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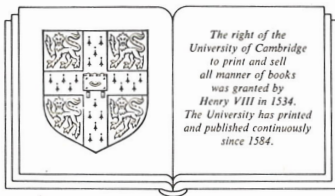
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THE ART OF ELECTRONICS

Second Edition

Paul Horowitz HARVARD UNIVERSITY

Winfield Hill ROWLAND INSTITUTE FOR SCIENCE, CAMBRIDGE, MASSACHUSETTS



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TO CAROL, JACOB, MISHA, AND GINGER

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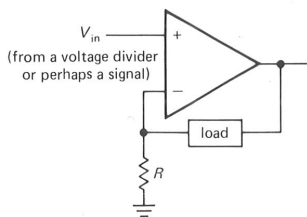


Figure 4.9

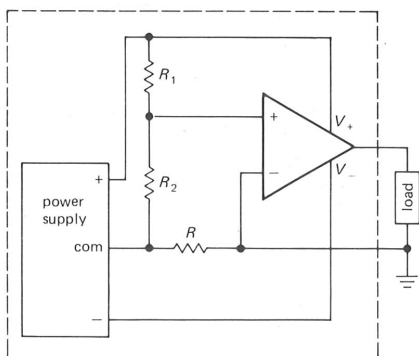


Figure 4.10. Current source with grounded load and floating power supply.

4.07 Current sources

The circuit in Figure 4.9 approximates an ideal current source, without the V_{BE} offset of a transistor current source. Negative feedback results in V_{in} at the inverting input, producing a current $I = V_{in}/R$ through the load. The major disadvantage of this circuit is the “floating” load (neither side grounded). You couldn’t generate a usable sawtooth wave with respect to ground with this current source, for instance. One solution is to float the whole circuit (power supplies and all) so that you can ground one side of the load (Fig. 4.10).

explicitly. R_1 and R_2 form a voltage divider to set the current. If this circuit seems confusing, it may help to remind yourself that “ground” is a relative concept. Any one point in a circuit could be called ground. This circuit is useful for generating currents into a load that is returned to ground, but it has the disadvantage that the control input is now floating, so you cannot program the output current with an input voltage referenced to ground. Some solutions to this problem are presented in Chapter 6 in the discussion of constant-current power supplies.

Current sources for loads returned to ground

With an op-amp and external transistor it is possible to make a simple high-quality current source for a load returned to ground; a little additional circuitry makes it possible to use a programming input referenced to ground (Fig. 4.11). In the first circuit, feedback forces a voltage $V_{CC} - V_{in}$ across R , giving an emitter current (and therefore an output current) $I_E = (V_{CC} - V_{in})/R$. There are no V_{BE} offsets, or their variations with temperature, I_C , V_{CE} , etc., to worry about. The current source is imperfect (ignoring op-amp errors: I_b , V_{os}) only insofar as the small base current may vary somewhat with V_{CE} (assuming the op-amp draws no input current), not too high a price to pay for the convenience of a grounded load; a Darlington for Q_1 would reduce this error considerably. This error comes about, of course, because the op-amp stabilizes the *emitter* current, whereas the load sees the *collector* current. A variation of this circuit, using a FET instead of a bipolar transistor, avoids this problem altogether, since FETs draw no gate current.

