Physics 334 Week 1 Lecture Notes

Electronics runs the world. Physicists use it in many aspects of research. Every well-rounded scientist needs to know about electronics, from the commonplace: oscilloscopes, antennae, radios, and computers to the more specialized: low noise amplifiers, phase-sensitive detectors, charge coupled devices, and various transducers (devices to convert physical quantities into electrical signals).

Electronics naturally divides into two categories: analog and digital. Analog electronics deals with electrical signals that take on a continuum of values. These signals are amplified, filtered (by frequency), rectified (made of one sign only), and turned into digital signals that can be manipulated by computers. Digital electronics deals with signals that take on only two values (eg. 0 and 5 Volts). These signals represent bits of information that are used for counting, calculating, and decision making. You will be introduced to both analog and digital electronics in this course. We will begin with the analog world.

Although electronics is an application of principles of electromagnetism which deals with charges, and electric and magnetic fields, we don't usually think about these quantities (although they are present in electrical circuits). Instead, electronics is concerned with two quantities, voltage and current, which may be and usually are functions of time.

VOLTAGE: (symbol V or sometimes E) is defined as the work required to move a unit charge from a reference point to another point. Because electrical forces are conservative forces, the work does not depend upon the path taken between the points. This leads to the definition of electrical potential energy: every point has an energy (potential energy) associated with it defined to be minus the electrical work required to move to that point from some pre-chosen reference point.

Voltage, then, is the electrical potential energy per unit charge at a point (like electric fields are the electrical force per unit charge at a point). **Remember**, only differences between potential energies are physically significant: we can add the same constant to all potential energies and nothing will change. A useful analogy is gravitational potential energy at the earth's surface = mgh, where h is the height. We can define zero height as we choose: what gives the gravitational force is the height difference between to points [$\vec{F} = -\vec{\nabla}(PE)$].

Voltage is also often referred to as "potential difference" and "EMF" (electromotive force). It is best to remember it as the electrical potential energy per unit charge.

The SI unit for voltage is the Volt. Typical values that we deal with are milli-Volts = mV = 10^{-3} Volts, micro-volts = μV = 10^{-6} Volts, Volts, and kilo-Volts = kV = 10^{3} Volts.

Note: Volts = Energy/charge: 1 Volt = 1 Joule/1 Coulomb

1 Joule = 1 Volt x (1 Coulomb = 6.3 x 10^{18} e)

Note: We always measure and refer to the voltage difference between 2 points in a circuit. We can only speak about the voltage at a point if we have already defined a reference point as having zero volts (like choosing what to call zero height in gravity problems). The point where we define the voltage to be zero is commonly called "ground" or "earth" or "common".

CURRENT: (symbol I or i) is defined as the rate of flow of charge past a point. Just like a rock falling when there is a difference between the gravitational potential energy (height) between two points, there is a force on a charge when there is a voltage difference between two points: if the charge is free, it will move in response to the electrical force and becomes a current.

The SI unit for current is the Ampere, Amp for short. Typical values are nano-Amps = nA = 10^{-9} Amps, μA, mA, and Amps.

Note: 1 Amp = 1 Coulomb/sec = dQ/dt, where Q = charge

We always measure and refer to the current through a point in a circuit. Voltage does not "flow", current does.

Another useful analogy is to think of voltage and current relative to water in a tank. Voltage is like the pressure in the tank and current is the amount of water that flows due to a pressure difference.

By convention, current flows from high voltage to lower voltage: this is the direction that a positive charge would move in response to the potential difference (electric field). Even though it is often electrons (negative charges) that physically move, the sign of the current is taken as the direction that positive charges would flow.

In real circuits, things are connected together by wires, which are conductors. In electrostatics, conductors are equipotential (constant voltage) surfaces. In almost all applications, we can treat the voltage as constant anywhere on a wire. (This means an actual circuit need not look like its schematic diagram.)

