PART I: ANALOG ELECTRONICS

Chapter 1: Passive DC circuits

In this section we will consider passive dc, i.e. direct current, circuits. These are circuits that involve resistors and constant voltage sources. **Much of this should be a review, so I'll be brief and assume you know the material through section D already**. Perhaps the most important circuit in this section is the voltage divider.

There are several basic concepts. The first is the concept of charge, Q, measured in Coulombs. The second is the concept of electric potential or electric potential difference, referred to as voltage and measured in volts.. (Note that EMF's are also measured in voltage. For the most part, I won't distinguish between EMF's and electric potential difference. However, I will often use the symbol E for the voltage or EMF developed by a battery or other voltage **source**, but not always. I may forget and just use V.) **I will usually use the term Voltage to refer to a potential difference**. You cannot measure the absolute potential at a point; you always measure the difference in electric potential between two points. (See your General Physics textbook.) Often you choose one point in the circuit to be a zero potential and then measure all other potentials with reference to that zero potential. The point chosen to be at zero potential is often called a **common** or a **ground**. (They aren't quite the same; see section F.) A battery or power supply generates a potential difference, or voltage, between two terminals, one of which is usually chosen as a common or ground, typically the more negative terminal.

The third concept is current, I or i, which measures the rate at which charge is flowing through a cross sectional area, e.g. through a copper wire. The units of current are coulombs per second or amps. A fourth concept is resistance, R, measured in amps/volt or ohms. Resistance is a measure of how hard it is to drive current through an object. I assume these concepts are familiar to you.

In the circuit at the right you will see a voltage source, the battery symbol, and a resistor. The straight solid lines represent connections by good conductors of essentially zero resistance. For most purposes, copper wires of reasonable thickness satisfy this criterion.

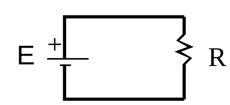


fig. 1.1

In this case, the voltage E developed by that voltage source all appears across the resistor R. Since the voltage drop across an ideal resistor is IR, a current I = E /R will flow in the circuit. This follows from the conservation of energy and conservation of charge. As a charge Q moves around the circuit, it is assumed that none can disappear, pile up, or leave the conductors, i.e. the wires or resistor, to go into the air.   Conservation of energy implies the sum of all the voltages changes must be 0 around a complete loop. (These are known as Kirchhoff's rules, which you should already know.)

In most cases the actual charge carriers are electrons flowing in the counterclockwise direction around the circuit. For our purposes this is equivalent to positive charges flowing in the clockwise direction. (Although it is difficult to tell whether you have positive charges flowing in the clockwise direction or negative charges moving counter clockwise, it can be determined using the Hall Effect; see your elementary Physics text.) When drawing the current it is customary to choose the current to be the equivalent flow of positive charges. I will follow this convention and say the (positive) current flows around this circuit in a clockwise direction.

A: Series circuits

When one has a battery and two resistors connected as shown at the right, the two resistors are said to be in series, because the current flowing through each resistor is the same. This is true because charge is conserved and the charge flowing through the first one has to flow through the second to get back to the negative terminal of the voltage source.

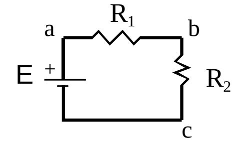


fig. 1.2

If the charge can't leave the wire or pile up, it must flow through the second resistor. Since the current I is the same through both, $E = IR_1 + IR_2 = I(R_1 + R_2) = I\,R_{eq}$. As far as the battery is concerned, the two resistors are equivalent to one resistor, $R_{eq} = R_1 + R_2$. Often we will be trying to replace complicated circuits by simpler **equivalent circuits**. (Note that circuit 1.1 is equivalent to circuit 1.2 if $R = R_1 + R_2$. However it is only equivalent from the battery's point of view. For any measurement we can make by connecting to the beginning of R_1, point a, and the end of R_2, point c, the two circuits are indistinguishable. However, if I connect to point b they may not be equivalent. Therefore we say that fig. 1.1 is equivalent to fig. 1.2 with respect to measurements made at points a and c in fig. 1.2.)

