

COMPARATORS

Voltage comparators are high gain differential input—logic output devices. They are specifically designed for open loop operation with a minimum of delay time. Although variations of the comparator are used in a host of applications, all uses depend upon the basic transfer function of Figure 1. As shown, device operation is simply a change of output voltage dependent upon whether the signal input is above or below the threshold input. The threshold in this example is 0 volts.

Comparator inputs are customarily marked with plus or minus signs to indicate their polarity. For example the circuit of Figure 2 produces a logic 1 level when the non-inverting input is more positive than the reference voltage.

DEFINITIONS

Many similarities exist between operational amplifiers and the amplifier section of voltage comparators. In fact op amps can be used to implement the comparator function at low frequencies.

Thus, the characteristic definitions presented here are similar to those reviewed for op amps.

Input Offset Voltage

As with operational amplifiers, the non-ideal comparator possesses some offset voltage. The definition differs slightly in that the output structure of comparators is digital rather than linear. Hence, input offset voltage is defined for comparators as the dc voltage required at the input to force the output to the logic threshold of ensuing devices (1.2 volts for TTL).

Input Offset Current

Imbalances of input bias current arise from small variances of the junction geometry of the differential input amplifier. As for op amps, the imbalance is referred to as input offset current.

Bias Current

As with op amps the input structure of comparators is usually a differential bipolar stage. Input bias current is the average of the two input currents.

Common Mode Range

When specifying voltage comparators one of the key parameters is common mode range, which is defined as the range of voltages over which both inputs can be varied simultaneously without abnormal output voltage transitions or device degradation. This parameter

must be kept uppermost in the designer's mind because the reference and signal voltages become common mode signals at threshold. All ranges of input signals thus must be within the common mode range of the input amplifier.

Voltage Gain

Specifications of voltage gain refer to the overall gain of the device, the bulk of which occurs in the amplifier section.

In general, higher gains would be advantageous for resolving smaller input signals. Of course, the propagation delay suffers due to the more severe saturation of the transistors. Typical gains for TTL output devices are set for 5000 volts per volt. This gain provides 5 volts of output swing with 1mV input signal change for reasonable accuracy but does not contribute severely to the overload recovery delay.

Propagation Delay

Voltage comparisons of analog signals with a reference voltage usually require that the operation take as little time as possible. Long delays in the comparator cause a pulse position error at the output since the analog signal in the meantime has changed value. At low frequencies the delay is of small consequence but, at higher frequencies, transit

time becomes intolerable. Design of voltage comparator devices includes, as a prime goal, the minimizing of transit times.

Propagation delay testing is done under worst case conditions. The recovery from saturation varies depending upon the initial state of the amplifier and the overdrive. Worst case conditions begin by applying a 100mV signal on the reference terminal. With no signal applied the amplifier is in saturation in one direction. A step input pulse on the signal line of $100\text{mV} \pm V_{OS}$ will bring the amplifier to a threshold level. Propagation delay at this point is undefined since the output has not switched.

To attain output switching a small overdrive is necessary. Propagation delay is tested in a configuration such as Figure 3. The input is a step function of 100mV plus a specified excess or overdrive signal. This causes the amplifier to be exercised from saturation in one direction to saturation in the other for worst case propagation delay. Note that larger overdrive reduces delay time as can be seen in Figure 4. An overdrive of 5mV causes 12ns delay, whereas a 100mV overdrive improves transit time to only 6ns.

