

Basic Op Amps

The operational amplifier (Op Amp) is useful for a wide variety of applications. In the previous part of this article basic theory and a few elementary circuits were discussed. In order to further ones understanding of op amps, or most anything else, some hands on experience helps a lot. It is suggested that a simple breadboard circuit as shown in Fig 1 be constructed, to make a basic functioning op amp circuit available for experimentation. An 8 pin DIP op amp can be used, such as a 741 or TLO81, as only one amplifier section will be needed. The TLO81 is cheap readily available, and is a JFET type that is an excellent general purpose amplifier for experimentation and hobby circuits. Of course, other types can be used if you have them handy, but JFET types are probably preferable if you have them since they allow the use of more reasonable component values (capacitors especially). The op amp should be rated to work with the supply voltages you will use. 5 to 12 volts will be OK. You will need two supplies of equal voltage, one delivering a positive (plus) voltage and one delivering a negative (minus) voltage. Ideally a laboratory type AC powered adjustable DC supply delivering plus and minus voltages would be desirable. However, several AA batteries with two suitable battery holders, two 9 volt transistor radio batteries, or two 6 volt lantern batteries will work just as well. AA battery holders are widely available to hold four to eight AA cells and two such holders can be used to make up a suitable supply. The batteries should last a very long time in this application. Dedicated “universal” experimenter breadboard setups are available (approx \$ 20-40) that feature connectors and sockets allowing one to plug in most components and jumpers to configure most any circuit. These will prove to be time savers and will eliminate much or all soldering, if preferred. Some source of signal should be handy. This can be a function generator, audio oscillator, or even audio from a CD or tape player can be used. Access to an oscilloscope would be desirable, but not necessary.

A few op amp circuits will be discussed. These circuits are for demonstration and teaching purposes in illustrating the principles of op amps, and these circuits are not claimed to be optimized for any specific application. There are refinements that can be added in some cases, but were omitted for simplicity. There are literally millions of op amp circuits and in a short column we cannot cover very much. The reader is strongly advised to consult the literature and manufacturers application notes. Several years ago National Semiconductor had a publication titled “Linear Applications Handbook” (Our copy is dated 1994) and it is an excellent reference text full of ideas and applications using op amps. The devices in older literature may be out of production and no longer available, but the circuit principles and ideas are relatively timeless, and can be applied to currently available devices

The first circuit (Fig 2) is the voltage follower. This is a unity gain amplifier using a TLO81 or similar JFET op amp as a buffer and driver. A very high impedance source (microphone, sample and hold circuit, transducer, etc) can be interfaced to a lower impedance load with no loss in voltage. The gain here is all current gain. Since the feedback factor is unity, the output voltage will equal the

input voltage minus e_{in} . Since e_{in} is very small and the gain of the amplifier is high (10,000), the output voltage will equal the input voltage within 0.01 percent. This can be used as a simple, high impedance meter amplifier. If a DVM is connected to the op amp output and a single 1.5 volt AA cell is connected to the input through a 22 meg resistor (highest commonly available resistor value), the resistor will have practically no effect on the voltage reading of the battery. This demonstrates the high input impedance available with this circuit, in the thousands of megohms. By using a voltage divider network and appropriate switching, a high impedance voltmeter can be made that will have input impedance of hundreds of megohms or more. By using CMOS type op amps, a simple electrometer able to read currents as low as 1 trillionth of an ampere, (or 1 picoampere, if you prefer) can be constructed.

If the input of the amplifier is connected to a short wire (3") a body charged with electricity (hard rubber comb rubbed on flannel, or a glass rod rubbed with silk, etc) brought near this wire will produce a change in the op amp output voltage. This can be a static charge detector circuit. However, practically, a high resistance should be connected between the noninverting input and ground to establish a stable operating point. This resistor could be several thousand megohms in practice.

Another useful circuit (Fig 3) is an AC voltmeter circuit. The meter rectifier is in the feedback circuit. This compensates for the diode forward drop. A conventional meter rectifier using a diode bridge rectifier is compressed at the low end of the meter scale since small AC voltages may not overcome the diode forward voltage of 0.6 volt. This causes nonlinearity at the low end of the scale. When the bridge is placed in the feedback loop, the AC signal current in the feedback loop must equal the input current through R1. This forces the op amp to produce sufficient voltage to overcome the 0.6 - volt diode drop irrespective of the input level. Therefore the meter will read linearly. It is easy to make an AC voltmeter with a full- scale deflection of 100 millivolts or less with this circuit, with a perfectly linear scale. This ac voltmeter circuit will work well and will be fairly accurate in the audio and into the low frequency RF range (100 kHz) or higher with fast diodes and a wideband op amp

A voltage follower can be used as a peak detector, (Fig 4) to give the peak voltage of a waveform. The signal is applied to the noninverting input as shown. The capacitor C1 will charge to the peak voltage of the input signal. Since the diode is in series with the amplifier output, the diode drop will be compensated for. The output voltage will equal the peak value of the input voltage.

Op amps can be used as comparators to compare two voltages. Fig 5 shows a typical circuit. The reference voltage is applied to the inverting input. Any voltage greater than this reference voltage will drive the op amp output in a positive direction. Since the gain of the op amp is several thousand, this transition is very sharp. Voltages less than this amount will cause the output to go in a negative direction. Output can be fed to an LED indicator or logic circuit as an indicator, or used to drive another circuit. Several op amps can be connected to a resistive

divider and have their inputs connected to a common input. (See fig 6). The outputs can be fed to a system of logic gates that will produce a binary pattern that is a function of how many comparators are on or off. The output can be made to be a binary value representing the number of on or off comparators. This idea is used to make what is known as a “flash” analog to digital (A-D) converter, since the output is an instantaneous function of input. The flash A-D converter is useful for digitizing fast waveforms, and is widely used in digitization of video signals. By summing the comparator outputs, a staircase wave can be generated from a ramp waveform input.

