

Electronic Concepts

First Edition

By Bill of Science-Ebook.com

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Hybrid e-book:

This e-book teaches electronics theory with focus on fault isolation. It is a very short book, yet it covers basic networks, transistor circuits and integrated circuit operation. Each chapter in this book links to our online circuit animations, and online tutorials. The book is designed to be a quick read. It is not intended to be the most comprehensive book ever written, but is intended to be the best free interactive Internet orientated e-book available today. This e-book is unique in that it teaches fault isolation in parallel with basic electronics. It is short because it does not include calculations too complex to perform while troubleshooting. I also have not included any topics that pertain to the brick and mortar world, such as safety, using tools or operating test equipment. For those of you who wish to specialize in electronics much more study will be required. **Click number 33** to see a large selection of online resources. Also, don't forget that most public libraries usually have a good selection of electronics books. This book is special in that the text of book works in conjunction with Web graphics and animation to provide a true multi-media experience.

Interactive Performance Orientated Education:

Students' performance is measured by their ability to perform realistic troubleshooting and circuit analysis. I have left testing of student by having them perform calculations on paper to conventional textbooks. However, I do teach how to perform calculations using JavaScript. See my online JavaScript site **Click number 35!** Each time I introduce a new electronics concept, I try to illustrate its usage with circuit animations and troubleshooting simulations. This teaches future technicians how to apply these new concepts to circuit troubleshooting, and teaches future engineers how these concepts are applied to circuits. Troubleshooting a circuit is the best way to test your comprehension of electronic topics. Simply reading about electronics can often be a bit boring, this can result in poor comprehension and concentration. Having student apply newly acquired knowledge to fault isolation assures meaningful learning.

Important Note: Asterisk (*) indicate multiplication. $Z = XY$ will be written as $Z = X*Y$. This convention is consistent with JavaScript.

Virtual Training (The new reality.)

Many aspects of electronic troubleshooting require the use of tools, test equipment and physical contact with Unit Under Test (UUT). Some faults can be seen or smelled. My simulations only include voltage, frequency, and current data. However, more and more of troubleshooting consists of interpreting data on a computer display. At times, automobile mechanics use computers to troubleshoot modern cars. Thus, virtual fault isolation is the new reality.

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Directions for using Hybrid e-book

Hybrid e-book:

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Chapter 1

Matter and Electricity

Charge, Fields, Voltage, Current, and Beams:

Review main points: This should be a review for those who have taken High school Physics or have read a book on physics or electricity.

1. Conventional current flows in the direction of E field. That is it flows from positive to negative potential. From here on "current flow" means conventional current flow.
2. Current normally flows in the direction of arrows on transistors and diode symbols.
3. Current in wire and resistors is due solely to electron flow.
4. Current in transistors and diodes is due to hole flow (positively charged molecules) and electron flow. The holes and the electrons move towards each other.
5. Positive charged particles flow in the direction of current and E fields.
6. Negative charged particles flow in opposite direction of current or E fields.
7. The EMF of a battery forces positive ions to move to the positive plate of a battery.
8. The EMF of a battery forces negative ions to move to the negative plate of a battery.
9. Holes (positively charged molecules) in silicon crystal lattice carry charge in semiconductors and move in direction of current. Current is in the direction of E field. Current direction is indicated by direction of arrow on transistor or diode.

About direction of current:

Case A: At this very moment a beam of electrons is traveling from the gun in the back or neck of the CRT directly towards your face (pretend you are looking at **Cathode Ray Tube [CRT]** if you have a flat screen monitor). Luckily for you the beam strikes the phosphorous-coated surface of the CRT prior to striking you. Now make a fist with your **left** hand directly in front of your face. Now point your thumb directly in the direction of your face. Your thumb is now pointing in the same direction as the electron beam. This electron beam produces a magnetic flux that curls about the beam in the direction of the fingers on your left hand.

Case B: Next, I want you to imagine that your CRT was actually an ion propulsion engine, and instead of electrons coming straight at you there were positive ions coming straight at you. Now make a fist with your **right** hand directly in front of your face. Now point your thumb directly in the direction of your face. Your thumb is now pointing in the

same direction as the positive ion beam. This ion beam produces a magnetic flux that curls about beam in the direction of the fingers on your right hand. Next, point your thumbs towards each other. Note that your fingers curl in the same direction. When a negative ion (or electron) and a positive ion move towards each other, the curl of the magnetic flux around the negative or positive ion curl in the same direction. The positive ion moves in the same direction as the electrostatic field vector, \mathbf{E} . Conventional current flow is in the same direction as the field vector \mathbf{E} , and hence is in the same direction as the positive ion or charge carrier. Electrons or negative ion flow is in the opposite direction of the \mathbf{E} vector.

The Right Hand Rule states that when you point your thumb in the direction of the electrostatic field (\mathbf{E}) that is driving the beam, the curl of your fingers indicates the direction of the Magnetic \mathbf{H} field. The remainder of my lectures will focus on teaching you how to troubleshoot, and actually allow you to self test your ability by using my simulations.

Chapter 2

Kirchhoff's and Ohm's Laws

Today Kirchhoff's laws appear fairly intuitive. If water in a pipe branched into two lines, then we would expect that the sum of the rate water flows out of the two pipes equals the rate of flow in the single pipe. However, in Mr. Ohm and Kirchhoff's time no one new of electrons, current was observed strictly in terms of the associated magnetic field about a wire. Thus, Kirchhoff's Laws revealed the nature of electric current. Likewise the linear relationship expressed by Ohm's law could not be implied from fluid mechanics. In fluid mechanics or hydraulics, pressure drop is not linear with respect to flow rate.

On a more practical note consider what it means if Kirchhoff's law does not appear to be being obeyed. What if you had three wires attached to a terminal, and measurement indicated that the current going into the terminal from one wire did not equal the current leaving the terminal in the remaining two wires. This would indicate that some current was going to ground via the terminal and traveling a path not shown on your circuit schematic. An obvious solder splash or a less obvious contaminant on surface of printed circuit board could cause this. In the case of multi-layer boards, a breakdown of insulation between layers is also a possible path of current flow.

Ohm's law states that current (in amperes) is equal to voltage (in volts) divided by the resistance (in ohms). This form of Ohm's law is most useful for technicians, because it is easy to measure voltage with a single probe of a grounded voltmeter. Connect the negative lead of your voltmeter to ground, circuit common, or power source return line, and you can measure the voltage on as many component junctions (commonly called circuit nodes) as are accessible to your meter probe. You can determine the current through a resistor by measuring the voltage on both sides of the resistor, calculating the difference in voltage, and then dividing the difference voltage (ΔV) by the resistance of the resistor. This resistance is written on the resistor in letters or frequently indicated by a color code. Resistor value can also be read from the circuit schematic. Usually one current calculation and a few voltage measurements tell you all you need to know about transistor, diode, operational amplifier, or vacuum tube circuits. Thus, you must be able to use Ohm's law to analyze what is going on not only in purely resistive circuits but also in the more complex circuits that you will study in future lessons.

