Revisit to Bipolar Analog Circuits: Two Base Current Compensation Techniques

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1.Introduction

This paper investigates two kinds of the base current compensation techniques used for bipolar analog circuits. The first one is for current mirror circuit where we combine the base current compensation technique with the cascode and level-shift configuration. The second one is for the input stage of the differential amplifier circuit with high input impedance and cascode configuration utilizing active load. The SPICE simulation results demonstrate the effectiveness of the proposed circuit techniques.

Bipolar analog circuits are still used in industry, such as for monolithic operational amplifiers and comparators, thanks to their low 1/f noise characteristics and low input offset voltage. Also even in pure CMOS LSIs, parasitic bipolar transistors are used for bandgap reference circuits; the authors believe that studying the bipolar circuit techniques are useful for realizing competitive ICs [1-6].

2. Bipolar Current Mirrors with Base Current Compensation

2.1 Basic Bipolar Transistor Current Mirror Circuit

Current mirrors are basic blocks of analog circuit design. They can copy the current multiplied by a coefficient by choosing an appropriate channel width ratio. As shown in Fig 1, there can be several output branches when the current steering DAC is designed, and they have the same base current $\frac{Io}{\beta}$. The deviation between the input and output currents is $\frac{(N+1)\,Io}{\beta}$, due to the base currents. Here, β is current gain of the bipolar transistor, and throughout this paper, N=16 is used for simulation. We consider to compensate for the base current so that the input and output currents are almost the same.

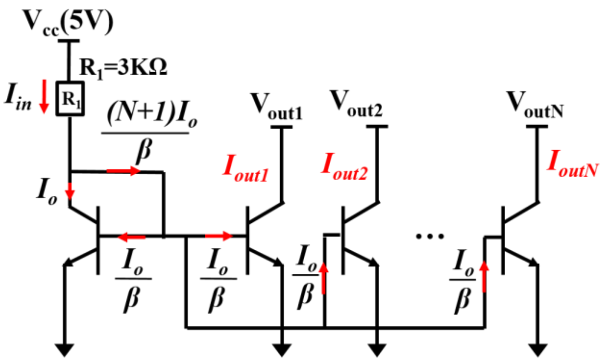


Fig 1. Basic bipolar transistor current mirror

2.2 Bipolar Transistor Current Mirrors Circuit with Base Current Compensation

To improve the input and output current deviation due to the finite base current, the current mirror circuit with the base current compensation is often used, as shown in Fig. 2. The deviation between the input and output currents in this circuit is only the base current of Q1. Since the base current of every output branch is $\frac{Io}{\beta}$, the emitter current of Q1 is $(N+1) * \frac{Io}{\beta}$. Thus, the base current of Q1 is $\frac{(N+1)\ Io}{\beta(1+\beta)}$. Compared with the deviation in the basic current mirror in Fig. 1, the deviation in this circuit is reduced by $\frac{1}{1+\beta}$.

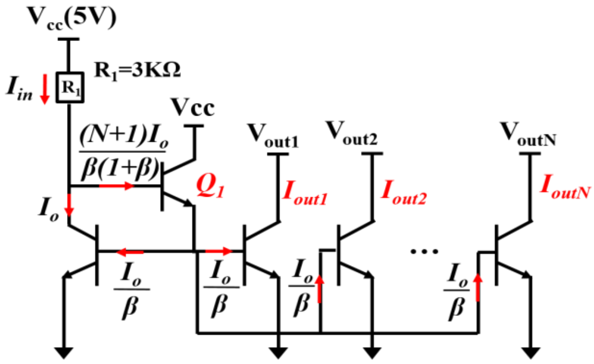
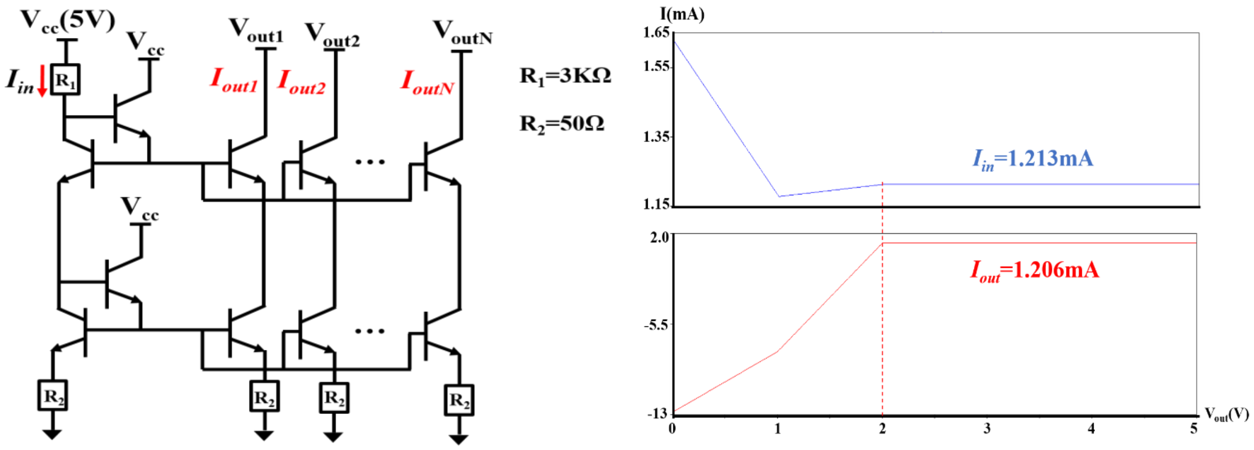


