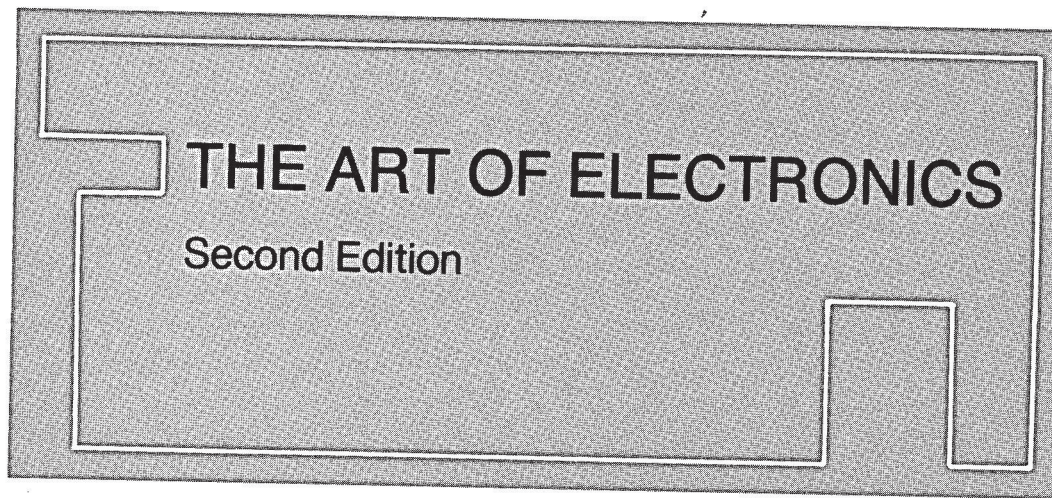


# THE **ART** OF ELECTRONICS

PAUL HOROWITZ  
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should have FET input transistors, to keep input current near zero) prevents loading of the capacitor, so it holds its voltage until the FET switch is again closed.

#### EXERCISE 3.13

The input buffer must supply current to keep the capacitor following a varying signal. Calculate the buffer's peak output current when the circuit is driven by an input sine wave of 1 volt amplitude at 10kHz.

#### Flying-capacitor voltage converter

Here's a nice way (Fig. 3.55) to generate a needed negative power-supply voltage in a circuit that is powered by a single positive supply. The pair of FET switches on the left connects  $C_1$  across the positive supply, charging it to  $V_{in}$ , while the switches on the right are kept open. Then the input switches are opened, and the switches on the right are closed, connecting charged  $C_1$  across the output, transferring some of its charge onto  $C_2$ . The switches are diabolistically arranged so that  $C_1$  gets turned upside down, generating a *negative* output! This particular circuit is available as the 7662 voltage converter chip, which we'll talk about in Sections 6.22 and 14.07. The device labeled "inverter" turns a HIGH voltage into a LOW voltage, and vice versa. We'll show you how to make one in the next section (and we'll really

get you up to speed on them in Chapters 8–11!).

#### 3.14 MOSFET logic and power switches

The *other* kinds of FET switch applications are *logic* and *power switching* circuits. The distinction is simple: In analog signal switching you use a FET as a series switch, passing or blocking a signal that has some range of analog voltage. The analog signal is usually a low-level signal, at insignificant power levels. In logic switching, on the other hand, MOSFET switches open and close to generate full swings between the power supply voltages. The "signals" here are really digital, rather than analog—they swing between the power supply voltages, representing the two states HIGH and LOW. In-between voltages are not useful or desirable; in fact, they're not even legal! Finally, "power switching" refers to turning on or off the power to a load such as a lamp, relay coil, or motor winding; in these applications, both voltages and currents tend to be large. We'll take logic switching first.

#### Logic switching

Figure 3.56 shows the simplest kind of logic switching with MOSFETs: Both circuits use a resistor as load and perform the logical function of *inversion* – a HIGH

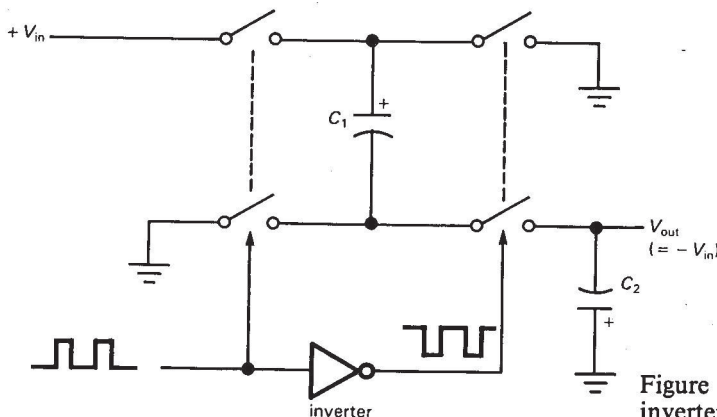


Figure 3.55. Flying-capacitor voltage inverter.

Check that the gain is as advertised. How does the variable offset circuitry work?