By using both positive and negative feedback, it is possible to make oscillators with different types of output waveform. Fig 7 shows a square wave oscillator. Capacitor C1 charges toward the positive supply rail through R1. After it reaches the reference voltage derived from R3 and R4, the comparator output goes low. This also changes the reference voltage to a lower (more negative) level. This forces the comparator to a negative output. Now the capacitor discharges towards the negative supply rail. This will continue until the voltage at the inverting input reaches the new reference voltage. At this point the comparator switches to high (positive) output. The cycle is repeated. A square wave output results. By using diodes and two separate feedback resistors, the charge and discharge paths can be made dissimilar, allowing two different time constants. This allows generation of a variable duty cycle waveform. A pot and resistor combination Rt and Ra can be used in place of R1 to adjust this duty cycle, as shown in Fig 8.

It is possible to generate a sine wave using a circuit known as a Wein Bridge. At a frequency $f = 1/(2\pi RC)$ the network shown in Fig 9 will have a transfer function of 1/3 with zero phaseshift between input and output. This allows its use as a frequency determining network. The Wein bridge is connected between the output and noninverting output as shown in Fig 9. This allows positive feedback and oscillation. However, the amplifier would generate a poor waveform, since limiting of output can only be accomplished by driving the amplifier to its positive and negative limits, resulting in severe clipping of any generated sine wave. However, another feedback network is used to introduce negative feedback. A resistive divider R3 and R4 with a division ratio of slightly more than 1/3 is used. This reduces the gain to a little over 3, enough to sustain oscillation. But, limiting would still be obtained by clipping in the output, although the waveform would be somewhat improved. By using a voltage dependent resistor for R4, automatic gain control could be achieved. R4 is selected to have a resistance that increases with applied voltage. A thermistor can be used for this purpose, but a more common approach is to use an ordinary tungsten filament lamp. This kind of lamp has the exact characteristic we need. As more voltage is applied across the lamp, the filament heats up, and its resistance increases. This increases the negative feedback, lowering the gain of the op amp. This tends to reduce the amplitude of oscillation to a level that will not drive the op amp into limiting. Very pure sinewaves can be generated in this manner, and less than 1 percent distortion is easy to achieve. By making R1 and R2 a ganged potentiometer, variable frequency operation can be obtained. This

circuit was widely used in the vacuum tube days, and a 120 volt 3 watt tungsten lamp was used for R4. For an op amp version, one of the 5 volt 10 ma subminiature lamps will work well. The lamp is typically operated at 10 to 20 percent of rated voltage, and the filament should barely glow. R3 is actually a fixed resistor R3A in series with a pot R3B to adjust the amplitude of oscillation at that level which yields satisfactory operation.

Finally, the use of both positive and negative feedback enables one to make a tuned amplifier having desired given center frequency and bandwidth. A simple bandpass stage is shown in Fig 10. We will not go into the design details except as to present the design equations for one simple type of stage.. Combining several of these stages allows one to derive a filter network of desired characteristics. These are called active filter networks. There are a number of circuit configurations, yielding low pass, bandpass, and high pass types of filters. We will refer the reader to a book on active filters for more detailed information. In addition, software programs are available from manufacturers that allow a PC to be used for the design of almost any needed active filter.

For the filter shown (suitable for bandpass audio use) with bandwidth B and center frequency f , and gain A:

$$\omega = 2\pi f \quad Q = f / B \quad \alpha = 1 / Q \quad H = \alpha|A| \quad \text{and } Q > \sqrt{(A / 2)}$$

$$R1 = 1 / (H \times \omega \times C1)$$

$$Req = 1/Q (C1 + C2)\omega$$

$$R2 = R1 \times Req / (R1 - Req)$$

$$R3 = A \times R1(1 + C1/C2)$$

In practice, suitable values are chosen for C1 and C2 (generally they are made equal) and the resistors calculated. At audio frequencies, a suitable range of values may be around .001 to 0. 1 μ F. Note that the exact type of op amp is not specified, an ideal op amp is assumed. The TLO81 comes close enough.

As an example, design a filter for 1 kHz with a bandwidth of 100 Hz. We will try to use capacitors of 0. 01 uf at C1 and C2. The filter should have a gain A of 10X (or 20 dB)

$$\text{First check } Q \text{ required} = f/B = 1000/100 = 10 ; \alpha = 1 / Q = 0.1 \text{ and } H = 1$$

$$\omega = 2\pi f = 6.28 \times 1000 = 6280$$

$$\text{Then Check to see if } Q > \sqrt{A/2} ; \quad 10 > \sqrt{10/2} \quad \sqrt{10/2} = \sqrt{5} = 2.23$$

Since $10 > 2.23$ this condition is satisfied

$$\text{Then } R1 = 1 / (1)(6280)(10 \text{ exp } -8) = 15.9 \text{ K (16K)}$$

$$R_{eq} = 1/10 (2 \times 10 \text{ exp } -8)6280 = 796 \Omega$$

$$R2 = 15.9 \times 796 / 15.9 - 7.96 = 838 \Omega \text{ (820 } \Omega)$$

$$R3 = 10 \times 15.9 (2) = 318 \text{ K (330 K)}$$

Values in parentheses are nearest standard 5% resistor values

This circuit was built and tested and results agreed with theory, as did a SPICE simulation. This circuit in itself is useful as a 1 kHz tuned amplifier is useful for testing and in ham radio work as a CW filter. The design of this filter is rather simple, and the reader should try other frequencies and bandwidths as an exercise.

