Tracing current by inductive pickup tracks logic faults precisely

Instrument yields more information than do voltage sensors; use with logic pulser broadens applications

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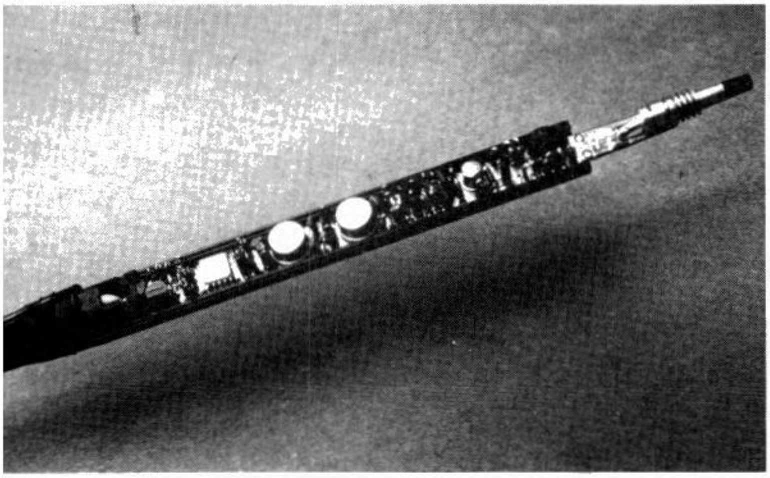
☐ Without the wide range of voltage-sensing instruments available, faultfinding in digital circuits would be like driving from New York to Los Angeles without a map. Yet such instruments give what amounts to a map that is missing route numbers. What will fill in the blanks and make the faultfinder happier is a new current tracer that, by itself or with a logic pulser, easily provides more complete fault information.

Voltage-sensing instruments—which range from low-cost logic probes and clips to computer-controlled automatic test systems—can localize failures down to the faulty node, tracking the fault to a collection of integrated-circuit terminals and the network of printed-circuit traces or wires connecting them. But to make a repair, it's usually necessary to determine precisely which IC has failed, or, if the problem is in the interconnection, where the short or open circuit is located.

Voltage measurements cannot provide this data, but variations in current provide exactly the information needed to pinpoint the faulty element. A map of current distributions will locate the precise point along a node at which an undesirable path, such as a short, exists.

Yet, despite this capability, little use has been made of the information provided by nodal current distributions simply because of the difficulty of measuring current flow. Traditional methods, such as cutting the trace and inserting an ammeter, or encircling the trace with a magnetic pickup, are clearly very awkward to use on pc boards.



1. Fault tracker. By picking up current spikes via inductive coupling instead of checking voltage levels, a current tracer can uncover the precise location of a printed-circuit-board fault, such as a short or open circuit in the printed wiring or within an IC.

Coupling signals

A technique that permits an engineer or technician to follow the flow of current in digital systems is to couple current pulses flowing in the system under test to a measuring probe via an inductive pickup. This method is implemented in Hewlett-Packard Co.'s model 547A current tracer (Fig. 1), a hand-held, self-contained probe that incorporates a display lamp to indicate the relative level of current steps.

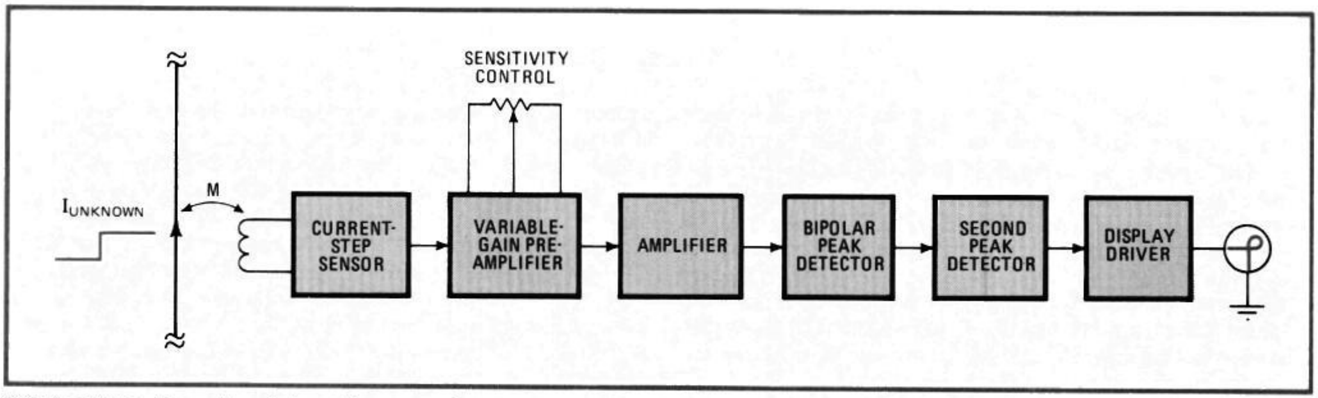
The tracer is compatible with all logic families, since it responds only to current. It is sensitive enough and has a wide enough dynamic range to detect currents resulting from faults in any of the presently available families. It can be powered from any dc source between 4.5 and 18 volts. Since this power source does not have to be referenced to the ground potential of the system under test, a floating power supply or battery may be used.