Figure 4.75 shows a clever circuit, borrowed from the application notes of several manufacturers. IC<sub>1</sub> is an integrator, rigged up so that the capacitor current ( $V_{in}/200k$ ) changes sign, but not magnitude, when  $Q_1$  conducts. IC<sub>2</sub> is connected as a Schmitt trigger, with thresholds at one-third and two-thirds of  $V_+$ .  $Q_1$  is an  $n$ -channel MOSFET, used here as a switch; it is simpler to use than bipolar transistors in this sort of application, but an alternative circuit using  $nnpn$  transistors is shown in addition. In either case, the bottom side of  $R_4$  is pulled to ground when the output

An unusual feature of this circuit is its operation from a single positive supply. The 3160 (internally compensated version of the 3130) has FETs as output transistors, guaranteeing a full swing between  $V_+$  and ground at the output; this ensures that the thresholds of the Schmitt don't drift, as they would with an op-amp of conventional output-stage design, with its ill-defined limits of output swing. In this case this means that the frequency and amplitude of the triangle wave will be stable. Note that the frequency depends on the ratio  $V_{in}/V_+$ ; this means that if  $V_{in}$  is generated from  $V_+$  by a resistive divider (made from some sort of resistive transducer, say), the output frequency won't vary with  $V_+$ , only with changes in resistance.

**Figure 4.75. Voltage-controlled waveform generator.**

There are some other interesting timer chips available. The 322 timer from National includes its own internal precision voltage reference for determining the threshold. That makes it an excellent choice for generating a frequency proportional to an externally supplied current, as, for example, from a photodiode. Another class of timers uses a relaxation oscillator followed by a digital counter, in order to generate long delay times without resorting to large resistor and capacitor values. Examples of this are the 74HC4060, the Exar 2243, and the Intersil ICM7242 (also made by Maxim). The latter is CMOS, runs on a fraction of a milliamp, and generates an output pulse every 128 oscillator cycles. These timers (and their near relatives) are great for generating delays from a few seconds to a few minutes.

### 5.15 Voltage-controlled oscillators

Other IC oscillators are available as voltage-controlled oscillators (VCO's), with the output rate variable over some range according to an input control voltage. Some of these have frequency ranges exceeding 1000:1. Examples are the original NE566 and later designs like the LM331, 8038, 2206, and 74LS624-9 series.

The 74LS624 series, for example, generates digital-logic-level outputs up to 20 MHz and uses external  $RC$ 's to set the nominal frequency. Faster VCOs like the 1648 can produce outputs to 200MHz, and in Chapter 13 we'll see how to make VCOs that operate in the *gigahertz* range. The LM331 is actually an example of a voltage-to-frequency (V/F) converter, designed for good linearity (see Sections 9.20 and 9.27). Where linearity is important, recent V/F converters like the AD650 really do the job, with linearity of 0.005%. Most VCOs use internal current sources to generate triangle-wave outputs, and the 8038 and 2206 even include a set of "soft" clamps to convert the triangle wave to a

not-too-great sine wave. VCO chips sometimes have an awkward reference for the control voltage (e.g., the positive supply) and complicated symmetrizing schemes for sine-wave output. It is our opinion that the ideal VCO has yet to be developed. Many of these chips can be used with an external quartz crystal, as we will discuss shortly, for much higher accuracy and stability; in such cases the crystal simply replaces the capacitor. Figure 5.37 shows a VCO circuit with an output frequency range of 10Hz to 10kHz built with the LM331.

When shopping for VCO chips, don't overlook the ICs known as *phase-locked loops* (PLL), which contain both a VCO and a phase detector. An example is the popular CMOS 4046 (and its faster cousin, the 74HC4046). We will discuss PLLs in Sections 9.27-9.31. Table 5.4 lists most of the available VCOs.

### 5.16 Quadrature oscillators

There are times when you need an oscillator that generates a simultaneous *pair* of equal-amplitude sine waves, *90° out of phase*. You can think of the pair as sine and cosine. This is referred to as a *quadrature pair* (the signals are "in quadrature"). One important application is in radio communications circuits (quadrature mixers, single-sideband generation). Furthermore, as we'll explain below, a quadrature pair is all you need to generate any arbitrary phase.

The first idea you might invent is to apply a sine-wave signal to an integrator (or differentiator), thus generating a 90°-shifted cosine wave. The phase shift is right, but the amplitude is wrong (figure out why). Here are some methods that do work:

#### □ Switched-capacitor resonator

Figure 5.38 shows how to use an MF5 switched-capacitor filter IC as a self-excited

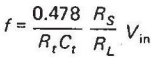
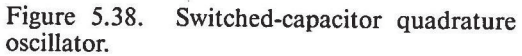


Figure 5.37. Typical V/F converter IC (0 to 10kHz VCO).



bandpass filter to generate a quadrature sine-wave pair. The easiest way to under-

stand it is to assume there is already a sine-wave output present; the comparator

