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Data-domain instrument for troubleshooting microcomputers and other digital equipment

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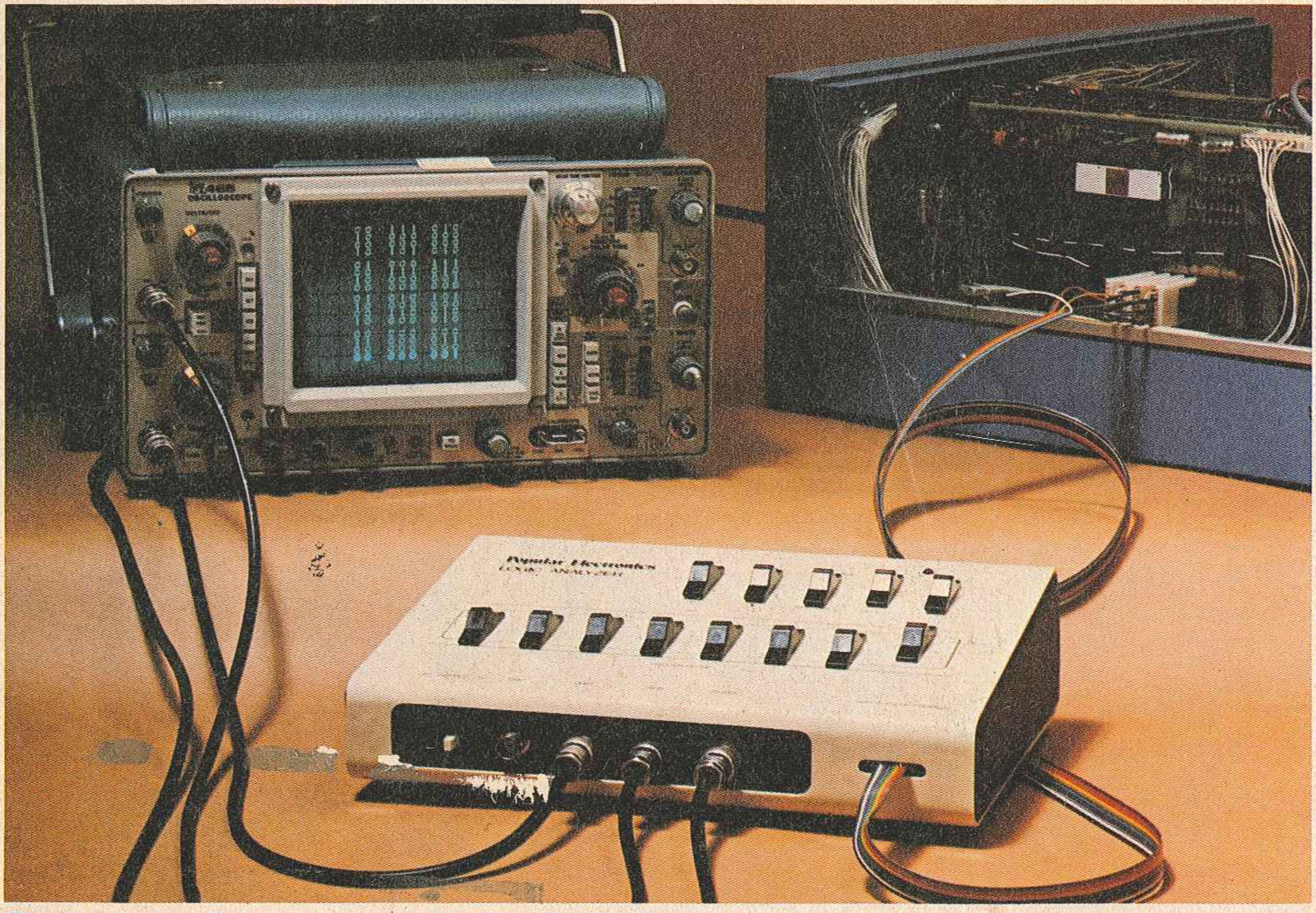


Retailers: Notice of display-allowance plan is within last three pages.

BREAKTHROUGH PROJECT

Low-Cost Digital Logic Analyzer

Data-domain instrument for troubleshooting any type of digital system including microcomputers.

BY G. MUETHING, I. SPECTOR, AND C. WONG

Digital circuitry has spawned a variety of troubleshooting aids, including logic probes, pulse generators, IC clip-type testers, logic comparators, and multiple-trace oscilloscopes. All are most useful—up to a point. That point is reached when the digital equipment contains a microprocessor, as in computers, scanning monitors, video games, microwave ovens, etc.

In such cases, how does one examine a number of operating interdependent circuit lines for debugging purposes? Industry knows how—with a "logic analyzer," an instrument with a bottom price of about $2500. Now, however, you can build your own logic analyzer for less than $190.

The Logic Analyzer presented here features eight input lines and an ability to examine sequential data before or after a reference event, displaying a truth table consisting of 1's and 0's on any oscilloscope CRT. This is called a data-domain logic analyzer. (There are, of course, other types of analyzers, one of which displays a timing diagram on a scope's CRT.)

Why a Logic Analyzer? Because digital logic operates at two different voltage levels (0's and 1's), the first special-digital test instrument was the simple digital probe. The digital probe uses some type of indicator, usually a LED, to indicate the presence or absence of a signal at any selected single point in a circuit. Since digital circuits usually consist of a number of IC's that all operate from a common timing clock, even if a single digital probe gives a proper indication at a given test point, there is no way of determining if the observed pulse is correctly timed.

The shortcomings of the digital probe led to the development of the IC "clip" tester in which 14 or 16 LED's could indicate the logic states at each of the IC pins. Note that the status of the logic is of interest only at a specified instant in time related to the clock. This brings up another problem—clock speed. With most clock rates, single 14/16-pin LED indicator probes may display only a blur (except at the ground and power pins of the IC), with the blur rate, or light intensity, a function of the clock speed. Hence, unless you are able to drastically slow down the clock rate, you still will not be able to discover anything but the presence or absence of signals, whether or not they are correctly timed.