We have presented a number of circuits that should give a novice some starting experience with op amps. It would be a good idea to try some of these circuits and others that can be found in books on op amps and manufacturers application notes and literature. There is no substitute for experience, and undoubtedly you will come up with some circuits of your own that can be custom tailored for your applications

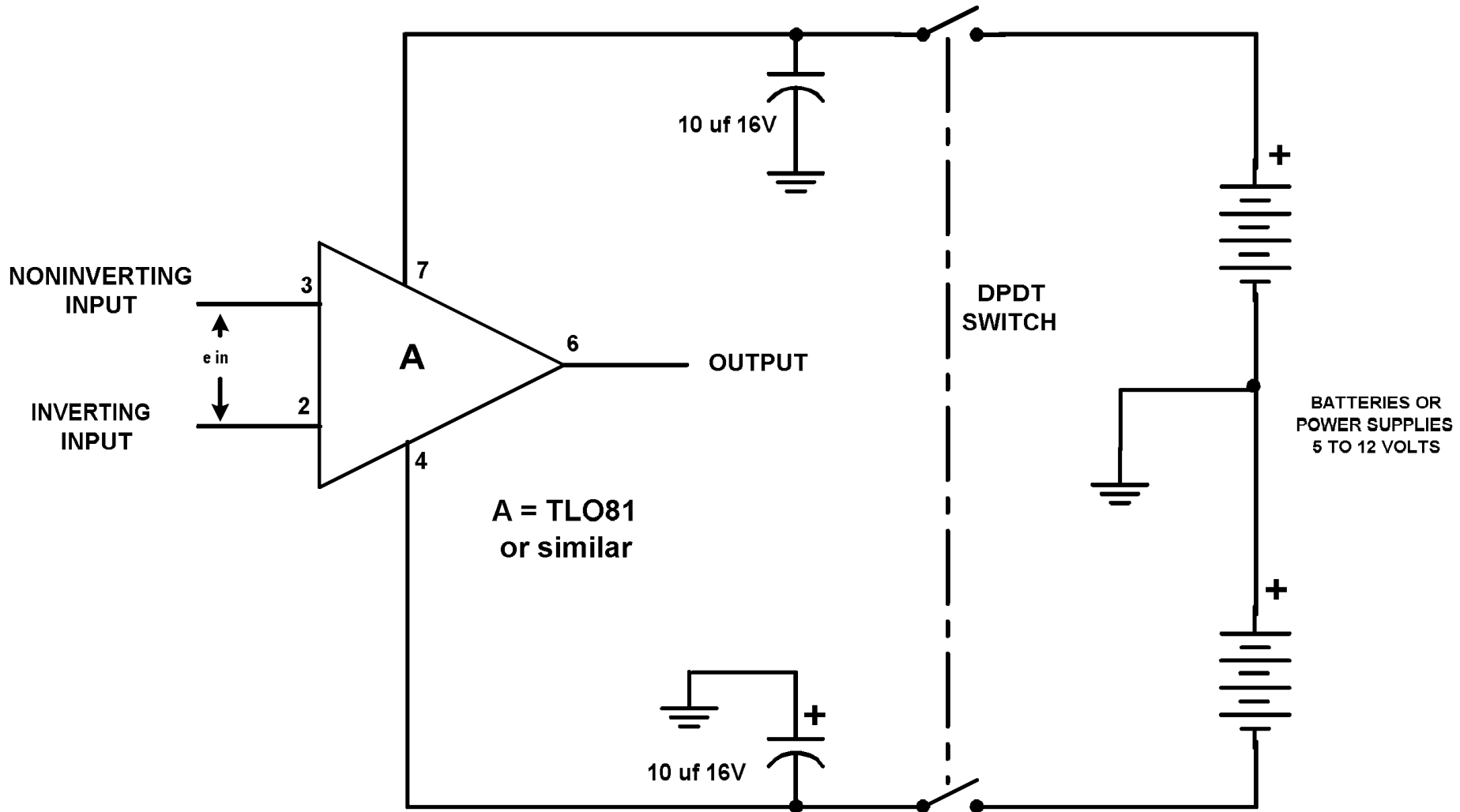
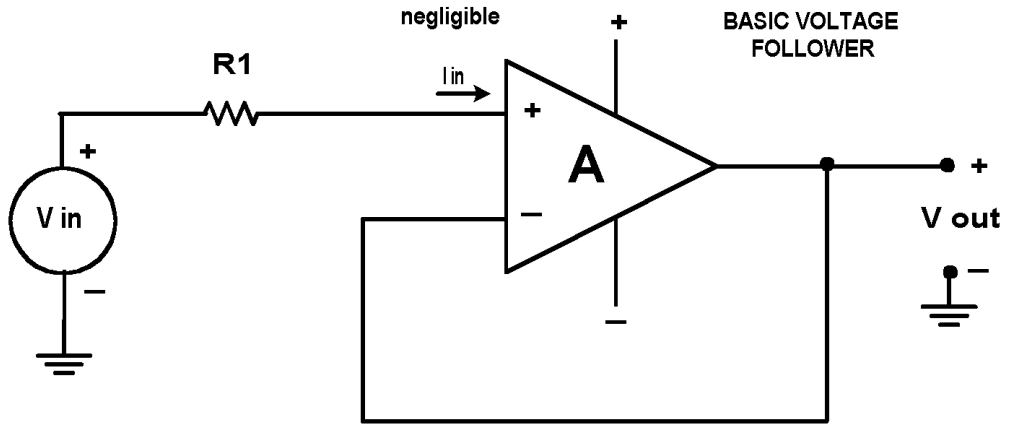


