LIQUID CRYSTAL DISPLAYS

BY ROBIN C. H. MOORSHEAD B.Sc.

AS DAY FOLLOWS NIGHT, there are certain patterns of change in the physical world which we hold to be always true. Perhaps one of the earliest that we learn is that matter exists in three states, solid (crystalline), liquid or gas. The particular state a substance exists in depends on temperature. At low temperatures substances tend to be solid, at higher temperatures liquid, and yet higher, gaseous. Further more, the transition between the states is clear and precise, for example, ice changes to water at 0° C, there is no gradual transition.

This pattern of change is explained by the "Kinetic theory." This theory is based on several assumptions: That matter consists of minute, more or less spherical particles which are held together by "cohesive forces" which are spread evenly over their surface. In the solid (crystalline) state the particles are tightly bound by the cohesive forces and are perfectly ordered like bricks in a wall. As the temperature increases, the particles begin to vibrate and the cohesive forces weaken so the particles can move about but are still attached to one another:

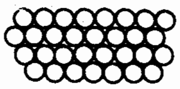


Fig. 1

At higher temperatures the cohesive forces are vanishingly small and the (gas) particles fly about at random.

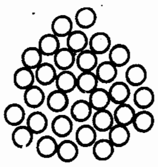


Fig. 2

Simple materials which fit into this description have another property, that their physical characteristics are the same from whichever direction they are approached. This is termed "Isotropic." Examples of isotropic materials are glass, steel or water. Their electrical resistance, refractive index and strength are the same from whichever direction we measure them.

Against the grain

However, by no means all materials are isotropic, wood for example is much stronger across the grain than with the grain, graphite has a higher electrical resistance when measured through it's "plate" structure than when it is measured along the plates. Such materials as these are termed "Anisotropic."

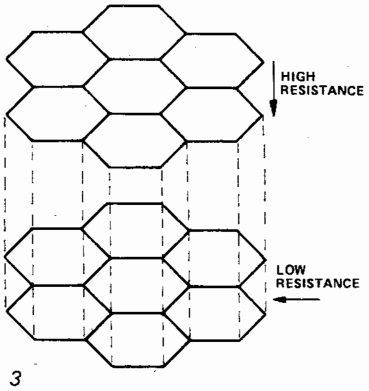


Fig. 3

It would be surprising if wood and graphite were isotropic, since they are constructed of rods (cellulose fibres) and plates (the graphite). In the same way we would not expect roof slates to fall into a box in a random arrangement, they will have a strong tendency to fall flat and so order themselves into an anistropic arrangement.

Rods and plates

In exactly the same way many of the large molecules found in organic chemistry have rod- or plate-like shapes and have anisotropic crystal structures. The tendency towards ordered arrangements in these substances is so great, that when they melt they retain a degree of order until the temperature is considerably increased. As a result the liquid has anisotropic properties, some flowing in a gliding stepwise fashion, or interfering with the passage of light. When this happens the substance is said to possess a liquid crystalline phase (sometimes termed a mesomorphic or paracrystalline state).

So we have:

	Increasing temperature →
For an isotropic material:	solid → liquid → gas
For an anisotropic material:	solid → liquid crystal → isotropic liquid → gas

It is of interest to note that this property has been well known since 1890, and some 0.6% (15,000-20,000) of organic chemicals show this behaviour.

Nematic and smectic

Liquid crystals fall into two main categories: Nematic (from the Greek thread) and Smectic (from the Greek for soap).

Smectic liquid crystals have many interesting properties but have found little practical application, so they will not enter into the article any further.

The nematic liquid crystals have many applications and form the substance of this article. There are several types of nematic materials. The difference in these types is shown in fig. 4.

Some nematic liquid crystals possess properties which cause them to interfere with the passage of light in an applied electric field, or with changing temperature. They are of great interest in modern electronic displays for several reasons:

(1) The power consumption of such displays is extremely small, between 2μA and 0.2μA per segment of a 7-segment display, about 10μW per Cm^2 of display, where as a similar LED display consumes 500 mW.

(2) They are made of the commonest elements, carbon, hydrogen, oxygen, nitrogen, rather than the more expensive elements

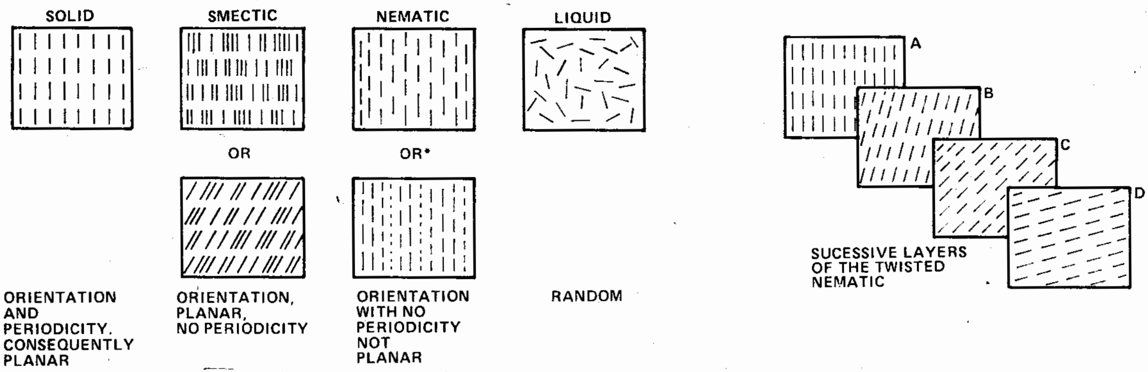


Fig. 4 The second form of nematic structure is 'twisted' each plane being rotated a few degrees with respect to the last; this is known as twisted nematic or more commonly cholesteric (yes, basically the same type of chemicals that cause heart disease!). This type is most important.*

such as gallium, germanium, etc.

(3) Since they do not emit light themselves, but interfere with the passage of incident light, they cannot be "washed out" by strong incident light.

(4) They are compatible with PMOS circuits.

There are, needless to say, disadvantages as well:

(1) Since they are passive, i.e. they do not emit light, they cannot be read in the dark, however, this can be overcome by providing background illumination. This increases power consumption; the power consumed however does not have to pass through the addressing circuit, as it does in LED displays.

(2) Since they are operating in a phase between solid and liquid their temperature range is limited, at a maximum between −20°C and 100°C, but more typically 0°C to 60°C.

Below this temperature the display freezes, above the maximum the liquid is isotropic and no display is visible. Furthermore the response time near the freezing point is rather slow, in the order of 0.2-second rise time and 0.6-second fall time. Freezing or or liquifying the display does no permanent damage, but temperatures in excess of 150°C may cause irreversible damage. There is no doubt that future development will broaden this temperature range considerably.

(3) The lifetime is still limited, but provided conditions are ideal it is now well in excess of 10,000 hours. Future development of materials with higher purity, and chemical stability will improve this a great deal.

Stability may be affected by several factors. Firstly, certain liquid crystalline materials undergo irreversible chemical changes under d.c. conditions, it is critical that such display have no d.c. components whatsoever in the addressing circuit, secondly chemical changes are caused by impurities. Thirdly, certain liquid crystalline materials are effected by ultra violet light.

Chemistry

We have no intention of discussing the detailed chemistry of the materials used — it is quite complex — and most names are longer than those found in the small print on toothpaste tubes. However, an outline of the structure of a typical nematic and a typical cholesteric material are included for comparison:

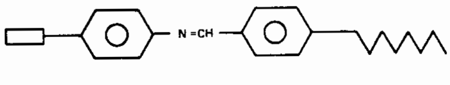


Fig. 5. A 'Shiffs' Base. This has a fairly straight structure about seven times as long as it is broad.

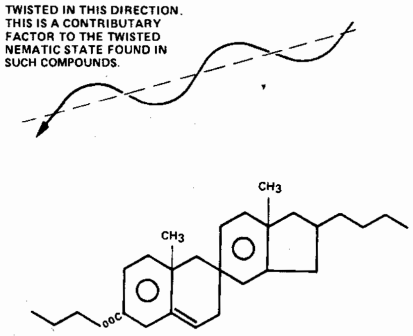


Fig. 6. A cholesterol ester. The molecule is about 8-10 times longer than it is broad.

The actual material used in a display is not usually pure, it is more frequently a mixture of two or more nemetics. This has the advantage of increasing the liquid range by the creation of a "Eutectic" mixture.

The anisotropic properties that materials suitable for display purposes must include are:

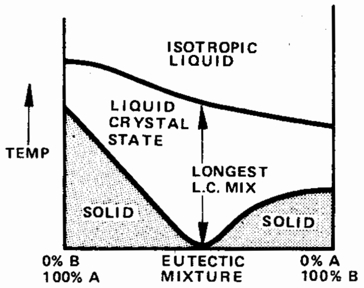


Fig. 7.

(1) The refractive index is different as the material is viewed from different aspects, i.e. the light is bent more as it passes through the material in one direction then another.

(2) The molecule must possess a dipole. This is an uneven distribution of change on the molecule, which causes it to align in an electric field thus:

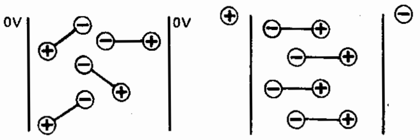


Fig. 8.

A large proportion of organic molecules possess such dipoles. The dipole on the materials used in liquid crystalline displays have two components, one along the long axis ($\epsilon \|$) and one perpendicular ($\epsilon \perp$) to it.

If the dipole along the long axis A is greater than dipole perpendicular to it, it is said to possess positive dielectric anisotrophy. If the dipole is greater on the perpendicular axis it is said to possess negative dielectric anisotropy.

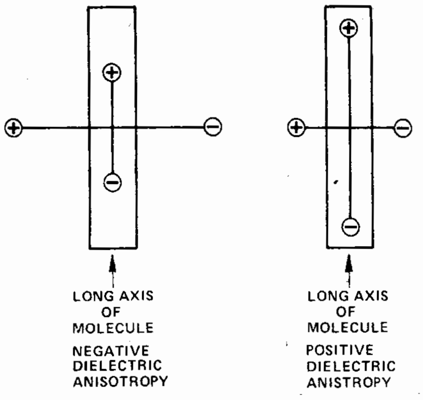


Fig. 9.

(3) The material also must possess anisotropic conductivity (as graphite does). The conductivity in nematic liquid crystals is greater along the long axis than perpendicular to it.

(4) The material should have a resistivity of the order of 10^9 Ω Cm.

Display construction

The displays work in two different ways, but the construction of the cells are similar, the differences are mainly in the filters on the back and faces of the display and of the type of background.

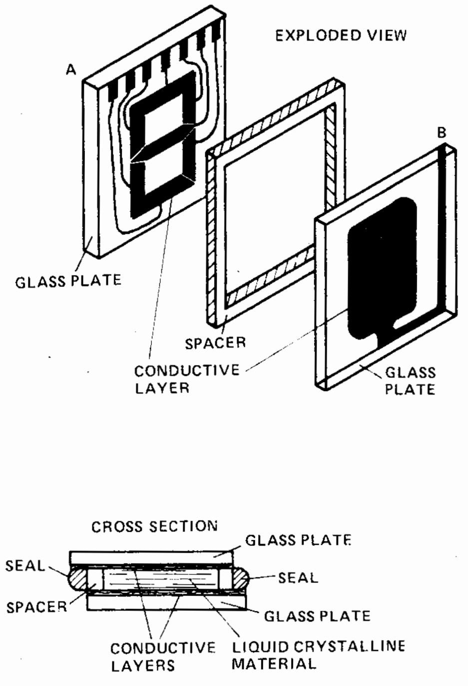


Fig. 10.

The cell consists of a very thin layer (about 12 µm) of the liquid crystalline material between two sheets of glass which have a conductive coating on their inside. One glass plate (a) has the actual seven-segment display etched on it. The other plate (b) has a common electrode etched on it. This conductive coating is either tin oxide, or a mixture of tin and indium oxides This provides an electrode with about 90% transmission of light.

This conductive coat is further treated so that the molecules align themselves with the surface while an electric field is not applied.

This provides a more or less translucent display. When an electric field is applied, the molecules move so as to align their dipoles with the electric field. This causes changes in the optical properties of the liquid crystal material which appears as the display.

There are two principle techniques used here, dynamic scattering and polarization modes.

Dynamic scattering:

In this mode the liquid crystalline material is chosen such that it has negative dielectric anisotropy, with the greater electrical conductivity along its long axis. The molecules are normally perpendicular to the surface when an ac field is applied the molecules, in clusters, move to re-align their dipoles with the field. The re-alignment of the dipole is in opposition to the conductivity and the liquid becomes turbulent. This turbulence is seen as milkiness in the display.

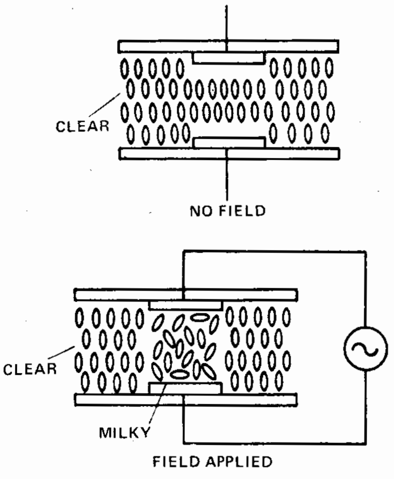


Fig. 11.

Since there is no light emitted the display must be used to modify the passage of incident light. This may be done either by passing light through the display, or more usually by reflecting light from a mirror behind the display.

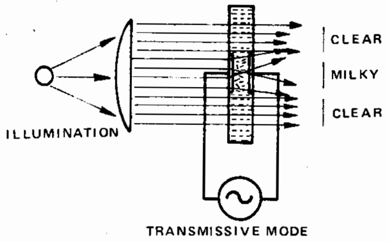
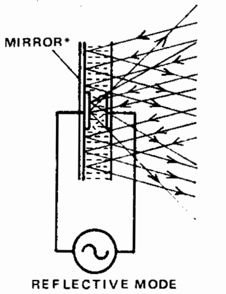


Fig. 12.



* THE MIRROR IS OFTEN THE BACK ELECTRODE

Fig. 13.

The transmissive cell will appear to glow where the segments are switched on. The reflective cell will appear misty where the segments are switched on. These displays have the shortcoming of a rather low "contrast ratio." That is, the apparent difference between the switched on and switched off display is not very great.

Polarization modes

The display is constructed in basically the same way as the dynamic scattering cell. The difference lies in the type of liquid crystalline material. The material used is one which assumed a twisted nematic structure, and has positive dielectric anisotrophy (the major component of its dipole along its long axis).

In this case the inside faces of the cell are coated so that the molecules are parallel to them and aligned in a particular direction when no electric field is applied.

The cell thickness is designed so that there is a complete 90 turn of molecules between the top and bottom faces. The twisted nematic has the property that it twists light that passes through it. Polaroid filters are fitted above and below the cell so that light is polarized as it enters, and is twisted through 90 exiting through a filter opposed at 90 to the first. The light is then reflected off a mirror and returns via the same pathway.

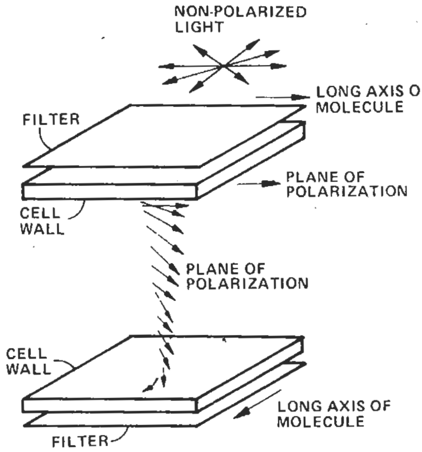


Fig. 14.

In this state the cell is clear. When an electric field is applied the molecules re-orientate to lie perpendicular to the faces of the cell and no longer twist the light. The light is now polarized as it enters the cell, and without being twisted, meets the second filter which is at right angles to the first and so does not pass the light. Hence that portion of the display with the field applied appears black (since no light is re-flected).

If you have not seen this effect before take take two pairs of polaroid sun glasses, look at a source of light with one in front of the other, thus:

Fig. 15.

Held in this way light, although polarized, is free to pass through the second filter since the plane of polarization is the same for both lenses. If one lens is now rotated through 90° thus:

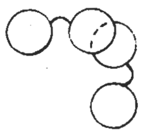


Fig. 16.

No light passes since the light polarized by the first lens will not pass through the second.

The effect of having the "crossed polaroids" in the cell causes almost total extinction of reflected light and consequently a high contrast ratio, an almost completely black and white display. This is many times better than the dynamic scattering cells.

Addressing technique:

The cells are normally operated under ac conditions (although some cholesteric cells may operate under dc.

The technique commonly used is to have dc pulses of identical amplitude, one applied to the back, the other to the display segment via an exclusive — or gate. In the off state the two signals are in phase, in the on state they are out of phase.

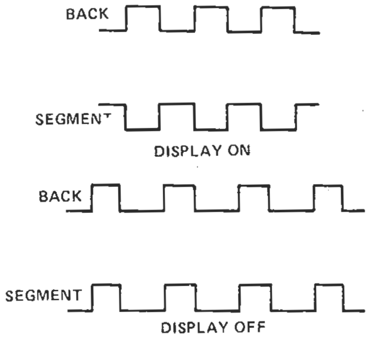


Fig. 17.

This technique has limitations due to the large number of both circuits and connections, however this has been overcome by putting the circuit on the glass of the display using thick film techniques!

Alternatives to this form of drive are to use multiplexed addressing, or m.o.s. shift register memory.

Other uses of liquid crystals:

The use of liquid crystal is not restricted to electrical displays.

Temperature measurement:

Certain nematic liquid crystals (cholesteric) change colour over the whole range of the spectrum (red to violet) as their temperature changes. Furthermore the colour change is over a very narrow temperature range, usually 2 or 3 C. The temperature at which this happens, and the range over which the change takes place can be adjusted by use of mixtures of different cholesterics.

A set of 10 or 12 of such cells in a row, the following one starting to show colour at 2 C higher temperature than the previous one, forms a useful thermometer working over a fairly restricted range. They have found application as living room and refrigerator thermometers.

Liquid crystal displays have made big in roads into the watch market but this may only be the beginning of the story.

Perhaps a more important application is using liquid crystals which have a very narrow range over which they change colour (0.5 C). They have found application in medicine since they can resolve differences of 0.05 C.

