Measuring Charging Currents:
RC Circuits, Electrochemical Capacitors and Electrochromism.

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When a battery is connected to a circuit consisting of wires and other circuit elements like resistors and capacitors, voltages can develop across those elements and currents can flow through them. In this lab we will investigate the currents that can be measured from electrochemical cells. As a starting point, we consider circuits with a battery, a resistor and a capacitor -- an RC circuit.

RC circuits

Imagine you wish to measure the voltage drop across and current through a resistor in a circuit. Recall that there is a linear relationship between current through and potential difference across resistors (Ohm's law: $V = IR$). To do make this measurement, you would use a voltmeter and an ammeter – similar devices that measure the amount of current flowing in one lead, through the device, and out the other lead. But they have an important difference. An ammeter has a very low resistance, so when placed in series with the resistor, the current measured is not significantly affected (Fig. 1a). A voltmeter, on the other hand, has a very high resistance, so when placed in parallel with the resistor (thus seeing the same voltage drop) it will draw only a very small amount of current (which it can convert to voltage using Ohm's Law $V_R = V_{meter} = I_{meter}R_{meter}$), and again will not appreciably change the circuit (Fig. 1b).

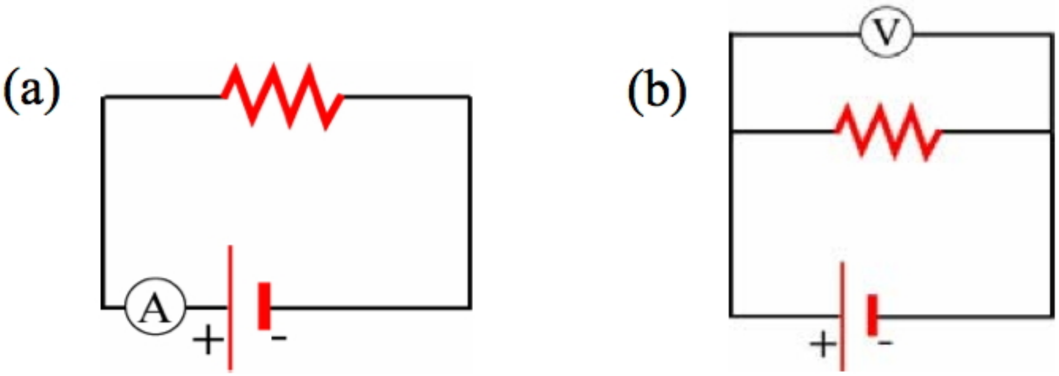

Figure 1: Measuring current and voltage in a simple circuit. To measure current through the resistor (a) the ammeter is placed in series with it. To measure the voltage drop across the resistor (b) the voltmeter is placed in parallel with it.

Capacitors store charge, and develop a voltage drop V across them proportional to the amount of charge Q that they have stored: $V = Q/C$. The constant of proportionality C is the capacitance (measured in Farads = Coulombs/Volt), and determines how easily the capacitor can store charge. Typical circuit capacitors range from picofarads (1 pF = 10^{-12} F) to millifarads (1 mF = 10^{-3} F). In this lab we will use microfarad capacitors (1 μF = 10^{-6} F).

Consider the circuit shown in Figure 2. The capacitor (initially uncharged) is connected to a constant voltage source (e.g., a battery). At t = 0, the switch S is closed.