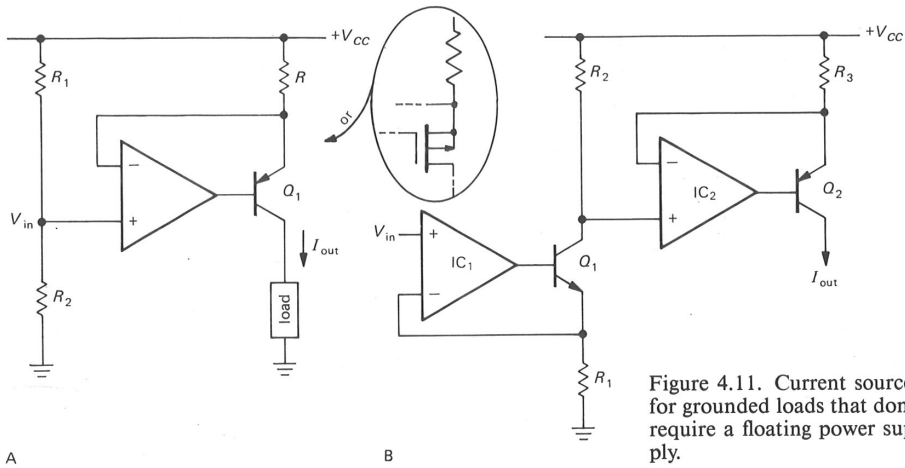


Figure 4.11. Current sources for grounded loads that don't require a floating power supply.

With this circuit the output current is proportional to the voltage drop below V_{CC} applied to the op-amp's noninverting input; in other words, the programming voltage is referenced to V_{CC} , which is fine if V_{in} is a fixed voltage generated by a voltage divider, but an awkward situation if an external input is to be used. This is remedied in the second circuit, in which a similar current source with *npn* transistor is used to convert an input voltage (referenced to ground) to a V_{CC} -referenced source. Op-amps and transistors are inexpensive. Don't hesitate to use a few extra components to improve performance or convenience in circuit design.

One important note about the last circuit: The op-amp must be able to operate with its inputs near or at the positive supply voltage. An op-amp like the 307, 355, or OP-41 is good here. Alternatively, the op-amp could be powered from a separate V_+ voltage higher than V_{CC} .

EXERCISE 4.1

What is the output current in the last circuit for a given input voltage V_{in} ?

Figure 4.12 shows an interesting variation on the op-amp/transistor current

source. It has the advantage of zero base current error, which you get with FETs, without being restricted to output currents less than $I_{DS(ON)}$. In this circuit (actually a current *sink*), Q_2 begins to

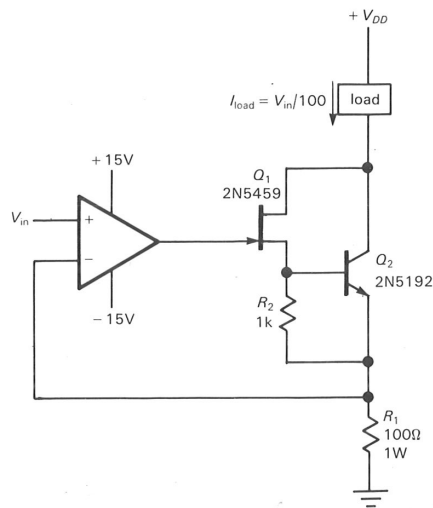


Figure 4.12. FET/bipolar current source suitable for high currents.

conduct when Q_1 is drawing about 0.6mA drain current. With Q_1 's minimum I_{DS}

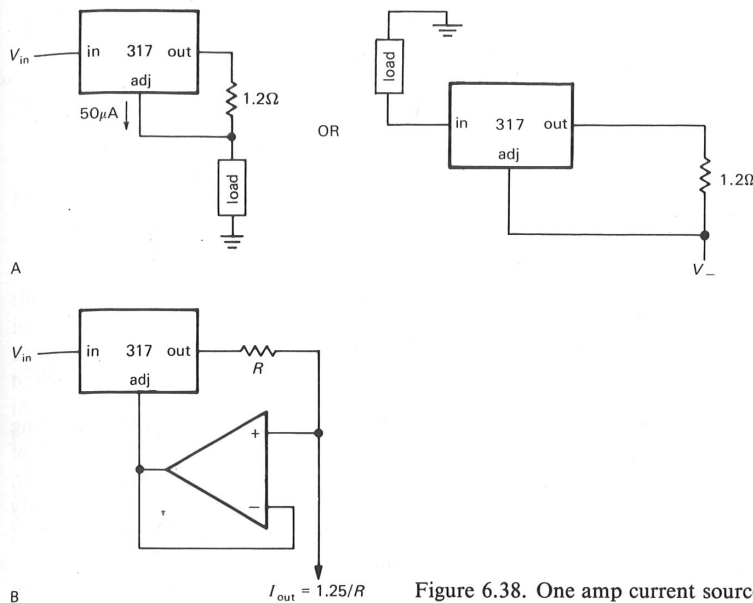


Figure 6.38. One amp current sources.

to sink current from a load returned to ground (of course, you could always use the negative-polarity 337, in the configuration analogous to Fig. 6.38A).