Using a logic analyzer with an oscilloscope, you can display a "truth table" of the digital circuit being tested under actual operating conditions. Simply by selecting a "trigger word" consisting of a particular set of 1's and 0's, the analyzer will freeze the 15 8-bit digital words that precede the selected trigger word and display the data so that it can be analyzed at your leisure. A switch also allows the observation of the 15 digital words that follow the trigger word if the problem is thought to lie in that direction. By changing the trigger word, which is brightness accented in the display, as you step through the truth table, it becomes possible to examine the digital logic from start to finish. In essence, then, the Logic Analyzer is a form of electronic "time machine" that can freeze digital events before or after any selected point in time.

Because a computer consists of a number of interlocking digital circuits, each carefully timed from a common clock signal, the misplacement of one bit among thousands can cause a great deal of trouble. Programs that can be properly written will not run because of an erroneous bit being generated within the system.

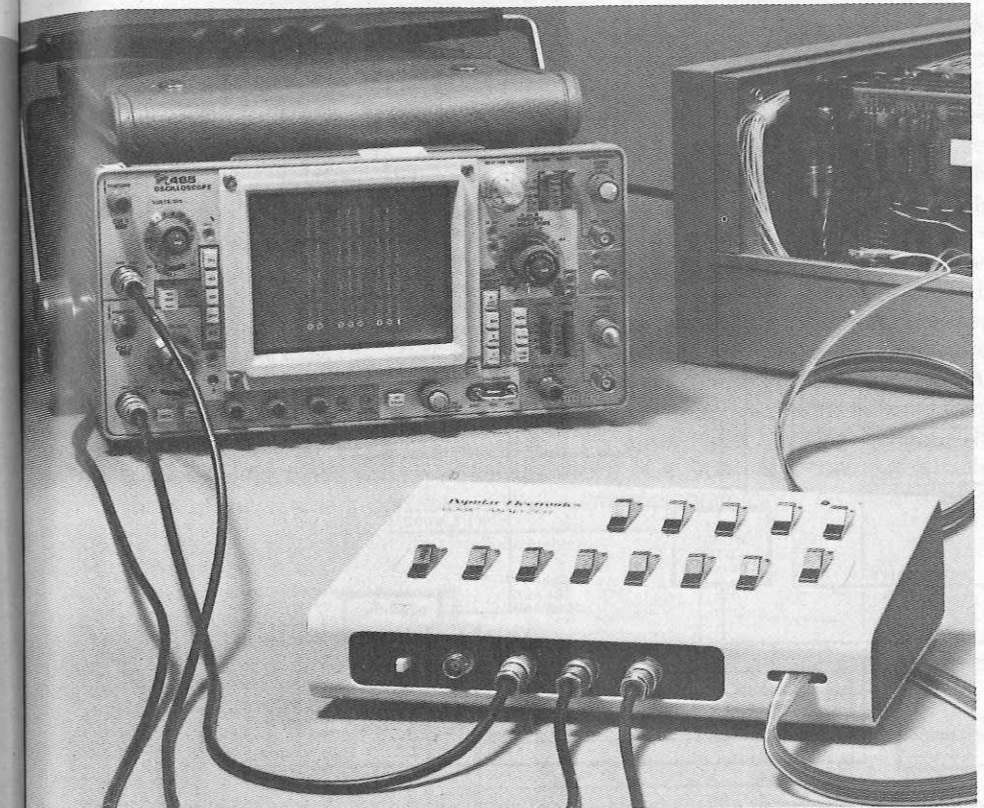
Why not use a conventional oscilloscope? True, you can see a small group of bits at any given time. But if the system under test is running at the usual clock rates, the picture displayed will keep changing and be blurred. The scope can display a signal only after it has been triggered. If you happen to trigger on the problem itself, you have further complications. Because computers, peripherals, ROM's, and other digital devices may not repeat the same state over and over again, a scope without storage capability cannot display a "snapshot" of a one-time logic event for subsequent analysis. In some cases, the scope is a necessity, as only a scope can display the detailed waveform information that can give the user an insight by an intuitive process where a waveform "just doesn't look right". A good scope can also show up fast transient "glitches" that, although they disturb circuit operation, may not show up on an analyzer. However, if you rely strictly on a scope for analysis, solving many system problems would be virtually impossible.

The low-cost Logic Analyzer in this article will add a form of storage to any oscilloscope, perform the sixteen 8-bit data word freeze as previously described, and provide the electronics experimenter with a state-of-the-art digital test instrument that rivals those costing several hundred dollars more. In use, you simply connect the three analyzer outputs to the horizontal, vertical, and blanking inputs of a scope and connect the eight data-input and the clock and ground probes to the circuit being analyzed. When the trigger word keyed in via control-panel switches appears, the Analyzer will automatically trigger, collect, store, and display 16 sequential 8-bit words in either octal or hex format, as shown in Fig. 1. The analyzer will accept data rates as high as 8-million bytes/second.

Another front-panel control allows the user to select either "positive time" in which the selected trigger word appears intensified on the top of the CRT screen with the next 15 sequential data words below it, or "negative time" in which the 15 data words leading up to the trigger word appear first with the brightened trigger word at the bottom of the screen.

One other control provides the choice of a "snapshot" that catches and displays an individual 16-word table for as long as you like or a "moving picture" display in which the data for each table is collected and automatically displayed so you can dynamically observe the operation of the circuit. The specifications for the logic analyzer are shown in the box.

Circuit Operation. Operation of the analyzer can best be understood by referring to the block diagram of Fig. 2. (The complete schematic diagram is shown in sections in Figs. 3 through 7.) The inputs to the system are the 8-bit signals (BIT 0 through BIT 7), the system clock, and the common or ground bus of the digital circuit under test. The data and clock inputs are buffered by *IC1* and *IC2*. The eight data signals are latched by *IC4* and *IC5* before loading into data memory *IC6* and *IC7*. This 16-word data memory is the "heart" of the analyzer. It stores sequential data words from the digital system under test.



