

- To work with the ultra low energy levels of MFCs – which range from 20mV to 200mV on average - the PMCs have to themselves run on low energy. Until making a circuit sensitive enough to harvest low energy sources was extremely difficult. With the new wave of interest in green technologies we're slowly seeing that change.

- The PMC we're creating is largely the LTC3108-1 but it requires a few modifications.

TRANSFORMERS

- The first modification is required in any configuration, the LTC3108-1 comes without a *transformer*. The transform is going to convert our low voltage for a series of steps inside the LTCs *step-up converter*. Each transformer has a ratio, depending on your input voltage the required ratio changes, which is why its excluded. We need a 1:100 transformer since we have an extremely low voltage.

- The LTC3108-1 at least provides us with recommended transformers, so if you buy an LTC3108-1 make sure to also buy one of these.

Table 5. Recommended Transformers

VENDOR	PART NUMBER
Coilcraft www.coilcraft.com	LPR6235-752SML (1:100 Ratio) LPR6235-253PML (1:20 Ratio) LPR6235-123QML (1:50 Ratio)
Würth www.we-online	74488540070 (1:100 Ratio) 74488540120 (1:50 Ratio) 74488540250 (1:20 Ratio)

One of Coilcraft's relevant transformers

SUPERCAPACITORS

- Once you received the LTC3108-1 and your transformer you'll need to solder the transformer on. A hot air gun works best but a soldering iron will due. An advantage of buying a premade board like this is it eliminates almost all SMD soldering which can be very tedious.

- You'll need to research some supercapacitors that work for your application, almost any will do but you don't want to buy a relatively large capacitance (above 1 Farad) supercapacitor as it will take a long time to charge. It needs to be rated above 3.3V but most will come in 5.5V which is fine.

- The supercapacitors will be the area where your PMC stores its output voltage. It acts like a battery of sorts. Configuring all the parts may sound daunting but there's a guide to putting it all together within the LTC3108-1 datasheet.

