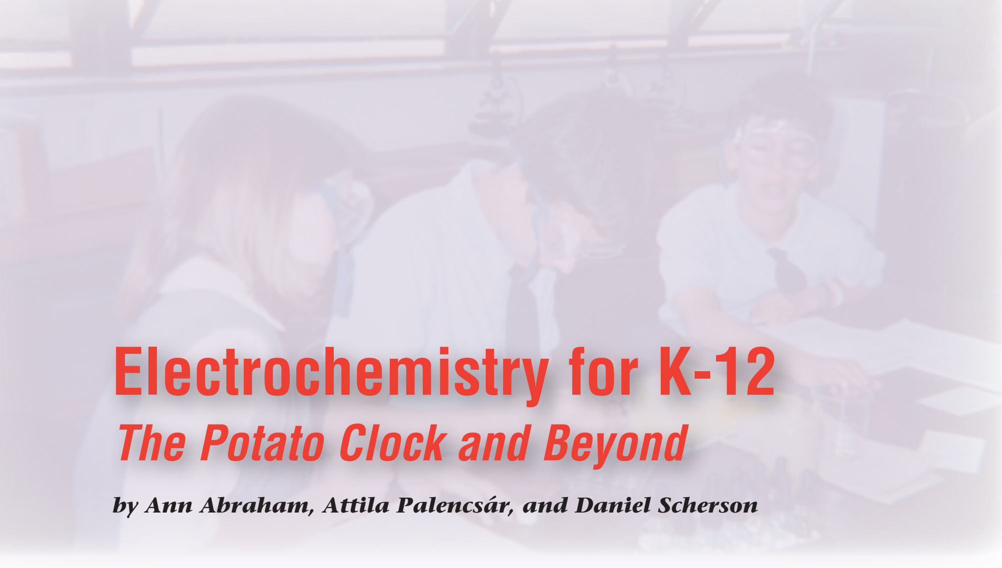

Electrochemistry for K-12

The Potato Clock and Beyond

by Ann Abraham, Attila Palencsár, and Daniel Scherson

Hybrid vehicles, fuel cells, and, particularly, market demands for longer lasting batteries to power portable communication and entertainment devices have propelled electrochemistry to the forefront of news media and advertisement. Despite this welcome awakening, an understanding of the fundamental principles that govern this highly multidisciplinary field by the public at large appears to be lacking. This state of affairs can be traced, at least in part, to our K-12 educational system, which fails, in great measure, to introduce electrochemistry as part of the curriculum. Regrettably, a golden opportunity to capitalize on batteries and rust, terms familiar to children very early in life and precious sources of experiential learning, is irrevocably lost. It thus becomes of pressing interest to explore possible avenues to remedy this situation and bring awareness to the next generation of the importance of electrochemistry as a scientific and technical discipline and its impact on energy and the environment.

The challenges we face as a community toward accomplishing this laudable goal are by no means minor. Glamorous topics, such as space and dinosaurs, have captured the minds not only of children but their parents as well, through the Hollywood industry and its glitz. Nothing of this sort can be said about electrochemistry. Our field continues to hide behind a perceived lack of luster, exacerbated by the unfortunate paucity of eye-catching, adrenaline-powered experiments and classroom material with which to engage such fierce and formidable attention-seeking competitors. Even if these seemingly insurmountable hurdles are overcome, it still remains a delicate pedagogical duty for educators to maximize conceptual simplicity, without compromising scientific accuracy.

This article seeks to prospect the problem and trace a possible road map toward achieving the desired educational aims. We review as a starting point, the recommendations of the *National Science Education Standards* (hereinafter, "the *Standards*") that bear relevance to electrochemistry, and highlight the ways in which electrochemical concepts are gradually introduced through the various stages of schooling. Later, we critically assess the pedagogical value and scientific accuracy of selected books and videos available to K-12 educators and students, and, finally, we share our personal field experiences teaching electrochemistry through experiments to a younger audience.

National Science Education Standards

The website for the *Standards* (www.nap.edu/readingroom/books/nses/html) provides guidelines for achieving scientific literacy through the K-12 educational system. The sections in italics below are excerpts with relevance to electrochemistry extracted from that document.