National makes a special 3-terminal device, the LM334, optimized for use as a low-power current source. It comes in the small plastic transistor package (TO-92), as well as the standard DIP IC package. You can use it all the way down to $1\mu A$, because the "adj" current is a small fraction of the total current. It has one peculiarity, however: The output current is temperature-dependent, in fact, precisely proportional to absolute temperature. So although it is not the world's most stable current source, you can use it (Section 15.01) as a temperature sensor!

6.19 Switching regulators and dc-dc converters

All the voltage regulator circuits we have discussed so far work the same way: A

linear control element (the "pass transistor") in series with the unregulated dc is used, with feedback, to maintain constant output voltage (or perhaps constant current). The output voltage is always lower in voltage than the unregulated input voltage, and some power is dissipated in the control element [the average value of $I_{out}(V_{in} - V_{out})$, to be precise]. A minor variation on this theme is the *shunt regulator*, in which the control element is tied from the output to ground, rather than in series with the load; the simple resistor-plus-zener is an example.

There is another way to generate a regulated dc voltage, fundamentally different from what we've seen so far; look at Figure 6.39. In such a *switching regulator* a transistor operated as a saturated switch periodically applies the full unregulated voltage across an inductor for short intervals. The inductor's current builds up during each pulse, storing $\frac{1}{2}LI^2$ of energy in its magnetic field; the stored energy is transferred to a filter capacitor at the output,

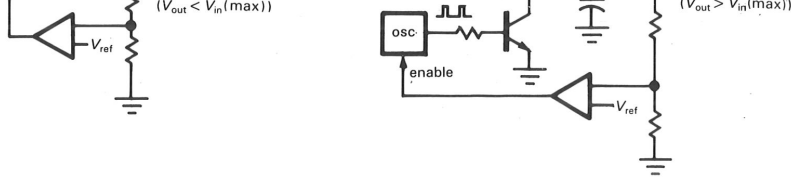


Figure 6.39. Two kinds of regulators.
A. Linear (series).
B. Step-up switcher.

which also smooths the output (to carry the output load between charging pulses). As with a linear regulator, feedback compares the output with a voltage reference – but in a switching regulator it controls the output by changing the oscillator’s pulse width or switching frequency, rather than by linearly controlling the base or gate drive.

Switching regulators have unusual properties that have made them very popular: Since the control element is either off or saturated, there is very little power dissipation; switching supplies are thus very efficient, even if there is a large drop from input to output. Switchers (slang for “switching power supplies”) can generate output voltages *higher* than the unregulated input, as in Figure 6.39B; they can just as easily generate outputs *opposite in polarity* to the input! Finally, switchers can be designed with no dc path from input to output; that means they can run directly from the rectified power line, with no ac power transformer! The result is a very small, lightweight, and efficient dc supply. For these reasons, switching supplies are used almost universally in computers.

Switching supplies have their problems, too. The dc output has some switching “noise,” and they can put hash back onto the power line. They used to have a bad reputation for reliability, with occasional

spectacular pyrotechnic displays during episodes of catastrophic failure. Most of these problems have been solved, however, and the switching supply is now firmly entrenched in electronic instruments and computers.

In this section we’ll tell you all about switching supplies, in two steps: First, we’ll describe the basic switching regulator, operating from a conventional unregulated dc supply. There are three circuits, used for (a) step-down (output voltage less than input), (b) step-up (output voltage greater than input), and (c) inverting (output polarity opposite to input). Then we’ll take a radical step, describing the heretical (and most widely used!) designs that run straight from the rectified ac power line, without an isolation transformer. Both kinds of power supplies are in wide use, so our treatment is practical (not just pedagogically pleasing). Finally, we’ll give you plenty of advice on the subject: When to use switchers, when to avoid them; when to design your own, when to buy them. With characteristic overstatement, we won’t leave you in any doubt!

