THIS BOOK is for those who design, use or understand electronic circuits. It contains the information previously included on sets 21 to 30 of Circards, corrected where necessary, and supplemented with ten pages of new circuits. Introductory articles originally published in Wireless World complement each section.

In October 1972, Wireless World launched a circuit information system called Circards. The system was based on issued sets of 8 x 5 in cards suitable for personal filing systems. Published in conjunction with introductory articles in Wireless World, Circards gave the subscriber descriptions of circuit operation, component values and ranges, circuit limitations and modifications, performance data and graphs.

Circuit Designs No. 1 and No. 2, containing information on Sets 1 to 10 and 11 to 20 respectively, are now out of print. However, sets of cards are still available at £2 per set, supplied post free in plastic wallets.
circuit designs

Collected Circards

P Williams/J Carruthers/J H Evans/J Kinsler
Paisley College of Technology, Renfrewshire

A WIRELESS WORLD PUBLICATION
LONDON
IPC BUSINESS PRESS LTD
Contents

Preface page 5

Set 21: Voltage-to-frequency converters page 7
Background article/v-to-f converter using unijunction/multiplier converter/delta-sigma converter/sinewave converters/multiphase converter/monolithic i.c. converters/unijunction converter linearized/linear types/diode pump converter/converter with differential input/up-date circuits

Set 22: Amplitude modulators page 21
Background article/i.c. package modulators/linear modulator/modulator using precision rectifiers/modulated crystal oscillator/diode bridge modulators/s.s.b. generation/f.e.t. modulators/long-tailed pair modulators/micropower a.m./direct tuned-circuit modulator/up-date circuits

Set 23: Reference circuits page 35
Background article/zener diode characteristics/Williams ring-of-two reference/variable reference diodes/bipolar references/low temperature coefficient voltage references/μA-mA and mV-V calibrator/non-zener device characteristics/compensated reference circuits/simple current reference/monolithic i.c. reference/up-date circuits

Set 24: Voltage regulators page 49
Background article/zener diode shunt regulator/simple transistor regulators/feedback series regulators/bipolar-m.o.s. op-amp regulator/monolithic i.c. regulators—l/monolithic i.c. regulators—2/voltage regulation using current differencing amplifiers/dual-polarity circuit/switching regulator/self-regulating d.c.-d.c. converter/up-date circuits

Set 25: RC oscillators- I page 63
Background article/null, networks and n.i.cs/current-driven Wien oscillator/voltage-current Wien circuit/op-amp Wien oscillator/micropower circuit/amplitude control methods/Baxandall RC oscillator/oscillators using n.i.cs/single-element oscillators—l/single-element oscillators—2/up-date circuits

Set 26: RC oscillators- II page 78

Set 27: c.m.o.s.- I page 89
Background article/linear c.m.o.s. circuits/devices and characteristics/linear circuit characteristics/de ice configurations/d.c. amplifiers/a.c. amplifiers/gain-controlled amplifiers/controlled resistances/non-linear circuits—l/non-linear circuits—2/square-triangle generator/up-date circuits.

Set 28: c.m.o.s.- II page 103
D.C. feedback pair/low-pass, high-pass filters/band-pass, notch filters/D-type analogue circuits—l/D-type analogue circuits—2/three-phase oscillator/frequency to voltage converter/two-integrator oscillator/current-differencing amplifier/ transistor outputs/up-date circuits.

Set 29: Analogue multipliers page 115
Background article/quarter-squares multiplier/v-to-f converter multiplier/delta-sigma modulator, multiplier/log-antilog multiplier/triangle-wave averaging multiplier/four-quadrant multiplier—applications/translinear multipler/multiplier using Hall-effect devices/f.e.t. analogue multiplier/up-date circuits

Set 30: r.m.s./log/power law circuits page 129
Background article introducing non-linear circuits/root-law array/voltage divider/ramp-to-sinewave converter/r.m.s.-to-d.c. converter/D-type delta-sigma converter/cube-law converter/logarithmic amplifier/resolvers/applications of i.c. multipliers/computation of \( (x^2 + y^2) \)/up-date circuits

Contents of sets1–20 page 143
Preface

While writing Circards we have often felt like acting out the parts of latter-day Canutes as the tide of innovations sweeps in. There is the feeling that the tide must be halted long enough at least to learn to swim. The biggest worry in electronics can be to pace the learning process so that new knowledge is both absorbed and applied. Too little reading and study, and the designer is continually forced back on a standard repertoire of solutions; too much and there is no time left to apply that knowledge.

The analogy is appropriate in other ways: new developments come in waves, each building on the ones before. A single technical article or new device can set a whole generation of designers off with fresh momentum, each contributing to that tide. In an age when power is assumed to reside only in organizations it is cheering to note how often the origin of such a sequence of waves can be traced to a few individuals. Just as Blumlein in an earlier age provided new and fundamental innovations such as the Blumlein integrator and the long-tailed pair, so in the i.c. age Bob Widlar changed the whole approach to design by such innovations as the current-mirror and band-gap regulators. Some of the most useful and innovative designs in the last couple of years have come from Barrie Gilbert, whose papers are always a source of ideas (if you are going to steal an idea at least steal a good one). The common feature to such designers is their ability to approach problems in a more open way—a state of mind that says “what happens if...?”

This approach is refreshingly present in much published work in recent years. It would have been all too easy as integrated circuits were produced for particular purposes to close the mind to other alternatives or applications.

Fortunately the manufacturers are continually forced to broaden the range of applications of each device. From a production standpoint the i.c.s have to be as standardized as possible with the fewest possible connections and simplest processing. A good example is the three-terminal voltage regulator aimed initially at on-card regulation in digital systems. No sooner had it appeared than the applications engineers were set to work to show that it could also be used for variable voltage regulation, as a switching regulator, a current limiter and so on.

It is important for each of us to continue that spirit of controlled curiosity. In Circards we have tried to provide an optimum blend of standard and novel circuits. Clearly with readers having a wide range of interests and expertise we will offend some with out naivety, and baffle others with our obtuseness. Our hope is that the circuits will be useful, but that in addition they will include sufficient new ideas to start a few fresh waves. The nearest tide to sweep in on the analogue shore, that of the functional blocks such as multipliers, V-f and d/a converters, presents a superb opportunity for good design and good designers. To mix the metaphor a little, the alternatives are to sit in the deck-chair or start surfing.

We would like to acknowledge the continuing support and encouragement of the Principal and Governors of Paisley College, the help and advice of colleagues; the excellent judgement of Wireless World in supporting this project; and the apparently limitless patience of our wives and families.

To these last, this book is dedicated with love.

Peter Williams
Set 21: Voltage-to-frequency converters.

You may not find many voltage-to-frequency converter circuits classified as such. They are likely as not to be found under such headings as voltage-controlled oscillators, frequency modulators, astable circuits, and even waveform generators, as the following article—an elementary introduction to their operation—points out. Decisions on which kind to use may often centre on linearity. The closed loop designs generally have better linearity, typically 0.1 to 0.5%, than the simpler open-loop designs, especially the “charge dispensing” kind, discussed in the article (see, for example, page 19). The unijunction type, page 10, also crops up on pages 116 & 130, and a further ΔΣ circuit on page 117.

Background article 8
Unijunction converter 10
Multiplier converter 11
Delta-sigma converter 12
Sinewave converter 13
Multiphase converter 14
Monolithic converters 15
Linearized converter 16
Linear converters 17
Diode-pump converter 18
Differential input converter 19
Up-date circuits 20
Voltage-controlled oscillators—astable multivibrators—waveform generators—frequency modulators: under each of these headings one finds circuits that have an important common property, that the output frequency is a function of some reference or control signal. Such circuits are multi-variable systems in which several parameters of the output waveform are controlled singly or in various combinations by other parameters at the input. Thus the same circuit can appear under different headings depending on which input/output relationship is of priority concern.

As an example, some recent integrated circuits have been designed as waveform generators with square/triangle/sine wave outputs. If the output waveform is of no particular concern, the fact that the frequency of each output is proportional to a direct control voltage assumes a greater importance. The circuit can then be called a voltage-controlled oscillator. Now assume that the control voltage is set to a particular quiescent value with a smaller alternating voltage superimposed. Then the output frequency is modulated by the a.c. input, with the carrier frequency corresponding to the quiescent value of control voltage. The label for this circuit is frequency modulator.

In set 21 of Circars the primary property of interest is the relationship between an input voltage or current and the frequency of the output, with much less importance being attached to the wave shape or amplitude. A particularly desirable property is that the voltage-to-frequency relationship be linear, and in extreme cases departures from linearity of as little as 0.01% may be desired. In the process of achieving this, the output pulse height and width may have to be equally well controlled but these are a means to the end and not an end in themselves. There are other cases where the frequency needs to be varied only over a limited range, demanding only a small linear region to the V/f characteristic. A good example is found in the design of v.c.o.s for high-frequency phase-locked loops. Restriction of the frequency range and of linearity is a compromise accepted more or less willingly in exchange for a speed capability that matches that of the associated digital circuits.

In nearly all of these examples, the basic timing mechanism is that of charging a capacitor from a control voltage or current. The voltage change across the capacitor is sensed by some level-detecting circuit which activates an electronic switch to discharge the capacitor and restart the cycle. Two categories of circuit can be clearly distinguished:

- where the discharge time of the capacitor is made short compared with the shortest charging time and need not be under the control of the input voltage, and
- where both charge and discharge times are controlled in common by the input. The first-mentioned circuits produce sawtooth waveforms across the capacitor and short duration output pulses, while the last-mentioned commonly develops a triangular wave across the capacitor, in association with a square wave at a separate output.

These ideas are illustrated in Figs 1 to 4. In Fig. 1, constant current results in a constant rate-of-change of voltage across the capacitor, i.e. the time taken to charge to a given p.d. will be inverse to the charging current. If that level can be sensed and caused to end the cycle or half-cycle, then the repetition frequency (being inverse to the period of the waveform) will be proportional to the current and a linear V/f converter results. The simplest way of causing the cycle to recommence is to place a low-value resistor across the capacitor to discharge it in the shortest possible time. If the discharge current is large compared to the charging current, then it is immaterial whether the charging current is disabled or not and Fig. 3 represents the basic principle of many V/f converters, with the switch periodically closing at the instant when the p.d. across the capacitor reaches a defined value.

An alternative principle is shown in Fig. 4. The current generator is applied to the capacitor in the reverse direction giving an opposing slope to the ramp but of equal magnitude. The resulting waveform is triangular with the repetition frequency linearly related to the current if the points at which switching is initiated are defined. The provision of a purely electronic two-pole change-over switch is difficult, and the reversal of current direction is more often achieved by using a single-pole switch or its equivalent to control the current generator directly.

A second problem that often arises is that the changing p.d. across the capacitor affects the nominally constant current. This is obvious in terms of the non-linearity of the ramp, but may not affect the linearity of the
V/f function provided the waveshape is well controlled, e.g., accurate V/f conversion is possible with simple R-C charge and discharge circuits though the wave shape is highly non-linear. Where waveshape is also of importance, the capacitor forms part of an operational amplifier integrator circuit, with the virtual earth action ensuring that the charging current is independent of the p.d. The discharge element now has no point connected to ground which can raise problems in activating it (Fig. 5.).

This technique leads to a simple form of triangular-wave generator shown in Fig. 6 where both the +V and -V inputs have to vary together if the slopes are to remain of equal magnitude. By using both the input and the output of an amplifier with a voltage gain of -1, this is readily achieved (Fig. 7). Alternative methods include the design of amplifiers whose voltage gain is switched from +1 to -1, and of integrators in which the direction of capacitor current is reversed by a switch while the magnitude is controlled by a single input voltage.

In all of these circuits there remains the problem of the level-sensitive circuitry that is to determine the instant of switching; both switching speed and accuracy of level are important making the design of a fast, accurate V/f converter still a difficult one.

The term charge-dispersing is a big one in the literature on precision V/f converters. A feedback system is set up in which the output pulses from a generator (basically monostable in form) are arranged to feed back a constant amount of charge for each output pulse. If these units of charge are combined at the input of the system with the control signal, and the overall feedback is negative, then the pulse rate will be proportional to the control signal.

In block diagram form in Fig. 8, the principle is illustrated by a combination of V/f and an f/V converter. Assuming that the amplifier gain is high, and that the f/V converter is very linear then the feedback overcomes any non-linearities in the V/f converter, i.e., \( V_{oc} = V \) to a high accuracy because of the feedback while \( V_{oc} \) ensuring that \( f(V) \) without reference to the linearity of the V/f converter. The f/V converter might be of the diode-pump variety which with suitable design can transfer a fixed charge into a load for each output pulse rate.

A level-sensing monostable gives an output pulse when the input level rises above a critical value. If the input then falls a second pulse is generated on the next excursion through the set level in the same sense. An important restriction is that the capacitor shall have been completely discharged prior to the second pulse—otherwise the time taken for recharging will be shortened and the output pulse-width reduced. The output of such a monostable would ideally be a train of constant-amplitude constant-width pulses, which could be smoothed and fed back to the input amplifier as in Fig. 9.

A better arrangement dispenses these units of charge into a summing integrator—Fig. 10. For positive pulses a negative control voltage is required, the integrator output ramping up until a pulse is produced from the monostable. The charge dispensed into the summing junction causes the output of the integrator to fall, again rising slowly under the action of the control current. On average, the net charge inflow has to be zero, the charge dispensed per pulse is constant and hence the pulse-rate is a linear function of the control voltage/current.

Other recent i.c.s revert to the separate constant current circuit for timing circuits and waveform generators, and the resulting f/V linearity can be accurate enough for many applications. One technique is to have two current sources one set by the external control voltage, the other of opposite polarity but of twice the magnitude—Fig. 11. Keeping the former permanently on and switching the latter on and off makes the net current in the capacitor change from +I to -I. A circuit configuration to use this technique to produce a triangular-wave generator is shown in Fig. 12.

Two comparators sense the capacitor voltage, their reference inputs being set to -V/3 and +2V/3 by an internal potential divider. Assume the current at I; the capacitor charges until its p.d. reaches +2V/3. Comparator 1 changes its output and resets the flip-flop. This reverses the direction of current flow until the capacitor discharges to +V/3. The comparator 2 operates setting the flip-flop into its original state and restarting the cycle.
Unijunction voltage-to-frequency converter

Circuit description
With the removal of the unijunction transistor the circuit of Fig. 1 is simply an integrator which, with a positive $V_{in}$, gives a negative-going ramp $V_o$. If the i.c. gain is sufficiently high then $V_o = -V_{int}/RC$. The unijunction serves to discharge the capacitor each time the voltage between $a$ and $b_1$ reaches the unijunction trigger voltage. The circuit therefore goes through the cycle shown right. Upper limit of $-1.8V$ is the voltage at which the unijunction reverts to being an open circuit. Lower limit of $-11.7V$ is arbitrary and is the result of choosing $V'$, $R$ and $C$ so that $V_{in}=10V$ gave a frequency of $1kHz$. With $\pm15V$ supplies this obviously cannot be extended beyond $15V$.

The degree of linearity in the plot of frequency against $V_{in}$ shown in Fig. 2 is quite high e.g. $10V$ gave $1kHz$, $5V$ gave $498Hz$, $1V$ gave $96Hz$ and $0.15V$ gave $16Hz$.

Rise time of the output waveform (Fig. 1 circuit gave the waveform of Fig. 3) corresponding to the time when $C$ is discharging, was $15us$ i.e. $1.5\%$ of the period at $1kHz$, so the circuit cannot be recommended for much higher frequencies.

But from the expression for the downward ramp it is clear that the same frequency range can be achieved by the use of different values of $R$ and $C$, and also of $V'$. It will, of course, be generally desirable to keep $R$ relatively high to give high input impedance.

Circuit modifications
The modification shown in Fig. 4 to the circuitry around the unijunction transistor will provide a pulse train at $V_o$, the frequency being the same as that of the main circuit. The leading edge of this pulse train will correspond to the rising edge of $V_o$ shown in Fig. 3. This $V_o$ will, of course, have the advantage of going much closer to zero in the time between the pulses.

An alternative voltage-to-frequency converter reported by Swarup and Banerjee is shown in Fig. 5. It is basically a unijunction oscillator with constant-current drive to the capacitor, this current being proportional to the voltage $V_R$. A linear relationship between $V_R$ and the output frequency is claimed in the range 0 to 500Hz. The basic action of the unijunction oscillator and modifications to reduce the discharge time of $C$ are fully described in Circards set 3 (waveform generators) card 4.

Reference
Swarup & Banerjee, Linear voltage to frequency and voltage to pulse width converters using unijunction transistors. *Int. J. Electronics*, vol. 32, 1972, pp. 377-81.
Multiplier voltage-to-frequency converter

Fig. 1

Circuit description
The circuit of Fig. 1 is basically a closed-loop integrator-comparator square-triangle generator, comprising IC4 and IC5, with a multiplier (IC1) inserted in the loop to provide control of frequency. The value of the output voltage from the multiplier is a scaled version of the product of Voout and the control voltage Vc. Thus the amplitude of the signal to be integrated is directly proportional to a scaled value of the control voltage. A positive voltage applied to the inverting integrator charges C3 with its output end negative relative to the input end (held close to 0V by negative feedback through C2 and the high gain of IC5). Thus, Voout goes negative until the current it feeds through R4 exceeds the positive current in R1b, resulting in a negative current to the non-inverting input of the Schmitt comparator. Voout then rapidly switches to a negative value due to positive feedback applied to IC5, causing the multiplier output to go negative (Vc is always positive). The output from the integrator then starts rising until it reaches a positive voltage sufficient to make the comparator change its state again, returning Voout and the multiplier output to their original positive values. Hence, Voout is a triangular wave and Vc a square wave with frequency linearly dependent on the control voltage.

Component changes
Useful range of supplies: ±7 to ±16V.
Increase C3 to reduce upper frequency limit.
Useful range of Vc is about 0 to +11V.
Changing IC5 to a 301 type op-amp increases slew-rate capability.
R4 can have a wide range of values the lower limit being imposed by heavy loading of IC5 and the upper limit by the failure of IC5 to switch before it saturates.

Circuit modifications
- Accuracy of frequency control largely depends on the nonlinearity and offset voltages in the multiplier part of the loop. Output offset adjustment is provided by R1 and independent adjustment of the offset voltages at the multiplier's X and Y inputs (pins 3 and 5) can be obtained by the 25-kΩ potentiometers R12, R13 shown in Fig. 4, where R14, R15 are 100kΩ.
- For a given value of control voltage frequency depends on the scale factor of the multiplier. Adjusting this allows the output frequency to be made a simple linear function of Vc. The factor can be adjusted in three ways: (1) by adjusting the op-amp gain in the multiplier block by means of R3, (2) by adjusting the gain of the multiplier block by varying R1 and R5, and (3) by connecting the Voout signal to the X input of the multiplier (pin 5) through a ground-referred potentiometer.
- Asymmetry in the output waveforms due to mismatched Zener diodes can be corrected by applying a bias voltage Vb of suitable polarity to the comparator input via R16, as shown in Fig. 5. Alternatively, this arrangement with Vb=±V and R16=10kΩ can be used to purposely introduce a d.c. offset into the output waveforms.
- Other methods may be used to limit the amplitude of the output voltage from the comparator, e.g. by using a diode bridge limiter or by replacing IC5 with an op-amp of the type providing access to the drive point of its output stage, such as a 748. This allows the comparator output to be clamped by zener diodes or suitably-biased transistors connected to the output stage drive point.

Further reading

Cross references
Set 2, card 1
Set 3, cards 1, 5
Set 13, card 9
Set 17, cards 3, 6
Set 21, card 4
**Delta-sigma voltage-to-frequency converter**

![Fig. 1](image1)

**Fig. 1** Typical performance of Fig. 1
IC1 741, IC2
1/2 × CD4013AE
IC3 1/2 × CD4011AE
Supplies VDD +10V
VSS −10V
R1, R2 100kΩ
R4 1kΩ
C1 100nF
Clock 6V positive pulses,
p.r.f. 1kHz, duty cycle 10%
See Figs 4 and 5.

![Fig. 2](image2)

**Fig. 2**

![Fig. 3](image3)

**Fig. 3**

**Fig. 4**

Control Voltage (V)

![Fig. 5](image4)

**Fig. 5**

![Fig. 6](image5)

**Circuit description**

A class of voltage-to-frequency converter gives an output in the form of a pulse train where the repetition frequency is directly proportional to the instantaneous value of the control voltage but the pulses are generated asynchronously. The output from a delta-sigma encoder is again a pulse train but its average pulse repetition frequency is proportional to the control voltage and the pulses are generated in synchronism with a clock pulse waveform. The basic form of a delta-sigma modulator is essentially a voltage-to-pulse ratio converter (Fig. 3). The circuit maintains a constant voltage across C3 as the input voltage is varied, which requires that the charging current from the voltage reference source to be switched into C3 at a repetition rate that attempts to keep the net change in voltage across C3 at zero. Thus the rate at which the reference current must be switched into the capacitor must be proportional to the input voltage. If the reference current is switched under the control of a stable clock-pulse generator the output pulses will be proportional to VDC and synchronized with the clock pulse source. Assuming that the net voltage across C3 is zero, that VDC is negative, that Vref is positive and IC3 is a high-gain op-amp then I1 = I2, Vout (mean) = 0 and Iout (mean) = 0. As the inverting input of IC3 is a virtual earth, I1 = VDC/R3 and I2 = kVref/R3 where k is pulse duty cycle required to keep I1 = I2. Equating these currents gives

\[
V_{DC} = \frac{kV_{ref}}{R_3}
\]

where k is the ratio of the output pulse repetition rate (f) to the clock pulse repetition rate (f0). Hence

\[
f = \frac{R_3f_0}{R_3V_{ref}} \cdot V_{in}
\]

By making R4 = R2 and V1(max) = Vref the maximum output p.r.f. is that of the clock source and the average output pulse rate is proportionally smaller for smaller values of V1.

The arrangement of Fig. 2 uses an analogue transmission gate to realize the switch S.

IC3 is a precision comparator which determines when the reference voltage source is to be switched to R3 by monitoring the polarity of the output from the integrator IC1. This switching action is synchronized to the clock pulses by using gating pulses derived from the output of a D-type flip-flop which receives the comparator's output at its data input. The circuit of Fig. 1 is that to which the typical performance data refers. This is a simplified form of the arrangement previously discussed with the electronic switch, separate reference source and precision comparator removed. (Note that whilst the integrator used both positive and negative supplies the D-type flip-flop is connected only across the positive supply.) As the D-type produces output pulses equal in amplitude to the VDD rail voltage only when its data input receives a positive pulse from the integrator, a separate switched reference is not essential. Also, the precision comparator can be replaced by R3 which limits the negative-going pulses to the data input of the D-type which acts as the comparator. Average frequency/Vref graph (Fig. 4) has a linearity of ±0.1% up to f = f0 when Vref = VDD. No further increase in frequency is possible except by increasing the p.r.f. of the clock source. Output pulse waveform of Fig. 5, inverted by IC3, is of Vref = VDD/2, the dashed pulse only being present when Vref is raised to VDD.

The circuit of Fig. 6 is another simplified form of the more general system where the comparator had been omitted and the electronic switch is realized by a junction f.e.t. The positive supply rail is used as the voltage reference source and the output is taken from the Q terminal of the D-type flip-flop IC6, which is a complementary m.o.s. version to conserve power. This circuit is capable of linear v-t conversion within ±0.05% almost independently of temperature changes. Typical values are:

V = 2.7V
IC1 LM4250C
IC3 1/2 × MC14013CL
R1, R2, R3, R4 100kΩ
R5 5.6MΩ, C1 100nF
Tr1 2N4396

**Further reading**

Defreitas, R. Low-cost way to send digital data, *Electronics Design*, pp. 68-73, Jan. 18, 1974
Ross, P. J. Simple accurate voltage to frequency converter. *Int. of Physics E*, vol. 7, pp. 706/7.
Sinewave voltage-to-frequency converters

**Typical performance**
- Supplies $\pm 15V$
- $IC_1, IC_3$ 741
- $TR_1, TR_3$ 1/6$\times$ CD4007A
- $R_1$ 150$\Omega$
- $R_2$ thermistor type R13
- $C_p, C_s$ 100nF
- $V_{out1}$ 520mV pk-pk
- $V_{out2}$ 1.04V pk-pk
- See graph for $f/V_e$ (Fig. 2)

**Circuit description**

This circuit (Fig. 1) is one of the many forms of Wien bridge oscillators with $TR_1$ and $C_1$ forming the series-connected frequency-dependent arm with $TR_3$ and $C_3$ forming the parallel connected arm of the bridge. For oscillation to occur the closed-loop gain must be unity, the required amount of gain being provided by the inverting operational amplifier $IC_1$, the gain being determined by the ratio $R_2/R_1$. With this configuration the common-points of the frequency-determining resistors are connected to the virtual-earth inverting input of $IC_1$. This is a convenient arrangement for replacing these resistors with elements which have a resistance that can be controlled by a ground-referred voltage source. In the above circuit these elements take the form of a pair of matched c.m.o.s. transistors which have gate-source resistances that depend on the control voltage $V_e$.

Linearity of the voltage-to-frequency conversion characteristic is not particularly good over a wide range of frequencies but may be adequate for many purposes where only a restricted frequency range is required. Resistance of the f.e.t.s depends on their drain-source signal voltages as well as on the control voltage $V_e$ but this can be reduced, and the linearity of f.e.t. resistance-to-control voltage characteristic linearized, by using local feedback around the f.e.t.s as shown in Fig. 3, where $R_a, R_b, R_c$ and $R_d$ may be of the order of 1M$\Omega$.

If the closed-loop gain deviates from unity the amplitude of oscillation will vary with time, so to avoid extremely precise setting of gain it is initially set slightly high and then automatically controlled the a.g.c. being achieved with a thermistor in the above circuit. In addition to the use of local feedback on the f.e.t.s, these elements could be connected to form only part of the frequency-determining resistances with bulk of the values in the form of series-connected resistors which would tend to swamp out the non-linearities in the f.e.t. whilst restricting the range of control.

The f.e.t.s could be replaced by matched photoconductive resistors or by bipolar transistors which are switched on and off by current pulses to the bases, the mean collector-emitter resistance being controlled by the pulse repetition frequency.

A voltage-to-frequency converter using a pair of all-pass active networks is shown in Fig. 4. These networks, using $A_1$ and $A_2$, have a constant gain magnitude but a phase shift given by

$$\phi_1 = -2\tan^{-1}(\omega CR_3) - 180^\circ$$

and

$$\phi_2 = -2\tan^{-1}(\omega CR_1) - 180^\circ$$

respectively. With the $180^\circ$ phase shift through the a.g.c. amplifier $A_1$ the circuit will oscillate at a frequency $1/(2\pi C_1 R_1 R_2)$Hz, which shows that a voltage-to-frequency conversion may be obtained by making $R_1$ or $R_2$ or both voltage-dependent resistors, e.g. f.e.t.s. For a wide range of frequency variations $R_1$ could be a voltage-dependent resistor and $R_2$ a range-switching resistor. For $R = R_1 = R_2$ the outputs are generated with a controllable phase difference $\phi = (\phi_1 + \phi_2) = -2\tan^{-1}(\omega CR)$. Circuit of Fig. 5 uses two active integrators and two multipliers to produce a voltage-to-frequency converter having quadrature outputs that can have a very fast response to changes in $V_e$ provided a fast a.g.c. system is added to the basic circuit. Under this condition the circuit will oscillate at a frequency which allows the double integration to take place without changing the amplitude of the signal. Multiplier $M_2$ provides an output $V_1 = -V_e V_{out1}/10$ and $M_1$, given an inverted output, to maintain the loop phase shift, of $V_1 = -V_e V_{out2}/10$. With the 1/10 scaling factor, frequency of oscillation is $V_e/20mRC$. Multiplier $M_1$ could be replaced by an inverting operational amplifier.

**Further reading**

Multiphase voltage-to-frequency converter

Circuit description
This is a twin circuit based on R-C integration to provide the triangular waveform and level sensing to provide a square wave which operates an electronic switch controlling polarity applied to the integrator. Outputs X and Y are cross-connected giving control of electronic switches \( T_1 \) and \( T_2 \) respectively and triangular waveforms which are 90° out of phase. IC4 and IC5 provide high open-loop gain, and at low frequencies provide faster switching than comparators. \( V_{\text{bus}} \) is a positive-going ramp until \( T_1 \) changes state and this occurs at the instant of zero-crossing of \( V_{\text{bus}} \), which then switches IC4. \( V_{\text{bus}} \) then ramps down and changes the state of \( T_2 \) when a zero-crossing point is reached. The time taken to go from say a positive peak to zero level depends on the RC time constant and the value of \( V_{\text{control}} \). It should be noted that as no amplitude controls for the output are imposed, one or other of the integrators will reach saturation before the other output reaches its zero crossing point.

Circuit modifications
- Use a switched integrator rather than a switched gain amplifier. This makes IC1, IC2 redundant (Circard Set 3, No. 5). LM3900 quad package may be now arranged to provide the two outputs.
- Phase shift oscillator (above) provides three outputs with 60° phase relationship. \( IC_1-IC_4: \frac{1}{6} \times CD4049, \ R: 10k\Omega, \ C: 2700pF, \ frequency: 13kHz \)

As the c.m.o.s. gates are being used in their linear region, both the n- and p-type transistors will be conducting and hence power consumption will depend on the supply voltage. Typically the total current drain from the supply for the above network is \( V_{\text{DD}}-V_{\text{SS}} = 3V \) \( I_T = 0 \)
\( V_{\text{DD}}-V_{\text{SS}} = 10V \) \( I_T = 12mA \)
\( V_{\text{DD}}-V_{\text{SS}} = 15V \) \( I_T = 30mA \)

Frequency may be controlled by substituting voltage-dependent resistors for each \( R_1 \) and maintaining as close a ratio as possible between the \( R \) values. Frequency is approximately \( \frac{1}{3RC} \).

Note that with the CR values necessary for 60° phase shift at a specific frequency, the output of each buffer stage is attenuated by about one half and hence the minimum gain of each stage must be \( > 2 \).
- An alternative arrangement is shown above right, using similar c.m.o.s. buffer inverters. In this case the resistor ratio is critical and theoretically for infinite gain amplifiers \( R_1 = R_2 \) and a much better approximation to sinusoidal outputs is obtainable from each buffer, again phase shifted by 60°. Typical values \( R_1: \frac{1}{100k}\Omega, \ R_2: 33 \text{ to } 39k\Omega, \ C: 2700pF, \ V_{\text{DD}}-V_{\text{SS}} = 6V, \ frequency 1kHz \).

These buffers have gain-frequency responses which give higher gains for lower supply voltages. Typically 50dB at +3V up to 100Hz, and 30dB at +10V up to 10kHz. Hence since the gains are finite, then \( R_2 \) must be less than \( R_2/2 \). But at the lower values of the supply range 3 to 15V, some flexibility of this value between each \( R_2 \) is permitted. At higher levels the ratio is more critical, \( R_2 \) may be replaced by f.e.t.s employed as v.c.r. to obtain a restricted frequency range.

Further reading
AN-88 CMOS Linear Applications, National Semiconductor, p. 170.

Cross references
Set 11, card 6.
Set 8, card 1.
Monolithic voltage-to-frequency converters

**Circuit description**
An emitter-coupled astable multivibrator uses a single capacitor for timing. The circuit has high switching speed because charge storage effects are avoided by using the transistors in a non-saturated mode. This circuit is the basis of the above medium-scale integration package, where variable frequencies are obtained by charging the external capacitor at different rates via an internal voltage-controlled current source. The i.c. package contains two identical networks, but if only one is being used, it is essential that both ground connections (pins 8 & 9) are earthed to ensure earthing of the substrate and good isolation. The enable terminal (no. 11) must be grounded for continuous output at the output terminal. Output is disabled if this terminal is taken to logic high or open-circuited. Graphs opposite indicate linearity over a restricted range for each capacitor value, and waveform deteriorates at very low values of \( C \), and thus at high frequencies.

**Circuit modification**
- Emitter-coupled astable output swings are usually restricted. An additional output stage supplied via \( V_a \) permits the output swing to be approximately 0V up to \( V_a \) and hence t.t.I. compatibility is easily achieved, i.e. \( V_a \) and \( V_a \) need not be the same.
- Variable-capacitance diodes may provide a wider frequency range, depending on type (see over). Supply voltage 4.5 to 6.5V, frequency maintained constant.

---

**Components (circuit above)**
- Supply ±10V
- \( I_C \): SH74S124N, \( I_C \): LM301
- \( R_1 \), \( R_2 \) 10kΩ
- \( C_1 \), \( C_2 \) 1μF
- \( C_1 \), \( C_2 \) MV16408

\( I_C \) is connected as a non-inverting amplifier with a voltage gain of two, so that the biasing voltage in this case is twice the control voltage. This gain can be altered for appropriate voltage range.

A claimed frequency range of 2 to 20MHz using varactors MV1403 and MCI456 for \( I_C \) is documented in the referenced literature.

**Components (circuit right)**
- \( I_C \): LM566, SE/NE566

General-purpose voltage-controlled oscillator.
- \( C_T \): 4.7nF
- \( C_T \): 0.047μF
- \( R_T \): 4.7kΩ
- \( R_T \): 10kΩ

Maximum sweep rate 1MHz.

\( R_T \) and \( C_T \) are the frequency range determining components. For a fixed value of \( C_T \): 10:1 variation in frequency is possible via a variable input at \( V_{control} \) which should be within the range 3 to 5.5V for \( V_{ee} = ±6V \).

The above values provide for a maximum free-running frequency of about 10kHz for \( T_T \) off. For \( V_a = ±3V \), \( T_T \) is saturated, hence increasing timing capacitor 10 times, free-running frequency is then approximately 1kHz.

Control voltage measured between pins 8 and 5 should be in the range 0 to 0.25V.

(If this voltage divided by \( RC \) which defines capacitor charging current.) Frequency is

\[
\frac{2(V_{ee} - V_{control})}{R_T C_T \cdot V_{ee}}
\]

**Further reading**
-Klein, E. Medium-scale integration for instrumentation and control, Semiconductors (Motorola) vol. 2 no. 1 1971, p. 20.

Signetics: SE/NE566 function generator data sheet.

**Cross references**
- Set 17, card 3
- Set 8, card 9
Linearized voltage-to-frequency converter

Components
R 100kΩ, C 0.22μF
IC 741
Unijunction V-f converter—see over.

Performance
Graphs of f0 and f0 are shown in Figs. 2 and 3. Graph of V against f0, corresponding to open-loop v-f conversion, is shown in Fig. 2, with V1n against f0 shown in Fig. 3. Linearity achieved was better than 0.5%—clearly much better than the open-loop performance.

System description
If the loop gain of a closed-loop system is high then the effect of non-linearities in the forward path is much reduced. In this case we have a highly non-linear V to f0 converter and an integrator/error detector is then included to provide the feedback. In d.c. terms, the integrator can be regarded as having infinite gain since for finite input voltage the output voltage after infinite time is infinite, ignoring the effect of saturation. Alternatively: \[ AV = \frac{1}{RC} \int_{0}^{t} V_{1n} dt + \frac{1}{RC} \int_{0}^{t} 15dt \]

The steady-state condition of constant f0 can only occur when V is constant and this occurs when \( \Delta V \) is zero i.e. when the integral of the input signal and the integral of the feedback signal exactly cancel. Hence exact correspondence between \( V_{1n} \) and f0 can be expected if the integrator and feedback signal are "perfect". Immediate improvement in the system would be effected if an i.c. with much lower input current requirements were used e.g. 308. Further improvement would be obtained by the use of a low-loss capacitor. The c.m.o.s. monostable was included to give an output pulse train of well defined height and width and overall shape. A better f0 to f0 converter could have been used. It should be noted that the overall characteristics are now dictated by the feedback signal and the integrator so that forward path changes, causing changes in f0, will be completely cancelled, apart from transient effects. Changes in the shape of f0, e.g. impulse height and width, will however have an effect on f0, although not linearity.

System modification
Effectively, the combination of the monostable and integrator is an f0 to v converter. The system could therefore be changed to that shown in Fig. 4. K would be chosen to be sufficiently high such that the linearity of the overall system is equivalent to that of the f0 to v converter. This is only satisfactory if the shape of the f0 pulses is satisfactory.

Element description
The circuit of Fig. 5 shows the detail of the monostable v to f converter (card 1) used. The opto-elements are included to show that their inherent isolating properties can be used not least to produce a very non-linear v to f0 characteristic. This is because D2 requires approximately 1.6V to conduct and there is non-linearity in the device current transfer ratio.

Resistor R5 is included to protect the transistor and R4 is large to produce a sufficiently large pulse to trigger the monostable. Resistor R3 may be reduced to allow much lower input voltages to be used. The limit is set by the opto-diode input current. Any opto-isolator may be used e.g. TIL112.

Components
R1 2.2kΩ, R2 1kΩ, R3 100Ω
R4 10kΩ
Opto-isolators 4330
U.j.t. 2N2664 V6 15V C 0.01μF

Circuit of Fig. 6 is the c.m.o.s. monostable used. It is identical in format to that described in set 18, card 8 but includes an extra diode to allow the capacitor to discharge closer to zero volts to improve linearity.

Components
R 100kΩ
C 2.2nF
D 1N914
IC CD4013E
wireless world  circard

Set 21: V to f converters—8

Linear voltage-to-frequency converters

![Circuit diagram]

Circuit description

The circuit comprises an integrator whose output ramps toward positive and negative target values defined by diodes D2 and D3 i.e. the potential at the non-inverting input of comparator IC2 is \( V_{OH} + V_{OC} \) (or \( V_{OL} \)) about \( \pm 9V \). When the transistor is off (\( V_{OC} \) negative), capacitor current is

\[
I = \frac{1 - \frac{R_3}{R_2}}{R_3 + R_2} \quad (1)
\]

When \( T_r \) conducts, \( I \) is

\[
I = -V_{OC} \left( \frac{R_3}{R_2 + R_2} \right) \quad (2)
\]

For equal slopes at the triangular output, \( V_{OH} \), the current magnitudes are equal, provided

\[
R_2 = 1 + \frac{R_3}{R_2}
\]

If \( V_{OC} \) is positive, \( T_r \) is on, and integrator output rises towards \( +9V \) at which level the comparator IC2 switches over to make \( V_{OC} \) negative, bringing \( T_r \) out of conduction. \( C_2 \) charges according to the first equation, and integrator output ramps towards \( -9V \), when comparator again changes state.

Components \( C_2, R_2, R_3 \) form a phase-advance network to compensate for the switching delays of IC2 and \( T_r \) at the higher frequencies. The inverting mode of \( T_r \) provides a very low collector-emitter drop (few millivolts), i.e. the effect on the second equation is neglected. Linearity is better than 0.5% over the range of control voltage, 0.1V to 8V, based on deviation from 6V value.

Component changes

This slew rate is typically 10V/\( \mu \)s. If 741 used, slew rate (0.5V/\( \mu \)s) restricts higher frequency to which linearity is maintained (see graph).

Range of \( C_2 \): Typically 47 to 200pF. Frequency variation shown on graphs. Frequency is power supply dependent, hence need for good stability of supply.

Vary mark/space ratio of output at \( V_{OH} \) by \( R_3/R_2 \) ratio change; this also modifies frequency.

Range of \( R_3, R_2 \) IS to 68k\( \Omega \)

Circuit modifications

- A variable output voltage is obtainable via the circuit shown in Fig. 1. Comparator hysteresis can be changed by varying the fraction fed back via a potentiometer RV1. This will control the output amplitude. The triangular output is shaped by the circuit of Fig. 2. Potentiometer RV3 is adjusted for a minimum even-harmonic content, to provide an approximate sinusoidal waveform at \( V_{OUT} \).

- The field-effect transistors of Fig. 3 provide a similar switching action to \( T_r \) in first circuit to provide the integrator capacitor current charging paths. IC5 as an integrator employs a speed-up network of 150pF in series with 10M\( \Omega \) resistor.

Transistors \( T_r \) and \( T_s \) controlled by square-wave output from the Schmitt circuit of IC2. When \( T_r \) is on, \( T_s \) is off and \( C_2 \) charges via \( T_r \) and 10k\( \Omega \) resistor. With \( T_r \) off, and \( T_s \) on, current reverses through the capacitor with magnitude defined by \( V_{control}/2R_2 \). RV3 should be adjusted to provide a symmetrical square-wave output when \( V_{control} \) is 5mV. Input control voltage range: 5mV up to 5V.

Frequency range 10Hz to 10kHz.

Further reading

Wright, M.J. Linear voltage to frequency converter, Electronic Engineering, July 1973.


Linear Integrated Circuits, National Semiconductor, 1972, p. 255.

Cross references

Set 3, cards 1, 5, 11

Set 17, card 3
Diode-pump voltage-to-frequency converter

![Diode-pump circuit diagram]

**Components**
- Supplies ±15V
- IC 748C
- R₁ 12kΩ, R₃ 3.9kΩ
- R₈ 10kΩ, R₄ 4.7kΩ
- C₁ 4.7μF, C₃ 1nF
- C₉ 33μF, C₄ 56pF
- C₅ 500pF
- D₁ to D₄ 1N914

**Performance**
- Vᵢᵣ: 0 to +4.00V
- Output pulse train: pulse width about 20μs swinging from +14V to −14V with a maximum frequency of around 14kHz, corresponding to a mark-space ratio approaching 3:1.
- Linearity better than 0.3% over two decades.

**Circuit description**

Elements R₁, R₈, D₁, D₄ and C₁ are not basic to the action of this circuit and will be ignored initially. Suppose the i.c. output is sitting at +14V. Then C₂ will have been charged to this level via D₃.

However as C₂ charges via R₈ under the influence of Vᵢᵣ, the negative terminal of the i.c. eventually reaches 0V and the amplifier output swings negative. The network comprising C₆, R₄ and C₄ provides sufficient positive feedback to make this swing very rapid—hence the use of a high speed op-amp. Capacitor C₇ then deposits its charge via D₄ into C₁ in a diode pump fashion thereby lowering the voltage across C₂. However the positive feedback network consists of elements with a short time constant and the voltage on the positive terminal quickly becomes less negative than the negative terminal voltage and so the amplifier voltage swings back to +14V.

In the −14V period the circuit is acting rather like a monostable, the delay being fixed by the C₆, R₄, C₅ network and by the R₈, C₃ network. Because there is again positive feedback the rising edge will be equally sharp but the period will be difficult to define accurately, partly because of the complexity of the CR networks and partly because two voltages both going in the same direction (positive) are being compared.

This, however, is not serious since the pulse width does not affect the amount of charge on C₂, and it is this charge which is being balanced by the current in the input network. The maximum frequency we obtained was close to the limit of the op-amp but the mark-space ratio could have been made even lower if required by reducing C₃, R₉ or lengthening the time constant of C₆, R₄, C₅. The network comprising R₁, R₈, C₉ and D₄ prevents the device from locking into a saturated condition by too large an input voltage (positive). Diode D₅ prevents the negative input terminal being overdriven by a negative input voltage.

**Circuit modifications**

- A high-speed comparator would be preferable to an op-amp which was used in our experiments.
- The pulse width does not theoretically affect the result but the pulse height does. A c.m.o.s. buffer amplifier could be included to give a well defined output pulse height—see reference 2.

- An alternative approach to the pulse height problem is to use internal clamping of the output level—see references 3.

**References**

2. Set 3 (waveform generators) card 11.
   Set 2, card 1.
Differential input voltage-to-frequency converter

Circuit description
The above circuit is of a form published by Woodward but with what appear to us as corrections, although we have to admit to not achieving the performance claimed in his article, viz linearity better than 0.05% from 10Hz to 10kHz. The results we achieved are shown roughly in Fig. 2, measured linearity being 0.15% over the two decades, 100Hz to 10kHz.

Pin c of IC3 is the R (reset) terminal and its action is not necessary in a brief explanation. Pins a and b are the trigger and threshold terminals of the i.e. When the C3 capacitor voltage goes below the trigger potential, \( V_s/3 \), the output swings high, and when the voltage exceeds the threshold voltage, \( 2V_s/3 \), the output swings low—see waveforms of Fig. 3.

The basic principle is that of charge dispensing in which a current proportional to a voltage is balanced by the periodic charging of a capacitor to a precise voltage. In this case, the current through the f.e.t. is fixed by the input voltage at \( V_in/R_in \). This current flows for time \( T \) as a result of the charging of \( C_3 \) from \( V_s/3 \) to \( 2V_s/3 \). Thus

\[
\frac{V_in}{R_in} = \frac{C_3V_s}{3}
\]

and

\[
f_0 = \frac{3V_in}{R_inC_3vF}
\]

This expression is valid so long as \( T \) is large compared with the pulse width.
When the output goes high \( C_3 \) charges via \( R_3 \) and \( D_4 \) from \( V_s/3 \) toward \( V_s \). During this period \( D_3 \) is reverse biased and at the same time \( C_1 \) is providing some current to the f.e.t. When \( C_4 \) reaches \( 2V_s/3 \) the output goes low, \( D_3 \) conducts, \( C_1 \) and \( C_4 \) share the charge on \( C_2 \) and the parallel combination discharges linearly through the f.e.t. Diode \( D_4 \) is reverse biased in this period.

The charging of the charge between \( C_1 \) and \( C_4 \) causes the sharp drop in the \( C_2 \) voltage when \( 2V_s/3 \) is reached. The discharge is linear because the f.e.t. current is fixed by the input voltage. The results obtained required adjusting of the op-amp offset voltage to zero. Common-mode rejection ratio is independent of input resistor match and is dictated by the op-amp used. However, common-mode voltage should not exceed \( \pm 2V \).

Component changes
The charging time depends on \( C_1R_2 \) and should be short without \( R_2 \) being so low as to overload IC5. This is not difficult to achieve since if it is the open collector terminal which is used to charge \( C_2 \), capacitor \( C_2 \) serves to cut off \( D_3 \) whilst \( C_2 \) is charging, so its value is not critical. Generally speaking though it should be less than \( C_4 \) to minimize the drop in \( C_3 \) voltage when \( D_3 \) starts conducting again, thereby keeping the slope of the downwards ramp as large as possible and clearly defining the time at which the voltage drops below \( V_s/3 \). Actually, \( C_1 \) and \( D_4 \) can be removed altogether without complete failure of the circuit, although linearity and output pulse shape are affected.
Diodes \( D_1 \) and \( D_4 \) can be any general-purpose diodes unless very high speed operation is required.

Reducing the values of the op-amp input resistors and choosing a suitable op-amp will allow values of \( V_in \) in the millivolt region to be used to give the same output frequencies.

Circuit modifications
Any circuit which will successfully draw constant current from the junction of \( C_1 \) and \( D_1 \) will produce the same result and such a circuit is shown in Fig. 4. The photodiode current is proportional to light intensity so an intensity-to-frequency converter would be produced by this arrangement. The differential input aspect is lost, however, unless one puts a second photodiode, connected the opposite way round, across the one shown.

Reference
Most of the circuits described have been aimed at linearizing the v-f conversion, as in measurement of modulation systems. Sometimes it is required to have a converter in which the v-f conversion is highly non-linear with the frequency following, for example, an exponential or logarithmic function or sharply changing at some threshold voltage. The circuit indicates a simple way of changing the frequency over a claimed five-decade range.

A linear voltage variation is applied to the base-emitter junction of a transistor to charge a capacitor. The capacitor forms part of an astable circuit based on the well-known 555 timer, with a sawtooth waveform generated across the capacitor swinging between V/3 and 2V/3. The reference indicates additional components to set the frequency to zero for V=0 and for buffering the output waveform. More generally a linear v-f converter is combined with a non-linear amplifier whose non-linearity is predictable, rather than introducing non-linearity into the conversion process itself.

Reference

The new generation of linear integrated circuits includes complete v-f modules that will compete with the hybrid and modular versions for many applications. One such monolithic device RC4151 is in line of succession to the 555. It includes a monostable comparator and output stage, but adds a switched current generator. It can be used without additional active devices, but for improved linearity is combined with an op-amp to form a charge-balancing system. The input current to the summing junction is balanced by the constant-height constant-width current pulses returned by the monostable ensuring a linear relationship. A zero-offset voltage fed to the non-inverting terminal ensures that f→0 as V→0. Resistor R, sets the scale-factor for 0–10kHz corresponding to 0–10V.

Reference
Cate, T. IC V-f converters readily handle other functions such as f-V, A-D, EDN, Jan. 5, 1977, pp. 82–6.

The same article shows amongst other applications a linear thermometer, with some similarity to the band-gap reference circuits of set 23. The temperature-sensing pair are forced to operate at a 10:1 ratio of collector currents giving a ΔP_ref that is a controlled linear function of temperature. The precise scaling factor is set by the 5kΩ resistor. The amplifier requires to be a true differential input amplifier of controlled gain. Again the overall function is split into two parts: a linear v-f converter, and a separate circuit to provide the linear or non-linear response. It would be proper to describe this as a T-V-f converter.
Set 22: Amplitude modulators

The term amplitude modulation here includes modulation with either one or two sidebands, with or without a carrier present, by one of four methods—multiplication, switching, non-linearity, or direct tuned-circuit modulation in a class C amplifier. The circuits using 741s are limited to use with carrier frequencies of a few tens of kilohertz, but two other i.c. designs—the modulated crystal oscillator of page 27, the “micropower” circuit of page 32 and those of page 24—operate with carriers of the order of megahertz. And examples of v.h.f. modulators are given on page 33.

The i.c. modulator of page 24 can double as a with-carrier or suppressed-carrier circuit, and uses a biased gating-control input for the modulation. Balanced i.c. modulators appear in place of circuit modifications on this page (see also page 31).

Operating conditions for the lower circuit on card 7, originally omitted, have been added and further reading for the bridge modulator added.

Background article 22
IC package modulators 24
Linear amplitude modulator 25
Modulator using precision rectifiers 26
Modulated crystal oscillator 27
Diode bridge modulators 28
Single-sideband generation 29
FET modulators 30
Long-tailed pair modulators 31
Micropower amplitude modulator 32
Direct tuned-circuit modulator 33
Update circuits 34
Amplitude modulators

If the amplitude of a high-frequency sinusoidal carrier, \( c(t) = A \cos \omega_0 t \) is made to vary in sympathy with the instantaneous value of a low-frequency signal \( x(t) \) an amplitude-modulated signal is generated which has a spectrum concentrated in the vicinity of the unmodulated carrier frequency, \( f_0 \). The effect is to shift, or frequency-translate, the spectrum of the modulating signal to produce a pair of sidebands symmetrically disposed with respect to \( f_0 \) as shown in Fig. 1. The resulting wave may be described by: \( y(t) = [A + x(t)] \cos \omega_0 t \), so if, for example, \( x(t) \) is a pure tone modulating signal represented by \( x(t) = A \cos \omega_0 t \) the a.m. output becomes \( y(t) = [A + A \cos \omega_0 t] \cos \omega_0 t \) which may be written as \( y(t) = A [1 + m \cos \omega_0 t] \cos \omega_0 t \) where \( m = A / A \) is the modulation index, or modulation depth, and has a value \( \leq 1 \) if over-modulation is to be avoided.

The amplitude modulated waveform is shown in Fig. 2, and if this is displayed on an oscilloscope the modulation index may be found from \( m = (B - C)/(B + C) \). As well as measuring the modulation index, the oscilloscope may be used to examine the linearity of the modulation process if it has an X-Y facility. If the amplitude modulated wave is applied to the Y-amplifier and the low-frequency modulating signal applied to the X-amplifier a Lissajous figure of \( y(t)/x(t) \) is obtained as shown in Fig. 3.

The above process is what is generally accepted as understood when referring to a.m. However a family of processes may together be considered as amplitude modulation techniques which include:

- a pair of sidebands with carrier (a.m.)
- a pair of sidebands without carrier (d.s.b. or d.s.b.s.c.) or with diminished carrier (d.s.b.d.c.)
- an upper or lower sideband without carrier (s.s.b.) or with diminished carrier (s.s.b.d.c.)
- a pair of single sidebands with independent modulation (s.s.b.)
- one sideband, carrier and a vestige of the other sideband (v.s.b.)

In general, the above systems depend in some way on the use of four basic methods of producing amplitude modulation:

- analogue multiplication
- chopper modulation
- non-linear-device modulation
- direct tuned-circuit modulation

Except for the last method listed, modulation is normally performed at low power levels and the required output power obtained by class-B amplification of the modulated signal.

