University of California at Berkeley
Physics 111 Laboratory
Basic Semiconductor Circuits (BSC)

Week 8

Op Amps II

Reading:

Sedra & Smith	Chapter 2, skim Chapter 10.
Hayes & Horowitz	Chapter 4.
Horowitz & Hill	Chapter 4.

In this week's lab you will continue your study of ideal op amp circuits. Circuits to be constructed include a current to voltage converter, a NIC (negative impedance converter), a gyrator, and an oscillator. The lab ends with the construction of a complex circuit that calculates root mean squares.

Pre-lab questions:

1. How does a NIC work?
2. How does the logarithmic converter in **8.6** work?
3. How does the exponentiator (**8.8**) work?
4. Derive the oscillator frequency of the circuit in 8.3. Draw the two output signals.

The Laboratory Staff will not help debug any circuit whose power supplies have not been properly decoupled!

Background:

Almost all the circuits in this lab can be analyzed with the op amp golden rules.

Oscillators

Oscillators are circuit designed to put out periodic waveforms like sine or square waves. For example, oscillators are at the heart of our waveform generator, form a basic part of any radio or TV tuner[1], and generate the 33, 66, 90, or 200MHz (etc.) clock signals that characterize and control all computer CPUs.

You may have already encountered accidental parasitic oscillations. Many types of deliberate oscillator circuits exist, but the simplest is called a relaxation oscillator.[2] In this lab you will build a relaxation oscillator with an op amp. In practice, relaxation oscillators are usually built with a special purpose chip called a 555.

Filters

Filter design is one of the most complicated subjects in analog circuit design; the UCB libraries, for example, have ten entire books on the subject. The ideal filter is called a brick-wall filter; it has exactly unity gain in its pass region, exactly zero gain everywhere else, and does not induce any phase shifts. Unfortunately brick wall filters are impossible to construct.[3] Many different filter designs exist, each attempting to optimize different aspects of filter performance. For example, the simple RC low and high pass filters you constructed at the beginning of this course, and other filters constructed entirely from passive components, suffer from gradual frequency response, unwanted phase shifts, and high output impedance. Better filters can be constructed with op amps. The Chebyshev active filter constructed in this lab is optimized for a sharp fall in its transition, or skirt region.

[1] You might wonder why an oscillator is necessary in a tuner. It turns out that it is difficult to build sharp, variable-frequency bandpass filters, but is easy to build variable frequency oscillators. To exploit this difference, tuners use a complicated circuit called a superheterodyne receiver. Superheterodyne receivers use a tunable bandpass filter stage to crudely select the desired station, followed by a stage that mixes (multiplies) the signal with a signal from a variable frequency oscillator. As the receiver's tuning knob is adjusted, the oscillator frequency shifts so that its beat frequency with the desired station is always at the same frequency: usually 455kHz for AM, and 10.7MHz for FM. The beat signal is then passed to a sharply tuned, single frequency filter which rejects all but the desired station.

The oscillator in the tuner is responsible for the ban on operating radio receivers during airplane takeoffs and landings. The FAA is afraid that the oscillator might accidentally broadcast a signal that would interfere with the cockpit instruments. Computers, CD players, gameboys, etc. are banned because of their clock oscillators. The ban is based more on paranoia than reality.

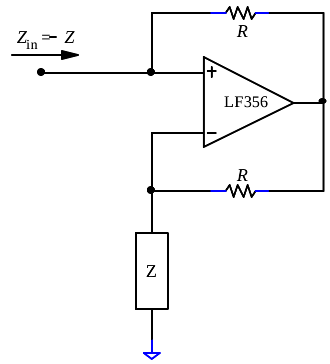
[2] The term relaxation oscillator dates from when these circuits were built with neon bulbs. A capacitor would be charged until it reached the neon bulb's turn-on, or breakdown voltage. The bulb would then avalanche or *relax* down to its much lower turn-off voltage, discharging the capacitor, after which the process repeats.

[3] Actually, brickwall filters can be constructed digitally at the expense of a long time delay between the input and output signals. This delay allows a digital filter to use information from future times to calculate the response at the current time. Use of this future information allows the filter to be perfect. Analog filters, however, must be causal; as they cannot anticipate the future, their response can only depend on past information, and they can never be perfect.

