# Building improvised microbial fuel cells

## Activities for minds-on engagement and STEM integration

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## INTRODUCTION

Teaching and learning across disciplines is known to be difficult. It is also recognised that such integration is increasingly necessary, particularly in science, technology, engineering, and mathematics (STEM) education for genuine knowledge to advance. A major difficulty, however, arises from the historical entrenchment of discipline-based education and its pervading influence at nearly all levels. Syllabi and curricula are typically tied to discipline-specific content and instructional goals, teachers often lack the appropriate professional development to rise above their own discipline-

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based training, and there is still only a relatively small number of teaching tools and learning resources that specifically support such cross-disciplinary integration.

Microbial fuel cells (MFCs) are a recent class of devices with features that make them especially suited for use in the teaching and learning of science with a strong inquiry-based and transdisciplinary approach [1,2]. MFCs produce modest amounts of electricity biochemically derived from the living processes of microbes and simple kits [3] are available for school experimentation to be constructed fairly easily.

We describe here our efforts in developing an MFC-based set of activities for use at high-school level focussing on a design-based inquiry (DBI) approach that incorporates elements of integrative science, STEM integration, and engineering design. This approach is known by many alternatives such as design-based learning and design-based science learning [4]. We also summarise on-going work that examines the use of these activities to foster “minds-on” engagement (as opposed to mere “hands-on” action) that is a key pitfall in STEM teaching [5].

# 1 MICROBIAL FUEL CELLS IN TEACHING

## 1.1 Teaching with MFCs

The MFC was chosen as the central device for teaching purposes for several reasons: Firstly, the principles of operation of an MFC would encompass various concepts from the three natural sciences, biology, chemistry and physics, and perhaps more importantly, also covers the transdisciplinary interactions between them. These can potentially be covered at a variety of academic and ability levels, from the basic (“living things derive energy from food and some of that energy can be chemically ‘stolen’ and converted to electricity”), to the advanced (“respiratory chain electrons are harvested via redox reactions and electrochemical interactions, thereby producing a potential difference”).

Secondly, the nature of the hands-on laboratory activities described below also feature a broader STEM integration. Technology aspects would be encountered in terms of possible uses and applications of MFCs and in the instrumentation used (e.g., dataloggers). Engineering and design are significant components and will be discussed later. The measurement and processing of the experimental data would also engage various scientific process and mathematical skills.

Thirdly, the MFC readily lends itself to current real-world and topical issues such as the search for alternative energy sources and environmental issues since MFCs can be designed to use sewage as fuel.

Finally, it has been our experience that MFC-based activities have broad appeal and engage everyone from high-school students through to adult-learners [2].

## 1.2 Affordances for Authentic Inquiry

The relative novelty and paucity of research in the mechanisms of function of the MFC affords opportunities for authentic scientific experimentation and opportunities to experience scientific practices [6]. Even straightforward controlled experiments can serve to generate the atmosphere of “discovery” simply because there are few accessible sources of known data for such experiments, nor are the expected results necessarily intuitive. Put another way, student experimentation is unlikely to be coloured by anticipating a “known result”. Students are thus induced to engage in authentic inquiry practices beyond the traditional accumulation of content knowledge, thereby building holistic scientific literacy across the content, epistemic and social domains of what Duschl [7] calls “science education in three-part harmony”.

The nature of the MFC and the approaches taken below also readily affords infusing and integration with other STEM domains, particularly that of engineering and engineering design. Indeed, the bulk of research and development efforts involving the MFC are centred in engineering faculties, typically aimed at the industrial applications of MFCs in environmental and wastewater management. Even simple MFCs have a wide range of design and process parameters that influence their performance and students can readily manipulate these variables towards optimisation, and/or achieving engineering design goals.

## 1.3 Instructional Approaches

There are several distinct but related modes of employing the MFC in laboratory-based activities for teaching purposes. These run the gamut from the commonplace, to the lesser used but desirable approaches to the teaching and learning of science through inquiry-based practical work. This versatility could be said to be one of the key affordances of MFCs as teaching tools, for the same basic setup can be adapted to suit the instructional intent, teacher’s and learners’ ability and comfort level.

### *1.3.1 Cookbook*

One simple and obvious approach is the classic school practical “experiment” to follow a tried-and-tested protocol, then to observe and record the result. This type of use of the MFC is predictably common, and typically the first “experimental” activity undertaken when working with MFCs: Follow the steps to assemble and fill the MFC, then measure and record the voltage produced [3]. This can be easily extended temporally by taking a time-course set of measurements of open-circuit voltage, which will slowly vary over time. Thus, a limited set of process skills could be covered, and/or the use of selected apparatus such as a voltmeter or datalogger.

