Op-amps and Comparators

Op-amps (operational amplifiers) and comparators are very useful devices which are in some ways similar to one another. These devices can be configured to suit a wide range of design applications, many of which are routinely applied to meet design needs in the *Embedded Control* course. An op-amp is commonly used as one component of an amplifier circuit, while a comparator is used to determine whether one voltage is *lower* or *higher* than a *reference* voltage and produces a digital, *LOW* or *HIGH*, output.

The Op-Amp

The op-amp is one of the most useful electronic devices ever developed. It finds common application as an integral component in such devices as *inverting* and *non-inverting amplifiers*, *inverting* and *non-inverting summers*, *voltage followers*, *difference amplifiers*, *waveform generators*, and *active filters*. The specific application described in this chapter will be that of a *non-inverting amplifier*. For those who are interested, there are a number of very good books on the subject of circuit design with operational amplifiers including [Jacob, 1982][1].

The ideal and the real op-amp

Figure 0.1 illustrates the use of an op-amp as a component in a non-inverting amplifier circuit. To understand how this circuit works, it helps to understand some of the characteristics of an *ideal* op-amp. An ideal op-amp has five terminals (as does a real op-amp) which are the *inverting* and *non-inverting* input terminals labeled (-) and (+) respectively, the *output* terminal (V_{out}), and the V_{CC} and V_{EE} supply voltages that are commonly connected to power and ground, respectively. An ideal op-amp has *infinite* gain, which means that it multiplies (amplifies) the voltage difference between the (+) and (-) terminals to the limit of the V_{CC} and V_{EE} supply voltages,

$$V_{out} = \infty \cdot (V_{CC} - V_{\mathrm{EE}}) \qquad V_{EE} \leq \; V_{out} \; \leq \; V_{CC}$$

Moreover, an ideal op-amp draws no current into its (+) and (-) terminals, i.e., it has infinite input impedance, meaning that it won't *load-down* a device that is trying to supply input to either of the (+) and (-) terminals, no matter how small the driving device. Furthermore, if the voltage at the (+) terminal is greater than the voltage at the (-) terminal, then the op-amp's output will be the same as the voltage at its V_{CC} terminal. Similarly, if the voltage at the (-) terminal is greater than the voltage at the (+) terminal, then the op-amp's output will match the voltage at its V_{EE} terminal.

Real op-amps, on the other hand, have typical gains of around $2\text{x}10^5$, input impedances on the order of 10^6 ohms, and maximum output voltages that are typically 1.5 volts *less* than the V_{CC}

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[1] Jacob, J. Michael, *Application and Design with Analog Integrated Circuits*, Reston VA: Reston Publishing Co., Inc., 1982

supply connected to them, not to mention current driving capabilities which are device dependent. However, when designing with op-amps, engineers typically assume that the op-amp has infinite input impedance and infinite gain.

The non-inverting amplifier

As was mentioned in the previous section, ideal op-amps have infinite gain (useless for linear amplification), and real op-amps have gains in the neighborhood of $2x10^5$. In applications requiring a linear amplifier, the designer needs to be able to select the exact amplification needed, or perhaps make the amplification level user-adjustable (e.g., the volume-level control on a stereo). The beauty of an op-amp with its enormously high gain is that it can be configured with a *feedback loop* and a couple of resistors into an amplifier circuit with *any gain*, nearly to the rating of the op-amp[1].

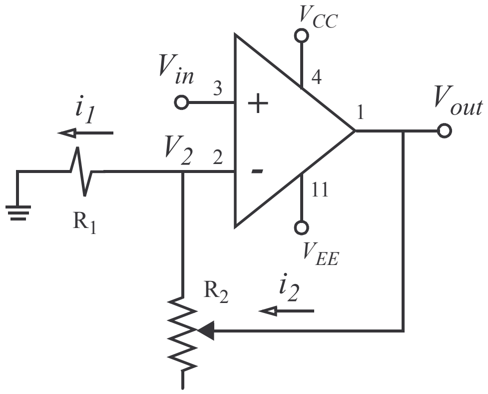

Figure 0.1 - Non-inverting amplifier[2]