There are other physical phenomena and techniques for determining current distributions, but none is as convenient as inductive pickup. Liquid crystals could display the temperature rises resulting from power losses in the conductors because their reflectivity varies with temperature. However, this scheme has insufficient sensitivity and resolution to detect the smaller currents typically found on digital pc boards.

Another approach is to measure the voltage drops along the traces and thus uncover the directions of current flow. But the magnitudes of the drops along the typically short trace lengths found in digital systems are often on the same order as thermal emfs, and are therefore masked.

The faulty node could be stimulated by a sinusoidal signal and the current flow could be traced with an inductive pickup and a frequency-selective filter. But this method, which is often used by utility companies for locating cable faults, is awkward to use in practice. The injected stimulus must first be connected to the circuit, and it is not always obvious where the return connection should be made.

Another approach is to inject a pulse stimulus and then detect the resulting current flow with an inductive



2. Gain stages. The voltage induced from an unknown current spike as small as 1 milliampere requires multiple stages within the tracer to be amplified and stretched enough to drive an incandescent lamp to visible levels.

pickup coupled to a time-domain filter that rejects unwanted signals. This method can be quite effective, but requires a cable to synchronize the pulser with the pickup. This, along with the size of the instrument needed to perform the task, makes this system also somewhat awkward to use.

Simplifying the task

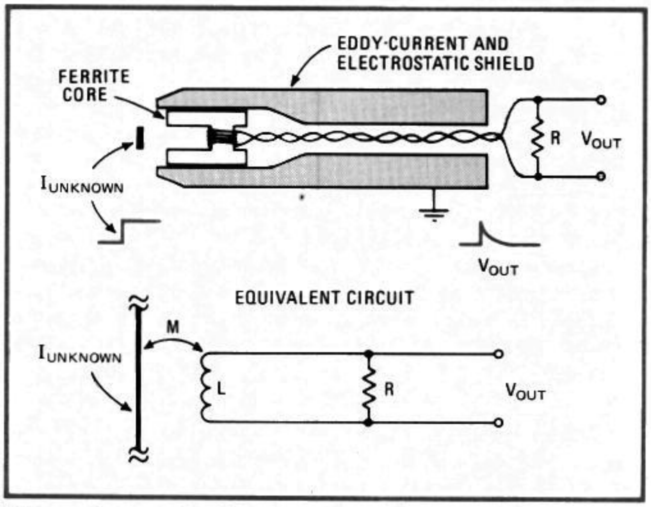
The HP current tracer is more compact than synchronized-signal tracers and is simpler to use. Since its dynamic range is large enough to respond to current changes present in most digital circuits, it typically does not require a stimulating signal. If a stimulus is required, as when testing an unpowered system, a signal can be provided by a logic pulser such as the HP 546A, or other models from HP and other logic-tester manufacturers. Even then, the tracer's shielding eliminates pickup from adjacent signal paths, so no synchronizing signal is needed.

The current tracer's tip is first placed near the driving point of the node, which is usually one of the IC terminals or the tip of the logic pulser. The tracer's sensitivity-control thumbwheel, which provides a range from 1 milliampere to 1 ampere, is adjusted until the display lamp is between half and fully lit. The thumbwheel is designed so that its position yields some indication of the magnitude of the current flowing, which may be useful in determining the nature of the fault. For example, if it indicates an abnormally high current, the fault is due to a low impedance on the node.

The tip of the tracer is then moved along the conducting path, and the display remains at the same brightness as long as the same current is present. If the current is diverted to another path, then the increased separation between the tip and the current lowers the output of the current-step sensor, and the display becomes less bright. The operator gets enough information to track the actual path followed by the current as it flows toward the fault.