K-4 grades: … *In most children's minds, electricity begins at a source and goes to a target. This mental model can be seen in students' first attempts to light a bulb using a battery and wire by attaching one wire to a bulb. Repeated activities will help students develop an idea of a circuit late in this grade range and begin to grasp the effect of more than one battery. … Electricity in circuits can produce light, heat, sound, and magnetic effects. Electrical circuits require a complete loop through which an electrical current can pass.*

At this early stage of education, batteries are introduced within the context of electricity, as devices which can power other devices, for example, lighting a bulb. Utility takes priority over principles of operation—emphasis is placed on what batteries can do, NOT on how batteries work.

5-8 grades: *Chemical elements do not break down during normal laboratory reactions involving such treatments as heating, exposure to electric current, or reaction with acids. There are more than 100 known elements that combine in a multitude of ways to produce compounds, which account for the living and nonliving substances that we encounter. … Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced. In most chemical and nuclear reactions, energy is transferred into or out of a system. Heat, light, mechanical motion, or electricity might all be involved in such transfers.*

In this intermediate stage, electricity and chemistry become intertwined. Electricity provides a means of doing chemistry. General aspects of energy conversion are first introduced.

9-12 grades: *When students observe and integrate a wide variety of evidence, such as seeing copper "dissolved" by an acid into a solution and then retrieved as pure copper when it is displaced by zinc, the idea that copper atoms are the same for any copper object begins to make sense. In each of these reactions, the knowledge that the mass of the substance does not change can be interpreted by assuming that the number of particles does not change during their rearrangement in the reaction …. A large number of important reactions involve the transfer of either electrons (oxidation/reduction reactions), or hydrogen ions (acid/base reactions) between reacting ions, molecules, or atoms. In other reactions, chemical bonds are broken by heat or light to form very reactive radicals with electrons ready to form new bonds.*

The last four years of basic education address redox chemistry *per se,* although the term electrochemistry is not being mentioned explicitly. Redox reactions are a kind of chemical reaction. It must be recognized that chemistry at this stage is only a part of their science academic requirements, which also includes physics and biology. It is our view that

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at this stage, electrochemistry should be used to illustrate the commonality of processes, which to the K-12 student would seem utterly disparate, such as respiration and photosynthesis and the operation of fuel cells and Graetzel's dye-sensitized photoelectrochemical cells. Nature is governed by only a surprisingly small set of rules, a concept that permeates college science education.

What Are They Teaching Our Children?

Advantage can be taken within the framework of the *Standards*, to design well-conceived experiments and graphic material, as vehicles to instill electrochemical curiosity among the young. Aware of this potential market, a few commercial enterprises have produced attractive educational videos, books, and kits. A few Sunday afternoon journeys to the local bookstores, coupled with several hours of browsing the Web, unveiled a number of surprising and often puzzling results. Although by no means exhaustive, some of our most interesting findings of the extent to which electrochemistry is presented as a scientific discipline, and the wide spectrum of the quality of the information available are summarized next.

Video Material – A Great Idea!

It was exciting to find a set of commercial educational videos devoted solely to electrochemistry, and be able to examine their content free of charge thanks to the kind willingness of the distributor, www.films.com. This series consists of six, 10 min modules: *Building Blocks of Electrochemistry, Electrochemical Cells, Designing Electrochemical Cells, Commercial Electrochemical Cells, Corrosion,* and *Electroplating*. The choice of topics is highly appropriate, as it capitalizes on everyone's familiarity with batteries (as electrochemical devices) and corrosion (as an electrochemical process) to introduce some of the underlying principles involved. Somewhat charming, at least initially, was the introduction of a robot as the central character, equipped with a battery heart and a metallic body particularly prone to corrosion when exposed to the salty tear drops of the (non-robot) woman of his dreams. Although such an organic–inorganic amorous liaison may well be effective in grasping the short attention span of the youngest viewers, the degree of complexity of the more serious subject matter is definitely targeted toward a much older audience, who may regard the motif as too childish and thus beneath them. It did not remain unnoticed, at the outset, that about 10% of the precious time was just filler, and, also, that segments of the technical material were repeated in many of the modules. A sizable amount of corrosion was included in the electrodeposition module. Nevertheless, and with only a few exceptions, most of the material presented was technically correct. Particularly noteworthy was the emphasis placed on both positive and negative ions as responsible for electrical conduction in the electrolyte solution (for which the concentrations are forgivably expressed in highly unconventional kmol/m^3 units), as well as on corrosion, as being a two-redox reaction process. The introduction to cathodic protection was especially well delivered. Also welcome were analogies to common experiences, such as a pitcher–catcher duet representing oxidation–reduction, with the baseball playing the role of the electron. In stark contrast, attention to detail was lacking, ranging from the anachronic (such as an original Volta pile powering a light bulb) to the outdated (a Leclanche battery as a model energy storage device, or a museum-type voltmeter displaying a needle that flickered mystifyingly when connected to an electrochemical cell). A cursory review by expert consultants would have uncovered far more serious errors, such as referring to the release of electrons by Zn metal as a reduction, the generation of hydrogen atoms in the electrolyte solution, and depicting the role of the separator as the element that prevents contact of the anode with the electrolyte.

