Test your analog-design IQ

Skilled analog-circuit designers are rapidly becoming a rare breed; for you diehards, here's a good test of your circuit-design acumen.

Jim Williams

Circuit design is very much the art of making imperfect components function "perfectly" together. Prepared with this consideration in mind, the questions in this test require a knowledge of components and circuit configurations, as well as an ability to identify and focus on the important issues affecting a circuit. The answers given are accurate, although in a few cases they have been left incomplete in a deliberate attempt to stimulate the kind of discussion that should occur in a circuit-design lab.

These problems are practical ones—solving them requires both experience and thought. The solutions are open to debate—alternative, perhaps better, ones are possible. But leave your Karnaugh maps at home and forget everything you know about bits and bytes; wonderful things are going on in the forgotten land between ONE and ZERO. This is Real Electronics.

Pencils ready? Begin!

1. Synthesizing the variable-resistance function (2-terminal) with decade switches is easy; clever designs minimize the number of resistors per decade by using series-parallel resistor combinations. Synthesizing the potentiometer (3-terminal) or ratio function, however, is not so obvious. Design a 4-decade switched potentiometer that has a constant impedance from end to end, regardless of the wiper arm's setting. You may use a standard pot for the final decade.

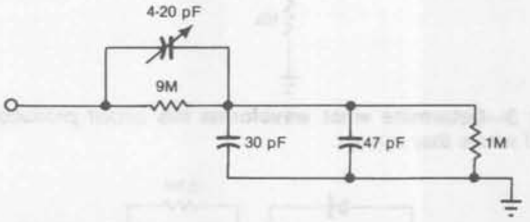


Fig 2—What function *might this network serve? Determine its response characteristics.*

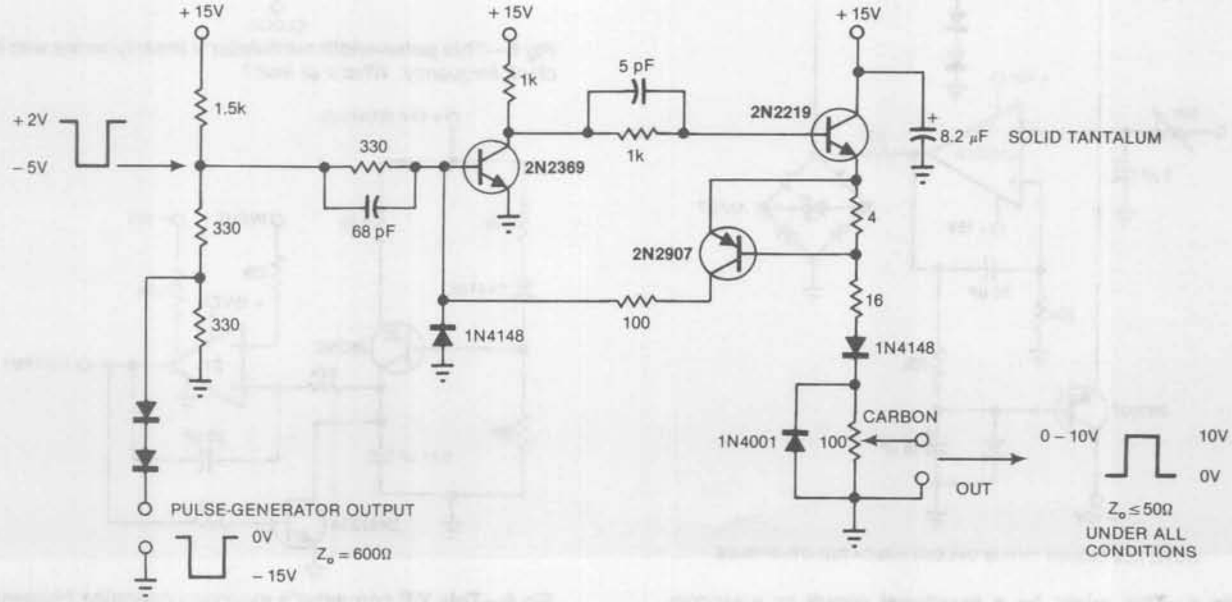


Fig 1—Reconfigure *this converter to correct its shortcomings: 30-nsec rise time and duty-cycle inversion.*

Why does a pulse-width modulator's linearity vary with clock frequency?

2. The circuit shown in **Fig 1** converts the negative-going output of pulse generators used in vacuum-tube work into a positive-going output compatible with solid-state circuits. Its low-impedance output is fully variable and capable of withstanding shorts to ground or either power-supply rail. This circuit works well, with two exceptions: First, the output appears as the inverse of the input, and second, the output pulse's rise time is about 30 nsec—a respectable time span that's nonetheless relatively short for a pulse-generator output. Reconfigure the circuit to correct these deficiencies, using a minimum number of component additions.

3. Determine the response characteristics of the network shown in **Fig 2**. What useful function might such a network serve? Why?

4. The circuit shown in **Fig 3** produces three waveforms. What are they and at what points do they appear?

5. What is the function of the circuit depicted in **Fig 4**? Does this circuit really do anything or is it just a random collection of parts?

6. Assuming the circuit shown in **Fig 4** does provide some useful function, what role does the 2N2907 play?

7. The circuit shown in **Fig 5** is a pulse-width modulator. At a given clock frequency, its linearity (E_X vs pulse width out) is good (typically 0.01%), but when the clock frequency changes, the linearity varies slightly. What is at fault and why?

8. The circuit displayed in **Fig 6** is a voltage-to-frequency converter. What is this circuit's chief limitation on maximum operating frequency? If you snip out the 20-pF capacitor, what would happen? Why? Are there any other significant considerations involved in setting up and using this circuit?

