Class 4: Transistors I: First Model

Topics:

- Two simple views of transistor operation:
  - Simple: $I_C = I_B \bullet \beta$
  - Simpler: $I_C \approx I_E$; $V_{BE} = 0.6V$
- Applying the models: standard circuits:
  - Follower
  - Current source
  - common-emitter amp
  - push-pull
- Recapitulation: what the standard circuits look like

Preliminary: **Introductory Sketch**

An Intuitive Model:

A transistor is a *valve*:

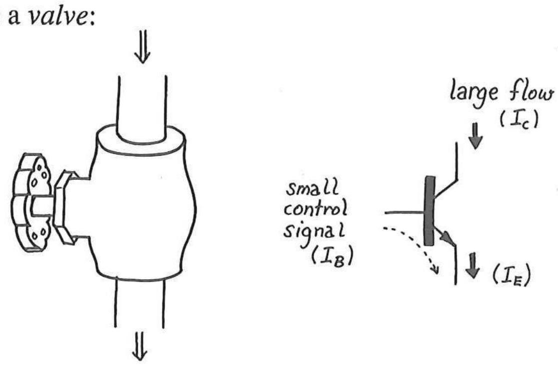

Figure N4.1: A transistor is a valve (not a pump!)

Notice, particularly, that the transistor is not a *pump*: it does not force current to flow; it permits it to flow, to a controllable degree, when the remainder of the circuit tries to force current through the device.

Ground Rules:

Text sec. 2.01

Ground Rules:

For NPN type:

1. $V_C > V_E$ (by at least a couple of tenths of a volt)
2. "things are arranged" so that $V_B - V_E$ = about 0.6 v (V_{BE} is a diode junction, and must be forward biased)

We begin with ***two views of the transistor***: one simple, the other *very* simple. (Next time we will complicate things.)

Text sec. 2.01

Pretty simple: current amplifier: $I_C = \text{Beta} \bullet I_B$

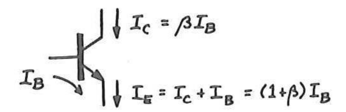

Figure N4.2: Transistor as *current*-controlled valve or amplifier

Very simple: say nothing of Beta (though assume it's at work);

- Call V_{BE} constant (at about 0.6 v);
- call $I_C = I_E$.

A. The simple view: using Beta explicitly

You need the first view to understand how a ***follower*** changes impedances: small (change in-) current in —> large (change in-) current out:

Text sec. 2.03
Lab 4-2

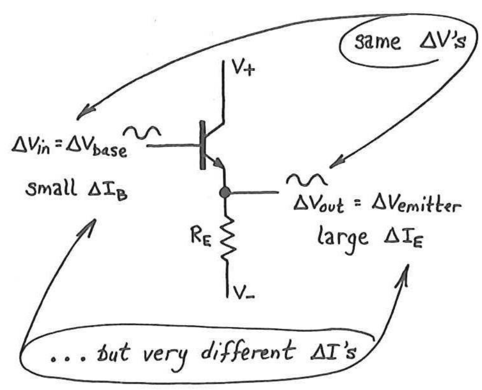

Figure N4.3: How a follower changes impedances

And here is a corny mnemonic device to describe this impedance-changing effect. Imagine an ill-matched couple gazing at each other in a dimly-lit cocktail lounge—and gazing through a rose-colored lens that happens to be a follower. Each sees what he or she wants to see:

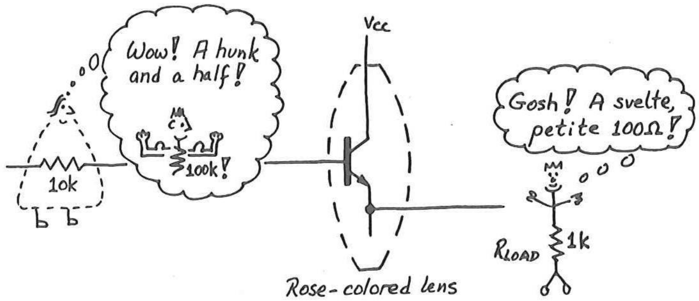

Figure N4.4: Follower as rose-colored lens: it shows what one would *like* to see

*Complication: **Biasing***

Text sec. 2.05

We can use a *single* power supply, rather than *two* (both positive and negative) by pulling the transistor's *quiescent* voltages ***off-center***—biasing it away from zero volts:

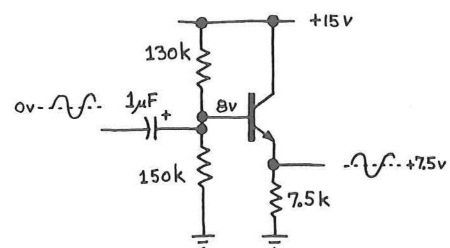

Figure N4.5: Single-supply follower uses *biasing*

The biasing divider must be stiff enough to hold the transistor where we want it (with V_{out} around the midpoint between V_{CC} and ground). It must not be too stiff: the *signal* source must be able to wiggle the transistor's base without much interference from the biasing divider.

