APPENDIX

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Admittance: For sinusoidal signals, the incremental ratio of a current to a voltage. A self-admittance describes the current-voltage relationship in a two-terminal element, admittance relates the current into a terminal to the voltage between that terminal and common; a trans-admittance, in general, relates a current into any terminal of a circuit to a voltage between any pair of terminals.

Arbitrary Function Fitter: A circuit having an output voltage or current that is a presetable, adjustable, (usually non-linear) function of the input voltage(s) or current(s) fed to it.

Bandwidth: Generally, the frequency range over which a particular transfer characteristic (i.e., gain, attenuation, phase-shift, etc.) is maintained between two sets of terminals (i.e., input and output). In an Operational Amplifier, the frequency range over which the open-loop gain exceeds unity. In an Operational-Amplifier circuit, the frequency range over which the (small-signal) loop gain maintains the desired response, to the desired accuracy.

Bias Circuit: A fixed (or adjustable) circuit that is used to set or control (zero-signal) input-current or input-voltage level to an arbitrary value (normally zero). May be temperature-compensating...etc. able to track the variation of amplifier input voltage or current with temperature, more or less perfectly.

Booster Amplifier: A circuit used to increase the output current or voltage capabilities of an Operational Amplifier circuit, without loss of accuracy (ideally) or inversion of polarity. Usually applied inside the loop, for accuracy.

Bound Circuit: A circuit designed to limit the excitation of a signal. The limit value it establishes may be nominal (when used for protection), or highly-precise (when used operationally).

Chopper: A circuit provided for interrupting (or at least modifying) a low-frequency signal path at a constant rate (i.e., carrier frequency), producing a wave, which is modulated by the DC signal magnitude, preserving the polarity of the DC signal. Generally associated with a synchronous demodulator, following amplification.

Common-Mode Error (CME): (referred to the input) A (generally) small offset voltage appearing between the input terminals of a differential operational amplifier, as a function of the common-mode voltage.

Common-Mode Rejection Ratio (CMRR): The ratio of common-mode voltage to common-mode error in a differential amplifier circuit.

Input Voltage: The voltage between the output signal return and (in this book) the positive input terminal of a differential operational amplifier.

Comparator, Precision: A high-gain amplifier circuit whose output changes decisively between two definite levels whenever the sum of the input voltages changes sign.

Controller: A portion of a feedback system in which the unregulated imbalance (or error) is amplified on by adjustable dynamic elements (proportional, integral, derivative, lead-lag, etc.) to affect the manipulated variable in such a way that desirable response criteria for the loop (stability, speed, accuracy) may be met.

Current Bias: See Bias.

Current Pump: A circuit that drives, through an external (load) circuit, an adjustable variable or constant value of current, regardless of the reaction of that load to the current, within rated limits of current, voltage, and load impedance.

Damping Circuit: A circuit used to limit, control, or prevent transient instability (oscillation or "ringing") in a closed-loop active circuit, or in a complex passive network having appreciable second-order (or higher-order) response.

Dead Zone: A range in which no output change is produced by substantial input variations; a circuit element having such response (or lack of response).

Differential-Input Amplifier: One in which the output is (ideally) a function only of the difference between the signals applied to its two inputs, both signals being measured with respect to a common "low," or "ground" reference point.

Differentiator: Ideally, a circuit having a response (output) proportional to time-derivative(s) of one or more input signals.

Diode Bounding: A form of Bounding in which the nonlinear conducting properties of a diode (or diodes) are used to accomplish the magnitude-limiting action.

DC Beta: The DC current gain of a transistor, the ratio of the collector current to the base current that caused it, measured at constant collector to emitter voltage.

Drift: A gradually-developing deviation in any voltage, current or impedance. For an Operational Amplifier, a gradually-developing change in the offset voltage or in either of the offset currents. Also, the bottommost frequency range of the noise spectrum.

Electrometer Amplifier: An Amplifier circuit having sufficiently low-current drift and other noise components, sufficiently low amplifier input-current offsets, and adequate r-f power and current sensitivities to be usable for measuring current variations considerably less than $10^{-13}$ A.

Emitter-Follower: In principle, a single-transistor amplifier in which the load is connected between the emitter and signal ground, so that the base-to-emitter-to-ground path (for the input signal) contains 100% negative feedback of the output voltage. The collector is returned (in principle) directly to the power supply. The gain is very nearly unity and the output signal is not inverted (i.e., it "follows" the input).

Error-Factor, Finite-Gain: That factor by which the "ideal" closed-loop response expression must be multiplied to yield the response for an amplifier with finite gain, $A$, rather than infinite gain, as is assumed in computing the "ideal" response.

Fault Current: The current that may flow in any part of a circuit or amplifier under (specified) abnormal conditions.

