Voltage Following

A questioning look at the emitter-follower and an outline of alternatives that have been used

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Single transistors of either polarity may be used as emitter-followers (Fig.1). The collector is at ground potential for a.c. purposes (via the supply) and this configuration may then also be called grounded collector. The emitter-follower is often used as a buffer to present a high input impedance to a source where the circuit input impedance is much lower (Fig.2). Conversely, used at the output, it has to drive the load, providing a low output impedance irrespective of that of the circuit (Fig.3). Inside an amplifier it may isolate two stages, to permit the former to reach a high voltage gain fixed only by the values of resistance used (Fig.4). Thus the ideal emitter-follower would have input and output impedances that are infinite and zero respectively. This is not enough since there might be a constant potential difference between input and output. A further embarrassment in d.c. applications would be temperature induced drift in this p.d. Hence a third property of an ideal emitter-follower would be equality of input and output potentials regardless of temperature. Where a circuit comes close to meeting all these conditions it merits the description voltage follower, a name that has found favour with the designers of operational amplifiers operating with 100% series, applied, shunt-derived negative feedback. In Fig. 5 a high gain amplifier with single ended output and differential input, has its inverting input tied to the output. The p.d. between input terminals is much less than V_0, leaving V_0 substantially equal to V_i. The circuit is then dubbed a voltage follower.

Limitations

A single transistor in the common collector configuration cannot satisfy any of these conditions completely. Thus to a first approximation, the input impedance will equal the load impedance multiplied by the common-collector current gain; the output impedance approximates to source impedance divided by the current gain. If in Fig. 6

$$V_0 = V_i \text{ and } i_e = h_{fe}\, i_b$$

$$Z_i = \frac{V_i}{i_b} = \frac{i_e Z_L}{i_b} = h_{fe} Z_L$$

As the load resistance is increased, a limit on input impedance is imposed by the shunt path between base and collector. Similarly a lower limit to output impedance is fixed by the r_{ex} term of the equivalent-T circuit. The output potential of an emitter-follower differs from that of the input by the base-emitter p.d. of the transistor. This may lie between 0.5V and 0.7V for silicon devices depending on the type and operating current, and falls typically by 2mV for each rise in temperature of 1 deg C. This need not be a disadvantage for a.c. circuits but clearly is so when it is a d.c. level that is to be transferred. The single emitter-follower presents problems for d.c. signals below a few volts.

The Darlington circuit

First consider the usual Darlington configuration of two transistors (Fig. 7). The combination may still be treated as a single transistor but having a current gain approximating to the product of the individual gains. A detailed analysis has been made[1] of this super alpha combination. The minimum p.d. between input and output circuits is now twice that for a single transistor and the temperature drift in that p.d. is also doubled. A simple alternative, Fig.8, has a comparable current gain but with only one base-emitter path between input and output. It is perhaps best considered as two inverting stages having a high overall voltage gain but with 100% series-applied feedback. This gives a voltage gain just less than unity. Note that a complementary version of the above circuit is equally valid.

Both of these two-transistor circuits can lay traps for the unwary. In the earlier paragraphs a combined current gain equal to the "product of the current gains" has been glibly quoted. This statement needs qualification. As drawn, the first transistor in Fig.7 has an emitter current equal to the base current of the second. Operating at a low current level it may then have a value of current gain much less than that obtaining at normal currents. A more fundamental over-simplification in the above has been the assumption that the actual value of current gain is comparable with the h_{fe} of the transistor. This is true only for a short circuit output, the way in which the h_f parameter is defined. In most cases the observed current gain is reduced below the h_f value by less than the spread in h_f occurring in the manufacturing process. A useful guide to typical performance might then be to expect the actual current