The biasing problem is the familiar one: Device A drives B; B drives C. As usual, we want Z_{out} for each element to be low relative to Z_{in} for the next:

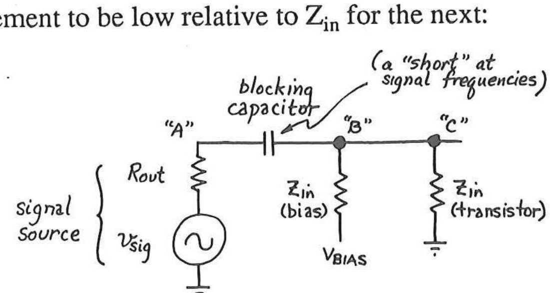

Figure N4.6: Biasing arrangement

You will notice that the biasing divider reduce the circuit's input impedance by a factor of ten. That is regrettable; if you want to peek ahead to complications, see the "bootstrap" circuit (sec. 2.17) for a way around this degradation.

You will have to get used to a funny convention: you will hear us talk about impedances not only *at* points in a circuit, but also *looking* in a particular direction.

Text sec. 2.05

For example: we will talk about the impedance "at the base" in two ways:

- the impedance "looking into the base" (this is a characteristic of the transistor and its emitter load)
- the impedance at the base, looking back toward the input (this characteristic is *not* determined by the transistor; it depends on the *biasing* network, and (at signal frequencies) on the *source impedance*.

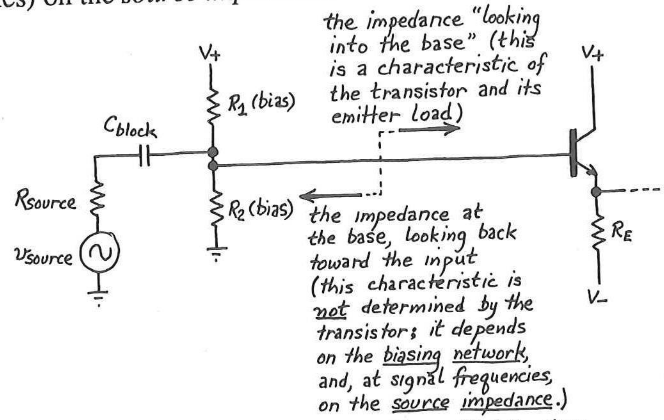

Figure N4.7: Impedances "looking" in specified directions

B. The simplest view: forgetting Beta

We can understand—and even design—many circuits without thinking explicitly about Beta. Try the simplest view:

- Call V_{BE} constant (at about 0.6 v);
- call $I_C = I_E$.

This is enough to let one predict the performance of many important circuits. This view lets one see—

- That a follower follows:

Text Sec. 2.03

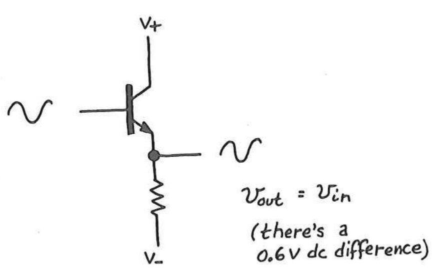

Figure N4.8: Follower

- That a current source provides a constant output current:

Text sec. 2.06

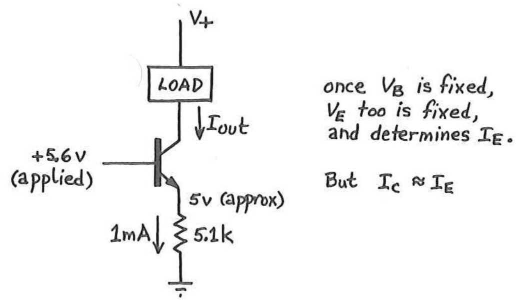

Figure N4.9: Current source

- That a common-emitter amplifier shows voltage gain as advertised:

Text sec. 2.07

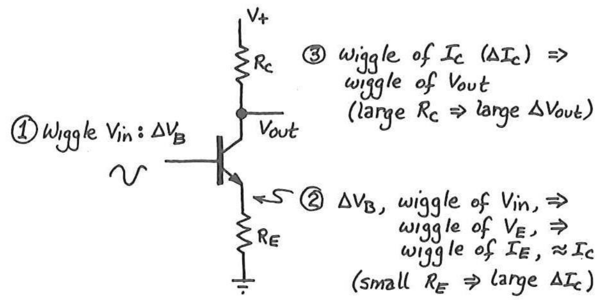

Figure N4.10: Common-emitter amp

- That a push-pull works, and also shows distortion:

Text sec. 2.14,

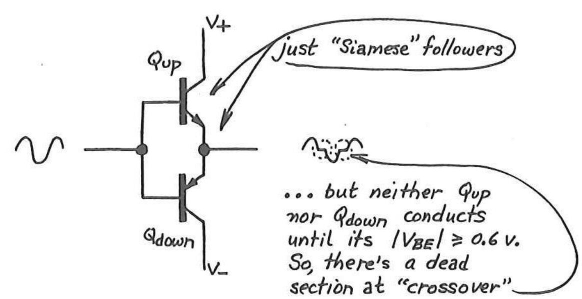

Figure N4.11: Push-pull

Recapitulation: the important transistor circuits at a glance

To get you started on the process of getting used to what bipolar transistor circuits look like, and to the crucial differences that come from what *terminal* you treat as output, here is a family portrait, stripped of all detail:

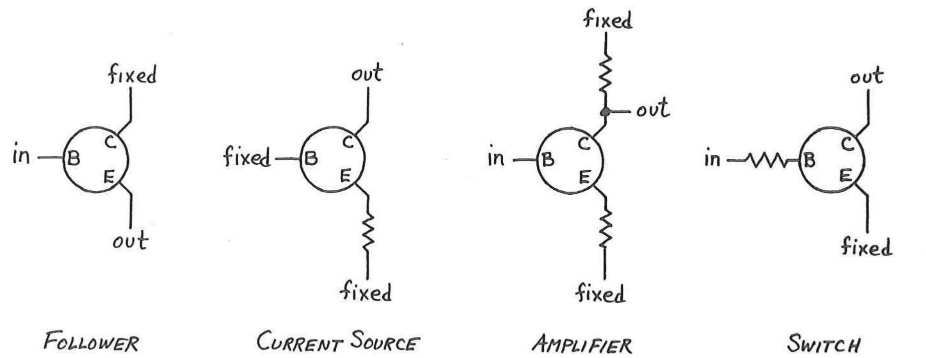

Figure N4.12: The most important bipolar transistor circuits: sketch

Next time, we will begin to use the more complicated *Ebers-Moll* model for the transistor. But the simplest model of the transistor, presented today, will remain important. We will always try to use the simplest view that explains circuit performance, and often the very simplest will suffice.

Class 5: Transistors II:
Corrections to the first model: Ebers-Moll: r_e; applying this new view

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Topics:

- *old:*
  - Our first transistor model:
    - ♦ Simple: $I_C = \beta \times I_B$
    - ♦ Simpler: $I_C \approx I_E$; $V_{BE} = 0.6V$
- *new:*
  - transistor is controlled by V_{BE}: Ebers-Moll view
  - applications: circuits that baffle our earlier view:
    - ♦ current mirror
    - ♦ common-emitter amp with *no* R_E
    - ♦ R_{out} of follower driven by R_{source} of moderate value
  - complications:
    - ♦ temperature effects
    - ♦ Early Effect

Our first view of transistors held that two truths were pretty much sufficient to describe what was going on—

1. $V_{BE} = 0.6$,
   and
2. $I_E \approx I_C = \beta \times I_B$

This account can take us a long way; V_{BE} = *constant* = *0.6V* is often a good enough approximation to allow understanding a schematic or, say, designing a not-bad current source.