FIG 1
BASIC OP AMP BREADBOARD

Note: I_{in} is almost zero and is negligible



A = TLO81 or similar

SHORT ANTENNA OR PROBE

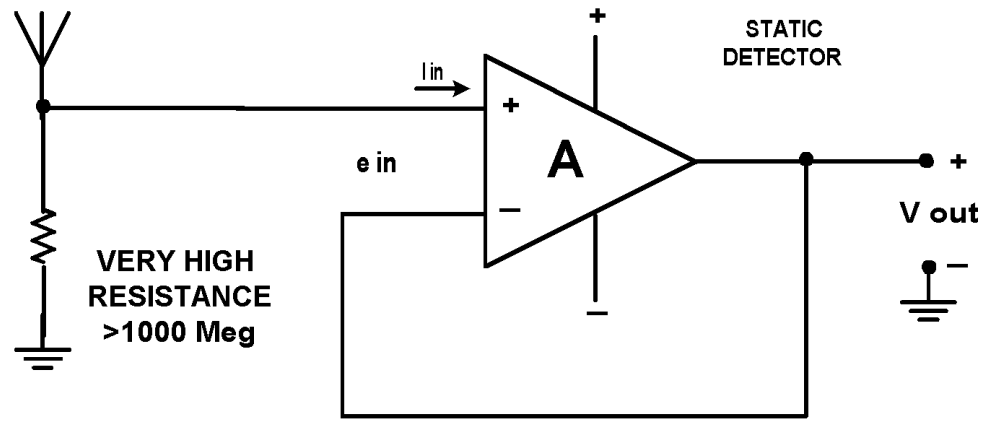


FIG 2
VOLTAGE FOLLOWER

A = TLO81 or similar

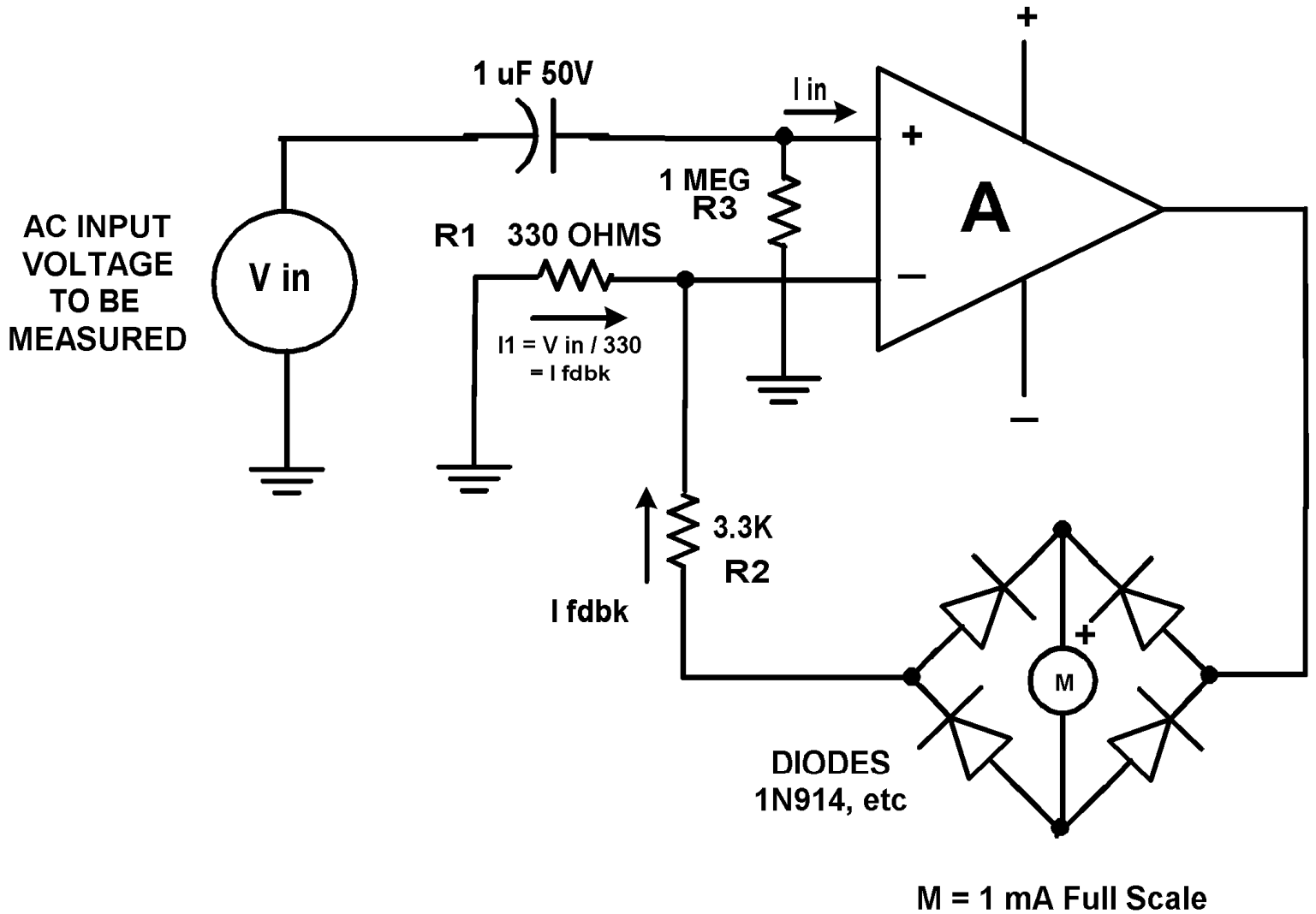
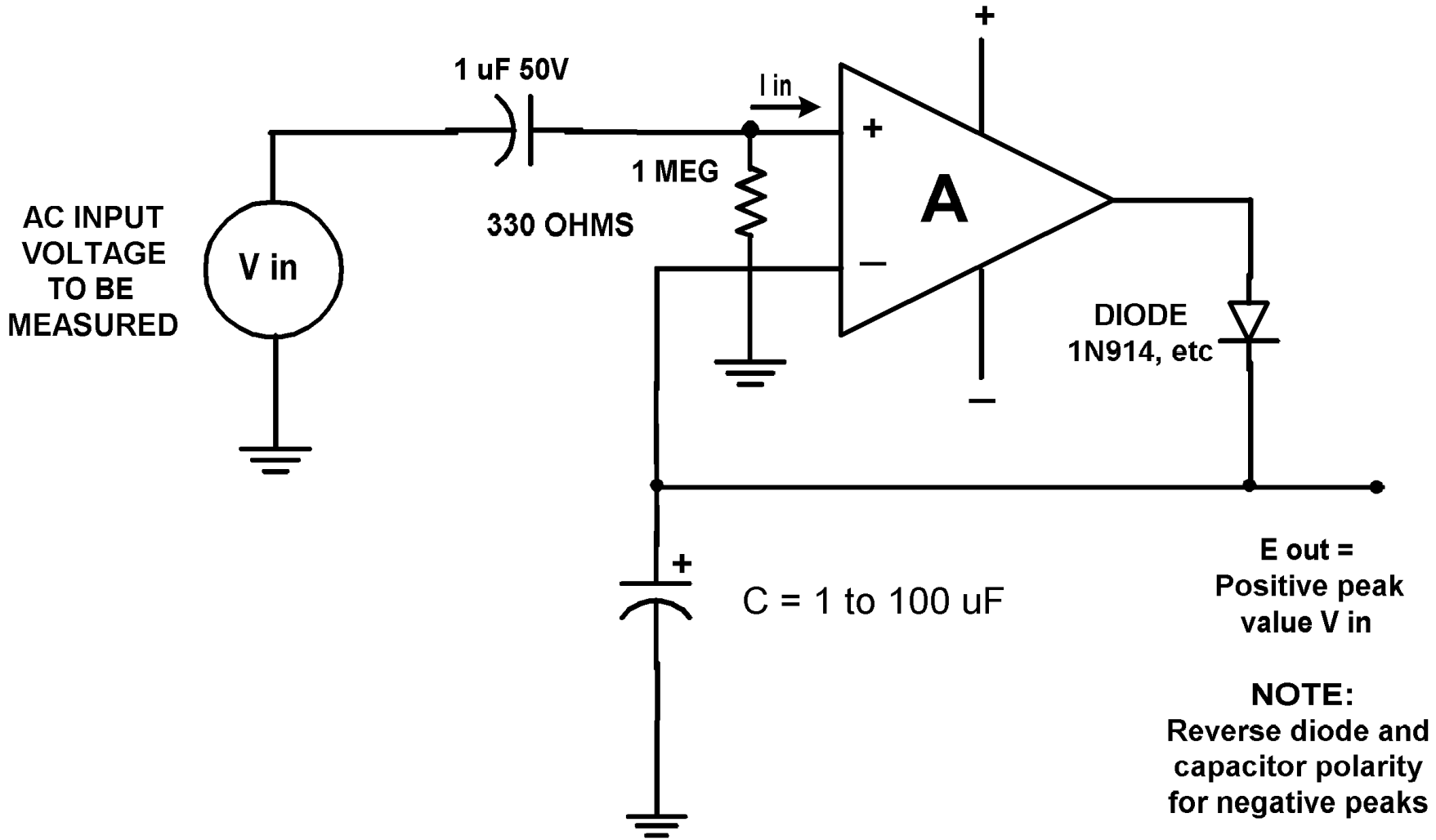


