Approximating the Universal Active Element

Hanspeter Schmid

***Abstract*—The classification of universal amplifiers presented in this paper places all operational amplifiers and current conveyors known from the literature into a common framework, together with abstract concepts such as the universal active element and the nullor. Our approach is new in that we base it on four-terminal theory, which results in a classification that is more extensive but not more complex than classifications derived using two-port theory. It turns out that our classification contains a new type of operational amplifier, which we call current-feedback operational transconductance amplifier (CFB OTA), and also a new class of voltage-inverting current conveyors. We then demonstrate that our classification is very closely related to integrated-amplifier design by showing how all operational amplifiers and current conveyors can be implemented in CMOS using only a few CMOS circuits. Since the basic ideas behind CMOS and bipolar circuits are very similar, this paper is not process specific and can be seen as an attempt to bridge the gap between amplifier theory and amplifier design that has become ever wider in the past few years.**

***Index Terms*—Amplifier classification, CMOS amplifiers, current conveyors, current-feedback OTA (CFB OTA), nullor, operational amplifier.**

I. Introduction

CIRCUIT simulators such as SPICE or Spectre process netlists, in which a circuit is described by elements such as resistors, capacitors, controlled sources, transistors, etc. There is much redundancy in the set of elements provided by circuit simulators, since many of them can also be expressed as sub-circuits containing other elements. The question is: *how much redundancy is there?* Tellegen discussed a minimum-sized set of elements in 1954 with which *any* linear and nonlinear driving-point impedance or transfer characteristic can be synthesized [1]. Surprisingly, all but one of the elements are passive. Only one active element is necessary, which we therefore call *the universal active element*. It is the pathological two-port whose input voltage and input current are both zero, irrespective of its output voltage and output current.

Zero input current and voltage is what an ideal operational amplifier (opamp) achieves if it is used in a stable feedback configuration. Thus, as we will show later, the opamp is a universal active element. This means that if a suitable set of linear and nonlinear passive elements is available, then no active elements other than opamps are needed to implement any linear (e.g., filter) or nonlinear (e.g., oscillator) circuit function, as has been demonstrated in several decades of opamp design practice. In this sense, the ideal opamp is *universally versatile*. In the following, we call an amplifier *universal* if its ideal form, i.e., the amplifier with ideal port impedances and ideal transfer functions, is a universal active element.

It is not difficult at all to find other universal active elements. For example, the current-feedback (CFB) opamp, the second-generation current conveyor (CCII−), and the operational transconductance amplifier (OTA) are all universal. Actually, so many universal active elements have been published that most IC designers and circuit theorists have long lost track of their development. This is a pity, since having many different universal active elements available is clearly advantageous: Synthesizing a circuit *function* on the system level with different amplifiers may result in *systems* with differing numbers of amplifiers and passive components. The properties of the systems, e.g., the sensitivity of system parameters to component value variations, may also come out differently. The number of *circuits* approximating the functions of the systems is even larger than the number of systems, since there are always many different ways of implementing a system: the universal active elements can be replaced by circuits approximating them, or sub-blocks of arbitrary complexity can be identified and replaced by circuits that approximately perform the same function. For example, when filters are synthesized using the ideal CCII−, it may happen that one CCII− forms an integrator together with one resistor and one capacitor. Then one can either replace the ideal CCII− by a circuit approximating its function, or one can replace all three elements by an integrator built using a different amplifier, e.g., by a Gm-C integrator containing one OTA and one capacitor. The result may then be the same that could be obtained by synthesizing the circuit function using OTAs in the first place.

One more problem for the circuit designer is that the same name, e.g., CCII−, is conventionally used both on the system level for a universal active element and on the circuit level for several different transistor circuits that approximate the ideal CCII−. Furthermore, it frequently happens that a circuit which can be used as an implementation of a certain universal active element is published under a different name. For example, the monolithic nullor in [2], the input stage of the CFB opamp in [3], and the transconductance amplifier or "ideal transistor" in [4] all approximate ideal current conveyors.

This situation is highly obscure and needs to be clarified. Especially the connection between universal active elements used on the system level and their implementation as integrated circuits needs to be addressed, both to help circuit designers with finding the best possible implementation of a system for a specific application and to help system designers who are looking for possible applications of a new integrated amplifier circuit. In order to achieve these goals, we introduce a new classification of universal active elements that provides a direct link be-

Manuscript received December 1999; revised May 2000. This paper was recommended by Associate Editor W. Serdijn.

H. Schmid is with the Signal and Information Processing Laboratory, Swiss Federal Institute of Technology, 8092 Zürich, Switzerland (e-mail: h.p.schmid@ieee.org).

Publisher Item Identifier S 1057-7130(00)09923-7.

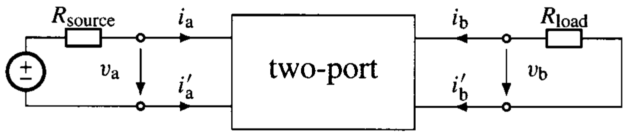

Fig. 1. Two-port configurations.

tween the highly abstract concept of *the* universal active element and integrated-circuit implementations. To provide this link, we will show that the abstract concept of the universal active element fundamentally differs from transistor implementations in two respects: First, the universal active element is defined by *two ports*, whereas the *four terminals* of a transistor circuit can be used independently. Second, the universal active element is defined by its *state*, whereas a transistor circuit implements *controlled sources*. In Section II, the step from two-ports to four-terminals is made. There are infinitely many universal four-terminals, but we will identify the two most widespread ones as the *nullor* and the *second-generation current conveyor with negative unity gain (CCII−)*. The next two sections demonstrate the step from state representations to controlled-source representations. In Section III, a set of nine different *operational amplifiers* is derived from the nullor, and twelve different *current conveyors* are derived from the CCII− in Section IV. Several of these amplifiers appear to be new, namely the *current-feedback* OTA (CFB OTA) and a set of voltage-inverting current conveyors. Finally, we demonstrate in Section V how *all* amplifiers discussed in this paper can be implemented in CMOS using a small number of transistor building blocks. To compare like with like, we had to choose one technology. We chose CMOS mainly because we have experience in CMOS amplifier design but not in bipolar amplifier design. This should not affect the generality of our discussion, since the basic operation principles of CMOS and bipolar amplifiers are very similar.

