Experiment 3:
The Howland Current Pump

Objective

The objective of this experiment is to gain experience using operational amplifiers, and to understand their use in constructing a circuit that behaves as an "independent current source."

Background

An independent current source is a two-terminal component that delivers a specific current flow without regard to the voltage developed across its terminals; the terminal voltage depends on the network to which the source is connected. In other words, an ideal independent current source provides a specified amount of current regardless of the impedance it is driving.

The current source has a value, $i_S(t)$, measured in units of *amperes*, (A), which are frequently abbreviated to *amps*.

The Ideal Independent Current Source

The symbol for a current source includes an arrow to indicate the reference direction for the current. If $i_S(t)$ does not vary with respect to time, then the current source is called a "constant current source".
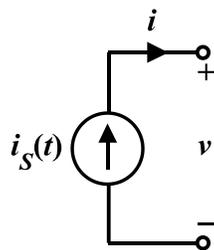

Figure 1. Symbol for an Ideal Independent Current Source.

For a current source, there is no simple physical "almost-matching" component like the familiar battery that corresponds to a voltage source. Though they may not be found in nature, a current source is a valuable modeling technique because, over a fairly wide range, some things behave like current sources. Also, it's sometimes useful to build current sources as a subcomponent of other circuits, systems or models.

The Non-Ideal (Practical) Independent Current Source

As batteries are often modeled with voltage sources, it's important to remember that real electrochemical battery cells have internal resistance. This resistance depends on battery chemistry, construction, and history. Fresh, high-quality batteries typically have lower internal resistance than old, used batteries. The internal resistance is modeled as a *series* resistance as shown in Figure 2(a).

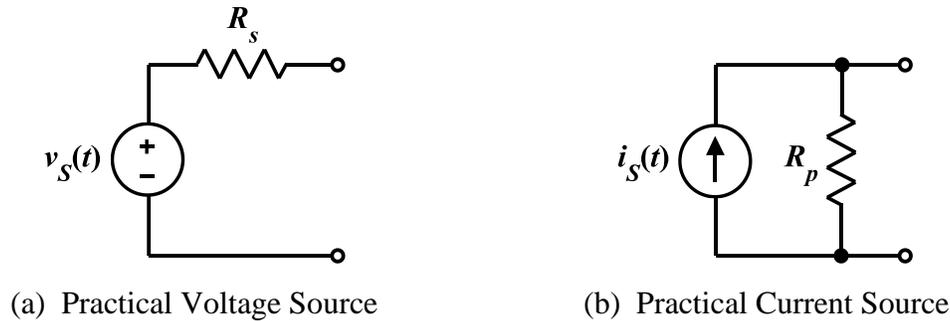(a) Practical Voltage Source   (b) Practical Current Source

Figure 2. Practical Source Models Including Internal Resistance.

A practical current source is modeled, instead, with a *parallel* internal resistance. The parallel resistor indicates that the current drawn will vary with the terminal voltage; and both the internal resistor and the load will draw current from the ideal source simultaneously.

