EE 221L Circuits II Laboratory #7

Linear Regulators

By

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Background

Most ICs require a stable, fixed voltage source to operate properly. An electronic device containing many ICs may require multiple fixed voltages when only one main voltage source is available. A common situation where this is the case is battery operated circuits. The solution to this common problem is the use of linear regulators. A linear regulator takes a certain range of input voltages and outputs a constant voltage. The device uses its internal circuitry to maintain its set voltage. Linear regulators can come in fixed value outputs, such as 12V or 5V, or can be user adjustable to a range of voltages. Although this is a topic that is not covered in the circuits lecture courses, it is important to be able to know how to use linear regulators for general electronic circuit design.

Most linear regulator ICs have three terminals. These are the voltage input, ground and voltage output terminals. For an adjustable regulator the ground terminal is replaced by an “adjust” terminal. Linear regulators can also come in two polarities. A positive regulator takes a positive input voltage and regulates it down to a lower positive voltage. A negative regulator does the same but with negative voltages. In this lab we will use both positive and negative regulators and learn how to set up a dual supply. Fig. 1 shows the pinouts for the most popular linear regulator series. The MC7800 series are positive voltage regulators and the MC7900 series are negative voltage regulators. The last two numbers indicate the output voltage. For example, an MC7805 has a positive 5 V output and a MC7915 has a negative 15 V output. The reason that the pin outs are different is because usually in an IC, the metal tab is connected to the substrate which needs to be at the lowest voltage for the chip to function properly. Always double check the pin outs otherwise the chip could fry as it could present a short to the power supply.

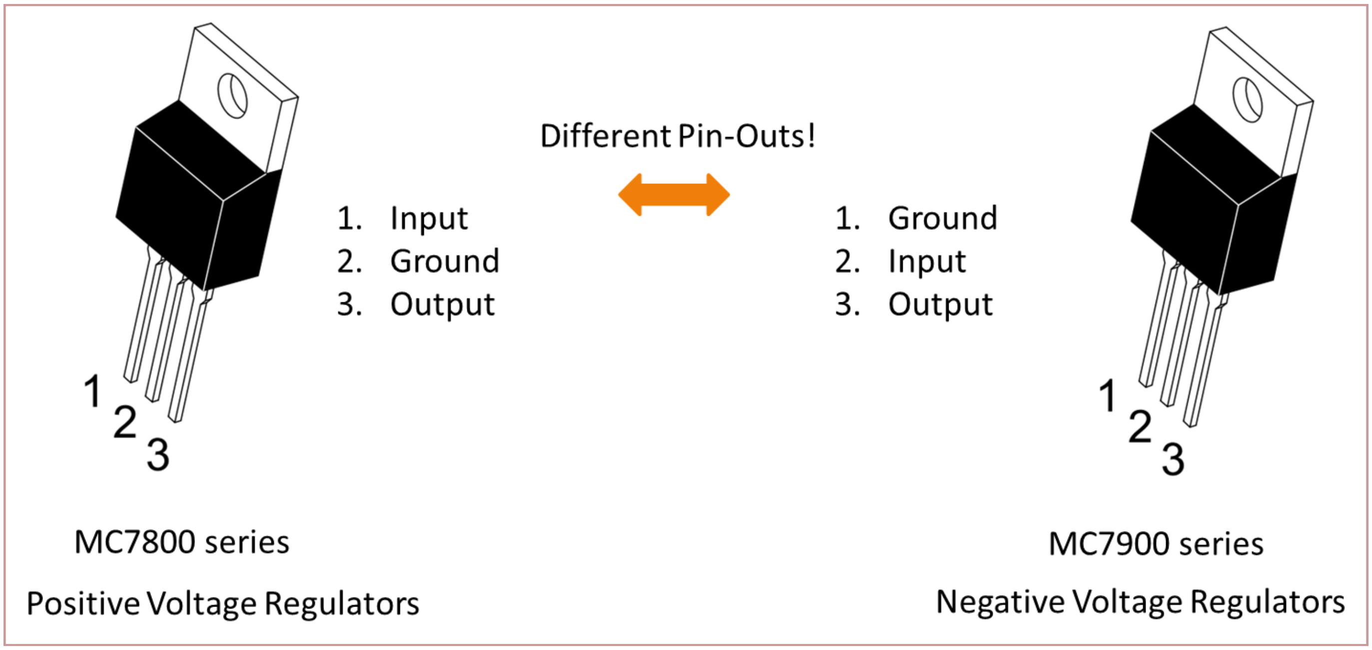


Figure 1. Pinouts for 7800 and 7900 series regulators are different!

In order to determine if a linear regulator is suitable for your applications, you have to look at the datasheet for some key parameters. The seven main parameters you need to determine are the maximum input voltage, drop-out voltage, quiescent current, maximum current output, output resistance, power dissipation and thermal resistance. Examples of these parameters are taken from the datasheet of the MC7805 regulator are shown in Table 1. The symbol is the typical symbol that is used for the characteristic. Datasheets generally give up to three values for each parameter which are minimum, typical and maximum values. These values are used by circuit designers to determine how the circuit will behave under a wide range of conditions. Typically it is good practice to use the most conservative value for a design. For example, for a power dissipation calculation it is best to use maximum values to get a good worst case estimate. Typical specifications are okay to use too if they are needed to meet a certain performance goal. However, for production units each part may need to be tested to ensure they meet this target. It is up to the designer and their application to determine which values to use for their calculations and the margins of tolerable error.

Characteristic (7805)	Symbol	Min	Typ	Max	Unit
Maximum Input Voltage	V_I			35	V
Dropout Voltage	$V_I - V_o$		2.0		V
Quiescent Current	I_B		3.2	6.0	mA
Peak Output Current	I_{max}		2.2		A
Power Dissipation	P_D		Internally Limited		W
Thermal Resistance (Junction to Ambient)	$R_{\theta JA}$		65		$^\circ C/W$
Output Resistance	r_o		0.9		mΩ
Short Circuit Current Limit	I_{SC}		0.2		A
Line Regulation (7.3V to 20 V)	Reg_{line}		4.5	10	mV
Load Regulation (5mA to 1.5 A)	Reg_{load}		1.3	25	mV
Ripple Rejection	RR	68	83		dB

Table 1. A selection of important specifications from the datasheet of the MC7805 regulator.