When the power to a circuit is off, resistance of circuit component can be measured with an ohmmeter. Sometimes when you measure resistance across any component, measurement may also include resistance of parallel circuit branches. You can prevent this by lifting one end of the resistor from the circuit board. This e-book does not teach troubleshooting using an ohmmeter. It teaches fault isolation using only voltage, current, and frequency data.

Ohm's Law Animated Lesson:

Click number 1! There are two quantities that technicians keep track of in order to monitor circuit performance, for the purpose of fault isolation. They are current and voltage. The top circuit on this page shows current as a function of voltage. Or otherwise stated, it animates the equation $\text{current} = \text{voltage} \div \text{resistance}$. This relationship is known as Ohm's law. Voltage is usually the easiest quantity to measure, because it can be read simply by probing a single point. You can record the voltage on both ends of a resistor, and then read the resistor value from the circuit schematic. With this data Ohm's law can be used to calculate the current flowing through the resistor. The Animation shows current increasing as the voltage increases.

Click number 2! This circuit shows that when a constant current goes through a variable resistance, the voltage increases in proportion to the resistance. This is in accordance with Ohm's law in the form of $\text{Voltage} = \text{Current} \times \text{Resistance}$. Power dissipation in a resistor is proportional to the product of current and voltage. In this case current is constant; therefore, power dissipation is directly proportional to the voltage. This relationship is clearly demonstrated by the animation, when voltage and power are observed. Note that the power meter is connected in series with and across resistor, so that meter monitors both current and voltage.

Click number 3! This animation shows that the current through a fixed resistor is proportional to the applied voltage. Power is proportional to the product of voltage and current which are both increasing in step. From the equation, $\text{Power} = \text{Voltage} \times \text{current}$, it follows that $\text{Power} = \text{voltage squared} \div \text{resistance}$. If you care to do the algebra, simply substitute voltage divided by resistance into the equation. Remember to convert milli-amps, and milli-volts, to volts when you calculate power in units of watts. It is easy to do this using scientific notation.

$$P = I * V$$

$$I = V/R$$

$$P = V^2/R$$

Chapter 3

Series Circuits

Calculating Series Resistance:

Click number 4! In a series resistive circuit the same current flows in each resistor. That is the same current flows through R1, R2, R3, R4 and Rs (Rs is the internal resistance of the power source.) Note that all the resistors in the power circuit are equal to one ohm. Therefore, the voltage drop across each resistor is the same. Click TP1 button and note the voltage across the whole circuit is 8 volts. Click the other buttons and note the voltage at each test point. Calculate the voltage across each resistor. The results should be 2 volts.

The current in the circuit can be calculated using ohm's law. $I = 2 \text{ volts} / 1 \text{ ohm} = 2$ amperes, or $8 \text{ volts} / 4 \text{ ohms} = 2$ amperes.

Note that Rs, the internal resistance of the power source, and Vs, the electromotive force of the power source (EMF) have not been measured. To measure these quantities you must follow the following procedure:

1. Break the circuit. Removing a resistor would break circuit.
2. Measure voltage at TP1. The result would be 10 volts. (This step not simulated)
3. $V_s = \text{EMF} = 10 \text{ volts}$. In the closed circuit, 2 volts was dropped across Rs of the power source. In the case of a battery Rs is distributed throughout the battery.
4. Thus $R_s = V/I = 2 \text{ volts} / 2 \text{ amperes} = 1 \text{ ohm}$.

The total resistance of a series circuit is the sum of resistors in the circuit. In this case $R_t = R_1 + R_2 + R_3 + R_4 = 4 \text{ ohms}$. $I = V_{tp1} / 4 \text{ ohms} = 8 \text{ volts} / 4 \text{ ohms} = 2 \text{ Amps}$. Where: V_{tp1} is the voltage at TP1.

General procedure for testing resistors in series:

To test a two-resistor series circuit, measure the voltage drop across each resistor. Use Ohm's law to calculate current through each resistor. If they are not equal (within the limits of tolerance specified on the resistors), then one of the resistors is defective. If you have three or more resistors in series, calculate the current through each of the resistors. If they are not equal (within the limits of tolerance specified on the resistors), then one of the resistors is defective. The resistor with a significantly different calculated current is the defective one. The two resistors with the same calculated current are good.

Chapter 4

Parallel Circuits

Calculating Parallel Resistance:

Click number 5! In parallel circuits the same voltage is present across each resistor in the circuit. The current through R_1 is: $I_1 = V/R_1$ and the current through R_2 is: $I_2 = V/R_2$. For any number branch elements we can say: $I_N = V/R_N$. The total current in a parallel circuit is simply the sum of the currents in each branch:

$$I_T = I_1 + I_2 \dots + I_N$$

$$I_T = V/R_1 + V/R_2 \dots + V/R_N$$

$$I_T = V/R_T$$

$$I_T = V/R_1 + V/R_2 \dots + V/R_N$$

$$V/R_T = V/R_1 + V/R_2 \dots + V/R_N$$

$$1/R_T = 1/R_1 + 1/R_2 \dots + 1/R_N$$

You can use above equation to calculate value R_T . Substitute resistor values into right side of equations, and calculate the decimal value of each fraction on right side of equation. Then add the fractions and take the reciprocal. I teach how to program this calculation on my JavaScript site. **Click number 35**, if you wish to see my JavaScript site.

Estimating and Measuring Parallel Resistance:

In the parallel circuits the applied voltage is the same across each parallel branch, and the current in each branch equals the applied voltage divided by the resistance of the branch. The total current in a parallel circuit is always more than the current in any one branch even if one branch carries most of the current. This is true because the total current is simply the sum of the branch currents. This is usually obvious to most students. What this implies that is not always obvious to many students is the relationship of the total resistance to the branch resistance. The combined resistance of resistors in parallel is always less than the smallest branch resistance. For example, if you had 100,000, 10,000 and 1000 ohm resistor in parallel, the combined resistance would be less than 1000-ohms. If you connected an ohmmeter across the 1000-ohm resistor you should measure slightly less than 1000-ohms. If you measure across the 10,000 or 100,000 ohm resistor you

should also measure slightly less than 1000-ohm. If you measure across the 1000-ohm resistor and read more than 1000-ohms, then you can be certain the 1000-ohm resistor is out of tolerance or open. If you don't measure the same resistance across all three resistors then they are not really connected in parallel anymore, and you should start looking for an open wire or land or a cold solder joint at one of the resistor nodes.