A second feature of this circuit is that the voltage E is divided between the two series resistors and since the current $I = E/(R_1 + R_2)$, the voltage drops across each resistor, V_1 and V_2, are given by

$$V_1 = E\frac{R_1}{R_1 + R_2} \quad \text{and} \quad V_2 = E\frac{R_2}{R_1 + R_2} \qquad 1.1.$$

This circuit is therefore known as a **voltage divider**, and often it is used to produce a selectable, smaller voltage from the "input" voltage E. You select the value by choosing the proper value for the two resistors. This is used in volume controls and similar circuitry, where the two resistors are really part of a potentiometer, or pot for short. **You should get to know this circuit very well.**

B: Parallel Circuits

The second type of common circuit is the parallel circuit shown at the right. In this configuration, the voltage drop across the two resistors must be the same, it is the current that divides between the two resistors. In this case $V_1 = V_2 = E$, so $E = I_1R_1 = I_2R_2$, or $I_1 = E/R_1$ and $I_2 = E/R_2$. The total current supplied by the voltage source is $I = I_1 + I_2$ and it is given by

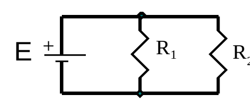


fig. 1.3

$$I = \frac{E}{R_1} + \frac{E}{R_2} = E\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = E\left(\frac{R_1R_2}{R_1 + R_2}\right) = ER_{eq} \text{ where } R_{eq} = \left(\frac{R_1R_2}{R_1 + R_2}\right) \qquad 1.2$$

This means that as far as the battery is concerned, the two resistors act like one resistor of value R_{eq}.

If you have n > 2 resistors in parallel, the equivalent resistance cannot be written so neatly and

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n} \qquad 1.3$$

C: Combination Circuits

Many complicated circuits can be viewed as equivalent to combinations of series and parallel circuits and simplified by reducing them to those series and parallel combinations. This is often faster than using Kirchhoff's rules. However, **Kirchhoff's rules will always work, but you cannot always reduce complicated circuits using the simple series and parallel combination rules**.

Consider the circuit at the right. Here R_2 and R_3 are in parallel with each other and **as far as the rest of the circuit is concerned**, they can be replaced by their equivalent, in this case by a 120Ω resistor. The circuit is then a voltage divider circuit like the one discussed above with the values shown in fig. 1.5

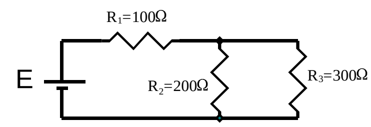


fig. 1.4

below. As a result the total current flowing in the circuit is just $\mathcal{E}/(100\ \Omega + 120\ \Omega) = \mathcal{E}/(220\ \Omega)$. If the voltage is 11V, then the current is 0.05A or 50mA. This is the total current supplied by the battery, and it is also the current in R_1. The currents through R_2 and R_3 can be

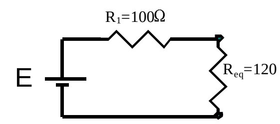


fig. 1.5

determined by finding the voltage across R_{eq}, $V_{eq} = \mathcal{E} - I_{total}R_1 = 11V - 5V = 6V$, and then calculating the current through each resistor. $I_2 = 6V/200\Omega = 30mA$ and $I_3 = 6V/300\Omega = 20mA$. In accordance with Kirchoff's rules, $I_{total} = I_2 + I_3$.

This is the easiest example. Sometimes one has to look at complex circuits for a while and even redraw them to see which resistors are in series or parallel with each other. An elementary Physics text, e.g. Halliday & Resnick, will have many instructive examples.

D: Multiple Battery Circuits

If you have more than one battery in your circuit, you may have to go back and use Kirchhoff's rules to generate a set of linear equations to solve. Consider the circuit at the right. This circuit has two batteries and three resistors. If we know the $\mathcal{E}$'s and R's we should be able to find the current through each resistor. One can see that there are three possible loops, two of which are independent, i.e. the third is redundant. The three possible loops are ABCDEFA, ABEFA and BCDEB. There are three currents, I_1, through R_1, I_2,