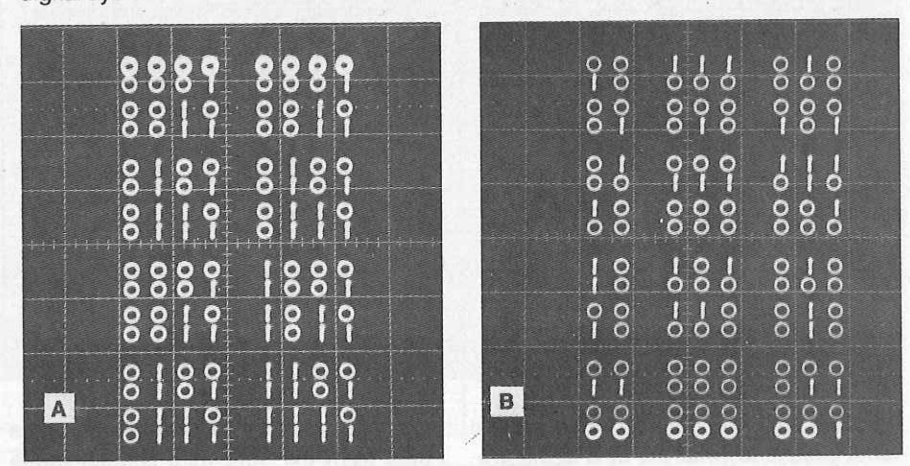


Fig. 1. Trigger word is intensified at top of hex display (A) with the 15 following data words. In octal display (B), trigger word is at bottom with the 15 data words leading up to it.

The buffered clock signal is fed to half of *IC2* that can be set to operate on either the negative or positive edge, depending on the setting of *S10*. This signal is applied to the display control logic made up of *IC11* through *IC15*. The other input to the display logic is from comparator *IC3*. This circuit uses *S1* through *S8* to set up the desired trigger word, with the switches set to either 1, 0, or X as required. (The X is a "don't care" state.) When the comparator receives the input data word that matches its switches, a signal is passed to the display control logic. When *S11* is set to the POS TIME position, for example, data collection begins when the comparator detects the trigger word. After 16 clock pulses, data collection stops so that the memory contains the trigger word followed by the next 15 data words. In the NEG TIME position of *S11*, the memory stores data continuously until the trigger word occurs. When this happens, data collection is halted, leaving the memory with the 15 data words leading up to the trigger, plus the trigger word itself.

During the data collection period, the display control logic sends a signal to the blanking logic system made up of *IC22* through *IC24*, *Q1*, and *Q2* to inhibit the display. At the end of this period, the blanking signal is removed and a bit-by-bit scan of the memory contents is initiated. Scanning is accomplished by data multiplexer *IC16*, which is controlled by three of the eight output bits of horizontal control ROM *IC19*. Thus, even though the data memory provides a full 8-bit wide data word to the input of the multiplexer, only one bit at a time is sent to the 1-0 character generator made up of half of *IC20*, and *Q3*.

The character generator uses this information and the CRT beam positioning signals from the *IC20* horizontal D/A (di-

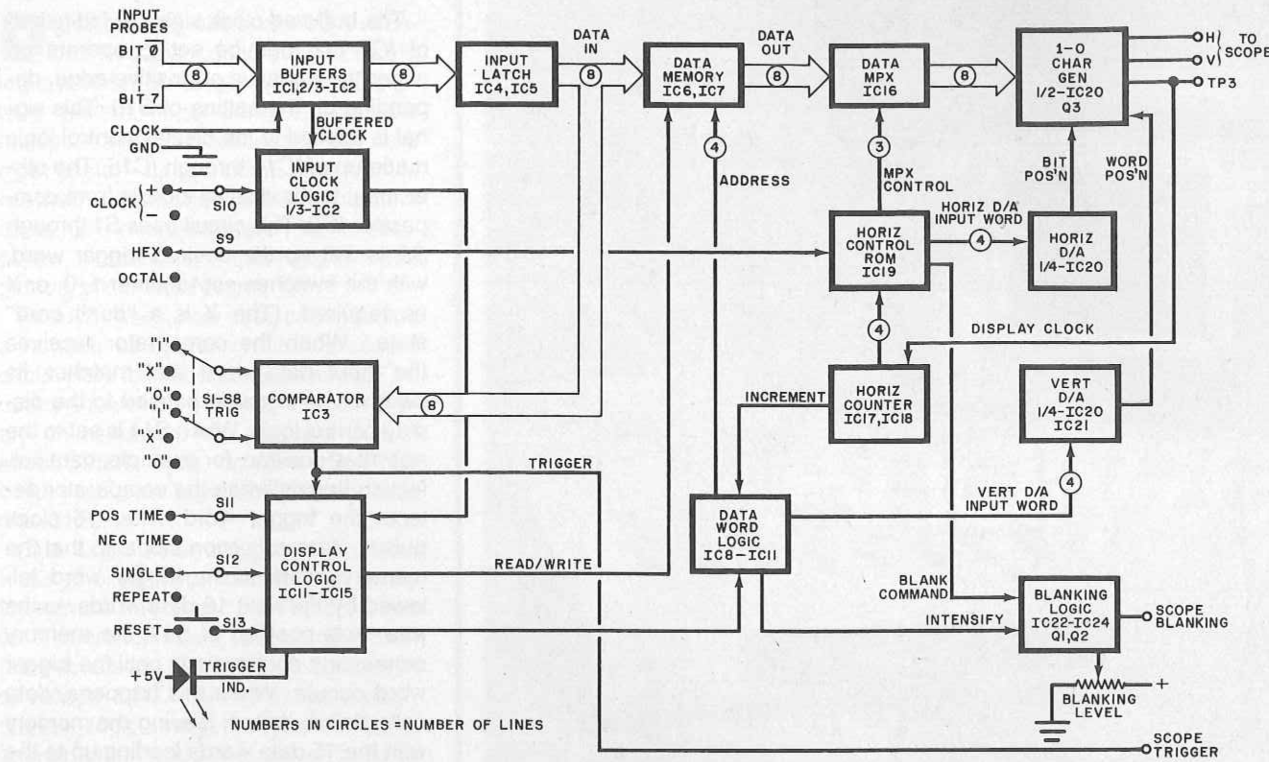


Fig. 2. Block diagram of analyzer shows basic signal routing.