Fig 2. Current mirror with the base current compensation circuit

2.3 Bipolar Transistor Current Mirror Circuits with Cascode and Base Current Compensation Configuration

Because of the Early effect in bipolar transistor, there can be some deviation between the input and output currents in the basic bipolar transistor current mirror circuit in Fig. 1. We consider here the base current compensation configuration in the cascode current mirror circuit as shown in Fig.3 (a). Fig. 3 (b) shows its simulation result of the input current(I_{in}) and the output current(I_{out}). We can see that I_{out} is fairly close to I_{in} in the saturation state. However, the output current in this circuit cannot maintain a constant value when the output voltage is lower than 2V; the output voltage provided by the external load has to be smaller than 2V.

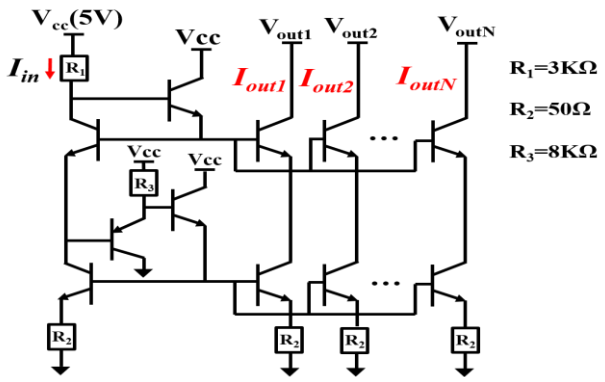


(a) Circuit schematic (b) Simulation result

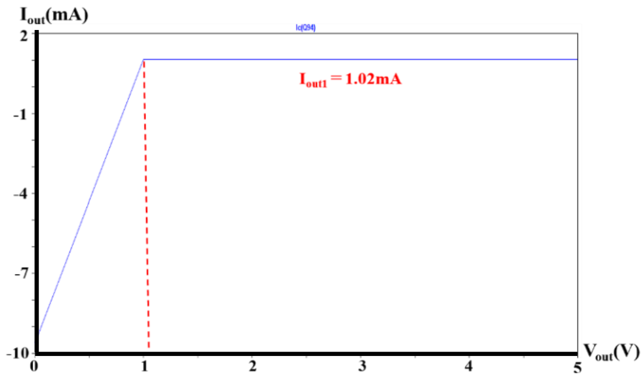
Fig 3. Current mirror circuit with the cascode and base current compensation configuration

