Lab 6: Instrumentation Amplifier

INTRODUCTION:

A fundamental building block for electrical measurements of biological signals is an instrumentation amplifier. In this lab, you will explore the operation of instrumentation amplifiers by designing, building, and characterizing the most basic instrumentation amplifier structure. The circuit will be further developed in the next lab.

REQUIRED PARTS AND MATERIALS:

This lab assignment is performed using:

- Results from Lab 6 Prelab Grading Sheet
- 1 breadboard (for each lab team)
- 1 OP467 quad opamp (for each lab team)
- 2 10kΩ resistors
- 7 resistors with values determined in the prelab assignment
- Philips PM 3365 Oscilloscope
- HP 33120A Function Generator
- Fluke 8840A Digital Multimeter
- HP 6216C DC power supply
- Breadboard wires and cables
- OP467 operational amplifier data sheet (for reference)

PRELAB:

1. Print the Prelab and Lab 6 Grading Sheets. Answer all of the questions in the Prelab Grading Sheet and bring the Lab 6 Grading Sheet with you when you come to lab. ***The Prelab Grading Sheet must be turned in to the TA before beginning your lab assignment.***
2. Read through the LABORATORY PROCEDURE before coming to lab. Note: you are not required to print the lab procedure; you can view it on the PC at your lab bench.

BACKGROUND:

Part 1: Instrumentation Amplifier

The schematic below shows a basic instrumentation amplifier consisting of three opamps and various resistors. This structure is often used in many instrumentation circuits to provide differential gain while ensuring a very high input impedance. The circuit is basically a differential gain stage (opamp on the right) preceded by two voltage followers that provide a very high input impedance. However, rather than using voltage follower structures, non-inverting structures are used to provide some gain along with very high input impedance. The overall 3-amp structure realizes very small common mode gain and thus has a large common mode rejection ratio (CMRR) that is desirable for differential amplifiers. Operation of this structure is governed by the following equations.

Differential voltage gain, A_d, of this structure is given by

$$A_d = \left| \frac{v_o}{v_1 - v_2} \right| = \left| \frac{2R_2 + R_1}{R_1} \cdot \frac{R_4}{R_3} \right|$$

where the sign (positive or negative) of the gain is determined by the arbitrary choice of v_1 or v_2 as the differential input reference, i.e., v_1-v_2 or v_2-v_1. In commercial instrumentation amplifiers, often all resistor values are set within the component except R_1, which is externally controllable to set the differential gain.

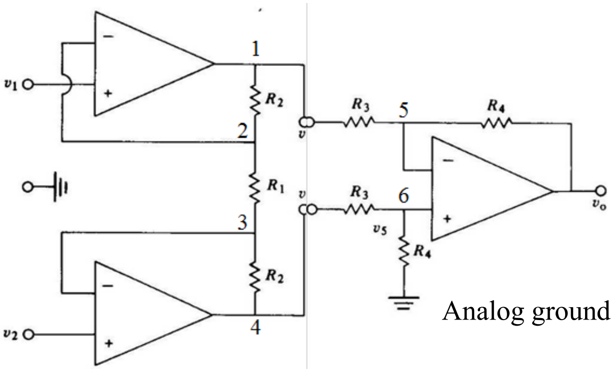


Figure 1: Basic instrumentation amplifier configuration.

OpAmp Selection

Selecting from a wide range of commercial opamps to implement an amplifier configuration should be based on performance requirements set by the application. Typical considerations include noise performance, input signal voltage range, amplifier bandwidth, response time, and power consumption. You must also consider what load your output needs to drive. In instrumentation applications, typically the load is some sort of recording device, oscilloscope or A/D converter, that would have a high input impedance and thus not be a major performance consideration. However, if you have to drive a low resistance load, you must ensure your amplifier can drive such a load and still maintain other performance goals. Always select the opamp that best suits your application needs. In this course, we will be using the commercial component from Analog Devices, OP467. This is a rugged BJT-based opamp with a class AB output stage suitable for driving a wide range of loads with high speed. The data sheet for this device is available on the class website.

Resistor Selection

Generally, resistor ratios can be determined from gain specifications, but how do you decide the absolute value of resistors to be used? Keep in mind that lower resistor values (relative to higher values) have lower noise but require stronger drive current (max amplifier output current) and result in higher power consumption. Typically, resistor values in the 1kΩ – 1MΩ range provide a good compromise between noise performance and power consumption. In biomedical applications, noise is often a primary performance limiter, so it may be preferable to stick closer to the lower end of this range. Resistance below 1kΩ can be used, but if they are not in series with other higher resistance components they might require a large drive current; consider that only 1V across a 100Ω resistor means it's pulling 10mA, which is pretty significant current in the IC world.