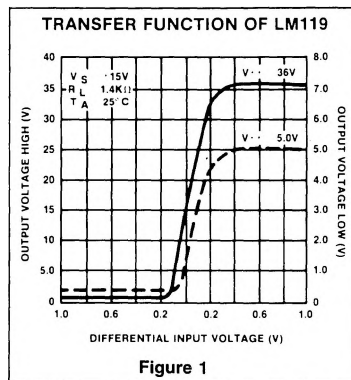


Figure 1

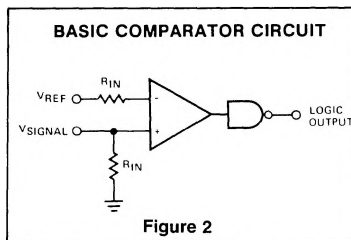


Figure 2

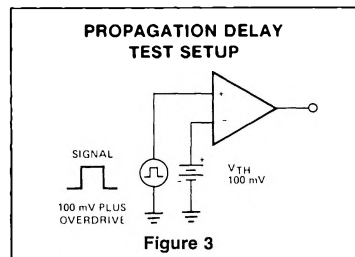


Figure 3

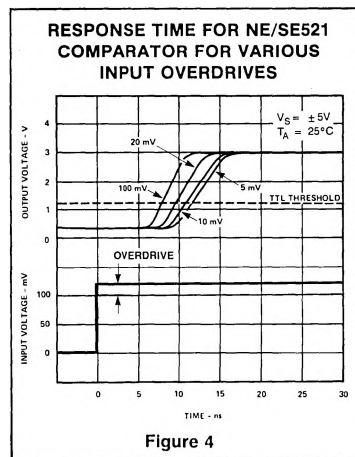


Figure 4

If the measurement were made without initial saturation (less than 100mV V threshold) the delay time would be less, due to the decreased storage times of unsaturated transistors.

STATE-OF-THE-ART

Comparator design has always been optimized for four basic parameters. They are:

1. High Speed
2. Wide Input Voltage Range
3. Low Input Current
4. Good Resolution

Unfortunately these four parameters are not compatible. For instance gain and input current can be improved by using thinner diffusions for higher beta, but only at the expense of input voltage range. Higher gain also means higher saturation for an increase in delay time. So it becomes obvious that older comparators such as the 710 were designed with the best compromises in mind using standard processing.

One method of improving overall response adds gold doping to the processing flow. The gold dopant causes a decrease in minority carrier lifetime which aids the recombination process and shortens the saturation recovery time. Unfortunately, the transistor beta is adversely affected by gold causing slightly higher bias and offset currents.

It was not until advent of the Schottky clamp that a vast improvement in speed without input degradation was possible. A very familiar term in the semiconductor industry, the Schottky barrier diode's (SBD) location is illustrated in Figure 5.

The Schottky clamped transistor is formed by paralleling the Schottky diode with the base-collector junction of the npn transistor. Without the clamp, as base drive is increased the collector voltage falls until hard saturation occurs. At this point the collector voltage is very near the emitter voltage, and stored charges in the junctions causes slow recovery from saturation after

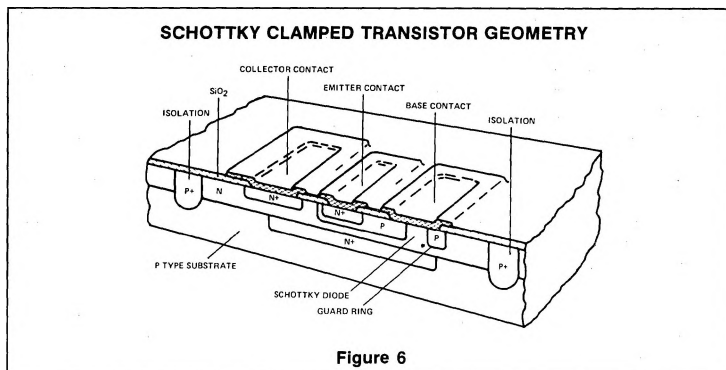


Figure 6

base drive has been removed. The forward voltage drop of the Schottky diode is 0.4 volts—less than the forward drop of silicon diodes. This difference in forward drop is used by placing the diode across the transistor base-collector junction. The Schottky diode becomes forward biased when the collector voltage falls 0.4 volts below the base voltage. Excess base drive is then

shunted into the collector circuit prohibiting the transistor from reaching classic saturation. With almost no stored charge in either the SBD or the transistor, there is a large reduction in storage time. Thus, transistor switching time is significantly reduced.

A cross sectional area of the Schottky diode is shown in Figure 6.

COMPARATOR SELECTION GUIDE

Device	Propagation Delay (ns)	V_{OS} (mV)	I_{OS} (μ A)	I_{bias} (μ A)	Gain	CMR (V)	Benefits
NE521	12	7.5	5	20	5000	± 3	Dual, very fast, standard supplies, TTL compatible, individual & common strobe.
NE522	15	7.5	5	20	5000	± 3	Same as NE521 plus open collector outputs for additional decoding.
NE527	26	6	0.75	2	5000	± 6	Fast, very low input current, differential outputs, flexible surplus wide common mode range.
NE529	22	6	5	20	5000	± 6	Same as NE527 but with faster response.
LM311	200	7.5	0.05	0.25	200K	± 30	High common mode input range, $\pm 5V$ to $\pm 15V$ supply, strobe input, open collector output.
LM319	80	8	0.2	1.2	40K	± 5	Low input bias, dual, $+5V$ to $\pm 15V$ supply, open collector output.
LM339	1300	2	0.05	0.25	200K	$V+ - 1.5V$	High common mode input range, low input bias, quad, $+5V$ to $\pm 15V$ supply, open collector output.
LM393	1300	2	0.05	0.25	200K	$V+ - 1.5V$	Same as LM339 but dual.