Introduction

One way to construct a circuit that behaves as an independent current source is shown in Figure 3. This circuit is known as ***The Howland Current Pump***. Invented in 1962 by MIT Professor Bradford Howland, it consists of an op amp and a balanced bridge capable of delivering current in either direction. It converts the voltage source (V_S) into a current source capable of driving a grounded load (represented by the resistor R_L), with $I_{out} = V_S / R_1$, regardless of the value of R_L.
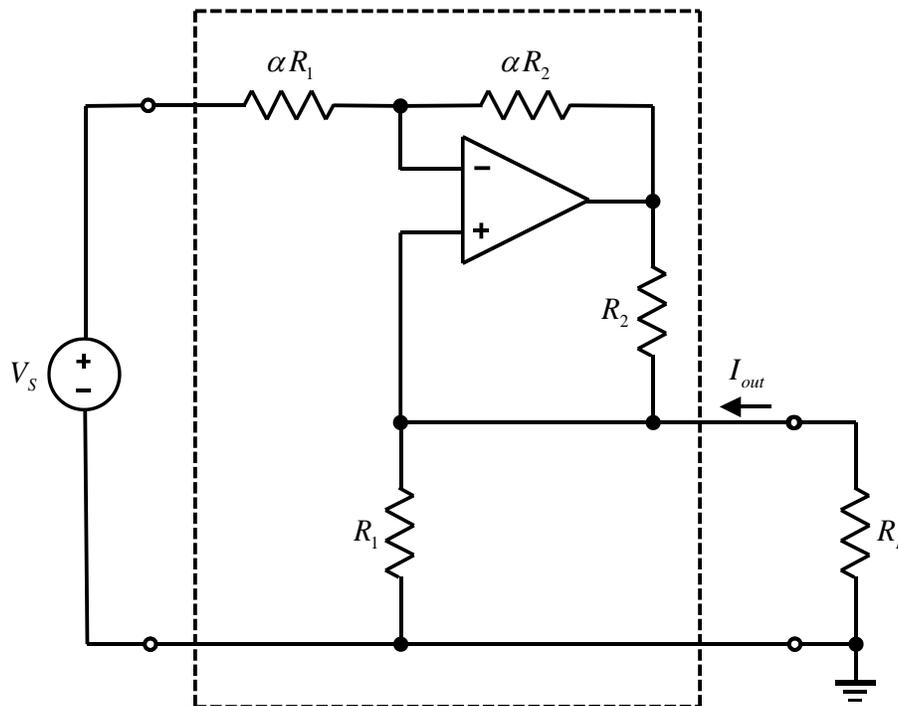
Figure 3. The Howland Current Pump.

What Will You Do?

1. Analytically show that, regardless of the value of R_L, the output current of this circuit is $I_{out} = V_S/R_1$.

2. Simulate operation of the circuit with LTspice to verify that $I_{out} = V_S/R_1$, regardless of the value of R_L. (Choose an opamp from your parts kit and use the appropriate LTspice model subcircuit for this.)

3. Use Fritzing to design the component/wiring layout you will construct to test the circuit with your lab Parts Kit and breadboard.

4. Construct the actual circuit and take measurements to verify that it works as you expect.

What Will You Need?

- ADALM2000 Active Learning Module
- Laptop Computer with LTspice, Fritzing, and Scopy Software
- Breadboard and Jumper Wire Kit
- DMM
- Several Resistors (See the discussion.)
- Op Amp (See the discussion.)

Procedure

1. Analytically show that, regardless of the value of R_L, the output current of this circuit is $I_{out} = V_S / R_1$. (Assume the opamp is ideal.).

   See References 5-7 for example analyses of a **very** similar circuit.
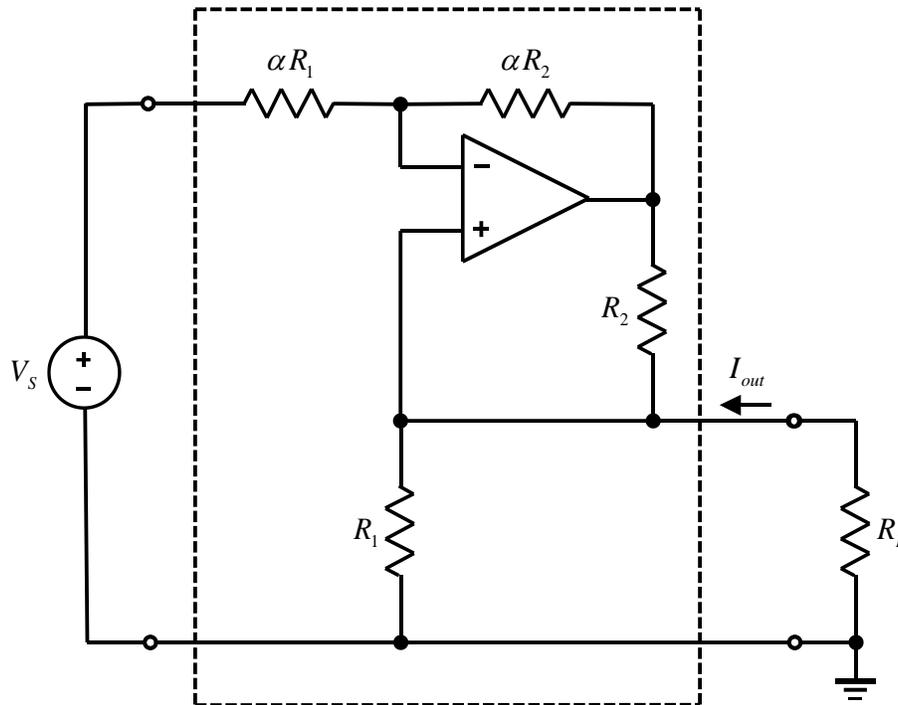

Figure 4. Circuit for Analytical Consideration.