Part 2: SPICE Simulations

You need SPICE to simulate an instrumentation amplifier and determine the proper value of resistor elements to meet performance specifications. Additional information about SPICE simulations can be found in your notes and lab material from pervious courses and several useful internet sites, e.g., http://www.ecircuitcenter.com/SPICEsummary.htm

OpAmp Model

As shown below, the most basic model for an opamp is a voltage controlled voltage source (VCVS). While we could model our opamps this way for simulation, the VCVS tends to suffer from convergence problems in SPICE. Thus, it is generally preferable to use a macro model for opamps. These more complex, typically empirically derived models, do a good job of simulating the performance of an opamp while remaining much less complex (and therefore faster to simulate) that a full transistor-level model. Nowadays, macro models for many commercial opamps can readily be found on the web and then included as subcircuits in SPICE simulations. A text file macro model subcircuit for the OP467 used in this class is available on the class website.

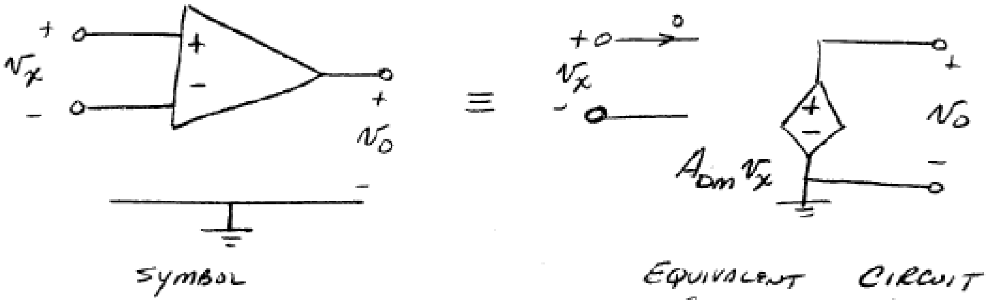
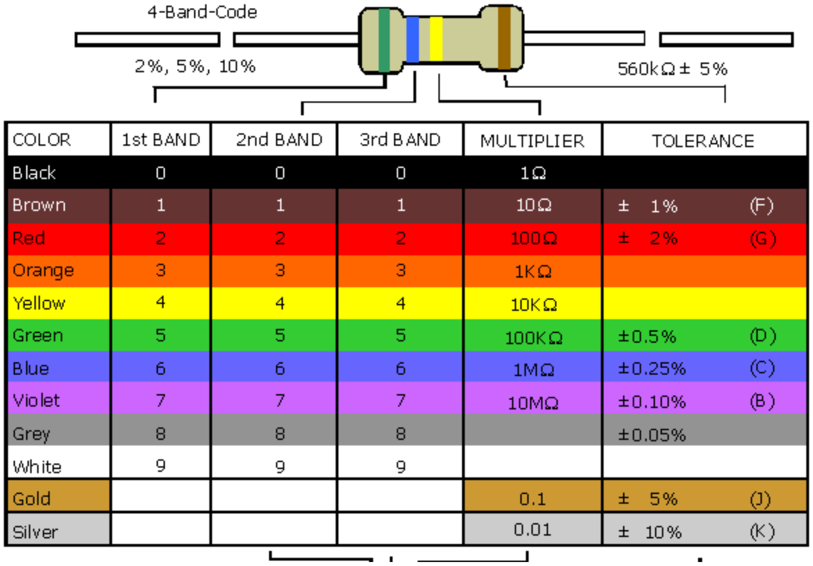


Figure 2: Opamp modeled as a voltage controlled voltage source.

Part 3: Resistor Color Codes

The figure below shows how color bands are used to show the value of the discrete resistor component. Notice that color-coded resistors are therefore only available in a few discrete values. When choosing values for your amplifier circuit, the absolute value is often not as important as the ratio of values, so the limited resistances available are generally sufficient.



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	±0.5% (D)
Blue	6	6	6	1MΩ	±0.25% (C)
Violet	7	7	7	10MΩ	±0.10% (B)
Grey	8	8	8		±0.05%
White	9	9	9		
Gold				0.1	± 5% (J)
Silver				0.01	± 10% (K)

Figure 3: Resistor color codes. For this course we use resistors with only 2 value color bands, as illustrated at the top of the figure (ignore the 3rd Band column).

