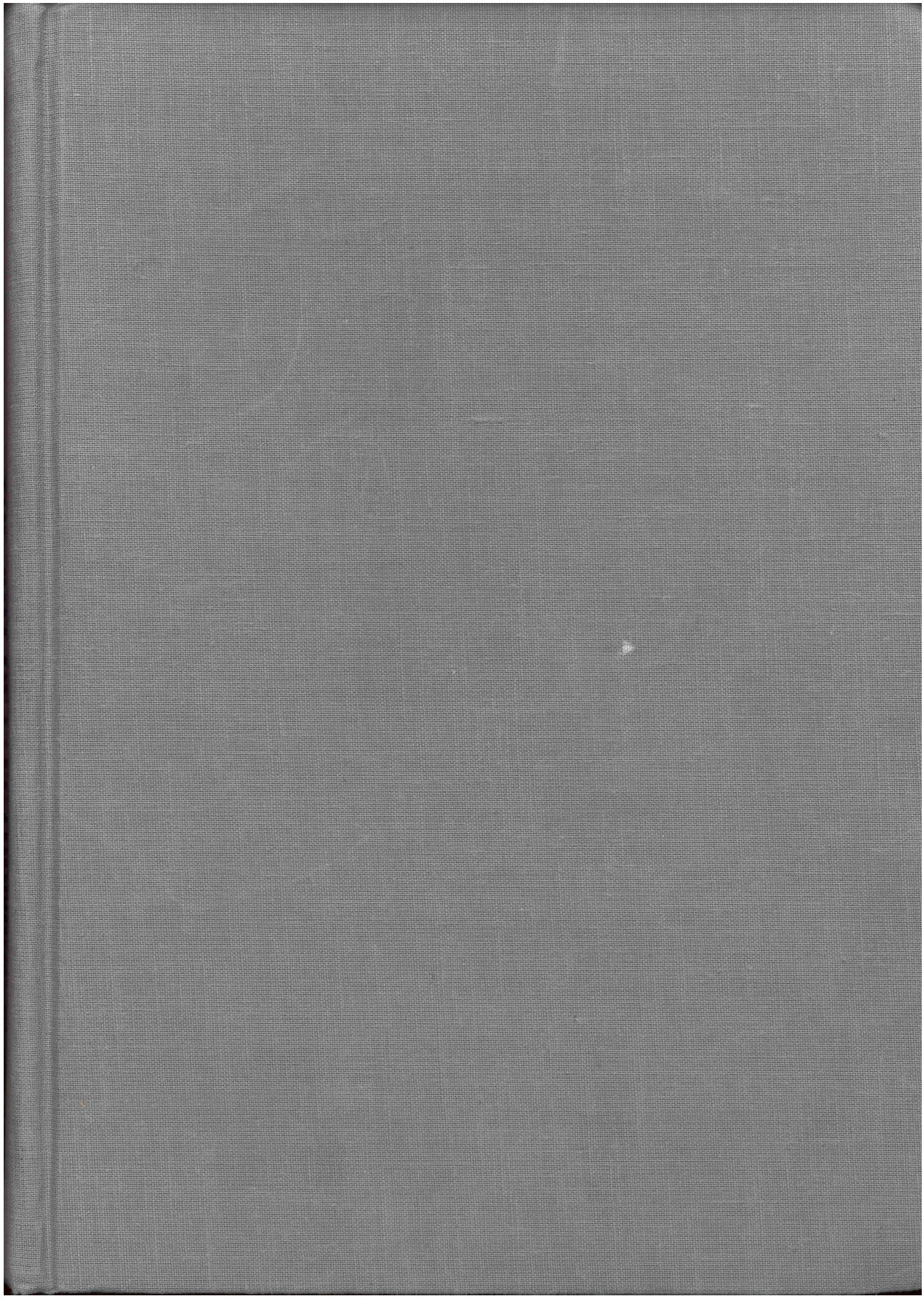


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THE ART OF ELECTRONICS

Second Edition

Paul Horowitz HARVARD UNIVERSITY

Winfield Hill ROWLAND INSTITUTE FOR SCIENCE, CAMBRIDGE, MASSACHUSETTS

CAMBRIDGE UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge CB2 1RP, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http: //www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http: //www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

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First edition published 1980
Second edition published 1989
Reprinted 1990 (twice), 1991, 1993, 1994 (twice), 1995, 1996, 1997,
1998 (twice)

Printed in the United States of America

Typeset in Times

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing-in-Publication Data is available

ISBN 0-521-37095-7 hardback

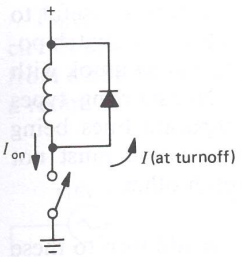


Figure 1.95. Blocking inductive kick.

The only disadvantage of this protection circuit is that it lengthens the decay of current through the inductor, since the rate of change of inductor current is proportional to the voltage across it. For applications where the current must decay quickly (high-speed impact printers, high-speed relays, etc.), it may be better to put a resistor across the inductor, choosing its value so that $V_{supply} + IR$ is less than the maximum allowed voltage across the switch. (For fastest decay with a given maximum voltage, a zener could be used instead, giving a ramp-down of current rather than an exponential decay.)

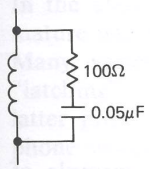


Figure 1.96. *RC* "snubber" for suppressing inductive kick.

For inductors driven from ac (transformers, ac relays), the diode protection just described will not work, since the diode will conduct on alternate half cycles when the switch is closed. In that case a good solution is an *RC* "snubber" network (Fig. 1.96). The values shown are typical for small inductive loads driven from the ac power line. Such a snubber should be included in all instruments that run from the ac power line, since a transformer is inductive. An alternative protection device is a metal-oxide varistor, or transient suppressor, an inexpensive device that looks something like a disc ceramic capacitor and behaves electrically like a bi-directional zener diode. They are available at voltage ratings from 10 to 1000 volts and can handle transient currents up to thousands of amperes (see Section 6.11 and Table 6.2). Putting a transient suppressor across the ac power-line terminals makes good sense in a piece of electronic equipment, not only to prevent inductive spike interference to other nearby instruments but also to prevent occasional large power-line spikes from damaging the instrument itself.

OTHER PASSIVE COMPONENTS

In the following sections we would like to introduce briefly an assortment of miscellaneous but essential components. If you are experienced in electronic construction, you may wish to proceed to the next chapter.

1.32 Electromechanical devices

Switches

These mundane but important devices seem to wind up in most electronic equipment. It is worth spending a few paragraphs on the subject. Figure 1.97 shows some common switch types.

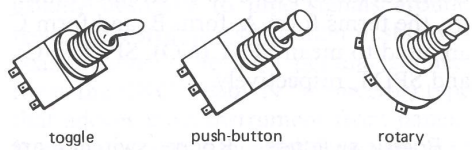


Figure 1.97. Panel switches.

Toggle switches. The simple toggle switch is available in various configurations, depending on the number of poles; Figure 1.98 shows the usual ones (SPDT

indicates a single-pole double-throw switch, etc.). Toggle switches are also available with "center OFF" positions and with up to 4 poles switched simultaneously. Toggle switches are always "break before make," e.g., the moving contact never connects to both terminals in an SPDT switch.

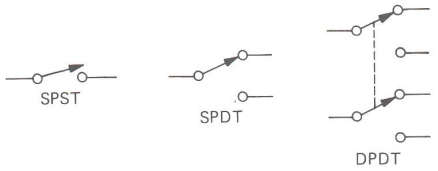


Figure 1.98. Fundamental switch types.

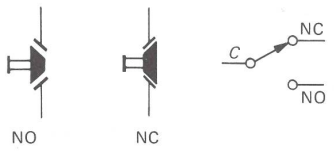


Figure 1.99. Momentary-contact (push-button) switches.

Push-button switches. Push-button switches are useful for momentary-contact applications; they are drawn schematically as shown in Figure 1.99 (NO and NC mean normally open and normally closed). For SPDT momentary-contact switches, the terminals must be labeled NO and NC, whereas for SPST types the symbol is self-explanatory. Momentary-contact switches are always "break before make." In the electrical (as opposed to electronic) industry, the terms form A, form B, and form C are used to mean SPST (NO), SPST (NC), and SPDT, respectively.

Rotary switches. Rotary switches are available with many poles and many positions, often as kits with individual wafers and shaft hardware. Both shorting (make before break) and nonshorting (break before make) types are available, and they can be mixed on the same switch. In many applications the shorting type is useful to prevent an open circuit between switch positions, because circuits can go amok with unconnected inputs. Nonshorting types are necessary if the separate lines being switched to one common line must not ever be connected to each other.

Other switch types. In addition to these basic switch types, there are available various exotic switches such as Hall-effect switches, reed switches, proximity switches, etc. All switches carry maximum current and voltage ratings; a small toggle switch might be rated at 150 volts and 5 amps. Operation with inductive loads drastically reduces switch life because of arcing during turn-off.