□ Step-down regulator

Figure 6.40 shows the basic step-down (or “bucking”) switching circuit, with feedback omitted for simplicity. When the MOS

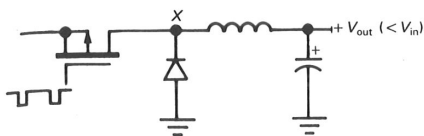


Figure 6.40. Step-down switcher.

switch is closed, $V_{out} - V_{in}$ is applied across the inductor, causing a linearly increasing current (recall $dI/dt = V/L$) to flow through the inductor. (This current flows to the load and capacitor, of course.) When the switch opens, inductor current continues to flow in the same direction (remember that inductors don't like to change their current suddenly, according to the last equation), with the "catch diode" now

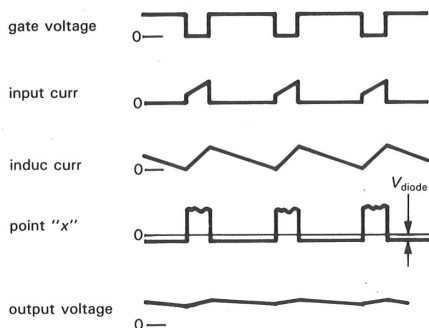


Figure 6.41

conducting to complete the circuit. The output capacitor acts as an energy "fly-wheel," smoothing the inevitable sawtooth ripple (the larger the capacitor, the less the ripple). The inductor current now finds fixed voltage $V_{out} - 0.6V$ across it, causing its current to decrease linearly. Figure 6.41 shows the corresponding voltage and current waveforms. To complete the circuit as a *regulator*, you would of course add feedback, controlling either the pulse width (at constant pulse repetition rate) or the

repetition rate (with constant pulse width) from an error amplifier that compares the output voltage with a reference.

Figure 6.42 shows a low-current +5 volt regulator using the MAX638 from Maxim. This nice chip gives you a choice of fixed +5 volt output (no external divider needed) or adjustable positive output, with external resistive divider. It includes nearly all components in a convenient mini-DIP package. In the MAX638 the oscillator runs at a constant 65kHz, with the error amplifier either permitting or cutting off gate drive pulses, according to the output voltage. The circuit shown gives about 85% efficiency, pretty much independent of the input voltage. Compare that with a linear regulator by doing the next problem:

EXERCISE 6.8

What is the maximum theoretical efficiency of a linear (series pass) regulator, when used to generate regulated +5 volt from a +12 volt unregulated input?

EXERCISE 6.9

What does a step-down regulator's high efficiency imply about the ratio of output current to input current? What is the corresponding ratio of currents, for a linear regulator?

□ **Step-up regulator; inverting regulator**

Apart from its high efficiency, the step-down switching regulator of the previous paragraph has no significant advantage (and some significant disadvantages – component count, switching noise) over a linear regulator. However, when there is a need for an output voltage greater than the unregulated input, or for an output voltage of opposite polarity to the unregulated input, switching supplies become very attractive indeed. Figure 6.43 shows the basic step-up (or "boosting") and inverting (sometimes called "flyback") circuits.

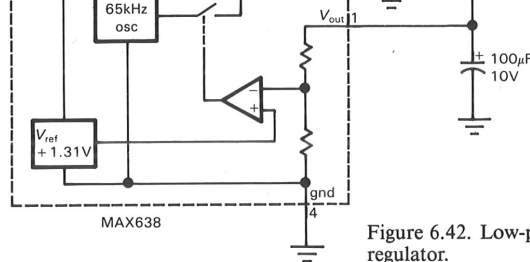


Figure 6.42. Low-power +5 volt switching regulator.

We showed the step-up circuit of Figure 6.39A earlier, in comparison with the linear regulator. The inductor current ramps up during switch conduction (point X near ground); when the switch is turned off, the voltage at point X rises rapidly as the inductor attempts to maintain constant current. The diode turns on, and the inductor dumps current into the capacitor. The output voltage can be much larger than the input voltage.