Of course you can also make ohmmeter measurements when circuit or system power is off. You may not realize that it is also better to make resistance measurement with the circuit board out of the electronic system. For example, if you had 1000-ohm resistor in series with a 2000-ohm resistor and one resistor went to ground and the other resistor went to 5 volts. Then, when you measured across both resistors you would get a reading of 3000 ohms if the board were out of the system. However, a measurement made on the same circuit board when circuit board is in system might be much lower. In above example, even though the power is turned off you might still read much less than 3000 ohms. That is because the power source provides a parallel pathway for meter current to flow from the 5-volt bus to ground. That is the power supply is in parallel with the 1000-ohm and 2000-ohm series combination.

Parallel Circuits Animated Lesson:

Click number 5! In a parallel circuit the voltage across each resistor is the same. Thus, current is strictly a function of resistance. In the animation shown on this page, resistors are switched in and out of a parallel circuit, causing total current to the circuit to vary. You are asked to deduce from the total current variations whether the circuit is defective. If it is defective, you should determine which resistor is suspect. Previously I stated that current is not easy to measure. However, total current readings are frequently available. Sometimes they can be read directly off a laboratory power supply. Sometimes it is easy to connect a current probe around a wire between the power source and the circuit board.

Chapter 5

Series and Parallel Combination

We analyze series-parallel circuits in stages. We replace several resistor values with a single one. For example, if two series resistors (R1 and R2) were in series with a parallel pair of resistors (R3 + R4) we would write.

$R_{sumA} = R1 + R2$, Where two resistors R1 and R2 are in series.

$1/R_{sumB} = 1/R3 + 1/R4$, Where two resistors R3 and R4 are in parallel.

$R_{total} = R_{sumA} + R_{sumB}$

Recommended outside reading: **Click 26**

Click number 6! Most electronic circuits are a combination of series and parallel components. When we analyze parallel, series circuits we reduce the circuit to an equivalent purely series circuit or equivalent purely parallel circuit. For example, when the two-milli-ampere range is selected, resistor one, two, and three can be combined into a single resistor, that we can call "branch one total". Now we have a parallel circuit consisting of "branch one total" resistance and the meter resistance. We can now calculate the current that should be flowing through the three resistors and the resistance of the meter. Troubleshooting is often much easier. If a circuit has a fault, we can simply measure the voltage drop across each resistor of the voltage divider. Then using Ohm's law calculate the current in each resistor. If for example, we find that resistor number two's calculated current is different than the other two calculated currents, we know that "resistor number two" is the defective component. Our troubleshooting is complete. If we find that the voltage divider is not defective, then the meter must be the problem.

Click number 7! Here you see a JavaScript version of the same circuit that we just saw in GIF format. Observe that the **Unit Under Test (UUT)** meter reading is not intended to simulate a digital meter, but indicates the position of a needle on an analog meter movement. The Meter reads pegged when the reading is more than 105% of full scale. You can study normal operation of the meter or insert a fault. You must step the voltage up or down in order to activate the simulation. Then you will have total control of the power supply, and meter switch position. You can also select which point you wish to probe with your virtual voltmeter.

Click number 25! Here we see a GIF circuit animation consisting of a parallel circuit in series with a resistor R_s (R series). Recall that in the previous chapters, I stated that the total resistance of resistors in parallel was always less than the smallest parallel resistor. In this case the smallest resistor is 1k. Thus, I would estimate that the resistance of the 1k and 10k resistor was .9k. The exact calculated value of the 1k and 10k resistor in parallel is 909 ohms ($R_p = 909$ ohms). The reason I emphasize estimating techniques is that it is hard to use a calculator when you have a voltmeter probe in your hands. Thus we have reduced this complex circuit to a simple series circuit with the equation: $R_{total} = R_s + R_p$.

Chapter 6

Alternating Current

Power Generation:

Rotating a coil in a magnetic field creates alternating current, and is the method that is used to create most of the world's electricity. Even DC generators create a sinusoidal voltage that is rectified by a commutator. AC electricity is better suited for long distance power transmission than DC electricity. Alternating current voltage can be stepped up to over 100,000 volts, making it possible to transmit power for hundreds of miles over High Voltage transmission lines. The voltage can then be reduced to 120 volts (US single phase) or 220 volts (European single phase) for safe home use. The transformers that you see on poles or behind chain link fences are used to step down high voltage to a safer level.

Click number 28! Open reading list, then select *Generator Applet*:

Power Generation is the province of electrical engineering not electronic engineering. One aspect of electronics deals with AC signal generation, filtering, and amplification. It encompasses audio signals, radio signals, radar signals and the like. Of course most electronic system do have power supplies that convert AC to the DC voltages required by vacuum tube, transistor, and integrated circuits.

Electronic AC Signal Generation:

Click number 28! Select **Electromagnetic Oscillating Circuit**. This is one of the simplest ways to generate a sinusoidal signal. The capacitor is charged by DC supply voltage. Potential energy is stored in the electrostatic E field between the plates of the capacitor. The capacitor discharges through the coil. When the capacitor discharges to zero volts the current in coil reaches a maximum. At this point the potential energy of the E field is reduced to zero and the current is at a maximum. All the potential energy of capacitor is now kinetic energy stored in the coil magnetic H field. As the H field collapses, the change in magnetic flux sustains the current flow through it. This current causes the capacitor to charge to a level opposite in polarity with respect to original voltage. This transfers the energy back to the capacitor E field. This cycle repeats indefinitely unless damped. This oscillating circuit is frequently referred to as a tank circuit. An ideal tank circuit has no resistance and will oscillate indefinitely. Of course the wire of the inductors has some resistance, which will cause some damping of the oscillations. Heat can also be generated in the electrolyte of the capacitor. This will also contribute to oscillation damping. An electromagnetic oscillator can also radiate energy in the form of electromagnetic radiation. Electromagnetic radiation consists of an oscillating E and H fields in space. This radiation propagates at the speed of light.

AC Signals are usually sinusoidal:

The equation below defines a sinusoidal waveform. Electromagnetic radiation in space propagates as a sinusoidal wave moving at the speed of light.

$V = A \sin \omega t$ where $\omega = 2 \pi f$ or angular velocity.

Ohm's and Kirchhoff's Laws:

In purely capacitive and purely inductive circuits, Ohm's and Kirchhoff's Laws still apply. Perform AC calculation in the same manner as you performed DC calculations. Simply substitute V_{ac} for V_{dc} . In purely inductive or purely capacitive circuits, you must first calculate the inductive or capacitive reactance before applying Ohm's law. Inductive and capacitive reactance are a function of frequency. Reactance is expressed in ohms.

Chapter 7

Capacitive Reactance

Capacitive Reactance:

Capacitors block direct current and pass high frequencies. Capacitance reactance is high for low frequencies and low for high frequencies.

$$X_C = 1/\omega C \text{ where } \omega = 2\pi f \text{ or } \omega = \text{angular velocity.}$$
$$\pi = 3.141... \text{ and } f = \text{frequency.}$$

Click number 8! Observe how current increases with frequency. **Click number 34!**
View example 2 to see how current increases with increasing capacitance, C. Example 3 shows capacitors in series.

