

Objectives

Upon completion of this module, you should be able to:

- define voltage, current, and charge for DC circuits;
- describe the roles of voltage and current in electronic circuits;
- specify a DC power supply or battery source for a DC circuit; and
- solve simple DC circuits with switches and resistors.

What makes it go?

Electricity “makes things happen” by moving *charge* down conductors. For most engineered applications, the flow of charge is moving *electrons* down wires and connectors and through circuit elements. Electronic circuits is the study of designing components to manipulate the flow of charge to accomplish a task, such as lighting a light or amplifying a sound.

Electric circuits are both designed and analyzed in terms of two physical quantities that are co-dependent upon one another: *voltage* and *current*. Voltage is a measure of the potential force available to move charge. Current is a measure of the flow of moving charges. Charges can have both positive and negative sign. In a continuous conductive material, positive charges flow from a higher potential to a lower potential.

While current flow is ultimately what enables circuits to perform their actions, voltage is the quantity that is most easily controlled, measured and passed between electronic circuits.

Definitions, conventions, and units

The unit of charge is a *coulomb* (C). A single electron has a charge of 1.6×10^{-19} C. The mathematical symbol for charge is q .

The unit of voltage is *volts* (V). The mathematical symbol for volts is V .

The unit of current is *amps* (A). The mathematical symbol for current is I . Current is a measure of the rate of flow of electrons: 1 amp = 1 coulomb/second. While the electrons flowing in circuits have negative charge, the standard convention is to define it in terms of the direction of flow of positive charge. In virtually all of your ECE courses, the direction of current flow used in class and on your exams is actually the opposite direction of how the electrons are actually moving!

While the concepts of voltage and current will be used throughout this course, we will rarely use the term coulomb. Charge storage ability (for example, by a battery) is usually described in terms of amp-hours (A·h). An amp-hour is a scaled version of coulombs (see problem

Prefix	Value	Name
p	10^{-12}	pico
n	10^{-9}	nano
μ	10^{-6}	micro
m	10^{-3}	milli
k	10^3	kilo
M	10^6	mega
G	10^9	giga

Table 1: SI Prefixes

sets) but is more intuitive to work with. For example, a battery that stores 3 amp-hours is potentially capable of sourcing 6 amps of current for 30 minutes (or 3 amps for 1 hour, etc).

Both voltage and current can be specified using standard prefixes. Commonly used prefixes are shown in Table 1.

Making it real!

- Amount of current in a bolt of lightning: 30 kA
- Amount of current required to start a car: 100 A
- Amount of current drawn by a kitchen blender: 5 A
- Amount of current sourced by a typical *wall wart* (those box-shaped plugs that come with many consumer electronic devices): 1 A
- Approximate amount of current consumed by the NXT brick when the motors are off: 100 mA
- Amount of current required to feel a tingling sensation on your skin: 3 mA
- A Van de Graaff generator produces 20 kV at only 0.5 μ A!
- Maximum amount of current passing in an out of a single cell in your heart during one heartbeat: 2 nA.
- Voltage of a typical lightning bolt: 30 MV
- Voltage of high voltage transmission lines: 85-550 kV
- Voltage of a US residential electrical outlet: 110 V
- Voltage of a car battery: 12 V
- Voltage required for most electronic circuits: 12 V or less
- Voltage of a AA, AAA, C, or D cell battery: 1.5 V

Practice Problems

1. A typical 1.5V AA battery has a nominal charge storage of 2600 mAh. What is this charge storage in terms of Coulombs?

2. How many mV is a typical lightning bolt?
3. Suppose the battery in the NXT brick is rated at 2600 mAh. An idle powered NXT brick consumes approximately 100 mA. Assuming all of these numbers are ideal, what is the longest duration of time that the brick will have power?

Batteries and DC Power Sources

Most consumer electronic devices, including your NXT brick, operate from *DC* power. DC stands for “direct current” and indicates circuitry is designed for power to be supplied from a constant voltage. This is in contrast to *AC* circuits, where AC stands for “alternating current.” In AC circuits, the voltage oscillates as a sine wave with a frequency of 60 Hz and a voltage of approximately 110 V. This is the form in which power is supplied to electrical outlets.