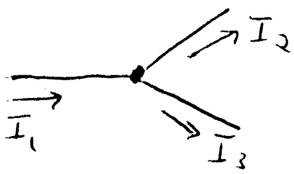
KIRCHOFF'S LAWS: In nature, conserved quantities like energy, momentum, and electric charge are of fundamental importance. In electronics, conservation of energy and electric charge lead to Kirchoff's voltage and current laws:

<u>Kirchoff's Current Law:</u> In a circuit, the sum of the currents into a point equals the sum of the currents flowing out of that point. $\Sigma I_{in} = \Sigma I_{out}$. This is equivalent to saying that the sum of all of the current flowing into a point is zero: $\Sigma_k I_k = 0$.

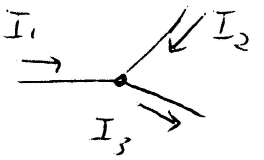
This law follows from the conservation of electric charge and the observation that charge cannot accumulate at a point, because of the strong electrostatic repulsion forces that would develop. (Again, if you think of current as the flow of water in pipes, the water has to go somewhere because you don't destroy mass.)

Here are three useful consequences of Kirchoff's current law:

1. At a node (connection point) in a circuit, the currents are related:

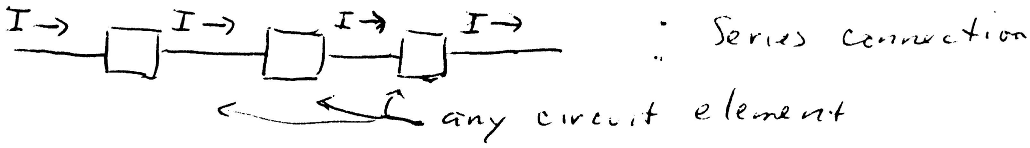


$I_1 = I_2 + I_3$;

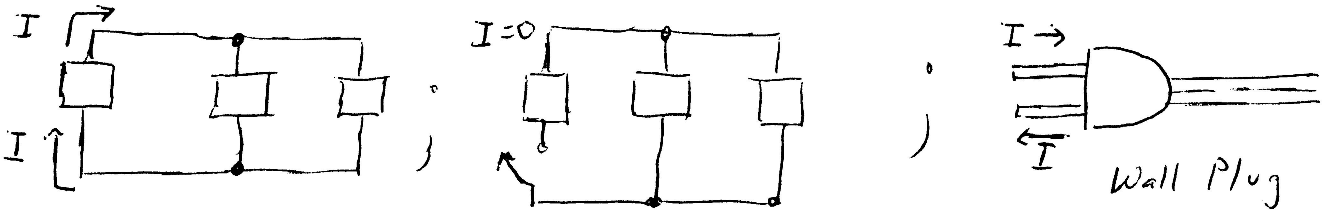


$I_1 + I_2 = I_3$

2. For circuit elements connected in series (head to tail), the current is the same everywhere:

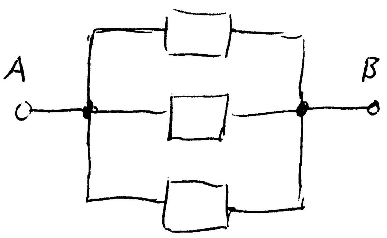


3. The current that leaves a point (or device) in a circuit must return to the same point (or device). This means that current can flow only if the circuit forms a closed loop. That is why the wires in your house comes in pairs: the current flows out of the wall plug into one wire and returns to the plug through the second wire.



Kirchoff's Voltage Law: The algebraic sum of the voltage differences around a closed loop is zero: $\Sigma_{\text{closed loop}} \Delta V = 0$. This is obviously a consequence of the conservation of energy and the fact that electric forces are conservative: the work required to move a charge from point A back to point A equals the change in potential energy = 0, because there is a unique potential energy at point A.