II. Nullors and the Universal Active Element

As mentioned in the introduction, Tellegen showed that *the* universal active element (he called it “amplificateur idéal” ideal amplifier) has an all-zero chain matrix [1]

$$\begin{bmatrix} v_a \\ i_a \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_b \\ -i_b \end{bmatrix} \tag{1}$$

with voltages and currents as defined in Fig. 1. Equation (1) cannot be used to derive implementations directly, because describing a circuit with four terminals as a two-port means describing it *under the condition that* $i_a = -i'_a$ (see Fig. 1). An amplifier with one voltage input and one current input, such as the CFB opamp (see Section III for a definition), cannot operate under this condition, since its voltage input will make $i_a = 0$ and prevent any current from flowing through its current input. For this reason, the CFB opamp has to be treated as a special case in amplifier classifications based on (1) [5]. In contrast, a four-terminal classification includes the CFB opamp, as will be shown in Section III.

The mapping of four-terminals onto two-ports is not one to one, because two-ports are described by two equations, and four-terminal networks by three equations. To derive a universal four-terminal element from (1), one equation must be added, which can be chosen freely as long as it does not contradict (1). The added equation need not be linear. This means that there is an infinite number of qualitatively different universal four-terminal elements. The two simplest and most widespread ones are the *four-terminal nullor* and the *three-terminal nullor*, which were both introduced in [6] and will now be briefly described.

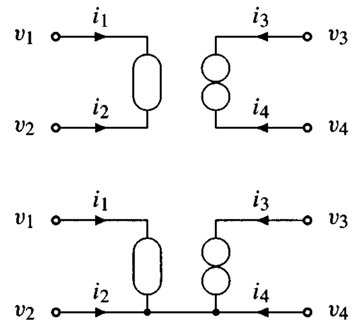

Fig. 2. Top: Four-terminal nullor (or simply nullor). Bottom: three-terminal nullor (CCII−).

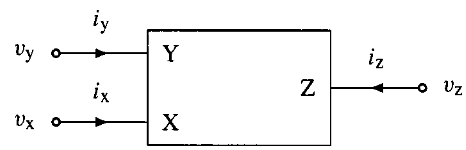

Fig. 3. Second-generation current conveyor (CCII).

A. Four-Terminal Nullor

The four-terminal nullor consists of two pathological two-terminal elements called a *nullator* (terminals 1 and 2) and *norator* (terminals 3 and 4), as shown in Fig. 2. The nullator is described by three equations, but the norator only by one:

$$\begin{aligned} \text{Nullator:} &\quad i_1 = -i_2, \quad i_1 = 0, \quad v_1 - v_2 = 0 \\ \text{Norator:} &\quad i_3 = -i_4 \end{aligned} \tag{2}$$

The equation $i_3 = -i_4$ makes the nullor fulfil Kirchhoff’s current law; $i_1 = -i_2$ is the equation added to (1). This means that the four-terminal nullor meets $i_a = -i'_a$, which was discussed above, by itself. From all universal active elements, the four-terminal nullor is the most straightforward to derive. It has unfortunately become common practice in the literature to define the four-terminal nullor by (1) and then use the device defined by (2). The concepts of four-terminal nullors, nullators, and norators have proven to be very valuable network analysis and synthesis tools (cf. [7] for the analysis of linear circuits, [8] for nonlinear circuits, [9] for the nullor’s use in CAD software, [10], [11] for the synthesis of linear circuits and filters, [12] on nullors and circuit transposition, and [13] on the realization of inverse transfer functions using nullors). We will use the four-terminal nullor in Section III to derive the nine fundamentally different operational amplifiers.

TABLE I
COMMON NAMES OF THE NINE OPERATIONAL AMPLIFIERS

Class	Gain Equation	Operational for	Common Name
$\mathbb{V}$–$\mathbb{I}$	$i_3 = g_m(v_1 - v_2)$	$g_m R_{in} \to \infty$	operational transconductance amplifier (OTA)
$\mathbb{V}$–$\mathbb{V}$	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	operational amplifier (opamp)
$\mathbb{V}$–$\mathbb{H}$	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	floating opamp (operational floating amplifier, OFA)
$\mathbb{I}$–$\mathbb{I}$	$i_3 = A_i i_1$	$A_i \to \infty$	current-mode opamp
$\mathbb{I}$–$\mathbb{V}$	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	operational transresistance amplifier (OTRA)
$\mathbb{I}$–$\mathbb{H}$	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	floating OTRA
$\mathbb{H}$–$\mathbb{I}$	$i_3 = A_i i_2$	$A_i \to \infty$	current-feedback OTA (CFB OTA)†
$\mathbb{H}$–$\mathbb{V}$	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	current-feedback opamp (CFB opamp)
$\mathbb{H}$–$\mathbb{H}$	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	operational floating conveyor (OFC)

†THIS NAME IS PROPOSED BY US

B. *Three-Terminal Nullor*

The three-terminal nullor is fully equivalent to the four-terminal nullor on the system level, as will be shown presently. It is described by

$$i_1 = 0, \quad v_2 = v_1, \quad v_2 = v_4, \quad i_3 = -(i_2 + i_4). \tag{3}$$

Here, $i_3 = -(i_2 + i_4)$ describes the Kirchhoff current law, and $v_2 = v_4$ is the equation added to (1). The latter equation describes a direct connection between the terminals 2 and 4, which can thus be seen as one terminal, hence the name *three-terminal* nullor. The three-terminal nullor can be represented using one nullator and one norator, i.e., as a four-terminal nullor that has one output connected to one input (cf. Fig. 2). For didactic reasons, we prefer to use an alternative representation of the three-terminal nullor: The second-generation current conveyor with current gain −1, the CCII− [14], [15] whose circuit symbol is shown in Fig. 3. The CCII− is described by three equations

$$i_y = 0, \quad v_x = v_y, \quad i_z = -i_x \tag{4}$$

which are the same as the equations in (3), but written in different variables. We will use the CCII− to discuss several current conveyors in Section IV and to prove that *all* of them are universal.