Sometimes, however, we cannot settle for this first view. Some circuits require that we recognize that in fact V_{BE} varies with I_C. In fact, the relation looks just like the diode curve already familiar to you (it differs only in slope):

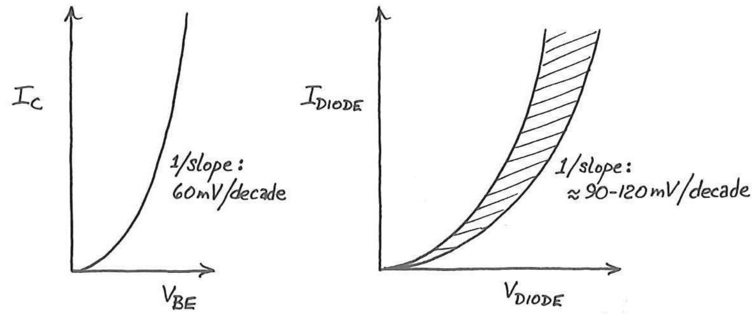

Figure N5.1: V_{BE} *does* vary with I_C, after all. In fact, I_C vs. V_{BE} looks a lot like a diode's curve

You knew, anyway, that the transistor had limited gain, so you would guess that a circuit like the one just below has a gain limited by the properties of the transistor—the I_C vs V_{BE} curve shown above.

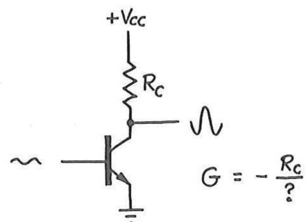

Figure N5.2: Infinite-gain amplifier?

A naive application of the rule $G = -R_C/R_E$ would imply infinite gain; but you know better. Wiggling the input = wiggling V_{BE}, and that produces a limited variation of I_C, which in turn produces a limited variation in V_{out}.

"Intrinsic emitter resistance:" r_e

You can describe this effect handily by drawing it as a little resistor in series with the emitter (for a derivation of r_e, see end of these notes):

Text sec. 2.10
"Rule of Thumb No. 2"

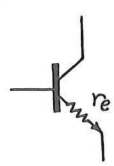

Figure N5.3: "Little r_e"—the intrinsic emitter resistance

This "resistance" we call "little r_e;" please note that it is ***not*** a resistor planted in the transistor; it only models the limited gain of the device.

Another way to say this is to say that r_e is the slope of the gain curve—but with the curve plotted on its side, with V_{BE} vertical (just so it will have the conventional units of resistance):

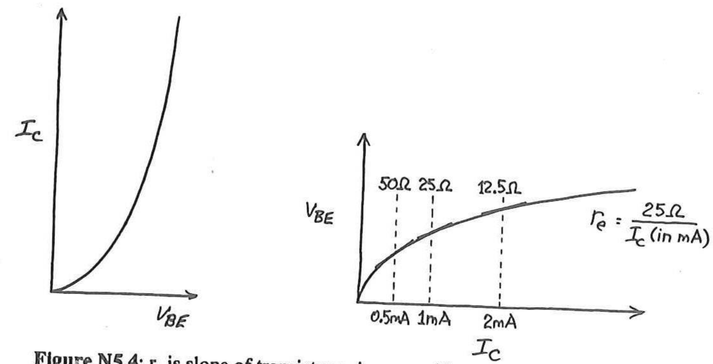

Figure N5.4: r_e is slope of transistor gain curve, if you turn the plot on its side

Evidently the value of r_e varies with I_C. Specifically, here's our rule of thumb:

$$r_e = 25 \text{ ohms}/(I_C \text{ (in mA)})$$

Watch out for the denominator: you must write "1 mA" as 1, not $1 \cdot 10^{-3}$. If you forget this, your answers will be off by even more than what we tolerate in this course!

r_e, "little r e," expresses the Ebers-Moll equation in a convenient form, and you will use this simplifying model more often than you will use the equation.

But we should notice what the Ebers-Moll equation says, before we go on:

Text sec. 2.10

Ebers-Moll

$$I_C = I_S(e^{V_{BE}/(kT/q)} - 1)$$

(treat I_S as a constant, for any particular transistor, except that I_S grows fast with temperature; more on this later)

(negligible)

Ignoring the "-1" term, we can say simply that I_C grows exponentially with V_{BE}.

