Note 5: Current Mirrors

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Abstract This will be a quick note-sheet in our march towards the operational amplifier. There are many good resources online and in textbooks on current mirrors; we will therefore focus more on the practical considerations, especially for BJTs.

1 The Diode-Connected Transistor

A transistor in the diode configuration becomes a two terminal device; in the case of the BJT, it is actually a PN junction diode (convince yourself this is the case). BJTs came before MOSFETs so we still call the MOSFET version diode connected, even though the "diode" mosfet is a quadratic device, not exponential.

1.1 The Diode-Connected BJT

A diode connected BJT is essentially just a PN junction diode.

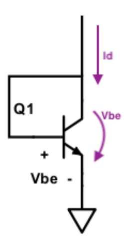

Fig. 1 The diode-connected BJT. It provides a nice diode drop across itself.

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This configuration is very handy for DC biasing, as it provides a diode drop (0.6-0.9V), *equivalent to a* V_{be}, across itself.

1.2 The Diode-Connected MOSFET

The MOSFET version is set up essentially the same way:

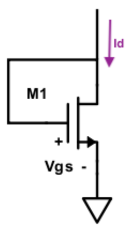

Fig. 2 The diode-connected MOSFET. Note that it is not an actual diode, since the MOSFET's V_{gs} has only a quadratic dependence (at best) with I_d.

The MOSFET version is also a two terminal device, but not actually a PN diode. It too is used often for DC biasing purposes, though it is a bit more tricky than the BJT version. To find the output voltage (note it is the same as V_{gs} here, in **Fig. 3**),

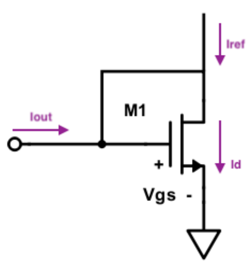

Fig. 3 The diode-connected MOSFET, except used as a voltage source/biasing method, assuming I_d is held fixed.

using the square law assumption:

$$I_d = I_{ref} + I_{out} = \frac{W}{L}\frac{\mu_n C_{ox}}{2}(V_{GS} - V_{Tn})^2 \tag{1}$$

$$V_{out} = V_{GS} = V_{Tn} + \sqrt{\frac{I_{ref} + I_{out}}{\frac{1}{2}\frac{W}{L}\mu_n C_{ox}}} \tag{2}$$

1.3 Output/Input Resistance of the Diode-Connected Transistor

Luckily the analysis is quick and easy in this case. We take the output to be the gate or base of the transistor (the same node as the source/collector). **Fig. 4** shows the setup for the output impedance (same as the input). By observation:

$$R_{out} = R_s = 1/g_m \parallel r_o \approx 1/g_m \tag{3}$$

Notice that it has a low impedance- this is a good thing (as we will see later). This

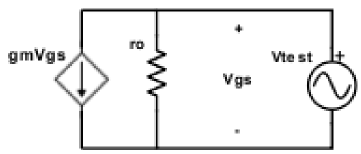

Fig. 4 Output resistance setup of the diode Connected transistor.

holds true for both the BJT and the MOSFET.

2 The MOSFET Current Mirror

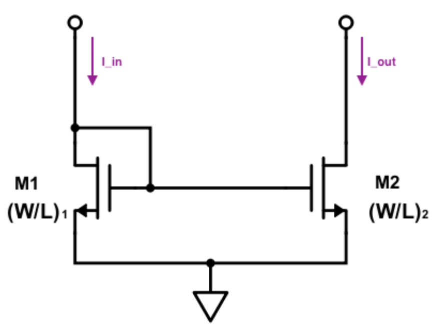

Fig. 5 The basic MOSFET current mirror. $I_{out} = \frac{(W/L)_2}{(W/L)_1} I_{in}$

Consider **Fig. 5**; if we apply some input current I_{in} to M1, then this current will flow through the source of M1 to ground because the gate of M2 has infinite resistance. This current will produce a suitable gate voltage (relative to ground) on M1, to satisfy the I-V square law relationship of the MOSFET. Notice then that the gate voltage of M1 is shared with the gate of M2. Therefore, M2 will have the same V_{gs} drop, and therefore the same current (if its W/L is the same).

$$I_{out} = \frac{(W/L)_2}{(W/L)_1} I_{in} \tag{4}$$

Notice as well that the input impedance is low: $1/g_{m1}$, which is perfect for a current input. Likewise notice that the output impedance is high: r_o, which is great for a current source.