Another statement of Kirchoff's voltage law is that the sum of voltage differences between point A and point B is independent of the path taken from point A to B: this leads to the observation that circuit elements connected in parallel (head to head, tail to tail) have the same voltage difference across them. (Remember, the wires connecting the elements have the same voltage at all points on the wire.)



parallel connection: $V_A - V_B$ is the same for each device (even though the current through each device may be different).

Electrical Power: When a charge moves in response to a voltage difference, work is done on the charge: (work = force x distance). The rate at which work is done is the power consumed by the circuit. Our definitions of voltage and current then give us:

Power = P = $\Delta V \times I$: Watts = Joules/time = Joules/Coulomb x Coulombs/time = Volts x Amps

A 1 Amp current flowing though a potential difference of 100 Volts generates 100 Watts of power. This power often appears as heat, which is what makes light bulbs glow.

The Relationship Between Voltage and Current: This is the essence of electronics: picking devices to generate the desired relationship between input and output signals (V's and I's). We'll start with the simplest devices and work our way to the more exotic.

RESISTORS: A resistor is a device for which the current flowing through it is linearly proportional to the voltage difference across it. (Analogous to a water pipe: the rate of water flow is proportional to the pressure difference between the two ends.)

We can write this relationaship as: $I = G \times \Delta V$, where G is the 'conductance". This form is rarely used, however.

Instead, we write $\underline{\Delta V = I \times R}$ (Ohm's Law), where R is the "resistance" measures in Ohms (Ω).

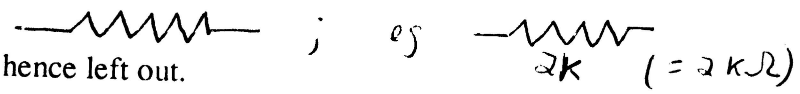
1 Ohm = 1 Ω = 1 Volt/ 1 Amp

Note: $G = 1/R$

Usually, we write Ohm's Law as $V = IR$, but in doing so it is understood that V means the voltage difference between the two sides of the resistors.

Typical values for resistors range from Ω (ohm's) to kΩ ('kay') to MΩ ('meg').

The symbol for a resistor in a circuit is:
The symbol 'Ω' is usually understood and hence left out.



SCHEMATICS and CIRCUITS: In a schematic, conductors (wires) are drawn as simple lines and current flows through them infinitely easily. Ideal components are symbolized and connected. Each real component may need to be represented by several ideal ones, depending on how accurately we want to predict the behavior of the real circuit. See H & H (your text) appendix E for schematic rules.

Below are some schematic elements that we will be using:

Conductor (wire):

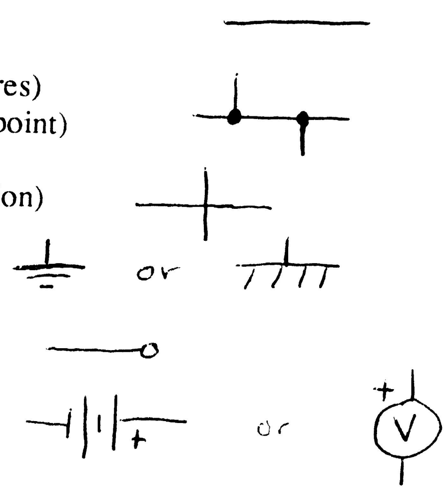
Node: (connection point of wires)
(never more than 3 at a point)

Conductors cross: (no connection)

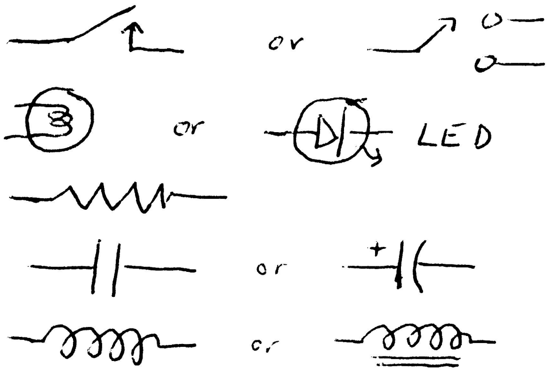
Ground (Earth):