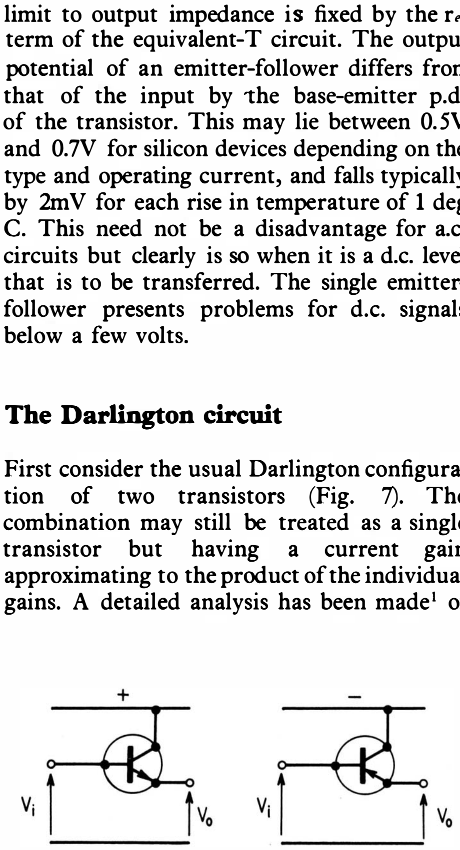
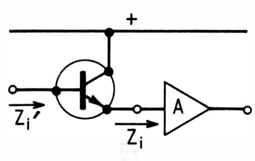
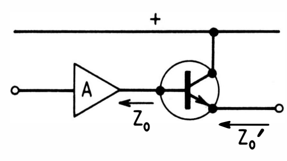


Fig. 1. Emitter-followers. The collectors are at ground potential.





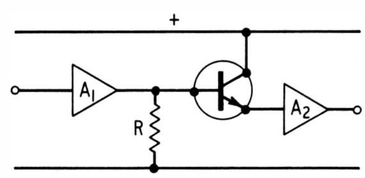
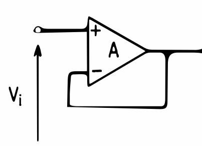
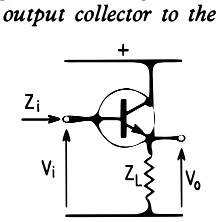
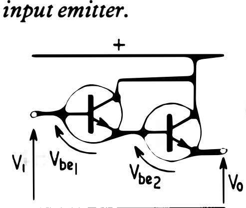


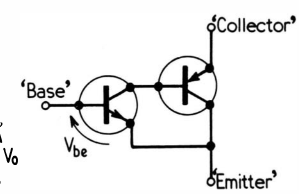
Fig. 2. (Left) A buffer stage for presenting high input impedance to the source. Fig. 3. (Centre) A buffer stage for presenting low impedance at the output. Fig. 4. (Right) If the voltage gain of A_1 is a function of load resistance R, a single emitter-follower can effectively isolate A_1 from the loading effect of A_2.

(Left to Right) Fig. 5. A differential amplifier wired as a voltage follower. Fig. 6. A common collector circuit with load Z_L. Fig. 7. A Darlington transistor pair. Fig.8. A complementary pair of transistors with feedback from the output collector to the input emitter.









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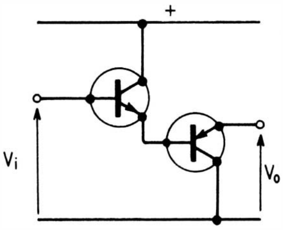
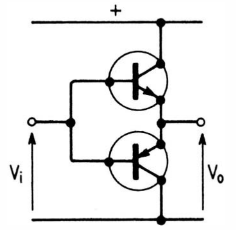




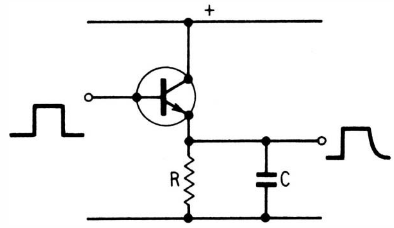
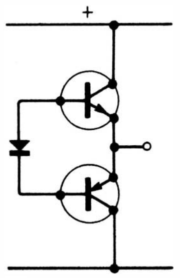


Fig. 9. (Left) Two transistors of opposite polarity in cascade. Fig. 10. (Centre) A bi-directional emitter-follower used where high drive currents are required in both directions. Fig. 11 (Right) A class A stage feeding a capacitative load.



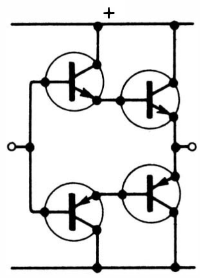
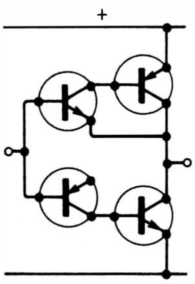


Fig. 12. A forward biased diode between the bases provides bias approaching class B.
Fig. 13. A Darlington version of Fig. 10.



