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Advanced Digital Trainer

EXPERIMENTS

Volume 1

PART NO. 2766-00-321

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LAB HANDBOOK

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Welcome to RIMS Advanced Digital Trainer

List of experiments:

1. Commutating diode
2. Half-wave rectifier
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5. Voltage regulator
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13. Differential amplifier

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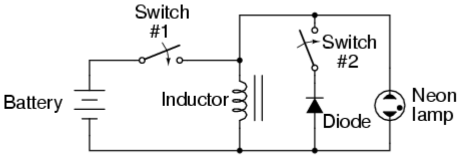
STEP 1	COMMUTATING DIODE

Objective:
- Review inductive "kickback"
- Learn how to suppress "kickback" using a diode

Required Components and Equipments:
- 6 volt battery
- Power transformer, 220VAC step-down to 12VAC
- One 1N4001 rectifying diode
- One neon lamp
- Two toggle switches, SPST ("Single-Pole, Single-Throw")

Diagram of Circuit:



Procedure:
When assembling the circuit, be very careful of the diode's orientation. The cathode end of the diode must face the positive (+) side of the battery. The diode should be reverse-biased and non-conducting with switch #1 in the "on" position. Use the high-voltage (120 V) winding of the transformer for the inductor coil. The primary winding of a step-down transformer has more inductance than the secondary winding, and will give a greater lamp-flashing effect.
Set switch #2 to the "off" position. This disconnects the diode from the circuit so that it has no effect. Quickly close and open (turn "on" and then "off") switch #1. When that switch is opened, the neon bulb will flash from the effect of inductive "kickback." Rapid current decrease caused by the switch's opening causes the inductor to create a large voltage drop as it attempts to keep current at the same magnitude and going in the same direction.
Inductive kickback is detrimental to switch contacts, as it causes excessive arcing whenever they are opened. In this circuit, the neon lamp actually diminishes the effect by providing an alternate current path for the inductor's current when the switch opens, dissipating the inductors stored energy harmlessly in the form of light and heat.
If switch #2 is closed (turned "on"), the diode will now be a part of the circuit. Quickly close and open switch #1 again, noting the difference in circuit behavior. This time, the neon lamp does not flash. Connect a voltmeter across the inductor to verify that the inductor is still receiving full battery voltage with switch #1 closed. If the voltmeter registers only a small voltage with switch #1 "on," the diode is probably connected backward, creating a short-circuit.

STEP 2 HALF-WAVE RECTIFIER

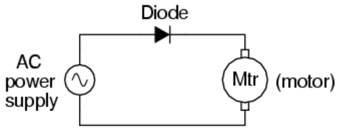
Objective:

- Function of a diode as a rectifier
- Permanent-magnet motor operation on AC versus DC power
- Measuring "ripple" voltage with a voltmeter

Required Components and Equipments:

- Low-voltage AC power supply (6 volt output)
- 6 volt battery
- One 1N4001 rectifying diode
- Small "hobby" motor, permanent-magnet type

Diagram of Circuit:



Procedure:

Connect the motor to the low-voltage AC power supply through the rectifying diode as shown. The diode only allows current to pass through during one half-cycle of a full positive-and-negative cycle of power supply voltage, eliminating one half-cycle from ever reaching the motor. As a result, the motor only "sees" current in one direction, albeit a pulsating current, allowing it to spin in one direction.

Take a jumper wire and short past the diode momentarily, noting the effect on the motor's operation:

As you can see, permanent-magnet "DC" motors do not function well on alternating current. Remove the temporary jumper wire and reverse the diode's orientation in the circuit. Note the effect on the motor.

Measure DC voltage across the motor: Then, measure AC voltage across the motor as well:

Most digital multi-meters do a good job of discriminating AC from DC voltage, and these two measurements show the DC average and AC "ripple" voltages, respectively of the power "seen" by the motor. Ripple voltage is the varying portion of the voltage, interpreted as an AC quantity by measurement equipment although the voltage waveform never actually reverses polarity. Ripple may be envisioned as an AC signal superimposed on a steady DC "bias" or "offset" signal. Compare these measurements of DC and AC with voltage measurements taken across the motor while powered by a battery:

Batteries give very "pure" DC power, and as a result there should be very little AC voltage measured across the motor in this circuit. Whatever AC voltage is measured across the motor is due to the motor's pulsating current draw as the brushes make and break contact with the rotating commutator bars.

STEP 3 | FULL-WAVE CENTER-TAP RECTIFIER

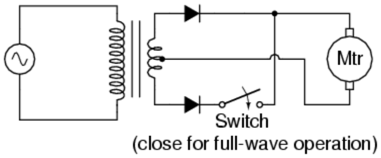
Objective:

- Design of a center-tap rectifier circuit
- Measuring "ripple" voltage with a voltmeter

Required Components and Equipments:

- Low-voltage AC power supply (6 volt output)
- Two 1N4001 rectifying diodes
- Small "hobby" motor, permanent-magnet type
- One toggle switch, SPST ("Single-Pole, Single-Throw")

Diagram of Circuit:



Procedure:

This rectifier circuit is called full-wave because it makes use of the entire waveform, both positive and negative half-cycles, of the AC source voltage in powering the DC load. As a result, there is less "ripple" voltage seen at the load. The RMS (Root-Mean-Square) value of the rectifier's output is also greater for this circuit than for the half-wave rectifier.

