Logic troubleshooting tools and techniques

Digital circuitry has had an explosive growth over the past decade and now pervades virtually every facet of electronics. Whilst the reliability of devices and equipment has improved dramatically during that period, things still do go wrong and equipment still needs servicing when it breaks down. 'Board level' servicing can solve problems quickly in the field, but economics demands those removed boards be repaired and recycled. This article details the problems encountered and the tools and techniques employed to fix them.

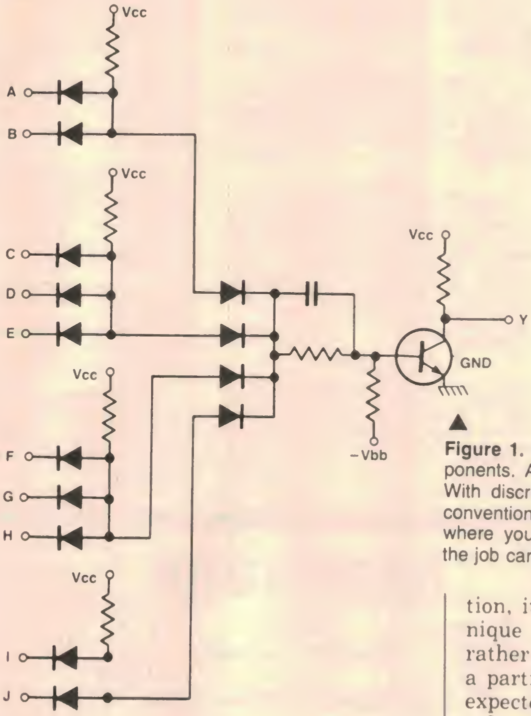
DIGITAL integrated circuits range from simple buffers and two-input gate packages through to complex purpose-built controllers and microprocessors. Finding faults in digital equipment requires a *fundamentally different* approach from fault-finding in analogue circuitry, where the multimeter and oscillator are the prime tools and component characteristics can be individually measured. In digital electronics, most 'components' are contained within the ICs — which are often multi-functional. Thus there is need for a different troubleshooting approach to be developed, and different tools used, based on the type of faults that develop and the 'signatures' they leave. Of necessity, this article does not cover microprocessor-based equipment — *that's* a whole subject on its own!

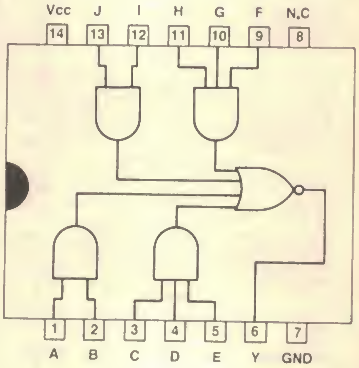
Faults & effects

When fault-finding circuits built from discrete components, the task is one of verifying relatively simple characteristics such as resistance, capacitance, or turn-on voltages of components with two or at most three nodes. (A 'node' is an active junction in a circuit, usually an input or an output.) While the function of the total circuit may be quite complex, each component in that circuit performs a relatively simple task and proper operation is easily verified.

In Figure 1, each diode, resistor, capacitor and transistor can be treated using a signal generator and a voltmeter, ohmmeter, diode checker or oscilloscope — the traditional servicing tools. But when this circuit is built in integrated circuit form, these components are no longer accessible. It now becomes necessary to test the operation of the complete circuit function.

Thus an important difference between discrete circuitry and circuits built from digital ICs is in the complexity of the functions performed by these 'components'. Unlike the resistor, capacitor, diode or transistor, which must be interconnected to form a circuit function, digital ICs perform complete, complex functions. Instead of observing simple characteristics, it is now necessary to observe complex digital signals and decide if these signals are correct according to the function the IC is meant to perform.





▲

Figure 1. This 10-input gate is made up from 23 components. An IC to do the same job is shown at right. With discrete components, finding faults is easy with conventional meters, etc. When it's all inside an IC, where you've only got access to inputs and outputs, the job can be much harder. But there are ways.

Verifying proper component operation now requires 'stimulating' and observing many inputs (in Figure 1 there are 10 inputs) while simultaneously observing several outputs (up to two or three and at times as many as eight).

Thus another fundamental difference between circuitry built from discrete components and digital ICs is the number of inputs and outputs associated with each component, and the need to stimulate and observe these simultaneously.