Only a few key parameters are usually needed for design even though datasheets may list hundreds of parameters. Let's examine the nine selected parameters in Table 1. The first parameter, maximum input voltage is an "absolute maximum rating" and should never be exceeded or the part may be damaged. Whenever manufacturers list a parameter as an "absolute maximum rating" it does not guarantee correct circuit operation at this value but rather is a limit beyond which the part could be damaged. The second parameter, dropout voltage indicates how much voltage is dropped across the regulator's input and output. This is used to calculate the minimum operating voltage. For example, a minimum 7V input is required for a 5V regulator with a 2V dropout voltage. If the input voltage falls below this, then the regulator will not be able to regulate to a set voltage anymore. Special "low dropout" regulators are available that reduce the dropout voltage to less than 100 mV.

The next two parameters relate to the current parameters of the regulator. The quiescent current is the current that the regulator consumes to maintain normal operation with no load. Even with nothing connected to the output, a linear regulator always consumes power. The quiescent power consumption is calculated by multiplying the voltage drop across the linear regulator by the quiescent current which is calculated as,

$$P_{quiescent} = (V_{in} - V_{out}) \cdot I_B$$

This equation indicates that there may be quite high power dissipation even with no load connected if the voltage drop is high. For example to regulate a 32 V supply to 5 V with a 6 mA bias current results in a power dissipation of 162 mW. The other important current parameter is the peak output current. For the MC7805, this is given at 2.2 A. However, the MC7805 is marketed as a 1 A regulator. Why did they select this value instead of the peak value? Well the peak value will require significant heatsinking and is not realistic for most situations. The 1 A peak current is a value that can be achieved with minimal heatsinking for most applications.

This brings us to the next two parameters, power dissipation and thermal resistance. The power dissipation is the maximum power that the device can burn up as heat without being damaged. This is different from the power flowing out of the device. Generally, power dissipation ratings are given in the form of "safe operating area" curves or SOA curves. At higher temperatures the power ratings decrease. There is internal circuitry that limits the power dissipation in MC7800 and MC7900 series regulators to within the SOA curve. These regulators accomplish this by measuring their internal temperature and using that value to limit their maximum output current. This curve is not provided to the user as the device ensures that it is always operating within the SOA. In short, this means that the user can't damage the regulator in typical operation through overcurrent. The power dissipation is given by

$$P_D = (V_{in} - V_{out}) \cdot (I_{Out} + I_B)$$

For high output currents the bias current can be neglected. Again, the power dissipation can get quite high if large voltage differences are required. For example, a 5 V regulator with 1 A of output current and 24 V applied to the input will dissipate 19 watts of power. The regulator's internal circuitry will never allow this and will limit the output current.

The user may wish to cool the regulator to ensure that it can provide a certain level of power. The thermal resistance is a slope that indicates the rise in temperature per watt of power dissipated. The table gives this as 65 degrees Celsius per watt meaning that the chip temperature (junction) inside the package will increase 65 degrees Celsius per watt. The junction temperature is given by the equation,

$$T_j = T_{ambient} + R_{\theta JA} \cdot P_D$$

The outer case of the regulator will be slightly lower than this, but for safety it is good to assume that it is also at the junction temperature. For example, with an ambient temperature of 27^{o} C (room temperature) and a power dissipation of 1 W, the junction temperature will be 92^{o} C. This is hot enough to burn you if you touch the package. A heatsink will reduce this temperature. A graph showing maximum power dissipation as a function of ambient temperature is shown in Fig. 2. Each line indicates a heatsink with a particular thermal resistance. From the graph, it is apparent that at room temperature and no heatsink the maximum power dissipation is 2 W. With a perfect heatsink (0^{o}C/W) the maximum power dissipation is 14 W.

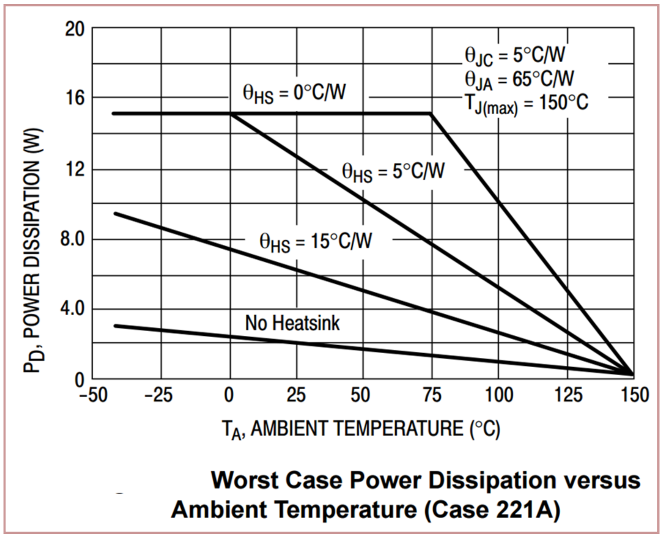


Figure 2. Maximum power dissipation as a function of ambient temperature. Each line indicates a heatsink with a particular thermal resistance.

The next parameters listed in Table 1 are the output resistance and short circuit current. The output resistance is the same as Thevenin resistance from previous labs. The regulator can be modeled as a 5 V source with a 0.1 mΩ resistor in series. If we were to short this source, the output current would be 50,000 A. Obviously this is not possible from a regulator that is the size of a thumbnail. The output resistance is a *small-signal* resistance meaning that an incremental increase in current causes an incremental increase in the voltage drop across the series resistor and consequently a decrease in output voltage from the regulator. All the limiting values shown in Table 1 and Fig. 2 still apply. For example, if a properly heatsinked 5 V regulator is outputting 1 A of current, there would be a 0.0001 V voltage drop to 4.9999 V. For most applications, this is an inconsequential drop and the reason it is so small is because the regulator is actively trying to maintain its nominal voltage. Furthermore, during a short circuit the regulator limits the current to 200 mA. Although in practice, the variation in output voltage with junction temperature is far greater than the variation due to output resistance. The lesson here is that a small output resistance does not necessarily imply an ability to supply a high output current.