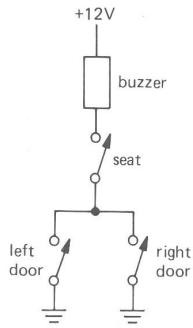


Figure 1.100

Switch examples. As an example of what can be done with simple switches, let's consider the following problem: Suppose you want to sound a warning buzzer if the driver of a car is seated and one of the car doors is open. Both doors and the driver's seat have switches, all normally open. Figure 1.100 shows a circuit that does what you want. If one OR the other door is open (switch closed) AND the seat switch is closed, the buzzer sounds. The words OR and AND are used in a logic sense here, and we will see this example again in Chapters 2 and 8 when we talk about transistors and digital logic.

Figure 1.101 shows a classic switch circuit used to turn a ceiling lamp on or off from a switch at either of two entrances to a room.

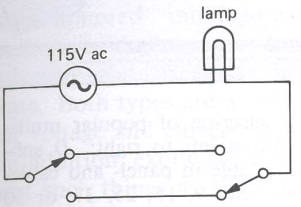


Figure 1.101. Electrician's "three-way" switch wiring.

EXERCISE 1.31

Although few electronic circuit designers know how, every *electrician* can wire up a light fixture so that any of N switches can turn it on or off. See if you can figure out this generalization of Figure 1.101. It requires two SPDT switches and $N-2$ DPDT switches. (Hint: First figure out how to use a DPDT switch to crisscross a pair of wires.)

Relays

Relays are electrically controlled switches. In the usual type, a coil pulls in an armature when sufficient coil current flows. Many varieties are available, including "latching" and "stepping" relays; the latter provided the cornerstone for telephone switching stations, and they're still popular in pinball machines. Relays are available for dc or ac excitation, and coil voltages from 5 volts up to 110 volts are common. "Mercury-wetted" and "reed" relays are intended for high-speed (~1ms) applications, and giant relays intended to switch thousands of amps are used by power companies. Many previous relay applications are now handled with transistor or FET switches, and devices known as solid-state relays are now available to handle ac switching applications. The primary uses of relays are in remote switching and high-voltage (or high-current) switching. Because it is important to keep electronic circuits electrically isolated from the ac power line, relays are useful to switch ac power while keeping the control signals electrically isolated.

Connectors

Bringing signals in and out of an instrument, routing signal and dc power around between the various parts of an instrument, providing flexibility by permitting circuit boards and larger modules of the instrument to be unplugged (and replaced) – these are the functions of the connector, an essential ingredient (and usually the most unreliable part) of any piece of electronic equipment. Connectors come in a bewildering variety of sizes and shapes.

Single-wire connectors. The simplest kind of connector is the simple pin jack or banana jack used on multimeters, power supplies, etc. It is handy and inexpensive, but not as useful as the shielded-cable or multiwire connectors you often need. The humble binding post is another form of single-wire connector, notable for the clumsiness it inspires in those who try to use it.

Shielded-cable connectors. In order to prevent capacitive pickup, and for other reasons we'll go into in Chapter 13, it is usually desirable to pipe signals around from one instrument to another in shielded coaxial cable. The most popular connector is the BNC ("baby N" connector) type that adorns most instrument front panels. It connects with a quarter-turn twist and completes both the shield (ground) circuit and inner conductor (signal) circuit simultaneously. Like all connectors used to mate a cable to an instrument, it comes in both panel-mounting and cable-terminating varieties (Fig. 1.102).

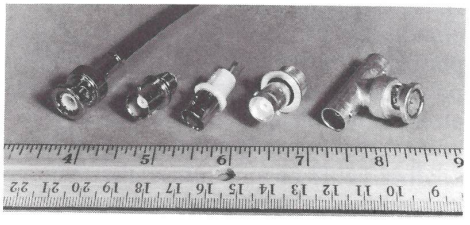


Figure 1.102. BNC connectors are the most popular type for use with shielded (coaxial) cable. From left to right: A male connector on a length of cable, a standard panel-mounted female connector, two varieties of insulated panel-mounted female connectors, and a BNC "T," a handy device to have in the laboratory.

Among the other connectors for use with coaxial cable are the TNC (a close cousin of the BNC, but with threaded outer shell), the high-performance but bulky type N, the miniature SMA, the subminiature LEMO and SMC, and the MHV, a high-voltage version of the standard BNC connector. The so-called phono jack used in audio equipment is a nice lesson in bad design, because the inner conductor mates before the shield when you plug it in; furthermore, the design of the connector is such that both shield and center conductor tend to make poor contact. You've undoubtedly *heard* the results! Not to be outdone, the television industry has responded with its own bad standard, the type F coax "connector," which uses the unsupported inner wire of the coax as the pin of the male plug, and a shoddy arrangement to mate the shield.

Multipin connectors. Very frequently electronic instruments demand multiwire cables and connectors. There are literally dozens of different kinds. The simplest example is a 3-wire line cord connector. Among the more popular are the excellent type D subminiature, the Winchester MRA series, the venerable MS type, and the flat ribbon-cable mass-termination connectors (Fig. 1.103).

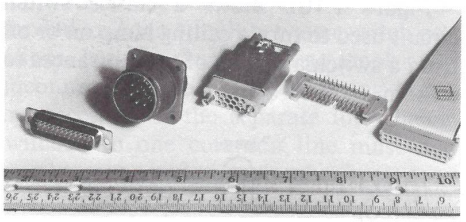


Figure 1.103. A selection of popular multipin connectors. From left to right: *D* subminiature type, available in panel- and cable-mounting versions, with 9, 15, 25, 37, or 50 pins; the venerable MS-type connector, available in many (too many!) pin and mounting configurations, including types suitable for shielded cables; a miniature rectangular connector (Winchester MRA type) with integral securing jackscrews, available in several sizes; a circuit-board-mounting mass-termination connector with its mating female ribbon connector.

Beware of connectors that can't tolerate being dropped on the floor (the miniature hexagon connectors are classic) or that don't provide a secure locking mechanism (e.g., the Jones 300 series).

Card-edge connectors. The most common method used to make connection to printed-circuit cards is the card-edge connector, which mates to a row of gold-plated contacts at the edge of the card. Card-edge connectors may have from 15 to 100 pins, and they come with different lug styles according to the method of connection. You can solder them to a "motherboard" or "backplane," which is itself just another printed-circuit board containing the interconnecting wiring between the individual circuit cards. Alternatively, you may want to use edge connectors with standard solder-lug terminations, particularly in a system with only a few cards (see Chapter 12 for some photographs).

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1.33 Indicators

Meters

To read out the value of some voltage or current, you have a choice between the time-honored moving-pointer type of meter and digital-readout meters. The latter are more expensive and more accurate. Both types are available in a variety of voltage and current ranges. There are, in addition, exotic panel meters that read out such things as VU (volume units, an audio dB scale), expanded-scale ac volts (e.g., 105 to 130 volts), temperature (from a thermocouple), percentage motor load, frequency, etc. Digital panel meters often provide the option of logic-level outputs, in addition to the visible display, for internal use by the instrument.

Lamps and LEDs

Flashing lights, screens full of numbers and letters, eerie sounds – these are the stuff of science fiction movies, and except for the latter, they form the subject of lamps and displays (see Section 9.10). Small incandescent lamps used to be standard for front-panel indicators, but they have been replaced by light-emitting diodes (LEDs). The latter behave electrically like ordinary diodes, but with a forward voltage drop in the range of 1.5 to 2.5 volts. When current flows in the forward direction, they light up. Typically, 5mA to 20mA produces adequate brightness. LEDs are cheaper than incandescent lamps, they last forever, and they are even available in three colors (red, yellow, and green). They come in convenient panel-mounting packages; some even provide built-in current limiting.

LEDs are also used for digital displays, most often the familiar 7-segment numeric display you see in calculators. For displaying letters as well as numbers (alphanumeric display), you can get 16-segment displays or dot-matrix displays. For low power or outdoor use, liquid-crystal displays are superior.

1.34 Variable components

Resistors

Variable resistors (also called volume controls, potentiometers, pots, or trimmers) are useful as panel controls or internal adjustments in circuits. The most common panel type is known as a 2 watt type AB potentiometer; it uses the same basic material as the fixed carbon-composition resistor, with a rotatable "wiper" contact. Other panel types are available with ceramic or plastic resistance elements, with improved characteristics. Multiturn types (3, 5, or 10 turns) are available, with counting dials, for improved resolution and linearity. "Ganged" pots (several independent sections on one shaft) are also manufactured, although in limited variety, for applications that demand them.

For use inside an instrument, rather than on the front panel, *trimmer pots* come in single-turn and multiturn styles, most intended for printed-circuit mounting. These are handy for calibration adjustments of the "set-and-forget" type. Good advice: Resist the temptation to use lots of trimmers in your circuits. Use good design instead.

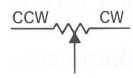


Figure 1.104. Potentiometer (3-terminal variable resistor).

The symbol for a variable resistor, or pot, is shown in Figure 1.104. Sometimes the symbols CW and CCW are used to indicate clockwise and counterclockwise.