In addition to the problems of simultaneity of signals and complexity of functions at the component level, the digital IC has introduced a new degree of complexity at the circuit level. Circuits which perplex all but their designer are commonplace. Given enough time, these circuits can be studied and their operation understood, but this is not an affordable luxury for those involved in troubleshooting electronic circuits. Without understanding a circuit's intricate operation, it becomes necessary to have a technique of quickly testing each component rather than attempting to isolate a failure to a particular circuit segment by testing for expected signals.

In order to solve these problems and make fault-finding of digital circuits more efficient, it is necessary to take advantage of the digital nature of the signals involved. Tools and techniques designed to service analogue circuits do not take advantage of this digital nature and thus are less efficient when used to troubleshoot digital circuits.

Figure 2 shows a typical TTL (Transistor-Transistor-Logic) signal. This might as well be any analogue signal when viewed on an oscilloscope. The oscilloscope displays absolute voltage with respect to time, but in the digital world absolute values are unimportant.

A digital signal exists in one of two or three states — high, low and undefined or in-between level — each determined by a threshold voltage. It is the relative value of the signal voltage with respect to these thresholds that determines the state of the digital signal, and this digital state determines the operation of the IC, not absolute levels.

In Figure 2, if the signal is greater than 2.4 volts, it is a high state and it is unimportant whether the level is 2.8 or 3.0 volts. Similarly for a low state the voltage must be below 0.4 volts. It is not important what the absolute level *is* as long as it is below this threshold. Thus when using an oscilloscope, the serviceman must over and over again determine if the signal meets the threshold requirement for the desired digital state.

Within a digital logic family, such as TTL, the timing characteristics of each component are well defined. Each gate in the TTL logic family displays a characteristic propagation delay time, rise time and fall time. The effects of these timing parameters on circuit operation are taken into account by the designer. Once a design has been developed beyond breadboard or prototype stage and is into production, problems due to design have (hopefully) been corrected.

An important characteristic of digital ICs is that when they fail, *they fail catastrophically*. This means that timing parameters rarely degrade or become marginal. Thus, observing on an oscilloscope and making repeated decisions on the validity of timing parameters is time consuming and contributes very little to the fault-finding process. Once problems due to design are corrected, the fact that pulse activity *exists* is usually enough indication of proper IC operation without further observation of pulse width, repetition rate, rise time or fall time.

Figure 3 shows a problem created by the TTL logic family. The output stage of a TTL device is a transistor totem pole. In either the high or low state, it is a low impedance. In the low state it is a saturated transistor to ground. It thus appears as 5-10 ohms to ground. This presents a problem to in-circuit stimulation.

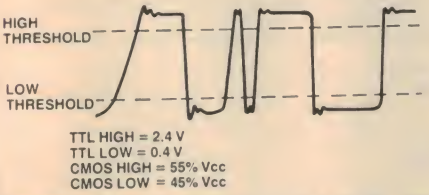


Figure 2. Digital circuits work on 'thresholds', and signals must be 'above' or 'below' the given high and low thresholds, which are different for the different 'families' — CMOS and TTL. ▲

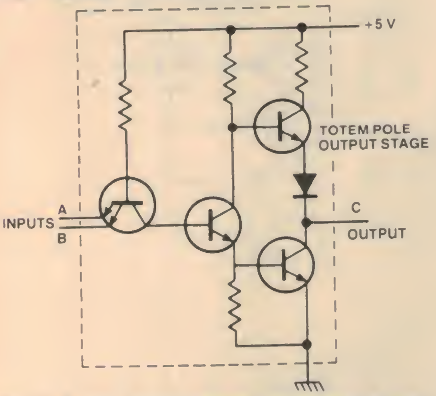


Figure 3. TTL ICs have 'totem pole' output stages, as shown above. When attempting to 'stimulate' an output node, such as C above, it is necessary to override the low impedance output stage, which consists of a saturated transistor. ▲

A signal source used to inject a pulse at a node which is driven by a TTL output must have sufficient power to override the low impedance output state. If you use a square-wave signal generator for fault-finding it must provide this capability, otherwise it is necessary either to cut printed circuit traces or pull out IC leads in order to stimulate the circuit being tested. Both of these practices are time consuming and lead to unreliable repairs.

Thus the use of the traditional oscilloscope and the traditional signal sources is inefficient. Since the diodes and transistors are packaged in the IC, use of diode checkers is also marginal, if not impossible.

