

The OP AMP

Amplifiers, in general, taking as input, one or more electrical signals, and produce as output, one or more variations of these signals. The most common use of an amplifier is to accept a small electrical signal and increase the voltage or power, for example the amplifiers inside of a stereo.

OP AMP's (Operational Amplifiers) are a fundamental building block for handling analog electrical signals. Typically an OP AMP has two inputs called "+", and "-", (or V_{IN+} and V_{IN-}) and a single output. The output depends only on the difference of the voltage on the two inputs. If the difference of the two input voltages is ΔV_{IN} , the output voltage is V_{OUT} , then $V_{OUT} = \Delta V_{IN} G_V$. This defines the (voltage) gain, G_V .

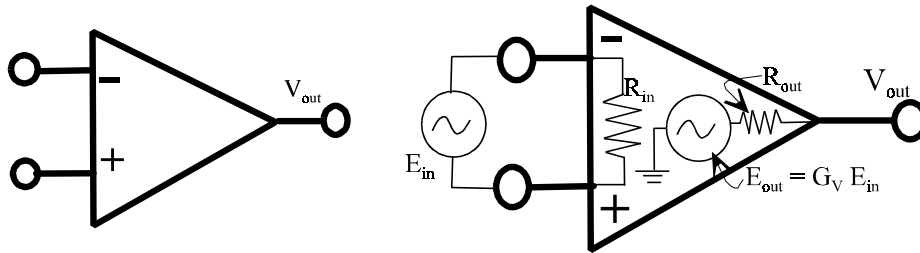


Figure 1 The drawing on the left is the standard diagrammatical representation of an OP AMP with two inputs and one output. The drawing on the right indicates the conceptual operation of an OP AMP by displaying an idealized equivalent circuit.

An ideal OP AMP would have the following characteristics:

1. The input resistance R_{IN} would be infinite
2. The output resistance R_{OUT} would be zero
3. The voltage gain, G_V would be infinite
4. The bandwidth (how quickly the output will follow the input) would be infinite.
5. If the voltages on the two inputs are equal than the output voltage is zero (If the output is not zero it is said to have an offset.)

These characteristics lead to a couple of secondary characteristics, which often are considered to be the core of the axiomatic definition of an OP AMP

- A. Because R_{IN} is infinite, there is no current through the two input leads.
- B. Because the gain is infinite, the voltage difference between the two inputs must be vanishing small, i.e., ZERO. (Usually a feedback resistor is used to insure this. If there is a non-zero difference between the voltages on V_{IN+} and V_{IN-} , V_{OUT} will be drive to its positive or negative extreme. This clipping limits the functional gain of the device.)

These two derived characteristics seem strange, but usually they are enough to figure out how an OP AMP should work in a circuit. This will be show in the first circuit below.

The Real World

In Figure 1, the drawing on the left, the device has only three connections. When one looks at an actual OP AMP or the manufacturer's diagram, there are several additional leads or "pins." In the Real World, an OP AMP needs a source electrical power. Usually the power supply must provide both positive and negative voltages that are equal magnitude. On diagrams these may be indicated by $V+$ and $V-$. Often OP AMPS have a pair of leads marked **Null Offset** which are used to make the output voltage zero if the two input voltages are equal (Characteristic #5 above.) For most of our work we will not connect these to anything. Finally there may be leads that the diagram indicates are **NC** which means NOT CONNECTED. Note also the inputs and output all have return connections through ground but these are usually not shown.

OP AMP's often are embedded in little rectangular solids of plastic with a number of little legs. These packages are called a DIP for Dual Inline Package. The whole thing looks like centipede. Often the manufacture will provide a description that states something like pin 4 is connected to the negative power supply. But which is pin 4?

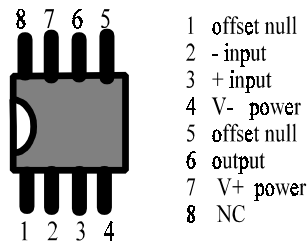


Figure 2 A diagram indicating the numbering of the leads or pins on a dual in-line packaged (DIP) OP AMP. Note that 1 is below the semicircular mark and the then the number progress counterclockwise. To the right is a common assignment of function with pin number for an OP AMP such as the common 741.