### *1.3.2 Predict-Observe-Explain (POE)*

The POE model [8] is an easy extension of the above experimental protocol. Having been provided suitable background information or scaffolding, the learner predicts expected value of the parameter(s) of interest, say, the change in open-circuit voltage or pH within the MFC over time. From the observed data, sound explanations to fit and explicate are constructed from prior knowledge or scaffolded for discovery.

The use of two or more MFCs connected to a multi-channel datalogger would allow the learner to carry out a fundamental precept of the scientific method, a comparative or controlled experiment. Examples of such simple comparisons are to compare the effect of: Using different “fuels” to feed the microbes (different types of sugar); Concentration of sugar added; Different resistance loads on voltage/power output over time; or, Temperature on voltage/current output.

### *1.3.3 Discovery and Exploratory Learning*

The MFC can be seen as an authentic apparatus of science, and hence utilised as such for experimentation, where we argue it is also working at its finest from an instructional point of view. For example, suitable forms of the MFC setup could potentially act as biosensors. Should changes in environmental factors influence the living microbes’ biological processes, this might alter the easily measured and tracked voltage produced by the system, thus signalling that change. The pedagogical question for learners could thus be: What chemicals “poison” the MFC? There are various metabolic poisons, such as sodium azide, many antibiotics, and so on, and it might be expected that these should affect the output of the MFC. But in an example where a superficially conceived prediction of the “obvious” effect would be met with a dissonant observation, the use of sodium azide (an inhibitor of cellular respiration) would actually *increase* the power output of the, not “kill” it. There is a reasonable biochemical explanation for this effect: By disrupting the respiratory chain at the final electron acceptor, more electrons are available to be shunted to the external circuit of the MFC. Students with a strong grasp of the biochemistry of living cells *can* potentially deduce this outcome, thereby reinforcing their conceptual understanding. But for learners who have not, this situation serves the role of meaningful learning by discovery and/or exploration.

### *1.3.4 Non-Laboratory-based Activities*

The use of the MFC for teaching is not limited to laboratory-based practical work. In a non-laboratory setting, learners can be asked to apply prior knowledge or engage in literature-review style work by posing questions such as how do MFCs differ from hydrogen fuel cells, and galvanic or voltaic cells, such as household dry-cells, lead-acid car batteries, and so on. More challenging work might entail discussing novel uses for MFCs in real-world settings, or designing hypothetical machines such as those described below.

### *1.3.5 Design-based Inquiry*

The use of DBI with the MFC is a central tenet of this research. In DBI, learners attempt to build a successful prototype during iterative cycles of design and re-design. The goal is firstly that of task/product completion, while learning of content and processes are a by-product of the former [9]. As far we are aware, the MFC has not been used with the DBI approach elsewhere. Sample productive activities include:

1. Design and build an improvised MFC battery to achieve given performance goals, such as lighting up light-emitting diodes (LED) with various current requirements, turning a micro-motor, or if implemented as inter-group competition tasks, compare which has the highest voltage or current, or is able to power an LED or device such as a digital clock for the longest duration. There might typically be some constraints imposed as part of this “MFC Challenge”, such as having only limited quantities of essential components, such as amount of carbon tissue electrode material, or anolyte/catholyte reagents. Such constraints influence design decisions by forcing the learner to make (a hopefully informed and considered) choice between, for example, fewer but larger electrodes (to make fewer fuel cells but with lower internal resistance and hence higher current) or more numerous but smaller electrodes (to make more fuel cells to get higher series voltage at the expense of current). Even if there were few resource constraints, the open-ended nature of such a task requires many such design decisions and compromises to be considered and discussed in group-work settings.

2. Design and draw or mock-up a hypothetical device or apparatus to meet some given scenario or purpose. For example, powering miniature environmental monitoring devices in a remote rainforest, or designing a “gastrobot”, a roving robot that scavenges for organic matter to “feed” on in its internal MFCs.

3. Design and carry out an experiment to prove or disprove some hypothesis, either self-generated or proposed by the teacher. One example question: How do we know the yeast is actually contributing energy/electrons in the MFC, that it is not merely a chemical reaction between the other reagents?

In all the above DBI example tasks, the tasks are very suited to group-based work and are identifiably “real-world” and ill-structured scenarios. There are also good opportunities for learners to present their novel designs and/or findings to their peers. Finally, the easily measurable and quantifiable output of the MFC from the improvised batteries designed and built in the first example makes it easy to inject the competitive edge to the activity: Which MFC battery has the highest power/voltage/current? Which can sustain the running of the clock the longest?

