I.32 DIODES.

I.32 DIODES. Diodes (or transistors connected as diodes) have many applications in analog circuits. Among these are bounding, current selection, voltage selection, and signal steering or gating.

In bounding, diodes are often used in parallel-opposing configurations, so that they never become reverse-biased by more than a fraction of a volt (typically 0.6 V). In these applications, very low leakage and high incremental resistance may be required when the (reverse) voltage drop is of the order of tens of millivolts or less, whereas, in the same application, very low incremental *forward* resistance is valued when the current is high. These can be estimated using the equation for forward current:

$$i = I_0\left(\epsilon^{\frac{qv}{mkT}} - 1\right) \qquad (1\text{-}14)$$

where:
q = electron charge
v = voltage drop
m = correction factor, typically between 1 & 2
k = Boltzmann's Constant
T = absolute temperature, degrees Kelvin
i = diode current

The incremental conductance (slope of the current-voltage curve shown)

$$\frac{di}{dv} = \frac{q}{mkT}\left[i + I_0\right] \approx \frac{40}{m}\left[i + I_0\right] \qquad (1\text{-}15)$$

for bounding and other "switch-function" applications (see I.25 for an example), a low value of I_0 is particularly necessary. The FD300 has proved satisfactory in many applications. It has, typically, I_0 less than 10^{-11} amperes at room temperature, doubling in value with each 8 to 10°C of temperature rise.

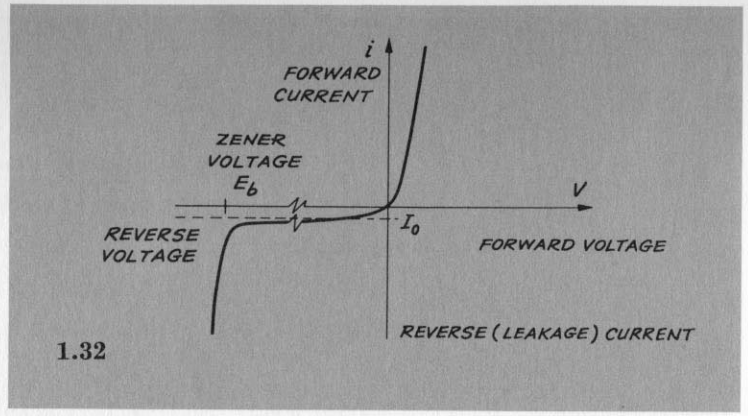
For current selection, switching speed may be an important criterion. A fast diode must have low shunt capacitance (or stored charge) under as much as 0.5 V of reverse bias. For this class of applications, (see II.23) we have used the 1N914 successfully.

When the characteristics of two or more diodes must be matched over a substantial current range, transistors connected as diodes (which have a factor m of almost exactly 1) are far superior. (See II.22.)

Voltage selection may require that diodes be able to withstand substantial reverse voltage. 1N914 diodes can be used for 10-volt systems, and FD200 diodes work well in 100-volt systems. (See II.34.)

Signal steering or gating applications (see II.36 and II.40) often require diodes with high speed, low leakage, and the ability to withstand significant reverse-voltage. A good choice for a 10-volt system is again, the 1N914.

When very low reverse leakage is required, the collector-base junctions of selected silicon small-signal transistors (such as the 2N930) have been found to be as low in leakage as any commercially-available diodes,* at reverse voltages as high as 30 volts.



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The zener or reverse breakdown characteristic of a diode may be exploited to provide a stable reference voltage. The stiffness of such a reference with respect to loading and to temperature depends upon the current flowing through the diode. Typically two to ten milliamperes of reverse current may be required to achieve optimum temperature insensitivity. For low-voltage applications (less than 10 volts) the base-emitter breakdown characteristic of many transistor types can be used in the place of an expensive and perhaps not readily available zener diode. For this purpose the transistor should be connected as a diode; i.e., base and collector tied together. Breakdown diodes are also commonly used for bounding as recommended in I.25.