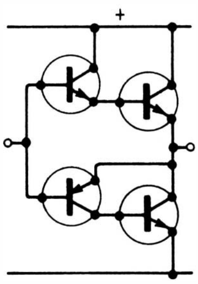
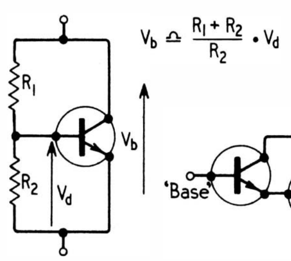


Fig. 14. The configuration in Fig.8 can be used to provide the high gain and bi-directional action.
Fig.15. Quasi-complementary symmetry using identical output transistors.



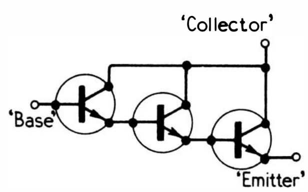


Fig. 16. (Left) The "amplified diode" provides variable bias voltage equivalent to a string of diodes. Suitable for use in the circuits of Figs. 12 to 15.
Fig. 17. (Right) The Darlington triple in which the overall current gain approximates to h_{fe}^3 where h_{fe} is large.

gain to lie close to the minimum specified value of h_{fe}.

Fig. 9 shows a cascaded emitter-follower using complementary transistors in which the V_{be} drops in the two transistors largely cancel. The characteristics of n-p-n and p-n-p will not match exactly and the two are operating at different currents. There will thus be some residual offset voltage between input and output and a drift in this offset, though both should be in order of magnitude less than for any of the previously described circuits. This circuit could be used to drive a d.c. voltmeter of low resistance from a high resistance source with a voltage error of perhaps a couple of tens of millivolts. Complementary versions simplify the choice of transistor since the type having highest current gain at low currents can be used as the first transistor.

Push-pull operation

Operating in class A, a single emitter-follower, or these alternatives, can transfer a sinusoidal or other bi-directional signal to a load. There are many cases where operation in class B or C is desirable and Fig.10 shows a combination of two complementary transistors which are biased just into class C. A particular example where class-A operation is undesirable is the transmission of pulses into capacitive loads (Fig.11). On the positive-going input step the transistor can supply sufficient current to charge the capacitance rapidly. On the negative going step the capacitor will temporarily hold the emitter above the base potential until the exponential decay at a rate determined by the RC time-constant is completed. Throughout this time the transistor is out of conduction and plays no part in determining the output. To shorten the fall-time of the pulse, the resistance of R can be reduced since the two are proportional. In so doing the current drawn during the pulse is considerably increased and transistor dissipation and supply current drain follow suit. This is an inefficient way of discharging the capacitor since a large transient current is being provided at the expense of large mean current. The circuit of Fig.10 has complementary symmetry permitting one transistor to charge the capacitor rapidly during the pulse mark with the other discharging it equally rapidly during the space. The circuit finds applications in transmitting pulses along highly capacitive cables.

Because the biasing is class C, distortion ($\sim 2V_{be}$) results with sinusoidal signals. Fig. 12 shows the basic method used to ensure class B or AB operation. The bases are separated by a diode in forward conduction, normally being part of the resistive load of the previous stage. The voltage across that diode may be made sufficient for each transistor to conduct slightly taking them to the borderline of class-B. Unfortunately the non-linearity of the voltage-current characteristic for transistors still results in cross-over distortion unless they are biased forward into class AB. A difficulty in this arrangement is that the current is a function both of the diode forward voltage and the V_{be} for each transistor.