2. Simulate the operation of the circuit with LTspice to verify that $I_{out} = V_S / R_1$, regardless of the value of R_L. (Choose an opamp from your parts kit and use the appropriate LTspice model for this. You will be using the actual op amp itself in part 4 of this experiment to verify circuit operation with hardware.) Sweep the value of R_L from 40 Ω to 4 kΩ and plot I_{out} vs. R_L.
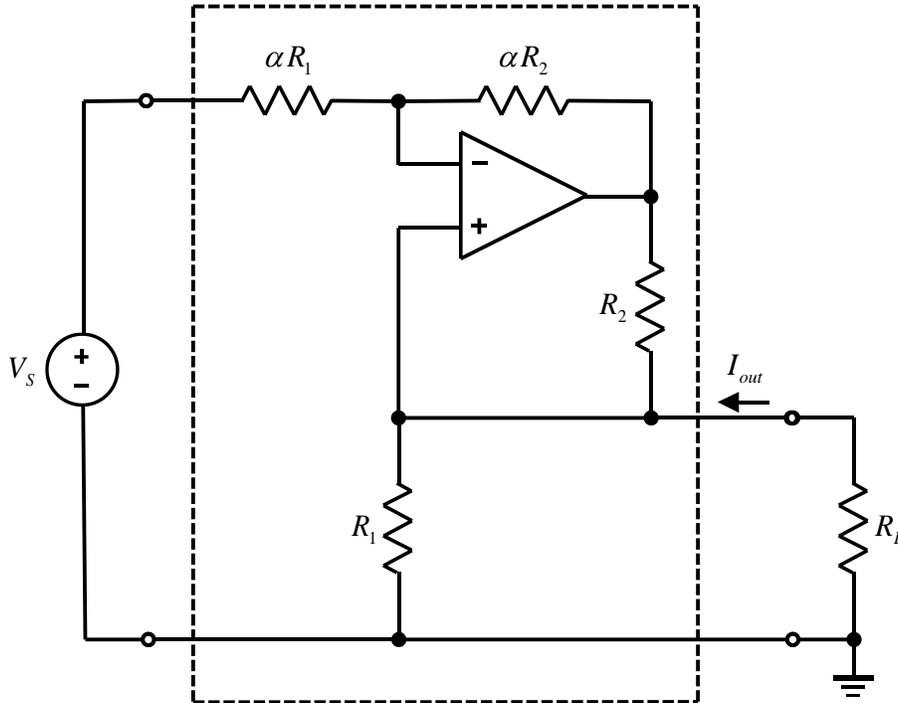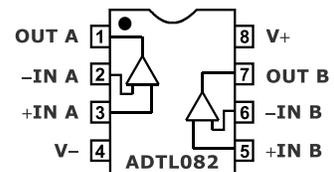
Figure 5. Circuit for Modeling and Simulation.

Operational amplifiers included in your Parts Kit are:

a. Analog Devices ADTL082 Low Cost JFET Input Dual
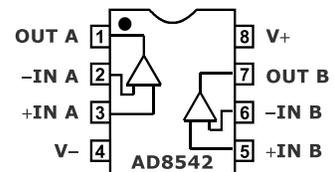Operational Amplifier (2 op amps in the same package)

Data Sheet & SPICE model:
https://www.analog.com/en/products/ADTL082.html

b. Analog Devices AD8542 General-Purpose CMOS Dual
Rail-to-Rail Amplifier (2 op amps in the same package)