2.4 Bipolar Mirror Circuits with Cascode, Level-Shift and Base Current Compensation Configuration

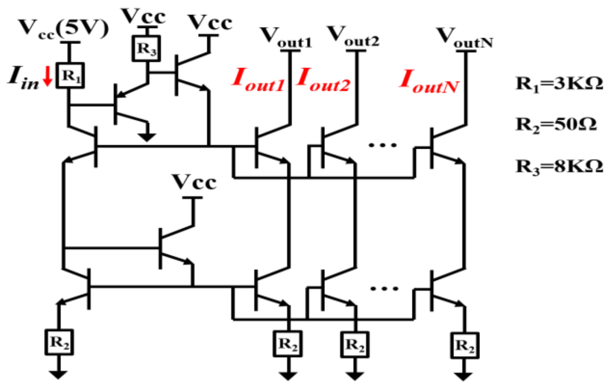
For the problem that previously mentioned, we add a PNP transistor and a resistor (PNP emitter follower circuit) into the current compensation configuration to form a level-shift configuration as well as further base current compensation, similar to the Darlington configuration (Figs. 4 (a), (c), (e)). There the level-shift by the base-emitter voltage of the NPN transistor is cancelled by that of the PNP.



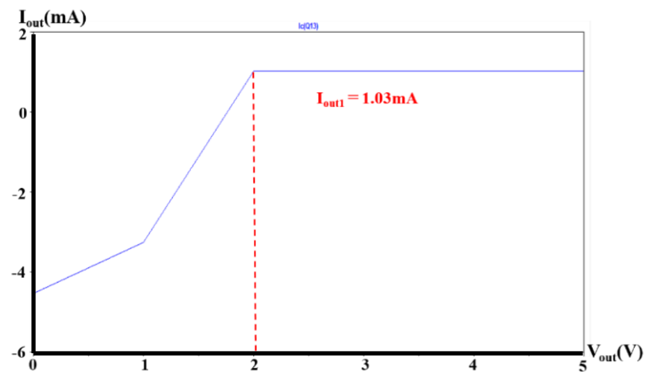
(a) Circuit schematic



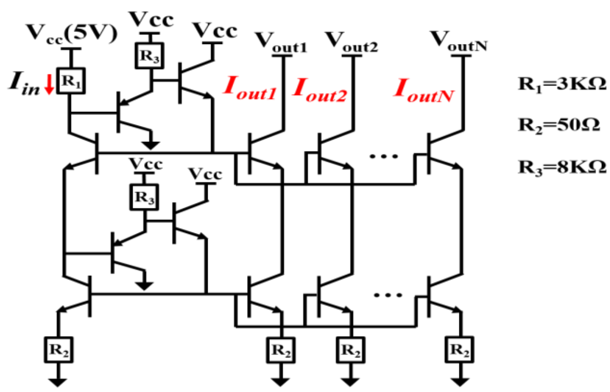
(b) Simulation result



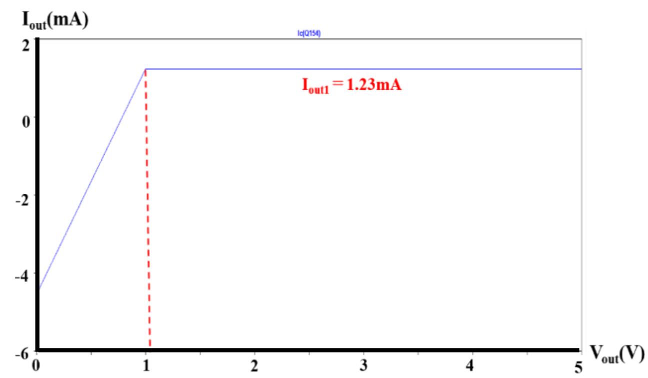
(c) Circuit schematic



(d) Simulation result



(e) Circuit schematic



(f) Simulation result

Fig 4. Current mirror circuit with the cascode, level-shift and base current compensation configuration

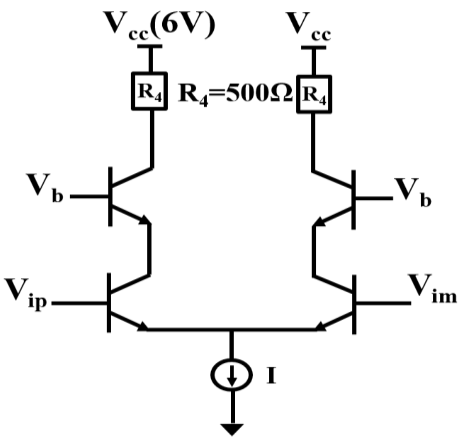
Their output current I_{out} simulation results are shown in Figs. 4 (b), (d), (f). Compared with the circuit in Fig. 4 (c), the circuits in Figs. 4 (a), (e) can operate with a lower output voltage (as low as 1V) that can maintain the output current constant. The circuit in Fig. 4 (e) has the further smaller deviation between the input and output currents compared with the circuit in Fig. 4 (a).