For the remainder of this paper, we will use the name *nullor* for the four-terminal nullor and the name CCII− for the three-terminal nullor. Note that the nullor and the CCII− are equivalent on the system level, meaning that any circuit containing only nullors can be redrawn using only CCII−s, and vice versa. This is easy to show: On the one hand, the CCII− can be drawn using one nullor, as indicated by Fig. 2, and one way to implement a CCII− is in fact to connect two terminals of a nullor implementation (cf. Section V). On the other hand, a nullor can simply be redrawn by using two CCII−s and connecting their X terminals. It was demonstrated in [5], [16], [17] that a four-terminal nullor can also be implemented by connecting the X terminals of two CCII− implementations.

III. OPERATIONAL AMPLIFIERS

In electronics textbooks, the conventional operational amplifier is often described by the "Two Golden Opamp Rules." These two rules are: 1) the output attempts to do whatever is necessary to make the voltage difference between the inputs zero and 2) the inputs draw no current [18]. These rules both contain the information of the nullator equations in (2) and the statement that feedback is necessary such that the opamp can approximate the nullator equations. Thus, we call an amplifier *operational* if it can approximate the nullor in certain feedback configurations. It follows directly from this definition that all operational amplifiers are universal. It will become apparent in the forthcoming discussion that our definition of "operational" agrees closely with the common sense of amplifier designers.

The nullor cannot be implemented in a straightforward way. Being described by its state only, its terminal impedances are undefined, whereas the terminal impedances of an ideal amplifier are either zero (low) or infinite (high). There are three different ways of choosing the impedances of the input terminals: both low, both high, or one low and one high. The same applies to the outputs. Therefore there exist nine fundamentally different operational amplifiers, described by Table I, whose circuit symbols are shown in Fig. 4.

The nine operational amplifiers are ordered according to their input and output stages in Fig. 4. The three rows of Fig. 4 contain the amplifiers with voltage ($\mathbb{V}$), current ($\mathbb{I}$), and hybrid ($\mathbb{H}$) input stages, and the three columns contain the amplifiers with $\mathbb{I}$, $\mathbb{V}$, and $\mathbb{H}$ output stages (we will presently describe all stages). The names of the various amplifiers are listed in Table I. All amplifiers have already been named in the literature, with the exception of the $\mathbb{H}$-$\mathbb{I}$ amplifier, which we call *current-feedback* OTA (CFB OTA) because its relation to the OTA is the same as the CFB opamp's relation to the opamp. Both names are misleading, since the CFB OTA is actually a current amplifier and not a transconductance amplifier, just as the CFB opamp is a transresistance amplifier and not a voltage amplifier. We decided to use the name CFB OTA anyway to preserve some symmetry in the nomenclature. In a perfectly symmetrical nomenclature, the $\mathbb{H}$-$\mathbb{H}$ amplifier would be called floating CFB opamp; however, to remain consistent with the literature, we prefer to use its conventional name, operational floating conveyor (OFC) [19], [20].

Table I also contains the gain equations of the amplifiers and the conditions under which they are operational in a feedback configuration. These conditions will be derived presently. Table I states that the four amplifiers with voltage gain or current gain are only operational if their gains A_v and A_i are very

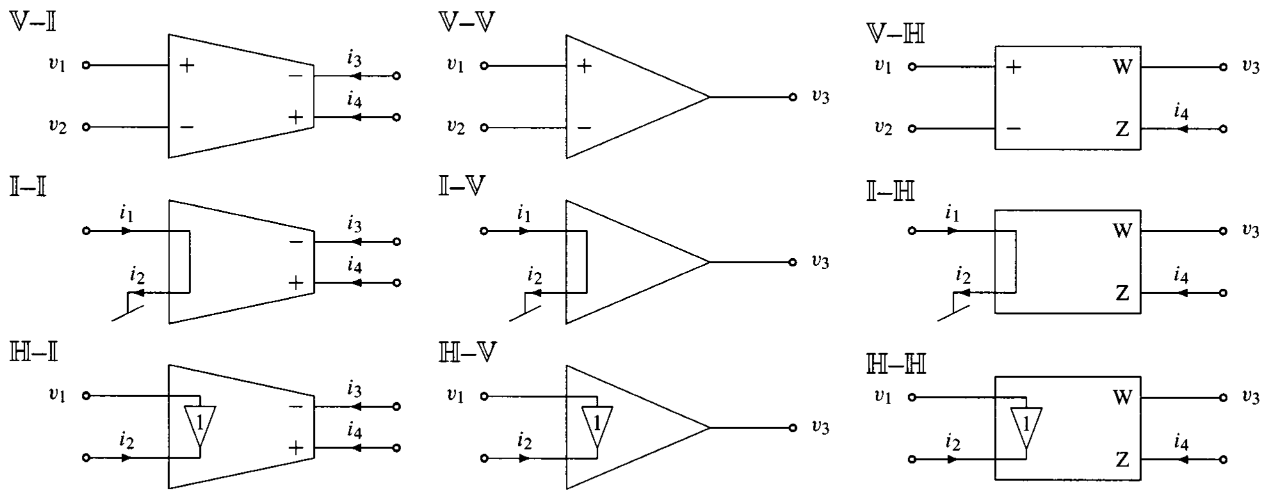

Fig. 4. Symbols of the nine operational amplifiers.

high. These four amplifiers need a high-gain stage between the input and the output stage (see Section V). This is not the case for the OTA. If one output terminal is directly connected to one input terminal, the loop gain becomes $g_m \cdot R_{\text{in}}$, where g_m and R_{in} are the OTA's transconductance and input resistance. Integrated OTAs normally have a very high input resistance, so an OTA is operational even if its g_m is low. Similarly, if direct feedback is applied to any of the four transresistance amplifiers, the feedback loop has a gain of r_m/R_{in}. Looking at integrated circuits again, one finds that it is difficult to make R_{in} very low. Thus, many implementations of such transresistance amplifiers, most notably implementations of CFB opamps, do contain a high-gain stage that makes the transresistance r_m very high.