Follower-Without-A: A Follower (which see) in which only a part of the output voltage is fed back in series opposition to the input signal...hence, closed-loop gain greater than unity is obtained over the rated range of operation.

Feedback Circuit: A causal circuit configuration in which (for the simplest circuit) the input and the output variables are combined and together determine the output.

Flicker: Noise in an amplifier, of higher frequency than drift, but lower than power-line or chopper-drive frequency noise. Also called "jitter" or "wobble."

Followers: A circuit in which the output of a high-gain amplifier is fed directly back to its negative input. The input signal is reproduced without polarity reversal. See also Emitter Follower, and Follower with Gain.

Flip-Flop: See Multivibrator, Bistable.

Frequency, Angular: The rate of change of the angle of a sine wave, expressed in radians per second, where $2\pi$ radians (360°) = 1 alternation (cycle).

Frequency, Break: In a plot of log gain (attenuation) vs. log frequency, the frequency at which the asymptotes of two adjacent linear slope segments meet.

Gain-Bandwidth Product: (1) The product of a specific frequency and the gain of a circuit, amplifier, or system at that frequency.

(2) For an Operational Amplifier, or any other circuit or device having the special property that its gain is inversely proportional to frequency, the G. B. P. is equal to the frequency at which the gain falls (by extrapolation) to unity.

Gain, Closed-Loop: The response of a feedback circuit to a voltage inserted in series with the amplifier input. Also the "noise gain."

Gain, Loop: In an Operational Amplifier circuit, the product of the transfer characteristics of all of the elements (active or passive) encountered in a complete trip around the loop, starting at any point and returning to that point.

Gain, Open Loop: The ratio of the (loaded) output of an Amplifier to its net input, at any frequency. Usually implies voltage gain.

Gate, Precision: A circuit that may be switched from closed-to-open-circuit or vice versa without error (time, bias, impedance) in response to a command signal (voltage or current).
Ground, Chassis: The potential (assumed uniform) of the (metallic) structure on or in which the circuit is built.

Ground, Power-Common: The potential of the terminal or circuit point to which the output of a power supply (and often an amplifier output load) is returned (i.e., power-supply "zero").

Ground, Signal (or High-Quality): The potential of a terminal or circuit point to which all signal voltages are referenced, by convention or arbitrary assumption. Usually the signal-return of the lowest-level signal in a system.

“Hold” Mode: In integrators or other charge-storage circuits, a condition (or time-interval) in which input(s) are removed and the circuit is commanded (or expected) to maintain constant output.

Hysteresis: A form of non-linearity in which the response of a circuit to a particular set of input conditions depends, not only on the instantaneous values of those conditions, but also on the immediate past (recent history) of the input and output signals. Hysteresis behaviour is characterized by inability to "retrace" exactly on the reverse swing a particular locus of input/output conditions.

Idling Current: The zero-signal power supply current drawn by a circuit, or by a complete amplifier. Also called "Quiescent" current.

Impedance, Input, Common-Mode: The (internal) impedance between either one of the input terminals of a differential Operational Amplifier and signal ground.

Impedance, Input, Differential: The (internal) impedance observed between the input terminals of an Operational Amplifier.

Impedance, Negative: In general, the driving-point impedance of circuit in which a current increase produces a voltage decrease (and vice versa); for a negative admittance, a voltage increase produces a current decrease, and vice versa.

Integrator: A circuit having a response (output) proportional to the time-integral of one or more input signals.

Inverter, Voltage: A circuit having a response (output) proportional to a constant (the gain) times the input signal, but opposite in sign to it. In a unity-gain inverter, the output is (−1) times the input.

Lag: (noun) a delayed-response characteristic, or a circuit having such a delayed response. Usually 1st-order lag is implied unless otherwise specified.

(verb) to respond to a stimulus in delayed fashion.

Lag-Lead (lead-lag): A circuit whose response includes lag components and their derivatives.

Leakage: (Unwanted) current flow through a nominally-blocked (non-conducting) circuit or circuit element due to imperfections in its blocking behavior.

Limits: (See Bounds)

Memory, Peak or Valley Readout: A circuit in which the output remains at the condition corresponding to the most positive (least negative) or vice versa input signal since the circuit was set to initial conditions, until reset to those conditions.

Multiplier, Quarter-Square: A circuit that achieves true four-quadrant multiplication by taking advantage of the mathematical relationship that the product of two variables is equal to one quarter of the difference of the squares of the sum and the difference of the variables.

Multiplier, Astable (free-running): A circuit having two momentarily stable states, between which it continuously alternates, remaining in each for a period controlled by the circuit parameters, and switching rapidly from one to the other.