An average supercapacitor

LTC3108-1

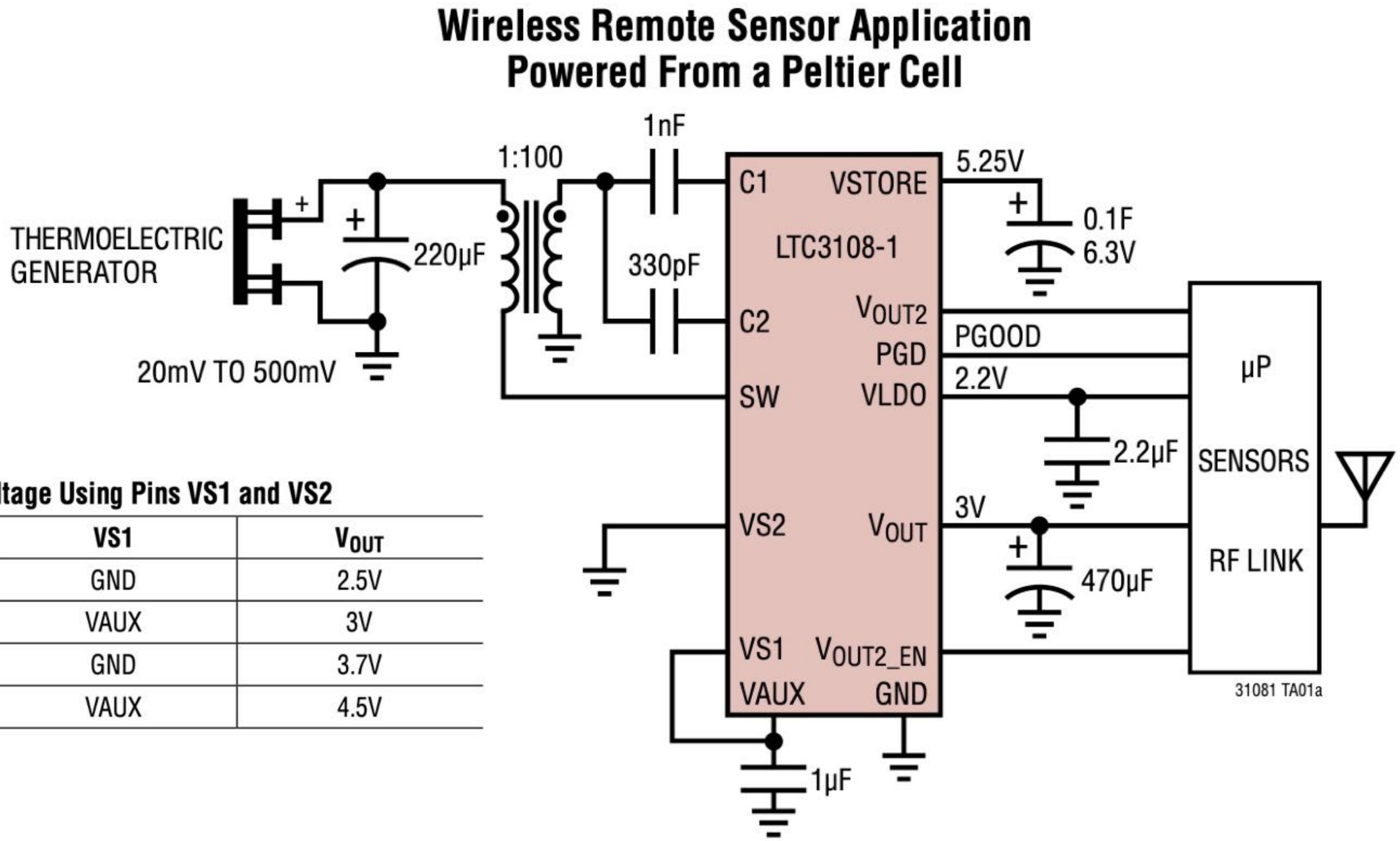


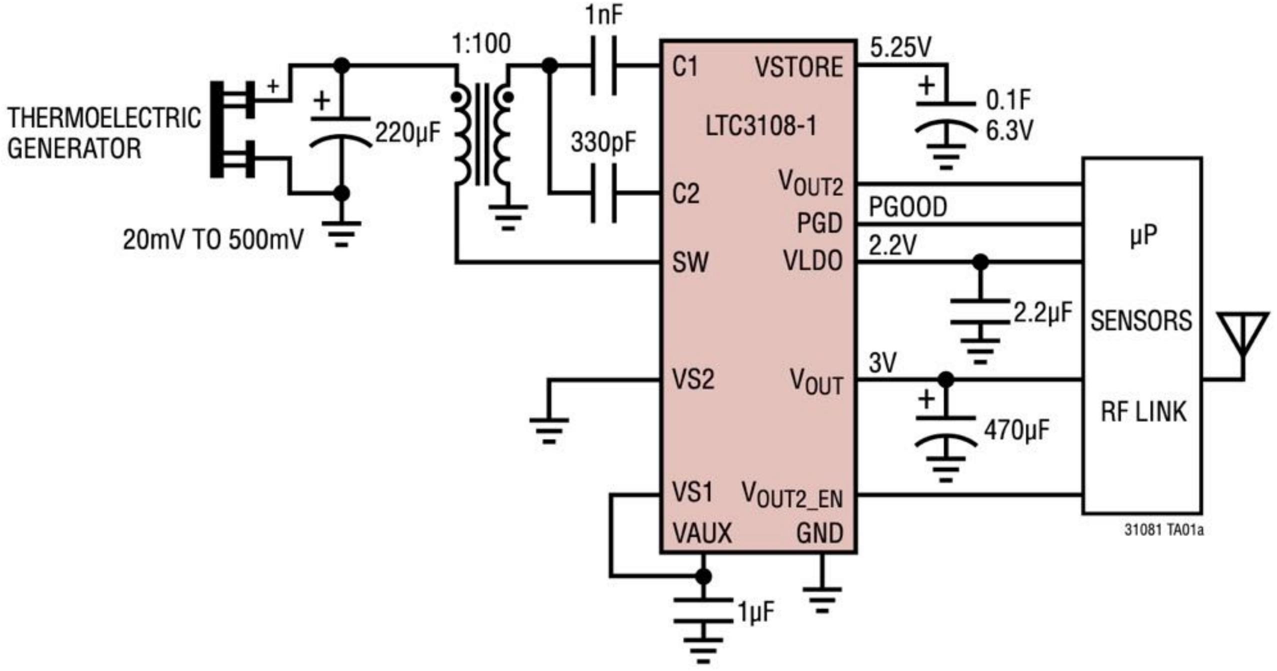
Table 1. Regulated Voltage Using Pins VS1 and VS2