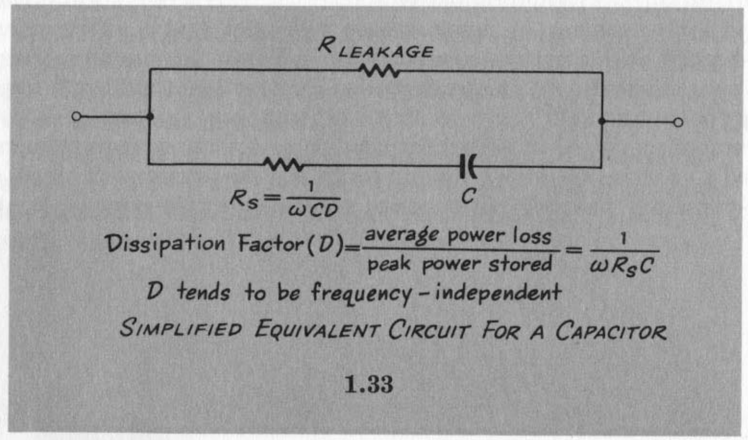
I.33 CAPACITORS.

I.33 CAPACITORS. Capacitors are critical primarily in two kinds of circuits: (1) in Integrators and "Sample-and-Holds," in which a capacitor must be charged precisely, and in which leakage, soakage,* and (often) exact capacitance value matter most; and (2) in by-passing and sometimes stability compensation (C_c in I.42a) in which resonance, losses, and sometimes leakage matter most.

Polystyrene capacitors offer the best leakage/soakage combination. For tolerances of the order of 0.01%, we recommend a constant-temperature oven.

Polycarbonate or mylar capacitors are excellent low-cost alternatives to polystyrene where the ultimate in performance is not required, and they have less leakage than ceramic. In "Track and Hold" circuits for repetitive computation they are quite often entirely adequate—availability is also good. As for leakage in small capacitors, mica capacitors of the MC-15 style dependably exhibit a leakage resistance of at least 7,500 megohms, and the excellent (and unjustifiably maligned) ceramic discs are even better. Our favorite designs typically measure 80–100 thousand megohms.

*Capacitors with low soakage come up to charge rapidly, without excessive losses, or voltage lag or creep during or after charging.



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I.34 CONVENTIONAL RESISTORS. Resistors are the most important and widest-ranging (in value) of all the external components used in Operational-Amplifier circuits. There are probably more kinds of resistors than there are of any other component. To compound the matter, in some 90% of all our circuits, the ultimate limitation to accuracy and stability is not the amplifier, the power supply, nor any other component, but the *resistors.*

Beyond initial tolerance, the largest component of resistor error is its temperature coefficient. Following closely are: leakage (particularly in values above 100 kΩ), humidity effects, drift with time, voltage coefficient, and (rarely in Operational-Amplifier circuits) self-heating and hysteresis after self-heating.

Resistors also exhibit several kinds of noise-generation effects, including thermal EMF's (Seebeck effect), and, as mentioned in earlier sections, stray capacitance across the terminals, as well as series inductance (particularly in wire-wound types), and susceptibility to undesired coupling.

For computing components we use and recommend resistor types in the following order of preference.

WIRE-WOUND RESISTORS ARE FINE (1) Nothing beats them for initial accuracy and stability. (2) Their noise levels approach theoretical minima. (3) They are available in many (relatively expensive) special forms: shielded, hermetically sealed, encapsulated, oil-filled, guarded, etc.; small, moderately-priced sealed units in various tolerance ranges are available from several sources. But . . . (4) Above about 1 Megohm, they begin to be quite expensive. (5) Reliable designs much smaller than 1″ long x ½″ O.D. *per megohm* are hard to find. (6) For a given resistance value, they have higher shunt capacitance and series inductance (even the "non-inductive" types) than any other kind of resistor. The smaller they are per megohm, the worse is the reactance problem.

COMPOSITION RESISTORS . . . of the familiar military type (Ohmite AB) are excellent choices for experiment and not-so-critical bread board applications but are generally not employed as feedback or feed forward resistors in final operational circuits. These resistors are extremely reliable for almost all other functions in the production of Operational Amplifiers themselves and as low power pull downs, etc.

THERE ARE SOME GOOD FILM RESISTORS . . . We like some designs such as the so-called "metal-grid," for (1) their flicker-free behavior and (2) the fact that their "white noise" approaches theoretical. We also like some military grade film resistors because (3) their T.C. range lies within ±150 ppm/°C, (4) their shunt capacitance and series inductance are low, (5) up to 10 megohms, they are highly reliable, and cost less than wirewound resistors.