Analogical modulation, or multiplication, is obtained by applying the modulating signal and the carrier to a circuit providing an output which is a function of the product of its inputs. Output from the multiplier or balanced modulator is ideally a d.s.b.s.c. signal. This arrangement is often convenient for producing an s.s.b.s.c. signal by removing the unwanted sideband and any residual carrier by means of band-pass sideband filter.

Many multipliers or balanced modulators are available in the form of purpose-designed integrated circuits for operation at carrier frequencies of at least 100MHz. Depending on the nature of the modulating signal, the carrier frequency and the required degree of unwanted-sideband and carrier suppression, the filter can be realized using L-C networks, quartz crystal lattice networks, ceramic disc resonators or mechanical filters. If the same signal is applied to both inputs of a multiplier it acts as a squarer and it, or any other square-law device, may be used to produce an a.m. output as shown in Fig. 4 if \( v_1(t) = A + x(t) \) and \( v_2(t) = V \cos \omega_0 t \).

Chopper modulation is obtained by chopping the modulating signal at the carrier rate, using either a sinusoidal or a square-wave carrier, and then passing the resulting wave through a band-pass filter centred on the carrier frequency.
The bandpass filter will normally remove the component at the modulating frequency as well as the sidebands centred on the harmonics of the carrier frequency. To ease the requirements of the band-pass filter a balanced chopper modulator removes the low-frequency modulating signal component. The carrier-driven switches are normally realized using diode bridges or field-effect transistors.

Modulation using a non-linear device is achieved by adding the modulating- and carrier-frequency components and then passing the resultant through a bandpass filter centred on the carrier frequency to extract the a.m. signal. The non-linear device should have non-linearity not exceeding second-order and the highest significant modulation frequency should not exceed one-third of the carrier frequency.

Direct tuned-circuit modulation is achieved by controlling the voltage across a parallel-tuned circuit, tuned to the carrier frequency, by means of the modulating signal and pulsing the tuned circuit at the carrier rate with a highpower, class-C amplified carrier pulse. If modulating frequency is too high its rate of increase can be such as to cause the envelope of the a.m. wave to become distorted due to the failure to follow the modulation.

The modulation techniques discussed above which use band-pass filters must provide a filter bandwidth suited to the transmission of the desired signal whilst rejecting all unwanted components. For a.m. and d.s.b. this bandwidth must be twice the highest modulating frequency and for s.s.b. it must be equal to the bandwidth of the modulating signal. In virtually all these cases the sharp cut-off required from the bandpass filter is only obtainable if the centre frequency of the filter is relatively low. Normally the filtration is achieved in the region of 50Hz to about 1MHz and the resulting modulated wave heterodyned, or frequency translated, to the required carrier frequency for transmission.

Another way is the phasing method of generating an s.s.b. signal which avoids the problems associated with filter design, but replaces them with the problem of designing a pair of networks (A and B) which are required to maintain a constant 90° phase difference between their outputs whilst their output amplitudes are held constant over the bandwidth of the modulating signal. Selection of either sideband is achieved by reversing the output from one of the balanced modulators or by reversing the phase of either the carrier or the modulation to one balanced modulator. Because of the relative ease of inverting an audio signal, the modulating signal reversal is normally the simplest to accomplish in practice.
I.C. package modulators

Typical performance
Supplies ±10V, 10mA
IC1 MC1445L
R1 47Ω
R2 4.7kΩ, R3 220Ω
C1, C2 100nF

Amplitude modulator
V0 = 2V d.c.
Vin1 (carrier) 130mV pk-pk
f0 = 1MHz
Vin2 (modulation) 1.3V pk-pk
f0 = 10kHz, to produce maximum useful modulation depth of ≈78%.

Vin1 C1
Vin2
C2
R2
R3
R1
Vout

Vout (pin 1 or 7) 800mV pk-pk unmodulated, see waveform opposite.

Balanced modulator
V0 = 2.5V d.c. to balance out carrier
Vin1 (carrier) 130mV pk-pk
f0 = 1MHz
Vin2 (modulation) 2.4V pk-pk (max)
f0 = 10kHz
Vout (pin 1 or 7) see waveform opposite.

Circuit description
Many integrated circuit packages are available either in the form of purpose-designed modulators for producing a.m. or d.s.b. outputs or in the forms which can be readily adapted to these applications. An example of the latter type is the gate-controlled, two-channel-input wideband amplifier shown. This integrated circuit consists of a pair of differential-input amplifiers having a constant current switched between them under the control of a gating signal which cuts off one amplifier when the other is conducting. The output from each of these amplifiers is available via low-output-

impedance Darlington emitter followers. Although the gating signal would normally be at t.t.l.-compatible logic levels, the characteristics of the gate circuit allows the i.c. to be used as an amplitude modulator

\[ V_{in1} \times 1000 \times V_{in2} \]

The resulting balanced modulator is as shown, but with pin 5 earthed and the junction of R2 and C1 taken to pins 6 and 3. If the carrier has sufficient amplitude to switch these channels completely off and on, the modulating signal is switched between the channels at the carrier frequency, which is equivalent to multiplying the modulating signal by a switching function—the required condition for producing a pair of side-frequencies and suppressing the carrier. If a reduced-amplitude carrier is required, this can be produced by slightly changing the d.c. bias applied to the gate terminal by means of R6.

Component changes
Useful range of supply ±4 to 12V
Maximum useful carrier input ≈280mV pk-pk producing unmodulated carrier output of ≈3.3V pk-pk
f0(max) ≈75MHz
Maximum load current ≈25mA.
Examples of integrated circuits purpose-designed as balanced modulators are the MC1596G and the SL640C. These packages are essentially intended to replace diode-bridge or ring modulators with transistor double-balanced modulators to overcome the disadvantages of the former type of less than unity gain the need for a high level signal at one input and the need to use up to three transformers. The inherently good matching of the monolithic transistors ensures that excellent carrier suppression is obtained with little need for balancing by external components when the devices are used as double-sideband suppressed-carrier generators.

An arrangement of the SL640C for this purpose is shown
Typically, \( V = \pm 6V \), R1, R4 10kΩ, R5, R6 330kΩ, C1, C2 and C4 should have low reactance compared with the source and output resistance, except for high frequency applications (i.e. f0 approaching 75MHz) where the modulating source resistance should be low and C4 of comparable reactance C5 is a base-decoupling capacitor and must have a very low reactance at all frequencies used to minimize carrier and modulation feed-through. Resistors R1 and R4 are adjusted to minimize modulation and carrier leakage respectively.

The circuit below shows the MC1596G used as an amplitude modulator.

Typically \( V = \pm 8V \), R4 47Ω
R5, R6, R8, R9, R1 1kΩ
R7 470Ω, R8 6.8kΩ, R9, R10 3.9kΩ, C1 1μF.

Further reading

Cross reference
Set 21, card 2.
Linear amplitude modulator

Typical performance
Supplies ±15V ±7.5mA
-9.3mA, $V_{BB} \pm 5V$ 0.75mA
$A_1$ to $A_4$ 741
$R_1$, $R_2$, $R_7$, $R_8$, $R_{11}$, $R_{12}$ 10kΩ
$R_3$ 100kΩ, $R_4$ 33kΩ
$R_5$, $R_6$ 4.7kΩ, $R_9$, $R_{10}$ 1.5kΩ
$R_{13}$, $R_{14}$, $R_{15}$ 22kΩ, $R_{16}$ 39kΩ
$T_1$, $BC125$, $T_2$, $BC126$
$V_x = -5.5V$

$v_{in1}$ (carrier) 8V pk-pk square wave at $f_c$ 10kHz
$v_{in2}$ (modulation) 1.2V pk-pk sine wave at $f_m$ 1kHz to produce a.m. output with 100% modulation (see graph right) $v_{out}$ see waveforms opposite for 100% modulation.

Circuit description
The modulating signal ($v_{in2}$) is applied via $R_4$ to the inverting, summing operational amplifier $A_1$ and receives a gain of $-R_4/R_3$. Although this input is bipolar in nature the output from $A_1$ is not permitted to go more negative than 0V due to the presence of a d.c. bias obtained from the $V$ rail via $R_1$ ($V_T$) which receives an inverting “gain” of $R_3/R_4$.

This composite, positive signal is applied over separate paths to the inverting input of $A_2$ (via $R_7$ and $R_8$) and to the non-inverting input of $A_3$ via $R_9$ and $R_10$. The junctions of these pairs of resistors are connected to ground through $T_1$ and $T_2$ when these “chopper” transistors are switched on by the square-wave carrier ($v_{in1}$).

In the absence of a carrier input, $T_1$ is held off by the reverse bias on its base from the $V_{BB}$ supply via $R_4$ and $T_2$ is held in the off state by the reverse base bias from the $V_{BB}$ rail through $R_{16}$. With $R_9 \approx 3R_7$ and $R_{10} \approx 3R_6$ a square-wave carrier having a peak value slightly less than $V_{BB}$ is sufficient to overcome the reverse base voltages in the transistors and drive them hard into conduction. On positive half-cycles of the carrier, $T_3$ remains off and $T_1$ is switched on causing the junction of $R_7$ and $R_11$ to fall to within $V_{Clamp}$ of ground, effectively removing the modulation input to $A_4$. On the following negative half-cycles of the carrier, $T_2$ is switched off and $T_3$ switches on taking the junction of $R_8$ and $R_9$ to within $V_{Clamp}$ of ground, effectively removing the modulation input to $A_3$. Thus, the signals applied to $A_3$ and $A_4$ are in the form of the modulating signal which has been chopped at the carrier rate. As the inverting input of $A_3$ is a virtual earth and $R_7 = R_9$ the signal applied to $A_4$ is effectively half the amplitude at the output of $A_1$. Hence, the output from $A_3$ is an inverted form of the signal at $T_1$ emitter which receives a gain of $R_{13}/R_1$ and by making this gain 2 the output from $A_3$ has the amplitude of that at $A_2$ output. $A_4$ is connected as a unity gain follower so the signal applied to its non-inverting input is fed to a high-impedance point. Therefore, although $T_3$ chops the modulating signal at the carrier rate the full peak-to-peak $A_1$ output is applied to $A_3$ and this chopped signal appears at the follower’s output. $A_3$ and $A_4$ therefore provide equal-amplitude anti-phase chopped output signals. These two outputs are applied through equal resistors ($R_{14}$ and $R_{15}$) to the inverting, summing amplifier $A_4$ which, with component values shown, provides a gain of magnitude 1.77 to produce a composite output signal which is the linear sum of its inputs. The output waveform will contain the original carrier frequency and its harmonics with sets of upper and lower sidebands centred around each of the carrier components. For a pure amplitude-modulated wave the output waveform should be passed through a bandpass filter centred on the input carrier frequency and having a bandwidth sufficient to accommodate the sidebands of the highest modulating frequency.

As shown left, modulation depth is a linear function of the modulating signal input voltage, 100% modulation being achieved when the peak value of the modulation at $A_1$ output is equal to the d.c. bias at that point.

With the low-cost operational amplifiers shown the circuit can function with carrier frequencies up to about 25kHz. Higher carrier frequencies can be used if operational amplifiers having a high gain-bandwidth product than the 741 are used, and in principle, the circuit should operate with carrier up to several MHz. With suitable adjustment of the input signal levels and bias voltages the circuit can work from supplies between about ±4 and ±18V. For the circuit as shown the maximum and minimum useful carrier-frequency inputs are approximately 11V pk-pk and 6.4V pk-pk respectively.

Further reading

Cross reference
Set 22, card 3.
Modulator using precision rectifiers

Circuit description
IC1 acts as inverter for the carrier signal. The lower frequency modulation signal $v_m$ is summed with the carrier and its inversion, via the absolute half-wave rectifier circuits of IC2 and IC4 respectively. When the summed input is positive, the output of IC3 tends toward a negative level due to inverter action and hence $D_2$ is forward biased. Therefore the negative peak outputs are clipped to a level approaching zero because $D_2$ is in the feedback loop. The output is characterized by $V_{op}$, that at $V_{op}$ being similar, but of course the carrier is inverted. Non-linearity of the rectifier impedances introduces some distortion which is evident in the troughs of the modulated output and very slightly distorted at the higher levels of modulated carrier, though not the peaks of the envelope.

Output filtering is unnecessary and hence drift of carrier-frequency offers no great problem.

Component changes
Maximum carrier amplitude to obtain 100% modulation 8V pk-pk ($v_m \approx 8V$ pk-pk).
Maximum carrier frequency 23kHz before peaks distort (measured at $f_m = 1kHz$ and $m = 1$).
Maximum $f_m$ at this $f_c$ to minimize phase errors about 4kHz; then minimum carrier amplitude is 8V.

Typical data
Supply ±10V
IC1 741
$R_{1-15}$, $R_{16}$ 10kΩ
$R_{17}$ 4.7kΩ
$R_{18}$, $R_{14}$ 3.3kΩ
$D_1-4$ 1N914
$V_{mod}$ 1V pk-pk at 1500Hz
$V_{carrier}$ 2V pk-pk at 10kHz

limited by slew rate and gain of the op-amp in turning off say diode $D_1$ and turning on diode $D_2$. This switching speed is increased by the circuit shown middle. Additional gain is added during the switching transition of the order of 250 up to 30kHz obtained with the addition of $T_{1} \rightarrow T_{4}$ circuitry. At the switching instant, $D_1$ and $D_2$ are off, thus opening the feedback loop, and do not shunt this additional network. When conduction recommences, one diode heavily conducts, shunts the high output impedance of this additional stage giving again an overall gain of near unity. Low-value resistors provide small time constants for stray capacitance.

Frequency response will be above that of op-amp when additional stage driven from supply currents of the i.c. This reduces peak-to-peak swing requirement of amplifier and should be within slew-rate limit at higher frequencies. Typical data
Small-signal bandwidth 30kHz to 300kHz
IC1 741
R 100Ω. Chosen to limit rated output current for a 1V swing at output. Other components as before.

Further reading
Graeme, J. Boost precision rectifier BW above that of op-amp used. EDN, July 5, 1974.

Cross references
Set 4, card 3
Set 22, cards 2, 5
Set 15, card 1
Modulated crystal oscillator

Components
- Crystal 1MHz
- $R_1$, $R_2$ 1kΩ
- $R_3$ 600Ω
- $R_4$ 100kΩ
- $C$ 27pF
- $V_2$ 6V
- IC CA3000
- C.r.o. probe used had impedance of 10MΩ in parallel with 10pF.

Performance
Graph shown of $v_o$ (not $v_n$) was obtained with d.c. values of $v_m$ and indicates a modulation sensitivity of 1.07V/V and a modulation depth of approximately 25% over the range shown. Range was limited by the fact that increasing $v_m$ beyond -700mV caused limiting on the negative peaks of $v_o$. Lower limit was very much lower than that shown but there is no point in going beyond a symmetrical condition.

With the c.r.o. probe on $v_o$, the modulation depth fell to 11% (due to the loading of the probe) and this was maintained from d.c. to approximately 2kHz without appreciable distortion. Higher frequencies caused phase distortion.

With $R_1$ set at 500Ω no carrier oscillations were obtained. With higher $R_2$, however, little effect was observed, e.g. $R_2=10kΩ$ produced a modulation depth of 10.5% although with approximately 12% increase in carrier amplitude.

Variation of $R_3$ in the range 1.5Ω to 1500Ω produced very little effect; thereafter limiting occurred.

Description
The CA3000 is a d.c. amplifier in a 10-pin T0-5 package. The schematic is shown above. Emitter follower inputs $T_{R_1}$ and $T_{R_2}$ provide high input impedance (0.2MΩ), the remainder of the circuit being conventional long-tailed pair (Tr3 and Tr4) differential amplifier design with constant-current tail (Tr2). With external connections as shown in the main diagram the circuit becomes a crystal oscillator with feedback to pin 1. These oscillations are modulated by $v_m$ which controls the tail current. Output at pin 10 contains the (carrier) oscillations plus harmonics modulated by $v_m$, plus $v_n$ itself, plus d.c. The high-pass filter consisting of $C$ and $R_1$ eliminates the d.c. and $v_m$, leaving the amplitude modulated signal.

Since the oscillator is a crystal oscillator the frequency of oscillation is extremely well defined so variations in other components, supply voltages etc., will produce very little frequency modulation.

Modifications
Due to the symmetry of the CA3000 one can reverse the roles of pins 10, 8 and pins 1, 6; no advantage or disadvantage accrues.

All the unwanted terms in $v_o$ (including carrier harmonics) can be removed by use of a suitable bandpass filter. Because the output impedance of the amplifier is high (8kΩ) a tuned L-C filter may be used as shown below in our case with a carrier of 1MHz and modulating signal of 2kHz.

A Q of 250 is permissible but would reduce the modulation depth by 0.707 at 2kHz. Since the modulation depth is inherently low, a lower Q would appear advisable and if possible one would be better with a more rectangular bandpass filter.

If one simply wants to remove the modulating signal from $v_o$, the arrangement shown below can, with suitable adjustment of $R$ simply cancel the offending term. We achieved this with a value of $R$ of approximately 15kΩ. This has the additional effect of reducing the carrier at $v_o$ by approximately 30%, but enabled one to increase the modulation depth to approximately 43%, $v_m$ being 6.8V pk-pk. $C$ and $R_4$ were retained for direct comparison but obviously do not help to give the max. obtainable.

Modulation depth of approximately 47% at $v_o$ was achieved by increasing the positive supply to 12V. Alteration of the negative supply had little effect. No change in carrier amplitude was observed with this increased supply. One cannot guarantee this performance since the device is being driven outside the manufacturer's recommendations. Presumably if the alterations of modification no. 1 were used it would be the negative supply which would require alteration.

References
RCA applications notes ICANS5030.
Card 8, this set.
Low-cost 2-stage circuit forms versatile a.m. oscillator. 100 Ideas for Design, Hayden, 1966.
Diode bridge modulators

**Typical performance**

- **D<sub>1</sub> to D<sub>4</sub>, PS101**
  - V<sub>in</sub> carrier 10V pk-pk
  - f<sub>in</sub> 10kHz from 600-Ω source.
  - V<sub>in</sub> modulation 6V pk-pk
  - f<sub>mod</sub> 200Hz from 600-Ω source.
  - V<sub>out</sub> see waveform below.

- **D<sub>5</sub> to D<sub>8</sub>, PS101, T<sub>n</sub>, T<sub>1</sub>, RS type T/T1, ratio 1:1**
  - V<sub>in</sub> carrier 1.2V pk-pk
  - f<sub>in</sub> 4kHz from 600-Ω source.
  - V<sub>in</sub> modulation 2V pk-pk
  - f<sub>mod</sub> 200Hz from 600-Ω source.
  - V<sub>out</sub> see waveform below.

**Component changes**

- **D<sub>1</sub> to D<sub>4</sub>** Any general purpose, discrete or monolithic silicon, germanium or Schottky types.

A square-wave carrier source may be used in either circuit together with an output filter.

A floating source for carrier in Cowan modulator (left) can be simulated from grounded-type using a transformer.

**Circuit descriptions and modifications**

Both modulators are widely used at low carrier frequencies. In the Cowan arrangement diode switching in the bridge is under the control of the carrier alone provided that its amplitude is much greater than that of the modulating signal. Assuming this condition exists, then during the half-cycles of the carrier when point C is positive with respect to point A, the diodes will be reverse-biased and they present a high impedance shunted across the path between the modulation source and the output. When the carrier goes through its other alternate half-cycles, point A is positive with respect to point C, the diodes become forward-biased and the bridge provides a low-impedance shunt path across the modulation source. The higher frequency carrier voltage therefore causes the diode bridge to act as a single-pole single-throw switch which passes the modulating signal to the output during one half-cycle of the carrier and attenuates the modulation during the other half-cycle. As the magnitude of the modulating signal increases the carrier controlled switching of the diodes becomes less perfect (see waveform and a ripple appears on the output waveform at the modulation frequency. This ripple is due to the larger-amplitude modulating signal causing some small amount of conduction on the diodes during their off state. When V<sub>in</sub> polarity makes point B positive with respect to point D a diode leakage path exists through D<sub>5</sub>, the carrier source and D<sub>6</sub>, and through D<sub>1</sub>, the carrier source and D<sub>4</sub>, when B becomes negative with respect to D. This modulator produces an output waveform containing the original modulating-frequency components and sets of upper and lower sidebands centred on the original carrier frequency and its harmonics, all of which are ideally suppressed. To remove all components except the sidebands around the original carrier frequency a band-pass filter must be incorporated at the output.

A simple method of achieving this filtration, at the same time isolating the output from the bridge and simulating the floating-source carrier by means of a transformer is shown top. In this arrangement R<sub>1</sub> should be about 10R<sub>2</sub> (1 + h<sub:auto</sub>) R<sub>4</sub> should be much greater than R<sub>6</sub>, and R<sub>4</sub> chosen to damp the output tuned circuit sufficiently to pass the desired sidebands.

The double-balanced bridge ring modulator obtained its name from its ability to suppress both the original modulating signal and the carrier from its output. Hence it is to be preferred to the Cowan modulator when the carrier frequency does not greatly exceed the highest modulating frequency. In the circuit shown, when point A is positive with respect to point B, D<sub>1</sub> and D<sub>4</sub> are forward-biased and D<sub>2</sub> and D<sub>3</sub> reverse-biased. When B becomes positive with respect to A, D<sub>3</sub> and D<sub>4</sub> are forward-biased with D<sub>2</sub> and D<sub>3</sub> reverse-biased. Hence the modulating signal will pass from T<sub>1</sub> to T<sub>4</sub> over two different paths during alternate half cycles of the carrier causing a 180° phase shift of the output after each carrier half-cycle. When wideband transformers are used the output waveform consists of sets of upper and lower sidebands centred on the original carrier frequency and its harmonics, all of which are, ideally, suppressed. The output waveform differs from the above due to the use of a.f. transformers with a 10-kHz carrier so that very little of the sidebands of harmonic carrier frequencies are present at the output due to transformer imperfections. Many other forms of bridge ring modulators exist, the basic form of one type using two diode bridges to simulate the effect of a reversing switch.

**Further reading**


**Cross reference**

Set 22, card 3.
Single sideband generation

Filter method
A single-sideband signal can be produced by feeding the carrier \( v_{in} \) and modulating signal \( v_{m} \) to a balanced modulator to produce a double-sideband suppressed-carrier output which is then passed through a bandpass filter to select either the upper or lower sideband as required. The degree of carrier suppression depends on the design of the balanced modulator and the rate of cut of the sideband filter, which must have a bandwidth equal to that of the baseband modulating signal. A number of different filter realizations may be used, their suitability depending on the carrier frequency at which the filtration is performed. The use of L-C ladder filters is normally restricted to carriers in the approximate range of 20kHz to about 100kHz due to the relatively low Q-factor values obtainable with low-cost inductors. The much higher Qs obtainable with quartz crystals allow the design of bandpass filters using a lattice structure at frequencies above about 500kHz. Ladder-type mechanical filters provide much higher Qs than L-C resonant circuits, which give them excellent selectivity characteristics in a useful carrier range of about 50kHz to 1MHz. Ceramic elements using the piezo-electric effect, but having lower Q values than quartz crystals, can be used in a ladder structure over a carrier range of about 250kHz to 1MHz. Whatever the nature of the bandpass filter the same filter could be used to select either the upper sideband or the lower sideband by shifting the carrier frequency to the appropriate edge of the filter response, assuming the filter to have a similar rate of cut at both edges. The balanced modulator could be replaced by an amplitude modulator in certain applications, the degree of carrier suppression depending on the filter attenuation characteristic. The unwanted sideband can be removed without the use of bandpass filters by means of phase shift techniques. The basic form of a phasing method s.s.b. generator is shown below. The carrier frequency is applied to balanced modulators A and B with a 90° phase shift introduced in one path. The modulating signal is also applied to both balanced modulators, to A directly and to B via a wideband 90° phase-shifting network. The output signals from the modulators, when combined, result in the suppression of one sideband. If the other sideband is required instead this can be achieved by reversing the phase of the carrier applied to one modulator, or by reversing the phase of the modulating signal to one modulator, or by reversing the output of one of the modulators. Of these methods the second is usually preferred due to the relative ease of inverting a.f. signals. In this method of s.s.b. generation, the modulating signals applied to both balanced modulators should ideally differ by 90° over their complete frequency range whilst retaining equal magnitudes. This is virtually impossible to achieve in a single network as shown over, so practical forms use a pair of networks to more closely approach the ideal requirements as shown below.

The number of different networks that could be used to realize the \( \pi \) and \( \beta \)-networks is almost limitless, but to meet the required conditions over the range of frequencies indicates the need to combine an all-pass characteristic with a non-uniform time delay as a function of frequency over the required frequency range, which results in a type of ladder structure. An example of such a realization is shown above. This configuration is capable of maintaining the phase difference at the outputs to within about \( \pm 1^\circ \) of the desired 90° phase difference over a frequency range of about 10:1. For the speech bandwidth of approximately 300Hz to 3kHz typical values are given below.

Supply +15V, \( T_1, T_2 \) general-purpose, reasonably well-matched silicon n-p-n transistors.
\( R_6, R_9, R_2, 680\Omega \)
\( R_4 15k\Omega, R_4 6.8k\Omega, R_5, R_{11} 1.75k\Omega, R_8, R_{12} 10k\Omega \)
\( R_6, R_{12} 4.02k\Omega, C_1 100nF \)
\( C_2 43.9nF, C_3 8.2nF, C_4 21nF \)
\( C_3 32.4nF, C_4 181nF, C_5 83.1nF \).

The required 90° phase shift between the carrier frequency inputs to the two balanced modulators can be achieved in a number of different ways, for example from a quadrature sinusoidal oscillator. A simple arrangement for a fixed carrier frequency using a parallel pair of L-R and C-R branches is shown right, the 90° phase shift occurring at the frequency where the inductive and capacitative reactances equal \( R_{14} \) and \( R_{13} \) respectively. For example with \( R_{13}, R_{14} 502 \)
\( C_1 8nF \) and \( L_1 20\mu H \) the carrier should be set to 397.8kHz with \( v_{in} \) derived from a 600-\( \Omega \) source.

Further reading
Dome, R. B. Wideband phase-shift networks,
Electronics, Dec. 1946, pp.112-5.
FET modulators

Typical data
IC: 741, Tr, 2N5457
Supply ±15V
R, 10kΩ
Vmod 1V pk-pk fmod 1kHz
Vcarrier 100mV pk-pk
fcarrier 10kHz
Vos 0.75V
Output at vo as shown top.
D.C. transfer function between input carrier and vo for varying VSG of f.e.t., provides information on linear regions.

Circuit description
This circuit uses an n-channel junction f.e.t. in its voltage-controlled resistance mode, and hence the gain of the inverter-amplifier will be dependent on the slope resistance of Tr1. The drain-source conductance gDS of Tr1 is fairly well defined by 

\[ g_{DS} = \frac{2I_{DSS}}{V_{DS}} \]

i.e., proportional to the product of the carrier and modulation signals. Note that point x is a virtual earth point and \( V_{	ext{carrier}} = V_{DS} \). This restricts the carrier to a maximum of 100mV pk-pk to limit distortion. Positive values of \( V_{mod} \) much greater than \( |V_{P}| + 0.7V \) will forward-bias the gate-source junction, hence this determines the maximum allowable modulating signal.

Component changes
R1, 10 to 20kΩ to provide increased output.
Carrier peaks can be equalised by biasing carrier with \( V_x \), say. For \( V_S = 29mV \), other parameters as before, output envelope is shown below.

Circuit modification
- Operational amplifier may be replaced by a single transistor in circuit shown (ref. 1).
- Output will contain a signal proportional to the carrier and modulating signal product which can be applied to a bandpass filter centred at fC. It is large enough to be an a.c. short-circuit for the carrier frequency. Is is chosen to make \( h_{ib} \) of the transistor small, given by \( h_{ib} = 26/I_{E\text{max}} \).
- This ensures that \( V_{carrier} \approx V_{DS} \).

Also, since \( I_E = g_{DS} V_{mod} \) and \( I_C = g_{ds} V_{carrier} \), then \( V_0 = V_{CE} - \frac{V_{CE}}{R_L} = g_{ds} R_L V_{carrier} \). This provides, an a.c. product of \( 2a_{RL} V_{DSS} V_{P} \) (Vcarrier) (Vmod). Similar limitations to levels apply in this circuit (a common base current gain).

- Figure (bottom) comprises a combination of a dual gate m.o.s.f.e.t. and inverting amplifier.

Tr, 40841, IC, SN72709 supply ±12V.
For double-sideband suppressed-carrier operation, the carrier is fed forward through R4.

If \( V_{mod} \gg V_{carrier} \), then gain \( V_{DS} \) is given by 

\[ R_{10} \frac{V_{mod}}{V_{P}} \]

i.e., \( V_{DS} = \frac{R_1}{R_2} V_{0} - \frac{R_2}{R_1} V_{mod} \).
Provided \( (R_1/R_2) V_{0} = (R_1/R_2) K_1 V_{0} \), then the above condition is obtained, i.e. \( V_{out} \) is proportional to the product of the two signals.
To obtain amplitude modulation the circuit is opened at X. Modulation depth must be limited to around 60%. At these levels of carrier and modulating signals where \( V_{mod} \) is no longer much greater than \( V_{P} \) the \( g_{m} \) of the f.e.t. is a function of both signals causing unwanted harmonics.
Modulation depth may be increased if output filters are employed. Note that other analogue multipliers may be used as amplitude modulators, but an important limitation will be their frequency responses.

Further reading

Cross reference
Set 22, card 1.
Long-tailed pair modulators

Typical performance
Supply ±12V, ±2.7mA
\( V_{1N} \) to \( V_{1N} \) 1/5 of CA3086 (pin 13 substrate connected to \(-V_{EE}\)
\( R_1, R_2 \) 4.7kΩ

\( V_{1N} \) carrier 100mV pk-pk
sinewave at \( f_e \) 1.61MHz to produce unmodulated carrier output from tuned circuit of 3.6V pk-pk.
\( V_{1N} \) modulation 25V pk-pk
(max) sinewave at \( f_m \) 1kHz to produce approximately 100% modulation depth output from tuned circuit.

\( V_{out} \) see waveform left.

Circuit description
Circuit shown above is an example of an amplitude modulator having one input channel which is linear and the other channel highly non-linear. Although the multiplication from such a circuit is far from ideal, amplitude modulation can be obtained by applying the carrier to the non-linear input channel, applying the modulating signal to the linear input channel and taking the output across a bandpass filter centred on the carrier frequency.

In this circuit the collector current of \( T_3 \) is a linear function of the common base current but a highly non-linear function of the voltage between the bases of \( T_1 \) and \( T_2 \) due to the voltage drive from the carrier source to \( T_3 \) base. Transistors \( T_2 \) and \( T_3 \) form a current mirror that acts as a current source for the differential pair \( T_1 \) and \( T_2 \). Quiescent tail current is determined by \( R_3 \) with the single-ended (grounded) modulation source \( V_{1N} \) set to zero. This quiescent current is then varied by the modulating signal. The collector current of \( T_3 \) thus contains the modulating signal as well as the carrier and its sidebands, together with carrier harmonics and their sidebands due to the non-linear relationship between the collector current and the carrier drive voltage between \( T_1 \) and \( T_2 \) bases.

To obtain an output amplitude-modulated wave the bandpass filter, in this case the parallel tuned circuit \( L_C R_4 \) must have a sufficiently high loaded circuited, the modulating signal is applied between the differential pair bases \( V_{1N} \) and the carrier applied to the base of the constant-current transistor \( T_4 \) via transformer \( T_5 \). The differential-output double-sideband suppressed-carrier signal between \( T_3 \) and \( T_5 \) collectors is converted to a single-ended output by the tuned transformer \( T_5 \) which suppresses the unwanted output components. Attention should be paid to careful printed circuit layout and screening to obtain the best performance. Typically the carrier suppression is around 25dB below the wanted double-sideband output when \( V_{1N} \) is adjusted to produce 16V pk-pk at pin 1 and \( V_{1N} \) adjusted to produce 31.5V pk-pk across the primary winding of \( T_3 \) at a frequency of 1.75MHz. Typical values: Supplies \( V_{CC} \) +6V, \( V_{EE} \) -6V, \( R_1, R_2, R_3 \) part of \( i_c \), \( R_4, R_5, R_6 \) 50Ω, \( C_1 \) 560 to

Further reading
Cross reference
Set 20, card 4
Micropower amplitude modulator

Performance

$V_a$ was set to 1.5V, $V_{1r}$ to zero and the carrier frequency adjusted to give maximum $V_d$; this occurred at about 460kHz. $V_{1r}$ was then adjusted to give maximum modulation depth, $m$, and $R_s$ was varied. It was found that maximum $m$ occurred at 1V pk-pk for $V_{1r}$ for all $R_s$. The resulting graph of $m$ versus $R_s$ is shown above. Higher values of $R_s$ produced non-linear modulation and lower values gave a rapidly diminishing value of $m$. Maximum carrier amplitude was 1.32V pk-pk with $R_s=15k\Omega$. The modulating frequency was 400Hz and linear modulation was maintained over the frequency range 10Hz to 1kHz typical. Maintaining $R_s$ at 6.8kΩ, the frequency of $V_{1r}$ at 400Hz, and altering the magnitude of $V_{1r}$ at all points to produce maximum $m$ produced the graph of $m$ versus $V_{1r}$, above right. The lower limit of 0.85V was chosen as being that of the end-of-life voltage of a dry cell. The corresponding range of $V_{1r}$ was 0.48 to 1.25V pk-pk. Power consumption is less than 500μW throughout the voltage range; considerably so at the lower end.

Circuit description

This circuit is due to Venkateswaulu & Sonde (see ref.) who claim slightly better results than we achieved. Consider first the circuit shown above. This is a gain-stabilized block for which $I_c/I_e \approx \exp(\lambda V_a)$ (Ref. 1) over a wide range of operating conditions ($\lambda$ having the usual connotation). To understand the circuit in a simplified manner assume that both base currents are negligible. Both transistors are governed by the same exponential relationship such that for a given $\Delta V_{be}$ (which must be the same for both transistors) the collector currents change by the same percentage. Hence, if $V_a$ sets different initial values of collector currents, which it will, a signal $V_a$ at $A$ will result in the same ratio of a.c. to d.c. in each transistor. As the direct current ratio is fixed by $V_a$ (at e.g. 10:1), the ratio of a.c. is also fixed and since the collector current of the diode connected transistor is approximately equal to the input current $I_1$, then the current gain $I_c/I_e$ both small signal and large signal is likewise fixed or stabilized. Clearly changes in $V_a$ cause changes in $I_e$ if $I_1$ is fed from a current source, i.e. $I_2$ can be modulated. It can be shown (see ref.) that $m = -\Delta I_e/I_e \approx \exp(\lambda \Delta V_a) - 1$.

The above block can be seen in the main diagram in the form of $T_{R1}$ and $T_{R2}$. $V_a$ is produced across $R_s$, $C_s$ simply acting as a short to carrier frequency signals. The section of the main diagram enclosed effectively take the anti-log. $T_{R3}$ is a cascaded transistor to improve the voltage gain characteristics and may be omitted at the expense of reduced $m$.

The tapped transformer is included to minimize the leading effect of $R_s$, again improving voltage gain characteristics. A straightforward L-C circuit could be used at the expense of reduced $m$.

Circuit modifications

Possible modifications in respect of $T_{R4}$ and the transformer have already been mentioned. In addition it appears possible to remove $R_t$, $R_s$ and $C$ altogether and simply current drive $T_{R3}$ and $T_{R4}$ by increasing $R_s$. Any linear to log converter may be used e.g., the circuit above right may be used although the micro power aspect is lost and a bias signal would be required with $V_t$.

Reference

Direct tuned-circuit modulator

Applications
In certain situations, a.m. is performed at low power levels, and power levels suitable for transmission are developed by power amplifiers. An example of such a circuit is shown over², with top. To preserve a wideband performance, a push-pull configuration of Tr₂, Tr₃ minimizes unwanted harmonic content. Typical performance data:

\[ V_{CC} = 12.5V \]
\[ \text{Peak envelope power: } 40W \]
\[ \text{Modulation: } 95\% \]
\[ \text{Carrier frequency: } 118 \text{ to } 136MHz \]
\[ \text{Carrier input power: } 5\text{mW} \]

A similar concept but at a low power is described in the circuit shown below, with bottom. Typical output 100mW depending on transmitter at a carrier frequency of 27MHz (US citizens band). Collectors are supplied push-pull, but the bases are paralleled, as distinct from above circuit.

Further reading
2 RCA application note AN-3749, 1968.
3 100 ideas for design, no. 4, Hayden 1964.
5 100 ideas for design, no. 3, Hayden 1964.

Circuit notes
- Tuned circuit Q in the range 30 to 50.
- Filter circuit (high pass) of \( C_6 R_6 \) provides useful demonstration technique only. Normally output coupled out via tapped-down transformer where L is the primary.
- \( R_6 \) value chosen empirically to minimize phase shift of positive and negative carrier peaks of waveform.
- Frequency range of modulating signal 1Hz to 20kHz, but some reduction in \( R_6 \) is necessary at the higher frequency to maintain symmetry of waveform.

Cross reference
Set 7, card 6.
The transconductance operational amplifier triple array CA 3060, when connected as a four-quadrant multiplier may be used as a modulator in the arrangement shown.

The output current from amplifier 1 and 2 is in the form

\[ I_{\text{out}} = g_m V_{\text{in}} \]

where \( g_m \) is the forward transconductance.

Hence \( I_{\text{out}} = -g_1 V_1 \) and

\[ I_{\text{out}} = +g_s V_s \]

\( V_{\text{out}} = (I_{\text{out}} + I_{\text{out}}) R_L = V_s R_L (g_m - g_s) \).

Because the \( g_m \) is almost proportional to bias current, \( I_B \), then

\[ I_{\text{out}} \approx \frac{V_s}{R_s} \]

where \( -V_s \) is the negative supply.

Therefore

\[ g_m \approx k_1 (V_k + V_s) \]

Because the bias current for \( A_1 \) depends on \( -V_s \), then

\[ g_m \approx k_2 (V_k + V_s) \]

This means that the output voltage is approximately \( 2k_2 R_s V_k V_s \) or

\[ V_{\text{out}} \approx V_k V_s \]

Fuller circuits are given in the reference, allowing for gain equalization and examples of modulated waveforms are shown.

Reference

RCA Integrated Circuits 1976, p. 171.

The analogue multiplier/divider is assumed to have a characteristic given by

\[ I_o = K I_1 I_2 I_3 \]

where \( I_1, I_2, I_3 \) are input currents, \( I_o \) is the output current and where \( K \) is a parameter dependent on temperature, device ageing etc. Such a circuit is suitable as a precision modulator, where a product term should be generated to an accuracy of around 0.1\%.

For this condition, the effects of \( K \) must be eliminated. The above configuration using negative feedback is shown to provide an a.c. gain proportional to a modulating signal, but independent of the constant \( K \).

Reference

Faulkner, E. A. *Electronics Letters*, 11th Nov. 1976, vol. 12,
Set 23: Reference circuits

First described by one of the authors a little over a decade ago, the ring-of-two reference has become almost a classic constant voltage reference, with many variants coming to light since (See also set 6, especially card 5). The article reminds readers that zener diodes are not the only reference component; any device with a slope or dynamic resistance sufficiently different from its static resistance can be used. And as well as presenting measured characteristics of four zener types, the set includes characteristics of other kinds of device—v.d.rs, conventional diodes and i.e.ds.

Some circuits shown may be familiar under their alternative names—the amplified diode for the technique of page 40, and a constant current diode for the f.e.t. of page 46. (This last-mentioned page has some changes incorporated from the original card.) And band-gap reference circuits are briefly explained in the article on page 36. (Owners of set 23 of Circards will have noticed that Figs 1 & 2 on page 39 were originally in error on card 2.)

Background article 36
Zener diode characteristics 38
Williams ring-of-two reference 39
Variable reference diodes 40
Bipolar references 41
Low-temperature-coefficient voltage reference 42
\( \mu A \text{ to mA and mV to V calibrator} \) 43
Non-zener device characteristics 44
Compensated reference circuits 45
Simple current reference 46
Monolithic reference 47
Up-date circuits 48
Some semiconductor devices have highly non-linear characteristics, in which the non-linearity is well-defined with predictable and small dependence on temperature. If a region of the characteristic is found for which the slope resistance is either very much greater than or very much less than the static resistance then the device can be used as a current or voltage reference respectively.

In Fig. 1 (a) there is an extended region over which the voltage varies little for large changes in current. Fig. 1 shows the dual characteristic with current being maintained constant against changes in bias voltage. The most commonly used device belonging to the former category is the zener diode, the reverse characteristic having a sharp breakdown region. There are two physical mechanisms that can control the reverse conduction of a p-n junction: zener breakdown and avalanche breakdown.

Zener breakdown is a field effect which dominates for heavily-doped narrow junctions, where even small p.d.s of three or four volts can provide a sufficiently intense field for the direct production of hole-electron pairs. The observed characteristics are that the current increases steadily as the operating region is approached, with a rounded knee, and with a temperature drift of about $-2mVK^{-1}$. To a first order the slope resistance of such diodes is inverse to the quiescent current.

At higher p.d.s, which can only exist with more lightly doped broader junctions where the zener effect is unable to limit the voltage, thermally generated holes and electrons are accelerated by the field. If the p.d. is large enough some will gain sufficient kinetic energy before colliding with other atoms, to produce further hole-electron pairs by collision. These in turn may generate further pairs and at a particular voltage there is a very sharp increase in current. Below breakdown the current is negligible, while above it the slope resistance is low. The voltage changes with temperature by less than $+0.1 \% \text{K}^{-1}$.

There is an intermediate doping level resulting in breakdown voltages between five and seven volts where both processes contribute significantly to the total current. The proportion is dependent both on the junction and on the current level, but it is possible for diodes between 5.5 and 6.5V to have negligible drift with temperature if biased correctly (lower currents for the higher voltage devices). An identical breakdown occurs in the base-emitter region of a transistor, and planar silicon transistors can be used as low-current zener diodes with good slope resistance. Breakdown voltage for the base-emitter junction is typically 6 to 10V, varying little for a given device. (Breakdown diodes are commonly described as zener diodes regardless of which physical process dominates.)

A simplified equivalent circuit for such a diode if biased into the low slope region is shown in Fig. 2. It consists of a constant e.m.f. in series with a small resistance. The resistance is assumed constant i.e. the characteristic is approximated to by the 'piecewise linear' graph shown. A circuit for a simple zener diode regulator is shown in Fig. 3.

Fig. 3. For changes in the supply voltage, load current etc the constant e.m.f. may be suppressed e.g. for an input voltage change $\Delta V_S$, the output voltage changes by

$$\frac{r R_L}{r + R_L} \Delta V_S$$

Since $r \ll R_L$ and $r \ll R_b$ are reasonable assumptions for a correctly designed circuit, the result simplifies to $\Delta V_S/\Delta V_Z \approx r/R_b$. Similarly the output resistance is $\approx r$.

Where the diode is used simply to produce a stable reference voltage, the load current can usually be arranged to be negligible, or at least reasonably constant. This leaves only supply voltage and temperature variations to be dealt with, though for high-stability designs ageing of the device may be equally important in bringing long-term drift. The two problems require different solutions.

The effect of supply voltage is determined by the circuit design, while temperature effects can be minimized by choosing the right diode. In some
cases the reference diode may have one or more forward-biased diodes added in series. By selecting as the reverse-biased diode, one with a breakdown voltage $>7V$, its positive drift can be balanced against the negative drift of the forward-biased diode(s). In the circuits of Figs 4 to 7 the single zener diode could be replaced with any such combination.

Though the diode has a low slope resistance its voltage stability will be ideal if fed from a constant current (Fig 4). A practical way of realizing this is to use a transistor with a fixed base potential and large emitter resistor. Any variation in supply voltage causes only a small variation in the transistor current and hence a still smaller change in the output voltage. An extension of the method, the ring-of-two reference (Fig. 5) has two zener diodes each controlling the constancy of current fed to the other. In this and other related circuits the variation in output voltage due to supply charges can be reduced to a few tens of microvolts - generally far lower than the variation due to temperature changes.

Most i.e. voltage reference/regulator circuits are based on similar principles while exploiting the matched-characteristics of adjacent transistors as in Fig. 6. The transistors $Tr_1$ and $Tr_2$ comprise a current mirror forcing the zener diode current to equal the current in $R_E$, which in turn is closely defined by the zener voltage. Both circuits contain a positive feedback loop, clamped by the zener, but they are essentially bistable in nature i.e. all devices could remain non-conducting indefinitely. To inhibit this condition the resistor $R_E$ (which can be very much greater than $R_2$) provides a starting current without significantly impairing the regulation.

Where the reference voltage is of an inconvenient value then a voltage amplifier may be added as in Fig. 7. Further advantages accrue from this approach. The current drawn from the diode is reduced to negligible proportions; the output current capability is increased without forcing the zener to operate at a high current; the output impedance is very low because of the shunt-derived negative feedback; the diode can be biased either from a separate supply, or from the amplifier output provided it is sufficiently greater than the zener voltage. This last method is of the same nature as those adopted in the circuits of Figs 5 and 6 viz that the zener voltage indirectly controls its own bias current. The stability can be extremely high, but the non-conducting state can also occur and may require a separate starting circuit.

Although zener diodes are the most common voltage reference units, they can be replaced by any element conforming to Fig. 2). Examples include forward-biased silicon diodes, asymmetric voltage dependent resistors (down to 1V), forward and reverse biased junctions of transistors. A useful circuit where high stability can be sacrificed in exchange for flexibility is the amplified diode circuit of Fig. 8. If a transistor is biased by a potential divider between collector and emitter then under certain constraints, the terminal p.d. approximates to that of $(n+1)$ diodes in series. The current in the potential divider must be much greater than the transistor base current, but not much in excess of the collector current. Note that $n$ need not be an integer and that by replacing the base-collector resistor with a variable control, we have a simple variable zener diode. The temperature drift is relatively large, about $+0.3\%K^{-1}$, but an overall stability of a few percent is readily achievable under laboratory conditions.

A completely different principle is embodied in the circuit of Fig. 9. While the $V_{be}$ of a transistor falls as the temperature rises, $\Delta V_{be}$ between two identical transistors operated at differ-
Zener diode characteristics

**Performance** (see graphs)
Constant current source: 0.20mA from commercial generator, ±0.05%.
Vz measured with 5-digit d.v.m.
D1: (a) BZX83C3V3
(b) BZX83C4V7
(c) BZX83C6V2
(d) BZX83C10.

**Description**
The zener diode exhibits three distinct regions: forward, leakage and breakdown. The forward-bias region is virtually identical with a normal diode, the forward-voltage temperature coefficient for a constant forward current being about −1.4 to −2.0mV/degC. Under reverse bias, up to the breakdown region, a leakage current exists which, although being temperature dependent, is normally less than 1μA over the whole temperature range. When the reverse bias reaches some definite value, which depends on the p-n junction doping levels, the diode current rapidly increases and the breakdown or zener region has been reached. This region is the one used to provide a d.c. reference voltage by supplying the device from a constant-current source, as shown above left. At the onset of breakdown the resistance of the zener diode will be high but as the current increases the number of breakdown sites increases and the resistance falls to a small value. The reverse-breakdown resistance is much larger than that of the zener diode. This would indicate the use of high-voltage supplies and high-voltage zener diodes operated at relatively low current levels. However, high voltages are not necessarily available and a compromise must normally be made between wasted volts and required stability of the reference voltage. Often the stability of the reference voltage against temperature changes is of prime importance and the choice of zener diode will depend on its temperature coefficient. Typical plots at room temperature are shown above centre right which indicate the use of diodes having a breakdown voltage of about 5V. Note that all these curves indicate that a positive temperature coefficient may be a distinct advantage as all the curves emerge at a temperature coefficient exceeding about +4mV/degC. Thus a temperature-stable reference may be produced by replacing the single zener diode with a temperature-compensated reference unit consisting of the reverse-biased zener diode in series with n forward-biased normal diodes which exhibit a negative temperature coefficient of about 2mV/degC.

**Further reading**

**Cross references**
Set 23, cards 2, 3, 4.
Williams ring-of-two reference

Typical data
Tr1, BC126, Tr2, BC125
Z1, Z2, 202Y88 (3.9V)
R1, R2, 680Ω

For test requirement, I was determined by measuring voltage across a standard resistance 50Ω ± 0.05% with a 5 digit voltmeter. Temperature levels obtained in a controlled oven.

Minimum V_T ≈ 10V.

Circuit description
This circuit may be used to supply a constant current to a high capability reference diode, which is itself used as the voltage reference source. If it is assumed that diode Z2 provides a constant voltage at the base of transistor Tr1, then this forces a constant current to flow through the emitter resistor R2. For reasonably high gain transistors, the collector-current will almost equal the emitter current, and hence the current through Z1 will be constant. But this diode will maintain a constant potential at the base of transistor Tr2, which in turn forces a constant current through R1, Tr1. To operate the original diode Z2, which was initially assumed to provide a stable voltage. The total current drawn by the circuit is the sum of the collector currents and is substantially constant. An increase in the supply voltage $V_s$ largely appears between the collector and emitter of the transistors.

At 22°C, change in $V_s$ = 6.4mV
change in $V_s$ = 20V

Stability $\frac{\Delta V_s}{V_s}$ ≈ 3300
At $V_s$ = 20V, $\Delta V_s$ = $\pm$ 84mV for overall temperature change from 50°C to −5°C.
The temperature coefficient is $-1.5\, \text{mA}/\text{degC}.$

Note that the graph plots are obtained from a circuit using unselected diodes, and no attempt was made at temperature compensation. Maximum supply voltage allowable will depend on permitted V_CE of transistors. For $V_s$ = 20V, $I = 0.224\, \text{mA}$ for $T = 55°C.$

$\frac{\Delta I}{\Delta T} = 4\, \text{μA/degC}$
At 22°C, $\Delta I_s = 20V$,
$\Delta I = 128\, \text{μA}$
$\frac{\Delta I}{\Delta V_s} = 4\, \text{μA/V}$

Percentage change ≈ $+1.3\%$

Note. If self-starting difficulties arise, a resistor between bases or resistors across collector-

emitter terminals may be used.

Circuit modifications
Stabilization ratio $\frac{\Delta V_s}{V_s}$ of $10^3$: 1 is claimed for the circuit (Ferranti) using reverse biased base-emitter junctions of transistors ZTX303/300 as reference diodes. Tr1, ZTX302, Tr2, ZTX500. Circuit current 1mA for R1, R2 6.8kΩ. Supply range 14 to 25V.

The voltage reference circuit of Fig. 1 may provide a stability factor of the order of 10^5 for a voltage range of 20-40V.

Z1, Z2 6V planar zeners
Tr1, 2N3702, Tr2, 2N3820
Tr1, 2N3819, Tr2, 2N3707

Circuit Fig. 2 uses forward biased diodes as references to achieve a low voltage reference. Stability is maintained down to 1.1V supply.

Temperature change compensation is obtained by matching forward voltage drift on the silicon diode against that of base-emitter junction of germanium transistor. The circuit of Fig. 3 includes diode connected transistors to offset the base-emitter voltage variation with temperature.

As temperature also affects the transistor common emitter current gains, this effect is minimized by feeding these via op-amps. Notice in Fig. 4 current feedback is to inverting inputs. Also slight variations in base current will still affect the collector currents. The use of junction f.e.t.s in Fig. 5 reduces this dependence.