Since the current tracer is picking up current pulses by inductive coupling, its tip need not make physical contact with the conductive path. Thus, insulated wires and inner traces of multilayer pc boards can be tested.

The current tracer contains six stages of signal processing and amplifying circuitry within its cigar-size case (Fig. 2). A step change in current at the tracer's tip is coupled, via mutual inductance, to the current-step sensor. This produces a voltage spike proportional in amplitude to the current step.



3. Current converter. Fine wires wrapped around a ferrite core act as a current transformer loaded by a small resistance that produces an output voltage. A conductive shield protects against unwanted magnetic and electrostatic fields.

The spike is fed to a variable-gain preamplifier, which produces an output of about 1 millivolt when the sensitivity control is properly adjusted. This signal is further amplified, then stretched in time by two peak detectors in order to produce a pulse of sufficient height and width to light the incandescent lamp that serves as the tracer's display.

The current-step sensor (Fig. 3) operates like a current transformer. It provides information about current changes, not a quantitative display of the total value of the current, but this is sufficient for faultfinding in digital systems.

A step change in current near the tip of the tracer attempts to induce an emf in the windings on the coil within the sensor. But, because the coil is nearly shorted by a low-value resistor, a current is induced in the coil large enough to cancel the flux change caused by the unknown current step. The current step induced in the pickup coil has a magnitude that is proportional to that of the unknown current.

The induced current flows through the resistor, producing a voltage that forms the output signal of the sensor. The resistor also causes the current in the pickup coil, and hence the output voltage, to decay from its peak value at a rate determined by the time constant L/R. This constant is such that the sensor's output is a spike with a peak value proportional to the change in the unknown current. The peak value is independent of the rise time of the input current change for rise times of less than about 200 nanoseconds.

There are a number of conflicting design criteria that the sensor must meet. It must be able to reject magnetic flux from locations other than the tracer's tip; it must not respond to voltage changes, and it must provide a detectable output for the smallest current steps likely to be encountered in properly functioning systems. It also must be small so that currents in closely spaced traces can be distinguished from each other; it must be mechanically rugged, and it must have reasonable manufacturing costs.

To meet these demands, a ferrite core is enclosed within a relatively thick, highly conductive shield. Besides providing mechanical support and protection for the core, the shield protects it from time-changing magnetic fields by inducing eddy currents that oppose the changing flux. It is electrically grounded and thus protects the coil winding from electrostatic coupling with the voltages on the board. Electrical fields are attenuated by more than 110 decibels, so the tracer's tip will ignore voltage steps of 5 v but still react to current steps of 1 mA. For such a step, the sensor provides a 100-microvolt output spike, about 150 ns wide.

Considerable amplification is necessary to bring this pulse up to a level that will drive a lamp and make the signal visible. Designing such an amplifier is difficult enough, but package constraints make it all the more difficult; for maximum convenience of operation, all the necessary electronics had to be housed within the body of the probe.

The shape and small size of the probe body make physical isolation of the amplifier stages impractical. The small volume within the probe also rules out effective high-frequency decoupling capacitors because of their large size. Yet another constraint is the requirement that the tracer operate from whatever power supplies are in digital circuits, typically 5 v or less.

Adding gain

Nevertheless, it was possible to package 80 dB of stable linear amplification, with 20 megahertz of bandwidth, on a pc board about 0.5 inch wide and 4 in. long. This was accomplished by carefully locating components to minimize capacitive coupling and orienting them to cancel destabilizing parasitic mutual inductive coupling. Shielding of the sensitive amplifier from external electric and magnetic fields is provided by the tracer housing, which is aluminum and thus makes both an electrostatic and an eddy-current shield.

There were other problems to be solved in the design of the current tracer. For example, an incandescent lamp was chosen for the display and was placed at the tip of the probe immediately behind the current-step sensor. This is a convenient and clearly visible location. But it creates a difficult stability problem, since a pulse at the sensor is amplified and then returns to the display. The

Troubleshooters in action

Some applications of the current tracer and pulser show the usefulness of the additional information they provide.

Stuck node caused by dead driver. A frequently occurring fault symptom is a node on which the voltage is not changing. The question to be settled: is the driver dead, or is something on the node clamping it to a fixed value, for example, a shorted input or a short on the board to ground or some other voltage? The answer comes from placing the tracer at the driving terminal of the node and observing the current activity. If the driver is dead, the tracer will indicate no current flowing.

Stuck node caused by an input short. With exactly the same voltage symptoms as in the previous case, the tracer might indicate a large current flowing from the driver, which means it is functioning. It will also enable the operator to follow the current to precisely the cause of the problem—in this example, a shorted input. The same procedure will also localize the fault when the short is on the interconnecting path of the node, such as a solder bridge to another node.