Use a voltmeter to measure both the DC and AC voltage delivered to the motor. You should notice the advantages of the full-wave rectifier immediately by the greater DC and lower AC indications as compared to the last experiment.

An experimental advantage of this circuit is the ease of which it may be "de-converted" to a half-wave rectifier: simply disconnect the short jumper wire connecting the two diodes' cathode ends together on the terminal strip. Better yet, for quick comparison between half and full-wave rectification, you may add a switch in the circuit to open and close this connection at will:

STEP 4 FULL-WAVE BRIDGE RECTIFIER

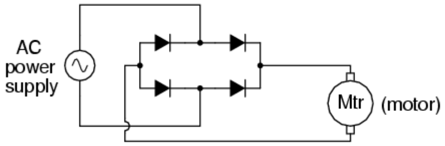
Objective:

- Design of a bridge rectifier circuit
- Advantages and disadvantages of the bridge rectifier circuit, compared to the center-tap circuit

Required Components and Equipments:

- Low-voltage AC power supply (6 volt output)
- Four 1N4001 rectifying diodes
- Small "hobby" motor, permanent-magnet type

Diagram of Circuit:



Procedure:

This circuit provides full-wave rectification without the necessity of a center-tapped transformer. In applications where a center-tapped, or split-phase, source is unavailable, this is the only practical method of full-wave rectification.

In addition to requiring more diodes than the center-tap circuit, the full-wave bridge suffers a slight performance disadvantage as well: the additional voltage drop caused by current having to go through two diodes in each half-cycle rather than through only one. With a low-voltage source such as the one you're using (6 volts RMS), this disadvantage is easily measured. Compare the DC voltage reading across the motor terminals with the reading obtained from the last experiment, given the same AC power supply and the same motor.

STEP 5	VOLTAGE REGULATOR INTEGRATOR

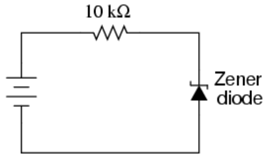
Objective:

- Zener diode function

Required Components and Equipments:

- Four 6 volt batteries
- Zener diode, 12 volt -- type 1N4742
- One 10 kΩ resistor

Diagram of Circuit:



Procedure:

As you can see from the schematic diagram, the potentiometer is connected to the "rails" of the power source through 100 kΩ resistors, one on each end. This is to Build this simple circuit, being sure to connect the diode in "reverse-bias" fashion (cathode positive and anode negative), and measure the voltage across the diode with one battery as a power source. Record this voltage drop for future reference. Also, measure and record the voltage drop across the 10 kΩ resistors.
Modify the circuit by connecting two 6-volt batteries in series, for 12 volts total power source voltage. Re-measure the diode's voltage drop, as well as the resistor's voltage drop, with a voltmeter:
Connect three, then four 6-volt batteries together in series, forming an 18 volt and 24 volt power source, respectively. Measure and record the diode's and resistor's voltage drops for each new power supply voltage. What do you notice about the diode's voltage drop for these four different source voltages? Do you see how the diode voltage never exceeds a level of 12 volts? What do you notice about the resistor's voltage drop for these four different source voltage levels?
Zener diodes are frequently used as voltage regulating devices, because they act to clamp the voltage drop across themselves at a predetermined level. Whatever excess voltage is supplied by the power source becomes dropped across the series resistor. However, it is important to note that a zener diode cannot make up for a deficiency in source voltage. For instance, this 12-volt zener diode does not drop 12 volts when the power source is only 6 volts strong. It is helpful to think of a zener diode as a voltage limiter: establishing a maximum voltage drop, but not a minimum voltage drop

STEP 6 TRANSISTOR AS A SWITCH

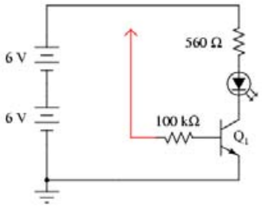
Objective:

- Study of a transistor as a switch.

Required Components and Equipments:

- Two 6-volt batteries
- One NPN transistor -- models 2N2222 or 2N3403 recommended
- One 100 kΩ resistor
- One 560 Ω resistor
- One light-emitting diode (Radio Shack catalog # 276-026 or equivalent)

Diagram of Circuit:



Procedure:

The red wire shown in the diagram (the one terminating in an arrowhead, connected to one end of the 100 kΩ resistor) is intended to remain loose, so that you may touch it momentarily to other points in the circuit.

If you touch the end of the loose wire to any point in the circuit more positive than it, such as the positive side of the DC power source, the LED should light up. It takes 20 mA to fully illuminate a standard LED, so this behavior should strike you as interesting, because the 100 kΩ resistor to which the loose wire is attached restricts current through it to a far lesser value than 20 mA. At most, a total voltage of 12 volts across a 100 kΩ resistance yields a current of only 0.12 mA, or 120 µA! The connection made by your touching the wire to a positive point in the circuit conducts far less current than 1 mA, yet through the amplifying action of the transistor, is able to control a much greater current through the LED.

Try using an ammeter to connect the loose wire to the positive side of the power source, to measure the current flowing through 100 kΩ.