9. The configuration shown in **Fig 7** is a pulse-width-to-voltage converter—it provides a voltage proportion-

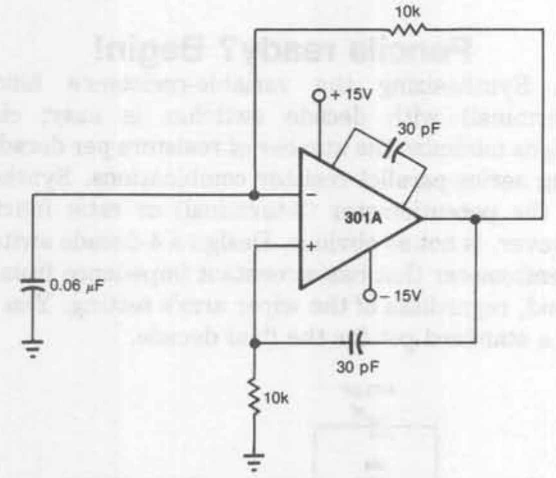
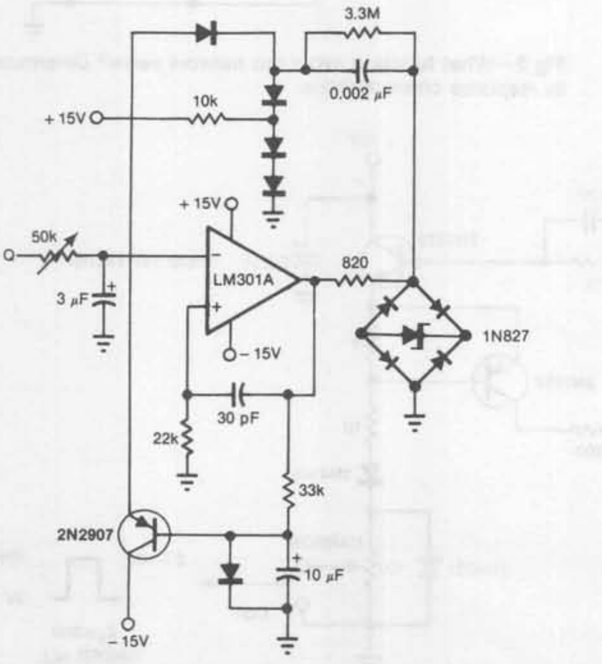


Fig 3—Determine what waveforms *this circuit produces and where they appear.*



NOTE: ALL DIODES 1N4148 UNLESS INDICATED OTHERWISE

Fig 4—This might be a functional circuit *or a random collection of components—can you tell which?*

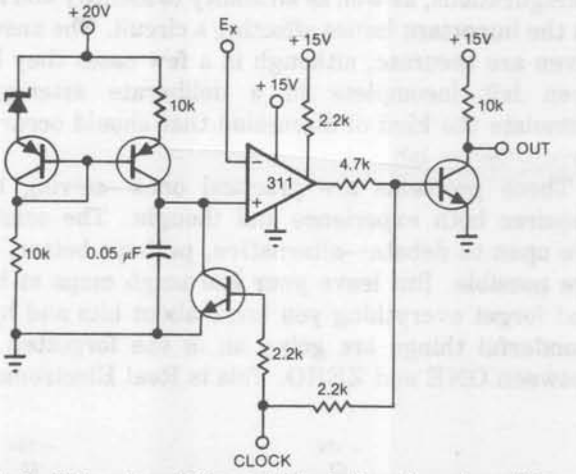


Fig 5—This pulse-width modulator's *linearity varies with its clock frequency. What's at fault?*

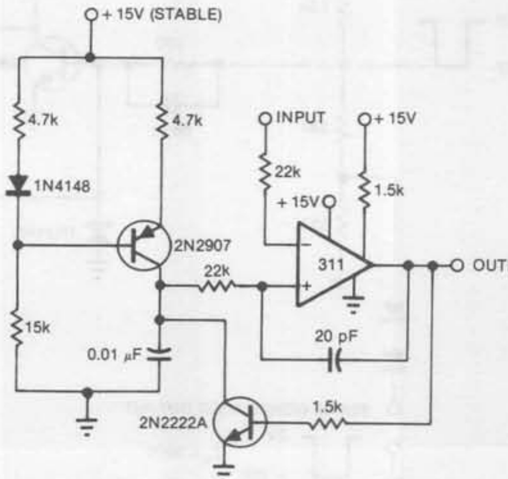


Fig 6—This V/F converter's *maximum operating frequency is limited by which component?*

al to the width of the most recent pulse applied to its input. Typically, this voltage must be "held" by the integrating capacitor for a few milliseconds. Aside from the small error caused by the reset one-shot's "holding down" the integrating capacitor for a few microseconds, performance is adequate. Unfortunately, the circuit suffers serious errors above about 8 or 9V output. Why? Add whatever components are necessary to fix this problem.

10. Given four 7.5V batteries and a Type 741 operational amplifier, construct a unity-gain, noninverting follower. The 741's positive input cannot be the signal input. Assume that the signal to be followed will range between +2 and −3.4V.

11. A 3-terminal black box is connected to the base, emitter and collector terminals of a transistor curve tracer. With the curve tracer set up to display the characteristics of an npn transistor, the familiar family

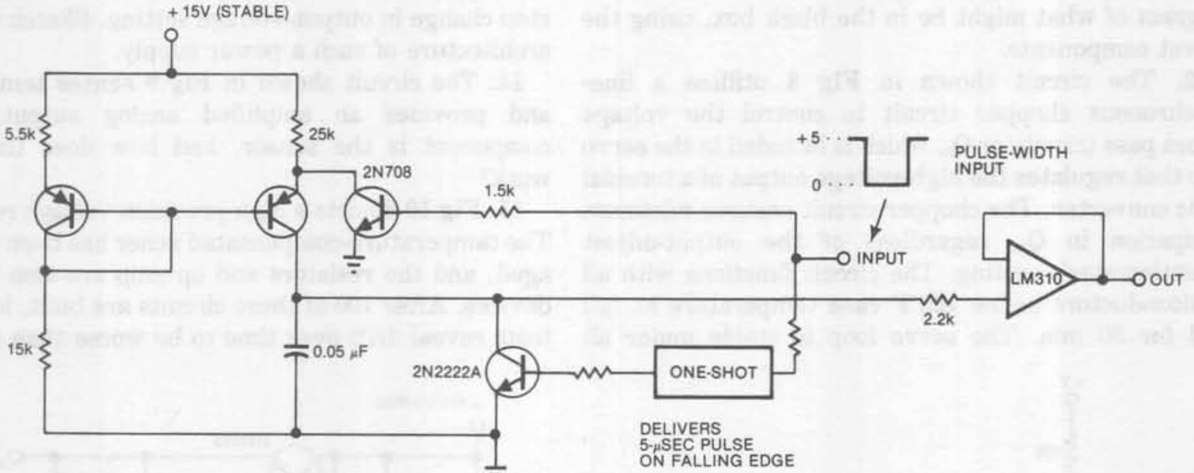


Fig 7—Conversion of pulse widths to voltages *suffers serious errors above 8 or 9V when this circuit is configured as shown. What's the problem?*

