UNIVERSITY OF UTAH
ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

ANALOG INTEGRATED CIRCUITS LAB

LAB 3
Cascoding and Common-Source Amplifiers

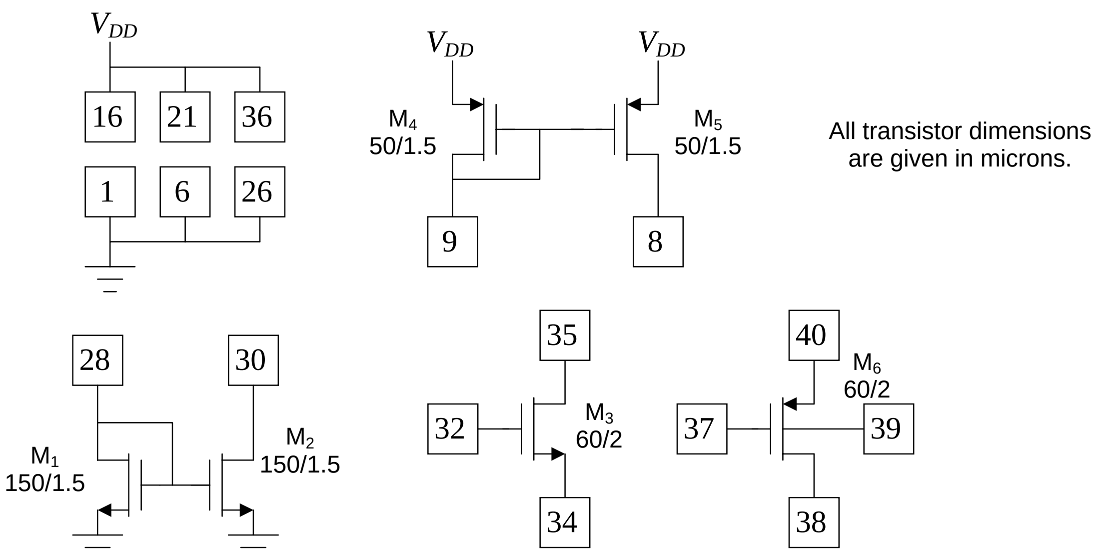
Objective: In this lab, you will explore cascoding, a circuit technique used to increase the output (drain) resistance of a MOSFET. You will also characterize the common-source amplifier, and show how cascoding can greatly increase this circuit's gain. You should review sections 3.2, 3.6, and 3.7 in Johns & Martin.

Power: We will be using a single-polarity power supply for this lab. Connect pins 1, 6, and 26 to ground. Connect pins 16, 21, and 36 to V_{DD} = 5.0 V. (Use the +25V power supply for V_{DD}). Leave these power connections in place for all experiments.

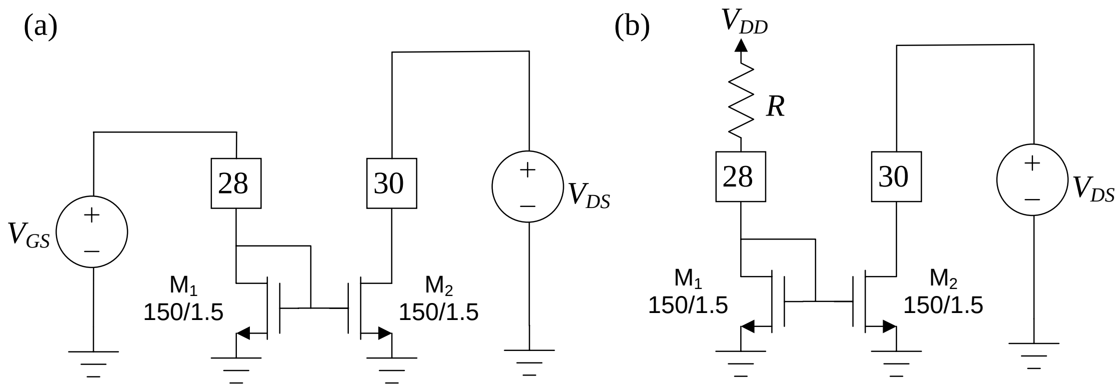
Experiment 1: Cascoded Current Mirrors

The following figure shows the subcircuits on Chip A that we will use for this characterization of cascoded current mirrors. **Be sure to connect pins 1, 6, and 26 to ground, and pins 16, 21, and 36 to V_{DD} (5.0 V) for all the experiments in this assignment.**

Pin-out for Lab 3, Experiment 1 – Chip A



(a) Output resistance of basic *n*MOS current mirror. Set up the basic current mirror circuit shown in part (a) of the figure below. You may wish to use the HP function generator as one of the voltage sources. If so, remember to set it to HIGH-Z load mode.