Terminal post, contact:

Battery (DC voltage source):

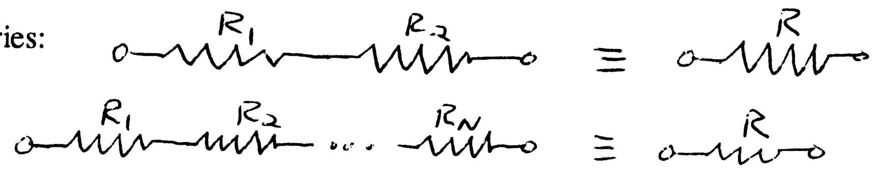


Switch:
Lamp:
Resistor:
Capacitor:
Inductor:



RESISTOR CIRCUITS: Simple rules for resistor circuits follow from Kirchoff's laws and the linear relationship between volatge and current for resistors:

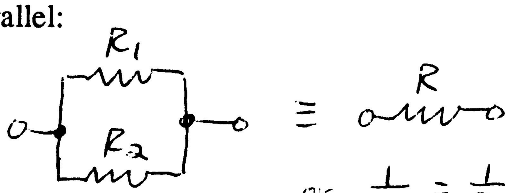
Series:



$$R = R_1 + R_2$$

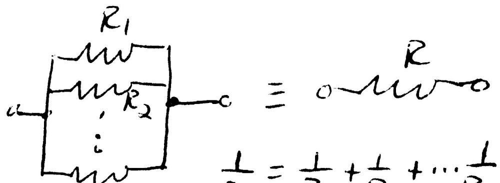
$$R = R_1 + R_2 + \dots R_N$$

Parallel:



$$R = \frac{R_1 R_2}{R_1 + R_2}$$

or $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$;



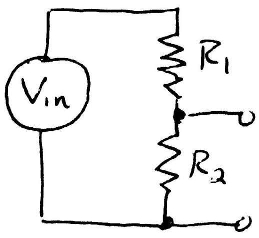
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_N}$$

These are useful because resistors come with only certain values. If you need a different value, you make it by combining the standard values in series and parallel.

VOLTAGE DIVIDER: This is a very common resistor circuit:

What is V_{out}?
The current is the same everywhere
So $I = V_{in}/(R_1 + R_2)$.
This current flows through R_2, giving:

$V_{out} = I \times R_2 = V_{in} \times R_2/(R_1 + R_2)$



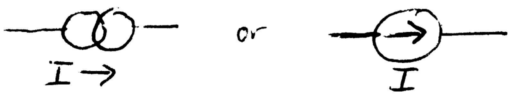
$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

We will use this circuit throughout the quarter so be sure you understand it. The potential difference across R_2 is a fraction of the potential difference across the entire circuit. Note the limits when $R_2 >> R_1$ and $R_2 << R_1$.

IDEAL VOLTAGE and CURRENT SOURCES: In circuits, we usually represent voltage sources (batteries or power supplies) as ideal: they provide the specified voltage difference independent of how much current flows from them. Similarly, an ideal current source (less common) provides the specified current independent of how much voltage is required to create that current. **Real** voltage and current sources have limitations that we can include if needed.

Ideal voltage source or batttery:

Ideal current source:



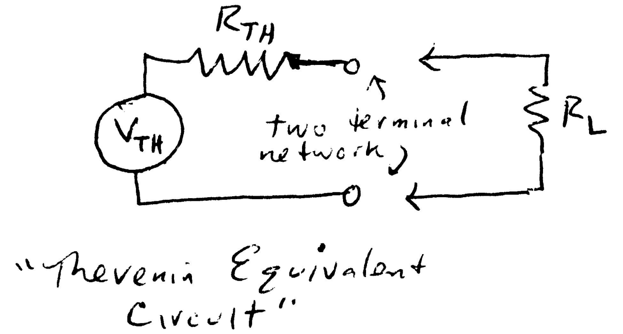
THEVENIN and NORTON THEOREMS: For circuits that contain only some combination of voltage sources, current sources, and resistors, the linear relationship between these devices always leads to results of the form: $\Delta V = aI + b$, where a and b are constants. That is, it takes only two parameters, a and b, to describe any two terminal network.