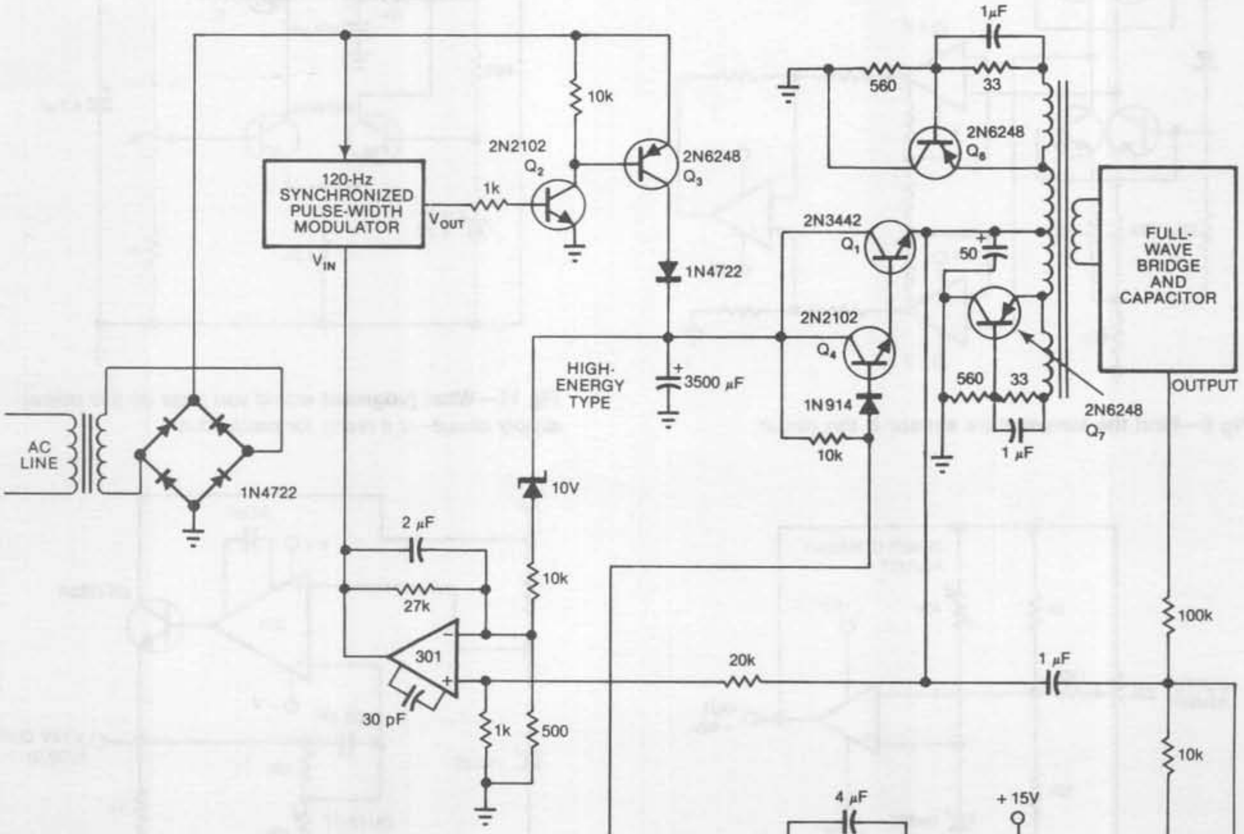


Fig 8—A dominant failure mode *could exist in this circuit. Can you spot it?*

Discover the source of erratic unit-to-unit performance

of curves appears on the screen. The gain appears quite low. Without touching the lead connections from the black box, you can reconfigure the curve tracer to display the curves of a pnp transistor…and they appear! Again, the gain is quite low. Draw the circuit diagram of what might be in the black box, using the fewest components.

12. The circuit shown in **Fig 8** utilizes a line-synchronous chopper circuit to control the voltage across pass transistor Q_3, which is included in the servo loop that regulates the high-voltage output of a toroidal dc/dc converter. The chopper circuit ensures minimum dissipation in Q_3, regardless of the output-adjust potentiometer's setting. The circuit functions with all semiconductors below 125°F case temperature at full load for 30 min. The servo loop is stable under all conditions, and performance appears good. But before you ship 100 of these systems, think twice. A dominant failure mode could exist. What might it be?

13. A requirement for a power supply with a 2000V output capable of providing 30 mA at 0.01% regulation (dc to 100 kHz) sends you to the design board. The load is active and inductive and also presents a 10Ω equivalent impedance for 100 msec every 2.5 min; during these periods, regulation may suffer. Finally, the supply should be able to settle within 100 µsec for a step change in output-voltage setting. Sketch the basic architecture of such a power supply.

14. The circuit shown in **Fig 9** senses temperature and provides an amplified analog output. Which component is the sensor, and how does the circuit work?

15. **Fig 10** depicts a high-precision voltage reference. The temperature-compensated zener has been carefully aged, and the resistors and op amp are also low-drift devices. After 100 of these circuits are built, long-term tests reveal drift over time to be worse than expected

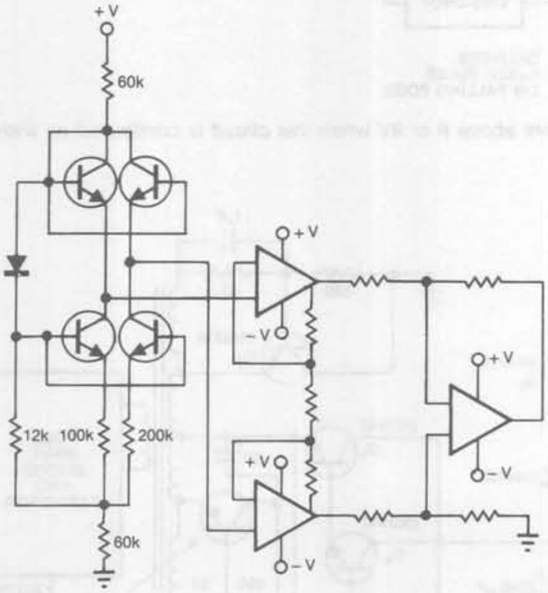


Fig 9—Find the temperature sensor *in this circuit.*

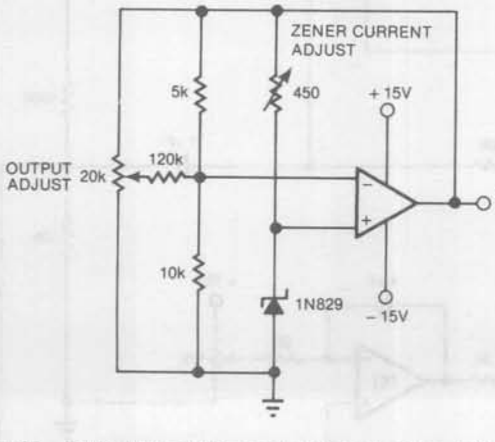


Fig 10—Build 100 of these circuits *and some drift, some work and some don't function at all—what's happening?*