Capacitive Reactance in Series Circuit:

Once you calculate impedance for a strictly capacitive circuit, use Ohm's law directly. For example let us consider a voltage divider consisting of three capacitors C1, C2, and C3 in series. Total impedance (**Z total**) of the series circuit is as follows:

$$Z_{\text{total}} = X_{C1} + X_{C2} + X_{C3}, \quad I = V / Z_{\text{total}}$$
$$V = I(Z_{\text{total}}) \text{ where } V \text{ is the voltage across the three capacitors.}$$

The voltage across each component is given by:

$$V1 = I * X_{C1}, \quad V2 = I * X_{C2}, \quad V3 = I * X_{C3}$$

The general form of the equation is:

$$Z_{\text{total}} = X_{C1} + X_{C2} + X_{C3} \dots + X_{CN}$$

Capacitive Reactance in a Parallel Circuit:

$$1/Z_{\text{total}} = 1/X_{C1} + 1/X_{C2} + 1/X_{C3} \dots + 1/X_{CN}$$

Capacitor and Resistor in Series:

The analysis of **RCL** circuit usually involves vectors or complex algebra. **RC** circuit's vector analysis only requires a straightforward application of the Pythagorean theorem to derive the following formulae.

$$\mathbf{Z\ total} = (\mathbf{X_c^2 + R^2})^{1/2}, \mathbf{I = V / Z\ total}, \text{ where V is the total voltage across RC circuit.}$$

The above equation is the result of vector addition using the Pythagorean theorem. **Z** total is the hypotenuse, and vectors **X_C** and **R** form the two sides of the triangle.

Animated Lesson about Vector analysis of Reactance

Click number 28! Select *AC Tutorial with Animations* from Reading list. This tutorial has great graphics and explains alternating current and reactance rather well. This site teaches using animated vectors and graphs. A full understanding of AC, reactance and vector analysis requires much mathematics and physics. I would recommend that my readers not spend too much time on this subject at present. Continue reading this book. You can always come back to sites on my reading lists when you complete this chapter.

Capacitors in Series:

Capacitors in series result in a total capacitance less than the smallest capacitor in the series circuit. Two 4-microfarad capacitors in series produce a total capacitance of 2 microfarad.

$$1/C_{\text{total}} = 1/C_1 + 1/C_2 + 1/C_3 \dots + 1/C_N$$

Capacitors in Parallel:

Capacitors in parallel result in a total capacitance equal to the sum of the capacitor values.

$$\mathbf{C_{total} = C_1 + C_2 + C_3 \dots C_N}$$

Chapter 8

Inductive Reactance

Inductive Reactance:

Inductors block high frequencies and pass direct current. Inductive reactance is high for high frequencies and low for low frequencies.

$$X_L = \omega * L, \text{ where } \omega = 2 * \pi * f \text{ or } \omega = \text{angular velocity.}$$

Inductive Reactance in Series Circuit:

Once you calculate impedance for a strictly capacitive circuit you can apply Ohm's law. For example, let us consider a voltage divider consisting of three inductor L1, L2, and L3 in series. Total impedance (**Z total**) of the series circuit is as follows:

$$\begin{aligned} \mathbf{Z \text{ total} = } X_{L1} + X_{L2} + X_{L3}, \mathbf{I = } V / \mathbf{Z \text{ total}} \\ V = I(\mathbf{Z \text{ total}}) \text{ where } V \text{ is the voltage across the three capacitors.} \end{aligned}$$

The voltage across each component is given by:

$$\mathbf{V1 = I } X_{L1}, \mathbf{V2 = I } X_{L2}, \mathbf{V3 = I } X_{L3}$$

The general form of the equation is:

$$\mathbf{Z \text{ total} = } X_{L1} + X_{L2} + X_{L3} \dots + X_{LN}$$

Inductive Reactance in a Parallel Circuit:

$$\mathbf{1/Z \text{ total} = } 1/ X_{L1} + 1/ X_{L2} + 1/ X_{L3} \dots + 1/ X_{LN}$$

Inductor and Resistor in Series:

The analysis of **RCL** circuit usually involves vectors or complex algebra. **RL** circuit's vector analysis only requires a straightforward application of the Pythagorean to derive the following formulae.

$$\mathbf{Z \text{ total} = (X_L^2 + R^2)^{1/2}}, \mathbf{I = V / Z \text{ total}}, \text{ where } V \text{ is the total voltage across RL circuit.}$$

The above equation is the result of vector addition using the Pythagorean theorem. **Z total** is the hypotenuse, and vectors **X_L** and **R** form the two sides of the triangle.

Inductors in Parallel:

Inductors in parallel result in a total inductance less than the smallest inductor in the series circuit. Two 4 milli-henry inductors in parallel produce an inductance of 2 milli-henries.

$$1/L_{\text{total}} = 1/L_1 + 1/L_2 + 1/L_3 \dots + 1/L_N$$

Inductors in Series:

Inductors in series result in a total inductance equal to the sum of the inductor values.

$$L_{\text{total}} = L_1 + L_2 + L_3 \dots L_N$$

Inductor Physics:

Self-inductance is the ability of wire to produce an induced voltage in opposition to the applied voltage. The inductance unit of measure is the Henry (symbol H). Typical values are usually in the milli-henry (symbol mH) or micro-henry (μH) range. The longer a wire the greater the inductance of the wire. Inductance effects power transmission lines, communication lines, and antennas. Electronics circuits use inductors consisting of coils of wire. For air core inductors inductance is proportional to the area of loop and the number loops. Iron cores increase an inductor's inductance greatly.

Chapter 9

Resonance

The inductance reactance vector and the capacitive reactance vector point in the opposite directions. Thus, when an inductor and capacitor are placed in series, their reactances subtract from one another. At high frequencies the series circuit will appear as an inductive reactance. At low frequencies the inductor and capacitor series circuit will appear as a capacitive reactance. At some in between frequency the inductance and the capacitance will be equal. The sum of these vector quantities will be zero. This frequency is called the resonant frequency.

$$\omega = 1/(LC)^{1/2} \text{ where } \omega = 2\pi f \text{ or simply } \omega = \text{angular velocity.}$$

$\pi = 3.141\dots$, and f = frequency.

If you want online impedance calculators, **click number 8**. Near the bottom of page, you will find a link to some handy calculators. You might want to bookmark these calculators for future use.

Click number 37! Observe the Chepyshev filter, bottom animation. Note that at frequency of about 700 kHz, the voltage at TP1 dips to 2.23 V. At 700 kHz the series circuit formed by C1 and L1 exhibits resonance. The impedance of a resonant circuit is low compared to R_s , and therefore a dip in signal amplitude occurs at TP1. At this resonant frequency the current in the series circuit $R_s/C1/L1$ is maximum. Thus, the voltage across L1 peaks to 16.29 volts. This is characteristic of resonance.