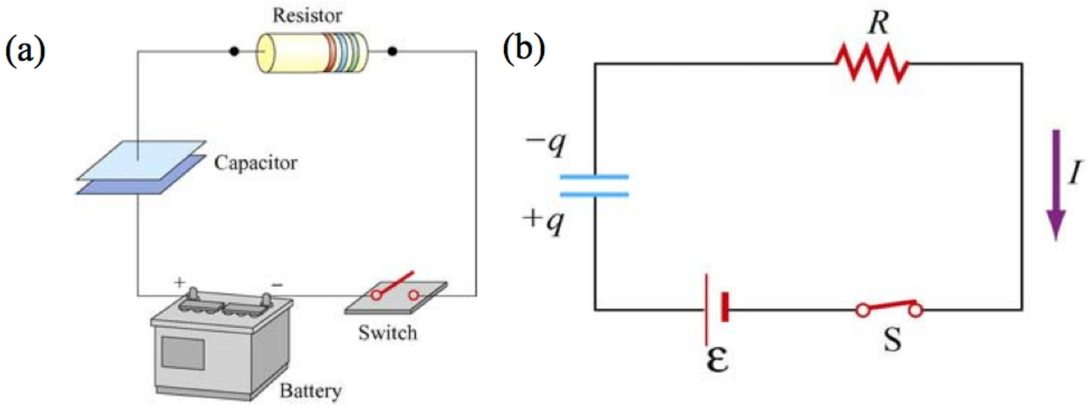

Figure 2. (a) RC circuit and (b) Circuit diagram for t > 0

Initially the capacitor is uncharged and hence has no voltage drop across it (it acts like a wire or "short circuit"). This means that the full voltage rise of the battery is dropped across the resistor, and hence current must be flowing in the circuit (V_R = IR). As time goes on, this current will "charge up" the capacitor – the charge on it and the voltage drop across it will increase, and hence the voltage drop across the resistor and the current in the circuit will decrease. This idea is captured in the graphs of Fig. 3.

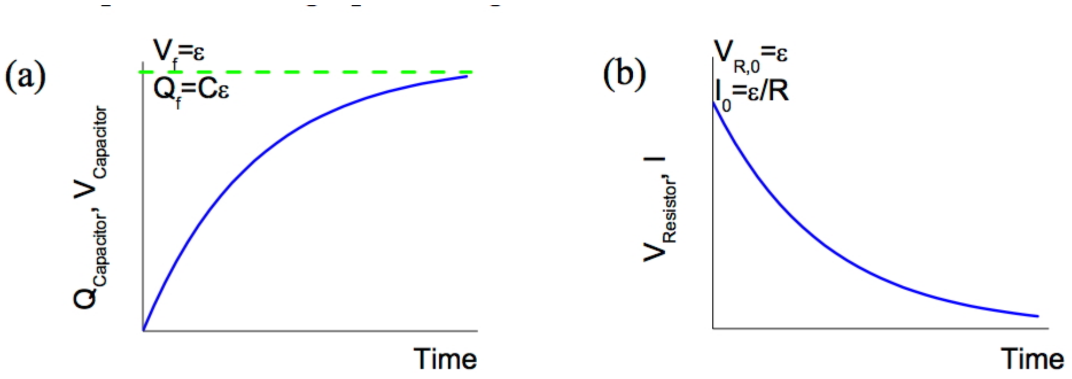

Figure 3 (a) Voltage across and charge on the capacitor increase as a function of time while (b) the voltage across the resistor and hence current in the circuit decrease.

After the capacitor is “fully charged,” with its voltage essentially equal to the voltage of the battery, the capacitor acts like a break in the wire or “open circuit,” and the current is essentially zero. Now we “shut off” the battery (replace it with a wire). The capacitor will then release its charge, driving current through the circuit. In this case, the voltage across the capacitor is equal to the voltage across the resistor, and hence the charge, voltage and current all decrease with time. This decay is exponential in nature, characterized by a time constant t, as pictured in Fig. 4.