You may have to select the most sensitive current range on the meter to measure this small flow. After measuring this controlling current, try measuring the LED's current (the controlled current) and compare magnitudes. Don't be surprised if you find a ratio in excess of 200 (the controlled current 200 times as great as the controlling current)!

As you can see, the transistor is acting as a kind of electrically-controlled switch, switching current on and off to the LED at the command of a much smaller current signal conducted through its base terminal.

STEP 7 | STATIC ELECTRICITY SENSOR

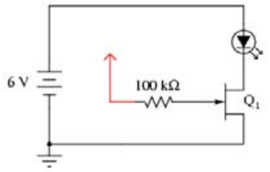
Objective:

- How the JFET is used as an on/off switch
- How JFET current gain differs from a bipolar transistor

Required Components and Equipments:

- One N-channel junction field-effect transistor, models 2N3819 or J309 recommended
- One 6 volt battery
- One 100 kΩ resistor
- One light-emitting diode
- Plastic comb

Diagram of Circuit:



Procedure:

This experiment is very similar to the previous experiment using a bipolar junction transistor (BJT) as a switching device to control current through an LED. In this experiment, a junction field-effect transistor is used instead, giving dramatically improved sensitivity.

Build this circuit and touch the loose wire end (the wire shown in red on the schematic diagram and in the illustration, connected to the 100 kΩ resistor) with your hand. Simply touching this wire will likely have an effect on the LED's status. This circuit makes a fine sensor of static electricity! Try scuffing your feet on a carpet and then touching the wire end if no effect on the light is seen yet.

For a more controlled test, touch the wire with one hand and alternately touch the positive (+) and negative (-) terminals of the battery with one finger of your other hand. Your body acts as a conductor (albeit a poor one), connecting the gate terminal of the JFET to either terminal of the battery as you touch them. Make note which terminal makes the LED turn on and which makes the LED turn off. Try to relate this behavior with what you've read about JFETs in chapter 5 of the Semiconductor volume.

The fact that a JFET is turned on and off so easily (requiring so little control current), as evidenced by full on-and-off control simply by conduction of a control current through your body, demonstrates how great of a current gain it has. With the BJT "switch" experiment, a much more "solid" connection between the transistor's gate terminal and a source of voltage was needed to turn it on. Not so with the JFET. In fact, the mere presence of static electricity can turn it on and off

at a distance.
To further experiment with the effects of static electricity on this circuit, brush your hair with the plastic comb and then wave the comb near the transistor, watching the effect on the LED. The action of combing your hair with a plastic object creates a high static voltage between the comb and your body. The strong electric field produced between these two objects should be detectable by this circuit from a significant distance!
In case you're wondering why there is no 560 Ω "dropping" resistor to limit current through the LED, many small-signal JFETs tend to self-limit their controlled current to a level acceptable by LEDs. The model 2N3819, for example, has a typical saturated drain current (IDSS) of 10 mA and a maximum of 20 mA. Since most LEDs are rated at a forward current of 20 mA, there is no need for a dropping resistor to limit circuit current: the JFET does it intrinsically

STEP 8 VOLTAGE FOLLOWER

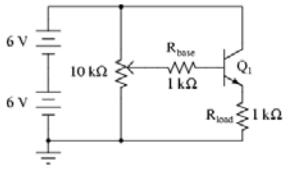
Objective:

- Purpose of circuit "ground" when there is no actual connection to earth ground
- Using a shunt resistor to measure current with a voltmeter
- Measure amplifier voltage gain
- Measure amplifier current gain
- Amplifier impedance transformation

Required Components and Equipments:

- One NPN transistor models 2N2222 or 2N3403 recommended
- Two 6-volt batteries
- Two 1 kΩ resistors
- One 10 kΩ potentiometer, single-turn, linear taper

Diagram of Circuit:



Procedure:

The voltage follower is the safest and easiest transistor amplifier circuit to build. Its purpose is to provide approximately the same voltage to a load as what is input to the amplifier, but at a much greater current. In other words, it has no voltage gain, but it does have current gain.

Note that the negative (-) side of the power supply is shown in the schematic diagram to be connected to ground, as indicated by the symbol in the lower-left corner of the diagram. This does not necessarily represent a connection to the actual earth. What it means is that this point in the circuit and all points electrically common to it constitute the default reference point for all voltage measurements in the circuit. Since voltage is by necessity a quantity relative between two points, a "common" point of reference designated in a circuit gives us the ability to speak meaningfully of voltage at particular, single points in that circuit.

For example, if I were to speak of voltage at the base of the transistor (VB), I would mean the voltage measured between the transistor's base terminal and the negative side of the power supply (ground), with the red probe touching the base terminal and the black probe touching ground. Normally, it is nonsense to speak of voltage at a single point, but having an implicit reference point for voltage measurements makes such statements meaningful:

Build this circuit, and measure output voltage versus input voltage for several different potentiometer settings. Input voltage is the voltage at the potentiometer's wiper (voltage between the wiper and circuit ground), while output voltage is the load resistor voltage (voltage across the load resistor, or emitter voltage: between emitter and circuit ground). You should see a close correlation between these two voltages: one is just a little bit greater than the other (about 0.6 volts or so?), but a change in the input voltage gives almost equal change in the output voltage. Because the relationship between input change and output change is almost 1:1, we say that the AC voltage gain of this amplifier is nearly 1.