Further reading

References

Cross references
Set 23, card 1
Set 6, card 5
Variable reference diodes

**Typical performance**
- $+V_{cc} = +15V$
- $R_1 = 4.7k\Omega \pm 5\%$, $R_3 = 10k\Omega$
- Multiturn $\pm 1\%$, linearity $\pm 0.1\%$
- $T_{Tr_1} BC125$

**Currents for $n=1$ condition**
- $I_1 = 2.91mA$, $I_2 = 2.77mA$
- $I_3 = 144.6\mu A$, $I_4 = 16\mu A$

(see graph opposite)

**Voltages for $n=1$ condition**
- $V_{RR} = 644mV$, $V_{REF} = 1.371V$

(see graph opposite)

**Description**
Although the zener diode is the most common device used to produce a stable reference voltage, it may be replaced by any device, combination of devices or circuit that behaves as a two-terminal element having a stable p.d. across it and some internal resistance. Like the zener diode, such elements can normally only produce a definable, fixed reference. Many instances arise, especially under laboratory conditions, where a variable reference voltage is required and which has a range of required values that are not necessarily available from a single device or a combination of devices. The circuit shown above left is an example of a simple d.c. reference which can often meet these requirements. If the transistor is assumed to have infinite current gain, $I_B$ tends to zero, and the current $I_C$ in $R_3$ will produce p.d.s across $R$ and $nR$ proportional to the current flowing. The p.d. across $R$ is $V_{RR}$, which is dependent on the transistor current, and the p.d. across resistor $nR$ will be $n$ times that across $R_1$, i.e., $nV_{REF}$. Hence, the reference voltage will be $V_{REF} = V_{REF} = (n+1)V_{REF}$. Since the factor $(n+1)$ cannot be less than unity the circuit is normally referred to as the amplified diode or the $V_{REF}$ multiplier. In practice most commonly-available transistors have sufficiently high current gain to allow predictable performance. Departure from the ideal condition of $V_{REF} = (n+1)V_{REF}$ will occur at both high and low current levels, the first because $I_B$ eventually becomes an appreciable part of the current in the bias resistors and the second because the collector current becomes a relatively small part of the total current and ceases to exercise control of the voltage. In most applications $R$ will be held constant and $nR$ will be a variable resistance used to set $V_{REF}$ to the desired value. The major advantage of this circuit is that $V_{REF}$ can be made almost any number of times greater than $V_{REF}$ including non-integral values. The graphs shown overleaf show the linearity obtainable in practice between desired value of $(n+1)$ and actual value of $(V_{REF}/V_{REF})$ up to $(n+1) = 10$. This graph was obtained by keeping $R_3$ fixed, by using a potentiometer, and varying the ratio of $nR$ to $R$. The second graph overleaf shows the corresponding ratios of collector current to bias-chain current and bias-chain current to base current. Whilst the design aim should be to keep the bias-chain current much greater than the base current and the collector current much greater than the bias-chain current, the last requirement is not nearly so important. The temperature dependence of $V_{REF}$ is related to that of $V_{REF}$ of $Tr_1$ which is typically $-2mV/degC$ so $V_{REF}$ will have a temperature coefficient of approximately $-2n\ mV/degC$.

The current source to feed the amplified diode can be realized by a current mirror so that three transistors in an i.e. transistor array may be used. At the expense of raising the lower limit of $V_{REF}$ a zener diode with a suitably chosen positive temperature coefficient can be included in series with the emitter as shown in Fig. 1. To provide a negative, variable reference voltage a p-n-p transistor and zener diode are connected as shown in Fig. 2. Circuits of the amplified diode type are available in monolithic, integrated circuit form which can be operated over a wide range of voltages and currents and which have a definable temperature coefficient. An example of this form is the General Electric D13V which is a combination of a Darlington-type transistor pair and a zener diode. The internal circuitry and normal connection arrangements are shown in Fig. 3.

**Further reading**

**Cross references**
Set 6, card 4
Set 23, cards 1, 6
Set 7, card 8
Bipolar references

Typical performance
Supply ±15V, +3.4mA.

R1 4.7kΩ ±5%
R2, R3 22kΩ ±5%
I1 1.9mA
VREF1, V2 +6.16V
−VREF2 −6.20V

Circuit description
The reference element is the zener diode D1, the basic reference circuit consisting of R1 and D1 in series, the current in D1 being determined by R1 for a given positive supply voltage. In the above arrangement the positive supply to the zener is, for convenience, made the same as that provided for the operational amplifier A1. The reference voltage VREF1, which is positive and equal to the zener voltage, is fed to the inverting operational amplifier so that

\[ V_{REF2} = -V_{REF1} R_2/R_1 \]

Thus, with \( R_2 = R_3 \), a simple bipolar reference circuit is obtained with outputs having the same voltage magnitude. In the experimental arrangement, the resistors were ±5% tolerance types which were not selected for equality resulting in

\[ V_{REF2} = -1.0065 V_{REF1} \]

A close match between the reference voltages can be obtained by carefully matching \( R_2 \) and \( R_3 \). Note that whilst \( V_{REF1} \) is fixed for a given zener diode and choice of supply and component values, \( V_{REF2} \) may be varied over a wide range by adjusting the ratio \( R_2/R_1 \). However, the values of these resistors should not be so small as to appreciably load \( V_{REF1} \).

The negative reference voltage output can be much more heavily loaded than the \( V_{REF2} \) output, since the former is available from the low-output-resistance operational amplifier. The change in the values of the reference voltages with temperature changes are essentially due to the zener diode characteristics, since the operational amplifier drift is very small in comparison and with \( R_2 = R_3 \), the resistor temperature coefficients match to maintain a unity gain inversion of \( V_{REF1} \).

Circuit modifications
To allow the \( V_{REF2} \) output to be more heavily loaded an operational amplifier voltage follower may be added to the basic circuit as shown in Fig. 1; this reference then being available from a low-output-resistance source.

Although this arrangement makes the current in the zener diode independent of the load currents taken from the \( V_{REF1} \) and \( V_{REF2} \); the zener current is still subject to variations in the positive supply rail voltage. Since an operational amplifier is a device which provides an output voltage that is inherently isolated from supply rail variations, the circuits above can be improved by supplying the direct voltage to \( R_1 \) from an operational amplifier instead of directly from the supply rail.

Irrespective of how the zener diode is supplied, its operating current may be more precisely defined and made independent of loading by replacing the zener diode in the feedback path of an operational amplifier. This technique also allows the ability to provide a pair of opposite-polarity reference voltages having a summation equal to the zener voltage, including the particular case where they have equal magnitude. The basic form is shown in Fig. 2.

In this circuit \( R_1 \) again supplies the current to \( R_2 \) and \( R_3 \) as well as the zener diode current. Since the junction of \( R_3 \) and \( R_3 \) is a virtual earth, the output voltages are given by

\[ V_{REF1} = V_a R_3/(R_2 + R_3) \]

\[ V_{REF2} = -V_a R_2/(R_2 + R_3) \]

so with \( R_2 = R_3 \),

\[ V_{REF2} = -V_{REF1} = V_a/2 \]

The operational amplifier must be capable of sinking all currents except the load current at the \( V_{REF1} \) output. If the operational amplifier is to be an inexpensive type a transistor current booster can be added as shown in Fig. 3.

The operational amplifier now only has to supply the base current to \( T_1 \). Diode \( D_2 \) is included to ensure that the amplifier turns on correctly.

A complete bipolar reference circuit using booster transistors at each output and having the zener current supplied from an operational amplifier is shown in Fig. 4.

In this circuit the magnitude of each output is equal to \( V_a \). Typical component values are ±V ±15V, A1, A2 301A

2N3964, T2 2N2222

1N829 (6.2 volt zener)

D1, D2 1N914, R2, R3 6.2kΩ

R1 826Ω, R4, R5 300Ω

R6 3.1kΩ

Further reading
Low temperature coefficient voltage reference

**Typical data**
- Tr1, Tr2: Matched pair or † CA3086
- IC1: CA3130AT
- R1: 4.7kΩ, R2: 47kΩ
- R3: 10kΩ (variable)
- RV1: 100kΩ
- C1: 1000pF
- VBE: +10V

At ambient temperature:
- \( V_{\text{out}} = 600\text{mV} + 10(26\text{mV}) \)
- \( V_{\text{out}} = 1200\text{mV} \)

**Component changes**
- Supply voltage 10V-19V maximum. Change in \( V_{\text{out}} = 0.75\% \).
- Op-amp has heavy negative feedback and hence output impedance is low. This allows full current capability of op-amp to be drawn.
- Typically, \( I_{\text{out}} = 0 \), \( V_{\text{out}} = 1.251V \)
- \( I_{\text{out}} = 10\text{mA}, V_{\text{out}} = 1.249V \)
- Maximum \( I_{\text{out}} = 22\text{mA} \)
- Percentage sensitivity graph based on initial supply voltage \( V_S = +9V \). Effective over load current range 0 to 20mA.

**Circuit description**

Transistors Tr1 and Tr2 have identical parameters and hence similar saturation currents whose ratio is therefore temperature independent. The op-amp gain may be considered infinite and therefore the potentials of terminals 2 and 3 can be considered equal, for a finite output, \( V_{\text{out}} \).

\[ V_{\text{out}} = V_{\text{BE}} + I_1 R_2 \]

It is arranged by choice of \( R_1 \) and \( R_2 \) that \( I_1 \) is about ten times \( R_2 \). Since \( V_{\text{BE}} = (KT/\alpha) \ln(I_1 I_2 + 1) \) and \( V_{\text{BE}} = V_{\text{BE1}} + V_{\text{BE2}}, \) then

\[ V_{\text{out}} = V_{\text{BE1}} + (R_1/R_2) \cdot \ln\left(I_1 I_2\right) \ln(I_1 I_2) \]

\[ = V_{\text{BE1}} + (R_2/R_1) \cdot (KT/\alpha) \ln(I_1) \]

\[ R_2/R_1 \text{ because } I_1/I_2 \text{ is in the ratio of } R_2/R_1 \text{ and } I_2 = I_{\text{out}}. \]

For \( R_2/R_1 = 10 \), then \( V_{\text{out}} \) is approximately defined at 1.2V at room temperature, for \( R_2/R_1 = 10 \). See typical data.

The base emitter junction voltage is also approximately given by \( V_{\text{BE}} = CT \) where \( V_{\text{BE}} \) is gap energy voltage at 0 K and \( C \) is a constant. When the negative temperature coefficient of \( V_{\text{BE}} \) and the positive temperature coefficient of the second term above, cancel, then \( V_{\text{out}} = V_{\text{BE}} \), and is then essentially temperature independent. Quoted value at 300K for \( V_{\text{out}} \) is 1.236V.

Although the op-amp used in this circuit has temperature drift in excess of bipolar op-amp, it has the advantage of operating from a single-ended supply and provides the facility of strobing such that a pulsed output is clamped below 0V (due to the c.m.o.s. output stage) and the temperature independent reference level. Centre voltage is the value at ambient, adjusted by \( R_2 \). Temperature range imposed on transistor package was +70° to -50°.

Minimum drift obtained at \( V_{\text{out}} \approx 1.25V \).

Further reading
**Circuit description**

When used as a current reference the circuit above simplifies to Fig. 1, and as a voltage reference, Fig. 2 shows the relationship between the output voltage and the input reference. The potential difference between the inverting and non-inverting inputs of IC2 is very small for a high gain amplifier used in this negative feedback mode, and hence \( V_{\text{ref}} \) appears across the resistor chain \( R_4 \) to \( R_{11} \). The current drawn from the \( V_{CC} \) supply depends on \( V_{\text{ref}}/\Sigma R \), giving for the above values, a range from about 10\( \mu \)A to a safe maximum of 10mA (approx.) if \( R_4 = R_9 \) are shorted. Operation is such that if \( I_L \) did tend to increase, the voltage across \( \Sigma R \) increases, which would thus tend to increase the voltage applied to the non-inverting terminal of IC2. This will reduce base drive to transistor Tr6 and compensate for the assumed increase.

Different values of current are achieved by varying \( R_V \), in association with varying the shorting points across \( \Sigma R \).

**Resistor \( R_{11} \) is chosen to provide an integer-multiplier for the voltage calibrator function.** In this case the junction of \( R_4 \) and \( R_7 \) is connected to the inverting input of IC3. This provides a ratio of exactly \( 10 \times \) for the values chosen, and a case for 1% tolerance resistors is justifiable for an accurate source. Continuous variation of the output from 0-10V is available for this arrangement.

**Component changes**

Graph over indicates percentage current variation (100k and 10k\( \Omega \) short-circuited) within \( \pm 0.01\% \) for power supply variations of IC4 up to 50\% in \( \pm V_4 \). Range of \( V_4 \) 3.5 to 20V for above setting. Minimum value depends on current required and load \( R \).

Graph left shows change of output voltage for 30% change in \( \pm V_4 \) is within \( \pm 0.01\% \). Change in \( V_4 \) of IC3 changes power dissipation of its input transistors and hence changes chip temperature. This slightly alters offset voltage due to unbalanced heating of input pair.

**Value of \( R_7 \) not critical because drive current is a small percentage of load current e.g. \( R_7 \) 1k\( \Omega \), \( I_L \) 0.3\( \mu \)A, \( I_{LOAD} \) 10mA, \( R_4 \) 100k\( \Omega \), \( I_L \) 0.365\( \mu \)A.

**Circuit modifications**

- Drive current error can be minimized by using a f.e.t. bipolar combination as Fig. 3. Current capability can be increased provided appropriate transistors used for \( Tr_3, Tr_4 \) combination e.g. Darlington package.
- IC MC1566L allows a variable constant current adjustable from 200\( \mu \)A to 100mA (depending on rating of output transistor \( Tr_3 \).

A simpler constant reference, programmed by resistor \( R_L \), is shown right and uses a combination of bipolar p-n-p and n-type junction f.e.t. to provide a low cost arrangement with claimed drift better than 0.03%/degC at 20mA.

**References**


**Further reading**

CA3130 Data Sheet 817, RCA. Constant-current regulator 10m to 100mA, Electronic Engineering, July 1973.

**Cross references**

Set 23, cards 3, 5
Set 6, card 1
Non-zener device characteristics

1. Asymmetric voltage dependent resistors—low voltage
   Non-linear resistors are made of certain polycrystalline materials having a voltage-current relationship given by $V = C I^\beta$ where $C$ and $\beta$ are constants. This can be expressed as $\log V = \beta \log I + \log C$ giving on log-log paper a straight line of slope $\beta$ and intercept $C$.
   
   In the case of asymmetric devices $\beta$ and $C$ change with current direction and a zener diode type characteristic can be obtained as shown above. The particular devices shown have knee voltages intermediate between that of zener diodes and that of Si or Ge diodes. The temperature coefficient of forward voltage for both these types is $-0.2\%$ per degC maximum.

2. Symmetrical voltage dependent resistors—high voltage
   These devices have the same form of relationship as that of the asymmetric device but are essentially simpler in that $C$ and $\beta$ do not change with current direction. They are frequently used as transient suppressors or over voltage protection devices in high power systems but may be used to regulate supplies. They are also used in some control applications where the non-linear characteristic is used intentionally. The characteristics shown are those obtained for a ZS02A3 metal-oxide varistor. The temperature stability is claimed to be excellent, our device at 500µA on test giving a temperature coefficient of $-0.13$mV per degC.

3. Semiconductor diodes
   All semiconductor diodes are governed by the same form of exponential equation over a wide range of currents. Below is shown the characteristic curves that are obtained as a result of replotting current on a log. scale. The slopes differ according to the material used as do the approximate constant voltages obtained across the diodes when conduction starts. The voltage obtained falls in general by 60mV for each decade drop in current although falls of up to 120mV per decade of current can occur at very high or very low values of current. Again for semiconductor junctions the temperature drift is of the order of $-2$mV per degC, no matter the material, although this increases at lower current densities.
   
   The range of voltages to be expected from Si diodes is 0.5 to 0.8V and from Ge diodes is 0.1 to 0.3V. Schottky diodes are intermediate. The diode connected transistor shown above will exhibit an exponential relationship between $I_e$ and $V_{be}$ over a much wider range of currents than is usual with simple diodes. The exponential relationship falls off at very low and very high currents due to loss of gain since basically it is $I_e$ and $V_{be}$ which are exponentially linked and the relationship between $I_e$ and $V_{be}$ being exponential depends on $I_b$ being negligible.

4. Light emitting diodes
   Light emitting diodes are semiconductor diodes which tend to be used for their light emitting properties rather than for their other properties which are identical in form to those of any semiconductor diode. They happen to have larger knee voltages than Si etc diodes, values in the range from 1.5V to 2.2V being common for medium current operation (several mA usually). This knee value is reduced by the normal 60mV per decade of current. Low current operation may extinguish the light but does not alter the simple exponential action. As before the temperature drift is $-2$mV per degC.
   
   The graph shows the results from a GaAs I.e.d. Higher knee voltages are obtained with the other common I.e.d. material viz. GaAsP.
Compensated reference circuits

Circuit 1
Components
R₁ 470Ω, R₂ 220Ω
Tr₁ BC125
D₁ 5082-4850 (Hewlett Packard)

Performance—see graphs 1 and 2

Description
V"ref" is given by \(-V_{be} + V_d\)
i.e. \(-0.7 + 1.6 = 0.9V\) to a first order approximately. The variation of V"ref" with respect to supply voltage changes is shown in Fig.2(a). From this we observe a variation of approximately 10% in V"ref" over the range shown so that compensation with respect to \(V_S\) is poor. The graph is approximately linear with slope +12mV per volt of \(V_S\). Fig.2(b) shows the variation of V"ref" with temperature, V"s" being 5V. The graph is linear in the range shown with slope +0.27mV/degC. The variation of an independent p-n junction with temperature is approximately -2mV/degC. Clearly there is an element of temperature compensation involved, arising from the fact that V"ref" is the difference in two junction voltages. In this case the effect of temperature variation on V"be" is greater than the effect on V"d". For any junction the variation of junction voltage with temperature is dependent on the voltage itself and is approximately +3μV/degC for each change of +1mV. Hence, increasing the i.e.d. current and/or decreasing the transistor current could improve the drift due to temperature. This can be done by decreasing \(R_1\) and/or increasing \(R_2\).

Component changes
For any given \(V_S\), \(R_1\) and \(R_2\) are not critical if only first-order temperature compensation is required. \(R_1\) effectively controls the i.e.d. current since the transistor base current will be negligible and obviously \(R_1\) should not be so high as to prevent i.e.d. conduction. Likewise \(R_2\) carries the transistor current and should not be so low as to cause saturation of the transistor. Hence \(R_1\) and \(R_2\) are dictated by the particular i.e.d. and Tr₁ used.

Most i.e.s and Si transistors will give the same reference voltage but if the transistor is replaced by a Ge transistor V"ref" will become 1.3V approximately.

Circuit 2
The first circuit is not well compensated for supply voltage changes. In Fig. 3 Tr₁ is a Ge transistor and Tr₂ is a Si transistor and, hence, V"ref" is approximately 0.4V—giving the circuit the added attraction of being a very low voltage reference. Ref. 1 quotes regulation 1% over supply current ranges of 100:1; the reason for this excellent regulation is that both transistors carry the same current so that the effects on V"be" due to different currents (or different values of V"s") are the same for both transistors. For the same reasons as before the circuit is also temperature compensated and indeed if the difference in the extrapolated band gaps at 0K is 0.43V complete temperature compensation is obtainable (Ref. 2). Achieving this requires selection of appropriate transistors.

Circuit 3
Components
R₁ 220Ω
R₂ 560Ω, R₃ 22kΩ
Tr₃ BC126, Tr₄ BC125
D₂ 5082-4850 (HP)

Performance
Fig. 5 shows the regulation achievable with this circuit viz 1.5mV per volt of \(V_S\) in the range 4 to 10V. For lower values of \(V_S\) saturation of the transistors occurs.

Description
Fig. 4 shows a different approach to achieving simultaneous temperature compensation and supply voltage insensitivity. In this case the i.e.d. and transistor of Fig. 1 are incorporated in a ring-of-two reference circuit (Ref. 4). As in Fig. 1, V"ref" is given by \(V_d - V_{be}\) so that similar ambient temperature compensation is effected. In addition however, the current through Tr₃ is largely independent of the supply voltage so that effects due to varying \(V_S\) are minimal. The action of the ring-of-two circuit is independent of \(V_S\) and is briefly as follows.

Suppose \(D_2\) is made to conduct (insured by presence of \(R_2\) and \(R_3\)). Then \(V_{d}\) is approximately 1.6V and \(Tr_3\) will conduct with \(V_{be}\) approximately 0.7V. The current in \(R_3\) is, therefore, defined by \(V_{d} - V_{be}\) and this current all flows through \(R_3\) (ignoring base currents). This defines the voltage across \(R_3\) and this voltage and the \(V_{be}\) of \(Tr_3\) defines the current in \(R_4\) which is the current in \(D_2\) (ignoring current in \(R_3\)). Hence, once \(D_2\) conducts the current through it is fixed and so are all the other currents. Hence \(V_{d} - V_{be}\) is supply insensitive. Only the transistor collector-emitter voltages are supply dependent.

References
1 Very low voltage d.c. reference, P. Williams, Electronic Engineering, June 1968, pp. 348-349.
2 National Semiconductor LM311 voltage comparator data sheets.
3 Set 6, card 5
**Simple current reference**

**FET 2N5457**

**Performance**

Graph 1 was obtained with $R_S = 10\Omega$ and $R = 0$. Graph 2 was obtained with $R_S \approx 1k\Omega$. $V_S$ was set at 10V and $I_L$ noted; $V_S$ was then changed to 15V and the new $I_L$ noted. From this was obtained the graph of $\%$ change in $I_L$ for various values of $R$, the marked values of $I_L$ on the graph being those at $V_S \approx 10V$. The figure of merit (f.o.m.) shown is defined as the slope resistance $\Delta V/I_L$ + static resistance ($V_S/I_L$ at $V_S = 10V$).

For a perfect current source this should be $\infty$ (see main text). As $R$ increases the quiescent current $I$ decreases but the f.o.m. increases, so we see clearly that the arrangement works best as a current source at low values of $I_L$. Note that from the graph of $\%$ change in $I_L$ we can deduce the static and slope resistances which ranged from 8.1k$\Omega$ and 794k$\Omega$ to 1M$\Omega$ and 109M$\Omega$ respectively over the range of $R$ shown.

Graph 3 shows the percentage change in $I_L$ as a result of a temperature change from $-5^\circ C$ to $+70^\circ C$, for various $R$. This was obtained with $R_L = 1k\Omega$ and $V_S = 11.4V$ (a choice intended to produce 10V across $R_L$ with $R = 0$, but of no material significance). In this respect it should be noted that although $V_S$ is constant neither $V_{de}$ nor $V_L$ is constant because of the varying $I_L$. The main point, however, is that a temperature independent condition is achieved at approximately $R = 1k\Omega$ for the particular f.e.t. that we used. Whilst graph 3 shows the effect of a large temperature change, results were taken at intermediate temperatures. These indicated that to a first approximation, for any given $R$, the change in $I_L$ is proportional to the change in temperature.

**Circuit description**

No matter the value of $R$, the gate current in a f.e.t. is negligible so that $I_L$ and $I_G$ can be equated. With $R = 0$ $V_{es}$ is zero and graph 1 is simply the normal f.e.t. characteristic for this value of $V_{es}$. With increasing $R$ more and more negative current feedback is used and consequently, the circuit behaves more like a current source with the ensuing drop in output as graph 2 shows.

Some explanation of the figure of merit used seems in order because some people use different figures of merit (Ref. 1 & 2) and notably slope resistance is at least implied as being all important. Consider Fig. 1 and the device characteristics shown, all passing through the same operating point, X. From this most people would agree that $OCD = $ perfect voltage source $OFG = $ imperfect voltage source $OAB = $ perfect current source $OHN = $ imperfect current source $OEH = $ indeterminate case.

From this we conclude that for a current source then (1) the slope resistance must be greater than the static resistance ($HJ$ closer to horizontal than $OE$) (2) given I then the greater the slope resistance the better.

From this, one is tempted to conclude that slope resistance is all important. Consider, however, Fig. 2 where we have the same slope resistance but different static resistances at points P and Q. Is the device whose characteristic is ORPQ a better current source at P or at Q? At P we find that the device between the given characteristic and the indeterminate case (OP) is the same as $\beta > \gamma$ i.e. at P we have a better current source. We could propose the figure of merit $(\alpha + \beta)/\alpha$, which becomes larger as the device approaches a perfect current source but is rather devoid of meaning. However, we take $\tan(\alpha + \beta)/\tan\alpha$ we obtain the same overall picture with the merit that $\tan(\alpha + \beta)/\tan\beta = $ slope resistance $+ $ static resistance.

Since slope resistance and static resistance are meaningful we adopt this as our figure of merit. The inverse of this we would adopt for a voltage source since we want any f.o.m. to become bigger the more the source resembles a perfect source.

With regard to the temperature dependence of the circuit one should note that to a first order approx. the temperature independent condition is in any f.e.t. obtained when $V_{es} = V_{p} + 0.63$

For our circuit this can be achieved when

$$R = \frac{[V_p - 0.63]}{I_o} \times \frac{V_p^2}{0.63^2}$$

where $V_p$ is the pinch-off voltage and $I_o = I_{L}$ when $V_{es} = 0$. The usefulness of these formulae is restricted because of the large range of $R_P$ and $I_o$ quoted by the manufacturer for any device and the difficulty of measuring both for any single device. However, Graph 3 has been plotted over a very large range of $R$ and consequently tends to exaggerate the effect of temperature.

**References**

1. I.R.C. zener diode handbook.
2. Motorola zener diode handbook.
Reference circuits

Circuit description
Internal reference circuits are based on the simpler voltage reference shown in Fig. 1, found in the low-cost LM376 voltage regulator. The self-starting technique used here employs a f.e.t. Tr1, with gate-source connected to ensure a constant current from drain to source. Tr1 will draw current initially via the base emitter-junctions of transistors Tr2 and Tr3. These transistors are therefore turned-on, and due to the current-mirror connection the current I through avalanche diode D2 is defined, and hence its voltage. This turns on transistor Tr4 and now produce a current through the D2, R1, R2, D3 chain. The circuit has no feedback loop, and an alternative is shown in Fig. 2. As it stands, this is not inherently self-starting, but with Tr4 conducting, the voltage V4 developed across avalanche diode D3 will maintain a constant current through resistor R. The collector current I of Tr5 is mirrored in the collector of Tr4 again to maintain a constant current through D3 thus completing the loop. This is shown more detailed in Fig. 3, reference circuit contained in the LM100 voltage regulator. The multi-collector transistor Tr3 in conjunction with Tr7, Tr8 forms a closed loop. The Vbe’s of these transistors will be

current through R is constant ($V_a - V_b$)/R. This would imply a reduction in the base current of Tr6, which negates the original assumption. D2 in association with Vbe drops across Tr6, Tr7 provide self-starting. The reference terminal can have a 0.1μF to ground to bypass possible noise from zener diode D5. An alternative low impedance voltage reference point is available if the output and feedback terminal via a 2.2kΩ resistor. The internal circuit in principle is shown in Fig.4 where 5 and 6 are the base terminals of transistors connected as a long-tail pair. Diode connected transistors Tr11, Tr12 and resistors R5, R6, R7 provide a temperature compensation which is optimized to about 1.8V.

Fig. 5 is a function block for the LM104 negative voltage regulator which uses an internal current reference network. An external 2.4kΩ resistor provides a current Iref of 1mA. When this conducts through an external programming resistor R, the output voltage available is regulated up to zero volts.

If the output voltage is a linear function of temperature, then the temp-coefficient of voltage is a constant, and the total change in voltage (often called the stability) is the product of temperature coefficient and the total temperature change $dV=(6V/ΔT)dT$.

The temperature coefficient of voltage changes with temperature because it results from a number of different sources of drift, and the actual $dV/dT$ at a given temperature might be greater or smaller than the average value implied by overall stability figure.

Further reading
Linear applications—National Semiconductor Corporation.
Linear Integrated Circuits—National Semiconductor Corporation.

Cross reference
Set 23, card 1.
The strongest trend in reference designs in recent years has been that toward band-gap techniques. This is particularly true for low-voltage applications where zener diodes cannot be used. When dissimilar junctions or similar junctions with different current densities are used to generate a reference voltage, then temperature-independence is observed when that voltage is related to the band-gap voltages of the semiconductor materials. Two related approaches led to three-terminal reference elements as in the circuit shown or two-terminal devices such as LM113 or ZN423. These last-mentioned have a terminal voltage equal to the band-gap of silicon, about 1.2V. The three terminal devices can accept a wide range of input voltages with a fixed output voltage scaled up from the band-gap voltage internally. The output of the device shown is 2.5V but 5V and 10V versions have also been reported. The circuit shows a simple means of converting to other output voltages with the additional advantages that (i) both reference unit and amplifier are supplied from the stabilized output markedly reducing supply dependence (ii) visual indication is provided by the i.e.d. whose main purpose is to keep the op-amp output terminal within its linear range.

**Reference**


The Si-Ge band-gap circuit using only two transistors is the simplest capable of negligible variation against both supply and temperature changes. It requires a match between the Si and Ge transistors such that \( \Delta V_{BE} \) equals the band-gap difference of \( \sim 0.43V \). This is an acceptable limitation in return for its simplicity and very low voltage requirement (<1V). If the transistor current densities can be adjusted then any pair of transistors can be used without prior matching. The circuit exploits this idea with the 20k potentiometer being adjusted to force 0.43V across the 100Ω resistor hence meeting the stability condition. Although the example shown is for a 5V output this can be reduced, and there is the further advantage that the temperature coefficient can be made either positive or negative as required by readjusting the current densities.

**References**


Set 24: Voltage regulators

This set covers integrated-circuit regulators with and without foldback on the one hand, and discrete-component series and shunt types on the other, but with some special cases in between. The exceptions are two dual-polarity circuits, a switching regulator and one using a current differencing or Norton amplifier. On card 7 the field-effect transistor was wrongly drawn; page 56 shows the correct wiring, and on card 1 the last equation should have shown a product and not a difference. Incidentally, on this set and others, unnumbered circuits on the bottom half of the page generally refer to items under circuit modifications and are in the same sequence as the text, unless made otherwise obvious.

Background article 50
Zener diode shunt regulator 51
Simple transistor regulators 52
Feedback series regulators 53
Bipolar/cmos op-amp regulator 54
Monolithic regulators — 1 55
Monolithic regulators — 2 56
Voltage regulation using current differencing amplifiers 57
Dual-polarity regulator 58
Switching regulator 59
Self-regulating dc–dc converter 60
Up-date circuits 61
Voltage regulators

The regulator is divided into the reference section and a d.c. power amplifier. These both require supply voltages; the convenience of having a single supply may outweigh the improved stability that can be obtained. The output current can cause the amplifier supply to vary; the source impedance including increased ripple if it is a rectified a.c. supply. Because the current required by the reference circuit is low and constant, it is easier to avoid any serious ripple/;regulation effects. It is essential that the d.c. amplifier have (a) an accurately defined voltage gain, (b) a low output resistance, (c) a sufficiently high output current/voltage capability, (d) a temperature drift that is either low or of the appropriate sign and magnitude to compensate for any drift in the reference section.

A simple configuration that meets these requirements in principle is shown in Fig. 1. The amplifier can be a standard operational amplifier if the output current is not much in excess of 10mA, and single-ended supply operation is permissible in many cases. The method is extended in Fig. 2 to the provision of output voltages that differ from the reference voltage. The output voltage is of opposite polarity to the reference voltage requiring a separate negative supply. The op-amp can be replaced by any circuit meeting conditions (a) to (d) above. Before turning to detailed study of possible configurations it is important to consider an alternative viewpoint.

A discrete component circuit that has all elements of a practical regulator is given in Fig. 3. Three transistors comprise a voltage amplifier of gain \((R_2/R_1+1)\) with high input- and low output-impedance (alternatively \(T_{r_1}\)), \(T_{r_2}\) are the error amplifier and \(T_r\), the series-pass transistor).

A serious problem arises in all regulators with emitter-follower outputs. The minimum input-output differential includes the \(V_{be}\) of \(T_r\) plus the voltage-drop across \(R_s\). This figure is markedly increased when \(T_r\) is replaced by compound transistors for greater output current capability. This property has serious implications for the maximum efficiency of which the circuit is capable, and also for the maximum dissipation the output stage may be called on to tolerate.

A possible solution is to replace \(T_r\) by a common-emitter p-n-p transistor, driving its base from the collector of \(T_1\) to restore the feedback condition (\(T_r\) would then be providing an additional inversion). A simplified form of the circuit for which this is not possible is shown in Fig. 3.) The effective reference voltage in this circuit is \((V_s+V_{be})\) and for best temperature stability, \(V_s\) would be chosen to have a drift of \(+2\text{mV/K}\) to cancel the negative \(V_{be}\) drift. This circuit is the basis of a large number of commercial regulators, though the functional similarity may be hard to recognize amongst the welter of extra functions such as current limiting variable output voltage etc.

Although the basic form can be designed for output currents of 100mA, any further increase forces the base current of \(T_r\), too high — normally \(T_{r_1}\) collector current has to be at least as great as the base current of \(T_r\). It may not be convenient for the zener current to exceed about 10mA since the regulation is impaired. To keep the zener/error amplifier current low, it is sufficient to replace the output stage by a pair of transistors connected to give increased current gain.

A major problem in the design of voltage regulators is to protect against load resistances falling below specified levels, and the size and cost of transistors, heatsinks and power supplies is dictated by the occasional fault condition rather than by the ratings into any intended value of load. For this reason the technique described as foldback or re-entrant current limiting was devised. The resulting characteristic is shown in Fig. 4(b), with the current falling back to a short-circuit value close to zero as the short-circuit condition is approached. The technique involves a current-limit reference voltage which depends on the output voltage. As soon as the current-limit circuit is activated the output voltage begins to fall simultaneously reducing the current as shown.
Zener diode shunt regulator

**Typical performance**

\[ I_{\text{constant}}, V_{\text{IN,variable}} \]

D: BZY963CV, I: 50mA

\[ V_{\text{IN(min)}} = 12V, V_{\text{IN(max)}} = 18V \]

\[ R_s = 54\Omega \ (39\Omega + 15\Omega) \]

RL = 195Ω (3 × 56Ω + 27Ω) to set I_L at 50mA

**Measured results**

<table>
<thead>
<tr>
<th>V_{\text{IN}}(V)</th>
<th>V_{\text{OUT}}(V)</th>
<th>I_L(mA)</th>
<th>I_Z(mA)</th>
<th>P_Z(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>9.16</td>
<td>48</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>9.49</td>
<td>48</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>9.72</td>
<td>50.5</td>
<td>1.03</td>
<td></td>
</tr>
</tbody>
</table>

**Typical performance**

\[ V_{\text{IN,constant}}, I_{\text{variable}} \]

D: BZY963CV, V_{\text{IN}} = 15V

\[ I_L(\text{max}) = 100mA, I_L(\text{min}) = 80mA \]

\[ R_s = 39\Omega + 15\Omega \]

RL = 95Ω to set I_L at 100mA

RL = 124Ω to set I_L at 80mA

**Measured results**

<table>
<thead>
<tr>
<th>I_L(mA)</th>
<th>V_{\text{OUT}}(V)</th>
<th>I_Z(mA)</th>
<th>P_Z(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>9.27</td>
<td>7</td>
<td>64.5</td>
</tr>
<tr>
<td>95</td>
<td>9.36</td>
<td>26</td>
<td>248.6</td>
</tr>
</tbody>
</table>

**Description**

A voltage regulator should ideally provide a form of buffer action which makes its output voltage independent of changes that occur in its input voltage or its load current. The extent to which a particular regulator circuit approaches this ideal usually depends on the complexity of the electronic regulation element used. The simplest form of electronic shunt regulation element is the zener diode which may be considered to consist of an internal reference voltage source (V_Z) in series with an internal resistance (r_Z), both of which have values that depend on the operating point and junction temperature. The basic form of a zener diode shunt regulator is shown above where the input voltage must be larger than the required regulated output voltage. The input voltage will be derived from the a.c. mains by rectification and will have a value that varies with mains input voltage and with load current, due to imperfect power supply regulation. The current in R_s is the sum of the load current (I_L) and the zener diode current (I_Z). If V_{\text{IN}} increases, the current in the zener diode and the load increases. But at the same time, a shift occurs in the zener diode operating point causing its internal resistance to fall. Thus the combined effects of the increase in I_Z and the decrease in r_Z tends to maintain the output voltage at its former value. Similar but opposite effects occur if V_{\text{IN}} decreases. Ability of the circuit to maintain the output voltage depends on the zener resistance and on the temperature coefficient of the zener voltage. The output voltage will not, in general, be equal to the nominal zener voltage because V_Z and r_Z have values that depend on I_Z and junction temperature. In some applications the load current may be virtually constant and in others it may vary over a wide range. If the load current decreases, the current shunted by the zener diode will increase, and vice versa, resulting in a substantially constant output voltage. Protection against excessive load current can be obtained with a fuse, but protection of the zener diode under light loading or open-circuit load conditions must be catered for by choosing a diode that can safely dissipate the power generated when I_L → 0, if there is any possibility of the load being removed. The design of this shunt regulator therefore becomes a matter of determining the value of R_s and the maximum power dissipated in the zener diode under specified conditions of variable V_{\text{IN}} and/or variable I_L. Although more precise results can be obtained by measuring and plotting the zener diode characteristics, for all practical purposes the nominal value of V_Z can be used to approximate the value of V_{\text{OUT}} in order to determine the component values. The Kirchhoff voltage equation for the circuit is

\[ V_{\text{IN}} = I_L \cdot R_s + V_Z \]

\[ R_s = \frac{(V_{\text{IN}} - V_Z)}{(I_L + I_L)} \]

\[ I_L = I_Z + I_L \]

\[ P_Z = \left[ (V_{\text{IN}} - V_Z) \right] \cdot (R_s - I_L) \]

Determination of suitable values for R_s and P_{\text{Z(max)}} depends on the specification. The value of R_s must be such that the zener current will not fall below some minimum value, I_{\text{Z(min)}} required to keep the diode in the breakdown region so that V_Z is maintained. Minimum zener current occurs when V_{\text{IN}} is a minimum, V_Z is a maximum and I_L is a maximum, so that

\[ R_s = \frac{V_{\text{IN(min)}} - V_Z}{I_L(\text{max}) - I_L(\text{min})} \]

Using the nominal zener voltage V_Z and an empirical factor of 10% of I_L(\text{max}) for I_L(\text{min}) gives

\[ R_s = \frac{V_{\text{IN(min)}} - V_Z}{1.11 \cdot I_L(\text{max})} \]

for the condition where either V_{\text{IN}} or both V_{\text{Z}} and I_L are variable. When only I_L is variable

\[ R_s = \frac{V_{\text{IN}} - V_Z}{I_L(\text{max})} \]

for constant V_{\text{IN}} and variable I_L,

\[ R_s = \frac{(V_{\text{IN(max)}} - V_Z)}{I_L(\text{min})} \]

for constant I_L and variable V_{\text{IN}}.

A zener diode is then chosen having the desired nominal voltage and capable of safely dissipating this maximum power. It may be necessary to design a heat sink of suitable area and/or to derate the diode's dissipation capability as a function of ambient temperature. Most zener diodes are rated at a temperature of 25°C, a typical derating curve for a 1 watt diode being as shown on this card. For increased power capability the zener diode can be connected in the base of a power transistor as shown.

**Further reading**


**Cross references**

Set 23, card 1.

Set 24, cards 3, 4.
Simple transistor regulators

Typical performance
Tr1, BFR41, D1, ESM18
R1, 330Ω, 3W; R2, 100Ω
RL, 1kΩ, 1W
VIN, 32.5±7.5V
VOUT see graphs opposite

Description
Although less efficient than series regulators, the shunt regulator is normally a simpler circuit and is useful where an existing supply is to be used to provide a lower-value regulated output voltage. A simple regulator is shown above which includes a zener diode reference-voltage element and a transistor, in shunt with the load, acting as the regulator element. Note that the circuit is simply a common-emitter d.c. amplifier. The value of R2 is chosen to provide a current in D1 that is greater than the minimum value required to maintain the zener diode in its breakdown region without exceeding the rated dissipation.

Output voltage remains essentially constant because the transistor collector current changes as the input voltage and/or the load current changes, causing a corresponding change in the p.d. across R1. Transistor Tr1 must be chosen to accommodate the maximum dissipation that can occur under specified input voltage and load current variations, including open-circuit load if this is a possibility.

Circuit modifications
To reduce changes in zener diode current, due to Tr1 base current, cascaded transistors may be used to increase the current gain of the regulating element, as Fig. 1. The base current of Tr2 is then only equal to JzR1R2, which can be made much smaller than the zener diode current by choice of R2.

An alternative form of simple shunt regulator is Fig. 2 where the zener diode is in series with Tr1 emitter.

A fraction of the output voltage VOUT/(R2 + R3) is compared with VZ. If VOUT increases the base potential rises causing an increase in collector and emitter currents and hence a larger p.d. across R1, which tends to return VOUT to its previous, lower value. The zener current is now the emitter current of Tr1 which is much larger than the base current, and to make Ie less dependent on IZ a resistor can be added between D1 cathode and VOUT.

Note that VOUT is now adjustable over a wide range, for a given zener voltage by choice of the ratio R2: R1.

The Fig. 3 circuit is a simple transistor series voltage regulator, i.e. the regulating element Tr1 is in series with the load.

Note that the circuit is an emitter follower d.c. amplifier where ideally VOUT = VZ but in practice VOUT = (VZ - VB). If the output voltage tends to decrease due to changes in input voltage or load current, the base-emitter voltage of Tr1 increases causing the transistor to feed a larger current to the load which will tend to restore VOUT to its previous value. The current in the zener diode can be made much larger than the base current of Tr1 but this current, hence VZ and VOUT, will be subject to variation as VIN changes. The circuit is inherently safe with open-circuit loads but Tr1 must be chosen to dissipate the maximum power generated under VIN(max) and RL(min) conditions.

Typical performance
Tr1, BFR41, D1, ESM18
R1, 1kΩ, 1W; R2, 200Ω, 3W
VIN, 22.5±4.5V
VOUT see graphs above

The variation of current in the zener diode with base current can be reduced by replacing Tr1 by a Darlington pair as in Fig. 4, where the base current of Tr2 is then only IZ(1 + hFE)R2/(1 + hFB).

This principle can be extended to a number of emitter followers or a complementary pair may be used, Fig. 5, to keep VOUT = (VZ - VB).

Further reading

Cross references
Set 24, card 4.
Set 23, card 1.
Feedback series regulators

Long-tailed pair regulator
A very common type of feedback voltage regulator is shown above where the control amplifier is in the form of a long-tailed pair, or differential-input amplifier containing transistors $T_1$ and $T_2$. Resistor $R_1$ and $D_1$ act as a simple voltage reference circuit making $T_1$ base potential $V_Z$. The base potential of $T_2$ is a fraction of the output voltage, determined by the ratio of the resistors in the potential divider $R_4$ and $R_5$, so that the output voltage is continuously monitored. The output from the long-tailed pair is taken from $T_2$ collector and controls the base drive to the series transistor $T_3$ (an emitter follower). The differential amplifier attempts to keep its two inputs equal by altering the p.d. across the series transistor in order to hold the regulated output voltage constant despite changes that occur in the input voltage or load current. With a load current of 50mA, the circuit shown typically provides a load regulation of about 0.03% and a line regulation of approximately 0.5% for a $\pm 20\%$ change in $V_{IN}$.

For a fixed input voltage the output voltage may be varied conveniently by realizing $R_4$ and $R_5$ in the form of a potentiometer e.g. with $(R_4 + R_5) = 1k\Omega$ and $R_5$ varied over the range 100 to 900$\Omega$. $V_{OUT}$ may be varied over the range 16.86 to 6.4V.

Frequency stability is important in the design of feedback regulators. Because negative feedback is used in the control amplifier element, a total phase shift around the loop (including the series element) of 180° at high frequencies can result in oscillations unless the closed-loop gain is less than unity. Therefore, at the frequency where the total phase shift is 180°, provision should be made to reduce the closed-loop gain to less than unity. The use of shunt capacitance at the output, or elsewhere in the amplifier section produces the required gain “roll-off” with frequency. The degree of voltage stabilization depends mainly on the stability of the reference voltage, best results being obtained when $T_1$ and $T_2$ are a matched pair.

The differential-input amplifier is the basis of most operational amplifier designs so the long-tailed pair may be replaced by such an amplifier as shown below. In this arrangement the operational amplifier isolates the zener reference from load changes improving the load regulation. Potentiometer $R_4$ allows the output voltage to vary over a limited range.

Typical performance
$V_{IN}$ $= 18V$
$R_5 = 480\Omega$

$V_{OUT}$ may be varied over the range 5 to 25V with load currents up to 100mA. Output impedance is less than 0.1$\Omega$. Useful minimum $V_{IN}$ $= 20V$.

Another type of feedback regulator in common use is the d.c. feedback pair shown below. In this circuit the effective reference voltage is $V_Z + V_{REF}$ of $T_1$, and for best results, the temperature stability of the effective reference source should be optimized by choosing a zener diode that provides a temperature drift of approximately $\pm 2mV/degC$ to cancel the negative drift in the $V_{REF}$ of $T_1$. In the basic form shown, load currents of up to about 100mA can be accommodated and for higher output currents $T_3$ may be replaced by a higher-current-gain transistor pair.

Further reading
Potted power, Design Electronics, January 1971, pp. 34/5.

Cross references
Set 24, cards 1, 4, 5, 6.
Set 23, card 3.
Set 20, cards 1, 2, 4, 10.
Bipolar/c.m.o.s. op-amp regulator

The voltage regulator shown above uses three monolithic integrated circuits. $A_1$ is a bipolar/c.m.o.s. hybrid operational amplifier, $Tr_1$ to $Tr_4$ are contained within one bipolar array package, and $D_1$ to $D_4$ plus $Tr_4$ are contained in another identical package. Diodes $D_1$, $D_2$ and $D_3$ are bipolar transistors with collector and emitter strapped and operating in reverse bias in the breakdown region to serve as zener diodes having a zener voltage of about 7.3V. Diode $D_4$ is forward-biased and consists of a transistor in the same package with its collector and base strapped. Resistor $R_1$ and the series-connected zener diodes $D_1$ and $D_2$ act as a simple shunt regulator across the input to provide a regulated supply of $2V$ for the CA3130 operational amplifier. The output from this part of the circuit also serves as a pre-regulated input to the low-impedance, temperature-compensated voltage reference source consisting of $R_3$, $R_4$, $R_5$, $R_6$ and $Tr_4$—the diodes and transistor being part of the same monolithic structure. The output from this reference source is taken to the non-inverting input of the error amplifier via potentiometer $R_w$ which allows the amplifier's reference to be varied continuously over the range 0V to about 8.3V allowing the output voltage to be controlled over the range 0V to about 13.9V. A fraction of the output voltage is fed to the inverting input of the error amplifier by means of the potential divider $R_{10}$ and $R_{11}$.

Transistors $Tr_1$ to $Tr_4$ are contained in a single integrated circuit package and are all connected in parallel to act as an equivalent series transistor (emitter follower) which is capable of handling the full-load current, when driven from the output of the error amplifier. Transistor $Tr_3$ (in the same package) in conjunction with $R_4$, $R_5$ and $R_6$ serves as a current limiting device. If the load current increases the p.d. across $R_4 + R_5$ increases and since the base voltage of $Tr_2$ is held at approximately 600mV above $V_{OUT}$ the base current to $Tr_3$ through $R_6$ increases. Hence the collector current of $Tr_3$ increases, diverting the base current from the series pass transistors. Thus the collector currents of these transistors, and hence the load current, falls back to its previous value. The value of load current at which the current limit becomes operative is set by $R_4$, the maximum limited current being determined by $R_6$, a 3-$\Omega$ resistor. Capacitor $C_8$ provides compensation for the operational amplifier the other capacitors serving to remove residual hum at the input and to control the closed-loop gain of the amplifier at high frequencies.

Modification

Careful layout of the printed circuit is essential otherwise the circuit may oscillate. This form of circuit may be modified to provide output voltages in the range 100mV to 50V at currents up to 1A with a 55V input by making the following changes. $R_1$ is increased to 4.3k$\Omega$, 1W and a 1k$\Omega$ resistor connected between $D_4$ anode and $Tr_4$ base; otherwise the pre-regulator and voltage reference circuits are basically unchanged. The sliding contact of $R_4$ is connected directly to the inverting input of $A_1$, $R_5$ is omitted along with $C_4$ and the compensation capacitor $C_8$ is increased to 1nF. $R_{10}$ and $R_{11}$ are changed to 43k$\Omega$ and 8.2k$\Omega$ respectively, and their junction taken to the non-inverting input of $A_1$. This inversion of the inputs to $A_1$ is required because of the addition of an inverting current-boosting stage at the output of $A_1$ as shown.

Darlington-connected series transistors $Tr_4$ and $Tr_8$ replace $Tr_1$ to $Tr_3$ and $Tr_8$ provides current limiting by adjustment of $R_{15}$.

Typical components are

Tr$R_{3}2N3055$, $Tr_{3}2N2102$
Tr$R_{5}2N294$, $R_{10}3.3k\Omega$, 1W
$R_{13}1k\Omega$, $R_{14}1\Omega$, $R_{15}10k\Omega$
$C_{4}100\mu F$, $C_{5}5\mu F$

Full load regulation 0.05%
Line regulation 0.01%/V

Cross references

Set 24, cards 1, 2, 3, 5, 6.
Set 23, card 3.
Set 20, cards 1, 2.

Further reading

Monolithic regulators—1

Circuit description
The schematic diagram of this regulator package is shown above, with the external components for a high voltage regulator circuit. The series-pass transistor is connected as an emitter-follower, and the amount of feedback to the internal operational-amplifier is defined by \( R_1 \) and \( R_2 \). \( V_I \) is approximately equal to \( V_{REF} \) because the differential input to the op-amp is very small, and hence, as \( R_{SC} \equiv R_1 \) or \( R_2 \), \( V_{OUT} = V_{REF}(R_1 + R_2)/R_2 \) i.e. the emitter of the series-pass transistor is constrained to be a multiple of \( V_{REF} \). Therefore, if the unregulated input \( V_{IN} \) increases, this increase must be absorbed by an increase in the collector-emitter voltage of series transistor. Conceptually, if the emitter potential tends to increase, then \( V_I \) to the inverting input would increase, which would cause a decrease in potential at the base of the series transistor, and due to emitter-follower action, this opposes the assumed increase. Load regulation. Percentage change in output voltage for a specified load current change. Line regulation. Percentage change in output voltage for a defined change in input voltage. Note—above are defined for a constant junction temp. Ripple rejection. Ratio of pk-pk input ripple voltage to pk-pk output ripple voltage.

Input-output differential. Working range of regulator based on difference between supply and regulated voltage. Standby current. Current drain for no load on output or reference. Note—regulation is sometimes defined on basis of a percentage change in input.

Typical data
IC \( \mu A723C \) or LM723C
Temperature range 0 to 70°C
Line regulation for \( V_{IN} \) 12 to 40V 0.1%.
For 12-15V, 0.01%
Load regulation 0.03% for 1 to 50mA current range
\( R_1 \) 7.87kΩ ±5%
\( R_2 \) 7.15kΩ ±5%
\( V_{REG} \) +12V, \( C_1 \) 100pF
Ripple rejection 74dB
Temp. coeff. of 0.003%/degC
\( V_{REF} \) 7.15V
Standby current 2.3mA for \( V_{IN} \) 30V
Input voltage range 9.5 to 40V
Output voltage range 7 to 37V

Further reading
\( \mu A723 \) The Universal Voltage Regulator, Fairchild.
Monolithic regulators—2

The schematic diagram of the LM305/205/305 group is within the dashed box.

External components provide a basic low current positive regulator circuit.

LM305, Fig. 1
- Temperature range: 0 to 70°C
- Input voltage range: 8.5 to 40V
- Output voltage range: 4.5 to 30V
- Output current: 20mA
- Load regulation: 0.03% for load current 0 to 12mA
- Line regulation: depends on $V_{IN} - V_{OUT}$ differential
- 0.025%/V
- Parallel combination of $R_5$ and $R_4$ should be about 2kΩ
- LM305A can provide 45mA.

Negative voltage regulator (LM104, Fig. 2, Current reference is temperature compensated. Output voltage programmed by value of $R_{ADJ}$. $R_{LM}$ provides short-circuit protection. $C_1$ (tantalum) prevents oscillation.
- Output current: 25mA
- Input range: -50 to -8V
- Output range: -40V to -15mV
- Typical load regulation: 0.05% from 0 to 25mA
- Typical line regulation: better than 0.2% for ±20% input change
- $V_{OUT}$: $R_{ADJ}$/500 V
- The LM104/LM105 interconnection, Fig. 2, provides a dual polarity tracking regulator.

Using the LM104 as an inverting amplifier i.e. $V_{OUT}$ at pin 9 appears as $-V_{OUT}$ at pin 8. $V_{IN}$ = ±18V, $V_{OUT}$ = ±15V defined by potential divider chain $R_1$, $R_2$
- Output current: 200mA
- The RC4195 or MC1468 in Fig. 3 provide a dual balanced ±15V supply in one package, with current capability of around 100mA.
- Input voltage range 18 to 30V.
- The RC4194 is a dual tracking voltage regulator in which the positive and negative output voltages are adjustable over the range 0.05 to ±32V by variation of $R_1$. This should be 2.5kΩ for each volt required.
- Input voltage range: 9.5 to 35V
- Load regulation (1 to 100mA) 0.001% $V_{OUT}$/mA
- Line regulation: For a 10% change in $V_{IN}$ 0.02% $V_{OUT}$
- Load current: 100mA
- An unbalanced output (+12V, -6V) suitable for comparators is obtainable with $R_s$ of 15kΩ and the addition of $R_6$ of 20kΩ. (LM340) is a three-terminal series positive regulator. It uses an internal temperature independent voltage reference dependent on the predictable gap-energy voltage (card 6, set 23).