FIG 3
LINEAR AC VOLTMETER CIRCUIT

**A = TLO81 or
similar**



**FIG 4
PEAK DETECTOR CIRCUIT**

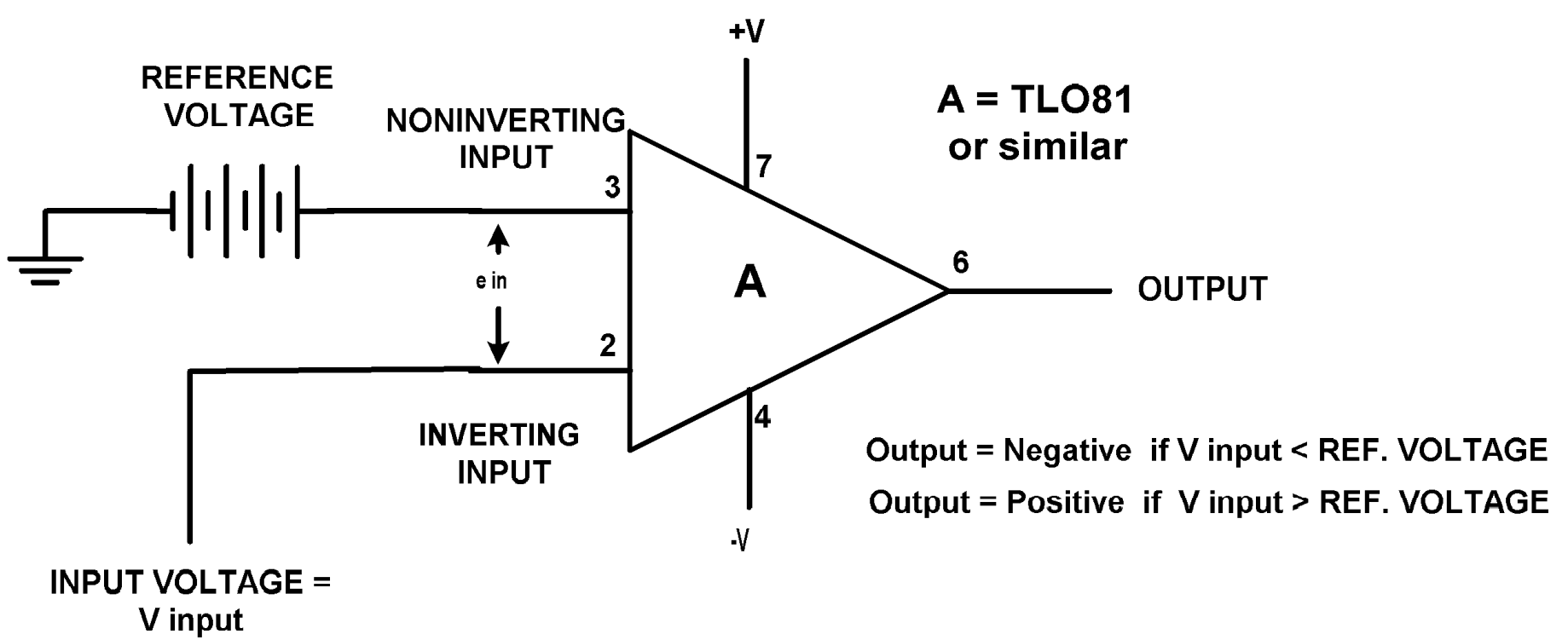