LABORATORY PROCEDURE:

Message from the instructor: Before beginning this lab, we want you to understand that, in this senior elective course, we expect you to begin to show some level of independence. It would be ideal if this lab assignment simply said, “Construct the circuit you designed in the prelab and test it to verify functionality,” but we realize that most of you need more practical experience with building and testing circuits before we can do this. So, we’ve tried to provide a step-by-step assignment guide to walk you through. That said, we’d like to know you have the ability to notice when things are not going as expected, and can access your toolbox of skills to both track down what is not working right and also find a way to fix it. To that end, do not get frustrated if the steps in this lab don’t work out exactly as they are presented. Rather, use your knowledge and skills to identify the problem and fix it. You’ll find that’s a great step toward becoming an effective engineer. The real world is not a fixed set of problems with known solutions; debugging is an everyday way of life. To help you experience this, some of the steps in this assignment are intentionally vague or may require taking actions not specifically defined.

Think about the things you are doing, and most of all have fun taking a box of parts and making something that works!

Deliverables

- functional breadboard instrumentation amplifier
- calculation & simulations results specified on the Lab6 Prelab Grading Sheet

Assignment

A. Preparation

Note: The description below is somewhat generic to allow different versions of breadboards to be used. If you have any questions, please ask the TA before moving to the next step.

1. Collect the following items from the TA
    - 1 breadboard
    - 1 OP467 opamp
    - 2 10kΩ resistors
    - resistors you need to construct your circuit (determined by you in the prelab)
2. Put a small piece of tape on your breadboard and write your initials on the tape so you can identify which breadboard is yours.
3. Carefully inset the OP467 into the center of the breadboard with the alley in the board running underneath the chip so that the two sides of the chip are not connected together through the board.
4. Turn on the power supply and set it up to produce a 10V output, i.e. the + terminal should be +10V relative to the - terminal. Hereafter, consider the – terminal of the power supply to be ground. Turn on the multimeter and verify you have 10V between the two power supply outputs.
5. Turn off the power supply and use cables to connect its outputs to your breadboard. If necessary, you may need to use wires to connect the banana plugs to the breadboard.

Be sure you have properly connected the positive and negative terminals of the power supply to your board. Reversing them could damage your chip. Also, you should always turn off the power supply when connecting the supply to boards/components or altering power supply connections.

6. Turn on the power supply. Use the multimeter to verify you have 0V and 10V at the proper locations on your breadboard. Study the board to make sure you know where you can put a wire to connect to each of these voltages. Turn off the power supply before continuing.

Remember that this wire is still at 10V and be careful not to let any other wire touch the cable while it's disconnected from your board. You only need to disconnect one of the power supply leads to create an open circuit.

B. Initial Wiring

When cutting wires to make connections on the breadboard, try to keep the wires close to the needed length. Try to remove only as much insulation from the end of each wire to make good connection with the board. This will help avoid undesirable shorts when wires cross each other. It helps a lot with debugging later if you dedicate specific wire colors to specific nodes, like +power, -power and agnd.

Be careful when cutting/stripping wires; try not to let cast-off materials fly around the room. Finally, be sure to clean up your wire cutting mess and place scraps in the garbage.

1. The pin diagram for the chip is shown in Fig. 4. To assist in wiring the circuits for this lab, there is a wiring sketch pad at the end of this document in Fig. 5. You may want to sketch out the connections required in the following step before cutting wires and making connections on your breadboard.

2. With the power supply turned off, connect the power supply pins of the OP467 chip as follows: V+ to 10V, V- to 0V.
3. The OP467 chip includes four opamps. Three will be used for your instrumentation amplifier and the forth will be used for the analog ground voltage generator. Select one of the opamps and wire it in the voltage follower configuration. With the two 10kΩ resistors, create a voltage divider between 10V and ground, and connect them to your voltage follower opamp to generate **agnd**, as discussed in the prelab.