EXERCISE 6.10

Draw waveforms for the step-up switcher, showing voltage at point X , inductor current, and output voltage.

EXERCISE 6.11

Why can't the step-up circuit be used as a step-down regulator?

The inverting circuit is shown in Figure 6.43B. During switch conduction, a linearly increasing current flows from point X to ground. To maintain the current when the switch is open, the inductor pulls point X negative, as much as needed to maintain current flow. Now, however, the current is flowing *into* the inductor from the filter capacitor. The output is thus negative, and its average value can be larger or smaller in magnitude than the input (as determined by feedback); in other words,

the inverting regulator can be either step-up or step-down.

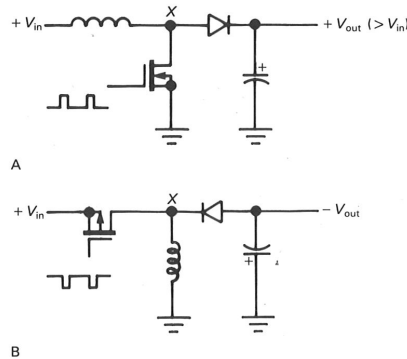


Figure 6.43. Two switching-element configurations.

A. Step-up ("boost").
B. Inverting.

EXERCISE 6.12

Draw waveforms for the inverting switcher, showing voltage at point X , inductor current, and output voltage.

Figure 6.44 shows how you might use low-power switching regulators to generate ± 15 volt op-amp supply voltages from a single +12 volt automotive battery, a trick that is impossible with linear regulators. Here we've again used low-power

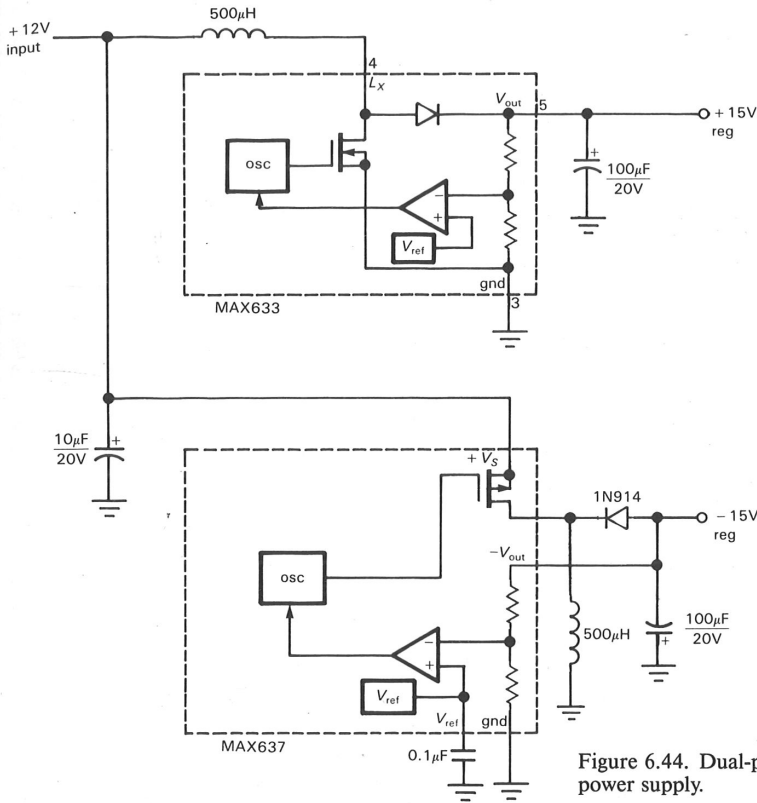


Figure 6.44. Dual-polarity switching power supply.

fixed-output ICs from Maxim, in this case the step-up MAX633 and the inverting MAX637. The external components shown were chosen according to the manufacturer's data sheets. They're not critical, but, as always in electronic design, there are trade-offs. For example, a larger value of inductor lowers the peak currents and increases the efficiency, at the expense of maximum available output current. This circuit is rather insensitive to input voltage, as long as it doesn't exceed the output voltage, and will work all the way down to +2 volts input, with greatly reduced maximum output current.