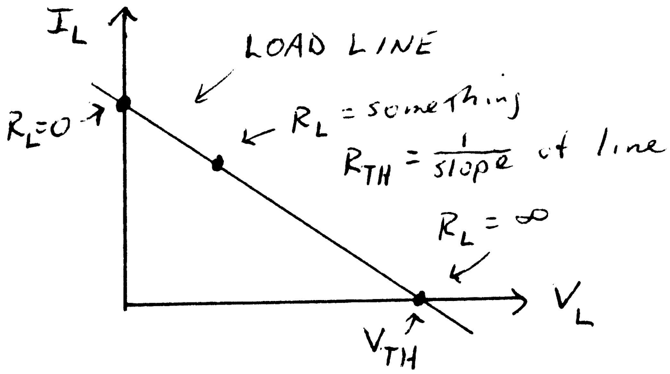
Thevenin's Theorem: Any two terminal network of sources and resistors is equivalent to a single resistor, R_{TH}, in series with a single voltage source, V_{TH}. (The two parameters are R_{TH} and V_{TH}.)

Norton's Theorem: (less useful) Any two terminal network of sources and resistors is equivalent to a single resistor, R_N, in parallel with a single current source, I_N.

These theorems are useful for reducing a complex part of a circuit into just two components, a voltage (current) source and a single resistor. BUT, it only works for linear circuit elements.

The equivalent circuit is defined by its 'load line', which is the plot of the current vs. voltage of an external 'load resistor' connected between the two terminals, with the load resistance as a parameter. Any two points on the load line are sufficient to determine V_{TH} and R_{TH}.





Easy Way: 1. Calculate or measure the open circuit voltage (when $R_L = \infty$)

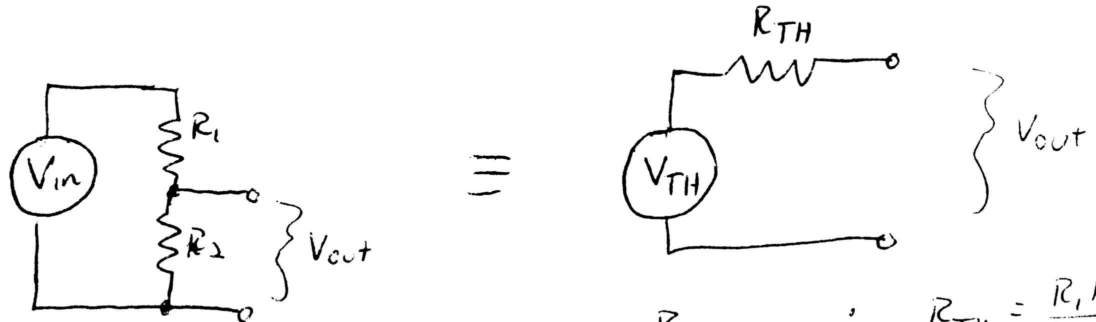
$$V_{open\text{-}circuit} = V_{TH}$$

2. Calculate or measure the short circuit current, I_{ss} (when $R_L = 0$)

$$R_{TH} = V_{TH}/I_{ss}$$

In the lab, it is not wise to short circuit two terminals together to measure a current, so instead, you normally connect a known load resistor, R_X, measure the current, and compute R_{TH}.