Multiplier, Bistable (Flip-Flop): A circuit having two stable states, in either one of which it will stay indefinitely, until triggered appropriately, immediately after which it switches to the other state.

Multiplier, Monostable (one-shot): A circuit having only one stable state, from which it can be triggered to change state, but only for a predetermined interval, after which it returns to the original state.

Noise, Amplifier: All spurious or unwanted signals, random or otherwise, that can be observed in a completely isolated amplifier in the absence of a genuine input signal. (See also: Drift and Flicker.)

Null Detector: A comparator (which see) having zero reference voltage. A graded-null detector has decreasing sensitivity away from the null.

Offset Current: A DC error current appearing at either input terminal of a DC amplifier.

Offset Voltage: A DC error voltage appearing in series with either input terminal of a DC amplifier.

Offset, End-Resistance: In potentiometers, the residual resistance between a terminal and the moving contact, at a position corresponding to full rotation against that terminal.

Passive Network: A network whose net influx (or efflux) of available energy is stored or dissipated within the network. There may be no sources of energy other than those explicitly bookkept as inputs.

Phase Characteristic: A graph of phase shift vs. frequency, assuming sinusoidal input and output.

Phase Shift: Phase angle between two related variables in a circuit (usually input and output voltage) when excited by sinusoidal signal(s).

Rate Limiting: Non-linear behavior in an amplifier due to its limited ability to produce large, rapid changes in output voltage (slew)—restricting it to rates of change of voltage lower than might be predicted by observing the small-signal frequency response.

Reset Mode (Set Mode): In integrators, memories, or other charge-storage circuits, a state (or time-interval) in which the circuit is forced to return to a set of initial conditions and time dependent on the conditions of its previous condition.

RMS Value: The square root of the time average of the square of a variable signal.

Roll-Off: The decrease in magnitude of gain with frequency. Typical roll-off (low-pass) of a circuit for which the dominant lag is first-order is 6 dB per octave (increasingly proportional to frequency). "Steepest" roll-off might be at 12 or 18 dB per octave (proportional to the inverse square or cube of frequency) or more.

Saturation Voltage: Generally, the voltage excursion at which a circuit saturates. . . . i.e., is unable to respond to excitation in a proportional manner. In Operational Amplifiers, the output-voltage saturation limits may be imposed by any stage, from the input to the output, depending in part on the external loading and feedback parameters.

Sealing: Adjusting the coefficient of a circuit to each of its one or more input signal terminals. The relative sealing (of one input to another) is called "weighting." In computing, relating problem variables to machine variables.

Slew Rate: See Rate Limiting.

Soakage: The disability of a capacitor to come up to voltage instantaneously, without voltage lag or creep, during or after charging. The lower the soakage, the lower the lag and creep.

Stabilizer: (DC) A circuit that uses a chopper and preamplifier to maintain the net offset near zero at the input terminals of an Operational Amplifier. (See Chopper-Stabilized Amplifier.)

(Dynamic) An element or circuit employed to promote dynamic stability, also damper.

Subtractor: An Operational Amplifier circuit in which the output is proportional to the difference between its two input voltages (or between the net sums of its positive and negative inputs).

Time Interval: The definite integral of a variable over an interval of time. Also the area under a curve of a function of time during that period. Divide it by the time interval to obtain the average value of the argument over that period.

Track-Hold Memory: A circuit that, in its "track" mode, develops an output that follows (ideally) the input exactly, or is proportional to it; and then, in its "hold" mode, maintains the output constant (ideally) at the value it had at the instant the circuit was commanded to change from "track" to "hold."

Transconductor: A device that produces a current at a given point in the circuit (usually an amplifier's summing point) as a function of a voltage or voltages, usually at its input or output.

Transdiode: A transistor so connected that base and collector are actively maintained at equal potentials, though not connected together. The logarithmic transfer relationship between collector current and base-emitter voltage very closely approximates that of an ideal diode.

Uncertainty, Input: In an Operational Amplifier, the algebraic sum of all the factors, including environmental and inherent error sources, that contribute to the non-ideal behavior of the input circuit. See Sections 1.7–14.

Weighting: See Sealing.
NOTE: This list includes terms used more or less frequently throughout the preceding pages, some of them in special senses. It omits familiar conventional symbols such as A (amperes), Hz (cycles/sec), \( \pi \) (3.1416), and \( \Omega \) (ohms). Specific references, where given, are to modules where the symbol is first, or characteristically, used. Such physical quantities as voltage, current, etc., are described by lower-case symbols when circuit variables, upper case when constants or magnitudes.