Why AC and DC? Originally, both AC and DC were proposed as competing standards for supplying power in the early days of the industrial revolution. In the end, AC won: it is much more efficient for transmitting electricity over long-distances via power-lines, and also preferred for designing electric motors, such as those found in ceiling fans and home kitchen appliances.

In this course, we will only be concerned with devices that operate from DC power. This includes most consumer electronic devices. Typically, these devices are powered from batteries or an external DC power supply - those annoying box-shaped plugs that don't fit well together in a power strip. These so-called “wall-warts” serve two functions: they “step-down” the supplied AC voltage to a lower voltage, and they convert that voltage from AC to DC.

Many other devices have a more complex internal power supply that converts the AC voltage to several DC voltages required by internal circuitry. One example is the personal computer, which has a power supply that typically outputs DC voltages of +12 V, -12 V, +5 V, and 0 V (ground).

Batteries

Batteries are charge storage devices. They are generally specified to output a specific voltage for a range of current outputs from 0 to a specified maximal value. The amount of charge stored in a battery is often specified in terms of milliamp-hours (mAh). For example, a AA battery will output 1.5 V and has a rating of approximately 2600 mAh. In theory, it could output 100 mA for 26 hours, or 1 A for 2.6 hours. In practice, this relationship is nonlinear, and batteries last disproportionately longer when supplying lower currents vs. higher currents.

Battery cells are stacked in series to create larger voltage. For example, the flashlight that requires 4 D batteries requires 6 V. However, all batteries supply the same current. Voltages add in series, while currents add in parallel. Thus batteries will be arranged in series to provide a necessary minimum voltage for a device, and will be arranged in parallel to provide

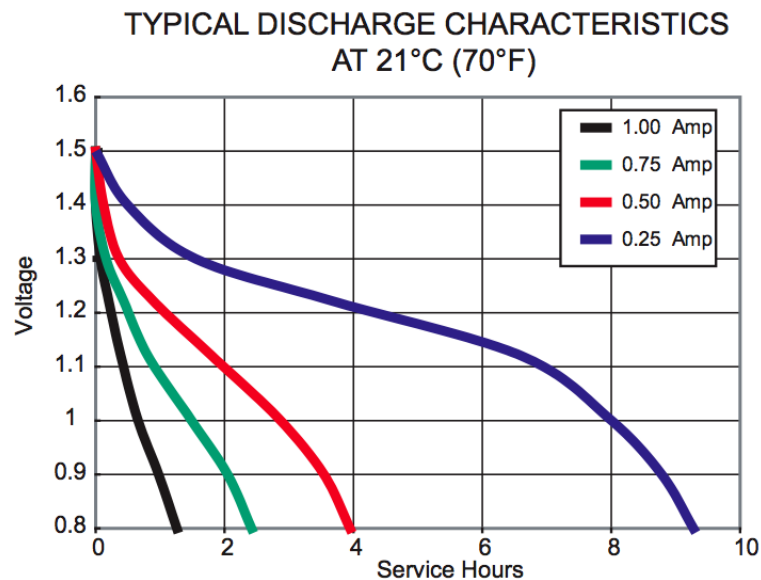


Figure 1: Discharge characteristics of a Duracell AA battery at several different loads of current demand. Figure reproduced from Duracell.com.

a necessary amount of current to a device.

Batteries decrease in voltage as they discharge; this decrease in voltage is a function of the amount of current that is being provided, and is not linear. Most circuits have a *cutoff voltage* below which they will not operate. The discharge curve for a Duracell AA battery is shown in Fig. 1. For example, suppose a AA battery is powering a circuit that has a nominal requirement of 1.5V and a cutoff voltage of 1.2V. A circuit drawing 0.25 A of current will operate about 8 times longer than a circuit drawing 1 A of current. This is why mAh are not a completely accurate measure of the amount of charge available in a battery – it is also a function of the usage patterns of the current being drawn.