We will now show how the set of nine operational amplifiers can be derived from the nullor equations (2). If the input stage is identified with the nullator and the output stage with the norator, it becomes apparent that the input stage is over-defined by the three nullator equations, whereas the output stage is under-defined by the single norator equation. The principle underlying all nine operational amplifiers is that the output stage fulfils one additional equation, a gain equation, which enables the amplifier to satisfy all three nullator equations *if it is used in a stable infinite-gain feedback configuration.* Choosing the nullator equation to be satisfied by feedback determines both the type of the input stage and the quantity to be amplified. There are three possible choices.

1) Satisfy $v_1 - v_2 = 0$ by feedback. Then $v_1 - v_2$ must be amplified, and the input stage must fulfill the nullator equations $i_1 = 0$ and $i_1 = -i_2$ by itself. Substituting the former equation into the latter results in $i_2 = 0$, thus both terminals must have a high impedance. This describes the $\mathbb{V}$ input stage.
2) Satisfy $i_1 = 0$ by feedback. The input stage must then meet $i_1 = -i_2$ and $v_1 - v_2 = 0$, which describes a short circuit. Because $i_1 = -i_2$, either i_2 or i_1 can be amplified. In Fig. 4, all $\mathbb{I}$ input stages are shown with one of the inputs grounded, because integrated $\mathbb{I}$ input stages normally have only one current input. More is not necessary; an $\mathbb{I}$-input amplifier is still universal if it has only one input terminal, since the current-adding capability of the current input makes it possible to use the single $\mathbb{I}$ input terminal both for applying the feedback necessary to force $i_1 = 0$ and to transport a signal current. The only difficulty is that a synthesis technique different from conventional nullator-norator synthesis must then be used to ensure that no floating nullators occur in the system.
3) Satisfy $i_1 = -i_2$ by feedback. The equations fulfilled by the input stage are then $i_1 = 0$ and $v_1 - v_2 = 0$, and the signal to be amplified is i_2. Thus, terminal 1 must have high impedance, terminal 2 low impedance, and the voltage from terminal 1 must be replicated at terminal 2. This is the $\mathbb{H}$ input stage, which has become well known through the CFB opamp. The $\mathbb{H}$ input stage can also be understood as an extended $\mathbb{I}$ input stage whose analog-ground voltage is not fixed, but can be set through an additional terminal.

We will show in Section V that many current input stages can easily be used as hybrid stages, simply by using a circuit node that was formerly connected to analog ground as an additional voltage input terminal.

The output signal of an amplifier can be either a voltage or a current. This choice and the choice of the input stage determine the amplifier's gain equation. The output stage must also meet the single norator equation $i_3 = -i_4$. There are again three possibilities.

1) An $\mathbb{I}$ output stage just requires two balanced current outputs.
2) building a $\mathbb{V}$ output stage that fulfils $i_3 = -i_4$ means building a floating controlled voltage source with invertible polarity. Fortunately, doing this is not necessary, since only one voltage output is really needed. The voltage-fan-out capability of the $\mathbb{V}$ output makes it possible to drive the feedback and deliver an output signal simultaneously. Thus integrated $\mathbb{V}$ output stages normally have only one output voltage, which is reflected in the symbols used in Fig. 4.
3) Like the $\mathbb{I}$ input stage, the $\mathbb{V}$ output can also be extended to a hybrid stage. Since the hybrid output stage must meet $i_3 = -i_4$, it must copy the current flowing into the voltage output terminal to an additional current output

terminal. This technique, which is called *output current sensing* or *supply current sensing*, will play an important role in the following two sections.

In Fig. 4, we denote the voltage output terminal of the $\mathbb{H}$ output stage by W and the current output terminal by Z, a convention taken from the symbol normally used for the OFC [19], [20].

Fig. 4 does not show special types of amplifiers, like differencing-input current amplifiers [21], [22], differential difference amplifiers [23], or balanced-output opamps [24]. This is because, e.g., a balanced voltage output stage cannot be described as a single $\mathbb{V}$ output stage fulfilling the gain equation and the norator equation. The balanced-output opamp must rather be seen as an *extended* voltage opamp, a voltage opamp that has an additional voltage output stage. Similarly, the differential difference amplifier has an additional pair of voltage inputs, and the differencing-input current amplifier has an additional current input. All extended amplifiers are trivially universal, since one can just leave the additional inputs or outputs unused to get one of the amplifiers in Fig. 4. It now becomes apparent that any number of universal active elements can be constructed from the ones in Fig. 4, which is the main reason why new universal amplifiers are still being published now and then.

IV. Current Conveyors

In the previous section, nine operational amplifiers that fulfil the nullor equations were derived. We will now use the CCII− to discuss several current conveyors. They do *not* meet the CCII− equations in (4), but are still universal. It could be shown mathematically that every one of these current conveyors is universal, but we will pursue a more intuitive approach: we will show for every current conveyor that, on the system level, the CCII− can be replaced by a network containing only resistors and one or more instances of the current conveyor in question.

In contrast to the nullor, the CCII− can be implemented directly and does not require a high-gain stage. The three equations in (4) can be interpreted as a description of two interlinked controlled sources: $i_y = 0$ states that Y's terminal impedance is high. $v_x = v_y$ can be interpreted as a voltage buffer from terminal Y to terminal X. Under this interpretation, $i_z = -i_x$ states that the current flowing into the output of the voltage buffer is sensed and copied to terminal Z, which therefore has high impedance. This sounds familiar, since the sensing of the current flowing into a voltage output is used both in the $\mathbb{H}$ input stage and the $\mathbb{H}$ output stage discussed in the previous section. We will show in the following section that the two are indeed current conveyors. Note that current sensing applied to a voltage buffer is only one possible interpretation of the CCII− equations, the other important interpretation was already mentioned in Section II and describes the CCII− as a nullor with one output connected to one input.