Figure 7

NOTE: Parameters are based on min/max limits at 25°C as defined in the individual data sheet.

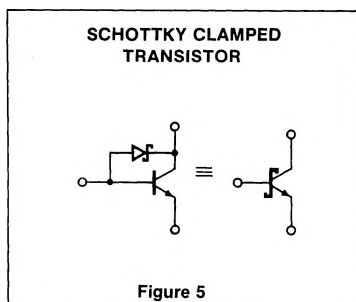


Figure 5

COMPARING THE COMPARATORS

Presently available comparator ICs range from the ultra fast SE/NE521 to the general purpose comparator fashioned from an inexpensive op amp. Selection of the device depends upon the application in which it will be used. Speed of conversion is often of primary importance to minimize pulse position errors of high frequency signals. At other times the requirements are much less stringent allowing the use of a general purpose comparator.

A handy reference guide to the major parameters is summarized in Figure 7. The necessary parameters can be chosen to select the proper device.

A general description of the comparator devices is included here to familiarize the user with available devices and their advantages.

SE/NE521/522 Comparators

Processed with state-of-the-art Schottky barrier diodes, the NE521/522 series devices provide good input characteristics while providing the fastest analog to TTL conversion to date. Total delay from input to output is typically 6ns with a guaranteed speed of 12ns. Additional features of this device include the dual configuration and individual output strobes to simplify system logic. The NE522, although sacrificing some speed, features open collector outputs for party line or wired-OR configurations for additional system flexibility.

NE/SE527 Comparator

Featuring darlington inputs for very low bias current, the NE527 is generically related to the NE529 comparator. Emitter follower inputs to the differential amplifier are used to trade better input parameters for slightly less speed. As Figure 7 shows, a factor of 10 improvement in I_{BIAS} is gained with a propagation delay increase of only 4ns maximum.

NE529 Comparator

The NE529 is manufactured using Schottky technology. Although a few nano seconds slower than the NE521, the NE529 features variable supplies from ± 5 to ± 10 volts with a high common mode range of ± 6 volts. Both the NE527 and NE529 Schottky comparators boast complimentary logic outputs with output A being in phase with input A. In addition, the supplies of both the NE527 and NE529 may be non-symmetrical to produce a desired shift in the common mode range.

This technique is illustrated by the ECL to TTL and TTL to ECL transistor of Figures 17 and 18 respectively. The only major require-

ment of the supplies is that the negative supply be at least 5 volts more negative than the ground terminal of the gate. This is necessary to insure that the internal bias arrangement has sufficient voltage to operate normally.

APPLICATIONS

Today's state-of-the-art ultra-high speed comparators are capable of making logic decisions in less than 10 nano seconds. They are easily applied and possess good input and power supply noise rejection. As with all linear ICs however, some preliminary steps should be taken in their use.

General Precautions

Layout

The comparator is capable of resolving sub-millivolt signals. To prevent unwanted signals from appearing at signal ports, good physical layout is required. For any high speed design, ground planes should be used to guard against ground loops and other sources of spurious signals. At high frequencies hidden signal paths become dominant. Distributed capacitance is a particular nuisance. If care is not taken to isolate output from input, distributed capacitance can couple a few millivolts into the input, causing oscillation.

Another source of spurious signals is ground current. Input structures are relatively high impedance while the gate structures of comparators run with large signal and ground currents. If this gate ground current is allowed to pass near the input signal path, the small impedances of the ground circuit will cause millivolt changes in reference or signal voltages producing errors, sustained oscillation, ringing, or excessive V_{OS} . A ground plane arranged such that output currents do not flow near input areas is highly recommended.

Power Supplies

Another general precaution that should always be exercised is power supply bypassing. As mentioned the name of the game is speed. Very high speed gates are used to produce the desired output logic levels. Maximizing response speed also requires higher current levels, giving rise to power supply noise. For this reason, good power supply bypassing very close to the device itself is always mandatory. A tantalum capacitor of 1 to 10 μ F in parallel with 500 to 1000pF will prove effective in most cases. Lead lengths should be as short as physically possible to preserve low impedances at high frequency.

