40 PROJECTS

Using COSMOS Digital IC's

Are you up on COSMOS, the latest in solid-state technology?

If not, learn what its about with these simple circuits.

DIGITAL INTEGRATED CIRCUITS HAVE BEEN available for a good many years now and most readers will be familiar with common family logic names like RTL (*R*esistor-*T*ransistor *L*ogic), DTL (*D*iode-*T*ransistor *L*ogic), TTL (*T*ransistor-*T*ransistor *L*ogic) and ECL (*E*mitter-*C*oupled *L*ogic). Each of these families offers its own particular advantages when compared to the other types, but all the families share a number of common disadvantages.

The chief disadvantages of the more common logic families are, (1), high quiescent current requirements (typically 5 mA per gate), (2), tight power supply requirements (power supplies typically have to be regulated to ± 10%), (3), low input impedances (typically a few hundred ohms per gate) and (4), poor noise immunity (meaning that gates can be easily triggered by spikes on the supply lines).

Recently, a new and rather amazing type of digital IC has appeared on the scene and seems set to push all the other families into rapid obsolescence in low- to medium-speed applications. This new family of devices are known as COSMOS or CMOS (*C*omplimentary *M*etal *O*xide *S*ilicon) digital IC's and suffer from none of the disadvantages of the earlier families.

Typically, COSMOS draws the incredibly low quiescent current of only 0.001 μA per gate and can be used with unstabilized power supplies giving voltages anywhere in the range 5 to 15 volts (special versions of COSMOS can operate as low as 1.3 volts). Each COSMOS logic gate has an input impedance of about a million megohms, but is fully protected against damage by static charges via built-in safety circuitry.

COSMOS has inherently good noise immunity and can safely tolerate input spikes up to nearly 50% of the supply voltage without being upset. Finally, COSMOS has excellent thermal characteristics: low-cost "commercial" types of COSMOS are designed to operate over the temperature range −40°C to +85°C, while the more expensive military versions can operate from −55°C to +125°C.

The performance of COSMOS is so unbelievable that we have decided, in this series of articles, to PROVE just how good it really is by presenting forty practical projects that you, the reader, can build around a single low-cost COSMOS digital IC. These projects range from simple pulse inverters to high-output multi-input burglar alarms, etc. The IC that forms the basis of these forty circuits is a quad 2-input NOR gate and is available from a number of advertisers in this magazine at a cost of less than one dollar.

Before going on to look at the first of these practical projects, however, let's digress a little and find out just why COSMOS is so good. You might also check the article "All About CMOS" by Don Lancaster in **Radio-Electronics** December 1973.

Understanding COSMOS IC's

The simplest type of digital circuit that you get in any logic family is the inverter or NOT gate. The symbol for a NOT gate is in Fig. 1-a and its resistor-transistor equivalent is in Fig. 1-b. Circuit operation is quite simple. Input and output are always either low (grounded or at logic 0) or high (at positive supply voltage or logic 1). Suppose that the input to the circuit is at logic 0. In this case, zero base drive is applied to transistor Q1, so the transistor is cut off and the output is at logic level 1. In this case, the quiescent current of the circuit is equal to the leakage current of the transistor and is virtually zero.

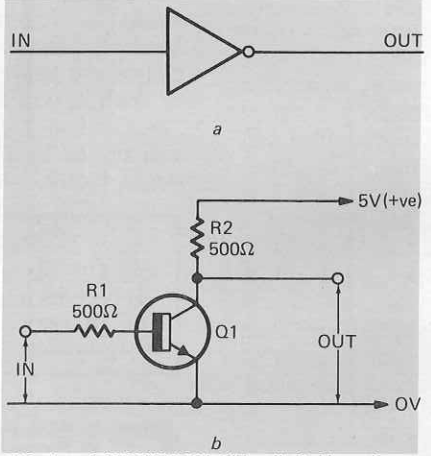


FIG. 1-a—THE SYMBOL OF a digital inverter or NOT gate. b—RESISTOR-TRANSISTOR equivalent circuit.

Suppose now that the input to the Fig. 1 circuit is set to the high or logic 1 level. In this case, heavy base drive is applied to Q1 via R1, so the transistor is driven to saturation and the output falls to logic level 0. Under this condition, the quiescent current of the circuit rises to about 10 mA. Also note that the output of this simple circuit is always inverted relative to the input.