In the lab:

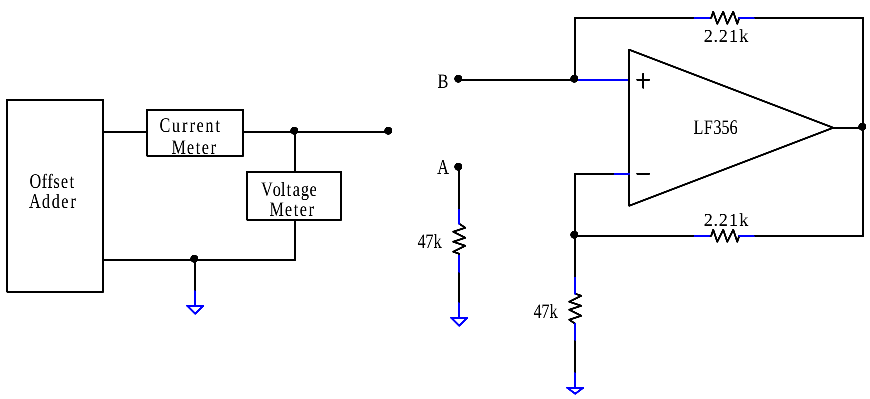
(A) NICs and Gyrators

A NIC, shown below, is a negative impedance converter. Looking into V_{in}, the NIC appears to have



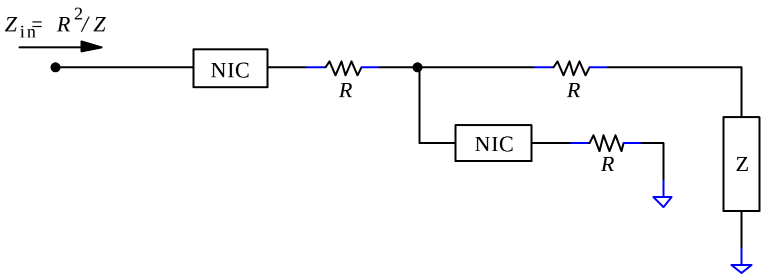
an impedance $-Z$ to ground. In other words, the circuit inverts it internal impedance, Z, to $-Z$.

8.1 Construct the circuit below.



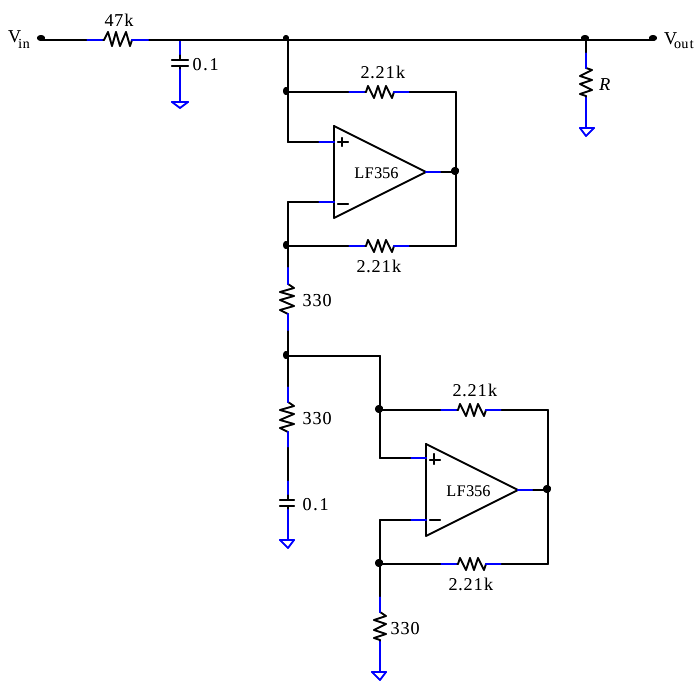
Use 1%, 2.21k precision resistors, available from the laboratory staff. First connect the meters to point A. Vary the offset adder voltage, and prove that the 47k resistor does indeed behave appropriately. (This purpose of this step is to check your meter polarities.) Next connect the meters to point B. Vary the offset adder voltage and measure the current. Prove that the NIC appears to be a -47k resistor.

A gyrator is a circuit that converts an impedance from Z to R^2/Z. Gyrators can be synthesized from two NICs as show in the block diagram below. The components to right of each individual NIC form the impedance Z of that particular NIC.



With Z set to $1/j\omega C$, the gyrator will look like it has an impedance $j\omega CR^2$; i.e. it will look like an inductor. As high quality inductors are difficult to obtain, bulky, and impossible to fabricate on integrated circuits, they are often replaced with gyrators, particularly in filters and resonant circuits.