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>TERM</th>
<th>UNITS</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gain</td>
<td></td>
<td>Operational Amplifier open-loop voltage gain</td>
</tr>
<tr>
<td>A&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Gain</td>
<td></td>
<td>Same, at DC</td>
</tr>
<tr>
<td>B</td>
<td>Booster Amplifier Normalized Bandwidth Bias Supply</td>
<td>Hz (cps) Radians/sec</td>
<td>See I.8</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance, capacitor</td>
<td>Farads</td>
<td>Often with identifying subscripts e.g. ( C_{b1}, C_1 )</td>
</tr>
<tr>
<td>C&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Compensating capacitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Capacitance of load, or capacitor that is part of load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;ST&lt;/sub&gt;</td>
<td>Stray capacitance (general); capacitance from negative summing point to common</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CME</td>
<td>Common-mode error</td>
<td>Volts</td>
<td>The effective offset voltage appearing between the amplifier input terminals as a consequence of the voltage level of the positive input (Common-mode voltage)</td>
</tr>
<tr>
<td>CMRR</td>
<td>Common-mode rejection ratio</td>
<td></td>
<td>The logarithmic form of CMRR. ( CMR = 20 \log_{10} CMRR )</td>
</tr>
<tr>
<td>CMR</td>
<td>Decibels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMV</td>
<td>Common-mode voltage</td>
<td>Volts</td>
<td>See Nomenclature</td>
</tr>
<tr>
<td>D</td>
<td>Diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Voltage</td>
<td>Volts</td>
<td>DC reference voltage level, or effective reference voltage level</td>
</tr>
<tr>
<td>E&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Power supply or zener diode breakdown voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Power supply or battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;b0&lt;/sub&gt;</td>
<td>Battery terminal voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;in&lt;/sub&gt;</td>
<td>DC input signal level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;n&lt;/sub&gt;, E&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Voltage, constant</td>
<td>Volts</td>
<td>DC null (or error) voltage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>TERM</th>
<th>UNITS</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>E&lt;sub&gt;R&lt;/sub&gt;</td>
<td>Generally, the voltage across a resistor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;i&lt;/sub&gt;, E&lt;sub&gt;REF&lt;/sub&gt;</td>
<td>Reference or bias</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;RESET&lt;/sub&gt;</td>
<td>Level at which an initial condition is set</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Generally, the reference level around which a signal varies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Voltage across a Zener diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>Signal voltage</td>
<td>Volts</td>
<td>Output of operational circuit. Rarely ( e_0 ) (never ( e_i )) in Philbrick Literature</td>
</tr>
<tr>
<td>e&lt;sub&gt;0&lt;/sub&gt;, e&lt;sub&gt;i&lt;/sub&gt;, e&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Input signal, also ( e_{in}, e_s )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;A&lt;/sub&gt;, e&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Signal voltages at points A and B in a circuit (to ground)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Signal generator output voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;1&lt;/sub&gt;, e&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Two signal voltages in a numbered series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;1&lt;/sub&gt;</td>
<td>AC signal voltage introduced by power line coupling to or from ground (see I.28)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Noise voltage source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Null voltage of an Operational Amplifier (error voltage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
<td>Hertz (cps)</td>
<td>The frequency at which amplifier open-loop gain is unity gain-bandwidth product product (see also ( f_H ))</td>
</tr>
<tr>
<td>f&lt;sub&gt;H&lt;/sub&gt;</td>
<td>Frequency, high</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Conductance</td>
<td>mho, ( \Omega )</td>
<td>Signal ground; reference for lowest-level signal in the system (as opposed to chassis ground, earth, or power common)</td>
</tr>
<tr>
<td>HQG</td>
<td>High Quality Ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>DC current</td>
<td>Ampere</td>
<td></td>
</tr>
<tr>
<td>SYMBOL</td>
<td>TERM</td>
<td>UNITS</td>
<td>EXPLANATION</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>$I_A, I_B$</td>
<td>Bias or reference current into or out of amplifier input terminal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_o$</td>
<td>Offset current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_{oa}, I_{ob}$</td>
<td>Offset currents associated with amplifier input terminals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_s$</td>
<td>Current (Amperes)</td>
<td></td>
<td>Idling current or steady-state component of current</td>
</tr>
<tr>
<td>$i_D$</td>
<td>Diode current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_n$</td>
<td>Input current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_L$</td>
<td>Load current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_M, I_M$</td>
<td>Meter current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_{oa}, x_{ob}$</td>
<td>Noise current associated with amplifier input terminals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_s$</td>