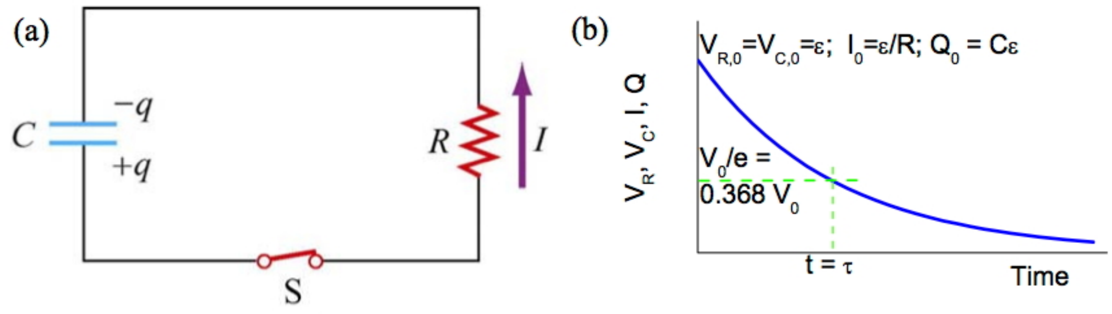

Figure 4. Once the battery is “turned off,” the voltages across the capacitor and resistor, and hence the charge on the capacitor and current in the circuit all decay exponentially. (a) Circuit (b) Voltage time course. The time constant τ is how long it takes for the initial voltage to drop by 1/e.

In electrochemical measurements, solutions can be thought of as resistors, and electrodes as capacitors. The amount of capacitance is proportional to the area of the electrode. Electrochemists have designed special electrodes with very high surface area for energy storage called ultracapacitors.

In electrochromic thin films, electrons are stored when charged:

$$\mathrm{WO_3} + x\mathrm{M^+} + x\mathrm{e^-} \leftrightarrow \mathrm{M}_x\mathrm{WO_3}$$

with $\mathrm{M^+} = \mathrm{H^+}$, $\mathrm{Li^+}$, $\mathrm{Na^+}$, or $\mathrm{K^+}$, and $\mathrm{e^-}$ denoting electrons.

(In our case, M+ = H+).

Here is the structure of an electrochromic thin film:

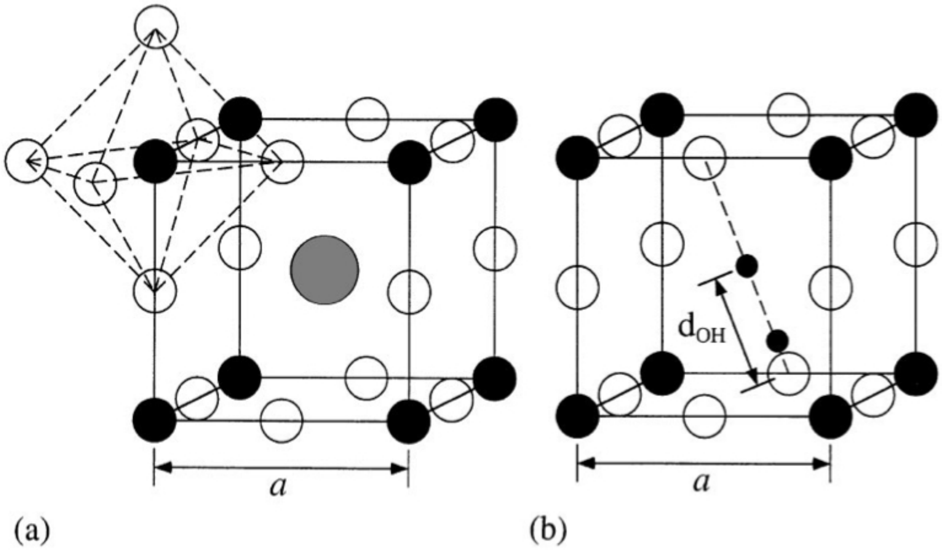

Fig. 1. Unit cells for cubic (Li,Na)WO_3 (part a) and HWO_3 (part b) with tungsten atoms as large solid circles, oxygen atoms as open circles, lithium or sodium atoms as large dashed circle, and hydrogen atoms as small solid circles located on a line between an oxygen site and the central position. The distance between the hydrogen and oxygen sites is denoted d_{OH}. The ReO_3 structure, used as an approximation for monoclinic WO_3, is obtained by considering only the tungsten and oxygen atoms. The lattice constant a is defined, and the octahedron, built up by oxygen atoms surrounding the tungsten atom, is shown.