The final set of parameters describes how well the device regulates the output voltage and rejects ripple. The line regulation is the amount that the output voltage can change with a change in input voltage. Over an input voltage range of 7.3 V to 20V, the output voltage will remain within a 10 mV window according to the datasheet. The load regulation is the amount that the output voltage can change with a change in load current. For example, if the output current was at 5 mA and then was increased to 1.5 A, the output voltage will remain within a 25 mV window of the nominal voltage. The last parameter is ripple rejection which describes how well the regulator suppresses an AC ripple voltage from flowing from the input to the output. When an AC voltage is rectified into DC, some residual AC remains at 60 Hz and 120 Hz. This AC voltage adds noise to circuits which can cause interference and other issues. An example of this is the “hum” heard in poorly designed audio equipment (although hum can also be caused by ground loops). The datasheet specifies a minimum ripple rejection of 68 dB. This means that a ripple applied to the input will become 2500 times smaller.

Next let’s look at the typical application for a linear regulator. This is shown in Fig. 3. Two capacitors are added to the regulator for stability and better transient response. The first capacitor, C1 can be either the unregulated power supply’s filter capacitor or a dedicated input capacitor for the linear regulator. If the regulator is physically far away (greater than 2 inches) from the power supply’s filter capacitor, it is a good idea to include this capacitor. In this lab, you must include this capacitor as the power supply itself is physically quite far from your breadboard. The value is not critical as long it is larger than the minimum value. For a linear regulator there isn’t much benefit to using a very large filtering capacitor and values beyond 100 uF can be wasteful. The second capacitor C2 improves transient response meaning that the regulator will respond to changes in load better. However the datasheet indicates a value below 0.1 uF can cause instability. To get a good margin of safety, we will double this value and use 0.2 uF as a minimum value. In most cases the minimum values will be very large film capacitors which are unwieldy and expensive. Instead, it is cheaper and easier to use small electrolytic capacitors such as 4.7 uF, 6.8 uF or 10 uF.

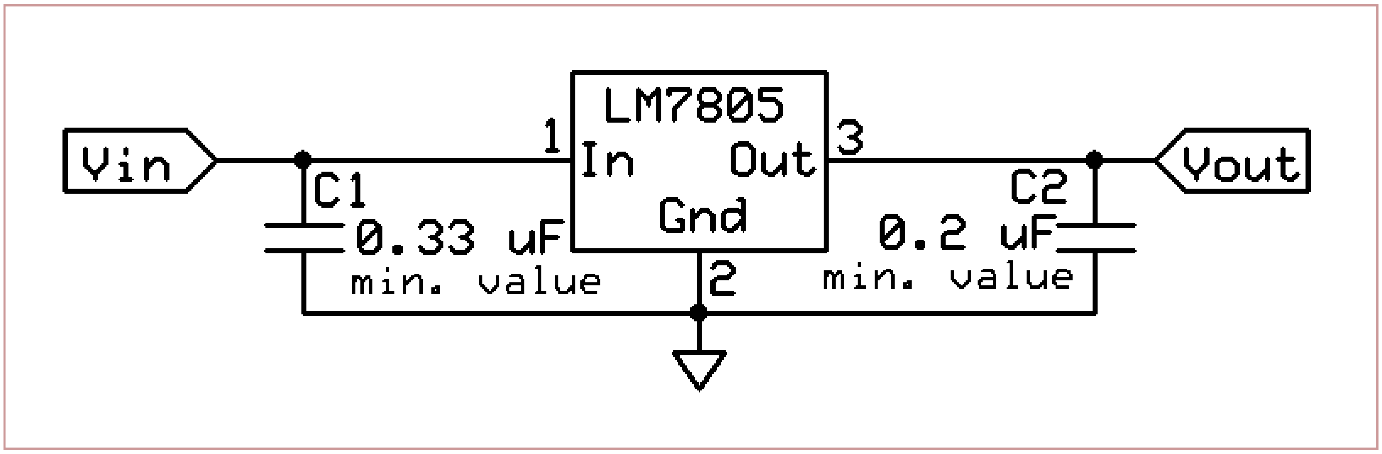


Figure 3. Typical application for MC7805 regulator.

Linear regulators can be used to create a simple dual supply. A dual supply has both a positive supply and a negative supply which share the same ground. The lab exercise section will explain how to set up the lab power supply as a dual supply. The schematic of the regulated dual supply is shown in Fig. 4. In this schematic the circuits of the positive and negative regulators mirror each other. Note the different pin connections listed in the schematic. If the pins are connected wrong, the regulator can present a short circuit to the power supply. The capacitor polarities are important too. You may be used to connecting the negative terminal of electrolytic capacitors to ground, but remember that the negative terminal has to be at a lower potential than the positive terminal. This is why the positive terminals of the capacitors used for the negative supply connect to ground, and the negative terminals connect to the negative voltage input or output. Be sure to understand this before proceeding with building this circuit.