A simple manually-triggered 'memory' circuit can be made up from two NOT gates by cross-coupling them as shown in Fig 2. If we press S1, we set the input of Q2 to logic 0 so the output of Q2 goes to logic 1 and drives Q1 on and thus reduces the Q1 output to logic 0. Because of the cross-coupling, the circuit stays locked in this state once S1 is released so the circuit acts as a simple memory. The state of the memory can be changed, if required, by momentarily closing S2, in which case the output of Q1 goes to logic 1 and the output of Q2 goes to logic 0. The important point to note here is that one or other of the transistor NOT gates is switched hard on (saturated) at all times, irrespective of the state of the memory, so the circuit draws a constant quiescent current of 10 mA.

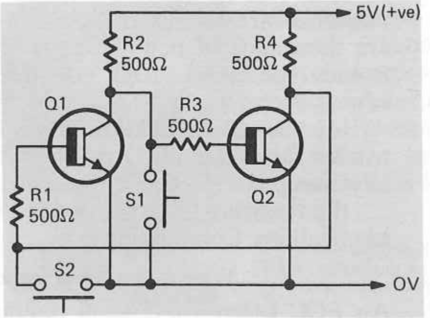


FIG. 2—SIMPLE MANUALLY TRIGGERED resistor-transistor "memory" circuit draws a quiescent current of 10 mA.

So much for resistor-transistor logic. Let's now go on and see what happens in its COSMOS equivalent.

Figure 3 shows the basic circuit of a COSMOS inverter or NOT gate. The circuit consists simply of one p-channel and one n-channel insulated-gate field-effect transistor (IGFET), wired in series between the two supply lines, with the IGFET gates tied together at the input terminal and with the output taken from the junction of the two devices.

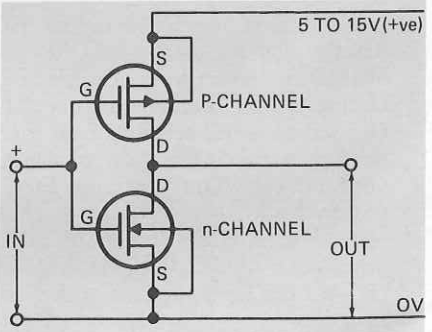


FIG. 3—BASIC COSMOS digital inverter or NOT gate.

Essentially, an IGFET can be regarded as a 3-terminal voltage-controlled variable resistance. The variable resistance appears between the two terminals known as the source and the drain, and the control voltage is applied between the source and the third terminal, known as the gate. The gate typically presents an impedance of about a million megohms to incoming voltages or signals, so the IGFET can be regarded as a voltage (rather than current) controlled device.

When a very low (near-zero) voltage is applied to the IGFET gate, the drain-to-source path of the device acts like an open-circuit resistance and typically presents an impedance in the order of thousands of megohms. Near-zero current thus flows through the device under this condition. If the gate voltage is steadily increased, a point is reached where the drain-to-source resistance just starts to fall: this point is known as the THRESHOLD and threshold voltages are usually between 2 and 3 volts in COSMOS IGFET's.

As the gate voltage is increased beyond the threshold, the drain-to-source resistance falls further and eventually falls to a minimum effective value of about 400 ohms: the resistance cannot fall below this value no matter how much further the gate voltage is increased, so a safe limit is automatically set on the maximum current that can flow through the device.

Let's go back to our Fig. 3 circuit in which we are concerned mainly with input signals that are *low* (below the threshold of the n-channel IGFET but above that of the p-channel device) or *high* (above the threshold of the n-channel IGFET but below that of the p-channel device.

Suppose first that we have a logic 0 (low) input to the circuit. In this case, the n-channel (lower) IGFET is cut off and is acting like a virtual open-circuit resistor with an impedance of about 10,000 megohms, but the p-channel (upper) IGFET is biased hard on and acts like an impedance of only 400 ohms.

This situation is clearly illustrated in the equivalent circuit of Fig. 4-a where it can be seen that the two IGFET's act like a resistive voltage divider in which the output is high (at logic 1) and is essentially strapped to the positive supply line via the 400-ohm resistance and in which the quiescent current of the divider is limited to the nanoamp region by the high value of the 10,000-megohm resistor.

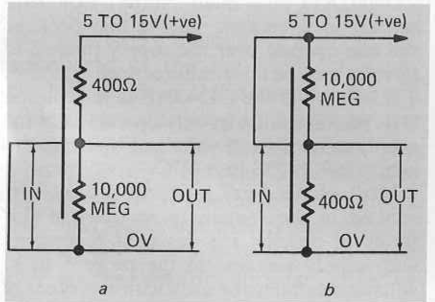


FIG. 4—EQUIVALENT CIRCUIT OF COSMOS NOT gate circuit with (a) logic 0 input and (b) logic 1 input.

