A3 Lemon batteries and other batteries – Electricity from chemical energy

The sequence of the subexperiments forms a learning unit that builds upon itself – from the first qualitative investigation of the “electrochemical cell” phenomenon based on simple fruit and vegetable batteries, to the explanation based on the electrochemical series of metals, to the building of powerful accumulators and batteries. This unit can be used both to develop the subject of electrochemistry and to put knowledge learned about redox chemistry into practice. Of course, the subexperiments can also be conducted individually. Teachers may freely choose the degree of emphasis for each topic. The materials and apparatus supplied allow eight groups of students to conduct the experiments simultaneously.

1 Main question

Batteries play a major role in students’ and adults’ everyday lives in our high-technology world. Without them, cell phones, MP3 players, and flashlights would not work. An understanding of the source of this chemically generated electrical energy is to be developed in the simplest case of combining two metals or their half cells.
The starting point is the popular, but often misunderstood experiment with the lemon battery; this battery will be systematically “demystified” in this unit so that the students will have developed a basic understanding of chemical batteries after conducting all the experiments.
They will learn to tell the difference between noble and base metals, come to understand the importance of electrolytes, and recognize what an electric circuit for combined half cells looks like.
In the spirit of the scientific method, by systematically varying an experiment the students will have the opportunity to make the underlying principles more tangible and gain a deeper understanding of where chemically generated electrical energy comes from.

2 Integrating the experiment into the teaching context

2.1 Basic principles

The electrochemical voltage series of metals is an essential element of scientific understanding of phenomena, which play a significant role in everyday life. At the same time, taking advantage of the electrochemical differences between metals in batteries is its most important technical application.
These experiments at the level of the phenomena prepare the students for deepening their understanding in terms of redox processes, in which electrons are released and absorbed and in which, if the processes run freely, energy is released and can be used.
The students should have prior knowledge from the electricity lessons. In particular, they should be familiar with the rules of parallel and series connections.

2.2 Relevance to the curriculum

Redox processes like those occurring in batteries fundamentally belong to the curriculum oriented to basic science education. Depending on the country, these processes are included in the curricula for 13- to 16-year-old students, and then repeated in more depth for age groups above 16. Since 10- and 12-year-olds are already growing curious about how their electronic devices work, the suggested experiments are designed so that they can be used for even younger students.

Conversely, modules for expansion and further study of the topic at the level of particles and electron transfers can be added easily at any point.
Although batteries have traditionally been considered a topic in chemistry, modern accumulators are at least equally a part of physics. Therefore, the topic has the potential to be used on an interdisciplinary basis.

Topics and terms: accumulator, acids, alkali, bases, battery, current, driving force of chemical reactions, electrochemical voltage series of metals, electrolyte, energy balance in chemical reactions, galvanic deposition of metals, half cell in electrochemistry, hydrogen, redox reactions, salt solutions, separator, series connection, voltage

2.3 Skills

The students will …

- learn to understand an important driving force (electric potential, electromotive force EMF) of chemical reactions.
- recognize the degree of nobility of metals as a measure of their reactivity and potential to serve as energy suppliers.
- become familiar with two of the four basic concepts of chemistry, the “chemical reaction” and the “energy balance in chemical reactions”.
- learn to investigate a phenomenon using the scientific method, specifically by systematically adjusting the variables of the experiments. In terms of education standards, this will make an important contribution toward development and consolidation of the “knowledge acquisition” skill area.

2.4 Explaining the experiment in the teaching context

A total of six subexperiments are suggested in this unit. However, some of them can also be combined. Viewed collectively, they should lead from amazement at a phenomenon to understanding at an initial level of reasoning and the causal link.

2.4.1 Subexperiment 1: How well does the “fruit and vegetable battery” work?

A “lemon battery” will be recreated with copper (Cu) and zinc (Zn) as in the original and tested with respect to its capacity. The regularly used terms and circuits will be introduced.
Note: If the LED connected to the fruit/vegetable battery does not light up, an error has not occurred. Our battery delivers no more than 1.1 V in an ideal case. However, the LED used for verification does not light up until the voltage reaches a minimum of approx. 1.7 V. The students will find out that the LED lights up when they use the fruit/vegetable batteries connected in series. Depending on the fruit/vegetable used and the oxidation state of the electrodes, the power generated by our fruit/vegetable battery may be too low to operate an electric motor. If at all, this will work only with the small solar motor with the bell-type armature. (By the way, this is a good opportunity for the teacher and students to discuss the problem of sufficient power from electric power sources.) The power of the fruit/vegetable battery is too low primarily because the surface area of our nail electrodes is too small and thus the internal resistance is too high and the current is too low. When the solar motor is connected, our battery’s voltage breaks down. However, the reason for the low power is not only the small electrode surface, but most of all the lack of copper ions at the copper electrode (see subexperiments 2.4.4 and 2.4.6!).