One important point about variable resistors: Don't attempt to use a potentiometer as a substitute for a precise resistor value somewhere within a circuit. This is tempting, because you can trim the resistance to the value you want. The trouble is that potentiometers are not as stable as good (1%) resistors, and in addition

they may not have good resolution (i.e., they can't be set to a precise value). If you must have a precise and settable resistor value somewhere, use a combination of a 1% (or better) precision resistor and a potentiometer, with the fixed resistor contributing most of the resistance. For example, if you need a 23.4k resistor, use a 22.6k (a 1% value) 1% fixed resistor in series with a 2k trimmer pot. Another possibility is to use a series combination of several precision resistors, choosing the last (and smallest) resistor to give the desired series resistance.

As you will see later, it is possible to use FETs as voltage-controlled variable resistors in some applications. Transistors can be used as variable-gain amplifiers, again controlled by a voltage. Keep an open mind when design brainstorming.



Figure 1.105. Variable capacitor.

Capacitors

Variable capacitors are primarily confined to the smaller capacitance values (up to about 1000pF) and are commonly used in radiofrequency (RF) circuits. Trimmers are available for in-circuit adjustments, in addition to the panel type for user tuning. Figure 1.105 shows the symbol for a variable capacitor.

Diodes operated with applied reverse voltage can be used as voltage-variable capacitors; in this application they're called varactors, or sometimes varicaps or epicaps. They're very important in RF applications, especially automatic frequency control (AFC), modulators, and parametric amplifiers.

Inductors

Variable inductors are usually made by arranging to move a piece of core material in a fixed coil. In this form they're available with inductances ranging from microhenrys to henrys, typically with a 2:1 tuning range for any given inductor. Also available are rotary inductors (coreless coils with a rolling contact).

Transformers

Variable transformers are very handy devices, especially the ones operated from the 115 volt ac line. They're usually "autoformers," which means that they have only one winding, with a sliding contact. They're also commonly called Variacs, and they are made by Technipower, Superior Electric, and others. Typically they provide 0 to 135 volts ac output when operated from 115 volts, and they come in current ratings from 1 amp to 20 amps or more. They're good for testing instruments that seem to be affected by power-line variations, and in any case to verify worst-case performance. Warning: Don't forget that the output is not electrically isolated from the power line, as it would be with a transformer!

ADDITIONAL EXERCISES

(1) Find the Norton equivalent circuit (a current source in parallel with a resistor) for the voltage divider in Figure 1.106. Show that the Norton equivalent gives the same output voltage as the actual circuit when loaded by a 5k resistor.

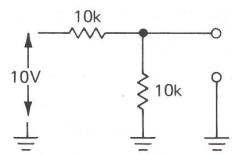


Figure 1.106

(2) Find the Thévenin equivalent for the circuit shown in Figure 1.107. Is it the

same as the Thévenin equivalent for exercise 1?

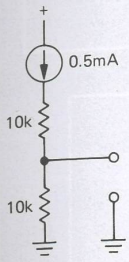


Figure 1.107

(3) Design a "rumble filter" for audio. It should pass frequencies greater than 20Hz (set the −3dB point at 10Hz). Assume zero source impedance (perfect voltage source) and 10k (minimum) load impedance (that's important so that you can choose R and C such that the load doesn't affect the filter operation significantly).

(4) Design a "scratch filter" for audio signals (3dB down at 10kHz). Use the same source and load impedances as in exercise 3.

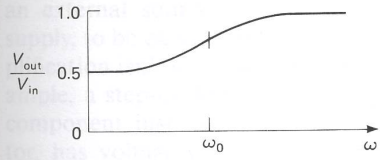


Figure 1.108

(5) How would you make a filter with Rs and Cs to give the response shown in Figure 1.108?

(6) Design a bandpass RC filter (as in Fig. 1.109); f_1 and f_2 are the 3dB points. Choose impedances so that the first stage isn't much affected by the loading of the second stage.

(7) Sketch the output for the circuit shown in Figure 1.110.

(8) Design an oscilloscope "×10 probe"

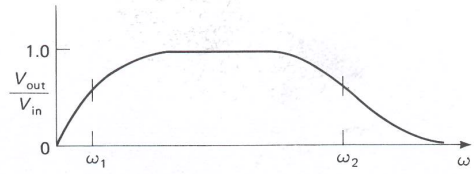


Figure 1.109

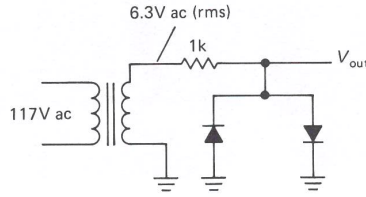


Figure 1.110

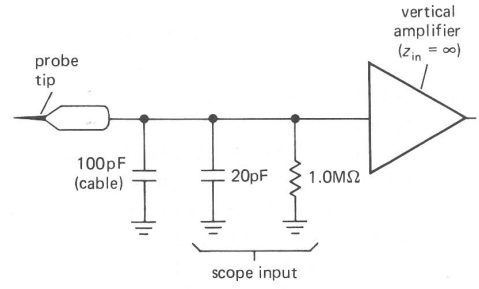


Figure 1.111

(see Appendix A) to use with a scope whose input impedance is 1MΩ in parallel with 20pF. Assume that the probe cable adds an additional 100pF and that the probe components are placed at the tip end (rather than at the scope end) of the cable (Fig. 1.111). The resultant network should have 20dB (×10) attenuation at all frequencies, including dc. The reason for using a ×10 probe is to increase the load impedance seen by the circuit under test, which reduces loading effects. What input impedance (R in parallel with C) does your ×10 probe present to the circuit under test, when used with the scope?

DIGITAL MEETS ANALOG

CHAPTER 9

Although sheer "number crunching" is an important application of digital electronics, the real power of digital techniques is seen when digital methods are applied to analog (or "linear") signals and processes. In this chapter we will begin with a brief chronology of the rise and fall of digital logic families and a review of the input and output properties of the surviving TTL and CMOS families that you are likely to use in circuit design. This is essential to understand how to interface logic families to each other and to digital input devices (switches, keyboards, comparators, etc.) and output devices (indicator lamps, relays, etc.). We will also look at n-channel MOS logic, since it is widely used in LSI functions. We will continue with the important subject of bringing digital signals on and off circuit boards, in and out of instruments, and through cables. Then we will discuss the major subject of conversion between analog and digital signals. Finally, with an understanding of these techniques, we will look at a number of applications in which combined analog and digital techniques provide powerful solutions to interesting problems.

CMOS AND TTL LOGIC INTERFACING

□ 9.01 Logic family chronology

In the prehistoric early 1960s, adventurous people who didn't want to build their logic from discrete transistors struggled with RTL (resistor-transistor logic), a simple logic family introduced by Fairchild and characterized by poor fanout and poor noise immunity. Figure 9.1 shows the problem, namely a logic threshold at one V_{BE} above ground, and miserable fanout (in some cases one output could drive only one input!) caused by passive pullup and a low-impedance current-sinking load. Those were the days of small integration, and the most complicated function you could get was a dual flip-flop, which would operate to 4MHz. We bravely built circuits with RTL; they sometimes malfunctioned when you switched on a soldering iron in the same room.

The death knell for RTL came a few years later with the introduction by Signetics of DTL (diode-transistor logic) and, soon thereafter, Sylvania's SUHL – "Sylvania Universal High Speed Logic" –