PARTS LIST

C1—2200-µF, 16-volt electrolytic capacitor
C2—220-µF, 50-volt electrolytic capacitor
C3—10-µF, 50-volt electrolytic capacitor
C4,C5—150-pF, 10% disc capacitor
C6—15-pF, 10% disc capacitor
C7,C8,C9,C10—0.1-µF, 20% disc capacitor
C11—300-pF, 10% disc capacitor
C12—180-pF, 10% disc capacitor
C13—0.01-µF, 20% disc capacitor
D1,D2,D3—1N4002 or similar rectifier diode
IC1,IC2—74LS14 Schmitt-trigger input hex inverter (Fairchild 15-V input only)
IC3—74S15 open-collector output triple three-input AND gate
IC4,IC5,IC9—74LS175 quad latch
IC6,IC7—7489 RAM (16×4)
IC8—74LS161 four-bit synchronous counter
IC10—74LS83 four-bit adder
IC11,IC12,IC22—7400 quad two-input NAND gate
IC13,IC14,IC18—74LS73 dual JK flip-flop (do not substitute)
IC15—7473 dual JK flip-flop (do not substitute)
IC16—74LS151 8-to-1 multiplexer
IC17—74LS90 decade counter
IC19—8223 256-bit open-collector output PROM, or similar
IC20—LM3900 quad current amplifier
IC21—7407 open-collector output hex buffer
IC23—74LS21 dual four-input AND gate
IC24—7406 open-collector output hex inverter
IC25—LM309K 5-volt regulator
J1 through J4—UG-625 BNC connector
LED1—Light-emitting diode (any color)
Q1,Q3—2N3904 silicon transistor
Q2—2N3905 silicon transistor
The following resistors ¼ watt, 5%:
R1 through R27—4700 ohms
R28—3300 ohms
R29—470 ohms
R30—1000 ohms
R31,R32,R33—8200 ohms
R34,R35,R36—2700 ohms
R37—1800 ohms
R38—2000 ohms
R39,R40—33,000 ohms
R41,R42—56,000 ohms
R43,R44,R45—22,000 ohms
R46,R47—24,000 ohms
R48,R49—130,000 ohms
R51,R52—180 ohms
R53—47,000 ohms
R54,R55—11,000 ohms
The following resistors ¼-watt, **2%** tolerance:
R56—4700 ohms
R57—2400 ohms
R58—5100 ohms
R59—2700 ohms
R50—5000-ohm trimmer potentiometer (Spectrol 43P502 or similar)
S1 through S8—double-pole 3-position pc-mounted switch
S9 through S12—dpdt pc-mounted switch
S13—momentary-action dpst pc-mounted switch
S14—spst switch (panel mount)
T1—dual-winding power transformer with 16-volt CT and 22-volt winding
Misc.—Line cord, strain relief, mounting hardware, 3 feet of Spectra-Strip multicolored flat ribbon cable (26 gauge), 16-pin DIP socket, 16-pin flat ribbon DIP plug, heat sink for voltage regulator, hookup wire, solder, suitable case and mounting brackets, probe tip connectors, etc.
Note: The following items are available from Paratronics, Inc., Dept. 100, Los Gatos, CA 95030: Complete kit of parts, No. LA-100KIT, with tested IC's, power supply, pc board, case, and manual for $189.00. For separate parts: drilled double-sided printed circuit board, No. LA-100 PC, $29.95; programmed horizontal control ROM, No. LA-100ROM, $15.95; power supply, No. LA-100PS, $39.95; complete set of switches, connectors, hardware and data probes, No. LA-100HW, $39.95; Case, No. LA-100CASE, $39.95. Comprehensive applications and assembly manual, LA-100MAN $4.95. Please add 5% to above items for shipping and handling within U.S., 10% outside the U.S. California residents, add 6% sales tax.
Free copies of etching and drilling guides for the pc board, components-placement diagram, and horizontal control PROM programming information are available on request by sending a self-addressed stamped 9″ × 12″ envelope with 26¢ postage to: Popular Electronics, Dept. LA, One Park Ave., New York, NY 10016.

gital/analog) and the *IC20-IC21* vertical D/A circuits to write a 1 or 0 at the proper location on the CRT screen.

The horizontal D/A circuit receives its 4-bit data word from the horizontal control ROM, which receives its address data from the horizontal counter made up of *IC17* and *IC18*. It is the incrementing of the horizontal counter that causes the beam to move from right to left across the face of the CRT as the data word is written.

When the last bit is displayed, horizontal counter *IC17-IC18* "rolls over" to 0 and sends the increment signal to the data word logic *IC8* through *IC11*. This causes the address of the data memory to advance to the next word location and simultaneously sends a command to the vertical D/A converter that causes the CRT beam to move down one row in preparation for display of the next word. This process continues until all sixteen of the words of interest have been written on the CRT screen.

If *S12* is set to the SINGLE mode, the display control logic prevents the data memory from collecting new input data so that the same information is written on the CRT screen. The writing speed is fast enough so that a flicker-free "snapshot" of the memory contents is displayed. This snapshot will remain on the screen until the RESET switch *S13* is operated, at which time the TRIGGER LED comes on and the analyzer is armed to "capture" another 16-word data set. When *S12* is in the REPEAT mode, the display control logic provides an automatic reset signal after the display of each 16-word truth table.

Blanking between bits is provided by the remaining bit of the horizontal control ROM. This ROM performs three separate functions: control of the data multiplexer, control of the horizontal D/A converter, and blanking control. This use of a ROM as a controller is called "microprogramming," an efficient design technique used in a number of high-level computers. An "intensify" command from the data-word logic permits the trigger word to appear brighter than the other data words on the CRT screen.

The trigger pulse generated by comparator *IC3* occurs each time the trigger word appears. The resultant output pulse can be connected to the sync input of an oscilloscope anytime it is necessary to "look" at a specific signal in the circuit under test. This important feature is useful for troubleshooting equipment for glitches, timing, or intermittent problems that occur only during particular logic states.