An op-amp in a *non-inverting amplifier configuration* is shown in *Figure 0.1*. To understand how this configuration works, remember that current cannot flow into or out of the *inverting* (-) or *non-inverting* (+) inputs because they have infinite impedance. Therefore, the voltages at the (-) and (+) terminals must be the same; otherwise the output of the op-amp would be saturated ("max'ed out") at either V_{EE} or V_{CC}, and linear amplification of V_{in} would not be occurring. In order for the voltage at the (+) and (-) terminals to be the same, a current equivalent to V_{in} / R_1 must be flowing through resistor R_1. Since current cannot come from the inverting input, it must be coming from the op-amp's output terminal. Using this reasoning and treating resistors R_1 and R_2 as being connected in series, we can write the following relations for the currents and voltages in this circuit:

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[1] In practice, the maximum gain of an amplifier should be significantly less than the rating of the op-amp, and if additional amplification is required, amplifier stages can be cascaded.

[2] Pin numbers are associated with the *MAX475* op-amp chip in *Figure 0.3*. Since there are four op-amps per package with distinct pin numbers for each, op-amp #1 with associated pin numbers (1, 2, and 3) was the device used in the example circuit.

$V_2 = V_{in}$ *inverting terminal voltage = non-inverting terminal voltage*

$V_2 = i_1 R_1$ *Ohm's law*

$i_1 = i_2$ *current cannot enter the inverting terminal*

Using only Ohm's law and the relations above, we can solve for V_{out} in terms of V_{in}:

$$V_{out} - V_2 = i_2 R_2$$

$$V_{out} - V_{in} = i_2 R_2$$

$$V_{out} - V_{in} = V_{in}\frac{R_2}{R_1}$$

$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_1}\right)$$

For example, to obtain a gain of 5, we'll need $R_2 / R_1 = 4$, so we could choose resistor values $R_1 = 1\text{k}\Omega$ and $R_2 = 4\text{k}\Omega$.

Saturation

With an ideal op-amp configured as a non-inverting amplifier, the output voltage will increase linearly as the input voltage increases without limit. For a real op-amp, the output voltage will not exceed a maximum voltage that is dependent on the type of op-amp. Saturation occurs when the projected output voltages exceeds the maximum allowable output voltage, or saturation voltage. Once saturation occurs, the amplifier no longer behaves linearly. The output voltage *levels off* at the saturation voltage of the chip as shown by Figure 0.2. Different op-amp chips may have different saturation levels, at or below V_{CC}, or may not output negative voltages.

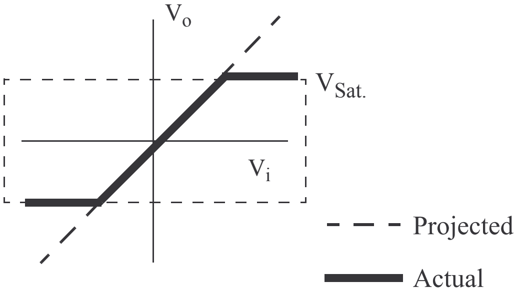

Figure 0.2 - Saturation Level Chart

The Maxim MAX475CPD

The lab for *Embedded Control* commonly stocks the general purpose *Maxim MAX475CPD* (or *MAX475*) op-amp which comes in a 14-pin DIP (Dual In-line Package) with four independent op-amps as shown in Figure 0.3. The supply voltages for the *MAX475* are considered safe when in the range of V_{CC} - V_{EE} < 7.0V. The *MAX475* op-amp has rail-to-rail output characteristics, which means that the output saturates at approximately V_{CC}. With the circuitry used in the *Embedded Control* lab, V_{CC} will be set to 5.0V, V_{EE} will be ground, and the output will saturate at 5.0V.