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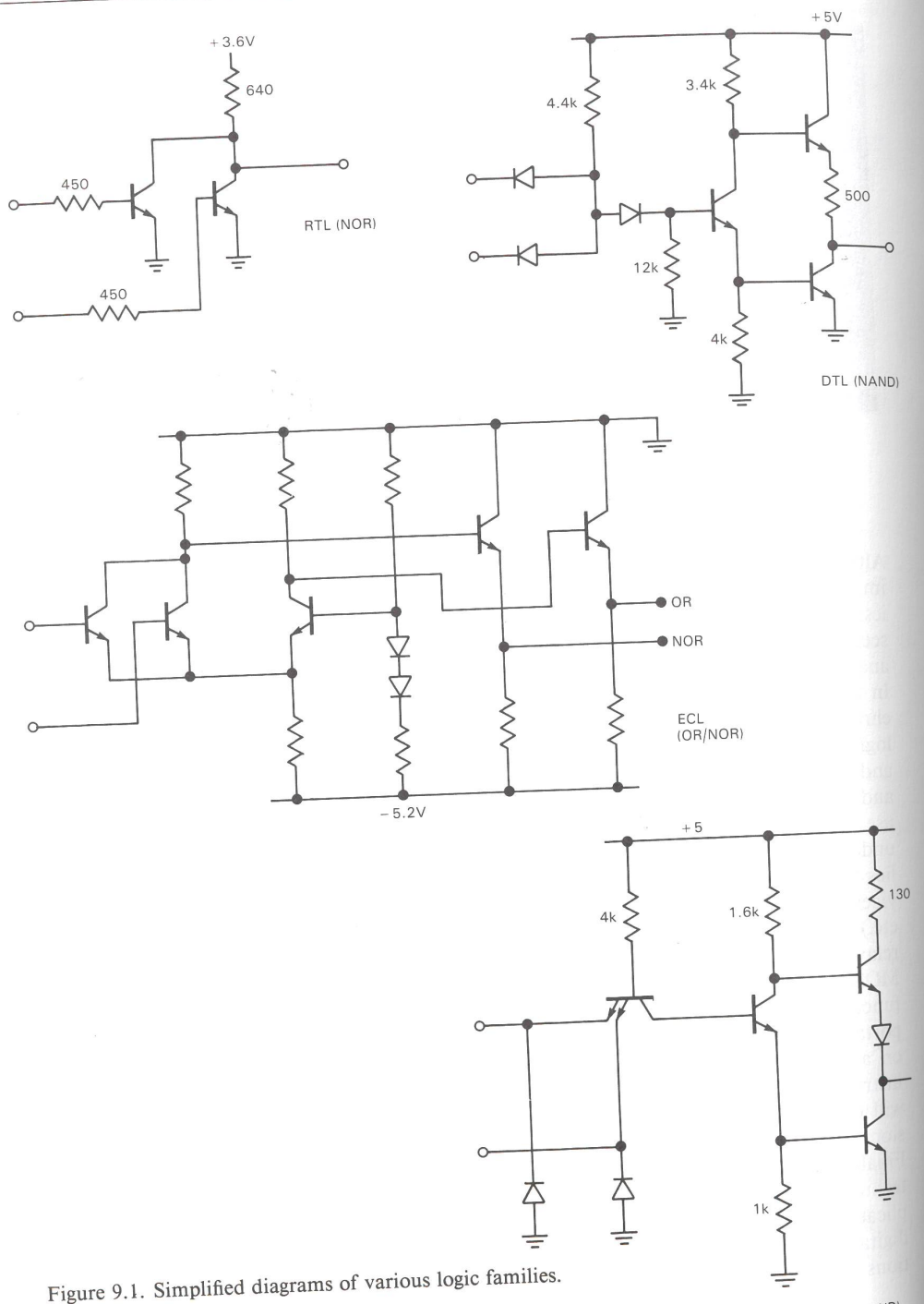
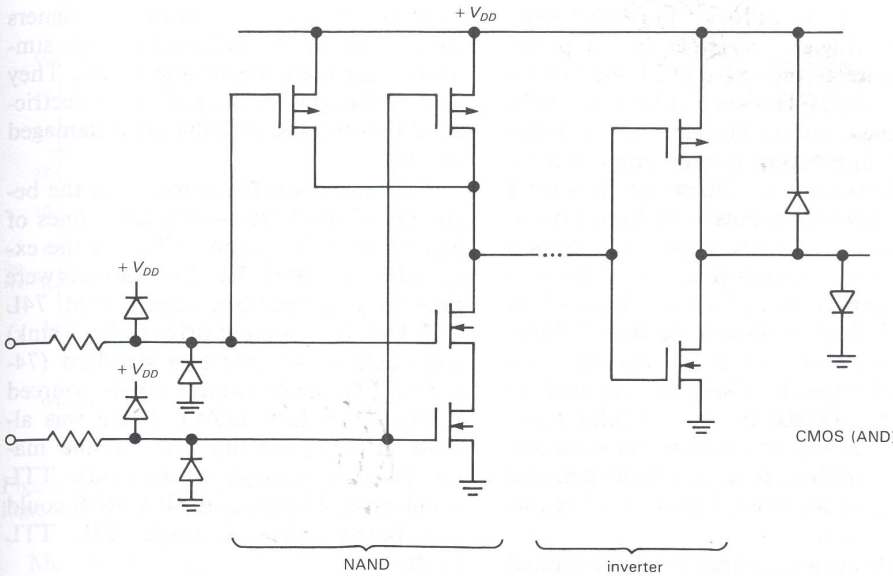


Figure 9.1. Simplified diagrams of various logic families.



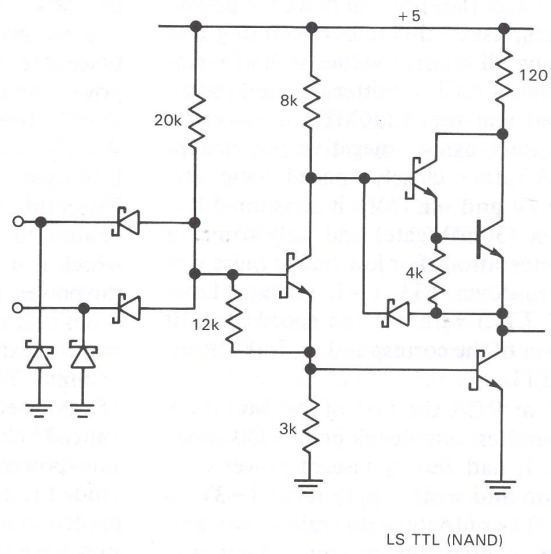


Figure 9.1 (*cont*).

which is now called TTL (transistor-transistor logic). Signetics had a popular mixture of the two, called 8000-series DCL Utilogic ("Designer's Choice Logic"). TTL caught on quickly, particularly in the "74xx" numbering system originated by Texas Instruments. These families used current-*sourcing* inputs with logic threshold at two V_{BE}s and (usually) push-pull "totem-pole" outputs (Fig. 9.1). DTL and TTL began the era of +5 volt logic (RTL used +3.6V), and offered speeds of 25MHz and fanouts of 10 (i.e., an output could drive 10 inputs). Designers rejoiced at the speed, reliability, and complex functions (divide-by-10 counters, for example) of these families. It seemed to us that you couldn't ask for more; TTL would live forever.

People are greedy, though. They wanted more speed. They wanted less power consumption. They soon got both, sort of. In the high-speed arena, a souped-up TTL (74H series; "High-speed" TTL) delivered roughly twice the speed, at twice the power! (It accomplished this underwhelming feat by cutting all resistor values in half.) Another family, ECL (emitter-coupled logic), delivered real speed (30MHz in its original version), using a negative power supply and rather closely spaced logic levels (−0.9V and −1.75V); it consumed lots of power (30mW/gate) and only came in small integration. For low power there was a souped-down TTL (74L series; "Low-power" TTL) with 1/4 the speed at 1/10 the power of the corresponding 7400 "standard" TTL.

Back at RCA the first of the MOSFET logic families was developed, 4000-series CMOS. It had zero quiescent power consumption and wide supply range (+3V to +12V). The outputs swung rail-to-rail, and the inputs drew no current. That was the good news. The bad news was the speed (1MHz at 10V supply) and the price (about $20 for a package of 4 gates). In spite of the price, a whole generation of battery-powered instrument designers grew up on the micropower CMOS, simply because there was no alternative. They learned the true meaning of static electricity as they worked with the easily damaged inputs.

This, then, was the situation at the beginning of the 1970s – two main lines of bipolar logic (TTL and ECL) and the extraordinary CMOS. The TTL variants were essentially compatible, except that 74L TTL had feeble output drive (3.6mA sink) and could drive only two standard (74-series) TTL loads (whose inputs sourced 1.6mA when held LOW). There was almost no compatibility between the major families (though a pulled-up TTL could drive CMOS, and 5V CMOS could just barely drive a single 74L TTL load).

During the 1970s there were steady improvements on all fronts. TTL sprouted the non-saturating "Schottky-clamped" (Section 13.23) families: first the 74S (Schottky) series, which made 74H obsolete by giving three times the speed at twice the power; then the 74LS ("Low-power Schottky"), which made the "standard" 74-series TTL obsolete by delivering slightly improved speed at 1/5 the power. Life with 74LS and 74S was nice, but then Fairchild came up with 74F (F for FAST: "Fairchild Advanced Schottky TTL"), which is up to 50% faster than 74S at 1/3 the power; it also has other improved properties that make it extremely nice to design with. Texas Instruments, the originators of many 74xx lines, came up with a pair of advanced Schottky families, 74AS ("Advanced Schottky") and 74ALS ("Advanced Low-power Schottky"); the former is intended to replace 74S, and the latter is intended to replace 74LS. All these TTL families have the same logic levels and plenty of output drive, and so they can be mixed within a circuit. Table 9.1 and Figure 9.2 compare the speed and power of these families.

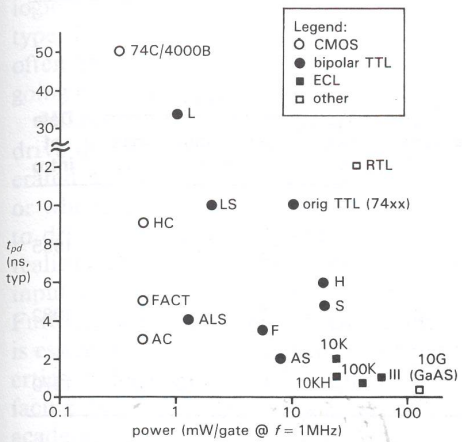


Figure 9.2. Speed versus power for various logic families.

Meanwhile, the 4000-series CMOS evolved into the improved 4000B series, with wider supply range (3V to 18V), better input protection, and higher speed (3.5MHz at 5V). The 74C series is essentially the same, with 74-family functions and pinouts to take advantage of the tremendous success of the 74-family bipolar logic. ECL sprouted the ECL II, ECL III, ECL 10,000, and ECL 100,000 series, with speeds to 500MHz.