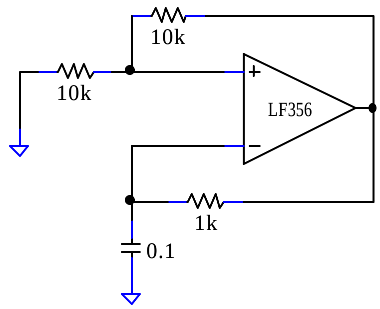
8.2 Construct the resonant (fake L)C circuit below. Use 1% 2.21k and 330Ω resistors. If possible leave out the resistor marked *R* (See the note at the end of this exercise.)



Drive the circuit with a sine wave in the neighborhood of 1kHz. (The 47k resistor is used to isolate the wavefunction generator from the rest of the circuit.) What is the circuit's resonant frequency? What is its calculated resonant frequency? Change the drive to a 10Hz, high amplitude square wave, and watch the circuit ring. What is its Q? Change the 0.1μF capacitor in the RLC circuit to a 1μF capacitor. Does the resonant frequency change appropriately? ***Note-Due to small variations from their nominal values of the resistors in this circuit, the circuit may resonate spontaneously. If it does oscillate, try inserting the resistor marked R into the circuit***. Use the largest possible value of *R*; a good starting value is 22k. (What happens when *R* is made small?) . If the circuit continues to misbehave, trying turning the circuit's power off, turning down the driving signal, and then turning the power back on.

(B) Relaxation Oscillator

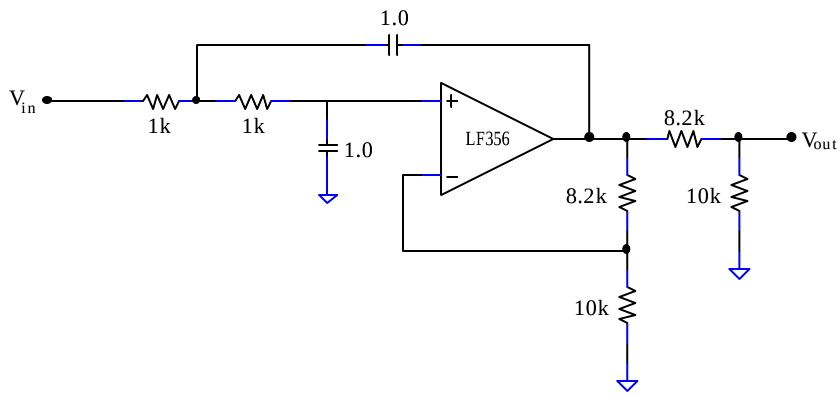
8.3 Build the relaxation oscillator below.



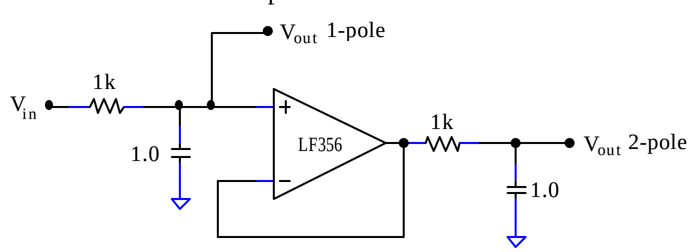
Draw the signal at both the op amp output and across the capacitor. How does the circuit work? (Hint-Think about the hysteretic comparator circuit.) What is the oscillator's output frequency? How does it compare to theory?

(C) Chebyshev Filters

8.4 Construct the 2-pole Chebyshev low pass filter shown below.



For comparison, also construct this 1 and 2-pole RC filter:



Carefully plot the transfer function for all three filters on both linear-log and log-log paper. Your data should be taken geometrically except around the skirt where it should be taken arithmetically. Also plot the theoretical curves for the RC filters. You should find that the Chebyshev filter skirt is far narrower than the RC filters' skirts, at the expense of it overshooting just before the cutoff frequency. Far into the stopband, the response of the Chebyshev filter should match that of the 2-pole RC filter.

(D) RMS Converter

This lab culminates with the construction of an RMS converter, similar to the RMS converter found in the DMMs. The circuit calculates

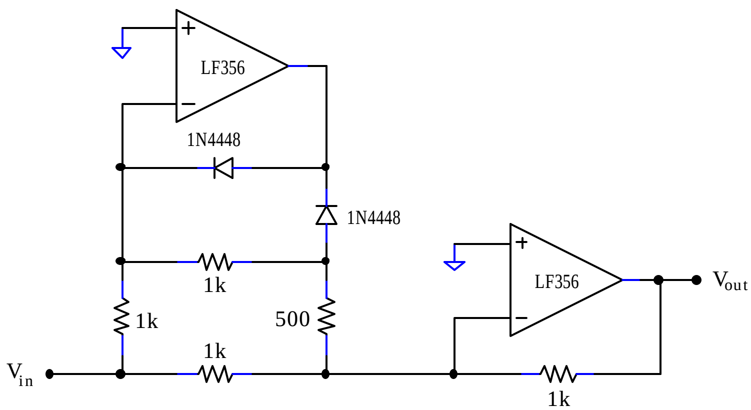
$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int^{T}[F(t)]^2\,dt}.$$

The circuit is quite complicated, and involves nine op amps. Fortunately the circuit is quite modular, and each module can be tested individually. The functions performed by the modules are, in sequence: absolute value, square, time average, and square root. The square (and square root) modules consist of three sub modules: a logarithm, doubler (halfer) and exponentiator.