If you calculated the resonant frequency for L1 and C1 you would get 877 kHz, not the 700 kHz we observed in the bottom animation. That is because the second stage of this filter affects the resonant frequency of the first stage. In the top animation the first stage of the filter has been isolated. Note that the voltage at TP1 dips to 43 milli-volts at 877 kHz. The voltage at TP1 would dip even lower if L1 were an ideal inductor. L1 has a resistance of .1 ohms. This prevents the impedance of L1/C1 series circuit from going to zero at the resonant frequency.

Chapter 10

Filters

An electronic filter separates signals of different frequencies from one another. For example, an audio signal could also be carrying a radio frequency (RF) signal on it. A low-pass filter could be used to pass audio frequencies below 20 kHz and stop RF signals, which are well above 20 kHz. A low-pass filter is also used to separate DC power from AC ripple passed by the power source. A simple RC circuit can be used as a filter. **Click number 8!** Observe RC filter near bottom of page. For a simple RC circuit the cutoff frequency can be calculated as $1/2 \cdot \pi \cdot R \cdot C$ ($\pi = 3.141\dots$). Thus, we can relate cutoff frequency directly to the time constant ($R \cdot C$) of a circuit. The product RC is referred to as the time constant. A time constant is the time it takes a capacitor to charge to 63% of DC voltage applied through a resistor. You can see the effect of a time constant on a square wave in oscilloscope animation (center of Web page).

The cutoff frequency is the point that the amplitude of the output signal is half the value of the input signal. Comparing input to output is the standard method of defining the cutoff frequency of a filter. A second method is to simply compare the amplitude of the signal output in the pass band to the signal output above the pass band. This second method allows you to find the cutoff frequency with only a single meter or scope connection. Simply connect probe to output of filter and adjust frequency roughly to where you get highest output. This puts you in the band pass range of the filter. When frequency is well in the pass band, you can vary the frequency up and down without causing a change in the output amplitude. Next, increase or decrease the frequencies rapidly until the output signal amplitude starts to drop off rapidly. Now adjust the frequency carefully until the output voltage amplitude is halved.

Click number 9! You are now looking at a 5 element Chebyshev High Pass Filter. View the circuit response curve. The power fall off rate is far greater than the 6 decibels per octave power fall off rate of a simple RC filter. This filter is designed for a fifty-ohm signal source and a fifty-ohm load. Note that at high frequencies the filter acts almost like a short. If you think of the filter as a short, the circuit reduces to a voltage divider consisting of two fifty-ohm resistors. Thus, at all frequencies in the band pass the resistors divide the voltage by a factor of two, which is a three decibel reduction in voltage, and a six-decibel reduction in power. Note that at some frequencies the output is greater than the input at test point one. This makes sense if you consider that the capacitors and inductors form series resonant circuits.

Click number 10! The Chebyshev Low Pass Filter is similar to the Chebyshev High Pass Filter with respect to fall off rate and number of components. However, the coils pass low frequencies, while the capacitor short circuit very high frequencies to ground. In the High Pass filter the capacitors passed high frequencies and the coils shorted low frequencies to ground. The Radio Frequency and Microwave filters that you are likely to encounter in industry will be inside of metal containers. This type of construction prevents radiation output and external radiation pickup. It also provides a defined ground plane for the filter components. The metal container does not eliminate stray capacitance between

components and ground, but provides the filter designer with a well-defined ground plane on which filter components can be mounted. A design engineer can consider the ground plane of the metal container as constant rather variable that is subject to the placement of other system components or wires. Encapsulation also ensures that once the filter is built, touching any component cannot effect the tuning. Encapsulation also simplifies fault isolation, because repair is accomplished simply by replacing the entire encapsulated filter.

Chapter 11

Diodes

A simple pn-junction forms a diode. Current can flow through diode only in one direction. If you think of the diode symbol as an arrowhead touching a vertical line, then the arrowhead points in the direction of conventional current. I hope you recall that conventional current flow is in the opposite direction of electrons. The arrowhead represents the anode of the diode, and the vertical line represents the cathode of the diode. The anode is composed of the p-type material and the cathode is made of the n-type material. When the diode is reverse biased no current will flow, and the diode appears open. When a diode is forward biased current flows freely through the diode. The ideal forward biased diode acts as a short. Silicon diodes require .6V and a germanium diode requires only .3V to be forward biased. An ideal diode can be viewed as a switch that closes when forward biased and opens when reverse biased. This simple view of a diode is adequate for qualitative analysis of circuits and is often all that is required to troubleshoot a system. For the purpose of discussion we will assume a diode is silicon unless otherwise specified.

PN-Junction Physics:

Pure silicon is an insulator. The silicon is doped with impurities to produce n-type and p-type silicon. The doped silicon is a semiconductor. The n-type silicon is doped with a metal such as Aluminum or Gallium. The n-type silicon has an excess of electrons in its outer shell. Free electrons carry the current in n-type material. The p-type material is doped with a none-metal such as phosphorous or arsenic. The p-type material is said to have a shortage of electrons in its outer shell. In the p-type material current is carried by positively charged holes. Note that having excess or a shortage of electrons describes the outer band of an element and does not imply that the elements carry a static charge. For those of you who have had High school chemistry recall the chapter on valance. You do not need to understand valance or chemistry to understand diode or transistor electronics. Just remember that we call the positive charge carriers in p-type silicon *holes* and the excess charge carriers in the n-type material free electrons. Both holes and free electrons make the silicon more conductive than an insulator and less conductive than a metal. What occurs at the junction of these semiconductors makes solid state diodes and transistors possible.

Current in a diode consists of a combination of hole and free electron flow. In the n-type material electrons move toward the PN junction. In the p-type material positively charged holes move toward the junction. The holes move in the direction of the arrowhead on the diode symbol. When the forward bias becomes strong enough to overcome the barrier potential of the junction (referred to as depletion layer), then the electrons from the valance band of the n-type materials can cross the depletion layer and fill the holes in the p-type material resulting in current. Note that current consists of electrons and positive holes moving towards each other. Note that the arrow on a diode symbol points in direction of positive hole flow and conventional current flow. The electrons move in the opposite direction of conventional current. You can learn more

about the physics of semiconductors from sites on our Reading List ([Click number 30 for reading list](#)). Semiconductor physics is not required to troubleshoot or even to design and build a circuit; therefore, I will not spend much time on the solid state physics or quantum mechanics.