The former interpretation is, however, more productive than the latter. A different current conveyor results if $i_z = -i_x$ is replaced by $i_z = +i_x$: the CCII+ [14], [15]. The CCII+ is not a true three-terminal network anymore, since its terminals do not meet Kirchhoff's current law. It must rather be seen as a four-terminal network of which one terminal is not accessible to the user. To prove that the CCII+ is universal, it is sufficient

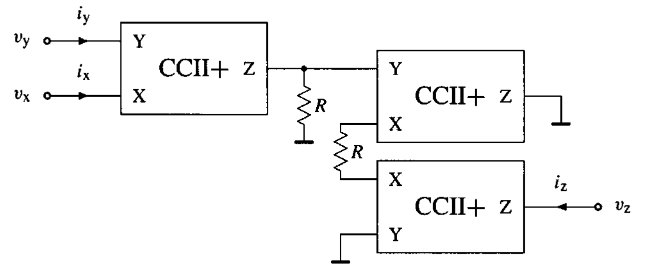

Fig. 5. CCII− built using three CCII+ and two resistors.

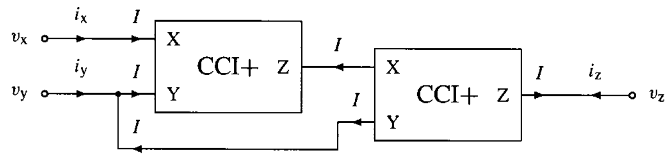

Fig. 6. CCII− built using two CCI+.

to show that a CCII− can be replaced by a circuit consisting of three CCII+ and two resistors with equal resistance. Such a circuit is shown in Fig. 5.

In general, the CCII with positive or negative current gain α_i is described by the current equation $i_z = \alpha_i i_x$ [25], [26]. It is universal for any nonzero α_i. To prove this for positive α_i, it suffices to show that the circuit in Fig. 5 is a CCII− if the two resistances are chosen such that the overall current gain becomes one. The same circuit can also be used to prove universality for negative α_i: just use the Z terminal of the top right CCII as the output of the composite CCII−. (The bottom right CCII can then be omitted.)

The CCII was originally derived from a device introduced as "the current conveyor" which is now called *first-generation current conveyor*, or CCI+. The CCI+ is described by the following three equations (5)–(7) [27]:

$$i_y = i_x, \quad v_x = v_y, \quad i_z = i_x. \tag{5}$$

To prove that it is universal, it is sufficient to show that a CCII− can be built using two instances of the CCI+. One way to do this is shown in Fig. 6. Defining $i_x = I$ and drawing this current I wherever it occurs makes it obvious that the circuit in Fig. 6 meets (4), and thus is a CCII−. Other current conveyors similar to the CCI+ are the CCI− $(i_z = -i_x)$, the $\mathrm{CCI}\alpha_i$ $(i_z = \alpha_i, i_x)$, and the third-generation current conveyor, CCIII ($i_y = -i_x$, cf. [28]) or, more generally, the $\mathrm{CCIII}\alpha_i$. All first- and third-generation current conveyors are universal amplifiers, which can in every case be shown by a constructive proof, as for the CCII+ and the CCI+. Finally, it is also possible to choose a nonunity current gain from X to Y, i.e., to choose $i_y = \pm\alpha_j i_x$. The resulting amplifier is universal for any α_j.

A further idea is to use a voltage inverter instead of a voltage buffer at the input of any of these current conveyors, such that $v_x = -v_y$. It is not clear yet what kind of applications current conveyors containing a voltage inverter may have, we only include this case for the sake of completeness, and also because this functionality was used to build a filter (but not explicitly described) in [29, Fig. 10]. We propose the name *voltage-inverting current conveyor* (VICC) for such devices. Current conveyors

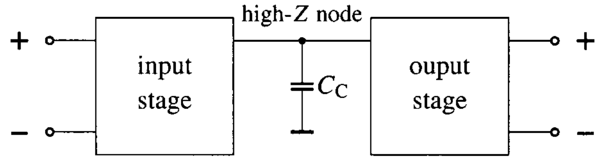

Fig. 7. Block diagram of an operational amplifier.

TABLE II
FUNCTIONS OF THE OPAMP STAGES

	input stage	output stage
$\mathbb{V}$	single-ended OTA	voltage buffer
$\mathbb{I}$	current buffer	balanced-output OTA
$\mathbb{H}$	CCII±	CCII−

of all three generations can be built with a voltage inverter, thus there exist VICCIs, VICCIIs, and VICCIIIs. All are universal, since two VICCs can be used to build one normal current conveyor, namely by using its voltage inverter to convert the inverting Y terminal to a noninverting one. Note that using two VICCIs or two VICCIIIs gives a CCIII, whereas two VICCIIs give a CCII. Further research will show whether the VICCs are actually useful for network synthesis.

It depends on the viewpoint how many different current conveyors our classification contains. If nonunity gains are just seen as a generalization of a given current conveyor, then there exist twelve different current conveyors named according to the scheme $xx\,\mathrm{CC}\,yyzz$, where xx is either "VI" or nothing to denote the polarity of the voltage buffer, yy is either "I", "II", or "III" to denote the polarity or the absence of a Y-terminal current, and zz is "$+$" or "$-$" to denote the polarity of the output current buffer.

More universal amplifiers based on these twelve current conveyors can be derived by adding more current inputs and outputs (cf. the balanced-signal CCII in [25], [26] or more voltage inputs (cf. the differential difference CCII in [29]). Like the extended operational amplifiers from Section III, they are all trivially universal.