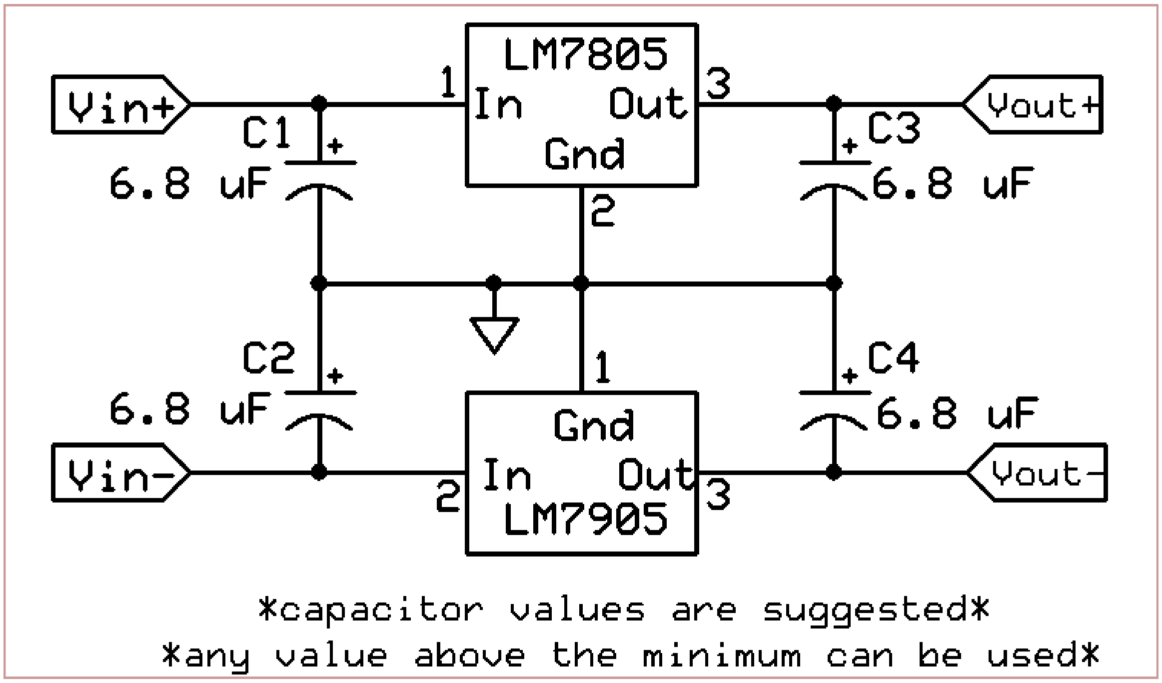


Figure 4. Creating a +/- 5V dual supply with MC7805 and MC7905 regulators.

A clever application of the linear regulator is as a constant current source. In previous labs we tried to power LEDs by setting the current on the power supply. But this was not a constant current source as it could not adjust its voltage to maintain its set current. A linear regulator can be used as a constant current source over a limited range of voltages. The reason this can be done is because the circuit tries to always keep the voltage difference between the ground terminal and the output terminal at its nominal voltage. A MC7805 maintains a 5 V difference between these terminals. If a resistor is connected between them, the constant voltage is divided by a resistance resulting in a constant current. This circuit is shown in Fig. 5. The current setting resistor is labeled “Rset” and the load is labeled “Rload”. Other devices such as LEDs can also be used as the load. One issue that arises is that the operating bias current for the MC7805 comes out of the ground pin. This combines with the current from the output pin to become the total current flowing out of the MC7805 and into the load. The equation for the total output current is,

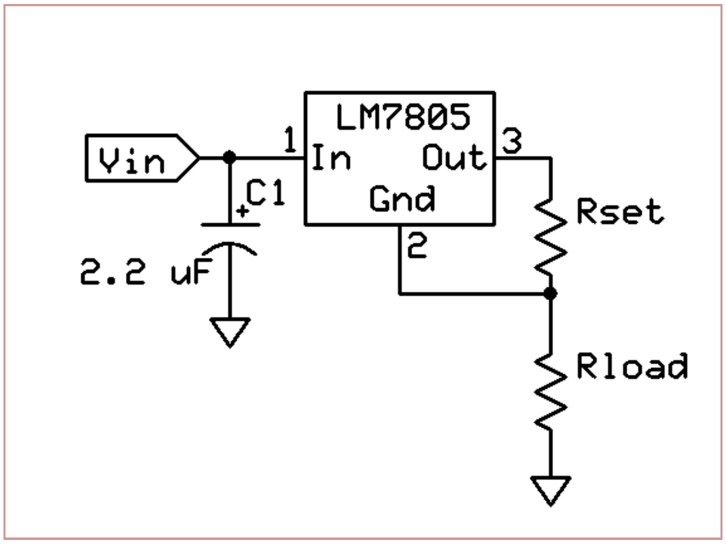


Figure 5. MC7805 as a constant current source.

$$I_{out} = \frac{V_{ref}}{R_{set}} + I_B = \frac{5V}{R_{set}} + 3.2mA$$

The typical values from table 1 are used. If a different regulator is used be sure to substitute the correct reference voltage and bias current.

For high output powers, it is a good idea to heatsink the regulator. Although thermodynamics is a complicated field, we can use electrical circuit analysis to model thermal elements. This allows simple modeling of complex thermal systems. The interface between two different materials is modeled as a thermal resistance which is given in units of ^{o}C/W. When two different materials are attached together there is a resistance to heat flowing between the materials. Examples of thermal interfaces in electronics are the attachment between the chip die and the package; between the package and an insulator pad; and the insulator pad and a heatsink. Insulator pads are used to electrically isolate packages from heatsinks so that users and other circuits are protected from potentially hazardous voltages. We will not be using insulator pads in this lab.

You may have noticed that it takes time for an object to heat up. A larger object takes longer to heat up than a small object. The reason for this is due to the "thermal mass" of the object. Thermal mass is modeled with a capacitor. This is because the time it takes for a capacitor to charge up is analogous to the time it takes an object to heat up. The units of thermal mass are joules/^{o}C. This is a measure of how much energy is needed to heat up the object by 1^{o}C. The electrical models for thermal elements are shown in Fig. 6. Heat is modeled as a current since both heat and current can flow from one location to another. Thermal resistance and mass are modeled as resistances and capacitances respectively. Temperature is modeled as voltage. A simple model of a linear regulator dissipating heat into a heatsink is shown in Fig. 7. The model is an electrical circuit with electrical units and represents the thermal circuit with thermal units listed in the table below. Circuit analysis can be used to determine the temperature behavior as a function of time. This can be complex due to the three time constants so it is best to simulate this in LTSpice. The capacitors are not needed for steady state analysis. If only the final temperatures need to be calculated only the thermal resistances need to be used and the voltage calculated at each node represents the temperature at that node.