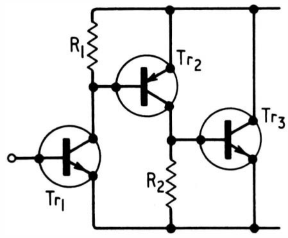
Turning to Figs. 13-16, we have a group of circuits which represent the extension of the bi-directional circuits just discussed to those cases where increased current gain is required. Thus Fig.13 has each single transistor replaced by the appropriate Darlington pair, while in Fig.14 the complementary Darlington pairs are used. The relative merits and demerits of the circuits of Figs. 13 and 14 hinge on the properties of the Darlington pairs as outlined earlier. In particular that of Fig.13 has four base-emitter paths between input and output, which would make the selection of a diode biasing network in the input bases difficult. A problem common to the two circuits is that the output transistors in each are of opposite polarity. Since this basic form of circuit is of such general application in audio power amplifiers the need arose for complementary transistors of high power rating. This need has still not been completely fulfilled—at least not as cheaply as one would like. In the early years, when only germanium devices were available, these were mainly p-n-p although some low-power n-p-n devices were produced. H. C. Lin of U.S. General Electric devised the quasi-complementary output stage shown in Fig. 15. The two halves of the circuit are no longer identical though for similar transistors the current gains will be comparable. It has the key merit that the output transistors can be of the same type which may readily be obtained as a matched pair. The key to the quasi-complementary circuit is that a power transistor of one polarity may be made to behave as one of the opposite type by incorporating it in a 100% series-applied feedback circuit with a low power device of the opposite type. If the problems of biasing are difficult with class B circuits having two transistor base-emitter p.ds. within the bias loop, they can appear insurmountable with three or four present. A compromise involving two or more diodes together with series resistors is often adopted but an idea has recently been put forward that is elegant and effective[3,4]. Fig.16 shows a transistor with resistors between base and emitter, and emitter and collector. If the base current is a small fraction of the potential divider current, then the collector-emitter voltage is a defined multiple of the base-emitter voltage, i.e. we have a two-terminal device which over a reasonable range of operating currents has a voltage drop and corresponding drift with temperature, equivalent to a series chain of n diodes where n includes non-integral values depending on the ratio of R_1 to R_2. The designer of this circuit has made a notable contribution to the armoury of those fighting the great enemy—bias-point instability. A suggested name for this circuit is "the amplified diode" since with it we can provide a voltage which is any desired multiple of that across a normal semiconductor diode when forward-biased.

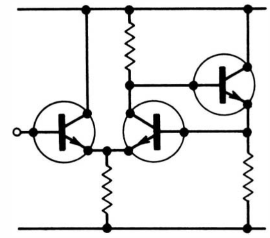
Triples

Another major use of compound emitter-followers is in the output stages of d.c. voltage regulators. Load currents of several amps may be needed while the driver stage may conveniently deliver less than a milliamp. Two transistors will not then provide sufficient current gain, particularly since the transistors may have to operate close to saturation to minimize voltage loss in the output. Hence a Darlington triple is sometimes employed (Fig. 17). Unless the base can be supplied from some auxiliary constant current source the minimum difference between supply and output may be in excess of 1.8V—three base-emitter voltage drops. Allowing for some voltage drop across the base drive resistor this voltage may rise to 2.5V or more making this triple a particularly undesirable one at low supply voltages. Just as a complementary Darlington offered some advantages over the "straight" one, so complementarity is worth investigating in more detail here. We shall limit ourselves to combinations of three transistors in which (a) the output of each (collector or emitter) shall be coupled into the base of the next, i.e. excluding common base connection (b) each transistor shall provide the bias current for the next.

We can derive the configurations which meet the above conditions by returning to Figs. 7 and 8 and considering the Darlington and complementary Darlington pairs having n-p-n polarity. If we replace each transistor, of which there are four in the two circuits, in turn by a Darlington pair and then by a complementary Darlington pair, then we generate eight triples having n-p-n polarity. Of these, six only are shown in Fig. 18 since two of them are duplicated [(a) and (f)]. A complementary set of six can be drawn having p-n-p polarity. The triple shown in Fig. 23(f) has already been discussed. Of the remaining five, Fig. 23(b) has much to commend it. It is used in regulators and has been recently advocated in a letter drawing attention to its merits. In particular the p.ds. between "collector" and "emitter" (0.7V) and "base and emitter" (0.6V) are the lowest possible for a triple. These approximations assume a V_{be} of about 0.6V and a V_{ce} of 0.1V in saturation. For example in 18 (e) the comparable values are 1.3V and 1.2V respectively for the equivalent collector-emitter and base-emitter minimum p.ds.