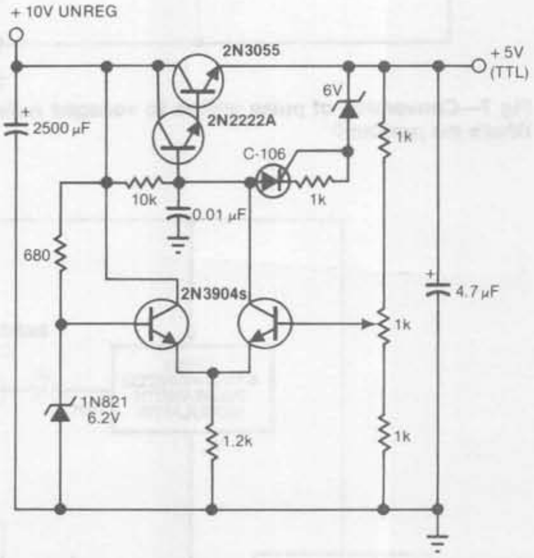


Fig 11—What judgment *would you pass on this power-supply circuit—is it ready for production?*

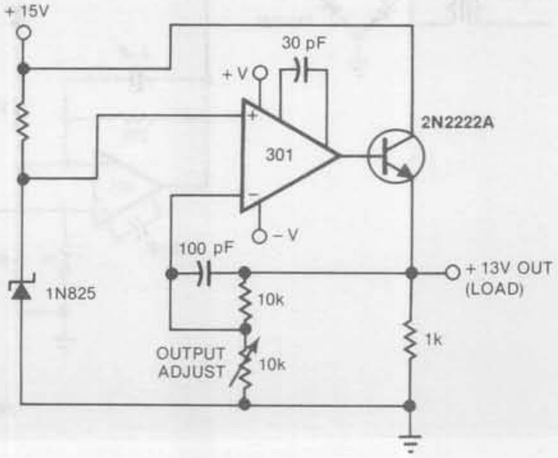


Fig 12—You could stop *this voltage reference from oscillating by adding one capacitor to load the emitter, but there's a better fix. What is it?*

in many units. Others work, while the remainder do not function properly at all. What's going on, what's the fix and why?

16. The data-acquisition power-supply circuit shown in **Fig 11** is on your desk for final approval before going to production. Any comments?

17. Fig 12 shows another voltage-reference circuit. Its output, instead of being dc, oscillates at 10 MHz. Using a 10-µF capacitor to load the emitter stops the oscillation, but this is a crude solution to the problem. What's the real fix?

18. Fig 13 shows a high-efficiency, precision temperature-control circuit designed to maintain a small oven at 198°C. Any comments?

19. In response to an input positive step function, what will be the output of the circuit shown in **Fig 14?** When the input steps back to zero, what will the output do?

20. The voltage-to-frequency-converter circuit shown in **Fig 15,** intended for electronic-music applications, features an output frequency exponentially related to its input voltage. For the values shown, the circuit produces a precise doubling of frequency output for each volt of input applied, from 20 Hz to 14 kHz. From 15 to 45°C, the circuit achieves negligible drift and exponential conformity within 0.2% over its entire operating range. The op amps run off ±15V supplies, the transistors are contained within a monolithic-array IC and the metal-film resistors specified are RN55 types. The current into the LM301A input is exponentially related to the circuit's input voltage because of the well-known logarithmic relationship between current and V_{be} in a transistor. The 301A and its associated components convert the emitter current into the output-frequency sawtooth. The 1N825 provides a reference for stability against supply changes. The 3-kΩ resistor establishes a 20-Hz frequency for 0V input, while the 10.5-kΩ resistor trims the gain to 1V in for each doubling of frequency out. The 1-MΩ/1.2-kΩ divider constitutes a first-order pass at canceling nonideal parasitic vagaries of Q_1. Most of the error in this circuit at low frequencies comes from the bias current of the LM301A and may be eliminated by substituting an FET device, such as an LF356. Discuss the function of the 741 op amp and its associated components. What are they doing and why?

21. Absolute zero is the temperature at which

(a) Type 3762 Josephson-effect ICs operate

(b) All molecular motion ceases

(c) Power transistors run most effectively

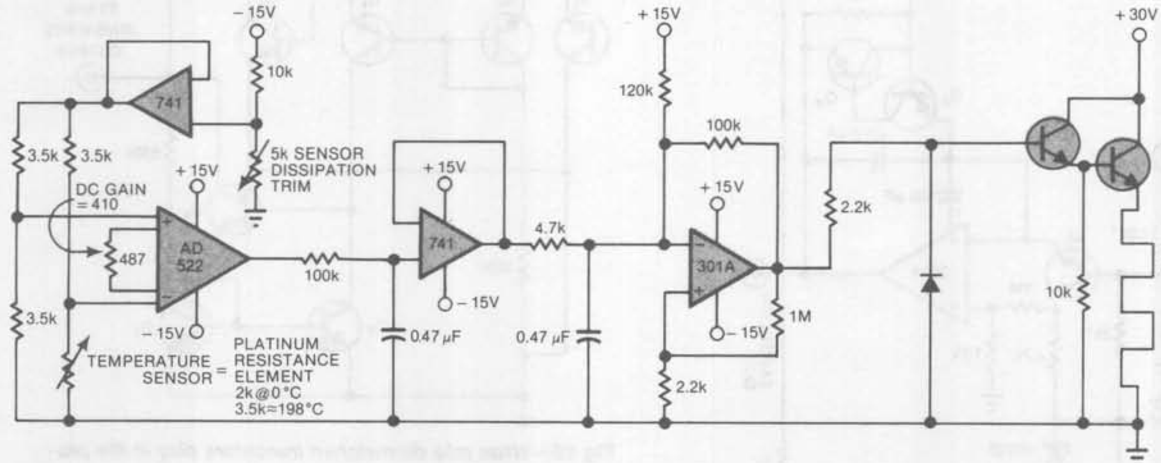
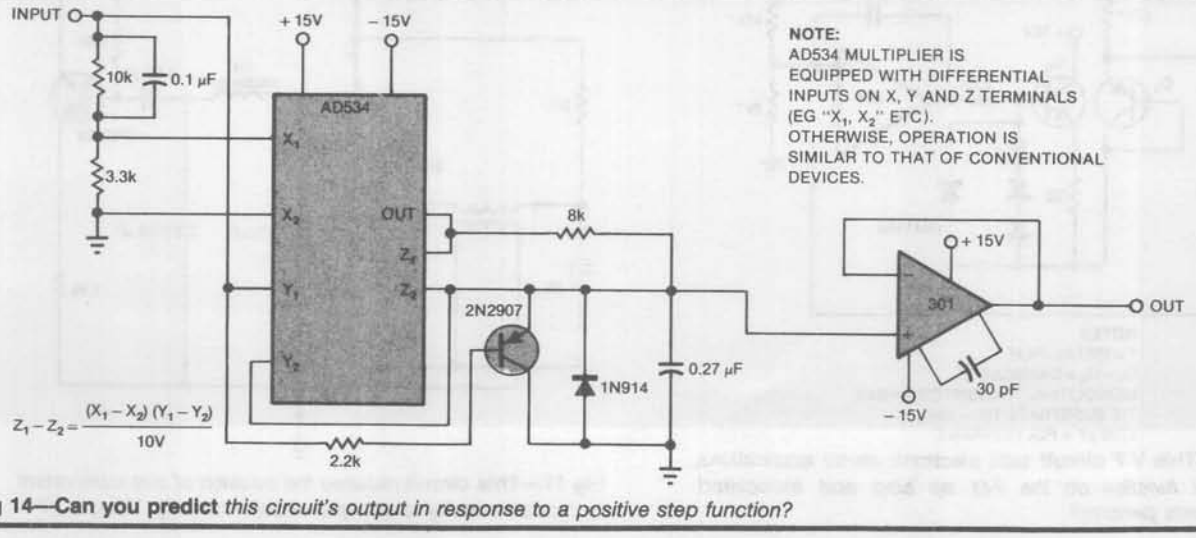