You will be using a "breadboard" to wire your circuit. These have a large number of holes which are connected in groups. If you put a wire into one of the holes it will be held by a spring clip and will make electrical contact with other wires inserted into holes in the same grouping. Either experimentally find how the holes are interconnected or ask your TA. You can use either a standalone breadboard or one with a built-in power supply and a few other components.

The power supply should produce two equal and opposite voltages relative to a common ground. Often two 9 Volt batteries are used. At first you will be using the power supply that is part of a breadboard unit. The plus and minus voltage can be adjusted independently, so each should be set to 12 volts and check with a volt meter.

Connecting + or - 12 volts to the inputs, is not going to be much fun or interesting or educational. The breadboard unit has a function generator, which will produce a varying voltage but it is too fast for your initial work. A better source of input voltage is produced by connecting the two ends of a potentiometer to the + and - power supplies. Then by turning the potentiometer's knob, the voltage on the "wiper" lead will vary for $+V_{\text{POWER}}$ to $-V_{\text{POWER}}$ relative to the common ground. The breadboard unit has two built-in potentiometers.

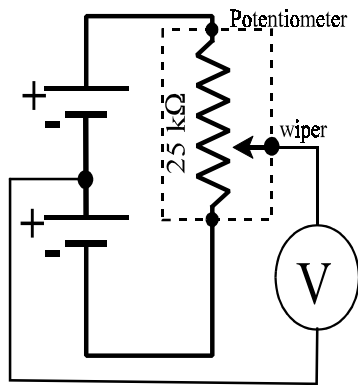


Figure 3 Using a potentiometer to produce a variable voltage from a dual power supply.

Be aware that the output of an OP AMP is limited to the range of $-V_{\text{POWER}}$ to $+V_{\text{POWER}}$. If you have setup a circuit in which the amplifier gain is 10, then the range of the input signal should be limited to $-V_{\text{POWER}}/10$ to $+V_{\text{POWER}}/10$, otherwise OP AMP will “saturate” and “clipping” will occur. For high gain amplifiers it is possible that the usable input range is so small (like a few millivolts) that you might miss it as you turn the potentiometer knob and the output will jump from full negative to full positive.

Voltmeters or DMM’s are the best measuring devices for many of the circuits built in this lab. One on the output and one across the two input leads should be enough. If you use a fast varying signal from a function generator on the input, you probably will need to use an oscilloscope to make measurements. It is assumed you have a basic familiarity with the operation of an oscilloscope from your introductory E&M lab. But you should consult your TA or instructor concern the operation of the specific oscilloscope that you are using. As always be aware of grounding loops, unintentional loops, and incomplete circuits when connecting external function generators or oscilloscopes to your circuit.

You will be using a 741 or equivalent OP AMP for your work. Sometimes these come in a package that contains two or four identical OP AMP’s in a single DIP. The full manufacturer’s data sheet is available at

<http://www.national.com/ds/LM/LM741.pdf>

From this one can compare the LM741 against the ideal OP AMP

	Characteristic	Ideal	Typical for real 741
1	Input Resistance	∞	6 M Ω
2	Output Resistance	0	50 Ω
3	Voltage Gain	∞	50,000 to 100,000
4	Bandwidth	∞	1 MHz , changes at 0.7 V / μ s
5	Offset voltage	0	1 mV
A	Input Current	0	30 nanoVolts (3 X 10 ⁻⁸ volts)
B	Voltage difference of inputs	0	????

The Circuits

Unity Gain Inverting Amplifier

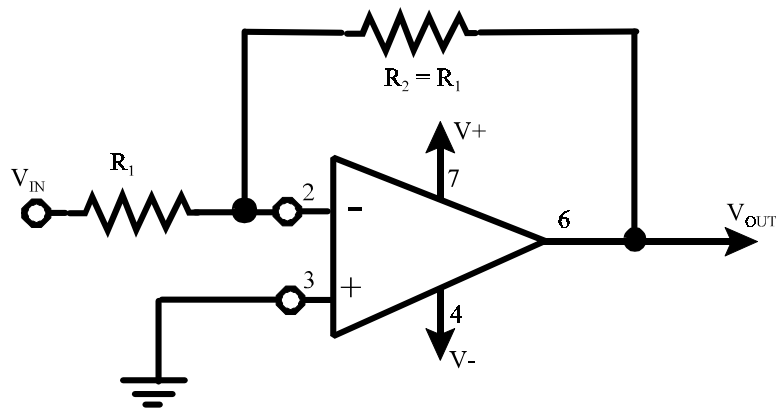


Figure 4 An circuit for a Unity Gain Inverting Amplifier using a 741 OP AMP. Note the two resistors have the same resistance. R_2 is a **FEEDBACK RESISTOR**.

