Lab 1:Output Resistance and Practical Circuits

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Lab Day: Monday ○ Tuesday ○ Wednesday ◉ Thursday ○ Friday ○

Lab Time: Mornings ◉ Afternoons: ○

Introduction:

The concept of an **output resistance** is commonly used to characterize how changes in the current drawn from a source changes the source's output voltage. For linear circuits, the output resistance is equivalent to the Thévenin or Norton resistance. For non-linear circuits, the output resistance or R_{out} is defined as

$$R_{out} = -\frac{\partial v_O}{\partial i_O} \tag{1}$$

where v_O is the total output voltage (includes large and small signal components) and i_O is the total output current. The negative sign in eqn. 1 arises because the output current is defined as flowing out of the source. Small output resistances imply the source's output voltage does not change much as the output current or "load" is varied. In this case the source behaves like a voltage source. Conversely, a large output resistance implies that the source's output current remains almost constant for a wide range of output voltages and the source behaves like a current source.

Preparation:

1. In practical circuits, we do not have access to internal voltage and current sources. As a result, when measuring a circuit's R_{out} in the lab, we cannot "set all independent sources to zero". Hence, while it may be obvious, by inspection, what the value of R_{out} is for the source enclosed by the dotted line in Fig. 1, we would like to calculate it by:

   1) applying a test voltage, V_T,
   2) determining the resulting test current I_T ,
   3) and then using V_T and I_T to calculate R_{out}.

   This can be done by filling out Table 1. For the fifth and sixth columns, in each row i, $\Delta V_{Ti} = V_{Ti} - V_{Ti-1}$ and $\Delta I_{Ti} = I_{Ti} - I_{Ti-1}$. Then determine R_{out}.

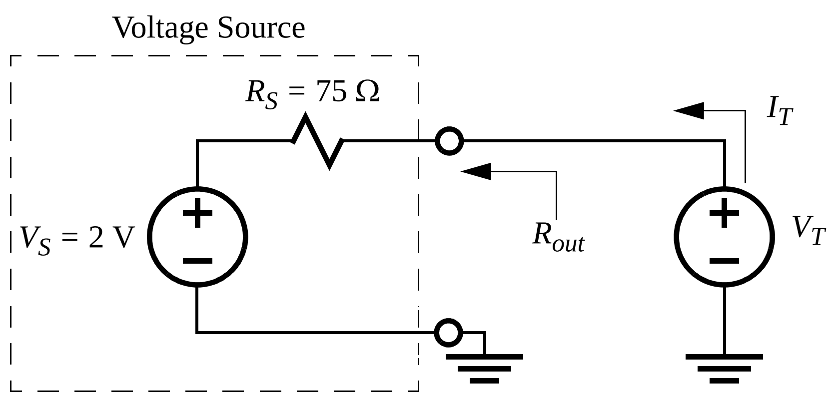

Figure 1) Finding the output resistance.

Table 1: Computing the Output Resistance of the Circuit in Fig. 1.

	V_{Test} (V)	I_{Test} (mA)	$\lvert V_T/I_T \rvert$ (Ω)	ΔV_T (V)	ΔI_T (mA)	$\Delta V_T/\Delta I_T$ (Ω)
V_{T1}	0					
V_{T2}	1					
V_{T3}	2					
V_{T4}	3					
V_{T5}	4					
R_{out} = ________ kΩ						

Preparation Continued,

2. For the circuit shown in Fig. 2, determine the voltage at Q_1's base (V_B), emitter (V_E) and collector (V_C) and **enter these values directly on the circuit diagram** in the appropriate locations.[1] Assume $\beta = \infty$, $|V_{BE}| = 0.7$ V and $R_L = \infty$, when in the active region.