Example, Voltage Divider: We already computed that $V_{out} = V_{open\text{-}circuit} = V_{in} \times R_2/(R_1 + R_2)$
So $V_{TH} = V_{in} \times R_2/(R_1 + R_2)$



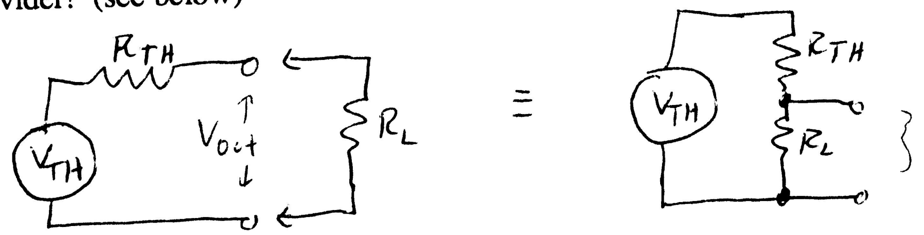
$V_{TH} = \frac{R_2}{R_1 + R_2} V_{in}$; $R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = R_1 // R_2$

And $I_{ss} = V_{in}/R_1$ (because when $R_L = 0$, no current flows through R_2 because there is no voltage difference across it).

This gives $R_{TH} = V_{TH}/I_{ss} = R_1 \times R_2/(R_1 + R_2) = R_1$ in parallel with R_2.

Note: this is just what you 'see' if you look into the V_{out} terminal.

So what? Well, a voltage divider isn't much good unless you connect something to it. That something is usually another resistor (or a circuit that acts as if it were a resistor). So what happens to a voltage divider if we connect a resistor, R_L, to it? We replace the voltage divider by its Thevenin equivalent circuit and connect R_L to it and find that we have made another voltage divider! (see below)



$V_{out} = \frac{R_L}{R_{TH} + R_L} \times V_{TH}$

Now we use our general result for voltage dividers to find that :

(1) $V_{out} = V_{TH} \times R_L/(R_{TH} + R_L)$

Eg. If $R_1 = R_2 = R_L = 10k$, and $V_{in} = 15$ V, then $V_{TH} = 7.5$ V and $R_{TH} = 5k$ and when we connect R_L to the circuit, $V_{out} = 5$ V. That is, connecting R_L to our voltage divider caused its output voltage to drop from 7.5 V to 5 V. In other words, our voltage divider is not a very good voltage source, as soon as we connect something to it, its voltage drops!

When will a voltage divider act as a good voltage source? Well by inspection of equation (1), we see that $V_{out} \approx V_{TH}$ when $R_L >> R_{TH}$. That is, the output of a voltage divider will not change much if we only steal a small fraction of the current flowing in it. In general, you would choose the resistors in the divider, R_1 and R_2, to be much smaller than the load resistance you want to connect to the divider.

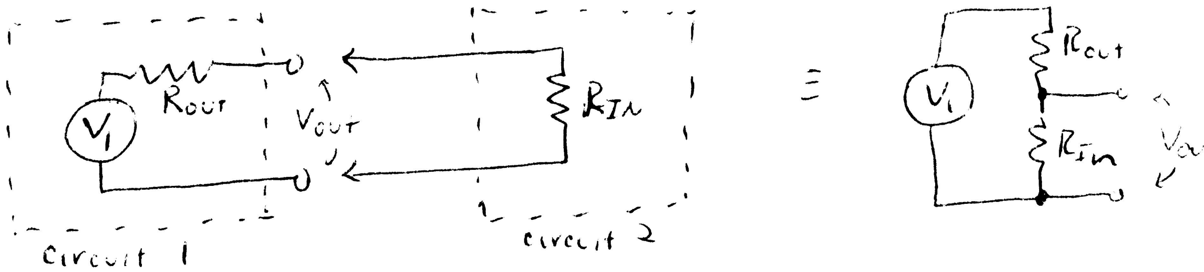
A good battery or voltage source is one whose output voltage does not change when a load is connected to it (and current flows). By Thevenin's theorem, a real battery or voltage source is equivalent to:

When talking about batteries or voltage sources, R_{TH} is often called R_{INT}, standing for the 'internal' resistance of the source. An ideal battery or voltage source has $R_{TH} = R_{INT} = 0$. The smaller the R_{INT}, the better the voltage source.

