I.1 OPERATIONAL AMPLIFIERS. An amplifier that activates a passive Network to form an active Analog is called an Operational Amplifier. It is this amplifier that enforces the Null in the Network, and allows the Network to impart to the performance of the combined circuit its own (passive) parameters.

Practical Operational Amplifiers are characterized by extremely high "DC" (static) and low-frequency gain, so that the input (or "error") signal required for full output is generally negligible, both in current and in voltage. General-purpose Operational Amplifiers are also characterized by low closed-loop output impedance, and by a fairly uniform roll-off in gain with frequency over many decades. As we shall see, this "linear" roll-off characteristic gives the operational amplifier its *universality*—the ability to accept feedback from a wide variety of feedback networks with excellent dynamic stability.

I.1

EDITOR'S NOTE

A Dictionary of Nomenclature and Symbology will be found on pp. 106-9. A glance at it now, and occasional references to it in times of stress, might speed the reader's progress through these pages.

I.2 ELECTRONIC AMPLIFIERS. Both vacuum-tube and solid-state Operational Amplifiers are in wide use, although the number of solid-state units has already exceeded the number of vacuum-tube units still in service. Without in any way detracting from the glorious record established by Philbrick vacuum-tube amplifiers, it is manifest that modern solid-state circuits have by now almost eclipsed that radiance. The day of the vacuum-tube Operational Amplifier may not be over, but it is Twilight . . .

Solid-state or Vacuum-tube, the Rules of the Game are immutable. Designing and manufacturing dependable yet economical Operational Amplifiers demands the greatest care—from circuit selection and component quality assurance to flawless workmanship under controlled conditions. If the "Solid-State Revolution" has changed any of the Rules, the effect has been to make Philbrick's depth of experience, design integrity, and vigilance even more important.

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1.38
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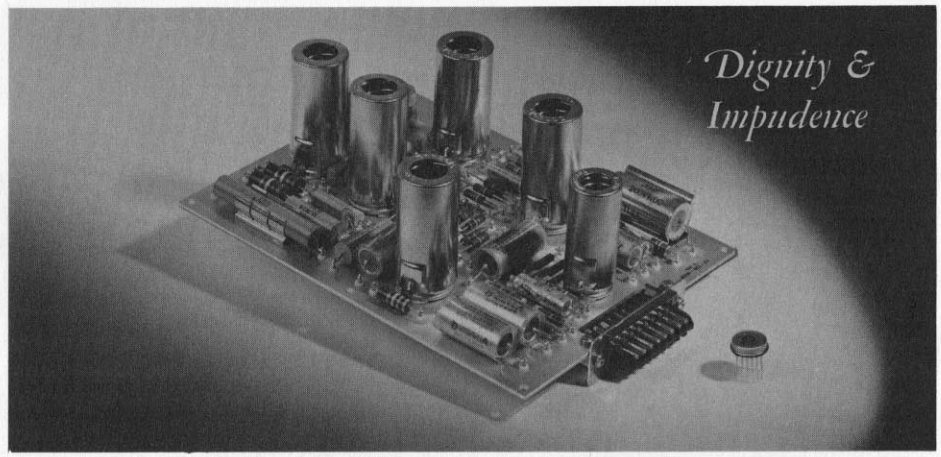
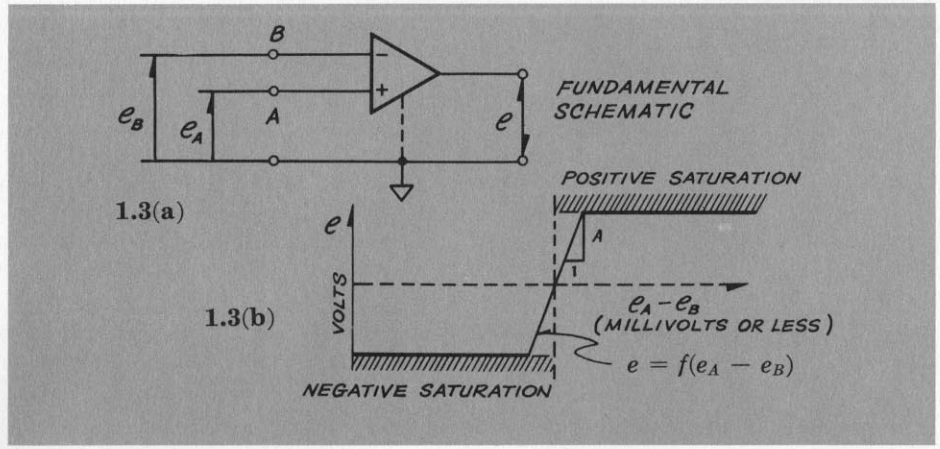


I.3 FUNCTIONAL DESCRIPTION OF AN AMPLIFIER. The schematic symbol of an Operational Amplifier, shown here, is a triangle that indicates the causal direction of signal flow. A ground reference is implied by the dashed lines. Almost all Philbrick Operational Amplifiers are provided with balanced inputs, "A" and "B", to which are applied the input signals, e_A and e_B.