The current capability of most voltage regulators can be boosted with additional external series transistors. A typical configuration extending the LM105 capability to 2A is shown in Fig. 6.
- Foldback current limiting allows control of the current when the output is short circuit.
- Approximatively, for a short circuit voltage across $R_{SC}$ = $V_{be} - mV_{be}$. At full load, voltage across $R_{SC}$ is $(1-m)V_{be} + kV_{out}$
- Hence $I_{L_{max}} = \frac{1}{1-(1-m)V_{be}}$
- For a specific $V_{out}$, the current ratio is controlled by $k$. The typical V-I curve is given by $I_{L} = \frac{(1-m)V_{be} + kV_{out}}{R_{SC}}$

Further reading
- Application notes AN103 (LM340); AN23 (LM105), AN82 (precision tracking regulators), National Semiconductor.
- Total Linear, Raytheon, 1974.

Cross references
- Set 24, cards 8, 3, 4
- Set 23, card 6
- Set 6, cards 2, 10
- Set 7, card 11
- Set 20, cards 1, 2, 9.
Voltage regulation using current-differencing amplifiers

Circuit description
The basic voltage regulators described previously using a current-differencing amplifier had two distinct limitations. The obvious one is the very limited output current available, and this can be overcome by adding an emitter follower inside the feedback loop. This actually increases the second problem—that the minimum value of the supply voltage has to be one or more volts above the regulated output. It is possible to solve both problems while simultaneously improving the regulation against supply changes, if the amplifier is supplied from the regulator output (simultaneously regulating the supply to the three other amplifiers in the package). The trick is to make use of the ability of the output stage to sink current safely even when the output potential is greater than that on the amplifier positive supply terminal (provided the difference does not exceed 5V, breakdown in the internal p-n junctions is avoided). The minimum sink current in this mode is 1.3mA and R1 is chosen so that Tr1 is kept out of conduction when minimum output current is required. In the simplest form shown 'nFbe' biasing is used that fixes the output voltage at (R1/R3+1)FB where the Vbe is that of the internal transistor at the amplifier non-inverting input. R1 provides a small bias current to the inverting input. (Improved regulation would follow from the replacement of R3 by a suitable zener diode.) The main problem remaining is that the circuit is not self-starting since with output temporarily at zero no current flows and the state is held permanently. One solution is to add a junction f.e.t. of low pinch-off voltage and on-current sufficient to bring Tr1 into conduction. Once the output voltage is established, the reverse bias on the f.e.t. gate-source cuts it off and prevents it from disturbing the normal operation.

Component changes
Tr1: Any silicon p-n-p transistor with suitable current/power rating—circuit can supply up to 200mA but maximum VIN - VOUT rating limited by internal breakdown of amplifier to 5V i.e. 1W dissipation is adequate. BFR81. Tr2: Junction f.e.t. n-channel. Pinch-off voltage—regulated output. Zero-bias on-current must be sufficient to drive Tr1 into conduction—typically >2mA.
R1: 150 to 390Ω. If resistor is too high the minimum sink current of 1.3mA drives Tr1 into conduction losing control at light loading. If R1 is too low, insufficient drive current is available for Tr1.
R3, R4: In this mode of operation, the potential at the non-inverting input is 0.6V and the ratio of R3: R4 scales this up to [(Rf/Rg)+1] 0.6V. Stability is considerably increased by replacing R3 with a zener diode when V=Vs+0.6V.
R5: Not critical. Sets operating currents of input transistors. Suitable values 1 to 10MΩ.

Circuit modifications
- For increased input-output voltage differential the amplifier is supplied directly from V+. To allow the amplifier output to be out of saturation the base of Tr1 is driven through a potential divider. Without this, Tr1 could not be driven off. The upper voltage limit is then the rating of the i.c. (36V for the LM3900). All other amplifiers in the package are subject to the full supply voltage variations.
- To increase the supply voltage rating further while retaining a low (VIN - VOUT) a second transistor is added such that all terminals of the amplifier are operated at a low voltage while Tr1, Tr2 must be chosen for a suitable voltage rating. An alternative zener circuit is shown in which R5, R4 set the output voltage R5/2R4 in the absence of R1. A Resistor to ground from either input causes current flow in either R5 or R4, and the resulting contribution to the output voltage has a temperature coefficient which can be used for overall temperature compensation. As shown R1 contributes -[1+1/(R1+R2)]FB to the output.
- To remove the effect of supply variations via R1, a diode network is chosen that ensures self-starting but has D3 dropping out of conduction after starting has been achieved.

Further reading
Frederiksen, T. M., Howard, W. M., Sleeth, R. S. The LM3900, A New Current-Differencing Quad Of ± Input Amplifiers, National Semiconductor application note AN72
Dual-polarity regulator

Typical performance
IC\textsubscript{1-2} 741
TR\textsubscript{1} BFR41, TR\textsubscript{2} 2N3055
TR\textsubscript{3} BFR81, TR\textsubscript{4} 2N2955
D\textsubscript{1-3} 6.8V zener diodes

\[ R_{1-2} = 82k\Omega, \quad R_{3} = 3.9k\Omega \]
\[ R_{2} = 2.2k\Omega, \quad R_{4} = 10k\Omega \]
\[ R_{6} = 22k\Omega, \quad C_{1-2} = 47\mu F \]
\[ V_{8} = \pm 15V \]
\[ V_{0} = \pm 10V, \quad I_{0} = 0.1A \]

Circuit description
In a dual regulator it can be very important that the outputs track well. This can be achieved by having one section dependent on a particular zener diode or other reference element; the other output uses the output of the first as its own reference. Any variation in the zener voltage whether due to supply or temperature changes affects each equally. To maximize the regulation the zener diode and the error amplifiers should if possible be supplied from the regulated outputs. This can complicate the coupling network between each amplifier and the power output stage. The positive regulator compares a variable portion of the output via \( R_{6} \) with the constant voltage across \( D_{1} \). Any difference is amplified by IC\textsubscript{1}, whose output is coupled via \( D_{2} \) to the Darlington pair composed of TR\textsubscript{1}, 2. The negative output is controlled by IC\textsubscript{2} via TR\textsubscript{3,4}, the amplifier operating in the virtual earth mode with \( R_{1-2} \) defining the inverting gain.

For \( R_{3} = R_{6} \) the positive and negative output voltages are equal in magnitude. As shown the positive output is restricted to values greater than the zener voltage, but the negative output can take up values from zero to just short of the negative supply. The outputs are highly stabilized against both supply and load current changes (typically to within 1 or 2mV) and the stability is limited by that of the zener diode \( D_{1} \).

Component changes
IC\textsubscript{1,2} Most compensated op-amps may be directly substituted. The output stage contributes no additional voltage gain and hence no change in compensation is warranted. TR\textsubscript{1,4}. The drive transistors are standard silicon medium-power devices and a maximum collector current of a few tens of milliamperes is sufficient for output currents beyond 1A. The power devices may then have to dissipate considerable power under short circuit conditions, i.e. current limiting should be added or adequate heat-sinking provided. 

D\textsubscript{2} Zener diode with low temperature coefficient for minimum drift.

D\textsubscript{2+} Not critical. Included to allow op-amp outputs to remain in linear region while retaining control of output. Diodes can be replaced by resistors typically of same value as \( R_{4-5} \).

R\textsubscript{1+} Equal for precise tracking of outputs. 1 to 100k\Omega.

R\textsubscript{3} Minimizes offset if \( R_{3} = R_{4} / R_{5} \). Can be omitted.

R\textsubscript{4} Sets zener diode current to optimum for low drift. 470\Omega to 10k\Omega.

R\textsubscript{5} May be padded out with series resistors where pot. is to provide trimming action only 1 to 100k\Omega. Lower range for least offset/drift though overall drift likely to be dominated by zener anyway.

R\textsubscript{6+} Set maximum base drive and hence, give coarse limiting of output 1 to 100k\Omega.

C\textsubscript{1-2} Suppress h.f. oscillation. Not critical but must be close to output or load inductance may initiate instability.

V\textsubscript{8} Because amplifiers powered from regulated outputs, \( V_{8} \) can be high if transistors have appropriate ratings. Increase \( D_{1-2} \) voltages to match.

Circuit modifications
- The error amplifier outputs may be coupled to the power stage in several ways. Direct coupling reduces the component count but requires that the op-amp be powered from the supply rail. The input-output differential is increased to \( >3V \) in many cases.

  - To reduce this, the output stage is operated in common emitter (with or without an intermediate driver). The inversion requires the op-amp inputs to be reversed and the resulting circuits are typically non-self-starting and require additional components for starting.

  - As in previous power amplifiers the amplifier may drive a dummy load resistor \( R_{o} \), the resulting current bringing the output transistor into conduction when the p.d. across \( R_{o} \) exceeds 0.6V.

  - A simple discrete form of the circuit has a good performance with few components but requires to be started either by a CR network together with the switch-on transient or by a separate switch.

Further reading
Switching regulator

Typical performance
IC1 CA3130 (RCA)
TR1 BFR81
D1 1N4148
L1 680μH
C1 15μF
R1 1kΩ
R2 470kΩ
R3 680Ω
VREF 5V
R4 50Ω
V5 10V

Circuit description
Switching regulators are related to Class-D switching amplifiers. The power stage TR1 conducts for a varying portion of the time. If the switching frequency is high, the current in L1 varies little throughout the cycle, with D1 sustaining the current in the load when the transistor is off. The inverting gain provided by TR1 reverse the effective polarity of gain at the amplifier inputs; 100% negative feedback is applied from the load to one input and with L1 short circuit, a linear regulator would result were VREF to be fed directly to the other input. A small amount of hysteresis via R2, R3, combined with the L1R1 creates an astable—the LR equivalent of the standard op-amp CR astable. The load voltage has a similar exponential waveform with a ripple of the order (R1/R3)V5 and a mean value of VREF when the hysteresis is small. Power losses include those due to the speed of switching including core losses in L1, and the “d.c.” losses such as Vce (sat) for TR1 and the on voltage of D1. For low output voltages the latter limits the efficiency—between 70 and 90% is common even where the output voltage is < V5/2. As the supply voltage varies the mean current changes in the opposite sense because the mark-space ratio is adjusted automatically via the astable action. Hence the mean power drawn from the supply depends mainly on the power required by the load.

Component changes
IC1: This op-amp is particularly suitable for several reasons:
(i) high input resistance (m.o.s.) allows high R5: R6 ratio without R6 becoming too low.
(ii) input common-mode range includes zero line allowing control of output down to zero.
(iii) high slew-rate allows switching speeds to be increased to suit optimum frequency-range of ferrite-cored inductor.
(iv) c.m.o.s. output stage allows direct coupling to TR1 if needed with rapid switch-off reducing charge-storage problems.

Most other un-compensated op-amps and comparators can be used provided following precautions observed: VREF must lie within input common-mode range; the output may not be able to swing high enough to switch TR1 off and a resistive network such as R5, R6 may be needed (left); current capability must be sufficient to saturate TR1 at max. load current—say 1A/20.
TR1 p-n-p silicon, peak current equal to mean load current; low saturation voltage; switching speed fast enough to make rise/fall times much less than the period of waveform; high frequency minimizes dissipation in transistor it above observed.

D1: current rating mean output current; peak inverse voltage rating (p.i.v.) V5; efficiency increased at low output voltages by reducing diode on-voltage (Schottky or germanium diodes if temperature not too high).
L1: Typically 200μH—10mH depending on current/frequency used. Ferrite cores reduce size provide high Q, low losses; saturation of core at higher currents can inhibit oscillations. C1: Modifies frequencies for given L1 R1 combination. Not essential to operation, but reduces transients in load.
R1, R2: Ratio sets hysteresis and hence ripple. As ripple is reduced, so is time taken for completion of cycle i.e. frequency increases. By keeping R1, R2 as large as possible injection of switching current into VREF is minimized.
Ratio R5/R6 typ. 100 to 1,000; high value gives low ripple provided increased frequency does not bring transient problems in.
R5: Not critical. 100Ω to 1kΩ with this op-amp.
VREF: Equal to required output.
R7: Load currents up to 200mA possible V5: +5 to +15V.

Circuit modifications
Paralleled c.m.o.s. buffers may be used to boost output drive (centre). See op-amp data sheet. Alternatively use additional transistors (right).
Final stage should be common emitter for highest efficiency.
R1, R2 100 to 470Ω. Outputs to 1A.

Cross references
Set 6, card 7.
Set 24, card 10.
Set 7, card 12.
Self-regulating d.c.-d.c. converter

Circuit description
Dual-polarity supplies are needed in many systems where only a single supply is initially available. The circuit shown achieves this by acting as a free-running astable oscillator producing an output voltage just less than the supply. This is applied via a diode-capacitor network D1 to C4 to produce a negative output voltage. Assume ideal diodes, D1 clamps the right hand side of C4 to zero on positive output swings; similarly D2 clamps the right hand side of C3 to C4.

On negative swings, C4 transfers charge via D2 into C3 as does C3 through D1 into C4. Eventually C3, C4 each acquire a p.d. equal to the output swing, while C5, C6 achieve double that value. Two factors reduce this output voltage: losses across the diodes drop the maximum output by about 2V. The timer has a reset terminal; when the potential on this approaches ground the oscillations are inhibited.

A potential divider composed of R5, R6 and D8 provides a potential at the RESET terminal such that each time the magnitude of the negative output increases, the oscillation is inhibited and the magnitude decreases. The diodes optimize the tracking for $|V_O| = V_S$.

Typical performance
- IC: 555 timer
- D1-D7: 1N4148
- C2-C4: 47μF, C5: 0.015μF
- R1: 12kΩ, R2: 10kΩ, R6: 22kΩ
- $+V_S = +10V$
- $-V_S = -10V$
- $I_O$: 0 to 20mA
- $V_O/V_S$ ± 0.5% for $V_S$ 7 to 14V

Component changes
- IC: The circuit depends on the particular characteristics of the 555 timer available from most i.c. suppliers.
- D1-D7: Not critical. Any fast silicon diodes.
- C1: 470pF to 0.1μF. At low frequencies ripple increases and at high frequencies switching losses.
- R1: 470 to 10kΩ. Too low a value wastes current.
- R2: 2kΩ to 22kΩ. Select for frequency of oscillation.
- R3: R4 can be replaced by a potentiometer for variable output. Value not critical.
- $V_S$: +5V to +20V
- $V_O$: Up to 2V in magnitude.

Circuit modifications
- For some applications the circuit can be considerably simplified. Where the negative voltage required is less than the positive supply available then the rectifying network can be simplified as shown. If the precise tracking of the two supplies is not important then the compensating diodes D1-D7 can be omitted. With R1 replaced by a potentiometer, the result is a convenient circuit for producing, say, −6V from a +12V supply as required by widely used i.c. comparators.
- A second modification allows the negative output to be regulated rather than be proportional to the supply voltage. Replacing R4 by a zener diode, the oscillator is reset each time the negative output pulls the reset terminal close to zero. The resulting ripple characteristics are comparable to the previous circuits. N.B. the regulation and ripple for a single diode pair is significantly better than for the voltage doubler, loads down to 100Ω being tolerated.
- The same oscillator circuit can be used to generate a voltage more positive than the supply as shown. To regulate the output, a separate sensing circuit would be required since the original depended on using the RESET as a virtual earth. The circuit has affinities with certain re-triggerable monostables, and those based on op-amps in which the switching action is controlled by positive feedback can be adapted.
- The two functions performed by the timer can be separated, with a clock generator driving a monostable. The latter is gated off each time the required output voltage is exceeded. Where the output swing of the timer is insufficient, a clock generator driving a monostable, and the latter is gated off each time the required output voltage is exceeded. Where the output swing of the timer is insufficient, a clock generator driving a monostable, and the latter is gated off each time the required output voltage is exceeded. Where the output swing of the timer is insufficient, a clock generator driving a monostable, and the latter is gated off each time the required output voltage is exceeded. Where the output swing of the timer is insufficient, a clock generator driving a monostable, and the latter is gated off each time the required output voltage is exceeded.

Further reading

Cross references
Set 21, card 9.
Set 10, card 2.
Set 10, card 10.
Set 24, card 9.
The most significant advance in regulator design is arguably the appearance of the i.c. three-terminal regulator. These are now available in a range of voltage and current ratings, but there are bound to be gaps in this range that can be filled by more conventional variable-voltage multi-terminal devices. Alternatively the three-terminal devices can themselves be adapted if their nature is clearly understood. To find a suitable equivalent circuit compare Figs 1(a)–1(d). A nullor (combined with a voltage reference) equivalent to an ideal transistor with infinite voltage and current gain would provide the same performance as an ideal three-terminal regulator, viz that for all conditions for which $V_{IN} > V_o$, then $V_o = V_x$. This follows from the nullor/ideal transistor properties that a nullor/base-emitter voltage is always zero and the norator/collector-emitter voltage may have any arbitrary value, with the load and supply currents being equal. Just as practical transistors and reference elements require biasing so practical voltage regulators carry a small but finite current in $Z$ rendering the X and Y currents unequal. This current in $Z$ is much less than typical load current and is also kept moderately constant by careful internal design of the i.c. If the equivalent circuit has a potential-divider of low resistance then $V_o = (R_2/R_1 + 1)VR$ and the regulator gives a regulated voltage of any required output value $V_o$ up to the device breakdown limits.

Fig. 3(a) shows a modification that is proposed for increasing the output current. By redrawing as in Fig. 3(b) the circuit is seen to be equivalent to a complementary Darlington pair (again assumed to be ideal) fed from the same voltage reference i.e. the current capability is scaled up by $h_{FE}$ with no change in output voltage. If the load is placed in series with the device as in Fig. 4 but with a dummy resistor $R$ added between $Z$ and $Y$, then the load current is defined as $V_o/R$, with the addition of the small current in $Z$ mentioned above.

Reference

As the performance/cost ratio of integrated-circuit voltage regulators continues to improve it is tempting to ignore discrete-component designs altogether.

This is dangerous because the constraints of i.c. processing, for example absence of high performance p-n-p transistors, can bring limitations. In particular for highest efficiency the output transistor has to operate in common emitter, and if a separate power device has to be added the advantages of a single-chip solution are abated. The circuit shown is a neat solution in that the input-output voltage differential can fall to $\sim 0.5V$ or even towards zero if the current limiting network is eliminated (the 0.5Ω resistor $T_4$ etc). The performance claimed for this circuit is particularly good in respect of regulation against supply and load changes, the current-limiting is of the fold-back variety and the transistor types are non-critical.

Sets 25 & 26: RC oscillators

One might have expected the introductory article to deal with the point of theory concerning nullors. They are instead introduced in a concise and easily assimilable way on page 67, making any explanation here superfluous. Those unfamiliar with nullors will see from page 60 the usefulness of the concept in rearranging and regrouping circuits to generate new circuits (even though the method gives no phase information). See also Circuit Designs 1, pp.122/3. Circuits covered are obvious from the titles, the first ten or 11 covering Wien circuits, single-component frequency control and amplitude control methods. Set 26 deals mainly with phase shift and T-circuits.

Background article 64
Nullors, networks and n.i.cs 67
Current-driven Wien oscillator 68
Voltage-current Wien oscillator 69
Op-amp Wien oscillator 70
Micropower oscillator 71
Amplitude-control methods 72
Baxandall RC oscillator 73
NIC oscillators 74
Single-element-control oscillators — 1 75
Single-element-control oscillators — 2 76
Up-date circuits 77
Passive and active networks 78
Parallel-T oscillators 79
Phase-shift oscillators 80
FET phase shift oscillators 81
CDA oscillator 82
Two-integrator loop oscillator 83
Four-phase oscillator 84
All-pass network oscillator 85
Gyrator oscillators 86
Wide-range gyrator oscillator 87
Up-date circuits 88
Amplifiers oscillate; oscillators may not. These guiding principles have been developed and confirmed over many years of patient experimenting, not least during the preparation of Circards. Early versions of operational amplifiers were particularly critical of the source/load/supply impedances and were prone to oscillate at high frequencies unless carefully used. Early transistors had low values of current gain and cut-off frequencies making it difficult to produce controlled oscillations.

These properties point to a dividing line between oscillators and amplifiers with feedback viz that they are of the same kind, differing only in the quantity and nature of the feedback. The point can be illustrated by Fig. 1 in which an amplifier of gain $A$ has a portion of its output voltage $B$ subtracted from the signal at the input. The gain of the amplifier with feedback can be greater or less than $A$, and the output will in general differ in phase. For well-controlled characteristics, the phase-frequency response has to be such that the feedback does not become regenerative until the magnitude of the $\beta A$ term is below unity.

Feedback theory is formally expressed in many different ways, but one graphical approach that is helpful is to consider the root locus (Fig. 2). The graph plots the locus of the system transfer function as the frequency varies. Points on the horizontal axis correspond to phase shifts of zero (to the right of the origin) and 180° (to the left). Points on the vertical axis represent phase shifts of +90° and -90°. The distance of a point from the origin represents the magnitude of the transfer function. Thus in many amplifiers the region of the locus near the horizontal axis would represent a very wide range of frequencies since the gain remains constant and the phase-shift is zero or 180° over this range.

An important point on this graph is the point $1 \angle 0°$. A general criterion, due to Barkhausen, suggests that if the locus of the system response does not enclose this point then the loop may be safely closed and the feedback will not cause the amplifier to become unstable. An exceptional state of conditional stability can result where the amplifier/feedback network has multiple reactive elements producing a complex locus which would enclose the point in the event of a fall in the magnitude of the gain.

When the locus passes through the point, we have $\beta A = 1 \angle 0°$ commonly called positive feedback and this constitutes an oscillator of constant but undefined amplitude, i.e. the signal feedback is just sufficient to sustain the output unchanged and without the need for an input signal. Alternatively we may view it as an amplifier of infinite gain, the denominator of the expression, $1 - \beta A$, having gone to zero.

The inevitable small variations in $\beta$ and $A$ caused by temperature, supply or load conditions as well as by long term drift in component values, cause the amplitude either to decay away ($\beta A > 1$) or to increase ($\beta A < 1$). The limit is set by non-linearities in the system either inherent to the amplifier or deliberately added externally in the feedback network(s). These reduce $\beta A$ and the oscillations settle down to a stable situation in which the mean value of $\beta A$ over the cycle is unity.

For good frequency stability a number of precautions have to be observed (1) the amplifier should have negligible or very closely controlled phase-shift at the frequency of oscillation. (2) Amplitude of oscillation should be controlled to minimize distortion, since harmonics are fed back to the

![Fig. 1. A fraction of the output is added to the source at the input in deriving a standard form of the basic feedback equation. Positive feedback occurs when $\beta A$ is positive.](image)

![Fig. 3. These three networks have an identical transfer function and can be used interchangeably in oscillators.](image)

![Fig. 2. If the in-phase and quadrature components of the overall loop gain are used as axes, the locus as the frequency is varied indicates the stability of the system.](image)
input and the resulting intermodulation reduces the frequency of oscillation below that predicted from the simple theory. (3) Input and output impedances of the amplifier must not load the RC networks significantly.

A major class of oscillators which includes the Wien bridge circuits, uses networks as in Fig. 3. Using equal values of R, C throughout, the transfer function of each of these circuits is the same, with the output reaching a maximum of one third of the input when the phase shift is zero. Frequency is \(\frac{1}{2\pi RC}\). Each can be used with an amplifier of gain +3 to produce sustained oscillation. Many other combinations of these networks and amplifiers can be devised, by using current, transconductance and transresistance amplifiers.

Amplitude control may be via a gain-controlled amplifier whose gain is reduced as the output exceeds a given value, usually via a peak- or mean-rectifier and f.e.t. or similar controlled resistor. The classical solution is to use the RC network as part of a bridge configuration with a high-gain amplifier monitoring the bridge unbalance. One of the bridge resistors is made amplitude sensitive, e.g. a filament lamp or thermistor arranged so that increasing amplitude of oscillation increases the amount of negative feedback thus stabilizing the oscillation amplitude Fig. 4.

These oscillators are controlled in frequency over a very wide range commonly by switching in pairs of capacitors as the coarse control or range-setting, with ganged resistors for fine control. The reverse is possible with high input-impedance amplifiers where high resistances allow the use of ganged tuning capacitors. Single-element control has obvious advantages of simplicity and economy, as well as the possibility of remote control via light dependent resistors and the like. Most solutions to this problem require a larger number of amplifiers to provide separate feedback paths by splitting the passive network in some way, and in addition there is an effective loss in Q of the system that results in increased distortion. One example out of many that have been designed is shown in Fig. 6. Frequency ranges of up to three decades have been reported, while the amplitude control mechanisms are similar to those above.

T, phase-shift, and two integrators

Since both inverting and non-inverting amplifiers are obtainable, circuits can be designed in which the phase-shifts in the external networks are 180° and 0° (or 360°) respectively. An example of the former is the classical three section phase-shift circuit shown in Fig. 7. Using equal values of resistors and capacitors the network attenuation is rather large, the output being 1/29th of the input at the frequency where the overall phase-shift is 180°. It is usually preferred to the alternative form using interchanged Rs and Cs, because the increased attenuation at high frequencies reduces the harmonic distortion and with it the corresponding shift in frequency.

If the RC values are scaled, then with \(n\) large each section can be analysed separately since the loading effects of the following section can be ignored. The phase shift of each section is then close to 60° at the critical frequency with a halving of the signal level. The amplifier then needs a voltage gain of -8 but the demands on input and output impedances are more severe (the current that can be drawn from the network without loading it becomes very small while the current needed to supply it increases). Alternative methods are to separate the phase-shift networks, using one amplifier of gain -2 between each section. Fig. 8 shows a related circuit that combines the gain and phase-shifting sections. Variants such as this are convenient for three-phase oscillators particularly as gain required from each stage is minimal.

A separate class of oscillators is based on null/notch/hand-stop RC networks in which the signal transfer function tends to zero or a low value at a particular frequency (Fig. 9). These can give improved sharpness of tuning with lowered distortion, but interaction between the impedances can make them less tolerant of component drift. More important is the difficulty of tuning such circuits since several components need to be changed simultaneously. Separating the paths through these networks and driving them with individual amplifiers can allow control of the frequency without change in the amplitude condition.

There is a very close relationship between active filters and oscillators. They share common passive networks, and in many cases one can be converted simply into the other by adjusting the damping factor (sharpness of tuning). A very important configuration which has wide application in both fields is the
two-integrator loop (Fig. 10). Well-known in analogue computing, it and its near relatives appear under a number of names including 'bi-quad,' 'triple,' 'state-space,' 'gyrator' etc. For ideal amplifiers the circuit Q is infinite without the need for positive feedback and it is particularly suited to the design of high-Q active filters by the addition of a small amount of negative feedback. In practice the net feedback will depend on internal phase-shifts as well as finite-amplifier gains, and both positive and negative feedback may be used to produce controlled oscillations.

If a single resistor or capacitor is varied then with ideal amplifiers, the circuit is still on the edge of oscillation, but the frequency at which oscillation can be sustained is varied. Single-element control of frequency is of considerable advantage in simplifying the construction of oscillators, since dual-gang controls are difficult to keep in a well-matched condition over a wide range. The feedback needed remains small under these conditions, being sufficient only to overcome amplifier imperfections and the finite Q of the capacitors.

Because the amount of feedback required is small it can be introduced via a clipping network that comes into action sharply at a particular amplitude without bringing in significant distortion. This gives instantaneous control of amplitude without the time delay due to heating effects with thermal control. In addition there are three separate outputs with 90° phase differences and the addition of another inverting amplifier gives the fourth phase if required. Again there are a number of combinations of amplifiers and network which share these desirable properties as in Fig. 11. In all of them there is a tendency to instability at high frequencies where the slew-rate limiting of the amplifiers produces a jump phenomenon that locks the oscillator into an output oscillation of higher frequency and uncontrolled amplitude.

Some of these networks are more usually interpreted as forms of impedance inverters/converters, in particular the gyrator, viz. a circuit that with a capacitor across one port synthesizes a purely inductive reactance across a second port. If that port has a second capacitor placed across it, a resonant circuit is established which sustains oscillation if a small amount of positive feedback is introduced. It is instructive to draw out the passive networks in such circuits since this clarifies the interrelationships between the various forms of oscillator and filter (Fig. 12).

Fig. 7. If the impedances are graded to minimize loading of each section on the preceding one, each contributes 60° to the overall phase-shift at the frequency of oscillation.

Fig. 8. Three amplifier stages with defined gain/phase characteristics comprise a three-phase oscillator.

Fig. 9. T-networks can have zero-transmission at a particular frequency. Oscillators utilize positive feedback with the T-network in a negative feedback path.

Fig. 10. Two integrators plus an inverter form the nucleus of a number of oscillators and filters.

Fig. 11. Gyrators are a class of circuits that synthesize an inductive reactance from a capacitor. An oscillator results from resonating the reactance with a second capacitor.

Fig. 12. The previous two oscillators share a common passive network and can be shown to be functionally identical.
Nullors, networks and n.i.cs

Two circuit elements were devised to complement the short-circuit (zero p.d. at any current) and the open-circuit (zero current at any p.d.). They are the nullator (zero V, I) and norator (arbitrary V, I). Neither has a separate real existence but a high-gain amplifier embedded in a feedback network approximates to the combination. Such an amplifier can be replaced in circuits by a nullor, the name given to the combination, and this can simplify drawings by allowing the separation of input and output networks.

An op-amp has the constraint that one end of the norator is grounded, a transistor that of a common point between nullator and norator. An f.e.t. has a lower gain and requires an additional resistor to simulate it. With multi-amplifier systems if several points are equipotential because of nullator action there are multiple ways of achieving this effect.

To illustrate this consider the differentiator circuit. Feedback theory indicates the alternative of placing an integrator in the feedback path of an amplifier, and this solution can be convenient in analogue computing. Re-drawing in nullor form, and combining the nullators and norators, shows that the system is equivalent to an amplifier followed by a differentiator. It suggests that drawing in nullor form, and then re-pairing is another method of generating new circuits. Yet another method is that of interchanging the positions of a nullator and a norator in changing the source and load in bridge measurements. This lead to four forms of oscillator derived from a common passive network.

A standard network in RC oscillator design is that due to Wien, having a transfer-function

\[ \frac{V_o}{V_i} = \frac{1}{3 + j(\frac{f}{f_0} - \frac{f_0}{f})} \]

where \( f_0 = 1/2\pi CR \). Two other networks of cascaded lead and lag sections have identical transfer functions for identical R, C values. The response is a maximum of 1/3 with zero phase shift at \( f = f_0 \), falling at both high and low frequencies. If the network is inverted (taking the lead-lag as an example) the response has a minimum value at \( f = f_0 \). The former network can be used as a feedback path, balanced against resistive negative feedback to inhibit oscillation except at the peak of the response; the latter network is balanced against positive feedback, the latter dominating only at the trough in the network's response.

Re-drawing this inverted network gives the bridged-T. The nullor gives no information on the phasing of input-output to be used in practical amplifiers that implement it. A class of circuits called negative impedance converters (n.i.cs) show the advantages and snags. Resistive feedback across an amplifier with positive voltage gain leads to a negative input resistance \( R_i = \frac{V_i}{I_i} = \frac{V_i}{-V_o/R} = -R \). If the input phasing is reversed the input impedance is still found to be \( -R \), but is now stable only for source resistances \( > R \) instead of \( < R \).

Extracting the amplifier and feedback resistances leads to a form of n.i.c. which can be generalized to the form shown, where \( Z_1 = -Z_2/Z_3. \) This allows negative resistances, capacitances and inductances to be synthesized using only Rs and Cs. If a n.i.c. is combined with parallel and series RC networks which cancel at a single frequency, oscillations result.
Current-driven Wien oscillator

![Circuit diagram]

**Typical performance**
- $V_{CC} = +9V$, 2.7mA
- $R_1 = 2.2k\Omega$, $C_1 = 56pF$
- $R_2 = 4.7k\Omega$, $R_3 = 1.5k\Omega$
- $R_4 = 470\Omega$, $R_5 = 470\Omega$
- $T_{TR1}, T_{TR2} 1/5 \times CA3086$
  (Note: $T_{RE}$ emitter is pin 13)

![Waveform]

Circuit description

Many RC oscillators use a Wien network as the frequency-determining part of the closed loop and very often the Wien network is used where it may be driven from a low-impedance source and loaded by a high-impedance load as shown right.

However, in many applications it is more convenient to use the current dual of the above network which is driven from a current source and ideally is loaded by a short circuit. The reciprocity principle requires that this network has the same transfer function as the voltage-driven form, which is $V_{out} = V_{in}Z_2/(Z_1 + Z_2)$ where $Z_1$ is the impedance of the series-connected RC pair and $Z_2$ is the impedance of the shunt-connected RC pair. The resulting dual network is then as shown top right.

The transfer function of this network is given by $i_{out} = i_{in}Z_2/(Z_1 + Z_2)$.

The circuit shown above left is an RC oscillator employing the current-dual network to close the loop of a bipolar transistor amplifier which is in the form of a d.c. feedback pair. The Wien network is supplied from the collector of the dual transistor network which serves as a reasonably good current source due to the increase in output impedance provided by the feedback network. The output of the Wien network is loaded by the d.c. feedback network in shunt with the input impedance at the base.

Tr1. Whilst not an ideal load negative feedback through $R_2$ provides a sufficient approximation to the desired low value.

In order to provide sustained oscillations the closed-loop phase-shift must be zero and the amplifier must provide sufficient gain to overcome the losses in the Wien network.

For the usual case of equal $R_1$ and equal $C_1$ in the series and shunt parts of the Wien network the frequency of zero phase shift occurs at $f_0 = 1/(2\pi RC)$ and at this frequency $f_{out} = f_{in}/3$.

Hence, the minimum gain required from the amplifier is 3. In the d.c. feedback pair shown this current gain is given approximately by $A = 1 + R_2/(R_3 + R_4)$. Resistor $R_4$ is provided in the form of a variable to allow convenient adjustment of the loop gain to provide a reasonably-sinusoidal output waveform. The more the gain exceeds the critical value the more distorted will the output waveform become and the lower will be the frequency of oscillation. (See graphs for effect of increasing supply voltage, for example, after setting the critical condition at a lower value of $V_{CC}$.)

Component changes

Useful range of $V_{CC} = 4$ to $+20V$. Scale RC values for lower-frequency operation. For higher oscillation frequencies, $f_0$ will become less accurately predictable due to presence of internal transistor capacitance and any shunt capacitance of load. $R_4$ will need readjustment if operating frequency is changed.

Separate transistors may be used or the whole circuit excluding capacitors and $R_4$ integrated on a single monolithic chip.

Circuit modifications

- Any other frequency-determining network which operates with an optimum source impedance tending to infinity (a current source) and an optimum load impedance tending to zero can be used in place of that shown.

Two examples are given.
- D.c. feedback pair forms of these networks are shown below. C, R and R to $R_4$ same values as original circuit. $X_C$ tends to zero at $f_0$ and $R_4$ is large, say 10kΩ.

Further reading

RC oscillators

The above oscillator circuit uses a Wien-network which is fed from an emitter-follower Tr1 and is loaded by a common-base Tr2. This realization is an example of an RC oscillator which has the Wien-network ideally fed from a voltage source and loaded by a short-circuit as shown below. At the frequency of oscillation, the loop phase shift is zero and the transadmittance of this frequency-determining network is (1/3R) siemens. Hence, to sustain impedance of the common-base stage only an approximation to a short-circuit load on the network. However, as R3 is much greater than the common-base stage input impedance, virtually all of the output current from the RC network enters the emitter of Tr1. Since Tr1 has a reasonably large current gain, the base current is neglected to a first approximation, so that the collector current in Tr1 is virtually equal to the output current from the RC network. Thus, assuming that the voltage gain of the emitter follower is only slightly less than unity, the amplifier gain \( A_2 = \frac{V_{out}}{I_{in}} \) is essentially equal to R3. The circuit will oscillate, theoretically, provided that R1 is made three times the value of R with C chosen to determine the frequency of oscillation.

Typical performance

\[ V_{cc} + 9V \]
\[ R = 4.7k \Omega, C = 4.7nF \]
\[ R_3 = 50k \Omega \text{ var. (typically 15k \Omega)} \]
\[ R_2 = 22k \Omega, R_4, R_5 = 2.7k \Omega \]
\[ C_1 = 2.2 \mu F \]
\[ Tr_1, Tr_2 \text{ 1/5 \times CA3086} \]
(Note Tr1 emitter is pin 13)

Circuit description

In the above circuit, for example, where R was selected oscillations the amplifier must provide a current-to-voltage gain \( A_2 \) of 3R ohms to make the closed-loop gain unity i.e. \( A_2 = 1 \).

In the circuit arrangement the emitter follower is only an approximation to the ideal voltage source to feed the RC network and the input as 4.7k \( \Omega \). R3 should be 3 x 4.7k \( \Omega \) = 14.1k \( \Omega \) and in practice, using 5\% tolerance resistors, the circuit just oscillated with \( R_1 \approx 15k \Omega \).

Component changes

The useful range of supply voltage is approximately +4 to +20V, but note that changing the supply will change the operating currents and hence the overall gain of the amplifier. Hence, large changes in supply voltage will change the loop gain sufficiently to either prevent oscillation or to severely distort the output waveform. For example, in the above circuit the oscillations cease at \( V_{cc} \) of +6V (having adjusted \( R_1 \) with \( V_{cc} \) of +9V) and the output waveform becomes clipped on positive peaks when \( V_{cc} \) exceeds about +11V. Thus, change of \( V_{cc} \) will normally require a readjustment of \( R_1 \) for a reasonable sine wave output waveform.

Scale RC values for different oscillation frequencies but note that C scaling only allows \( R_1 : R \) ratio to be maintained without changing \( R_1 \) significantly.

Circuit modifications

- If it is desired to change the frequency of oscillation by changing both the R and C values, but without changing the d.c. operating conditions, then \( R_1 \) can be fixed and the a.c. closed-loop gain adjusted by the arrangement shown.
- Another network having the same transfer function as that shown already at the frequency of oscillation is shown on the left. Again the frequency of oscillation is given by \( f_0 = \frac{1}{2 \pi CR} \) Hz and the required amplifier gain is again \( A_2 = R_3 \) in the ideal case.
- A practical realization is shown bottom again using an emitter follower and a common-base stage.
- The same component values may be used for the same frequency of oscillation.

Further reading

Op-amp Wien oscillator

Typical data
- $\pm V_s \pm 15V$
- IC 741
- $R_p, R_d \ 4.7k\Omega \ \pm 5\%$
- $C_i, C_d \ 0.1\mu F$
- Frequency 355Hz
- $R_j \ 3.4k\Omega, \ R_s \ 6.6k\Omega$
- Harmonic distortion 0.4%.
- Output 26V pk-pk up to 14kHz
- Drops to 16V pk-pk at 27kHz

Circuit description
This is a single-frequency oscillator circuit which may be envisaged as a bridge network, where oscillation will occur when the bridge is balanced and the differential input to the amplifier is near zero. Positive feedback is applied via two reactive arms, and negative feedback via the resistor potential divider $R_i, R_s$. The gain of this loop is $(R_s + R_i)/R_i$. The gain of the positive feedback loop is real at a positive loop frequency that makes $A_s = 1 + R_d/R_s + C_d/C_i$ and if $R_s = R_i$, $C_i, C_d = C_i$, then $A_s = 3$. Oscillation then occurs when $A_s = 3$, or when $A_s \approx 2R_i$. This oscillatory condition will require a minimum distortion to maintain a stable output. However, if the $A_s$ gain falls below this value, oscillation will stop due to the negative feedback being more than the positive feedback, and if the gain increases, the output amplitude will increase until it is limited by non-linear distortion. This could be the power supply limitations or additional network limiting.

In general the frequency of oscillation is given by $f = 1/2\pi \sqrt{C_i C_d R_j R_s}$ Hz for $C$ in farads, and $R$ in ohms.

Component changes
- Varying $C_i (= C_d)$ over the range of 4.7uF to 220pF provides frequency range above. (Slew rate-limiting of the op-amp causes fall-off at lower C values.)
- Simpler technique maintains $C$ constant, but demands ganged potentiometer for $R_s$ and $R_j$ for frequency adjustment with single control, i.e. ratio $R_j, R_s$ is maintained constant.
- Amplitude limiting is available using either of the additions shown in Fig. 2.
- Nominally $R_s$ should be much greater than $R_d$, and $R_s$ in parallel with $R_j$ should be less than 2$R_j$ when the diodes are conducting (see Fig. 2). $R_j \ 3.3k\Omega, \ R_s \ 8.62k\Omega$
- $R_j \ 22k\Omega$, frequency $354 \pm 1Hz, \ V_s \pm 12V$
- Amplitude is stable then for power supply increases up to $\pm 18V$. With diode or zener diode limiting, the frequency is more independent of the power supply, but is more dependent on the break level of the limiting network. Another advantage is that instantaneous oscillation is available at low frequencies. With no limiting, time for build up of amplitude is frequency dependent.
- Note that at high frequencies, since gain of amplifier is finite, it is more noticeable that a small differential input must exist, which demands an adjustment of the $R_j, R_s$ ratio (see second graph).

Circuit modifications
Circuits above, Figs. 3 to 5, provide exactly the same performance as the basic circuit. Notice that the output and ground terminals are shifted depending on op-amp connection (see Nullors, card 1).

Fig. 2

Fig. 3

Fig. 4

Fig. 5

With limiting network, typical performance given below.
- Diode limiting for circuits 1, 3, 4, 5.
- Outputs: 16.8, 16.8, 16, 15.6V pk-pk, harmonic distortion: 0.95%, 0.95%, 0.9%, 0.89%, respectively.
- $R_j \ 6.39k\Omega, \ R_s \ 3.61k\Omega$ for $R_s 22k\Omega$.
- Zener limiting for circuits 1, 3, 4, 5.
- Outputs: 21.5, 26.5, 26.5, 19V pk-pk, frequency: 350, 352, 352Hz, harmonic distortion 5, 5.9, 5.9, 5.1%, respectively.
- $R_j \ 6.9k\Omega, \ R_s$

In general, a trade can be made between distortion and amplitude stability.

Further reading

Cross references
- Set 25, cards 6, 5.
- Set 21, card 4.
Micropower oscillator

Circuit description
This is one form of a negative impedance converter circuit. It may be considered as a two terminal device, and be inserted in a constant current path that may already exist in a circuit. The circuit will provide a low voltage amplitude sinusoidal oscillation (but not necessary low distortion) with a minimum of components, no biasing being necessary but the choice of components is critical. Provided the appropriate gain and phase shift are possible, transient analysis shows that oscillations will build up exponentially in such a network after shock excitation, if the circuit losses are negligible. This is achieved by presenting a negative resistance across an existing circuit resistance. Oscillations are sustained when the average value of the negative resistance provides the correct ratio for the frequency chosen.

In the above circuit, $V_{be}$ of the transistor is neglected, and hence the direction of current through the impedance $Z$ must be as shown: through the collectors. The impedance presented at the input terminals,

then is $Z_{in} = V/(V/Z) = -Z$. The loop impedance for the given network is:

$$R_2 + \frac{1}{\omega C_1} - \frac{R_1/\omega C_1}{1 + \frac{R_1}{\omega C_1}} - \frac{R_1}{\omega C_1}$$

The loop reduces to

$$1 - \frac{1}{\omega C_1 R_2 R_3} + \frac{R_1 + \omega C_1 R_2}{\omega C_1 R_2 - \omega C_1 R_3}$$

For oscillation, the loop impedance should be onset of visible distortion. Circuit will operate at lower currents but with lower output — see graph.

Typical data for absolute minimum current of 1.58µA, $R_1 = 13.6k\Omega$, $R_2 = 8k\Omega$, $C_1 = 10nF$, $C_2 = 22nF$, $C_3 = 3\mu M\Omega$, $V_1 = -20V$. To obtain low currents demands scaling of zero giving $C_1/C_2 + R_2/R_1 = 1$ or $R_1 = 2R_2$, $C_1 = C_2/2$ and $f = 1/(2\pi \sqrt{C_1 R_2 C_1 R_1})$

Component changes
Minimum value of $R_1 = 2.73k\Omega$
Frequency 320Hz
Variation of output with $R_1$ shown over.

$R_2$ maximum 2.9kΩ before resistors for optimum performance.

Circuit modification
- Micropower operation with the classical Wien network (this series, card 4) is possible with the LM4250 programmable operational amplifier. For a fixed dual polarity supply, one external resistor determines the quiescent current and consequently the slew rate and gain-bandwidth product.

Voltage range is $\pm 1$ to $\pm 18V$.
Care is necessary in the choice of frequency in relation to the programmed set-current because of the slew-rate and gain-bandwidth dependence.

For a cosine waveform

$$\text{frequency (Hz)} = \frac{\text{slew rate}}{2\pi \sqrt{V_{\text{max}}}} (V/s)$$

where $V_{\text{max}}$ is the peak value

of the output.

Working range of an op-amp should not exceed 1 to 10% of the unity gain frequency to avoid severe unbalance at the bridge input, i.e. at $I_{\text{set}} = 1\mu A$, gain-bandwidth product is 70kHz. If oscillator frequency is 700Hz, amplifier gain is 100, and hence input required is 1% of output. If set current is reduced to 0.1µA, then for same frequency gain is only 10.

Hence for the same output greater unbalance required at the input.

- Normal diode limiting possible at much lower currents.
- High values of resistance usable to minimize power drain, however stray-capacitance effects may then be significant for designed frequency. High input impedance of op-amp will not load bridge arms.

Oscillator may be gated using a c.m.o.s. inverter to sink the programmed set-current, shown left.

Further reading
Linear Integrated Circuits, LM4250, National Semiconductor.

Cross references
Set 10, card 8.
Set 25, cards 8, 1, 4.
Amplitude-control methods

**Thermistor**
A bulk semiconducting resistor with negative temperature coefficient. Placed in series with a resistor, and with an increasing voltage applied, the thermistor is heated by the resulting flow of current; its resistance falls and the attenuation of the network decreases. There will be a single amplitude at which a desired attenuation is achieved. If the network is incorporated into an oscillator, where the frequency-determining network has zero phase shift together with the same attenuation (at a particular frequency) then oscillations will be sustained.

**Lamp**
Place in series with a resistor which is low enough to permit sufficient current to heat the lamp. As the voltage increases, the lamp resistance rises and again the attenuation decreases. The lamp can operate at a higher temperature than the thermistor and is less sensitive to ambient temperature changes. Its power consumption is considerably higher and the sensitivity to amplitude changes markedly less (dissipation for significant temperature rise >50mW for most lamps—as little as 3mW for thermistors designed for this application).

**Non-linear network**
Self-sustaining oscillation can also be achieved by passing the feedback through a non-linear network. At low amplitudes the diodes are non-conducting and the attenuation is determined by \( R_1 \) and \( R_2 \). For larger peaks, the diodes conduct and \( R_2 \) appears in parallel with \( R_4 \) increasing the attenuation. There will be a single amplitude of input at which the average value of the output meets the condition. There is a compromise between distortion and sensitivity of the amplitude to small changes in the resistor values.

**Peak rectifier**
A field-effect transistor has an output slope resistance that is moderately linear and is controlled by the gate-source voltage. If the amplitude of the input increases, the peak rectifier has an increased output. It is applied to the gate of a p-channel junction f.e.t. reverse biasing it and increasing its resistance. This decreases the a.c. attenuation of the network. The range is small as the f.e.t. cannot accept a large drain-source voltage in this mode without increasing the distortion.

**Thermistor**
Maximum device dissipation of 3mW for the quoted device changes its resistance by two orders of magnitude. The rise in temperature is relatively small and the final amplitude when used in an oscillator is slightly temperature dependent. A 25% change in the transfer function of the oscillator (due to either passive components or fall in amplifier gain at high frequencies) would be accommodated by an amplitude change of as little as 2% when oscillations re-stabilize.

**Lamp**
For the same change in the oscillator network (25%) the amplitude using a lamp might only be stabilized to within 20-40%. The power consumption is 10-100 times greater making it more difficult to choose a suitable amplifier. The lamp costs less and, operating at a higher temperature, is less affected by ambient changes. To extend the lamp life it is advisable to limit the power input which brings its performance somewhat nearer to that of a thermistor.

**Non-linear network**
The ratio \( R_2 : R_1 \) is set to give an attenuation less than that needed to inhibit oscillation. The diodes begin to conduct when the peak voltage across \( R_3 \) exceeds 0.6V. At some higher voltage the attenuation exceeds the critical value. With \( R_3 =0 \) this state is rapidly reached and the attenuation is controlled within reasonable limits—50% change for a change in the oscillator network of 15%. With \( R_3 = 22k\Omega \) the amplitude has to change by a much larger amount to cope with a corresponding change in the network—in this example a greater than 5:1 range. In return the resulting distortion is much lower.

**Peak-rectifier/f.e.t.**
The network consisting of \( D_o, C_2, R_3 \) feeds the gate of the f.e.t. with a voltage equal to the peak input less the diode forward drop. For input amplitudes above 0.6V peak the f.e.t. becomes reverse-biased with a drain-source resistance increasing from about 500G to many times that value. At high values of reverse bias, the range of drain-source voltages for low distortion is reduced. This conflicts with the increased p.d.s across the network that cause the bias and limits the range attenuations that can be achieved—a range of about 12% in this case which is sufficient to cope with the usual spreads.
Baxandall RC oscillator

Circuit description
The circuit below is a bipolar transistor version of a Wien network oscillator due to Baxandall. In comparison with its more common operational amplifier form it has the merit of simplicity. The usual negative supply rail for the operational amplifiers may be dispensed with, and only two resistors (R₁ and R₂) are required in addition to the Wien bridge resistors (R₃ and R₄) and frequency-determining components (R and C). Also, the Wien network resistors are arranged so that the circuit is self-biasing. This circuit simplicity is achieved at the expense of departure from the frequency of oscillation from the ideal value of \( f_0 = \frac{1}{2\pi RC} \) Hz.

In the ideal case, the circuit would just oscillate when \( R₇/R₅ = 2 \) but the finite gains in the transistors cause the critical condition to be achieved with an \( R₇/R₅ \) ratio somewhat in excess of this value. Also, as the supply voltage is varied the operating conditions of the transistors, and hence their gains, change which will require readjustment of the \( R₅ \) and \( R₆ \) ratio either to sustain oscillation or to restore the output waveforms to reasonably undistorted sinusoids. Although, with the component values shown, the output waveforms from Tr₁ and Tr₂ collectors are of different magnitudes, they have the useful feature of being in antiphase.

Component changes
Useful supply range \(+3 \text{ to } +20\text{V}\)
Useful range of R 100 to 100kΩ
Useful range of C 1n to 10µF
With given R values the frequency of oscillation can be changed without changing the d.c. conditions by changing the capacitor values only.

Circuit modifications
The output waveforms from Tr₁ and Tr₂ collectors can be made of equal amplitude as well as being in antiphase, without changing the frequency of the oscillation, by scaling the frequency-determining RC components of the Wien network as shown below. With this arrangement the impedances of the series and parallel RC components are the same (\( R₃ \)) at the frequency of oscillation so that ideally, the gain from Tr₁ collector to Tr₂ collector is \(-1\). Hence, in the ideal case \( R₇/R₅ = 1 \) for the critical oscillation condition; i.e. the gain from Tr₂ collector to Tr₁ collector is also \(-1\) giving a closed-loop gain of \(+1\).
In practice, with the circuit values R 10kΩ, C 10nF the frequency of oscillation was virtually unchanged, and \( R₇/R₅ \) was typically 1.1 to sustain oscillations with \( V_{out₁} \) and \( V_{out₂} \) typically 1 volt pk-pk and 980mV pk-pk respectively. A closer approach to the ideal state can be obtained by using two inverting operational amplifiers in place of Tr₁ and Tr₂ as shown below.

R, C, R₅ and R₆ are direct replacements from the bipolar transistor version and A₁ and A₂, which could be 741s, replace Tr₁ and Tr₂ respectively. The same scaling of the R and C values to provide equal-amplitude outputs may be used as before. These outputs are now available from low output impedance points.