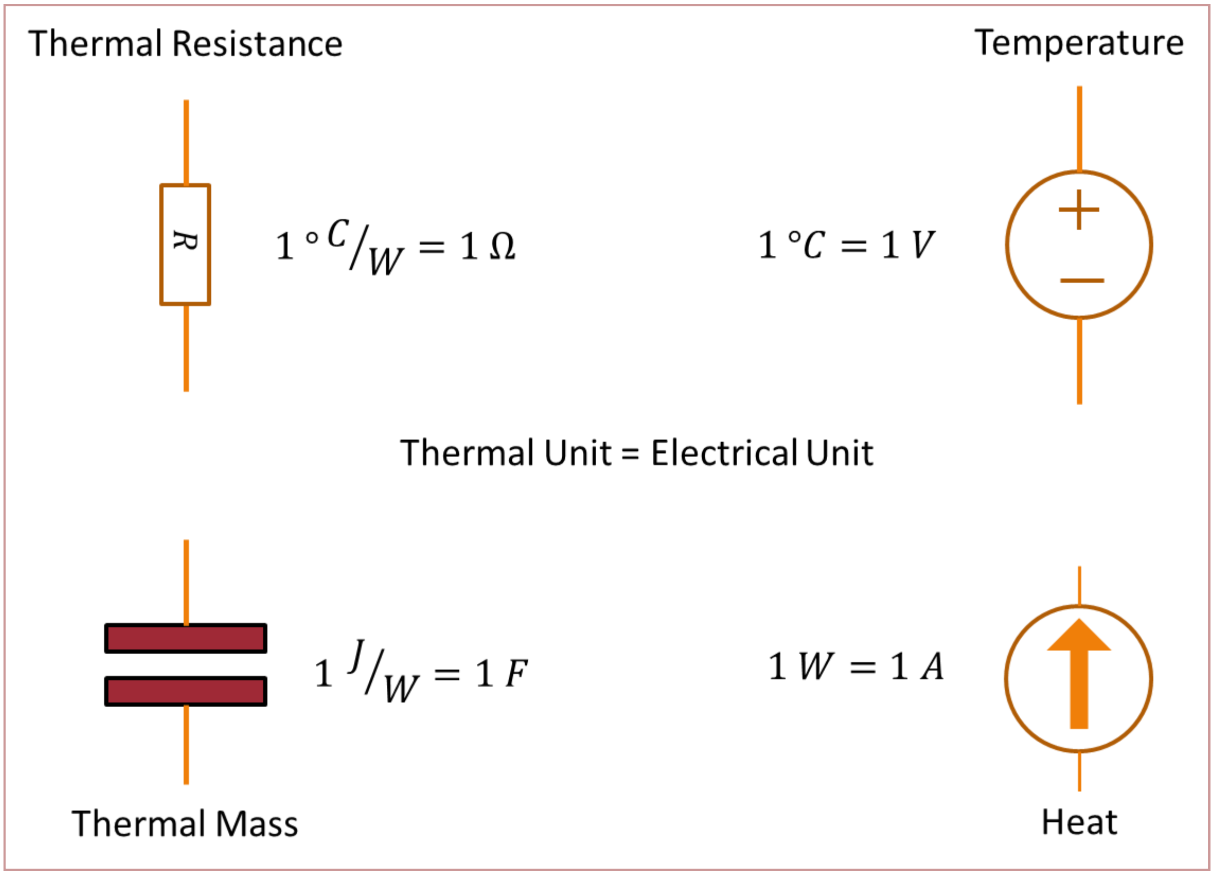
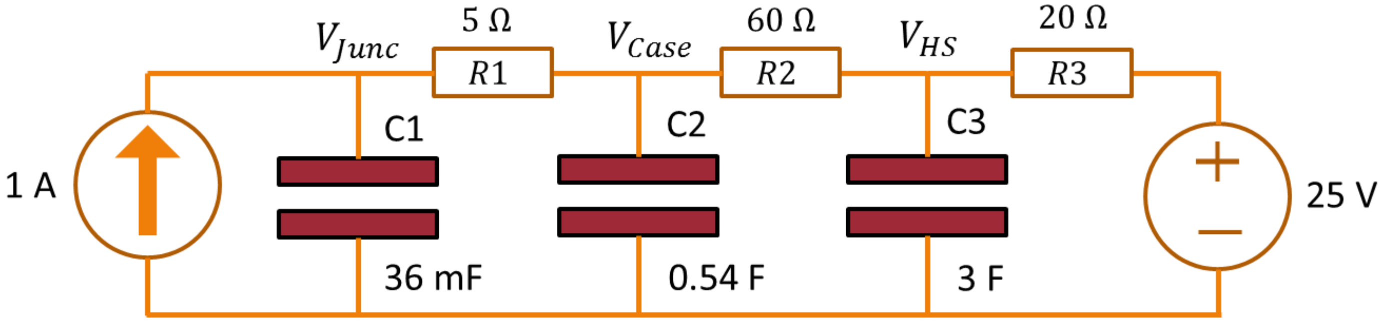


Figure 6. Representing thermal units as electrical units.



Sources

Heat Source: 1 W

Ambient Temperature: 25 $°C$

Thermal Elements

Junction Thermal Mass: 36 $m\ {}^{J}/_{W}$

Junction to Case Thermal Resistance: 5 $°\ {}^{C}/_{W}$

Case Thermal Mass: 0.54 ${}^{J}/_{W}$

Case to Heatsink Thermal Resistance: 60 $°\ {}^{C}/_{W}$

Heatsink Thermal Mass: 3 $°\ {}^{C}/_{W}$

Heatsink to Air Thermal Resistance: 20 $°\ {}^{C}/_{W}$

Temperatures

Junction Temperature

Case Temperature

Heatsink Temperature

Figure 7. Thermal model using electrical analogs of a linear regulator connected to a heatsink.

Prelab Summary

You will simulate linear regulators and basic RC circuits in this lab. A thermal model will be simulated as an RC circuit.