### 1.4 Choice of Instructional Approach

The choice of the above instructional approaches is dependent on several factors. The particular objective(s) for a given lesson is perhaps the key consideration. The MFC can be employed in practical work with relatively little inquiry saturation (e.g., for initial familiarisation with the MFC and its assembly), for which a straightforward cookbook approach might be the most efficient use of lesson time. Should the MFC be used as a platform for conducting experimental investigations (e.g., “scientific method” experiments: manipulate the independent variable and observe/measure the dependent variable), POE and/or discovery approaches can be used. And the use of DBI-based challenge can be used to foreground the inquiry aspect as described earlier.

### 1.5 Collaboration, Challenge, and Competition

We consider *collaboration*, *challenge*, and *competition* as three essential features of DBI-based laboratory activities [10]. The use of the MFC in DBI-based instruction already provides the *challenge* as discussed above, hence, the instructional grouping of students should be done in such a way as to foster these aspects. Students will typically be organised into small groups of perhaps three to five students for all MFC activities and investigations. The degree of heterogeneity among the group, in terms of ability level, learning style, and so on, would be dependent on the teachers’ intended objectives for the lesson and group dynamic. The exclusive use of group-based work taps on social-constructivist principles for intra-group learning, but also enables the organisation of inter-group competition for motivational purposes.

In order to extend this competition-as-motivation aspect of the DBI-based challenge, it is planned that inter-group and inter-school “competition” can be fostered through the use of eventual use of internet-based resources.

### 1.6 Scenarios for MFC-based Intervention

The MFC-based activities can be packaged for curriculum intervention with whole-class groups (Grade 8 or 9 onwards) or as enrichment learning for smaller talent-development groups. The former obviously requires significantly more planning, logistics and management of teacher professional development.

In either mode of intervention, the kit form of the MFC would serve as the platform for a **starter set of activities** based on a blend of the cookbook, POE and exploratory learning approaches. In this initial period, the teacher will serve as instructor and guide. Subsequently, there will be a shift towards a **design-goal oriented challenge** in which they are tasked to brainstorm, design, and build their own improvised MFC battery.

## 2 CURRICULUM GOALS AND CURRENT PROGRESS

### 2.1 DEVELOPING for Minds-on Engagement

The MFC was chosen as the platform for the development of an innovative curriculum for science instruction because of its key affordances for minds-on engagement and for transdisciplinary STEM integration. The unusual and surprising premise of the MFC (electricity from living things) is an immediate attention-grabbing one, quite often assumed to only exist in science-fiction. We have preliminary findings of the strong affective engagement MFC activities have with both school student and adult-learner (science educators) groups [2], and have on-going investigations that suggest the combination of hands-on work, competitive challenge and novel context are key drivers of this engagement. Students also display genuine curiosity and a keenness to pursue investigations that satisfy it. More importantly, we believe the MFC serves to focus students to take a minds-on approach, applying knowledge and adopting established practices, and we are working to unpack the problem-solving strategies (e.g., science reasoning vs. design-focused) and practices (e.g., “scientist” vs. “engineer”) learners use to do these [11].

### 2.2 STEM Integration

Capitalising on the affective and intellectual engagement the MFC affords, the development of the curriculum intervention materials seeks to drive student learning in the sciences by taking an integrative approach within and across multiple STEM domains. The considerations for and potential benefits from this integration are:

1. Enabling learners to grasp the “links” between each science discipline and that each are merely disciplinary perspectives on natural phenomena, for example, the electron which can be described from both chemical and physical ontologies.
2. Fostering the often called for [6] breakdown of disciplinary boundaries, particularly in the preparation of learners for current and future real-world challenges that require transdisciplinary competencies and approaches.
3. Enabling integration and infusion of engineering, technology and design domain experiences into science classrooms without significant demands on curriculum time allocation. Since these domain experiences are embedded within what is essentially a reworking of existing science-based curricula, the need to justify “additional time” is minimised.

The key challenges encountered and identified so far are:

1. The need for teacher professional development and support to overcome real and perceived barriers, primarily due to the unfamiliarity of transdisciplinary and integrative approaches to learning.
2. The lack of assessment and evaluation frameworks and tools that adequately support these forms of instruction.

## 3 SUMMARY AND ACKNOWLEDGMENTS

The MFC is a rare example of a platform for science instruction that incorporates all three natural sciences in its fundamental operation and hence affords an integrated system in which to observe and learn about various science concepts and the connections between them. We describe an approach that further incorporates engineering, technology and design aspects that are appropriate for implementation at high-school through to higher education levels. This integrated approach supports current aims for science education [6] while engaging students affectively, which further promotes efforts to motivate students to consider engineering careers [4].

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