Stuck wired-AND node. Another difficult troubleshooting problem for voltage-sensing instruments is a fault in a node formed by tying together a number of open-collector outputs. The tracer can resolve this problem if the output of each gate is forced to its high-impedance state while a logic pulser stimulates the node. If the gate is good, the tracer will indicate no current at its terminal, but a stuck gate will draw a large current. The need to force the output of the gate to the high-impedance state by a jumper at the input can be eliminated if the duty cycle of the high-impedance state (while the circuitry is running) is high enough. Then the pulser and tracer may be used in the single-pulse mode. If the gate is not stuck, the operator will observe a random appearance of current at the gate output while single-pulsing the node. If it is stuck, each pulse will result in a large current.

Malfunctioning three-state data buses. Data buses such as microprocessor data and address buses usually are spread over large board areas and tie many integrated circuits together. Since voltage cannot provide sufficient resolution to locate the fault, the additional data provided by the current tracer is of maximum value. For example, if there is a "bus fight" between two drivers attempting to simultaneously control the bus, the current tracer will indicate abnormally large currents at the competing drivers. Other malfunctions can be localized in a manner similar to that used for wired-AND faults.

There are a number of other applications for the tracer and pulser. Whenever a low-impedance fault exists, the shorted node can be stimulated with a logic pulser and the current traced by the tracer. This combination has been effective in finding shorts in cables, motherboards, analog printed-circuit boards (including inner layers of multilayer boards), and voltage-distribution networks.

energy content of the pulse that flashes the display can be greater than 10^{14} times that of the energy captured by the sensor.

With the shielding of the sensor, with the orientation of the amplifier components, and with careful pc board design, it is possible to electrically decouple the input from the output. In fact, the current pulse that drives the display lamp actually passes right through the amplifier area of the pc board.

Running the supply and return traces on the inner layers of the multilayer board, one above the other and separated by a very thin insulating layer, and covering them with an outer-layer ground plane confines the fields from the display pulse to a very small space. The ground plane also was designed so that the charging currents of the parasitic capacitance between the grounded eddy-current shield and the trace under investigation can pass through the amplifier area of the board without inductive coupling of unwanted signals.

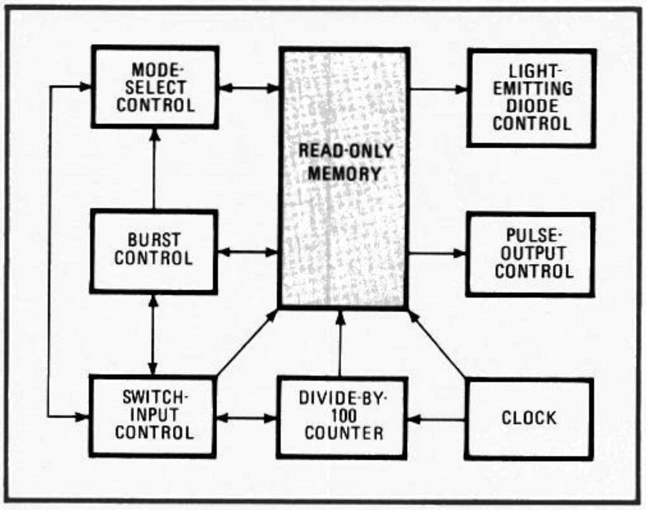
Resolving problems

This still does not solve all the problems of designing a wideband, high-gain amplifier for the tracer. It is necessary to bring the fault currents in the various logic families and pulse stimulators to a common reference level so that the operator sees only the value of the current at the tracer's tip relative to that at the driving point of the node. The 60-dB (1,000:1) gain variation demanded by currents from 1 mA to 1 A cannot be achieved with a potentiometric divider, since the parasitic inductances and capacitances at the extreme positions of the divider destroy the required high-frequency response. It is also necessary to insert the gain control at the initial stages of the amplifier chain because the requirement for operation from 5-V supplies severely restricts the linear operating range of the amplifiers.

To solve these problems, the entire 60 dB of gain control was placed in the first amplifier stage. The basic configuration of the stage is a single transistor with an emitter resistor that is approximately equal to the collector resistor and has no bypass capacitor. Current-controlled variable resistances, in the form of Schottky and silicon diodes, are ac-coupled to the collector and emitter resistors. When the sensitivity control on the tracer is in the 1-mA position, the emitter resistance is low and the collector resistance is high, forming a common-emitter amplifier of 20 dB gain. When the sensitivity control is in the 1-A position, the collector resistance becomes very small and the emitter resistance large, so the circuit becomes a 40-dB attenuator.