VS2	VS1	V_{OUT}
GND	GND	2.5V
GND	VAUX	3V
VAUX	GND	3.7V
VAUX	VAUX	4.5V

SETUP

- You’ll need to connect the LTCs pins according to the diagram below to get your desired output voltage.
- We need to add the supercapacitor at VOUT, this will be how we power any sensors, radio, or auxiliary loads.
- You can optionally setup a supercapacitor at VSTORE which will start charging when VOUT reaches its maximum capacity.
- The “Thermoelectric Generator” is your MFC, there’s a VIN and GROUND on the board ready for you to plug in.

Wireless Remote Sensor Application Powered From a Peltier Cell



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VS2	VS1	V_{OUT}
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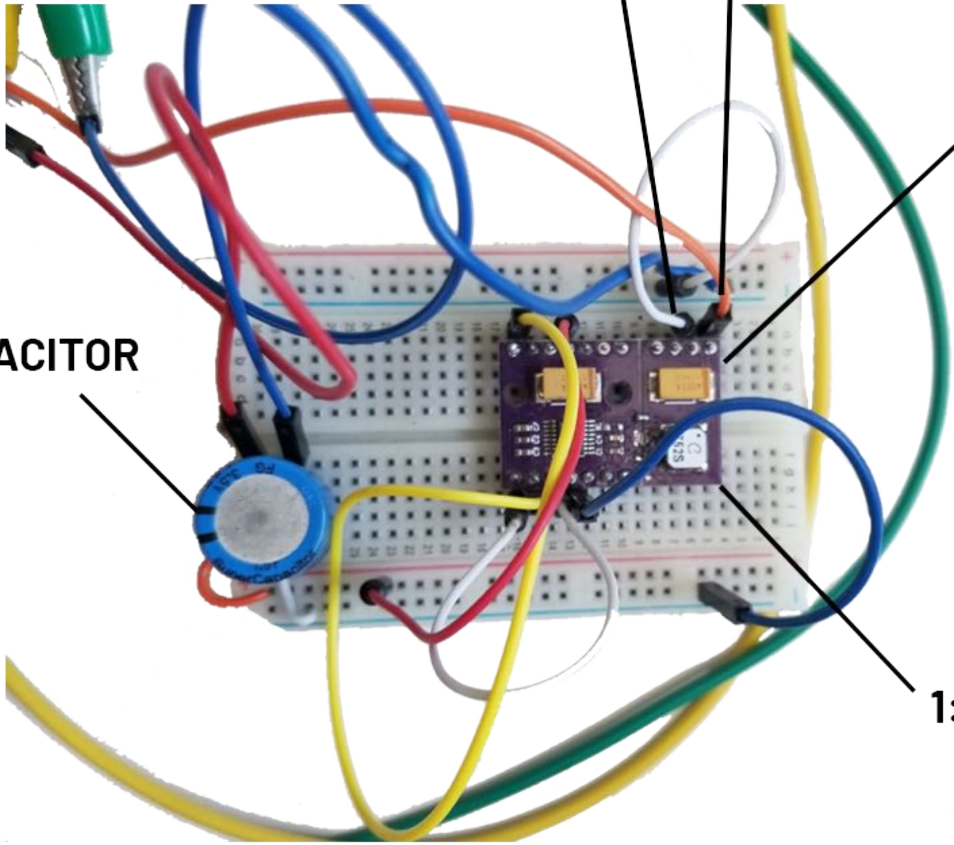
SETUP

- At this point it should look something like this:



MICROCONTROLLERS

- Nearly any microcontroller can be used in an MFC circuit, but we need to be cognizant of their power consumption.
- There are controllers out there that specialize in *sleep* and *hibernation* modes such as the ESP-01, ESP-32, Arduino Nano, and a variety of controllers from STM32 - a favorite in the low-power community is the STM32 "Blue Pill".
- Depending on your programming skills its easiest to go with something familiar instead of the most optimized controller. For most people this may be Arduino.
- The "blue pill" is an STM32duino, meaning it's a low power STM32 controller but can be programmed in Arduino rather than a lower-level language.