Not very impressive, is it? Now measure current through the base of the transistor (input current) versus current through the load resistor (output current). Before you break the circuit and insert your ammeter to take these measurements, consider an alternative method: measure voltage across the base and load resistors, whose resistance values are known. Using Ohm's Law, current through each resistor may be easily calculated: divide the measured voltage by the known resistance (I=E/R). This calculation is particularly easy with resistors of 1 kΩ value: there will be 1 milliamp of current for every volt of drop across them. For best precision, you may measure the resistance of each resistor rather than assume an exact value of 1 kΩ, but it really doesn't matter much for the purposes of this experiment. When resistors are used to take current measurements by "translating" a current into a corresponding voltage, they are often referred to as shunt resistors.

You should expect to find huge differences between input and output currents for this amplifier circuit. In fact, it is not uncommon to experience current gains well in excess of 200 for a small-signal transistor operating at low current levels. This is the primary purpose of a voltage follower circuit: to boost the current capacity of a "weak" signal without altering its voltage.

Another way of thinking of this circuit's function is in terms of impedance. The input side of this amplifier accepts a voltage signal without drawing much current. The output side of this amplifier delivers the same voltage, but at a current limited only by load resistance and the current-handling ability of the transistor. Cast in terms of impedance, we could say that this amplifier has a high input impedance (voltage dropped with very little current drawn) and a low output impedance (voltage dropped with almost unlimited current-sourcing capacity).

STEP 9 | COMMON-EMITTER AMPLIFIER

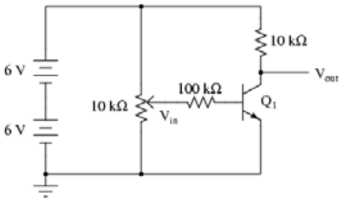
Objective:

- Design of a simple common-emitter amplifier circuit
- How to measure amplifier voltage gain
- The difference between an inverting and a noninverting amplifier
- Ways to introduce negative feedback in an amplifier circuit

Required Components and Equipments:

- One NPN transistor -- model 2N2222 or 2N3403 recommended
- Two 6-volt batteries
- One 10 kΩ potentiometer, single-turn, linear taper
- One 1 MΩ resistor
- One 100 kΩ resistor
- One 10 kΩ resistor
- One 1.5 kΩ resistor

Diagram of Circuit:



Procedure:

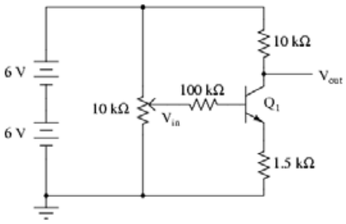
Build this circuit and measure output voltage (voltage measured between the transistor's collector terminal and ground) and input voltage (voltage measured between the potentiometer's wiper terminal and ground) for several position settings of the potentiometer. I recommend determining the output voltage range as the potentiometer is adjusted through its entire range of motion, then choosing several voltages spanning that output range to take measurements at. For example, if full rotation on the potentiometer drives the amplifier circuit's output voltage from 0.1 volts (low) to 11.7 volts (high), choose several voltage levels between those limits (1 volt, 3 volts, 5 volts, 7 volts, 9 volts, and 11 volts). Measuring the output voltage with a meter, adjust the potentiometer to obtain each of these predetermined voltages at the output, noting the exact figure for later reference. Then, measure the exact input voltage producing that output voltage, and record that voltage figure as well.

In the end, you should have a table of numbers representing several different output voltages along with their corresponding input voltages. Take any two pairs of voltage figures and calculate voltage gain by dividing the difference in output voltages by the difference in input voltages. For example, if an input voltage of 1.5 volts gives me an output voltage of 7.0 volts and an input voltage of 1.66 volts gives me an output voltage of 1.0 volt, the amplifier's voltage gain is (7.0 - 1.0)/(1.66 - 1.5), or 6 divided by 0.16: a gain ratio of 37.50.

You should immediately notice two characteristics while taking these voltage measurements: first, that the input-to-output effect is "reversed;" that is, an increasing input voltage results in a decreasing output voltage. This effect is known as signal inversion, and this kind of amplifier as an inverting amplifier. Secondly, this amplifier exhibits a very strong voltage gain: a small change in input voltage results in a large change in output voltage. This should stand in stark contrast to the "voltage follower" amplifier circuit discussed earlier, which had a voltage gain of about 1.

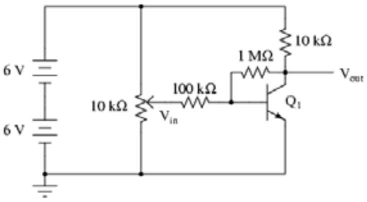
Common-emitter amplifiers are widely used due to their high voltage gain, but they are rarely used in as crude a form as this. Although this amplifier circuit works to demonstrate the basic concept, it is very susceptible to changes in temperature. Try leaving the potentiometer in one position and heating the transistor by grasping it firmly with your hand or heating it with some other source of heat such as an electric hair dryer (WARNING: be careful not to get it so hot that your plastic breadboard melts!). You may also explore temperature effects by cooling the transistor: touch an ice cube to its surface and note the change in output voltage. When the transistor's temperature changes, its base-emitter diode characteristics change, resulting in different amounts of base current for the same input voltage. This in turn alters the controlled current through the collector terminal, thus affecting output voltage. Such changes may be minimized through the use of signal feedback, whereby a portion of the output voltage is "fed back" to the amplifier's input so as to have a negative, or canceling, effect on voltage gain. Stability is improved at the expense of voltage gain, a compromise solution, but practical nonetheless.