Let's try to analyze this circuit. Note that + input which is pin # 3 is connected to ground. Characteristic **B** this implies that the voltage applied to the - input or pin # 2 must also be zero. Note the current into pin # 2 is zero by Characteristic **A**. For a given input V_{IN} what can V_{OUT} be so that this condition is satisfied. Think about the circuit from V_{IN} through the two resistors to V_{OUT} . If $V_{OUT} = -V_{IN}$ then the wire between the two resistors will be a zero potential, thus satisfying characteristic **B**. Note the function of the **feedback resistor** R_2 .

Inverting Amplifier

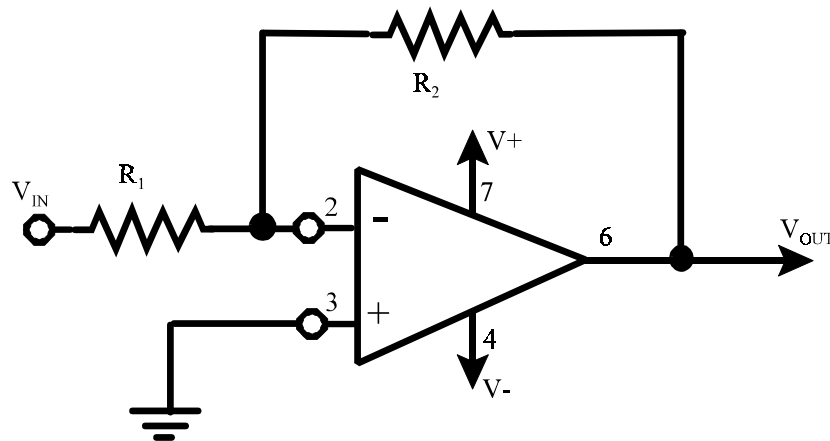


Figure 5 An circuit for a **Inverting Amplifier** using a 741 OP AMP. The Gain defined as $V_{OUT} / V_{IN} = R_2 / R_1$.

Q Try to analyze this circuit. First find the current between V_{IN} and V_{OUT} , and then the voltage drop across, R_1 and/or R_2 . This should be enough to let you solve for V_{OUT} in terms of V_{IN} , R_1 , and R_2 .

Level Detector or comparator

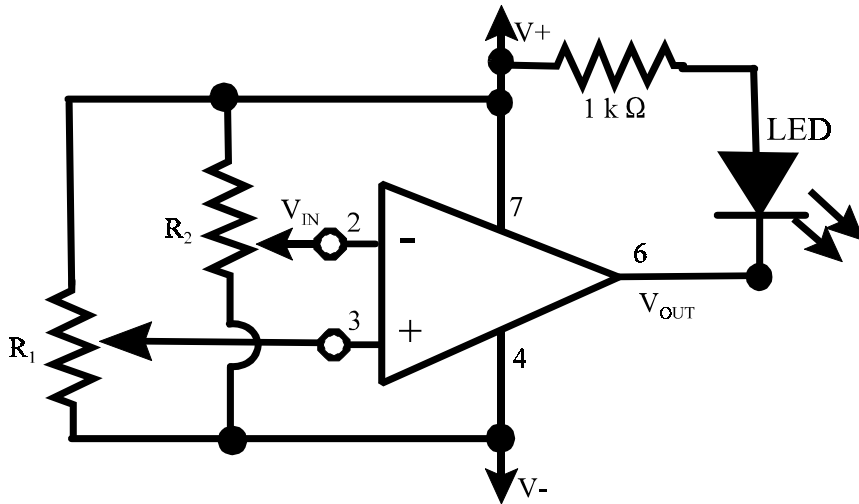


Figure 6 In this **Level Detector**, the potentiometer R_1 set the trigger level and when the voltage at V_{IN} (here controlled by R_2) equals that the LED goes on (or off .) Some other more interesting source of a voltage level could be used rather than a potentiometer. Note the absence of any feedback.