Prelab Tasks

Prelab #1: PCB and Netlist Required
Prelab #2: PCB or Netlist Not Required
Prelab #3: PCB or Netlist Not Required
Prelab #4: PCB or Netlist Not Required

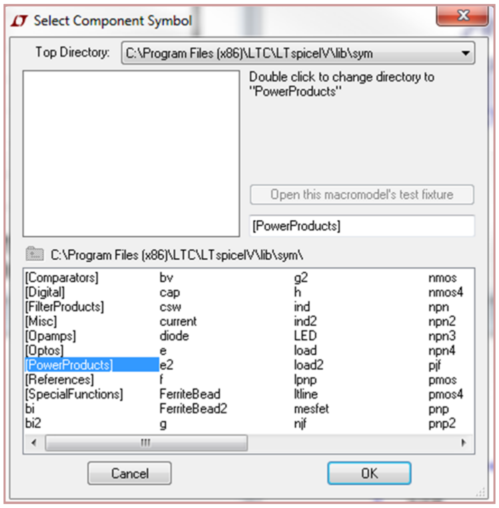
Prelab

This prelab will extensively use LTSpice. It is assumed that the student has some familiarity with LTSpice and will not go over basic functions. More complex functions will be detailed however. There are many LTSpice tutorial resources available on the web.

Prelab #1

Follow the steps below. Deliverables are in bold.

1. For this prelab we will use the LT1083-5 regulator instead of the MC7805. This is because there is a model for the LT1083-5 regulator in LTSpice. This is a 5V regulator with much better specs than the MC7805 but it will still let us observe the general behavior of linear regulators. This regulator is found in the "PowerProducts" folder as shown in Fig. 8.
2. Simulate the schematic shown in Fig. 9. Hold the ALT key while left clicking over the regulator to view the power dissipated for inputs of 12V, 24V and 36V. Be sure to put the value of the voltage source as {V}. **(Schematic, Plot)**



Select Component Symbol

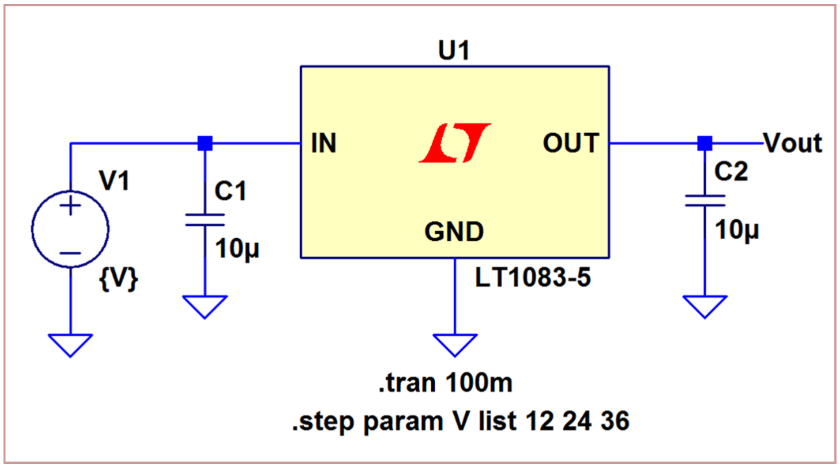
Top Directory: C:\Program Files (x86)\LTC\LTspiceIV\lib\sym

Double click to change directory to "PowerProducts"

[PowerProducts]

C:\Program Files (x86)\LTC\LTspiceIV\lib\sym\

Figure 8. Where to find the LT1083-5



```
.tran 100m
.step param V list 12 24 36
```

Figure 9. Stepping the input voltage to 12V, 24V and 36V.

Prelab #2

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 10. What is the minimum input voltage for the regulator to output 5V? What is the drop-out voltage? **(Schematic, Plot, Answers)**

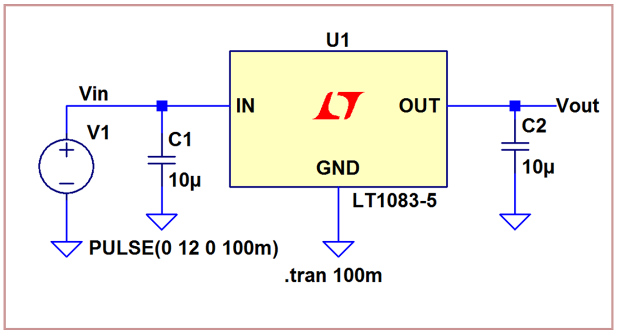


Figure 10. Minimum input voltage and drop-out voltage simulation.

Prelab #3

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 11. Be sure to set the current source to be an active load as shown in Fig. 12. The current source represents a load that suddenly increases. This is how load regulation is tested. Compare the output voltage before and after the current step. The difference is the load regulation. What is the load regulation? **(Schematic, Plot, Answers)**

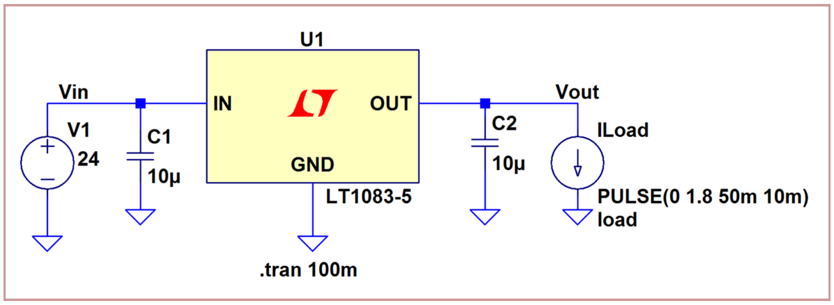
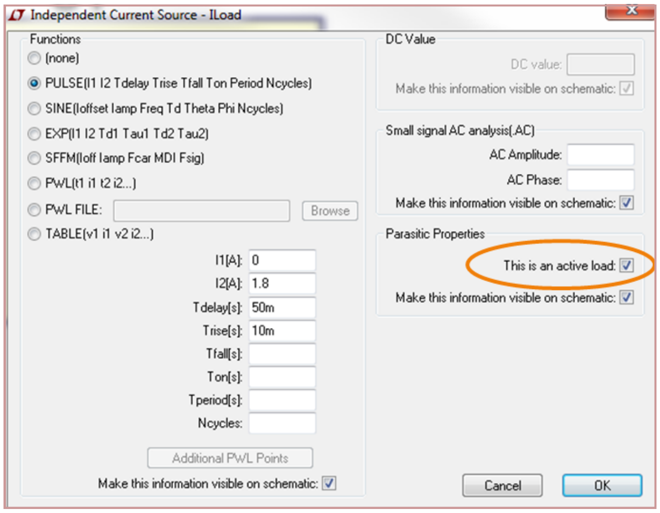


Figure 11. Load regulation simulation.