- Find the value of V_{GS} that gives you an input current close to 100 µA. Record this value of V_{GS} along with the exact value of I_{D1}.

- For this experiment, we wish to keep V_{GS} (and hence I_{in}) constant. Instead of using a voltage source to set the input current, we will use a resistor as shown in part (b) of the above figure. Based on V_{DD}, V_{GS}, and the input current measured, calculate the proper value of R. Set up the circuit shown in part (b) of the figure, and use an ammeter to verify that the input current is still around 100 µA. If you wish, you may use the variable resistance box available at some lab stations. Don't worry about getting an exact value; as long as you are within about 5% of your calculated value, you are fine. What value of R did you use?

Now, with the resistor keeping the input current constant, sweep V_{DS} from zero to 5.0 V in steps of 0.25 V while measuring I_{DS2}.

- Plot I_{DS} vs. V_{DS} for M_2. Use the MATLAB `axis` command to make sure the *x* and *y* axes of your plot begin at zero, so you can see the relative change in current. For example, after you plot, type

```
axis([0 5 0 120]);
```

This will set your *x* axis to go from zero to five, and your *y* axis to go from zero to 120. If you plotted current as microamps, you should have a good picture of the "compliance" of your current mirror – how much the current changes with V_{DS}.

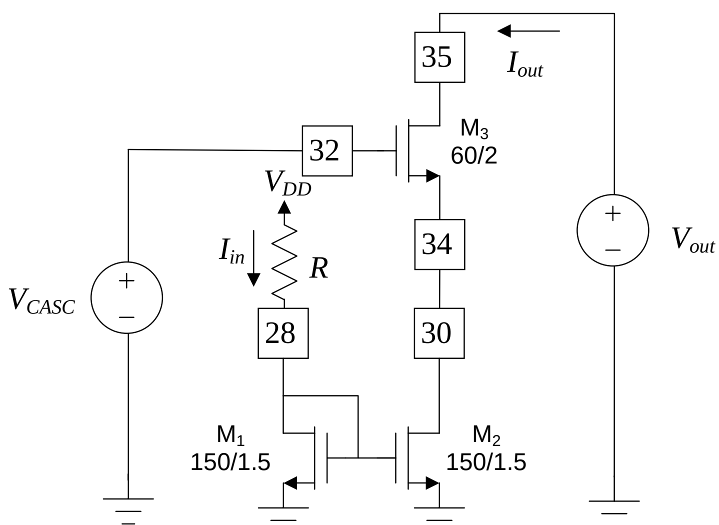
- Where would you expect the boundary between triode and saturation region to lie? Does your data agree with this calculation?

- Add a linear fit to the saturation region, and from the slope of this line, calculate the Early voltage V_A of M_2. (Remember, always report the Early voltage as a *positive* value.) What is the output resistance of this current mirror?

- In Lab 1, you measured the Early voltage of an *n*FET with L = 2.0 μm. How does this Early voltage compare with the one measured today with L = 1.5 μm? Is this what you expect? Why?

- Now plot the gain of this current mirror (I_{out}/I_{in}) vs. V_{DS}. Ideally, this current mirror should have a gain of one. What is the error in the gain (expressed as a percentage) when V_{DS} = 5.0 V?

(b) Cascoded *n*MOS current mirror. Now add the *n*FET M_3 to the output of your current mirror as shown below. Use a voltage source to set V_{CASC} to 1.5 V and V_{out} to 5.0 V for now.



M_3 acts as a *cascode*, shielding the drain of M_2 from the large changes in output voltage. Verify that the drain current of M_3 is close to 100 μA.

- Now, ignoring the body effect, calculate the expected source voltage of M_3. (Use your previous estimates of V_t and $\mu_n C_{ox}$') Would the body effect make this actual voltage lower or higher than your simple calculation? Using a voltmeter, measure the dc voltage at the source of M_3.