The designer of a portable electronic device needs to consider: 1) what is the required voltage? 2) how much current will the device draw? 3) how long will I want it to run? Larger batteries store more charge and thus last longer, with a trade-off of more weight. Figure 2 illustrates the service life of various size batteries as a function of current demand.

External DC power sources

External DC power sources are rated to provide a guaranteed voltage and a range of currents up to a maximal value. They are usually labeled with the DC voltage output and the maximal amount of current that can be sourced. Their bulky size is due to the need of a *transformer* that steps down the AC voltage from 110V to a value closer to what is needed by the circuitry.

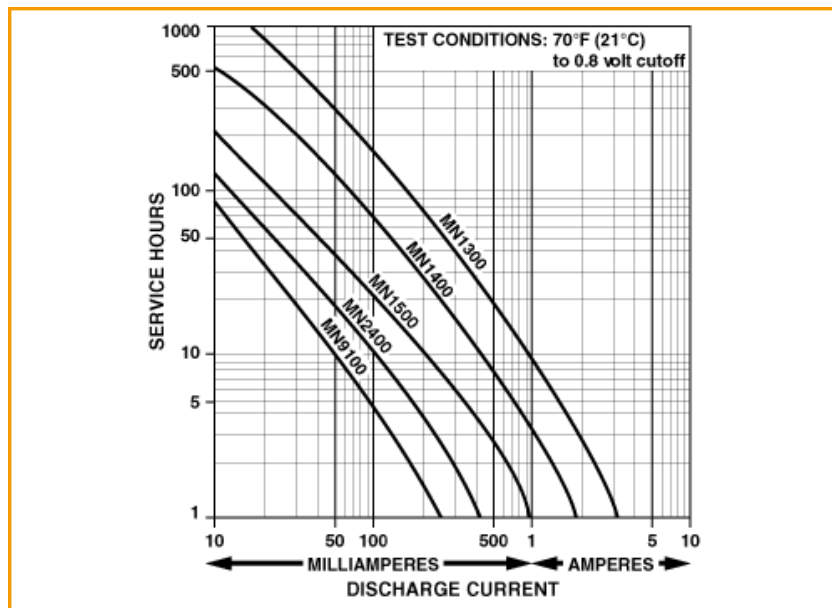


Figure 2: Time to discharge to 0.8V for several sizes of 1.5V battery as a function of current load. Curves are Duracell models numbers corresponding to D, C, AA, AAA, and N (in increasing numerical order).

Since they are plugged into a wall, the designer is not concerned with longevity. However, it is critically important that a DC power supply not be connected to a circuit that requires more current than the power supply can provide: this may result in not only an improperly operating circuit but a very hot power supply that could melt or cause a fire!

Practice Problems

The NXT brick draws a maximal current of 3 A (when powering a motor that has a load) and a nominal current of 114 mA (all motors off, no sensors or noise making), and requires a 9V power supply. The power supply is 6 AA batteries connected in series. For the purposes of analysis, assume that the system on average usage consumes 250 mA of current and requires a supply voltage of 6V to operate properly. Referring to the information in Figs. 1 and 2, answer the following questions.

1. Using the criteria above, about how long will the NXT operate?
2. Chloe likes to run the motors all the time, which can draw up to 3A. Assuming they are running about 33% of the time, assume a nominal current draw of 1A. How long will the NXT operate under these conditions?

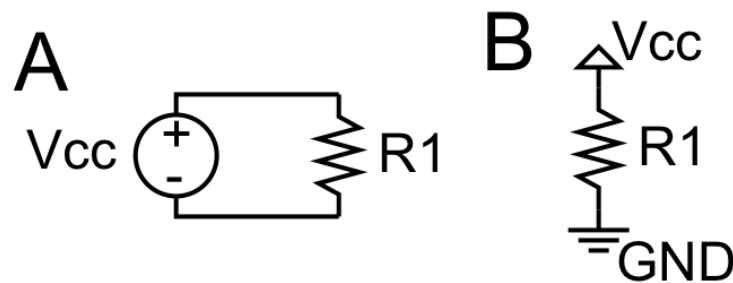


Figure 3: Two ways to denote a simple resistive circuit with an applied DC voltage

Simple DC circuits: switches and resistors

To understand how most sensors convert their sensing information into simple circuits, it is necessary to understand some basic circuit theory. Circuit theory is the topic of ECE 2040 and not a focus of this course, but you should be able to solve simple DC circuits with resistive elements and switches. This is a brief review of DC circuit theory that you have likely seen in a high school physics class.