These tools are general purpose tools that can be applied to any situation if you have enough time. But with the quantity and complexity of today's electronic circuits, it makes sense to find the most efficient solution to the problem at hand. This suggests using the oscilloscope, diode checkers and voltmeters on analogue circuits where they really shine, and using instruments that take advantage of the digital nature of signals on the digital circuitry to be repaired. We'll get to them a little later.

In order to repair digital equipment efficiently, it is important to understand the type of failures found in digital circuits. These can be categorised into two main classes — those caused by a failure *internal* to an IC and those caused by a failure in the circuit *external* to the IC.

Four types of failures can occur internally to an IC. These are (1) an open bond on either an input or output, (2) a short between an input or output and Vcc or ground, (3) a short between two pins (neither of which are Vcc or ground), and (4) a failure in the internal circuitry (often called the steering circuitry) of the IC.

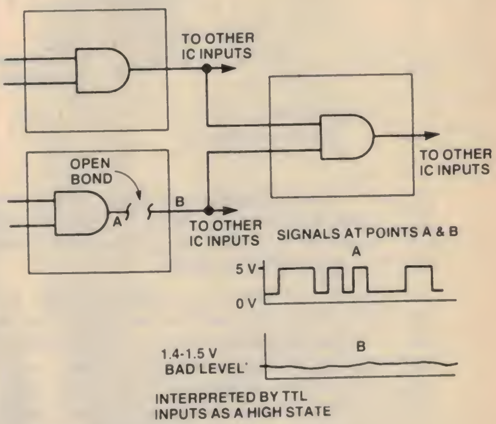
In addition to these four failures internal to an IC, there are four failures that can occur in the circuit external to the IC. These are (1) a short between a node and Vcc or ground, (2) a short between two nodes (neither of which are Vcc or ground), (3) an open signal path, and (4) a failure of an analogue component.

Before showing how to detect each of these failures we will discuss the effect each has upon circuit operation.

The first failure (internal to an IC) mentioned was an open bond on either an input or output. The failure has a different effect depending on whether it is an open output or an open input bond. In the case of an open output bond (Figure 4), the inputs driven by that output are left to float. In TTL circuits a floating input rises to approximately 1.4 to 1.5 volts and usually has the same effect on circuit operation as a high logic level. Thus an open output bond will cause all inputs driven by that output to float to a bad level since 1.5 volts is less than the high threshold level of 2.0 volts and greater than the low threshold level of 0.4 volt. In TTL a floating input is interpreted as a high level. Thus the effect will be that these inputs will respond to this bad level as though it were a static high signal.

In the case of an open input bond (Figure 5), we find that the open circuit blocks the signal driving the input from entering the IC chip. The input on the chip is thus allowed to float and will respond as though it were a static high signal. It is important to realise that since the open circuit occurs on the input inside the IC, the digital signal driving this input will be unaffected by the open circuit and will be detectable when looking at the input pin (such as at Point A in Figure 5). The effect will be to block this signal inside the IC and the resulting IC operation will be as though the input were a static high.

Figure 4. An open output bond allows all inputs driven by that output to float to a 'bad level', usually interpreted as a high. Signals at points A and B illustrated below. ▼



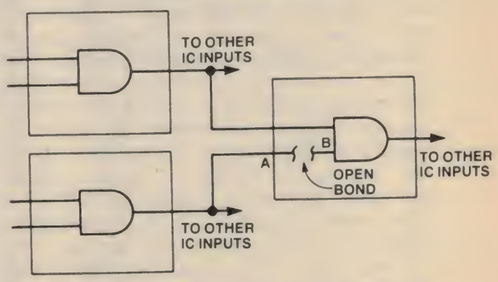


Figure 5. An open input bond blocks the incoming signal, allowing the input to float to a 'bad level' — interpreted as a high. Signals at points A and B illustrated above. ▲

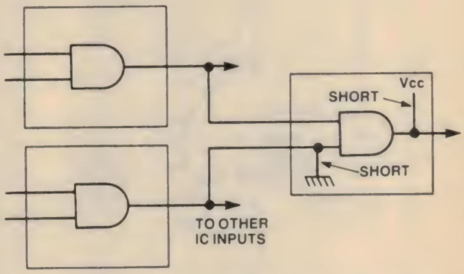
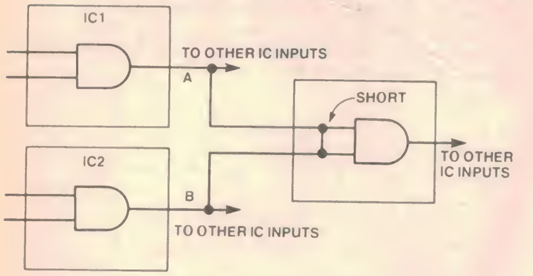