Build your circuits cleanly; neatness will pay off. Lay out the circuit from left to right. As you go along, make sure that you leave enough space for all nine op amps.

(D.1) Absolute Value

8.5 ✍ The first module in the RMS converter takes the absolute value of the signal. Construct the circuit below, **Use 1% resistors, doubling two 1k's to get 500.**



Drive it with a variety of signals, amplitudes, and offsets from the waveform generator and offset adder. How well does the circuit work? See NOTE at the end of this write-up.

Disassemble the ***second*** op amp in this module, leaving the first op amp and its associated feedback network in place for the RMS converter.

(D.2) Squarer

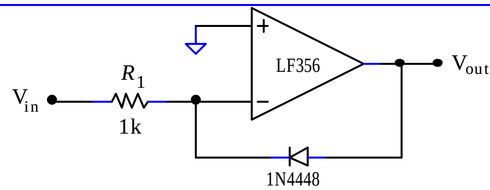
We need to square the signal after taking its absolute value. This operation is performed by taking the log of the signal, multiplying it by two, and then exponentiating.

(D.2.1) Logarithm

8.6 The circuit below takes advantage of the exponential dependence of diode current on voltage,

$$i(V) \approx i_{\text{sat}} \exp\left(\frac{eV}{nkT}\right),$$ [Note in Eq.: i(V) = I(V)]

to take the logarithm of its input signal.

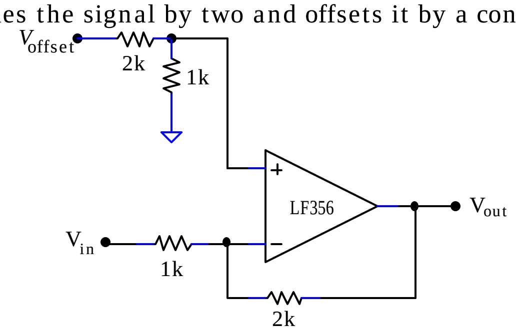


As with all the remaining circuits, a good initial debugging signal is an offset triangular wave. Note that this circuit expects a ***negative*** signal.

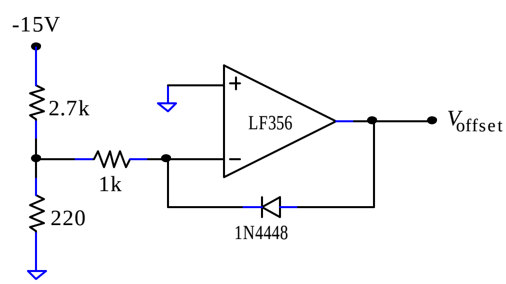
With the offset adder, drive the circuit with a series of DC input voltages, and record the input and output voltages at each point. Plot your data; how close is it to a true logarithm?

(D.2.2) Multiplier and shifter

8.7 The circuit below multiplies the signal by two and offsets it by a constant.



The offset is necessary to normalize the signal. (When exponentiated, the offset becomes a multiplicative constant.) Rather than calculating a specific value (which depends on the values of n, T and i_{sat}), the offset can computed electronically with this circuit.

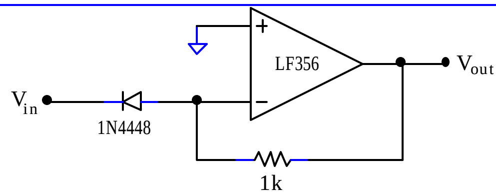


The output from this circuit should be approximately 0.6V. What do you get? Feed this output to the multiplier.

Drive the multiplier with the log output, and check to make sure that it doubles and offsets its signal. You do not need to record anything.