Sources of Error It is important to note that for MOSFETs there is that pesky λV_{ds} term. Without this (meaning infinite output resistance) we would have a perfect current mirror. This factor however usually adds roughly 10-20% error. One way to limit this is to increase the output impedance of the circuit (notice right now it is r_o); this can be done for instance with a source resistor, but more commonly for MOSFET another set of transistors is used (cascode current mirror). The only drawback is the decreased voltage headroom allowed at the output (two pairs of transistors, each with at least a V_{ov} needed).

The Improved Cascode Current Mirror A simple cascode has limited voltage headroom; I will therefore show as well the more popular improved version, which can be used in low voltage supply applications.

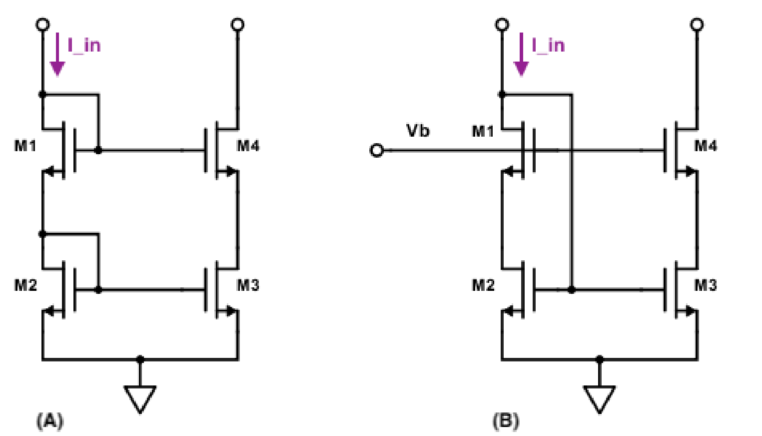

Fig. 6 A: the cascode current mirror. B: the low voltage cascode version.

First note that the output resistance has been improved to approximately $g_m r_o^2$, while keeping the same input impedance of $1/g_m$, for both of the two designs. The difference in comes in the minimum output voltage allowed.

For the basic cascode mirror in **Fig. 6 (A)**, it can be shown (and is a great exercise for the reader to do):

$$V_{out,min} = V_{ov1} + V_{ov2} + V_{tn} \tag{5}$$

The threshold requirement is removed by the use of **Fig 6 (B)**, which allows for:

$$V_{out,min} = V_{ov3} + V_{ov4} \tag{6}$$

This works so long as V_b is chosen appropriately to put M2 at the edge of saturation while keeping M1 in saturation as well. This occurs if:

$$V_{GS1} + (V_{GS2} - V_{tn2}) \leq V_b \leq V_{GS2} + V_{tn1} \tag{7}$$
$$and\ V_{ov1} \ll V_{tn2} \tag{8}$$

A fantastic discussion on the cascode current mirror and its improved version can be found in [1]. It is a highly recommended read.

3 BJT Current Mirrors

The BJT current mirror operates by the same method as the MOSFET version, but with a few key differences.

First and foremost is the issue of base-drive: a current mirror supplying large amounts of current throughout a circuit may result in unacceptable base currents.

The basic emitter degenerated BJT mirror The first major difference in BJT mirrors is that in almost all practical implementations, they must be used with emitter degeneration. The reason is simple: V_{be} (think "diode turn on voltage") variation. This is caused by a variety of factors: temperature, process variation, and mismatches[1]. Due to the BJT's exponential response however, even a tiny change in V_{be} causes *significant* error in the output. Emitter degeneration mitigates this by instead making the current dependent on the *magnitude of the emitter resistor*, which generally is less susceptible to process variation and mismatches[2]. Neglecting the finite base impedance, we can see by simple KVL (**Fig. 7**):

$$I_1 R_1 + V_{be1} = I_2 R_2 + V_{be2} \tag{9}$$
$$I_2 R_2 = I_1 R_1 + \Delta V_{be} \tag{10}$$
$$I_2 \simeq I_1 \frac{R_1}{R_2} \quad \text{if } \Delta V_{be} \text{ is small} \tag{11}$$

Notice how ΔV_{be} no longer has an exponential effect on the current, with the resistors setting the output current as expected. Also note as a bonus that emitter degeneration increases the output impedance of the mirror, though at the cost of voltage headroom (extra IR drop across the resistor). Emitter degeneration is not used as commonly for MOSFETs, since it is easier to just increase the length for increased output resistance, and because they do not have the same exponential error BJTs have.