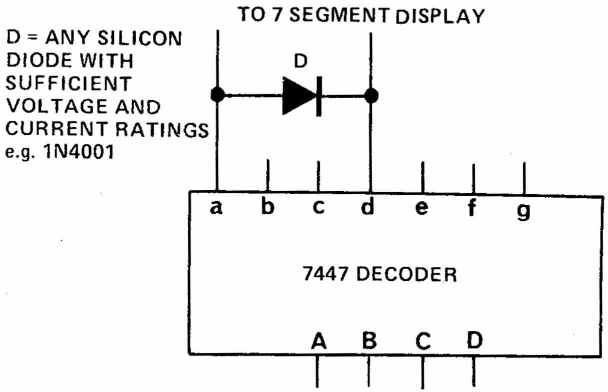
Assuming the liquid crystal is set to show colour at normal skin temperature any local deviation from the correct temperature will show as a different colour. This has applications in detecting cancers, since they tend to be hotter than normal body heat. They can also be used to see areas of poor blood flow, or where allergic reactions are taking place, since they are slightly hotter or colder than the normal body temperature.

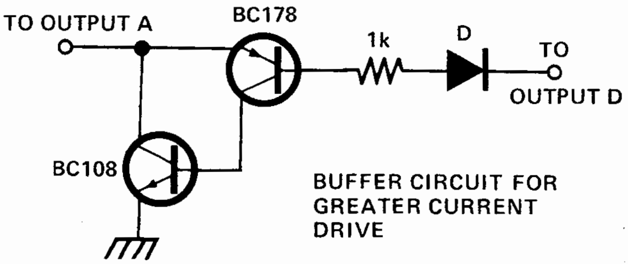
Cells with extremely low temperature resolution can even detect field intensity patterns of microwaves and ultrasonic sound fields due to local heating effects.

As might be expected there are also cells which change colour with applied electric field. This would appear to have interesting prospects for the future.

Other interesting possibilities which occur include the "memory effect". Certain cholesterics take hours, or some cases weeks, to return to their clear liquid crystalline state after they have been scattered by an applied electric field. The clear state can be restored by applying a different electric field.

Clearly liquid crystal technology has an enormous amount to offer a wide variety of fields — electronics, medicine and others. We are likely to see further interesting developments in the next few years as this technology takes over, and improves on existing display techniques. How about an alpha numeric display with independently variable colour segments? ●





BUFFER CIRCUIT FOR GREATER CURRENT DRIVE

IMPROVING 7-SEGMENT DIGIT APPEARANCE

The display font of some 7-segment output devices produce the digit 6 without the top bar. Examination of the font reveals that whenever the bottom segment ('d' segment) is on, so is the top segment ('a' segment) for all the other digits. Hence all that is needed is a diode connected so as to light segment 'a' whenever segment 'd' is on. The diagram shows the idea applied to a 7447 decoder. The drive capability of the device may be exceeded by this addition, so a buffer circuit may be required as shown.

PROM converts binary code to drive 1½-digit display

by V.R. Godbole
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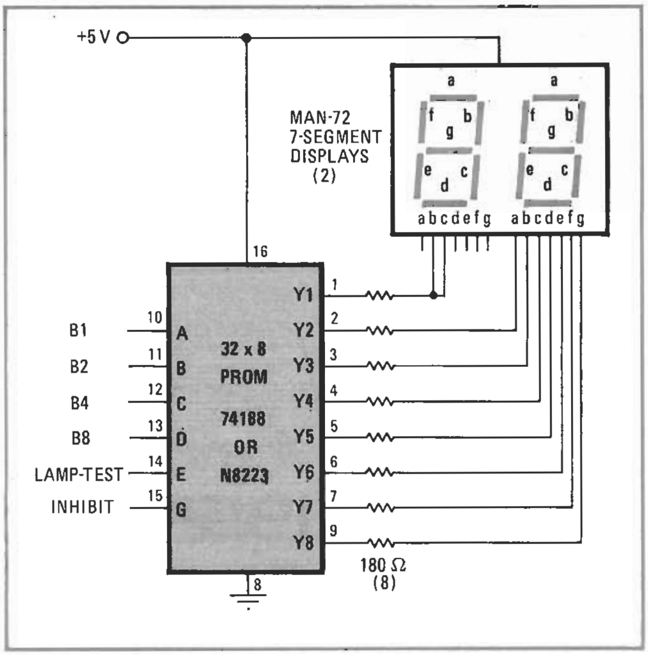
In providing visual readouts for test circuits, inspection equipment, error indicators, and the like, it is often necessary to go from a machine-generated 4-bit binary code to a 1½-digit display of the numbers 0 to 15. This process is usually performed in two steps, but a programable read-only memory can handle it in one.

In the usual approach, the first step is to convert the binary code into a BCD code by any one of the several available techniques. The second step is to use standard BCD seven-segment decoder/driver integrated circuits to drive the popular seven-segment visual readouts. The PROM, however, can be programed to accept the binary input signals and generate the proper outputs to drive the display directly.

This use of a PROM has several advantages. Conversion and driving are done in one step, thus providing direct interface to the visual display. Blanking and lamp-test can be included at no extra cost. Space is conserved, and cost is competitive with other approaches.

Binary coding of the numbers from 0 to 15 requires only four binary bits. The most-significant-digit position of the visual decimal display requires only a 1 or else no indication at all; therefore, this digit can be driven by generating only a single output signal that can turn on the segments to show a 1 when required. To drive the seven segments of the least significant digit, seven outputs are needed. Thus the converter/driver must accept four binary inputs and produce eight outputs to drive display segments.



Here's how. PROM drives seven-segment display to show decimal value of 4-bit input signal. This compact interface is convenient in microprocessor circuits, which often have spare PROM capacity. A 32-by-8-bit PROM can provide the drive signals for numbers 0 through 15 and also accommodate lamp-test and inhibit commands. Applications include test-number indication in small test instruments and display of settings on binary-output touch switches.

A 32-by-8-bit PROM, type 74188 or N8223, can serve this purpose. The PROM has open-collector outputs with sink capability of 16 milliamperes per output at output voltage of 0.5 volt, enabling it to interface directly with the display segments through suitable resistors. Also, besides performing the necessary conversion, the PROM has additional word capacity that can be used for desirable features such as blanking and lamp-testing at no additional expense. The figure shows the complete circuit diagram for the converter; it requires only the display devices and eight resistors in addition to the memory IC. The truth table lists the instructions required to program the PROM.

Locations 0 through 15 contain the bit patterns that generate segment drives to produce numbers from 0 to 15. Locations 16 through 31 are left unprogramed; therefore when the lamp-test input is taken to a logic 1, one of locations 16 through 31 is addressed. This circuit state causes all outputs to be set at logic 0, turns all segments on, and produces the number 18. When the inhibit input is taken to a logic 1, the PROM outputs are turned off and cause the display to be blanked. □

TRUTH TABLE AND PROGRAM FOR DRIVING 1½-DIGIT DISPLAY

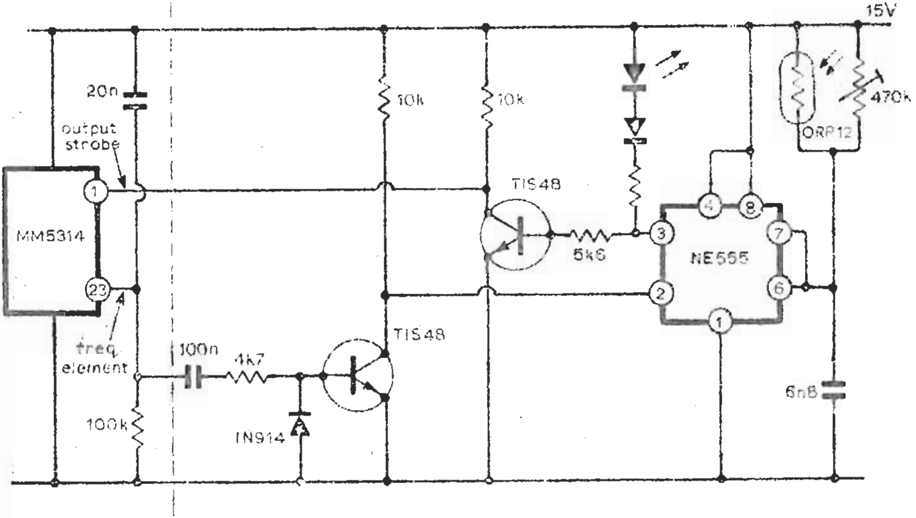
Inhibit ↓							Program in memory							
	Lamp test	B8	B4	B2	B1	Display	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
0	0	0	0	0	1	1	1	1	0	0	1	1	1	1
0	0	0	0	1	0	2	1	0	0	1	0	0	1	0
0	0	0	0	1	1	3	1	0	0	0	0	1	1	0
0	0	0	1	0	0	4	1	1	0	0	1	1	0	0
0	0	0	1	0	1	5	1	0	1	0	0	1	0	0
0	0	0	1	1	0	6	1	1	1	0	0	0	0	0
0	0	0	1	1	1	7	1	0	0	0	1	1	1	1
0	0	1	0	0	0	8	1	0	0	0	0	0	0	0
0	0	1	0	0	1	9	1	0	0	0	1	1	0	0
0	0	1	0	1	0	10	0	0	0	0	0	0	0	1
0	0	1	0	1	1	11	0	1	0	0	1	1	1	1
0	0	1	1	0	0	12	0	0	0	1	0	0	1	0
0	0	1	1	0	1	13	0	0	0	0	0	1	1	0
0	0	1	1	1	0	14	0	1	0	0	1	1	0	0
0	0	1	1	1	1	15	0	0	1	0	0	1	0	0
1	X	X	X	X	X	(OFF)	1	1	1	1	1	1	1	1
0	1	X	X	X	X	18	0	0	0	0	0	0	0	0

1 = HIGH 0 = LOW X = DON'T CARE

Automatic display-brightness control

It is quite easy to modulate the intensity of a display by switching it on and off with a varying duty cycle. With single-chip clocks where multiplexing is used, the display on time must be synchronised to the multiplex frequency. This circuit was designed around an MM5314 clock chip but should be usable wherever there are external multiplex-oscillator and strobe-enable outputs. The 555 timer is used in the monostable mode, triggered by the multiplex oscillator to determine the display off time. In bright conditions the ORP12 resistance is low and the display is on most of the time. It is necessary to set an upper limit to the pulse length, otherwise the 555 will not retrigger on each cycle of the multiplex oscillator and only alternate digits will be displayed. The potentiometer should be set to give low light output without mistriggering in dark conditions. The simplest way to control the rate of brightness increase with ambient light is to partially obscure the ORP12 surface. The 555 can also drive a decimal point directly, giving a matched brightness.

M. G. Martin,
Maybush,
Southampton.



LED display shows beat frequency

by Sergio Franco
Oberlin College, Oberlin, Ohio

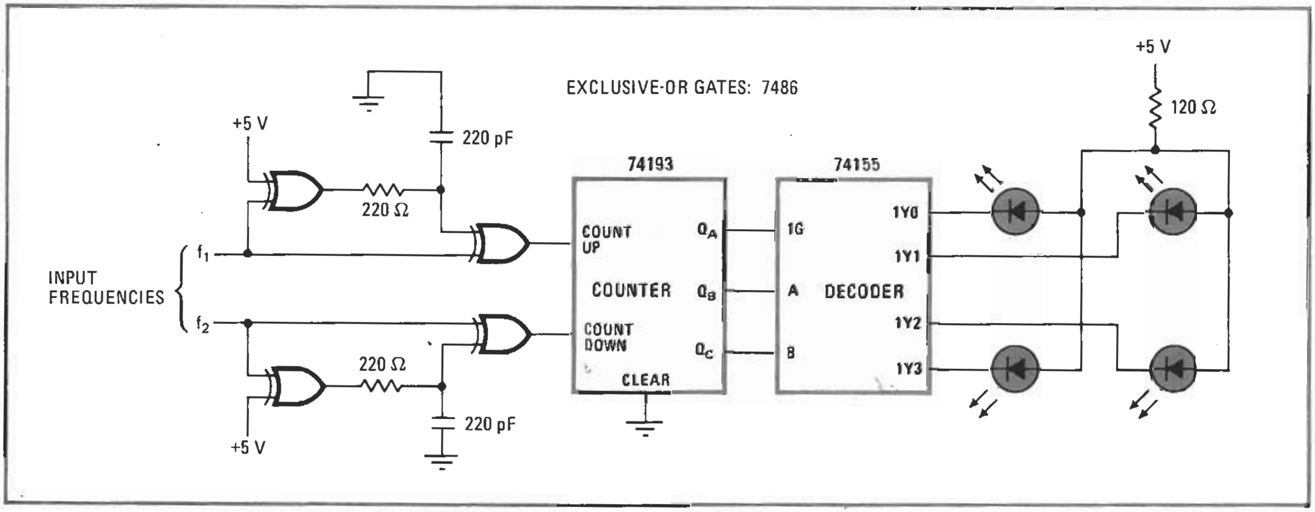
A simple, easy-to-use beat-frequency indicator can be built at a cost of only about $5. The circuit, which employs four light-emitting diodes as its display, can be used in a variety of applications, but is particularly suited to the tuning of musical instruments.

The heart of the circuit is a 4-bit synchronous up/down binary counter. After undergoing proper shaping by exclusive-OR gates, input frequencies f_1 and f_2 are applied, respectively, to the count-up and count-down terminals of the counter. The net count, therefore, will be in either the up or the down direction, depending on whether f_1 is greater than or less than f_2. When f_1 equals f_2, the counter alternates between two consecutive states, producing a net count of zero.

These three input conditions can be easily displayed by means of four LEDs arranged in a circle. (A decoder is used to drive the LEDs from the counter output lines.) Only one LED is on at a time. Therefore, when f_1 is greater than f_2, a dot of light is produced that rotates clockwise; when f_1 is less than f_2, the dot rotates counterclockwise; and when f_1 equals f_2, there is no rotation.

Furthermore, since the exclusive-OR shaping network produces a sharp negative pulse for each transition of the two inputs, the dot of light moves one step for every beat. The rate of apparent rotation of the dot, then, is an exact indication of the beat frequency. □

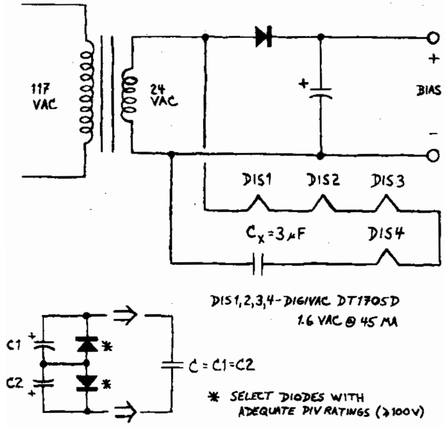
Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.



LEDs show the beat. Economical circuit displays the difference frequency between its two inputs, as well as indicating their relative magnitude. Since only one LED conducts at a time, what is displayed is a dot of light. The dot rotates clockwise when f_1 is greater than f_2 and counterclockwise when f_1 is smaller. The rate of rotation is the beat frequency. When f_1 equals f_2, the dot remains stationary.

FILAMENT POWER FOR FLUORESCENT READOUTS

You *can* supply power to the filaments of fluorescent readouts without using expensive transformers or dropping resistors that generate a lot of heat. Simply insert a non-polarized capacitor in series with the filament string, and use the transformer in the bias supply as a voltage source. The capacitor will act as a voltage-dropping reactance without "consuming" any power. Experiment to find the value of C_x. Start with a small (about 0.5-µF) capacitance and gradually increase until the desired effect is obtained. When this idea was applied to a four-digit clock readout, as shown, only 3 µF was needed. You can buy nonpolarized electrolytics (designed for speaker crossovers), or make your own as shown.—*Gregory Whittier*



Three LEDs display response of null-detector circuit

by William A. Palm
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Three light-emitting diodes provide a visual readout for this null-detector/bridge circuit that can be used to match resistors to within 0.5%. The LED display is better suited for production-line measurement purposes than an output meter, is lower in cost, and takes up less space.

Circuit operation is straightforward. Transistors Q_1 and Q_2 will both be on when bridge resistor R_x, the resistor to be tested, is approximately equal to R_{ref}, the reference resistance, because the differential voltage at the input ports of the 741 operation amplifier is near zero. Thus the output of the 741 assumes its midrange value of 4.5 volts, and LED A turns on. At this time, the voltage dropped across A and the 100-ohm collector resistors connected to Q_1 and Q_2 ensure that D_1 and D_2 cannot conduct, and so B and C cannot light.

When the differential voltage at the inputs of the op amp increases or decreases because of a change in R_x, one transistor will turn off, and this action will divert all current through LED B or C instead, depending on the polarity of the input voltage.

The null-detector response is illustrated within the circuit diagram. Note that there is no single step-transition from one region to another, but rather two small regions where two LEDs may be on simultaneously. These regions correspond to a value of R_x that is about 0.5% to either side of R_{ref}. ☐

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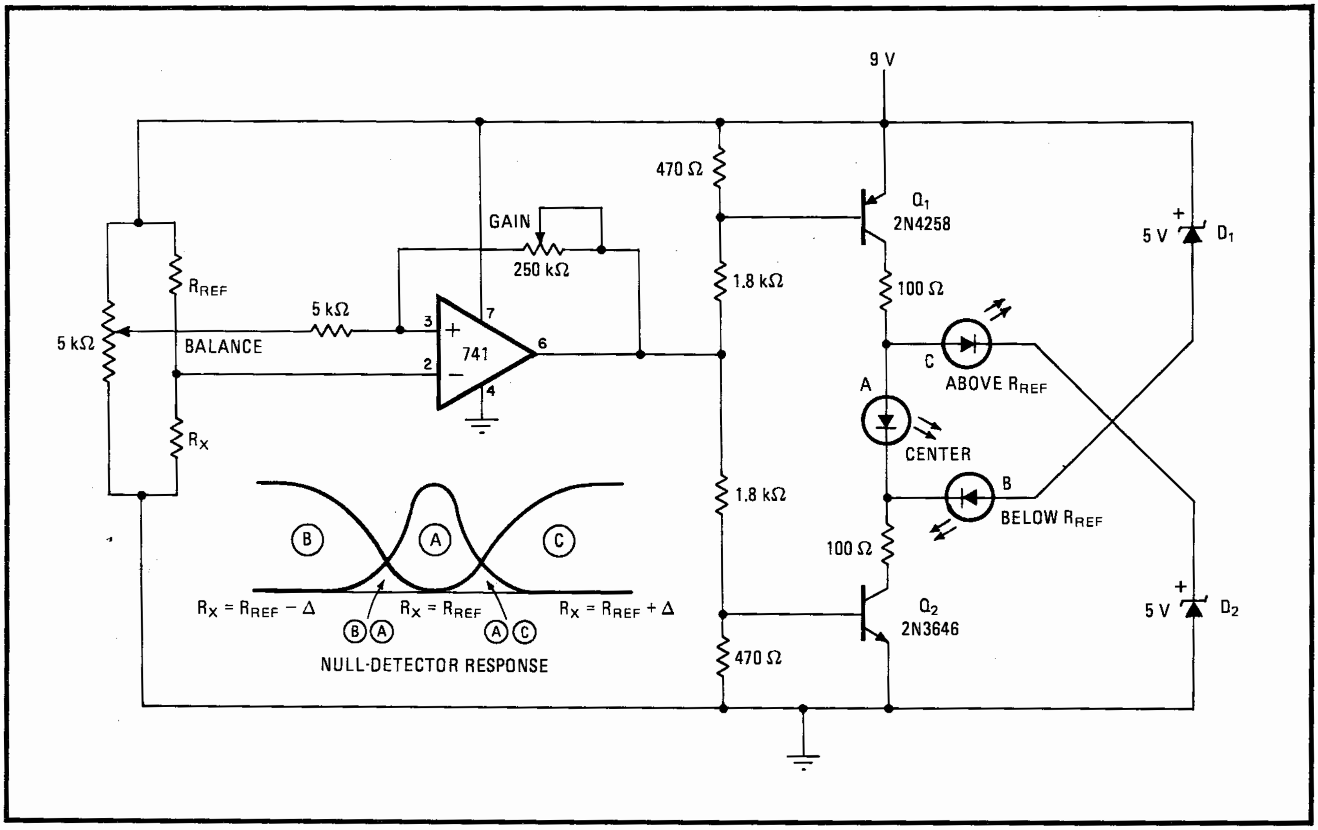

Light reaction. Null detector uses simple LED readout to indicate if test resistor R_x is below, equal to, or greater than test resistance R_{ref}. If $R_x = R_{ref}$, 741 output sits at midpoint value of 4.5 volts and LED A lights. Otherwise, output of 741 turns off one transistor, diverts current from other transistor through B or C, depending on polarity of input voltage difference. Null-detector response is illustrated.