Unused Inputs

Some currently available comparators such as the NE521 and NE522 are dual devices. Most often both sections of these devices

will be utilized. Should a system utilize one device, the unused inputs should be biased in a known condition. The high gain-bandwidth may otherwise cause oscillations in the unused comparator section. A low impedance should be provided from both unused inputs to ground. A resistor of relatively high impedance may then be used to supply a differential input on the order of 100mV to insure the comparator assumes a known state.

If the inverting input is tied to the positive differential voltage the gate output will be low. The strobe inputs then provide a means of utilizing the Schottky gate for other system logic functions.

If the strobe inputs are not used, they should be connected to the output of a logic gate that is always high, or to the +5 volt supply through a 5 to 10 K-ohm resistor. They should never be tied directly to the +5 volt supply as the relatively minor spiking on the supply may damage these inputs.

Common Mode Signals

Manufacturers specify the maximum voltage range over which the inputs may be taken. In addition the maximum differential voltage that may be safely applied to the inputs is specified. In the case of the NE529 comparator the differential voltage is restricted to less than ± 5 volts, with a common mode of ± 6 volts. That these two quantities interact cannot be overlooked. For instance, with both inputs at ± 4 volts the common mode restriction is satisfied. If V_{ref} is now left at +4 volts the signal input may not be taken more than 1 volt below ground because the differential signal becomes 5 volts.

It is important to observe this maximum rating since exceeding the differential input voltage limit and drawing excessive current in breaking down the emitter-base junctions of the input transistors could cause gross degradation in the input offset current and bias current parameters.

Exceeding the absolute maximum positive input voltage limit of the device will saturate the input transistor and possibly cause damage through excessive current. However, even if the current is limited to a reasonable value so that the device is not damaged, erratic operation can result.

Input Impedance

The differential bias and offset currents of comparators are minimized by design. As was pointed out for op amps, the input resistance seen by both inputs should be equal. This reduces to a minimum the contribution of offset current to threshold error. Unbalanced input impedance also adds to

the offset error due to the difference in voltage drop across the input resistances.

BASIC APPLICATIONS

The basic comparator circuit and its transfer function were presented by Figures 1 and 2.

When the input exceeds the reference voltage, the output switches either positive or negative, depending on how the inputs are connected.

The vast majority of specific applications involve only the basic configuration with a change of reference voltage. A to D converters are realized by applying the signal to one terminal and the voltage derived from a ladder network to the other. Limit detectors are likewise made from only the very basic circuit. Both are only a small deviation from the basic level detector.

Hysteresis

Normally saturated high or low, the amplifiers used in voltage comparators are seldom held in their threshold region.

They possess high gain-bandwidth products and are not compensated to preserve switching speed. Therefore, if the compared voltages remain at or near the threshold for long periods of time, the comparator may oscillate or respond to noise pulses. For instance, this is a common problem with successive approximation D/A converters where the differential voltage seen by the comparator becomes successively smaller until noise signals cause indecision. To avoid this oscillation in the linear range, hysteresis can be employed from output to input. Figure 8 defines the arrangement. Both positive and negative feedback is provided by R_{IN} and R_F .

Hysteresis occurs because a small portion of the "one" level output voltage is fed back in phase and added to the input signal. This

feedback aids the signal in crossing the threshold. When the signal returns to the threshold, the positive feedback must be overcome by the signal before switching can occur. The switching process is then assured and oscillations cannot occur. The threshold "dead zone" created by this method, illustrated in Figure 9, prevents output chatter with signals having slow and erratic zero crossings.

As shown in Figure 8, the voltage feedback is calculated from the expression:

$$V_{HYST} = \frac{E_{OUT} \cdot R_{IN}}{R_{IN} + R_F}$$

where E_{OUT} is the gate high output voltage. The hysteresis voltage is bounded by the common mode range and the ability of the gate to source the current required by the feedback network. If symmetrical hysteresis is desired an additional inverting gate is required if the comparator does not have differential outputs. The NE527 and NE529 devices provide inverted signals from differential outputs while the NE521 and NE522 devices will require the inverter. Care should be taken in the selection of the inverter that propagation delay is minimum, especially for very high speed comparators such as the NE521.

Line Receiver

Retrieving signals which have been transmitted over long cables in the presence of high electrical noise is a perfect application for differential comparators. Such systems as automated production lines and large computer systems must transmit high frequency digital signals over long distances.