Figure 6. When you get an internal short to ground, the affected node is always pulled low. When shorted to Vcc (supply), the affected node is always pulled high. ▲

A short between an input or output and Vcc or ground has the effect of holding all signal lines connected to that input or output either high (in the case of a short to Vcc) or low (if shorted to ground) (Figure 6). In many cases, this will cause expected signal activity at points beyond the short to disppear, and thus this type of failure is catastrophic in terms of circuit operation. ▶



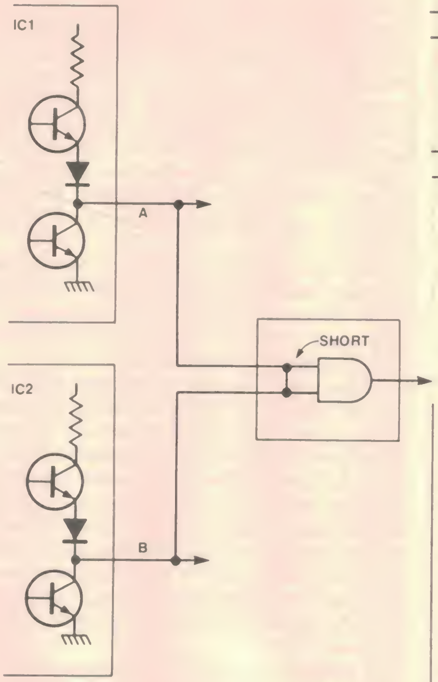


Figure 7. A short between two inputs makes a low-going driver pull the other driver low too. In IC2 at right, if B is low, it is pulled low by a saturated transistor, which pulls A low too. ▲ ▶

A short between two pins is not as straightforward to analyse as the short to Vcc or ground. When two pins are shorted, the outputs driving those pins oppose each other when one attempts to pull the pins high while the other attempts to pull them low (Figure 7). In this situation the output attempting to go high will supply current through the upper saturated transistor of its totem pole output stage, while the output attempting to go low will sink this current through the lower saturated transistor of its totem pole output stage. The net effect is that the short will be pulled to a low state by the saturated transistor to ground. Whenever both outputs attempt to go high simultaneously, or to go low simultaneously, the shorted pins will respond promptly. But whenever one output attempts to go low the short will be constrained to be low.

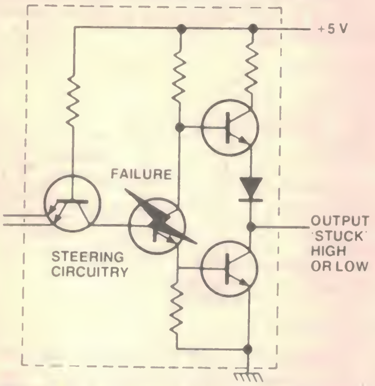


Figure 8. An internal failure of the steering circuitry will either cause the output to be 'stuck' high or low. ▲

The fourth failure internal to an IC is a failure of the internal steering circuitry of the IC (Figure 8). This has the effect of permanently turning on either the upper transistor of the output totem pole, thus locking the output in the high state, or turning on the lower transistor of the totem pole, thus locking the output in the low state. Thus this failure blocks the signal flow and has a catastrophic effect on circuit operation.

A short between a node and Vcc or ground external to the IC is indistinguishable from a short internal to the IC. Both will cause the signal lines connected to the node to be either always high (for shorts to Vcc) or always low (for shorts to ground). When this type of failure is encountered a very close physical examination of the circuit may reveal if the failure is external to the IC, but it can be determined using 'pulsing' and 'tracing' tools, as explained later.

An open signal path in the circuit has a similar effect to an open output bond driving the node (Figure 9). All inputs to the right of the open will be allowed to float to a bad level and will thus appear as a static high level in circuit operation. Those inputs to the left of the open will be unaffected by the open and will thus respond as expected.