Time-shared counters simplify multiplexed display

by Darryl Morris
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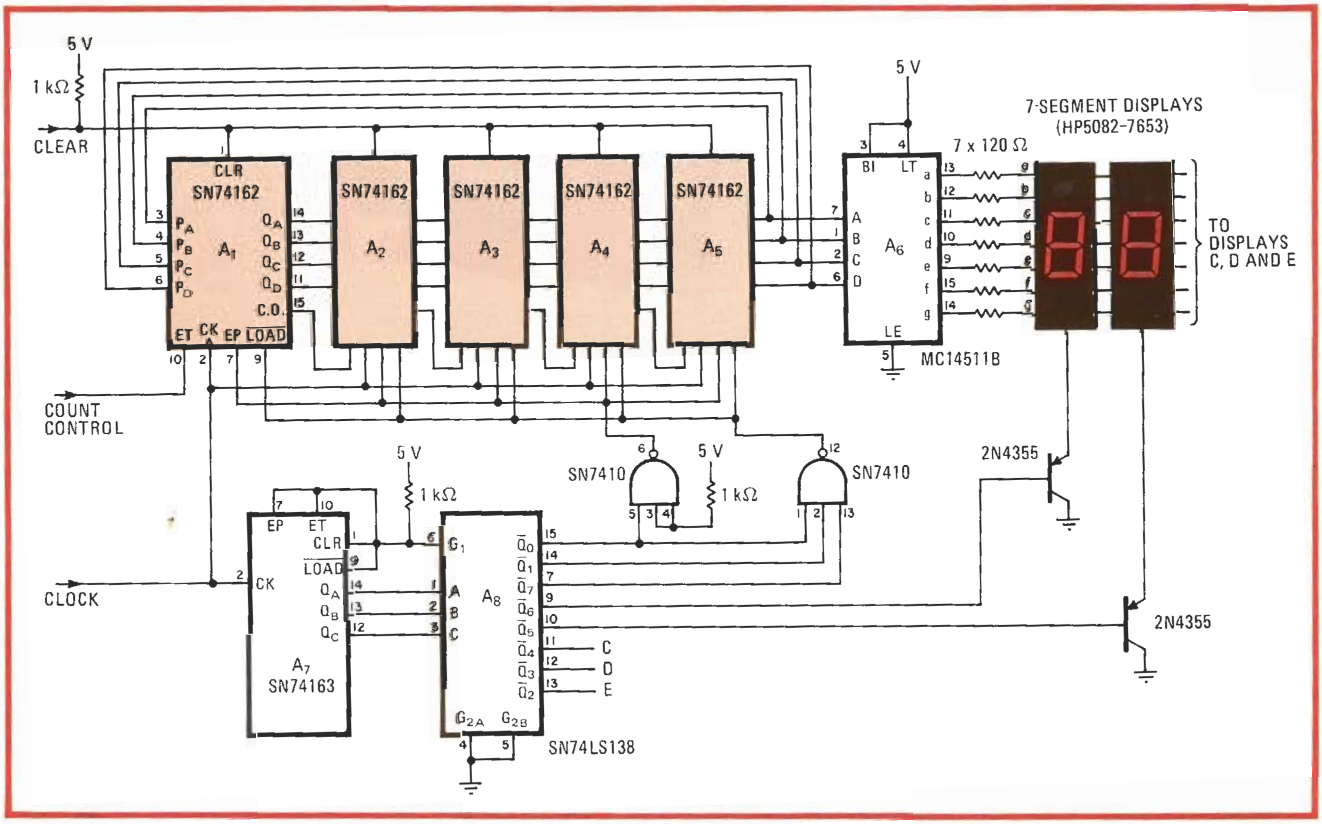
Although multiplexed display circuits reduce the number of components otherwise required for decoding on a per-digit basis, additional hardware is then needed to select and multiplex various lines to the display. But if a display is driven by a frequency counter, as is often the case, the counter itself can be made to perform the multiplexing with only minimal extra circuitry.

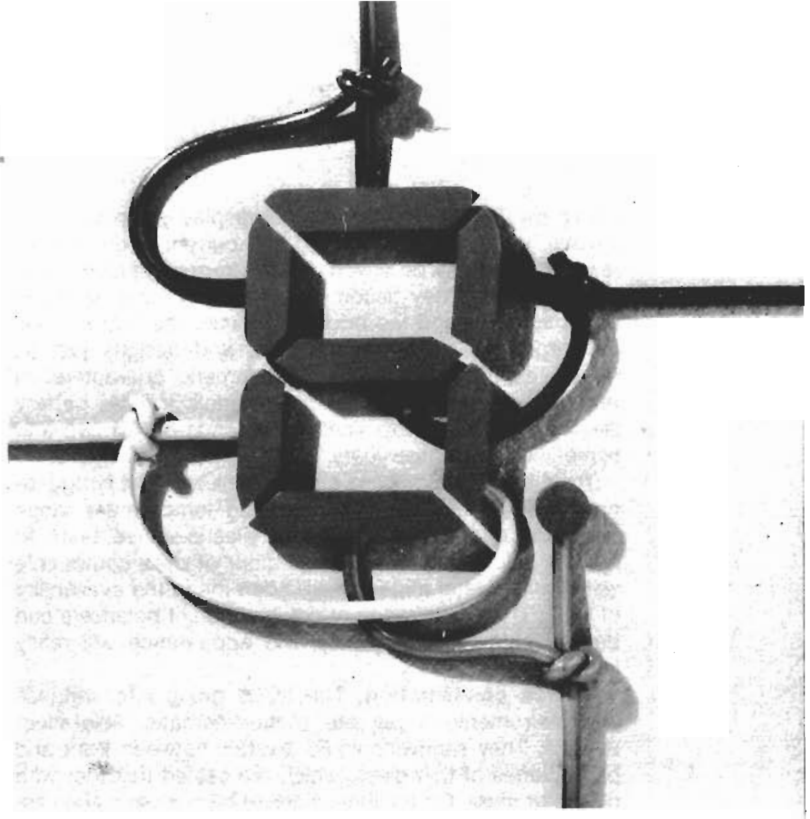
Multiplexing is done by using a master clock having several times the frequency of the normal clock, depending on the number of digits to be multiplexed, and by time-sharing the counters between the count and display mode. In the count mode, the $\overline{\text{LOAD}}$ and enable-P (EP) inputs of the counters shown are high and A_1–A_5 function as a conventional cascaded counter circuit under control of the enable-T (ET) input of A_1. The counter circuit advances one count for each clock period during which the count control line is high.

During the display mode, the control line and $\overline{\text{LOAD}}$ input of A_1–A_5 move low. The counters now accept data at their preload inputs, P_A–P_D. Because the preload inputs are connected to each preceding set of a counter's outputs, A_1–A_5 operates as a 4-bit-wide recirculating shift register when clocked. Thus, the contents of each counter is rotated past the seven-segment decoder (A_6) during its display interval, and the appropriate digit in the display is strobed by the mode controller, A_7 and A_8.

This technique offers the best saving in chip count when the count rate is slow or numbers are to be displayed only after the counted event has terminated. ☐



Time-shared. Counter circuit switches between count and display modes without selector devices. Counter operates as 4-bit-wide recirculating shift register. Master clock frequency is assumed to be several times that used for the counting circuits.



MULTIPLEXING LIQUID-CRYSTAL DISPLAYS

Suitable LCDs can be found, and addressing them as a matrix works

by Paul Smith

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☐ They use so little power and stay so visible even in bright sunlight that liquid-crystal displays would seem a natural choice for large-area, multiple-character applications. But there is one big obstacle: the prohibitive cost of driving and terminating LCDs made up of six or more characters.

Multiplexing, of course, could halve the number of leads required, simplify the drive electronics, and permit direct interfacing to microprocessors. But few LCDs are good candidates for multiplexing, and although more suitable ones are becoming available, the complex characteristics of their electrooptic response still have to be taken into account. Nevertheless, determining which LCDs are the right ones and then multiplexing them together is by no means an impossible task, even if more difficult than for other display technologies.

In any multiplexed display, the various segments of different symbols are not independent but are interconnected. The method of interconnection commonly used with light-emitting-diode displays is to tie together all those segments that have the same location in each symbol (Fig. 1a) and then address the symbols sequentially. But this method of time-division multiplexing is not widely used with LCDs at present because limitations in their electrooptic response make it impossible to address more than three or four digits sequentially.

Alternatively, though, each digit could be configured as a matrix, and if that is done, any number of digits may be addressed at the same time. In this approach, the displays are wired so that interconnected segments do not share the same symbol backplane. Figure 1b shows how pairs of segments of different digits may be interconnected even though each member of a given pair belongs to a different half of the digit's backplane. Generally, alphanumeric characters may be configured as matrixes of three by four, four by four, or three by six segments or the familiar five by seven dots.

With a matrix-addressed LCD, each segment plus its associated backplane is electrically equivalent to a lossy, nonlinear, voltage-dependent capacitor (see "Examining liquid-crystal displays inside and out," p. 114). In fact, the entire array may be represented schematically as rows and columns interconnected by capacitors at each intersection (Fig. 2a). A series of select pulses ($\pm V_s$) drives each row, while a series of data pulses ($\pm V_d$), which are either in phase or out of phase with the select pulses, drives each column. In this example, there are four segment lines ($N = 4$), which are sequentially addressed (Fig. 2b), so the duty cycle (η) is one fourth and the display is said to be one-fourth multiplexed.

How matrix-addressed multiplexing works

In such a matrix-addressed multiplexed display, simultaneously applying a select signal and a data signal determines the select or nonselect status of any particular segment. For a ¼-multiplexed LCD, the frame period (T_f) of the select waveform is divided into four equally spaced intervals corresponding to the time segments in which each row is addressed. Essentially, the matrix is addressed by multiplexing N rows with a voltage of $\pm V_s$ and presenting data information with a voltage of $\pm V_d$. At the intersection of a row and column, the voltage that appears across an LCD segment is the difference between the select and data signals. On the average, for a period T_f, a segment will be on if the voltage during the interval of ηT_f is $V_s - (-V_d)$ and off if the voltage is $V_s - V_d$. For the rest of the frame period $(1 - \eta T_f)$, the segment sees only $\pm V_d$.

Since LCDs are sensitive to the root-mean-square voltage between their segments and backplane, they are similar to incandescent lamps, in that their brightness is independent of the waveshape so long as the rms value of applied voltage remains constant. If the off-segment (nonselect) rms voltage is V_1, and the on-segment

Examining liquid-crystal displays inside and out

Liquid-crystal displays excel other display technologies in several respects. Their voltage and current needs are so low that they may be driven directly from complementary-MOS circuitry. They become not less but more legible in direct sunlight, and the brighter the sun, the better. They can reproduce graphics, symbols, and designs just as readily as the more usual alphanumeric characters. In portable equipment, yet another benefit is long battery life, which in watch applications extends out to two and sometimes even three years.

Their future looks even more promising. Their ruggedness is improving as their operating temperature range broadens and the resistance of plastic-sealed units to humidity increases. The development of dyes compatible with liquid-crystal materials will soon mean the availability of LCDs in a whole range of colors. Then, if polarizers can be eliminated also, legibility and appearance will really improve.

Device construction. The LCDs going into watches and instruments today are twisted-nematic, field-effect devices. They sandwich liquid crystals between front and back planes of thin glass, which are sealed together with plastic or glass. On the inner sides of both glass planes are transparent conductor patterns that are coated with a special chemical film that aligns liquid-crystal molecules. To the outside of both pieces of glass are laminated polarizers, each of which passes only those components of light that are parallel to its polarizing axis. As shown in (a), these axes are perpendicular to each other, so that light is blocked.

Liquid crystals, as their name implies, are materials that are neither fully liquid nor fully solid. Within a finite temperature range, they have properties intermediate between the liquid and solid states. Their cylinder-like molecules can exist in any of three mesophases—smectic, cholesteric, or nematic, of which the last is most useful for display purposes. In it, the long axes of the molecules are parallel to each other but not arranged in planes, rather like the raindrops in a shower of rain.

However, the twisted-nematic LCD literally imparts a 90° twist to those axes. The orientation of the long axes of its liquid-crystal molecules varies all the way from parallel with the axis of the front polarizer to parallel with the axis of the rear polarizer, so that the display now passes light. Causing this twist are the surface characteristics of the alignment film on the conductor patterns. This film yanks the molecules nearest it into the fully twisted position and in so doing exerts a similar but decreasing influence on those molecules more and more remote from it.

Natural phenomena like temperature, pressure, or an electrical or magnetic field can modify this twist. With field-effect LCDs, for instance, an electric field impressed via the conductor patterns aligns the long molecules parallel to itself, making those under its influence perpendicular to the rear polarizer's axis. These energized molecules now block light, causing dark images in the shape of the conductor patterns to appear on a light background.

However, the display could be constructed to produce light images on a dark background instead. Depending on the orientation of the polarizers, the unenergized LCD either transmits all incident light or blocks (absorbs) it. If the back polarizer is oriented to absorb light, application of the electric field will produce light images on a dark background. Conversely, with the back polarizer oriented to transmit light, the display has dark images on a light background, which is most often the case.

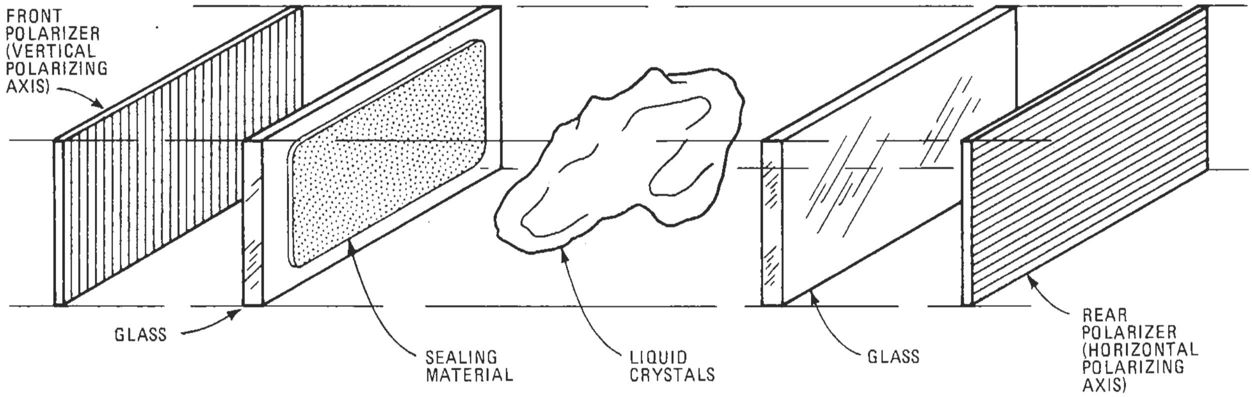
Conductors on the glass frontpiece shape the images, while others on the glass backplane complete the circuit. These conductors are applied by means of screening or, for finer resolution, photolithography.

Weakest link. The polarizers are the LCD's weakest link, because they are very susceptible to temperature and moisture degradation. Under extended high-temperature and high-humidity conditions, polarizer material fades and peels. Recent developments are beginning to improve matters, however.

Liquid-crystal displays may be purchased with or without polarizers, which are readily available as plastic sheets. If the sheet is cemented to the display, bubbles may form in the adhesive. So some users prefer to clamp it on instead, despite the resultant small loss in light transmission due to reflection at the glass-polarizer interfaces. Adhesives, as it happens, reduce this reflection.

Polarizers come in different colors and afford varying degrees of light transmission. Three of the most common grades provide 42%, 48%, or 55% light transmission. Combining different grades permits the contrast and to some extent the color of the dark areas to be altered. For example, with 42%/42% polarizers (42% front and 42% back), the dark portions of the display are black. With 42%/55% or 48%/48% polarizers instead, the appearance is blue to dark blue but the light portions of the display are brighter.

Most LCDs have a reflector attached to the rear polar-



(a) CONSTRUCTION

izer. This may be either reflective or transflective in type. Reflective material, of course, simply reflects all light, whereas transflective material is partially reflective and partially transmissive and is helpful in backlighting LCDs intended for use in low ambient light. A transflective back coating permits light from a source behind the display to pass through it in low ambient light while permitting the display to operate as usual under normal ambient light. On the other hand, such a coating reflects less well than a reflective material because it lets some of the light entering the cell from the front leak through it, dimming the display and yielding less of a contrast than the reflective types.

All but one of the many schemes currently in use for back-lighting LCDs require an external power source to light a lamp. The fairly recent technique that eliminates this need utilizes tritium, a radioactive material, to activate a phosphor coating. Unlike other radioactive materials, tritium need not be encapsulated and shielded to prevent radiation hazards. The beta rays emitted by the tritium impinge on the phosphor, causing it to light up, much as in a television picture tube. Light from the phosphor passes through the LCD's transflective back coating, thus illuminating the display.

Drive considerations. Basically, LCDs are low-voltage ac devices, typically operating at 3 to 6 volts root mean square. Much higher drive voltages are possible, but it is the rms value that is of interest. Even with ac, the dc component of the drive signal must be kept in the low millivolt range, because dc tends to degrade the liquid-crystal material and thus shorten display life.