(D.2.3) Exponentiator 

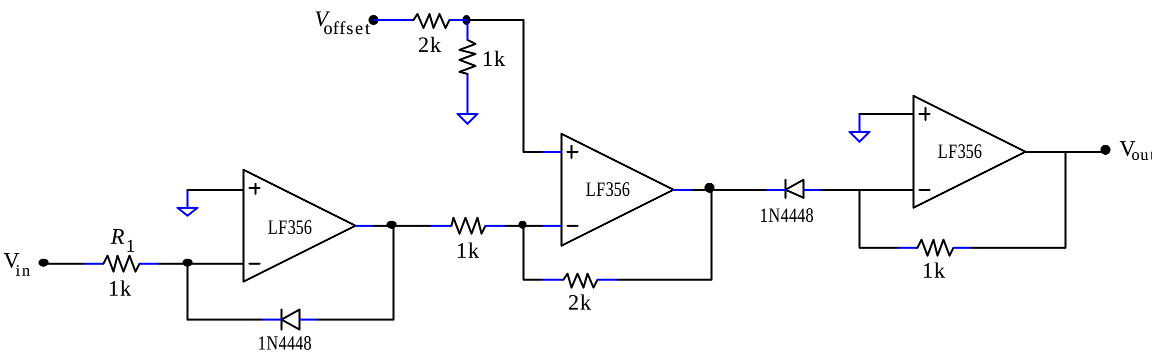
8.8 To exponentiate the signal, build the circuit below.



Use an offset triangle wave to debug your circuit. (The circuit requires a negative input.) Then use the offset adder to drive the circuit with a series of DC input voltages, and record the input and output voltage at each point. Plot your data; how close is it to a true exponential?

(D.2.4) Squarer

8.9 ✍ Finish the squaring module by hooking all the circuits together.



Use the offset adder to drive the circuit with a series of DC input voltages, and record the input and output voltages at each point. Plot your data; how well does the module square its input signal? What is the largest input signal accepted by the module before it saturates?

Remove the input resistor R_1, but keep the rest of the circuit.

(D.3) Time Averager

The next step is to time average the signal. The time average of a signal $H(t)$ is found by integrating:

$$\langle H(T)\rangle = \frac{1}{T_f - T_i}\int_{T_i}^{T_f} H(t)\,dt$$

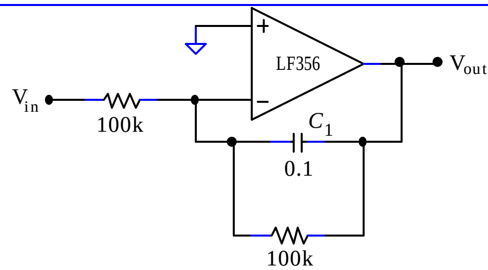
If the signal is repetitive, the limits of integration are over one cycle. What if the signal is not repetitive or we do not know the repetition frequency? The integral

$$\langle H(T)\rangle = \frac{1}{\tau}\int_{-\infty}^{T} H(t)\exp(-t/\tau)\ dt$$

(1)

generalizes the averaging formula. This formula is easy to implement electronically.

8.10 Build this integrating averager.

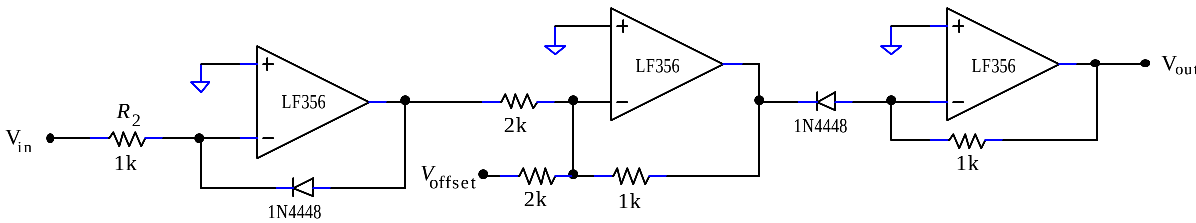


Using the offset adder and waveform generator to drive the circuit, show that its output is the average of its input. Over what frequency range does the circuit work? What sets this range?

(D.4) Square Root

Finally, we need to take the square root of the averager signal. The required circuit is very similar to the squaring circuit.