Suppose now that the input voltage is slowly increased in a positive direction. The device current is virtually zero until the input voltage exceeds the threshold of the n-channel IGFET, at which point the effective resistance of the n-channel device starts to decrease and that of the p-channel IGFET starts to increase. Under this condition, the device current is dictated by the larger of the two resistances and is of measurable proportions.

When the input voltage is appreciably *less* than half of the supply volts, the resistance of the n-channel IGFET is much greater than that of the p-channel device, so the output of the circuit is high or at logic level 1: when the input voltage is appreciably *more* than half of the supply volts, the resistance of the n-channel IGFET is much less than that of the p-channel device, so the output of the circuit is low or at logic level 0.

When the input voltage is at approximately half-supply volts, a point is reached where both IGFET's attain the same value and at this point the output voltage starts to switch from one logic level to the other and a current of several milliamps may flow through the circuit: in practice, a semi-regenerative switching action takes place at this point and the output switches abruptly from one state to the other.

The value of input voltage needed to initiate this switching action is known as the TRANSITION voltage and is usually specified as a percentage of the supply voltage. Transition voltages vary between 30% and 70% of the supply voltage in COSMOS devices.

Finally, consider the case where the input to the Fig. 3 circuit is high or at logic 1. In this case, the p-channel IGFET is cut off and acting like a virtual open circuit while the n-channel IGFET is biased hard on and is acting like a 400-ohm resistor. This situation is shown in Fig. 4-b where it can be seen that the two IGFET's again act like a voltage divider, but in this case the 400-ohm resistor is at the low end, so the output is low (at logic 0) and is essentially strapped to ground via 400 ohms. The quiescent current of the network is again limited to the nanoamp region by the larger of the two resistors.

Thus, the Fig. 3 circuit acts as a conventional digital inverter or NOT gate, but has the following unique properties:

1. An exceptionally high input impedance (about a million megohms).

2. It draws negligible quiescent current from the supplies (about one nanoamp), irrespective of its logic state.

3. It can be operated from a wide range of supply voltages (typically 5 to 15 volts), since its minimum voltage requirement is limited only by the threshold characteristics of its IGFET's and the maximum is limited only by the breakdown characteristics of the devices.

4. Its output can swing from zero to the full positive supply rail voltage since no potentials are lost in the circuit as a result of saturation voltages or forward biased junction voltages.

5. The device cannot be damaged by shorts at its output since the maximum current of the device is automatically limited by the 400 ohms minimum impedance of its ON IGFET.

Figure 5 shows how two COSMOS NOT gates can be cross-coupled to form a simple manually-triggered memory circuit. This circuit operates in a similar way to that of Fig. 2. When S1 is momentarily closed, the input to gate B is set at logic 0, so the output of gate B goes to logic 1 and in turn drives the output of gate A to logic 0.

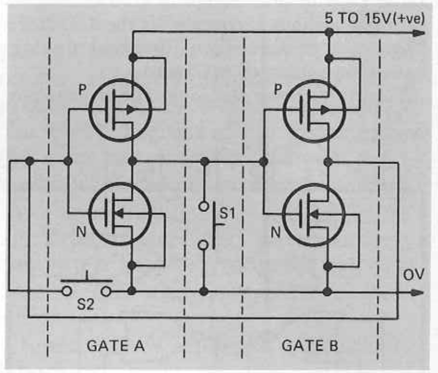


FIG. 5—MANUALLY TRIGGERED COSMOS "memory" circuit draws a quiescent current of .002 μA.

The circuit remains in this state when S1 is released due to the cross-coupling between the two gates, so the circuit acts as a simple memory. The state of the memory can be changed by momentarily closing S2, in which case the output of gate A goes to logic 1 and the output of gate B goes to logic 0.

The most important practical difference between the resistor-transistor memory circuit of Fig. 2 and the COSMOS circuit of Fig. 5 is that the resistor-transistor circuit draws a quiescent current of 10 mA while the COSMOS version draws a quiescent current of only 0.002 μA. Thus, the resistor-transistor version draws five million times more quiescent current than its COSMOS equivalent.

The reader may at this stage be thinking that this notion of a logic circuit drawing virtually zero supply current sounds too good to be true and that there must be a catch in this COSMOS business somewhere. The simple answer to that is that a COSMOS circuit does in fact draw a significant current, but only as it is going through the actual motion of changing logic states and not when it is in the quiescent condition.