For example, a 12 V car battery has $R_{INT} \approx 0.02\ \Omega$, so that I = 50 Amps can be provided (to turn the starter motor) before the output voltage drops by 1 Volt to 11 Volts. Power supplies (with feedback -- more on this later) can have $R_{INT} \approx 0.0001\ \Omega$.

GENERALIZED OUTPUT RESISTANCE: The concept of R_{TH} or R_{INT} is central to the understanding of electronics. Even when you don't have just voltage sources and resistors (and hence a well defined R_{TH}), you can still think of any two terminal network as being a voltage source in series with a resistor, now referred to as the equivalent output resistance, or R_{out}. For any two terminal circuit, there is some voltage between the terminals, and if we connect a load resistance to the terminals, some current will flow. The relationship between ΔV and I may no longer be linear in general, but near any operating point, we can define $R_{out} = \Delta V_{out}/\Delta I_{out}$ and treat the circuit as a Thevenin equivalent circuit near that operating point.

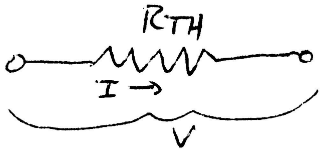
Similarly, when we connect any two terminal circuit to a second circuit (eg, the output of an amplifier to some speakers) we can think of the second circuit as being a load resistance (near the operating point). This equivalent load resistance is often called the 'input resistance', R_{in} of the second circuit. When we connect the two circuits together, we get a voltage divider! (see below)



Just like with our real voltage divider, to ensure that the second circuit does not change the output of the first circuit, we design things so that $R_{out} << R_{in}$.

This results applies, in particular to voltage measuring devices (like the oscilloscope or voltmeters). When we want to measure the voltage between two points, we don't want our measuring device to alter the voltage we want to measure. That is, we need the input resistance of our voltmeter to be much larger than the output resistance of the two terminals we are measuring. For this reason, the input resistance of voltmeters is made as high as possible (typically 10MΩ).

More on R_{TH}: More insight on the Thevenin equivalent resistance is obtained by considering small changes in the current and voltage:



$V = IR_{TH}$ implies $\delta V = R_{TH}\delta I$.

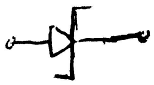
For an ideal voltage source, we want $\delta V = 0$ for all I. This can only happen if $R_{TH} = 0$, that is, an ideal voltage source has $R_{TH} = 0$.

For an ideal current source, we want $\delta I = \delta V/R_{TH} = 0$ for all V. This can only happen if $R_{TH} = \infty$, that is, an ideal current source has infinite R_{TH}.

DYNAMIC RESISTANCE: Even when V = IR is not true, such as for devices other than resistors, it is useful and always possible to define a dynamic resistance, R_{dyn}:

$R_{dyn} = dV/dI$ = slope of a graph of V vs. I for the device (which may change point to point).

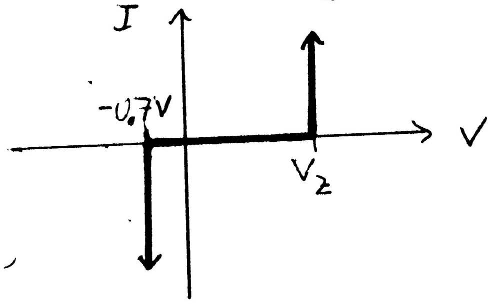
What we called R_{out} for a general two terminal circuit above is just R_{dyn} for that circuit. Near the operating point of the circuit, the circuit acts like a resistor whose value is R_{dyn}.