Where the high gain offered by a triple is needed it must be remembered that the standing current in the first transistor will be very low. This can result in loss of current gain in that stage sufficient to offset much of the advantage in going from a pair to a triple. If resistors are placed between base and emitter





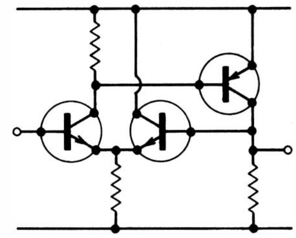


Fig. 19. (Left) The addition of resistors stabilizes the characteristics of Fig. 18 (b). Fig. 20. (Centre) A feedback amplifier using a long-tailed pair to compare input and output. Fig. 21. (Right) A circuit with many advantages. An inverting output stage is taken from the collector of the input transistor. The output and input can approach the positive line.

of each transistor as in Fig. 19 the operating currents of the earlier stages are raised but stabilized. Each resistor is chosen to carry a d.c. current, say, one to five times the expected base current of the following stage—the higher ratios being usable with very high gain transistors. For example, if T_2 has a collector current of 10mA it might have a base-emitter p.d. of about 600mV and a dynamic input resistance of a couple of hundred ohms. With a current gain of 100, the base current would be 0.1mA and a base emitter resistance R_1 of 2,000 would carry a d.c. current of 0.3mA. The shunting effect of R_1 on the base of T_2 would be small since R_1 is ten times the assumed dynamic input resistance at this base.

Voltage-follower

A completely different approach is needed when the main requirement is accuracy of transfer from input to output rather than, as in the previous circuits, maximizing of current gain. The circuits of Fig. 13 used complementary cascaded transistors in which the V_{be} is largely cancelled. Exact cancellation is extremely difficult since in general complementary transistors will differ in their manufacture and hence in characteristics. If a circuit is devised in which the V_{be} cancellation is achieved by transistors of the same polarity, then matched pairs taken from the same production batch or even produced on the same chip should solve the problem. Two of the simplest circuits in which such a matched pair can be used, while providing emitter-follower characteristics overall, are shown in Figs. 20 and 21.

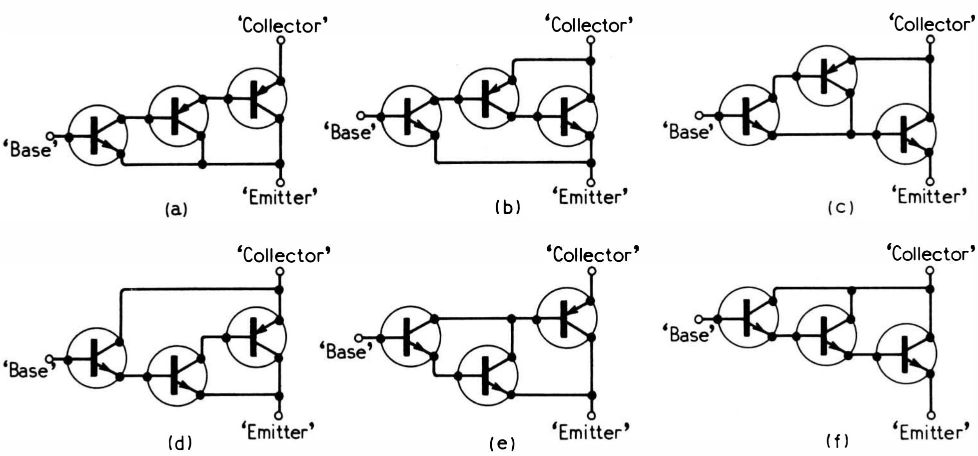
A defect of the circuit of Fig. 20 is that the output swing is limited (a) by the base-emitter voltage of the long-tailed pair which prevents input (and hence output) from falling below 0.6V (b) the necessity for current in the "tail" to keep the transistors in conduction (c) the voltage drop across base-emitter of the output transistor and its base-drive resistor. The first two terms cannot be eliminated, though the second can be eased if the "tail" is replaced by a constant-current source with low voltage drop. They specify the minimum value of input voltage below which the output will not adequately track. Fortunately the third limitation can be removed by a very simple change in the circuit. Replace the output transistor by one of opposite polarity, used as a common-emitter stage. This puts an additional signal inversion which would provide positive feedback. Accordingly the output transistor is fed from the collector of the input transistor instead leaving the overall feedback as negative (Fig. 21). This three-transistor circuit has a current gain provided by only two transistors, but the accuracy of matching of temperature drift makes it a very useful circuit. As it stands, supply variations may cause a change in current in the tail depending on whether the signal is applied with respect to the positive or negative rails. If the tail current increases, most of that increase is channelled into the right hand transistor of the pair since the other is forced to provide a relatively constant current. This is to maintain a base-emitter voltage for the output stage of just over half a volt. The current is thus unbalanced in the long-tailed pair and there is an input-output differential. For voltages above a volt or two, the output is not likely to differ from the input by more than, say, ten millivolts giving a voltage gain of 0.99 or greater. The input-impedance will be high and the output-impedance low.