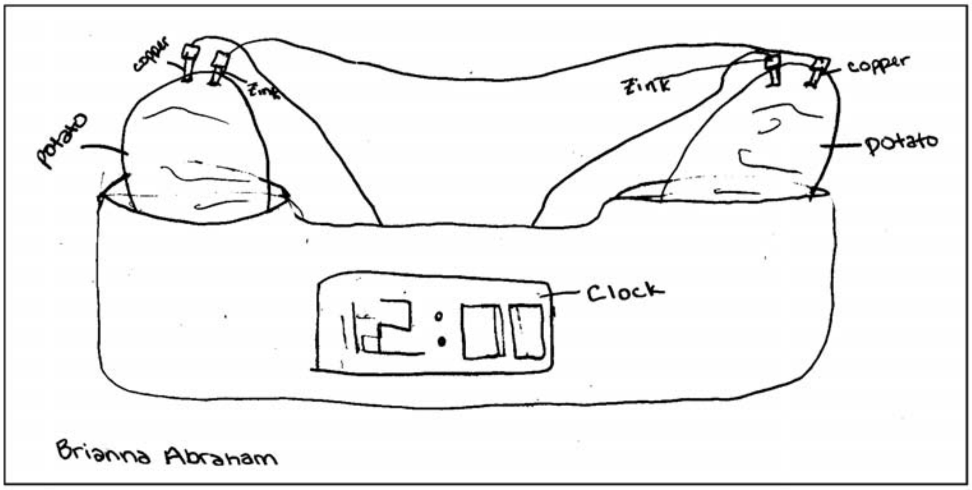

Fig. 1. *Potato clock experiment in progress. Drawing © Brianna Abraham, reproduced with permission.*

Printed Material – Is Anyone Watching?

Our pilgrimage through the limited array of electrochemically-related material available at the local national chain bookstore outlets was eventful. In contrast with the very small selection of science resources for children, and the few paragraphs devoted to electrochemistry within those sources, the conceptual electrochemical errors we found, without looking very hard, were comparatively many and highly disconcerting. A brief, and by no means comprehensive, selection of errors included: "All batteries contain two electrodes and an electrolyte, which produces the chemical reaction with the electrodes resulting in a current;" "In 'dry' batteries, the electrolyte is a paste of powdered chemicals;" and "A car battery produces a strong current by using a number of cells linked together." Furthermore, while explaining the principle of operation of a lemon battery, another publication states, in one case, that "The lemon juice will take electrodes (although probably the authors meant electrons) from the copper and transfer them to the iron creating an electric current"; and in another, involving Cu and Zn electrodes, that "The experiment creates an electric current of almost 1 volt"!