FOR VERY HIGH RESISTANCES, we look to such glass-enclosed, deposited-carbon resistors as are represented by the Pyrofilm and Victoreen designs. The Pyrofilms appear most suitable for the range from 10 megohms to 100 megohms, having (1) very low flicker, (2) T.C.'s in the range of ±300 ppm (matched, if we wish, to within ±5 ppm), (3) little or no aging effect, (4) excellent reliability. By the way, they are (5) excellent high-frequency resistors—at 10 megohms, only about 0.25 pF! The Victoreen design offers: (6) values to 10,000 megohms, (7) calibration to ±1% (with compatible stabilities) right up to 10^{10} Ω, and (8) high reliability, despite the range and accuracy. The glass-enclosure helps tremendously, and it deserves careful consideration as to the insulation on or in which it is mounted, of course.

Speaking of leakage prevention brings us to insulation—one extreme of resistance technology. (The *other* extreme—wiring for low impedance—has come up in I.28 and I.30.) The choice of good insulation for high-resistance circuits, in which leakage must be minimized, might well follow the listing below,* which has been arranged in the order of decreasing insulation effectiveness, with no regard to many other important properties, such as availability in the desired form, cost, machinability, strength, etc., etc.:

Vacuum, Dry gases

Polyethylene, Polystyrene, Teflon (TM)

Mylar

Mica, Glass-filled polystyrene, Polycarbonate (Lexan) (TM)

Polycrystalline glass (treated), Polyvinylchloride, Glass epoxy

Borosilicate glass, Lead silicate glass, Molded epoxy

Cast epoxy, Ceramics (untreated), Silicones

Phenolics (paper based)

* Ref: Materials in *Design Engineering* Vol. 62 No. 5 P. 18

I.35 POTENTIOMETERS. A potentiometer is essentially a resistive divider and must naturally be considered to suffer from many of the weaknesses inherent in resistors (see I.34); in addition, its performance of the division function is subject to certain anomalies. The following warnings should serve to create an appropriate mood of informed distrust:

- The "end-resistance offset" of some potentiometers is sufficiently large, and sufficiently variable from unit to unit, to create error in *calibrated* circuits—circuits in which the effect of adjusting a potentiometer must be related to the numerical readings on its control dial. Precision potentiometers bear a rating guaranteeing a certain maximum end-resistance offset.
- "Linear" potentiometers are never perfectly so. The reader of specifications must be particularly careful in interpreting such *exotica* as: "best-straight-line" linearity error, "maximum-deviation-from-chord" linearity error, and "absolute ratio" linearity.
- Good circuit design will usually eliminate the effect of pot-to-pot variations in over-all resistance. In divider applications, a second pass should be made
to anticipate and nullify the influence of this variation on the division I.35
function itself. I.34
- The stray effects—resistive, capacitance, and inductive—that are functions II.6
of the potentiometer *setting*. Clear thinking is needed, to avoid unpleasant II.7
surprises. II.16

In general, for reliable, accurate coefficient setting or signal-voltage division, a II.17
good grade of wire-wound single or multi-turn potentiometer is recommended. II.26
For single-turn, calibrated-scale applications, we have used such designs as III.48
the Clarostat 42 JA (with properly-specified linearity and tolerance) with excellent results in the region of $\pm 1.0\%$ calibrated accuracy.

Another good choice for this general class of applications is the General Radio type 972-Q. For multi-turn scaling, where loading effects are negligible, or can be "calibrated away," such potentiometers as the Helipot Type A, or the ingenious divider units manufactured by Fluke are excellent, moderately-priced choices. A variety of long-lived, reliably-stable readout-dial mechanisms are available (at a wide range of prices) for the potentiometers described above.

I.36 CHOPPERS AND RELAYS. Although the functions required of all of the choppers and many of the relays used in operational amplifiers would not at first appear to be similar, they have one outstanding similarity: their contacts are quite often connected at the lowest-level point of the circuit—the input terminal, the summing point, or the amplifier input. The nature of these applications imposes certain uniform burdens on the performance characteristic of the relay or chopper:

- The microampere and nanoampere current levels encountered make the "dry" circuit resistance of the "closed" contacts, and the resistive and capacitive leakage across them when "open," serious limitations in many designs. Either or both can be prohibitively high, unless the relay or chopper has been specifically designed to minimize them.
- Thermal EMF's (Seebeck effect) can be larger than the amplifier's input noise threshold; induced noise from the driving coil may be larger than the signal, in extreme cases—shielding can help, but "shaping" of the applied drive-current signal, to minimize its rate of change, may be necessary.
- In choppers particularly, but not exclusively, the closure synchronization, bounce, dwell time, and inherent delay between excitation and mechanical reaction may completely distort the circuit performance.