Fig 13—What performance *could you expect from this temperature-control circuit?*



NOTE:
AD534 MULTIPLIER IS EQUIPPED WITH DIFFERENTIAL INPUTS ON X, Y AND Z TERMINALS (EG "X_1, X_2" ETC). OTHERWISE, OPERATION IS SIMILAR TO THAT OF CONVENTIONAL DEVICES.

$$Z_1 - Z_2 = \frac{(X_1 - X_2)(Y_1 - Y_2)}{10V}$$

Fig 14—Can you predict *this circuit's output in response to a positive step function?*

Analyze the performance of an electronic-music circuit

(d) Lord Kelvin's body is refrigerated in the British Museum.

22. You want to invert (at unity gain) a 0 to +20V signal with a 741-type op amp. The 741 must run on ±15V supplies, although a −25V supply is available. Using no transistors, sketch the basic circuit.

23. Temperature is the most common physical phenomenon an EE is asked to consider. Which of these devices provides the most accurate and repeatable performance as a temperature sensor?

(a) Thermocouple
(b) Thermistor
(c) Type 8007 op amp
(d) Platinum wire
(e) 15-ft McPhearson thermometer.

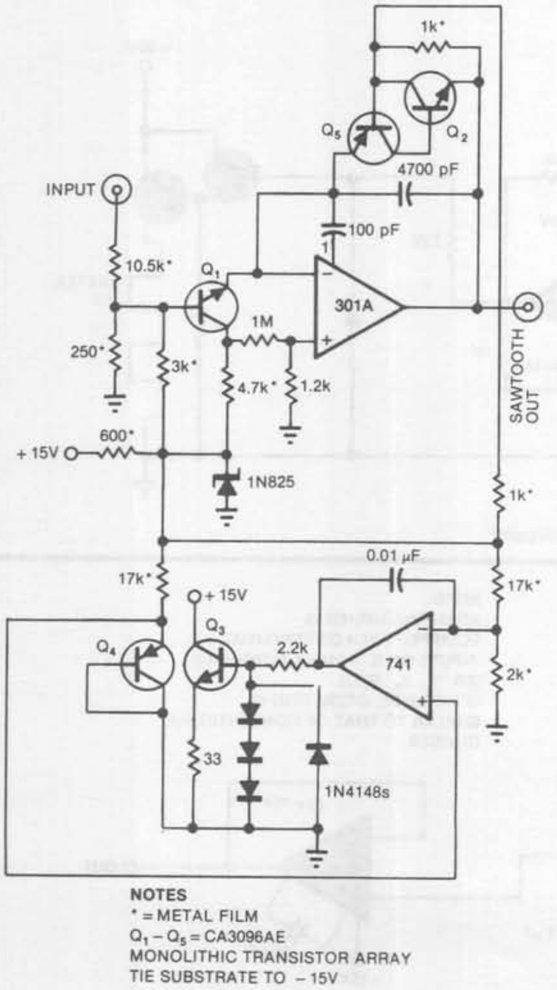
24. The circuit shown in **Fig 16** generates a 75-kHz sine wave with about 2% distortion. Total supply-current drain is about 2.5 µA. Q_1 functions as a temperature-compensated reference diode to stabilize the circuit against supply and temperature shifts. The Q_1/Q_5 combination bootstraps off the reference-diode potential to provide a 1.2V potential to Q_6 via the LC circuit. Q_2, Q_3, Q_6, Q_7 and Q_8 actually produce the sine wave. Explain how. Hint: Assume all the transistors are matched.

25. One component is required to make the circuit depicted in **Fig 17** oscillate with good stability and output-wave purity. Put it in.

Pencils down

After you're sure of your answers, compare them with the ones presented on pg 145. You'll even find a chart there that lets you score your performance. **EDN**

Article Interest Quotient (Circle One)
***High* 476 *Medium* 477 *Low* 478**



NOTES
* = METAL FILM
$Q_1 - Q_5$ = CA3096AE MONOLITHIC TRANSISTOR ARRAY
TIE SUBSTRATE TO −15V
4700 pF = POLYSTYRENE

Fig 15—This V/F circuit *suits electronic-music applications, but what function do the 741 op amp and associated components perform?*