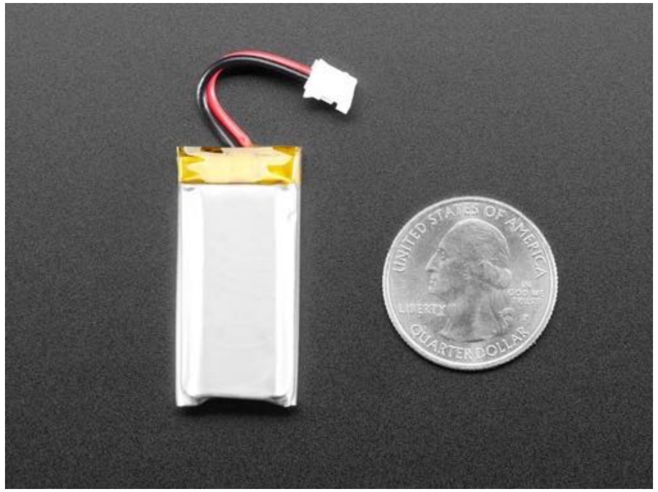
The STM32 "Blue Pill"

BATTERIES

- A portion of the research I was reading focused on creating remote sensor networks with MFCs for environmental monitoring. The aim of these projects and many other MFC projects is to effectively remove batteries from the equation.

- MFCs have the potential to power 'slow' electronics indefinitely using only residual energy from the environment. At our level of creation this is a stretch away. Some researchers use supercapacitors to store a constant energy backup using only the MFC's energy harvesting.

- The simplest method of using MFCs for non-engineers is to use a tiny li-poly or coin battery to keep a microcontroller in hibernation mode instead of aiming to power the microcontroller with the MFC itself. Having a battery backup allows the MFC to have fail safe mechanisms when operating without supervision and allows the controller to harvest slowly by drawing energy only during certain intervals.



3.7V 400mAh li-poly battery, photo by Adafruit

POWERING UP

- Now that we have all the pieces, we just need to connect a few components and we're ready to go. The microcontroller needs to be programmed to hibernate at whatever interval works for your needs. If you're using a common maker controller (Arduino/ESP) you can easily find the code online.

- Now wire PGOOD from the LTC3108-1 to one of your controller pins and code it to wake up and listen for a signal (a voltage increase). PGOOD tells the controller when your supercapacitor from VOUT is ready.

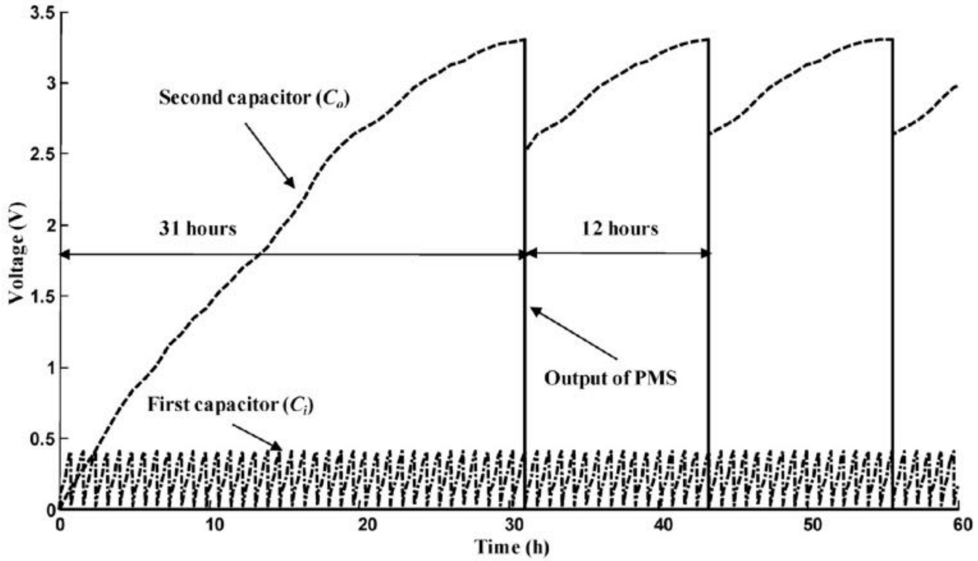
- Next code your microcontroller to send an analog voltage signal over to VOUT2_EN on the LTC3108-1, this will open a gate on the VOUT2 pin and let your supercapacitor discharge. Anything you want your MFC to power should be connected to VOUT2 – commonly people attach low-power sensors, radio transceivers (LoRa), and low-current LEDs.

