Commodity IC Data: CA3080, LM13600 and LM13700
by Dennis L Feucht

Q: I have noticed that not all the op amps offered commercially by companies such as National Semiconductor Corp. (NSC) or Harris are *normal*. What exactly is a *Norton* amplifier really good for? And also, why would I ever want to use a *transconductance* amplifier such as the CA3080, or the LM13600, LM13700?

A: In a previous article we looked at the LM3900 transresistance amplifier. Here, the other *unusual* parts are marveled over. These amplifiers either apply, or are the precursors of, Barrie Gilbert's translinear concept that he pioneered several decades ago. Translinear circuits are versatile and IC product designers at RCA (CA3080) and NSC (LM13600, LM13700) must have appreciated what Motorola did in implementing a four-quadrant translinear multiplier as the MC1495 (and MC1496).

Since RCA designed the 8-pin CA3080, it appeared in RCA linear circuits ideas literature in 1977. The dismantled company has been passed around, and the 1993 - 94 Harris Linear & Telecom ICs data book contains the part, calling it an *operational transconductance amplifier*. This part eventually landed at Intersil, another company which, like Fairchild, was resurrected from a prior acquisition. NSC also makes the part, as an LM3080. It is a low-cost ($0.51 US, last time I ordered 25), multi-sourced part: a *commodity* IC. Intersil has obsoleted this interesting part, http://www.intersil.com/cda/deviceinfo/0,1477,CA3080,00.html and National Semiconductor has also http://www.national.com/pf/LM/LM3080.html discontinued the LM3080. Why bother with it then? It serves as a first-generation diff-amp variable-gain amplifier (VGA) that was replaced by the LM13600 and LM13700. At $0.45 (1000, NSC price) for what is essentially a dual CA3080 with an additional feature -- *linearizing diodes* -- the LM13700 (or LM13600) is the part to migrate to: or begin with. This article will select the LM13700 for description, though it is very similar to the LM13600 and CA3080.

Despite the name, neither the CA3080 nor the LM13700 is a current-output amplifier, as a transconductance amplifier would be, but is a voltage amplifier with control of its open-loop voltage gain through control of the first-stage diff-amp transconductance. By controlling the emitter current source, the r_e of the two diff-amp BJTs varies inversely with emitter current, allowing gain control. The circuit topology is simplified below. It consists of a variable-gain transconductance diff-amp, Q1, Q2, Q3 and three current mirrors. The output of Q1 drives Q5, Q6, depicted as a simple, two-BJT current mirror, which inverts the current and drives the current-sinking output mirror, Q9, Q10. Q2 of the diff-amp drives current mirror Q8, Q7 which sources output current.

The CA3080 does not have the diodes Q11, Q12. (BJTs are used as diodes for better junction matching.) These diodes match Q1, Q2 and form a translinear *gain cell*. It has the property that the ratios of currents in the diodes equals the ratio of BJT currents. This is evident when KVL is used around the diode loop and the BJT input loop. Let $i(Q11) = i_{D-}$ and $i(Q12) = i_{D+}$. Then:

$$i_{D-} + i_{D+} = I_X$$

Also, for a perfect current mirror, $i(Q3) = I_Y = i(Q1) + i(Q2)$ for $\alpha = 1$ ($\beta >> 1$). The diff-amp output current is differential and is:

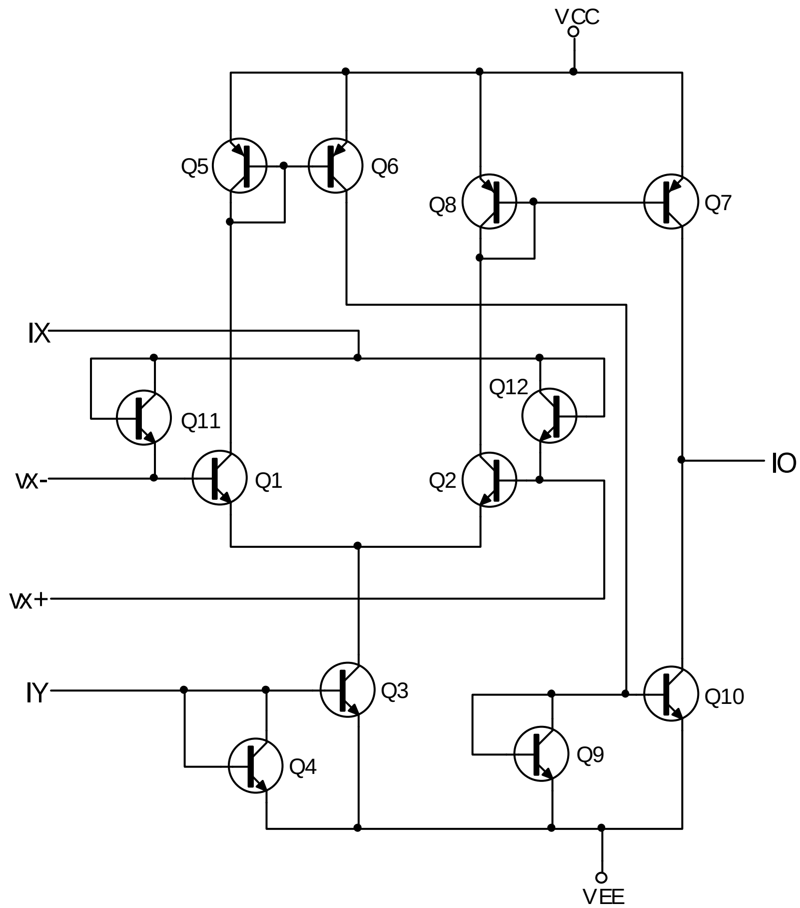
$$i_O = i_{o+} - i_{o-}$$

Then with this nomenclature, applying KVL to the diode loop:

$$v_x = v_{x+} - v_{x-} = -V_T \ln\left(\frac{i_{D+}}{I_s}\right) + V_T \ln\left(\frac{i_{D-}}{I_s}\right) = -V_T \ln\left(\frac{i_{D+}}{i_{D-}}\right)$$

And for the BJT *b-e* junctions:

$$v_x = v_{x+} - v_{x-} = V_T \ln\left(\frac{i_{o+}}{I_s}\right) - V_T \ln\left(\frac{i_{o-}}{I_s}\right) = V_T \ln\left(\frac{i_{o+}}{i_{o-}}\right)$$



Then equating and solving for the current ratios:

$$\frac{i_{o+}}{i_{o-}} = \frac{i_{D-}}{i_{D+}}$$

It can be shown algebraically that if:

$$\frac{a}{b} = \frac{c}{d}$$

then:

$$\frac{a-b}{a+b} = \frac{c-d}{c+d}$$

Applying this algebraic identity to the above circuit equations:

$$\frac{i_o}{I_Y} = -\frac{i_x}{I_X}$$

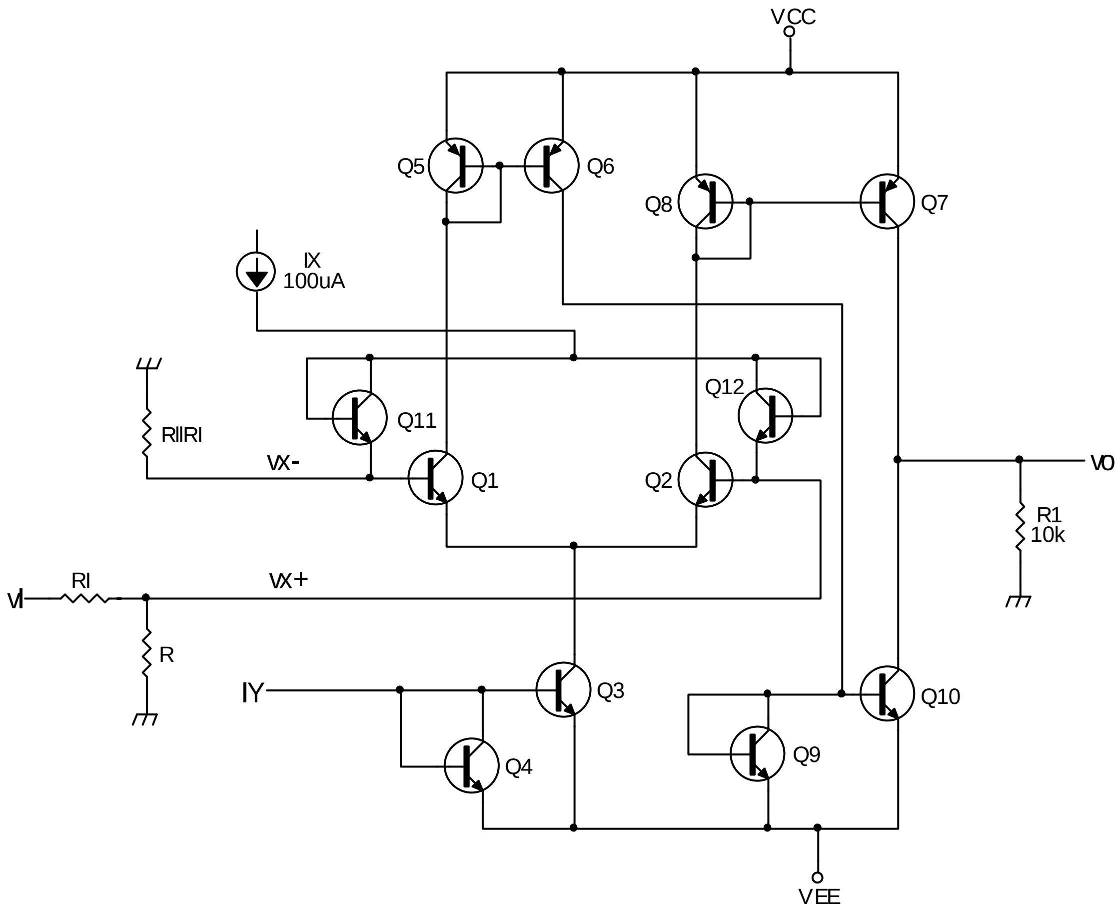
where, $i_x = i_{D+} - i_{D-}$.

This can also be expressed as a current-gain transfer function:

$$\frac{i_o}{i_x} = -\frac{I_Y}{I_X}$$

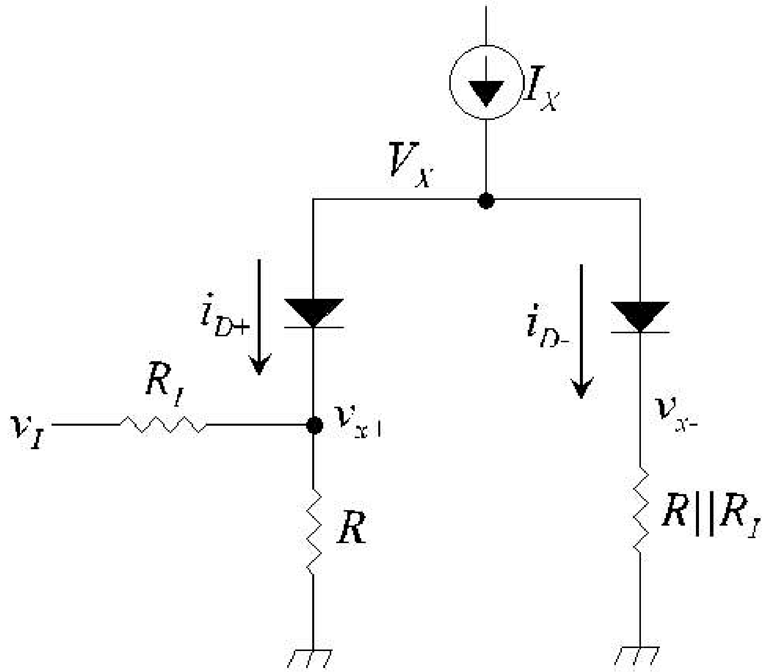
The translinear cell is a linear differential-input, differential-output current amplifier. Because the static current ratios involving I_X and I_Y set the current gain, by varying either of them the gain is varied. The diff-amp stage output current, through the unity-current-gain mirrors, is the amplifier output current, and the amplifier gain is given as the diff-amp stage gain above. It is inverting because the diodes are common-anode. An alternative common-cathode connection, with anodes connected to the diff-amp bases, eliminates the transfer function inversion.