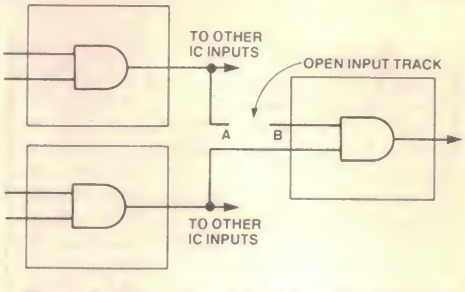


Figure 9. An open input track (external to the IC) has a similar effect as an open driver output bond. B will float to a bad level while A will still have signal on it. ▲

The problem of open-collector outputs — 'wired-ANDs', 'wired-ORs' — is different from the other cases described. Open-collector outputs differ in that they do not have an active logic-high current source. Instead, the output stage collector (Q3 in Figure 10a) is left unconnected. Thus the output stage can *sink* current in a logic low state, but cannot *source* any current in the high state. This is provided by the 'pullup' resistor R_L. Generally, you will find several open-collector gates are interconnected in parallel, as shown in Figure 10b.

So long as every output stage is turned off, the voltage at the common connection node is near Vcc, but when *any one* gate output is driven on, the node voltage drops to the low state (near 0 V). The common node thus acts as an AND gate in itself (hence 'wired-AND'). This circuit is 'wired-NAND' in TTL circuits if the inputs and outputs are active low. In other families, it's an OR function. When looking for faults here, the output has to be looked at in conjunction with the input. ▶

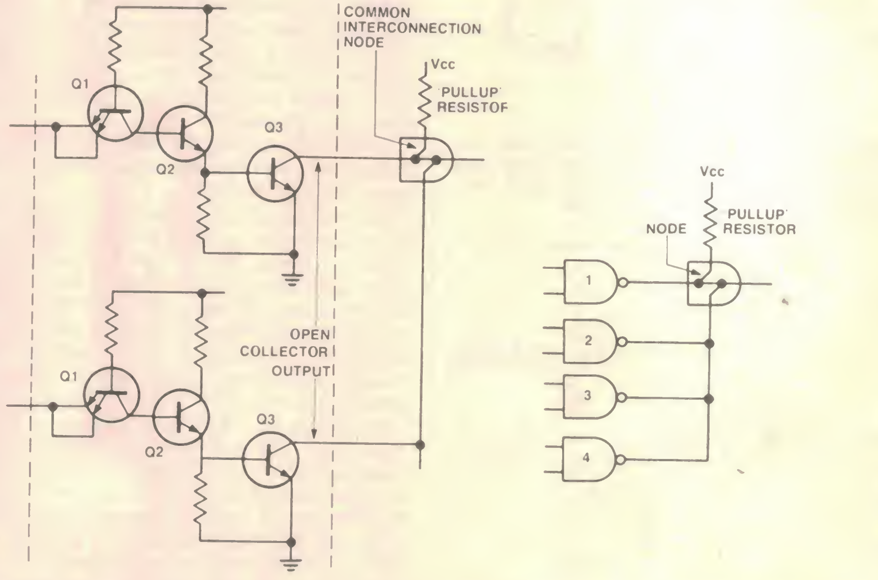


Figure 10. The 'open collector problem'. Open collector output stages do not have an active high source, this being provided externally by a 'pullup' resistor. When gates are connected in the 'wired-AND', 'wired-OR' configuration, the output of one IC can constratin the node to be in a state other than that defined by the gates' truth table.

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Logic troubleshooting

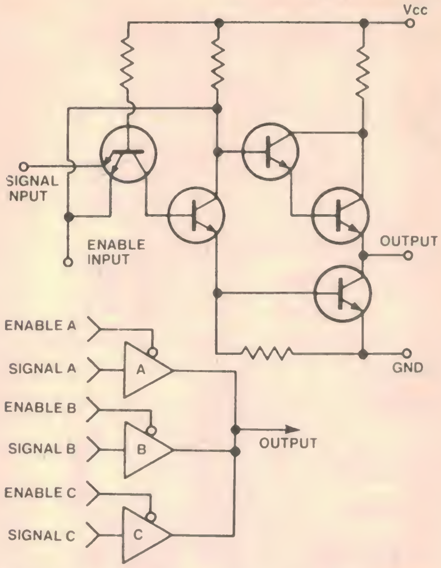


Figure 11. The internal circuitry of a 'tri-state' driver is shown above. The output can be high, low or open-circuit. Outputs are generally wired in parallel, as in the wired-AND circuit. ▲

A now widely used logic type, known as 'tri-state' logic, is a development of this idea. It is found extensively in microprocessor equipment. It is particularly found in *bussed* systems where a multitude of devices might share a common, multi-track buss. Figure 11a shows the general internal circuitry of tri-state logic. The output can be high, low or (virtually) open circuit. The control input determines whether the output is 'enabled' (i.e: operative) or not. The outputs of tri-state logic are wired in parallel, sharing the same line. Only one driver is enabled at a time. It operates in a similar fashion to the wired-AND, the difference being that an 'enable' signal *must* be present for a particular gate's output to be active, otherwise the outputs remain in the open state.