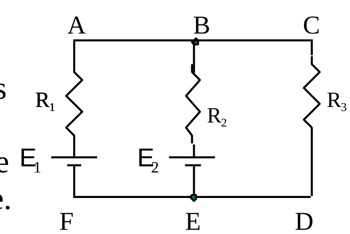


fig. 1.6

through R_2, and I_3, through R_3. **I will take them positive if they are going toward the top of the page**. If I apply Kirchhoff's rules to loop ABEFA, I have the sum of the voltage changes =0 or, going around the loop clockwise,

$$\mathcal{E}_1 - I_1R_1 + I_2R_2 - \mathcal{E}_2 = 0 \qquad 1.4$$

Note that I'm going through R_2 in a direction opposite to the direction of the positive current so the voltage change is $+ I_2R_2$. Also, I'm going through battery 2 from the + side to the – side, so the change in voltage is $-\mathcal{E}_2$. Applying the rules to BCDEB as I go around clockwise, I get

$$\mathcal{E}_2 - I_2R2 + I_3R_3 = 0 \qquad 1.5$$

These are two equations, but knowledge of the $\mathcal{E}$'s and R's must be enough information to determine the currents. To do this mathematically we need another equation. This equation comes from the fact that <u>the current flowing into any node must equal the current flowing out of that node</u>. In this case look at point B. If I_1, I_2 and I_3 all flow in, and nothing is flowing out, then

$$I_1 + I_2 + I_3 = 0 \qquad 1.6$$

These three equations, 1.4, 1.5, and 1.6, allow us to uniquely determine the currents as a function of the voltages and resistances. Unfortunately as the number of independent loops grows, the number of simultaneous equations to solve grows. However, there is a trick that can help. The equations for the currents are all linear in the $\mathcal{E}$'s, so I can write

$$I_1 = \mathcal{E}_1 f_1(R_1,R_2,R_3) + \mathcal{E}_2 f_2(R_1,R_2,R_3) \qquad 1.7$$

where f_1 and f_2 are **only** functions of the R's. As a result I can find the part of I_1 due to E_2 by setting $E_1 = 0$. Then I can find the part of I_1 due to E_1 by setting $E_2 = 0$. The actual current is the sum of the two parts. You have changed one slightly complex problem into two simpler ones. (Note that setting one of the E's = 0 is equivalent to replacing it by a short, i.e. by a resistor of 0Ω resistance.) Another way to approach this is to solve for f_1 and f_2, then you can get I_1 for any values of E_1 and E_2.

For example, to solve for $f_1(R_1,R_2,R_3)$, I merely solve for the current through R_1 in the circuit at the right and $f_1(R_1,R_2,R_3) = I_{1a}/E_1$. (Note that I have called this current I_{1a} because it is the current through R_1 for a "different" circuit; one with $E_2 = 0$.) Similarly I solve for $f_2(R_1,R_2,R_3)$ by setting $E_1 = 0$, with E_2 NOT 0, and solving for the current through R_1 due to E_2. Again one has $f_2(R_1,R_2,R_3) = I_{1b}/E_2$. Find f_1 and f_2 for the circuit in fig. 1.6.

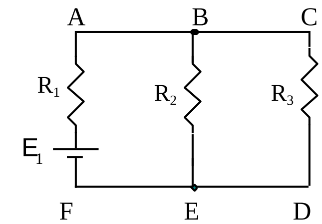


fig. 1.7

E: Thevenin's Theorem.

Thevenin's theorem says that any system of ideal voltage sources and resistors with two terminals (outputs) can be represented by a single voltage source in series with a battery, with respect to the two output terminals. The box below is an example. (Note that 9kΩ is abbreviated by 9k, the Ω being understood since it is obviously a resistance.)

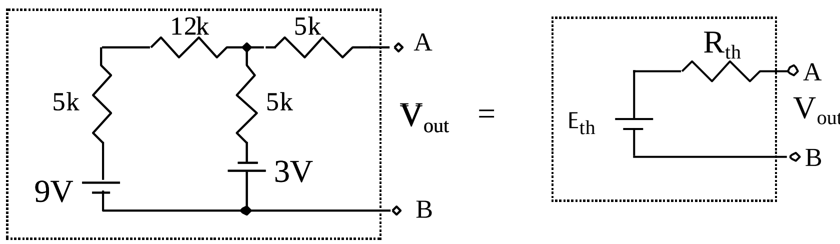


fig. 1.8

Everything inside the dotted box can be represented by the circuit to the right of it, with a proper choice of E_{th} and R_{th}. That is, nothing that I can measure at the output terminals (A & B) can distinguish between the two circuits. They are **equivalent** with respect to measurements made at the "output" of the circuit.