3. Bipolar Differential Amplifier with Base Current Compensation

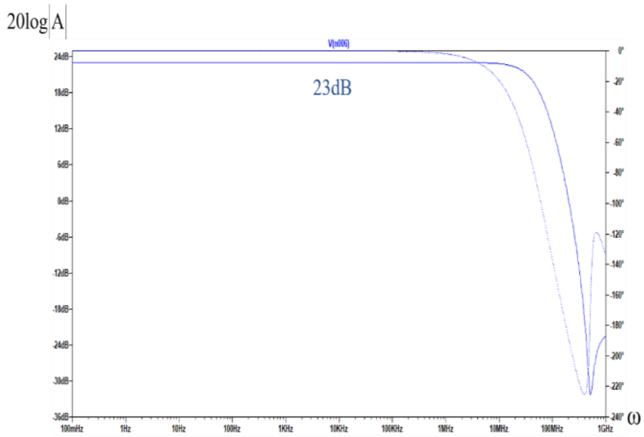
The base current compensation technique can be also used in the differential amplifier for high input impedance.

3.1 Basic Bipolar Differential Amplifier with Resistor Load

Fig. 5 shows a basic bipolar differential amplifier whose voltage gain is 23dB.



(a) Schematic

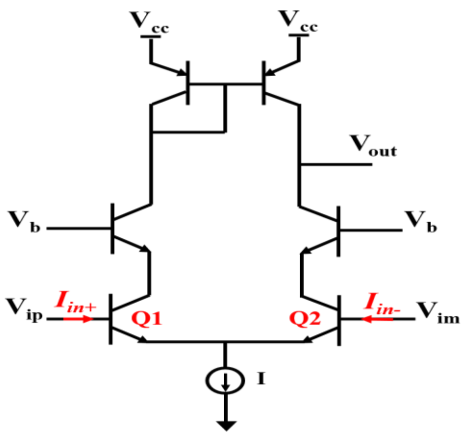


(b) Simulation result

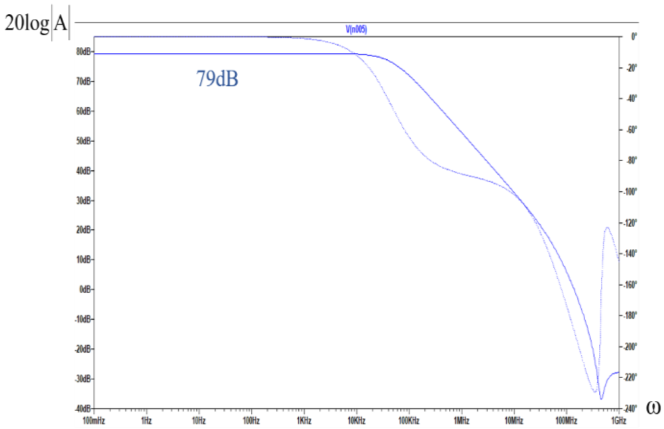
Fig 5. Differential amplifier with resistor load

3.2 Basic Bipolar Differential Amplifier with Active Load

In the circuit of Fig 6(a), we replace the resistor load with a simple active load, and the gain of the amplifier has been increased (Fig. 6 (b)).