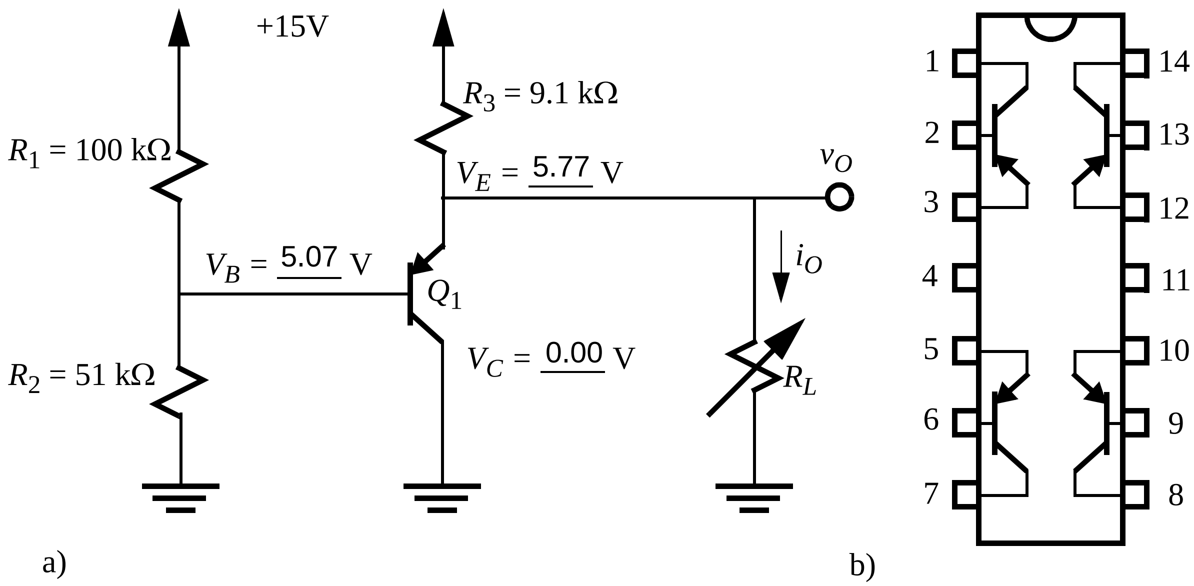

Figure 2) A voltage source (a) and the pin diagram for the NTE2322 (b).

3. Using your lab kit, pre-wire the circuit shown in Fig. 2, with R_L left as an open circuit.

Preparation continues on the next page.

1. The arrow through R_L indicates that R_L is a variable resistance and will be implemented with a decade box in the lab. A decade box is a special set of switch-selectable resistors.

Preparation Continued,

4. Download (from the class website) the workbook entitled *Lab 1.xlsx*. On the sheet labeled "Voltage & Current Source Data" (the first sheet in the workbook), prepare a spreadsheet[1] similar to that shown in Table 2. For the formula in the R_{out} columns, Δv_O is the difference between the v_O in the row above and the v_O in the current row while, Δi_O is the difference between the i_O in the row above and the i_O in the current row.

Table 2: Sample Spreadsheet for Lab 1

Resistance	*Results for the Voltage Source*			*Results for the Current Source*		
	v_{O1}(V)	i_{O1} (mA)	R_{out1} (Ω)	v_{O2} (V)	i_{O2} (mA)	R_{out2} (Ω)
999,999 Ω		$= v_{O1}/R_L$			$= v_{O2}/R_L$	
100 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
70 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
50 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
35 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
20 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
14 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
10 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
7 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
5 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
3.5 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
2 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
1 kΩ		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
700 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
500 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
350 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
200 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
140 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$
100 Ω		$= v_{O1}/R_L$	$= -\Delta v_{O1}/\Delta i_{O1}$		$= v_{O2}/R_L$	$= -\Delta v_{O2}/\Delta i_{O2}$

1. Use your favorite spreadsheet program. You will measure and enter the voltage values while the spreadsheet uses the formulae to calculate the values for i_O and R_{out}.