The situation in 1980, then, was this: Most design was done with 74LS, with 74F (or 74AS) mixed in where higher speed was needed. This same TTL was used as "glue" to hold together NMOS microprocessor circuits, whose inputs and outputs are TTL-compatible. Micropower design was always done with 4000B or 74C CMOS, equivalent and compatible with each other. And for the highest speeds (100MHz–500MHz), ECL was used. There wasn't much mixing between families, except occasional combination of CMOS and TTL, or perhaps TTL interfaces to an ECL high-speed circuit.

During the 1980s came the remarkable development of CMOS logic with the speed and output drive of TTL: first 74HC ("High-speed CMOS"), with the same speed as 74LS, and, of course, zero quiescent current; then 74AC ("Advanced CMOS"), with the same speed as 74F or 74AS. With rail-to-rail output swings, and input threshold at half the supply voltage, this logic combines the best features of previous TTL and CMOS and should gradually replace bipolar TTL. There is an incompatibility, though, since the logic HIGH output of TTL or NMOS (2.4V min) is insufficient to drive the HC and AC input. Since there is likely to be a period in which you want to use some of the older bipolar TTL or NMOS, each CMOS family is offered in a variant with the lower input threshold. These are named 74HCT and 74ACT ("High-speed CMOS with TTL threshold"). Don't be tempted to use them universally – the CMOS-threshold devices (HC, AC) have better noise immunity and are the families of choice. During the 1980s, also, LSI and VLSI (microprocessors, memory, etc.) have been gradually switching over from NMOS to CMOS (with consequent low power and CMOS compatibility), at the same time increasing speed and complexity. And at the extreme high-speed end, GaAs (gallium arsenide) devices are delivering speeds of several gigahertz.

Note that all CMOS families (which includes 4000B, 74C, HC, HCT, AC, and ACT) have the pleasant characteristic of zero "static" (i.e., nothing happening) power dissipation, with typical quiescent currents less than a microamp. But CMOS does draw "dynamic" current when logic levels are switching, because of the combined effects of (a) transient rail-to-rail conduction of internal push-pull pairs during the middle of the logic swing and (b) dynamic current needed to charge and discharge internal and load capacitances. Dynamic supply currents are proportional to switching frequency and can rival bipolar logic as you reach maximum operating frequencies. See Section 8.10 (Fig. 8.18)

TABLE 9.1. LOGIC FAMILIES

Family	t_{pd}('00) (C_L=50pF) typ (ns)	t_{pd}('00) (C_L=50pF) max (ns)	f_{clk}('74) max (MHz)	P_{diss} (C_L=0) @1MHz (mW/gate)	I_{OL} @0.5V max (mA)	I_{IL} max (mA)	V_{th} typ (V)	V_{supply} min (V)	V_{supply} nom (V)	V_{supply} max (V)	Date of intro
CMOS											
AC	3	5.1	125	0.5	24	0	$V_+/2$	2	5 or 3.3	6	1985
ACT							1.4	4.5	5	5.5	
HC	9	18	30	0.5	8	0	$V_+/2$	2	5	6	1982
HCT							1.4	4.5	5	5.5	
4000B/74C @10V	30	60	5	1.2	1.3	0	$V_+/2$	3	5-15	18	1970
4000B/74C @5V	50	90	2	0.3	0.5	0					
TTL											
AS	2	4.5	105	8	20	0.5	1.5	4.5	5	5.5	1980
F	3.5	5	100	5.4	20	0.6	1.6	4.75	5	5.25	1979
ALS	4	11	34	1.3	8	0.1	1.4	4.5	5	5.5	1980
LS	10	15	25	2	8	0.4	1.1	4.75	5	5.25	1976
ECL											
ECL III	1.0	1.5	500	60	–	–	-1.3	-5.19	-5.2	-5.21	1968
ECL 100K	0.75	1.0	350	40	–	–	-1.32	-4.2	-4.5	-5.2	1981
ECL 100KH	1.0	1.5	250	25	–	–	-1.29	-4.9	-5.2	-5.5	1981
ECL 10K	2.0	2.9	125	25	–	–	-1.29	-5.19	-5.2	-5.21	1971
GaAs											
10G	0.3	0.32	2700	125	–	–	-1.3	-3.3 -5.1	-3.4 -5.2	-3.5 -5.5	1986

and Section 14.16 (Fig. 14.38) for more detail.

We wrap up our brief history with a recommendation: Use 74HC logic for nearly all your new designs, mixing in (a) 74HCT for compatibility with existing NMOS or TTL and (b) 74AC(T) for speed. Bipolar TTL (74LS/ALS and 74F/AS) are OK to use, but probably are outclassed by CMOS. Choose the older 4000B/74C where the extended supply voltage range is needed and speed is unimportant (e.g., a portable device powered by an unregulated 9V battery).

9.02 Input and output characteristics

Digital logic families are designed so that the output from a chip can properly drive many inputs within the same logic family. A typical fanout capability is 10 loads, meaning that an output from a gate or flip-flop, for example, can be connected to 10 inputs and still perform within specifications. In other words, in normal digital design practice you can get by without knowing anything about the electrical properties of the chips you're using, as long as your circuit consists only of digital

logic driving more digital logic of the same type. In practice, this means that you don't often have to worry about what's actually going on at logic inputs and outputs.

However, as soon as you attempt to drive digital circuitry with externally generated signals, whether digital or analog, or whenever you use digital logic outputs to drive other devices, you must face the realities of what it takes to drive a logic input and what a logic output can drive. Furthermore, when mixing logic families it is essential to understand the circuit properties of logic inputs and outputs. Interfacing between logic families is not an academic question. In order to take advantage of advanced LSI chips, or special functions that are available in only one logic family, you must know how to mix logic types. In the next few sections we will consider the circuit properties of logic inputs and outputs in detail, with examples of interfacing between logic families and between logic devices and the outside world.

Input characteristics

The graphs in Figure 9.3 show the important properties of CMOS and TTL inputs: input current and output voltage (for an inverter) as a function of input voltage. We have extended the graphs to input voltages beyond the range normally encountered in digital circuits, since in interface situations the input signals might easily exceed the power-supply voltages. As the graphs imply, both CMOS and TTL are normally operated with the negative supply pin connected to ground.

A TTL input sources a sizable current when held LOW, and it draws only a small current when HIGH (typically a few microamperes, never more than 20μA). To drive a TTL input, you must be able to sink a milliamp or so (see Table 9.1 for exact values) while holding the input below 0.4 volt. Failure to understand this may lead to widespread circuit malfunction in interfacing situations! For input voltages below ground, a TTL input looks like a clamping diode to ground; for inputs above +5 volts, the current is set by breakdown of a diode (LS, F) or base-emitter junction (ALS, AS), with onset of current somewhere above 10 volts.

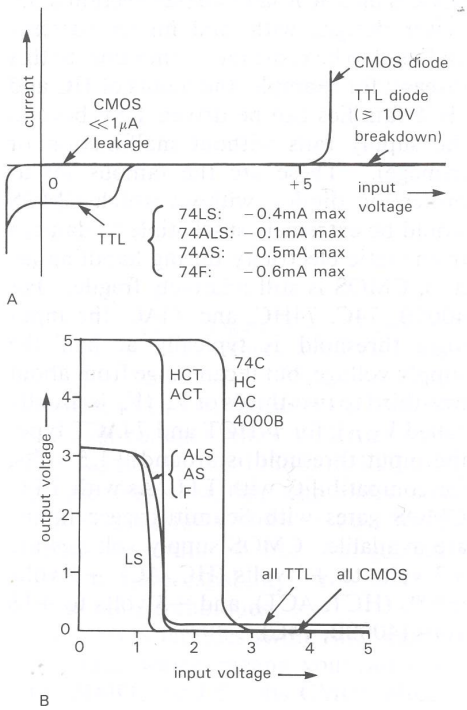


Figure 9.3. Logic gate characteristics.
A. Input current.
B. Transfer function.

The TTL input threshold is typically around +1.3 volts, although the specifications only guarantee that it is between +0.8 and +2.0 volts. TTL gates with Schmitt-trigger inputs are available ('13, '14, '132), with ±0.4 volt hysteresis; they are indicated by a hysteresis symbol within the gate outline (e.g., Fig. 9.9). V_{supply} (usually called V_{CC}) is +5.0 volts ±5%.