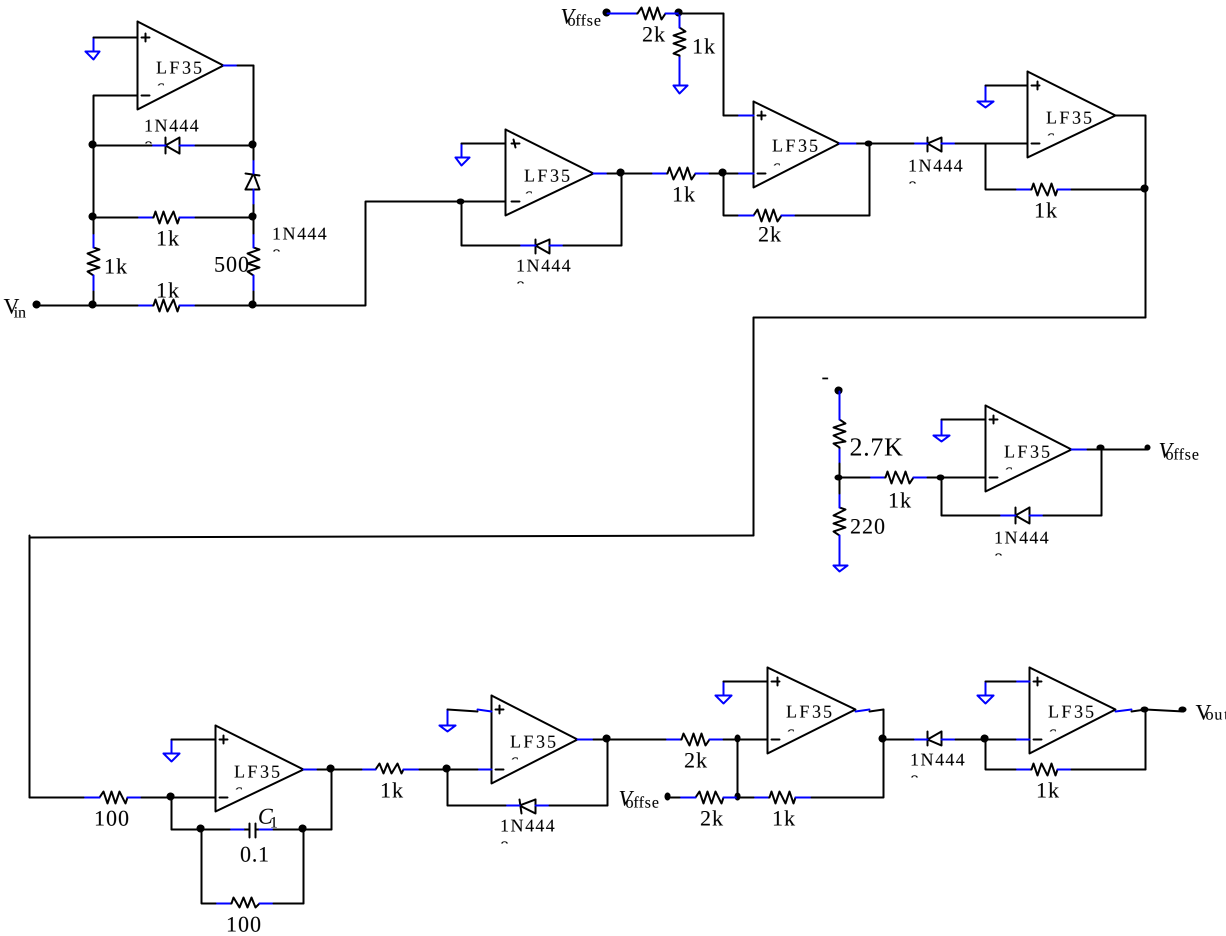
8.11 Built the circuit below. Debug each section independently. Use the offset voltage from **8.7**.



Use the offset adder to drive the circuit with a series of DC input voltages, and record the input and output voltage at each point. Plot your data; how well does the module take the square root of its input signal?

(D.5) RMS Converter 

8.12 ✍ Connect all the modules. Your circuit should now be as below:



Temporarily disconnect the averaging capacitor C_1. Use the waveform generator to drive the RMS converter. What output should you expect to see? Your signal will probably be off by a multiplicative constant. Fiddle with the values of the resistors in the time averager to obtain the (approximately) correct normalization.

8.13

Reconnect the averaging capacitor C_1. What happens to the output? Use the circuit to determine the RMS value of its input for a variety of input signals. For signals that are purely AC, compare the result with the reading from the DMM on the RMS setting. How well does your circuit work? Note that, unfortunately, your circuit will very temperature dependent, and will drift from moment to moment.

Analysis:

8.14 Analyze the gyrator block diagram, and prove that it behaves as claimed.

8.15 How does the absolute value converter work? Hint-Assume that the input signal is positive; will the op amp output be positive or negative? Which diodes are conducting? Redraw the circuit with the reverse biased diodes removed, and calculate the output voltage. Then repeat for a negative input signal.