- Using the value of gamma you measured in the previous lab, calculate the modified threshold voltage due to the body effect. (Assume $|2\Phi_F|$ = 0.8 V.) How close is the predicted V_{GS3} to your measured V_{GS3}? Note that the source of M_3 is connected to the drain of M_2. Is this voltage high enough to keep M_2 in saturation? Adjust V_{CASC} to equalize the drain voltages of M_1 and M_2 and bring I_{out} to equal I_{in}.

Now sweep V_{out} from zero to 5.0 V in 0.25 V steps. At each step, measure the drain current of M_3 *and* the drain voltage of M2.

- Plot I_{out} vs. V_{out}. Use the MATLAB `axis` command to make sure the *x* and *y* axes of your plot begin at zero, so you can see the relative change in current.

- At what output voltage does this circuit begin to act as good current source? How does this compare to part (a)?

- Add a linear fit to the part of this curve that approximates a constant current source. What is the "effective Early voltage" of this circuit?

- What is the output resistance of this cascoded current mirror?

Circuit theory predicts an output resistance of approximately $(g_{m3}r_{ds3})r_{ds2}$ for this circuit.

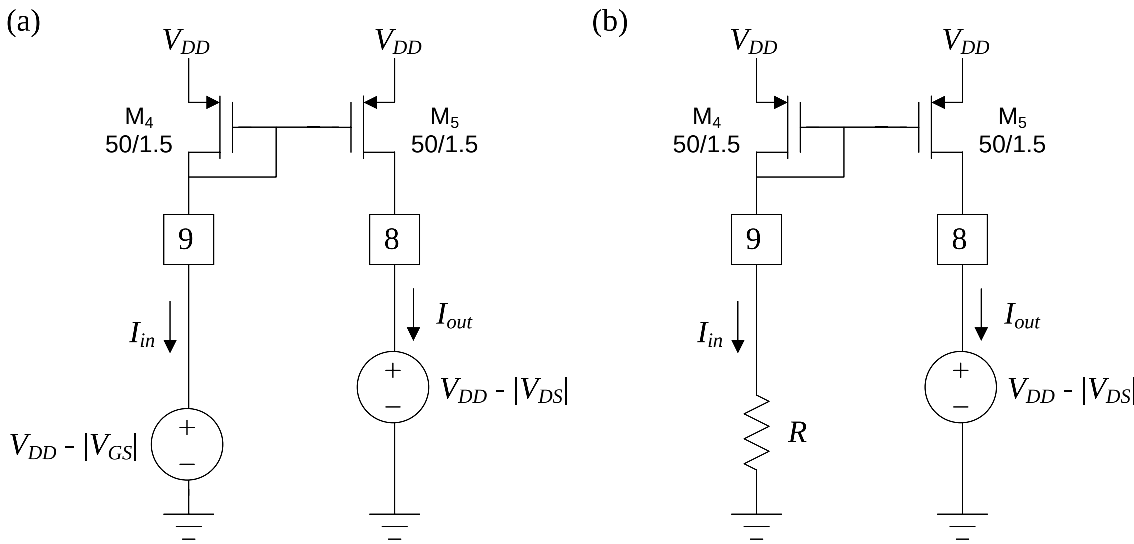
- Using data from Lab 1 (e.g., the Early voltage of M_3) and data measured in this lab (e.g., the Early voltage of M_2), calculate the expected output resistance. How do your calculations compare with the measured result?

- Plot the gain of this current mirror (I_{out}/I_{in}) vs. V_{out}. Ideally, this current mirror should have a gain of one. What is the error in the gain (expressed as a percentage) when V_{out} = 4.0 V?

- Plot the drain voltage of M_2 vs. V_{out}. As V_{out} changes from 4.0 V to 5.0 V, how much does the drain voltage of M_2 change?

- Discuss the advantages and disadvantages of using a cascode configuration.

(c) Output resistance of basic *p*MOS current mirror. Set up the basic current mirror circuit shown in part (a) of the figure below. You may wish to use the HP function generator as one of the voltage sources. If so, remember to set it to HIGH-Z load mode.



- Find the value of input voltage that gives you an input current close to 100 µA. Record the corresponding value of V_{GS4} along with the exact value of I_{in}.

- For this experiment, we wish to keep V_{GS4} (and hence I_{in}) constant. Instead of using a voltage source to set the input current, we will use a resistor as shown in part (b) of the above figure. Based on V_{DD}, V_{GS} and the input current measured, calculate the proper value of R. Set up the circuit shown in part (b) of the figure, and use an ammeter to verify that the input current is still around 100 µA. If you wish, you may use the variable resistance box available at some lab stations. Don't worry about getting an exact value; as long as you are within about 5% of your calculated value, you are fine. What value of R did you use?