Perhaps the simplest way to add negative feedback to a common-emitter amplifier is to add some resistance between the emitter terminal and ground, so that the input voltage becomes divided between the base-emitter PN junction and the voltage drop across the new resistance:



Repeat the same voltage measurement and recording exercise with the 1.5 kΩ resistor installed, calculating the new (reduced) voltage gain. Try altering the transistor's temperature again and noting the output voltage for a steady input voltage. Does it change more or less than without the 1.5 kΩ resistor?

Another method of introducing negative feedback to this amplifier circuit is to "couple" the output to the input through a high-value resistor. Connecting a 1 MΩ resistor between the transistor's collector and base terminals works well:



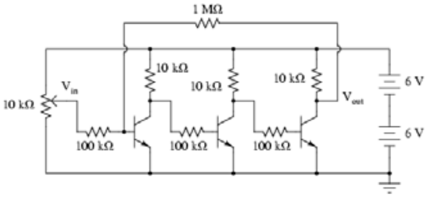
Although this different method of feedback accomplishes the same goal of increased stability by diminishing gain, the two feedback circuits will not behave identically. Note the range of possible output voltages with each feedback scheme (the low and high voltage values obtained with a full sweep of the input voltage potentiometer), and how this differs between the two circuits.

STEP 10 | MULTI-STAGE AMPLIFIER

Objective:
- Design of a multi-stage, direct-coupled common-emitter amplifier circuit
- Effect of negative feedback in an amplifier circuit

Required Components and Equipments:
- Three NPN transistors -- model 2N2222 or 2N3403 recommended
- Two 6-volt batteries
- One 10 kΩ potentiometer, single-turn, linear taper
- One 1 MΩ resistor
- Three 100 kΩ resistors
- Three 10 kΩ resistors

Diagram of Circuit:



Procedure:
As you can see from the schematic diagram, the potentiometer is connected to the "rails" of the power source through 100 kΩ resistors, one on each end. This is to By connecting three common-emitter amplifier circuit together -- the collector terminal of the previous transistor to the base (resistor) of the next transistor -- the voltage gains of each stage compound to give a very high overall voltage gain. I recommend building this circuit without the 1 MΩ feedback resistor to begin with, to see for yourself just how high the unrestricted voltage gain is. You may find it impossible to adjust the potentiometer for a stable output voltage (that isn't saturated at full supply voltage or zero), the gain being so high.

Even if you can't adjust the input voltage fine enough to stabilize the output voltage in the active range of the last transistor, you should be able to tell that the output-to-input relationship is inverting; that is, the output tends to drive to a high voltage when the input goes low, and vice versa. Since any one of the common-emitter "stages" is inverting in itself, an even number of staged common-emitter amplifiers gives noninverting response, while an odd number of stages gives inverting. You may experience these relationships by measuring the collector-to-ground voltage at each transistor while adjusting the input voltage potentiometer, noting whether or not the output voltage increases or decreases with an increase in input voltage.

Connect the 1 MΩ feedback resistor into the circuit, coupling the collector of the last transistor to the base of the first. Since the overall response of this three-stage amplifier is inverting, the feedback signal provided through the 1 MΩ resistor from the output of the last transistor to the input of the first should be negative in nature. As such, it will act to stabilize the amplifier's response and minimize the voltage gain. You should notice the reduction in gain immediately by the decreased sensitivity of the output signal on input signal changes (changes in potentiometer position). Simply put, the amplifier isn't nearly as "touchy" as it was without the feedback resistor in place.

As with the simple common-emitter amplifier discussed in an earlier experiment, it is a good idea here to make a table of input versus output voltage figures with which you may calculate voltage gain.

Experiment with different values of feedback resistance. What effect do you think a decrease in feedback resistance have on voltage gain? What about an increase in feedback resistance? Try it and find out!

An advantage of using negative feedback to "tame" a high-gain amplifier circuit is that the resulting voltage gain becomes more dependent upon the resistor values and less dependent upon the characteristics of the constituent transistors. This is good, because it is far easier to manufacture consistent resistors than consistent transistors. Thus, it is easier to design an amplifier with predictable gain by building a staged network of transistors with an arbitrarily high voltage gain, then mitigate that gain precisely through negative feedback. It is this same principle that is used to make operational amplifier circuits behave so predictably.

This amplifier circuit is a bit simplified from what you will normally encounter in practical multi-stage circuits. Rarely is a pure common-emitter configuration (i.e. with no emitter-to-ground resistor) used, and if the amplifier's service is for AC signals, the inter-stage coupling is often capacitive with voltage divider networks connected to each transistor base for proper biasing of each stage. Radio-frequency amplifier circuits are often transformer-coupled, with capacitors connected in parallel with the transformer windings for resonant tuning.