Stretching pulses

When the sensitivity control is set so that the display is at its reference level, the output of the current-step sensor emerges from the amplifier chain with an amplitude of about 500 mV and a width still of about 150 ns. The polarity of this output may be positive or negative, depending on the polarity of the current step and the randomly chosen orientation between the current path and the pickup coil in the tracer. Since the operator is interested only in the variation of this pulse as the tracer tip is moved from place to place, all that is required is a display-driving signal proportional to the amplitude of the output of the amplifier chain, but independent of its polarity and long enough to be visible.



4. Pulse control. Almost all the circuitry of a logic pulser is contained on a custom integrated circuit, including the read-only memory that controls all the operations of the instrument. Even circuitry regulating the power-supply voltage is on the chip.

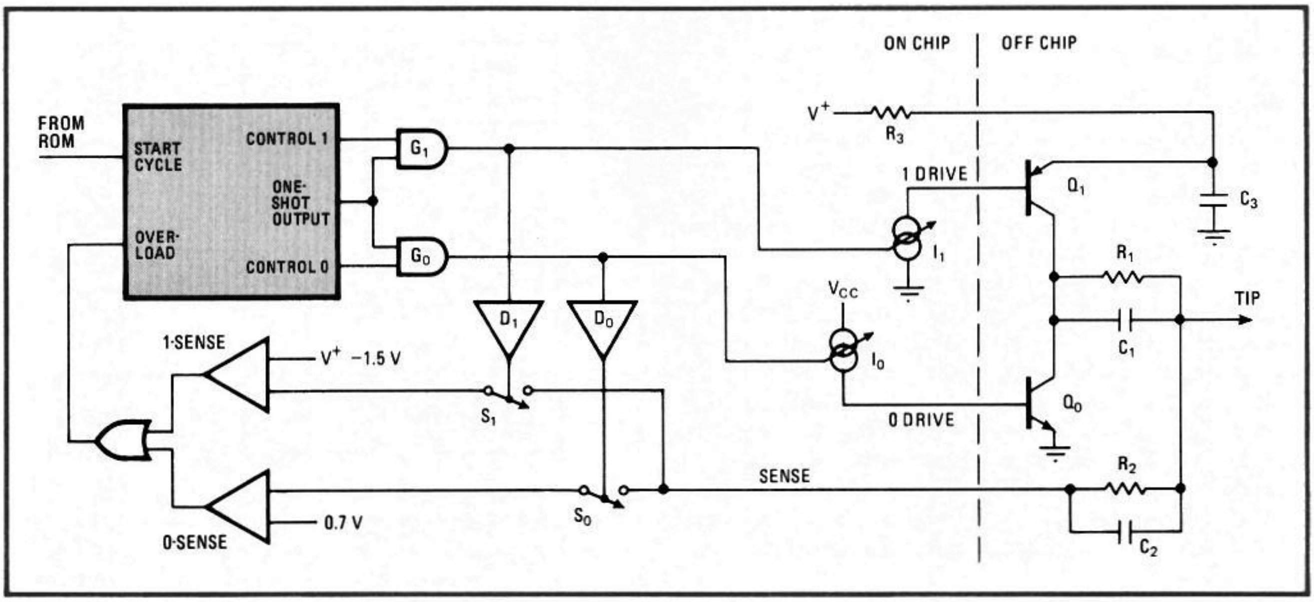
This signal processing is accomplished in two peak detectors and a display driver. The first, or bipolar, peak detector produces an output pulse of the same amplitude as the input pulse, but always positive in polarity. It also stretches the peak of the 150-ns input pulse from about 20 ns to about 40 μs. Since this is still not sufficient to produce a visible pulse, a second peak detector is employed to stretch the output of the bipolar peak detector to about 200 milliseconds, which is quite visible. The display driver then provides a signal of proper amplitude to drive the display lamp.

Driving nodes

Sometimes an external stimulus is required, or it may be more convenient than tracing the currents generated by the logic under test. A pulse generator or any of a number of logic pulsers can be used to perform this function.