Also, since the device is constructed as two conductors separated by a dielectric, it functions electrically like a capacitor, requiring very little drive current at low frequencies. In fact, its equivalent circuit is a capacitor, shunted by a very high resistance that accounts for some small current leakage. The frequency of the ac drive signal, while not critical, does have a preferable operating range. For any capacitive device, the higher the frequency, the lower the reactance and the greater the current drain. Alternatively, at the low end of the spectrum, flicker will develop as the display turns on and off with each cycle of the drive signal. As a rule, flicker becomes discernible at frequencies below 25 hertz.

To drive a display requires applying the appropriate ac voltages to on segments, off segments, and the backplane. As shown in (b), the drive signals to on segments and their associated backplane should be 180° out of phase. At the same time, off segments should be connected to the backplane to ensure that they are not partially turned on because of capacitive coupling between adjacent leads and segments.

When an electric field energizes a portion of a display, the molecules of the liquid-crystal material must move physically before the effect becomes visible. The time required for this reorientation depends on the temperature of the material and the strength of the field. In turn, the voltage applied and the spacing between conductors determines the field strength—the higher the voltage and the smaller the spacing, the stronger the field and the faster the switching time.

Contrast values. Because LCDs do not appear to turn on and off instantly, image contrast values of 90% and 10% generally serve as the on and off points for measurement purposes. These points are much easier to recognize than contrasts of 100% and 0%, which for a typical display are approached asymptotically, as depicted in (c). In this case, the device is over 95% turned on at a drive voltage of 3 V rms.

Temperature and humidity are the two greatest enemies of LCDs. Some liquid-crystal materials remain in a nematic state from −10°C to 75°C. Above and below these temperatures, the material undergoes a phase change, to either an isotropic liquid or a semi-solid crystal. A display raised to temperatures above its upper limit, or nematic-isotropic point, turns completely dark or completely clear, depending on the orientation of the polarizers. One approaching its lower temperature limit responds more and more sluggishly till it ceases to function at all. Displays usually recover from having exceeded the upper limit when returned to their normal operating range. Similarly, no damage is done if the lower limit is exceeded for only short periods of time. Research continues to extend the operating and storage temperature ranges of liquid-crystal materials, with some recent advances pushing the upper limit to over 80°C.

High temperature combined with high humidity is more of a problem for plastic-sealed LCDs than for glass-sealed units, which are truly hermetic. High temperatures increase the rate of moisture permeation through the plastic, although these seals are better than they used to be and getting even better all the time.

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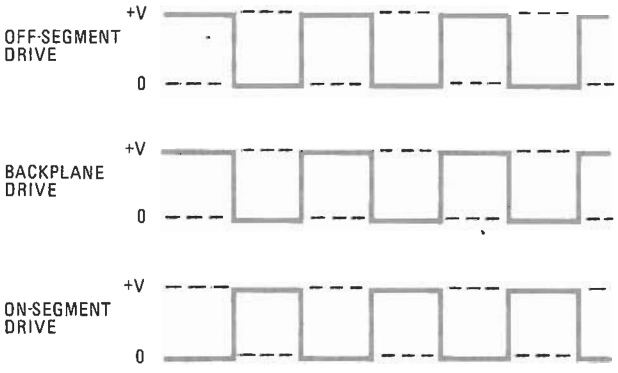
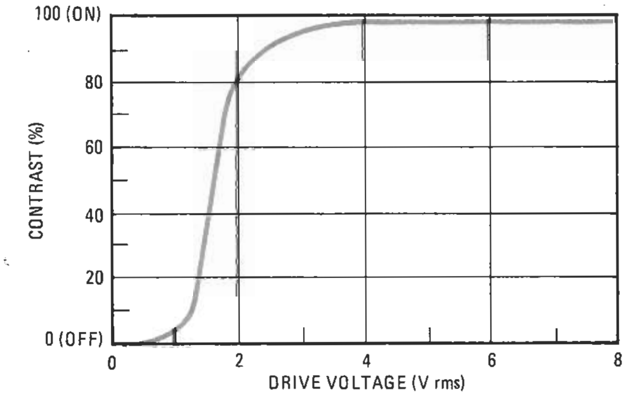
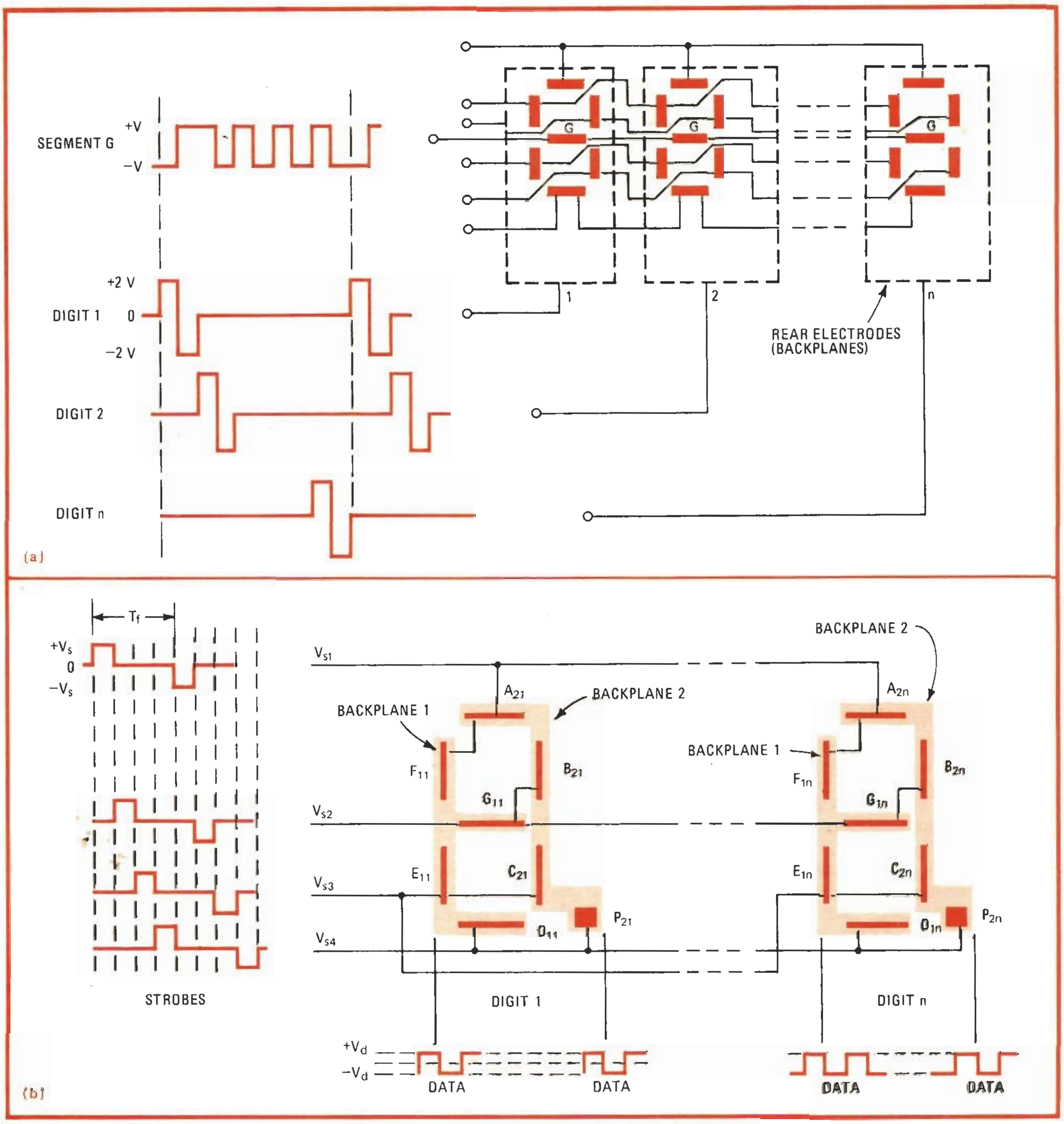


(b) DRIVE SIGNALS



(c) CONTRAST-VOLTAGE CURVE



1. Multiplexing schemes. Light-emitting-diode displays may be multiplexed by tying together all the segments that have the same location in each symbol (a). But this method permits multiplexing only three or four liquid-crystal displays, because of limitations in their electrooptic response. A better way (b) is to configure each LCD digit as a matrix so that interconnected segments belong to different backplanes.

(select) rms voltage is V_2, then the mean-squared on and off voltages are:

$$V_1^2 = \eta(V_s - V_d)^2 + V_d^2(1-\eta)$$
$$V_2^2 = \eta(V_s + V_d)^2 + V_d^2(1-\eta)$$

When the ratio of V_2/V_1 is maximum, the contrast between an on and off segment will be optimum. For a three-level select waveform ($\pm V_s$, 0), this optimum contrast will always occur when:

$$V_d = V_s\eta^{1/2}$$

For a ¼-multiplexed LCD, eight complete time segments constitute one scan period (T_s), or two frames. Each frame contains the same information and only the polarities of the strobe (select) and data pulses are reversed. This polarity reversal causes the average value of the select and nonselect voltages to be zero during a scan—an absolute must with LCDs. A nonzero average voltage across the display shortens its life through irreversible electrochemical action.

The first step in considering LCD suitability for multiplexing is to evaluate the display's optical response as a function of applied voltage. Since LCDs are light modifiers—as opposed to light emitters—the appropriate measure of optical response is either contrast or contrast ratio. Briefly, contrast is a measure of the amount of light that is reflected or transmitted by the symbol, whereas contrast ratio is the ratio of the unenergized to the energized image brightness. (See "Almost all about contrast and contrast ratio," p. 120.)

Figure 3 depicts the contrast characteristics of a typical symbol segment as a function of applied rms voltage for various viewing angles (θ). (This display has the best readability when viewed along the 225° direction—a typical wristwatch application.) The ideal electrooptic response curve for multiplexing purposes would exhibit an abrupt change in contrast from zero to some high value, followed by a plateau at that high level. However, in practice, as the viewing angle gets larger, the contrast reaches a maximum, and this maximum is then followed by a minimum value.

Moreover, while the off-segment condition can be determined with some degree of precision, the on-segment condition is not so easily defined. The operating points described by the intersections of lines $N = 2$ and $N = 8$ show that as more segments are multiplexed, the difference between the select and nonselect voltages becomes smaller. Also, the viewing angle required to obtain an acceptable level of contrast becomes smaller.

A practical definition of contrast

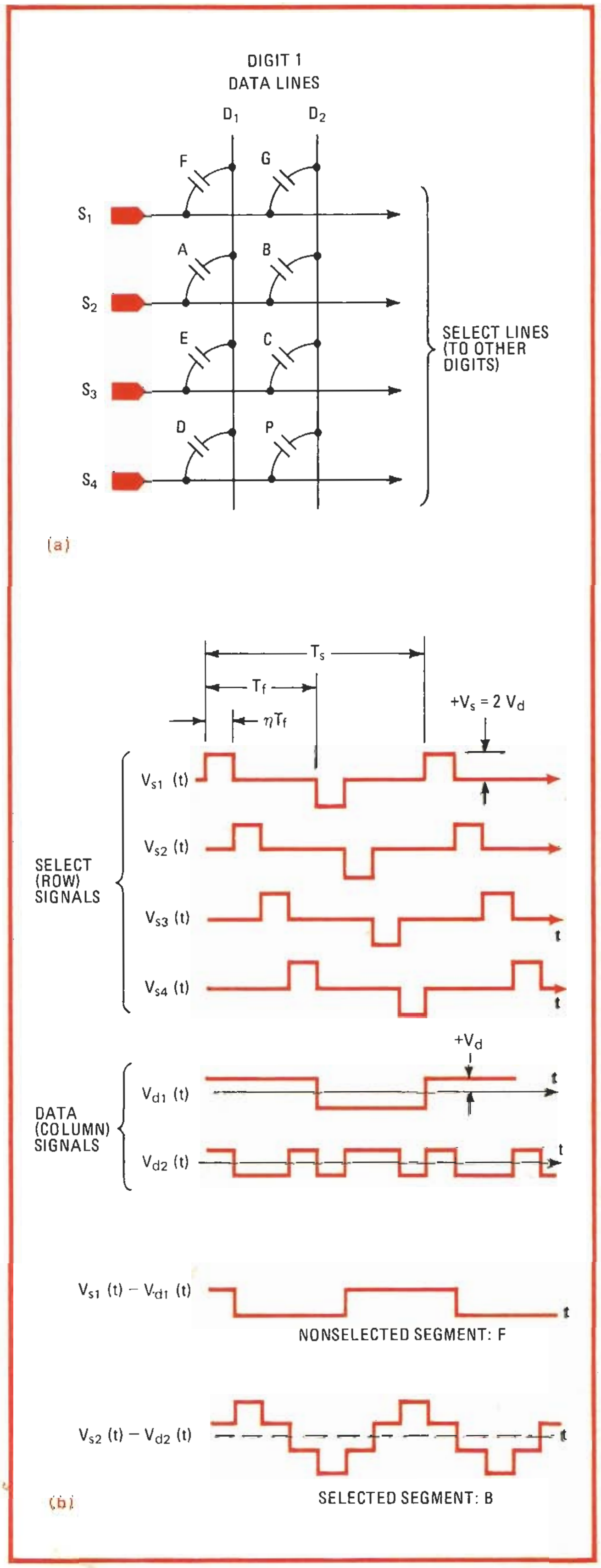
A useful parameter for describing the sharpness of the contrast-voltage curve is the threshold ratio (ρ), which may be expressed as:

$$\rho = E_{select}/E_{nonselect} \qquad (1)$$

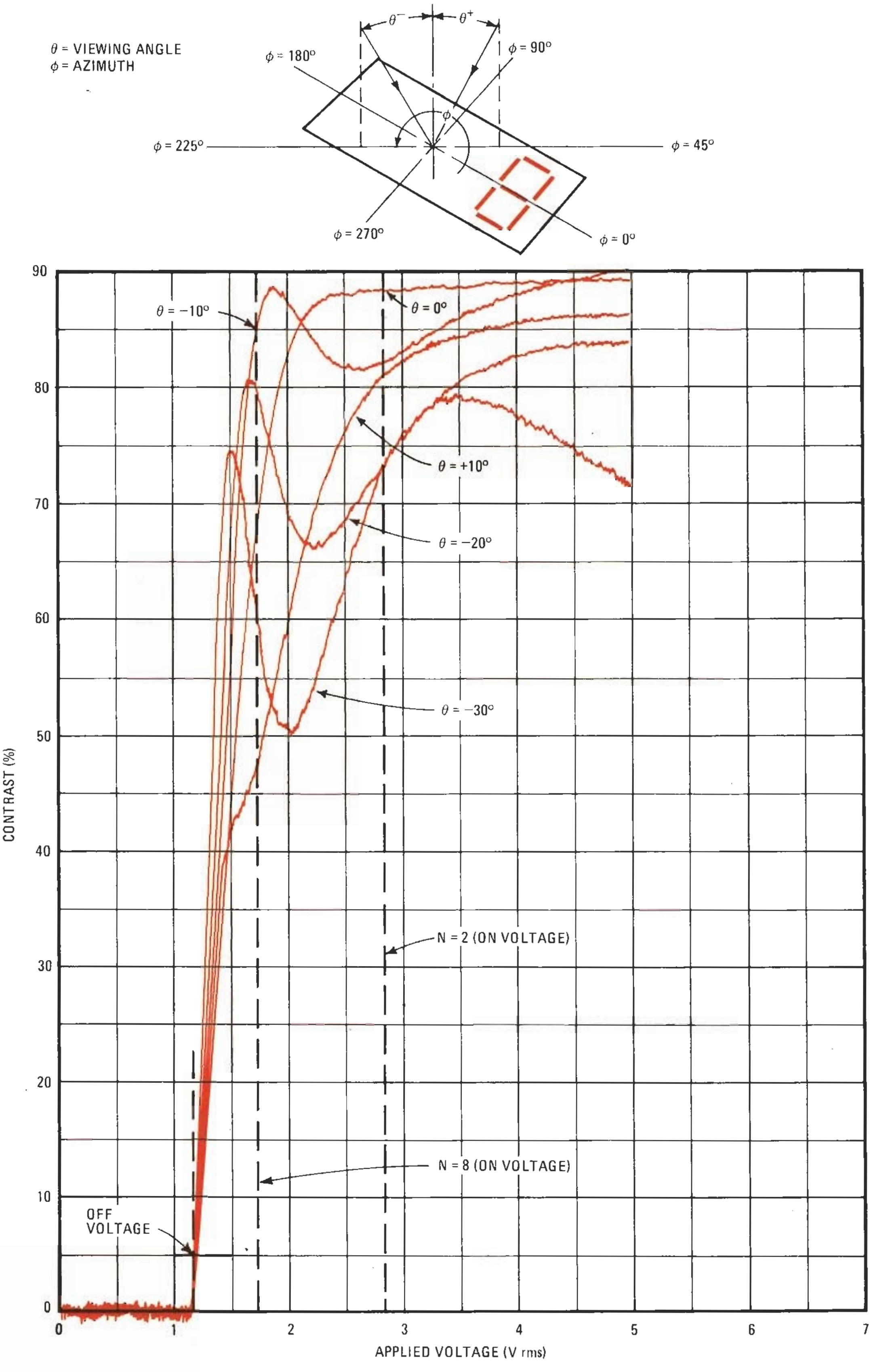
where E_{select} is the applied rms voltage that produces the on contrast and $E_{nonselect}$ is the rms voltage that results in the off contrast. Ideally, the threshold ratio should be unity, but it usually ranges between 1.1 and 2.4 for LCDs currently available for multiplexing. In practice, this parameter depends on various constants of the liquid-crystal materials, device construction, and viewing angle.

To minimize the connections to the display requires sequentially addressing a maximum number of select lines, but the LCD's electrooptic response limits this maximum number. Even if the threshold ratio were ideal ($\rho = 1$), the number of segments that could be sequentially addressed would be limited by other considerations, such as power-supply variations and the temperature coefficient of threshold voltage. Indeed, different liquid-crystal materials have different threshold-voltage temperature coefficients, typically ranging from −7 to −13 millivolts/°C. Moreover, if the number of multiplexed lines is large, the select and nonselect voltages will usually require temperature compensation, particularly if the power source is a battery, which has a positive temperature coefficient.

When the viewing angle increases in the 225° direction, the contrast-voltage curves shift to the left. This means that the nonselect voltage must be less than E_5 (the rms voltage that produces 5% of the maximum contrast) for the largest negative viewing angle expected, and the select voltage must be high enough to produce an



2. Driving the matrix. LCD segments and their associated backplanes behave electrically like lossy nonlinear capacitors, which interconnect the matrix' rows and columns (a). A series of select pulses drives each row, a series of data pulses each column (b).