The output, e, of an operational amplifier is related to its inputs by* $e = f(e_A - e_B)$ as indicated on the graph to the right. A useful output signal may be obtained by applying a minute signal $(e_A - e_B)$ between the input terminals; in fact, the amplifier output circuit can be saturated by a surprisingly small input. The slope of the non-saturated portion of the characteristics determines the DC gain, A.

*ignoring certain important error-factors, for which see I.7, I.18, and I.52.

I.3
1.4
1.7
to
1.18



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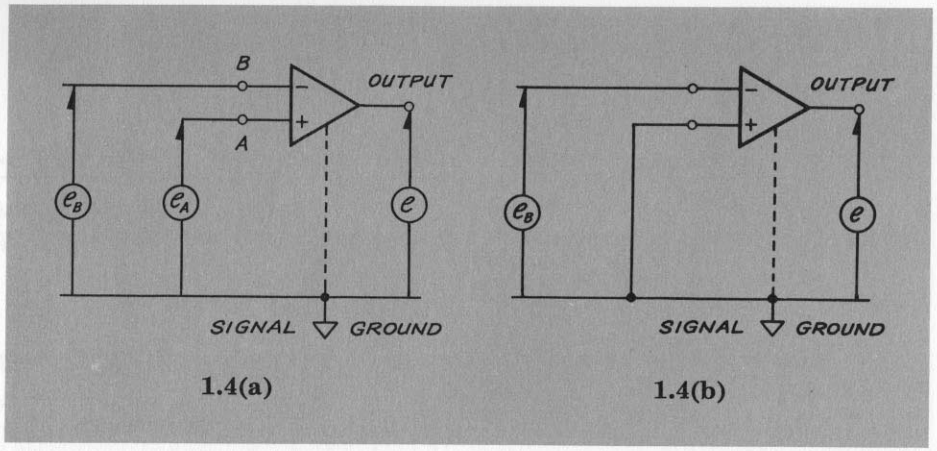
I.4 AMPLIFIER INPUT CONFIGURATIONS. Almost all Philbrick Operational Amplifiers provide balanced, differential inputs, as in (a), except for certain chopper-stabilized types, which are single-ended, as in (b), requiring grounding of the (+) terminal. Ideally, the output of (a) is:

$$e = f(e_A - e_B) \tag{1-1}$$

so that the output is independent of the *magnitudes* of either e_A or e_B, but depends only upon their *difference*. For example, if $e_A = 10$ volts and $e_B = 10.002$ volts, then the *effective* input is -2 millivolts, just as if $e_B = 0.002$ volts, and e_A were zero. Calling 10 volts the "*common-mode voltage*," or CMV, an ideal differential amplifier would reject the common 10 volts, responding *only* to the 2 mv difference. In practice, e_A and e_B are hardly ever given *exactly* the same weight (see I.16 for discussion of common-mode error).



1.4(a) 1.4(b)

I.4
I.7
I.8
I.16
I.18

I.5 TWO EXEMPLARY CIRCUITS. The time has come to introduce a *circuit*. We are not quite ready for a completely *practical* circuit, but we may now consider an *idealized* application—a peg, if you will, on which to hang impending discussions of practical circuits.

Circuit (a) is the popular and useful "unity-gain inverter", in which the output is (ideally) equal to and opposite in sign from the input. We are here only concerned with *how it functions*, ideally.

The ideal amplifier has infinite gain and infinite input impedance, draws zero input current (i_S), has zero output impedance, zero propagation delay, and a completely passive input . . . that is, it does not *generate* signals. Pickup is zero, $R = R_1 = 10\text{k}\Omega$ exactly, the power supply furnishes perfectly-constant noise-free DC, adverse environmental influences are absent, the Lark's on the wing, etc.

Since i_S is zero, $i_1 = i_2$, by Kirchoff's Law, taken at the summing point. With infinite gain, no input signal, however small, would be tolerated by the feedback, so that $e_n = 0$, terminal A is at zero, and e_S is also zero. From the above, we may develop a "Response" equation:

$$i_1 = \frac{e_1}{R_1} = i_2 = \frac{-e}{R}$$

or

$$e = -e_1\left(\frac{R}{R_1}\right) \tag{1-2}$$

In Figure 1.5(a), we have assumed quite arbitrarily an input signal that varies with time (in an asymmetrical manner, for clarity) and have indicated, in three small graphs, the variations with time of e_1, e_S, and e. How sweetly simple is the ideal!