Laboratory:

A Voltage Source

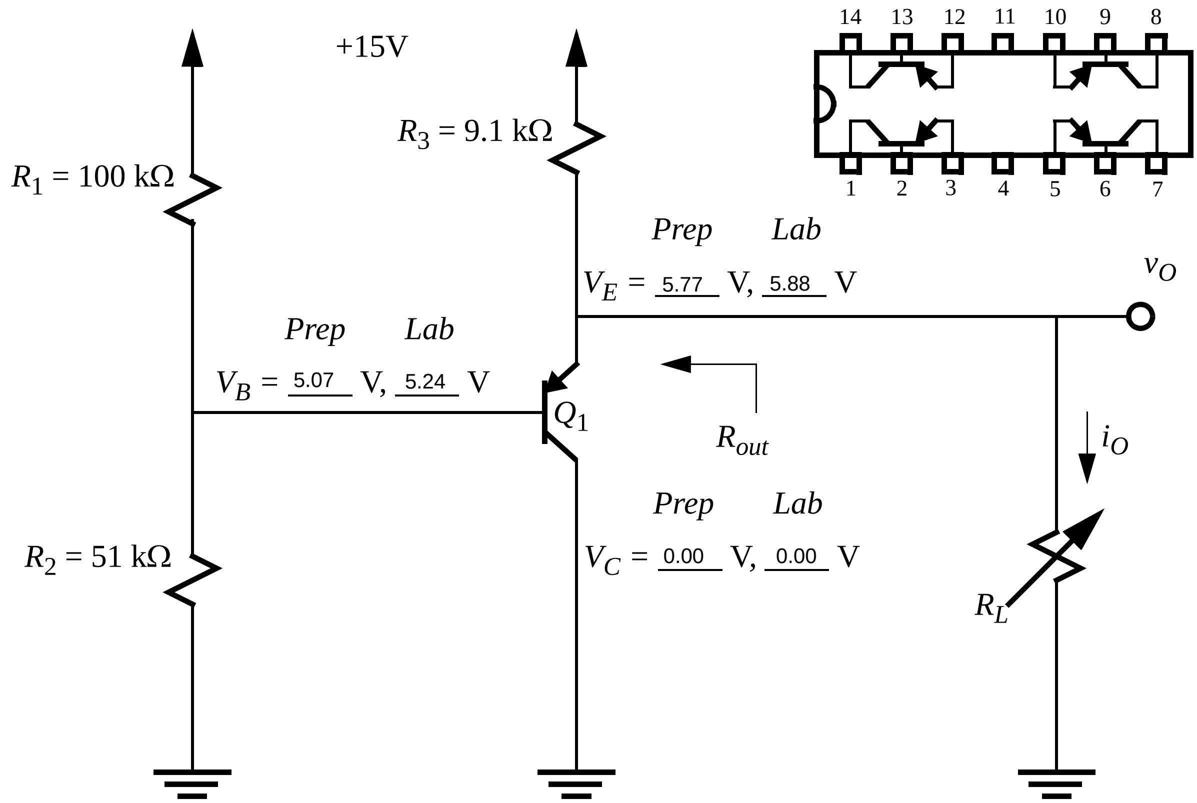

Figure 3) Schematic diagram of a voltage source.

1. Verify that your circuit analysis and pre-wiring are correct by applying 15 V and ground to your circuit and measuring the node voltages.[1] Record the measured voltages on Fig. 3.
2. Set the decade resistor box on the highest resistance setting (*i.e.*, 999,999 Ω). Then, connect the decade resistance box between v_O and ground, as shown in Fig. 3.
3. For each resistance value indicated in Table 2, measure and record the output voltage in your spreadsheet. Be sure to record at least four significant figures.
4. When the resistor setting is at its lowest value (*i.e.*, 100 Ω), measure and record the transistor's base, emitter and collector voltages.