Notation

Figure 3A illustrates a DC circuit with a single voltage source V_{cc} and a resistor R_1 . The voltage source is indicated by the circle and polarity indicated by the sign. The voltage difference across this source is V_{cc} . The solid lines indicate conductive paths (wires) connecting the resistor to the voltage source – for purposes of circuit analysis, the voltage is assumed to be the same across a conductive path. Thus the resistor R_1 has the voltage V_{cc} applied across it. An alternative notation, commonly used in electronic circuit schematics, is shown in panel B. In this case, the voltage source is indicated by the open upward triangle labeled V_{cc} , and the *reference ground* is indicated by the symbol next to GND . Most circuits have a reference ground that all voltages are measured with respect to; thus V_{cc} is V_{cc} voltage above GND , and the voltage across the R_1 is V_{cc} . Panels A and B indicate the same circuit, and are used to illustrate the different conventions that may be encountered. Typically, the notation in panel A is used in many classes and to indicate voltage sources that are inputs to a circuit, while the notation in panel B is used in most circuit diagrams for commercial products to indicate the voltages that are power sources to a circuit.

DC circuit rules

This section reviews some basic DC circuit rules used to solve for the voltages or currents flowing in a circuit. Fig. 4A illustrates a simple resistive circuit with a single voltage source,

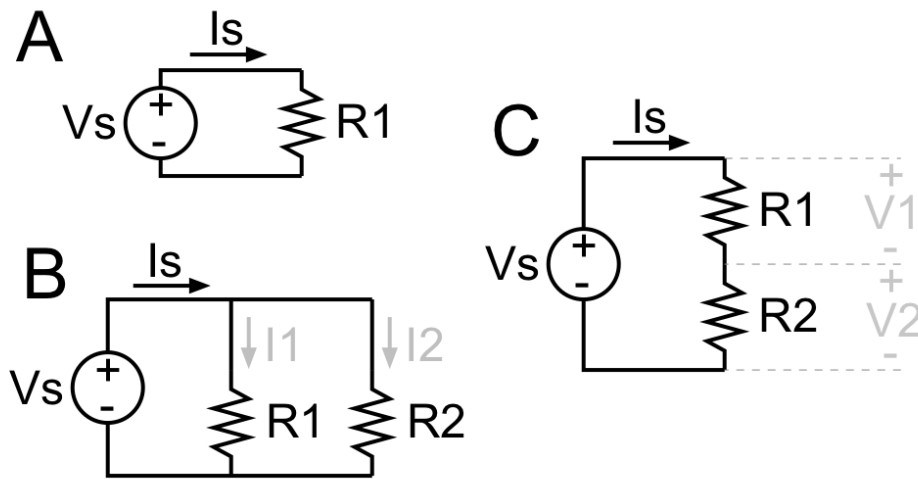


Figure 4: Simple RC circuits. A: single voltage, 1 resistor. B: Two resistors in parallel. C: Two resistors in series. For all panels, V_{ss} is the voltage source and I_{ss} is the total current provided by the voltage source.

similar to Fig. 3. *Ohm's law* states that $V = IR$: the voltage across a resistor is equal to the product of the resistor and the current flowing through it. Since the voltage V_{ss} is applied to R_1 , the current flowing through the resistor is $I_{ss} = V_{ss}/R_1$. An easy way to remember this is “more resistance, less current.”

A few simple principles are used to solve for the voltages and currents in a circuit:

- **Continuity:** The voltage is continuous and identical across all segments of a conductor (wire). A wire has no resistance.
- **Kirchoff's Current Law:** The sum of all currents flowing in and out of a single point on a circuit equal zero.
- **Kirchoff's Voltage Law:** The sum all the voltage drops of all circuit elements in a single closed loop around a circuit equal zero.