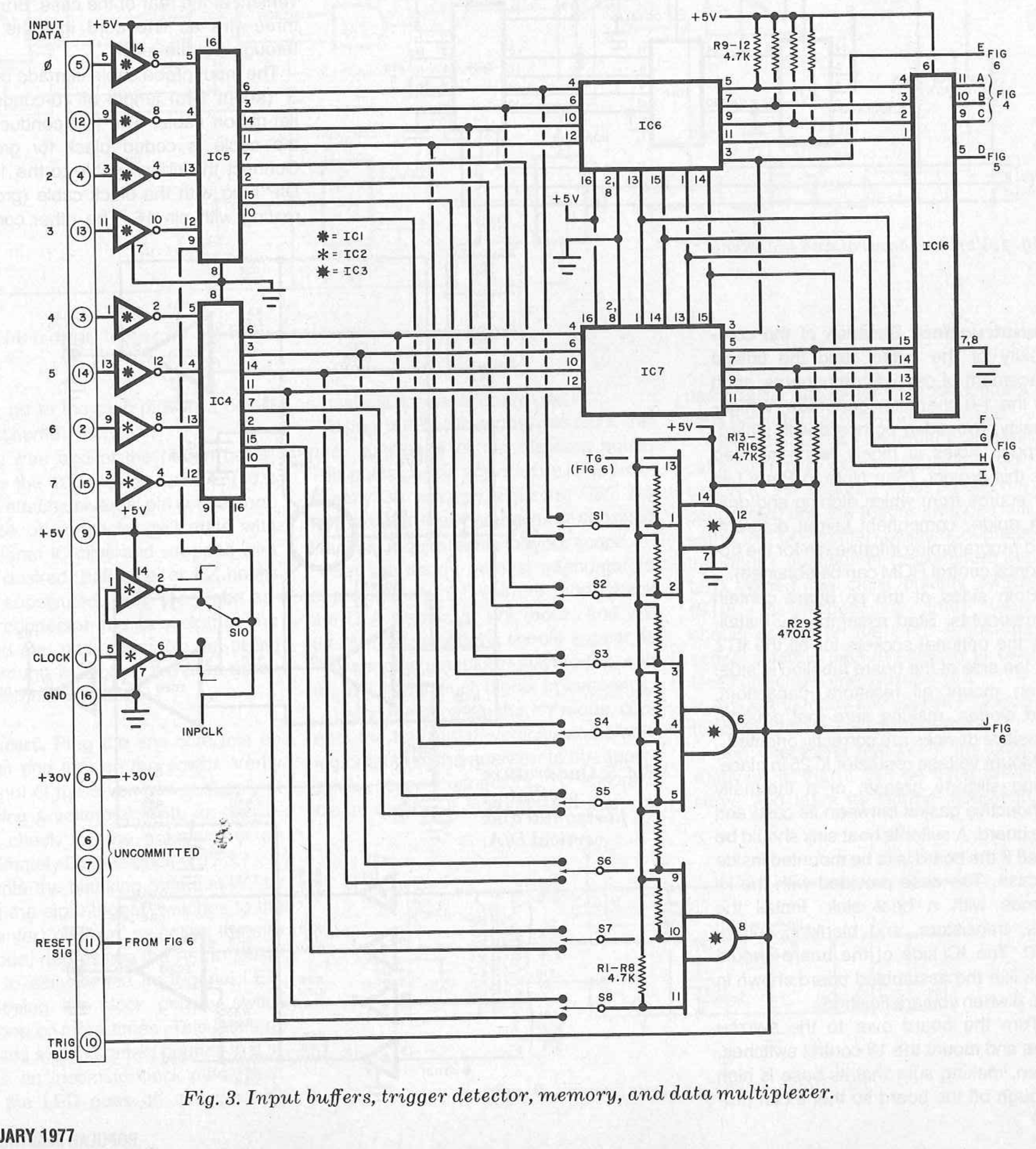


Fig. 3. Input buffers, trigger detector, memory, and data multiplexer.

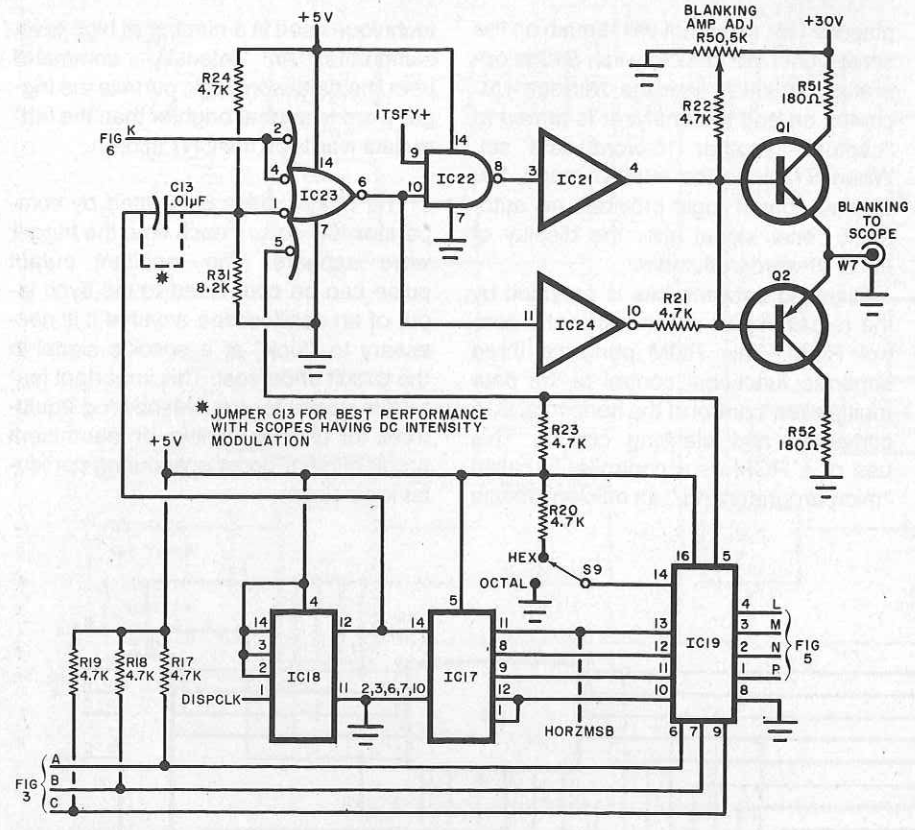


Fig. 4. Vertical control and blanking.

Construction. Because of the complexity of the circuit, and the critical placement of certain components, such as the 1-0 character generator, a high-quality, two-sided pc board with plated-through holes is highly recommended for this project. (See Note in Parts List for source from which etching and drilling guide, component layout diagram, and programming information for the horizontal control ROM can be obtained).

Both sides of the pc board contain components. Start assembly by installing the optional sockets for all the IC's on the side of the board labelled IC SIDE. Then mount all resistors, capacitors, and diodes, making sure that polarity-sensitive devices are correctly oriented.