Each time COSMOS changes state, it draws a pulse of current from the supply. The more often it changes state in a given time, the greater are the number of current pulses that it takes from the supply and the greater is the MEAN current that it consumes. Thus, the mean current that it takes is directly proportional to the frequency of its operation.

At frequencies of 5 MHz, COSMOS logic draws roughly the same current as its TTL equivalent: at 5 kHz, it draws only one-thousandth of the current of TTL. Consequently, COSMOS is best suited to low- or medium-speed applications, although it is capable of operating as high as 10 MHz when needed.

Having cleared up these basic points, let's go on and look at a practical COSMOS digital IC.

The CD4001

Several manufacturers produce ranges of COSMOS digital IC's. Leaders in the field are RCA, and one of the most useful and versatile IC's in their range is a quad 2-input NOR gate which is known as the CD4001: Motorola produces an identical device under the coding of MC14001.

Figure 6 shows the logic circuit and pin connections of the CD4001 IC which is encapsulated in a 14-pin dual-in-line plastic or ceramic package. As you can see, two of the pins are used for supply connections (pin 7 goes to ground and pin 14 goes to the positive supply line) and the rest of the pins connect to the input or output terminals of the NOR logic gates. There are four identical 2-input NOR logic gates in each IC package.

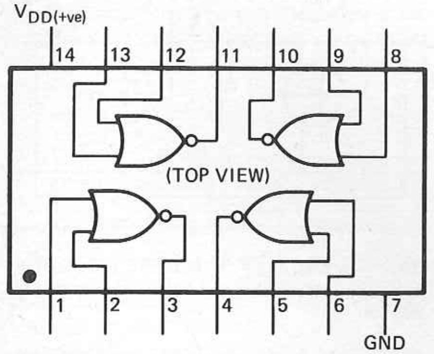


FIG. 6—LOGIC DIAGRAM and pin connections of the CD4001 quad 2-input NOR gate.

Figure 7-a shows the actual circuit that is used in each of the 2-input NOR gates. Here, two series-connected p-channel IGFET's are wired in series with two parallel-connected n-channel IGFET's: each of the two input terminals is connected to the gates of one of the p- and n-channel IGFET pairs. Circuit operation is as follows.

Suppose first that both input terminals are grounded or at logic level 0. In this case, both of the n-channel IGFET's are biased below their threshold points and act like open-circuit resistors and both of the p-channel IGFET's are saturated and act like 400-ohm resistors. The output of the circuit is thus high and at logic level 1 under this condition. The output is thus inverted relative to the inputs.

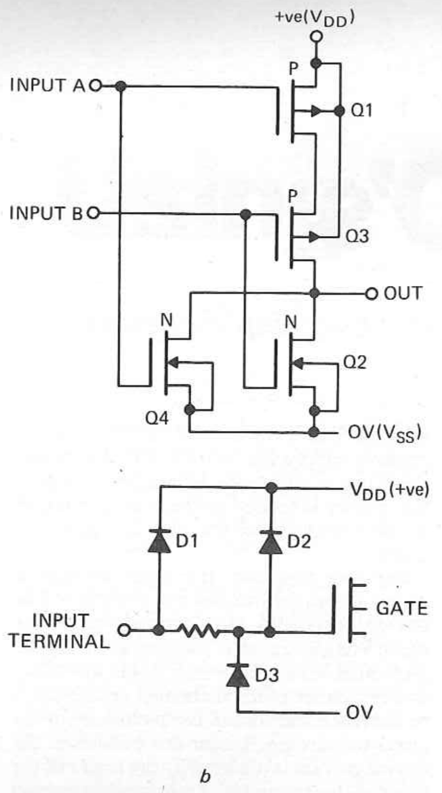


FIG. 7-a—CIRCUIT OF EACH of the four gates of the CD4001. b—COSMOS GATE INPUT protection circuit that is connected to each of the eight input terminals of the CD4001.

Suppose now that input A is at logic level 1 and that input B is at logic 0. Now Q2 acts like an open-circuit resistor and Q3 acts like 400 ohms due to the 0 input on terminal B, but Q1 acts like an open-circuit resistor and Q4 acts like 400 ohms due to the 1 input on terminal A. Since Q1 is in series with Q3 and Q2 is in parallel with Q4, the result is that the top half of the circuit acts like an open circuit and the lower half acts like 400 ohms. Consequently, the output of the circuit is low and at logic 0 under this condition.