Variations in these factors may be almost as oppressive.

Philbrick chopper-amplifiers and relay-controlled networks have been designed I.36
to minimize their susceptibility to all of these maladies (for really fast switching I.12
and chopping, we resort to electronics), but they can never be ignored as a II.12
source of trouble after age has taken its toll. II.46

Reed relays have become justifiably popular for general signal-switching. They II.49
are compact, operate in any position, are low in cost, high in reliability, relatively III.7
fast in operation; dry-circuit reliability and longevity are excellent; leakage III.16
resistance can exceed 500,000 megohms. They are not presently recommended III.33
for chopper service, which involves a million operations in less than five hours. III.53
Two such reed relays are used in the Philbrick SPREL Relay Control Unit.

Mercury-wetted-contact relays require more-or-less-upright mounting (within 30°–45° of vertical), but are excellent for dry-circuit switching; they are free of bounce, offer insulation up to 10,000 megohms, are hermetically sealed, and are extremely long-lived. As choppers, they are noisier than some, but cost far less, have adequate operating speed (2 msec), and can run for years at 5 million operations per day. Classical types are usually make-before-break, but non-shorting types have recently become available.

Two other relays deserve mention: the James Electronics, Inc., "Microscan," specified to have switching time of 650 μsec, less than 0.5 μV noise, and 10,000 megohms insulation at 200 V; and the Bristol "Synchroverter," specifying 200 μsec each, operate/release.

I.37 AMPLIFIER PERFORMANCE RATINGS. Throughout this text, the reader will find recommendations as to the performance characteristics of the Operational Amplifiers used in the circuits and applications treated. To assist you in evaluating the suitability of a particular Philbrick Amplifier to a particular application, we have devoted the fold-out back cover to a comprehensive Amplifier Characteristics chart. . . . and to speed your use of that chart, we offer this rapid-search table, which rates 18 families of Amplifiers in terms of their salient (•) superior (✓) or outstanding (!) properties. The criteria used are the ones most often mentioned in our circuit descriptions. The recommended procedure is to (1) note the characteristics most desired for the application; (2) use the chart to identify the families likely to satisfy; and (3) examine the detailed characteristics of those families in the Characteristics chart.

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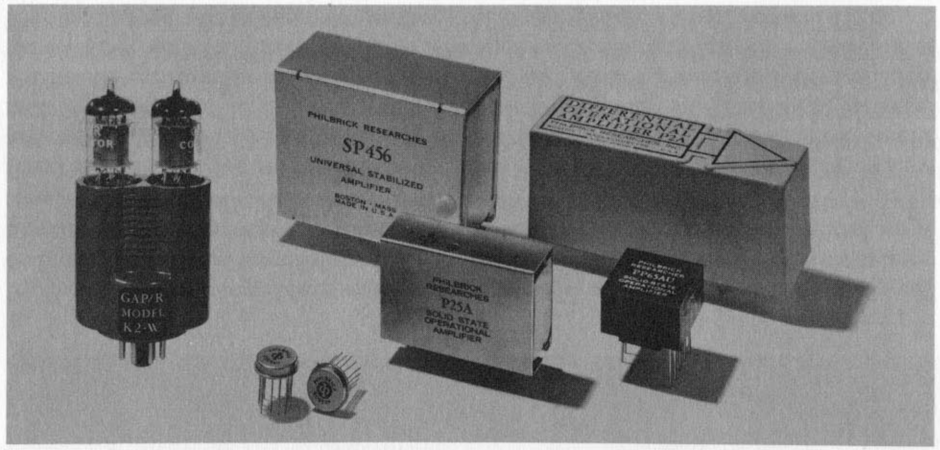
I.37	P25A	Q25AH	P35A	P35C	P45A	P45AL	P55A	P65A	P65AH	P75A	P85A	P85C	Q85AH	SP2A	SP65A	SP65AH	SP656	SP456
GAIN			✓	✓	•	•					•	•			!	!	!	!
BANDWIDTH		✓	•	•	!	•			✓				✓			✓		!
CMRR	•	•	✓	✓							✓	✓	✓	!				
INPUT IMPEDANCE	!	!	✓	✓						✓	•	✓	✓	!				
OFFSET VOLTAGE	•	•	✓	✓	•	•		•	•		✓	✓	✓		!	!	!	!
OFFSET CURRENT	✓	✓	•	✓						•		•		!	!	!	!	!
NOISE	✓	✓	•	•				•	•		•	•	•	!				
OUTPUT POWER					✓	✓											✓	✓