Before leaving the subject of inverting and step-up regulators, we should mention that there is one other way to accomplish the same goal, namely with "flying capacitors." The basic idea is to use MOS switches to (a) charge a capacitor from the dc input, and then (b) change the switches to connect the now-charged capacitor in series with another (step-up), or with reversed polarity across the output (inverting). Flying-capacitor voltage converters (e.g., the popular 7662) have some advantages (no inductors) and some disadvantages (low power, poor regulation, limited voltage). We'll discuss them later in the chapter.

As we've seen, the ability of switchers to generate stepped-up or inverted outputs makes them quite handy for making, say, low-current ± 12 volt supplies on an otherwise all-digital +5 volt circuit board. You'll often need such bipolarity supplies to power "serial ports" (more in Chapters 10 and 11) or linear circuitry using op-amps or A/D (analog-to-digital) and D/A (digital-to-analog) converters. Another good use for step-up switchers is to power displays that require relatively high voltage, for example using fluorescent or plasma technology. In these applications, where the dc input (typically +5V) is already regulated, you often use the phrase "dc-to-dc converter," rather than "switching regulator," although it's really the same circuit. Finally, in battery-operated equipment you often want high efficiency over a wide range of battery voltage; for example, a 9 volt alkaline "transistor" battery begins life at about 9.5 volts, dropping steadily to about 6 volts at the end of its useful life. A +5 volt low-power step-down regulator maintains high efficiency, with current step-up over most of the battery's life.

Note that the inductor and capacitor in a switching regulator are not functioning as an *LC* filter. In the simple step-down regulator, that might seem to be true, but obviously a circuit that *inverts* a dc level is hardly a filter! The inductor is a lossless energy-storage device (stored energy = $\frac{1}{2}LI^2$), able to transform impedance in order to conserve energy. This is an accurate statement from a physicist's point of view, in which the magnetic field contains stored energy. We're more used to thinking of capacitors as energy storage devices (stored energy = $\frac{1}{2}CV^2$), which is their role in switching supplies, as in conventional series regulators.

A bit of nomenclature: You sometimes see the phrases "PWM switch-mode

cording to the feedback (error) signal. In particular, PWM means pulse-width modulation, in which the error signal is used to control the conduction pulse width (at fixed frequency), whereas in current-mode control the error voltage is used to control the peak inductor current (as sensed by a resistor) via width on a pulse-by-pulse basis. Current-mode regulators have some significant advantages and are becoming more popular now that good current-mode controller ICs have become available.

Keep in mind, when considering any switching supply, the noise generated by the switching process. This takes three forms, namely (a) output ripple, at the switching frequency, typically of order 10mV–100mV peak-to-peak, (b) ripple, again at the switching frequency, impressed onto the input supply, and (c) radiated noise, at the switching frequency and its harmonics, from switching currents in the inductor and leads. You can get into plenty of trouble with switching supplies in a circuit that has low-level signals (say 100 μ V or less). Although an aggressive job of shielding and filtering may solve such problems, you're probably better off with linear regulators from the outset.

Line-powered switching supplies

As we have seen, switching supplies have high efficiency even when the output voltage is nowhere near the input voltage. It may help our understanding to think of the inductor as an "impedance converter," since the average dc output current can be larger (step-down) or smaller (step-up) than the average dc input current. This is in stark contrast to linear series regulators, where the average values of input and output currents are always equal (ignoring the quiescent current of the regulator circuitry, of course).

is handy if you want to make a modulo- n counter, for example. The load function can be either synchronous or asynchronous: the '160-'163 have synchronous load, which means that data on the input lines are transferred to the counter coincident with the next clock edge, if the LOAD' line is also asserted LOW; the '190-'193 are asynchronous, or *jam-load*, which means that input data are transferred to the counter when LOAD' is asserted, independent of the clock. The term "parallel load" is sometimes used, since all bits are loaded at the same time.