V. Implementation in CMOS

All operational amplifiers besides the OTA are normally implemented as an input stage and an output stage connected by a compensated high-impedance node. The simplest compensation circuit, shown in Fig. 7, is a compensation capacitor C_C between the high-impedance node and ground. More elaborate compensation schemes use local feedback to reduce the size of the compensation capacitor [30], [31]. The circuit that is dual to a capacitively compensated high-impedance node is a compensation inductor connecting two low-impedance nodes (as in [32, Fig. 3]), but it is seldom used because of the lack of very low terminal impedances and high-Q inductors on integrated circuits. Thus all opamp input stages must have a current output, and all opamp output stages must have a voltage input. The functions that have to be performed by the stages discussed in Section III can now easily be determined and are listed in Table II. The required building blocks are therefore a single-ended OTA, a balanced-output OTA, a voltage buffer, a current buffer, a CCII+

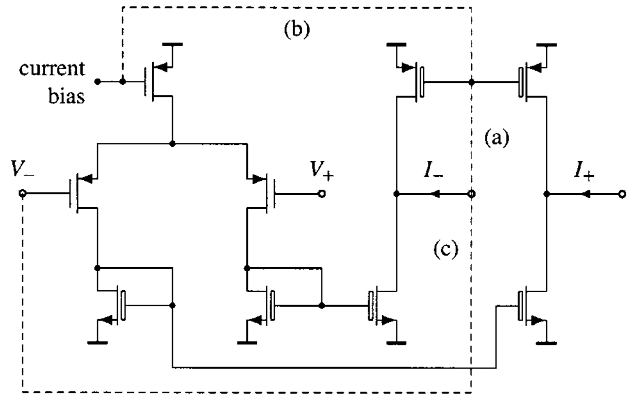

Fig. 8. Single-output OTA (if connection (a) is made), balanced-output OTA (if connection (b) is made), and OTA-based CCII− (if both connections (b) and (c) are made).

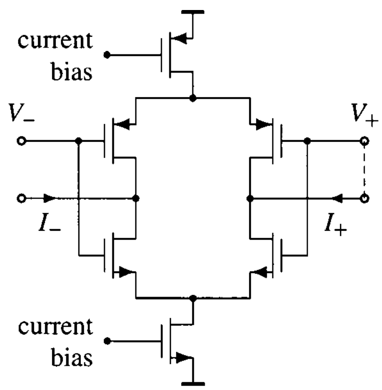

Fig. 9. Balanced-output OTA (or floating current source), and OTA-based CCII− (if the dashed connection is made).

and a CCII−, thus we will start this section with discussing implementations of OTAs and of the 12 current conveyors classified in the previous section.

All six stages can be shown in only three figures (Figs. 8–10), since the voltage buffer and the current buffer are already parts of the CCII shown in Fig. 10. To use that CCII as a voltage buffer, one can simply omit the output-current-sensing circuitry, and to use it as a current buffer, its Y terminal must be connected to analog ground. Note that most current input stages are actually built in this way. The input stage of every voltage opamp is an OTA, thus this device is well known. The differential-pair structure shown in Fig. 8 is conventionally called current-mirror OTA [30],[31]. The transistors having boxes as gates are composite transistors with high output resistance, e.g., normal cascodes, low-voltage cascodes, or regulated cascodes (cf. [30], [33], [34]). The OTA structure shown in Fig. 8 can be used to implement both a single-ended OTA and a balanced-output OTA. The latter is already an implementation of the $\mathbb{V}$-$\mathbb{I}$ operational amplifier, as discussed in Section III. It could also be used as a balanced current output stage, but many designers (e.g., [21]) have started to use the OTA shown in Fig. 9. This OTA is called *floating current source* [35] and essentially consist of two long-tailed pairs connected head to head. The advantage of this simple structure is that the relation $I_+ = -I_-$ is guaranteed by Kirchhoff's current law and is therefore very precise and very

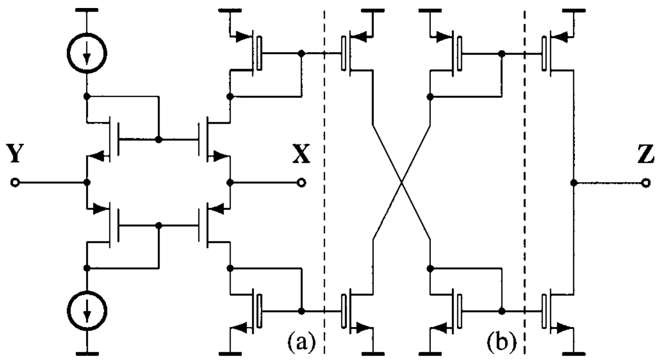

Fig. 10. CCII−, CCII+ (if the part between (a) and (b) is omitted), current buffer (if Y is connected to analog ground), and voltage buffer (if everything right of (a) and the two diode-connected transistors just left of (a) are omitted).

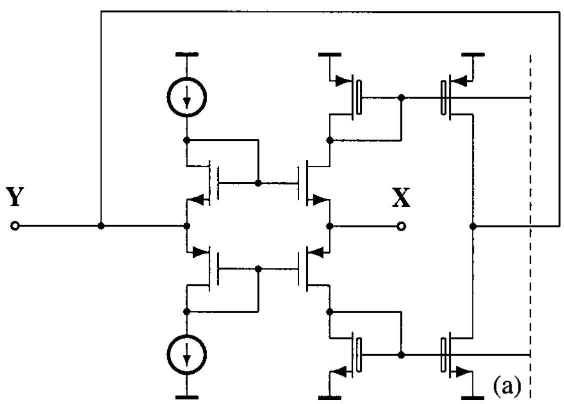

Fig. 11. Input circuit of a CCI.

linear, whereas in the OTA in Fig. 8, the precision of that relation depends on how well the two output current mirrors match.

We have already shown in Section II that a CCII− results if one of the outputs of a balanced-output OTA is connected to one of its inputs, which can be done with both OTAs we just discussed. An alternative way of implementing the CCII− as a class-AB circuit is as a voltage buffer with output current sensing, shown in Fig. 10 [36]. In contrast to an OTA with feedback, the circuit in Fig. 10 can easily be altered to obtain a CCII+: omit the current inverter between the dashed lines in Fig. 10. This stage is often preferred as a $\mathbb{H}$ input stage, mainly because using a CCII− is not always an option, which we will show presently when we discuss the CFB opamp. But first we explain briefly how these circuits can be used to implement the whole twelve classes of current conveyors.

A $\mathrm{CCII}\alpha_i$ can be built by taking the CCII+ or CCII− implementation in Fig. 10 and resizing some of the current mirror transistors. All CCIIs can be converted to CCIs if the voltage buffer left of the dashed line in Fig. 10(a) is replaced by the circuit in Fig. 11 [37]. CCIIIs can be built in much the same way, by simply using one more current inverter in Fig. 11, although they were implemented using two double-output CCIIs when they were first proposed [28]. Like the CCII, CCIs, or CCIIIs with nonunity gain can be built by resizing some of the current mirror transistors.