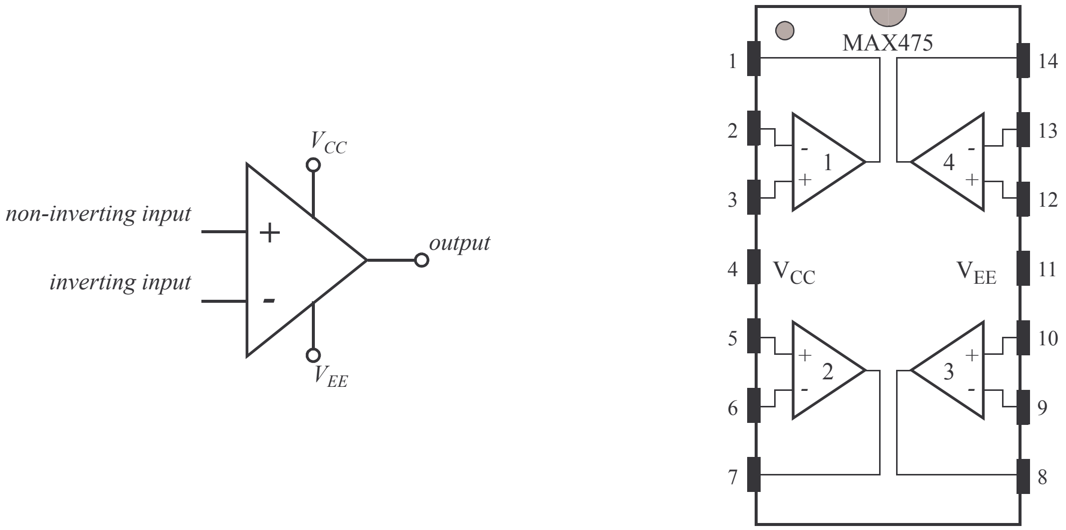

Figure 0.3 - Symbol for an op-amp (left) and a Maxim MAX475CPD quad op-amp IC

The Comparator

A comparator is commonly applied where it is necessary to determine whether one voltage is *greater than* or *less than* another voltage. The output of a comparator is either a *LOW* or a *HIGH* voltage, i.e., binary *FALSE* or *TRUE*. As shown in Figure 0.4, a comparator is essentially a special-purpose op-amp which has been optimized to produce two-state output for applications that require *switching* rather than linear amplification. While many different types of comparators are available, the lab for *Embedded Control* generally stocks the *Motorola LM311*, which is capable of operating on a single power supply (V_{EE} = 0 volts, V_{CC} = 30 volts) or on a split power supply (V_{EE} = -15 volts, V_{CC} = 15 volts)[1]. The LM311's output can also switch voltages up to 50 volts at currents up to 50mA, and thus it can be used to drive devices such as relays, LEDs, or solenoids. Complete details for the LM311 can be found in the *Motorola Linear and Interface ICs* handbook.

As an example of an application where a comparator would be useful, consider a circuit which can be used to determine if the light intensity on a phototransistor is *above* or *below* a certain threshold level. Since the impedance between the collector and emitter of the phototransistor is linear for a broad range of light intensities, and since we need to develop a circuit which outputs either a *LOW* or a *HIGH* voltage depending on the light intensity on the phototransistor, a

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[1] Note that these are maximum voltage ratings.

thresholding device like the comparator can probably be put to use somewhere in the desired circuit.