One such logic pulser is the HP model 546A. It can overdrive logic nodes with narrow pulses of controlled voltage, polarity, width, rate, and count. A single, serially encoded switch selects continuous pulse streams at 1, 10, or 100 hertz, bursts of 10 or 100 pulses with 1-second pauses between bursts, or single pulses. To program a mode, the button is pushed a set number of times in rapid succession. Holding it down after the last push causes the selected function to be executed. Sliding it forward locks it down and keeps the pulser in the selected mode. Mode-select control circuitry determines whether the instrument is in the programing, executing, or standby mode.

The overall parts count, size, power consumption, and cost of the pulser are kept low by employing a single custom chip to perform most functions. The chip (Fig. 4) contains a 256-bit read-only memory, 14 flip-flops, 41 gates, and other devices, including an on-chip voltage regulator, for a total of about 1,000 transistors on a 108-



5. Power provider. By cutting off the one-shot output after 10 μs or when C_1 is charged, the pulser output circuit compensates for different logic families. A low-current, wide pulse is fed to C-MOS devices, and a higher-current, shorter pulse drives TTL devices.

by-128 mil die. With micropower Schottky-transistor-logic cells, most of the IC operates at a low voltage, so two sets of layout rules were adopted to minimize total chip area. Using small cells for low-voltage and larger ones for higher-voltage circuits permits a standard, bipolar, single-level-metal manufacturing process.

Controlling the generator

The 256-bit ROM, which occupies less than 10% of the area on the chip, controls the operation of the logic pulser by decoding status information from other on-chip circuitry and translating this into binary commands. The ROM accepts inputs from switching, counting, and mode-selection circuitry, controls the pulse-tip output and light-emitting-diode indicator, and feeds status information back to timing and control circuits.

A free-running, 100-Hz clock circuit acts as a time base for the instrument. An external resistor and capacitor combination to control the 100-Hz rate makes accuracy better than 10% over a range of power-supply voltages and temperatures.

The divide-by-100 counter acts as a scaler for generating pulse and annunciator output rates, as a counter/controller for the bursts, and as a timer for mode detection and switch debounce. The switch-input control debounces the switch, presets the divide-by-100 counter and burst control, generates a single-shot output signal, and increments the mode-select control circuit.

The burst control governs the timing, count, and pause interval between burst outputs. The annunciator circuit is a constant-current sink that drives two high-efficiency LEDs mounted in the pulser's tip. The LEDs provide visual feedback of the pulser's mode and can be used to keep track of the number of pulses generated in the burst modes.

The pulse-output control delivers the pulse polarity, voltage, width, and rise time necessary to overdrive the logic node at the pulser's tip. The nature of the pulse depends on the logic family of the circuit under test. For example, the pulser can deliver a 0−3-V, 10-mA, 10-μs pulse to a 3-V complementary metal-oxide-semiconductor clock input, or a 0−5-V, 500-mA, 0.5-μs pulse to a transistor-transistor-logic line-driver output.

In the pulse-output circuit (Fig. 5), transistors Q_0 and Q_1 are usually off, switches S_0 and S_1 are open, and the tip presents a high impedance to the logic node. Any residual charge on coupling capacitor C_1 is bled off by resistor R_1. When a signal from the ROM initiates an output cycle, the one-shot is triggered, and transistor Q_0 turns on via a signal from the logic-0 control, which passes through G_0 and turns on a 100-mA current source, I_0. When Q_0 saturates, S_0 is closed and the 0-sense comparator is turned on through delay element D_0. The load on the pulser tip is pulled toward ground through C_1. Current flowing through C_1 is reflected as a voltage, $dV = I\,dt/C_1$, on the sense line via input resistor R_2 and a speed-up capacitor, C_2.

Forming an output

When the load current at the tip is low (less than 100 mA for C-MOS), C_1 charges slowly. Before it can reach 0.7 V, about 10 μs goes by, causing the one-shot to shut off the 0-output circuit through G_0. If the load is heavy, as when driving a TTL buffer, charge develops rapidly on C_1. When the voltage reaches 0.7 V, the 0-sense comparator fires the overload line, causing the one-shot to retrigger and the 0-output circuit to turn off. The heavier the load, the shorter will be the output pulse.

At the conclusion of the 0-output pulse, the logic-1 output circuit goes into action. Its operation is much the same. The 1-sense circuit has a variable threshold setting to adjust to the 3−18-V operating range. The 1-output circuit includes charge-storage capacitor C_3 and charging resistor R_3. Capacitor C_3 sets the 1-output-pulse amplitude and decouples potentially large current surges from the test circuit's supply line. Between output cycles, R_3 restores charge lost on C_3 during the preceding output. The output cycle ends when Q_1 turns off. ☐