SLOWNESS

- Biofilms require gestation periods; we must be patient with them before we get usable results.

- If a cell is hooked up to a circuit and too much power is continually drawn, the low number of ions in the soil/medium will vanish from overuse. When this happens the cell no longer becomes viable, so we need to employ a *slow* form of energy use.

- This can be done with timed hibernating microcontrollers. The can either wake at a certain interval and tell the LTC3108 (or other) to pull from the medium



Time required to send a radio signal by an MFC powered PMC. (Yang, et al., 2014)

CHALLENGES

- Some MFCs won't meet the required input voltage on their own, in this case a simple solution is chaining multiple MFCs together. In most cases you won't ever see just single MFC in use outside of the lab.

- If you have access to a multimeter, you can read your voltage and current to test your cells but often they fall on a very low end of the scale, and you will most likely be reading numbers far after the decimal point.

- Having a [common] digital power supply that can output a low 1mA of current is also a good way to test the limitations of your PMC, though its accuracy may vary without a precision power supply.

- Low voltage isn't the only culprit, low amperage will cause similar issues, an ideal amperage is around 1mA or higher. If you're not getting this it could be your electrodes not having enough surface area, they are too far apart, or the cell hasn't had enough time to form a biofilm.

SUSTAINABILITY: EMBODIED ENERGY

- In most of my work I dig into the embodied energy, how much energy is used in the manufacturing of the parts, but since we don't have time today, I'd just like to note that green washing often occurs with sustainable technologies but not all sustainable technologies offset carbon emissions.

- The embodied energy (which is often produced through coal and oil) of electronic PCBs is quite high. Some sustainable technologies produce more carbon than they save in their lifetime.

- Since MFCs are in the early stages I'm uncertain if they're currently reducing carbon emissions (since companies make calculating emissions extremely difficult) but I believe the greatest value MFCs provide is the conceptual slowness they operate under. We cannot expect them to produce vast amounts of power, just a slow patient trickle, encouraging patience and lowering consumption during use.

SUSTAINABILITY: PLASTICS

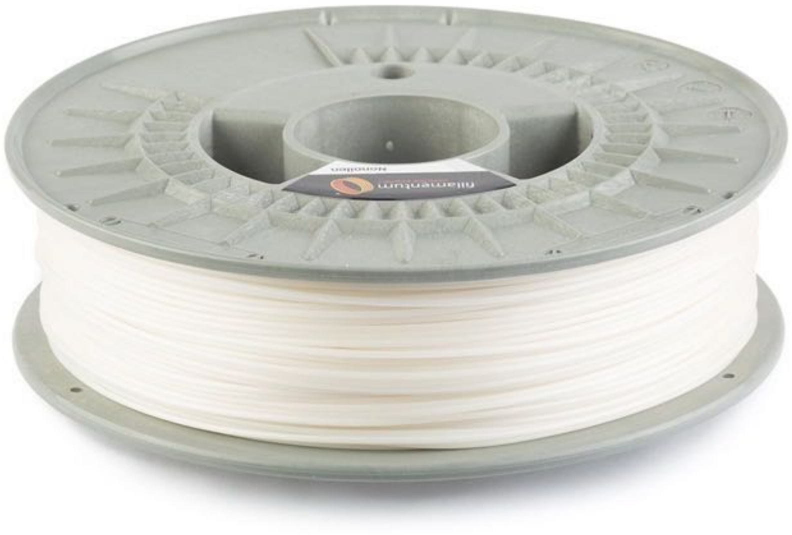
- During my research-creation I was constantly searching for more sustainable options. Generally, I print with PLA.

- All PLA is made from lactic acid within corn and as corn grows it absorbs carbon rendering it nearly carbon neutral when we emit that carbon during production. All PLA is upwards of 70% biodegradable, but many require special composters that require a constant run time of nearly a year.