STEP 11 | CURRENT MIRROR

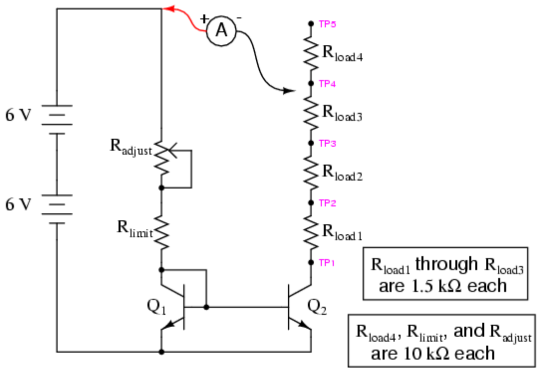
Objective:

- How to build a current mirror circuit
- Current limitations of a current mirror circuit
- Temperature dependence of BJTs
- Experience a controlled "thermal runaway" situation

Required Components and Equipments:

- Two NPN transistors models 2N2222 or 2N3403 recommended
- Two 6-volt batteries
- One 10 kΩ potentiometer, single-turn, linear taper
- Two 10 kΩ resistors
- Four 1.5 kΩ resistors

Diagram of Circuit:



Procedure:

A current mirror may be thought of as an adjustable current regulator, the current limit being easily set by a single resistance. It is a rather crude current regulator circuit, but one that finds wide use due to its simplicity. In this experiment, you will get the opportunity to build one of these circuits, explore its current-regulating properties, and also experience some of its practical limitations firsthand.

Build the circuit as shown in the schematic and illustration. You will have one extra 1.5 kΩ fixed-value resistor from the parts specified in the parts list. You will be using it in the last part of this experiment.

The potentiometer sets the amount of current through transistor Q1. This transistor is connected to act as a simple diode: just a PN junction. Why use a transistor instead of a regular diode? Because it is important to match the junction characteristics of these two transistors when using them in a current mirror circuit. Voltage dropped across the base-emitter junction of Q1 is impressed across the base-emitter junction of the other transistor, Q2, causing it to turn "on" and likewise conduct current.

Since voltage across the two transistors' base-emitter junctions is the same -- the two junction pairs being connected in parallel with each other -- so should the current be through their base terminals, assuming identical junction characteristics and identical junction temperatures. Matched transistors should have the same β ratios, as well, so equal base currents means equal collector currents. The practical result of all this is Q2's collector current mimicking whatever current magnitude has been established through the collector of Q1 by the potentiometer. In other words, current through Q2 mirrors the current through Q1.

Changes in load resistance (resistance connecting the collector of Q2 to the positive side of the battery) have no effect on Q1's current, and consequently have no effect upon the base-emitter voltage or base current of Q2. With a constant base current and a nearly constant β ratio, Q2 will drop as much or as little collector-emitter voltage as necessary to hold its collector (load) current constant. Thus, the current mirror circuit acts to regulate current at a value set by the potentiometer, without regard to load resistance.

Well, that is how it is supposed to work, anyway. Reality isn't quite so simple, as you are about to see. In the circuit diagram shown, the load circuit of Q2 is completed to the positive side of the battery through an ammeter, for easy current measurement. Rather than solidly connect the ammeter's black probe to a definite point in the circuit, I've marked five test points, TP1 through TP5, for you to touch the black test probe to while measuring current. This allows you to quickly and effortlessly change load resistance: touching the probe to TP1 results in practically no load resistance, while touching it to TP5 results in approximately 14.5 kΩ of load resistance.

To begin the experiment, touch the test probe to TP4 and adjust the potentiometer through its range of travel. You should see a small, changing current indicated by your ammeter as you move the potentiometer mechanism: no more than a few milliamps. Leave the potentiometer set to a position giving a round number of milliamps and move the meter's black test probe to TP3. The current indication should be very nearly the same as before. Move the probe to TP2, then TP1. Again, you should see a nearly unchanged amount of current. Try adjusting the potentiometer to another position, giving a different current indication, and touch the meter's black probe to test points TP1 through TP4, noting the stability of the current indications as you change load resistance. This demonstrates the current regulating behavior of this circuit.

You should note that the current regulation isn't perfect. Despite regulating the current at nearly the value for load resistances between 0 and 4.5 kΩ, there is some variation over this range. The regulation may be much worse if load resistance is allowed to rise too high. Try adjusting the potentiometer so that maximum current is obtained, as indicated with the ammeter test probe connected to TP1. Leaving the potentiometer at that position, move the meter probe to TP2, then TP3, then TP4, and finally TP5, noting the meter's indication at each connection point. The current should be regulated at a nearly constant value until the meter probe is moved to the last test point, TP5. There, the current indication will be substantially lower than at the other test points. Why is this? Because too much load resistance has been inserted into Q2's circuit. Simply put, Q2 cannot "turn on" any more than it already has, to maintain the same amount of current with this great a load resistance as with lesser load resistances.