Types of Diodes:

The diode is the simplest of the semiconductor components. There are many diode types with specific applications. The term " diode" by itself refers to a basic PN junction. The basic PN junction diode is most frequently used for rectification. All other types of diodes must be specified by type, such as Zener diode, Light Emitting Diode (LED), and many others. The n-type material of the PN junction is called the cathode, and the p-type material is called the anode. When the Anode is positive with respect to the cathode current will flow. The rules for diode conduction can be simply stated as:

- (1) The arrow must point toward the more negative terminal. In other words the anode must be positive.
- (2) The voltage difference across diode must exceed 0.3V for germanium and 0.7V for silicon. When forward biased, restriction of current by the depletion area is eliminated and resistance of diode is reduced to its bulk resistance (typically 25 Ohms).
- (3) When the diode is reverse biased the depletion area is enlarged and the current is reduced to near zero.

Diode Rectifier:

Click number 11! Observe rectifier circuit at top of page. The transformer provides a voltage changing in polarity to the anodes of both diodes. Current can only flow in the direction of diode arrows. The diode output current varies in amplitude, but it can only flow in direction of arrows. Thus, the output of the circuit is called direct current or rectified AC. The capacitor reduces the amplitude of the output variations. If the capacitor is made large enough, the output will appear to be a constant DC voltage. Observe the oscilloscope display of the rectifier output. The sine wave is the voltage at TP1. The second trace displays the output of the rectifier. Note that the output exhibits a peak voltage at both the maximum and minimum of the sine wave. The peak at the minimum is the result of current through CR2, while the in phase peak is the result of current flowing through CR1. This process is called rectification. The reduction of the output fluctuation amplitude by the capacitor is called filtration. Those fluctuations not filtered ride on the DC voltage and are called " ripple voltage". Note that the ripple voltage displayed on scope is twice the frequency of the AC input.

Zener Diode:

When diodes are reverse biased, they ideally draw no current. Real diodes draw very little current when reverse biased, because the depletion layer size increases as reverse

bias increases. This only holds true as long as the reverse bias is maintained below the *peak reverse voltage* (V_{RRM}). When this voltage is exceeded, the diode will break down and conduct hard preventing voltage from going much above the V_{RRM} . This sudden surge in current is called the avalanche current. Avalanche current results from free electrons bumping more electrons free of their molecular bonds, which in turn bump more electrons free. This chain reaction or avalanche will destroy the PN junction in the same manner that arcing would destroy an insulator in a cable or the dielectric of a capacitor. Zener diodes are specially designed to withstand this avalanche current; thus, their peak reverse voltage makes a good voltage regulator.

Click number 11! Observe regulator power supply circuit at middle of page. The voltage at TP2 is regulated at 7.4 V by the Zener diode. The current draw through the 220-ohm resistor is:

$$V_{R2} = 15V - 7.4V = 7.6V$$

$$I_{R2} = 7.6 V / R2 = 7.6 V / 220\text{-ohms} = 34.5\text{- milli amps.}$$

As long as less than 34 milli-amps is drawn through R2, the voltage at TP2 could be used directly as a regulated voltage source. Adding the transistor results in a regulated current output many times higher than 34 milli-amps. Note that the PN (Base Emitter) junction of the transistor drops the voltage regulator output voltage by **.7V** to 6.77V. At first glance you might think that the transistor has only added another diode to the *Regulated Power Supply*. In one respect it has, some current does flow from TP2 through the transistor base emitter junction to the *Rload*. The difference between a transistor and a pair of diodes is power amplification. When the base emitter PN junction is forward biased and conducts a small amount of current, a large current flows from TP1 to *Rload* via the collector to emitter current flow. This process of controlling a lot of power with a little power is called *Amplification*.

Varactor Diode:

A Varactor diode is designed to exhibit considerable capacitance when reversed biased. In this state it is like a polarized capacitor in that it does not conduct direct current. The p-type material constitutes the negative plate of the capacitor, and n-type material constitutes the positive plate of the capacitor. The depletion region of the diode is depleted of charge carriers; therefore it acts as an insulator or the dielectric of the capacitor. As negative bias is increased, the depletion region becomes greater and the distance between the two plates is effectively increased. Capacitance decreases as distance between plates increases. Thus, the capacitance decreases as reverse bias increases. This provides a way of varying capacitance with voltage. This means a circuit designer can use a Varactor to vary capacitance electronically. When this capacitor is part of a tuned radio frequency oscillator, the frequency of oscillator can be controlled electronically. If the inverse bias voltage were varied with an audio signal, the radio frequency oscillator frequency would vary with the amplitude of the audio frequency. This is called frequency modulation or simply FM.

Chapter 12

Transistors

You can spend a great deal of time learning about transistor physics. **Click number 30!** Select site from reading list. When you can picture the general structure of transistors and feel you have had enough physics, than read the following simplified explanation of transistor operation.

A transistor can be viewed as two diodes back to back. The base collector junction forms one diode, and the base emitter junction forms the other. In a circuit the transistor base collector PN junction should always be reverse biased. Ideally no current will flow between the base and collector. When the base emitter is reverse biased, no current will flow from the base to emitter, and the transistor will be off (no conduction). When the base emitter is forward biased, current will flow from the base to emitter, and the transistor will be on (conductive). Current will not only flow between base and emitter, but a much greater current will flow from collector to emitter. Current is amplified, and voltage is not attenuated; therefore, power is also amplified.

Click number 29! Consider a NPN transistor. The n-type collector should be positive with respect to both the n-type emitter and the p-type base. Ideally no current will flow from the base to collector, because the collector/base pn-junction is reverse biased. Observe animation! Note that the n-type collector of the transistor is connected to + 15V. The base is connected to ground. This arrangement assures that the collector/base pn-junction is reverse biased. The base/emitter pn-junction controls transistor operation. A negative voltage is applied to emitter to forward bias the base/emitter pn-junction. The current meters indicate a rapid increase of base current as the bias goes from .6 V to .8 V. The meters also indicate that the collector current also increases and contributes 99% of the emitter current. A small base current is controlling a large collector current. The current gain is well over a hundred. This clearly indicates that forward biasing of base/emitter junction results in collector to emitter current flow. Note, that this collector to emitter is n-type to n-type current flow. This current flow cannot be explained with the simple concept of back to back diodes. This current amplification is what makes the transistor different than back to back diodes. A simple explanation of this is that the forward bias reduces the depletion area, and therefore current can flow. The actual physics is not simple. **Click number 30,** and select a tutorial to read for a better understanding of the physics of the transistor. I choose not to teach physics in this e-book. Physics is not needed to troubleshoot a circuit or design a transistor circuit. Any explanation I would give would be too complex for those who have not had physics and chemistry, or it would appear lame to those who know solid state physics and quantum mechanics. I will teach transistor circuit operation and troubleshooting using simulations. We will study a transistor voltage regulator in chapter 14 and a transistor amplifier in chapter 15.

Click number 30! Select from reading list to learn more about transistor physics.