The question then becomes, how do I find E_{th} and R_{th}? The way I usually calculate them is the following. R_{th} is the resistance between the two terminals, A and B, with the voltage sources, i.e. batteries, **replaced** by short circuits as shown at the right. You should be able to verify that this resistance between A and B is about 8.9 k which is R_{th}. The Thevenin voltage is a little harder to calculate in this case. I have to calculate the voltage between A and B in the original circuit above to get E_{th}. You should try to verify that it is – 0.27V. (Note that the 3V battery is in "upside down" so that its polarity is opposite to the 9V battery!) The equivalent circuit is shown in fig. 1.10. Again note the orientation of the battery.

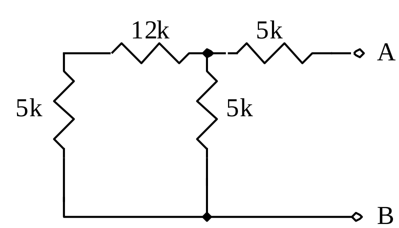


fig. 1.9

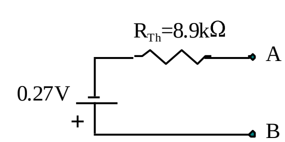


fig. 1.10

The reason Thevenin's theorem works is because the circuit is a linear circuit. The equations you get from Kirchhoff's rules are a set of linear equations relating the currents to the voltage sources. Thus the voltage at any point in the circuit is a linear function of the battery voltages or voltage sources in the circuit, just as the current through any resistor is a linear function of the voltage sources.

The simplest and one of the most useful circuits is the voltage divider mentioned earlier and shown at the right. You should be able to quickly verify that the Thevenin equivalent circuit has an R_{th} equal to the parallel combination of R_1 and R_2. or,

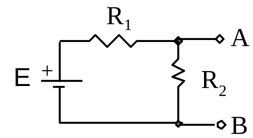


fig. 1.11

$$R_{Th} = \frac{R_1 R_2}{R_1 + R_2} \qquad 1.8$$

and a Thevenin voltage equal to the voltage across R_2 or

$$E_{Th} = E\frac{R_2}{R_1 + R_2} \qquad 1.9$$

If I connect something across A and B, e.g. a voltmeter, that device will have an input resistance, R_{in}, that creates a voltage divider when connected to the Thevenin equivalent circuit, i.e. connected between A and B. I immediately see that the voltage across A and B changes when I connect the device, and that the change is small if $R_{in} >> R_{th}$.

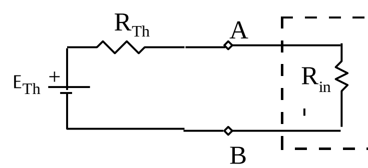
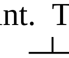


fig. 1.12

Thinking of the circuit in terms of the Thevenin equivalent often helps one see what will happen when you connect something else to the circuit. As a result, the Thevenin Resistance is often thought of as an **output resistance**, that is, it is the resistance the circuit presents to an external device. The output resistance is also called a **source resistance**.

There are other techniques for solving DC circuit problems, but I won't go into those. Thevenin's theorem is probably one of the most useful concepts and techniques for analyzing circuits, so I've chosen to introduce it. It even holds in a slightly modified form for AC circuits as long as the components are linear.

F: Grounds and Commons

In most circuits one chooses to arbitrarily define the potential at one point as 0V. (Remember from your basic Physics course that you cannot measure an absolute potential, only potential differences are measurable. You can change the potential by an arbitrary constant **EVERYWHERE** and not change the Physics of the system.) One can then talk about the potential of various points in the circuit relative to the 0V point. If one point is 2V more positive than the 0V point, we say the voltage there is +2V. It is understood that this is relative to the 0V point. The 0V point is often called a **common** or a **ground** for the circuit. The symbol for this is .