Q Using the OP AMP Characteristics A and B analyze this circuit.

The Summing Amplifier

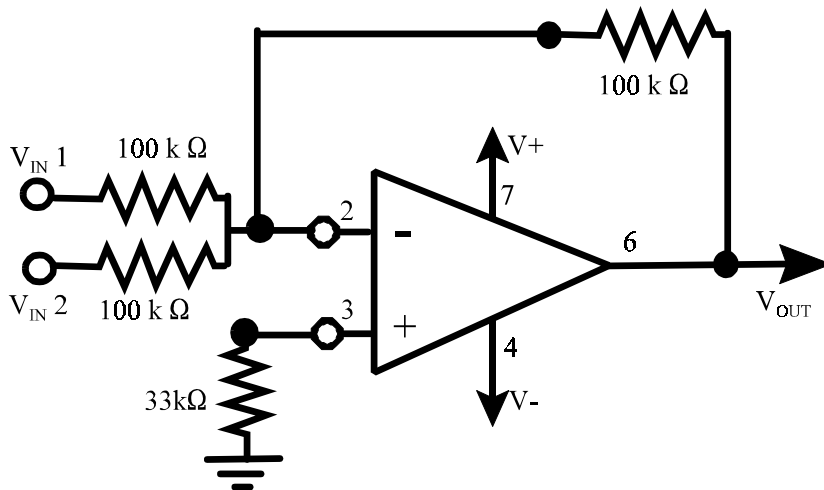


Figure 7 This is a **Summing Amplifier**. $V_{OUT} = - (V_{IN 1} + V_{IN 2})$

Q Using the OP AMP Characteristics A and B analyze this circuit.

Q In the circuit for the Summing Amplifier, could the value of the 330 kΩ resistor be halved without changing the function of the rest of the circuit?

The Difference Amplifier

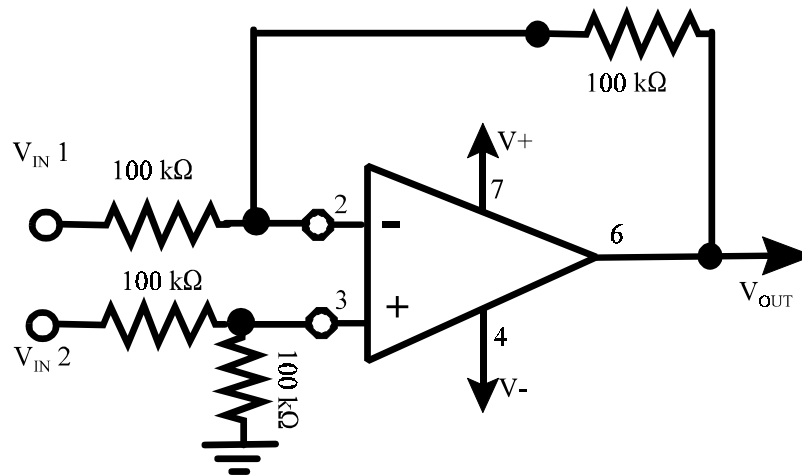
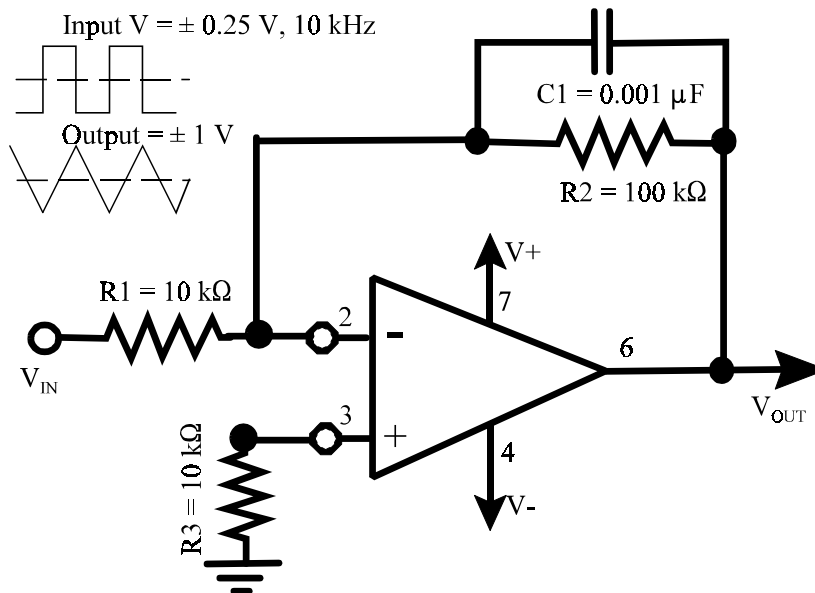