FIG 5
BASIC OP AMP COMPARATOR

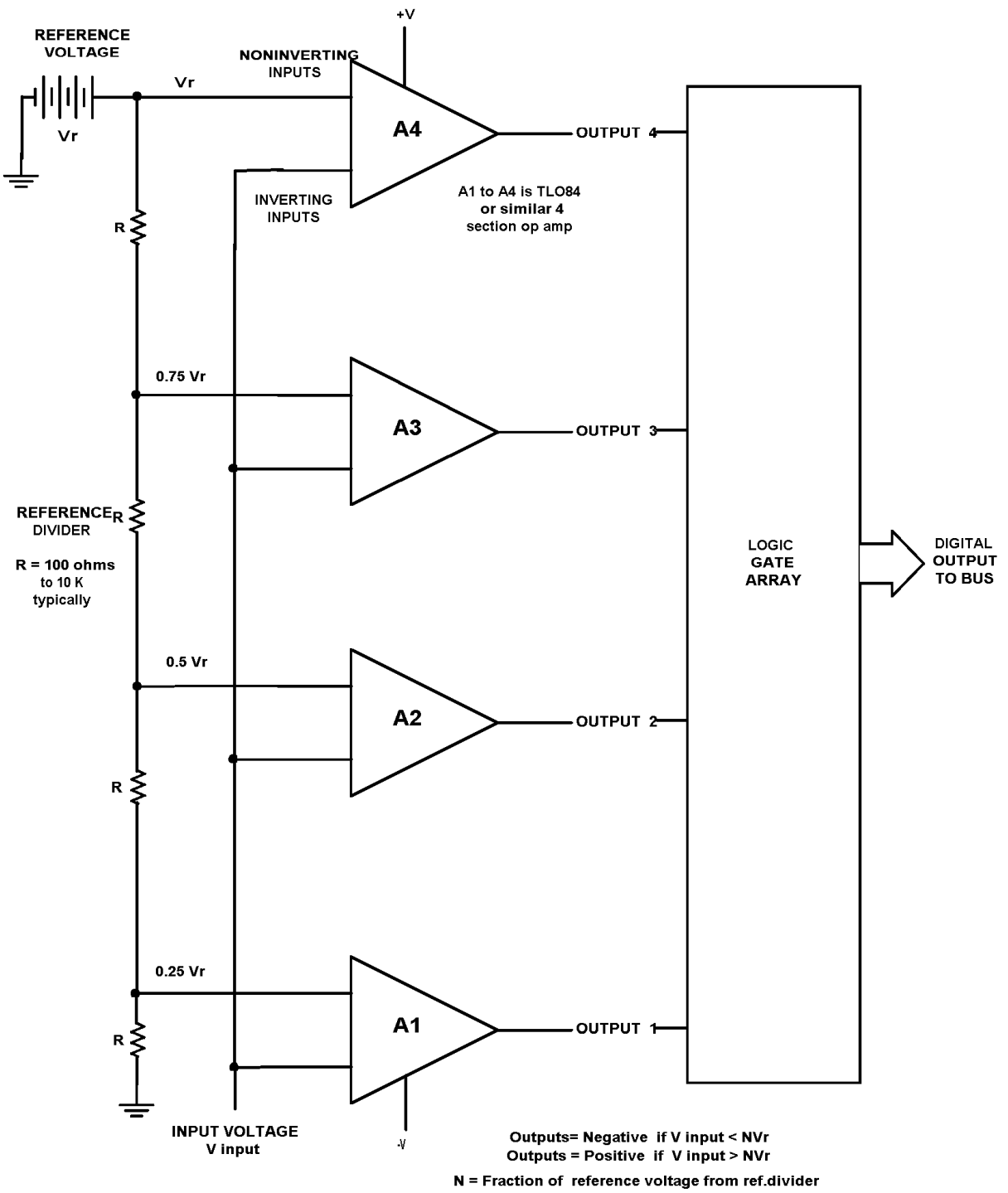
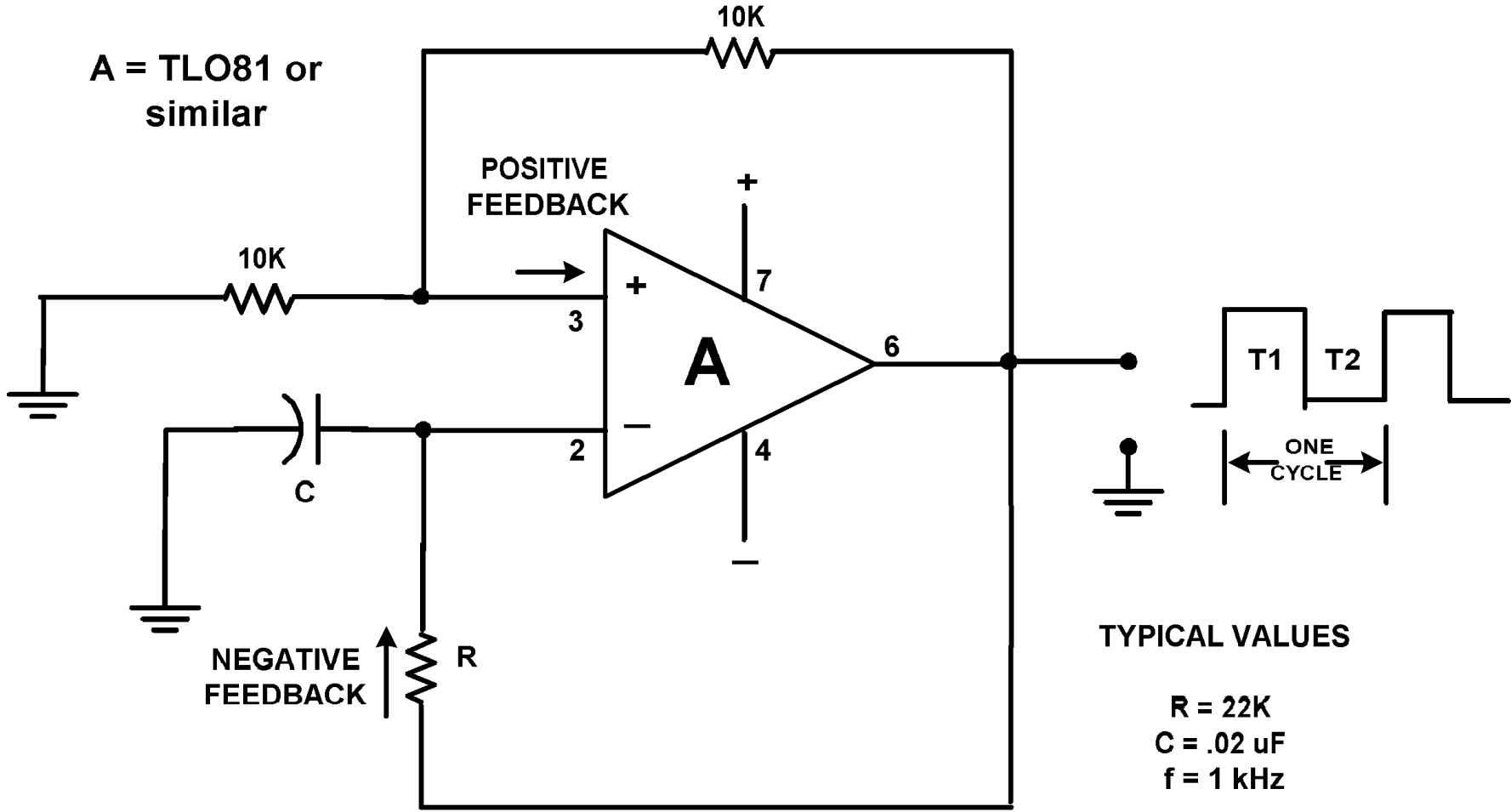