If the twisted pair of the system is driven differentially from ground, the signals can be reclaimed easily via a differential line receiver.

Since the electrical noise imposed upon a pair of wires takes the form of a common mode signal, the very high common mode rejection of the NE521/522 makes the unit ideal for differential line receivers. Figure 10 depicts the simple schematic arrangement. The NE521 is used as a differential amplifier having a logic level output. Because common mode signals are rejected, noise on the cable disappears and only the desired differential signal remains. Figure 11 illustrates the NE521 response to the 200mV peak to peak 10MHz differential signal. In Figure 12 the same signal has been buried in 5 volts peak to peak of 1MHz common mode "noise."

The circuit suffers no degradation of signal. If desired several NE522 comparators may be "wired OR'd," or latched output can be built as shown in Figure 10.

The NE521 and NE529 comparators have the advantage of wider bandwidth to permit higher data rates.

Double Ended Limit (Window) Detector

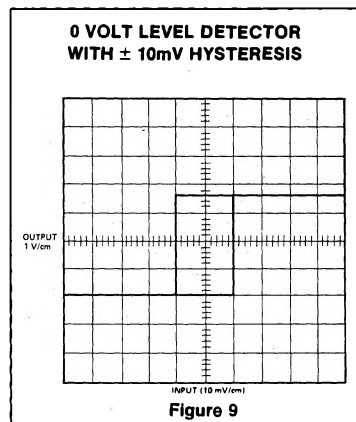
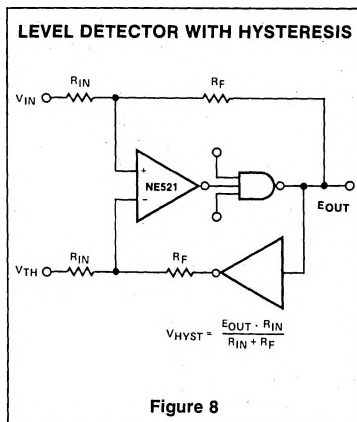
Many system designs require that it be known when a signal level lies between two limits. This function is easily accomplished with a single NE522 package. The schematic and transfer curve of the circuit is shown in Figure 13.

Each half of the NE522 is referenced to the desired upper or lower voltage limit producing the desired transfer curve shown. Taking advantage of the dual configuration and the open collectors of the NE522 minimize external components and connections.

Crystal Oscillator

Any device with a reasonable gain can be made to oscillate by applying positive feedback in controlled amounts. The NE521 will lend itself to crystal control easily, provided the crystal is used in its fundamental mode. Figure 14 shows a typical oscillator circuit.

The crystal is operated in its series resonant mode, providing the necessary feedback through the capacitor to the input of the NE521. The resistor R_{adj} is used to control the amount of feedback for symmetry. Oscillations will start whenever a circuit disturbance such as turning on the power supplies occurs. The NE521 will oscillate up to 70MHz. However, crystals with frequencies higher than about 20MHz are usually operated in one of their overtones. To build an oscillator for a specific overtone requires tuned circuits in addition to the crystal to provide the necessary mode suppression. If the spurious modes are not tuned out the crystal will oscillate at the fundamental frequency. Higher frequency oscillators could be realized using



LINE RECEIVER

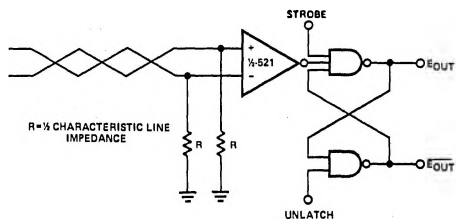


Figure 10

LINE RECEIVER RESPONSE

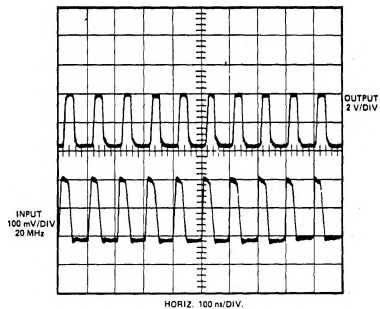


Figure 11

DOUBLE ENDED LIMIT DETECTOR

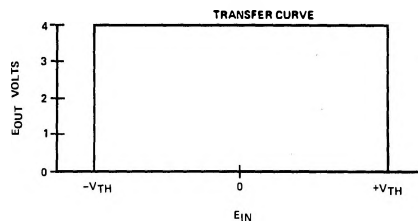
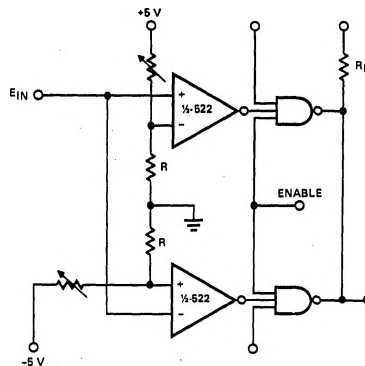