2.4.2 Subexperiment 2: The “lemon battery”: What role does each element play?

In a first step of varying the experimental conditions, the metals and the conductive medium (fruit or vegetable) will be systematically replaced. It should become clear to students as their first conclusions that the two combined metals must always be different, that the current by no means comes “from the lemon”, and that the conductive medium is replaceable.
A current is generated only when two different metals are used. The salt solution (ion solution) in the fruit or vegetable serves as the electrolyte, establishing the necessary link between the metal nails (electrodes): The circuit is thus closed.

2.4.3 Subexperiment 3: The “lemon battery” without the lemon

The “lemon battery” without the lemon varies the electrolytes. The experiment with the citric acid will still suggest that the current depends on the particular fruit or even on the acid. The successful use of table salt will make it clear that the medium must be an aqueous solution in which ions are dissolved. This will make the essential function of the electrolyte clear, specifically, closing the circuit through (ionic) conduction.

2.4.4 Subexperiment 4: Boosting battery performance

An important note in advance: If copper sulfate is not available to you, you must unfortunately skip this subexperiment. Based on the discussion from subexperiment 6, though, you can explain technically and didactically the statement from this subexperiment that the concentration of dissolved Cu^{2+} ions is crucial to the performance of the Cu/Zn element.

The copper-zinc battery with a fruit or vegetable and also acid or salt water is in reality a hydrogen-zinc cell. That’s because in a copper half cell, the copper electrode would have to be immersed in a Cu^{2+} solution. In reality, however, only traces of copper are dissolved on the copper side, so that after the copper electrode has been connected to a load for a short time, copper is no longer deposited, but instead hydrogen ions (from H^+ in the electrolyte). This can be explained to the students based on a “battery whose performance can be boosted”. In our experiment, replacing the table salt with copper sulfate converts the copper electrode from a hydrogen electrode to a genuine copper half cell.
Subexperiment 4 can also be used to define the first reference points of the electrochemical voltage series of metals based on the experimental values measured. However, it should not be expected that the results will match up very well with scientific data sets. Standardization to the standard hydrogen electrode must also take place elsewhere. If it is pointed out to the students that the values in the electrochemical voltage series of metals are standardized to normal concentrations, that is, the voltage depends on the concentration, there is no longer any discrepancy with their measured values. After all, everyone knows that the longer an ordinary battery is used, the lower its voltage.

2.4.5 Subexperiment 5: Spontaneous copper plating?

An important note in advance: If copper sulfate is not available to you, you must unfortunately skip this subexperiment. This subexperiment clarifies why batteries and accumulators always need separators. Without a separator, an internal short circuit will occur, which in our case will result in copper being deposited on the zinc electrode. You will therefore have to explain this to the students without doing the experiment. The second part of the subexperiment, the principle of galvanization, is not necessary for understanding how electrochemical elements work.

The surfaces of all metals that are immersed in the salt solution of a noble metal become coated with the noble metal deposited from the solution. Because the deposited copper is distributed very finely in the experiments, the deposition is reddish only initially, and then oxidizes to dark copper oxides when it comes in contact with oxygen in the air. At a room temperature of approx. 21°C, the visible deposition of the copper on the coin starts after approx. 20 to 30 minutes, and the coin is completely coated overnight at the latest. The process is considerably faster if the system is heated up. The aluminum foil is visibly corroded.
This experiment is used to separately show the effect that the salt of a more noble metal will deposit spontaneously on the base metal. Rust protection for galvanized iron is similar to currentless copper plating, but will not be carried out here. The cleaning of tarnished silver using aluminum foil in a solution of table salt is also based on the phenomenon of a local element. The citric acid in this experiment helps ensure that the copper deposition is uniform; citric acid forms a complex with copper ions in aqueous solution. With regard to driving force and energy balance, the experiment shows: During copper plating, the electrons are transferred directly between the metal atoms or metal ions, so to speak, as an internal electrical short circuit, and the energy is released as heat. In the electrochemical cell, the electrons are transferred via an external operating circuit, and electrical energy is released.

What role is played by the material of the used coins? The coins' material, such as nickel and brass, does not play an electrochemical role in our experiment. The chemical reaction takes place exclusively between the base aluminum (–1.66 V) and the noble copper (+0.35 V). The base aluminum dissolves, and the noble copper ions deposit on the coin. Thus, in our experiment the coin plays the role of an inert electrode. If a graphite rod, for example, were used in place of a coin, it would also become covered with copper.

2.4.6 Subexperiment 6: A professional zinc-copper battery

An important note in advance: If your students were unable to conduct subexperiment 4, you should use subexperiment 6 to clarify the aspects covered in subexperiment 4.