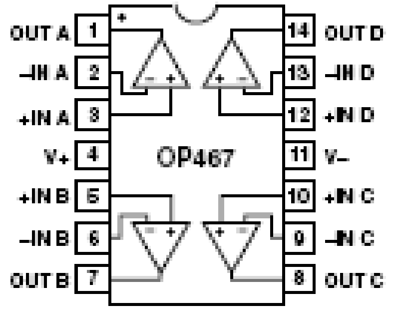


Fig. 4: OP467 Pin Diagram

4. Turn power on. Use the digital multimeter to measure the value of **agnd** from your circuit. Record this value on the Grading Sheet. If it is not very close to 5V, check your circuit and make any necessary corrections.
5. With the power off, use the three remaining opamps and resistors to construct the instrumentation amplifier by routing the proper connections with wires and resistors. Resistors have long exposed (conductive) legs, so make sure two resistors that should not touch do not get shorted. The best way to avoid this is to trim the legs of the resistors and insert them like components across the alley in the breadboard and then use wires with only their ends exposed to connect between resistors and opamps.
6. Once you have completed the wiring of the opamp circuit, double check your connections.

In next steps, you will verify and test your amplifier to see whether the function and performance are close to spice simulation. If your circuit fails to work, please see the Debugging Guidelines at the end of this lab.

C. Verification

1. Cut two longer wires (about the length of your hand) and strip their ends. These wires will be used to connect the inputs of the instrumentation amplifier to different voltage to confirm operation.
2. Study the routing of your circuit and determine which of the two inputs corresponds to $\mathbf{v_1}$ and which is **v2** in the schematic in Fig. 1.
3. With power off, connect $\mathbf{v_1}$ to ***agnd***. Then connect $\mathbf{v_2}$ to ***agnd***. Turn the power on and observe the voltage at the output of the instrumentation amplifier, v_o, using a multimeter. Is it what you expected based on your prelab simulation results? If not, turn power off and check for wiring mistakes. When the circuit is working as you expect, record your output voltage on the Grading Sheet.
4. Remove $\mathbf{v_2}$ from ***agnd*** and connect it to the positive voltage supply (10V). Observe the output voltage on the multimeter. If it is what you would expect, record this voltage on the Grading Sheet and continue. If not, look for bugs in your circuit and repeat this step until it is correct.
5. Move $\mathbf{v_2}$ to the negative supply voltage (ground). Observe and record the output voltage. By now you should have verified that your instrumentation amplifier is displaying the proper large signal DC response. If not, please get help from the TA. You need a functioning circuit to continue this lab.
6. Wire $\mathbf{v_2}$ to ***agnd*** and measure the output when $\mathbf{v_1}$ is connected to the positive supply, then the negative supply. When you think you have a clear understanding on of the inverting/non-inverting nature of the instrumentation amplifier, briefly describe it on the Grading Sheet.

D. Test and Characterization

1. Setup the function generator to produce a *slow rising* signal that will vary *linearly* from a low voltage (near the circuit's negative supply) to a high voltage (near the circuit's positive supply). The signal

should change slowly enough to be considered DC; generally below 10Hz is sufficient. It is left to you to determine exactly how to do this, but be sure that the voltage corresponding to ***agnd*** is near the middle of the function generator's output swing. This may not be a simple task. Before applying this signal to your circuit, be sure to verify the signal is correct by observing it on the oscilloscope. When you think you have it right, sketch the signal on the Grading Sheet and be sure to record the scale factors for the grid. (Hint: think triangles).

2. Now we want to test our signal on our circuit. It is not good to apply an input signal to a circuit that is not powered up, and it is not good to wire connections while things are powered up, but we can't turn the signal generator off or we'll lose the signal setup. The best option is to setup the circuit as much as possible, with its power off, without connecting the signal generator input. Then, power up the circuit, and finally connect the signal generator input. Following this procedure, connect $\mathbf{v_1}$ to ***agnd***, connect $\mathbf{v_2}$ to the signal generator, and connect both the signal generator and the circuit output to the oscilloscope.
3. Adjust the oscilloscope until it is displaying both the input and the output signals in a way that looks like a DC sweep simulation from your prelab assignment. Try to adjust the time scale to display only (or near to) the phase of the input signal that rises from minimum value to max value. You may have to play with triggering functions on the scope and may find storage mode useful. When you have a good result, roughly sketch the input and output signals on the Grading Sheet.
4. From the output signal produced in step 3, record the maximum output voltage, minimum output voltage, and describe in the Grading Sheet how to estimate the differential gain from the above test.
5. You will probably find it is hard to estimate gain from the test setup above. To estimate the DC differential gain more accurately, change the input signal to square wave with 100mV Vpp and 10Hz frequency. Make sure that the ground terminal from the signal generator is connected to ***agnd*** of your circuit, so the DC level of the input signal is at *agnd*. Measure the Vpp value of the output signal and record it on your Grading Sheet. Use this value to calculate a new differential gain estimation and record it on your Grading Sheet.
6. Record the high and low voltage value of the <u>output</u> square wave as precisely as you can. Measure and record your agnd voltage. Calculate and record the output offset voltage by

$$Voffset = \frac{Vmiddle - Vagnd}{A_d}$$

where Vmiddle is the center voltage of the output signal calculated by (Vhigh-Vlow)/2.