A CMOS input draws no current (except for leakage current, typically $10^{-5}\mu$A) for input voltages between ground and the supply voltage. For voltages beyond the supply range, the input looks like a pair of clamping diodes to the positive supply and ground (Fig. 9.1). Momentary currents greater than about 10mA through these diodes is all it takes to put many CMOS devices into SCR latchup (see Section 8.35; newer designs withstand higher currents and tend to be resistant, or immune, to this disease; for example, the inputs of HC and HCT families can be driven 1.5V beyond the supply rails without malfunction or damage). These are the famous input-protection diodes, without which CMOS would be extremely susceptible to damage from static electricity during handling (as it is, CMOS is still relatively fragile). For 4000B, 74C, 74HC, and 74AC, the input logic threshold is typically at half the supply voltage, but it can range from about one-third to two-thirds of V_+ (V_+ is usually called V_{DD}); for 74HCT and 74ACT types the input threshold is around +1.5 volts, for compatibility with TTL. As with TTL, CMOS gates with Schmitt-trigger inputs are available. CMOS supply voltages are +2 volts to +6 volts (HC, AC), +5 volts ±10% (HCT, ACT), and +3 volts to +18 volts (4000B, 74C).

Output characteristics

The TTL output circuit is an *npn* transistor to ground and an *npn* follower (or Darlington) to V_+ with a current-limiting resistor in its collector. One transistor is saturated and the other is off. As a result, a TTL device can sink a large current (8mA for 74LS, 24mA for 74F) to ground with a small (saturation) voltage drop and can source at least a few milliamps with its output HIGH (about +3.5V). The output circuit is designed to drive TTL inputs, with a fanout of 10.

The CMOS output circuit is a push-pull pair of complementary MOSFETs, one ON and the other OFF (Fig. 9.1). The output looks like a MOSFET r_{ON} to ground or to V_+ when it is within a volt or so of the respective rail, becoming something like a current source when you draw so much current that the output is forced more than a volt or two away from the supply rails. Typical values of r_{ON} are 200 ohms to 1k (4000B/74C), 50 ohms [74HC(T)], and 10 ohms [74AC(T)]. Figure 9.4 shows a summary of the output characteristics of CMOS and TTL.

We have plotted the typical output voltage, for both HIGH and LOW output states, against output current. To simplify the graph, output current is always drawn positive. Note that CMOS pulls its outputs all the way to V_+ or ground, generating a full swing unless heavily loaded; when driving only CMOS loads (zero dc current), the swing is fully rail-to-rail. TTL levels, by comparison, are typically 50 – 200mV (LOW) or +3.5 volts (HIGH) when driving other TTL devices as loads. With a pullup resistor (discussed later), HIGH TTL outputs go all the way to +5 volts.

9.03 Interfacing between logic families

It is important to know how to make different logic families talk to each other, because there are situations when you must mix logic types. For example, many desirable LSI chips are built with NMOS, which has TTL-like output levels (i.e., a HIGH output around +3V) that cannot directly drive 74HC. Another example is the nice 74C9*xx* series of counters, which you might want to use within an existing circuit built with 74LS. Or you might want to put some 5 volt logic around the edges of a 12 volt CMOS system, for easy connection to external TTL-compatible signals and for driving cables.

The three things that can keep you from connecting any pair of logic chips together

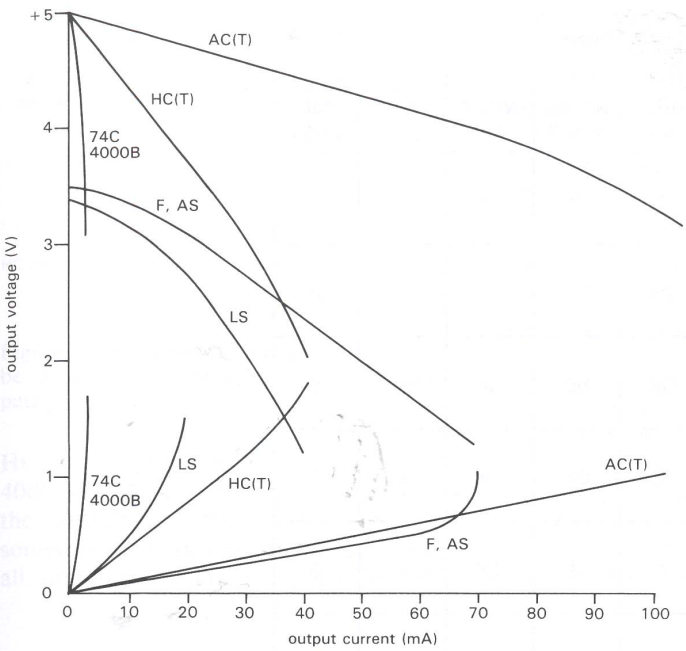


Figure 9.4. Logic gate output characteristics.

are (a) input logic-level incompatibility, (b) output drive capability, and (c) supply voltages. Rather than bore you with pages of explanations of what works and what doesn't, we've boiled down the interface problem to a simple table (Table 9.2). Let's take a quick tour.

TTL requires a +5 volt supply and typically pulls HIGH only to about +3.5 volts; it has good sinking, almost to ground. So it can drive logic with low threshold, namely TTL, HCT, ACT, and NMOS (which is routinely designed to be compatible). You need full swing to +5 volts to drive HC, AC, and 4000B/74C running at 5 volts, which you can do with a resistor pullup to +5 volts, or by interposing an HCT buffer (recall that HCT and ACT have full-swing outputs). If you use a pullup, note that the resistor value is a compromise – smaller is faster, but uses more power. A value of 4.7k is typical. A pullup resistor brings the TTL HIGH output all the way to +5 volts, though the last part of the rising waveform (during which the resistor is doing all the work) is slow. To drive high-voltage CMOS, use a level translator like the 40109, 14504, or LTC1045; they are very slow, but who cares, since you're driving slow CMOS anyway. NMOS outputs are similar to TTL, but generally with less drive capability. You therefore use the same techniques.

All CMOS families swing their outputs rail-to-rail, which means you can drive TTL, NMOS, and 5 volts CMOS directly from 5V-powered CMOS. Note, however, that old-fashioned CMOS (4000B/74C) has feeble drive when running from 5 volts (0.5mA sinking), crippling its ability to drive TTL. For all these families, use a level up-translator to drive high-voltage CMOS.

A nice solution to the CMOS-to-TTL/NMOS interface problem is to run the CMOS at reduced supply voltage; JEDEC Standard No. 8 specifies +3.3 volts, which puts the input threshold near the usual TTL value of 1.4 volts. Thus, TTL can drive 3.3V-powered HC/AC

TABLE 9.2. LOGIC FAMILY CONNECTIONS

TO → *FROM* ↓	TTL	HCT ACT	HC AC	HC, AC @3.3V	NMOS LSI	4000B, 74C @5V	4000B, 74C @10V
TTL	OK	OK	A	OK	OK	A	B
HCT ACT	OK	OK	OK	NO	OK	OK	B
HC AC	OK	OK	OK	NO	OK	OK	B
HC, AC @3.3V	OK	OK	NO	OK	OK	B	B
NMOS LSI	OK	OK	A	OK	OK	A	B
4000B, 74C @5V	OK[a]	OK	OK	NO	OK	OK	B
4000B, 74C @10V	C	C	C	C	C	C	OK

[a] with limited fanout. A – pullup to +5V, or use HCT as interface.
B – use *i)* OC pullup to +10V, or *ii)* 40109, 14504, or LTC1045 level translator.
C – use 74C901/2, 4049/50, 14504, or LTC1045 level translator.

directly, and vice versa. As an added bonus, 3.3 volt operation decreases dynamic power consumption (see Sections 8.10 and 14.16 and Figs. 8.18 and 14.38) by 55% from its 5 volt value, while increasing propagation delays by about 40%. Note, however, that you cannot interconnect (in either direction) 3.3 volt CMOS from other CMOS running at 5 volts.

EXERCISE 9.1.
Explain why the last statement is true.

Finally, high-voltage CMOS can drive 5 volt logic if you interpose a level translator (74C901/2, 14504, LTC1045, or 4049/4050) to generate 5 volt output swings. It is probably safe to drive LS TTL directly from high-voltage CMOS, since there are no input-protection diodes, and input breakdown usually exceeds 10 volts; however, a strict interpretation of LS specifications (7V absolute maximum input voltage) requires the translator.

Warning: Although the static logic levels are OK, there is an interesting *dynamic* incompatibility that sometimes crops up when you try to drive edge-sensitive inputs (e.g., clocking inputs of counters) of

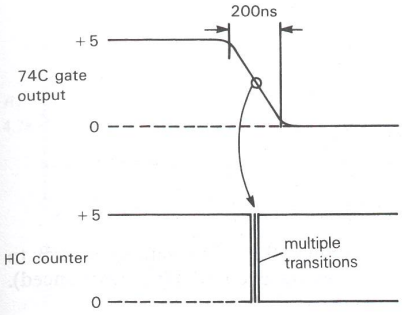


Figure 9.5. Edge-sensitive fast logic should not be driven with slow signals (e.g., slow logic parts).