(a) Circuit schematic

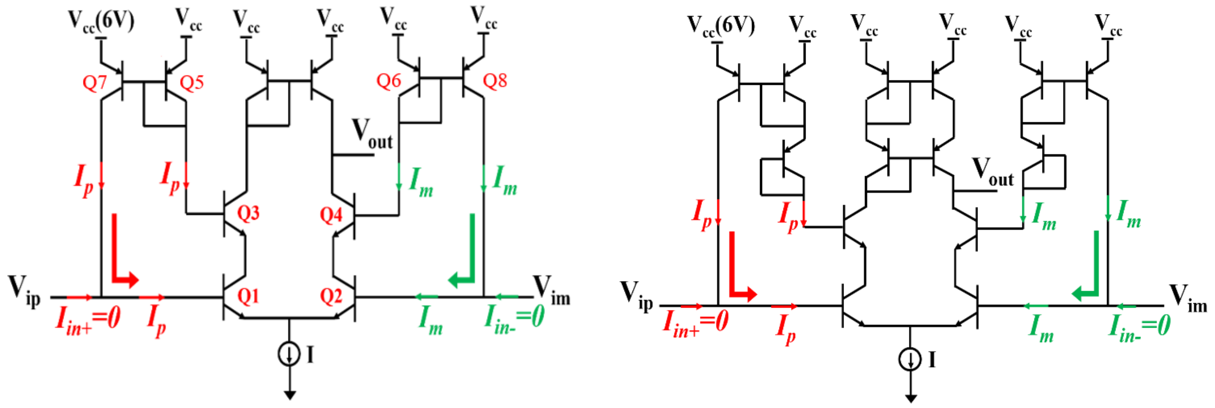


(b) Simulation result

Fig 6. Differential amplifier with simple active load

3.3 Bipolar Differential Amplifier with Base Current Compensation and Active Load

In order to obtain the high input impedance, we use the base current compensation technique to make the input current I_{in+} and I_{in-} as small as possible. In Fig 7(a), we connect two current mirrors (Q5, Q7) and (Q6, Q8) to the bases of Q1 and Q2 respectively. Since the current in the left part of the current mirror (Q5, Q7) is equal to the current in the right part and the base current of Q1 is equal to the base current of Q3, the input current I_{in} is very small. More specifically, compared with I_{in+} in Fig 6(a), I_{in+} in Fig 7(a) reduces to 1/24. The current mirror (Q6, Q8) and I_{in-} are in the same situation as the current mirror (Q5, Q7) and I_{in+}. Consequently, this amplifier has high input impedance. To improve the gain of the differential amplifier, we replace the simple active load with the cascade active load as shown in Fig. 7 (b).

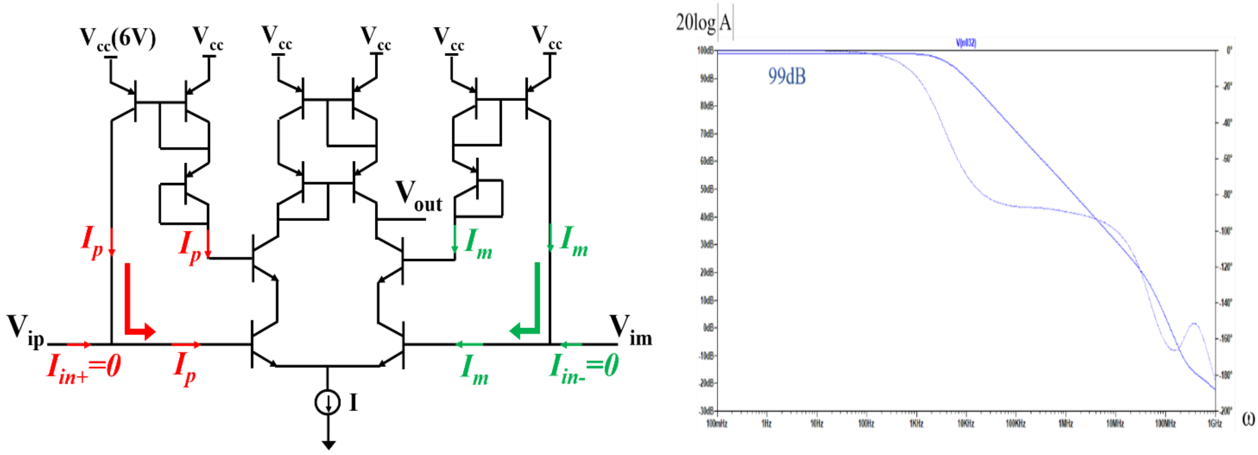


(a) Simple active load (b) Cascode active load

Fig 7. Differential amplifier with base current compensation and simple active load

3.4 Bipolar Differential Amplifier with Base Current Compensation and Wilson Active Load

In this subsection, we investigate theusage of the Wilson active load, which balances the base current effects of the active load right and left parts. We see from Fig. 8 (a), (b) that the differential amplifier with the Wilson active load has a high voltage gain, though the second pole effects have to be considered. At the same time, the input currents (I_{in+}, I_{in-}) is almost equal to 0.