- Throughout my research I've found more sustainable solutions, of which my favourites are:
  - Non-Olien PLA+
  - PolyTerra PLA+

SUSTAINABILITY: 100% Biodegradable Filament NonOilen®

- 100% made of polymers from renewable resources (bio-based)
- High strength, toughness, hardness (PLA+)
- Long-term durability of printed object
- Food-safe and waterproof (produces a water barrier)
- Polymer may be recycled many times with retention of the features
- 100% biodegradable in industrial compost and electric composters (less energy required)
- Decomposition in compost is about 3x faster than PLA
- No microplastics polluting the environment iare created during their biodegradation
- Decomposes only in a biologically active environment
- The byproducts from the decomposition process don't cause any greenhouse effect



NonOilen® Filament

SUSTAINABILITY: PolyTerra PLA+

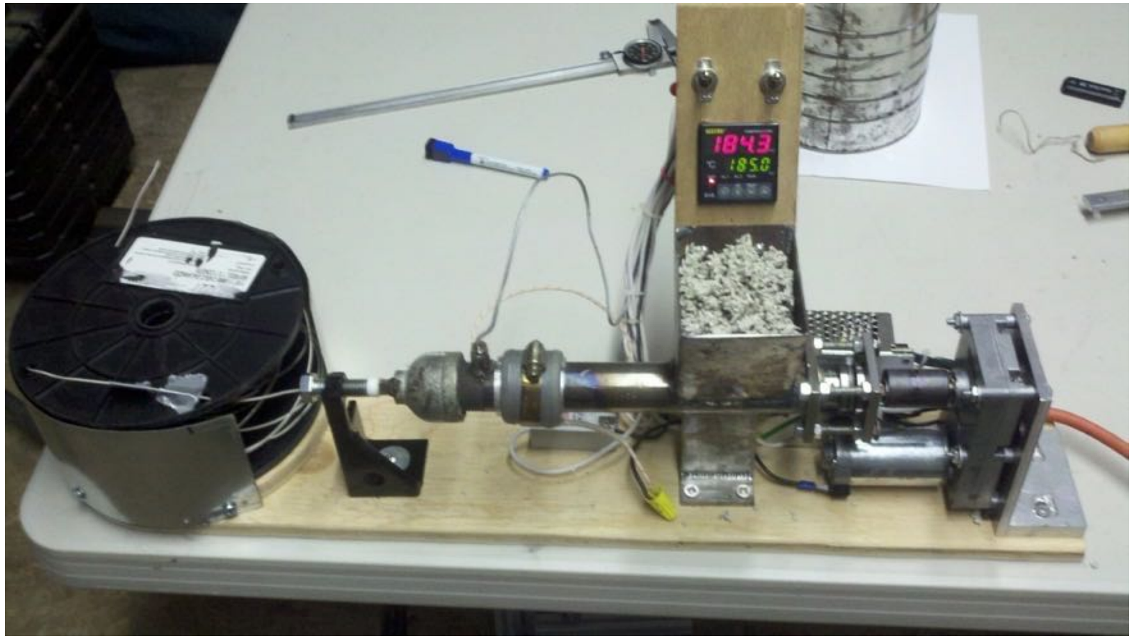
- 100% biodegradable PLA+ (industrial composter)
- One tree planted with ever purchase
- Biodegradable packaging
- Carbon footprint analysis of 4kg but carbon offset of ~22kg a year. (PolyMaker, 2020)
- Carbon offsetting isn't the most ideal solution but its something
- Very affordable (almost half the price of regular PLA)

PolyTerra filament

SUSTAINABILITY

- There's always the option to upcycle containers which reduces waste and saves products form landfills. This method is always encouraged but moving forward I hope we can one day reach a space where or manufacturing follows the principles of a circular economy and instead of planning for waste we plan for circular rotation of materials.

- If you save your 3D printer filament one can also always recycle their filament using either open-source projects like David McGahan's filament recycler or some cities have non-profits have the machinery already built and will recycle your filament for free or at low cost.



Open-Source filament recycler (plans included in resources)

RESOURCES

From this Presentation

- MFC Files & PDF

External Resources

- LTC3108-1 Datasheet
- Logan Labs MFC Guide
- Prusa 3D Printing Guide
- Making your own Graphene
- Open-Source filament recycler

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