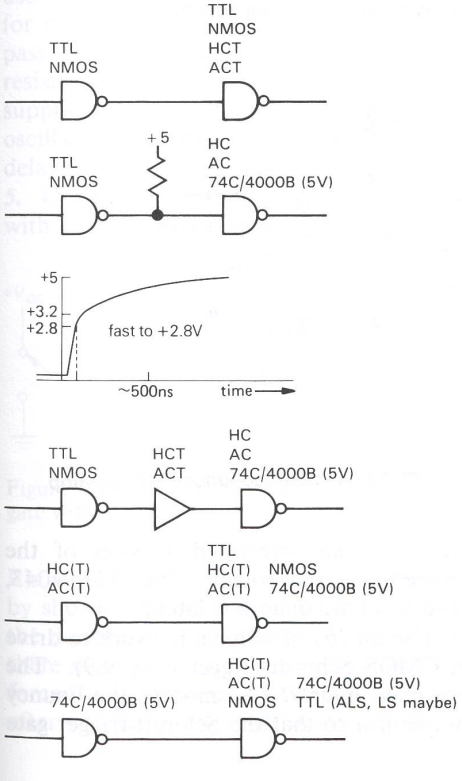
HC or AC logic from the outputs of slower 4000B- or 74C-type logic. Figure 9.5 shows the multiple logic transitions you often see; sometimes the HC chip refuses to count at all, unless an oscilloscope probe (or small capacitor) is attached! Apparently the combination of slow transition time and relatively high output impedance from the sluggish CMOS is the culprit.

Figure 9.6 illustrates most of the cross-family hookups that you're likely to encounter.

9.04 Driving CMOS and TTL inputs

Switches as input devices

It is easy to drive digital inputs from switches, keyboards, comparators, etc., if you keep in mind the input characteristics of the logic you're driving. The simplest way is with a pullup resistor (Fig. 9.7). When driving TTL, a pullup resistor with switch closure to ground is by far the best method, because of the input properties



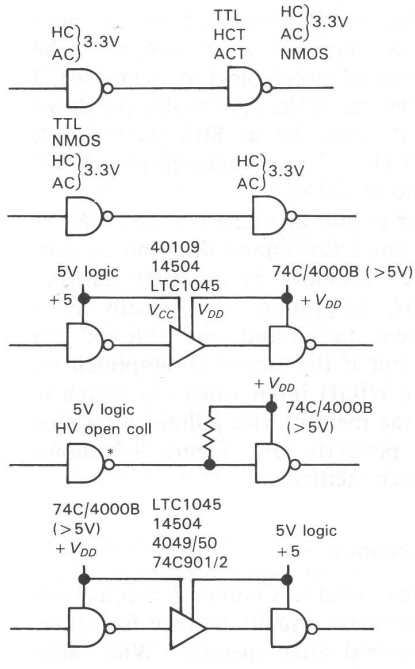


Figure 9.6. Logic family interconnections.

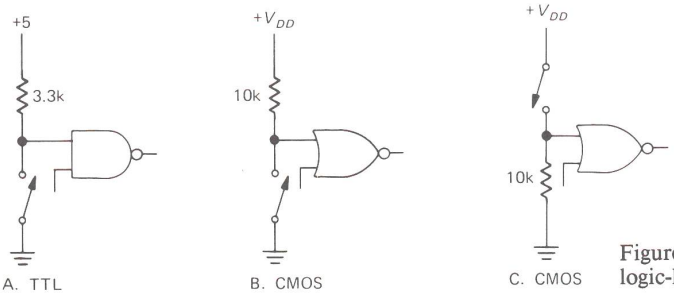


Figure 9.7. Mechanical switch to logic-level circuits (not debounced).

of TTL. The switch easily sinks the LOW-state input current, and the pullup brings the HIGH state to +5 volts, giving good noise immunity; in addition, it is convenient to have the switch return to ground.

The alternative possibility, a pulldown resistor to ground with switch closure to +5 volts, is undesirable because it requires a small pulldown resistor (such as 220 Ω) to guarantee a TTL LOW of a few tenths of a volt, which means you have rather large currents with the switch closed. In the pullup circuit, the noise immunity with the switch open (the worst case, from the standpoint of noise pickup) is at least 3 volts, whereas in the undesirable pulldown circuit it could be as little as 0.6 volt (FAST TTL, −0.6mA input current, LOW threshold at +0.8V).

Either pullup or pulldown with CMOS is fine, since the inputs draw no current and the threshold is typically halfway from V_{DD} to ground. It is usually more convenient to ground one side of the switch, but if the circuit is simplified by having a HIGH input when the switch is closed, the method with pulldown resistor will be perfectly OK. Figure 9.7 shows these three methods.

Switch bounce

As we remarked in Chapter 8, mechanical switch contacts usually bounce for about a millisecond after closure. With large switches the bounce can last for as much as 50ms. This can wreak havoc with circuits that are sensitive to changes of state, or "edges" (a flip-flop or counter would toggle many times if clocked directly from a switch input, for instance). In such cases it is essential to debounce the switch electronically. Here are a few methods:

1. Use a pair of gates to make a jam-type SR flip-flop. Use pullups at the inputs to the debouncer, of course (Fig. 9.8). You could use a flip-flop with SET and CLEAR inputs instead (e.g., a '74); in that case, ground the clocking input.

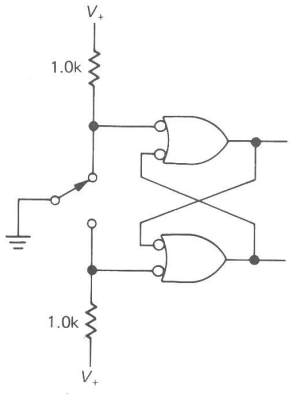


Figure 9.8. Switch debouncer: *SR* flip-flop.

2. Use an integrated version of the preceding arrangement. The '279, 4043, and 4044 are quad SR latches.

3. Use an RC slowdown network to drive a CMOS Schmitt trigger (Fig. 9.9). The low-pass filter R_2C_1 smooths the bouncy waveform so that the Schmitt-trigger gate

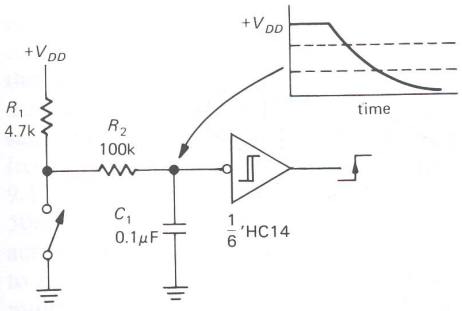


Figure 9.9. Switch debouncer: *RC* plus Schmitt trigger.

makes only one transition. A 10ms to 25ms *RC* time constant is generally long enough. This method isn't well suited to TTL because of the low driving impedance that TTL inputs require.

4. Use a chip like the 4490 "hex contact bounce eliminator," a nifty device that uses a digital delay (a 5-bit shift register for each switch) as a sort of digital low-pass filter. It includes internal pullup resistors and clock circuitry. The user supplies a timing capacitor that sets the oscillator frequency, thus determining the delay time.

5. Use the circuit shown in Figure 9.10, with either a noninverting gate or buffer.

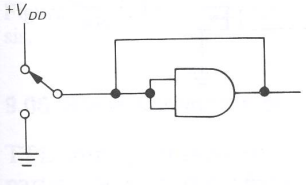


Figure 9.10. Switch debouncer: noninverting gate with feedback.

It's always OK to override a logic output by shorting it to V_+ or ground, providing the duration is kept short. In this circuit there is no problem, because the output is forced only for a gate propagation delay, after which it holds itself in the new state.

6. Use a device with built-in debouncer. Keyboard encoders, for instance, are designed with mechanical switches in mind as input devices, and they usually include debouncing circuitry.

7. Use a Hall-effect switch. These are magnetically operated solid-state switches, available as panel switches or keyboard switches. In either case the magnet and switch come as a complete assembly. They require +5 volts and produce a debounced logic output suitable for driving TTL or CMOS (operated from +5V). Since they have no mechanical contact assembly to wear out, Hall-effect switches last just about forever (although we once had an epidemic of progressive magnet anemia in a Hall-effect keyboard; we trust this disease has now been eradicated).

A few general comments on switches as input devices: Note that SPST switches (sometimes called "form A") can be used with methods 3 and 4 (and usually 6), whereas SPDT switches (form B) are necessary with the other methods. Keep in mind, also, that often it isn't necessary to debounce switch inputs, since they aren't always used to drive edge-sensitive circuitry. Another point: Well-designed switches are usually "self-wiping" to maintain a clean contact surface (take one apart to see what that means), but it's a good idea to choose circuit values so that a current of at least a few milliamps flows through the switch contacts to clean them. With suitable choice of contact material (e.g., gold) and mechanical design, switches can be designed to avoid this "dry-switching" problem and will work properly even when switching zero current.

9.05 Driving digital logic from comparators and op-amps

Comparators and op-amps, together with analog-to-digital converters, are the common input devices by which analog signals can drive digital circuits. Figure 9.11

shows some examples. In the first circuit, a comparator drives TTL directly. Since most comparators have an *npn* output transistor with open collector and grounded emitter, all that's needed is a pullup to +5 volts. The same scheme works for CMOS as well with pullup to $+V_{DD}$. The comparator may not have to run from a split supply, since many are designed for single-supply operation (V_- grounded), and some will even operate with a single 5 volt supply (e.g., the 311, 339, 393, or 372/4).