Tools

There are two fundamental classes of tools employed in logic troubleshooting — *'stimulators'* and *'indicators'*. A stimulator is nothing more than a relatively simple pulse signal generator that is used to 'stimulate' sections of a faulty circuit into action. Hence the generic name. However, they are often called simply 'pulsers'. An indicator is just that — a device that will indicate the state of a point in a digital circuit; whether it's high, low, sitting at a bad level or pulsing. Generally a LED or other light indicator is used to signal the condition, some makes using several, coloured indicators.

There are two types of indicators — the *contact* type, where a connection is actually made to the circuit, and the *non-contact* type which picks up currents flowing in the circuit interconnections (generally called 'current tracers').

For user convenience, these tools are generally built into handheld, pen-sized cases with a sharp 'probe' point at the business end. Hence they are generally known as probes — *pulser probes* for the stimulators, *logic probes* for the indicators (because they indicate logic states). Actually, the use of the word 'probe' here is a misnomer. A probe is in fact a blunt instrument. Examine a logic probe, and except for the current tracer type you'll find they have sharp points!

Since it is necessary to observe dynamic signal activity, as well as the static levels, logic probes usually have pulse stretching circuitry that can detect pulses as narrow as 10 ns and stretch them so that a readily visible blink can be seen. Thus if a low signal pulses high, the logic probe will blink 'on'. If a high signal pulses low, the probe will blink 'off'.

With some logic probes, a pulse memory may be provided. This enables the probe to monitor a signal line for single shot or low frequency pulses over extended periods of time. If a pulse occurs, this will be indicated by the device, which will remain 'on' until reset by the user.

The existence of a pulse train is indicated by flashing the lamp indicator at a constant rate (typically 10 Hz) when a pulse train is present.

Thus a logic probe enables you to view static (high or low) logic levels, single-shot pulses and pulse trains. Automatic threshold detection is generally included as it eliminates the need to determine repeatedly whether a signal is above or below the threshold, and can be employed to show open-circuit conditions also. A TTL/CMOS switch is a necessity so that a probe can be used on both device families. Some makes work on both families, without a switch.

Current tracer logic probes require no contact with the circuit at all. At the business end of a current tracer probe is a small magnetic pickup, generally consisting of a coil wound on a tiny core which has a split, permitting any external field to induce currents into the winding. Of necessity, it works on pulse (ac) signals, detecting *current change*, not dc levels. Pulses are stretched so that the display, usually a LED, can be easily seen. Sensitivity can be arranged so that the current tracer will detect the current it takes to charge the gate input capacitance of CMOS devices.

Current tracers are very useful in sorting out 'stuck' nodes, particularly where there are many elements common to the node and too few ways to isolate the one bad component. It can be done, too, without cutting pc board tracks or lifting IC pins. They are also very useful in tracing signals on multi-layer boards.

Poke & peek

The mainstay of all digital troubleshooting is stimulus-response testing. It is necessary to apply a signal and observe the response to determine if the device is operating properly. As was pointed out earlier, this can sometimes be very difficult to do in TTL circuitry.

A logic pulse provides the solution. It is used to inject into the circuit a single pulse of proper amplitude and polarity — *forcing* something to happen. If the node happens to be low, it will be pulsed high, and if high, it will be pulsed low.

Generally, logic pulsers are capable of supplying both continuous pulse trains and single-shot pulses.

A logic pulser used in conjunction with a current tracer probe is particularly useful in tracing supply rail short circuits and stuck nodes having many common elements.

These tools are useful in troubleshooting both sequential logic circuits (counter, timer and simple control systems, etc) and parallel bit circuitry (microprocessor systems, etc). However, in parallel systems which are partially working it becomes necessary to see the simultaneous action of many lines or nodes, and a more complex technique, called *signature analysis*, is necessary. A signature analyser is the appropriate tool hre, and they come in many forms. Signature analysis, though, is a whole subject in itself and we'll have to leave that to another time.