Experiences in the Field

One of the authors (A.A.), a parent of school age children and a PhD in organic chemistry, has had an opportunity to teach "Kid Chemistry" to K-8 graders as a volunteer for the past eight years. Intrigued by the uncertainties of the outcome, she used students as the subject of an experiment aimed at assessing their reaction when exposed to electrochemistry-related materials. Following a thorough search in science and educational supply catalogues, she encountered the Two Potato Clock™, a kit (http://www.starmagic.com/) that incorporates a digital clock that runs on two fresh potatoes (not included) hooked together by three metal wires (included). In addition to the plastic container, the kit included two zinc and two copper electrodes attached to the ends of the wires. Students were asked to follow the instructions provided with the kit and to draw a diagram of the setup (Fig. 1). Surprisingly, the more diligent students invariably failed to make the clock work. Far more successful was the plug-and-play cohort of students, who had not bothered to read the instructions that had erroneously directed them to "insert the copper probe end … into the first potato with the copper probe…," but who simply tried all possible combinations. After all, electrochemistry (as with chemistry in general) is an experimental science! This experience illustrates the two-track approach to education: do and learn and/or learn and do, as underscored by the *Standards*: "'Hands-on' activities, while essential, are not enough. Students must have 'minds-on' experiences as well." The harmonious interplay between theory and experiments is the key to research progress, as we professional scientists already know and practice.

Incidentally, the ball now is in the reader's court to figure out (without looking at the instructions) how to wire the potatoes correctly, and the nature of the electrochemical processes responsible for the battery operation. So, write down the balanced half-cell reactions, and with the help of suitable tables, make some predictions as to the cell potential the device should display. As a hint, other nourishing and non-nourishing products, such as tomatoes, lemons, and cola, also work. We will not divulge at this juncture whether a single, as opposed to the suggested two potatoes in series, may be sufficient to run the clock. Nevertheless, you are invited to report back to us at yces@yces.case.edu.

Beyond the Potato Clock

In yet another experiment (Fig. 2), students were given a variety of relatively inexpensive conductivity indicators available in the educational catalogues, including a ringing bell of variable intensity and pitch, and two different blinking LEDs (red light) of variable intensity and frequency (http://www.sciencekit.com; http://www.lab-aids.com). Students (4-6 graders) received a set of solutions of acids and bases, and a salt, of various concentrations, and well water, orange juice, milk, and a few soft drinks, together with two different types of indicators and a data sheet. Students were encouraged to use their own words to describe the outcome of their experiments, in terms of what they heard or saw. Once the initial thrill of listening to the ringing bell had quelled, students, appropriately classified, with little guidance, the responses obtained with the various solutions, as loud, medium, no sound, extra loud, and soft.

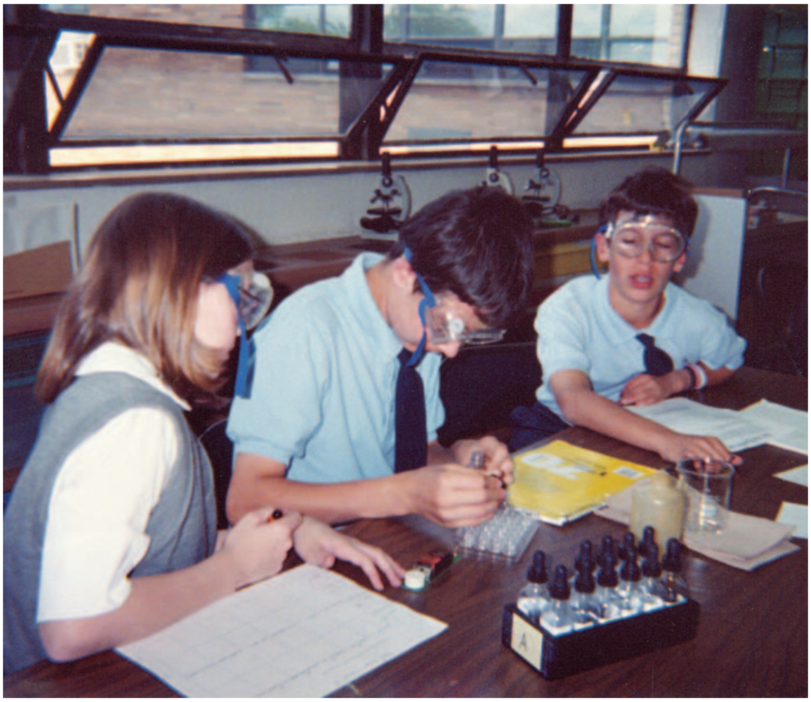

Fig. 2. *Conductivity experiment in progress. Middle scientist is testing solution in well-plate with a blinking LED indicator. Test solutions in dropper bottles and data sheet are also shown.*