Figure 8 This is a **Difference Amplifier**. $V_{OUT} = V_{IN2} - V_{IN1}$

Q Using the OP AMP Characteristics A and B analyze this circuit.

Q Could the value of the resistor between ground and pin # 3 be halved without affecting the operation of the rest of the circuit?

The Basic Integrator



You will need

Figure 9 This is a basic **Integrator** circuit using an OP AMP.

to

Use a function generator for the input and make measurements of the input and the output with an oscilloscope.

Q Using the OP AMP Characteristics A and B analyze this circuit. This time you will need to write down some time dependant equations for each half of the input cycle.

Q Try changing the value of the capacitor or R1 or R2 and see what happens.

Q Try changing the frequency of the input and see what happens.

The Basic Differentiator

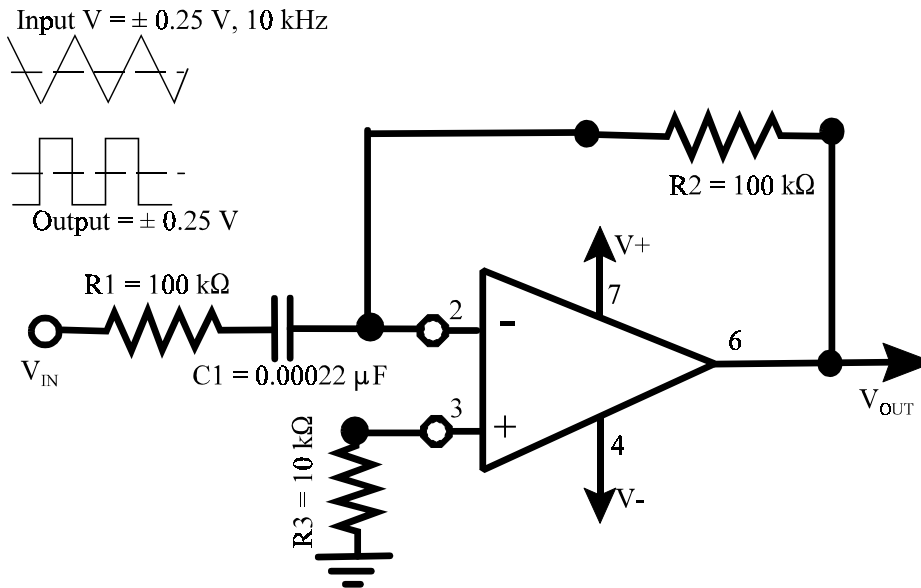


Figure 10 This is a basic Differentiator circuit.

You will need to use a function generator for the input and make measurements of the input and the output with an oscilloscope.

- Q** Using the OP AMP Characteristics A and B analyze this circuit. This time you will need to write down some time dependant equations for each half of the input cycle.
 - Q** Try changing the value of the capacitor or $R1$ or $R2$ and see what happens.
 - Q** Try changing the frequency of the input and see what happens.
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The Function Generator (The diagram is on the next page)

This circuit is rather complex, but the first trick is to note that it can be broken down into four “stages” that interact only a little. **NOTE: Neatness and order are very important to get the circuit wired correctly.** First let us pretend that each of the four stages operates independent of each other, except that the output of one is the input for the next stage. If that is true, then while constructing this circuit, you could just wire the first stage and see if it is operating correctly before wiring the next stage.