I.38 STANDARD AMPLIFIER PACKAGES. An amplifier has no inherent or classic shape of its own, but must be given one—as convenient and unobtrusive a configuration as its components and characteristics allow. Philbrick amplifiers have always been offered in compact and efficient mechanical forms, from the original vacuum-tube models in the electrically and mechanically stable plastic shell, through the newest encapsulated solid-state monoliths. The K2 Series has been augmented by SK2's in all-metal ventilated cases, K2-J militarized versions, and the USA Series of board-mounted units (and militarized counterparts, the USA-J Series). Solid-state condensation has sponsored the metal-cased P Series (2¼″ x 1½″ x ¾″), and SP Series (3³⁄₁₆″ x 2⅜″ x 1½″) modules intentionally compatible with the Q3 Modules described in I.39. Their miniature versions, the PP Series and the FP low-profile series are ideal for printed-circuit use. Then there is the cast-aluminum case used for potting such designs as the floating-input P2A. Finally, there is the little newcomer in the TO-8 transistor case, (0.60″ diameter, 0.150″ high) . . . where will it all end?



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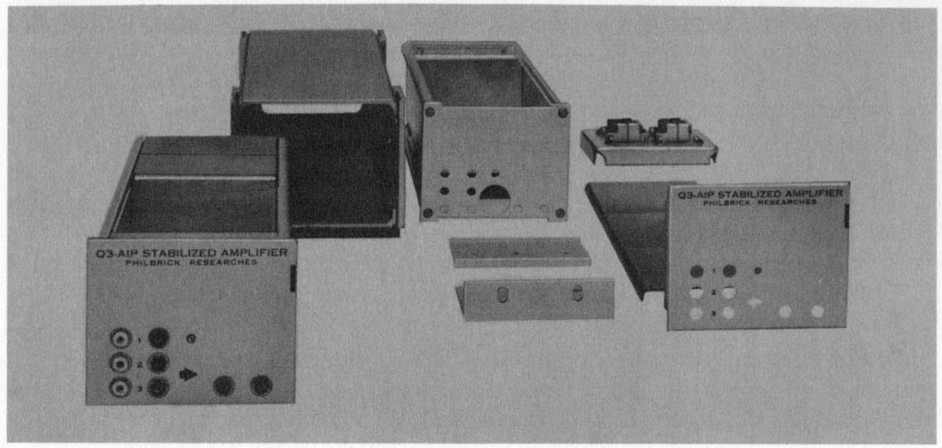
I.39 "HARDWARE" FOR CIRCUIT REALIZATION. The Q3 Modular Electronic Package shown at right was developed to make the process of translating schematics into equipment quick, economical, and almost painless. Efficiently accommodating a number of Philbrick plug-in units (see p. 96 and cover flap), the Q3 system also offers the equipment designer a broad selection of blank and pre-punched chassis and panels, plug-in circuit boards, and connectors. These extruded-aluminum, 4.2″ wide, 3.5″ high, 13″ long cells can be grouped, stacked, locked together, or assembled into 19″ relay rack combinations. Modules slide into their cases from the front, have mating connectors at the rear, and are secured and released by a ball-bearing latch. Thermal, electrostatic, and magnetic shielding are excellent. Q3 is available off-the-shelf.

For the designer with little time for building "from the ground up," there are the Q3-series "Universal Operational Modules," such as Model Q3A1P—self-sufficient devices, in which such distractions as socket-punching, service interconnection, noise pick-up, and instability have been minimized freeing him to concentrate on the signals, and the MP and RP manifolds for multi-amplifier circuitry with less-stringent requirements.



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