This phenomenon is common to all current-regulator circuits: there is a limited amount of resistance a current regulator can handle before it saturates. This stands to reason, as any current regulator circuit capable of supplying a constant amount of current through any load resistance imaginable would require an unlimited source of voltage to do it! Ohm's Law (E=IR) dictates the amount of voltage needed to push a given amount of current through a given amount of resistance, and with only 12 volts of power supply voltage at our disposal, a finite limit of load current and load resistance definitely exists for this circuit. For this reason, it may be helpful to think of current regulator circuits as being current limiter circuits, for all they can really do is limit current to some maximum value.

An important caveat for current mirror circuits in general is that of equal temperature between the two transistors. The current "mirroring" taking place between the two transistors' collector circuits depends on the base-emitter junctions of those two transistors having the exact same properties. As the "diode equation" describes, the voltage/current relationship for a PN junction strongly depends on junction temperature. The hotter a PN junction is, the more current it will pass for a given amount of voltage drop. If one transistor should become hotter than the other, it will pass more collector current than the other, and the circuit will no longer "mirror" current as expected. When building a real current mirror circuit using discrete transistors, the two transistors should be epoxy-glued together (back-to-back) so that they remain at approximately the same temperature.

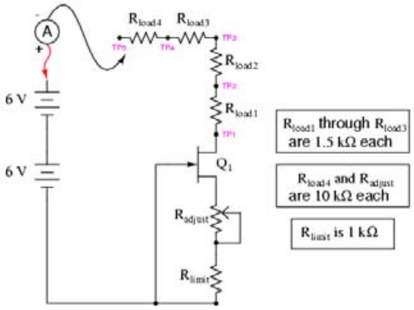
To illustrate this dependence on equal temperature, try grasping one transistor between your fingers to heat it up. What happens to the current through the load resistors as the transistor's temperature increases? Now, let go of the transistor and blow on it to cool it down to ambient temperature. Grasp the other transistor between your fingers to heat it up. What does the load current do now?

In this next phase of the experiment, we will intentionally allow one of the transistors to overheat and note the effects. To avoid damaging a transistor, this procedure should be conducted no longer than is necessary to observe load current begin to "run away." To begin, adjust the potentiometer for minimum current. Next, replace the 10 kΩ Rlimit resistor with a 1.5 kΩ resistor. This will allow a higher current to pass through Q1, and consequently through Q2 as well. Place the ammeter's black probe on TP1 and observe the current indication. Move the potentiometer in the direction of increasing current until you read about 10 mA through the ammeter. At that point, stop moving the potentiometer and just observe the current. You will notice current begin to increase all on its own, without

further potentiometer motion! Break the circuit by removing the meter probe from TP1 when the current exceeds 30 mA, to avoid damaging transistor Q2.
If you carefully touch both transistors with a finger, you should notice Q2 is warm, while Q1 is cool. Warning: if Q2's current has been allowed to "run away" too far or for too long a time, it may become very hot! You can receive a bad burn on your fingertip by touching an overheated semiconductor component, so be careful here!
What just happened to make Q2 overheat and lose current control? By connecting the ammeter to TP1, all load resistance was removed, so Q2 had to drop full battery voltage between collector and emitter as it regulated current. Transistor Q1 at least had the 1.5 kΩ resistance of Rlimit in place to drop most of the battery voltage, so its power dissipation was far less than that of Q2. This gross imbalance of power dissipation caused Q2 to heat more than Q1. As the temperature increased, Q2 began to pass more current for the same amount of base-emitter voltage drop. This caused it to heat up even faster, as it was passing more collector current while still dropping the full 12 volts between collector and emitter.
The effect is known as thermal runaway, and it is possible in many bipolar junction transistor circuits, not just current mirrors.

STEP 12 JFET CURRENT REGULATOR

Objective:
How to use a JFET as a current regulator
How the JFET is relatively immune to changes in temperature
Required Components and Equipments:
One N-channel junction field-effect transistor, models 2N3819 or J309 recommended
Two 6-volt batteries
One 10 kΩ potentiometer, single-turn, linear taper
One 1 kΩ resistor
One 10 kΩ resistor
Three 1.5 kΩ resistors
Diagram of Circuit:



Procedure:
This circuit performs the task of regulating current, but uses a single junction field-effect transistor (JFET) instead of two BJTs.
The two series resistors Radjust and Rlimit set the current regulation point, while the load resistors and the test points between them serve only to demonstrate constant current despite changes in load resistance.
To begin the experiment, touch the test probe to TP4 and adjust the potentiometer through its range of travel. You should see a small, changing current indicated by your ammeter as you move the potentiometer mechanism: no more than a few milliamps. Leave the potentiometer set to a position giving a round number of milliamps and move the meter's black test probe to TP3. The current indication should be very nearly the same as before. Move the probe to TP2, then TP1. Again, you should see a nearly unchanged amount of current. Try adjusting the potentiometer to another position, giving a different current indication, and touch the meter's black probe to test points TP1 through TP4, noting the stability of the current indications as you change load resistance. This demonstrates the current regulating behavior of this circuit.
TP5, at the end of a 10 kΩ resistor, is provided for introducing a large change in

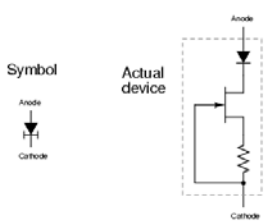
load resistance. Connecting the black test probe of your ammeter to that test point gives a combined load resistance of 14.5 kΩ, which will be too much resistance for the transistor to maintain maximum regulated current through. To experience what I'm describing here, touch the black test probe to TP1 and adjust the potentiometer for maximum current. Now, move the black test probe to TP2, then TP3, then TP4. For all these test point positions, the current will remain approximately constant. However, when you touch the black probe to TP5, the current will fall dramatically. Why? Because at this level of load resistance, there is insufficient voltage drop across the transistor to maintain regulation. In other words, the transistor will be saturated as it attempts to provide more current than the circuit resistance will allow.