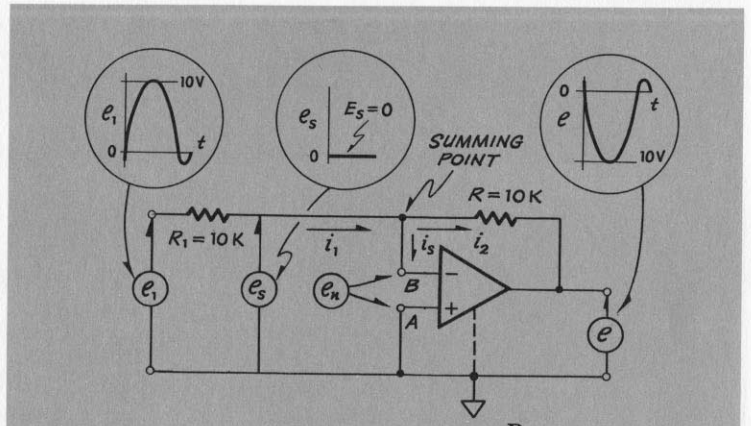
In circuit (b), we introduce a minor but important variation, in which a signal, E_r, is introduced into the positive terminal of the amplifier. Circuit (a) uses the amplifier in a single-ended manner; circuit (b) uses its differential configuration fully. By the way, we choose a battery for E_r for simplicity only. E_r could vary just as arbitrarily as e_1, without altering our analysis. The Response equation for (b), based on the same idealistic assumptions as for (a), is:

$$i_1 = \frac{e_1 - E_r}{R_1} = i_2 = \frac{E_r - e}{R}$$

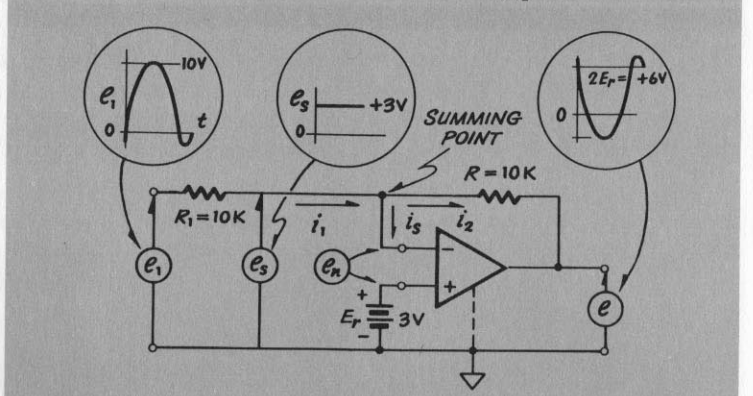
or, if $R = R_1$, $e = 2E_r - e_1$ (1-3)

We have assumed that e_n, often called the "null voltage", is zero, and that the gain infinite. Beginning with I.7, we shall face the facts: that the gain *is* finite, and that e_n is *not* zero, but is possibly appreciable, having the value $-e/A$.

To sum up: in (a), e_1 is perfectly reproduced, with inverted sign; in (b), we have linearly combined *two* signals, e_1 and E_r, in accordance with equation (1-3). Both circuits generate currents (i_2) precisely proportional to the difference of the input signals, if R_1 is linear.