Techniques

Your first 'port of call' should *always* be the power supply, particularly in the case of total collapse. If the power supply itself proves OK, but the rails on the pc board show a volt or less, then shorted rails should be suspected. If the supply rails are healthy, then the very next step is to attempt to narrow down the malfunctioning area as much as possible by examining the observable characteristics of the failure. Try to localise it to a circuit section or to as few sections as possible. Then you can proceed to eliminate circuit components step by step by looking for improper key signals between circuits — which is where the logic probe and current tracer come into their own. Table 1 details the general run of faults and how to detect them using the stimulus-response technique.

Dependence upon a well-written service manual is the key to this phase of troubleshooting. Isolating a failure to a single circuit requires knowledge of the instrument or system and its operating characteristics. A well-written manual will indicate key signals to be observed. The logic probe will provide a rapid means of observing the presence of these signals.

Once a failure has been isolated to a single circuit, the tools described can be used to observe the effect of the failure on circuit operation and to locate the failure to its cause (either an IC or a fault in the circuit external to the IC).

The logic probe is used to observe the signal activity on inputs and to view the resulting output signals. From this information, a decision can be made as to the proper operation of the IC.

For example, if a clock signal is occurring on a decade counter and the enabling inputs (usually reset lines) are in the enabled state, then the output should be counting. A logic probe will allow the clock and enabling inputs to be observed, and, if pulse activity is indicated on the outputs, then the IC can be assumed to be operating properly.

As stated before, usually it is not necessary to see the actual timing of the output signals, since ICs fail catastrophically. The occurrence of pulse activity is often enough indication of proper operation.

When more detailed study is desired, or when input signal activity is missing, the logic pulser can be used to inject input sig-.

TABLE 1.

FAULT	INDICATOR	STIMULUS	TEST METHOD
Shorted node	Current tracer	Pulser or circuit signals(1)	• Pulse node • Follow current pulses to short
Stuck data buss	Current tracer	Pulser or circuit signals(1)	• Pulse buss line • Trace current to device holding the buss line in a stuck condition.
Signal line short to Vcc or ground	Logic probe and/ or current tracer	Pulser	• Pulse and probe test point simultaneously • Short to Vcc or ground cannot be overridden by pulsing • Pulse test point, and follow current pulses to the short with tracer
Vcc to ground short	Current tracer	Pulser	• Remove power from test circuit • Disconnect electrolytic bypass capacitors • Pulse across Vcc and ground • Trace current to fault
Suspected internally open IC	Logic probe	Pulser or circuit signals(1)	• Pulse device input • Probe output for response
Solder bridge	Current tracer	Pulser or circuit signals(1)	• Pulse suspect line(s) • Trace current pulses to the fault (Light goes out when solder bridge passed)

1. Use the pulser to provide stimulus, or use normal circuit signals, whichever is most convenient.

nals, and the probe used to monitor the response. This technique is especially good when testing gates and other combinatorial devices. A logic pulser can be used to cause the inputs to go to a state which will cause a change in the output state.

For example, a three-input NAND gate which has high, low, low inputs will have a high output. By pulsing the two low inputs high using a logic pulser, the output will pulse low, and can be detected by a logic probe. This then indicates that the IC is operating properly.

A logic pulser is also valuable for replacing the clock in a digital circuit, thus allowing the circuit to be single-stepped while the logic probe is used to observe the changes in the circuit's state.

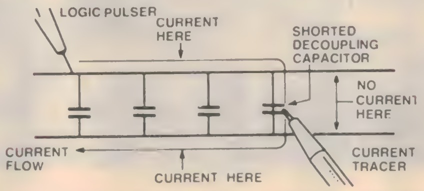
The first step might be called the 'mapping' step, since the effect is to *map out* the problem areas for further investigation. It is important to do a complete 'mapping' of the circuit before proceeding to analyse each of the indicated failures. Prematurely studying a fault can result in overlooking faults which cause multiple failures, such as shorts between two nodes. This often leads to the needless replacement of a good IC and much wasted time. With a complete trouble-area 'map' you can begin to determine the type and cause of the failures This is done by systematically eliminating the possible failures, as discussed earlier.

The first failure to test for is an open bond in the IC driving the failed node (the Figure 4 problem). A logic probe provides a quick and accurate test for this failure. If the output bond is open, then the node will float to a bad level. By probing the node, the logic probe will quickly indicate a bad level. If a bad level is indicated, then the IC driving the node should be replaced and retested.