Similar, descriptive words were used to explain the results observed with the blinking LED indicators, *e.g.,* consistent blinking, doesn't blink, faint light, bright light, very faint light, very very faint light, and blinking rapidly. One group, in an attempt to make the response of a qualitative indicator more quantitative, tried to record the number of blinks in 10 s. A range of 0 to 13 blinks was recorded for the various samples. Overall, the quantitative indicators (those showing actual numbers) were preferred by the students (an informal poll was conducted at the end of the experiment) because the response needed only a single number on the data sheet. As intended, the different types of indicators allowed students to match qualitative results with quantitative data.

Both the potato clock and the conductivity indicators fall within the *Standards* guidelines. In particular, both the conductivity measurements and the potato battery involve a complete loop through which an electrical current can pass, or circuit. In addition, they show that circuits (when wired properly) can be used to run a clock, elicit sounds, or generate light as in the conductivity experiments (K-4). Furthermore, the potato clock could, although no such experiment was performed, help students grasp the effect of more than one battery. They also illustrate, as suggested for grades 5-8, that electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced.

The Teenage Years

As was mentioned earlier, K-8 should set the stage for introducing in grades 9-12 the principles underlying the, by then familiar, electrochemically oriented experiments through experiential learning. Although not as yet tested by the authors in the field, commercial vendors have been identified who offer a variety of equipment suitable to meet the high school *Standards*. These include electrodeposition kits, which could serve to illustrate that the same metals atoms can be part of a solid or dissolve in a solution in a reversible fashion. Particularly interesting is a small car that incorporates an array of solar cells, which upon illumination generate sufficient power to electrolyze water to produce hydrogen and oxygen gas (http://www.fuelcellstore.com/). In a second stage, these gases are fed to the appropriate electrodes in a fuel cell, which then serves to power an electric motor that sets the car in motion. This ingenious instructional toy provides numerous opportunities to explore issues of energy conversion and storage and perhaps, with a bit more effort, introduce the concept of conversion efficiencies. Pedagogical links to biology can be readily introduced using the cathode of the fuel cell as a breathing component, in that it mimics respiration which involves the enzymatic reduction of oxygen to yield water.

Yet another equally ingenious kit

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(http://www.solideas.com/solrcell/cellkit.html) provides glass plates coated first with a transparent conductive layer (tin oxide), and then a porous titanium dioxide film, which is soaked into either freshly crushed raspberries or blackberries, pomegranate seeds mixed with a tablespoon of water, or red hibiscus tea (not included). A drop or two of a premade iodide/iodine solution (included) is then placed on the stained portion of the film to serve as the (redox active) electrolyte in the solar cell to complete the circuit. The cell is closed by placing a second tin oxide coated glass piece (counter electrode) on the porous film. Once assembled and exposed to full sun through the titanium dioxide side, the cell outputs approximately 0.43 V and 1 mA/cm^2. This device is capable of using light to carry out a redox reaction and, as such, shares common features with photosynthesis, which fundamentally is an electrochemical process.

We close this brief article by supporting wholeheartedly the National Science Education Standards general view that "No one group can implement the *Standards*. The challenge extends to everyone within the education system, including teachers, administrators, science teacher educators, curriculum designers, assessment specialists, local school boards, state departments of education, and the federal government. It also extends to all those outside the system who have an influence on science education, including students, parents, scientists, engineers, businesspeople, taxpayers, legislators, and other public officials. All of these individuals have unique and complementary roles to play in improving the education that we provide to our children."

ECS can greatly contribute to this mission through the collective efforts of its members. The Battery Division has taken a leading role in this regard by making available competitive small educational grants to support these activities financially through the Sections of ECS. Proposals could involve electrochemical summer camps to train K-12 teachers on the importance of electrochemistry, and introduce hands-on, minds-on experiments of the type we described, which the teachers can then implement in their classrooms. The newly formed Student Chapters in some of the ECS Sections could also help promote these activities.

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