○ (none)
● PULSE(I1 I2 Tdelay Trise Tfall Ton Period Ncycles)
○ SINE(Ioffset Iamp Freq Td Theta Phi Ncycles)
○ EXP(I1 I2 Td1 Tau1 Td2 Tau2)
○ SFFM(Ioff Iamp Fcar MDI Fsig)
○ PWL(t1 i1 t2 i2...)
○ PWL FILE:
○ TABLE(v1 i1 v2 i2...)

I1[A]: 0
I2[A]: 1.8
Tdelay[s]: 50m
Trise[s]: 10m
Tfall[s]:
Ton[s]:
Tperiod[s]:
Ncycles:
Make this information visible on schematic: ☑

DC value:
Make this information visible on schematic: ☑
AC Amplitude:
AC Phase:
Make this information visible on schematic: ☑
This is an active load: ☑
Make this information visible on schematic: ☑

Figure 12. Setting current source to be an active load.

Prelab #4

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 13. Be sure to set all the initial conditions as shown. This models everything being at room temperature before the heat is applied. The simulation time is 600 seconds or 10 minutes. Plot Vjunc, Vcase, and Vhs on the same plot. **(Schematic, Plot)**
2. Using this plot calculate the thermal time constant for each of the three points in the circuit. Hint: This is the same as RC charging circuits. **(Answers)**
3. Calculate the final temperature values for each of the three points by hand. Hint: Ignore the capacitors and solve for every node voltage. **(Hand Calc)**
4. Suppose we want to operate at the maximum possible junction temperature of 150 degrees C. Calculate the input power that will result in a final junction temperature of 150 degrees C. Hint: Find the current value that causes 150V to appear at Vjunc. **(Hand Calc)**
5. Suppose that we will only run our regulator for 1 minute. Using simulations adjust the current source until you find the maximum amount of power that keeps the junction temperature below 150 degrees C for 1 minute. **(Plot, Answer)**

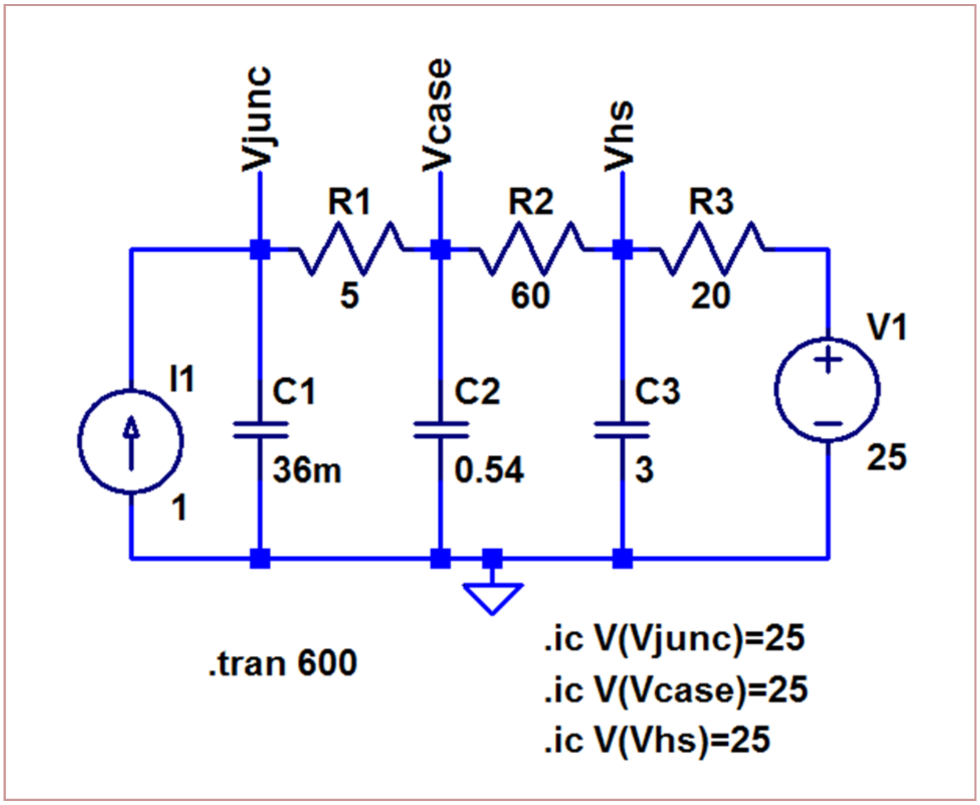


Figure 13. Electrical RC model of the thermal system representing a regulator on a heatsink.

Required Materials and Equipment

1. **Power Supply**
2. **Multimeter**
3. **LEDS, Resistors, Capacitors, Wire**
4. **MC7805, MC7905**
5. **Banana Jack Cables**
6. **Scope Probes**
7. **K-Type Thermocouple**

Postlab Tasks

Task 1: Dual Supply

Task 2: Constant Current Source

Measuring Equipment Basics

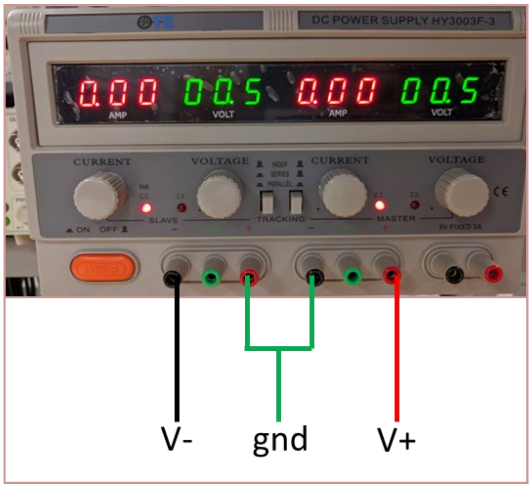


Figure 14. Dual supply connections.