Move the black test probe back to TP1 and adjust the potentiometer for minimum current. Now, touch the black test probe to TP2, then TP3, then TP4, and finally TP5. What do you notice about the current indication at all these points? When the current regulation point is adjusted to a lesser value, the transistor is able to maintain regulation over a much larger range of load resistance.

An important caveat with the BJT current mirror circuit is that both transistors must be at equal temperature for the two currents to be equal. With this circuit, however, transistor temperature is almost irrelevant. Try grasping the transistor between your fingers to heat it up, noting the load current with your ammeter. Try cooling it down afterward by blowing on it. Not only is the requirement of transistor matching eliminated (due to the use of just one transistor), but the thermal effects are all but eliminated as well due to the relative thermal immunity of the field-effect transistor. This behavior also makes field-effect transistors immune to thermal runaway; a decided advantage over bipolar junction transistors.

An interesting application of this current-regulator circuit is the so-called constant-current diode. Described in the "Diodes and Rectifiers" chapter of volume III, this diode isn't really a PN junction device at all. Instead, it is a JFET with a fixed resistance connected between the gate and source terminals:

Constant-current diode



A normal PN-junction diode is included in series with the JFET to protect the transistor against damage from reverse-bias voltage, but otherwise the current-regulating facility of this device is entirely provided by the field-effect transistor

STEP 13 DIFFERENTIAL AMPLIFIER

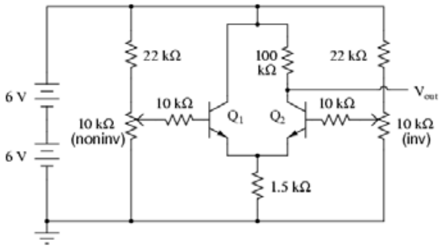
Objective:

- Basic design of a differential amplifier circuit.
- Working definitions of differential and common-mode voltages

Required Components and Equipments:

- Two 6-volt batteries
- Two NPN transistors -- models 2N2222 or 2N3403 recommended
- Two 10 kΩ potentiometers, single-turn, linear taper
- Two 22 kΩ resistors
- Two 10 kΩ resistors
- One 100 kΩ resistor
- One 1.5 kΩ resistor

Diagram of Circuit:



Procedure:

This circuit forms the heart of most operational amplifier circuits: the differential pair. In the form shown here, it is a rather crude differential amplifier, quite nonlinear and unsymmetrical with regard to output voltage versus input voltage(s). With a high voltage gain created by a large collector/emitter resistor ratio (100 kΩ/1.5 kΩ), though, it acts primarily as a comparator: the output voltage rapidly changing value as the two input voltage signals approach equality.

Measure the output voltage (voltage at the collector of Q2 with respect to ground) as the input voltages are varied. Note how the two potentiometers have different effects on the output voltage: one input tends to drive the output voltage in the same direction (non-inverting), while the other tends to drive the output voltage in the opposite direction (inverting). This is the essential nature of a differential amplifier: two complementary inputs, with contrary effects on the output signal. Ideally, the output voltage of such an amplifier is strictly a function of the difference between the two input signals. This circuit falls considerably short of the ideal, as even a cursory test will reveal.

An ideal differential amplifier ignores all common-mode voltage, which is whatever level of voltage common to both inputs. For example, if the inverting input is at 3 volts and the non-inverting input at 2.5 volts, the differential voltage will be 0.5 volts

(3 - 2.5) but the common-mode voltage will be 2.5 volts, since that is the lowest input signal level. Ideally, this condition should produce the same output signal voltage as if the inputs were set at 3.5 and 3 volts, respectively (0.5 volts differential, with a 3 volt common-mode voltage). However, this circuit does not give the same result for the two different input signal scenarios. In other words, its output voltage depends on both the differential voltage and the common-mode voltage.

As imperfect as this differential amplifier is, its behavior could be worse. Note how the input signal potentiometers have been limited by 22 kΩ resistors to an adjustable range of approximately 0 to 4 volts, given a power supply voltage of 12 volts. If you'd like to see how this circuit behaves without any input signal limiting, just bypass the 22 kΩ resistors with jumper wires, allowing full 0 to 12 volt adjustment range from each potentiometer.

Do not worry about building up excessive heat while adjusting potentiometers in this circuit! Unlike the current mirror circuit, this circuit is protected from thermal runaway by the emitter resistor (1.5 kΩ), which doesn't allow enough transistor current to cause any problem.

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EU, USA and Canada
Weston Villa, 37 Wolsey Road, Esher, Surrey
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www.rims-tech.co.uk

Middle East & Asia Pacific
632-B Chakala Scheme-III Rawalpindi
Pakistan 46000
www.rimsedu.com

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