Data Sheet & SPICE Model:
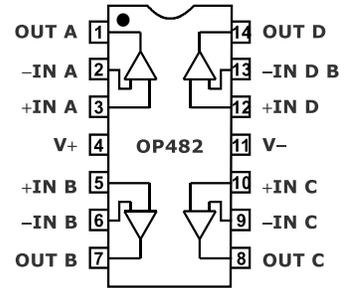https://www.analog.com/en/products/AD8542.html

c. Analog Devices OP482 Low Power, High Speed JFET
    Quad Operational Amplifier (4 op amps in the same
    package)

    Data Sheet & SPICE Model:
    https://www.analog.com/en/products/OP482.html
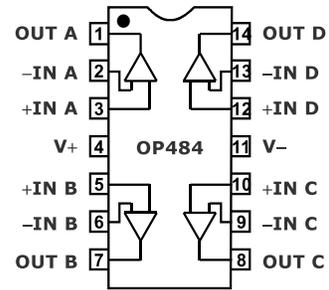
d. Analog Devices OP484 Precision Rail-to-Rail Input &
    Output Operational Amplifier 4 op amps in the same
    package)

    Data Sheet & SPICE Model:
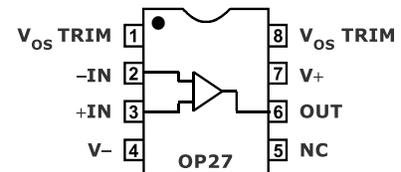   https://www.analog.com/en/products/OP484.html#

e. Analog Devices OP27 Low Noise, Precision
    Operational Amplifier (single op amp)

    Data Sheet & SPICE Model:
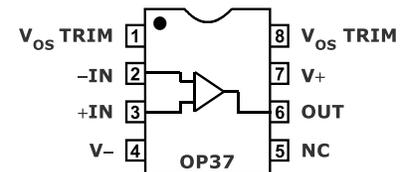   https://www.analog.com/en/products/OP27.html#

f. Analog Devices OP37 Low Noise, Precision, High
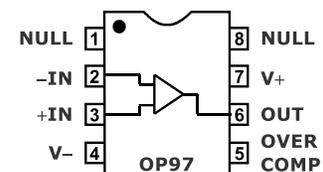   Speed Operational Amplifier (single op amp)

    Data Sheet & SPICE Model:
    https://www.analog.com/en/products/OP37.html#

g. Analog Devices OP97 Low Power, High Precision
    Operational Amplifier (single op amp)

    Data Sheet:
    https://www.analog.com/en/products/OP97.html#

    No SPICE model is available on the AD site, but a legacy model can be downloaded from:
    http://espice.ugr.es/espice/src/modelos_subckt/Anal%C3%B3gicos/op97.mod

Does the circuit work as you expected it to? At first glance, does it look like your circuit
doesn't work properly? Does the value of I_{out} appear to change with the value of R_L? Check

the vertical scaling of your plot. How much range does it cover with respect to the numbers involved? Is the variation you see significant enough to be of any consequence?

Things to Think About Before You Start Building the Circuit

Choose whatever resistance values you like, but note that most of the references cited here have chosen $\alpha = 1$ and $R_1 = R_2$, making all four resistor values the same for simplicity.

What op amp output voltage would be expected with your choice of resistance values? Does it exceed the saturation voltage of the op amp? (Note that with the ± 5 V supplies provided by your lab kit, you cannot get an output with magnitude of 5 V or more.)

Is there any danger of your ⅛-W resistors being damaged by your circuit requiring them to dissipate more power than their nominal rating?