If the node is not a bad level, then a test for a short to Vcc or ground should be made next (the Figure 6 problem). This is best done using a logic pulser and current tracer. The problem is to determine if the driver is dead, or if a shorted input is clamping the node to a fixed value.

Use a logic probe and pulser to test the node's logic state and to see if the state can be changed (shorts to Vcc or ground cannot be

Figure 12. Tracing a supply rail short. ▼



Use the probe and pulser to test the node's logic state and to see if the state can be changed (shorts to Vcc or ground cannot be overridden by pulsing). By pulsing the node you can follow the current directly to the faulty input using a current tracer (Figure 13).

If the node is shorted to Vcc or ground there are two possible causes. The first is a short in the circuit external to the ICs and the other is a short internal to one of the ICs attached to the node. The external short should be detected by an examination of the circuit. If no external short is found, then the cause is equally likely to be any one of the ICs attached to the node. The only suggestion that can be made (based on experience) is to first replace the IC driving the node, and if that does not solve the problem try each of the other ICs individually until the short is eliminated. (It might be noted that on occasion analogue components such as resistors or capacitors attached to the node have shorted.)

If the node is not shorted to Vcc or ground, nor is it an open output bond, then we should look for a short between two nodes. This can be done in one of two ways. First the logic pulser can be used to pulse the failing node being studied, and the logic probe can be used to observe each of the remaining failing nodes. If a short exists between the node being studied and one of the other failing nodes, then the pulser will cause the node being probed to change state (i.e: the probe will detect a pulse). To ensure that a short exists, the probe and pulser should be reversed and the test made again.

If the failure is a short there are two possible causes. The most likely is a problem in the circuit external to the ICs. This can be detected by physically examining the circuit, but shorts are not always obvious if only traced down to an area. A current tracer is best to pinpoint a short between tracks by tracing current from the pulser. When the short is passed, the signal disappears (see Figure 14).

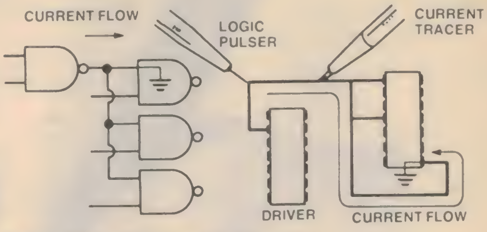


Figure 13. Tracing a stuck node. ▲

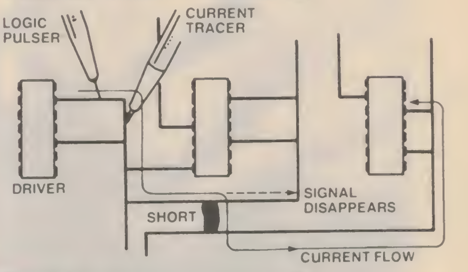


Figure 14. Tracing a track short. ▲

If the two nodes which are shorted are common to one IC, then the failure must be internal to that IC (the Figure 7 problem). If after examining the circuit no short can be found external to the IC, then the IC should be replaced.

If the failure is not a short between two nodes, then there are only two possibilities left. They are that the failure is an open input bond or a failure of the internal circuitry of the IC (Figures 5 and 8 problem). In either case, this IC should now be replaced. Thus by systematically eliminating the IC failures, the cause can be located.

An important step at any point where an IC is replaced is the retesting of the circuit. If the testing again indicates a failure, then more study of the problem must be made with the knowledge that the failure is not in the IC that has just been replaced.

An open track on the pc board (the Figure 9 problem) is best located with a logic probe, using either circuit signals or a pulser to provide the stimulus. The logic probe provides a rapid means of not only detecting but also physically locating the open.

Since an open signal path allows the input to the 'right' of the open to float to a bad level, the logic probe can be used to test the input of each IC for a bad level. Once an input floating at a bad level is detected, the logic probe can be used to follow the circuit back from the input looking for the open. This can be done because the circuit to the 'left' of the open will be a good logic level (either high, low or pulsing), while the circuit to the 'right' will be a bad level, precisely locating the open. The open can then be repaired and the circuit tested.

This systematic elimination of possible failures in digital circuits by the use of such special tools will ensure a rapid and accurate repair. Because these instruments provide a digital solution to the digital problem, improvements in servicing time of at last 4:1 are easily achieved over the use of analogue instruments. ●