A basic strategy is to label all the branches of the circuit for current flow and voltage drops, and apply these two rules to solve for the unknowns. We will demonstrate the application of these rules for circuits consisting of two parallel resistors and two resistors in series.

Two parallel resistive elements

Figure 4B illustrates a voltage source applied to two resistors in parallel. What is the voltage drop across each resistor? What is the current flow through each resistor? What is the entire current required by the circuit? The circuit has a voltage source V_{ss} .

Because of the continuity principle, the voltage across both R_1 and R_2 is V_{ss} . The top part of each resistor has an unbroken conductive path to the positive voltage source, and the bottom part of each resistor has an unbroken path to the negative voltage source. This could also be determined by Kirchoff's voltage law: starting at the + end of V_{ss} , the voltage drop across the resistors + the voltage drop from the - to + terminal of V_{ss} (which is $-V_{ss}$ if going from - to +) must sum to zero.

The current through each resistor is indicated by I_1 and I_2 . Applying Ohm's law, $I_1 = \frac{V_{ss}}{R_1}$ and $I_2 = \frac{V_{ss}}{R_2}$.

Finally, applying Kirchoff's current law, the total current flowing into the circuit from V_{ss} is $I_{ss} = I_1 + I_2$.

Figure 4B illustrates a voltage source applied to two resistors in parallel. What is the voltage drop across each resistor? What is the current flow through each resistor? What is the entire current required by the circuit? The circuit has a voltage source V_{ss} .

Two series resistive elements

Figure 4C illustrates a voltage source applied to two resistors in series. What is the voltage drop across each resistor? What is the current flow through each resistor? What is the entire current required by the circuit? The circuit has a voltage source V_{ss} .

Applying Kirchoff's current law, the current flowing through both resistors is I_{ss} , the current provided by the voltage source. This is because there are no branch points – the current only has one path to flow down.

The voltage drop across each resistor is found by applying Ohm's law: $V_1 = I_{ss}R_1$ and $V_2 = I_{ss}R_2$. As a self-check, applying Kirchoff's voltage law, $V_{ss} = V_1 + V_2$.

Simple forms of sensor transduction

How does a sensor transmit convert a physical quantity to an electrical signal that can be measured? This process is called *transduction*. There are a few common principles used in many electronic circuits that incorporate sensors:

- Sensors are circuit elements that alter current flow within a circuit.
- This change in current flow is measured by a change in voltage within the circuit.

Most measurements are ultimately passed to other electronic circuitry as a voltage, and not a current. This is because it is generally easier to measure a voltage and not significantly alter the current flow within the circuit that is being measured. Methods of circuit measurement are covered in much more detail in ECE 3041.

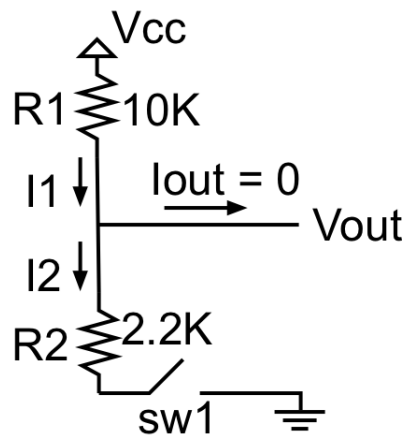


Figure 5: Schematic of circuitry used by the NXT brick and touch sensor to detect when the touch sensor is pressed. Additional notation provided for circuit analysis presented in text. Switch is indicated by sw1. V_{cc} is 5V. The switch and R_2 are physically located in the sensor, the remaining elements are on the NXT brick.

In this section we will describe some of the simple ways in which physical measurements are transduced into a voltage measured by an electronic system, such as the NXT brick. Most of the NXT sensors are analog: they have a voltage source provided to them, and they output a voltage to the NXT brick that is an indicator of the physical quantity being measured.