As is often the case, it is easier to analyze some part circuit other than the beginning. Doing this often lets you get started on the analysis that might otherwise seem overwhelming and reduces the remain problem to something a bit more manageable. The fourth stage is just an inverting amplifier.

- Q** What is the gain of the fourth stage?

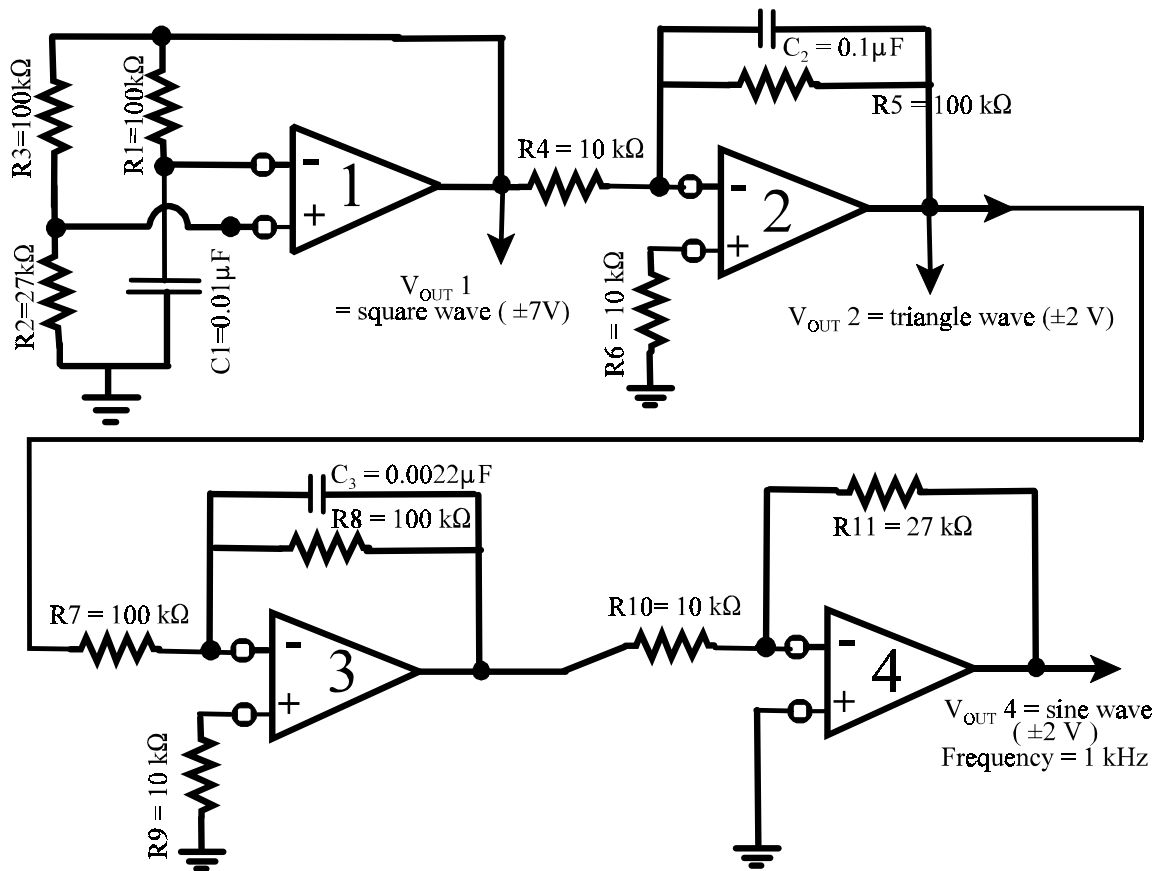


Figure 11 This **Function Generator** is designed to produce a frequency of 1 kHz and have the power supply set at ± 9 volts. It should produce a square wave, a triangle wave, and a sine wave.

Analyzing the second stage is easy, it is an integrator. The second stage accepts a square wave as its input and outputs a triangle wave. The third stage is also an integrator, but its input is a triangle wave. Well the integral of a triangle wave is not really quite a sine wave. But note how much smaller C_3 is compared to C_2 . This suggests that something odd might occur. With a short RC time constant, an integrator is more like a smoother, and a smoothed triangle wave is similar to a sine wave.