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3. Use Fritzing to design the component/wiring layout you will construct to test the circuit with your lab Parts Kit and breadboard. This design must be exactly the same as the actual breadboard circuit you construct in part 4 of this experiment. (Don't forget to include power for the op amp. It won't work otherwise.)
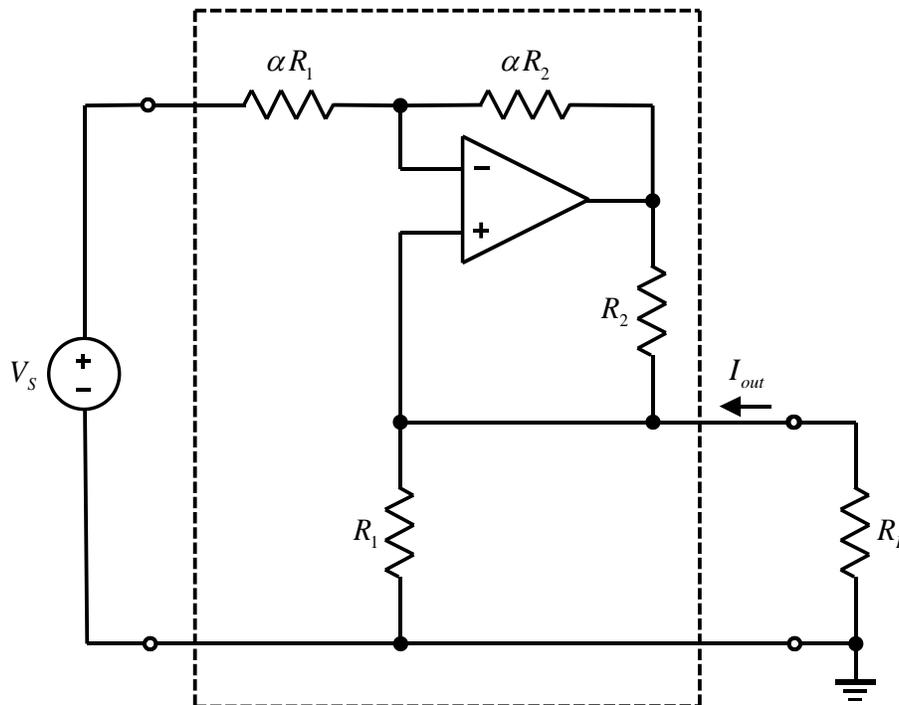

Figure 6. Circuit for Layout Planning with Fritzing.

4. Using your Fritzing design as a guide, construct the actual circuit with your Lab Kit hardware and take measurements with the software instrumentation and the DMM to verify that it works as you expect. Try several different resistors in the range $40 \le R_L \le 4\,\text{k}\Omega$ and plot I_{out} vs. R_L.

   While you're at it, use the resistance-measuring capability of your DMM to check the actual value of each of your resistors. These are $\pm 5\%$ resistors, so they could vary somewhat from the values you expect from reading their color codes. Can this cause errors in your experimental results? If so, are they significant?
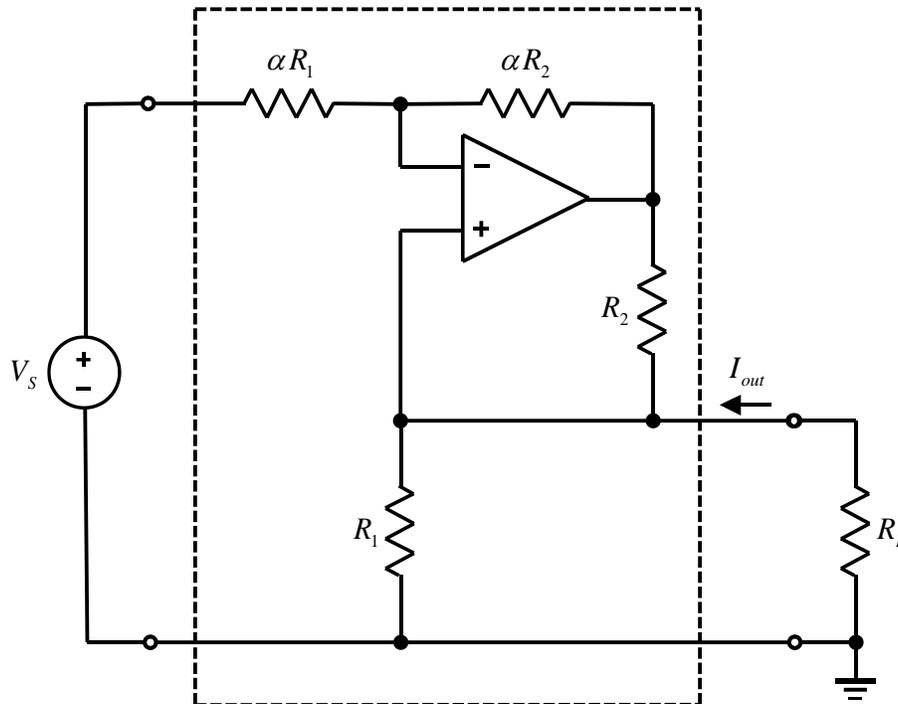