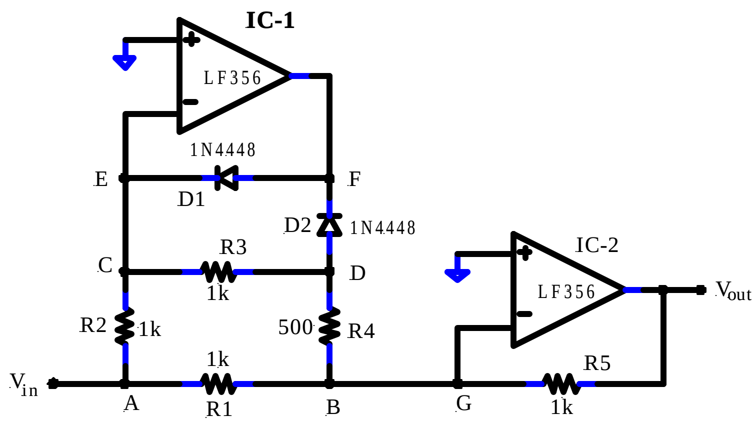
8.16 Show arithmetically that the circuit in 8.9 is a true squarer with no offsets or multiplicative factors.

Supplementary Problems:

8.17 Calculate the exact output of **8.10**'s integrating circuit for an arbitrary input signal, and prove that it implements Eq. (1). What is t?

8.18 Why is it possible to remove the second op amp in the absolute value converter when the converter is hooked up to the squarer?

BSC Lab-8 NOTE:
Analysis of Absolute Value Circuit (8.5)



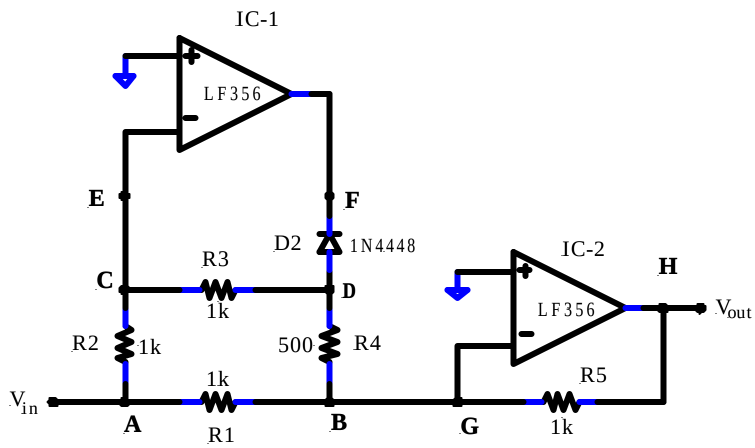
By Golden Rule #2 for the Circuit above, the V_- inputs of the op amps are at ground since the V_+ inputs are at ground. *That means nodes C, E, B, and G are at ground.*

Suppose $V_{in} > 0$.

Current flows from high to low potential so since nodes C and B are at ground and node A is at $V_{in} > 0$ *current will flow from node A to nodes B and C.* Indeed by Ohm's Law $I_{AB} = V_{in}/R_1$ and $I_{AC} = V_{in}/R_2$. And $I_{AB} = I_{AC}$ since $R_1 = R_2$.

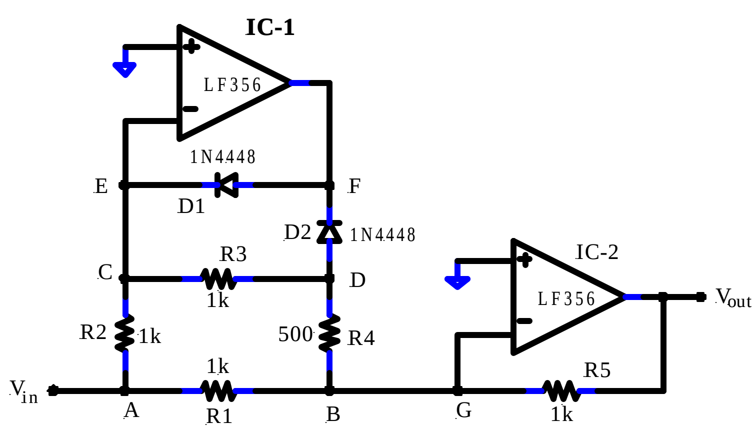
If there is any current flowing between nodes C and E it will flow *from* E *to* C because if it flowed from C to E it would have no where to go once it reached node E. It can't flow into the op amp input by Golden Rule #1 and it can't flow from E to F because diodes don't pass current in that direction. So current is coming into node C from A and that current must go somewhere. It cannot go to node E by the previous argument so *current must be flowing from C to D.* If current is flowing from C to D then *node D must be at negative potential* since node C is at ground and current flows towards lower potential.