Chapter 13

Transistor Regulated Power Supply

Click number 24! Observe transistor power supply. A power supply consists of an unregulated power source and a voltage regulator. The unregulated voltage must be higher than the desired regulated voltage to maintain proper bias for the series regulator transistor. Simply stated a series regulator reduces input voltage to the desired regulated output voltage. In this simulation, I used a battery for the unregulated input. Since a battery outputs only DC, I varied the load to generate changing current. This changing current resulted in a changing voltage drop across the internal resistance of battery, R_s . This enables simulation to show how regulator adjusts to accommodate a varying load.

Feedback is the key to regulator operation. Assume output voltage goes lower for any reason. Then, the lower voltage is picked off by the potentiometer, and this voltage is compared to the Zener reference via the base/emitter junction of the transistor. The lower voltage causes transistor to conduct less; thus, the voltage at the transistor collector goes higher. This higher voltage causes transistor T2 and T1 to conduct harder, and raises output voltage.

Click number 24! We are now looking at a transistor regulated power supply. Observe baseline operation of regulated power supply below. Then troubleshoot fault number one to fault number four below. This voltage regulator simulation uses a battery rather than a rectifier as a power source. Since batteries do not generate ripple voltage, I provided a dynamic load to demonstrate that voltage regulators not only adjust for slow changes in current but also can attenuate ripple voltages. They also adjust for rapid changes in load current demands. The frequencies I used were 50 hertz, 60, 400, and 1200 hertz corresponding to European, American, single-phase 400 hertz and three phase 400 hertz ripple frequencies respectively. Thus, it illustrates the effect of the regulator on ripple voltage or rapid load changes.

Chapter 14

Transistor Amplifiers

Click number 31! View the GIF animations. The first two frames of animation show DC levels. The latter frames show small signal amplification over a range of frequencies. The amplifier consists of three transistors with a common 12V ($V_{cc}=12V$) power source. A small signal input of 1 milli-volt is amplified to as much as 1 volt at 100 hz. Most of the current through Q1 and Q2 flows from collector to emitter. Only a very small amount of the current passes from the base to the emitter. Therefore, the same current flows through both the emitter and collector resistor. Likewise, a change in transistor conduction results in a small change in both the collector and emitter current, which we will refer to as **delta I**. The change in collector voltage is: **delta Vc = delta I * Rc**. The change in emitter voltage is: **delta V_E = delta I * R_E**. It follows that the ratio of **delta Vc/ delta V_E = Rc/ R_E**. For small signal variations the emitter voltage tracks the base voltage, **delta V_B = delta V_E**. As derived below **Voltage Gain = Rc/ R_E**.

$$\begin{aligned}\text{delta Vc/ delta V}_E &= \text{Rc/ R}_E \\ \text{delta V}_B &= \text{delta V}_E \\ \text{delta Vc/ delta V}_B &= \text{Rc/ R}_E \\ \text{delta Vc/ delta V}_B &= \text{Voltage Gain by definition.} \\ \text{Voltage Gain} &= \text{Rc/ R}_E\end{aligned}$$

In the first amplifier stage, the ratio of collector resistance to emitter resistance is 110 [22,000/200 = 110]. The animation shows us that at 100 Hz the voltage gain is about 90. The difference can be explained by other factors such as loading by the next stage. The transistor parameters will effect actual voltage output. The ratio **R_C/ R_E** is actually the maximum DC or low frequency gain that can be achieved by this transistor circuit. It is a handy indicator of how the circuit is intended to operate. When troubleshooting this calculation can be performed in ones head; thus, you don't have to waste time putting down a meter or scope probe in order to pick up a pencil or a calculator.

I set the operating point of the Q1 circuit at 2.7V by selecting a base resistance of 4.4-M (4,400,000.00-ohm) for the resistor in the base circuit of Q1. The Q1 operating point is not centered. Since only small signals are being amplified by the first stage, centering of operating point is not critical. There is little chance that the 1 milli-volt-input signal will drive the transistor into saturation or cutoff.

In the Amplifier second stage, Q2's operating point is better centered. The ratio R_C/R_E is 5.2 [12000/2300 = 5.217]. Observing the animation at 100 Hz, we see that the voltage gain is 5.38 [481.68/89.5 = 5.38]. Thus, the gain at low frequency is determined by the ratio of the collector resistance to the emitter resistance. The slightly higher actual gain is the result of some AC signal being bypassed by the 100 μ emitter capacitor.

At higher frequencies, the emitter impedance of Q2 is reduced to near zero, and the gain of transistor Q2 increases until limited by the transistor's band pass. The emitter bypass capacitor in the first and second stages of the amplifier increases the band pass of the amplifier. The voltage across the emitter resistors decreases the base emitter forward bias of the transistor. Thus, the voltage across the emitter resistor is a form of negative feedback. The more current driven through the emitter resistors, the greater the negative feedback. Looking at the animation we see that the emitter voltages (feedback) decrease as frequency increases. This results in the gain of amplifier increasing as frequency increases through the 10 kHz and 100kHz range. At 1 MHz and above transistor gain drops off drastically due to internal transistor capacitances. The emitter bypass capacitors still extend the band pass of the amplifier well past 1 MHz.

The third stage of the amplifier is called an emitter follower. The voltage gain of the Q3 circuit is unity and current gain is very large. This third stage gives the three-stage amplifier low output impedance and high current gain. The first two stages give the amplifier voltage gain that exceeds 100. Thus, the amplifier exhibits both high voltage and current gain. Or simply overall high power gain is $P = I \cdot V \cdot (\cosine A)$, where A is the phase angle between current and voltage. At low frequency **cosine A** goes to one, and power formulae reduces to $P = I \cdot V$. Note the circuit does not generate power. Signal output power increases by several orders of magnitude with respect to signal input power, but the signal output derives its energy from the DC supply voltage. Only a fraction of the DC power is transmitted to next stage of system. The remainder of power is converted to heat.

Transistor Circuit Troubleshooting:

To troubleshoot transistor circuits all that is required is a full understanding of Ohm's law and a little understanding of semiconductors. First measure the voltage drop across **R_C** and **R_E** , and then calculate the current across each transistor using Ohm's law. If they are close to equal you can conclude **R_C** and **R_E** are good. Thus, the fault must lie in the transistor or base-biasing resistor. This method only works when the transistor is conducting, because when the transistor is not conducting there is zero voltage drop across **R_C** and **R_E** .

Next, consider the case where the transistor is in cutoff ($V_{CE} = V_{CC}$). In this case that simply means the collector voltage reads 12V. With no current flowing through **R_C** , the ratio of voltage drops across **R_C** and **R_E** are meaningless; however, we can analyze the base/emitter circuit. In the absence of collector current, we have a series circuit consisting of **R_B** , a base/emitter pn-junction, and **R_E** . The same current flows through **R_B** and **R_E** . If the voltage drops across **R_B** and **R_E** are proportional to their specified values, then **R_B** and **R_E** are good, else one of the resistors is defective. The transistor pn-junction should exhibit a voltage drop of about .7V. If it exhibited 0 volts that would indicate that the pn-junction was shorted. If the voltage across the pn-junction were far above .7V, that would indicate an open junction. Either way the transistor would be bad.