<td>Signal current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$j$</td>
<td>Imaginary term operator in a complex expression (mathematical &quot;i&quot;)</td>
<td>$\sqrt{-1}$</td>
<td></td>
</tr>
<tr>
<td>$K, k$</td>
<td>Arbitrary constants (Often with subscripts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann's Constant $\text{Joule/degree K}$</td>
<td>$1.38054 \times 10^{-23}$</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td>Meter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Potentiometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td>Heaviside operator $\text{sec}^{-1}$</td>
<td>$dy dt \frac{dy}{p} = \int y dt$</td>
<td>Of a circuit or component; specifically the ratio of energy storage to energy dissipation therein. ($Q = \frac{1}{2} C V^2$). Also, charge (i.e., on a capacitor) (coulombs)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Quality factor</td>
<td></td>
<td>For example, charge of an electron</td>
</tr>
<tr>
<td>$q$</td>
<td>Charge $\text{Coulomb}$</td>
<td></td>
<td>Usually with identifying subscripts</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistance, resistor $\text{ohms} \ \Omega$</td>
<td></td>
<td>Input resistance, terminal A to terminal B</td>
</tr>
<tr>
<td>$R_{AB}$</td>
<td>Input resistance, terminal A to terminal B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{AB}$</td>
<td>Input resistance, terminal A to terminal B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m$</td>
<td>Base-emitter resistance of a transistor (sometimes $r_e$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_i$</td>
<td>Internal resistance of an Operational Amplifier output circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{vn}$</td>
<td>Input circuit resistance or resistor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_L$</td>
<td>Resistive component of load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m$</td>
<td>Meter resistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_s$</td>
<td>Source resistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{STD}$</td>
<td>Standard (or reference) resistance or resistor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_e$</td>
<td>Unknown resistor or resistor to be measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>Switch</td>
<td></td>
<td>Degrees K</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature</td>
<td></td>
<td>Seconds</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Voltmeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_e, V_i$</td>
<td>Offset voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{AB}$</td>
<td>Offset voltage between amplifier input terminals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_a$</td>
<td>Junction voltage drop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_f, v_f$</td>
<td>Diode forward drop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_c$</td>
<td>Capacitive reactance</td>
<td>ohms $\Omega$</td>
<td>The inverse of impedance, $Y = G + jB$ (for continuous sine waves)</td>
</tr>
<tr>
<td>$Z$</td>
<td>Impedance</td>
<td>ohms $\Omega$</td>
<td>$Z = R + jX$ (for continuous sine waves)</td>
</tr>
<tr>
<td>$Z_A, Z_B$</td>
<td>Input impedance, terminal A to ground, terminal B to ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{AB}$</td>
<td>Input impedance, terminal A to terminal B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{AB}, Z_{BD}$</td>
<td>Input impedance to ground, same as $Z_A, Z_B$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_f, Z_I$</td>
<td>Generally, feedback impedance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{in}$</td>
<td>Generally, input impedance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_L$</td>
<td>Load impedance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{REF}$</td>
<td>Reference impedance or $Z_{STD}$</td>
<td></td>
<td>Standard impedance</td>
</tr>
<tr>
<td>$Z_{oA}$</td>
<td>Impedance at $\omega_s$ i.e., at center frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Noise components, resistance ratio</td>
<td></td>
<td>Complex attenuation of feedback paths</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Feedback divider ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta e, \delta V$</td>
<td>Null or error voltage</td>
<td></td>
<td>Base of natural logarithms</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Base of natural logarithms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Phase angle</td>
<td>Degrees or radians</td>
<td>Leadership in feedback technology</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Phase, phase shift</td>
<td></td>
<td>Fractional rotation of $\alpha$ potentiometer or rheostat</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
<td>Radians/sec $= 2\pi f$</td>
<td>Also angle of phase shift</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>Critical frequency</td>
<td>Or cutoff frequency: $\omega_{pu}$ and $\omega_{pc}$ are upper and lower cutoff frequencies</td>
<td></td>
</tr>
<tr>
<td>$\omega_B$</td>
<td>Upper radian frequency</td>
<td>$2\pi f_h$ see $f_h$</td>
<td></td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Center frequency</td>
<td>$\omega_0 = \sqrt{\omega_{pu} \omega_{pc}}$</td>
<td></td>
</tr>
</tbody>
</table>
Following that list is one of articles and publications printed or reprinted by us in recent years and still available at no charge, arranged by subject. For a more comprehensive (though somewhat dated) list, see The Lightning Empirist, Volume 12, Number 2, April, 1964. Admittedly, even these are but a drop in the ocean of literature that has been and (especially) is yet to be written on this subject.