TABLE 5.4. SELECTED VCOs

| Type      | Mfg <sup>a</sup> | Family <sup>b</sup> | Max<br>freq<br>(MHz) | Outputs <sup>c</sup> | Supply voltage |            | Linearity<br>(at 10kHz) | Comments                     |
|-----------|------------------|---------------------|----------------------|----------------------|----------------|------------|-------------------------|------------------------------|
|           |                  |                     |                      |                      | min<br>(V)     | max<br>(V) |                         |                              |
| VFC32     | BB+              | L                   | 0.5                  | OC                   | ±9             | ±18        | 0.01%                   | indus. st'd; good linearity  |
| VFC62C    | BB               | L                   | 1                    | OC                   | ±13            | ±20        | 0.002%                  | excellent linearity          |
| VFC110B   | BB               | L                   | 4                    | OC                   | ±8             | ±18        | 0.005%                  | fast, exc lin, int $V_{ref}$ |
| 74S124    | TI               | T                   | 60                   | SQ                   | 4.75           | 5.25       |                         |                              |
| 74LS624-9 | TI               | T                   | 20                   | SQ                   | 4.75           | 5.25       |                         |                              |
| 74LS724   | TI               | T                   | 16                   | SQ                   | 4.75           | 5.25       |                         | mini-DIP                     |
| 215       | XR               | L                   | 35                   | SQ                   | 5              | 26         |                         | PLL                          |
| LM331     | NS               | L                   | 0.1                  | OC                   | 4              | 40         |                         | inexpensive, good linearity  |
| AD537     | AD               | L                   | 0.1                  | OC                   | 4.5            | 36         | 0.07%                   |                              |
| 566       | SN               | L                   | 1                    | SQ,T                 | 10             | 24         |                         |                              |
| AD650     | AD               | L                   | 1                    | OC                   | ±9             | ±18        | 0.005%                  | excellent linearity          |
| AD654     | AD               | L                   | 0.5                  | OC                   | 4.5            | 36         | 0.1% <sup>d</sup>       | inexpensive                  |
| 1648      | MO               | E                   | 200                  | P                    | -5.2           |            |                         |                              |
| 1658      | MO               | E                   | 130                  | P                    | -5.2           |            |                         |                              |
| XR2206    | XR               | L                   | 0.5                  | SQ,T,SW              | 10             | 26         | 2%                      | 0.5% sine dist (trimmed)     |
| XR2207    | XR               | L                   | 0.5                  | SQ,T                 | 8              | 26         | 1%                      |                              |
| XR2209    | XR               | L                   | 1                    | SQ,T                 | ±4             | ±13        | 1%                      |                              |
| XR2212    | XR               | L                   | 0.3                  | SQ                   | 4.5            | 20         |                         | PLL                          |
| XR2213    | XR               | L                   | 0.3                  | SQ                   | 4.5            | 15         |                         | PLL                          |
| 4024      | MO               | T                   | 25                   | SQ                   | 4.75           | 5.25       |                         |                              |
| 4046      | RC+              | C                   | 1                    | SQ                   | 3              | 15         |                         | CMOS PLL                     |
| HC4046    | RC+              | C                   | 15 <sup>†</sup>      | SQ                   | 3              | 6          |                         | fast 4046                    |
| 4151      | RA               | L                   | 0.1                  | OC                   | 8              | 22         | 0.013%                  |                              |
| 4152      | RA               | L                   | 0.1                  | OC                   | 7              | 18         | 0.007%                  |                              |
| 4153A     | RA               | L                   | 0.5                  | OC                   | ±12            | ±18        | 0.002%                  | excellent lin, easy to use   |
| 8038      | IL               | L                   | 0.1                  | SQ,T,SW              | 10             | 30         | 0.2%                    | Exar 8038 to 1MHz            |
| TSC9401   | TP               | L                   | 0.1                  | OC                   | ±4             | ±7.5       | 0.01%                   | V/F, linear, stable          |

(a) see footnotes to Table 4.1. (b) families: C – CMOS; E – ECL; L – linear; T – TTL. (c) outputs: OC – open collector, pulses; P – pulses; SQ – square waves; SW – sine waves; T – triangle. (d) at 250kHz.

converts this to a small-amplitude (1 diode drop) square wave, which is fed back as the filter's input. The filter has a narrow bandpass ( $Q = 10$ ), so it converts the input square wave to a sine-wave output, sustaining the oscillation. A square-wave clock input (CLK) determines the bandpass center frequency, hence the frequency of oscillation, in this case  $f_{clk}/100$ . The circuit is usable over a frequency range of a few hertz to about 10kHz and generates a quadrature pair of sine waves of equal amplitude. Note that this circuit will actually have a "staircase" approximation to the desired sine-wave output, owing to

the quantized output steps of the switched filter.

#### □ Analog trigonometric-function generator

Analog Devices makes an interesting non-linear "function IC" that converts an input voltage to an output voltage proportional to  $\sin(AV_{in})$ , where the gain  $A$  is fixed at 50° per volt. In fact, this chip, the AD639, can actually do a lot more: It has four inputs, called  $X_1$ ,  $X_2$ ,  $Y_1$ , and  $Y_2$ , and generates as output the voltage  $V_{out} = \sin(X_1 - X_2) / \sin(Y_1 - Y_2)$ . Thus, for example, by setting  $X_1 = Y_1 = 90^\circ$