As with other oscillator circuits, a bandpass filter may be obtained by setting the gain (by adjusting the ratio \( R₅, R₆ \)) just below the value needed to produce oscillation and injecting the signal through a reasonably high resistance at the inverting input to A₁. This can also be achieved with the bipolar transistor version by injecting the signal at Tr₂ base, where the need for a high impedance source is more stringent since this point is an imperfect virtual earth.

Typical performance
\( +V_{cc} = +10\text{V}, 2\text{mA} \)
\( R₃, R₆, R 10kΩ, C 10nF \)
\( R₇+R₅ 10kΩ \) (realized with 10kΩ potentiometer to adjust loop gain)
Tr₁, Tr₂ 1/5 × CA3086
(Note Tr₁ or Tr₂ emitter is pin 13)

Further reading

Cross references
Set 1, card 3.
Set 10, card 8.
N.I.C. oscillators
Circuit description
A negative impedance converter is a two-port active device which if loaded at one port with an impedance $Z$, can provide an impedance $-nZ$ at the other port. If the impedances are frequency dependent, then a frequency constraint exists, for at only one single frequency the serial and parallel RC networks have equivalent magnitudes and the appropriate phase angle to make the loop phase shift zero. The Fig. 1 circuit is of similar form to Fig. 2 for which an approximate analysis is given. Assume the base-emitter voltages are negligible. Then the signal $v_{in}$ will appear as $v_{out}$. The input signal current $i_{in}$ comprises $v_{in}/R_1$ and $i_{in} = v_{in}/R_1$ up through $T_1$. The voltage across $R_1$ is then $i_{in}R_1 - v_{in}$ which must be that across $R_3$. Therefore the emitter, thus collector, current of $T_2$ upwards is $i_{in}R_1/R_2 - v_{in}/R_2$. Thus $v_{out}$ is $-i_{in}R_1/R_2 - v_{in}R_2/R_2 = -i_{in}/R_2$. If an impedance $Z$ is across the $v_{out}$ terminals, then

$$Z_{in} = v_{in}/i_{in} = v_{out}/i_{in}$$

$$i_{out} = v_{out}/R_2 = -Z/R_2$$

If $R_1 = R_2$, $Z_{in} = -Z$.

Component changes
Another oscillator using a different n.i.c. is shown above. Separate voltage and current supplies are necessary, but low level operation is possible. Typically, for $V$ of 1V, I of 70μA, circuit will oscillate (f = 1/2πRC) to provide a peak output of about 1.2V. An advantage of these circuits is that the frequency-tuning networks have a common ground point, and a minimum of components is used. When these circuits are analysed using nullor concepts (card 7), the similarity is more obvious. The equivalent representations are given in the circuits showing nullator, norator interchange. Bridge oscillators using operational amplifiers (card 4) can also be considered as a form of n.i.c. oscillator. For the above general case $v_{2a} = v_{o2} = v_{2a}(Z_1 + Z_2) = v_{2a}$

$$i_2 = v_{2o}(Z_1 + Z_2)Z_2 - i_1$$

From Millman's theorem,

$$v_o = v_1y_1 + v_2y_2 = (v_1 + v_2)$$

$$v_o = v_1^2 + v_2^2$$

For high $A$, $v_o = v_1$ and

$$v_1 = v_1 + v_2 = v_2$$

Also

$$Z_{in} = v_{in}/i_{in} = -Z_2/Z_1$$

Further reading

Cross references
Set 25, cards 1, 5.
Single-element-control oscillators

Circuit description
As described earlier the lead/lag network, \( C_1R_1 \) followed by \( C_2R_3 \), is an alternative to the Wien network. If the network is driven by two amplifiers (see ref.) then it is possible to vary the frequency of oscillation by changing the gain of one amplifier, without changing the condition for sustaining the oscillations. This simplifies the amplitude control circuitry but still requires two amplifiers, one with variable gain. If instead the impedance level of the frequency dependent network is much greater than the resistance of the amplitude-controlling network, one amplifier can be eliminated. Resistor \( R_3 \) is tapped onto \( R_4 \). As \( k \) is reduced to zero the frequency of oscillation reverts to that of the basic Wien bridge/lead-lag oscillator viz. \( 1/2\pi RC \). As \( k \rightarrow 1 \) the frequency \( \rightarrow 0 \). This leads to a practical range of frequencies in excess of 10:1 on a single control without any serious increase in distortion. The component count is comparable to that with conventional oscillators, but the need for a twin-gang control which normally requires a good match is avoided. A further advantage of this circuit is that low frequencies are obtained without using large values of capacitance. Provided the thermistor has a large enough thermal time constant, frequencies down to 10Hz are possible with capacitances of 0.1\( \mu \)F.

Component changes
IC: any general-purpose compensated op-amp. For lower frequencies, i.e. input op-amps allow the use of larger resistors. This also minimizes the loading on the potentiometer and widens the range that can be covered by variation of \( k \) alone.
Supplies: not critical. Should be appreciably greater than required peak-peak output if rapid thermal stability of thermistor to be achieved. Typically \( \pm 6 \) to \( \pm 15V \).
\( C_1C_2 \): to suit frequency range, but 220\( \mu \)F to 1\( \mu \)F possible. Normally \( C_1=C_2=C \).
\( R_1, R_3 \): 1k to 1M\( \Omega \). High values only possible if i.e.t.

op-amp available, e.g. CA3130. Allows very low frequency with suitable amplitude control mechanism. Normally \( R_1=R_2=R \).
\( R_3 \): selected to suit thermistor.\( R_4 \approx R \), typically 100 to 470\( \Omega \).
\( R_5 \): not critical. Minimizes offset due to unbalanced input currents. Excessive offset disturbs amplitude control by permanently heating thermistor.

Circuit modifications
- Adding a unity gain buffer amplifier between \( R_4 \) and \( R_5 \) removes interaction permitting wider range for fixed Cs. End-resistance effects on \( R_4 \) prevent \( k \rightarrow 1 \) and a voltage gain \( >1 \) in the buffer stage corrects for this. Some versions of this circuit can achieve a range in excess of 100:1 on a single potentiometer.
- A simpler buffer may suffice in some applications where only the impedance levels are critical. A source follower removes the loading on \( R_4 \), though the maximum buffer gain is unlikely to exceed 0.9, i.e. range of frequencies is restricted.
- The original circuit again has a related form in which output and ground on the bridge are interchanged as are the inverting and non-inverting inputs. This is in line with the results on the basic Wien bridge oscillator (cards 2, 3, 4). Performance is basically similar to the original. The advantages of alternative configurations are that different components are grounded which can simplify frequency and amplitude control.

The nullor form is shown. It gives no information on phasing can make it easier to generate new versions. An alternative viewpoint is that of shifting the groundpoint in the system.
- Further oscillators (not shown) interchange the locations of the Cs and Rs to make lag-lead oscillators. These can be used with inverting buffer amplifiers where it is required to reduce the frequency of oscillation below the basic value \( 1/2\pi CR \).

Further reading

Cross reference
Set 25, card 10.
**Single element control oscillators—2**

**Circuit description**
A circuit given by Brokaw (see ref.) used a modified form of Wien bridge oscillator. In it, one of the frequency determining resistors is varied, while a second amplifier has a variable gain controlled by that same resistor. The form of circuit used (see over) gave a wide range of frequencies on a single control with no change in the amplitude control condition. By drawing the nullor equivalent circuit the alternative form was found in which one of the amplifiers was used as a voltage follower. This allows the substitution of specially optimized voltage followers such as the LM310 to minimize errors in this stage. For even simpler circuits less demanding of performance can be covered. Oscillator amplitude stability $\pm 1\%$ from 120Hz to 15kHz, $V_s \pm 10$ to $\pm 15\%$.

**Typical performance**
$V_{in} = 741$
$R_1, R_2 = 2.2k\Omega$
$C_1, C_2 = 0.047\mu F$
$R_3 = 2M\Omega$ log
$R_4 = 470\Omega$
$R_5$ ITT thermistor R54
At f 1kHz, $V_o = 6.4V$ pk-pk
T.h.d. 0.1%
$f_{max} > 18kHz$ as $R_5 \rightarrow 0$
$f_{min} < 120Hz$ as $R_5 \rightarrow 2M\Omega$

**Component changes**
$V_{in}$: any compensated op-amp. For low frequency operations, the increase in $R_3$ results in greater errors due to op-amp input currents, and f.e.t. input stages would be better. As indicated above, 100 : 1 range is readily obtained with general purpose units.
$C_1$ can be replaced by a voltage follower, source follower, Darlington-connected emitter-follower etc. A useful feature is that d.c. offset in this stage has no effect.
Supplies: Not critical. Usual range 5V to $\pm 15V$ for op-amps. Restriction mainly placed by choice of amplitude control devices/circuits.
$C_1, C_2$ to suit frequency range but typically 1nF to 1µF.
$R_3 = 1k$ to 100kΩ.
$R_5$ Range should be wide if frequency range is to be great $\frac{f_{max}}{f_{min}}$.

Since $\frac{c}{\sqrt{R_3}}$, typically $R_3$ may range from $100\Omega$ to $>1M\Omega$.

$R_4$ For $C_1 = C_2$, $R_4 = R_5$ for amplitude control and $R_5 = R_3$ is the remaining condition. $R_4$ chosen to suit the particular thermistor used—see manufacturer’s data.

**Circuit modifications**
- The input of each amplifier is replaced by a nullor, the output-ground port by a norator and the circuit is redrawn in this nullor form in Fig. 1. Points E, C, B and A may be at arbitrary relative potentials because of these norators. One alternative configuration having the same property is Fig. 2. This can also be interpreted as a shift of ground point from E to C.
- Re-pairing of these nullators and norators leads to the practical circuit of Fig. 3 given in a recent reference. It is a high performance oscillator with a frequency range 200 : 1 but again uses f.e.t. input amplifiers. A number of other oscillators can be similarly developed by moving the norators to change their common point, and then cross-pairing the nullators and norators in different ways.

The disadvantage of the nullor approach is that it gives no information as to the phasing of the amplifiers. This has to be deduced once the format of the circuit has been established by considering the feedback paths. The advantage is that by generating fresh circuits, particular units will have the merit of having anti-phase outputs, grounding of more convenient components or will suggest simplifications not apparent in the original.

- A suitable amplitude-control network for the circuit of Fig. 3 is suggested in ref. 1 and is shown below. As the amplitude increases the diodes conduct and the average value of $R_5$ is reduced until it equals $R_5$—the condition for stable oscillations.

**Further reading**

**Cross reference**
Set 25, card 9.
The reference quoted brings out two points worth noting. Amplitude control by non-linear feedback is a known method of rapidly stabilizing an oscillator. The disadvantage is that it can be difficult to combine stable amplitude and low distortion, the degree of non-linearity for the first inhibiting the second. One cause of distortion is unequal clipping because of unmatched zeners. By placing a zener inside a full-wave bridge of matched diodes the clipping is identical for both polarities minimizing distortion. The diodes are part of an array and the
temperature coefficients of zener and diodes are said to achieve good temperature compensation. The amplifier has p-mos. input devices allowing large resistors and hence small capacitances for low-frequency oscillations. The high slew-rate allows full output (~16V pk-pk, quoted) up to 180kHz. Better use of the high gain-bandwidth follows from scaling the series impedances down and reducing the minimum gain for oscillation. The modified relationships are:

\[ f = \frac{1}{2\pi \sqrt{R_a R_b C_1 C_2}} \]

\[ R_a = \frac{C_1}{C_2 + \frac{R_3}{R_1}} \]

**References**


Voltage control can be applied to lead-lag and Wien oscillators in various ways. One approach is via the Blumlein-Miller effect of Fig. 1 where the input resistance is reduced to very small values as \( A \to -\infty \). This requires grounded resistances and to modify the passive network to permit this the sustaining amplifier requires a controlled gain and differential inputs (Fig. 2). The resistors \( R' \) then represent a pair of circuits as in Fig. 1 with voltage-controlled amplifiers providing the variable gain to set \( R' \). Such an amplifier (Fig. 3), similar to Set 22, card 8, can be used as the sustaining amplifier of Fig. 2 with the control voltage pre-set or driven from a peak or mean-sensing circuit for amplitude control. The number of amplifiers can be reduced to two in a circuit related to that of card 9. The low-gain needed for sustaining oscillations (~3) is defined by the resistor \( R_p \) between the emitters while the variable gain amplifier setting the frequency can be as in Fig. 4. By extension the Blumlein-Miller effect can be applied to LC oscillators to replace a capacitor that normally appears in a feedback path by either a grounded capacitor or one small capacitance across a separate amplifier. If \( A_1 \) is fixed to sustain oscillations, then \( A_2 \) varies the effective capacitance and hence the frequency without disturbing the amplitude condition.

Saha, S. K. Electronically tunable RC sinusoidal oscillator,


Passive and active networks

**T-networks.** The parallel or twin-T network is widely used to obtain a sharp null at a given frequency. By combining this with a small amount of positive feedback oscillations may be sustained at the null frequency if the network is in a negative feedback path i.e. inhibiting oscillation at all other frequencies. For other ratios of parallel and series arm impedances, an inverted output of reduced magnitude is obtained, and this can be applied directly to the inverting input of an amplifier. An apparently new oscillator follows from a change in ground point on the T-network or by redrawing the circuit in nullor form. The output is still applied between A and C and the amplifier is driven by the resulting p.d. between B and C. The network now has an in phase output slightly greater than its input. If the original transfer function $T_1$ is negative then the new transfer function becomes $T_2 = 1 - T_1$ i.e. $> +1$. A second network has a minimum response at a given frequency and can also be used as negative feedback combined with resistive positive feedback to initiate oscillations. The network is the Bridged T, Fig. 2. Inverting it yields a network with a peak in its response if the output is taken between B and A, and this is the previously described lag-lead network. The response is identical to that of corresponding lead-lag and Wien networks.

*The oscillators may be interpreted as (i) frequency dependent n.f.b. with a minimum value at a given frequency just insufficient to neutralize the fixed positive feedback. (ii) frequency-dependent positive feedback just large enough at the same frequency to overcome the fixed negative feedback. Alternatively they may be recognized as particular forms of the bridge oscillators described in the previous set of Circards.*

**Phase-shift networks.** Cascaded RC networks produce a lagging phase-shift while attenuating the signal. A minimum of three sections is needed if the phase-shift is to reach 180° at a finite frequency. With three identical sections the attenuation for this condition is large requiring an amplifier with a gain of $-29$ to sustain oscillation. The amplifier may be an ideal voltage-amplifier (low output impedance high input impedance). Thus networks I or II (Fig. 4) may be used with an amplifier of voltage gain $A_v$ with signal flow as in Fig. 6(a) or with an amplifier of current-gain $A_i$ with signal flow as in Fig. 6(b). Network II can be adapted to provide a current output into a short-circuit, having the same phase relationship to the input, as does the voltage output in II. Thus network III should be fed from a voltage source, should feedback into a low impedance input and requires the amplifier to have a defined transimpedance. For the example shown this could be achieved using a standard shunt-feedback amplifier where $A_x = v/I = -R_x$. If $R_x = 29R$ the condition for sustained oscillation is met. Where this level of voltage-current gain cannot be obtained, the impedance levels can be graded reducing the interaction between the sections. This reduces the voltage gain requirements to around $-8$ if $n$ is large (Fig. 5).

**Cross references**
Set 25, cards 1, 4
Set 26, cards 2, 3, 4
Set 17, card 1
Parallel-T oscillators

Circuit description
It is often assumed that RC networks must attenuate any voltage signal applied to them, and that the voltage gain of the associated amplifier must exceed unity to sustain oscillations. Certain networks have a voltage output that slightly exceeds the input at a particular frequency (see Card 1). They can be derived from networks having phase inversion, and the parallel-T network is one such. The op-amp has a voltage gain very close to unity and with the components chosen there is a "voltage gain" due to the passive network of 1.09. This is sufficient to produce overdriven output with clipping. Adding $R_4$ to attenuate feedback allows the level of oscillation to be set for minimum distortion. The amplitude control methods shown on Set 25, card 6 are applicable, provided the value of $R_4$ is kept very much higher than $R_1$, $R_2$.

Let $R_1 = R_2 = R$
$C_1 = C_2 = C$
$R_3 = nR$
$C_3 = C/n$

The passive network transfer function is then given by

$$T_v = \frac{(f_0/f - ff_0) + j(kn - 1)}{(f_0/f - ff_0) + j(kn + 1 + 1/n)}$$

where $f_0 = 1/(2\pi RC)$. For $n = 1/3$, the response for zero phase-shift when $f = f_0$ is $T_v = f = f_0 = 1.094$.

Similarly for $n = 1/3$, $T_v = f = f_0 = 1.073$.

This suggests that the amplifier gain must not fall more than 5% or so below unity if oscillations are to be maintained.

Component changes
IC not critical. Any op-amp capable of accepting 100%, negative feedback, or an i.c. voltage follower.
Supply voltage: Normal range of op-amp supplies e.g. ±5 to ±15V.
$R_1$, $R_2$ 1k to 100k$\Omega$.
$R_3$ can range from $R_1/2$ downward. As $R_2 \leq R_1$, $R_2$ loading of the output or by the input becomes more critical.
$R_4 \gg R_1$, $R_2$. If the ratio is not 10 x or more, significant departure from predicted frequency occurs.
$C_1$, $C_2$ 1n to 1$\mu$F, select from frequency equation, when resistors have been chosen from loading requirements.
$C_3$, $C_1/n$

n typically 1/3 to 1/8.
Frequency change in graphed results because increasing feedback brings increased distortion.

Circuit modifications
- The first circuit can be derived from that overleaf either by shifting the ground-point on the passive network and determining the sign of the amplifier gain required or by drawing the nullor circuit and shifting the ground point on that. Redrawing in op-amp form then leaves the gain sign to be deduced. Again the loop gain is greater than is needed to sustain oscillation, and the feedback is attenuated to produce minimum distortion.
- The same constraints on impedance levels apply, and the performance is very similar to the original.
- A transistor has sufficient gain to be used with this network and in one form sometimes referred to as current-driven, the resistors of the T-network also provide the d.c. collector load. The circuit may use either a centre-tapped supply or the base may be fed from a decoupled potential divider across the single-supply. If the transistor is replaced by a nullor and/or the bias components, the supply replace by short-circuits, other forms of the circuit can be visualized. There are three in total, corresponding to which of the three device electrodes is grounded. Note that it is not correct to speak of "common-emitter" etc. since an oscillator has no input and there can be no "common" point.
- If the emitter is grounded then the resistors of the T-network provide d.c. negative feedback to the base. The collector load resistance loads the output circuit and can with advantage be replaced by a constant-current stage. The transistor needs to be operated at a low current to raise its input impedance so that the passive network is loaded as little as possible. The third transistor configuration corresponds to the op-amp circuit on the front of the card viz it is an emitter follower with a voltage gain slightly less than unity. Though not approaching the ideal as closely as an op-amp the gain in each of these configurations is sufficient for oscillation if biased carefully. The frequency response of a transistor can be so much higher than for a compensated op-amp that oscillation up to the MHz region could be possible.
Phase-shift oscillators

Circuit description
The conventional phase shift oscillator uses a cascade of three RC or CR networks giving an output with 180° of phase shift at a particular frequency. It is fed into an inverting amplifier with sufficient gain to overcome the network losses, and oscillation is achieved. An op-amp has an excess of voltage gain and could use a separate passive feedback network to control the gain to the precise level required. Alternatively the final resistor in the chain could be removed from ground and used to drive the virtual ground point of the amplifier as shown, with no change in loading on the passive network. The gain is then defined by \( R_4/R_4 \).

The nullor form of the circuit is shown and indicates another viewpoint—summing two signals, one in phase and one inverted, both derived from the output. When these are equal in magnitude oscillations are maintained at the frequency of zero phase-shift.

By changing the ground point an apparently new circuit is obtained as in Fig. 2 where the amplifier is used as a voltage follower. The frequency of oscillation and the gain condition are not identical for the two circuits since neither can be an exact realization of the nullor version. They will differ amongst other reasons because of input common-mode effects with circuit 2 not present in circuit 1. A disadvantage of the CR-sections is that harmonics are progressively less attenuated. When oscillations are vigorous, and distortion ensues, these harmonics are fed back introducing intermodulation distortion and shifting the frequency of oscillation away from the 180° phase-shift frequency of the network.

Component changes
IC: general purpose op-amp—high input impedance advantageous.
\( R_1, R_2, R_3 \), 1k to 33kΩ
\( C_1, C_2, C_3 \), 1n to 1μF
\( R_4 \approx 29R_1 \) if \( R_1 = R_2 = R_3 \).
Larger values needed to overcome losses in most circuits. If the network is graded with the impedances progressively increasing, then the voltage attenuation is reduced e.g. if succeeding resistors are increased by a factor of 2 and

Typical performance
IC 741
Supplies ±15V
\( R_1, R_2, R_3 \), 12kΩ
\( C_1, C_2, C_3 \), 33nF
\( R_4 \), 360kΩ
f 161Hz for circuit 1
156Hz for circuit 2
N.B. Normal attenuation of equal-valued 3-section phase-shift network is 1/29, indicating \( R_4 = 29 \times 12kΩ \).

For the voltage follower version, \( R_4 \) had to be increased to > 500kΩ suggesting loading effect of op-amp input impedance.

Circuit modifications
- The principle of the voltage follower circuit is illustrated above. The gain requirement of the amplifier ranges from 0.97 for the original network down to 0.90 for one with graded components as described above.
- In the original circuit the action could be viewed as summing in phase and inverted currents, derived from the input and output voltages of the phase-shift network. A dual form can be constructed in which the input and output currents generate voltages which are summed to zero at the amplifier input. It is shown in summary form in Fig. 4. Re-drawing in nullor form and shifting the ground point to alternate sides of the norator leads to different practical versions.
- The first employs a voltage follower, and the resistor \( R/n \) is used to set the condition for oscillation. For equal Rs and Cs in the remainder of the circuit \( n = 29 \) is the appropriate condition. For \( R \), 10kΩ, \( C \), 33nF, and \( R/n = 330 \), oscillations were sustained at a frequency of \( \approx 1.18kHz \).
- The second form has an op-amp with non-inverting input grounded and uses comparable component values to achieve the same frequency. Increasing the capacitance values to 0.1μF reduced the frequency to 375Hz. The components can again be graded to change the voltage- and current-gain requirements of the amplifier.

Theory. The transfer function of the CR network shown leads to a frequency of 180° phase-shift given by
\[ \omega_n = \frac{1}{C^2R^2} \sqrt{3(3+2n+1/n^2)} \]
and a gain condition,
\[ A_n = 1 - (3+2/n+1/n^2)(3+2/n) \]
For \( n = 1 \), \( \omega_n = 1/CR\sqrt{6} \),
\[ A_n = 29 \]
For \( n \to \infty \), \( \omega_n \to 1/CR\sqrt{3} \), \( A_n \to -8 \).

Cross references
Set 26, cards 1, 2, 4
F.e.t. phase shift oscillators

Circuit description
The basic principle is that of a passive network which has a frequency dependent transfer function such as in one configuration the output is 180° out of phase with the input at a particular frequency. The network contains a cascade of RC or CR sections and by grading the component values, the loading effects of successive sections is reduced. In the limit each section attenuates by \( \frac{1}{3} \) with a 60° lag leading to a gain requirement of -8. Practical ratios raise the magnitude of this figure to 10 or 12, within the range of a f.e.t., while the high f.e.t. input impedance prevents loading problems from being significant. The f.e.t., as a junction device, needs either a

zero gate/source p.d. or a reverse-biased gate for correct operation.

- This is achieved in the first circuit by allowing the final resistor of the phase-shift network to be connected directly between gate and source. The f.e.t. then has zero gate-source p.d. and operates at its maximum \( g_m \). This is not the condition for maximum voltage gain unless the load resistance can be replaced by a constant current load. This circuit corresponds directly to that of circuit 2 with the reduced gain of the f.e.t. just sustaining oscillation.

- Corresponding to circuit 3, the phase-shift network can be interposed between drain and gate with source grounded. Again the restricted voltage gain of the f.e.t. means that in the absence of a constant-current load, the supply voltage has to be raised to maximize the load resistance for a given operating current and \( g_m \). In general a junction f.e.t. has a greater voltage gain for a given supply voltage when operated at a lower current. This is because as the current falls, the \( g_m \) falls more slowly while the load resistance increases more proportionately to the reduction in current. Hence the voltage gain \( (-g_m R_L) \) increases in magnitude. The limit is set when the passive network exerts significant loading on the output.

- The third form (over) of the oscillator is that of grounded gate in which both source and drain loads have to be present. One method of increasing the voltage gain in each of these circuits is to include a decoupled resistor in the source lead. This lowering the current allowing the load resistors to be increased as indicated above.

- With the component values as indicated, the frequency of oscillation was \( \approx 75\text{Hz} \). Increasing the resistors to 300k, 1.2M and 3.3MΩ respectively reduced that frequency to \( \approx 30\text{Hz} \).

- A bipolar transistor requires a forward bias on its base-emitter junction. A resistive feedback path between collector and base provides this, and this leads to the use of the RC phase-shift network as opposed to the CR network with the junction f.e.t. (there is another advantage of this network, in that harmonics are attenuated reducing the shift in frequency due to intermodulation effects when the output distorts). The network is used in its reversed mode ideally requiring current drive and a low impedance load. By using a f.e.t. or other constant current load, the output impedance approaches the ideal while series feedback can increase the input impedance. The final network resistor is then grounded and the p.d. across it used as the feedback, more nearly satisfying the impedance conditions. Shunt feedback would improve the input matching but would drive the network more nearly from a voltage source. Any mismatch shifts the frequency of oscillation. A better solution is to combine the high output impedance arrangement of the amplifier with the network arrangement of card 3, circuit 6.

- Grounded-collector and grounded-base versions of the oscillator follow in the same way as for the f.e.t. oscillators and, feedback arrangements to control the amplitude of oscillation are indicated.

Cross references
Set 26, cards 1, 3
Set 1, card 9
Set 25, card 1
**C.d.a. oscillator**

**Circuit description**
This circuit* takes advantage of the quad current-differencing amplifier package and is in the form of a two-integrator loop (IC\(_3\), IC\(_4\)) plus inverter (IC\(_1\)), which does not contribute to the loop gain, but provides a 180° phase shift between \(V_{\text{out1}}\) and \(V_{\text{out3}}\). For \(R_3=R_6\), frequency of oscillation is given by \(\omega=1/(C_1R_1C_2R_6)\). Resistor \(R_3\) acts as a damping resistor. IC\(_1\) acts as a comparator and supplies the input square wave fed back to IC\(_3\) to keep “ringing” the circuit. IC\(_3\), IC\(_4\), IC\(_1\) is a bandpass filter with a Q defined by \(R_1C_1\). To initiate oscillation with the loop closed, the differential input to IC\(_1\), \((C_1\) charge initially zero) causes IC\(_1\) to rise initially to positive saturation, but rapidly changes to 0V when \(C_4\) charges. This shock-excites the loop (overall phase shift zero), amplitude of oscillation builds up until a balanced condition is reached, where the output across \(R_{18}\) is just sufficient to maintain a steady oscillation, approximately 220mV square waves.

**Component changes**
\(R_{18}\) 680Ω, \(V_{\text{out}}\) 4.2V pk-pk, t.h.d. 0.35%. For 1500Ω, \(V_{\text{out}}\) 8.6V pk-pk, t.h.d. 0.5%. \(R_{14}\) 39kΩ, \(V_{\text{out}}\) 8.6V pk-pk, t.h.d. 0.4%. For 56kΩ, \(V_{\text{out}}\) 5.6V pk-pk, t.h.d. 0.25%. \(R_4\) 220kΩ, \(V_{\text{out}}\) 8.8V pk-pk.

**Circuit modifications**
- Comparator can be replaced by diode limiter of I above. Control is less precise because square wave is not available across diode.
- More precise limiting achieved from II. \(V_{\text{out}}\) is half-wave rectified, capacitor current is \((I_1-I_2)\). If output increases, the p-type junction f.e.t. gate is driven negative to increase f.e.t. conduction, and \(V_{\text{out}}\) is attenuated to decrease overall positive feedback and thus reduce output.
- Alternative integrator-based oscillators. IC\(_1\) is connected as a low pass filter and IC\(_4\) as an integrator. Diode limiters \(D_1\), \(D_2\) introduce distortion. The symmetrical clipping minimizes even harmonics, and the predominant third harmonic is attenuated by about 40dB by low-pass filter action. Temperature compensation to stabilize amplitude is obtained if n-p-n transistors connected as diodes (base-emitter breakdown 6.3V) are used as limiters. Circuit between \(X\) and \(Y\) is a simulated inductor. \(C_4\) induces oscillation if amplifier gain is +2.

**Cross references**
Set 26, cards 6, 7 Set 17, card 2

**Typical data**
- \(IC_1\) to \(IC_4\) 4 × LM3900N or MC3401
- \(R_1\), \(R_2\), \(R_4\), \(R_6\), 100kΩ
- \(R_3\) 6.8MΩ, \(R_7\) 330kΩ
- \(R_{10}\), \(R_{11}\) 220kΩ, \(R_4\) 470kΩ
- \(R_{12}\) 22kΩ, \(R_{13}\) 270kΩ
- \(R_{14}\) 47kΩ, \(R_{15}\) 4kΩ, \(R_{16}\) 4.7kΩ
- \(C_1\), \(C_2\) 680pF, \(C_3\) 2.2μF
- \(C_4\) 10μF

**Vcc +10V**
- \(V_{\text{out1}}\), \(V_{\text{out2}}\), \(V_{\text{out3}}\) 6.9V pk-pk

**Oscillation frequency 2338Hz**
Phase difference between outputs 90° as shown in waveform diagram.
Total harmonic distortion: 0.55%.
Two-integrator loop oscillator

Components
Supply ±15V
IC 741 op-amps
R 10k ±5%
R1 22k ±5%
R2 220k ±5%
R3 100kΩ, R4 1kΩ
C 0.1μF ±5% polyester
D1, D2 IN914

Performance
With R3 set at 0.1, a value which caused the circuit to oscillate with slight clipping when R4 was at zero, variation of v0 plotted against the inverse of R4 setting is shown. Total harmonic distortion throughout this range lay between 0.96% and 0.86% and the frequency f0 was 159.35 ±10Hz. With perfect op-amps, identical R and lossless capacitors, the theoretical f0 is 1/2πCR. Typical traces for v2 and v3 are shown.

Circuit description
The circuit is a straightforward two-integrator oscillator\(^\text{4}\) with v4 providing sufficient positive feedback to overcome the damping inherent in the imperfect capacitors and op-amps thus ensuring oscillation. This positive feedback is of a constant nature in that once oscillation has reached a level to ensure conduction of the diodes D1, then v2 is approximately a square wave whose magnitude does not depend on v0.

Potentiometer R3 can provide a measure of amplitude control\(^\text{1}\) with the positive feedback always balancing out the inherent damping. However, although the circuit is invariably used as a low frequency oscillator (<1kHz) problems of amplitude control do arise at high frequencies when phase shifts in the imperfect components reduce the inherent damping\(^\text{2}\). Under these conditions the basic oscillator tends to go into oscillation limited only by saturation of the op-amps. To prevent such oscillation the dead zone limiter (the dotted section) is added. This section produces an output only when v0 is sufficient to cause the diodes D2 to conduct; when this happens a large amount of negative feedback is applied, thereby damping out any tendency to oscillate with too large a magnitude. One therefore has a section comprising D2 etc forcing oscillation and another section comprising the dead zone limiter holding down the oscillation, giving good overall control\(^\text{3}\).

Distortion content in the output v0 (or v1) which is 90° out of phase with v0, depends on circuit Q. With high quality passive components Q is approximately K/2 where K is the op-amp open-loop gain, should not be so low as to cause damage to the diodes D2.

Circuit modifications
- Because the negative feedback section prevents oscillations from growing without bound there is no need to include the limiter in the positive feedback path. The positive feedback can therefore be directly from the output of first integrator back to the summing inverter, and might be expected to produce lower distortion figures.
- Amplitude control with

sinusoidal negative feedback and limited positive feedback can be obtained as shown above. It can be shown\(^\text{1}\) that for this circuit the output is given by \(2\pi f0\sqrt{2/\pi}\) volts r.m.s. A possible voltage-controlled limiter is shown above

References

Component changes
Polycarbonate capacitors up to 10μF and higher values of R can reduce the operating frequency to a fraction of one hertz. Amplifiers of greater gain than that of the 741 would be necessary to increase the operating frequency much beyond 1kHz (for which Wien type oscillators are available, Set 25). The ratio R4/R3 should be kept large to give heavy negative feedback when...
Four phase oscillator

Components
R₁ to R₅, R₁₂, R₁₅: 10 kΩ
R₆, R₁₆: 47 kΩ
R₇, 100 kΩ, R₈, 220 kΩ
R₉, R₁₀, R₁₁, 2.2 MΩ
R₁₄: 10 kΩ, R₁₅: 50 kΩ
R₁₆: 220 kΩ
C₁, C₂: 22 nF
D₁ to D₅: 1N914
D₆: 6V zener, F.e.t. BF244
IC₁ to IC₄: 741 op-amps with ±15V supplies

Description
This oscillator is closely related to the two-integrator loop oscillator³.
It has only one inverter (IC₃) which enables one to produce four outputs all 90° apart.
This allows the use of a four-phase rectifier (D₅ to D₆) which requires little smoothing
to produce a direct voltage proportional to the output magnitude.
The oscillator works on the basis of fixed negative feedback (from D via R₁₃ to IC₁) being
balanced by a variable amount of positive feedback. The amount of positive feedback is
dependent on the discrepancy between the desired output voltage (set by D₅ and R₂₆) and
the actual output as sensed by D₅ to D₆. The positive feedback path is from the output of IC₁ via IC₄ and
R₁₄ to IC₅. IC₅ and its associated circuitry provide a path of positive gain, the
magnitude of which gain is set by the resistance of the
f.e.t. (n-channel). The output of IC₅ is

\[ v_p = \frac{R_{12}}{R_{21} + R_F} \cdot \frac{R_F}{R_F} \]

where \( R_F \) is the f.e.t. resistance. R₂₅ and R₁₄ serve to linearize the f.e.t. resistance and it is
possible to omit R₂₅ and replace R₁₄ by a short for the purpose of explanation.
Bearing in mind the f.e.t.'s characteristics note that a positive increment in Vᵣₑ
(corresponding to a reduction in output voltage) gives a lower value of R_F and a larger
positive feedback voltage, v_p, which will increase the magnitude of the oscillator.
A similar balancing effect occurs if the oscillators increase in magnitude. Note
that the d.c. value of vₑ must be slightly negative for correct f.e.t. operation and that this is
ensured by the integrator action of IC₅ and its associated circuitry.
A four-phase oscillator allows rapid amplitude stabilization since any change in amplitude
is quickly sensed; this is of importance in low frequency oscillators.

Circuit modifications
- Use of fixed positive feedback and variable negative feedback requires care with polarities of most of the items in
  the amplitude control loop.
- It is possible to remove the positive feedback link altogether and obtain either positive or
  negative feedback, depending on whether the output is low or high, by using the circuit
  above right to generate the

\[ v_p = v(1+n) \left( \frac{m}{m+1} - \frac{n}{n+1} \right) \]

Since m can be controlled by vₑ, positive and negative values of vₑ can be obtained giving
positive and negative feedback respectively.

- An alternative, though more expensive scheme, to provide the same function of positive and negative feedback
  control on the same path is to use a multiplier, one input of
  which is the output of IC₅ and the other is vₑ. The magnitude
  and sign of vₑ control the amount and nature of the feedback.

References
1. Circards this set, card 6.
2. Fast amplitude stabilisation of an R-C oscillator, Vannerson and Smith,
3. Circards, this set, cards 9, 10,
All-pass network oscillator

Circuit description
Most oscillators have a peak in their loop amplitude response at the frequency of zero loop-phase-shift. This stems from the band-pass nature of their transfer function. The Barkhausen criterion demands only that the loop-gain exceeds unity at this frequency and it is not necessary for the amplitude response to be frequency dependent—though it may assist in reducing the effect of distortion on frequency. If circuits having frequency dependent phase-shifts are combined such that the overall phase-shift is zero at a single frequency then oscillations can occur at that frequency. These circuits are called all-pass (non-minimal phase-shift circuits) and can be made with one op-amp three resistors and one capacitor. The gain can be trimmed about unity. The outputs are 90° out of phase and the frequency of oscillation is the same as for Wien, two-integrator and gyrator oscillators using the same components.

Transfer function of A to A'.

\[ T_{VA} \text{ given by equating potentials at inputs } \]
\[ \frac{v_0}{n+1} = \frac{v}{1+sCR} \]
\[ \therefore T_{VA} = \frac{v_0 - sCR}{v} \]

For \( n = 1 \), magnitude of transfer function is unity at all frequencies with the phase shift varying from zero as \( f \to 0 \) to \( -\pi \) as \( f \to \infty \). The phase shift is \( \pi/2 \) lagging at \( \omega = 1/C.R \).

Similarly \( T_{VB} = \frac{sCR - n}{1+sCR} \)
with unity gain for \( n = 1 \) and a \( \pi/2 \) phase-lead at \( \omega = 1/C.R \).

Component changes
IC₁, IC₂: compensated op-amps not critical except where high frequency operation required. R²: 1k to 100kΩ
nR²: Replace one of the resistors by a thermistor or other amplitude sensitive network for amplitude control. This may necessitate reducing R² to suit the operating resistance of the thermistor.
C: 1n to 1μF
R: The capacitors can be switched to change ranges as in Wien etc. oscillators and the resistors R replaced by a twin-gang potentiometer for continuous frequency control.
N.B. In the majority of oscillators of this kind the frequency of oscillation is of the form \( f = 1/(2\pi RC) \) where all Rs and Cs are equal.

Circuit modifications
The transfer function of an integrator is given by

\[ T_v = \frac{1}{1+sCR} \]

Combining this with the first all-pass circuit overleaf gives an overall transfer function.

\[ T_v = \left( n - sCR \right) \frac{1}{1+sCR} \]

For \( n = 1 \) this reduces to unity when \( (nCR)² = -1 \), i.e. at \( f = 1/(2\pi CR) \) the same frequency as in the previous circuit. The outputs differ in phase by 90° and amplitude control can be achieved by replacing nR² by a low-power thermistor, and R² by a low value resistor to match e.g. R54 (ITT) and a 1kΩ resistor. Many other oscillators have been designed using various combinations of lead, lag, all-pass and integrator networks and some examples are quoted in the references. In all cases some non-linearity is required to control and limit the amplitude of oscillation—these include diode clipping/limiting saturating high-gain amplifiers, thermistors lamps etc. A very simple form of oscillator based on the all-pass network idea can be implemented using only two transistors. The all-pass networks load the transistor outputs causing departures from the theoretical performance, but this can be allowed for by increasing one of the collector resistors as shown. The voltage swing is limited because the self-biasing action of the circuit leaves a relatively small collector-emitter p.d. for each transistor. The outputs should not be heavily loaded or the frequency/amplitude will be disturbed but the circuit gives roughly quadrature outputs with a low component count.
The transistors are general purpose silicon planar. The all-pass network behaves similarly to that using a transformer with a centre-tapped secondary as indicated.

Further reading
Gyrator oscillators

Circuit description
A gyrator is a circuit that synthesizes an impedance at one port that is related to the physical impedance presented at a second by the relationship

\[ Z_1 = \frac{R}{Z_2} \]

If one impedance is capacitive e.g. \( Z_2 = \frac{1}{j\omega C} \) then \( Z_1 = j\omega CR^2 \) equivalent to a pure inductor having \( L = CR^2 \). Such a circuit can be constructed using two ideal op-amps, four resistors and one capacitor. The circuit is widely used in active filters but can be used to make oscillators. Many variants are possible. First the passive network can be changed so that the locations of the capacitors vary. Two capacitors are used occupying any pair of the starred locations—circuit 2 is an example. Then the amplifier inputs may be moved so long as they maintain the circled junctions at equal potentials—circuit 3 is derived from circuit 2. An additional feedback path labelled \( R_{f1} \) or \( R_{f2} \) initiates oscillation.

Typical values
R 10kΩ, C 15nF, \( R_{f1} \) 680kΩ, \( f \) 1055Hz.

The p.d.s across \( Z_1 \) and \( Z_3 \), \( Z_4 \) and \( Z_6 \) are equal as are the currents in \( Z_1 \) and \( Z_3 \), \( Z_4 \) and \( Z_6 \) and \( Z_2 \) and the source. Thus the input current is given by

\[ I = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \frac{1}{Z_4} + \frac{1}{Z_5} \]

Input impedance of the circuit is \( \frac{1}{Z_1} \). If a capacitor replaces \( Z_1 \) or \( Z_2 \) and the other elements are resistive, the input impedance becomes inductive. If a capacitor is placed across the input port, it resonates with this synthesized inductor, and only a small amount of positive feedback is needed to overcome losses due to finite amplifier gain etc. and produce sustained oscillation. For \( Z_1 = Z_3 = Z_5 = Z_2 = R \) and \( Z_4 = 1/j\omega C, Z_1 = j\omega CR^2 \).

The combination of a capacitor \( C \) and a synthesized inductor, \( L = CR^2 \), formed by gyrating the other capacitor produces an equivalent parallel tuned circuit. The self resonant frequency is

\[ f_0 = \frac{1}{2\pi\sqrt{LC}} \]

\[ = \frac{1}{2\pi CR} \]

This is the same frequency as occurs in a Wien oscillator using the same component values in the frequency dependent network. Tuning of the oscillator frequency is obtained by varying any of the component values either singly or in pairs. For ideal op-amps there is no damping and the circuit is continuously on the point of oscillation regardless of component values. In practice an external component or network may be added to initiate and sustain oscillation.

Two-integrator loop
This circuit, described on cards 6, 7, uses the same passive components and has the same frequency of oscillation. Though developed separately these two are different forms of the same basic circuit. This can be seen by re-drawing the passive networks in a similar format.

Nullor version of two-integrator oscillator Nullor version of gyrator oscillator
Wide-range gyrator oscillator

Circuit description
Another version of the gyrator oscillator, this one uses a single variable resistor, $R_4$, to control the frequency of oscillation. For ideal active and passive elements only the smallest amount of positive feedback would ensure that the amplitude builds up until peak clipping restores the loop gain condition. Losses including those due to capacitor loss factors, require the presence of $R_4$ or other path to initiate the oscillations. As $R_4$ is varied, the value of $R_4$ at which oscillations just start also varies. Though much greater than $R_4$, $R_5$, $R_6$ at all settings of $R_4$, either $R_4$ has to be re-adjusted manually/automatically or set to a low enough value to ensure oscillation over the whole range. This brings increased clipping at high values of $R_4$. The circuit is of considerable interest because it illustrates the way in which gyrator oscillators can achieve a very wide range of frequencies using a single variable resistor —greater than 200:1 in this example. Amplitude control methods could include replacing $R_4$ by a network incorporating a f.e.t. whose on-resistance is varied via a peak-rectifier; or by replacing it by a non-linear network adjusted so that it has a low resistance at low amplitudes to excite the circuit, rising at higher amplitudes to levels where the loop gain is insufficient. A possible example for such a network is shown opposite. It is equally possible to change the frequency by varying both capacitors and/or a pair of resistors, making the components switchable or continuously variable. This reduces the variation needed in $R_4$ but does not eliminate it. In the original circuit, for capacitor to produce the effect of a self-resonant LC circuit. The example shown is best considered in two parts. First an integrator with overall resistive feedback from input to output via $R'$ simulates a parallel LR circuit. This is then combined with a negative resistance circuit (also viewable as a n.i.c. acting on $R_4$). If the integrator is fed from the output of the first amplifier, less compensation is required for the positive resistances in the system by this negative resistance circuit. For oscillation $R_5 = R_4$ with ideal amplifiers.

$R_4 = R_3 = R_6 = R$, $C_4 = C_2 = C$

$\frac{f}{2\pi CR} \approx \frac{R}{R_4}$

Component changes
The component values will be comparable to those used in the two integrator oscillators (cards 6 and 7). At high frequencies, cumulative phase-shifts can raise the effective Q of the circuit, while slew-rate limiting can lead to unpredictable jumps in the amplitude of oscillation. IC1 b: Compensated op-amp. High input impedance necessary if $R_4$ is to be made very large. $R_1$, $R_2$, $R_3$: 1k to 100kΩ $C_1$, $C_2$: 1n to 1μF $R_4$: 47 to 4.7MΩ $R_5$: Typically 220k to 2.2MΩ. Low resistance needed at high frequencies. Supplies: ±5 to ±15V.

Circuit modifications
- Any other circuit that synthesizes a pure inductor can be combined with a

Further reading

Cross references
Set 26, cards 6, 7, 9, 10
Set 25
Control of oscillator frequency from an external signal is of increasing importance in such diverse applications as computer-controlled test systems, electronic musical instruments and communication receivers. Rather than giving detailed information on one or two circuits this update surveys the novel and ingenious methods proposed in recent publications. To aid comparison they are shown applied to a two-integrator loop, the principles then serving for both oscillatory and filtering functions. The same methods can be applied to most other RC oscillators.

Consider a pair of identical blocks $K$ which change the voltage transferred from one stage to the next. Increasing the voltage by a factor $K$ increases the current fed to the capacitor by $K$ charging it more rapidly. It is equivalent to reducing the resistor by a factor $K$ i.e. the frequency of oscillation is increased $K$ times. (N.B. No amplitude control etc indicated; see details on preceding cards.) The block $K$ can be provided by an analogue multiplier in which $K$ becomes proportional to the control voltage $V_c$ fed to one of the multiplier inputs.

**Reference**

Any other amplifier or attenuator can be substituted including a simple field-effect transistor, for example, a n-channel m.o.s.f.e.t. from the CD 4007 package as shown. The control is then non-linear and to avoid distortion the signal levels must be low. A second remote-control method is via a digitally-controlled amplifier or attenuator. An $R/2R$ ladder network may be used directly if it can handle bipolar signals. A neat alternative is the balanced amplifier shown in which any additional conductance to ground produces a proportional output. The switches control a binary-weighted resistor network, and because the switches are grounded might be t.l. open-collector outputs or multiple m.o.s. devices from certain c.m.o.s. packages (Set 27 card 7), again provided the signal level is restricted. Any other electronic switches including analogue gates can be substituted.

**Reference**

To summarize the methods so far: in place of direct variation of the resistances necessitating a twin-gang potentiometer we have substituted (i) voltage-controlled amplifiers or attenuators (ii) digitally-controlled amplifiers that can be programmed in discrete, binary steps. A third principle that has been in use for more than twenty years is regularly re-invented. An electronic switch periodically opened and closed replaces the multiplier attenuator or amplifier. If the switching rate is high compared with the signal frequency the effect is to make the average current proportional to $\tau$, the on-period of the switch. A pair of switches inserted at locations $K$ (above) results in $\omega \propto \tau$. If switching and signal frequencies are widely separated, simple passive filtering serves to remove the output transients. This is a form of p.w.m. control and can be implemented via a voltage-controlled monostable or by a member of digital techniques including the counter-based idea indicated or binary rate multipliers and dividers.

**Reference**
Sets 27 & 28: Complementary m.o.s.

The first few cards of set 27 form a useful potted summary of the properties of complementary f.e.ts for readers not wholly familiar with c.m.o.s. devices. Properties that characterize these devices—high input impedance, low quiescent consumption, relatively wide supply range, large output swing—are dealt with first, page 92, followed by dynamic considerations and device equations on page 93, and then modes of connection on page 94. Another characteristic feature is the very wide variation in dissipation with supply voltage, page 93, and the pronounced sensitivity of c.m.o.s. devices to voltage is more fully illustrated by the curves of page 96.

Many circuits based on op-amps can be constructed using c.m.o.s. inverters and gates. Examples included are the rectangular-to-triangle wave converter of page 101, the two- and three-phase oscillators of pages 108 & 109, and the filters of pages 104 & 105. Eight sensing and detection applications are given in pages 106 & 107, using the D-type flip flop.

(Typographical slips on card 6 have been corrected on page 108—they involved incorrect inequality signs in the first and last few lines.)

Background article 90
Devices and characteristics 92
Linear circuit characteristics 93
Device configurations 94
DC amplifiers 95
AC amplifiers 96
Gain-controlled amplifiers 97
Controlled resistances 98
Non-linear circuits I 99
Non-linear circuits II 100
Square-triangle generator 101
Up-date circuits 102
DC feedback pair 103
Low-pass/high-pass filters 104
Band-pass/notch filters 105
D-type analogue circuits—I 106
D-type analogue circuits—II 107
Three-phase oscillator 108
Two-integrator oscillator 109
Frequency-voltage converter 110
Current-differencing amplifier 111
Transistor outputs 112
Up-date circuits 113
Linear c.m.o.s. circuits

By considering the various families of logic circuits one can deduce what parameters, designed-in to optimize digital operation, result in adverse performance if the circuits are used in the analogue mode. The most interesting family that is available at a low cost is complementary symmetry metal oxide semiconductor logic or c.m.o.s. By adding an extra diffusion to the processing steps needed for a single type of device, Fig. 1, the complementary type can be produced. Thus the p-channel device is obtained by diffusing p⁺ source and drain into the n-type substrate; a deeper p-type well is diffused to contain the n-channel device.

In addition to the conducting channels between the respective sources and drains, there are a number of p-n junctions. Though these are normally reverse-biased by the selected operating mode, their parasitic effects cannot always be ignored. Other p-n junctions are deliberately introduced at the inputs to prevent damage to the thin oxide films by high voltages that might be produced electrostatically or due to external transients.

The conductivity of the channels is increased by a forward bias on the gates. For an n-channel device this corresponds to a gate voltage positive with respect to the source. The conductivity tends to zero for zero gate-source voltage because the doping of the channel is such that there are virtually zero current carriers available. At a particular value of gate voltage, called the threshold voltage, charges induced in the channel by the resulting field allow conduction to commence. No gate current flows because of the insulation provided by the oxide layer. Drain-source conductivity continues to increase with rising gate-source voltage, while the current flow depends on both $V_{ds}$ and $V_{gs}$. At low values of $V_{ds}$, the slope resistance is reasonably linear and is controlled by $V_{gs}$. Ultimately, the output current reaches a limiting value again set by $V_{gs}$, i.e. the output slope resistance becomes very high making the device suitable for various forms of constant-current circuits.

The basic inverter stage is shown in Fig. 2 and the transfer function in Fig. 3. When the input voltage is low, there is insufficient forward bias on the n-channel device to bring it above the threshold of conduction. The reverse is true for the p-channel device which has a high conductivity i.e. the output is virtually equal to $+V_c$. Conversely a very positive input voltage pushes the output close to zero. When lightly loaded the output swings to within 1% of the supply voltage. At voltages in the region of $+V_g/2$ both transistors are conducting. This region is traversed rapidly when the inverter is used as a

Fig. 1. Structure of c.m.o.s. inverter.

Fig. 2. Basic c.m.o.s. inverter.

Fig. 3. Transfer function of c.m.o.s. inverter.

Fig. 4. Variation of inverter current with input voltage.
logic level inverter, but the transient current pulse as shown in Fig. 4 is then the only significant contribution to current drain, as one or other of the transistors is non-conducting in each of the logic states. (At high pulse rates power consumption is associated with the multiple charge/discharge of internal and load capacitances.)

For analogue systems this central region of the characteristic is of great interest. The slope is moderately high, corresponding to a voltage gain of the order −10 to −100 with the unusual property that the gain is greater at lower values of supply voltage (both transconductance and output conductance fall, the last-mentioned more rapidly than the first).

Although not designed for high d.c. stability, temperature dependence of the transfer function is small. Recently c.m.o.s. i.c.s have been produced designed specifically for analogue applications; though the configurations may be identical to particular logic circuits, the processing is optimized for linear operation.

Because each m.o.s. transistor can be used as a voltage-controlled resistor, packages containing several devices offer interesting possibilities. The drain-source resistance characteristic remains approximately linear for small values of reverse voltage and current, making a.c. operation feasible. The devices on a common chip will be similar and will be subject to the same temperature variations. Thus, operated from a common gate-source voltage supply, they offer closely-matched resistance characteristics for use in amplifiers etc.

An interesting extension of this technique is possible even where single devices are not accessible separately. By grounding the positive supply line of a package containing multiple inverters, the p-channel devices are kept out of conduction provided the p.d. applied between output and ground of each device is small. Thus a hex buffer inverter i.c. can be used as a set of six matched n-channel f.e.t.s.