7. In this step, you will measure the common mode gain of the instrument amplifier. Setup the signal generator to produce a 100Hz 1Vpp sinusoidal wave input referenced to ***agnd*** as in Step 5. Connect <u>both</u> ***v1*** and ***v2*** to the sinusoidal input. Observe the amplifier output sinusoid on the oscilloscope. Any gain here is called *common mode gain* because both amplifier inputs see the same signal. Record the common mode gain calculated by Vpp_out/Vpp_in.
8. Now let's test a few parameters of your circuit's AC characteristics (response to small signal sinusoidal inputs). First, consider that we want the circuit to work in its region of linear amplification. That is, we do not want to saturate the output at any stage, so we need to use small signal inputs. Determine what the input voltage amplitude should be by calculating the following:

$$\Delta vin = \frac{1}{2}\frac{v_o(\max) - v_o(\min)}{A_d}$$

where v_o(max/min) were determined from measurements above, A_d can be either the measured/estimated or simulated value (whichever you feel is more accurate), and the ½ factor is for safety, to make sure the signal does not saturate the output.

Next, consider that we are only applying the sinusoidal signal to one of the inputs, so we'd like it to vary around the other input value. Thus, the sinusoidal input must have a DC offset equal to the DC voltage on the other (reference) input. Setup the function generator to produce a signal that meets these characteristics. Initially, use a frequency of 1KHz. Observe the signal on the scope and verify it is correct before continuing.

9. Set $\mathbf{v_1}$ to ***agnd*** and apply the input signal to $\mathbf{v_2}$. Observe both the input and the output on the oscilloscope, adjusting its settings as necessary to see 2-3 periods of the waveforms. If the output is clipped, reduce the amplitude of your input. Record the input and output Vpp values and briefly describe the results you observe on your Grading Sheet (input and output signals have same frequency? same amplitude? same phase (inverting/non-inverting)?
10. Record output Vpp at frequencies of 10KHz, 100KHz, 1MHz and 10MHz. Describe what you observe when the frequency increases on the Grading Sheet.
11. Adjust the frequency until the output amplitude is half the value recorded at 1KHz in Step 9. This frequency is called the 3dB bandwidth of your amplifier. Record this frequency.
12. Sketch the frequency response on the Grading Sheet. Use a log scale for the X axis and normalize the Y axis to the output amplitude at 1KHz.
13. Demonstrate the proper operation of your circuit to the TA by showing it will amplify a small signal sinusoidal input. Ask the TA to check off your demonstration on the Grading Sheet.

E. Wrap Up

1. Once the TA has checked off your circuit, clean up your lab bench and put all wire trimmings in the trash. Store your breadboard in a locker for use in the next lab.
2. Turn in your Grading Sheet to the TA.

Debugging Guidelines

1. Use the multimeter to measure the value of the supply voltage and see whether it is set correctly.
2. Use the multimeter to measure the voltage between power pins of your chip and verify it is the same as the voltage of power supply.
3. Use the multimeter to measure the voltage of the analog ground. Check whether it is close to 5V.
4. Connect input v1 to analog ground and connect v2 to a signal generator. The signal generator can generates a sine signal with 100mV amplitude and 100Hz frequency. Notice that the negative terminal of your signal generator should be connected to analog ground.
5. Use oscilloscope to check the waveforms of node 2 and 3 in Fig 1. Because of the virtual short at an opamp's input, these voltages should follow (match) the voltages applied to their respective positive terminals. Namely, node 2 should be a constant at analog ground while node 3 should show the input 100mV sine wave.
6. If everything is fine in Step 5, now you need to check waveforms of node 1 and 4. Both waveforms should also be sine wave with frequency 100Hz. What you need to see is their amplitudes. For node 1, the amplitude should be 100mV×R2/R1 with a phase of 180 degrees compared to the signal generator. For node 2, the amplitude should be 100mV+100mV×R2/R1.
7. In this step, waveforms of node 5 and 6 should be checked. Because they are inputs of the same opamp, their waveforms should be the same with an amplitude of V4×R4/(R3+R4), where V4 is waveforms of node 4.