Voltage-inverting current conveyors require a voltage inverter between Y an Z. This can be achieved by using the two-differential-pair input stage of the differential difference amplifier [23] instead of a conventional OTA (cf. [29]). If this technique is applied to the OTA in Fig. 8, then the circuit in Fig. 12 results. The voltage at X is $V_X = V_{Y1} + V_{Y2} - V_{Y3}$, thus a VICCII+ results if both $Y1$ and $Y2$ are connected to ground. All other VICCs can be built based on this VICCII+ by adding current mirrors and current inverters.

Finally, extended current conveyors, such as multiple-output current conveyors or balanced-signal current conveyors, can be built by replicating parts of the circuits in Figs. 10 and 11 [25], [26], [38]. Many of these current conveyors can also be built as class-A circuits instead of class-AB circuits [26], [36], [38].

All stages necessary to build the operational amplifiers from Section III are now described. The following comments on each amplifier explain a few important design considerations and briefly describe other notable implementations of the nine operational amplifiers.

A. The OTA

($\mathbb{V}$-$\mathbb{I}$ amplifier) is normally built without an internal high-impedance node, since it is operational even if its transconductance is not high (see Section III). This makes it possible, in the extreme case, to build a CMOS OTA that only has input and output nodes, but no internal nodes at all [39]. Note that an OTA need not even be operational if it is used to build transconductance-C (Gm-C) filters. Nevertheless, there are OTAs having an internal high-impedance node, most notably the "monolithic nullor" proposed in [2], which is built as a cascade of two bipolar differential pairs.

B. Voltage Opamps

($\mathbb{V}$-$\mathbb{V}$ amplifiers) often contain a voltage buffer different from the one in Fig. 10, and most opamps are compensated by an internal feedback capacitor [30], [31] instead of a grounded capacitor.

C. The Floating Opamp

($\mathbb{V}$-$\mathbb{H}$ amplifier, also called operational floating amplifier) uses a CCII− as its output stage. As explained above, it can be seen as an extended voltage opamp whose output current is sensed and mirrored to another output. Most output stages used in CMOS and bipolar opamps can be modified in this way. It is also possible to sense and copy the supply currents of the whole opamp, since any current flowing into the opamp output must flow through the opamp's supplies. Thus off-the-shelf discrete opamps can be made floating by adding external current mirrors, as discussed in [40].

D. The CFB Opamp

($\mathbb{H}$-$\mathbb{V}$ amplifier) has become famous through its gain-independent bandwidth [20], [41]–[44]. Both the CCII− and the CCII+ could be used as its input stage, but the latter is preferable. If a CCII+ is used, external negative feedback goes from the output to the current input, which is then called the negative input, and the positive input can be used to feed a voltage signal into the feedback loop. However, if a CCII− were used, a negative feedback loop would go through both the voltage and the current buffer of the $\mathbb{H}$ input stage. The feedback signal would

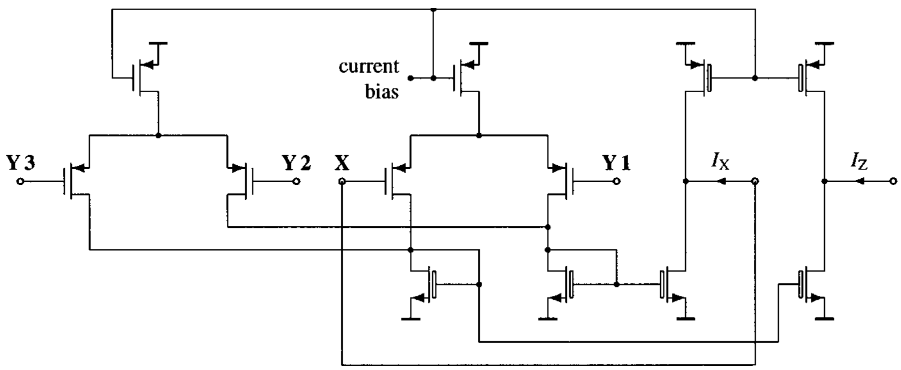

Fig. 12. Current conveyor with a differential difference input stage.

then again be a voltage, and the resulting ℍ-𝕍 opamp would be slower and would not have a gain-independent bandwidth anymore. Thus CFB opamps almost always have a CCII+ input stage. For example, the AD 844 CFB opamp [3] has a structure very similar to the structure presented here, although bipolar transistors are used. The AD 844 is special in that its internal high-impedance node is available as a chip pin. Thus its input stage can be used as an independent CCII+, which is often done to build CCII+ circuits with discrete components [45].

E. The OFC

(ℍ-ℍ amplifier) can be seen as a floating CFB opamp. The ℍ-ℍ structure implemented here is similar to the bipolar-transistor OFC described in [19], [20]. The OFC is basically a transresistance amplifier, as its gain equation shows.

F. OTRAs

(𝕀-𝕍 amplifiers) are only occasionally used in the literature. The OTRA developed for transresistance-C filters that was presented in [46] is very similar to the one described here, but normally OTRAs are used for special purposes only and are then implemented in special ways (c.f.[47]). As explained above, most amplifiers with 𝕀 input stages are already full-grown ℍ-input amplifiers with their voltage input grounded. This is also true for the OTRA in [46], which can thus very easily be converted into a CFB opamp.

G. The Floating OTRA

(𝕀-ℍ amplifier) can be used to couple current signals out of the loop of a transresistance-C filter, e.g., to make the filters from [46] more versatile. The relation between the OFC and the floating OTRA is the same as the relation between the CFB opamp and the OTRA. Thus any of the latter three can be interpreted as an OFC with one or two grounded terminals. Fast CMOS floating OTRAs have already been published under the name "current-mode opamp" [48], "current amplifier" [49], and "transresistance current amplifier" [50].