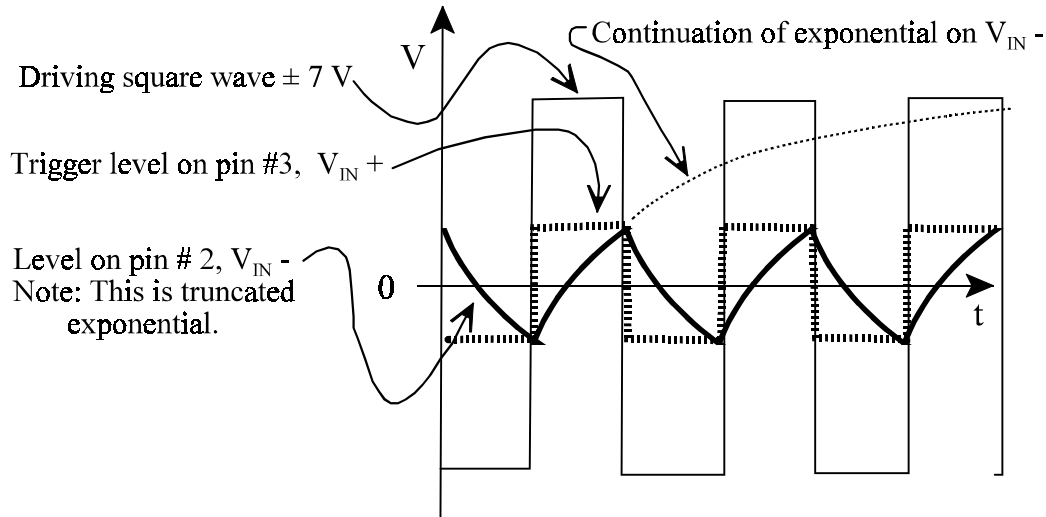
Q You should try to determine how accurate of a sine wave this unit produces.

The first stage is bit trickier to understand. Note that the center of an RC circuit element connects to pin 2 (the - input) of the first OP AMP. Pretend momentarily that the tops of R_1 and R_3 are not attached to the output of the first OP AMP, but rather are being driven by an external square wave that varies between ± 7 V. Think of the OP AMP in this first stage as a level detector with the trigger voltage set to about 0.2 times the driving voltage because R_3 and R_2 form a voltage divider.

The output of this first OP AMP is a square wave because, as the capacitor is charged in one direction, at some point, V_{IN} exceeds the trigger level and the output voltage goes to its maximum negative voltage. As the capacitor charges with the opposite polarity, at some point,

V_{IN} becomes smaller than the trigger level and the output voltage goes to its maximum positive voltage. This causes the output of the first OP AMP to be a square wave. If R1 is driven at the “correct” frequency the output voltage of the first OP AMP will match in frequency and phase the assumed square wave that was driving R1 and R3. Thus, the square wave will be self-perpetuating.

- Q** Set up and solve the time dependant equations for the charging (or discharging) of the capacitor during each half of the driving square wave. You should get something like:



- Q** Try doubling and halving the value of C1 and observe the changes in the output of the circuit.
- Q** Make two additional OP AMP circuits chosen from the one of the references below.

Good general references include:

.Forrest M. Mims III, **Engineer’s Notebook II**, (Radio Shack 1982 .) PP. 77-85. This is the source of most of the circuits that are presented here. This book shows many other useful OP AMP circuits.

Walter G. Jung, **IC Op-Amp Cookbook**, 3rd ed. (Howard W Sams and Co, Indianapolis, In, 1986.) This book is all about OP AMP’s, both understanding them and using them.

J.H. Moore, C.C. Davis and M.A.Coplan, **Building Scientific Apparatus, A Practical Guide to Design and Construction**, 2nd ed. (Perseus Books, Cambridge, MA, 1991.) This is a good practical text.

Paul Horowitz and Winfield Hill, **The Art of Electronics**, 2nd ed. (Cambridge University Press, Cambridge, 1989.) Many consider this the “bible” of applied electronics. This text is very complete, very dense, and very long.