[1] The temperature dependence of a V_{be} is actually utilized for temperature sensors and temperature independent biasing. This is covered in more advanced classes (DC biasing can actually be fun!).

[2] Emitter degeneration is actually a type of feedback, with the emitter resistor setting the feedback factor. As for the temperature dependence of the resistor? Well, resistances change with tempera-

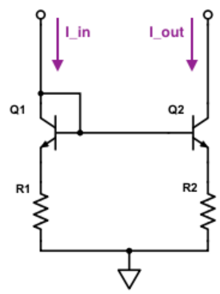

Fig. 7 The basic BJT mirror. $I_{out} = I_1 \frac{R_1}{R_2}$, ignoring base current.

3.1 The Improved BJT Current Mirror: Base Compensation

When large currents are mirrored, the base current of the BJT becomes a problem. Imagine for instance trying to provide a total of 10mA from an input current of $100\mu A$. Say $h_{fe} = 200$. Then $I_B = 10mA/200 = 50\mu A$. This is a problem, since this base current must come from the input current (and here we would lose half the input current)! What Q3 does therefore is supply the required large base current for us; essentially, it increases the equivalent "β" of the circuit to β^2 (because Q3 requires some base current as well; it would be $50\mu A/\beta$ in the previous example). This removes the error from the base current.

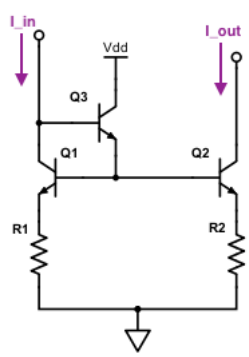

Fig. 8 The complete BJT current mirror, with Base compensation transistor Q3 and emitter degeneration.

ture, and it turns out this can be manipulated to help the analog designer (There really is a lot to DC biasing!).

3.2 BJT Cascode Version

While the same MOSFET cascode configurations can be used for BJT implementations, there are some useful tweaks made to improve the performance for BJTs. Shown in the figure below is the Full Wilson Current Mirror.

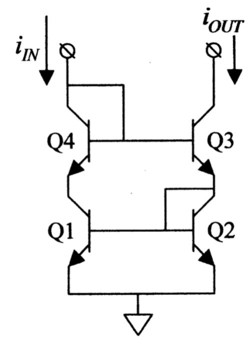

Fig. 9 The Full (4 transistor) NPN Wilson Current Mirror [4]

It can be shown (see the Analog Devices reference, [3]) that this configuration significantly reduces any base current mismatches that may occur. It also has a high output impedance due to the negative feedback from Q3, through Q1, and eventually back to the base of Q3.

3.3 The Simplest Current "Source" and Mirror

The big question of course is where does the reference current come from? Let's consider the simplest (and poorest) method: just sticking in a resistor[3]. Notice that in this circuit, the output current is now a function of the supply voltage. This is actually terrible: batteries for instance change over 50% over their lifetime, before "dying." A customer would be very mad if his product lasted only a week! In integrated circuits, supplies also have a tremendous amount of noise (from the rest of the chip)- you don't want this affecting your bias currents!

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[3] This is not even considered a current source by most textbooks since it has none of the properties a good current source should have, besides creating a current.

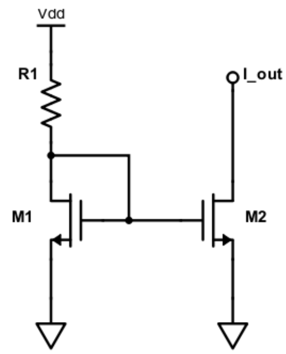

Fig. 10 Take One: Sticking in a resistor. Notice the output current is directly related to Vdd and R1!

3.4 Practical Supply-Independent Biasing: The Base-Emitter Referenced Current Source

For almost all circuits, Figure 10 just isn't going to cut it. Instead, consider the circuit shown below, in Figure 11.