H. The Current-Mode Opamp

(𝕀-𝕀 amplifier) in [21] uses the CCII+ from Fig. 10 as its input stage and the floating current source from Fig. 9 as its output stage.

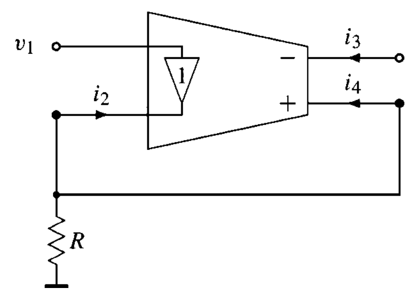

Fig. 13. Highly linear voltage-to-current converter.

I. The CFB OTA

(ℍ-𝕀 amplifier) was, to our knowledge, not discussed in the literature before, but it can easily be built from most current-mode opamp circuits, just as a CFB opamp can be built from an OTRA. To explain what it can be used for, a brief excursion to circuit transposition is necessary.

If a linear voltage-mode circuit is *transposed*, a current-mode circuit results which has the same transfer function. Under circuit transposition, the output terminals become the input terminals, and vice versa, but the terminal impedances remain the same. The transposed circuit is also called the *dual* circuit. The passive part of a linear circuit remains the same under circuit transposition, only the active devices must be exchanged, and the signal flow must be inverted (cf. [51]–[54]). It can be shown that the 𝕀 input stage is dual to the 𝕍 output stage, the 𝕍 input stage is dual to the 𝕀 output stage, and the ℍ input stage is dual to the ℍ output stage. Thus, three of the nine opamps are self-dual: the 𝕍-𝕀 amplifier, the 𝕀-𝕍 amplifier, and the ℍ-ℍ amplifier. This means, for example, that the transpose of a voltage-mode Gm-C filter is a current-mode Gm-C filter, and that the transpose of a voltage-to-current converter still is a voltage-to-current converter. Note that the three self-dual operational amplifiers lie on one diagonal in Fig. 4. Transposing all amplifiers in Fig. 4 amounts to mirroring the figure at this diagonal.

Now the use of the CFB OTA is apparent: since it is dual to the 𝕍-ℍ amplifier, it can be used to transpose any circuit containing floating opamps. To give a simple example for the potential of the CFB OTA, a voltage-to-current converter is shown in Fig. 13. It is the dual of a floating-opamp voltage-to-current converter presented in [40]. The CFB OTA circuit has two main advantages. First, it is easier to implement. As explained above, most current opamps can be used as CFB OTAs without adding a single transistor, whereas converting a voltage opamp into a floating opamp requires adding several current mirrors. Second, the CFB OTA circuit is more linear: Its harmonic distortion is mainly caused by the nonlinear output of the $\mathbb{H}$ input stage's voltage buffer. Since current feedback is used, i_2 is very low, and the buffer may consequently be very linear. If the $\mathbb{I}$ output stage is a floating current source, then the output current i_3 contains as little distortion as the feedback loop current i_4, since the two are related by Kirchhoff's current law. In contrast, the current output of the floating-opamp voltage-to-current converter is the mirrored terminal current of the floating opamp's voltage output. Thus the achievable linearity is limited by the current mirrors in the $\mathbb{H}$ output stage.

VI. Conclusion

The classification of universal amplifiers presented in this paper places all operational amplifiers and current conveyors known from the literature into a common framework, together with abstract concepts such as the universal active element and the nullor. We demonstrated how closely our classification is related to the way amplifiers are integrated by showing that all of them can be implemented in CMOS using only a few basic circuits. Although we only discussed CMOS, most of what we said applies to bipolar amplifiers as well, because the voltage buffers, current mirrors, and long-tailed pairs used in this paper can also be integrated with bipolar transistors.

In this paper, several universal active elements appeared that were not previously published. On the one hand, it occurred that first-, second-, and third-generation current conveyors still are universal if voltage inverters instead of voltage buffers are used as their input stages. The potential of these voltage-inverting current conveyors will be the topic of future research. On the other hand, a new operational amplifier, the CFB OTA was briefly discussed. It is dual to the floating opamp, but can be built from most current opamps without adding a single transistor. As an example, a voltage-to-current converter containing one CFB OTA and one resistor was discussed.

Our classification may be useful in different ways. Because of its close relation to IC design, it should give the readers some insight into the similarities of different integrated amplifiers, such that when they encounter an amplifier they have not seen before, they can quickly see what it does and also how it is related to the amplifiers they are already familiar with. It may also help IC designers with understanding the relevance of a newly introduced circuit-theoretical amplifier concept and enable them to find out in which way it should best be implemented for a certain application. From a purely theoretical point of view, and as far as we know, our classification is the most extensive of all recently published amplifier classifications, although it is not more complex.

Finally, we have shown in this paper shown that all broadband amplifiers that have been introduced in the past few decades and have been described as very versatile are in fact *universally* versatile, which means that *every* linear and nonlinear circuit function can be built from multiple instances of any one of these amplifiers and a set of linear and nonlinear passive components.

Acknowledgment

The author thanks Prof. G. S. Moschytz and Dr. Markus Helfenstein for the long and interesting discussions about the ideas presented in this paper. He also thanks the reviewers for the many valuable comments aimed at improving the clarity and readability of this paper.

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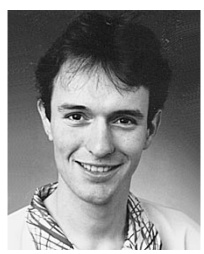

Hanspeter Schmid received the diploma in electrical engineering in 1994 and the post-graduate degree in information technologies in 1999, both from the Swiss Federal Institute of Technology (ETH Zürich), Zürich, Switzerland.

He joined the Signal and Information Processing Laboratory of the ETH Zürich as a Teaching Assistant in 1994, and is currently a Lecturer and Research Assistant in the field of analog integrated filters. He is presently finishing his doctoral thesis on single-amplifier biquadratic MOSFET-C filters, which covers the theoretical aspects of single-amplifier biquadratic filters, their implementation as video-frequency MOSFET-C filters, a comparison to other video-frequency filters, and a discussion of design tradeoffs (an electronic copy can be requested by contacting the author via e-mail).