Mount voltage regulator *IC25* in place, using silicone grease, or a thermally conductive gasket between its case and the board. A suitable heat sink should be used if the board is to be mounted inside a case. The case provided with the kit comes with a heat sink. Install the IC's, transistors, and blanking control *R50*. The IC side of the board should look like the assembled board shown in Fig. 8 when you are finished.

Turn the board over to the SWITCH SIDE and mount the 13 control switches. Then, making sure that its base is high enough off the board so that it can protrude through its hole on the top of the case, mount *LED1*. Install the 16-pin DIP socket for the flat ribbon probe cable. This completes the assembly of the board.

Mount the BNC scope connectors and on-off switch *S14* on the front of the case. Then drill a hole so that the blanking amplitude potentiometer mounted on the pc board can be adjusted from outside the case. The top of the case should be punched to accept the 13 switches and the LED indicator. Make sure that all switches can be moved into all their positions. Then put a slot in the front apron to accommodate the flat ribbon cable.

Mount the transformer wherever convenient at the rear of the case. Bring the three-wire ac line cord into the case through a strain-relief.

The input probe cable is made up of a 3′ (about 1-m) length of 10-conductor, flat-ribbon cable. The last conductor in the cable is coded black for ground. Connect the ribbon cable to the 16-pin DIP plug with the black cable (ground) mating with pin 16. The other conductors can go to the plug pins in a color-coding scheme.

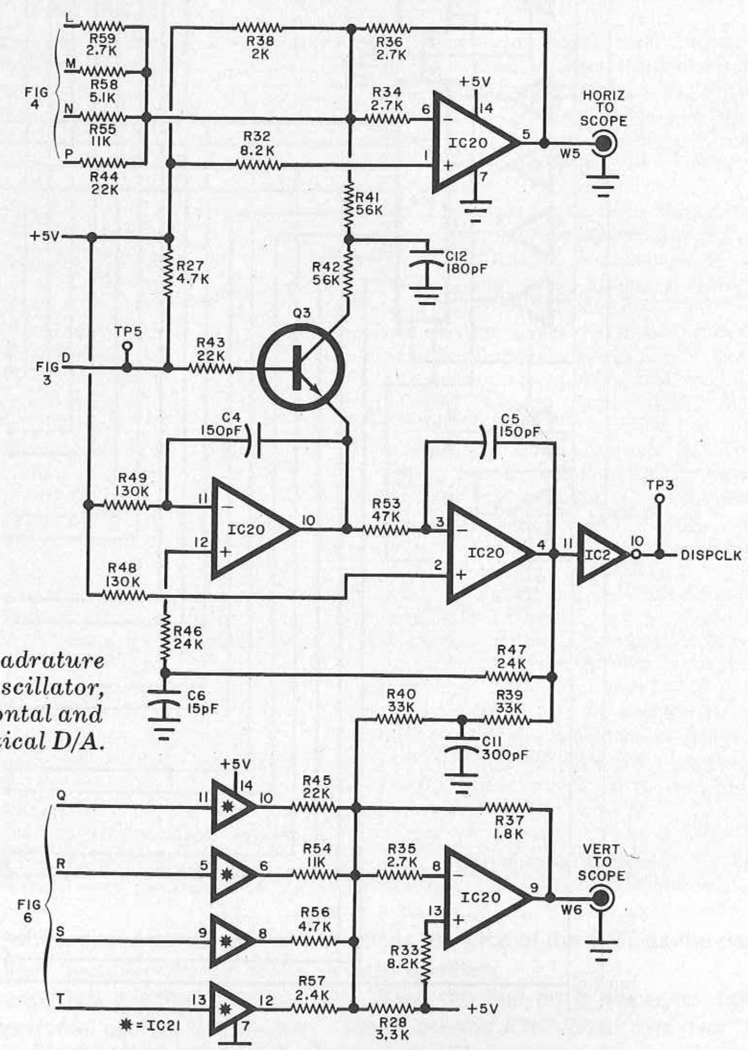


Fig. 5. Quadrature oscillator, horizontal and vertical D/A.