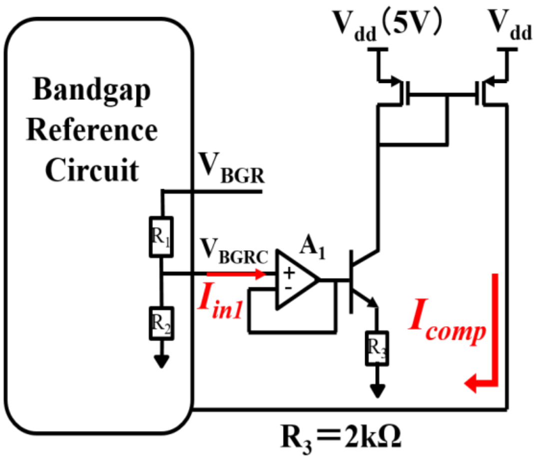
(a) Circuit schematic (b) Simulation result

Fig 8. Differential amplifier with the base current compensation and the Wilson active load.

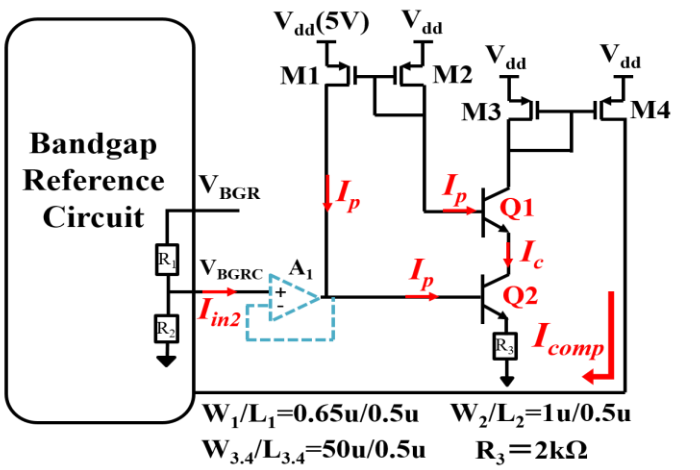
4. Curvature Compensation Circuit in Bandgap Reference Circuit with Base Current Compensation

Fig. 9(a) shows a bandgap reference circuit with curvature compensation circuit [5]. The curvature compensation circuit is in the right part and it effectively improves the total temperature characteristics of the output voltage. However, the current flowing from the bandgap reference circuit to curvature compensation circuit will induce the inaccuracy of V_{BGR}, so that a voltage follower circuit is used; however, it consumes some extra power.

Utilizing the base current compensation technique in this curvature compensation circuit can solve this problem as shown in Fig. 9 (b), by regulating the sizes of M_1, M_2, M_3, M_4 to make the base current of Q1 equal to the base current of Q2. Because of the current mirror, the base current of Q1 is also equal to the I_{ds} of M_1. Therefore, compared with I_{in1} in Fig. 9 (a), I_{in2} in Fig. 9 (b) can reduce to 2nA. Then the curvature compensation circuit has a high input impedance; in this case, the voltage follower A_1 is not required. The V_{BGR} has a reliable and simple curvature compensation circuit.



(a) Curvature compensation circuit



(b) Curvature compensation circuit with base current compensation

Fig. 9. Curvature Compensation Current in Bandgap Reference Circuit with base current compensation

5. Summary

In this paper, we have introduced two base current compensation techniques used in bipolar transistor current mirror circuit and in bipolar differential amplifier circuit respectively.

In current mirror circuit, we combine the base current compensation technique with PNP level-shift configuration in the cascode current mirror circuit; not only the deviation between the input current and the output current is reduced but also the circuit has a lower output voltage that can maintain the output current stable. This is suitable for low supply voltage operation with high output impedance current mirror.

Furthermore, we have investigated a bipolar differential amplifier circuit with base current compensation and Wilson active load, which has high input impedance and high gain. This is suitable as low power sensor interface circuit in the IoT system. Notice that this circuit needs to consider the values of β and Early voltage of the PNP transistors as well as the matching accuracy of pair PNP transistors, for mass production. In many bipolar processes, PNP transistor characteristics are not taken care of sufficiently, compared to NPN ones.

Lastly, we have demonstrated a curvature compensation circuit with the base current compensation that can provide a dependable and simple curvature compensation to the bandgap reference circuit.

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