Suppose next that input A is at logic level 0 and input B is at logic 1. This situation is similar to that outlined above except that in this case, Q3 and Q4 act like open circuits and Q1 and Q2 act like 400-ohm resistors. The net result is the same, however, and the top half of the circuit acts like an open circuit and the lower half acts like 400 ohms, so the output of the circuit is again at logic 0 under this condition.

Finally, suppose that both inputs are at logic level 1. In this case, both upper IGFET's act like open circuits and both lower IGFET's act like 400-ohm resistors, so the output is again low at logic level 0.

Thus, the output of the NOR gate goes to logic 1 only when both inputs are at logic 0. Note that the circuit can be made to function as a simple logic inverter or NOT gate by shorting inputs A and B together.

All input terminals of the CD4001 NOR gate IC (and all other digital IC's in the COSMOS family) have input impedances of about a million megohms, but are fully protected against damage from static charges via the input safety circuit shown in Fig. 7-b. Each of the eight input terminals of the CD4001 are protected by one of these diode-resistor safety circuits.

The CD4001, like all COSMOS digital IC's, is an extremely rugged device and can withstand considerable abuse without suffering permanent damage. Its output, for example, is fully short-circuit proof. There are in fact only three ways in which you can damage a COSMOS circuit and one of these is to connect the supply lines in the wrong polarity, in which case heavy current will flow through the D2 and D3 protection diodes and damage the substrate.

One other way you can damage the device is to connect a very low impedance input signal to it when its power supplies are switched off and the remaining way is to connect the device to a very low impedance input signal that has such a large amplitude that it goes above the positive supply line voltage. In either case, a heavy current will flow through protection diode D1 and the substrate will again be damaged. Both of these potential sources of damage can be eliminated by simply wiring a 1000-ohm resistor in series with each input terminal so that any current that does flow is limited to a safe value of a few milliamps.

Using the CD4001

The CD4001, like all other COSMOS digital IC's, is a very easy device to use, providing you obey the following basic rules.

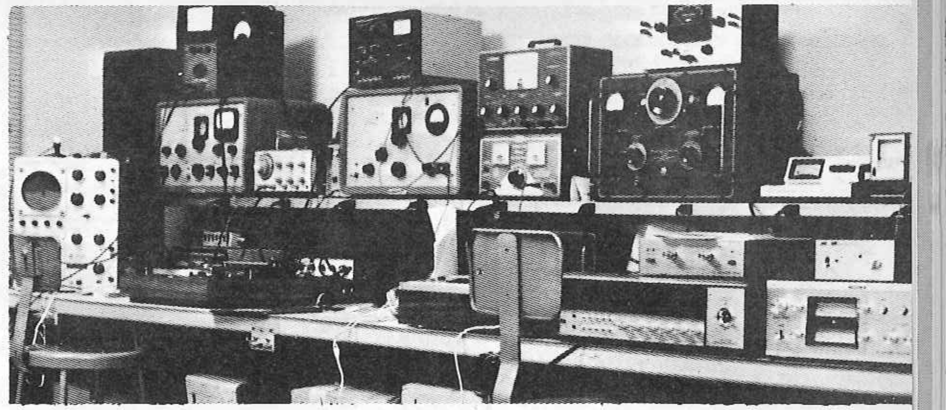
1. **Always make sure** that power lines are in the correct polarity before you apply power to the IC.
2. **Never connect** very low impedance energy sources (including storage capacitors) directly to the device input terminals: always connect them via a 1000-ohm or greater current-limiting resistor.
3. **Always tie unused input** terminals directly to ground or to the positive supply line, depending on the logic requirements.
4. **Never let used inputs float:** always take them to ground or to the positive line via a high value resistance.

When you buy your first CD4001 IC, you'll find that it has a one-or-two-letter suffix added at the end of its basic code number. This suffix relates to the style of packaging of the device and to its voltage and temperature operating ranges. Details of the meanings of the five available suffix codes are shown in Table 1. Thus, the CD4001AD is a quad 2-input NOR gate housed in a ceramic dual-in-line package and can operate over the supply range 3 to 15 volts and the temperature range −55°C to +125°C, while the CD4001E is in a plastic DIL package and can only operate over the supply range 5 to 15 volts and the temperature range −40°C to +85°C.

Most of the forty practical projects described in the remaining sections of this series of articles are designed to operate with supply voltages in the range 5 to 15 volts and can thus be used with any types of CD4001 IC. In most cases, however, the circuits can be made to operate with supply voltages as low as 3 volts by simply using them with CD4001 IC's that have suffix numbers AD, AE or AK.