3. Electrooptic response. For a typical LCD symbol segment, contrast will appear to vary with applied voltage, as well as with viewing angle. Also, as the number of multiplexed lines increases, the difference between the select and nonselect voltages becomes smaller.

acceptable value of contrast for the most positive viewing angle anticipated. Similarly, changing the azimuth of the viewing angle generates a different set of contrast-voltage curves. Just as the number of multiplexed lines will determine the operating points on these curves, a minimum contrast of 0.5 will define the viewing space. As the number of multiplexed lines increases, the viewing cone corresponding to a minimum contrast of 0.5 becomes smaller.

How many lines may be multiplexed?

The ratio of select to nonselect voltages (V_2/V_1) can be maximized for a specific duty cycle. This ratio, which depends on the number (N) of multiplexed lines, can be used to determine whether a particular electrooptic transfer characteristic is satisfactory for a given multiplexing application. If $\rho = V_2/V_1$ and ρ_{max} must be equal to or greater than E_{50}/E_5, then:

$$\left[\frac{(N_{max})^{1/2}+1}{(N_{max})^{1/2}-1}\right]^{1/2} > \rho_{max} > 1$$

where N_{max} is the maximum number of multiplexed lines. Solving this equation for N_{max} yields:

$$N_{max} \leq \left[\frac{(\rho_{max})^2+1}{(\rho_{max})^2-1}\right]^2 \qquad (2)$$

Now determining the maximum number of multiplexed lines becomes a matter of simple arithmetic. From the contrast-voltage curves of Fig. 3 for a −30° viewing angle, the applied (select) voltage for 50% contrast, or E_{50}, is 2 v rms, and the (nonselect) voltage for 5% contrast, or E_5, is 1.2 v rms. With a select voltage of 2 v, the symbol segment would appear to be black ($C = 0.83$) at a viewing angle ($\theta = 0°$) normal to the plane of the display and would appear to turn gray gradually as the display is tilted away from normal towards −30°. Using these values of select and nonselect voltages in Eq. 1 to find the threshold ratio gives $\rho = \rho_{max} = 1.67$, and substituting this result into Eq. 2 yields a value of 4.5 for N_{max}. Therefore, if the display is ¼-multiplexed, it will be readable over a 30° viewing angle. Note that acceptable contrast can still be obtained for larger values of N (i.e. N = 8) if some contrast is sacrificed at viewing angles greater than −10°.

The effect of temperature on multiplexing may also be evaluated. Suppose the display is to operate over a temperature range of 0°C to 40°C and that the temperature coefficients of E_5 and E_{50} are −8 and −12 mv/°C, respectively. The negative temperature coefficients imply that the entire family of contrast-voltage curves shifts left as temperature rises and right as temperature drops. As the display is heated, then, nonselected segments will tend to turn on when biased with a nonselect voltage equal to E_5. The effect of temperature on selected segments is more complex, but in general, the contrast of a selected segment tends to decrease as the display is cooled.

Since the effect of nonselected segments turning on is more critical to an application than the decrease in contrast of selected segments, the design strategy should be to make nonselect voltage V_1 equal to E_5 at the highest operating temperature expected. In the example, the nonselect voltage may be computed as:

$$\begin{aligned} V_1 &= E_5 + (-8\ \text{mV/°C})(40°\text{C} - 20°\text{C}) \\ &= 1.2 - 0.16 \\ &= 1\ \text{v rms} \end{aligned}$$

The select voltage can remain the same at $V_2 = E_{50} = 2$ v rms, so the threshold ratio becomes $\rho = \rho_{max} = 2/1 = 2$. Again using Eq. 2 to calculate N_{max} yields a value of 2.8, which suggests that without temperature compensation the display's multiplex potential is limited to ½- or ⅓-duty-cycle operation.

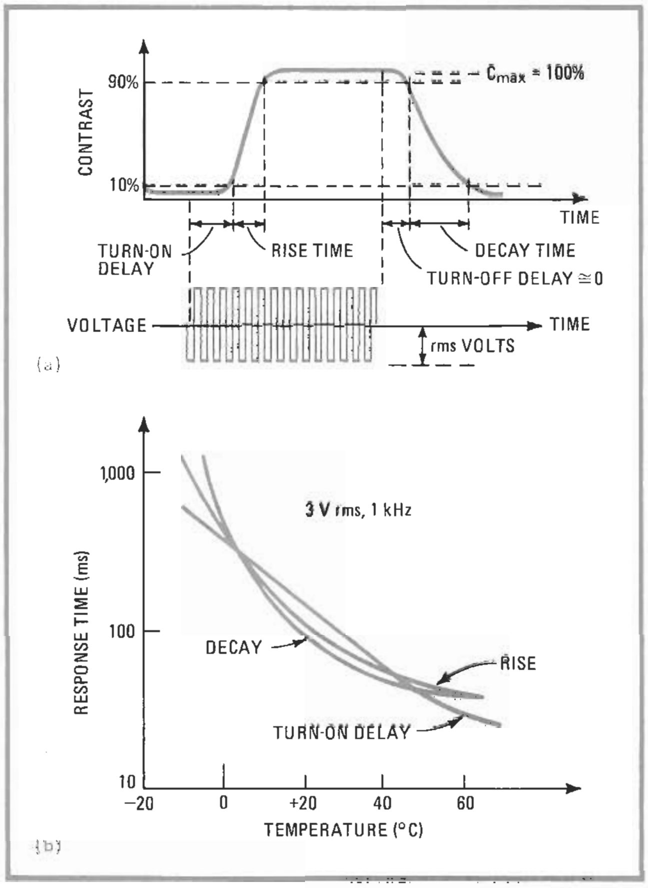
This example illustrates the effect of temperature on multiplexing capability in a general case where power-supply variations, manufacturing tolerances, and the like exist. Tolerances having an equal effect on both V_1 and V_2 may be expressed as:

$$(V_1)_t \geq V_1/(1+p)$$
$$(V_2)_t \leq V_2/(1-p)$$

where $(V_1)t$ and $(V_2)t$ are the new nonselect and select voltages, respectively, and p is the percent tolerance divided by 100. Also, the threshold ratio becomes:

$$(\rho_{max})_t = \frac{(V_2)t}{(V_1)t} = \frac{1+p}{1-p}\frac{V_1}{V_2}$$

Computing the value of N_{max} from Eq. 2 and setting the value of V_2/V_1 equal to 1 yields:



4. Speed of response. Turn-on and turn-off times (a) vary from 50 to 500 ms (b) between 0°C and 50°C. With multiplexing, because the nonselect voltage is greater than zero, turn-on delay—and thus turn-on time—is shorter than for nonmultiplexed operation.

Almost all about contrast and contrast ratio

A good measure of the optical response of a liquid-crystal display is the device's contrast or contrast ratio. In effect, these parameters provide a yardstick for rating an LCD's readability. How they are defined depends on whether the LCD is reflective, displaying dark symbols against a light background, or transmissive, showing light symbols on a dark background.

In brief, contrast ratio (C_r) is the ratio of the off-voltage to on-voltage image brightness. For practical displays, contrast ratio generally ranges from 0 to 20, although it seldom exceeds 10 for reflective devices under diffused lighting conditions. When the LCD is reflective, which is usually the case for watch and instrument displays:

$$C_r = B_o/B_s$$

where B_o, the background brightness, is greater than or equal to B_s, the symbol brightness. For a transmissive display, contrast ratio becomes:

$$C_r = B_s/B_o$$

where B_s is greater than or equal to B_o.

Similarly, contrast (C) may be defined as the ratio of the difference between the symbol and background luminances to the luminance of the symbol or background, or:

$$C = |\Delta B|/B$$

where ΔB is the brightness difference between symbol and background, and B is either the background brightness (B_o) or the symbol brightness (B_s).

If the display is reflective:

$$C = (B_o - B_s)/B_o$$

where B_o is greater than or equal to B_s. For a transmissive display:

$$C = (B_s - B_o)/B_s$$

where B_s is greater than or equal to B_o. Contrast seldom exceeds 0.9 for reflective or 0.95 for transmissive displays.

Both contrast and contrast ratio are dimensionless quantities that depend on the applied voltage and the viewing angle. The two parameters are related by:

$$C = 1 - 1/C_r$$

The use of contrast offers some measure of convenience, because the output of a photometer, which may be used to measure display brightness, can be directly calibrated in units of contrast. On the other hand, contrast ratio is often the preferred definition in display system design. The table shows some accepted values of contrast for common hard-copy symbols.

Display specialists may disagree on what minimum value of contrast is an acceptable one for LCDs, but generally a contrast of 0.5 is readable and easily verified. In some cases, a symbol that is supposed to be off can have a brightness just slightly greater than, or slightly less than, the surrounding background. Therefore, there is also the problem of defining an acceptable off contrast. As a rule, a value of 0.05 is both practical for design purposes and useful for evaluating LCD systems in operation.

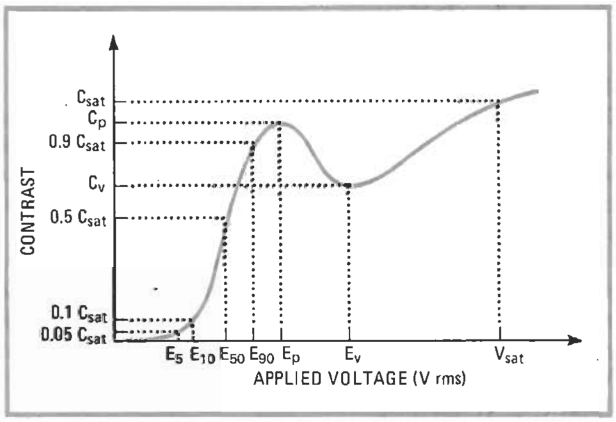
The figure shows the electrooptic response of a typical LCD at a specified azimuth and viewing angle. Some of the key contrast-voltage parameters along the curve are:

- V_{sat}, a reference voltage in the saturation region that defines a reference value of saturation contrast (C_{sat}).
- E_{90}, E_{50}, E_{10}, and E_5, the lowest applied root-mean-square voltages that, respectively, produce 90%, 50%, 10%, and 5% of the C_{sat} contrast.
- C_p, the relative maximum value of contrast occurring at E_p between an applied voltage of 0 and V_{sat}.
- C_v, the relative minimum value of contrast occurring at E_v between an applied voltage of E_p and V_{sat}.

In measurements of contrast, it is usually assumed that the illumination is constant over the area of the display, so that for a reflective display:

$$C = (R_b - R_s)/R_b$$

where R_b and R_s are the reflectivities of the display background and symbol, respectively. This equation is the basis for making practical measurements with either a photometric microscope or a reflectometer.



HARD-COPY CONTRAST

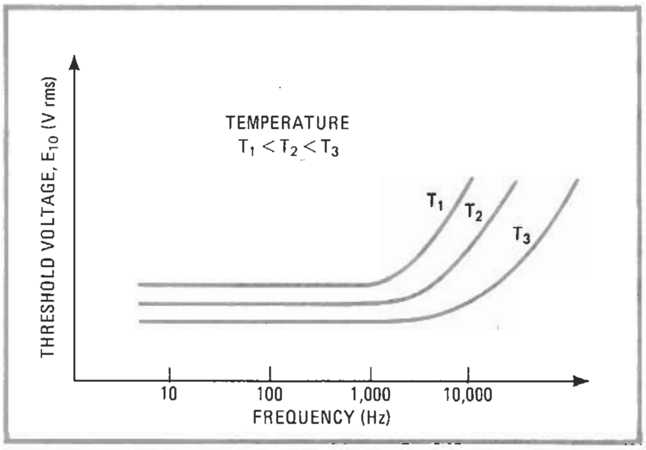
Type of hard copy	Contrast
Typewriter	0.79 – 0.87
Office copying machine	0.6 – 0.81
Handwritten copy	
Pencil	0.6 – 0.73
Ballpoint pen	0.76
Newspaper	0.85

$$N_{max} = \left[\frac{(1 + p^2)}{2p}\right]^2$$

Even if the threshold ratio is ideal, therefore, tolerances on operating points V_1 and V_2 will ultimately determine the LCD's multiplex potential.

Besides the static parameters just discussed, dynamic parameters, like speed of response and operating frequency, must also be taken into account. Speed of response, for instance, is a function of turn-on delay, rise time, and decay time. As shown in Fig. 4a, LCD rise and decay times are measured between 10% and 90% of maximum reflective contrast. Turn-on time is the sum of the turn-on delay and the rise time.

Between temperatures of 0°C and 50°C, LCDs have turn-on and turn-off times that vary from 50 to 500



5. Operating frequency. Threshold voltage varies with both operating frequency and temperature. To minimize this variation, as well as flicker, LCDs should be operated at 25 to 250 Hz. Moreover, the higher the frequency, the greater the drive power required.

milliseconds (Fig. 4b). In multiplexing, then, to avoid the perception of a visual flicker, the scan time should be set for 25 ms or less. (Since the turn-off time is much greater than 25 ms, the segments do not turn off between frames.) On the other hand, the turn-on time is smaller for multiplexed operation than for nonmultiplexed operation, because the turn-on delay is less. For multiplexed LCDs, the off voltage is greater than zero, which causes a shortening of the turn-on delay. There is no equivalent effect for the on voltage, so the turn-off time remains the same for multiplexed and nonmultiplexed operation.

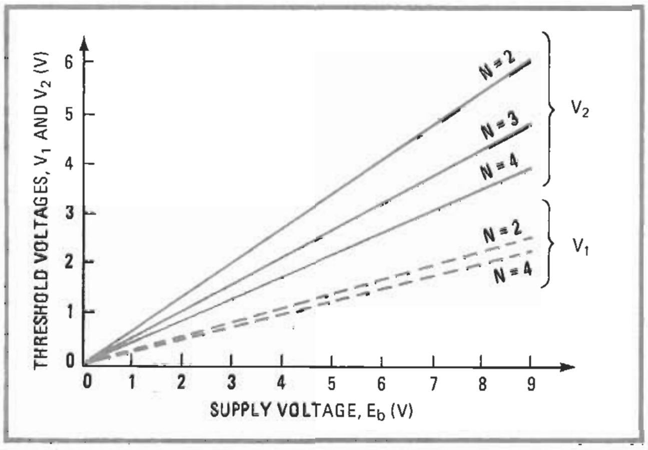
What about operating frequency?

Surprisingly, the highest operating frequency is not a function of the response time, but depends rather on device construction and the properties of the liquid-crystal material. Although some field-effect displays may be operated at multiplexing frequencies of up to tens of kilohertz, this is usually avoided for two reasons. First, the power required to drive the display increases with multiplexing frequency, and second, the cutoff characteristic of the liquid-crystal materials varies with both frequency and temperature (Fig. 5). For most field-effect materials, the operating frequency that minimizes both flicker and threshold voltage variation lies between 25 and 250 Hz.

As the number of multiplexed lines increases, the peak voltage on both the select and data lines must also increase to establish the correct on and off voltages. In some applications, especially those relying on a battery, the display must be selected to have a threshold voltage that matches the available supply voltage. Figure 6 shows the relationship between supply voltage (E_b) and the required LCD threshold voltages (V_1, V_2) for several segment drive conditions.

Calculating the threshold voltages

V_1 and V_2 may be expressed as a function of the number (N) of multiplexed lines, given the battery voltage available and assuming a unipolar select signal so that $V_s = E_b/2$. Under these conditions, the ratio of select to nonselect voltage is maximum, making the contrast ratio optimum. The thresholds become:



6. Selecting the right drive voltages. The thresholds for the select and nonselect voltages depend on both the available supply voltage and the number of multiplexed lines. The lower the supply and the larger the number of multiplexed lines, the smaller the select voltage will be. In contrast, the higher the supply voltage and the fewer the multiplexed lines, the greater will be the nonselect voltage required.

$$V_1 = E_b\left(\frac{N^{0.5}-1}{2N^{1.5}}\right)^{0.5}$$

$$V_2 = V_1\rho_{max}$$

With these equations, the required threshold voltages are easy to compute. For example, suppose a battery voltage between 4 and 5 v will power a ⅓-multiplexed (N = 3) display. The worst-case requirement on V_1 occurs when the supply is on the high side, because the higher the supply, the higher the nonselect voltage will be. Therefore, let E_b = 5 v and solve for V_1 = 1.3 v. Conversely, the lower the supply, the smaller will be the select voltage. So, threshold voltage V_2 may be found by letting E_b = 4 v, and thus V_2 = 2.1 v.

Most of the multiplexing considerations thus far have been limited to an examination of measurable parameters based on the electrooptic response curves of LCDs. But is there any correlation between these measurable parameters and what the viewer actually sees? The answer is yes. However, as with any art form, beauty is in the eye of the beholder. Contrast-voltage curves at a multiplicity of viewing angles and an iso-contrast map of the viewing space will help, but there is no substitute for actual tests by human observers. Only user judgment can take into account such factors as viewing distance and angle, character height and font, viewing background, and the effect of ambient light conditions.

Although multiplexing is more complex with LCDs than with other display technologies, the benefits are worthy of consideration. Multiplexing can greatly reduce the number of interconnects, while giving up very little in display contrast. Moreover, multiplexing permits direct interfacing to microprocessors—a practical alternative to expensive peripheral circuits. With improved liquid-crystal materials under development, multiplexing will become easier. Indeed, large dot-matrix arrays for video games and portable data terminals are just some examples of the possibilities open to LCD technology. ☐

improving the readability of seven-segment displays

Seven-segment displays of various types are now the most popular format for digital display in many applications. The most common decoder-driver used with these displays is the 7446 (or 7447) which may be used with displays of the LED or Minitron type.

The results obtained with these decoders are, in general, very good, but the format of the digits 6 and 9 leaves something to be desired. These digits are decoded as shown in figure 1b and most people would agree that they are greatly improved by the addition of segments 'a' and 'd' respectively, as in figure 1c. The Japanese tend to use this presentation in their electronic calculators.

This format may be obtained with the 7446/7 by parallelling the 'a' and 'd' outputs with external transistors which are turned on when either a 6 or a 9 is displayed (see figure 2). The only problem is to derive a suitable code from the BCD input to drive the transistors. A '1' must be applied to the base of the appropriate transistor when either a 6 or a 9 is displayed.