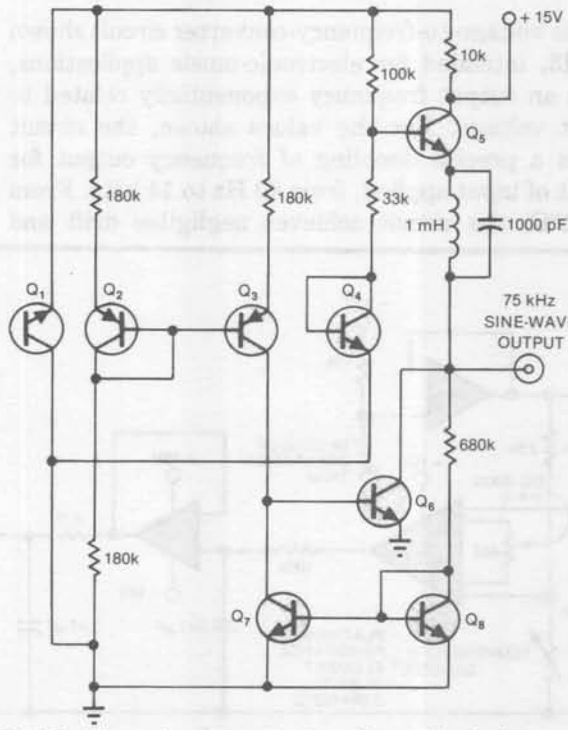


Fig 16—What role *do matched transistors play in the production of a sine wave?*

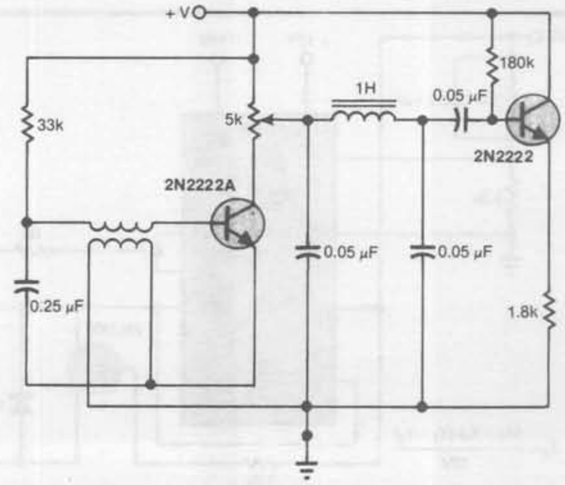


Fig 17—This circuit *requires the addition of one component to provide stability and output-waveform purity. What is it?*

Presenting the answers to EDN's analog-design quiz

Realizing that the answers might be debatable, get ready to score your paper. Each correct answer gets one point.

1. Several forms work; the most widely known solution is the Kelvin-Varley divider (named after Lord Kelvin) shown in **Fig 1.** All you must do is label the values of the resistors.

2. Less is better! In the original circuit, level shifting and voltage gain come from the popular high-speed 2N2639 transistor. The common-emitter configuration proves relatively slow (due to storage charge) and inverts the signal. The improved version (**Fig 2**) uses the common-base configuration because of its high speed and noninverting characteristics. This arrangement provides 10-nsec rise and fall times plus lower component count.

3. You should recognize the network as a common 10× scope probe connected to a scope. The variable capacitor allows you to precisely cancel the effects of cable and scope capacitance; the circuit provides high input impedance and very low input capacitance.

4. To understand this circuit (**Fig 3**), consider the effects of lightly compensating the 301. What if you put a very high-slew-rate amplifier in its place?

5. This circuit is a high-performance "charge-dispensing" voltage-to-frequency converter. "Packets" of charge, dumped into the summing junction by the amplifier output's switching action, servo-control the voltage there. The zener bridge and the 0.002-μF capacitor determine the amount of charge in each packet; the voltage applied to the input determines the number of packets dumped per unit time. The transistor and associated circuitry protect against lock-up, while the additional diodes provide the bridge's temperature compensation. For waveforms and details of operation, see EDN, August 5, 1978, pg 101.

SCORE YOURSELF

NUMBER OF QUESTIONS ANSWERED CORRECTLY	RATING
20-25	CIRCUIT DESIGNER
15-20	ELECTRICAL ENGINEER
10-15	TTL JOCKEY
5-10	MICROPROCESSOR SCHOLAR
0-5	COMPUTER PROGRAMMER

6. The 2N2907 provides latch-up reset—latch-up can occur if the circuit's input is driven above the normal operation range (0 to 12V). In normal operation, the transistor is biased off.

7. The villain of this piece is dielectric soakage in the capacitor.

8. Maximum frequency is limited by the saturation voltage of the 2N222A. If you snip out the 20-pF capacitor, the 311's output never stays high long

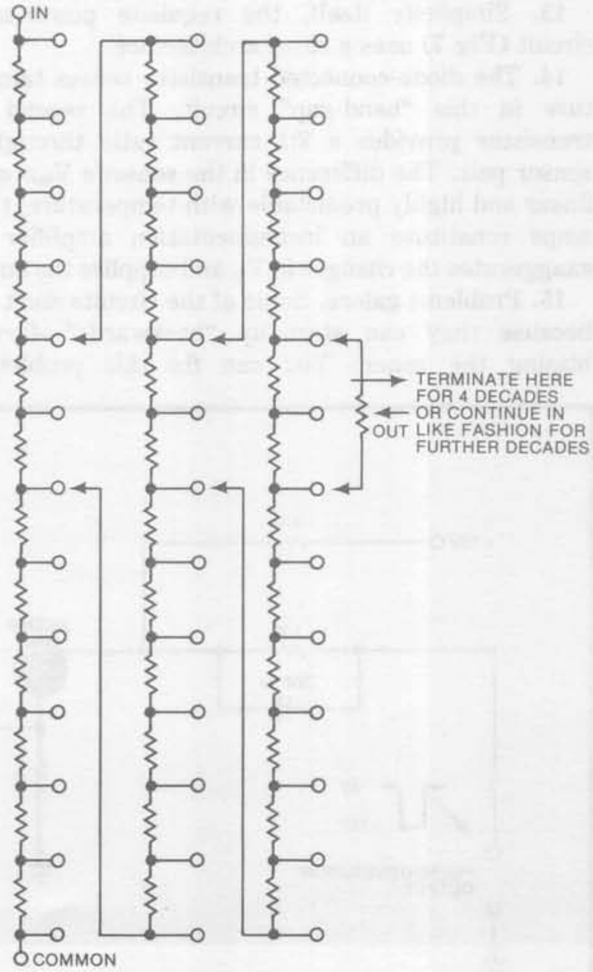


Fig 1—The Kelvin-Varley divider *allows you to add decades easily.*

A current-source transistor bleeds charge from a capacitor

enough for the 0.01-μF integrator to completely discharge—the circuit's transfer characteristics go awry. Incidentally, the transfer characteristic creates an *inverse* relationship between input voltage and output frequency, as shown in **Fig 4.**

9. The circuit works well—up to where the current-source transistor suffers reverse breakdown (typically 8 to 9V in a small transistor). When the 2N708 comes on, if the 0.05-μF capacitor's voltage is above 8 to 9V, the current-source transistor breaks down and bleeds charge from the capacitor. One fix adds a diode in each emitter; two diodes are required to maintain temperature stability in the current source.

10. The circuit shown in **Fig 5** produces an output equal to its input, satisfying the stated requirements.

11. The black box need contain only a C-106B SCR, as shown in **Fig 6.**

12. A number of weak spots exist—Q_3 drives an enormous load, for example—but the ac power transformer presents the most important problem. Unless carefully designed, it will burn up (literally). Can you figure out why?