But if $V_D < 0$ and $V_B = 0$ then *current will flow from B to D* since current flows from high to low potential. So *current is flowing into node D from C and B.* This current must go somewhere or else charge will build up at D. The only place it can go is to node F. So *current is flowing from D to F.* Node D is at negative potential so for current to flow from D to F through diode #2, node F must be at an even more negative potential. *So node F is at a negative potential.* That means diode #1 is reverse biased since $V_F < V_E$ so no current flows through it. So the circuit looks like:



By G.R. #1 the op amp input can produce no current so the current going into node C comes only from node A and that same amount of current goes from C to D because it has nowhere else to go. So $I_{CD} = I_{AC}$. Since the currents through R_2 and R_3 are the same and since $R_2 = R_3$ the voltage drops across R_2 and R_3 must be the same. From A to C the voltage drops from V_{in} to zero therefore from C to D it drops from zero to $-V_{in}$. So we have $V_D = -V_{in}$.

If $V_D = -V_{in}$ and $V_B = 0$ then the current from B to D is given by $I_{BD} = V_{in}/R_4$. Since $R_4 < R_1$ the current flowing out of node B into node D, $I_{BD} = V_{in}/R_4$ is greater than the current flowing into node B from node A, $I_{AB} = V_{in}/R_1$. This extra current can only be coming from node G. The value of this current is equal to the difference between I_{BD} and I_{AB} or $I_{GB} = (I_{BD} - I_{AB}) = (V_{in}/R_4 - V_{in}/R_1) = (V_{in}/500 - V_{in}/1000) = V_{in}/1000$. So $I_{GB} = V_{in}/1000$. By Golden Rule #1 none of the current from G to B can come from the op amp input so all of it must flow through R_5 from node H. So $I_{HG} = I_{GB}$ or $I_{HG} = V_{in}/1000$. Knowing the current through R_5 and the value of R_5 gives us the voltage drop across R_5. Indeed $(V_H - V_G) = I_{HG}R_5$ by Ohm's Law. But $V_G = 0$ and $I_{HG} = V_{in}/1000$ and $R_5 = 1000$ so we finally have $V_H = (V_{in}/1000)1000 = V_{in}$ or $V_{out} = V_{in}$ *when* $V_{in} > 0$.



Now suppose $V_{in} < 0$.

Nodes C, E, B, and G are still at ground by Golden Rule #2. Since $V_{in} < 0$ and B and C are at ground *current flows from C to A and from B to A.* The voltage at node D can be either positive, negative, or zero. I will show that if V_D were positive or negative there will be contradictions so V_D must be zero.

If $V_D < 0$ then current flows from C to D and from B to D because current flows from high to low potential. This current flowing into D must go somewhere and the only place it can go is to node F. So node F must be at an even more negative potential than node D if current is to flow from D to F through diode #2. If $V_F < 0$ and $V_E = 0$ then diode #1 is reverse biased and no current flows through it. The op amp input can produce no current so the currents flowing from C to A and from C to D have nowhere to originate from. It can't come through diode #1 since $V_F < V_E$ and it can't come from the

Now assume $V_D > 0$. In this case current flows from D to C and from D to B since $V_C = 0$ and $V_B = 0$. But this current flowing out of node D has nowhere to originate from. It can't be coming from node F because diode #2 doesn't pass current in that direction. Thus we have a contradiction if we assume $V_D > 0$.

By default $V_D = 0$. But $V_B = 0$ as well so no current flows through R_4. Thus, all the current that flows from B to A must be coming entirely from node G. So $I_{GB} = I_{BA}$. But since the op amp input can produce no current the current from G to B must be coming entirely from H so $I_{HG} = I_{GB} = I_{BA}$ and since current flows from high to low potential node H must be at positive potential since G is grounded. So we have:

$I_{BA} = (V_B - V_A)/R_1 = (0 - V_{in})/R_1 = -V_{in}/R_1$ and $I_{HG} = (V_H - V_G)/R_5 = (V_{out} - 0)/R_5 = V_{out}/R_5$

but

$$I_{HG} = I_{BA}$$

$$V_{out}/R_5 = -V_{in}/R_1$$

$$V_{out} = -V_{in}(R_5/R_1)$$

$$V_{out} = -V_{in}(1000/1000)$$

so $V_{out} = -V_{in}$ under the initial assumption that $V_{in} < 0$.

In conclusion, when $V_{in} > 0$ this circuit gives $V_{out} = V_{in}$. But when $V_{in} < 0$ this circuit gives $V_{out} = -V_{in}$. In other words this circuit gives the absolute value of the input.