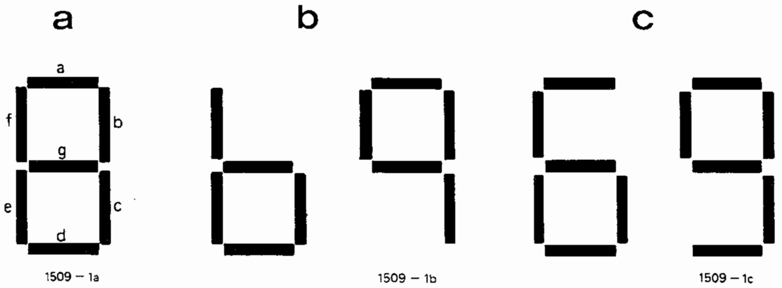
Looking at the truth table for the 7446/7 it is apparent that when a 6 is displayed columns B and C of the BCD input code are '1'. Column C cannot be used, however, for looking at the rest of this column it can be seen that column C is also a '1' for digit 4. Since 4 does not utilise segment 'a' input C cannot be used to drive the transistor for this segment. Input B may be used however since the other digits with a '1' in this column are 2, 3 and 7 which all use segment 'a'.
Turning to digit 9 it can be seen that there are '1's' in columns A and D of the BCD code. A obviously cannot be used since digit 1 also has a '1' in this column but does not contain segment 'd'. Column D may be used, however, since the only other digit with a '1' in this column is 8, which contains segment 'd' anyway. ◆

Figure 1. a. Alphabetic designation of the seven segments of a display. b. Usual format of digits 6 and 9. c. Improved format of digits 6 and 9.

Figure 2. The output stage of a 7446/7 seven-segment decoder with the external transistor in parallel.

Figure 3. The complete circuit for the improved readability display using a 7447. The 7446 has an identical pinout.

1



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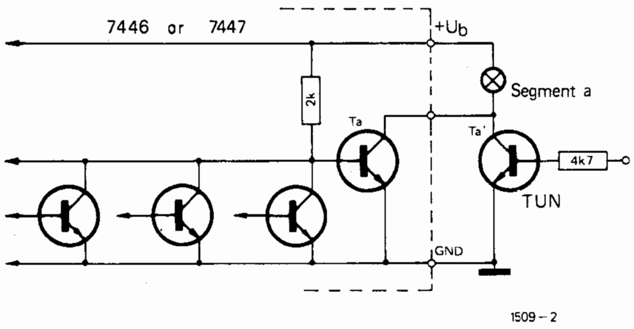
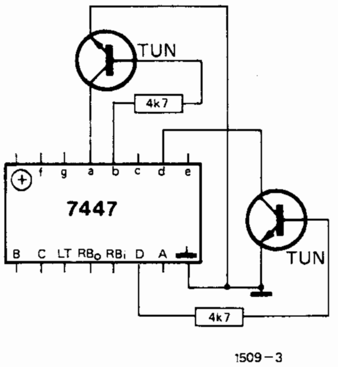


Truth table for the seven-segment decoder without the additional transistors.

Digit	D	C	B	A	a	b	c	d	e	f	g
0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	1	1	0	0	1	1	1	1
2	0	0	1	0	0	0	1	0	0	1	0
3	0	0	1	1	0	0	0	0	1	1	0
4	0	1	0	0	1	0	0	1	1	0	0
5	0	1	0	1	0	1	0	0	1	0	0
6	0	1	1	0	1	1	0	0	0	0	0
7	0	1	1	1	0	0	0	1	1	1	1
8	1	0	0	0	0	0	0	0	0	0	0
9	1	0	0	1	0	0	0	1	1	0	0

3



hexadecimal display

H.H. Arends

When working with microprocessors hexadecimal notation is frequently used to enter and read out data. Hexadecimal digits can be decoded and displayed in a number of ways. The first method is to use a commercial HEX display with built-in decoder, such as the Hewlett-Packard 5082-7340. However, these devices are fairly expensive. The second approach is to programme a display routine into the microprocessor. However, this must be stored in a ROM and occupies approximately 200 bytes of memory, depending on the microprocessor type.
The method described here uses a normal BCD to seven-segment decoder-driver to decode digits 0 to 9 in the conventional manner, whilst digits A to F are taken care of by a dual 1-of-4 decoder and a simple diode decoding matrix. This approach is considerably less expensive than commercial HEX decoders and does not require memory space nor a special ROM, which is the case with the software method.
The circuit of the HEX decoder is given in figure 1. To decode digits 0 to 9 a 7448 decoder is used with a common-cathode LED display instead of the more usual 7447 and common-anode display. This is to allow a wired-OR function between the outputs of the 7448 and the outputs of the 74155, which decodes A to F. The 7448 has active-high outputs. This means that when a particular segment of the display is not lit the relevant output transistor of the 7448 is turned on, shorting out the segment. When a segment is lit the output transistor of the 7448 is turned off, so current flows through the display segment via one of the series resistors R1 to R8.
Digits 0 to 9 are decoded in the usual manner by the 7448. Gates N1 and N2 perform the Boolean function $F = \overline{(B + C)}\ D$. As can be seen from the truth table the output of N2 is high for digits 0 to 9. This inhibits the 74155, so that all outputs of the 7407 buffers are turned off.
For digits A to F the output of N2 is low. This activates the lamp test input of the 7448 so that all outputs are switched off. This would result in all segments of the display being lit, but the 74155 is now active. Outputs 2 to 7 go low in turn for digits A to F, and via a diode matrix shown in figure 2 these outputs are used to short out the segments that are not required in each character.
One small disadvantage of this circuit is that, since the 7448 decodes a 6 without lighting segment 'a', the 6 is indistinguishable from b. To overcome this problem the decimal point of the display is lit for digits 0 to 9 and extinguished for A to F.

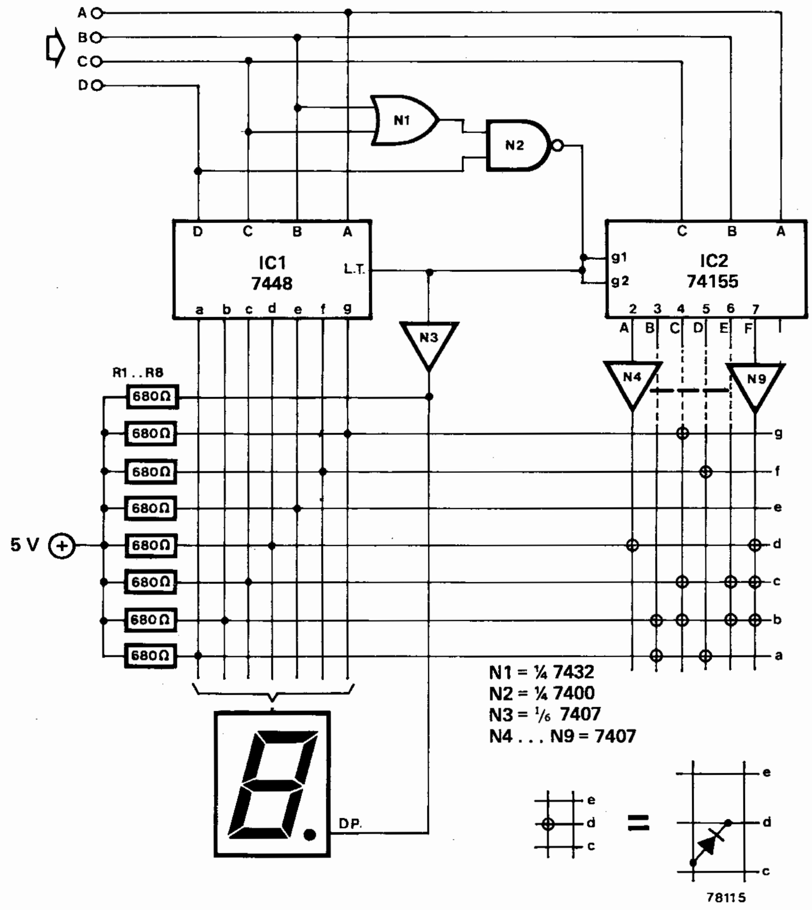


Table 1

	D	C	B	A	F	output 74155 2	3	4	5	6	7
0	0	0	0	0	1	1	1	1	1	1	1
1	0	0	0	1	1	1	1	1	1	1	1
2	0	0	1	0	1	1	1	1	1	1	1
3	0	0	1	1	1	1	1	1	1	1	1
4	0	1	0	0	1	1	1	1	1	1	1
5	0	1	0	1	1	1	1	1	1	1	1
6	0	1	1	0	1	1	1	1	1	1	1
7	0	1	1	1	1	1	1	1	1	1	1
8	1	0	0	0	1	1	1	1	1	1	1
9	1	0	0	1	1	1	1	1	1	1	1
A	1	0	1	0	0	0	1	1	1	1	1
B	1	0	1	1	0	1	0	1	1	1	1
C	1	1	0	0	0	1	1	0	1	1	1
D	1	1	0	1	0	1	1	1	0	1	1
E	1	1	1	0	0	1	1	1	1	0	1
F	1	1	1	1	0	1	1	1	1	1	0

References

1. Kartalopoulos, S.V. 'Display letters and symbols on a seven-segment display'. Electronic design 25, December 6th 1976, page 108.
2. Wesselhoeft, U. 'Mikrocomputer daten und adressen schrittweise angezeigt'. Mikroprozessoren hardware, p-p 139/140.
3. Kampschulte, H. Experimenting with the SC/MP. Elektor 34, February 1978, p-p 228-238.

Center Tuning Indicator

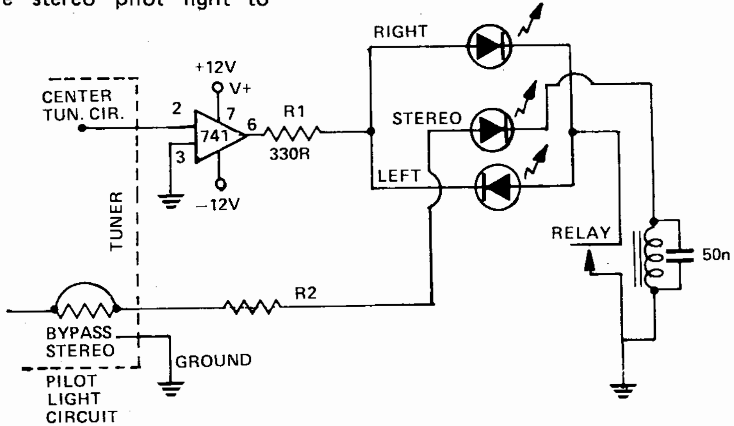
Gervais de Courval

The circuit proposed here, built around 741, is designed as a simple ultra low cost alternative.

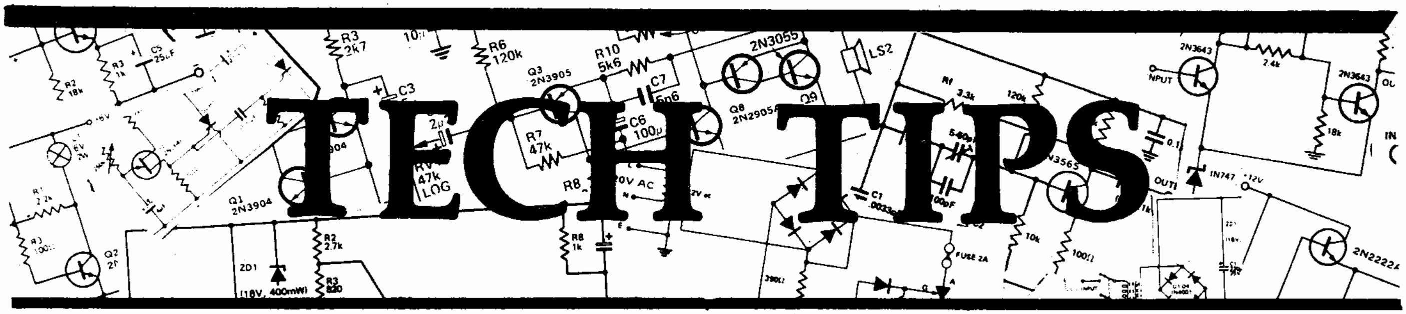
The opamp acts as a zero volt detector and will blink the LEDS within a few milivolts of either side of the virtual ground. When both LEDS appear to glow equally, the tuner cannot be nearer to optimal center tuning.

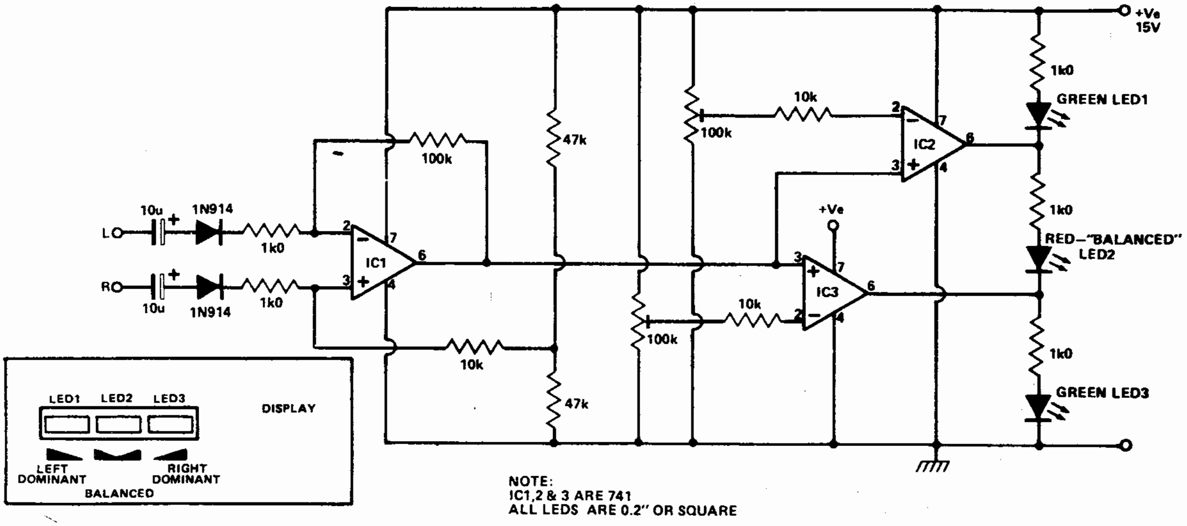
A reed relay has been included in series with the stereo pilot light to switch on the center tuning indicator only when a stereo program is detected: The result is an eye catching indication of what side of the channel you are on.

There are no critical values. Simply chose a reed relay to suit the voltage of the stereo pilot light circuit. Although you may have to change the value of the resistor (R2). This limits the current through the stereo pilot LED. If this is the case, play it safe and keep the current drain as small as possible for proper operation .



TECH TIPS





Stereo Balance Meter

G. Durant

Balance on a stereo amplifier is usually set by ear, but this of course can be very difficult to judge. If an amplifier has a balance meter at all, it is usually of the centre-zero moving coil type — bulky, old-fashioned looking and expensive. This circuit is designed to overcome all of these problems.

The outputs from each channel are fed to the two inputs of IC1, this being connected as a differential amplifer. If the left and right channels are of equal levels, the output of IC1 will have its output at about halfway between the supply rails. If the left channel gets above the level of the right channel, the output of IC1 will approach the 0 V rail. If the right channel is loudest, the output becomes positive.

IC2 and 3 are also differential amplifiers, but in this case they are driven by the output of IC1. LEDs form a dispiay at the outputs of the two ICs. Pin 2 of ICs 2 and 3 each go to a preset across the supply. In practice, the preset in conjunction with IC2 is set to hold pin 2 slightly above 0 V and the preset connected to IC3 is set to hold pin 2 just below supply voltage. These settings, however, must be set by trial and error so that the circuit works accurately.

The output of IC1 is connected to the non-inverting inputs of IC2 and 3. If the output of IC1 approaches the supply rail, the outputs of ICs 2 and 3 will also go high, thus illuminating LED 3. This would happen if the right channel were dominating. If the left channel were dominant, the outputs of ICs 2 and 3 would be low, thus illuminating LED 1. If the two channels were equal in amplitude, the outputs of ICs 2 and 3 would be high and low respectively, lighting up LED 2.

The circuit can easily be added on to a ready constructed unit without using up large amounts of panel space, or used as a add-on unit for a hi-fi system. The unit draws about 20 mA, so battery operation is practical.

LED display shows beat frequency

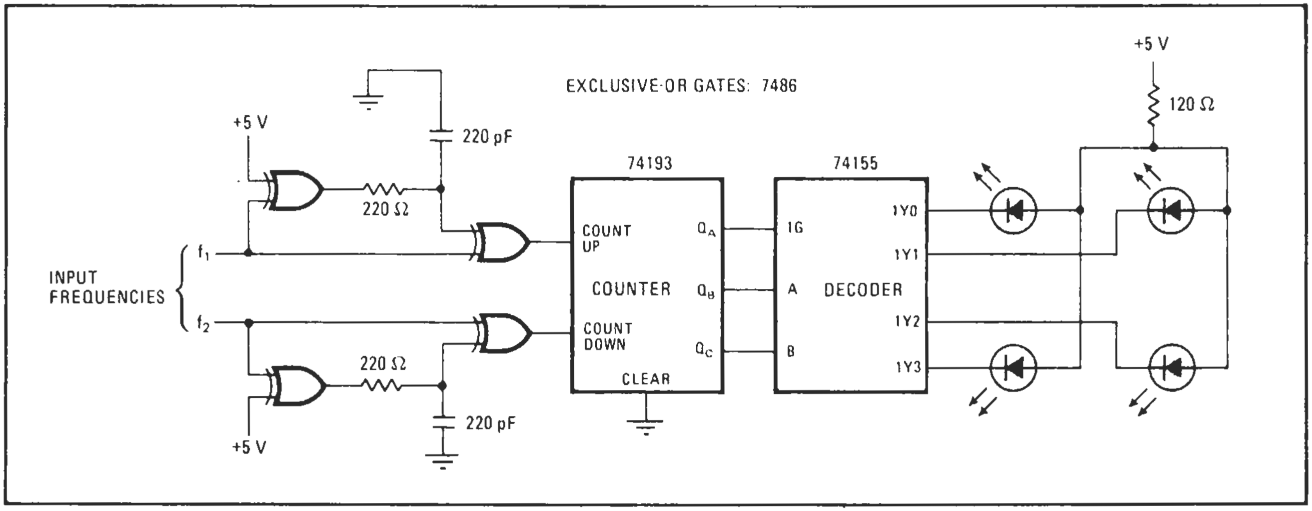
by Sergio Franco
Oberlin College, Oberlin, Ohio

A simple, easy-to-use beat-frequency indicator can be built at a cost of only about $5. The circuit, which employs four light-emitting diodes as its display, can be used in a variety of applications, but is particularly suited to the tuning of musical instruments.

The heart of the circuit is a 4-bit synchronous up/down binary counter. After undergoing proper shaping by exclusive-OR gates, input frequencies f_1 and f_2 are applied, respectively, to the count-up and count-down terminals of the counter. The net count, therefore, will be in either the up or the down direction, depending on whether f_1 is greater than or less than f_2. When f_1 equals f_2, the counter alternates between two consecutive states, producing a net count of zero.

These three input conditions can be easily displayed by means of four LEDs arranged in a circle. (A decoder is used to drive the LEDs from the counter output lines.) Only one LED is on at a time. Therefore, when f_1 is greater than f_2, a dot of light is produced that rotates clockwise; when f_1 is less than f_2, the dot rotates counterclockwise; and when f_1 equals f_2, there is no rotation.