The LM13700 can be used as a two-quadrant multiplier or VGA. The input circuit is shown below.



This amplifier inputs a unipolar I_Y and a unipolar (positive) v_I. When speed is a consideration, it is best to make v_I the gain control and I_Y (which becomes i_Y) the faster waveform.

This implementation has a voltage-source input as shown below. When $v_I = 0$ V, then the two sides of the circuit are symmetrical and $i_{D-} = i_{D+} = I_X/2$.



Let i_x be the differential current:

$$i_x = i_{D+} - i_{D-}$$

Translinear circuits are often easiest to analyze using the variable, x, to represent the fraction of current that is conducted by one side. Here, we let:

$$i_{D+} = x \cdot I_X$$

By KCL:

$$i_{D+} + i_{D-} = I_X$$

and thus:

$$i_{D-} = (1 - x) \cdot I_X$$

The range of x is ±∞ because to switch all the current from one diode to the other, an infinite voltage is required. This might seem counterintuitive because, in practice, only about ±150 mV will switch a differential BJT, or diode pair. However, because x is a hyperbolic tangent function of v_x, the current only asymptotically approaches a complete switchover. Huge voltages are required to switch orders of magnitude of currents at near-infinitesimal values. Translinear circuit design requires that a design decision be made about the full-scale value of x. The zero value is $x = 0.5$, where $i_{D+} = i_{D-}$. For a choice of $x(\text{fs}) = 0.75$, then the ratio of currents is 3 and $\ln(3) \approx 1.009 \approx 1$. The output fraction, i_o/I_Y at full-scale also is 0.5 and the full-scale multiplier (or VGA) gain is 0.5. Therefore, $i_Y(\text{fs})$ must be twice as large as the desired i_o.

Substituting into the previously derived equation for v_I and also equating to a KVL equation involving the resistors:

$$v_x = -V_T \cdot \ln\left(\frac{x}{1-x}\right) = (i_{D+} \cdot (R \,\|\, R_I) + v_I) - i_{D-} \cdot (R \,\|\, R_I) = i_x \cdot (R \,\|\, R_I) - \frac{(R \,\|\, R_I)}{R_I} \cdot v_I$$

$$= \left[(2 \cdot x - 1) \cdot I_X - \frac{v_I}{R_I}\right] \cdot (R \,\|\, R_I)$$

Applying the transfer function, the fractional output current becomes:

$$\frac{i_o}{I_Y} = -\frac{i_x}{I_X} = -\frac{v_I / R_I}{I_X} + \frac{V_T \cdot \ln\left(\frac{x}{1-x}\right)}{I_X \cdot (R \,\|\, R_I)}$$

This equation can be expressed in v_I as:

$$\frac{v_I}{R_I} = (2 \cdot x - 1) \cdot I_X + \frac{V_T \cdot \ln\left(\frac{x}{1-x}\right)}{R \,\|\, R_I}$$

This equation can be used to determine the required range for $\pm v_I$. At full-scale, let $x = 0.75$, $I_X = 100$ µA, and $R \| R_I = 10.0$ kΩ. Then:

$$\frac{v_I}{R_I} = \frac{100\,\mu\text{A}}{2} - \frac{(25.8\text{ mV}) \cdot \ln(3)}{10.0\text{ k}\Omega} \cong 47.17\ \mu\text{A}$$