Subexperiment 5 showed that the copper and zinc electrodes in principle should not be immersed together in the copper sulfate solution like in subexperiment 4. That's because in addition to the copper being deposited on the copper electrode, it is also deposited on the zinc electrode as an internal short circuit. The voltage and current drop rapidly when a load is attached. To prevent this, the students must separate the electrolyte spaces of the two electrodes (with a semipermeable membrane), as in all ordinary batteries and accumulators. This prevents mixing and thus an internal short circuit. As a final achievement, the students can build a sort of Daniell cell themselves. Even if we use just a paper towel as a separator, the principle is clear. (Today's technology usually uses a plastic sheet with a predefined pore size such that the ions [e.g., chloride or sulfate] required for the internal electric circuit pass through the separator and the metal ions do not.) Finally, the results worked out should be applied to the lemon battery from subexperiment 2. Students should recognize that the cell membranes of the lemon's plant cells play the role of the separator. Depending on the students' previous knowledge or their age group, they should conclude the experiment by writing the word and/or formula equations for the reactions taking place in the electrochemical cells.

2.5 Experimental variations

- All experiments can be conducted individually and in small groups. Group work is even advantageous for the metal variations and for long-term experiments.
- This also applies when conclusions are to be drawn from the results. In these situations, the 1-2-4 method has proven effective: First, each student draws his or her own conclusion. Then the students discuss their conclusions with one classmate, then a group of four must agree on an explanation and either write it down on paper or present it orally to the whole class (1-2-4-everyone).
- Widely varying measured values will be observed in all experiments. This is due to the numerous possible variations, such as the fruits' differing water or acid content, the quality of the metal surfaces, contacts between metal and clamps, etc. This situation can be remedied partially by sanding the metal surfaces to rough them up. Experiments with metallic aluminum are always problematic: Often, aluminum is anodized, and then the surfaces are nearly chemically inert. Even untreated aluminum is coated with an oxide layer that severely hinders electrochemical processes. If necessary, the aluminum must be roughened vigorously. In subexperiment 5 on copper plating, if the students add some citric acid as suggested, the invisibly thin oxide layer of the aluminum foil will be dissolved and the aluminum will become active, meaning it can react electrochemically.
- Depending on the learning group involved, the processes at the particle level can be studied more thoroughly. A basis for further study is an understanding of the notion of ions, including the knowledge that ions differ from their corresponding atoms in all properties and that they carry a charge.

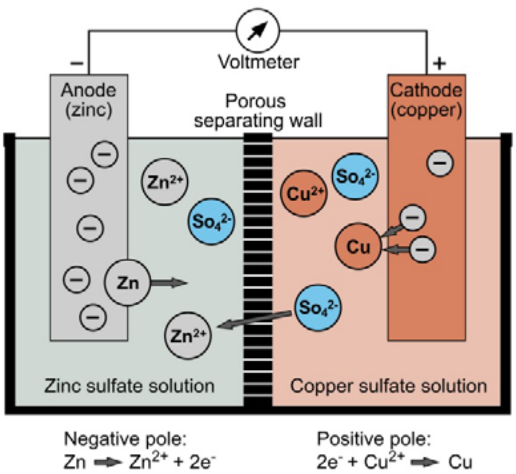

Fig. 1: Electrochemical cell using the example of zinc and copper (Daniell cell).

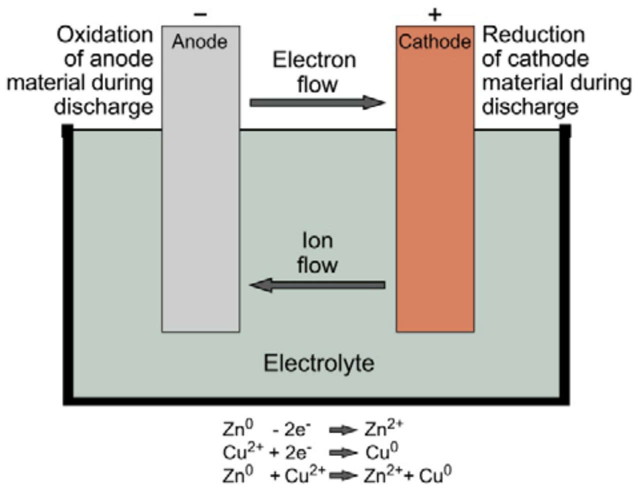

Fig. 2: General diagram of the electrochemical cell as a redox system.

- To highlight the meaning of simple batteries, students can also attach other loads (e.g., clock). If higher voltage is needed, several Daniell cells can be combined. Connecting the elements in series increases the voltage each time by approx. + 1 V. (**Attention:** Do not exceed 10 volts!)
- Another interesting variation is the voltaic pile, in which several metal plates are stacked vertically. Instructions are found in the next chapter.