In this lab, we will be setting up a dual power supply which will be an important foundation for all your future labs. The connections for a dual supply is shown in Fig. 14. Connect a banana cable between the positive terminal of one channel to the negative terminal of the other channel. This becomes the ground point. All measurements should be referenced to this point. The point where this cable plugs into your breadboard should have a bare stripped wire screwed into the “binding post”. The terminals where you plug in banana jack cables are also known as binding posts if they can unscrew to allow the connect of bare wires. This bare stripped wire will be the point where you will clip the oscilloscope ground lead, function generator ground lead, etc. The two power supply channels are connected in series with the remaining negative terminal being the negative voltage supply and the remaining positive terminal being the positive voltage supply. Be sure to adjust both voltages to the same value. For example, setting both voltages to 15V will result in a +/- 15V supply.

The thermocouple is a new device introduced in this lab. A thermocouple is a device that outputs a voltage difference which is proportional to the thermal difference between its two terminals. In this lab we will be using a K-type thermocouple, which is the most common and lowest cost type of thermocouple. Many multimeters have a thermocouple connection which automatically compensates for the ambient temperature. However any multimeter can be used with a thermocouple but the user has to do the math and know the ambient temperature. The thermocouple plugs into the voltage terminals of the multimeter and is used with the DC voltage setting. The reading should be very close to zero volts assuming the multimeter terminals are the same temperature as the air near the probe end of the thermocouple. The type K thermocouple has a slope of 41 uV/^{o}C. This means a one degree temperature difference between the end plugged into the meter and the end with the probe will result in a 41 microvolt difference. If the probe temperature is higher or lower then the meter end, the voltage will be positive or negative respectively. The formula to calculate the temperature is

$$T_{measured} = \left(\frac{V_{measured}}{41uV}\right) + T_{ambient}$$

Postlab #1: Dual Supply

Follow the steps below. Deliverables are in bold. All work must be typed.

1. The circuit built in this exercise will be used in the next exercise in this lab. Please spend some time to build this circuit properly. Build the circuit shown in Fig. 4 on your breadboard. You can substitute capacitors that are 2.2 uF if you can't find the values shown. Be sure the capacitors on the input side are rated to 35V or more. The capacitors on the output side should be 6.3V or more.
2. Set the input voltage to +/- 8V. Measure and record the output voltages **(Measured Values)**
3. Connect two red LEDs to the outputs of the dual supply. This is shown in Fig. 15. If red is not available use either yellow or green. The LED current will be around 30 mA so you may not want to leave this circuit on for a long time as it is at its maximum rating. The exact current isn't critical, rather we're using LEDs to represent a load. If you hooked up the circuit correctly the LEDs will light up.
4. Measure the output voltages with the multimeter right after turning on the power supply. If the circuit has been on for a while, let it cool down for about 30 seconds. Next turn up the input voltage to 30V. Measure the output voltages. Do this as quickly as possible because otherwise thermal effects will influence your measurement. Subtract these two values to get your line regulation. **(Measured Values, Answer)**

5. With the input voltage at 30V measure the temperature of the metal tab on the case of the regulator. Wait at least 3 minutes before making the measurement. A good place to do this is to put the probe inside the mounting hole. Be sure to use firm pressure so that there is good contact between the probe and the case. If you are provided with a multimeter with thermocouple input, simply use the thermocouple mode and read the temperature. If you don't have this you will need to measure the voltage and do the calculation as shown on the previous page. You only need to measure the temperature on one regulator. The device may get quite hot so be careful not to burn yourself. **(Measured Value)**

6. Next, mount the provided heatsink after waiting a few minutes for the regulator to cool down. Repeat step 5 and measure the temperature at the heatsink. **(Measured Value)**

7. Use the thermal model of Fig. 7 to calculated the estimated power dissipation of the regulator. Ignore the capacitances and use the measured value to represent the heatsink temperature. Calculate the power and junction temperature. **(Hand Calcs)**

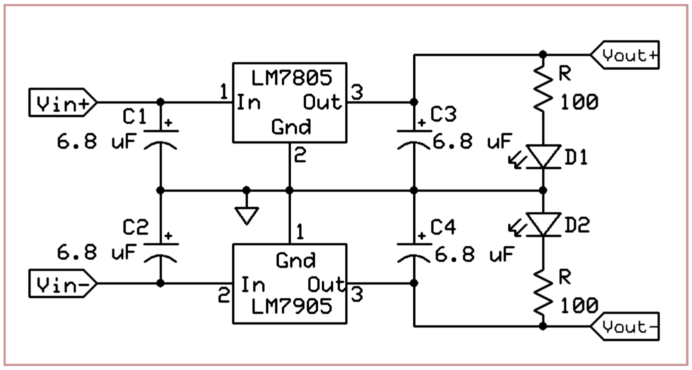


Figure 15. Dual supply with LEDs.

Postlab #2: Constant Current Source

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Built the circuit shown in Fig. 16. For the LED you can use any color that is available.
2. Calculate the value of Rset needed to create a 20 mA constant current source. The formula for this is in the background section of this document. **(Hand Calc)**
3. If you have built the circuit correctly the LED should light up. **(Picture)**
4. Measure the voltage between the output terminal and the ground terminal of the regulator. Note that this is not the circuit ground but rather the pin that is labeled ground on the regulator. Verify that this voltage is around 5V.

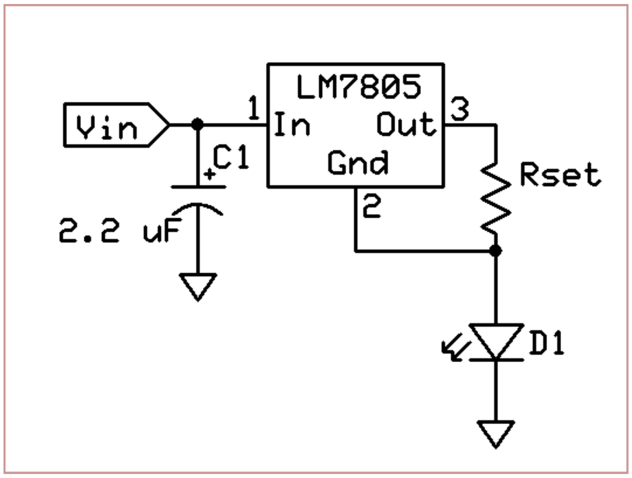


Figure 16. Constant current source driving an LED.