Furthermore, since the exclusive-OR shaping network produces a sharp negative pulse for each transition of the two inputs, the dot of light moves one step for every beat. The rate of apparent rotation of the dot, then, is an exact indication of the beat frequency. □



LEDs show the beat. Economical circuit displays the difference frequency between its two inputs, as well as indicating their relative magnitude. Since only one LED conducts at a time, what is displayed is a dot of light. The dot rotates clockwise when f_1 is greater than f_2 and counterclockwise when f_1 is smaller. The rate of rotation is the beat frequency. When f_1 equals f_2, the dot remains stationary.

Graduated-scale generator calibrates data display

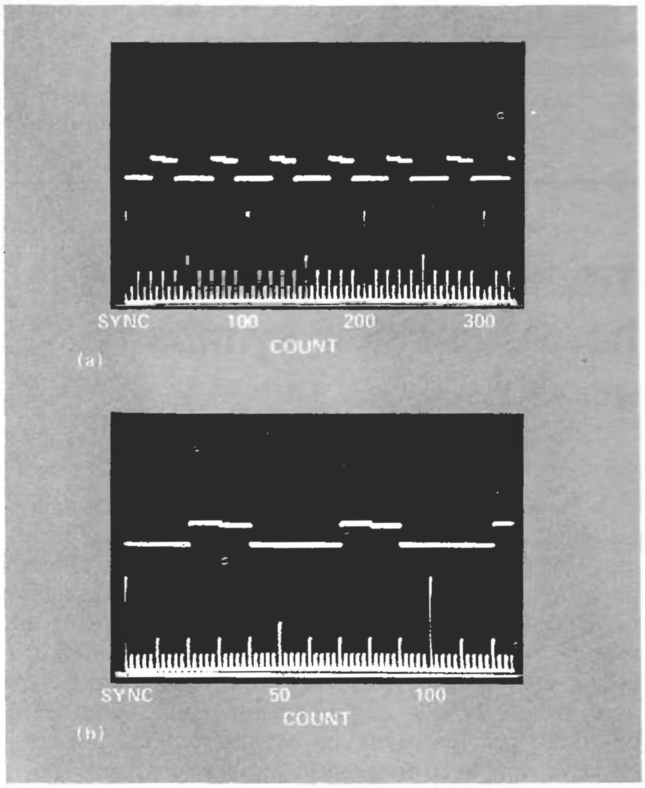
by Ken E. Anderson
IBME, University of Toronto, Canada

Scope and chart displays may require reference signals to indicate timing or counting scales. The circuit shown here is added to the display portion of a real-time digital data correlator at a cost of $3 or $4 to provide a graduated scale below the correlation display on a two-channel scope. Although it lacks the precision of a cursor, the continuous scale offers greater versatility and speed of operation. It also references the display data when stored on hard copy.

The photographs in Fig. 1 show two scales that can be generated to aid the observer in determining the pulse count or time at which a wave form rises or falls. In the lower trace of Fig. 1(a), every fifth clock pulse is indicated, and in Fig. 1(b), every second clock pulse is indicated. The upper trace in each photo shows a wave form that goes high at count 20, low at 40, high again at 70, low again at 90, and so forth. These counts can be read easily and accurately from the reference scales.

As shown in Fig. 2, the scale generator is remarkably simple. For two decades of unique graduations, two decade counters (7490) and one package of open-collector AND gates (7409) are required. These gates switch a crude voltage-divider digital-to-analog converter, generating the various pulse heights. Gate A in Fig. 2 ANDs the system clock with the basic scale unit—five in Fig. 2(a) or two in Fig. 2(b)—enabling the voltage-divider output to rise. Low gates B, C, or D (or combinations) clamp the output to appropriate levels as determined by R_1, R_2, R_3, and R_4. As higher-order counters progres-

1. Measurement aids. Graduated scales are generated on dual-trace scope or chart to facilitate probing of displayed data. In lower trace (a), every fifth clock pulse has a scale. In lower trace (b), every second clock has one. From these scales observer sees that upper trace rises at count 20 and falls at count 40. Circuits for generating scales are shown in Fig. 2.

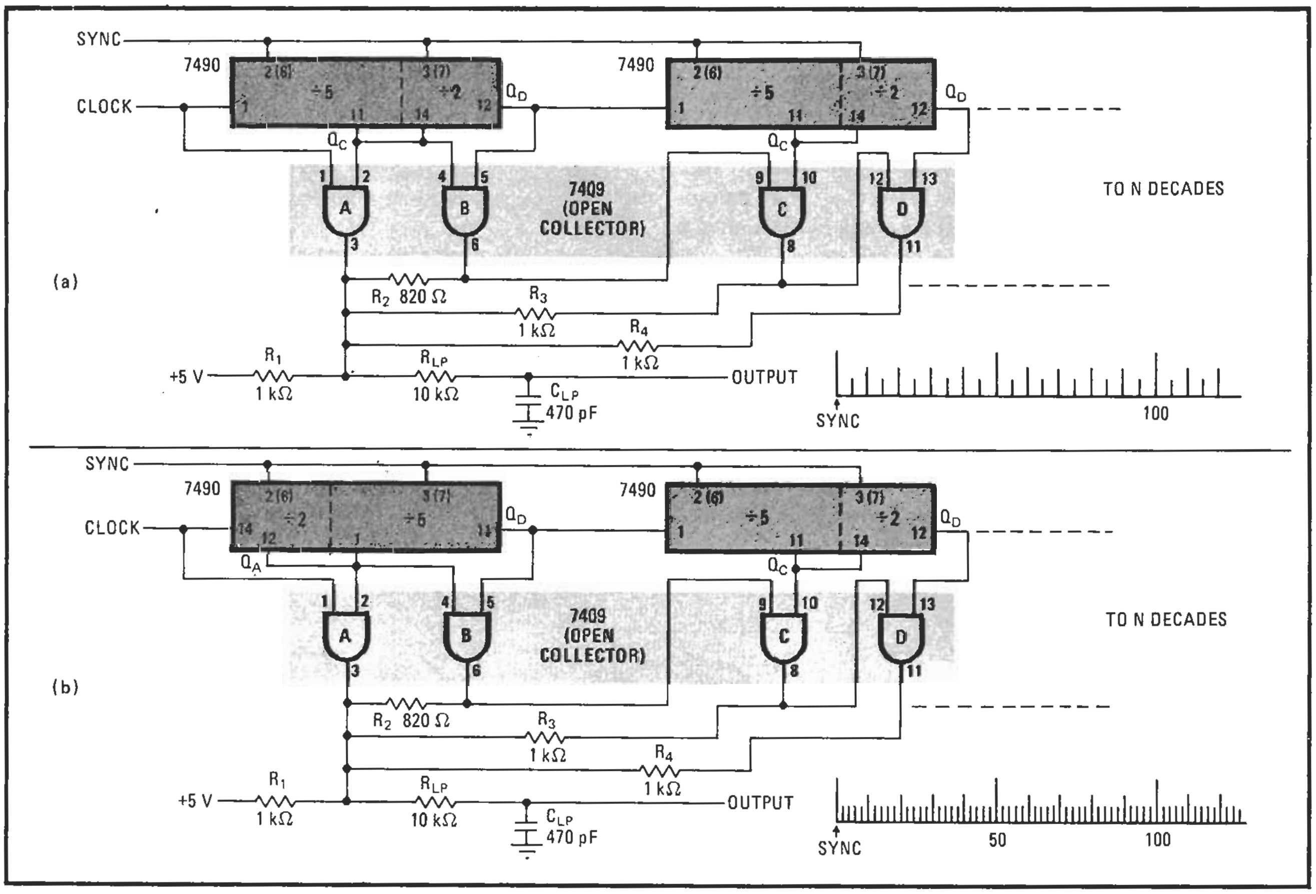


sively flip high, taller graduations are created.

Use of the 7490's quinary and binary counters obviates the need for extensive decoding. For example, the output of gate A in Fig. 2(a) goes high on the clock high of count 4, (9, 14, 19, etc): gate B ANDs this high signal with counts 5–9 (15–19, 25–29), thus decoding count 9 (19, 29). The cascaded decade circuit decodes counts 49 and 99. For display on a scope, a low-pass filter or integrator consisting of R_{LP} and C_{LP} is added to improve the appearance of the scale by increasing the rise and fall times of the pulses. Relative pulse heights may be altered via resistor ratios of R_1, R_2, R_3, and R_4. However, to ensure adequate noise margin at inputs of gates C and D, R_1 must not be greater than R_3 or R_4.

Synchronization of the scale generator to the scope and system output is accomplished by providing a pulse to reset the counters to zero (pins 2, 3) for graduations on counts 4, 9, 14, 19, etc. or to maximum (pins 6, 7) for graduations on counts 5, 10, 15, 20. . . .

The use of this graduated-scale generator can ensure



2. Here's how. Circuits for generating graduated scales of incoming clock pulses use decade counters. Two AND gates per decade switch voltage-divider d-a converter to produce various pulse heights; the AND gates have open collector outputs. Each counter in (a) divides by 5 and then by 2 to provide scale with a basic unit of 5 counts. In (b), first counter divides by 2 and then by 5 to provide a basic unit of 2. Second counter divides by 5 and then 2 to enhance pulses at 50 and 100. Values of R_{LP} and C_{LP} shown here are chosen for use with a 10-kHz clock.

precise tagging of displayed data even when the scope is being operated in the magnify, delayed-sweep, and uncalibrated-sweep modes. Other applications include generation of a time scale for sweep calibration of scopes (when clocked by a high-precision source) and generation of a clock-pulse scale for troubleshooting cyclic sequences. The latter application is illustrated by the upper traces in the two photographs; this waveform is actually the output of the second bit of the second quinary counter (pin 8 of the second 7490). □

DRAWING BOARD

ROBERT GROSSBLATT,
CIRCUITS EDITOR

Let's think about our display

ONE OF THE WORST, AND MOST COMMON traps you can fall into as a designer is not knowing when a job is finished. There's always that last minute brainstorm, the "one more terrific idea," that has to be worked into the final design. I can't tell you how many times that's happened to me. And even though I'm aware of the problem, it's really easy to get caught up in it.

The best way to avoid that is to know what you want to accomplish when you first sit down at the bench. A list of design goals and a set of criteria may seem silly at the onset of a design but, take it from me, you'll read them over and over as you get deeper into the project. No design is static—ideas mature and goals change. What you wind up with at the end is probably going to bear only a vague resemblance to what you originally set out to do.

The reason I'm mentioning that is because it's my way of apologizing again for changing my mind in last month's column. I had originally felt that a lot more could be learned by setting up a buffer-and-latch type arrangement for external access to the memory. When I began putting the design together, the number of chips started to pile up and before I realized it I was looking at designations like IC26! Clearly, the project was past what some people euphemistically like to refer to as "manageable size." Direct Memory Access (DMA) is a perfect way of getting in and out of our Z-80 system. It can be a little tricky, however, so let me know if you have any problems and I'll do my best to give you a hand.

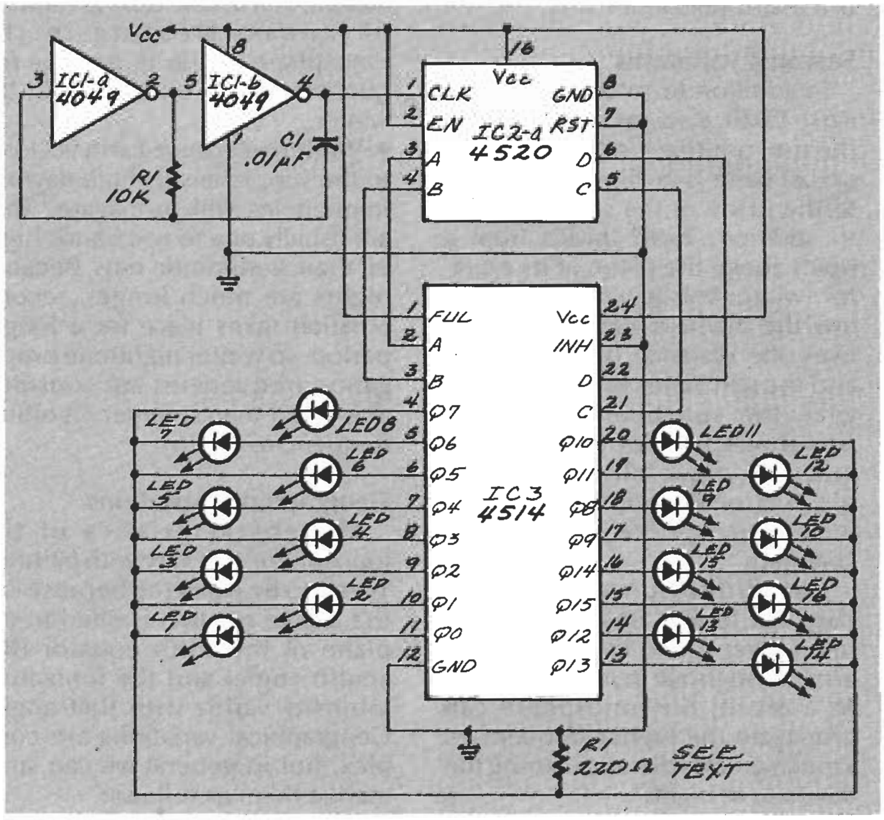


FIG. 2

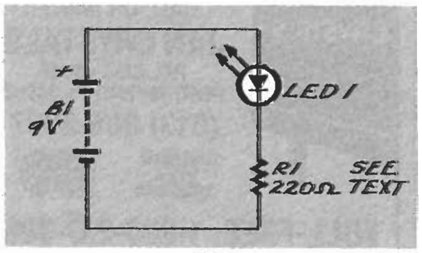


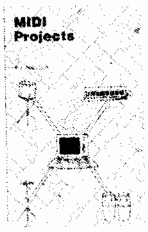
FIG. 1

But now for something completely different.

There are some things in electronics that show up no matter what kind of circuit you're designing. Just about everything from an electric toothbrush to Star Wars has to deal with the problem of how best to display data. Now, if all your circuit needs is a few LED's there's not much of a problem; but if you've got a lot of data that has to be displayed, you're going to have to give it some thought.

LED's are notoriously power hungry. Batteries can go dead really fast when you have more than a couple of LED's lit up at the same time. The standard way around that problem is to "multiplex" the display. That's a twelve

continued on page 97



DRAWING BOARD

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dollar word to indicate that you can take advantage of retinal persistence. If the LED's are turning on and off very quickly, it will seem like they are on continuously.

When you're dealing with LED-based displays, there are several ways to go about multiplexing them. LCD displays can be multiplexed as well, but they're much slower and don't respond well to rapid strobing. And since they basically run on flea power, there's not much of a point in multiplexing them.

To get started, let's suppose that you have sixteen LED's in your display; all of them will be on some of the time, and you're running the circuit off a 9-volt battery. If we do a bit of arithmetic, we can see what's going to happen to the battery. A fresh 9-volt battery is usually somewhere around 8 volts and a value of 220 ohms is a good ballpark figure for a current-limiting resistor. The simplest kind of circuit configuration is shown in Fig. 1. Assuming the voltage drop across each LED to be 1.7 volts, we can apply Ohm's law as follows:

$$I_{LED} = V/R$$
$$= (V_{BAT} - V_{LED})/R$$
$$= (8 - 1.7)/220$$
$$I_{LED} = 28.6 \text{ mA}$$

So if you were driving 16 LED's, you would have to supply almost half an amp—and that's a significant amount of power!

The circuit in Fig. 2 is one way of multiplexing the same 16 LED's. All we have is a simple clock driving a 4514. The outputs of the decoder are normally low and the selected output goes high. A similar chip, the 4515, has normally high outputs so you can use the circuit for LED's with a common leg tied to either ground or power, whichever you prefer.

The clock is a standard one made up of a pair of inverters driving a 4520 binary counter, which is being used to make the decoder scan across its outputs. You might consider that to be an unnecessarily complex way of doing a simple job, but the circuit is good for demonstrating the basic idea. There are lots of ways to do the same job with fewer IC's and we'll be looking at several of them later on.

The components shown for the clock cause it to oscillate at about 10 kHz. Assuming that it takes no time at all to switch between the outputs, and that the CMOS chips are using no power, you're going to be able to light all 16 LED's with even less current than the circuit in Fig. 1 uses. Even if you allow 10 mA for each of the IC's, you're still looking at only 60 mA for the entire circuit—and, for the record, there's no way those CMOS IC's are going to want 10 mA each.

The price you pay for multiplexing a display is that each of the LED's will appear to be dimmer—how much dimmer depends on a number of things. The efficiency, size, and color of the LED's are all going to have an effect on the apparent brightness; and don't forget that each LED is only on less than one sixteenth of the time.

The easiest way to boost the brightness of a multiplexed display is to drop the value of the current-limiting resistor. Unfortunately, there's no way to tell how much of an increase in brightness you're going to get as you increase the current. Each LED reacts differently. You can, however, choose a value for the current-limiting resistor that will give you the maximum allowable current through the LED—usually about 70 mA or so for the standard T-1 ¾-size LED's.

If the multiplexing frequency is high enough, you can push really huge amounts of current through the LED. Standard jumbo LED's can handle 1 amp if it's

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restricted to a 1 microsecond pulse and a .3% duty cycle! For the purposes of our test circuit (Fig. 2), don't drop R2 much below 47 ohms, because you won't get much more brightness below that—but there's a very good chance you'll send the LED up in smoke. Also, make a few calculations to be sure that you don't exceed the current-limiting resistor's power rating.

We have our clock running at about 10 kHz to make sure that there's no flickering in the display, but that's really overkill for a 16-LED display. Standard movie projectors run at 24 frames per second and provide a good illusion of continuous motion. Since they also use a 180 degree shutter, they have an effective duty cycle of 50 percent. Since our demonstration circuit keeps each LED illuminated for one complete clock cycle, the duty cycle isn't important yet; but keep it in mind.

In order to light our display at film speed, we have to use a clock with a frequency of 16×24 or 384 Hz. You can drop the clock to that frequency by replacing C1 with a 0.2 µF capacitor. The LED's should appear brighter and you shouldn't see them flickering. I say "shouldn't" because biology isn't as precise as electronics. Experiment with different clock frequencies on your own and see "how low you can go" while still maintaining the illusion of constant illumination. **R-E**

DRAWING BOARD

ROBERT GROSSBLATT,
CIRCUITS EDITOR

A complete circuit

OVER THE LAST COUPLE OF MONTHS we've gone through the steps needed to design custom-character generators and looked at some simple ways to use them. Now let's turn all the pieces into a useful circuit.

The handiest thing to come up with is a way to use one character generator to drive several digits.