Now, with the resistor keeping the input current constant, sweep the output voltage from 5.0 V to zero in steps of 0.25 V while measuring I_{out}. (Note that this is equivalent to sweeping V_{DS5} from zero to –5.0 V.)

- Plot I_{DS} vs. $|V_{DS}|$ for M_5. Use the MATLAB `axis` command to make sure the *x* and *y* axes of your plot begin at zero, so you can see the relative change in current.

- Where would you expect the boundary between triode and saturation region to lie? Does your data agree with this calculation?

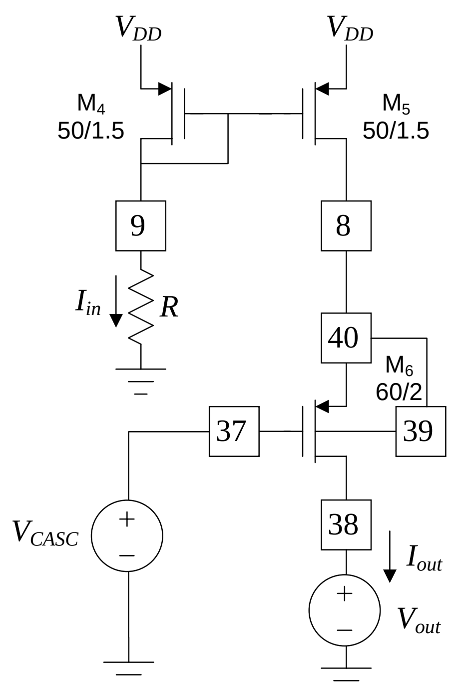
- Add a linear fit to the saturation region, and from the slope of this line, calculate the Early voltage V_A of M_5. (Remember, always report the Early voltage as a *positive* value.)

- What is the output resistance of this current mirror?

- In Lab 1, you measured the Early voltage of an *p*FET with L = 2.0 μm. How does this Early voltage compare with the one measured today with L = 1.5 μm? Is this what you expect? Why?

- Now plot the gain of this current mirror (I_{out}/I_{in}) vs. $|V_{DS}|$. Ideally, this current mirror should have a gain of one. What is the error in the gain (expressed as a percentage) when $|V_{DS}|$ = 5.0 V?

(d) Cascoded *p*MOS current mirror. Now add the *p*FET M_6 to the output of your current mirror as shown below. Use a voltage source to set V_{CASC} to 3.0 V and V_{out} to 0 V for now.



M_6 acts as a *cascode*, shielding the drain of M_5 from the large changes in output voltage. Verify that the drain current of M_6 is close to 100 μA.

- Now calculate the expected source voltage of M_6. (Use your previous estimates of V_t and $\mu_p C_{ox}$') Note that we can ignore the body effect due to the source-well connection of M_6.

- Using a voltmeter, measure the dc voltage at the source of M_6. How close is the predicted V_{GS6} to your measured V_{GS6}? Note that the source of M_6 is connected to the drain of M_5. Is this voltage low enough to keep M_5 in saturation? Adjust V_{CASC} to equalize the drain voltages of M_4 and M_5 and bring I_{out} to equal I_{in}.

Now sweep V_{out} from 5.0 V to zero in 0.25 V steps. At each step, measure the drain current of M_6.

- Plot I_{out} vs. (V_{DD} - V_{out}). Use the MATLAB `axis` command to make sure the x and y axes of your plot begin at zero, so you can see the relative change in current.

- At what output voltage does this circuit begin to act as good current source? How does this compare to part (c)?

- Add a linear fit to the part of this curve that approximates a constant current source. What is the "effective Early voltage" of this circuit?

- What is the output resistance of this cascoded current mirror?