Any inverting amplifier can be used with n.f.b. to give a see-saw amplifier of reduced but well-defined voltage gain. As only a single gain-stage is involved external compensation against high-frequency instability is not required even with 100% negative feedback. The bandwidth is not particularly high though well above the audio-frequency range, with some gain to beyond 1 MHz. High input impedances may be had without loading effects due to amplifier input impedance, though the resulting RC time constants due to strays can further reduce the bandwidth.

A recent example of the way in which device technologies change forces a warning note at this point. To improve the performance of gates/inverters for their main functions in purely digital applications, some manufacturers produce "fully-buffered" versions. These might contain three inverters in cascade to perform the function previously using a single inverter. The improved response is welcome to users with critical requirements in the digital field; those wishing to adapt them for analogue circuits as described in Circards Set 27, would find high-frequency instability resulting from the much-increased loop gain and multiple phase-shifts. Remember to check the characteristics of any device or circuit rather than assume that similar titles guarantee identical performance.

If logic circuits could be adapted only for amplifying functions, the exercise would still be worthwhile — it would avoid having to add separate operational amplifiers on those occasions when only simple signal processing is needed. In fact most other electronic circuits can be designed if care is taken to work with the characteristics of c.m.o.s. rather against them. A restriction is that two stages of inverting stages can be used with negative feedback, there being no equivalent to the series-applied feedback circuits (e.g. voltage followers) common in operational amplifier designs. Non-inverting buffers or cascaded inverters lend themselves to positive feedback functions such as Schmitt trigger circuits. A variety of circuits can be built using individual devices from certain c.m.o.s. i.c.s in combination with inverters and gates.

As a general rule it is simpler to adapt those familiar circuits that use inverting amplifiers, unless the function required cannot be performed in this way.

Circuits that can be designed using inverting amplifiers include active filters such as the two-integrator loop, three-stage phase-shift oscillators, and the like. There is no need to restrict ourselves to simple buffers and inverters; other i.c.s can be readily applied in analogue circuits of various kinds. For the more complex i.c.s, the degree of internal interconnection reduces flexibility and it is less easy to see ways in which non-logic functions can be performed.

One form of flip-flop, the D-type, has a pair of outputs Q and Q̅. When fed with a positive-going pulse on the clock input C, the output Q is forced to take up the logic state on the data input D at the instant of clocking. This state at the output is retained regardless of any variation at D until the next clock pulse. Such a flip-flop finds application in the processing of analogue signals, as in some forms of analogue to digital converters and phase-locked loops. In a particular application, the delta-sigma modulator, the integrator receives a current from the input voltage, which causes its output to change until the comparator output swings through zero. On the succeeding clock pulse the Q-output must change, since the D value has changed, and this changes the f.e.t. between its conducting and non-conducting states. The polarity of input and reference voltage must be opposite so that the f.e.t. can reverse the direction of integration. Combining the clock pulse with Q (or Q̅) in a suitable logic gate gives a pulse train in which the average number of pulses is proportional to input voltage.

The above appears to be a complex system, but two properties of c.m.o.s. allow efficient use of the flip-flop. The sharpness of the transfer-function means that the region of doubt at the D input is very small i.e. that even voltages close to V_1/2 are clearly distinguished as either logic 0 or logic 1. Hence the comparator can be dispensed with, the flip-flop acting as its own comparator. Similarly the output of the flip-flop is well-defined, and for a stable supply voltage the f.e.t. and separate voltage reference can also be eliminated reducing the system to one op-amp and a flip-flop.

Similar considerations lead to economical circuits for Schmitt trigger, astable and monostable circuits, by making use of the S and R or set and reset inputs, also available in D-type flip-flops. It must be remembered that such circuits may depend on properties which may not be covered directly by the manufacturer's data, although the experimental evidence for their satisfactory behaviour is clear.

A semi-digital mode of operation is where inverters are used to drive power transistors. Output stages for class-D power amplifiers are examples where this technique is of use, the c.m.o.s. drivers also helping to switch the transistors off rapidly, though delays may be needed at the input stages to avoid the possibility of simultaneous conduction of both transistors.

There is one family of c.m.o.s. circuits designed specifically for use in linear and non-linear analogue circuits viz the analogue gate/bilateral switch. By driving a parallel complementary pair of m.o.s. transistors with anti-phase logic level signals their conduction can be linearized so that the transfer of voltage is near unity when lightly loaded, this extends over the whole supply range and these gates can be used to switch components in and out of circuit as well as for direct gating of signals. Applications include d. to a. conversion, waveform synthesis and switched filters.

The technology developed for linear applications in c.m.o.s. has proved to have many characteristics that can be pressed into the service of linear circuit designers. The very low cost of these i.c.s must commend them, and with care their limitations can be overcome or side-stepped in a wide variety of applications.
Devices and characteristics

**Input protection**
A network of diodes at the input of each gate/inverter protects against transients. In linear applications they limit the range of input voltages that can be applied, in particular when the designer seeks access to individual devices, using a non-standard supply voltage to disable unwanted devices. Most packages conform to Fig. 1(a)—certain buffers to Fig. 1(b).

**Output diodes**
The processing steps needed to produce complementary devices leave a number of p-n junctions between source and drain and the supply terminals. In most devices the sources are already directly connected, but the junctions become apparent in certain i.c.s with access to individual devices.

**Device characteristics**
Each device has a current that is a function of both gate and drain potentials. Above a critical voltage on the drain, which varies with VGS, the drain current becomes large and the device is in a constant-current mode, and said to be saturated. Below this voltage the output resistance is lower, non-linear and is varied by the gate-source voltage.

**Transfer function**
The output voltage changes sharply with input voltage at a particular input that is remarkably stable against temperature, has a broad tolerance from device to device but is at a roughly fixed percentage of supply for a given device.

---

**Device temperature drift**
The drift in characteristics for individual f.e.t.s, is much larger than for a complete inverter, verifying the matching characteristics of p-channel and n-channel devices. The resistance increases by about 0.3%/degC. The current for any combination of VDS and VGS falls by around 30% for the temperature range indicated. The current depends on a square-law relationship involving VGS and VDS, except in saturation when VDS has little further effect.

**Analogue gate : on-resistance**
One class of c.m.o.s. i.c.s uses complementary pairs in parallel with the gates driven in antiphase, so that either they are conducting or non-conducting simultaneously. The result is an analogue gate or switch with a very high off-resistance and a low but non-linear on-resistance. Again the resistance is temperature dependent, with a comparable temperature coefficient (caused by the same change in mobility of the current carriers). The pattern repeats itself at all voltages and currents.

**Gate input leakage**
The input resistance of a f.e.t. is exceedingly high—in practice swamped by external leakage effects due to package pins or p.c. boards. The protective diodes at the input of c.m.o.s. circuits, provide leakage paths which leave the input current either positive or negative depending on the input voltage. Though still very small the current varies exponentially with temperature. A leakage current of 10pA at room temperature could increase a hundredfold at the device maximum temperature. It is generally safe to assume an input resistance in excess of 10MΩ.

**Propagation delay**
The self-capacitance of a device is a function of its geometry, and is not affected by temperature changes. The increase in resistance increases all the time-constants and, for example, the propagation delay increases at about 0.3%/degC. Similar figures apply to most pulse characteristics, the speed at higher voltages being markedly improved. This is because the sharp fall in resistance above the larger voltage swing to be achieved in a much shorter time. For linear operation, the bandwidth is much increased at higher voltages, and somewhat decreased at higher temperatures.
Linear circuit characteristics

Phase/frequency variation
The change in characteristics with supply, extends to the phase shift at high frequencies. In a multi-stage amplifier this could bring the frequency at which instability might occur below 100kHz (60° phase lag per stage at 6V supply would give a total phase shift of 180° in a three stage feedback amplifier). This together with the drastically increased output resistance makes it difficult to design linear amplifiers at supply voltages of 5V and below.

Basic device equations
The equation gives the drain current as a function of the p.d.s between gate and source, and drain and source in the unsaturated region. As V_D is increased to the point where \( V_{DS} = V_{GS} - V_T \) the current becomes substantially constant. Alternatively when \( V_{DD} \) exceeds the threshold \( V_T \), the channel is pinched-off to an extent that inhibits any further increase. Both regions of operation are of interest for different applications.

Below saturation
Both drain and gate potentials have an effect, but if \( V_{DS} \) is small then the equation approximates to a linear one—it extends below the origin but there is an additional constraint imposed by resistive diodes.

\[ I_D \approx k(V_{GS} - V_T) V_{DS} \]

Thus the slope resistance at low voltages becomes \( dV_{DS}/dI_D \approx 1/(V_{GS} - V_T) \) This is a voltage-controlled resistance though it is neither a linear resistor nor a linear function of the controlling voltage. The departure from linearity is small enough for \( V_{DS} < 100\text{mV} \) to use the resistor in feedback networks etc to control gain, but distortion prevents its use at higher voltages than a few hundred millivolts.

Above saturation
The current is assumed to be constant at the value it has for the condition given by *. Hence \( I_D = k(V_{GS} - V_T)^2/2 \) This is a square-law function requiring the elimination of \( V_T \) by some compensating circuit if a square law relationship is to be obtained between input and output voltages. Transconductance can be obtained by differentiating \( I_D \) with respect to \( V_{GS} \)

\[ g_m = dI_D/dV_{GS} = k(V_{GS} - V_T) \]

N.B. The basic form of these equations applies to all m.o.s.f.e.t.s; the coefficients of practical devices differ from those given and account has to be taken of this—see card 7.

Further reading
Santoni, A. & Trolese, G. Design ideas with COS/MOS, New Electronics, April 30, 1974, pp. 27-34.
Device configurations

Typical performance
IC CD4007AE
n-channel device
Supply +10V
R₁ 100kΩ
R₂ 10MΩ
C 100nF
Voltage gain +50

Circuit description
In certain c.m.o.s. ic's, access may be gained to the sources/drains of individual f.e.t.s (CD4007, CD3600 and similar). Where this is so, circuits may be constructed that are the counterparts of the more familiar common-base common-collector etc. Consider the common-gate amplifier shown above. The gate is grounded for a.c. purposes by the capacitor. The gate current is negligible and the p.d. across R₂ may be assumed to be zero. The d.c. operating conditions for the amplifier are thus VḊ-D=0 and R₁ defines the direct current flow. The alternating voltage gain depends on the parallel value of R₁, R₂. The input impedance is low, and to a good approximation is 1/gₘ where gₘ is the transconductance of the device as usually defined. This varies with the operating current being proportional to $\sqrt{I_D}$. Since $I_D \propto 1/R₁$, if the p.d. across R₁ is constant (a reasonable approximation when the supply voltage is well above the device threshold voltage) then the voltage gain ($\approx g_m R₁$) is proportional to $\sqrt{R₁}$. The approximation is not valid at very low currents and the voltage gain is limited to about +100. The voltage gain for a given value of R₁ is roughly proportional to the square root of the supply voltage by the same reasoning, falling more rapidly as this approaches the threshold values. The amplifier has a high non-inverting voltage gain, a low input-impedance and a high output-impedance.

Component changes
IC: must be package with separate access to drain. Any discrete m.o.s. device (enhancement mode can be used in these circuits—the aim here being to indicate where c.m.o.s. packages can be adapted to provide functions that would otherwise require separate discrete components). Supply: +5 to +15V. Some gain available at lower supply voltages. R₁: sets the quiescent levels and the output impedance. Can be replaced by current source for increased voltage gain. 10k to 1MΩ.

R₂, C: provide decoupling and the time-constant must be long compared with period of lowest frequency. R₂ 1M to 22MΩ.

Circuit modifications
• The gate can be connected directly to the positive supply, which reduces the component count, but removes the stabilizing action of the d.c. negative feedback. Otherwise, the a.c. properties are comparable.
• Each of the other device configurations is possible, the common-source version simply disregarding the presence of the p-channel device by ensuring that its source and/or drain is open circuit. The voltage gain is comparable to that for the common-gate stage but the input current is now zero, and the output is inverted.
• A common-drain or source-follower configuration can often be provided while using the other transistor of the complementary pair in some other circuit, e.g. astable oscillator. Whatever waveform appears at the common gate is transferred to the source with some attenuation but without loading the waveform. Since source and drain currents are equal an antiphase output can be obtained at the drain.

A novel arrangement joins the gate to the drain for 100% negative feedback. The device is now apparently a two-terminal device and might be expected to behave as a non-linear resistor. In fact it acts as a non-inverting voltage amplifier with a low voltage gain. This is because the substrate connection acts as a subsidiary gate and the operation is that of a grounded-gate amplifier with the gain much reduced by the feedback to the main gate.

Any of the multi-transistor circuits can be implemented using several devices from a package and the example illustrated is the cascade circuit useful for high voltage gains where input-output isolation is important.

Cross references
Set 27, card 2.
Set 20, card 8.

common source
common drain
two-terminal amplifier
cascade amplifier
DC amplifiers

Typical performance
IC CD4001AE NOR
gates with 2 inputs active
Supply +10V
R₁ 27kΩ
R₂ 1MΩ
R₃ 100kΩ

Circuit description
C.m.o.s. inverters are not
suited to the amplification of
small d.c. voltages. They
have a threshold voltage range below
and above which the output is
saturated. The simplest way of
biasing an inverter/gate into
its linear region is via direct or
resistive feedback from output
to input. This ensures
\( V_{\text{out}} = V_{\text{in}} \) where is
within the tolerance of
Vₜh or which is near the
middle of its linear region, the
to a change only of
1% for a change in
source resistance of 4.7MΩ.
The configuration is clearly
restricted to a floating source
(high impedance transducer
such as piezo-electric devices) or
would require a floating
power supply. The second
inverter compensates for most
of the quiescent output by its
matched characteristics, the
remainder being cancelled by
jecting a variable current via
R₅, R₆.

Component changes
- The only changes in the
resistors are to vary this offset
compensation. The values are
not critical, but \( R₃ > R₅ \) and
\( R₃/R₅ = \text{offset voltage/supply}
\) voltage, indicate the values.

The inverters can be buffers,
NOR and NAND gates or the
inverters constructed from
CD4007 or CD3600 packages.
None of these function in
performance with op-amps
constructed from the
appropriate m.o.s. and bipolar
transistors. They are intended
only to extend the applications
of inverters/gates to simple d.c.
applications where the signal
voltages are large enough that
significant offset can be
tolerated.

Circuit modifications
- A possible application is in
the amplification of small
currents from photo-diodes
used in their photo-voltaic
mode. For matched diodes
exposed to different light
intensities, there will be a
current of given polarity
representing the difference
between the light intensities.
This will drive the outputs of
the inverters in anti-phase, and
currents well into the
sub-microampere range could
be detected. \( Vₕ \approx 20MΩ \times I_{\text{attenuation}} \).

The voltage gain can be set to
between -1 and -10 with
good accuracy, with a second
inverter to provide an artificial
ground point. Both input and
output voltages are then
referred to this point. For
constant supply voltages, the
inverter can also be used as a
comparator since its input
threshold voltage varies little
with temperature
\(< 1mV K^{-1} \) for some gates i.e.
<0.01% of the supply voltage
at \( Vₕ = 10V \). A zener diode
placed in the feedback has a
current forced in if of
\( \approx Vₕ/2R₁ \) and the gate output
voltage is raised by \( Vₕ \) over its
normal threshold. This can be
used to define the compensation
current fed into other stages
used as d.c. amplifiers etc.

Further reading
McMOS Handbook, Motorola

Cross references
Set 27, card 1.
Set 11, cards 5, 6.
Set 20, card 8.
Set 9, card 11.
A C amplifiers

Circuit description
The basic open-loop behaviour of an amplifier can be predicted from its internal structure fairly readily in cases as simple as a c.m.o.s. inverter. For the resistive feedback bias as shown, the input and output potentials are equal. Hence each device operates with equal gate and drain potentials. This introduces opposing effects on the voltage gain as the supply voltage increases. First the increase in operating current which is very marked leads to an increase in the transconductance ($g_m$). At the same time the output resistance is markedly reduced because each device is operated on or below the knee of its output characteristic. The net effect is that the overall voltage gain is relatively constant varying by only 10dB over a 1,000:1 range in currents. The measurements were all made with a probe having an input resistance of 10MΩ and with a total input capacitance and strays of about 18pF. The high voltage gain at the lower supply voltages is hard to make use of, since even the high feedback resistance contributes to the loading effect. The increase in cut-off frequency as the current rises, can be explained if we assume a total output capacitance which is constant. If the output resistance is $r_o$, the cut-off frequency $f_c$ and the shunt capacitance $C$, then $f_c = 1/2\pi r_o C$, would be the appropriate relationship if the transconductance is assumed to contribute nothing to the frequency dependence. This implies $r_o R_e$ should be a constant. Comparison of the data shows a variation of around 2:1 over a 1000:1 range of currents. On these figures, the output capacitance would be around 20pF.

Circuit modifications
- Multi-stage amplifiers are possible, but since c.m.o.s. stages give sufficient gain/accuracy for routine functions, the additional complexity of the compensation networks would appear to be a bad bargain. With d.c. coupling, the low-frequency time constants are eliminated and over-all feedback can hold all three stages within their linear range.
- An inverter can be operated at low current from a high-voltage supply by adding a series resistor in the supply line and decoupling the inverter supply pin. N.B. The supply rejection ratio is only 6dB since the output of a device with feedback biasing is always of order $V_s/2$. If the series resistor is chosen so that the quiescent current is only a few microamperes, the devices must settle at $V_{GS}$ values close to the device thresholds. This sets the effective supply voltage $V_s$ to about the sum of the threshold voltages i.e. 3.6V.

- In devices with access to the sources (CD4007, CD3600 etc) resistors may be added as shown to define and reduce the $g_m$ values while increasing the output impedance.

Typical performance
IC ¼ × CD7001AE
Supply +10V
Quiescent current 1.9mA
Output resistance 25kΩ
Voltage gain = 53
Transconductance 2.1mS
Upper cut-off frequency 130kHz
$R_S$ 6.8MΩ
$C_1$, $C_2$ 100nF

Further reading
Fitchen, F. C. and Ellerbruch, V. G., Linear operation of the m.o.s.f.e.t. complementary pair,

Santoni, A. & Troelse, G. Design ideas with COS/MOS, New Electronics, April 30, 1974, pp. 27-34.

Cross references
Set 27, cards 1, 4, 6.
Set 27, cards 4, 6, 8.
Set 12, card 1.

Multistage amplifier: possible but not recommended as accumulated phase shifts make it difficult to apply sufficient feedback without oscillation and input stage noise can saturate the output stage.
Gain-controlled amplifiers

Typical performance
IC 2/3×CD4007
Supply 10V
R 220kΩ
C 1μF
Control Vc 0 to 10V voltage

Circuit description
A more familiar method of using a m.o.s.f.e.t. as part of a gain-controlled amplifier is to use it as the lower section of a potential-divider in either the forward or feedback paths of an amplifier. This allows the m.o.s.f.e.t. to operate with the source grounded and makes it easier to apply a control voltage to the gate. If the source is connected to any other point at a constant potential then a control signal may be applied, but it must be sufficient to take VGS above its threshold value VT. In the circuit shown, either or both of a complementary pair can be used with gates, sources and drains commoned, provided these are not already grounded internally. If the control voltage Vc is in the mid-range of the supply there is insufficient VGS to bring either device into conduction and the voltage gain is 0. When the control voltage is very low, the p-channel device is brought into its conducting state and the gain sharply increases. For Vc → V, the n-channel device has a low slope resistance and the gain increases. The graph shows that either characteristic can give a voltage gain which can be controlled from zero up to −30. At the low values of gain the control action is rather sharp. The amplifier is another m.o.s. pair used as an inverter with R providing shunt feedback defining the input potential by the virtual earth action.

Component changes
IC: Any single m.o.s.f.e.t. either p- or n-channel may be used.
Supply voltage: since each f.e.t. receives a gate-source voltage

which is $\sqrt{2}$ the supply voltage has to be > 8V in this circuit.
Rf: 10k to 1MΩ
C: not critical. Determines I.f. response. 0.1 to 10μF.

Circuit modifications
- A conventional op-amp circuit can be used as a virtual earth amplifier with the f.e.t. in the forward or reverse paths. Because the f.e.t. has a variable resistance, this complicates the design of the system unless the source has a very low internal resistance. By placing the f.e.t. in the series feedback path, the loading affects the output of the amplifier which can tolerate it.
- If two or more f.e.t.s are placed in parallel paths they may be gated on or off. This offers a simple alternative to a separate analogue gate i.e. if the performance requirements are not too critical. Both the gates and the inverting amplifier can be derived from a single low cost CD4007 or similar. If the gates of the m.o.s.f.e.t.s are paralleled the gain is switched between $-R/R_1$ and $-R/R_2$ provided the on-resistances are low compared with $R_1$, $R_2$. It is suitable for gains in the region −1 to −25.
- The f.e.t. can also be placed across the feedback path provided the voltage swing is small enough to prevent non-linearity from producing excessive distortion. One or more devices can be used across both input and feedback paths. Non-linear elements or reactive components can also be placed in series with the f.e.t.s. The on-resistance is high compared with devices designed specially as analogue gates.

Cross references
Set 27, cards 1, 5, 7.
Set 20, card 8.
Set 21, card 4.
Set 22, card 7.
Set 16, card 10.
**Controlled resistances**

**Circuit description**
Some I.C.s contain multiple inverters e.g. CD4049 hex buffer. Consideration of their internal structure shows that if the $V_{DD}$ line is shorted to the $V_{SS}$ and then used as the common line, then a positive control voltage on any input varies the slope resistance of that output as if it were a single n-channel F.E.T. If the p.d. across the drain source path is less than 0.5V the internal diodes are not brought into conduction. Hence the package is equivalent to six independent well-matched n-channel enhancement mode F.E.T.s. These can be used separately or in combinations in any circuits where voltage-controlled resistors are required. The slope resistance at the output is controllable over a 10:1 range though the resistance becomes non-linear at a progressively lower drain-source voltage as the gate voltage approaches the threshold value. The non-linearity is indicated for $V_{DS}$ of 3V. The devices match to within 5% with the samples tried but this is not covered by the package specifications since these were designed for digital applications. The resistance is non-linear. As the forward voltage drop across the drain-source path is increased, the value of $V_{GD}$ is reduced, this reduces the forward bias and decreases the channel conductivity.

Conversely, a negative current in the drain increases $V_{GD}$ and increases the channel conductivity. When $V_{DS}$ is large the contribution due to the small values of $V_{DS}$ (0 to 200mV) is negligible and

the on-resistance can be assumed linear for most applications. The example shown represents the lower limit of $V_{DS}$ at which use as a controlled resistance might be acceptable. The non-linearity is predictable from the basic device equation (Set 27, card 2)

$$I_{DS} = k[(V_{GS} - V_{PD})V_{DS} - nV_{DS}^2]$$

This theoretical equation represents a wide variety of devices over a range of currents and voltages, and it is common to assume $n = \frac{1}{2}$. Where this is true it leads to a particularly simple technique for removing the non-linearity from the on-resistance.

**Circuit modifications**
- Assume equation to be valid for $n = \frac{1}{2}$. If $V_{GS} = (V_{C} - V_{DS})/2$ achieved by using equal value resistors as shown, then substituting into the first equation gives $I_{DS} = k[(V_{C}/2 + V_{DS}/2 - V_{PD})V_{DS} - \frac{1}{2}V_{DS}^2] = k(V_{C}/2 - V_{PD})V_{DS}$ i.e. $V_{DS}$ is a linear function of $I_{DS}$ for all values of $I_{DS}$ within the device limits, but the slope is controlled by the direct voltage $V_{C}$. The resistors attenuate the control action and $V_{C}$ has to have twice the value it had in the simple circuit overleaf. Tests with devices from c.m.o.s. packages suggest that in this application considerably more feedback is needed to linearize the characteristic, though some improvement is offered. To test the principle the drain-source voltage has to be amplified before deriving the feedback.
- If the gain is made > minimum required to achieve compensation (e.g. $R_{S} = 9R_{S}$ giving a gain of +10) then compensation is achieved with $R_{S} = R_{S}$ and the above ratio for $R_{S}/R_{S}$ the on-resistance of a CD4049 n-channel device was controllable from 25 to 2002 with characteristics matched in the positive and negative quadrants to better than 0.5% and a non-linearity of less than 1.5% (less than 0.5% up to 100Ω). The range of control voltages required was from 3.4V (2002) to 16.5V (252). These resistor values feed back a portion of $V_{DS}$ to the gate given by

$$[V_{DS}R_{S}/(R_{S} + R_{S})](R_{S} + R_{S})/R_{S}]$$

$= 1.25V_{DS}$. This suggests using $n = 1.25$ for these devices to determine the necessary compensation. Unless $n < 1$ it would seem to be necessary to use an amplifier with each device to obtain accurate linearization.

- An alternative circuit combines the resistive networks to apply a voltage to the gate of $V_{C}/4 = 1.25V_{DS}$. Though simpler, this version requires a larger range for $V_{C}$.

**Further reading**
Santoni, A. & Troelsey, G.
Design ideas with COS/MOS, New Electronics, April 30, 1974, pp. 27-34.

**Cross references**
Set 27, cards 1, 6.
Set 22, card 7.

---

**Circuit modifications**

![Circuit diagram]
Non-linear circuits I

**Fig. 1**

**Circuit description 1**
The inverter transfer function is such that the output changes rapidly only when the input is close to a threshold voltage of about 45% to 55% of the supply. If the circuit is fed from ground-referred sine-wave with no d.c. blocking capacitor then the output will be severely distorted in most cases. As an example consider a device with threshold 50% of supply and with \( R_1 = R_2 \). When the input is at zero, the output must be at \(+V\) since there will be equal d.s across \( R_1 \) and \( R_2 \). For all negative inputs the output holds constant at \(+V\). For all positive inputs the change in the output is equal and opposite i.e. the positive half-cycle of input is reproduced as a negative half-cycle with respect to the positive line. The amplifier gain falls as the swing approaches the supply lines so that perfect half-wave rectification is not possible. If the circuit is followed by an identical second stage, the output is inverted and approximates to a non-inverted half-wave rectified version of the input. In each case the peak input has to approximately equal the supply for the output to swing through the whole supply range.

**Circuit description 2**
The resistors are made unequal to give an inverting gain to \(-10\) to \(-20\) depending on the open-loop gain. In this case the output remains at \(+V\) until the input approaches very closely to the inverter threshold voltage. It is only the positive peaks of the input signal that cause any change in the output. The output then consists of short-duration negative-going swings coinciding with the positive peaks of the input. If a second identical stage follows it, the peaks are further sharpened up and inverted. The result is a highly amplified version of the extreme positive peaks of the input. The threshold voltage of a given device is a well defined fraction of the supply and varies little with temperature. Thus each device would respond to a particular peak input but once adjusted the response could be maintained.

**Circuit description 3**
If the original waveform is unimportant, negative-feedback need not be used. The input is biased up to the supply rail and the output consists of negative-going pulses coinciding with the positive peaks of the input (the pulse width increases as the input-amplitude increases since the waveform lies above the threshold for a longer fraction of the cycle). If the output is applied directly to a second inverter the output is re-inverted and is sharpened into an almost rectangular pulse equal in height to the supply.

**Circuit description 4**
The output pulse from such a system can also be sharpened by introducing non-linear elements into the forward or feedback paths. As an example, a pair of parallel-connected back to back diodes limit the output swing to IV peak to peak since the currents are small. Further, this swing is centred on the threshold voltage which can assist in direct coupling to other stages.

**Circuit description 5**
A simple frequency-doubler uses a NOR gate together with a peak-selector circuit. If either of the NOR gate inputs goes above its threshold, the output goes to logic 0. This happens on positive peaks of the input via \( R \) (which serves to limit any input current for negative inputs). On negative peaks, the input of the inverter is pulled below its threshold and its output goes high. This again drives the NOR gate output to logic 0. Thus there are two negative peaks to the output during one cycle of the input, representing frequency doubling. In principle the circuit could be followed by an active filter to retrieve a sine-wave which would be available for further frequency doubling.

**Further reading**

**Cross references**
Set 27, card 9.
Non-linear circuits II

Circuit description
The circuit exploits the non-linear characteristics of c.m.o.s. pairs by cross-coupling sources and drains of a single pair having a common gate. This produces the novel transfer function shown. When the input voltage is high, the p-channel device $T_{R1}$ is non-conducting and the output voltages are determined only by the current in $T_{R2}$. This has resistor $R_4$ in its source making the transfer function somewhat less than unity but with a linear slope. At all times the currents in $R_2$, $R_3$ are equal making the slopes inverse. As the input is low the reverse occurs with $T_{R1}$ conducting, $T_{R2}$ off. If the devices are truly complementary the output voltage would be the same at two values of input voltage, $V_i$ and $V-i-V_0$. The minimum current and hence the minimum value of $V_{at}$ occurs for $V_i=V/2$. If the input is biased to this value and a sine-wave superimposed then the circuit behaves as a full-wave rectifier. This can be seen from the transfer function of an ideal full-wave rectifier in which $V_o = |V_i|$. Any other waveform can be applied, with bias offset if desired to further modify the output waveform. The output for a triangular wave input is a triangular wave of twice the fundamental frequency. In principle the process can be repeated by a.c. coupling into an identical second stage but waveform deterioration limits it to two or three stages at most.

Component changes
For anti-phase outputs $R_i = R_o$. Values not critical and similar shape of transfer function obtained for $R_1$, $1k$ to $100k\Omega$. Supply voltage: 5 to 15V.

IC: the circuit depends on having access to both sources and drains of a complementary pair and can only be implemented with CD4007 and similar devices.

Circuit modifications
- If the current in a c.m.o.s. pair is monitored, it is found to pass through a maximum value at $V_i \approx V/2$ i.e. when both devices are about equally forward biased. At the two extremes $V_i \rightarrow 0$, $V_i \rightarrow V$ the current falls to zero. This gives a similar non-linear relationship to the previous circuit. To exploit this shape, the current can be fed to a current mirror composed of $T_{R1}$, $T_{R2}$. Output current flowing in $R_3$ passes through a peak on each excursion of $V_i$ through the supply mid-point (with considerable variation from device to device in the actual values but all with a similar shape of transfer function). The value of $R_1$ depends on the supply as well as the devices but is typically $1k$ to $10k\Omega$.
- A triangular wave input gives a somewhat rounded wave output, there being no negative feedback in this circuit to linearize the transfer function.
- In addition to the above, there are a number of circuits that use the characteristics of the individual m.o.s. devices. By cancelling the threshold voltage, a close approximation to a square-law can be obtained. These will be covered in a later series of Circards.

Cross references
Set 27, cards 2, 8.
Square-triangle generator

Circuit description
Since a c.m.o.s. inverter has a voltage gain of between −20 and −100 it can be employed for many of the functions usually associated with op-amps. An integrator fed with a constant direct voltage delivers a constant current to the capacitor. The output is then a linear ramp. When the gain of the amplifier is finite, the current changes with output amplitude leading to non-linearity. Even the limited gain of these inverters is sufficient to hold the non-linearity to within one or two percent. A second limitation, that of finite input current, is not a problem with c.m.o.s. devices and the resistor values are limited only by the effects of stray capacitance on the waveforms. To make a free-running generator the ramp waveform is applied to an amplitude sensing switch—a pair of inverters with overall positive feedback suffices. The output of this switching circuit is a square-wave whose transitions coincide with the peaks of the triangular wave. Because the threshold voltage is not precisely 50% of the supply the positive and negative slopes are unequal as are the on-and-off periods of the square wave. This can be corrected as shown overleaf. There is a second square-wave in antiphase to the main output, while the frequency can be controlled without change in triangular wave amplitude by varying R1 or C1. Changing the ratio R2/R1 changes the amplitude of the triangular wave as well as the frequency. Since the slope remains the same under this change, the frequency is inverse to the amplitude.

Component changes
IC: any set of three inverters (or a single non-inverting buffer may replace the switch pair if available). NAND or NOR gates may be used with inputs paralleled.
Supply: +5 to +15V. At low voltages the rise in output impedance restricts the resistances to high values. R1: 10k to 10MΩ, R2, R4, 10k to 10MΩ. Triangular wave output should not exceed 50% of the supply if waveform distortion is to be minimized. Hence R2/R1 > 2 is required. If the ratio is too large, the triangular wave amplitude may be too small for convenience, and switching transients more troublesome.

C1: as low as 100pF with high values of resistance but generally 1n to 1μF. Very low-frequency triangular waves possible with this circuit.

Circuit modifications
- Many op-amp techniques can be adapted to improve or modify the output waveforms. N.B. The triangular wave has a large d.c. content being roughly centred on V/2. To change the slope a single fixed resistor may be taken from the integrator input to zero or +Vs. For controlled compensation, a potentiometer across the supply can be used.
- A good approximation to a sawtooth waveform follows, when R1 is shunted by a diode. With the cathode driven by the trigger circuit, the output positive ramp is greatly speeded up while the negative ramp remains under the control of R1. Reversing the diode gives a sharp negative edge followed by a controlled positive ramp.
- Replacing R1 by a potentiometer and a pair of diodes, the charge and discharge cycles are varied. For equal voltage swings, one part of the cycle is proportional to xR1 and the next to (1−x)R1. The total period remains broadly constant though there are second-order effects that prevent this from being completely achieved. It gives a variable mark-space ratio to the square-wave with a reasonably constant frequency.
- The triangular wave can be shaped into an approximate sine wave in a number of ways. An amplifier can be added with non-linear elements in the forward or feedback paths. An alternative is to use a second integrator with decoupled d.c. feedback. This converts the ramps into parabolic sections which match a sine-wave reasonably well (as little as 4% t.h.d.).

Further reading
Santoni, A. & Trolese, G. Design ideas with COS/MOS. New Electronics, April 30, 1974, pp. 27-34.
Inductive proximity detector
This employs a CD4007 package to provide an oscillator and Schmitt trigger circuit. The inductor L comprises 150 turns 34 gauge (USA) enamelled wire within half of a Ferroxcube 1811-P LOO-3B7 pot core set, giving around 2mH. The oscillator, operating normally with its high-Q coil at a frequency around 100kHz, drive circuit which maintains transistor Tr2 on, the input to inverter Tr3, Tr4 is low and hence the output high. When a metallic object is close to L, the Q of the coil drops, the oscillator output falls, causing the Schmitt circuit to go off and hence the output rises. Sensitivity is controllable via resistor R1.
Reference
Fichtenbaum, M. L. Electronics, January 22, 1976, p. 112.

CA3600E: This is a m.o.s. transistor-array package configured like the CD4007, but characterized for linear operation. A typical application is a post-amplifier for op-amps, where the high input impedance of an inverter-pair means that the op-amp is buffered from finite loads. This is shown for a CA3080 transconductance amplifier, where the overall gain is 130dB (30dB for the transistor-pair). Each transistor-pair can sink or source 10mA, but for greater current output, the two remaining pairs can be connected in parallel with the output stage.
Reference

This voltage controlled amplifier is derived from a CD4007 package. IC1 inverter is biased into its linear region by the 10MΩ resistor, and one of the n-type f.e.t. is used as a voltage variable resistor. Control voltage range is dependent on $|V_{DD} - V_{SS}|$. With above network gain is claimed variable from zero to just over unity.
Reference


**D.C. feedback pair**

**Typical performance**
- IC CD4007AE
- 2 n-channel devices
- Supply +10 V
- \( R_1 = 1.2 \, \text{M}\Omega \)
- \( R_2 = 470k\Omega \)
- \( R_3 = 5.6 \, \text{M}\Omega \)
- \( R_4 = 10k\Omega \)
- \( R_5 = 4.7k\Omega \)
- C 100nF
- Voltage gain output 1 \(-10.7\)
  output 2 \(-21.8\)

**Circuit description**
This classic form of circuit has proved so flexible in bipolar designs that it is worthwhile to consider its behaviour in m.o.s. form. It can be constructed using either n-channel or p-channel devices, and complementary forms are also possible. If \( R_1 \) is large, the current in \( T_{R_1} \) is low and it will require a \( V_{GS} \) little more than its threshold voltage i.e., around 2V. Input current is negligible and hence the p.d. across \( R_2 \) is zero. This defines the p.d. across \( R_3 \) and the corresponding current in \( T_{R_3} \) and \( R_4 \). This in turn fixes the \( V_{DS} \) of \( T_{R_2} \) and the drain potential of \( T_{R_1} (V_{GS} + V_{DS}) \). Provided the supply voltage is much greater than this value the current in \( R_1 \) is well-defined. For a.c. signals the gate of \( T_{R_1} \) is an imperfect virtual earth—the open-loop voltage gain is around \(-20 \rightarrow -40 \) and so closed-loop gains of \(-5 \rightarrow -10 \) can be defined with moderate accuracy. The input impedance is then \( \approx R_2 \) and as \( R_3 \) and \( R_2 \) can be very large, loading of any preceding stage is small. Outputs from source and drain of \( T_{R_2} \) are anti-phase and can be equal in magnitude or in any desired ratio, since the currents in \( R_4 \) and \( R_5 \) are almost identical (differing only due to the small current in \( R_3 \)). The frequency response is controlled by shunt capacitance across \( R_1 \) (internal plus strays).

**Component changes**
- IC: Access needed to individual devices—hence CD4007, CD3600 or equivalents.
- Supply: +5 V to +15 V. Gain and output swing fall sharply below 7.5 V.
- \( R_2, R_3: \approx 1 \, \text{k} \Omega \) to 10 k\( \Omega \). Compromise between output capability and quiescent current.
- \( R_2, R_3: \) Ratio sets gain, \( R_3 \) defines input impedance.
- Typically 100 k\( \Omega \) to 10 M\( \Omega \).
- \( R_3 \): sets current in \( T_{R_1} \). If \( R_1 \) is too high voltage gain increases but at expense of bandwidth. 10 k\( \Omega \) to 1 \( \text{M}\Omega \).

**Circuit modifications**
- To increase the voltage gain, the source of \( T_{R_2} \) may be decoupled to ground, removing the a.c. negative feedback.
- Stray coupling between output and input can cause instability because of the high input impedance. Frequency dependent networks may be used in parallel with or replace resistors in the system to produce a controlled frequency response provided d.c. feedback path remains.

**Cross references**
- Set 27, cards 3, 4, 5, 6
- Set 20, card 10
- Set 12, cards 7, 9
Low-pass/high-pass filters

Circuit description
Low-pass filters normally have a flat response up to a given frequency, a rapid roll-off at much higher frequencies, and very little if any increase in amplitude during the transition from the pass-band to the stop-band. This corresponds to damping-factors of the order of unity and Q-factors which are normally equal to or less than one (Q=1/√2 is the condition for a standard Butterworth filter). Such a characteristic places no great demands on the amplifier used to implement it unless the accuracy required is high as in multi-order filters. For routine attenuation of hum, noise, and other unwanted signals a voltage gain of -20 to -100 is more than adequate, and c.m.o.s. inverters can be used. In the circuit shown, C3 is a large value coupling capacitor that allows the d.c. feedback via R2 to provide self-bias for the inverter. It rolls off the response at low frequencies but can easily be set to a value that does not affect the normal pass-band. By keeping the resistors constant, the roll-off frequency is inverse to the product C1C2, while the Q is controlled by the ratio C2/C1. The very high impedance of the c.m.o.s. input makes it possible to use very large values for R1, R2 and hence drop the roll-off frequency below, say, 50Hz while using small capacitors. The output has a d.c. content that would make a coupling capacitor necessary in most cases.

Component changes
C1: 47p to 10μF
C2: Typically 4 to 5×C1, or can be varied to change the Q, R1, R2, R3: 10k to 10MΩ.
C3: Must be large enough to avoid attenuating lowest frequency signal. 100n to 10μF.
IC: Any c.m.o.s. inverter, gate.
Supply: +5V to +15V

Circuit modifications
- By transposing all the capacitors into resistors and vice versa, the circuit is converted into a high-pass filter. The input capacitor C3 automatically blocks d.c. and this reduced the component count by one. If a high Q is required, then the ratio R1/R2 has to be increased. For C1=C2=C3=C3, the cut-off frequency is f0=1/2π√R1R2C32 =1/2π√R1R2. The value of Q is given by R2/R1=4Q2 for an amplifier with infinite gain. In practice it would be difficult to obtain a Q of more than 5 while the usual range of Q-values needed in high-pass filters (say 0.5 to 1) is achieved with reasonable accuracy. Higher order filters can be constructed by cascading individual second-order filters. The presence of C4 at the input simplifies the coupling because each inverter is then self-biasing. It is unlikely that high-order filters would be sufficiently accurate and independent of supply etc to be worth designing by this technique.

- If precise control of the form of filter characteristics is not needed (i.e. Butterworth, Bessel etc) the order of the filter can be increased by adding separate RC sections at input and/or output.

- Any separate inverter in a system may have a lag introduced into its response by the addition of a capacitor or a series CR network across the feedback resistor. The noise characteristics of c.m.o.s. gates are poor compared with those of low-noise bipolar or FET discrete circuits, but acceptable results are obtainable for signals well above the millivolt level.

Further reading

Cross references
Set 1, cards 4, 5, Set 16, card 9
Band-pass/notch filters

**Band pass 1**

Typical performance
IC \( \frac{1}{4} \times CD4001 \)
- (quad NOR gates)
- Supply \( +10V \)
- \( C_1 \) 100pF
- \( C_2 \) 10nF
- \( R_1, R_2 \) 100kΩ
- \( f_o \) 1490Hz
- \( Q \) 2.5

(For an ideal inverter, \( C_2/C_1 = 4Q^2 \) but with the very limited gain the theoretical Q of 5 is reduced to 2.5, see Ref. 1.)

Circuit description
Band-pass filters commonly require differential input amplifiers or multiple amplifiers. This remains true if high Q is needed, particularly if sensitivity to gain and passive component changes is to be minimized.

Where a low value of Q is sufficient then simple band-pass filters can be based on single inverting amplifiers. At very low frequencies, the impedance of \( C_1 \rightarrow \infty \) and the gain \( \rightarrow 0 \).

At very high frequencies the impedance of \( C_1 \rightarrow 0 \) and the gain \( \rightarrow 0 \). At some intermediate frequency, the gain has a maximum value. The theoretical centre-frequency is \( 1/2\pi \sqrt{R_1 R_2 C_1 C_2} \) and commonly, \( R_1 = R_2 = R \) giving

\[ f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \]

Considerable departures from the predicted Q-values occur because of the low gain of the amplifier. The centre frequency lay within the tolerance range of the passive components in the samples tested. At the centre frequency, the output is anti-phase to the input. This leads to a simple means of obtaining a notch-characteristic as indicated over.

The high values of resistors that can be used make it easy to obtain a very low-frequency band-pass characteristic, while on the high-frequency side operation to beyond 100kHz is possible.

Alternative circuit
The second form of the band-pass filter has comparable performance, and no significant differences were observed. The input impedance will presumably differ from the first circuit, but both impedances can be made high enough for differences to be unimportant.

Component changes
IC: Any c.m.o.s. inverter, buffer, gate.
Supply: +5 to +15V.
At low voltages the available voltage gain is too far reduced by loading effects.
\( R_1, R_2 \): 10k to 10MΩ. Lower values possible if source impedance is low.

**Band pass 2**

Typical performance
IC \( \frac{1}{4} \times CD4001 \)
- (quad NOR gates)
- Supply \( +10V \)
- \( R_1 \) 220kΩ
- \( R_2 \) 2.2kΩ
- \( C_1 \) 15nF
- \( C_2 \) 15nF
- \( f_o \) 460Hz
- \( Q \) 2.1

\[ f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \]
& \( 4Q^2 = R_1/R_2 \)

In practice \( Q \rightarrow 5 \) difficult to achieve.

Circuit modifications
The third band-pass filter is based on that of Sallen & Key and the equations given in Ref. 1 are

\[ T_v = \frac{s\omega_o^2/2Q}{s^2 + 2s\omega_o/Q + \omega_o^2} \]

where \( s = j\alpha \)

Notch filters are often based on band pass networks, in which a bridge or other balancing system is arranged such that the output tends to zero at the centre-frequency of the band-pass. In this case, taking the first circuit overleaf, the input and inverted output are applied to the ends of a potentiometer. As the potentiometer setting is varied, a point is reached where the two signals exactly cancel at the original centre frequency. The principle can be extended to obtain a low impedance output by applying the signals via two resistors to the summing junction of a second inverter as shown. The overall transfer function is then of the form

\[ T_v = \frac{H_2s}{s^2 + s(\omega_o/Q) + \omega_o^2} - H_1 \]

allowing for the inversion due to the second amplifier. \((H_1 \propto 1/R_1, H_2 \propto 1/R_2)\)

\[ T_v = \frac{H_2s - H_1[s^2 + s(\omega_o/Q) + \omega_o^2]}{s^2 + s(\omega_o/Q) + \omega_o^2} \]

\[ = -H_1 \left[ \frac{s^2 + s(\omega_o/Q) + \omega_o^2}{s^2 + s(\omega_o/Q) + \omega_o^2} \right] \]

For a notch characteristic, there must be a frequency at which the output goes to zero. This is achieved for \( H_2/H_1 = -\omega_o/Q \) at \( s + \omega_o^2 = 0 \)

i.e. at the same frequency as the peak of the original bandpass function.

For \( C_2 = 47nF, C_1 = 100pF \) the notch was obtained at \( R_1/R_2 \approx 33 \).
An all pass filter (constant amplitude varying phase shift) follows when the coefficients of numerator and denominator are equal and opposite. This implies \( 2\omega_o/Q = H_2/H_1 \) and corresponds to \( R_1/R_2 \approx 16 \).

Further reading

Cross references
Set 1, card 8
Set 16, cards 7, 8
D-type analogue circuits-1

D.C. level sensing
The D-type flip-flop has a data input which responds to a 0 or 1 input by transferring these to the Q output when the device is clocked. The threshold between these two regions varies from device to device, but varies little with temperature. For moderate variations in supply voltage it is also a fixed fraction of that voltage and the transition between regions is sharp. If a varying d.c. voltage is applied to the data input, and the flip-flop is continually clocked, then each time the voltage passes through this threshold region, the output changes state on the next clock-pulse. The threshold remained between 44.7% and 45.0% of the supply voltage for $V_s$ 4 to 7V and the effect of temperature was of the order 1mV K$^{-1}$. If the unknown voltage is derived from a common supply rail regulation would not be required since both it and the device threshold would vary together. The output is 1 for $V_D > V_T$ and 0 for $V_D < V_T$.

Pulse height detector
The flip-flop is set up as a $\pm 2$ circuit by returning the data input to the Q output. For each normal clock pulse the Q output is thus set to the previous state held on the Q output i.e. the state of Q (and hence of Q) is reversed. If the clock pulses fall below the threshold value of the C input they are ignored and the output retains its previous state. This threshold level is controlled by gates similar to those at the D input and hence the threshold level is of the same order $-45/55\%$ of the supply, but with the same well-defined characteristics for any given device. The output is a square wave of half the input frequency for $V_{CL} > V_T$ and either 0 or 1 for $V_{CL} < V_T$. A small amount of inherent hysteresis appears to exist in such applications as these. The input amplitude has to reverse itself by up to about 1% after effecting a change in the output in order to reverse that change.

Pulse-height-sensing monostable
The Q output is returned by a short time-constant circuit composed of $R_1C_1$ to the re-set input. If the input pulse rate becomes too rapid, an additional diode across $R_1$ shortens the recovery time of the monostable and allows the output pulse-width to remain independent of pulse-rate. Provided the input pulses, applied to the clock input exceed the threshold then the circuit attempts to toggle. The rest state of the system must be $Q=0$, since for $Q=1$ the reset input would be activated after a short charging period and Q would return to 0. Every time a clock-pulse sets Q to 1, this is what happens, and Q remains on for the time it takes the reset input to reach its threshold value via the charging of $C_1$ through $R_1$.

There is one output pulse of defined height and width for every input pulse exceeding the threshold voltage. If a further clock pulse is received during the on-period, the output pulse is terminated. If this is not desired, the D input can be returned directly to logic 1 when such pulses are ignored.

Window comparator
Assume the input voltage is low and that $R_2 >> R_1$. The D input is below its threshold, and on the next clock pulse, Q is driven to (or held at) 0, and Q to 1. This change is insufficient to shift the D input above its threshold and Q stays permanently at 0. Conversely if $V_1$ is high, Q is held permanently at 1. When $V_1$ is close to the threshold, each transition of the Q shifts the D input across the threshold and the circuit toggles. There are now two effective threshold points $V_{LT}$ and $V_{UT}$, the lower and upper thresholds, separated by $V_3R_s/(R_1+R_3)$.

For $V_1 < V_{LT}$ Q is 0.
For $V_1 > V_{UT}$ Q is 1, and for $V_{LT} > V_1 > V_{UT}$, Q toggles at $f/2$.
For a steady clock rate ($f$ constant) the output mark-space ratio is unity. A moving coil indicator at the Q output would read zero, $V_{LT}/2$ and $V_4$ respectively for $V_1$ below and above the thresholds. Alternatively a i.e. would be off, flashing at $f/2$ or permanently on for these three ranges of input volts (this would require a slow-speed clock if the flash rate is to be visible).
D-type analogue circuits-2

Marks-space detector
If the input pulse-train has a large mark-space ratio, its mean value may be > 50% of \( V_c \), provided the input pulse height is equal to \( V_c \). If the voltage at \( D \) is smoothed by \( C_3 \) across the potential-divider formed by \( R_1, R_3 \), the threshold will be exceeded and an output pulse-train is obtained. When the mark-space ratio falls below the critical level, the monostable relaxes into its quiescent state with \( Q = 0 \). The circuit basically detects the mean level of the input pulse train and can be used to detect any of the separate variables that affect the area provided that all the others remain constant. Thus for height and frequency constant the circuit detects pulse-width, for height and pulse-width constant it detects a rise in frequency and so on. The pulse-height is well-defined if the previous stage is a c.m.o.s. gate/inverter.

Space-mark detector
The complementary nature of the circuit allows the reversal of the outputs, letting \( Q \) activate the set input. In each of these circuits the monostable period has to be less than the period of the incoming pulses. As shown, the output at \( Q \) remains low until the mean value on the D input falls below its threshold, when the \( Q \) output becomes a pulse train. To adjust the range of mark-space ratios that can be dealt with, a bias current can be provided from the supply or the CR network can be returned to a variable bias voltage. This would need to be supply proportional is using an unregulated supply for all other functions.

Phase detector
These are used directly in determining the phase difference between two signals of the same frequency. The signals are converted into pulses/square waves and the zero-crossings activate a switching circuit such that an output is on only for the interval between the zero-crossings of the two signals. If the output is filtered by an RC circuit the resulting direct voltage is a measure of the phase difference. Assume that the D-type flip-flop is clocked at an instant when \( Q = 0 \). This causes \( Q \) to go to 1, a state it retains until the reset goes to 1. The following clock pulse again drives \( Q \) to 1 with the period that \( Q \) remains at 1 varying as the positive going input at R varies in the delay with respect to the \( C_3 \) input i.e. according to their phase-difference. The unit is one example of phase-detectors used in phase-locked loops. As the variable frequency oscillator drifts it causes a progressive change in the phase difference between it and the reference oscillator. The resulting change in the mean output is used to control the v.f.o. returning it to synchronism with the reference oscillator.

Frequency differencer
Two signals at different frequencies are fed into the D and \( C_3 \) inputs of a D-type flip-flop. At each clock instant the D input may have either 0 or 1 and hence the output state may or may not change depending on its previous state. When the frequencies are very close it takes a large number of cycles, before a clocking instant coincides with a different value on the D input, i.e. the output rarely changes. When the frequencies are identical the D input always has the same value at the clocking instant and the output never changes. These results are consistent with the claim that the output pulse train has a frequency equal to the difference in the input frequencies. This can be very convenient in measuring small changes in a high frequency signal. It is compared by such a flip-flop with a stable frequency close to its value, and the result can be monitored on simple counters, or analogue frequency meters, on audio frequency amplifiers or displayed on an oscilloscope.