   If you have checked all of the above and your circuit still does not work, contact the TA for help.

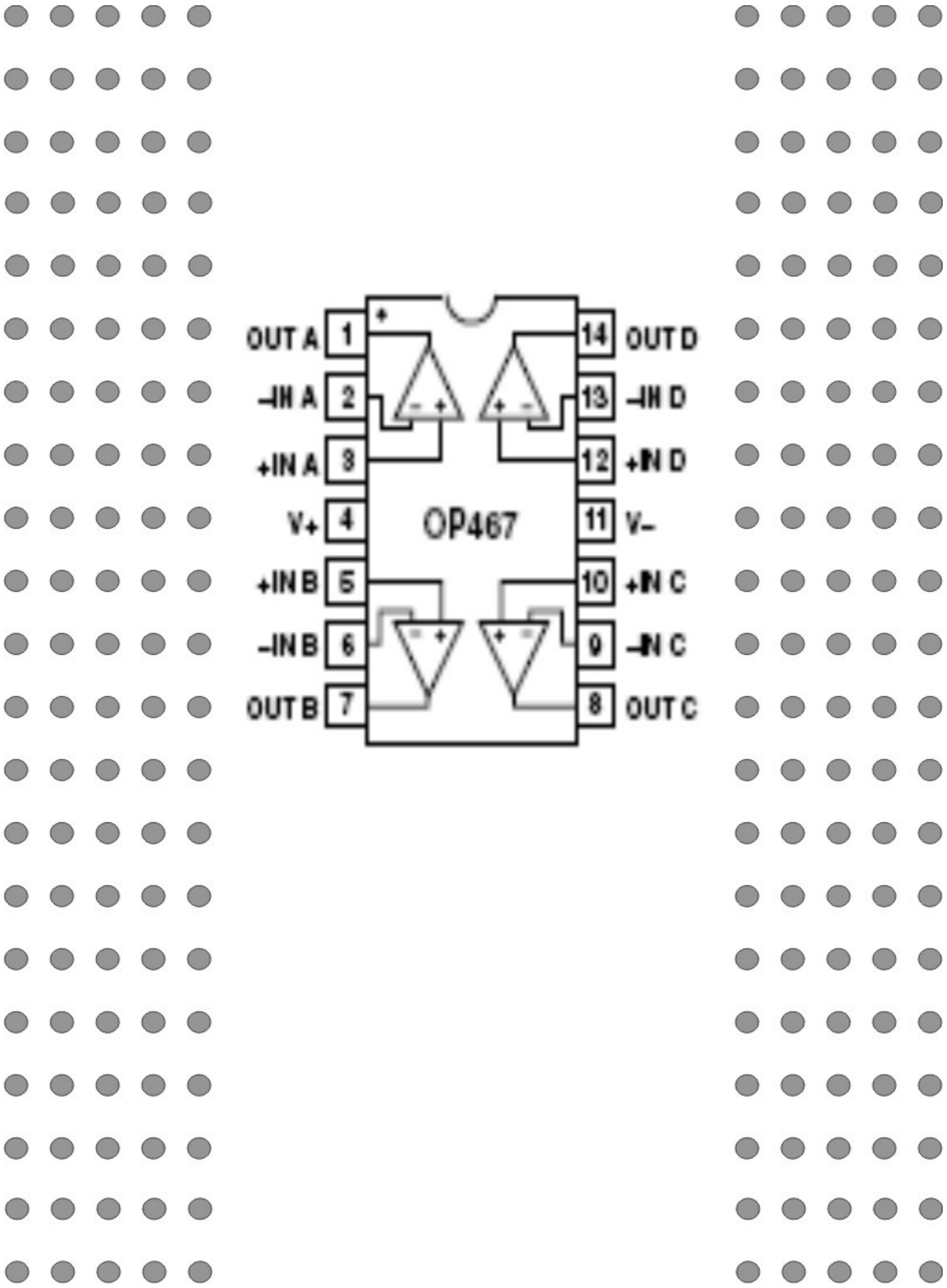


Figure 5: Wiring Sketch pad for opamp breadboard.