3 Additional information on the experiment

You will find supplemental media for preparing or for further study of this experiment on the Siemens Stiftung Media Portal:
https://medienportal.siemens-stiftung.org

4 Notes on conducting the subexperiments

4.1 Facilities

No special facilities are necessary.

4.2 Time required

	Preparation and carrying out	Analysis
Subexperiment 1	10 – 15 min.	15 min.
Subexperiment 2	15 – 20 min.	20 min.
Subexperiment 3	15 – 20 min.	10 min.
Subexperiment 4	Up to 1 hour (depending on how much attention is paid to details)	20 min.
Subexperiment 5	5 – 10 min.	15 min. Analysis possibly on following day, approx. 10 min.
Subexperiment 6	20 min. with writing of formulas 30 – 40 min.	15 min.

4.3 Safety aspects

The students may conduct the experiments only in the presence and under the supervision of the teacher. The teacher is to point out to the students that the provided materials may be used only according to the respective instructions.
For these experiments, pay attention to the following potential dangers and make your students aware of them:

- Make sure that no damage can occur to water-sensitive materials and apparatus.
- Care must be taken to ensure that the accumulator is not short-circuited. There is a risk of explosion and fire!
- When copper sulfate is being handled (subexperiment 4), make sure that it does not come into contact with skin, that none of it is swallowed, and that after the experiments are completed, all solutions containing copper sulfate are collected and disposed of. Copper sulfate is classified as harmful to health and the environment. However, it is harmful to health only if larger amounts are swallowed or if it is in contact with skin for extended periods of time.

According to the international hazardous substance labeling (GHS): “Danger”

Hazard Statements: H301, H315, H319, H410
Precautionary Statements: P273, P305, P351, P338, P352

- Citrid acid (subexperiment 5) can be irritant. However, it is harmless in small quantities (part of many foods, citric acid cycle in the human body). In case of contact with eyes, rinse immediately with plenty of water and seek medical advice. In experiments with citric acid, therefore, the students must wear safety goggles.

4.4 Apparatus and materials

Required materials that are not supplied:

- Fruit (lemon, orange, kiwi, apple)
- Vegetables (cucumber, potato, zucchini); as juicy as possible
- Water
- Copper sulfate
- Waste container for copper sulfate solution
- Paper tissues, paper towels, or toilet paper
- Brass or nickel coin

The copper sulfate required for subexperiments 4 and 5 unfortunately cannot be supplied in the kit. However, it is available from laboratory suppliers for schools. In addition, it is available worldwide from swimming pool and aquarium supply stores.

Supplied:
The apparatus and materials supplied are sufficient to allow **eight** groups of students to conduct the experiments simultaneously. The exception is the solar motor, which is available to only two groups of students at a time.
Depending on the students' level of knowledge, teachers should explain proper wiring and the proper use of multimeters, LEDs, and motors in advance, demonstrating if necessary.
The following materials included in the kit are needed for **one** group of students:

Material	Quantity
Accumulator, 9 V	1x
Aluminum foil, roll	1x
Bowl, plastic	1x
Citric acid, can	1x for entire class
Connecting cable, alligator clip to alligator clip	6x
Copper nail (as electrode)	2x
Digital multimeter	1x
Dual propeller for small solar motor	1x (must be shared with three other groups)
LED red (clear case), 1.7 V	1x
Measuring cable assembly, banana plug to alligator clip, one red and one black for each	1x
Nail (steel, “iron”)	1x
Plant clip (as motor holder)	1x
Plastic cup (clear), 500 ml	3x
Plastic cup, 100 ml	3x
Rubber band, package	2x
Safety goggles	1x*
Solar motor, small, bell-type armature, 0.1 V/2 mA	1x (must be shared with three other groups)
Table salt, box	1x
Teaspoon	1x
Zink nail (as electrode)	2x

*A total of 16 pairs of safety goggles are supplied for all students in all groups. If more than 16 students participate in the experiments, additional pairs may need to be provided by the school.

Fig. 3: Apparatus and materials supplied for one group of students

4.5 Cleanup, disposal, and recycling

All apparatus and nearly all materials from the kit can be reused. Therefore, after the students have completed the respective experiment, they should put the apparatus and materials back in the appropriate boxes and return them to the kit. This practice will ensure that you and your colleagues will find everything again quickly the next time the kit is used.
Apparatus that become dirty during the experiment, such as cups, bowls, spoons, and test tubes, should be cleaned before being returned to the kit. We recommend that you have the students do this immediately after they have completed the experiment.
Also make sure that the apparatus are in working order for the next time. For example, recharge used accumulators immediately (It makes sense to charge the accumulators even if they will not be used for an extended period.).
Materials that cannot be reused, such as used pH test strips and filter paper, should be disposed of properly.
The waste that accumulates during this experiment can be disposed of in the regular trash or poured down the sink.
Exception: The copper sulfate solution must be disposed of as inorganic chemical waste.