Figure 13

RESPONSE DURING COMMON MODE NOISE

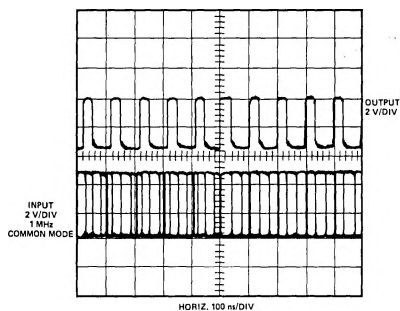


Figure 12

CRYSTAL OSCILLATOR

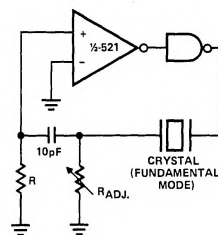


Figure 14

input and output mode suppression or tuning. The NE522 is especially desirable since the open collector topology allows the output to be collector tuned readily.

Analog to Digital Converter

There are many types of A to D converter designs, each having its own merits. However, where speed of conversion is of prime interest the multi-threshold conversion type is used exclusively. It is apparent from Figure 15, that the conversion speed of this design is the sum of the delay through the comparator and the decoding gates.

The sacrifices which must be made to obtain speed are the number of components, bit accuracy and cost. The number of comparators needed for an N-bit converter is $2^n - 1$. Although the NE521 provides two comparators per package, the length of parallel converters is usually limited to less than 4 bits. Accuracy of multi-threshold A-D converters also suffers since the integrity of each bit is dependent upon comparator threshold accuracy.

The implementation of a 3-bit parallel A-D converter is shown in Figure 16 with a 3-bit digital equivalent of an analog input shown in Figure 15.

Reference voltages for each bit are developed from a precision resistor ladder network. Values of R and 2R are chosen so that the threshold is one half of the least significant bit. This assures maximum accuracy of $\pm 1/2$ bit.

It is apparent from the schematic that the individual strobe line and duality features of the NE521 have greatly reduced the cost and complexity of the design. The speed of the converter is graphically illustrated by the photo of Figure 15. All 3-bit outputs have settled and are true a mere 15ns after the input step of 3 volts has arrived. The output is usually strobed into a register only after a certain time has elapsed to insure that all data has arrived.

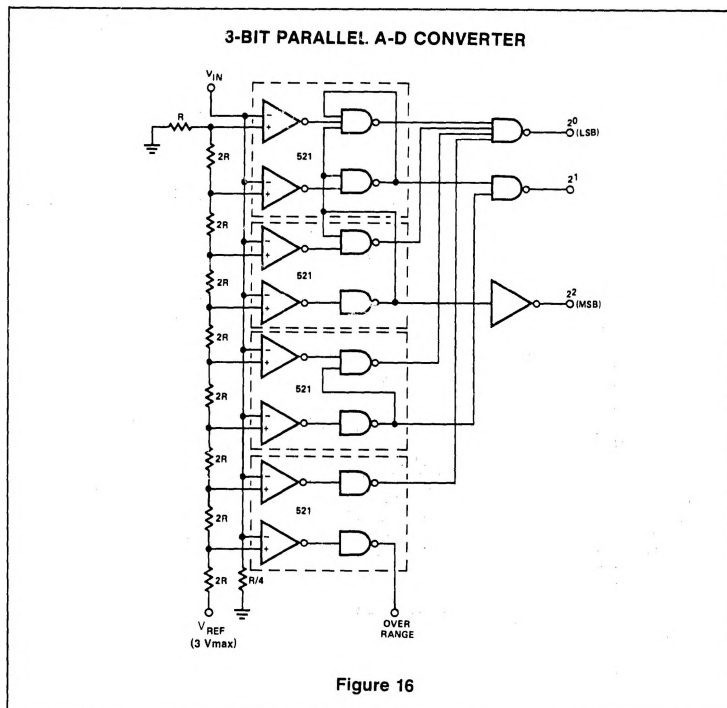
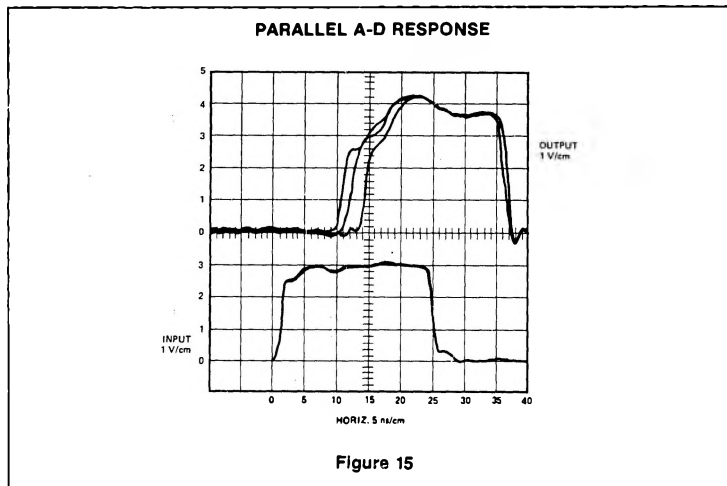
Logic Interface