Cross references
Set 28, card 4
Set 19, card 8
Set 21, card 7
Three-phase oscillator

Circuit description
Each inverter has a high input impedance and an inverting voltage gain of magnitude $\gg 1$. The CR network in the feedback path introduces a lagging response. If the system is to oscillate, the loop phase shift must be zero while the overall gain should just exceed unity. If the system is to be symmetrical then each stage must contribute the same phase shift and must separately have unity gain. If the inverter gain is large then with the three inversions, the sum of three equal phase shifts must equal 180° to meet the overall phase condition. This requires a 60° lag from each of the sections. To maintain the magnitude condition at unity, the magnitude of the impedance of $R_1$ in parallel with $C$ must equal the resistance of $R_2$. This gives $R_3 = R_2/2$ as the maintaining condition with $f = \sqrt{3/2\pi CR}$. In the practical case the amplifiers have gains ranging from 10 to 50, inverting and with little phase-shift in the audio band. The inherent matching of these inverters because they are formed on a common chip means that the provided resistors $R_3$ are reduced by the same amount to accommodate this finite gain, then the phase relationships between the outputs are maintained. Non-linearity of the gain provides a coarse form of amplitude limiting. Two effects stem from any change in supply voltage, each controlling the voltage gain of an inverter. The transconductance of each device increases as the current increases, while its output slope resistance falls. The voltage gain into open-circuit is higher at low supply voltages making it easier to define the required resistance of $R_3$; the increased output impedance makes it necessary to use higher value resistors to prevent loss of voltage gain under these circumstances. The output voltage and frequency are also supply dependent but oscillations can be sustained over the range 5V-12V with a broad peak in the output in the 7 to 10V region with the samples used. The phase differences are held to 120° with a deviation of only one or two degrees except where distortion is severe. With $R_4$ increased to 42.5kΩ, the point at which oscillations are just sustained, one output had a t.h.d. of 0.18%.

Component changes
IC: Any set of three matched inverters: CD4007, $\frac{1}{4} \times$ CD4049, $\frac{1}{4} \times$ CD4001 with unused inputs taken to '0', $\frac{1}{4} \times$ CD4011 with unused inputs taken to '1'.
Supply: In theory any supply voltage within device rating. In practice, at high voltages the open-circuit voltage gain falls; at low voltages the output impedance becomes too high. Best range 5 to 10V.

Typical performance
IC $\frac{1}{4} \times$ CD4001AE
quad 2-input NOR gates
Supply $\pm 10V$
$R_1$ 100kΩ
$R_2$ 40kΩ
$C$ 15nF
$f$ 213Hz
Amplitudes 3.6, 3.4, 3.5V pk-pk
Distortion 2.2%, 0.4%, 1.1%

Circuit modifications
- If the inverters are replaced by logic gates using one input for feedback, then the other input can be used to gate the oscillator. Using NOR gates, a logic '0' leaves the oscillator running, logic '1' drives the output of that gate low i.e. to logic '0'. This via the inverting action of the following stages drives their outputs to '1' and '0' respectively. If all free inputs are taken to '1' all outputs are driven to 0. The converse is true when using NAND gates.
- Most see-saw amplifier circuits can be implemented though at reduced performance because of the low open-loop gain. The outputs of the three-phase oscillator can be summed in any desired proportion by scaling $R_1, R_2, R_3, R_4$ to give an output at any other phase angle. Note that all outputs are at the same d.c. potential, which will vary from device to device but will be about 50% of the supply.
- A single-stage phase-shift oscillator requires a gain of $-8$ if the components are graded as shown and $n$ is large. Restricting $n$ to 10, and operating the inverter in the range 6 to 10V comfortably exceeds the condition for sustained oscillation, allowing non-linearity to limit the amplitude. Other combinations of networks and inverting stages can be used (see Set 26).
- An approximately 90° phase-shift can be introduced by passing the signal through the circuit shown. Provided $R_2, R_3 \gg R_1$, and $R_3, C_2 \gg R_1 C_1$, the circuit approximates to an integrator. If all the inverters are well matched, $R_3, R_4, C_2$ can be omitted.

Cross references
Set 26, cards 3, 4
Set 21, card 5

Circuit modifications
Two-integrator oscillator

Circuit description
Assume initially that the inverters have a high voltage gain and that the network impedances are high enough to avoid significant loading of the inverter outputs. The system is then a two-integrator oscillator (as described in Set 26). The integrators produce a total phase shift of 180° which combined with three inversions gives an overall phase shift of zero. The finite gains and output impedances of the inverters reduce the effective Q of the system, and a separate positive feedback path is introduced via $R_6$ to initiate oscillation. Amplitude control is via the non-linearity of the inverters— as $R_6$ is reduced in value, the amplitude increases until distortion reduces the average loop gain over the cycle to accommodate the increased feedback. An alternative method of controlling the oscillation is to increase the ratio of $R_2$ to $R_1$, while maintaining $R_6$ constant (or omitted in some cases). The three outputs are of different phase and somewhat different amplitude. The phase differences are of the order of ±90° with $V_1$ lagging and $V_3$ leading on $V_2$ (strictly these voltages lead and lag but with an additional inversion in each case). The resistor values may be large without the inverter inputs loading the network; the values should be large to minimize loading on the amplifier outputs. N.B. The low distortion obtained above is because only a small amount of positive feedback was used i.e. the output was not driven into its very non-linear region. For guaranteed oscillation more distortion would have to be accepted.

Component changes
IC: Any c.m.o.s. device containing at least three inverters, NAND or NOR gates.
Supply: Will not oscillate satisfactorily at either very high or very low voltages unless excessive feedback used. 5 to 10V is suitable range for most i.c.s.
R1 to R4: Normally equal; variation of any one changes $f$ with relationship $f \propto 1/\sqrt{R}$. For continuous variation in frequency with less change in amplitude, replace $R_3$ and $R_4$ by a twin-gang pot. Range of values for $R_1$ to $R_4$ typically 10k to 10MΩ. With high values it is more difficult to provide controlled positive feedback.

R6 $\gg$ $R_1$ etc typically $R_4/R_1 \simeq$ 5 to 20.
$C_6, C_7$: 1n to 10µF.
(To obtain very low frequencies use large capacitors but not polarized units. The leakage currents may restrict the Q and inhibit oscillation.)

Circuit modifications
- Spare gates/inverters can be used to provide anti-phase outputs. If used with a pair of resistors as in the first amplifier overleaf an inverted sine wave output can be obtained from any of the three outputs. If the outputs are fed directly to the gates of three inverters, then three square-waves are obtained with 120° phase differences. The rise and fall times are not very fast and Schmitt triggers using two inverters with overall positive feedback give a sharp switching action. All of these outputs are compatible with normal c.m.o.s. logic circuits operated from the same supplies.
- Most other RC oscillators based on inverting amplifiers, op-amp see-saw circuits etc can be constructed using c.m.o.s. gates/inverters. Because the gain is already low any further losses at high frequency worsens the performance, increasing the distortion to unacceptable levels. Nonetheless oscillation to beyond the audio band is possible. As an example consider the Baxandall version of the Wien-bridge oscillator. As with the previous circuit, using more than one amplifier helps to offset the limited gain of each stage. The RC values are scaled so that the outputs are antiphase and approximately equal in value. The maximum gain of the frequency-dependent stage is a little less than unity. Hence $R_2 > R_1$ is needed.

Further reading
Frequency-voltage converter

Typical performance
- IC 4×CD407AE
- Supply 10V
- C1 0.1μF
- Meter 500μA, 200Ω
- Input Logic level pulse train
  - 0 to 300Hz
  - C1 100μF
  - I fC1Vs

Circuit description
The circuit is simple in concept and exploits the characteristics of c.m.o.s. very well. The two devices are switched alternately in and out of conduction. When the p-channel device conducts it completely discharges the capacitor provided that it is left in conduction for a long enough period. When the n-channel device conducts, it charges the capacitor fully to the supply voltage. The current flows through the meter with the shunt capacitor limiting transient effects due to meter inductance. The total charge flow per pulse is C1V and if this occurs at a frequency f, the charge per second is fC1V. This is by definition the mean current flow, the parameter to which the moving-coil meter responds. A small non-linearity occurs when the meter p.d. increases, since this reduces the p.d. to which the capacitor charges on the following pulses. The effect at these levels is to reduce the full scale value by less than 1%. In addition to the external physical capacitance, various stray internal and external to the circuit add to the meter reading. For a 15V supply and a meter full-scale sensitivity of 1.5mA, the meter reading was 9% high at 100kHz with a 1nF capacitor. Removal of that capacitor confirmed the presence of strays by leaving a meter reading of just over 9% of full-scale at the same frequency. The full-scale frequency range is then inverse to the value of capacitance used. This is verified up to 1μF, where the full-scale reading corresponds to 100Hz. Using a 10V supply, a 1mA movement gives the same overall sensitivity.

Component changes
IC: Any pair of complementary enhancement mode m.o.s.f.e.t.s. Other manufacturers equivalents of this i.c. may vary in respect of minimum/maximum supply voltage, frequency range cost etc but the same principles apply.
- Supply: 3 to 15V. At low voltages meter sensitivity needs to be increased to 100μA. At high voltages a limiting resistor in series with the capacitor minimizes the peak current.
- C1: 1n to 10μF. For low values, a smaller capacitance than indicated in simple theory will be needed to allow for strays. At very low frequencies additional smoothing of the output is needed to reduce meter fluctuations.
- C2: Used to suppress transients and/or reduce meter fluctuations at low frequencies. Not critical —may be omitted.
- Meter: 50μA to 5mA depending on supply voltage and range required.

Further reading
Current-differencing amplifier

Circuit description
It is possible to duplicate bipolar circuits in m.o.s. form, but a flexible approach is needed if existing c.m.o.s. packages are to be adapted. As an example, consider the current-differencing amplifier (c.d.a., or Norton amplifier). In bipolar form this uses a current-mirror at the input such that the first transistor of the amplifier proper is fed with a current equal to the difference between the input currents. Substituting a pair of n-channel transistors the current-differencing action is still obtained but the p.d. is larger. Assuming the drain-source voltage on Trb is above the pinch-off level, its drain current is comparable with I1 (net current in R4 is then I1−I2). If R2 becomes too large, the output stage saturates and a large voltage change at the gate of Trb disturbs the relationship. The inverting amplifier, Tr4 has a constant-current load provided by Tr4 and R4, since the small voltage swing at the commoned gates of Trb and Tr4 produces a very small fractional change in the p.d. across R4. Thus R4 reduces the quiescent level of current and makes the system operate as a defined transconductance (Tr4) operating into the feedback resistor R5. This gives the very high output resistance indicated above. The current transfer ratio of the current mirror remains close to unity over a wide range of currents—a total change in the imbalance of 3% over a 1000:1 range. The absolute accuracy cannot be expected to be better than one or two percent even under favourable circumstances, but the circuit is capable of resolving minute changes in current i.e. with I1 as the unknown current, I2 is adjusted until the output voltage is at some reference level. Any change in I2 produces an output voltage swing dVout. Alternatively R5 may be a meter, reading the current difference directly.

Typical performance
IC: CD4007 (Tr4+4)
Supply +15V
R1: 10kΩ
R2: 1kΩ
I1, I2: 100μA
I1= I2−I3
Output resistance > 100MΩ
at I2=10μA
Max. R5 ≈ 0.5MΩ
at I2=10μA for good linearity

Component changes
IC: Requires access to individual devices
Supply: +10 to +15V
R1: 10k to 220kΩ

Circuit modifications
- The circuit can be used with any feedback element to define its overall transfer function.
- For example, with capacitive feedback an integrator results.
- If either or both of I1, I2 are switched in value then the magnitude or direction of the slope of the output waveform can be changed. This allows various triangular and ramp waveforms to be generated. When I1=I2 the net current is zero and the output voltage holds its last value.
- Because the currents can be extremely small, long integrating periods can be controlled and it could be the basis of a simple long-period timer. Tr4 can conduct heavily if overdriven so the output can be rapidly reset to a low value.
- The output stage alone can be gated by a logic level pulse, such that when the input is low Tr4 conducts as a low-current source and produces a linear ramp (Tr5 is off). When the input goes high Tr4 is cut-off and Tr5 rapidly discharges the capacitor to ground. A source-follower could be used to buffer the resulting triggered ramp.

Cross references
Sets 16, 17, 18
Circuit description
At low supply voltages the c.m.o.s. inverter carries a low current and has a high output resistance. Each of these facts restricts operation to high load resistances. By adding an emitter follower, the effective output impedance can be reduced and the output current increased, both by a factor of 100 or more with a suitable transistor. In the example shown, a peak current of up to 10mA was available for the load while the normal inverter quiescent current under these conditions would be < 1mA. To demonstrate the effect the resistor ratio defining the gain was varied from 1:1 to 10:1 with the c.m.o.s. device driving a 1kΩ load (i) with d.c. coupling to the load i.e. unbuffered (ii) with a transistor having $R_0 = 2.2kΩ$, circuit diagram as above. In the unbuffered case, the maximum value of voltage gain obtained was almost independent of the feedback values. This showed that the 1kΩ load was an effective short circuit i.e. that the gain without feedback would have been restricted to $-1.3$. This corresponds to a $g_m$ of 1.3mS, while the presence of the transistor would increase this to 130mS assuming a current gain of 100. This is enough to allow a practical gain of $-8.3$ for a resistive ratio of 10:1 even with the a.c. load being represented by $R_3$ in parallel with $R_4$.

Another advantage is that the c.m.o.s. output is buffered from the shunt-capacitance of the load plus strays, and the gain-bandwidth product is increased.

Component changes
IC: Any c.m.o.s. inverter, gate supply: $±5$ to $±15V$
Because of the current boosting of the output transistor, the c.m.o.s. stage can be operated at lower voltages than is usual for linear operation.
$R_0$, $R_3$: Not critical as $R_3$ no longer loads the output.
$R_2$, $R_4$: For class A operation, $R_3$ has to carry a quiescent current equal to or greater than the peak current required by $R_2$. This may be up to 100mA with a power transistor. $Tr_1$: Current/power rating to suit load. Not critical.

Circuit modifications
As usual, any compound pair of transistors may be added to increase gain-complementary versions if load is to be referred to positive supply rail.
An alternative configuration is to drive the base of a common emitter amplifier (a base limiting resistor may be added at higher voltages). The output is now in phase with the input and the combination is not suitable for the direct application of overall negative feedback. Shunt feedback over the inverter together with series feedback in the transistor (emitter resistor) would be another possibility with overall feedback from the emitter to the input—a form of d.c. feedback pair.
If the inverter supply current is monitored it can be used to switch an output stage; $R_3$ limits the peak current in the c.m.o.s. stage while $R_1$ holds the transistor off at lower inverter quiescent currents. In addition to the load current, the c.m.o.s. pair pass through a peak of current as the output swings through its linear region and this complicates the calculations.

Cross reference
Set 27, card 5
These notes offer some novel applications of D-type flip-flops within analogue systems. Where a number of c.m.o.s. devices are to be used for sensing, amplifying etc it can be very convenient to have a reference voltage close to the threshold values of these devices. Such a voltage automatically tracking with any supply or temperature changes by using one D-type flip flop as shown. When it is clocked the Q output switches either to 1 or 0 depending whether the D-input is above or below its sharply defined threshold. The inverted Q output attempts to return the D-input to the opposite state. By choosing the capacitor value in conjunction with the clock frequency, the ripple at the D-input is small and centred about its threshold. The almost-zero input current ensures that the mean voltage at Q equals that at D. If the output is smoothed a low-ripple direct voltage results with $V_0 \sim V_{TH}$ of the D-input.

By using the other terminals that may be available such as the R and S inputs novel functions are possible. Monostable action has been noted in previous sets, and it can be combined with feedback to the D-input as above. For a low input voltage, then at switch on either Q or Q may go to 1. Assume the former: at some later instant R is driven high driving Q high until the CL input is raised above its threshold and Q goes high again. A pulse train is developed in which the mean value at Q is a function of V. If the monostable action ensures pulses of constant height and width then the pulses rate is a linear function of V. If the output is taken from Q then by adjusting the value of m about unity it is possible to obtain a pulse rate that tends to zero for $V = 0$ and to some full-scale value as $V$ approaches $V_c$.

A ramp generator results if a current is fed to the capacitor at the clock input with a periodic discharge via the diode from Q. Resetting is again a function of the monostable that determines the output pulse width.

Several of these actions can be combined to provide complex functions using the bare minimum number of active devices. The circuit shown is a level-sensing, latching audible alarm. It is easiest to follow by assuming that at some point the input V has exceeded the CL threshold and that the alarm has been initiated. Diode $D_4$ acts as a half-wave rectifier charging the 15µF capacitor almost to supply level. This constant voltage attempts to raise CL input via $D_2$. Each time it does so, triggering the flip flop, Q goes high and Q low. The CL input is rapidly returned to zero via $D_1$ while the monostable action via the R input defines the output pulse width. After resetting $D_4$ is reverse-biased and the cycle restarts. The Q output is an audio-frequency pulse train whose frequency is only marginally affected by any further changes in V. Until V first exceeds the CL threshold, the circuit remains in a quiescent state with Q low Q high.
Set 29: Analogue multipliers

A most versatile i.c. appears in this set, incorporating four-quadrant multiplier, op-amp and buffer on the same chip, page 123, with an h.f. capability up to the order of MHz (higher in some applications). Squaring, suppressed carrier a.m., and demodulation of a.m. are uses of it shown on page 124 and page 000 (set 30) includes some further applications.

This is one of these subjects where it's difficult to avoid ending each card heading with the name of the circuit type! It is also a set containing an important class of circuit, card 8, that didn't quite do justice to its originator—Barrie Gilbert of Analog Devices. In the original card for the translinear multiplier $R_4$ was shown wired to the wrong end of $R_2$. And a missing minus sign, between $I_A$ and $I_B$ in circuit modifications and now corrected, made nonsense of the analysis.

The circuit of card 5 was originally incorrectly drawn too; inputs to $R_{111}$ and $R_{112}$ come from the series diode-resistor junction in the precision rectifier circuits. (Omission of $R_5$ occurred on card 4 and, on the same card, the lower-case abbreviation $i$ should have been shown as $I$ to correspond with the diagrams.)

Background article 116
Quarter-squares multiplier 118
V-to-f converter multiplier 119
$\Delta\Sigma$ modulator/multiplier 120
Log-antilog multiplier 121
Triangle-wave averaging multiplier 122
Four-quadrant multiplier—characteristics 123
Four-quadrant multiplier—applications 124
Translinear multiplier 125
Hall-effect multiplier 126
F.e.t. analogue multiplier 127
Up-date circuits 128
Introducing analogue multipliers

In the processing of electrical signals there is a need for circuits that can perform all the standard arithmetical processes — addition, subtraction, multiplication and division. The first two fall into the domain of linear amplifiers and present no great difficulty; the last-mentioned pair provide a real challenge to the ingenuity of circuit designers. Fig. 1 shows the waveforms of a particular example where an input signal \( Y \) is to be under the control of a second input \( X \), the output being of the form \( XY \). This is a gain-controlled amplifier and is one of the simpler forms of multiplier since usually the gain is required to be either positive or negative and not both. Hence \( X \) takes up only one polarity, and Fig. 2 shows the multiplier as needing to operate in only two of the four quadrants viz \( X \) positive, \( Y \) positive and \( X \) positive, \( Y \) negative. Such a system can be realized as in Fig. 3 where \( v_1 \) corresponds to \( Y \) and \( v_2 \) to \( X \). In many such circuits it is not even essential that the gain be a linear function of \( v_2 \), in which case the circuit ceases to be a multiplier. A problem with circuits based on this idea is that of finding a resistor having negligible non-linearity over a suitable range of currents and voltages, while being controllable by an external signal.

While true and direct multiplication would be ideal, and can be obtained by using suitable transducers such as Hall-effect devices (see card 9), the designer often has to resort to devices and circuits obeying other laws. These are then manipulated until some combination of them yields a term which is proportional to the product of two signals.

It can be very difficult to eliminate all unwanted terms consistently and over a wide range of temperatures and supply voltages. One well-established technique is to use a circuit with a square-law voltage transfer function. This can be synthesized by a "piece-wise linear" technique, where a network of diodes, resistors and reference voltages, provides a slope that changes progressively as the input increases (see card 1).

With a large enough number of segments, a power law can be approached to any desired degree of accuracy. For economy the number of segments has to be restricted particularly if both polarities of input have to be accommodated — twenty or so might be needed in such a case.

The quarter-squares multiplier applied in analogue computing uses two such squaring circuits as shown in Fig. 4. The sum of the two input signals is fed to one squarer, and the difference to a second. Each output contains a product term but also the square of each input signal. By subtracting the two outputs, these square terms cancel leaving only the product term, in this case \( 4XY \) i.e. a quarter of the output giving the desired multiplication of \( X \) by \( Y \) (card 1).

Of considerable interest in this respect are the characteristics of field-effect transistors. Both junction and m.o.s. devices have an on-resistance below pinch-off that is controlled by the gate-source voltage. The resistance is non-linear but can be linearized with feedback, while the control-law contains a square-law term (card 10).

Although bipolar transistors have output current/input voltage transfer characteristics which include square-law terms, their true nature is exponential with all their higher-order terms. It would be pointless to try to manipulate these transfer functions in the same way as above. Instead the exponential function is exploited directly in various ways. The exponential equation is reasonably accurate for p-n junctions over a few decades of currents. To ensure that the current in the diode/transistor is well-controlled the device can be placed in the feedback path of an operational amplifier, Fig. 5.
One problem introduced by the use of a transistor is that of the increased loop gain, the transistor operating effectively in common-base with a voltage gain dependent on the input voltage. This leads to h.f. oscillation unless the amplitude-frequency response is carefully controlled by means of external compensation - one possibility being capacitive feedback from output to inverting input, by-passing the transistor at high frequencies. To use this logarithmic function for multiplication (as in card 4) the system shown in block diagram form in Fig. 6 may be used. The antilog circuit is simply a log circuit with input (resistor) and feedback (diode/transistor) elements interchanged. Similar systems can be devised to provide other power law and ratio circuits by expressing the desired function in log/antilog forms first.

A related technique uses multiple transistors (card 8), shown in a general configuration in Fig. 7. It is assumed that the currents are controlled by external generators and/or feedback with one of them, or the difference between two of them, as the output. In the example shown, for \( I_2 \) maintained constant, \( I_1 \propto I_4 \) i.e. a multiplier. As shown, operation would be restricted to a single quadrant, but a large number of circuits have been published to extend the operation into all four quadrants and to produce a range of interrelationships such as those based on the log approach.

A totally different approach yielded many ingenious and effective multipliers, prior to the ready availability of matched transistors. It stems from the concept that the terms to be multiplied need not remain in the same physical domain while being processed e.g. the variables of interest may both be voltages and the output may also be required as a voltage but each input may be used separately to control a different parameter of an output waveform, while a third property might be proportional to the product of the other two.

Consider the pulse waveform shown in Fig. 8. The pulse height is \( V \), the repetition frequency \( f=1/T \) and the pulse width of \( \Delta t \). The mean output voltage as would be indicated on a moving coil meter is given by the product of these three variables, increases in each individually producing a proportional change in that mean value. Thus if any pair of these variables \( (f, V), (f, \Delta t) \) or \( (V, \Delta t) \) is brought under the separate and linear control of two input voltages, then the mean output voltage is a measure of the input product (card 2). There is a close relationship between these circuits and various forms of pulse modulators in the same way that the analogue multipliers described earlier are related to amplitude modulators.

There are purely digital methods of multiplication, but an intermediate solution is offered by the multiplying d.-to-a. converter. For a given binary input the converter has a number of output switches activated. If these operate on an external reference voltage the final output depends on the product of that reference voltage and the binary number. A class of digital circuits called binary-rate-multipliers is used to operate on a pulse train, producing a second train of pulses at a slower rate, card 3. At first sight this must cast doubts on the terminology since we associate multiplication with outputs greater than the inputs. The property of the circuit is however to multiply the input pulse rate by a factor such as \( n/100 \) where \( n < 100 \) and \( n \) can take up any value between 1 and 100, i.e. it is equivalent to multiplying by \( n \) but shifting the decimal point by two places.

The variety of methods available for achieving the multiplication of two variables electronically is growing, and modules are readily available to a high degree of accuracy. As the methods vary widely in both properties and in the physical processes involved it is important to consider the options carefully - it is a field where the opportunities to place one's foot firmly in it (unspecified) are remarkably high.
Quarter-squares multiplier

Description
Quarter square multipliers are found frequently in analogue/hybrid computers in which their high accuracy (0.05% of half scale) is required and their limited bandwidth (less than 10kHz) is no disadvantage. They implement the relationship

\[ xy = \frac{1}{2}[(x+y)^2 - (x-y)^2] \]

i.e. multiplication based on a square law device—this is usually a diode function generator permanently set to provide a square law action. Such generators are usually single quadrant devices, e.g. A (above) requires a positive input and this necessitates the use of an absolute value circuit prior to it. If, for instance, \((x+y)\) is positive then \(D_1\) conducts (and \(D_2\) does not) and a positive voltage is applied to A. Likewise if \((x+y)\) is negative \(D_2\) conducts (and \(D_1\) does not) but again it is a positive voltage that is applied to A. Hence the output of A is proportional to \((x+y)^2\), which is the same as \((x+y)^2\). A similar argument applies to the other absolute value circuit, B; being a 3rd quadrant device, it produces a current proportional to \(-(x-y)^2\).

The constant \(k\) appearing in the output expression depends on \(R\) and on the output characteristics of A and B. Generally, if the maximum value of \(X\) and \(Y\) is say P volts, then \(k\) is set to \(P\).

If an absolute value circuit does not precede the squaring section then a total of four squaring sections are necessary. Despite the apparent increased complexity this is still sometimes done to avoid errors due to the diodes \(D_1\) and \(D_2\) and to provide further functions.

An example of a square law generator circuit is shown (ref. 1). The current \(i\) has a total of 10 possible paths between P and the summing junction (SJ). Depending on the voltage at P, however, not all of these paths are open. If the voltage is very small, only one path, via the top R is open. With increasing voltage more paths become open so that the resistance between P and SJ decreases thus increasing the gain between P and the amplifier output in steps. The points at which these step changes in gain occur are termed breakpoints and are usually equally spaced as the figure above shows. Uniform breakpoint spacing allows identical slope increments and equal positive and negative errors. For this situation errors can be kept within \(10^{-4}\%\) of half scale with \(10/\sqrt{x}\) segments. Unequal spacing of the breakpoints makes no significant difference to the overall accuracy although it is common to have one or two extra breakpoints near zero for improved accuracy.

The use of the diode string to provide some of the biasing functions provides temperature compensation as well. The capacitors shown increase the frequency response.

Related circuits
If bandwidth is not essential but increased accuracy is, then use can be made of the relationship \(m^2 = \frac{1}{2}[1 + 2u + u^2]\) where \(u = 2|m| - 1\). The right hand side of this equation is not totally dependent on \(u^2\) so that errors produced by squaring a square circuit producing \(u^2\) have a reduced effect on the errors in \(m^2\). One can, of course, invert the situation and say that, for the same accuracy, fewer breakpoints are necessary and a less expensive squarer is produced. A-“card” mechanism is the right hand side of the equation is simply inserted as the A card in the circuit overlay and with minor modifications a B card is produced.

If we now examine

\[ xy = \frac{x+y^2}{2} - \frac{x-y^2}{2} = m_1^2 - m_2^2 \]

and apply the above equation for \(m\) we obtain

\[ xy = \frac{1}{2} \left[ (u_1^2 - u_2^2) + (u_1^2 - u_2^2) \right] \]

Reapplying the formula on the second bracketed term \((u_1^2 - u_2^2)\) and truncating the series which will result from repeated application gives

\[ xy = \frac{1}{2} \left[ (x+y) \right] + \frac{1}{2} \left[ (x-y) \right] \]

This does not require a squaring circuit and can be based on precision absolute value circuits such as those given in ref. 2

References
2. Set 4, card 3.
V-f converter multiplier

**Typical performance**
IC 741, ±15V supplies
Tr1 2N2646 u.j.t.
Tr2 2N5486 f.e.t. (n-channel)
R1 100Ω
R2 1kΩ
C 47nF
T1 100μs
Pulse height — 5V

**Circuit description**
The circuit is a modification of the v-f converter described in ref. 1. The f.e.t. Tr2 is the only addition. Graph 1 was obtained with f.e.t. permanently conducting, i.e. \( V_{in}=0 \), and shows \( f_0 \) to be proportional to \( V_{in} \). This graph was obtained with \( v_1 \) set to 3.3V which setting gave an \( f_0 \) of 2kHz with \( V_{in}=2V \). Control of the relationship between \( f_0 \) and \( V_{in} \) depends on the u.j.t. breakdown voltage and this is variable from device to device. The v-f conversion can be described as a conversion first from \( V_{in} \) to \( i_1 \) and secondly from \( i_1 \) to \( f_0 \). The greater \( i_1 \) the more rapidly does the capacitor charge and the more rapidly is the breakdown condition of the u.j.t. met. The downwards ramp of graph 2 shows this charging. On breakdown the u.j.t. shorts the capacitor so the output voltage rises towards zero until the u.j.t. assumes its normal non-conducting role.

If now pulses are fed to the f.e.t. gate as shown, \( i_1 \) will become a train of current pulses \( i_2 \), \( f_0 \) then depends on \( i_2 \):
\[
f_0=k_i=\frac{T_s}{C} \cdot \frac{V_{in}}{R_2} \cdot f_{in}
\]

Graph 3 shows that \( f_0 \) is indeed proportional to \( f_{in} \), the proportionality between \( f_0 \) and \( V_{in} \) being shown in graph 1. The multiplying action is thus experimentally verified.

If \( f_{in} \) is derived from another v-f converter we have \( f_{in}=k_2V_{in} \) and then \( f_0 = k_2V_{in} \cdot V_{in} \) so that \( f_0 \) is proportional to the product of two voltages.

**Component changes.** The value of \( R_2 \) quoted i.e. 1kΩ is the absolute minimum usable. \( R_1 \) should be much larger than the f.e.t. "on" resistance (≈ 200Ω). Max. \( R_1 \approx 100kΩ \); beyond this op-amp input currents become significant. The value of \( C \) is related to that for \( R_2 \) as the ramp slope is \( 1/R_2C \). With \( C=4.7nF \) and \( T_s=10μs \) we achieved a maximum \( f_0 \) of 10kHz. Higher values of \( f_0 \) are difficult to achieve because of charge-storage effects in the u.j.t. affecting the discharge time. Pulse height must be sufficient to cause pinch-off of f.e.t. but not so high as to cause breakdown. —1 to —10V with this device was satisfactory.

**Circuit modifications**
The circuit above shows a complete circuit whose output frequency, \( f_{in} \), is proportional to the product of the voltages \( v_1 \) and \( v_2 \). The second voltage to frequency converter, VFC2, is assumed to be identical to that shown in the main diagram overleaf with the omission of the f.e.t. gate; it will therefore produce an output as shown in graph 2. This output is fed to the c.m.o.s. monostable shown (ref. 2) in which \( V_{DD}=0V \) and \( V_{SS}=-10V \) (—15V would also be acceptable). This monostable is triggered when the c.p. voltage is about 50% of \( V_{DD} \), the rising edge being the only one which is effective. The output pulse width is controlled by the \( R_2C \) time constant, resetting occurring when the voltage at R is approximately 50% of the input resistors and feedback capacitors will be different. Voltages \( V_1 \) and \( V_2 \) also affect the frequencies of operation. As the maximum frequency attainable from a unijunction type of v-f converter is of the order of 10kHz it may be necessary to use different types for a particular application. There is certainly no need for VFC1 and VFC2 to be of the same type. V-f converters have been considered in ref. 3. If different v-f converters are used different gating arrangements may well be required and in particular different monostables may be needed ref. 4. A multiplier using two identical (in form) v-f converters designed for long term stability and able to accommodate floating inputs is described in detail in ref. 5.

**Related circuits**
1 Set 21, V-f converters, card 1
2 Set 19, Monostables, card 8
3 Set 21, V-f converters
4 Set 19, Monostables
Delta-sigma modulator/multiplier

Circuit description
If an output waveform has a constant pulse height and width but the pulse-rate is proportional to an input voltage, then the mean value of the output is also proportional to that voltage. If the pulse height is made proportional to a second voltage the mean output becomes proportional to the product of the two voltages. A delta-sigma modulator converts a pulse-train into one with a smaller number of pulses, using an integrator to control the voltage on the D input of a flip-flop. As the mean voltage at the inverting and non-inverting inputs are the same and the mean current in the capacitor is zero, the fraction of the time for which Q is high is controlled by the input voltage \( v_1 \). The circuit configuration has a negative input voltage and supply because it was designed to use the simplest arrangement, and certain op-amps (e.g. Signetics 741) have an input common-mode range that includes the positive supply rail. The circuit can be adapted for any other op-amp by providing a separate positive bias. With dual supplies the system may equally be used with positive inputs and outputs if the flip-flop is powered from the positive rail.

The Q output is used to gate a junction f.e.t. on and off. With Q high (zero volts), the diode is non-conducting and \( R_1 \) establishes zero gate-source bias. With Q low \((-V)\) the f.e.t. is off. This is true provided the second input voltage \( v_2 \) is small so that the reverse gate-source voltage is in excess of the pinch-off voltage. The load receives voltage pulses of duration equal to the inter pulse period and just less than \( v_1 \) in magnitude. The number of pulses in a given time is proportional to \( v_1 \). Hence the mean load voltage is \( \propto v_1 v_2 \). This can be read directly on a moving-coil meter, or filtered and fed to a d.v.m.

Component changes
IC\(_1\): Any op-amp if supply requirements observed. Output is always close to the flip-flop threshold voltage i.e. does not approach either supply line. Supplies can be single-ended negative or positive depending on op-amp. Must be large enough to gate f.e.t. 6 to 15V. Tr\(_1\): Any n-channel junction f.e.t. with pinch-off below, say, 5V. Low on-resistance preferred. D\(_1\): General purpose switching diode.
IC\(_2\): Any c.m.o.s. D-type flip-flop (set and reset grounded).
R\(_1\), R\(_2\), R\(_4\): Ratio sets 'gain' i.e. usual potential divider relationship defines ratio of mean output at Q to \( v_1 \). Total resistance 10k to 10M\(\Omega\).

Typical performance
IC\(_1\): N5741V (Signetics)
IC\(_2\): CD4013
D\(_1\): 1N4148
Tr\(_1\): 2N5457
R\(_1\): 4.7k\(\Omega\)
R\(_2\): 100k\(\Omega\) pot.
R\(_3\): 100k\(\Omega\)
R\(_4\): 15k\(\Omega\)
R\(_5\): 15k\(\Omega\)
Supply: –10V
\(v_1\), \(v_2\) 0 → –1V
\(v_0\) 0 → –1V
|\(v_0\)| = \(v_1 v_2\)

Circuit modifications
- To improve switching times without adding an extra i.e., it is possible to use a p.m.o.s. transistor from a CD4007 package. If the remainder of the package is connected as in the circuit shown, a clock generator results. Frequencies from 10kHz to >100kHz have been tested with this system. In general clock rates of several MHz are feasible but would make heavy demands on the analogue switches. The p.m.o.s. device prevents charge storage across the load resistance in the off-state, and allows the high load resistance represented by a d.v.m. to be used. This makes the input impedance at the \( v_2 \) input high, without restricting the switching rate.
- If positive input voltages are used, and standard analogue gates are available, then a series switch arrangement as shown may be driven from the Q output. Then when \( v_1 \) is at its maximum value, Q is almost permanently at logic 1 and \( v_2 \) is gated through to the load for almost 100% of the time. A shunt gate driven from Q completes the configuration for higher switching speeds or where \( R_1 \) is to be raised.
- In principle this can be interpreted as a combined \( V_1 - f \) and \( V_2 \)-amplitude converter system.

Related circuits
Set 15, card 9
Log-antilog multiplier

Components
IC1-4 741 (e.g. RC4136 quad package)
Tr1 to Tr4 1/5 CA3086
R1, R2, R3, R4, R5 100kΩ
R6 10kΩ, R7 2.2kΩ
C1 330pF, C2 200pF
C3 22pF
All passive components ±5%
Supply voltage ±7.5V

Performance
It can be shown (see text) that
\[ V_o = E_1E_2E_3/R_1R_2R_4 \]
With the resistor values chosen, assuming perfect components, \( V_o = E_1E_2E_3/R_1R_2R_4 \) and so the circuit can be used as a squarer (\( E_1 = E_2 \) and \( E_3 \) constant), as a multiplier (\( E_3 \) constant \( E_1 \) and \( E_2 \) variable), as a divider (\( E_1 \) as divisor \( E_2 \) or \( E_3 \) as dividend, the other fixed) or as a device for obtaining the reciprocal of \( E_2 \) (\( E_1 \) and \( E_3 \) fixed). Results as a squarer are shown in graph 1 from which it will be noted that \( E_3 \) was set at 0.92 rather than 1V to achieve the slope of 45° (making up for component inaccuracy) and that the maximum \( V_o \) obtainable is less than 4V. Saturation of the transistors occurs at higher voltages. Graph 2 shows similar linearity for operation as a multiplier, multiplying the variable \( E_1 \) by the constant \( E_3 \). Identical results were obtained when the roles of \( E_1 \) and \( E_3 \) were reversed. Similar linearity was obtained with the device operated as an arithmetic inverter (reciprocal).

Circuit description
Analysis of the circuit is as follows:
\[ I_1 = E_1/R_1 \] and \( V_{be1} = kT/\log E_1 \)
\[ I_2 = E_2/R_1 \] and \( V_{be2} = kT/\log E_2 \)
\[ V' = V_{be2} - V_{be1} = kT/\log E_2 \]
\[ V_{be1} = V + V_{be1} = kT/\log E_2R_1R_3 \]
\[ q \log E_2R_1R_3 \]
\[ q \log E_2R_1R_3 \]
\[ I_3 = E_3/R_3 \] as \( V_{be1} = kT/\log E_2 \) and \( I_3 = E_3/R_3 \)

But \( \log E_3 = qV_{be3}/kT \) and \( I_3 = V_{be3}/R_3 \)
Combining this last pair of equations with equation 1 gives
\[ E_3/R_3 = E_2/R_2 \]
A functional block diagram following from these equations is shown, right. The antilog function is performed by Tr4 and IC4. Principally it is Tr4 which performs the antilog function in converting its base-emitter voltage to a current: IC4 and R4 convert this current to a voltage, viz. \( V_o \).

The above analysis concerned d.c. conditions only, so all capacitors were ignored. Likewise \( R_3 \) and \( R_4 \) were ignored. The function of all of these components is to stabilize the loops in which they are contained. To see this, consider the simplest case viz. IC4 and its associated circuitry. The loop gain of this circuit is the open-loop gain of IC4 together with the gain of Tr3 which is in common base mode and has a voltage gain given approximately by \( g_m \times \) the load on Tr3. The loadable Tr2 is Ra (by superposition the Es input end of R5 is at ground). This voltage gain \( g_mR_a \) is large and the overall loop gain is, therefore, considerably enhanced and instability is a considerable problem. The inclusion of \( R_3 \) reduces the feedback path gain by a factor of the i.e. output voltage is applied to the base-emitter junction. For high frequency effects \( C_3 \) completely shorts out this feedback path amplifier, again improving stability. Note that \( g_m \) depends on the operating conditions i.e., in this case, on \( E_3 \), so that the problem is complex indeed. Note that all the input voltages must be positive to maintain correct transistor biasing. If a sinusoid is to be used it must be suitably biased to prevent negative going inputs and the output circuitry must be considerably rearranged to remove the effect of the biasing term on the output.

Component changes
This circuit was built from the cheapest possible components and no effort was made to null the i.e.s. Considerable improvement in accuracy is obtainable if the resistors \( R_1R_3R_5 \) and \( R_4 \) are chosen to a much tighter tolerance.

Further reading
National Semiconductor application notes AN-30.

Related circuits
Set 4, card 11
Triangle-wave averaging multiplier

Components
R₁ to R₁₄ 120kΩ
IC₁ 741
D₁ 1N914
Supplies ±15V

Performance
With v set at 4V and the inverted sum of e₁, e₂, and y. With x and y both at 1V and varying the frequency of the triangular wave the output accuracy was maintained within 1% up to 6kHz. The device is a 4-quadrant multiplier.

Description
The block comprising IC₂, R₃, R₄, R₅, R₆, D₁, and D₂ is a precision half-wave rectifier producing a negative output equal in magnitude to the sum of the input voltages when that sum is positive. The block producing e₂ can likewise be described. The sum of e₁, e₂, and y produces the output and at first sight the multiplier appears related to time-division (a.m./p.w.m.) multipliers. Analysis shows however that this multiplier is more closely related to the quadrature multiplier, the reason being that the height of e₂ is closely related to the base of the hatched triangle in graph 1 so that the area of the triangle becomes a square function.

A more general diagram is shown above: for this system it can be shown that the average value of Vₒ is:

\[ \frac{-R'}{R} \text{average of } e₁ + 1 \text{average of } e₂ \]

If \( R' = aR \), then this expression simplifies to

\[ V_{\text{avg}} = \frac{a}{cV} \]

Comparing this with the circuit overleaf we see that we have \( \alpha = a = b = 1 \) and \( cV = 4 \).

Returning now to the original circuit one can observe that the somewhat restricted input range is due to the fact that at no point should the bias voltage exceed the peak of the triangular wave. Clearly the input signal size can be increased by increasing the carrier magnitude and also by introducing factors a and b, reducing the effective input. The effect of these changes can be then cancelled by setting \( R' = aV/ab \).

The circuit is sensitive to d.c. components in the carrier and also to the carrier magnitude. The effect of a d.c. component is particularly noticeable at low signal levels.

Circuit modifications
Resistor values are not critical but lower values than those shown may be preferable to improve the bandwidth by reducing the time constants of stray and other capacitive paths. Resistor R' may be replaced by a filter to remove the a.c. components of Vₒ. The d.c. impedance of such a filter should still equal R'.

The system bandwidth can be increased by using a faster version of half-wave rectifiers.

- An alternative scheme is shown above; this arises from the fact that the product xy is obtained by biasing a triangular wave by x and limiting the resultant at ±y.

A suitable high speed limiter is shown above. The output is limited at \( r₁E/r₄ \) for negative inputs and at \( -r₃E/r₄ \) for positive inputs. These would be set to ±y respectively. Note that \( r₁ ≪ R \) for good limiting.

References
1 Set 22, card 3
Four-quadrant multiplier—characteristics

Pin designation
11 op-amp output
12 compensation
13 non-inverting op-amp input
14 inverting op-amp input
15 high-frequency output
16 positive supply

Description
The XR-2208/2308 is an op-amp combining a four-quadrant analogue multiplier, a high-frequency buffer amplifier and a differential-input op-amp on the same monolithic integrated circuit. The package is suitable for arithmetic operations and communication signal processing, maximum versatility being achieved by internally separating the amplifier and the multiplier-buffer section; suitable interconnections being made externally with passive components. The op-amp can be used as a post-detection amplifier in coherent detector applications or as a preamplifier for low-level input signals. The output from the buffer amplifier can be used for high-frequency signal processing, the multiplier-buffer section having a small-signal 3dB bandwidth of 8MHz and a transconductance bandwidth of 100MHz. The package can be operated from symmetrical supply rails in the range ±4.5 to ±16V. Very good power supply rejection and temperature stability are achieved by internally-regulating current and voltage levels. The multiplier inputs x and y are applied to pins 3 and 5 respectively, with pin 4 common—normally the reference or ground terminal. However, in some applications x and y inputs are strapped together and pin 4 used as an input terminal. The d.c. bias currents at pins 3 and 5 are typically 3μA and at pin 4 typically 6μA. The differential output voltage (v0) between pins 1 and 2 is often connected directly to the op-amp (pins 13 and 14), the final output (v4) being obtained from pin 11.

\[ v_0 = \frac{R_X R_Y}{R_X + R_Y} v_x v_y \]

where all voltages are in volts and the gain control resistances \((R_X\) and \(R_Y\)) for the x and y sections of the multiplier are in kΩ. Conversion gain of the multiplier is

\[ K_{V} = \frac{25}{R_X \cdot R_Y} (V_{x-1}) \]

resistors \(R_X\) and \(R_Y\) being connected as below, where the arrangement for adjusting the x and y offsets at pins 7 and 8 is also shown.

The operational amplifier is internally protected against short-circuit load conditions and can sink or source a current of 10mA into a resistive load. This amplifier can be compensated for unconditional stability by connecting a capacitor (C_y) of 20pF across pins 11 and 12. For higher voltage gains than unity, C_y is reduced to increase small-signal bandwidth and to improve slew-rate.

The unity-gain buffer amplifier if brought into use by connecting a resistor from pin 15 to ground and provides a low-impedance output for the multiplier section when the latter is used at high frequencies, in order to minimize capacitive loading of the multiplier output proper.

The buffer output is not short-circuit protected and typically has a direct voltage of \(-4.5\) volts. The maximum direct current extracted from pin 15 should not exceed 10mA.

NOTE: When only the multiplier section or op-amp section is being used the input terminals of the unused section must be connected to ground. The maximum peak x or y input signal that can be used for a given supply voltage without significant improvement of the linearity of the multiplier is shown.

Further reading
XR-2208 Operational Multiplier, New Electronics, 1 April 1975, pp. 27-31.

Related circuits
Set 29, card 7
Set 29: Analogue multipliers—7

Four-quadrant multiplier—applications

In most multiplication applications the operational amplifier and multiplier sections are interconnected as shown left providing a single-ended output signal and having a wide dynamic range. With the values shown below, the linear output swing is typically 10V for maximum input signals of 10V with a scale factor $K = 0.1$.

Setting-up procedure
1. With 0V applied to both inputs the output offset is adjusted to be 0V with $R_1$.
2. With a 20V pk-pk, 50Hz signal applied to the x-input and 0V to the y-input, $R_4$ is adjusted to provide minimum output voltage.
3. With a 20V pk-pk 50Hz signal applied to the y-input and 0V to the x-input, $R_3$ is adjusted to provide minimum output voltage.
4. Repeat step 1.
5. With +10V applied to both inputs, $R_3$ is adjusted to provide an output of +10V.
6. Step 5 may be repeated with different input voltages and different polarities to obtain best accuracy either over the whole input range or over some specific part of it.

Squaring circuit
As shown over, the circuit used for squaring is essentially that used for multiplication except that the input signal is applied simultaneously to the x and y input terminals and only one input offset adjustment is required. Adjustment procedure is:

1. With 0V applied to the input the output offset is adjusted to be 0V using $R_{11}$.
2. With +1V applied to the input $R_4$ is adjusted to make $V_0 = 0.1V$.
3. With +10V applied to the input the output is adjusted to be +10V using $R_4$.
4. With −10V applied to the input check that the output is +10V, if this is not so repeat steps 1 to 3.

Component values
Supplies ±15V
$V_{x\text{max}}, V_{y\text{max}}$ 10V
$R_1, R_2$ 5kΩ
$R_3, R_4, R_5, R_6, R_{11}$ 100kΩ
$R_4, R_5$ 240kΩ, $R_6$ 300kΩ
$R_7$ 62kΩ, $C_1$ 20pF
$V_2 = V_x V_y/10$
$R_4$ scale factor
$R_3$ y-offset
$R_5$ x-offset
$R_{11}$ output offset

Means of the 25kΩ potentiometer which sets the d.c. level at pin 3. In suppressed-carrier applications, the carrier level at the output can be further reduced by means of the $x$ and $y$ offset adjustment controls. The buffer amplifier provides a unity gain low-impedance output, but if not required pin 15 should be open circuited to reduce power dissipation. Carrier suppression of 40dB up to 1MHz and 30dB up to 10MHz is obtainable without the use of the $x$ and $y$ offset adjustments.

Synchronous a.m. detector
The circuit (right) is suitable for demodulation of a.m. signals with carrier frequencies up to 100MHz, with an input signal of at least 25mV r.m.s. The a.m. input is applied to the common terminal of the multiplier, the y-gain terminals are strapped allowing this section to act as a limiter for inputs greater than about 50mV r.m.s. and the x-section acts in its linear mode. Capacitors $C_1$ at pins 1 and 2 in the low-pass filter serve to reduce the carrier feedthrough to the output.

Further reading

Related circuits
Set 29, card 6
Translinear multiplier

The circuit currents above are related to a defined current unit \( I \), by the following:
\[ I_x = (1 + X)/2 \quad I_y = (1 - X)/2 \]
where \( X \) and \( Y \) are controlled variables, and \( I_{MT} \) between \( \text{Tr}_2 \) and \( \text{Tr}_3 \) collectors is \( XY \cdot I \).

The circuit operates in the current domain and depends for its temperature independence on the proportionality of bipolar transistor \( \beta_m \) (transconductance) to the collector current. Currents \( I_x \), \( I_y \), \( I_y \) are ideally current sources, and the above network comprising \( V_x \), \( V_y \), \( R_3 \) to \( R_5 \) is an attempt to simulate such a condition e.g. \( I_x \) is approximately equal to \(-V_x/(R_7+R_{14}/2) \approx 100 \mu A\) plus a multiple of \( 100 \mu A \) defined by \( V_x/R_w \) where \( V_x \) is increased in steps of 1V. These calculations assume that the base-emitter junction voltages are negligible. To obtain a balanced condition where \( I_{MT} = 0 \) if either \( V_x \) or \( V_y \) is zero demands trimming of resistor \( R_2 \) and \( R_4 \) to allow for the 1.2V potential at the emitters of \( \text{Tr}_2 \), \( \text{Tr}_3 \). Linearity of \( I_{MT} \) is shown in accompanying graphs. Note, that if \( V_x = +8V \), this is equivalent to eight units of current, and if \( V_y = +2V \), two units of current. Resulting product is 16.

**Parameter changes**

If \( X = Y \), the output function is a squared function of those variables. Graphs of the resulting current variation are given above. For each graph, the effect of \( Y \) being negative causes a slight deviation from the true square law. Possibly due to inexact compensation for \( V_{AB} \) drops with network employed.

**Component changes**

Circuit is supply sensitive, especially at the low levels of current \( I \). At \( V_e = \pm 15V \), a 20% reduction of \( V_e \) provides a -3% error for \( I_{MT} = 81 \mu A \), but at 9\( \mu A \), +30% error.

**Circuit modifications**

- Use of transistors \( \text{Tr}_4 \), \( \text{Tr}_5 \) in a current mirror configuration will permit the differential current to be obtained with respect to ground. \( R_4 \) and \( R_5 \) are adjusted to be similar to obtain equal collector currents in \( \text{Tr}_4 \), \( \text{Tr}_5 \). This current is converted to an equivalent voltage by driving into \( I_{C} \), such that \( V_{out} = -(I_x-I_y)R_6 \).

A more sophisticated technique with a wide frequency response, is shown extreme right. Transistor \( \text{Tr}_6 \), which has a double emitter, could be derived from a monolithic package by paralleling collectors and bases. The bias voltage which should be the silicon bandgap voltage (1.25V) minimizes the current ratio \( I_0/I_0 \) drift with temperature. If \( I_0 = I_0 \), then the base-emitter junction voltages of \( \text{Tr}_4 \) and \( \text{Tr}_5 \) are equal (for equal emitter areas). This implies that the emitters of \( \text{Tr}_4 \) are at the same potential, and hence the currents are equal.

**Further reading**


**Related circuits**

Set 6, card 4
Set 23, card 5
Hall-effect multiplier

Hall-effect multiplier

In a practical Hall plate, point electrodes between which the Hall voltage is developed are connected midway between the end-electrodes. Materials used for the plate are high mobility bulk semiconductors, with low conductivity: indium arsenide, germanium, indium antimonide.

Background

The device produces an output voltage dependent on the product of two inputs—the plate current $I_x$, and an external magnetic field $B_y$ (Tesla). Current flow is due to electrons $n$, charge $q$ and drift velocity $v_x$. Hence current density $j_x = I_x / A = n q v_x$.

Deflecting force on electrons in direction $Z$ due to $B_y$ is $F_Z = B_y q v_x$.

At equilibrium, this just balances the field force due to electron deflection, i.e. $q E_z = B_y q v_x$ and $E_z = B_y v_x = B_y I_x / n q t$.

The Hall voltage is $V_H = E_y b$

$V_H = B_y I_x / n q t = K_H I_x / t$

$K_H$ is known as the Hall coefficient and should be as large as possible for maximum output. Conductivity is $\sigma = n \mu q$, where $\mu$ is electron mobility $K_H = 1 / n q \mu = \mu_0 / \sigma$.

High mobility, low-conductivity optimizes device Hall voltage for specific thickness $t$.

Applications

- An appropriately dimensioned device can be inserted within the air gap of a rotating electrical machine to determine flux density variations, when $I_x$ is maintained constant.
- Both $I_x$ and $B_y$ can be generated by suitable voltages, and assuming fixed orientation between the Hall device and the field, then $V_{X=1} = V_{X=1}$, where $V_x$ and $V_y$ may assume an alternating or direct voltage.

Offset flux density $\pm 7.5 \times 10^{-4}$ Tesla.

Possible applications include isolated current sensing and control in high current situations, conversion of magnetic quantities into proportional currents, detection of positional movements of a rotating shaft.