13. Simplicity itself, the requisite power-supply circuit **(Fig 7)** uses a clean architecture.

14. The diode-connected transistor senses temperature in this "band-gap" circuit. The second dual transistor provides a 2:1 current ratio through the sensor pair. The difference in the sensor's V_{be}s will be linear and highly predictable with temperature; the op amps constitute an instrumentation amplifier that exaggerates the changes in V_{be} and supplies the output.

15. Problems galore. Some of the circuits don't work because they can start up "backwards"—forward-biasing the zener. You can fix this problem by grounding the op amp's −15V terminal or inserting a diode in the output line. If you add the diode, run a 33-kΩ resistor from the top of the bridge to +15V to ensure starting. The units with long-term drift suffer from transient forward biasing of the zener. Precision zeners respond to any applied forward bias, however brief, by drifting slowly over time.

16. Place the SCR crowbar across the supply's output. (If the pass or driver transistor failed, the SCR shunt path to ground wouldn't be worth much.) Add a slow-blow fuse in the collector line. The turn-on provided for the SCR works, but sloppily and slowly—perhaps too slowly to save the TTL. Also, the SCR requires a capacitive bypass to avoid "rate effect" nuisance tripping. Anything else? You bet.

17. Add 100Ω to the base of the transistor and the oscillation ceases. Can you explain why?

18. Precision is fine but efficiency only results when the heater is placed in the collector line. The 301A pulse-width modulator only swings to +12V—most of the 30V supply ends up across the poor emitter-follower "switch."

19. Initially, the multiplier's output responds to the derivative of the input step (signal); after the capacitor at the input settles from the step input, the output is filtered at a frequency determined by the input's dc potential. **Fig 8** shows the effective time-constant

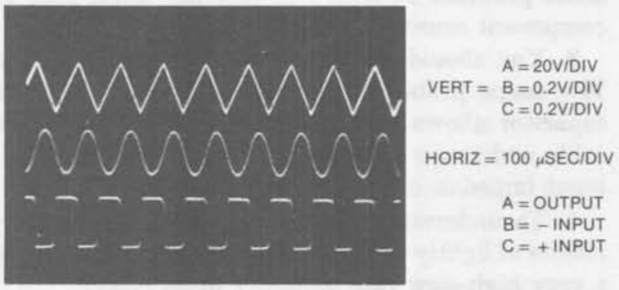


Fig 3—Three waveforms, *one at the negative input, one at the positive input and one at the output, characterize this circuit.*

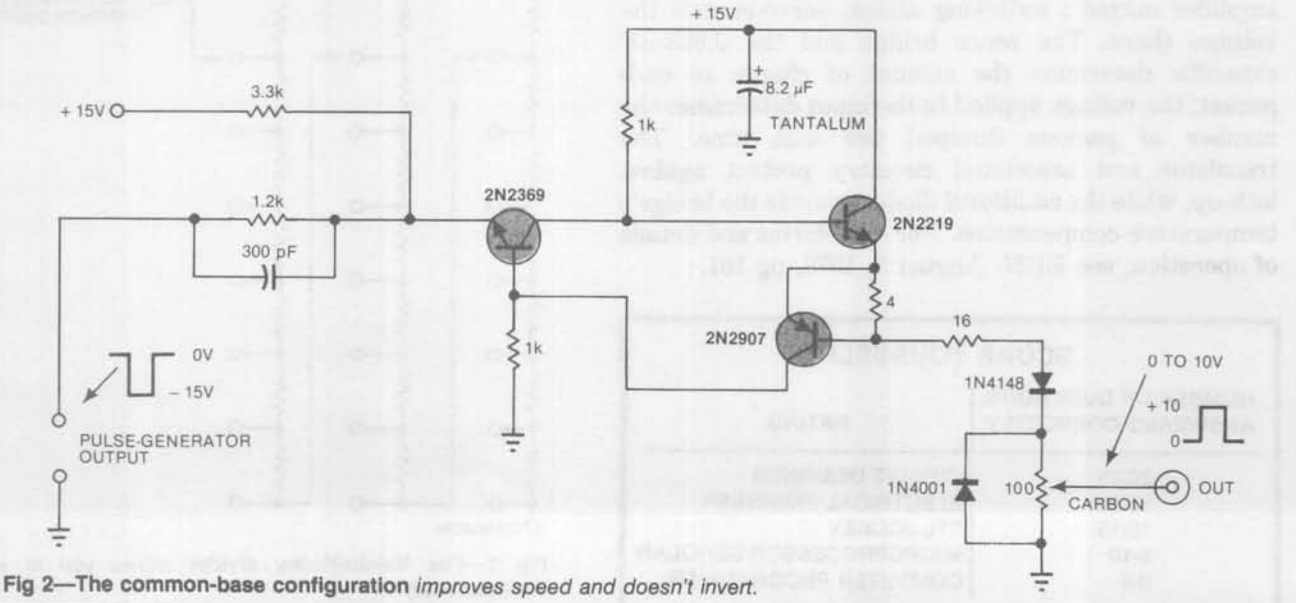


Fig 2—The common-base configuration *improves speed and doesn't invert.*

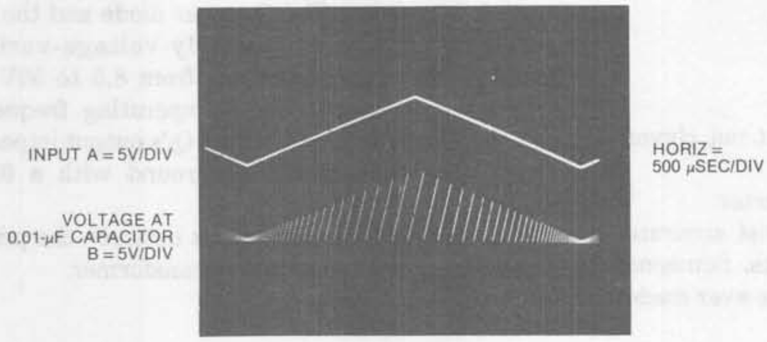


Fig 4—The V/F converter *provides an inverse relationship between input voltage and output frequency.*

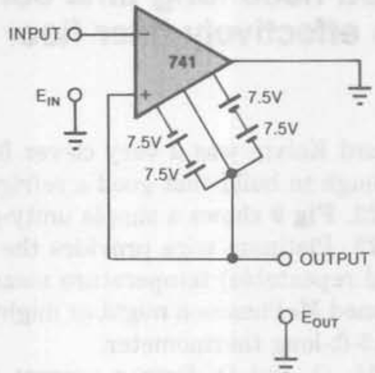


Fig 5—E_{IN} is mirrored by E_{OUT} *in this unity-gain, noninverting follower.*

change of the circuit caused by derivative response. The diode and transistor prevent derivative-controlled response on the trailing edge by clamping the 0.27-µF capacitor to ground. This circuit has proved itself in electronic weighing applications, where rapid signal acquisition is required yet "floor noise" calls for long time constants to provide effective filtering. Additional information on this circuit appears in the "Multiplier Application Guide," available free from Analog Devices Inc, Norwood, MA.