The second circuit shows an op-amp driving CMOS with only a series current-limiting resistor. The input-protection diodes of CMOS device form effective clamps to V_{DD} and ground, provided that input current is kept below 10mA. In the third circuit, an op-amp switches an *npn* transistor into saturation to drive a TTL load; the diode prevents base-emitter reverse breakdown (~6V). In this circuit you can eliminate R_1 and D_1 by replacing the *npn* transistor with an *n*-channel MOSFET. The final circuit is not highly recommended, but it does work. The input clamping diode of the TTL device limits negative swing to a diode drop below ground, and the external diode limits positive swing. The series resistor prevents damage if base-emitter reverse breakdown occurs in the TTL input transistor. The series resistor is chosen small enough to sink the TTL LOW-state input current when the op-amp output is a few volts negative.

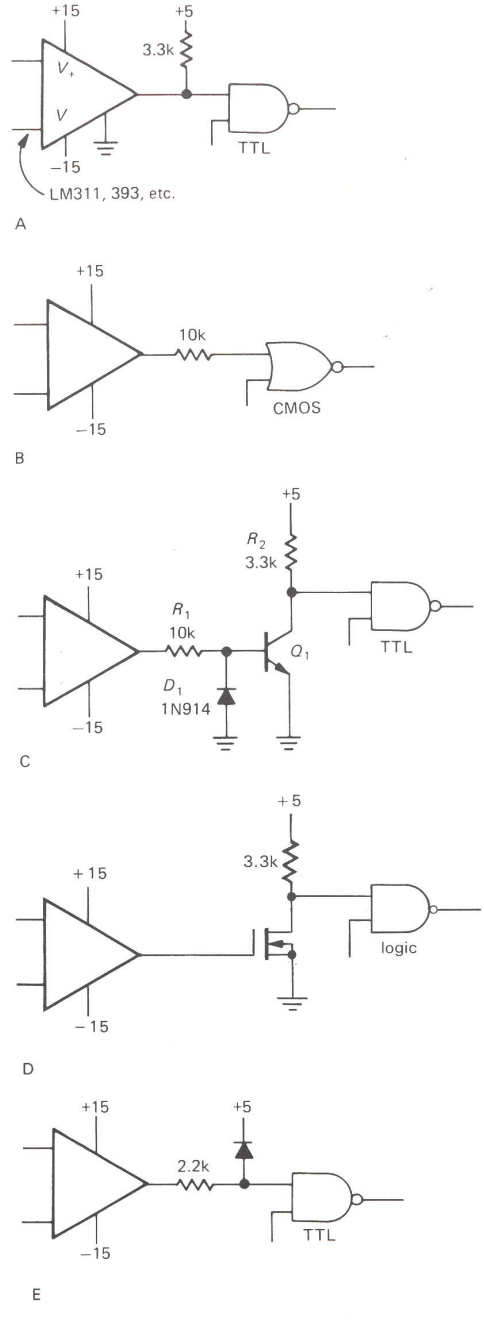


Figure 9.11. Driving logic from comparators and op-amps.

Clock inputs: hysteresis

A general comment about driving digital logic from op-amps: Don't try to drive clock inputs from these op-amp interfaces; the transition times are too long, and you may get glitches as the input signal passes through the logic threshold voltage. If you intend to drive clocking inputs (of flip-flops, shift registers, counters,

monostables, etc.), it is best to use a comparator with hysteresis or to buffer the input with a gate (or other logic device) with Schmitt-trigger input. The same comment goes for signals derived from transistor analog circuitry. Figure 9.12 shows the idea. R_2 is chosen for 50mV hysteresis. A small capacitor (C_2) across the feedback resistor is a good idea to ensure fast transitions and to prevent multiple pulses as the input passes through the threshold (the 311, in particular, has a tendency to do this). Bypass capacitor C_1 is also important in preventing glitches on the reference supply during transitions. In many cases the reference voltage will be ground, in which case C_1 is omitted.

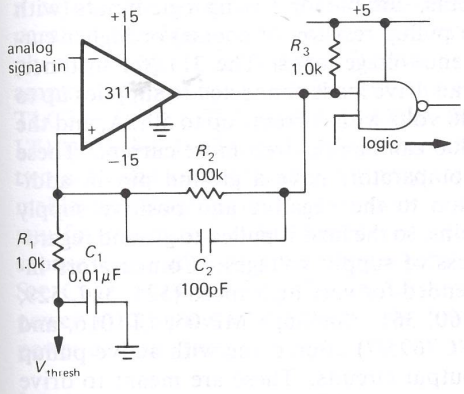


Figure 9.12. Threshold detector with hysteresis.

9.06 Some comments about logic inputs

TTL chips (and their HC and AC counterparts) tend to be designed with active LOW control inputs; for instance, flip-flops generally have SET and RESET inputs that are enabled when LOW. External digital signals used as inputs will therefore nearly always have a pullup resistor and will pull LOW (sinking current) when active, a convenient arrangement, because switches, etc., can use a common ground return. It also leads to greater noise immunity, since a line held near +5 volts has 3 volts of noise immunity, as compared with the 0.8 volt of noise immunity of a line held near ground. This intrinsic weakness of TTL logic (poor noise immunity in the LOW state) is particularly apparent when you realize that a negative 0.5 volt spike on the chip's ground line can be interpreted as a HIGH input by the chip. Such spikes are not uncommon, since they can be generated by short current spikes through the ground-line inductance. See Section 9.11 for further discussion of this troublesome problem.

With CMOS, the noise immunity is the same for either state, so you can use pullup or pulldown resistors as input terminations when driving from devices that have an open state. Pulldown resistors tend to be used more often, although you will see pullups when the driving device is something like a switch, with a ground return.

An open TTL input is "barely HIGH." It sits at the logic threshold (~1.3V), but since no current is being sunk, it does not turn on the input transistor. You may occasionally see "designs" in which inputs that should be tied HIGH on TTL devices are left open. Don't *ever* do this! It is foolish and dangerous: There is zero noise immunity on an open input, so capacitive coupling from nearby signals can generate short LOW spikes at the input. This generates glitches at the outputs of combinational devices (gates), which is bad enough, but in the case of a flip-flop or a register it can be devastating, since an open RESET′ input can clear the device at unpredictable times. The offending glitches may be impossible to see on a scope, since they may be "single-event" pulses of about 20ns duration. Although you may be able to get away with this unsavory practice most of the time, especially if there is low capacitance between the open pin and neighboring pins, it is still a very poor idea; if you try to

troubleshoot the circuit by clipping a logic analyzer or test clip over the IC, you've got a new circuit, since the additional capacitance of the test device is almost certain to cause transient LOWs at the open pin(s). Besides, why build unreliable circuits when you know how to make them reliable with a few simple connections? (End of tirade.)

Unused inputs

Unused inputs that affect the logic state of a chip (e.g., a RESET input of a flip-flop) must be tied HIGH or LOW, as appropriate. Inputs that have no effect (e.g., inputs of unused gate sections in the same package) may be left unconnected in TTL, but not in CMOS. An open input of an unused CMOS gate, for instance, can float up to the logic threshold, causing the output to go to half the supply voltage, with both MOS output transistors conducting, thus drawing considerable class A current. This results in excessive supply current and can even lead to failure in devices with hefty output stages. It is best to ground all inputs of unused functions on every CMOS chip.

With TTL you can ignore unused sections of a chip, as well as irrelevant inputs of circuits you are using. For instance, you can leave the parallel-load data lines of a counter unconnected if you never enable the LOAD line.

9.07 Comparators

Comparators were introduced briefly in Section 4.23 to illustrate the use of positive feedback (Schmitt trigger) and to show that special-purpose comparator ICs deliver considerably better performance than general-purpose op-amps used as comparators. These improvements (short delay times, high output slew rate, and relative immunity to large overdrive) come at the expense of the properties that make op-amps useful (in particular, careful control of phase shift versus frequency). Comparators are not frequency-compensated (Section 4.33) and cannot be used as linear amplifiers.

Comparators provide an important interface between analog (linear) input signals and the digital world. In this section we would like to look at comparators in some detail, with emphasis on their output properties, their flexibility regarding power-supply voltages, and the care and feeding of input stages.

Supply voltages and outputs

Most comparators have open-collector outputs, suitable for driving logic inputs (with a pullup resistor, of course) or higher current/voltage loads. The 311, for instance, can drive loads connected to supplies up to 40 volts with currents up to 50mA, and the 306 can handle even more current. These comparators have a ground pin in addition to the negative and positive supply pins, so the load is pulled to ground regardless of supply voltages. Comparators intended for very high speed (521, 527, 529, 360, 361, Am686, CMP-05, LT1016, and VC7695/7) often come with active pullup output circuits. These are meant to drive 5 volt digital logic, and they usually have 4 power-supply pins: V_+, V_-, V_{CC} (+5), and ground.

One thing to watch for is the fact that many comparators require positive and negative supplies, even if the inputs never go negative. Examples are the 306, 710, and 711, in addition to the comparators with active pullup listed previously. It is inconvenient to have to generate a negative supply just to run a comparator in an instrument that otherwise uses only positive supplies, so it is important to know about comparators that will run on a single positive supply (e.g., the 311, 319, 339, 393, 365, CA3290, HA4905,