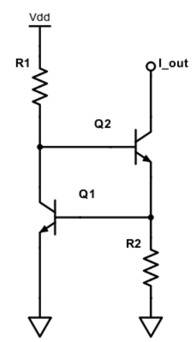

Fig. 11 The Vbe Current Reference. The current depends on the V_{be} of Q1. The feedback provided by Q2 provides the additional benefits of increased output impedance and less variation in output current from supply and mismatch variations. Instead of ground, use VSS.

To understand how this circuit works, first recognize that Q2 must supply enough current to allow Q1 to operate; for low supply voltages therefore, this circuit will not work. Neglecting base currents, and defining the current through R_1 as I_{IN}, we know that:

$$V_{be_1} = V_T \ln(\frac{I_{IN}}{I_{S_1}}) \tag{12}$$

We can then see that the output current is set by the voltage drop across R_2, set by Q1 to be V_{be_1}.

$$I_{OUT} = \frac{V_{be_1}}{R_2} = \frac{V_T}{R_2}\ln(\frac{I_{IN}}{I_{S_1}}) \tag{13}$$

$$I_{IN} = \frac{V_{dd} - 2V_{be}}{R_1} \tag{14}$$

Note that because the output current is proportional to the *log* of Vdd, we have significantly decreased the affect of the supply!

3.5 What about MOSFET Current Sources?

There are CMOS current sources. Replacing the BJTs in the Vbe Current Reference with MOSFETs results in the threshold voltage current reference. However, the equations are complicated, and even worse, for MOSFETs, threshold voltages are very imprecise and vary all over the place. Building a reference current based on a value you have no idea about is never a good idea! Most CMOS references actually use the *parasitic BJTs* that are intrinsic in the MOSFET's structure to create Vbe reference circuits! MOSFET implementations of these circuits will be further explored in later classes, in addition to the temperature and process dependencies of biasing.

3.6 Real Current Sources: Bootstrapping!

Previously we had looked at the effect of the power supply on the input current. We define an important term to relate the effect of the power supply on the output, known as the PSRR, or Power Supply Rejection Ratio. For current mirrors and sources, PSRR is defined as the change in output current due to a change in the supply voltage (for op-amps, it is the change in output voltage). Notice that while the V_{be} referenced source mentioned previously had a fairly good PSRR, the output current still depended slightly on the power supply due to the input resistor. To almost fully remove the dependence on the power supply, a technique known as self-biasing or bootstrapping is used.

In a self biased circuit, the input current depends on the output current itself (and vice versa!), *completely removing the power supply from the equation*. Too see how this works, look at figure 12, from Gray & Meyer- we can set the input current equal to the output current by the use of a current mirror! We know the current source will have some type of logarithmic input-output current behavior (as seen from the V_{be} reference), and we know that the current mirror demands a 1:1 input to output ratio. As seen in figure (b), this means that the intersection of these two equations represents the operating point of the circuit! Note that these circuits require a special start-up circuit. This is because a bootstrapped circuit will otherwise happily have its input and output currents both be zero.

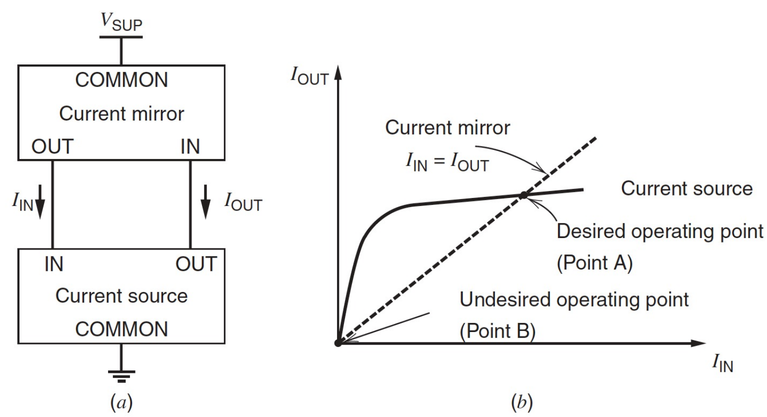

Fig. 12 (a): The concept of self biasing. (b) How to find the two possible operating points [2].