During the design of the NE527 and NE529 devices, particular attention was paid to the biasing network so that balanced supplies need not be provided. For example, if the "ground" terminal is set at -5.2 volts and the other supplies are adjusted accordingly, the output logic 1 state will be at -1.5 volts and logic 0 will be at -5.0 volts. With this freedom of power supply voltage, the user may adjust the output swings to match the desired logic levels even if that logic is other than TTL levels.

ECL to TTL Interface

Emitter coupled logic is very popular due to its speed. Systems are often built around standard TTL logic with those portions requiring higher speed being implemented with emitter coupled logic. As soon as such a decision is made the problem of interfacing TTL to ECL logic levels is encountered.

The standard logic output swings of ECL are -0.8V to -1.8V at room temperature. Converting these signals to TTL levels is accomplished simply by using the basic voltage comparator circuit with slight modifications. Figure 17 reveals that the power supplies have been shifted in order to shift the common mode range more negative. This insures



that the common mode range is not exceeded by the logic inputs. Since ECL is extremely fast the NE529 is usually selected because of its superior speed so that a minimum of time is lost in translation.

TTL to ECL

Operating in the reverse, TTL levels can also be converted to ECL levels by the NE529. Again the NE529 is selected as the fastest converter with the necessary power supply flexibility to accomplish the level shifting with a minimum of effort and cost.

A check of output voltage for the NE529 reveals that the voltage is slightly less than required by the ECL logic for fast switching R2 and the diode of Figure 18 raises the gate supply voltage and therefore the NE529 output voltage by 0.7 sufficient to guarantee fast switching of the translator. Resistive pull up from the NE529 output to V_{CC} can also be used with the gate supply grounded. This method is dependent upon RC time constants of distributed capacitance and is therefore much slower.

Photo Diode Detector

Responding to the presence or absence of light, the photo diode increases or decreases the current through it. Detecting the changes becomes a matter of converting light and dark currents to voltage across a resistor as shown in Figure 19. R1 is selected to be large enough to generate detectable differences between light and dark conditions. Once the signal levels are defined by R1 and the diode characteristics, the average between light and dark signals is used for V reference and is produced by the resistive divider consisting of R1 and R2. The comparator then produces an output dependent upon the presence or absence of light upon the diode.

SENSE AMPLIFIERS

Closely related to the comparator is the sense amplifier. Signals derived from the many sources, such as transducers, are not of sufficient amplitude to be compatible with subsequent logic. It then becomes necessary to amplify and convert the signal to TTL levels, which is the responsibility of the sense amplifier.

Some transducers produce an output current. It remains, then, for the user to convert these currents to TTL levels. A terminating resistor from the drain to ground provides a voltage output proportional to the current and the resistor size. Larger signals can be produced by larger resistors; but in practice resistors larger than 1k ohm are avoided because of increasing access time. Distributed capacitance forms a time constant with this output

resistance causing slow rise and fall times when the resistor is large, adding to the access time.

Virtually any voltage comparator or sense amplifier can be used. Since total time is the sum of all delays, the sense amplifier is most often the fastest available. Signetics comparators NE521 and NE522 are ideal in this application because of low input offset voltages and very fast response. Using these Schottky clamped comparators significantly reduces the total cycle time of the memory.