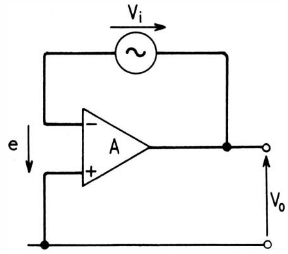
Common-collector

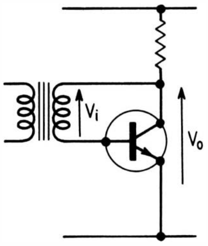
In all the circuits described so far both source and load have had one terminal at ground potential. Thus a single transistor used in this way may be called by three correct names (a) emitter-follower (b) grounded-collector stage (c) common-collector stage. It is the last of these that is the most general since as will be indicated there are circuits which are common-collector but in which the collector is not grounded. In these the emitter is grounded thus disposing of the term emitter-follower.

Returning to the common-collector form of circuit a block diagram is given in Fig. 22

Fig. 18. Six combinations of three transistors having characteristics similar to a single n-p-n transistor. A complementary set of six can be derived to function as a high gain p-n-p transistor. Type (b) has many advantages for regulator circuits.







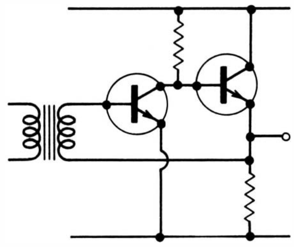
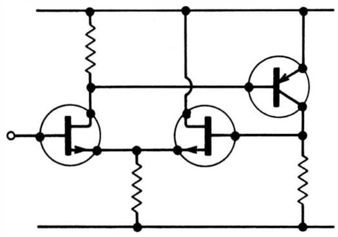
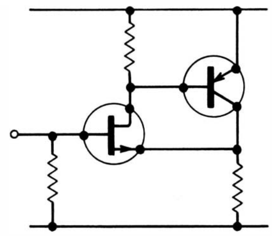


Fig. 22. (Left) The circuits in Figs 1 to 21 have referred input and output to a common line. This need not be ground. Fig. 23. (Centre) This circuit is in common collector but not grounded collector. Fig. 24 (Right) A d.c. feedback arrangement.





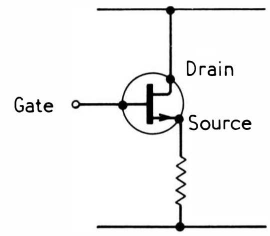


Fig. 25. (Left) F.E.Ts may be used together and in combination with bi-polar transistors to duplicate circuits designed earlier. Fig. 26. (Centre) In this circuit the G_m is boosted by the addition of a p-n-p transistor. This may be cheaper than a high g_m f.e.t. Fig. 27 (Right) A single field effect transistor stage with an output impedance of approximately $^1/g_m$.