For those who would dig even more deeply, we suggest reference to the applications publications of companies that manufacture analog products. Readers of this Publication are of course invited to keep up to date via the Philbrick mailing list. Among these, one should consider the continuing evolution of our own Applications Briefs, The Lightning Empirist, new reprints, technical data, and catalog documentation. We also recommend to our readers the splendid service, now performed by Simulation Councils, Inc., of La Jolla, California, in their journal, Simulation, entitled "Simulation Survey and Literature Review," formerly published at the Georgia Institute of Technology as Analog Computers Literature Review, by Mr. L. W. Ross.

**BOOKS**

**Analog Computation**
- Jackson
- Rogers & Connolly
- Karplus
- James, Smith, & Wolford
- Effer
- Eterman
- Fifer
- McGraw-Hill
- McGraw-Hill
- McGraw-Hill
- International Textbook Company
- McGraw-Hill
- Pergamon Press

**Analog Computing in Engineering Design**
- McGraw-Hill

**Analog Simulation**
- McGraw-Hill

**Analog and Digital Computer Methods in Engineering Analysis**
- Fifer
- Eterman
- McGraw-Hill

**Analog Computation (4 Vols.)**
- Effer
- Eterman

**Analog Computation (Translated from the Russian)**
- Effer
- Eterman
- McGraw-Hill

**Analog Computing at Ultra High Speed Computer Handbook**
- MacKay & Fisher
- Huskey & Korn
- Hall
- Howe
- Korn & Korn
- Malmstadt, Enke, & Toren
- McGraw-Hill
- McGraw-Hill
- Pergamon Press
- D. Van Nostrand Co.
- W. A. Benjamin, Inc.

**Computers in Education**
- Grabbe, Ramo, Wiley
- Woudridge (Editors)

**Design Fundamentals of Analog Computer Components**
- Grabbe, Ramo, Wiley

**Electronic Analog and Hybrid Computers**
- Tomovic & Karplus

**Electronics for Scientists**
- Ashley
- Warfield

**Experiments in Electronics**
- Harris
- Murray
- Paynter

**Generalized Instrumentation for Research and Teaching**
- Ayer

**Handbook of Computers and Control**
- Grabbe, Ramo, Wiley

**High Speed Analog Computers**
- Grabbe, Ramo, Wiley

**Introduction to Analog Computation**
- Grabbe, Ramo, Wiley

**Introduction to Electronic Analog Computers**
- Grabbe, Ramo, Wiley

**Introduction to Feedback Systems**
- Grabbe, Ramo, Wiley

**Mathematical Machines (Vol. 2)**
- Grabbe, Ramo, Wiley

**A Palimpsest on the Electronic Analog Art**
- Grabbe, Ramo, Wiley

**Ernst R. Oldenbourg, Munich**
- Prentice-Hall

**Evans Morrison**
- Washington State U. Press (reprinted by and available gratis from Philbrick Researches)

**REPRINTS & ARTICLES**

**I. APPLICATIONS**

**A. Bio-Medical Analysis**

"Analog Computation of Respiratory Response Curve" T. W. Murphy, Memorial Sloan-Kettering Cancer Center, and R. Crane, Electronic Gear, Inc. (Reprint No. 41)

"A New Instrument For The Summation Of Evoked Responses From The Nervous System" Burton S. Rosner, Ph.D., Truett Allison, M.A., Elliot Swanson, B.S.E.E., and William R. Goff, Ph.D., West Haven Veterans Administration Hospital, Yale University School of Medicine, and Ampex Corporation. (Reprint No. 37)

"Respiratory Carbon Dioxide Response Curve Computer" J. Weldon Bellville, Sloan-Kettering Institute, and J. C. Seed, Wellcome Research Laboratory. (Reprint No. 26)

"B. Computers"


"Automatic Digital Setup and Scaling of Analog Computers" Dr. Henry M. Paynter, Massachusetts Institute of Technology, and Julian Suez, International Business Machines Corporation. (Reprint No. 47)

"Intentionally Unconventional Analoguely " The Lightning Empirist (XI:1).

"Matrix Programming Of Electronic Analog Computers" R. E. Horn, Westinghouse Electric Corporation, and P. M. Honnell, Washington University. (Reprint No. 2)

"Modern Analog Computing Machines" G. A. Philbrick, Philbrick Researches, Inc.

"A New Active-Passive Network Simulator For Transient Field Problems" Walter J. Karplus, Dept. of Engineering, University of California. (Reprint No. 31)

"Precision Analog Memory Has Extended Frequency Response" T. A. Brubaker, Dept. of Electrical Engineering, University of Arizona. (Reprint No. 36)

"A Report To Engineer And Management" George A. Philbrick Researches, Inc. (Reprint No. 24)

"Ordering and Selection Processes and Ultra-Reliable Systems" H. M. Paynter, Massachusetts Institute of Technology.