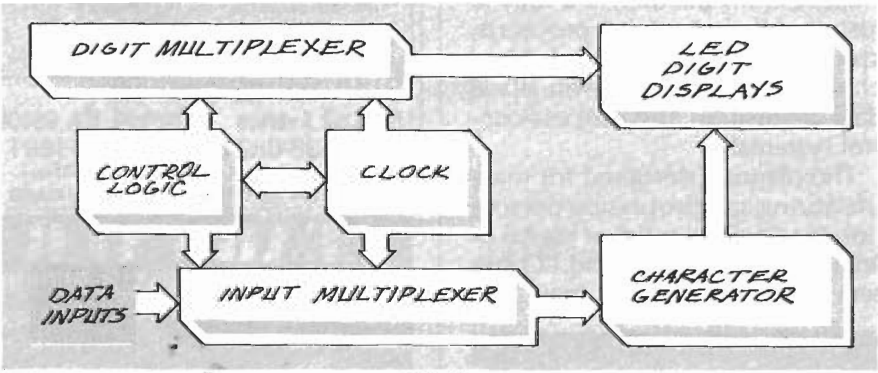

FIG. 1

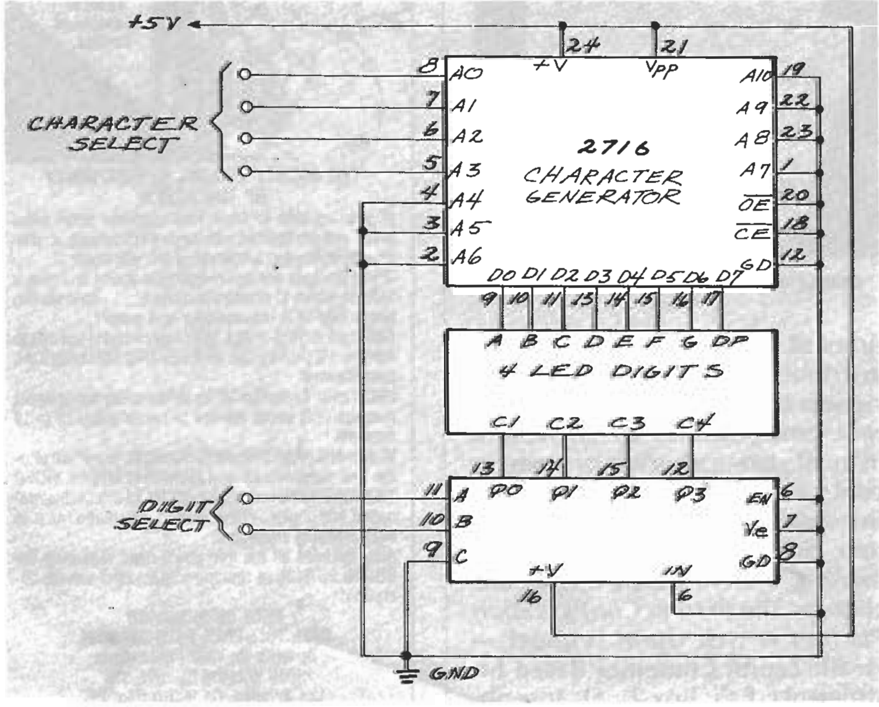

FIG. 2

257#1 OE	SEL	257#2 OE	SEL	DISPLAYED DIGIT
L	L	H	X	INPUT 1
L	H	H	X	INPUT 2
H	X	L	L	INPUT 3
H	X	L	H	INPUT 4

FIG. 3

OE	SEL#1	SEL#2	DISPLAY
L	L	X	INPUT 1
L	H	X	INPUT 2
H	X	L	INPUT 3
H	X	H	INPUT 4

FIG. 4

The basic idea here is to build a general-purpose display circuit.

Let's lay down some criteria:

1. The circuit will drive four digits.
2. Each digit will have its own set of inputs.
3. Only one character generator will be used.
4. The circuit will display all the hex digits from 0000h to FFFFh.

Even though we've been designing a character generator that can handle a lot of the ASCII characters, limiting our display to hex will keep the circuit simpler. If you absolutely must display ASCII characters, the circuit will be basically the same, but you'll need more bits assigned to each of the digits. A hex display only cares about the lower four bits while a full ASCII display has to deal with seven bits.

When you come right down to

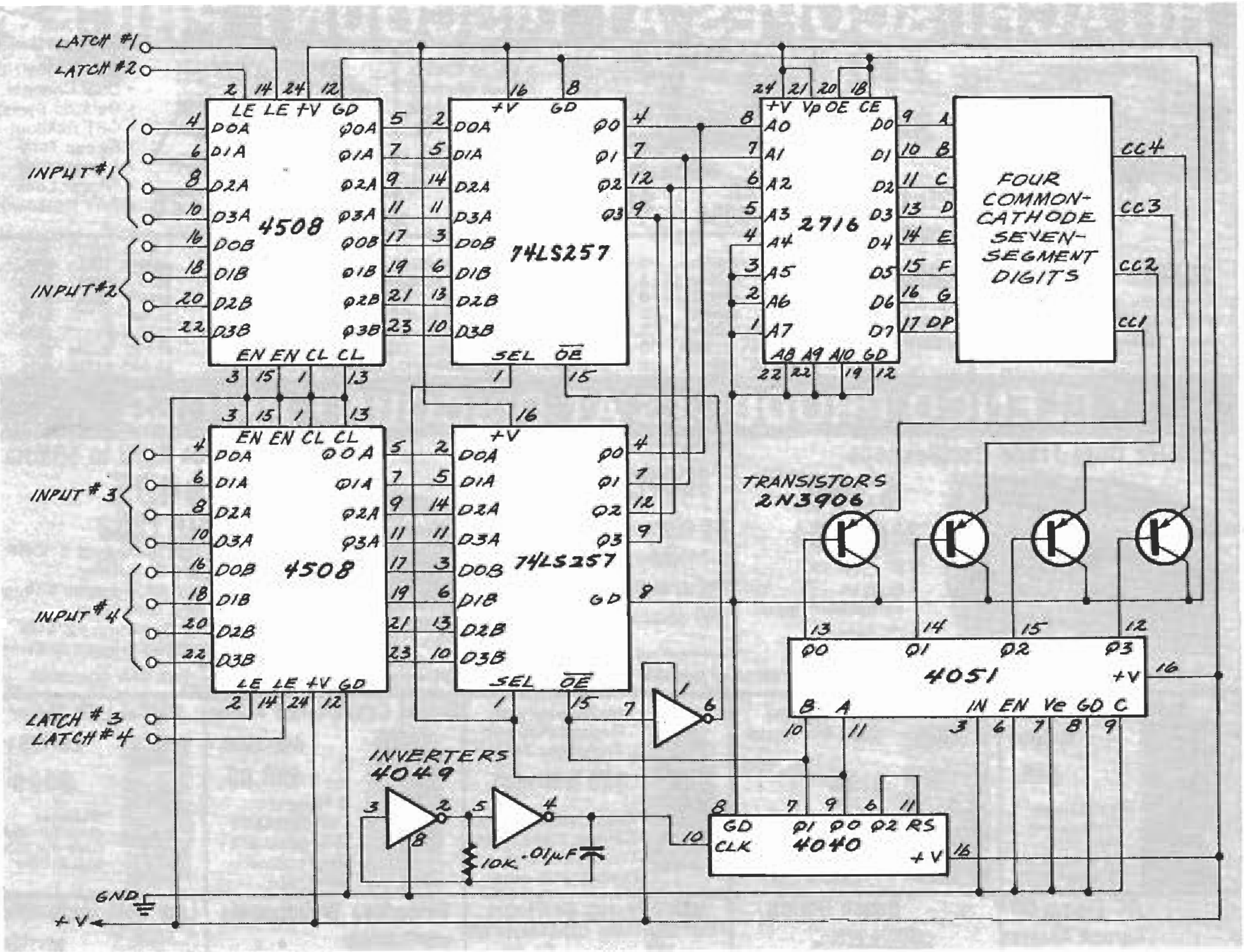

FIG. 5

it, we want the display circuit to be your basic black box with sixteen inputs—four for each of the four digits we'll be driving. Since we're actually building something that can be used elsewhere, we can eliminate some of the parameters we put into the EPROM. We're already disregarding the ASCII stuff and now we'll make the decision to use common-cathode displays.

That last decision is no big deal because it's a relatively trivial thing to convert the circuit to work with a common-anode digit...but we're getting ahead of ourselves.

The block diagram of the circuit we'll be designing is shown in Fig. 1. The heart of the circuit is really the control logic because it has the job of keeping everything in sync. We have to be sure that when we're sending character number 1 to the input multiplexer, that we're also turning on seven-segment LED number 1. If things get out of sync you might have something up on the display but it's not going to be anything useful.

The starting point of the circuit is shown in Fig. 2. It's similar to the circuit that we looked at in May, but there are two main differences. The first is that we're only using A0–A3 on the EPROM and the second is that the 4051 is going to drive only four digits so the "C" input (pin 9) is tied low. The same thing is done with all of the unused EPROM address lines.

We've already decided on the 4051 as the digit multiplexer so let's take a look at the input multiplexer as well before getting to the control logic. After all, you can't design control logic until you know what you have to control.

Just as the 4051 will sequentially turn on one digit after another, the input multiplexer has to select the corresponding digit data to be displayed. What we need is the electronic equivalent of a four-pole, four-position rotary switch, and one way to do that is to use a pair of 74LS257's. You can use the TTL version of the chip or the 74HC257 or 74HCT257 pin-equivalent CMOS parts.

The inputs that will appear at the outputs depend on the state of the SEL input. Making that pin low will select the first set of inputs and making it high will select the others. What makes the 257 a good IC for our application is that it also has an OUTPUT-ENABLE pin so that our output can have three states.

Now that we know what multiplexers we'll be using, we can work out what we need for control logic. Designing this kind of circuitry can be a really brain-bending exercise but one way to cut it down to size is to use a truth table like the one shown in Fig. 3.

It may seem a bit confusing at first glance, but one thing it tells us right away is that the OUTPUT-ENABLE pins of the 257's are always opposite each other. When one is high, the other is low, and vice versa. That means we can tie them

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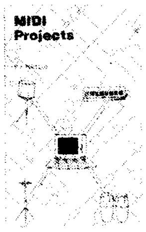

DRAWING BOARD

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together through an inverter and eliminate one column in the table. We can tie the two SEL inputs together as well since their state is only important when the chip is enabled. By re-arranging the truth table slightly we'll wind up with the one shown in Fig. 4, and that, as you should realize, is simple to implement because it's just counting up in a plain binary.

Not only that, but we can use a straight binary counter and use the "C" output to toggle the reset. Putting that into practice will produce a circuit like the one shown in Fig. 5. You should work out the logic in your own mind to make sure that you understand what's going on there.

The last part of the control logic is the counter and that can be any binary counter. You can use a 74LS93, 4040, half a 4520 or 4518, half a 74LS393, or just about anything that can count up to four in binary. The 4040 in Fig. 5 is a good choice because it's easy to use and is a mainstream CMOS part, but don't hesitate to use something you happen to have lying around.

The circuit we've come up with will fill all the design criteria we laid out earlier but it has three sections we still have to go over. The first is the clock, the second is the input latching, and the third is the use of pass transistors to drive the cathodes.

Some time ago we spent several columns talking about the ins and outs of scan oscillators and we found that you can use any frequency as long as it's high enough to eliminate flickering. Anything over 10 kHz or so will fill the bill and any oscillator capable of driving the clock inputs will be as good as any other. I've built mine out of a pair of inverters but if your application has a handy clock line that fills those minimal requirements, you may use that.

Input latches aren't really necessary but they can be useful if the data you want displayed doesn't stay around too long. That would be the case if you want to snatch bus data when a certain pulse shows up elsewhere in the circuit.

I'm using 4508 octal latches but only because I happened to have a bunch of them in the parts box. Notice that I didn't say "junkbox"—the only thing junk parts are good for is building junk. One thing that's nice about 4508's is that they're really two separate four-bit latches in a single package.

The last thing to talk about is the use of pass transistors. If you put together the circuit we showed you in May you probably noticed that the display was rather dim. There's nothing you can do about the scan time, but it is possible to zip more current through a digit when it's selected. That is exactly what the pass transistors are doing.

One disadvantage of that approach is that the brightness of the digit will depend somewhat on how many segments are being lit, but it's not enough of a problem to make the use of individual current-limiting resistors in your circuit an absolute necessity.

Breadboard the circuit of Fig. 5 and feed the sixteen inputs with two cascaded 4040's. You'll see the display count up in true binary, and you'll also know that the circuit works. The circuit is extremely useful and it's well worth the time to generate a PC board for it. The complexity is such that it will more than likely require a double-sided board, but once you've got it done, you can make as many of them as you want. I know it's not easy to produce a double-sided board, but there are some tricks you can use to make the job easier. We'll be looking at that, and some other things as well, next time. **R-E**

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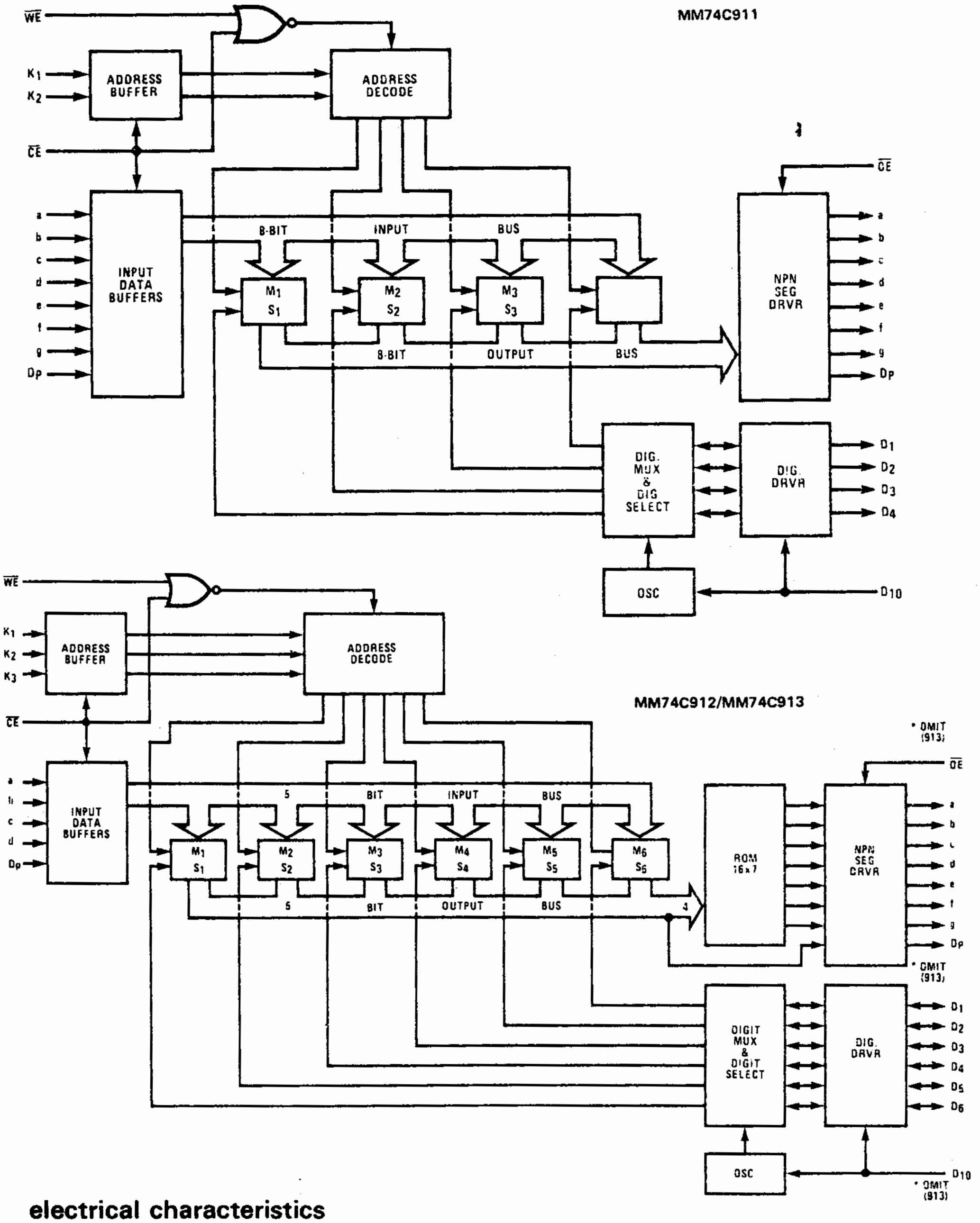
The display controller serves as an interface element between the bare machine and the controlled display. The display controller normally receives input data and digit address information and then controls a seven-segment display, providing direct segment drive and internal multiplexing of all digits. The display controller provides a random access to the master portion of an internal register selected by an address operation. Normally an internal oscillator will sequentially address the slave portion of the internal registers; however, it is also possible for the user to randomly address the slave portion of the internal registers via the digit lines by use of the digit I/0 control pin. The display controller will be capable of both segment and digit expansion, extending its use to alphanumeric 16-segment displays or 12-digit calculator stick displays.

The display controller is a CMOS circuit constructed on the buffed guard band process, limiting it to five-volt operation. The segment outputs has an NPN source transistor and an N-channel sink transistor. The segment outputs can be tri-stated by use of the output enable pin. The digit I/0 port is controlled by the digit I/0 pin. Used as an output the digit lines are sequentially strobed by the internal oscillator and the data multiplex to the segment outputs. Used as an input only one digit line at a time can be high. Data information from the selected digit appears at the segment output. The internal oscillator is inhibited. The register being addressed by the input address and input data is completely independent of the register being addressed by the digit input and segment output information. The digit output drive is a standard B series specification.

Three versions of the display controller will exist. The MM74C911 will multiplex four digits with 8 bits of input information and comes in a 28-pin package. The MM74C912 will multiplex six digits with ROM information with the ROM addressed by 4 data bits. The decimal point input does not address the ROM and goes directly to the output. The MM74C912 is capable of digit expansion. The MM74C911 is capable of both digit and segment expansion. A third version, the MM74C913, will be identical to the MM74C912 except that the decimal point input and output and the digit and segment tri-state controls will be omitted. The MM74C912 will be housed in a 24-pin package and is intended for the electronic pinball market.

Two input protection diodes will be present at all inputs. The diode to Vcc may be omitted via a simple metal option.



electrical characteristics

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNITS
V_{CC}	Supply Voltage		4.5		5.5	V
	Standby Voltage		3.0		5.5	V
$V_{IN(1)}$			V_{CC} – 2.0			V
$V_{IN(0)}$					0.8	V
I_{OS}	Segment Output Current	V_{CC} = 5 V, V_O = 3.4 V,	40	80		mA
I_{SINK}		All Outputs = 2 LP TTL				