For example, consider a Zener Diode, (symbol ), a very non-linear device:

Ideal Zener Diode:

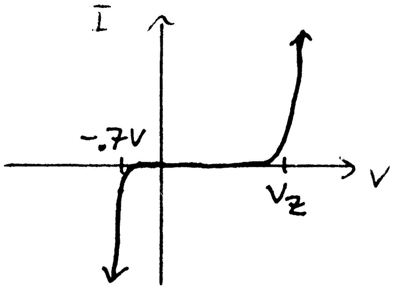
For $-.7V < V < V_Z$, $I = 0$ ($R_{dyn} = \infty$)

For $V < -.7V$ & $V > V_Z$, $R_{dyn} = 0$



Note, again, V refers to the voltage difference between the 2 ends of the diode

A real Zener diode has an I vs. V curve that looks as below, where the corners are exponential functions.



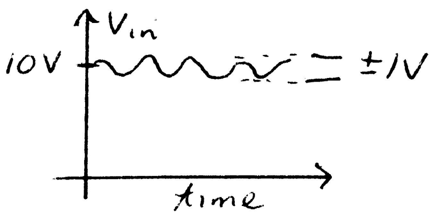
Real Zener Diode

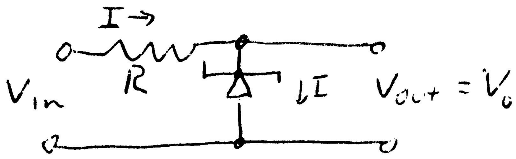
When you use a real Zener diode, you are given (in the spec sheets) R_{dyn} as a function of current.

For example, a 6 V Zener diode may have $R_{dyn} = 10\Omega$ for I = 1 mA and $R_{dyn} = 1\Omega$ for I = 10 mA.

If I = 1 mA is flowing through the diode, then a 10% change in I ($dI = 10^{-4}$ A) gives a change in voltage across the diode of $dV = R_{dyn} \times dI = 10\Omega \times 10^{-4}$ A = 1 mV. If you want a smaller change in voltage, run the zener with 10 mA flowing though it and dV = 0.1 mV for dI = 0.1 mA.

Zeners are typically used to generate stable voltages in a circuit. For example, if you have an unregulated 10 V voltage source that has a ripple of one volt on it and you want to generate a constant 6 V source, you might make the circuit below:





Then $I = (V_{in} - V_0)/R$ which gives $dI \times R = dV_{in} - dV_0$

But the zener itself gives $dV_0 = dI \times R_{dyn}$ and combining these two equations:

$dV_0 = dV_{in} \times R_{dyn}/(R + R_{dyn})$ -- the same as a voltage divider where R_{dyn} becomes the Zener

resistance! In fact, the circuit looks like a voltage divider where the Zener replaces R_2 and we have now learned that we can treat this circuit (and all others like it) as a voltage divider as long as we use the dynamic resistance of the non-linear elements. (The dynamic resistance linearizes the non-linear devices, making them act like resistors in circuit anaysis.)

In the example above, using V_{in} = 10 V +/- 1 V and selecting I = 1 mA (by making R = 4 kΩ)

And taking $R_{dyn} = 10\Omega$ for I = 1 mA, we have dV_0 = 1 V x 10/(4000 +10) = 2.5 mV,

That is, V_0 = 6V +/- 2.5 mV, a pretty good voltage source.

SUMMARY OF TERMINOLOGY:

For the output of a circuit, we refer to the equivalent output resistance, R_{out}, (which is the dynamic resistance of the output). If the circuit contains sources and resistors alone, $R_{out} = R_{TH}$.

R_{out} is also referred to as the resistance 'looking into the output'.

These all mean the same thing: $R_{out} = dV_{out}/dI_{out}$.

For the input to a circuit, $R_{in} = dV_{in}/dI_{in}$ and is called the input resistance, resistance 'looking into' the input, or the load resistance, R_L.

Usually when you are designing circuits, you pick components so that $R_{out} << R_{in}$ to ensure that connecting the circuits together does not alter the original output voltage. An exception to this rule is when you want to maximize the power transferred to the load circuit. In this case, it is easy to show that the maximum power transferred occurs when $R_{out} = R_{in}$.