**C. Industrial Process Analysis**

"Operational Amplifier Techniques in Process Control" Dr. Peter D. Hansen, Philbrick Researches, Inc. (Reprint No. 45)
II. CIRCUIT TECHNIQUES

A. Computer Techniques

"A Circuit With Logarithmic Transfer Response Over 9 Decades" J. F. Gibbons and H. S. Horn, Stanford University. (Reprint No. 49)

"Multiplication and Logarithmic Conversion By Operational Amplifier-Transistor Circuits" William L. Pateron, Litton Industries. (Reprint No. 46)

"New Integrating Circuit and Electronic Analog for Transient Diffusion and Flow" J. Ross MacDonald, Texas Instruments, Inc. (Reprint No. 14)

"Q3-MIP Multiplier" The Lightning Empiricist (XI:3:4).

"Rate-of-Change Indicator" The Lightning Empiricist (XI:4).

B. Fundamental Circuit Techniques

"Analogue Methods" Bruce Seddon, Philbrick Researches, Inc. (Reprint No. 27)

"Analogue Computer Techniques Applied To Industrial Instrumentation and Control" George A. Philbrick Researches, Inc. (Reprint No. 18)

"Operation Of The USA-3 Amplifier With Positive Open-Loop Polarity" Philbrick Researches, Inc. Application Brief.

"FP65 As Amplifier With High Input Impedance" Philbrick Researches, Inc. Application Brief.


"Stabilized Follower Amplifier" Prof. Donald Deford, Northwestern University. (Reprint No. 23)

"Typical Operational Amplifier Applications" D. H. Sheingold, Philbrick Researches, Inc.

C. Voltage/Current Regulation

"Analogue Computer Reference Supply" C. E. Foiles, J. P. Hartmann, and H. Koerner, University of Arizona. (Reprint No. 21)

"High Precision Large Current Regulator" K. C. Brog and F. J. Milford, Case Institute of Technology. (Reprint No. 32)

"Operational Amplifier As Constant Current Source—1" Philbrick Researches, Inc. Application Brief.

"Use Of Operational Amplifiers In Precision Current Regulators And Use Of Operational Amplifiers In Accelerator Beam Control Systems" Karl Eklund, Columbia University. (Reprint No. 22)
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Philbrick and Nexus, world leaders in electronic analog computing equipment, combine to offer you the best in modern technology and the highest product integrity in the industry. Philbrick/Nexus Research, a Teledyne Company, brings to the analog instrumentation field unequalled capabilities in design, development and production of analog components, modules, instruments and systems. Philbrick/Nexus also exhibits unusual all-around abilities in the area of electronic circuitry and hardware.

Philbrick/Nexus can fill your needs for anything analog from the industry’s broadest range of analog products — ranging from simple operational amplifiers to the most sophisticated analog systems. Philbrick/Nexus’ 26 years of combined experience offer you the advanced-technology of the pioneer and the vitality of the customer-oriented organization dedicated to producing the answers to any of your unsolved problems. For prompt, competent applications, engineering assistance or advice, call your local Philbrick/Nexus field-engineering representative listed below or write, Philbrick/Nexus Research, Allied Drive at Route 128, Dedham, Massachusetts 02026.
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DISCRETE-COMPONENT OPERATIONAL AMPLIFIERS
High-gain, low-gain, low-drift amplifiers for stable feedback loops. Provide precise, predictable operations on one or more input signals. Available in a wide variety of economy or premium grades (FET's, universal, wideband, high-voltage, general purpose) in plug-in or wire-in modules in every package style.

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Micro-Hybrids combine linear monolithic chip and discrete microminiature component technologies to offer immunity to overloads, shorts and supply voltage stresses. Other types available include monolithic thin-film in TO-5 and dual in-line packages and hybrid thick-film operational amplifiers.

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Ideal where drift and offset must be held over long operating periods through wide ambient temperature fluctuations. A wide variety of chopper-stabilized and parametric types are available.

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Compound-regulated, stable, noise-free power supplies designed to meet the needs of high-performance, low-level analog systems. Rack, cabinet, modular, plug-in or built-in models available. Voltage regulators and high powered booster amplifiers are also available.

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Analog systems components for linearizing or performing non-linear functions. Available in natural continuous function or straight-line approximation types. Non-linear function modules include networks that accurately exhibit logarithmic, trigonometric and quadratic behavior.

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Modular components for implementing both analog and hybrid computers, simulators and analyzers include: arbitrary function fillers, universal linear operators, multiplier-dividers and mixers. Modular front panels, chassis adaptors and accessories combine all modules into compact units.

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All-in-one self-powered analog instruments that virtually eliminate wiring problems. They simplify experimenting, simulation and instruction in the practical application of feedback techniques.

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Philbrick/Nexus Research welcomes opportunities to help you apply analog techniques and products in such areas as industrial and scientific instrumentation, process and quality control systems and in-line analog data processing. Customer services of Philbrick/Nexus include: applications engineering, technical bulletins, applications manuals, the "Lightning Empiricist," and factory or on-site application seminars.