20. Q_1, unless compensated for shifts in ambient temperature, drifts wildly, rendering the circuit virtually useless. This problem is characteristic of the logging configurations, and several methods can correct it. Q_3, Q_4 and the 741 form a temperature-control loop that thermally stabilizes the entire monolithic transistor array at about 50°C. The loop prevents shifts in ambient temperature from affecting Q_1, stabilizing its operating point. Q_4's V_{be} junction senses the temperature, while Q_3 acts as the chip heater. The 741 adjusts Q_3's conductivity, dissipating enough power on chip to keep the voltage across the 2-kΩ resistor equal to Q_4's V_{be} potential. The 33Ω resistor, along with the diode string, determines the maximum power Q_3 can dissipate and prevents servo lock-up during circuit start-up. Note that Q_2 and Q_5 (responsible for resetting the integrator) constitute part of the monolithic array and thus are immune to ambient-temperature shifts. The 4700-pF integrating capacitor, which should be polystyrene, creates all thermal drift of any consequence in this circuit.

21. (b). All molecular motion stops at absolute zero.

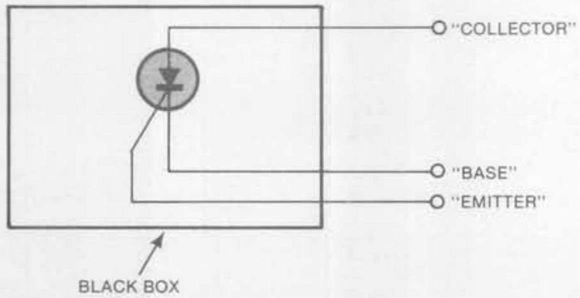


Fig 6—One C-106B SCR *satisfies the full set of requirements for the black box.*

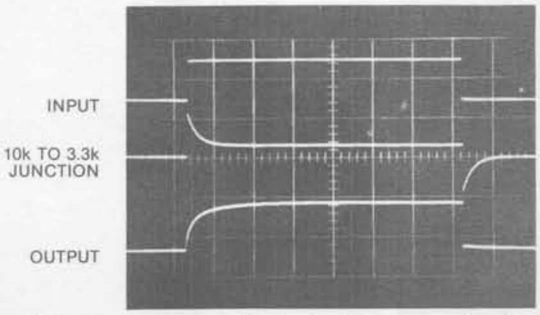


Fig 8—Derivative response *effectively changes the circuit's time constant.*

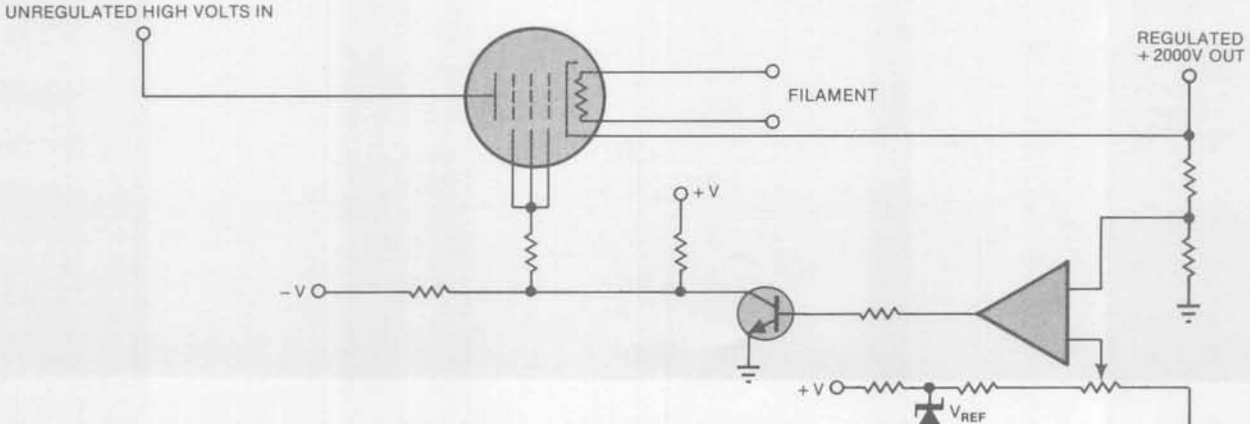


Fig 7—You get 2 kV at 30 mA *from this simple circuit.*

You need long time constants to effectively filter floor noise

(Lord Kelvin was a very clever fellow, but not clever enough to build that good a refrigerator.)

22. Fig 9 shows a simple unity-gain inverter.

23. Platinum wire provides the best (most accurate and repeatable) temperature measurements. Someone named McPhearson might or might not have ever made a 15-ft-long thermometer.

24. Q_2 and Q_3 form a current source that delivers about 15 μA to Q_3's collector. Q_3's collector current determines Q_6's peak collector current. The 680-kΩ resistor plus Q_7 and Q_8 accomplish a voltage-to-current conversion that decreases Q_6's base current whenever its collector potential rises. This provision gives the configuration a negative resistance characteristic that permits oscillation. The LC circuit determines the operating frequency. The Q_1 zener diode and the Q_4/Q_5 regulator provide supply-voltage-variation immunity—the circuit operates from 8.5 to 50V with constant output amplitude. At operating frequencies above 100 kHz, you might stiffen Q_5's output impedance by bypassing the emitter to ground with a 0.1-μF capacitor.

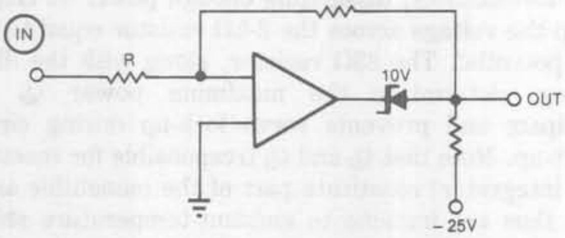


Fig 9—You can invert *a 0 to 20V input easily with one 741.*

25. Insert a 600-Hz tuning fork between the primary and secondary of the feedback transformer. **EDN**

Author's biography

Jim Williams, now unemployed, was a consultant at Arthur D Little Inc, Cambridge, MA, when this article was written. Before that, he was a senior engineer in MIT's Dept of Nutrition and Food Science, where he designed experimental biomedical instrumentation. Jim's interests transcend analog design to include sculpture, art, skiing, tennis and collecting antique scientific instruments.