- Current measurement. Very small alternating and direct currents may be measured by concentrating the flux established around the conductor via the magnetic cylinder shown.
- Linear displacement transducer. The Hall device will produce a voltage which is a function of the motion between the device and a stationary magnetic field.

Displacement laterally between the magnets will produce an output voltage when the device is moved from the mid-position. An alternative arrangement will provide a linear output proportional to the displacement direction shown. In this case the magnetic field strength varies along a central plane.

- Proximity detector

A non-contact proximity switch may detect the presence of a magnetic field or the disturbance of a field due to the presence of ferrous material. Hall voltage, $V_x$, variation in relation to relative position of magnetic and Hall device would be as shown.

References


F.e.t. analogue multiplier

Circuit description

The conductance $G_{DS}$ of the junction field-effect transistor depends on the junction voltage $V_x$. To linearize the f.e.t. in its pre-pinch-off region, $V_x$ must comprise one half of the sum of the separate drain and source voltages with respect to ground. In this case, that is equivalent to $\frac{1}{2}(V_x + V_y)$ (2). The total gate-voltage is then a fixed bias voltage $V_B$, a signal voltage $V_s$, and the required $\frac{1}{2}V_y$ is obtained via $A_3$ and $A_4$. With then the equivalence of conductances $G_1$, the output voltage $V_{out}$ is linearly proportional to the product of signals $V_1$ and $V_2$, when $G_{DS}$ is equal to $G_2$ plus an incremental value proportional to $V_x$. Equating the potentials at the inverting and non-inverting inputs of amplifier $A_4$ and using the parallel generator concept then

$$V_1(G_1 + KV_y) + V_2G_2 - V_4G_3$$

This gives

$$V_{out} = \frac{V_1G_1 + V_2G_2}{G_1 + G_2}$$

The drain current drain-source voltage relationship is

$$I_D \propto (V_D - V_p - V_s)G_{DS}$$

If $V_0$ does comprise $V_B$, $V_2$, and $(V_P + V_s)/2$, then $G_{DS} = f_I/V_{DS} \propto (V_D - V_P + V_s)$ for pre-pinch-off.

If the constant of proportionality $K_1 = K$, and is such a value that $K_1(V_n - V_P) = G_3$, then a linearised relationship between the

pinch-off should provide a wider working range. Also if the gate bias $V_B$ is arranged to be one half the pinch-off value, then

$$G_{DS} = \frac{KV_D}{2}$$

i.e. $G_3 = \frac{KV_D}{2}$

and if $G_1 = G_2$ then

$$V_{out} = -V_1V_2K/2G_2 = \frac{V_1V_2}{V_p}$$

Typical pinch-off is $–10V$ for results quoted, but no signal levels are identified. Accuracies claimed are within $\pm 1\%$ over a temperature range of $50K$ in the frequency range 0 to $20KHz$, using matched f.e.t.s whose conductances are within $\pm 5\%$.

Reference


Related circuits

Set 22, card 7
Analogue circuit design is on the edge of another of its periodic revolutions. The development includes analogue multipliers of performance that permits function-synthesis to an accuracy that is limited mainly by the external passive components. One variant has three separate differential-input transconductance amplifiers: two drive a translinear multiplier core whose output is summed with that from the third to produce the final output via a high gain amplifier. The signals are processed throughout in current form but inputs and outputs are voltages with the usual scaling factor so that \( W = \frac{10(X_1 - X_2)(Y_1 - Y_2) + Z_1 - Z_2}{10} \). Normally overall feedback together with the large value of \( A_0 \) ensures that the bracketed term tends to zero and the implicit identity \( (X_1 - X_2)(Y_1 - Y_2) = Z_1 - Z_2 \) follows. The operation is analogous to that at the summing junction of an op-amp. A similar flexibility is obtained with higher order functions to that which we have become used to in linear circuit design. To avoid the inconvenience of the scaling factor when devising new configurations it is helpful to write the variables in normalized form from \( x, y, z \): \( (x_1 - x_2)(y_1 - y_2) = z_1 - z_2 \).

The reference article offers more than 20 applications of many of them novel, and is essential reading for anyone who wants to exploit the possibilities of these new multipliers. At present they are precision devices laser-trimmed and are correspondingly priced but it is to be hoped that designers will overcome these limits and produce them at mass-market costs. A couple of examples indicate the simplicity of the solutions that are made possible by such circuits:

An even simpler configuration has, in normalized form,

\[
\begin{align*}
X_1 &= w \quad Y_1 = u \\
X_2 &= 0 \\nY_2 &= 0 \\nZ_1 &= w \\nZ_2 &= u
\end{align*}
\]

Hence \( wu = w - u \) and \( w = \frac{u}{1 - u} \).

This non-linearity is the exact inverse of that associated with a conventional Wheatstone bridge viz \( u = v(1 + v) \). Hence a single multiplier can linearize the output of such transducers as strain-gauge bridges. The functions can be implemented by conventional multipliers but may need additional summing amplifiers and inverters, which in turn limit the accuracy and bandwidth claimed ±0.25% and 1MHz with 35V/µs slew-rate.

This is established by observing

\[
\begin{align*}
X_3 &= W/10 \\
Y_3 &= 0 \\
Z_3 &= \frac{V}{U} \\
X_4 &= 0 \\
Y_4 &= V \\
Z_4 &= U
\end{align*}
\]

and substituting the second identity

\[
\frac{(W/10)(-V)}{V} = V - U
\]

\[
W = 100 \frac{U - V}{V}
\]

The feedback ratio can be adjusted to give 0.1V%/ to 10V%/ and the only restriction is that \( V \) must be positive.

References

Set 30: Non-linear circuits—r.m.s./log/power laws

Familiar mathematical functions—squares, square roots (page 136), cube law, r.m.s. conversion, resolvers, logarithms, frequency doubling (page 132)—are implemented in this set using a variety of techniques, including the use of the integrated multiplier (pages 135 & 140) introduced in set 29. No pretences at high precision are made in these circuits. Typically linearity is 1 or 2%, but as the following article points out errors often vary over the dynamic range because of the non-linear nature of the circuits. Manufacturers should be consulted directly over particular solutions to problems requiring greater precision.

On page 135 the output from the precision rectifier is now correctly shown as being taken from the junction of the $R_1$-diode series combination. And in connection with Barie Gilbert’s circuits, there were two additional brackets needed to enclose the last two terms in the expressions for $I_A$ and $I_B$.

Background article 130
Root-law array 132
Voltage divider 133
Ramp to sinewave converter 134
R.m.s. to d.c. converter 135
D-type ΔΣ converter 136
Cube-law generator 137
Logarithmic amplifier 138
Resolvers 139
Uses of i.c. multipliers 140
Computation of $(x^3 + y^3)$ 141
Up-date circuits 142
Introducing non-linear circuits
Logarithmic, power and r.m.s. laws

A growing need for a variety of mathematical function generation has led to a variety of circuit solutions. The problems range from the use of resolvers in servo systems in which sine/cosine function generation is needed, to the measurement of the true r.m.s. value of non-sinusoidal waveforms.

If we restrict ourselves to one or two variables, then Fig. 1 shows a sample of the functions that might occur in practical systems - either because the output of a system is required in some particular form such as a decibel representation of a voltage gain, or to correct for some non-linear property of a transducer. Few of these functions can be obtained directly from existing devices and circuits unless limited accuracy is acceptable. For example, the field-effect transistor has a square-law term in its $I_D/V_{GS}$ characteristic and this has been exploited to provide such functions as $X^2$ and $XY$.

However, the circuits have been fairly complex, have resulted in significant departure from the ideal law or have drifted badly with change in temperature and/or supply.

Some of these functions can be obtained by indirect means such as the parametric techniques of Hall-effect devices or varactor diodes. Others can be obtained via modulation processes as in the multiplier/divider circuits of Circards Set 29. The most valuable tool available to the designer in this area is the transistor, not because of its amplifying properties, but because the $I_C/V_{BE}$ characteristic follows a particular non-linear law precisely and over a wide range of currents.

In its simplest form that law can be written as: $I_C = k \exp V_{BE}$. This hides a number of inconvenient factors such as its dependence on temperature, but is an accurate representation of the shape of the characteristic. As indicated in the previous article this is the basis of logarithmic amplifiers in which the output voltage is a logarithmic function of the input voltage.

From the basic properties of logarithms various power-law operations can be implemented.

<table>
<thead>
<tr>
<th>one variable</th>
<th>two variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^2$</td>
<td>$XY$</td>
</tr>
<tr>
<td>$\sqrt{X}$</td>
<td>$X$</td>
</tr>
<tr>
<td>$1/X$</td>
<td>$Y$</td>
</tr>
<tr>
<td>$aX^2 + bX + c$</td>
<td>$\sqrt{X^2 + Y^2}$</td>
</tr>
<tr>
<td>$\log X$</td>
<td>$\sqrt{X^2 + Y^2}$</td>
</tr>
<tr>
<td>$e^x$</td>
<td>$\sqrt{X^2 - Y^2}$</td>
</tr>
<tr>
<td>$\sin X$</td>
<td>$\sqrt{X^2 - Y^2}$</td>
</tr>
<tr>
<td>$\sqrt{X^2}$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Common functions that can be obtained by passing $X$, $Y$ through circuits with corresponding transfer functions.

Let $V_s = K \log_{10} V_1$ and $V_b = K \log_{10} V_2$.

Then $V_s + V_b = K \log_{10} (V_1/V_2)$

$V_s - V_b = K \log_{10} (V_1/V_2)$

$nV_s = nK \log_{10} V_1 = K \log_{10} (V_1^n)$

Thus adding, subtracting or amplifying the input variables all of which are within the scope of normal linear circuit design, result in outputs that involve the product, ratio or powers of those variables. The remaining problem is that the output is still a logarithmic function; if it is succeeded by an antilog circuit then the process is completed. A typical configuration in Fig. 2.

A second family of circuits makes use of existing functional blocks such as the multiplier (XY) or the multiplier/divider (XY/2). Using various feedback and feedforward configurations, a number of the other functions such as square, square root and division can be performed. As an example, consider the circuit of Fig. 3. It illustrates how complex functions can be built up piecemeal. With care and ingenuity elegant and efficient solutions to such problems can be found using various interconnections to remove the need for additional functional blocks.

A group of four transistors in which the base-emitter voltages have a relationship of the form $V_1 + V_2 = V_3 + V_4$ must result in a corresponding collector current relationship $I_1I_2 = I_3I_4$ once the log characteristics are taken account of (see previous article). This leads directly to the implementation of a multiplier by making, say, $I_2$ constant and forcing $I_3$, $I_4$ to be proportional to the two input variables. Other interconnections of these transistors can yield functions such as square, vector sum, and division.

Some novel solutions demand devices not readily available to the average user - devices developed by manufacturers for use in their own instruments.

One such that shows an old idea brought very firmly up-to-date is given in Fig. 4. It uses what is effectively a balanced bridge to determine the true r.m.s. value of an input voltage. If two identical transistors are separately heated by equal resistors then they will remain in balance only if the flow of
heat to each is equal. Any unbalance is amplified by the operational amplifier forcing the direct output voltage to deliver the same power to the right-hand resistor as the input delivers to the other. Hence the r.m.s. values of the two voltages are equal. A neat idea, though one that requires a very carefully constructed chip if the sensing transistors are each to respond to only one of the heat sources.

A severe problem in many of these ideas is that of identifying and neutralizing the error sources. Because of the non-linear equations involved, the relative errors are different at all parts of the range. Manufacturers of modules and i.c.s directed at these applications devote a great deal of effort to this topic, and readers would be well-advised to consult them if high-precision functions are needed.

**Fig. 4.** Two identical transistors are heated separately by resistors supplied from an unknown input voltage and the output of an op-amp. High gain forces the transistors into balance by increasing $V_o$ until the power it supplies matches that delivered by $V_{r.m.s.}$.
Root-law array

Typical data
- $T_{R1} - T_{R3}$: 3/5 of CA3086
- $T_{R4} - T_{R7}$: 4/5 of CA3086
- $V_S = \pm 5V$, $R_S = 33k\Omega$

For graphs, currents $I_1$ and $I_2$ are derived from calibrated current sources.

$I_0 = \sqrt{I_1^2 + I_2^2}$. Percentage error shown in graphs.

Hence by substituting for $V_X/V_\Phi$ and $V_Z/V_\Phi$

$I_0 = \sum_{i=1}^{n} (\frac{I_i}{k})^m \cdot \frac{k}{I_0}$

$= \sum_{i=1}^{n} I_i^m / I_0$

giving $I_0 = \left[ \sum_{i=1}^{n} (I_i)^m \right]^{1/m}$. Above, $m=2$, $I_1 = I_2$ and $I_0 = (I_1^2 + I_2^2)^{1/2}$.

Current flow directions of $I_1$ and $I_2$ should be as shown. If these currents are to be derived from an alternating voltage source, then circuits must be provided to ensure the above polarities are maintained.

Circuit description

This circuit is a special case of a general root law circuit\(^1\) using bipolar transistor-array packages. The performance depends on the fairly precise relationship which exists between the collector current $I_C$ and the $V_{BE}$ of a transistor.

Assuming that the common-base current gain $a = 1$, then $I_C = k \exp \frac{V_{BE}}{V_\Phi}$, where $V_\Phi$ is the thermal potential. As $V_{BE} = V_\Phi \log I_C/k$, then in the path XY, $V_X = 2V_\Phi \log I_C/k$ because there are two diodes in series. There is only one diode in the $T_R$ path and hence $V_B = V_\Phi \log I_0/k$. $I_0$ can be written in terms of the base-emitter voltage of $T_R$, giving

$I_0 = k \sum_{i=1}^{n} \exp \frac{(V_X - V_B)}{V_\Phi}$

where $m$ is the number of paths like XY.

Circuit modifications

- The circuit has been used as a frequency doubler\(^4\) dependent on a similar mathematical relationship, and in this case, a sinusoidal input voltage drives current into the circuit of Fig. 2 to obtain unidirectional current flow, which is independent of the load. Current $I_2$ is drawn from the current mirror $T_{R1} - T_{R6}$, which in the same direction no matter the polarity of $V_{be}$ when $I_{in}$ is positive-going, the current mirror comprising transistors $T_{R1}$ and $T_{R6}$ is active, and the resulting collector current of $T_{R1}$ is mirrored by $T_{R4}, T_{R5}$. When therefore $I_{in}$ is negative-going, the equivalent current is delivered by current mirror $T_{R13}, T_{R13}$. P-n-p transistors are required for these current mirrors and are obtained in the CA3084 i.c. A voltage output is available via $R_3$.

- An alternative arrangement for obtaining unidirectional current is shown in Fig. 3 using an inverting amplifier, and a complementary pair in the feedback loop. This avoids the crossover distortion that may exist in the Fig. 1 arrangement due to the finite $V_{BB}$ drops of transistors $T_{R10}, T_{R12}$, though if $V_{in} > 0.6V$ this effect might be acceptable. The resistors $R_3$ and $R_4$ must be closely matched to optimise the current mirror action. $R_{V3}$ of Fig. 4 replaces $R_3, R_4$ and allows an alternative manual adjustment to match the collector currents.

- Another arrangement using the translinear multiplier\(^4\) concept is shown in Fig. 5. While this may be a configuration more likely met in a i.c. multiplier, transistor-array packages could be used, with $T_{R14}, T_{R17}$ being implemented by paralleling transistors.

Further reading

Related circuits
Set 30, cards 10, 5.
Voltage divider

Typical performance
IC1, 741 op-amp ±7.5V supplies
IC2, 3 of CD4013, D-type flip-flop
IC3, 1 of CD4016 f.e.t. switch
VDD = +7.5V, VSS = -7.5V
Clock pulses 3V pk-pk square wave, mean value zero, frequency 10kHz
V2 = -7.5V, V1 positive
R1 1MΩ, R2 100kΩ
C 2.2nF

Circuit description
Voltage V2 is a negative voltage which will cause the integrator IC1 to ramp positively. The slope of this is slow since R2 is large. When I1 is permitted to flow to the summing junction (f.e.t. switch of IC2 closed), the op-amp will ramp downwards provided I2 > I1. In ramping downwards VO will go below the threshold level of the D-type flip-flop IC2 and on the occurrence of the next negative going edge of the clock Q will go low, the switch will open; I1 is thus cut-off and the op-amp will begin to ramp positively again. This will continue until D is high on the trailing edge of a clock pulse when I1 will again be switched in. The trace above shows a typical VO (1C, output). The lower level of this waveform varied somewhat (from 2V to -0.25V for a large V2 to -0.25V for a small V2). The slope of the positive ramp is, of course, constant for constant V2 but as V2 is varied the negative-going slope varies.

Clearly in a complete period T the charge put in by V2 is cancelled by the charge withdrawn by V1 as the starting and finishing voltages are the same.

i.e. \[ I_2 T = I_1 T' \]
\[ \frac{1}{2} \frac{V_2}{R_1} R_2 \]
\[ \frac{1}{2} \frac{V_1}{R_3} \]

Hence, if R1, R2, and the clock frequency are constant we obtain a frequency proportional to \( V_2/V_1 \).

We fixed V2 at -7.5V for convenience and varied V1. For V1 in the range 1.5V to 6.5V the frequency \( f_0 \) varied from 865Hz to 3472Hz, the product \( V_1 f_0 \) remaining constant within 0.2% proving the division to be accurate.

Note that T' need not be one whole clock period as shown but will be an integral multiple of the clock period. Furthermore, in our description we have implied that the switching level of the D-type flip-flop is zero volts and this need not be so.

Component changes
With the values of R1 and R2 quoted, C, which does not appear in the expression for \( f_0 \), can be varied over a range of about 10:1. Low values of C cause saturation of IC1 before the flip-flop changes state and high values caused what appeared like subharmonic locking of some sort. This might have been obviated by use of a lower clock frequency.

Changing R1 to 10kΩ, R2 to 1MΩ and C to 22nF made little difference to the results. One would expect R2 max to be of the order of 1MΩ to prevent op amp input currents affecting the operation although since this is a constant effect it should not seriously affect the frequency of oscillation. The lower limit to R1 is set by the fact that the on resistance of the f.e.t. switch is approximately 300Ω (i.e. R1 > 300Ω).

The max. V2 is not seriously limited but V1 is limited to be less than VDD—the positive supply of the c.m.o.s. f.e.t. switch IC3.

Circuit modifications
- In essence we have been supplying voltage-controlled currents I2 and I1 to the integrator. There are several ways of doing this (e.g. ref. 1).

One method is as shown below in which the two dotted sections are accurate voltage to current converters, I1 for example being V1/R1. This circuit is very similar to the one shown above with the addition of an inessential comparator but has the disadvantage that V2 is referred to V0. This can be modified so that V2 is referred to ground (refs 2, 3).

Note that f0 is proportional to the ratio of two voltages, the numerator one in our case being fixed. Many v-f converters operate on the same principle but keep the denominator term fixed. Such v-f converters therefore can be converted to act as divider circuits. In fact the circuit shown above is identical to the delta-sigma voltage-to-frequency converter on card 3, set 21.

Another such v-f converter is the simple unijunction v-f converter (card 1, set 21).

Many multipliers require not only the two voltages to be multiplied but a reference voltage which appears in the denominator of the output voltage expression e.g. set 29, card 4.

References
1 Set 6, Constant-current circuits, card 1.

Related circuits
Set 21, card 3
Set 29, card 4
Ramp to sinewave converter

Typical data
\[ T_{R1}, T_{R2} \ 2/5 \text{ of CA3086} \]
\[ T_{R3}, T_{R4} \ 4/5 \text{ of CA3086} \]
\[ V_S \ \pm 10V \]
\[ R_{S1}, R_{S2} \ 47k\Omega, \ R_{S3} \ 100k\Omega \]
\[ R_{V1}, R_{V2} \ 10k\Omega \]
Above values are chosen to simulate the current-source relationships indicated in Fig. 1 and provide the d.c. characteristic shown in the graph.

Circuit description
The circuit is based on the translinear circuit of Fig. 1. Currents \( I_1, (1+X)I_2/2, (1-X)I_2/2 \), are controlled current sources, and the values are chosen to have a specific relationship. It is assumed that all the transistors are matched (\( T_{R1}, T_{R2} \) must be on the same chip, and also \( T_{R3} = T_{R4} \)).

Summation of the base-emitter voltages in Fig. 1 gives
\[ V_{BE1} + V_{BE2} = -V_{BE3} = V_{BE4} \]
Because the collector currents are of the form \( I_C = I_S \exp (qV_{BE}/kT) \) then by substitution
\[ (kT/q) \times \left[ \log I_S - \log I_2 - \log I_3 + I_3 \right] = 0 \]
and hence \( I_1 = I_2 = I_3 = I_4 \). Hence any one current can be chosen to be a dependent output current. In Fig. 2, an extra diode in each branch means an additional \( V_{BE} \) drop must be considered, and the current relationship is then
\[ I_1 = I_2 = I_3 \]

With \( I_1 = (1+X)I_2/2, I_2 = I_2 = I_2 \), it is easily shown that
\[ I_A = I_1 + I_2 \left[ (I_1/I_2)^2 + 1 \right] \]
and \( I_B = I_3 + I_2 \left[ (I_3/I_2)^2 + 1 \right] \).

Hence the differential current
\[ I_A - I_B = I_2 \left( 1 - X^2 \right) \]
\[ (1 + X^2) \]
With \(-1 < X < 1\), this difference-current is claimed to approximate a sine function within \( \pm 0.4\% \) full-scale. Over the range of control voltages used above \( (V_1 = V_2 = 0 \text{ to } 10V) \) the differential current is acceptably sinusoidal over half the range.

Circuit modifications
- Fig. 3 permits zero-setting of the differential current when factor \( X = 0 \).
- If terminals P and Q of Fig. 2 are driven from a ramp-function generator, via an inverting amplifier, then opposing ramp control voltages will produce a sinusoidal output in accordance with the first half of the graph over. The ramp inputs must be such a level to reach the point of inflexion of the curve, in this case about 4V.
- To obtain a single-ended voltage output from a differential current-input, a subtracting circuit such as Fig. 5 can be used, but in this case, matching of resistors R is necessary.
- An alternative differential current-to-voltage converter is achieved using the current mirror of Fig. 6. Resistor \( R_2 \) must be trimmed to optimise current-mirror action. If balancing is such that \( I_1 = I_2 \), then for zero voltage output, \( I_3 \) must equal \( I_4 \). Typical performance of this circuit provides a symmetrical 5.8V pk-pk cosoidal output for a 4V drive ramp signal. Maximum frequency 3.5kHz, when slight peak distortion may be encountered. Harmonic distortion is in fact quite small. Figures are quoted for a 1kHz drive signal.

Further reading

Related circuit
Set 29, card 8.
r.m.s. to d.c. converter

Circuit description
This circuit is based on an approach implemented in ref. 1, via an argument based on the explicit (Fig. 1) and implicit methods of establishing the r.m.s. value of a signal (Fig. 2). Notice that the squarer divider would require a device that would give an X/Y/Z output for X, Y, Z inputs (type AD433J). In each case, the integrator filters the fluctuating d.c. signal. The arrangement above is based on a i.c. multiplier. IC3 is connected as a subtractor to provide a single-ended output from the differential output currents of the multiplier section of the i.c. This is then proportional to the product \( (V_{in} - V_{out}) / (V_{in} + V_{out}) \) i.e. \( (V_{in}^2 - V_{out}^2) \). Under steady-state conditions, the d.c. feedback via \( V_X \) and \( V_Y \) will force the mean value of this voltage, \( V_{in} \), to be zero, any a.c. components being filtered by IC9. Hence \( V_{out} = (V_{in}^2)^{1/2} \). Initial setting up of the circuit to obtain the output equal to the input requires adjustment of \( R_4 \) which may shift the output zero level for \( V_{in} = 0 \). Zero adjustment is obtained via the circuit of Fig. 3, though further adjustment of \( R_4 \) may be necessary, etc. The inverting-gain amplifier must be precisely −1, either by trimming or using accurate values of \( R_3 \) and \( R_3 \).

Circuit modifications
- If pins 1 and 2, 3 and 5 are reversed, a negative d.c. output can be obtained without loss of accuracy.
- If terminals 1 and 2 (see Fig. 4)

are connected to a current mirror comprising transistors \( T_1 \) and \( T_2 \), then the integrator may be driven directly without using the internal op amp, or this may be used as the integrator. The reference potential of the non-inverting input cannot be grounded, it must be maintained fairly positive to ensure it's within the range of potential of terminal 1.
- Another possibility is shown in Fig. 5, where because the current mirror is a current source, the capacitor can be connected directly and the output derived from a unity gain non-inverting amplifier. Fig. 6 (ref. 2) is an example of the implicit method of conversion, where \( \Lambda_1 \) amplifier is arranged as an absolute rectifying circuit and transistors \( T_2-T_3 \) form a transconductance multiplier. To implement the circuit it is essential to optimise the frequency response and compensate for the limitations of the op-amps and transistors and some design guidance is given in the reference.

Further Reading
Handler, H. True r.m.s. voltage conversion, Electronic Design, vol. 4, 1974, pp. 66-72.
Related circuits
Set 30, cards 9, 3.
D-type delta-sigma converter

Typical performance
IC 1/4 of CD4013AE
IC2 1/4 of CD4001AE
Supply +10V
R1 100kΩ pot
C1 10nF
Clock freq. 100kHz
V1 0-10V
f0 ∝ V1
Note \( f_0 \approx f_{\text{clock}} \approx V_1 \equiv V_S \)

Circuit description
The delta-sigma modulator is a powerful tool in the processing of signals. Conceptually, it requires a number of different sections: a D-type flip-flop, an analogue gate, a reference voltage, a comparator, an integrator. Previous designs have combined the functions of gate, reference and comparator into the flip-flop itself, using the facts that (i) the threshold level of the flip-flop is sharply defined, obviating the need for a comparitor in simple applications; (ii) the gate/reference section is only required to define the feedback during the pulse on-state. This is achieved for a stable supply voltage by direct feedback from the Q output since c.m.o.s. outputs switch virtually to supply levels.

This leaves the op-amp integrator as the only analogue element in the system. If the feedback is taken from the Q output to the D-input with a capacitor to ground then a virtual-earth action is achieved without the need for an operational amplifier. This remarkable simplification has one drawback—the virtual earth has an offset voltage equal to the threshold voltage of the D-type flip-flop. This varies from device to device but is (i) a relatively fixed fraction of the supply (ii) varies little with temperature. Without any precautions, and setting \( R_1 \) to its centre value, the output pulse rate has an average value that is a linear function of \( V_1 \) (typically to much better than 1%). It is possible to remove the offset by the configuration shown. If the clock pulse together with the Q output is fed to a NOR gate, then when the input voltage is low the D-input will tend to drop. Once below the threshold the clock pulses keep Q high raising the D-input again. The Q output will need to be high most of the time. This implies that Q is only high occasionally and few pulses are obtained at the output—a direct representation of the low input voltage assumed. Set \( V_1 \) to zero and adjust \( R_1 \) until the output pulses are just barely inhibited. The setting is generally close to the centre-tap because the threshold is around \( V/2 \). This zero-setting varies the slope of the characteristic so that sensitivity controls must be adjusted after zero-setting.

Circuit modifications
- The basic circuit is a tool that can be used to implement square, square-root and multiplier functions.
- **Squaring circuit.** The flip-flop is set up for \( f_0 = kV_1 \) as above. \( V_1 \) is also applied via an analogue gate to the load. Hence the mean load voltage is proportional to \( (V_1)^2 \)—the voltage of magnitude \( V_1 \) is applied to the load for a fraction of the time proportional to \( V_1 \). In this mode the output pulses are not used directly and the NOR gate is not needed—unless transmission of the original variable \( V_1 \) in serial form is desired.
- **Square root circuit.** This is achieved by the implicit method.

Q, Q gate. the analogue switches, but \( R_2 C_2 \) smooth the Q output so it is the mean value at Q that is gated. Hence the mean voltage applied to \( R_3 \) is a function of the square of the mean output. If the input is applied with respect to ground the output is obtained from \( Q \) to the negative line. (The smoothed version across \( C_2 \) can be used directly if a high resistance is used).

\[ V_o \propto \sqrt{V_1} \]
- If positive supply/input operation is desired the gating is reversed and the output taken with respect to the positive rail.
- If the output is required as a pulse train, simply gate Q and the clock pulses with a NOR gate and the output pulse rate is proportional to \( \sqrt{V_1} \). When the initial zeroing has been correctly carried out, the square and square-root laws are followed with errors of \(<1\%\) of full-scale. As noted earlier the scaling factor is affected by the zero-setting.

Related circuits
Set 30, cards 1, 10
Set 29, card 3
Cube-law generator

Components
\[ R_x, R_y = 10 \text{k}\Omega \]
\[ R_x, R_y = 220 \Omega \]
\[ C_1 = 100 \text{pF}, C_3 = 1 \text{nF} \]

IC\(_1\), IC\(_2\) 741
\[ V_x = \pm 10 \text{V} \]
\[ T_x, T_y, T_z = 1/5 \text{ of CA3086} \]
\[ k_1 = 0.667, k_2 = 0.5 \]

Performance
With \( V_x \) at 10V, \( V_\text{x} \) was adjusted so that \( I_x = 1 \text{mA} \), achieved with \( V_\text{x} = 8.65V \). \( V_\text{x} \) was then varied and produced the graph of \( I_x \) versus \( V_\text{x}^3 \) shown.

Circuit description
In the following equations the subscripts \( 1, 2, 3 \) refer to transistors \( T_\text{r1}, T_\text{r2} \) and \( T_\text{r3} \) respectively.
\[ V_{\text{be}1k} = k_1V_x - V_{\text{be}}(k_1 - 1)V_x \]
\[ V_{\text{be}2} = V_{\text{be}}(1 - k_2) \]
Similarly \( V_{\text{be}} = V_{\text{be}}(1 - k_2) \).
Writing \( 1/(1-k_2) \) as \( n \) and \( 1/(1-k_2) \) as \( m \) one obtains
\[ V_{\text{be}1k} = V_{b} - V_{\text{be}}nV_{\text{be}} - mV_{\text{be}} \]
In general \( V_{\text{be}} = (kT/q) \log I_{\text{be}} \), which results in
\[ I_L = I_b \frac{V_x^3}{V_{\text{be}}^3} R_x = n - m \]

As \( I_b \) is dependent on the temperature, one can achieve some temperature compensation by maintaining \((n-m)=1\).

Circuit modifications
- If one requires a voltage output rather than a current output then the modification above will suffice. \( V_0 \) given by \( V_0 = I_xR_x \) where \( I_x \) is the current in \( T_x \).

The circuit is described as a cube generator, but from the expression for \( I_x \) it is clear that any power law can be generated, with the proviso that \( n-m=1 \) for temperature compensation, and that \( n \) and \( m \) are both greater than 1. This allows one to obtain \( V_0 = V_x^n \) but keeping \( V_x \) constant and using \( V_x \) as the input \((n=m=2)) \), but does not allow one to obtain fractional power laws. This can be overcome by implicit power law generation i.e. by putting a power law device \( y = x^n \) (output, \( x \) input) in the feedback path of an op-amp so that \( V_y = V_x^{1/n} \). A partial alternative is to modify the original circuit so that instead of \( V_x = nV_{\text{be}} \), \( V_y = mV_{\text{be}} \).

References
1. National Semiconductor application notes AN30.
2. Set 29, card 4
3. Set 30, card 7
Logarithmic amplifier

Circuit description
The following equations can immediately be given
\[ V_0 = V_{be1} - V_{be2} \]
\[ V_{be1} = -\frac{kT}{q} \log e \frac{I_2}{I_3} \]
\[ V_{be2} = -\frac{kT}{q} \log e \frac{I_2}{I_3} \]
\[ I_1 = \frac{V_1}{R_1} \]
\[ I_2 = \frac{V_2}{R_2} \]

Hence \[ V_0 = -\frac{kT}{q} \log e \frac{V_2}{V_1} \]

i.e. if \( V_2 \) is held constant then \( V_0 \) is proportional to the log of \( V_1 \). At room temperatures \( kT/q \approx 26mV \) and for any octave change in \( V_1 / V_2 \), \( V_0 \) will change by approximately 18mV.

Inclusion of \( R_3 \) and \( C_1 \) around \( IC_1 \) and of \( R_4 \) and \( C_3 \) around \( IC_3 \) prevents oscillation of the amplifiers. Considering \( IC_3 \), the loop gain includes the transistor gain. The transistor \( Tr_3 \) is in common-base mode and hence has a voltage gain \( g_m R_1, R_1 \) being the load on \( Tr_1 \) and is by superposition connected to ground. The loop gain can be very high. Resistor \( R_2 \) reduces the proportion of the output voltage fed to \( Tr_1 \) and hence reduces the gain. Likewise, high frequency gains are reduced to zero by the inclusion of \( C_1 \) across the amplifier.

Despite these safeguards the circuit does have a tendency to oscillate and care must be taken with wiring. Note that the transistor \( g_m \) is linearly related to the current so the problem is increased for high current levels. Further, at high current levels bulk resistance effects in the transistor come into play and destroy the simple logarithmic relationship. It is, therefore, important to keep \( V_1 / R_1 \) and \( V_2 / R_2 \) to levels which the transistors will accept.

Circuit modifications
Methods of temperature compensation using transistor arrays have recently been reported, refs. 1, 2. A simpler method has been devised using two of the transistors in the CA3086 package so that a controlled temperature can be achieved in this package at the same time as using two of the remainder for the logarithmic amplifier. Details will appear in a future set. The circuit shown above acts in a manner very similar to the basic circuit overleaf. It is easy to show that
\[ V_0 = \frac{R_3 + R_4}{R_4} (V_{be2} - V_{be1}) \]
from which
\[ V_0 = -\frac{kT}{q} \left( \frac{R_3 + R_4}{R_4} \right) \log e \left( \frac{V_1}{V_2} \right) \]

Note that \( V_0 \) is now referred to ground potential. Further, if \( R_3 \approx R_4 \) and if \( R_4 \) is a temperature-controlled resistor, then compensation is possible. As \( T \) is in Kelvins, \( V_0 \) will change by 0.33% per deg. C.

This circuit with the bias and compensation networks shown is described in some detail in ref. 3. It is claimed to have a dynamic range of 100DB. The circuit is slow, the output typically taking several milliseconds to settle within 1% of final value. The LM108 does not have great bandwidth but does have a low input current, making it suitable as an input stage. To speed up the system by replacing the LM108 by an LM101 requires some modification, shown above right. The LM102 is connected as a voltage follower so that the combination of LM102 and LM101A with \( Tr_1 \) in the feedback path is the same as that of the figure on the left except that the LM102 effectively diode connects \( Tr_1 \). This reduces the dynamic range (80dB is possible) but allows feedforward compensation on the LM101A, thereby increasing the speed of response by about two orders of magnitude. Very little current will flow through the 1kΩ resistor between the output of the LM102 and the LM101A and the input terminal of that LM101A is a virtual earth so that
\[ V_0 = \frac{R_3 + R_4}{R_4} (V_{be2} - V_{be1}) \]

For further details see ref. 3.

References
3 National Semiconductor application notes AN30.

Related circuits
Set 29, card 4
Set 30, card 6
Resolvers

A resolver is a device which with input \( v \) produces an output proportional to \( \sin \theta \) or \( \cos \theta \). Frequently both outputs are available giving \( a = R \sin \theta \) and \( b = R \cos \theta \) i.e. the vector \( R \angle \theta \) is resolved into its two rectangular components. These devices are used widely in navigation and range instrumentation, where high bandwidth is not required. The circuit above left consists of a simple servomechanism which will rotate through \( \theta \) degrees in response to some input. If \( A = 1 \) then \( \tau = \theta_0 \) in the steady state in response to a step.

In addition to the normal feedback potentiometer there is also attached to the shaft a sine-cosine potentiometer generally wound through 360° and having four slider arms as shown. The shaft of this potentiometer will rotate through the same angle as the output shaft. Such arrangements suffer from all the usual disadvantages of potentiometers, wear, resolution, accuracy, etc. By using a gear box between motor shaft and sine-cosine potentiometer shaft one can improve the accuracy and resolution to less than 0.5° (static). Use of a gear box requires scaling of the input to suit. Dynamic accuracy depends largely on the servomotor.

In the induction resolver (below) the sine-cosine potentiometer is replaced by an induction machine shown, having a stator winding and two mutually perpendicular rotor windings. The device is best regarded as a transformer, the output voltages being generated in the rotor windings by induction. The angle \( \theta \) shown in the output expression is the angle between the axes and is obtained by the servo arrangement shown left or by any other equivalent. The carrier frequency is usually 400 Hz. Induction resolvers have the considerable advantage of being relatively maintenance-free since there are no rubbing contacts, apart from slip rings. The main problem is the production of an accurate modulation/demodulation system.

By the addition of a second stator winding with input \( X \) perpendicular to that shown one can obtain outputs \( U = -X \sin \theta + Y \cos \theta \), \( V = X \cos \theta - Y \sin \theta \) which enable one to perform co-ordinate transformations. Electronic resolvers are not so common as the electromechanical types. The most common type is that using a diode function generator as described in the quarter squares multiplier card (set 29, card 1).

The cost of such a resolver depends on the range of input being considered, the simplest being that corresponding to \( 0^\circ \sim 90^\circ \).

The diagram below (top) shows a different approach which conceptually is very simple. A comparator is arranged to trigger a sample and hold circuit when its sawtooth input exceeds \( v \). It is essential that the sawtooth be synchronised with the input to the sample and hold circuit. This can be done fairly simply by generating the sawtooth from an integrator with a direct comparator, one fed from the sawtooth ramping from 0 to \( 2b \), the other ramping from \( -b/2 \) to \( +b/2 \). In the last case the bias voltage must be able to go negative to obtain angles in the fourth quadrant.

Other electronic methods use pulse width modulation and averaging circuits. Such a scheme is the one shown left which produces an output proportional to \( \cos \theta \). The modulator produces pulses of width \( (\pi - 2\pi \theta)/\omega \) symmetrically placed about the peaks of the sinusoidal input. When these are fed to the switch, e.g. CD4016AE analogue transmission gate, the output is a chopped sinusoidal waveform whose average can be shown to be proportional to \( \cos \theta \) if the output pulses from the pulse width modulator are centred about the zero-crossings of the sinusoid, the output will be proportional to \( \sin \theta \).

Reference
Applications of i.c. multipliers

Many multiplier modules are now available on the market (e.g. MC1594L, XR2308, AD433J). The reduced cost and improved capability and accuracy of them has produced an increasing usage; unfortunately the existence of different types has produced confusion to the uninitiated.

There are at least three distinct types: those having two inputs X and Y, the output being \( KXY \), with \( K \) a scale factor; those which have two differential inputs \( X \) and \( Y \), the output being \( KXY' \); those having three inputs \( X \), \( Y \) and \( Z \) the output being \( KXY/2 \).— this last one is obviously a combined multiplier/divider.

Adding to the confusion is the apparently magical way in which some functions are generated. It is easy to see that the final answer is correct but there is never a logical thought process shown by which the answer was arrived at.

Many of the uses of multipliers involve the implicit solution of some equation. This means that the output is fed back in some manner, thereby affecting itself. All of the circuits in this card involve an implicit solution.

Above left is shown a circuit for the generation of \( \sqrt{V} \). The output \( W \) is fed to a multiplier with both input terminals connected together to form a squarer. This squarer is in the feedback path of an op-amp \( A \). As the differential input voltage of the op-amp must be zero, \( V - W = 0 \). Note that \( V \) must be positive, as otherwise negative feedback round the loop is lost and latch-up will occur.

Above centre is a multiplier connected in the feedback path of an op-amp to provide an overall division function. Polarity inversion through the multiplier must be avoided to prevent positive feedback and this restricts \( U \) to being positive. On the other hand \( V \) can be either positive or negative so that in the \( U-V \) plane one is allowed to operate in the two quadrants for which \( U \) is positive. It is clearly impossible for \( U \) to be zero but additionally if \( U \) is very small one obtains a very small feedback signal so that offset voltages and currents can cause latch up.

Above right is a four-quadrant divider in which the output of \( M_2 \) is \( V/\sqrt{W-UV} \). If the inputs are d.c. then in the steady state the integrator output must be constant implying \( V/\sqrt{W-UV} = 0 \). \( W \) = \( U/V \). It is claimed (ref. 1) that \( U \) and \( V \) can even go through zero together in this circuit. It also claimed that improved accuracy and stability are achieved. Both of these characteristics appear to reside in the action of the integrator whose output must change till the input is zero and whose output, moreover, cannot change rapidly.

Turning now to the more complex multipliers, note the circuit simplicity of Figs 1 to 4. Fig. 1 shows a square root circuit, Fig. 2 an r.m.s. to d.c. converter (compare card 4) and Figs 3 and 4 show vector sum and vector differencing circuits. Note the vector sum relation can also be obtained by mechanising the relationship \( V^2/(W-U) = U = W \). The apparent simplicity vaporizes to an extent when one examines the actual implementations recommended by the module manufacturers. The modules are liberally surrounded by assorted external components the aim of which is to minimize errors. Fortunately these recommendations are fairly specific since the questions of errors and bandwidth are difficult for multipliers alone;

when combined in complex circuits the analysis really is awkward.

Another point which must be mentioned is that of scaling: it is always necessary to ensure that the design of a circuit is such that the multipliers do not saturate. This may seem obvious but with as many as six inputs, possible with the module of Fig. 4, it is all too easy to overlook this aspect or even to make a simple miscalculation.

The above circuits are intended only as a representative sample of some things that are possible with multipliers. Other applications will be found in the amplitude stabilization of oscillators (ref. 4), the design of voltage controlled oscillators, phase detectors and sample-and-hold circuits (ref. 3) and in the linearisation of a transducer output signal (ref. 4) among many.

References
An arrangement suitable for the application of the initial conditions on the integrators is shown below right, in which the switches may be f.e.i.s or analogue transmission gates such as the CD4016AE. For normal integration $S_1$ is closed, $S_2$ and $S_3$ are open. When applying the i.c.s, $S_1$ is opened and $S_2$ and $S_3$ are closed. If $r_1 = r_2$ then the integrator output rises to the i.c. voltage with time constant $r_2C$ which should be made short by choice of $r_2$. If the op-amps are capable of supplying current to $(r_1 + r_2)$ and to the following integrator/inverter then $S_3$ may be dispensed with.

Using an integrator time constant of 1s, an inverter gain of 0.9 and a sampling period of 2s, J. S. C. Tan has reported an accuracy of $\pm 2\%$ (approx) over a useful range of $x$ and $y$, amplifier finally limiting the accuracy.

Note that the system is a two integrator loop oscillator (Set 26, cards 5, 6, 7) with no mechanism for amplitude stabilization so that continuous updating of $x$ and $y$ is essential i.e. $T \gg 2\pi/\omega$ is undesirable.

**Reference**

**Related circuits**
Set 19, card 4
Set 15, cards 4, 6
Set 30, card 1

Alternative circuit
This circuit (middle) has the advantage that the inputs can be simple voltages, rather than pulse widths, but is restricted to two inputs (the previous scheme is readily extended to more than two inputs) and is less accurate.

The circuit is an analogue computer type circuit for the solution of
$$v(t)+\omega v(t)$$
where $v(t)$ is the inverter output voltage, $\omega$ is the "gain" of each integrator and the inverter gain is assumed to be $-1$. The solution of this equation is
$$v(t) = z \sin(\omega t + \phi)$$
where $z = (v(0) + v(0)/\omega^2)$. Hence if the initial conditions (i.e.) on the two integrators are made equal to the analogue voltages $x$ and $y$, the resulting oscillation has a peak value $(x^2 + y^2)$. Peak detectors suitable for this purpose are discussed in Set 4, card 2.

**Reference**

**Related circuit**
Set 30, cards 1, 5.
The above system employing multiplying d.a.c. converts digital polar co-ordinate information \((r, \sin \theta, \cos \theta)\) into analogue form. The output from IC1 is converted directly to a voltage through a resistive load, which is proportional to the digital value of \(r\). This is then the source of the variable reference currents for IC2 and IC3. The output current is the product of the reference input current and the digital input representing the sine or cosine information. The op-amps convert the currents into a positive-going voltages e.g. an all-ones \(r\) input provides \(-10V\) at IC2 output, and hence a 2mA reference current into the next stage, the output current then depending on the digital sine or cosine entered. For all-zeros at \(r\), the input reference current to IC2, IC3, is zero, giving zero output current and hence zero output voltage at X and Y.


Charging current of \(C_1\) is effectively \(V_1/R_1\) which generates a ramp voltage at the input of IC2, used as a comparator. Capacitor \(C_1\) periodically discharged by the pulse train into transistor Tr1. The ramp voltage at the output of IC2 will reach \(V_S\) after a time

\[
t = CV_1/I = C_1V_1R_1/I_1.
\]

Hence \(t/T = C_1V_1R_1V_1T\), where \(T\) is duty cycle at the output of \(A_2\). This modulates the input to the active filter IC3, which provides an output

\[
V_o = -C_1V_1R_1V_1T.
\]

If \(T\) is made equal to \(R_1C_1\), then \(V_o = -V_sV_1/V_1\). If \(V_S\) is kept constant, the circuit acts as a multiplier. If \(V_S\) is maintained constant, then an analogue divider is implemented. Input levels should be less than \(+10V\) (all signals must be positive) and \(V_S\) should be less than \(V_1\).

*Reference*


This circuit provides a means of controlling the frequency of the square/triangle generator comprising an integrator (IC1) and Schmitt comparator (IC2). The input signal to \(y\) is constrained by the back-to-back zener diodes to be \(\pm V_z\). This is multiplied by the control voltage \(V_c\), and hence multiplies the voltage at \(P\) by the same factor, which therefore modifies the charging rate of capacitor \(C\) and hence the frequency of oscillation.

*Reference*

Contents of Circuit Designs 1

Set 1: Basic active filters
Background article/Wien-bridge bandpass filter/Wien-bridge all-pass network/voltage-controlled filters/low-pass Sallen & Key filter/high-pass Sallen & Key filter/low, high and band-pass triple amplifier/op-amp triple with phase compensation/multi-feedback filter/adjustable-Q twin-T notch filter/easily-tuned notch filter/compound filters/n-path filter/up-date circuits.

Set 2: Comparators and Schmitt circuits

Set 3: Waveform generators
Background article/basic op-amp square/triangle generator/emitter-coupled triangular wave generator/diode-pump staircase generator/unjunction sawtooth generator/voltage-controlled square-triangle generator/complementary transistor sawtooth generator/digital-to-analogue converter waveform generator/triggered ramp-trapezium generator/stable waveform generator using single i.c./simple multi-waveform generator/op-amp-c.m.o.s. square-triangle generator/simple wave-shaping circuits/up-date circuits.

Set 4: A.C. measurement
Background article/basic diode rectifiers/peak-mean-r.m.s. calibrated rectifier/absolute-value circuits/high-frequency voltmeter for a.c./class-B economy rectifier/potentiometric peak-sensing circuit/low-frequency measurement of a.c. waveforms/high-current peak-mean rectifier/simple precision rectifiers/positive-negative peak detector/square-law meter circuit/a.c. adaptor for digital voltmeter/up-date circuits.

Set 5: Audio circuits
Background article/magnetic cartridges-RIAA equalization/tone control circuits-Baxandall/rumble filters/tape-head preamplifier/audio mixer-operational amplifier/multi-section tone control system/scratch filters/microphone preamplifiers/impedance matching and transforming/economy i.c. audio circuits (using LM3900)/ceramic cartridge preamplifier/multi-input preamplifier/up-date circuits.

Set 6: Constant-current circuits
Background article/hybrid constant-current circuit/constant-current use of voltage regulators/simple current-limiting circuits/current mirror/constant-current circuits/ring-of-two reference/switching current regulator/thyrstor control current regulator/low-voltage current regulators/high-power current regulators/constant-current applications/constant-current amplifiers/up-date circuits.

Set 7: Power amplifiers
Background article/basic power amplifiers/servo amplifier/pulse buffer amplifier/push-pull class A power amplifier/high-voltage amplifier/class C power amplifier/bridge output amplifiers/class B quasi-complementary output/broadband amplifier/class A op-amp power booster/d.c. power amplifier/class D switching amplifier/up-date circuits.

Set 8: Astable circuits
Background article/complementary m.o.s. astable circuit/r.t.l. astable circuit/complementary astable circuit/t.t.l. Schmitt astable circuit/operational amplifier astable circuit/astable blocking oscillator/t.t.l. dual inverter astable circuit/coupled logic gates astable circuit/emitter-coupled astable circuit/discrete-component Schmitt astable/dual-monostable astable circuit/astable circuit with f.e.t./up-date circuits.

Set 9: Optoelectronics
Background article/null, level and overload l.e.d. indicators/driving l.e.d.s: digital circuits/switching with an opto-isolator/integrated-circuit optoelectronic switch/characteristics and applications of l.e.d.s/op-amp comparator driving of l.e.d.s/photoransistor logic circuit drivers/optically-coupled isolator: static characteristics/optically-coupled isolator: pulse characteristics/photoconductive and photovoltaic cells/light intensity measurement and detection/choppers and rectifiers/up-date circuits.

Set 10: Micropower circuits
Background article/low-voltage a.c. amplifier/low-voltage astable circuit/low-voltage regulators/optical link with low standby power/signal-powered circuits/micropower crystal oscillator/micropower d.c. amplifier/RC oscillator for low voltages/class B low-voltage amplifier/low-voltage d.c. converter/low-current use of diodes/micropower active devices/up-date circuits.
Contents of Circuit Designs 2

Set 11: Basic logic gates
Background article/resistor-transistor and direct-coupled gates/d.t.l. gates/basic t.t.l. gate/NAND gate variations/c.m.o.s. gates/e.c.l./interfacing/threshold logic/optical logic/analogue gates/three-state and majority logic/up-date circuits.

Set 12: Wideband amplifiers
Background article/c.m.o.s. amplifier/shunt-peaked amplifier/high-gain amplifier/voltage followers/bipolar cascode amplifier/ e.c.l. amplifier/f.e.t. cascode amplifiers/amplifiers using t.t.l., r.t.l., d.t.l./d.c. feedback pair/gated video amplifier/high-speed op-amps/c.b. amplifier/up-date circuits.

Set 13: Alarm circuits
Background article/flame, smoke, gas detectors/bridge circuits/time delay and generator circuits/level sensing and load driving/uses of 555 timer/frequency sensing/digital annunciators/ filament lamps and relays/signal domain conversion/pressure, temperature and moisture-sensitive alarms/security, water level and automobile alarms/electromechanical alarms/up-date circuits.

Set 14: Digital counters
Background article/binary counters/one-out-of-n ring counter/Johnson counters/reversible counters/divide-by-n counters/ high-power counters/high-speed counters/low-power counters/decade counters/m-sequence generators/glossary/up-date circuits.

Set 15: Pulse modulators
Background article/p.a.m. with precision limiter/i.c. pulse duration modulator/p.a.m. with shunt gate/pulse duration-position modulator/variable slope modulator/pulse modulation using 555 timer/c.m.o.s. p.a.m.-p.d.m./d.c. motor control using p.d.m./delta modulators/d.c. amplifier-p.d.m./pulse position modulator/pulse code modulator/up-date circuits.

Set 16: Signal processing with current differencing amplifiers
Background article/c.d.as/basic amplifiers/logic gates/high voltage amplifiers/power amplifiers/bandpass filters/notch filters/low-pass, high-pass filters/gain-controlled amplifiers/up-date circuits.

Set 17: Signal generation with c.d.as
Background article/generators/RC oscillators/v.c.o.s/voltage regulators/constant-current circuits/Schmitts and comparators/astable multivibrators/monostable multivibrators/flip-flops/staircase generators/up-date circuits.

Set 18: Measurement and detection with c.d.as
Background article/measurement and detection/logic circuits/p.l.l./transducer driving/device testing/negative resistance/peak-mean rectifiers/sample and hold circuits/h.f. circuits/tachometers/up-date circuits.

Set 19: Monostable circuits
Background/discrete-component circuits/complementary circuits/op-amp circuits/t.t.l. circuit/ c.m.o.s./e.c. circuits/voltage-controlled monostable/long-delay circuits/dual monostable using 555 timer/high duty cycle circuit/up-date circuits.

Set 20: Transistor pairs
Background article/high current-gain pairs/cascode amplifier/long-tailed pair/current mirrors/complementary switching transistors/complementary emitter follower/c.m.o.s. circuits/triples and mixed pairs/pot pourri/up-date circuits.