1.5(a) Response: $e = -\frac{R}{R_1}e_1$



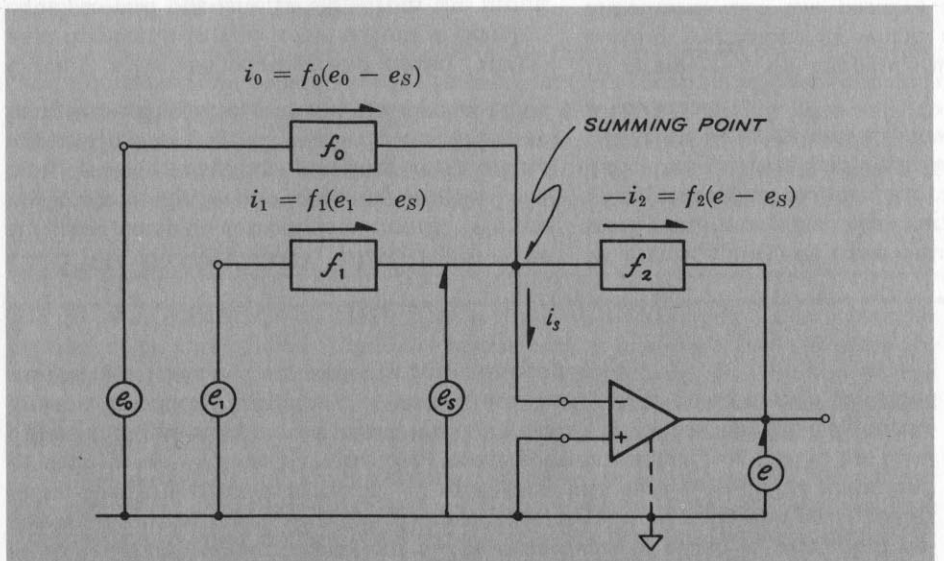
1.5(b) Response: $e = \left(1 + \frac{R}{R_1}\right)E_r - \frac{R}{R_1}e_1$

I.5
I.6
I.7
to
I.18
I.40
to
I.44
II.1

pages 10 & 11

I.6 GENERAL OBSERVATIONS ON IDEAL CIRCUIT PERFORMANCE. Since we shall, (like all philosophers) make frequent reference to the ideal when discussing the non-ideal, we have elected to use as the prototype of all ideal circuits a somewhat-generalized application circuit, not too far removed from the example just considered in 1.5(a). In this generalized circuit, e_0 and e_1 are applied to the summing point of an Operational Amplifier circuit through two-terminal* networks having the bifilar (linear or nonlinear) transfer properties described by f_0 and f_1. The output, e, is connected (fed) back through a Network having the transfer properties f_2, to the same point—a point at which, please note, a virtual *null* or zero potential with respect to ground is forced to exist by the feedback of the output voltage developed by the Operational Amplifier . . . thus effectively isolating the input networks from one another and from the output, despite their connection.

*For pedagogical simplicity.



$i_S = 0$ in ideal case

$e_S = 0$ in ideal case

1.6

Since an ideal case deserves an ideal amplifier, $i_S = 0$; therefore $i_0 + i_1 = i_2$, as before.

I.6 I.5 I.7 to I.18 I.40 to I.44

Now then—let us particularize as we did in I.5: assume that the gain of the amplifier is infinity for all frequencies of importance in the time-domain responses of f_0, f_1, and f_2 . . . to which frequency range we also restrict e_0 and e_1, and assume further that the circuit is stable.

If we now assign a form to f_0, f_1, and f_2 (not a *value*, but merely a *form*) by assuming that they are linear admittances given in operational form* by:

$$f_0 = \frac{1}{Z_0(p)}, \quad f_1 = \frac{1}{Z_1(p)}, \quad \text{and} \quad f_2 = \frac{1}{Z_2(p)}$$

$$i_0 = \frac{e_0 - e_S}{Z_0(p)}, \quad i_1 = \frac{e_1 - e_S}{Z_1(p)}, \quad \text{and} \quad -i_2 = \frac{e - e_S}{Z_2(p)}$$

we can derive a fundamental relationship between e and e_1:

$$\frac{e_0 - e_S}{Z_0(p)} + \frac{e_1 - e_S}{Z_1(p)} = \frac{e_S - e}{Z_2(p)}$$

which reduces, when e_S approaches zero (because of the high gain) to:

$$\frac{e_0}{Z_0(p)} + \frac{e_1}{Z_1(p)} = \frac{-e}{Z_2(p)}$$

$$\text{or} \quad -e = \frac{Z_2(p)}{Z_1(p)} e_1 + \frac{Z_2(p)}{Z_0(p)} e_0 \tag{1-4}$$

which relationship also depends upon two less obvious assumptions: that the amplifier is able to produce the necessary output current, including i_2, and that e is within its bounds.

Three additional fundamental relationships are already within our grasp:

$$i_0 = \frac{e_0}{Z_0(p)}, \quad i_1 = \frac{e_1}{Z_1(p)}, \quad \text{and} \quad i_2 = \frac{-e}{Z_2(p)} \tag{1-5}$$

demonstrating that each input current is constrained to depend *only* on the voltage applied to that input.

*The operator p is defined as follows:

$$y = \frac{dx}{dt} \equiv px$$

$$x = \int y\,dt = \frac{y}{p}$$

For sine waves, $x = X \sin \omega t$

$px = \omega X \cos \omega t$, and

$p^2x = -\omega^2 X \sin \omega t$

Hence, $p = \sqrt{-1}\,\omega \equiv j\omega$