In the circuit in fig. 1.13, D is the common or ground. As a result we would say the potential at A is + 10V, the potential at B is +5V and the potential at C is +2.5V. These are all relative

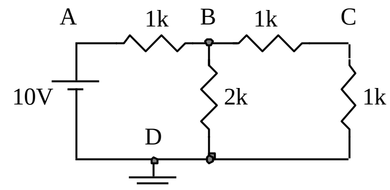
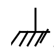


fig. 1.13

to the potential at D, which is chosen to be 0V. This common is only for this circuit. Sometimes we talk about an **earthed ground**. In this case the common is actually connected to the earth through a conductor. As a result we say the common is not just relative to that particular circuit, but also to any other circuit that has its common earthed.

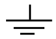
The symbol for an earthed common or earthed ground is .

A situation where this arises is when you connect an oscilloscope to a circuit and connect the ground lead to the circuit's common. The ground lead of the oscilloscope is usually connected to the earth through the 3rd prong of the electrical plug that connects the scope to the power mains. The common of the circuit is now **earthed**. If the common is <u>not earthed</u>, it is said to be **floating**. The ground lead on many multimeters is not earthed, but floating. Therefore if you connect such a multimeter to the circuit to measure a voltage with the meters ground connected to the circuit's common, it will not earth the common, but let it float.

When using multimeters, voltage sources, function generators, oscilloscopes, or other devices, it is best to check and see if their ground is earthed or not. Confusion about grounds can lead to some "interesting" results. For example in fig. 1.13, I can use a multimeter whose common floats to measure the voltage between B and C by connecting the hot lead (the red one) to B and the common to C. It will give me the voltage between B and C. I can use another multimeter to simultaneously measure the voltage between A and D by connecting this second meter's common to D and the hot lead to A. In this case the commons of the two meters will **NOT** be at the same potential, i.e. they will not share a common voltage. I will get the correct readings if the meters both float. This will be true even if the voltage source that produces the 10V is not floating but has its common lead earthed, as long as the multimeters are both floating. If the meters are floating they give the difference in potential between the two leads and do not force the point connected to the common lead to assume a particular voltage relative to the earth.

However if I use a dual channel oscilloscope and to read the voltages between A and D and between B and C at the same time I can have problems. If I connect the ground of the probe for channel 1 to D, that will earth D. I can connect the hot lead of the probe to A to measure the voltage at A relative to D, V_{AD}. I might be tempted to try to measure V_{BC} at the same time by connecting the ground of the probe for channel 2 to C and the hot lead to B. This earths point C, i.e. connects it to D directly, bypassing the 1k resistor. That changes the circuit and the voltage I read is not the voltage V_{BC} that existed in the original circuit. However, if I disconnect the ground of probe 1, then I should get the correct V_{BC}, as long as the voltage source that produces the 10V is floating. (By their nature batteries are floating, but some power supplies are earthed, so it will depend on the nature of the voltage source.) Another way of thinking about it is that the oscilloscope measures the potential between the hot lead and the earth. When you connect the ground lead to a point you are forcing it to assume the same potential as the earth.

If you are connecting several instruments to a circuit, you usually want them all to share the same reference point or common, so you would connect all their commons together. There are exceptions to this rule, but only violate it if you have a good reason for doing so and know what you are doing. <u>All instruments or devices that have earthed grounds must share the same common when connected to a circuit</u>.

Warning: <u>Some people use the term common for a floating reference point and ground for one that is earthed. Always check to determine their usage.</u> In that case the ground is usually the symbol  and the common is .

Establishing good grounds or commons in circuits is important and one can run into measurement problems when good grounding techniques are not followed. The idea of a common is that all conductors connected to that point share the same reference potential of 0V, hence the term common. However, if there is a current flowing in a ground lead, there will be a small variation of potential along the lead if the resistance is not zero, i.e. if it is not a superconductor. A one foot length of 24 gage copper wire, a typical size for hooking up small electrical circuits, may only have a resistance of a fraction of an ohm (1000 feet has a resistance of about 26Ω so one foot's resistance would be .026Ω). Nevertheless a current of 0.1A flowing in that lead will produce a potential difference between the two ends of about 2.6mV. It sounds like a small amount, but it can be significant if you're trying to measure a signal of 5mV. One can reduce the effect by going to a thicker wire, e.g. 20 gage wire has a resistance of 10Ω per 1000 feet or about 40% that of 24 gage wire, or a differential voltage measurement. (Even the earth is not an equipotential; so if two commons are earthed at different locations, they may not be at exactly the same potential.)