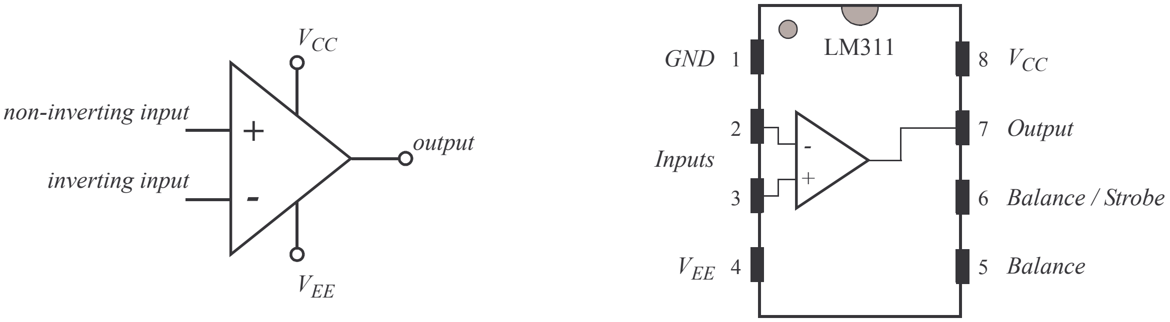

Figure 0.4 - Symbol for a comparator (left) and a Motorola LM311 comparator IC

Consider the optically controlled switching circuit shown in Figure 0.5, which can be used to provide input to a digital device such as one of the C8051's digital input ports. As an example of an application that might utilize this circuit, consider a security system where a beam of light shines on the face of a photodetector. If the beam of light is broken by an intruder, a digital *LOW* signal from the circuit will be fed into a C8051-based security system, which presumably may have been programmed to activate an alarm, call the police, turn on security cameras, etc.

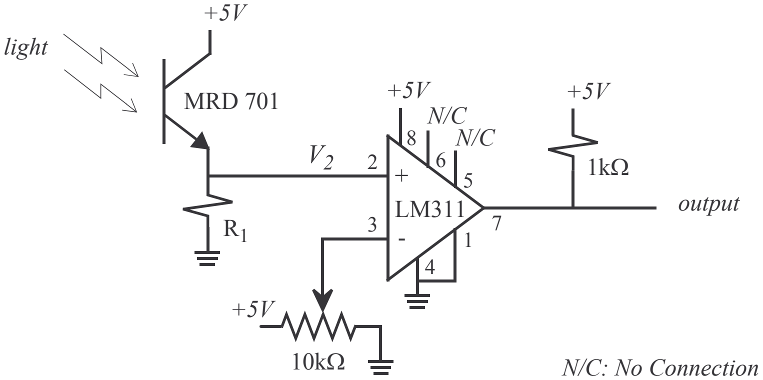

Figure 0.5 - Optically controlled switching circuit utilizing an LM311 comparator

Input to the circuit in Figure 0.5 is the light which impinges upon the face of an *MRD 701* phototransistor[1]. When the light is blocked, the phototransistor is *off*, and by Ohm's law, the voltage at the node labeled V_2 will be 0 volts because the current across the resistor labeled R_1 is also 0 ($V = i R$). When light shines on the face of the phototransistor it conducts current from its collector (which has been connected to +5 volts) to its emitter, which is connected to the resistor labeled R_1. Within the phototransistor's linear region of operation, the amount of current flowing across resistor R_1 will thus be modulated by the intensity of the light on the face of the

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[1] The *MRD 701* is just one of many types of photodetectors that could be used.

phototransistor. By Ohm's law, the voltage across R_1, which is proportional to current, will be controlled by the light intensity on the face of the phototransistor.

Depending on the physical situation of the phototransistor, the range of light intensities may be known or experimentally determined, and consequently the designer would be able to select an appropriate value for R_1 to maximize the range of voltages across R_1 for the extremes in light intensity. As an example, let's say that a value of $R_1 = 20\text{k}\Omega$ results in a range of V_2 from 1 volt to 3 volts for the extremes in light intensity in the physical environment where the photodetector is to operate. Since the output from the LM311 needs to be either 0 or 5 volts (to serve as TTL-compatible input to a C8051), and since it is known that if $V_{(+)} > V_{(-)}$ then the LM311's output will be V_{CC} (else the output will be V_{EE} if $V_{(-)} > V_{(+)}$), let's select, by using a potentiometer, a *threshold voltage* level on the (-) terminal of 2 volts (2 volts is half way between V_2's assumed range of 1 to 3 volts). The 1kΩ resistor shown connected between +5V and the output of the LM311 is known as a *pull-up resistor* and is used to aid the LM311's output to reach a full 5 volts when $V_{(+)} > V_{(-)}$.