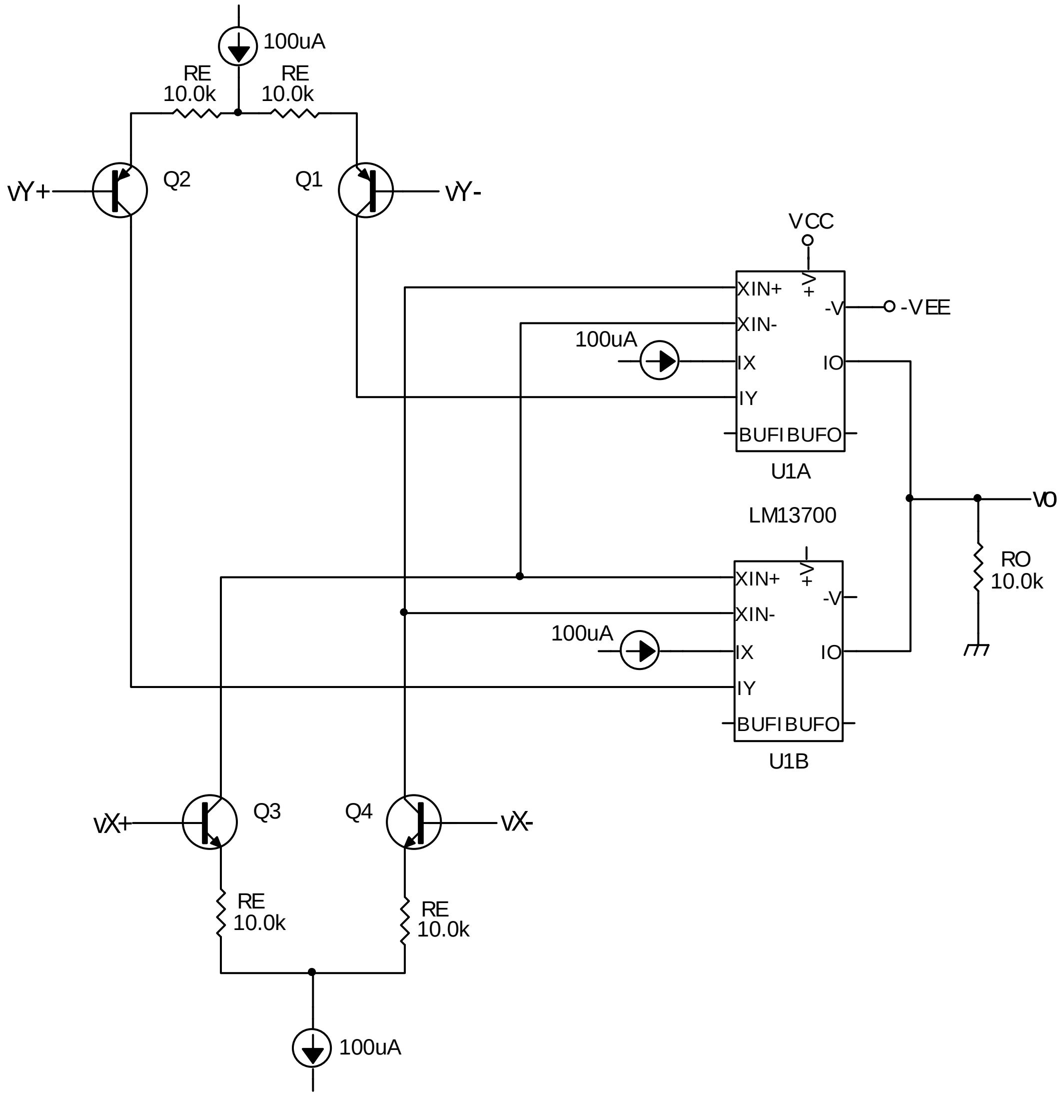
Then R_I can be chosen for a given v_I(fs) and R found from the parallel combination. The second term in the above equation accounts for the nonlinearity of the diodes in series with resistors. If $R \| R_I$ is made relatively large, the first term dominates and the output-current fraction is dominated by the linear function of the input voltage. Alternatively, if x is made only slightly larger than 0.5, the currents do not deviate much from balanced and the linearity is improved.

The v_I, R_I input can be replaced by a current source. This does not linearize the circuit though the corresponding equation to the previous one becomes:

$$i_I = (2 \cdot x - 1) \cdot I_X + \frac{V_T \cdot \ln\left(\frac{x}{1-x}\right)}{R}$$

where, R_I is effectively infinite

Happily, the LM13700 is a dual amplifier, and two are required to make a four-quadrant multiplier. The two-quadrant multiplier X input is bipolar but the Y input is unipolar. By combining two amplifiers and driving their Y inputs differentially, a four-quadrant multiplier results. The scheme is shown overleaf.



U1A and U1B have opposite-polarity X gains so that around zero volts of input, the gains must match to cancel Y outputs. As monolithic multipliers, the matching of amplifiers is good.

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