to illustrate the principle. The source is floated between output and inverting input of a high-gain amplifier. Two features emerge which tie in with the properties of an emitter-follower:—(a) because the gain is assumed high, the output voltage roughly equals the source voltage, differing from it only by the small voltage across the amplifier input terminals (b) the input current and hence the current drawn from the source is small since this current is caused only by the small voltage appearing across amplifier input terminals. A practical circuit is shown in Fig. 23 where the secondary of an input transformer is directly connected between collector and base of a transistor. The current drawn from the source now depends only on the transistor base current while it is the collector that supplies the load current. The voltage V_i and V_o are approximately equal. If the source is a moving-coil microphone or other component providing a low resistance d.c. path, it may be substituted for the transformer. In such a case we have an extremely simple impedance transforming circuit in which the only component additional to source and load need be the active device. The output impedance is low since the feedback (through the source) is shunt derived i.e. as the collector current increases and the collector voltage tries to fall, this fall is transferred back to the base reducing the collector current and opposing the original change. Assuming negligible d.c. voltage drop in the source (or transformer secondary) the collector potential is equal to the base potential. For input signals of only a hundred millivolts or so the minimum collector-emitter voltage still keeps the transistor out of bottoming. With silicon transistors this allows the collector to swing below the base by up to three or four hundred millivolts. Where the current gain is not high enough nor the output impedance low enough, the addition of an emitter-follower inside the amplifier has some advantages. This is shown in Fig. 24, and is an example of the d.c. feedback-pair. Again the economy of components is a feature of the circuit.

Field-effect transistors

With the increasing availabilities and falling costs of field-effect transistors it is worth indicating their behaviour in such circuits. The first and obvious advantage they have is near-infinite input-impedance. For a.c. applications where the frequency is not too high this may offset their disadvantages. Bias-point stability is in general less good since the drift in gate-source voltage with temperature is a function of operating current and varies considerably between units of a specified type. This is because there are two distinct terms to the drift, one equivalent to the V_{be} drift in ordinary or bi-polar transistors, and the other the change in resistivity of the source-drain path. Matched pairs are now available with differential drifts to within $10\mu V$ deg C^{-1} so allowing circuits such as that in Fig. 25 to be designed. Here the f.e.t.s are used as the long-tailed pair to realize high input impedance, but using bi-polar transistor where the equivalent g_m may be more important. Similarly a single f.e.t. may be used in a circuit similar to that of Fig. 8. This is shown in Fig.26 and the output impedance is lowered because the g_m of the combination is greater than that of the f.e.t alone. Fig.27. There is one further property of the f.e.t. that is of interest. The two temperature-dependent terms can be shown to cancel when the gate-source bias is about 0.6V short of pinch-off. Alternatively by changing the operating current and accepting the resulting drift we can adjust the initial gate-source voltage to zero. Only transistors with a particular value of pinch-off can meet these conditions simultaneously and presumably the tight selection would lead to excessive cost.

No details have been given of high frequency performance. This would require a great deal more space. Another aspect of impedance transformation is the use of positive feedback under the control of the overall negative feedback. The technique is widely applied to cancel out, for example, the small but finite output resistance remaining after the application of heavy shunt derived n.f.b. To be added to this list are those emitter followers in which the emitter resistor is modified, either by replacing it with a constant current source or by making the effective resistance a function of load current (as in the White Cathode follower). In summary we can say that the designer has no need to limit himself to the conventional emitter follower for impedance transformation. There are a very wide range of more complex circuits with particular advantages such as low d.c. drift, pulse capability etc. With such a choice we should be able to get away from the limiting approach that turns the mind automatically to the emitter follower just because the term is so closely associated with the problems to which it is but one possible solution.

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Position-sensitive particle detector

In certain nuclear scattering experiments it is necessary not only to count the number of particles emitted but to determine their spatial distribution. For this purpose Philips Research Laboratories (Netherlands) have developed a new kind of detector based on a "checkerboard" or matrix principle, providing 80 separate detection cells in a sensitive area of about 2cm^2. This consists of a silicon monocrystal, circular and 0.3mm thick, with ten contact strips on the top surface, arranged at right angles to ten other contact strips on the bottom surface. The result is an array of 80 reverse-biased diodes of the surface-barrier type. When a charged particle falls on one of these detection cells it generates a fast pulse (25ns duration) in each of the two contact strips forming the cell, and from these the co-ordinates of the impact position can be determined. The energy loss of the particles can be obtained from the heigths of the pulses detected and from this the particles can be identified. Such detectors are being used in an apparatus at the Institute for Nuclear Physics Research in Amsterdam, each detector being mounted on the end of a "telescope" carrying associated electronics. There are 64 of these telescopes distributed round the target from which the particles are emitted, covering a total solid angle of 0.4 steradian.