In addition, we might as well plug in the room-temperature value for that complicated expression "kT/q:" 25 mV. Then Ebers-Moll doesn't look so bad:

Ebers-Moll: (slightly simplified)

$$I_C \approx I_S\, e^{V_{BE}/25\text{mV}}$$

This equation is most often useful to reveal the relative values of I_C as V_{BE} changes. What happens, for example, if you increase V_{BE} by 18mV? Let's call the old I_C "I_{C_1}," the new one "I_{C_2}:

$$I_{C_2} / I_{C_1} = \{I_S\, e^{V_{BE_2}/25\text{mV}}\} / \{I_S\, e^{V_{BE_1}/25\text{mV}}\}$$

But that is just

$$e^{(18\text{mV}/25\text{mV})} \approx 2$$

This is a number perhaps worth remembering: 18mV ΔV_{BE} for a doubling of I_C; also sometimes handy: 60mV ΔV_{BE} per *decade* (that is, *10X*) change in I_C.

Applying the Ebers-Moll view to circuits

Here, for example, is a circuit that makes no sense without the help of this view of transistors:

* *current mirror*

Text sec. 2.14
Lab 5-3

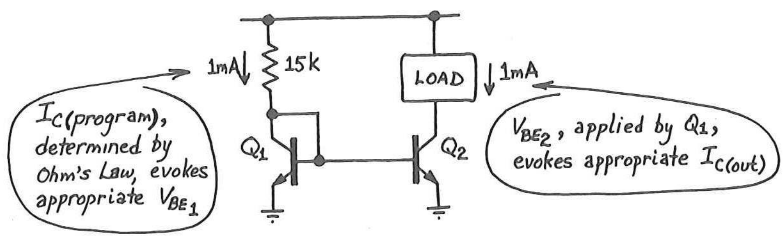

Figure N5.5: Current mirror: Ebers-Moll view *required*

Why is a mirror Useful? It makes it easy to link currents in a circuit, matching one to another. It also shows very wide *output compliance*. But for our present purposes it is most useful as a device to demonstrate the power of the Ebers-Moll view.

It's easy to make $I_{\text{C-program}} = I_{\text{C-out}}$, and only a little harder to scale $I_{\text{C-out}}$ relative to $I_{\text{C-program}}$.

You will find in Lab 5 that the mirror departs rather far from this ideal model. *Early effect* and *temperature* effects both disturb it. We will learn later how to fight these problems; for now, let's leave the mirror in its simplest form, as shown above.

Other consequences of this amended view of transistor operation:

It brings some circuits down to earth:

* *a ceiling on gain* (a recapitulation): no infinite-gain amps

Text sec. 2.12

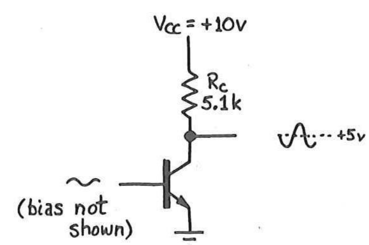

Figure N5.6: What gain? Not infinite

* *a floor under* Z_{out}

Text sec. 2.11

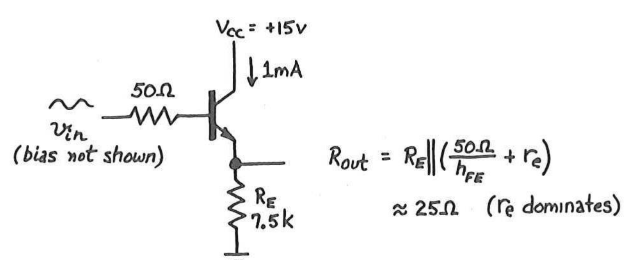

Figure N5.7: What R_{out}? Not 0.5 ohms

Let's look closely at the problem of the ***grounded-emitter*** amplifier. You knew, anyway, that its gain was not infinite. Now, with the help of r_e, we can evaluate the gain.

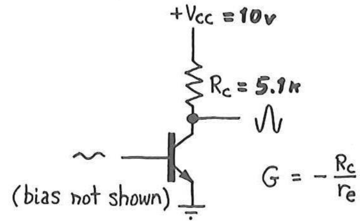

Figure N5.8: Grounded emitter amp again

We can use our familiar rule to evaluate gain here, simply drawing in r_e (at least in our heads). To evaluate r_e we need a value of I_C. There is no single right answer; the best we can do is specify I_C at the quiescent point—where V_{out} is centered.

Roughly, then,

$$G = -5.1k\Omega/25\Omega \approx -200$$

That's high. But evidently the gain is *not constant*, since I_C must vary as v_{out} moves (indeed, it is variation in I_C that *causes* v_{out} to move.)