Figure 7. Circuit for Hardware Construction.
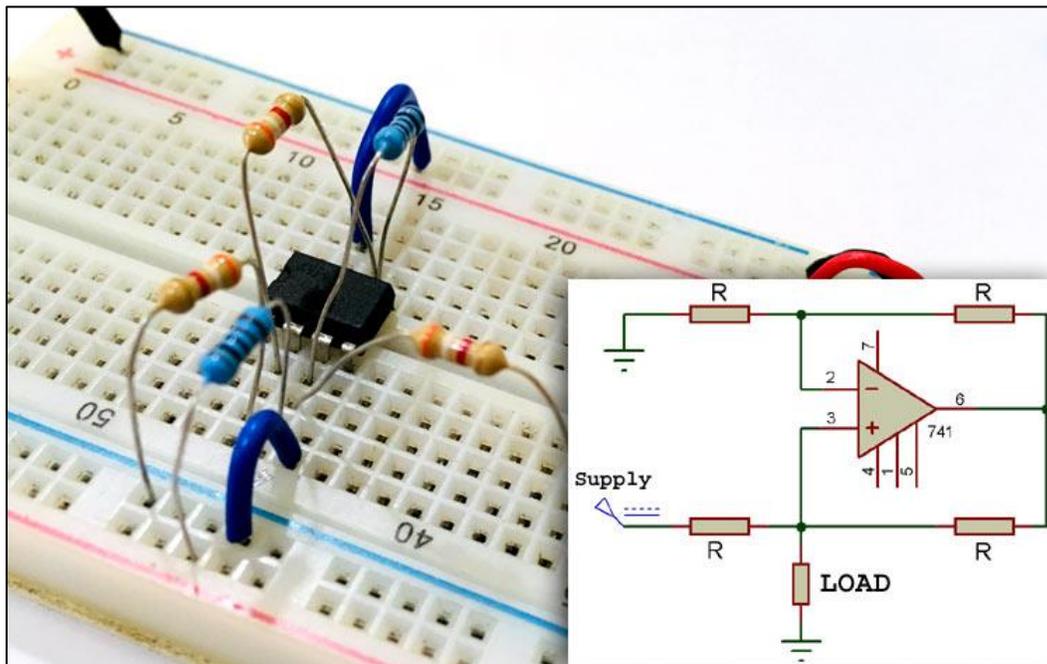
Did you learn anything?

Suggestions? Hints?

Do you have any suggestions for modification of this experiment to make it a more-worthy experience for the next class? Bonus points may be awarded for constructive suggestions.

Note that, if the input voltage is allowed to vary with time, then this circuit is actually a Voltage-Controlled Current Source (VCCS), with $i_{out}(t) = g_m v_S(t)$, where $g_m = \dfrac{1}{R_1}$.

References

1. Texas Instruments Application Report: AN-1515 A Comprehensive Study of the Howland Current Pump, https://www.ti.com/lit/an/snoa474a/snoa474a.pdf.

2. Sergio Franco, The Howland Current Pump, https://www.allaboutcircuits.com/technical-articles/the-howland-current-pump/

3. Texas Instruments Application Report: Analysis of Improved Howland Current Pump Configurations, https://www.ti.com/lit/an/sboa437/sboa437.pdf?ts=1614195288774&ref_url=https%253A%252F%252Fwww.google.com%252F

4. Pankaj Khatri, Circuit Digest: Howland Current Pump Circuit, https://circuitdigest.com/electronic-circuits/howland-current-pump-circuit

5. Op-Amp Circuits: Howland Current Source (VCIS), https://www.youtube.com/watch?v=26jwvYAA4bg

6. Review of Op-Amps: Howland Current Source, https://www.youtube.com/watch?v=pgD-s6XtfZY

7. What is a Howland Current Pump?, https://www.youtube.com/watch?v=_x4aqCCz_Iw

Extracted from Reference 4.