   V_B = 5.089 V V_E = 0.167 V V_C = 0.000 V

5. Using the spreadsheet, generate two plots; v_{O1} *versus* R_L and v_{O1} *versus* i_{O1}. Be sure to put these two plots on the sheet entitled "V versus Rl & I" (the second sheet) in the workbook.

1. The measured voltages should be within a few hundred millivolts of the values found in the preparation.

A Current Source

1. With the decade resistor box still set to 100 Ω, change your circuit to that shown in Fig. 4.

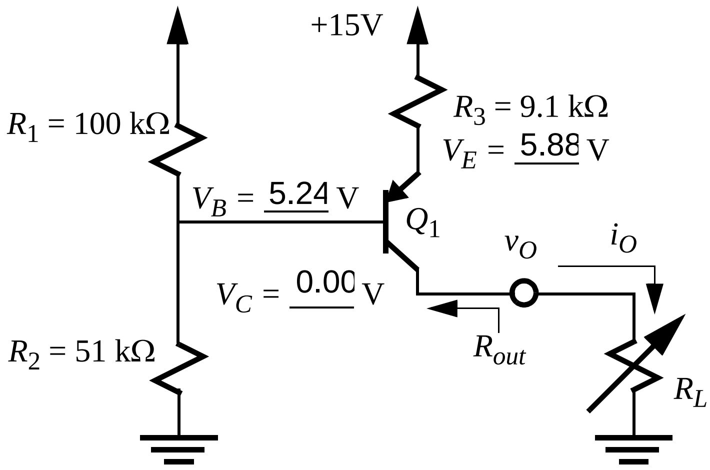

Figure 4) A BJT based current source.

2. Verify that Q_1's base and emitter voltages are similar to the values measured earlier in part 1 of *A Voltage Source,* as shown on Fig. 4.
3. For each resistance value indicated in Table 2, measure and record the output voltage.
4. When the resistor setting is at its highest value (~1 MΩ), measure and record the transistor's base (V_B), emitter (V_E) and collector (V_C) voltages on Fig. 4.

   V_B = 12.37 V V_E = 13.01 V V_C = 13.008 V

5. Using the spreadsheet, generate two plots; One, i_{O2} *versus* R_L and two, i_{O2} *versus* v_{O2}. Be sure to put these two plots on the sheet entitled "I versus Rl & V" (the third sheet) in the workbook.
6. Measure and record the actual value of your 15V supply. The supply voltage = 15.0960 V. Then measure and record the actual values of R_1, R_2 and R_3.

   R_1 = 98.20 kΩ R_2 = 50.49 kΩ R_3 = 9.00 kΩ

A Sensor

Solar cells are commonly made from pn junctions. When the pn junction is illuminated, electron-hole pairs are generated in the pn junction's depletion region. Since these charged particles find themselves in an electrical field, the electrons are immediately swept to the cathode or n side and the holes to the anode or p side. If an external current path (*i.e.*, a load) exists, current will flow and power will be delivered from the source (the solar cell) to the load (R_L).

A simple circuit using a solar cell and a load resistance (the decade resistor box) is shown in Fig. 5. By allowing light to illuminate the solar cell, power will be supplied to the load (R_L). We would now like to model the solar cell with its Thévenin or Norton equivalent model.

1. Prepare a spreadsheet, in your workbook on the sheet labeled "Solar Cell Data", similar to the first four columns of Table 2. Note you will have to determine an appropriate range of resistor values to use in column 1.

2. Place the solar cell on top of your oscilloscope and be sure to not shade it while taking measurements. Vary R_L and complete the second column of the spreadsheet.