Below we present an example bootstrapped current source, in figure 3.6. Note that this circuit is a bit different than the V_{be} reference used in 2.4. Instead, this is known as a V_T reference. To see how it works, consider transistors Q1 and Q2. First assume that n=1 and ignore the Wilson current mirror Q4-Q7. We know that for a BJT $I_c = I_s e^{V_{be}/V_T}$, ignoring the Early effect. Using this, (and ignoring the base current) derive the following transcendental equation (hint: find the base voltage due to I_{in} first):

$$I_{out} R_1 = V_T \ln \frac{I_{in}}{I_{out}} \frac{I_{s1}}{I_{s2}} \tag{15}$$

Now we can consider the effect of the mirror and the multiple emitters of Q1. In general, multiple emitter BJTs act as a single device, except that the emitter current is split evenly between the two emitters; basically the base drive sets the *total* collector current, which is then split between both emitters. Here however the emitters are all connected to R1. The trick is that adding an extra emitter increases the reverse-saturation current (remember from diodes this current is proportional to the area). Because we have n emitters in Q1, $I_{s1} = nI_{s2}$. Then, using the fact that the mirror forces $I_{in} = I_{out}$, and plugging into 15 we have the final result:

$$I_{out} = \frac{V_T}{R2} \ln n \tag{16}$$

Now we will explain the startup circuit. At time equals zero, assume all nodes except the supply have zero voltage. We will therefore have a current flowing through R2. Some of this current will flow into the base of Q3 and turn it "on". Q3 will then force a current through Q7 and Q5, which is mirrored by Q6 and Q4 into Q2,

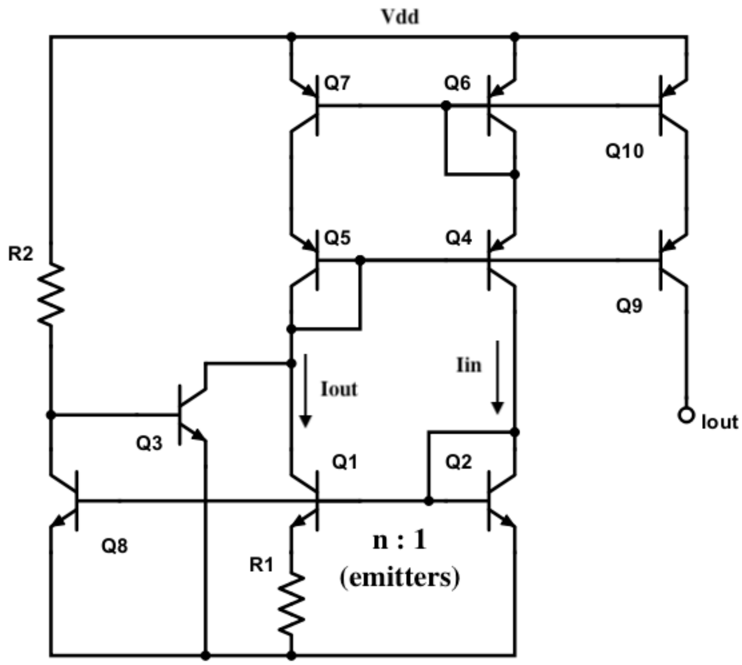

Fig. 13 A basic self biased current source with a start up circuit.

turning on the entire circuit! Once on, notice that Q8 turns on as well, which pulls current through R2 and then turns off Q3!

This circuit will turn up many times in your analog career. In later classes, you will discover that (with some tweaks) this circuit can be used to create what is known as a bandgap reference, which creates a reference voltage equal to the bandgap of silicon *across all temperatures* (as a preview, notice that the thermal voltage is proportional to temperature, whereas resistors are inversely proportional to temperature. With some tweaks can theoretically tune these temperature coefficients to cancel each other out).

4 Summary

In this notesheet we have observed some common current mirrors, which will continue to show up in many op amp examples. This notesheet was purposely short (lest the reader become *too* tired of my writing) due to the many resources already available . Some useful references are of course the ubiquitous Gray & Meyer [2], and [3]. Note that I chose not to describe current sources and temperature effects since they are best left for more advanced classes and notes (despite their interesting nature).

References

1. Razavi, Behzad. *Design of Analog CMOS Integrated Circuits*, 2nd Ed. pp. 138-146.
2. Gray, Hurst, Lewis, & Meyer (2001). *Analysis and Design of Analog Integrated Circuits*. New York: Wiley.
3. Analog Device's Educational Content `https://wiki.analog.com/university/courses/electronics/text/chapter-11`
4. Wikipedia Wilson Current Mirror. `https://en.wikipedia.org/wiki/Wilson_current_mirror#/media/File:WilsonModified4.gif`