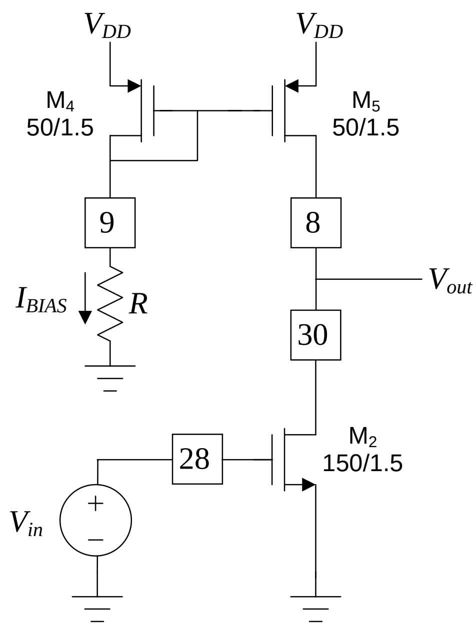
Circuit theory predicts an output resistance of approximately $(g_{m6}r_{ds6})r_{ds5}$ for this circuit.

- Using data from Lab 1 (e.g., the Early voltage of M_3) and data measured in this lab (e.g., the Early voltage of M_2), calculate the expected output resistance. How do your calculations compare with the measured result?

- Plot the gain of this current mirror (I_{out}/I_{in}) vs. (V_{DD} - V_{out}). Ideally, this current mirror should have a gain of one. What is the error in the gain (expressed as a percentage) when V_{out} = 1 V?

Experiment 2: Common Source Amplifier

(a) *n*MOS common source amplifier. Connect the circuit shown in the figure below. Use the function generator for V_{in}. (Note that we are ignoring the diode-connected transistor M_1. It is still present, of course, but since we are fixing the gate voltage of M_1 and M_2 with a voltage source, it doesn't matter that some current is flowing into M_1.)



Use the value of R you used in Experiment 1(c) and (d) to set I_{BIAS} to around 100 μA.

- Now set V_{in} to zero and measure V_{out}. Now set V_{in} to 1.5 V and measure V_{out}. Can you see that this will be an inverting (negative gain) amplifier? For both of these cases, comment on whether M_2 and M_5 are in the triode or saturation region.

We now wish to explore the behavior of this circuit when both M_2 and M_5 are operating in saturation. Observe V_{out} while adjusting V_{in}. Adjust V_{in} until V_{out} is about 2.5 V, halfway between the power supply rails.

- What value of V_{in} is required? Let's call this voltage V_{MID}. What would you expect the drain current of M_2 to be at this point?

Now vary V_{in} in steps of 1 mV, from (V_{MID} – 10 mV) to (V_{MID} + 10 mV). Record V_{out} at each point.

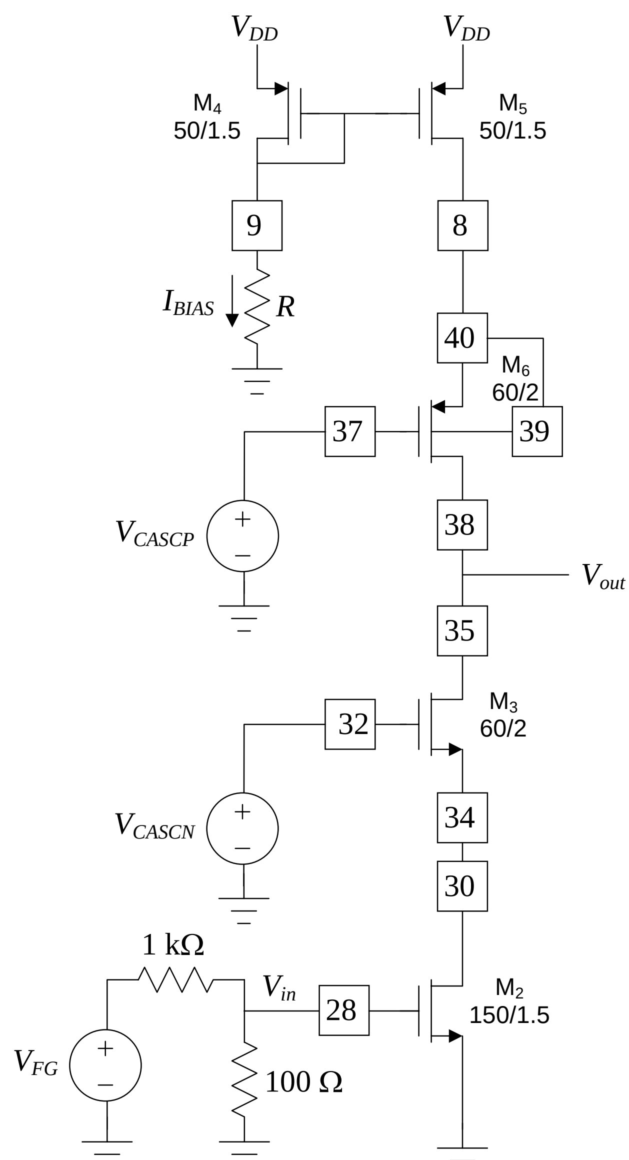
- Plot V_{out} vs. V_{in}, and fit the data points with a line.