The CLEAR (or RESET) function is a form of presetting. The majority of counters have a jam-type CLEAR function, though some have synchronous CLEAR; for example, the '160/161 are jam CLEAR, while the '162/163 are synchronous CLEAR.

Other counter features

Some counters feature latches on the output lines; these are always of the transparent type, so the counter can be used as if no latch were present. (Keep in mind that any counter with parallel-load inputs can function as latch, but you can't count at the same time as data are held, as you can with a counter/latch chip.) The combination of counter plus latch is sometimes very convenient, e.g., if you want to display or output the previous count while beginning a new counting cycle. In a frequency counter this would allow a stable display, with updating after each counting cycle, rather than a display that repeatedly gets reset to zero and then counts up.

There are counters with three-state outputs. These are great for applications where the digits (or 4-bit groups) are multiplexed onto a bus for display or transfer to some other device. An example is the '779, an 8-bit synchronous binary counter whose three-state outputs also serve as parallel inputs; by sharing input/output lines, the

counter fits in a 16-pin package. The '593 is similar, but in a 20-pin package.

If you want a counter to use with a display, there are several that combine counter, latch, 7-segment decoder, and driver on one chip. An example is the 74C925-74C928 series of 4-digit counters. Another amusing chip is the TIL306/7, a counter *with display* on one chip: You just look at the IC, which lights up with a digit telling the count! Figure 8.71 shows a nice LSI (large-scale-integration) counter circuit that doesn't require a lot of support circuits.

Table 8.10 at the end of the chapter lists most of the counter chips that you might want to use. Many of them are only available in one family (e.g., LS or F), so be sure to check the data books before you design with them.

8.26 Shift registers

If you connect a series of flip-flops so that each Q output drives the next D input, and all clock inputs are driven simultaneously, you get what's called a "shift register." At each clock pulse the pattern of 0's and 1's in the register shifts to the right, with the data at the first D input entering from the left. As with flip-flops, the data present at the serial input just prior to the clock pulse are entered, and there is the usual propagation delay to the outputs. Thus they may be cascaded without fear of a logic race. Shift registers are very useful for conversion of parallel data (n bits present simultaneously, on n separate lines) to serial data (one bit after another, on a single data line), and vice versa. They're also handy as memories, particularly if the data are always read and written in order. As with counters and latches, shift registers come in a pleasant variety of prefab styles. The important things to look for are the following:

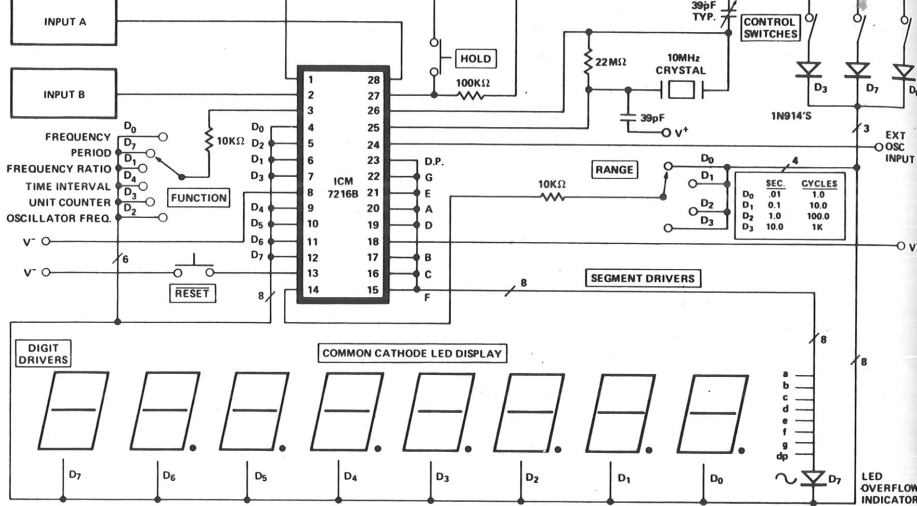


Figure 8.71. Intersil 7216 8-digit 10MHz universal counter on a chip. (Courtesy of Intersil, Inc.)