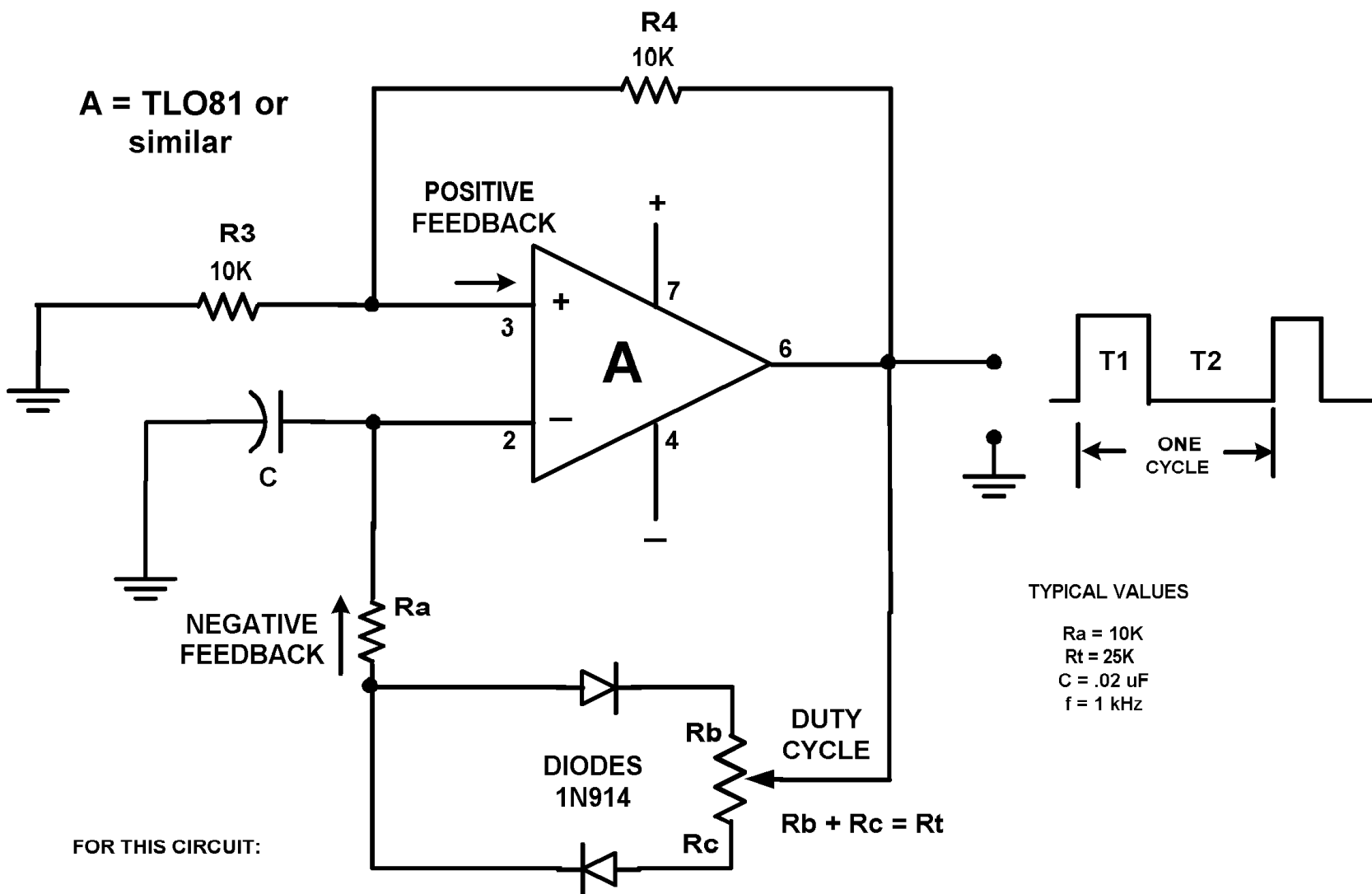
FIG 6
 BASIC FLASH A-D CONVERTER



FOR THIS CIRCUIT:

- T1 = T2 = 1.1 RC APPROX
- T1 + T2 = ONE CYCLE
- F = 1 / 2.2 RC APPROX

FIG 7
SQUARE WAVE OSCILLATOR CIRCUIT



FOR THIS CIRCUIT:

$$T1 = 1.1 (R_a + R_b) C \text{ APPROX}$$

$$T2 = 1.1 (R_a + R_c) C \text{ APPROX}$$

$$T1 + T2 = \text{ONE CYCLE}$$

$$T1 + T2 = 1 / [2.2 R_a + 1.1 R_t) C] \text{ APPROX}$$

FIG 8
SQUARE WAVE OSCILLATOR CIRCUIT
VARIABLE DUTY CYCLE

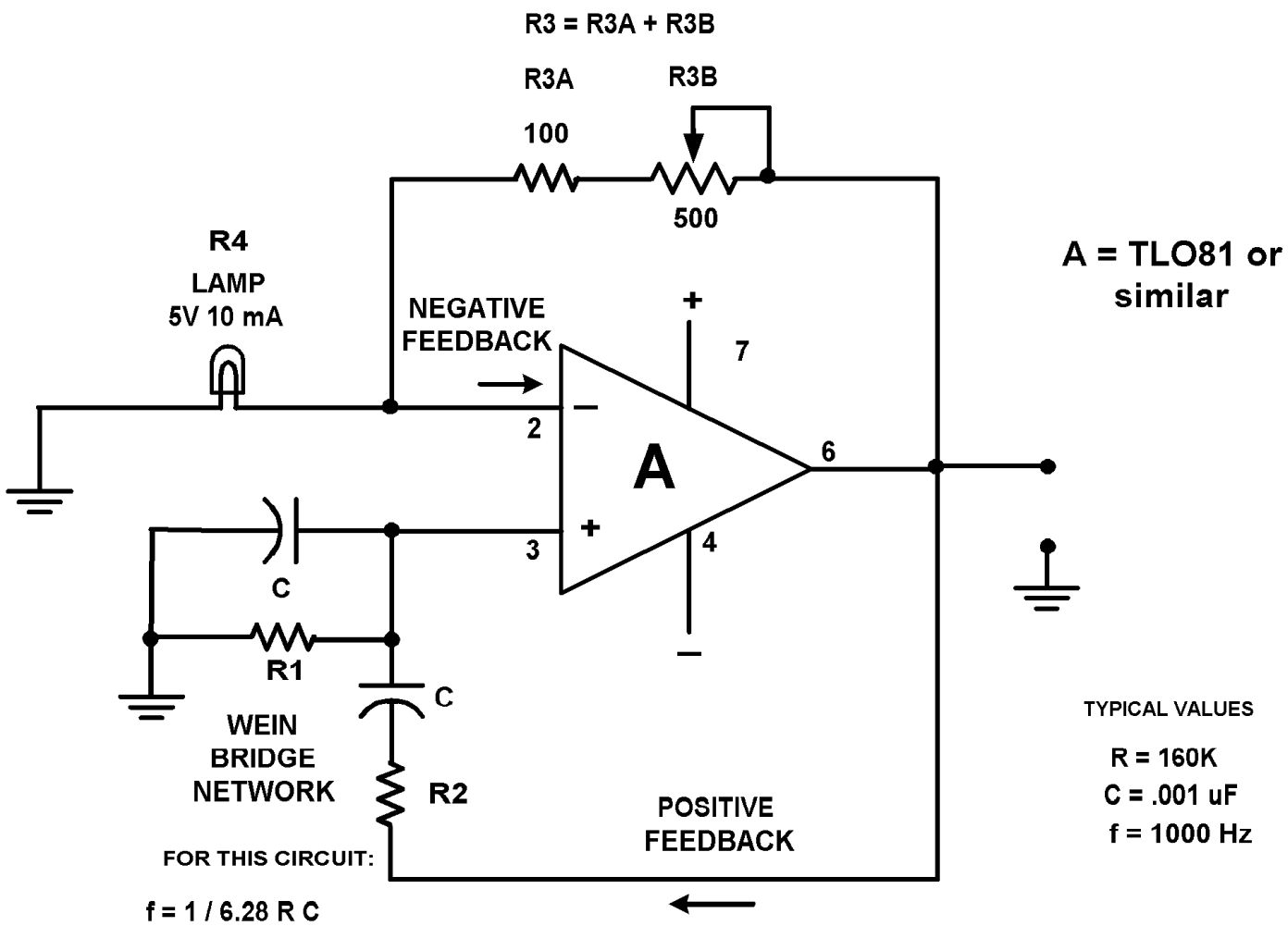
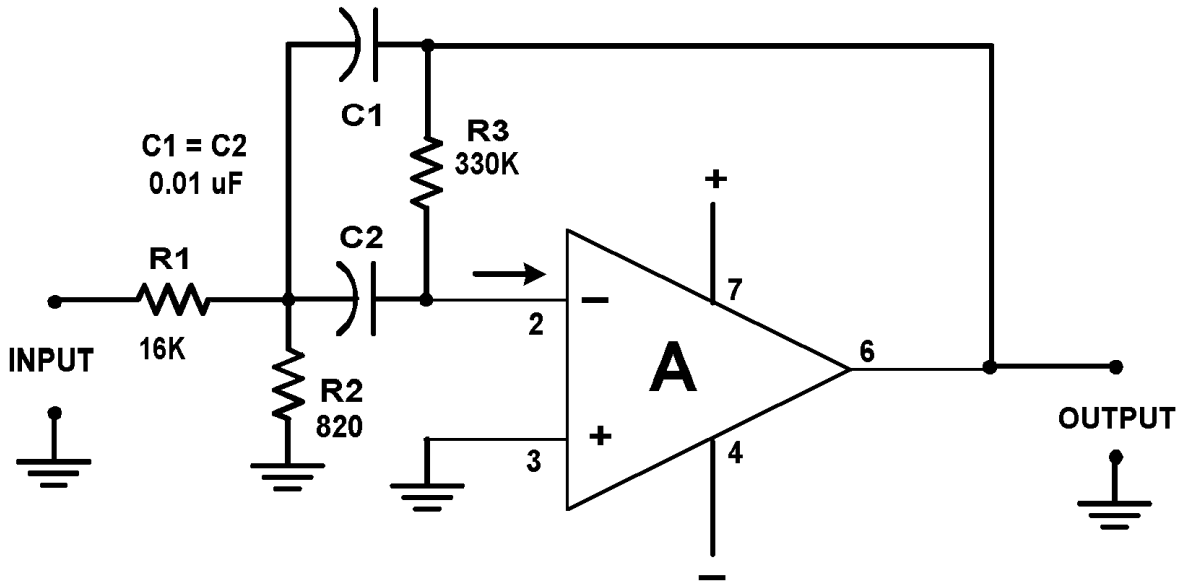


FIG 9
WIEN BRIDGE OSCILLATOR CIRCUIT
SINE WAVE OUTPUT

A = TLO81 or similar



Values Shown for:

Freq = 1000 Hz
Gain = 10X
BW = 100 Hz
Q = 10

FIG 10
BANDPASS ACTIVE FILTER