- What is the gain of this amplifier? How does your measured gain compare with the theoretical gain of $g_{m2}(r_{ds2}||r_{ds5})$? (Use Early voltage measurement from Experiment 1 to compute r_{ds}.)

- If we were to decrease the bias current to 50 μA, would the gain increase, decrease, or stay the same?

  For extra credit, measure the gain with I_{BIAS} = 50 μA. Include a plot with fit, and a comparison of your measured gain to theory.

(b) Using cascoding to increase gain. Build the circuit shown in the following figure. If you did the extra credit, make sure to set I_{BIAS} back to 100 μA.



This circuit is a common-source amplifier with cascode transistors M_3 and M_6 used to increase the r_{ds} of M_2 and M_5, which should increase the overall gain to $g_{m2}[(g_{m3}r_{ds3})r_{ds2}||(g_{m6}r_{ds6})r_{ds5}]$. This gain will be *very* high, so we will need to change our input voltage in very small increments – less than the 1 mV resolution of the function generator. The resistor voltage divider shown will allow us to change V_{in} with a resolution of better than 0.1 mV.

Note that the output resistance of this circuit will also be very high: $R_{out} = (g_{m3}r_{ds3})r_{ds2}||(g_{m6}r_{ds6})r_{ds5}$. This will likely be higher than the nominal 10 MΩ input resistance of the HP 34401A digital multimeter. Luckily, this multimeter can be set to an "ultra-high input impedance" mode where the input resistance is >10 GΩ. Use the Menu key (Shift – Menu On/Off) to display "A: MEAS MENU" on the screen. Now navigate through the menu from "1: AC FILTER" to "2: CONTINUITY" to "3: INPUT R". Now use the right arrow key to change the input resistance from "10 MOHM" to ">10 GOHM". Press Enter, and the screen should say "Change Saved". (Note that if you turn the multimeter off, it will come back in the normal 10 MΩ mode.)

- Set the bias voltages V_{CASCN} and V_{CASCP} so that M_2 and M_5 are guaranteed to be in saturation. Don't set V_{CASCN} too high (or V_{CASCP} too low), because we want the output voltage V_{out} to be able to swing over a relatively wide range without pushing M_3 or M_6 out of saturation. Report the values you use for these bias voltages.

Now adjust V_{in} until V_{out} is around 2.5 V. (You will need to *measure* the voltage at V_{in} for highest accuracy. Don't calculate it using the voltage divider relationship.) Sweep the input voltage above and below this point, recording V_{out}. The gain should be very high, so you won't be able to change V_{in} much while keeping all the transistors saturated. Try to take enough points to get a nice linear region for your gain fit.

- Plot V_{out} vs. V_{in} with a fit to the linear region.

- What is the gain of this circuit? How well does it match the theoretical calculation of gain?

REPORT

Each lab group (two students) should submit a lab report that is separate from the lab notebook. (In this class, lab notebooks will not be turned in.) The report should be typed, not handwritten, although it is acceptable to add neat handwritten notes to figures where appropriate (e.g., to label different curves). Lab reports are due in your lab section one week after a two-week lab ends.

Begin your lab report with a title page containing your names, email addresses, T.A., lab section, and the title of the lab. Next, write one or two paragraphs outlining the overall goal of the lab. Describe how you performed each experiment, listing any problems you encountered and how you overcame them. Figures are preferably included in line with the text. You should number the figures and refer to them from the text.

- Every sentence labeled with a “bullet” like this indicates either a figure you should include or an answer you should explicitly provide in your report.

The grading for Lab 3 will be as follows:

MATLAB Plots (11):	3 points each
Answers (30):	2 points each
Introduction and conclusion:	4 points
Format and style:	3 points
Total:	100 points
Extra credit:	5 points

Your lab report should contain a description of all experiments performed, data plots (with fits) requested throughout this assignment, and a discussion of how the measured data (and fit parameters) compare with circuit theory.