If current is flowing through **R_B** and **R_E** via the base emitter junction, then the transistor should be conducting. If base/emitter current does not induce collector current, then the transistor is defective.

Troubleshooting Frequency Response Problems:

If this amplifier worked well at low frequency but exhibited to little gain at high frequency, one would expect that a capacitor or a transistor was at fault. At a frequency of 10 kHz you expect that all bypass and coupling capacitors would exhibit very little voltage drop. The bypass capacitors would exhibit near zero AC signals. The coupling capacitors (capacitors between stages) should exhibit nearly the same voltage at both ends of capacitor. That is to say that no significant attenuation should be observed across any of the coupling capacitors at frequencies above the lower band pass limit. A bad capacitor will exhibit far greater voltage drop across it than a good capacitor would. If frequency response problem does not localize to a capacitor, then a transistor probably has poor frequency response.

The point that I am trying make here is that simple network analysis is often all that is required to troubleshoot transistor circuits. My Web sites include many troubleshooting exercises. Use them to practice fault isolation. You will see that Ohm's law and simple network analysis leads to fault isolation. This is not only true for transistor circuits but also applies to integrated circuits such as operational amplifiers.

Chapter 15

Differential Amplifiers

Differential Amplifiers:

A differential amplifier has two ungrounded inputs. Its output is proportional to the difference between the two inputs. This means that when both inputs are zero volts the output should be zero, and if both inputs are 6V the output should still be zero. In an ideal differential amplifier no output is produced when the input signals are identical; only the difference in input signals are amplified. Signals common to both inputs are known as common mode signals. Sometimes common mode signals could be a DC level from a bridge type sensor, or they could be radio frequency noise riding on both input lines. The ability of a differential amplifier to prevent conversion of a common-mode signal to an output signal is referred to as the common mode rejection ratio (CMRR). CMRR is the ratio of normal mode gain to common mode gain. If differential amplifier inputs were 0.0V and 0.1V and an output was 1.40 V, its normal mode gain would be 14. If both inputs changed from 0.00V to 0.10V and output changed from .000V to .001V, then the common mode gain would be .10. The CMRR would be 140 [CMRR = $14 / .1 = 140$].

Click number 18! The schematic shows a Whetstone Bridge connected to a differential amplifier. The technician balances the bridge so that the differential output of the bridge is zero. When the bridge is balanced, both outputs of the bridge are 2.50 volts. When the Whetstone Bridge is balanced the value of R_x can be calculated from the value that R_s is set to. $R_x/R_s = 1000/200$ reduces to $R_x = 5 R_s$. In the past scientists would test the bridge for balance with a sensitive Galvanometer. When the bridge was balanced the galvanometer would not deflect because no current would flow through galvanometer. Since the galvanometer draws no current, it does not effect precision of the bridge. Here, the differential amplifier replaces the galvanometer as the bridge interface.

The differential amplifier also allows us to measure only the difference voltage output of the bridge. The common mode rejection of the amplifier makes the bridge operation independent of the supply voltage. Differential amplifiers consist of a constant current source feeding the emitters of a matched pair of transistors. If the voltage at the bases of matched transistor pair increase an equal amount, the current through each transistor does not increase. The current through both transistors cannot decrease or increase in unison, because both transistors are fed by a single constant current source. Since the current does not change, there is no voltage change at the collector output of the first stage differential amplifier. This gives it low (ideally zero) common mode gain. If the voltage increases on one of the differential inputs, the current will increase through that transistor. Since the current to the transistor pair is constant, the current to the other transistor decreases. This results in high normal mode gain.

Chapter 16

Operational Amplifiers

Operational amplifiers are very high gain, DC differential amplifiers. Their circuits are extremely complex and have many transistors, resistors and other discrete components. Fortunately, the development of integrated circuits simplified electronic system design and troubleshooting. **Click number 39!** View operational amplifier animations. The triangular symbols represent operational amplifiers. Integrated circuits (IC's) can contain thousands of discrete components in a single package. One integrated circuit can contain several operational amplifiers. Frequently the schematics of large systems show only signal input and output pins. Other inputs such as power and ground are listed on separate tables.

Open loop gain (gain with no feedback) of most operational amplifiers exceeds 200,000. Thus, if there was as much as one milli-volt difference in the input voltages, the output tries to slew to over 200 volts. Since typical supply voltages for operational amplifiers are in the +15 to -15 volt range, less than one milli-volt would drive the amplifiers into saturation. Therefore, these high gain amplifiers require negative feedback to stabilize their operation. This negative feedback determines the closed loop gain of amplifier. The feedback resistor current forces voltage between IC inputs below one milli-volt. For an ideal operational amplifier the gain approaches infinity. The input impedance also approaches infinity, which implies that the ideal operational draws no current. Real operational amplifiers have gains far above 200,000 and input impedance well above four million ohms. These parameters result in operational amplifier gain being a function of the feedback resistors. Only Ohm's law is required to calculate their gain.

Click number 39! Observe the top operational amplifier animation. Since one input is connected to ground, the other input is forced to zero volts via feedback resistor. When the input is 2 mV, the circuit input current is $[2\text{mV}/1\text{k-ohm} = 2\text{ }\mu\text{A}]$. The operational amplifier input draws no current, thus the only path for the $2\text{ }\mu\text{A}$ current flow is the 100k-ohm feedback resistor. Applying Ohm's law to calculate the output voltage indicates the output should be negative 400mV $[2\text{ }\mu\text{A} * 100\text{k-ohm} = 400\text{mV}]$. That is to say that the output must be -400mV, in order to maintain the voltage at the inverting input at zero. If the voltage at the output drifts a little bit negative of 400mV, than in accordance with Ohm's law the inverting input node would also go negative. This negative voltage at the inverting node would drive the output of operational amplifier positive, back towards negative 400mV.

Remember that the inputs of operational amplifiers need not be maintained at zero volts, but the difference between inputs must be maintained at zero volts. In the lower animation both operational amplifier inputs are forced to level of the signal input. The non-inverting input is connected to signal. Feedback forces the inverting input to same level as the non-inverting input. The output can then be calculated with Ohm's Law. Try it and compare your results with values displayed by the animation.

Conclusion

This e-book is very short, but it does interface with many of my Web pages. My sites include many more animations and troubleshooting simulations. **Click number 40** to see a listing of all my sites and e-books. I believe that interactive troubleshooting is a good method of teaching electronics, but I do not believe that it should be the only method. Therefore, I recommend to anyone who desires more resources to refer to my reading list (links). **Click number 38** to see reading list! Several comprehensive books should be owned by anyone who studies electronics. Buy some from my Webs or visit your public library. If you're in school, keep your science textbooks. My banner ads are the only source of income for this site at present. Please visit our sponsors on my WEB sites.

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