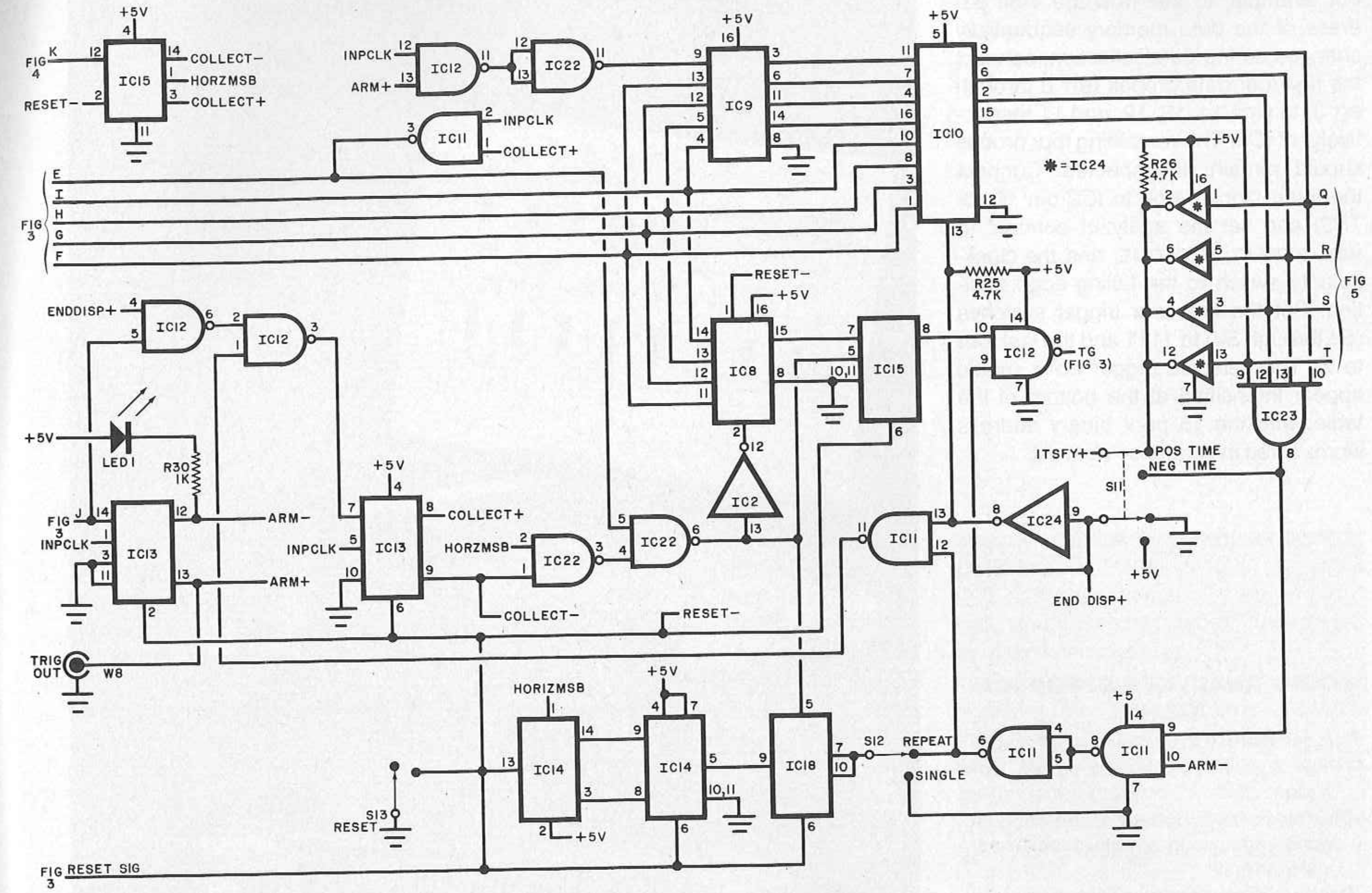


Fig. 6. Horizontal logic and mode control logic.

At the free end of the ribbon cable, separate the 10 leads at least 4″ (10.2 cm) and attach universal pin connectors. This type of connector will mate with conventional IC clips and wrapped-wire pins. If desired, ball clips or EZ hooks can be substituted. Plug the probe assembly connector into its socket on the pc board and pass the cable out of the case through its slot on the front apron and assemble the case.

Checkout. Plug the line cord into an ac outlet and turn on the power. Verify the output of the 5-volt power supply at *TP1* using a voltmeter. With an oscilloscope, check for the presence of an approximately 20-kHz clock at *TP3*.

Activate the blanking output at *W7* by placing the eight trigger switches to the "X" (center) position, selecting the SINGLE mode, depressing the RESET pushbutton to activate the front-panel LED, and flipping the clock polarity switch (*S10*) one or more times. This last step generates switch contact bounce that simulates an incoming clock pulse train. When the LED goes off, the blanking signal will appear at board pad *W7*.

Using the oscilloscope, measure the peak amplitude of the blanking pulse. This pulse can be adjusted up to approximately 30 volts by adjusting *R50*. ***Do not*** exceed the manufacturer-specified blanking requirements for your scope.

Set the scope vertical attenuator to approximately 0.5-volt/cm and check the D/A signals at *W5* (horiz) and *W6* (vert). The waveforms should appear as "descending staircase" waveforms, with the *W5* signal much higher in frequency.

Using the scope in the XY mode, connect the horizontal, vertical, and blanking outputs of the analyzer to the appropriate scope connectors. To assure a clean display, it is suggested that you use coaxial cables for the interconnections between the analyzer and scope.

Place the scope horizontal and vertical amplifiers to approximately 0.5-volt/cm. With the analyzer *input* probes unconnected, and the trigger switches still set to the "X" (center) position, depress the RESET pushbutton to illuminate the LED. When the clock polarity switch (*S10*) is flipped, a truth table should appear on the CRT. Adjust the scope controls until the display is centered on screen and fills most of it.

Adjust the focus and intensity controls to obtain a clear well-defined display.

One interesting feature of the Logic Analyzer is that it can be used to observe and learn its internal operation.

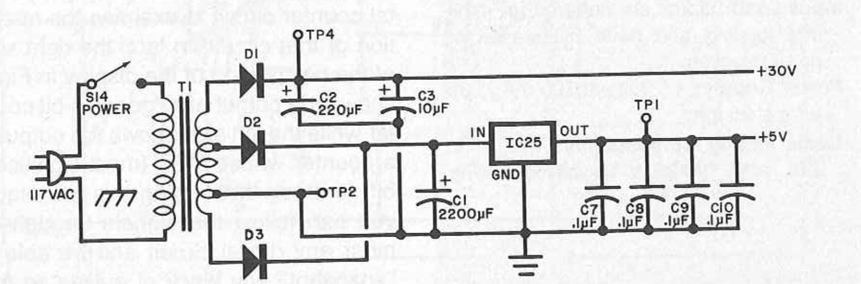


Fig. 7. Power supply is 5 volts, regulated.

For example, to see how the 4-bit address of the data memory sequentially changes during data collection, connect the first four data probes (BIT 0 through BIT 3) to pins 14, 13, 12, and 11 respectively, of *IC8*. The remaining four probes should remain unconnected. Connect the input clock probe to *IC2* pin 10 (or *TP3*) and set the analyzer controls to HEX, REPEAT, NEG TIME, and the clock-polarity switch to the falling edge position. Set the first four trigger switches (*S1* through *S4*) to 1111 and the last four to X. The selected trigger word should appear intensified at the bottom of the table, with the 15 prior binary address words listed in sequence above it.

LOGIC ANALYZER SPECIFICATIONS

Trigger Word: 0 to 8 bits wide; selected by eight 3-position switches; choose 0, 1, or X (don't care).

Display Format: Sixteen sequential 8-bit words arranged in an octal or hexadecimal truth table.

Positive Time Display: Trigger word intensified at top of truth table with next 15 data words listed *below*.

Negative Time Display: Trigger word intensified at bottom of truth table with prior 15 data words listed *above*.

Single Mode: Continuous display of one 16-word truth-table until RESET button is activated.

Repeat Mode: Display of sequential 16-word truth tables.

Maximum Input Data Rate: 8 million bytes/second.

Input Clock: Provides timing reference for input data; selectable positive or negative clock edge.

Trigger Indicator: LED on front panel indicates when trigger word has occurred.

Trigger Output: Auxiliary scope sync pulse; generated when trigger word occurs.