Switches

The simplest form of sensor is the switch, such as the touch sensors of the NXT system. Figure 5 illustrates the circuitry used within the NXT brick and touch sensor. The voltage at V_{out} changes depending on whether or not the switch is pressed. The NXT brick draws negligible current where it measures V_{out} , thus assume that $I_{out} = 0$ (this assumption is because whatever the output is connected to has *high input resistance*).

A switch operates by making or breaking current flow within a circuit. When the switch is closed, it is simply treated as a wire. When the switch is open, current is unable to flow down that branch. Switched circuits can be understood by analyzing the circuit when the switch is open and closed.

SW1 is open. By applying Kirchoff's current law, $I_1 = I_{out} = 0$ (the branch with I_2 is disconnected from the circuit). When no current flows through a resistor, the voltage drop across it is zero (it is still a continuous path and a voltage exists!). Thus V_{out} is approximately equal to V_{cc} , so the sensor sees 5V when the switch is not pressed.

SW1 is closed. Again applying Kirchoff's current law:

$$\begin{aligned}I_1 &= I_2 + I_{out} \\ &= I_2\end{aligned}$$

Applying Kirchoff's voltage law:

$$\begin{aligned}V_{cc} &= R_1 I_1 + R_2 I_2 \\ V_{cc} &= R_1 I_1 + R_2 I_1 \\ V_{cc} &= (R_1 + R_2) I_1 \\ I_1 &= \frac{V_{cc}}{R_1 + R_2} \\ I_1 &= \frac{5\text{V}}{12.2\text{k}\Omega} \\ I_1 &= 0.4\text{mA}\end{aligned}$$

Once I_1 (and thus I_2) are known, V_{out} can be solved for. V_{out} is the same as the voltage drop across R_2 . Therefore:

$$\begin{aligned}V_{out} &= I_2 R_2 \\ V_{out} &= I_1 R_2 \\ V_{out} &= (0.4\text{mA}) \cdot (2.2\text{k}\Omega) \\ V_{out} &= 0.88\text{V}\end{aligned}$$

In summary, when the switch is open (touch sensor is not bumped), the NXT brick measures approximately 5 V; when the switch is closed (touch sensor is bumped) the NXT brick measures 0.88 V. A key principle when detecting switch positions is to ensure that whether the switch is open or closed, V_{out} has a conductive pathway to a voltage that can be measured. For example, suppose that R_1 and the connection to V_{cc} did not exist in Fig. 5. When the switch is closed, no current would flow but V_{out} would connect to ground (0 V). However, when the switch is open, V_{out} is simply disconnected - its voltage would be undetermined. The use of R_1 is often referred to as a *pull-up resistor*, in that if nothing else is connected to V_{out} , V_{out} is pulled up to V_{cc} .

Photoelectric Cell

The photoelectric cell, or photocell, is a device whose electric properties change as a function of the amount of light sensed by the photocell. It is the fundamental basis of light sensors. There are many types of photocells, but the most common is the phototransistor.

A phototransistor is a device where the current flow through the device is determined by the amount of incident light. This change in current flow can be measured by the voltage across a known resistance that this current passes through.

Practice Problems

A flashlight is a circuit not too different from Fig. 4A with a switch. It consists of a voltage source, a resistor (the bulb), and a switch to open and close the circuit to allow the current to flow. The light-bulb is a 10 ohm resistor that illuminates with sufficient current flow.

1. Which results in a brighter light bulb (i.e. more current), using two AA batteries or 2 D batteries? Why?
2. Draw a circuit diagram for the flashlight, including the switch.
3. Assuming that two 1.5 V batteries are the power source, calculate the current flowing through the bulb when the flashlight is turned on.
4. Assume the flashlight provides a useful amount of light when at least 1.6 V is provided across the bulb. Calculate the expected battery life for two AA batteries, C batteries, and D batteries.
5. You have 6 V power supply. Design a circuit that outputs 0 V when the switch is open and 5 V when the switch is closed. Assume the output does not draw any current and that the circuit itself cannot draw more than 2 mA of current from the power supply.