Design of the sense amplifier network depends upon the transducer used and the input characteristics of the sense amplifier. The significant specifications are given in Table 1.

Consideration must first be given to the differential input voltage requirements of the sense amplifier. The required reference voltage is calculated from the relationship:

$$V_{ref} \leq (I_1 - I_2) R_1 - V_{diff}$$

Table 1
IMPORTANT SENSE
AMPLIFIER PARAMETERS

DEVICE	V_{OS} (mV)	I_B (μA)	V_{IN} (MIN) (mV)	SPEED (NS) ($V_{IN} = 100$ mV)	GAIN
521	10	40	15	12	5000
522	10	40	15	15	5000

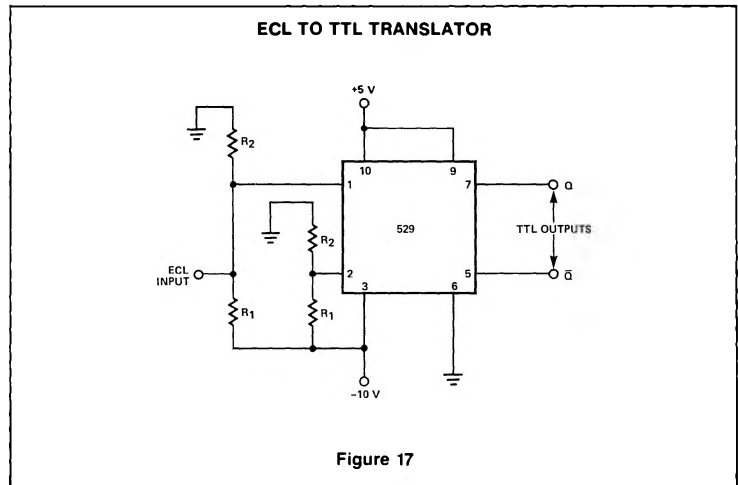


Figure 17

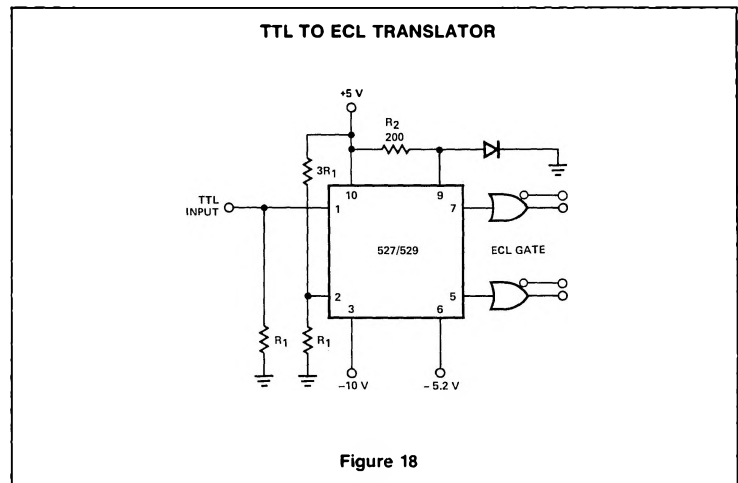
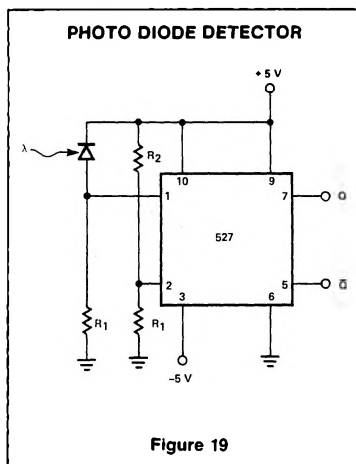


Figure 18



Where I_t is the transducer output current, I_B is sense amplifier bias current and V_{diff} is minimum differential voltage to switch the sense amplifier.

In large systems, noise coupled into the sense lines by stray capacitance can be very troublesome. Judicious layout patterns with sense lines as short as possible will help, but will not always be sufficient. One method of eliminating noise is to use a balance sense line as shown in Figure 20.

A dummy line should be run parallel to the actual sense line in as close proximity as possible. One end is connected to the sense amplifier at the V_{ref} point while the other end is left open. The normal sense line is connected as usual. Electrical noise imposed upon the pair of sense lines takes the form of a common mode signal and will be rejected by the sense amplifier. Signal currents in the sense line, on the other hand, form differential signals at the sense amp causing the output to switch.