Input Probes: Constructed of color-coded flat-ribbon cable terminated in universal pin connectors.

Input Load: Inputs are buffered for minimal loading and have hysteresis for noise rejection.

Power Supply: +5 volts at 700 mA, +30 volts at 25 mA.

Logic Family Compatibility: TTL, DTL, RTL, MOS, CMOS, to 15-volt logic swing.

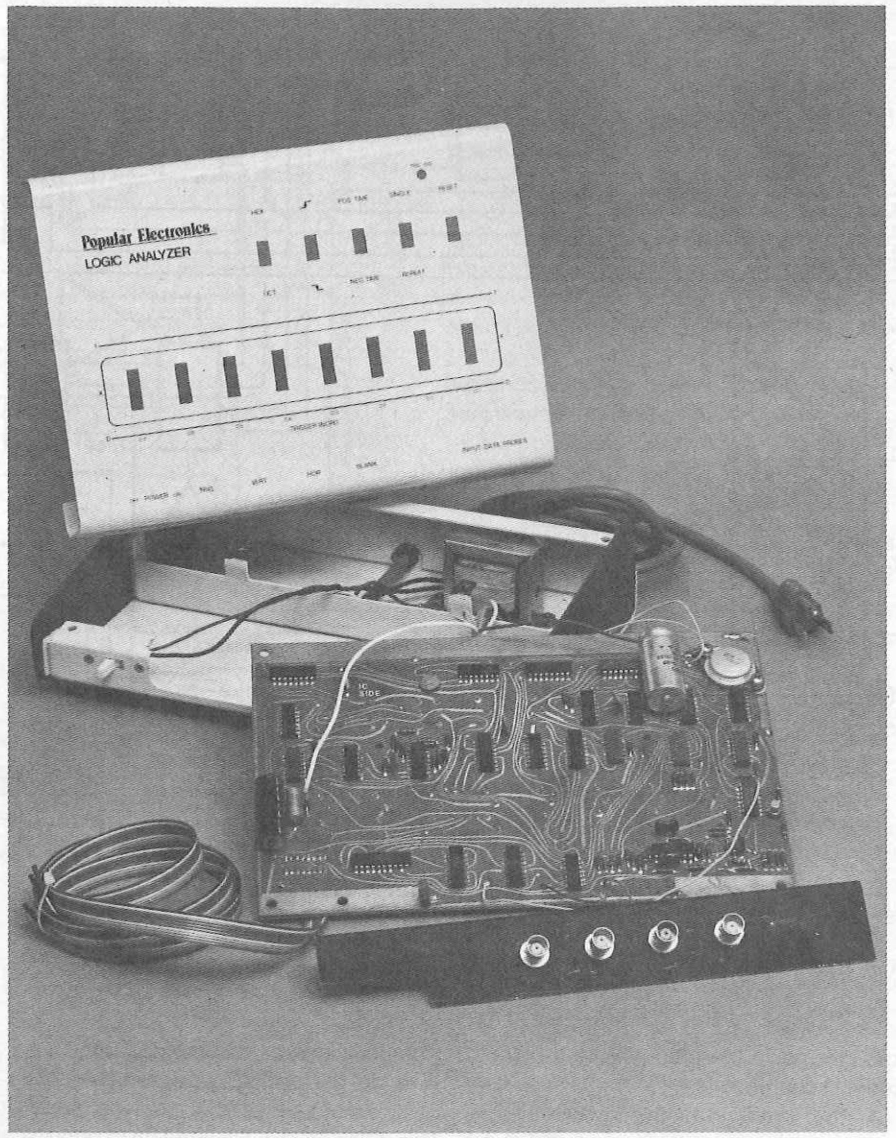


Fig. 8. Completed board and connector panel ready for assembly.

Continue to familiarize yourself with the operation of the analyzer by triggering from different address locations and changing the settings of the display control switches. The probes can be moved to other portions of the circuit, such as the horizontal counter, display-control logic, and the data-word logic.

You can couple the first four probes to the counter (7490 or similar) in any digital counter circuit to examine the operation of that circuit. In fact, the right side of the hex portion of the display in Fig. 1 shows the output of a "good" 4-bit counter while the left side shows the output of a counter whose MSB (most significant bit) is stuck at 0. Using this technique, you can follow the signals through almost any digital circuit and be able to "snapshot" any block of pulses so that they can be examined for faulty pulses.

The analyzer shows its flexibility when used to check a computer or program. The octal portion of Fig. 1 shows the steps of a typical 8080 ADD and STORE program leading up to a branch instruction. The trigger word 00 000 001 is the branch address and is intensified at the bottom of the display.

In Closing. The Logic Analyzer we have described can be used for all types of testing and troubleshooting of digital circuits and systems. However, its true flexibility is revealed when the instrument is used for testing and troubleshooting digital-computer and other time-dependent circuits and systems. What makes our Logic Analyzer particularly attractive is its relatively low price. Used as an accessory to an existing oscilloscope and built from scratch, it costs only a fraction of commercially made logic analyzers on the market. ◇

NEW, PRACTICAL OP AMP CIRCUITS

including a differential pc board tester

BY SOL D. PRENSKY

AS WE WILL learn from the two very useful circuit applications described here, the operational amplifier (or op amp) can be used in strikingly different ways.

In-Circuit Current Testing. Since an op amp is basically a differential amplifier, it can be used in a unique metering circuit to determine the presence of current flow in a conductor—and approximately the amount of current—whether or not the conductor is a copper wire or a pc foil trace. This can be done without breaking the conductor.

Such a metering device can come in handy if you have a crowded pc board and you suspect one of the active elements (transistor, diode, or IC) is not working. Instead of risking pc board damage due to the heat required to remove the suspect semiconductor, or having to cut a trace to insert a meter, all you have to do is press a couple of sharp probe tips to the copper trace at (for example) the supply bus, and see if that particular element is drawing current, and if the magnitude of the current is within specifications.

The circuit for the current tester is shown in Fig. 1 in two forms—depending on whether you want to use a low-level (1-volt) dc voltmeter or a current meter as the readout.

Operation is based on the fact that at room temperatures, all conductors have

Fig. 1. Op amp in (A) measures slight voltage differential between two probes, amplifies it, and drives dc voltmeter. Addition of another op amp in (B) permits driving ammeter.