This has been a <u>brief</u> discussion of grounding. It is not meant to be comprehensive, but rather to acquaint you to the basics of grounding and grounds and make you aware of some of the problems that can arise from improper grounding techniques. A more complete discussion can be found in Morrison's book *Grounding and Shielding Techniques in Instrumentation*. It's a good book.

G: Input and Output Resistances

Batteries or other voltage sources have some limits. They are not ideal. An **IDEAL** voltage source would supply whatever current is necessary to maintain the stated potential difference between its terminals. **REAL** sources often act like an ideal source in series with a resistor. (Think of a Thevenin equivalent circuit.) This resistance is called a source or output resistance or source resistance. Most sources are designed to have a low source resistance. Power supplies with voltage regulators often have source resistances of a fraction of an Ohm, e.g. a 7812 (a 12V regulator) will have an output resistance of < 0.01Ω at low frequencies. These resistances are often negligible, and you don't have to worry about them. However, if you are trying to measure the voltage across an isolated capacitor, it may have an enormous source resistance at low frequencies. (We should talk about source impedance, but the concept of impedance won't be introduced until later.)

When you connect a voltage source to "something", the "something" you connect it to will have an input resistance. The interaction of the output resistance of the source and the input resistance of the "something" will change the apparent output voltage of the source. For example, if you connect a voltage source to a voltage divider circuit as shown in fig. 1.2, the divider circuit will present a load resistance of $R_1 + R_2$ to the battery. If the source is a battery of source resistance 0.5Ω, and $R_1 + R_2 = 2k\Omega$, adding the divider will change the batteries output voltage by a fraction

$$\frac{\Delta V}{V} = \frac{R_{source}}{R_1 + R_2 + R_{source}} = \frac{0.5}{2000.5} = 0.025\% \qquad 1.10$$

This is <u>usually</u> negligible. However, if $R_1 + R_2 = 20\Omega$, the change will be about 2.4%.

If you have an ideal voltage source connected to a divider (fig. 1.2 again) where both R_1 and $R_2 = 1.00M\Omega$ and try to measure the voltage across R_2 with a multimeter, you may not get the value you would expect to get. The reason is that the source <u>plus divider</u> has an output resistance of

500kΩ, while the meter will probably have an input resistance of about 10MΩ. As a result the voltage the meter measures will not be the original voltage across R_2, but will be reduced because of the 10MΩ input resistance. It will be reduced by almost 5%. If you try to measure it with an oscilloscope with a X1 probe, the input resistance will only be 1MΩ. What do you think you will measure then?

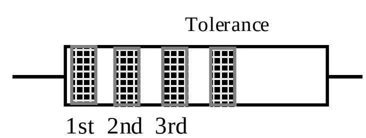
Resistors

Resistor values are identified by color bands on the resistors. For our 5% resistors the first two bands are the two most significant figures and the third band indicates the power of ten that multiplies the two most significant figures. The fourth band indicated the tolerance or uncertainty in the value. The values are shown below. For the tolerance, Gold indicates a ±5% tolerance and Silver a ±10% tolerance.

1 = Brown	2 = Red	3 = Orange	4 = Yellow	5 = Green
6 = Blue	7 = Violet	8 = Grey	9 = White	0 = Black

We will be using carbon film resistors in this class and most of these have tolerances of ±5%. Metal film resistors often have a ±1% tolerance or less.

A resistor that is Green, Blue, Red and Gold is a $56\times10^2\Omega$ resistor, or a 5.6kΩ resistor with a ± 5% tolerance. (Most of the time these 5% resistors are within ±3% of the stated value. A 1.0k resistor is usually between 970Ω and 1,030Ω.)



As long as the temperature of a resistor is constant, its resistance should be approximately constant, i.e. independent of the voltage across it. For the resistors we are using this is a good approximation. However, the resistance does depend on temperature. For the carbon film resistors it varies by roughly −300ppm per degree C. Graphite's resistivity changes about −500 ppm/degC. A 33°C increase in temperature would decrease the resistance by about 1%. (The negative 300ppm means an increase in temperature decreases the resistance.) This is can be a problem in precision circuits, but it can also be used to measure the temperature.