Next month we will go on and look at the first of our 40 IC projects. **RE**

HOW TO



Measure HI-FI Amplifier Performance

Checking hi-fi component performance is a job that requires precise measurements with lab-grade test equipment. Our audio consultant describes his test gear and how it's used.

by LEN FELDMAN
CONTRIBUTING HIGH-FIDELITY EDITOR

HIGH-FIDELITY COMPONENTS HAVE reached a level of perfection which would have seemed impossible even for so-called professional sound equipment just a few years ago. Frequency response of audio amplifiers extends well below and above human audibility. Recognized forms of distortion such as IM and harmonic have been reduced in modern solid-state amplifiers to percentages so low as to defy measurement using the very best test equipment available just a few years ago. Power output of solid-state amplifiers is fast approaching kilowatt levels.

Whether or not you agree that these last orders of refinement are worth the money the consumer pays for them is secondary. Admittedly, there are experts in the field who steadfastly maintain that harmonic distortion of less then 0.5% contributes no further improvement to audible fidelity and that the ability of an amplifier to reproduce frequencies below 20 Hz or above 20 kHz is equally academic. Still, in the real world of the knowledgeable audiophile, there *are* consumers who are willing to pay for the ultimately low distortion figures and the wideband response. More important, these same consumers want continued assurances that their equipment is performing as well as when it was purchased. The fully equipped audio service center or laboratory of a few years ago is just not capable of accurately measuring and reporting on the important audio parameters of a modern hi-fi amplifier or preamplifier, however heavy the initial investment in test equipment many have been.

Take my own case. In addition to engaging in fundamental audio and rf design from time to time, I regularly test and report on a variety of audio products and occasionally am commissioned to confirm the performance of new prototype products which manufacturers submit to my laboratories.

Distortion measurements

Up until recently, the measurement of harmonic distortion or power output capability of an amplifier on my lab bench involved the use of at least four separate pieces of equipment, arrayed in the photo of Fig. 1. These included a Hewlett-Packard 650A signal generator, an HP 330A harmonic distortion analyzer, a Tektronix dual trace wideband oscilloscope, model 533, a pair of Ballantine ac vtvm's and, of course, suitable non-inductive loads of proper 8-ohm or 4-ohm impedances. The block diagram of Fig. 2 illustrates the usual setup. Since line voltage invariably affects power output capability of an audio amplifier, a variable voltage transformer and an accurately calibrated ac line voltmeter are also part of this elaborate measurement setup.

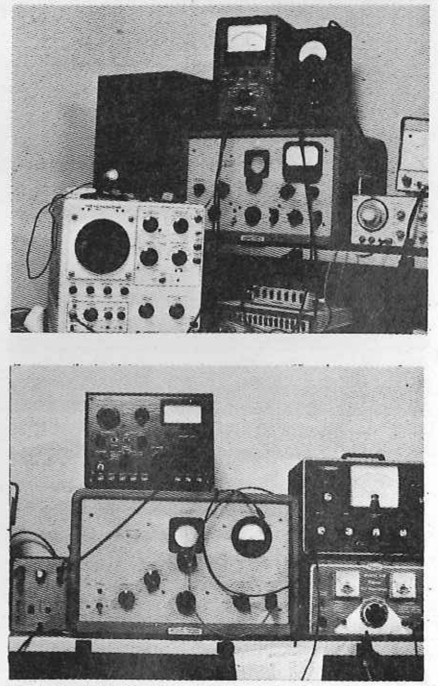


FIG. 1—PHOTOS SHOW MAJOR pieces of equipment used to check audio amplifier performance.

Since a fully equipped high-fidelity laboratory must also be capable of measuring the performance of FM tuner sections, a variety of additional equipment is arrayed across the test bench as shown in Fig. 3 and additional items are detailed in Figs. 4, 5 and 6. The inherent distortion of the HP 650A audio generator was known to be just under 0.1%, but there are amplifiers on the market today which boast THD figures of 0.02% and even lower at nominal power output levels. In addition, to perform a series of THD measurements over the entire audio spectrum involved tedious repeated voltage readings, resetting of frequency at both generator and distortion analyzer and repeated nulling and balancing of the null filter in the analyzer. At best, readings were subject to errors based upon meter and load accuracies. Particularly at maximum power output of an amplifier where an error of 3% in voltage can result in significant power errors, it was difficult to get two successive read-