3. Use the spreadsheet to compute the load current and output resistance.

4. Plot v_O *versus* i_O. Put this plot on the sheet entitled "Solar Cell V versus I" (the fifth sheet) in the workbook.

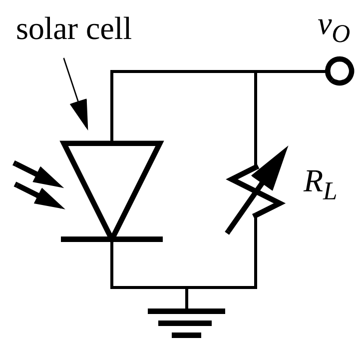

Figure 5) A photodiode or solar cell connected to a load

Report:

A Voltage Source

1. Using the voltages measured in part 1 of the *Voltage Source* section and the resistor values measured in part 6 of the *Current Source* section, along with Fig. 3, determine your transistor's β.

   β = _______

2. If you have not already done so, using the spreadsheet created in the *Voltage Source* section of the Lab, generate a plot of v_{O1} *versus* R_L and a plot of v_{O1} *versus* i_{O1} on the sheet entitled "V versus R & I". On the plots, identify the region (*i.e.*, the range of resistor and current values) over which the circuit shown in Fig. 3 behaves as a voltage source. Indicate the range on each plot by using the "Insert" "Shapes" tool to draw a line with arrow heads on each end that spans the range of interest. Then, determine the voltage source's output resistance, R_{out}, based on measured values..

   R_{out} = ______Ω

3. In the space provided below, draw a Thévenin equivalent model of Fig. 3. Clearly label the value of the independent source, the output resistance and state the range of output currents over which the model is valid. To draw the model, use the markup tools in **Adobe Reader**[1].

   I_{OUT_MAX} = ______ mA

   I_{OUT_MIN} = ______ mA

4. Using a small signal model and the value of β, found in part 1 above, analyze the circuit of Fig. 3 to find its output resistance, R_{out}. Assume R_L is an open circuit and $r_o = \infty$, when determining R_{out}.

   R_{out} = ______Ω

1. To use the markup tools, open this file using Adobe Reader, open the pull-down menu entitled "View", highlight "Comment" and select "Drawing Markups". These tools allow you to draw shapes, lines and add text. Marks will be deducted for messy drawings!

5. Compare the R_{out} found in part 2 to the R_{out} found in part 4.
   Almost the same ○
   Reasonably close ○
   Wildly different ○

6. Why, when analyzing linear circuits to determine their output resistance, do we set the circuit's independent sources to zero and then apply a 1 V test voltage (or a 1 A test current)?

7. What mode of operation is the transistor in when $R_L = 100\ \Omega$? How do you know this?

   The operating mode is: ____________________

A Current Source

1. If you have not already done so, using the spreadsheet created in the *Current Source* section of the Lab, generate a plot of i_{O2} *versus* R_L and a plot of i_{O2} *versus* v_{O2} on the sheet entitled "I versus Rl & V" in the workbook. On the plots, identify the region (*i.e.*, the range of resistor and voltage values), using a double headed arrow, for which the circuit shown in Fig. 4 behaves as a current source and determine its output resistance (based on measured values)..

   R_{out} = ______ kΩ

2. In the space provided below, draw a Norton equivalent model of Fig. 4. Clearly label the value of the independent source, the output resistance and state the range of output voltages over which the model is valid. To draw the model, use the markup tools in Adobe Reader.

   V_{OUT_MAX} = _______ V

   V_{OUT_MIN} = _______ V

3. What mode of operation is the transistor in when the resistance is set to 999,999 Ω? How do you know this?

   The operating mode is: ____________________

A Sensor

1. If you have not already done so, plot v_O *versus* i_O for the solar cell on the sheet entitled “Solar Cell V versus I. Then, using the plots, determine if the solar cell should be modeled as a voltage (Thévenin) or current (Norton) source.

   The solar cell should be modeled as a (select one):

   Voltage source ◯
   Current source ◯

2. Draw the appropriate Thévenin or Norton equivalent circuit model (with component values) for the solar cell and specify the range of load resistances for which the model is valid.

R_{LOAD_MAX} = ________ kΩ

R_{LOAD_MIN} = ________ Ω