Size

The 4-bit and 8-bit registers are standard, with some larger sizes available (up to 64 bits or more). There are even variable-length registers (e.g., the 4557: 1 to 64 stages, set by a 6-bit input).

Organization

Shift registers are usually 1 bit wide, but there are also dual-, quad-, and hex-width registers. Most shift registers only shift right, but there are bidirectional registers like the '194 and '323 that have a "direction" input (Fig. 8.72). Watch out for trickery like the "bidirectional" '95, which can shift left only by tying each output bit to the previous input, then doing a parallel load.

Inputs and outputs

Small shift registers can provide parallel inputs or outputs, and usually do; an example is the '395, a 4-bit parallel-in, parallel-out (PI/PO) shift register with three-state outputs. Larger registers may only provide *serial* input or output, i.e., only the input to the first flip-flop or the output from the last is accessible. In some cases a few selected intermediate taps are provided. One way to provide both parallel input and output in a small package is to share input and output (three-state) on the same pins, e.g., the '299, an 8-bit bidirectional PI/PO register in a 20-pin package. Some shift registers include a latch at the input or output, so shifting can go on while data are being loaded or unloaded.

As with counters, parallel LOAD and

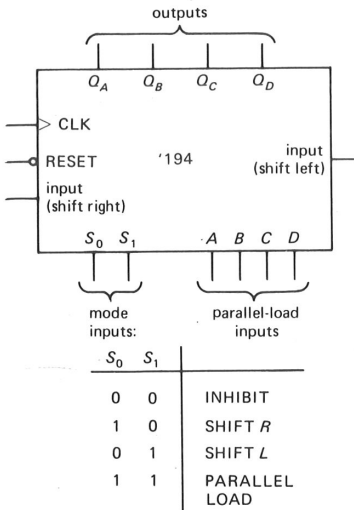


Figure 8.72. '194 4-bit bidirectional shift register.

CLEAR can be either synchronous or jam-load; for example, the '323 is the same as the '299, but with synchronous clear.

Table 8.11 at the end of the chapter lists the shift registers you're likely to use. As always, not all types are available in all logic families; be sure to check the data books.

RAMs as shift registers

A random-access memory can always be used as a shift register (but not vice versa) by using an external counter to generate successive addresses. Figure 8.73 shows the idea. An 8-bit synchronous up/down counter generates successive addresses for a 256-word×4-bit CMOS RAM. The combination behaves like a quad 256-bit shift register, with left/right direction of shift selected by the counter's UP/DOWN' control line. The other inputs of the counter are shown enabled for counting. By choosing a fast counter and memory, we were able to achieve a maximum clocking rate

of 30MHz (see timing diagram), which is the same as that of an integrated (but much smaller) HC-type shift register. This technique can be used to produce very large shift registers, if desired.

EXERCISE 8.28

In the circuit of Figure 8.73, input data seem to go into the same location that output data are read from. Nevertheless, the circuit behaves identically to a classic 256-word shift register. Explain why.

8.27 Sequential PALs

The combinational (gates-only) PALs we talked about in Section 8.15 belong to a larger family that includes devices with various numbers of on-chip *D*-type registers (called "registered PALs"). Typical of these PALs is the 16R8, shown in Figure 8.74. The programmable-AND/fixed-OR array typical of combinational PALs generates the input levels for 8 synchronously clocked *D*-type registers with three-state outputs; the register outputs (and their inverses) are available, along with the standard input pins, as inputs to the logic array. If you look back at Figure 8.57, you'll see that a registered PAL is a general-purpose sequential circuit element; within limits set by the number of registers and gates available, you can construct just about anything you want. For instance, you could make a shift register or counter, or some of both! In practice, you're more likely to make some custom piece of logic that is part of a larger circuit, for which the alternative is "discrete" logic built with gates and flip-flops. Let's look at some examples.

Hand-generated fuse maps

Simple designs can be implemented in PALs by figuring out the logic, then burning the appropriate pattern into the fuse array with a "PAL programmer." As an

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