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TAIWAN
INDUSTRIAL ELECTRONICS
Taipei — Tel: 74287
### Class I: Natural Function Logarithmic Transconductors

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Fundamental e-i Relationship and Operating Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL1-N/P</td>
<td>Dual Element, connectable as diodes, transdiodes, or transistors; uncommitted to interconnections.</td>
<td>$e = E_e \log \frac{i}{I_0} \approx 60 \text{ mV/decade of } i$</td>
</tr>
<tr>
<td>PPL1-N/P</td>
<td>Quad Element, transdiode-connected, with all four bases connected together, and brought out on one terminal.</td>
<td>$e = E_e \log \left( \frac{i}{I_0} \right) \beta &lt; i &lt; 1 \text{ mA (9 decades)}$</td>
</tr>
<tr>
<td>PL2-N/P</td>
<td>Quad Element, diode-connected; uncommitted to polarity or interconnections.</td>
<td>$e = E_0 \log \frac{i}{I_0} \beta + 1 \quad 1 \text{ pA} &lt; i &lt; 1 \text{ mA (6 decades)}$</td>
</tr>
<tr>
<td>PPL2-N/P</td>
<td>Temperature-Compensated Transconductor: transistor connected log element, plus integral current-error and voltage-error compensation.</td>
<td>$e = E_R \log \frac{i}{I_R} \quad \text{where } E_R \text{ is selectable between } 0.3 \text{ V and } 2 \text{ V. Nominal value of } I_R = 10^{-4} \text{A.}$</td>
</tr>
<tr>
<td>PPL4-N/P</td>
<td>Same as PPL4 plus gain and reference current controls.</td>
<td>$10 \text{ nA} &lt; i &lt; 100 \text{ µA (4 decades)}$</td>
</tr>
<tr>
<td>SPL4-N/P</td>
<td>Log-of-Ratio Transconductor: a pair of transistors as basic log elements, plus dual-purpose current-pump / scaling amplifier. Requires external activating amplifier.</td>
<td>$e = -nE_0 \log \left( \frac{e_3}{e_1} \right)$ or $e = e_2 \cdot 10 \left( \frac{e_1}{nE_0} \right)$ $-10 \text{ V} &lt; e &lt; 10 \text{ V}$ $10 \mu V &lt; e_1, e_2 &lt; 10 \text{ V}$</td>
</tr>
</tbody>
</table>

### Class II: Straight-Line Approximation Transconductors

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPLOG-N/P</td>
<td>Logarithmic Transconductor</td>
<td>$-i = 5 \cdot 10^{-(c/5) \mu A} \quad 50 \text{ nA} &lt; i &lt; 500 \text{ µA (4 decades)}$</td>
</tr>
<tr>
<td>PSQ-N/P</td>
<td>Quadratic Transconductor with two inputs and built-in lower (I) or upper (U) input voltage selector respectively.</td>
<td>$i_{(mA)} = 0.5 \left[ \frac{\Omega (e_1, e_2, 0)}{10 \text{ V}} \right] \quad \text{or } i_{(mA)} = 0.5 \left[ \frac{U (e_1, e_2, 0)}{10 \text{ V}} \right]$ $-10 \text{ V} &lt; e_1, e_2 &lt; +10 \text{ V}$</td>
</tr>
<tr>
<td>SPSIN-N/P</td>
<td>Trigonometric Transconductor</td>
<td>$i_{(mA)} = 0.5 \sin e \frac{\pi}{18}$ $-10 \text{ V} &lt; e &lt; +10 \text{ V}$</td>
</tr>
<tr>
<td>SPCOS-N/P</td>
<td>Trigonometric Transconductor</td>
<td>$i_{(mA)} = 0.5 \cos e \frac{\pi}{18}$ $-10 \text{ V} &lt; e &lt; +10 \text{ V}$</td>
</tr>
<tr>
<td>SPFX-N/P</td>
<td>Arbitary Function Transconductor: 10 break points at 0.5, 1.5, ...9.5 V. Slopes screwdriver adjustable.</td>
<td>$i = f(e)$ $-10 \text{ V} &lt; e &lt; 0$ or $0 &lt; e &lt; 10 \text{ V}$</td>
</tr>
</tbody>
</table>

### Class III: Multiplier-Divider Transconductor

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPM1</td>
<td>Multiplier-Divider (Triangular Wave Bounding principle) when used with external Operational Amplifier. Nominal accuracy 1%.</td>
<td>$-10 \text{ V} &lt; e_1, e_2 &lt; 10 \text{ V}$ $0 &lt; e_3 &lt; 10 \text{ V}$</td>
</tr>
</tbody>
</table>