Here's the funny "barn-roof" distortion you see (this name is not standard, incidentally) if you feed this circuit a small triangle:

Text sec. 2.12; compare fig. 2.36; Lab 5-2

Vout ⇒	Ic ⇒	re ⇒	Gain
7.5v	0.5 mA	50Ω	100
5v	1mA	25Ω	200
0.2v	2mA	12.5Ω	400

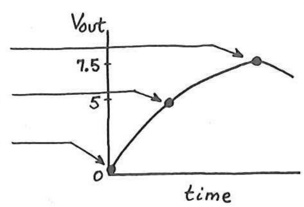

Figure N5.9: Gain of grounded-emitter amp varies during output swing (call it "barn-roof" distortion): Gain evaluated at 3 points in output swing

The plots below show how gain varies (continuously) during the output swing:

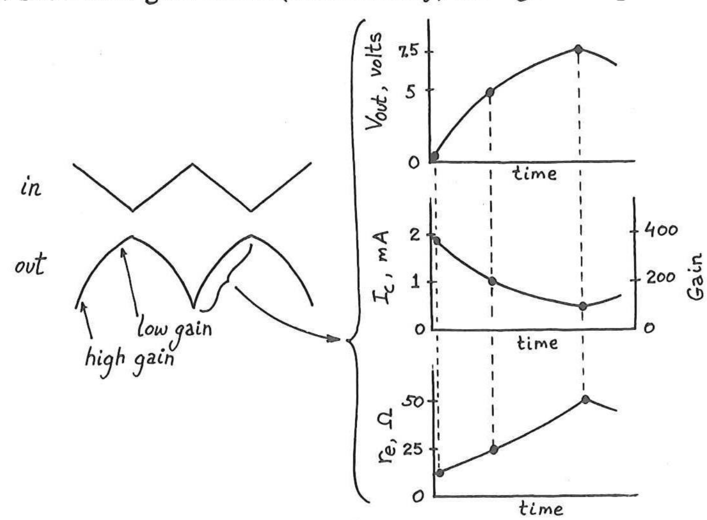

Figure N5.10: During swing of V_{out}, I_C and thus r_e and gain *vary*

This is bad distortion: –50% to +100%! What is to be done?

Remedy: emitter resistor

One cannot eliminate this variation in r_e (—can one?), but one can make its effects negligible. Just add a constant resistance much larger than the varying r_e. That will hold the denominator of the gain equation nearly constant.

Text sec. 2.12

With emitter resistor added, gain variation shrinks sharply:

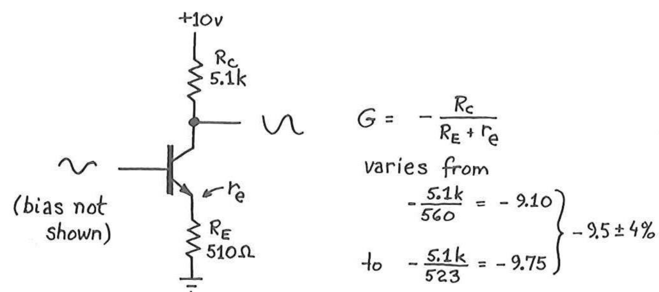

Figure N5.11: Emitter resistor cuts gain, but also cuts gain *variation*

r_e still varies as widely as before; but its variation is buried by the big constant in the denominator.

Circuit gain now varies only from a low of –9.1 to a high of –9.75: a –4%, +3% variation about the midpoint gain of 9.5.

Punchline: emitter resistor greatly reduces error (variation in gain, and consequent distortion). This we get at the price of giving up some gain. (This is one of many instances of Electronic Justice: here, *those greedy for gain will be punished: their output waveforms will be rendered grotesque.*)

We will see shortly that the emitter resistor helps solve other problems as well: the problem of temperature instability, and even distortion caused by *Early effect*. How can a humble resistor do so much? It can because in the latter two cases the resistor is applying *negative feedback*, a design remedy of almost magical power. Later in these notes, we will look more closely at how the emitter resistor does its job. And in Chapter 4 we will see negative feedback blossom from marginal remedy to central technique. Negative feedback is lovely to watch. Many such treats lie ahead.

If you are in the mood to find negative feedback at work in today's lab, you can find it in the simple-looking circuit fragment: the *program* side of the current mirror:

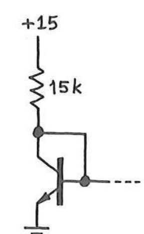

Figure N5.12: Subtle negative feedback: programming side of the current mirror

See if you can explain to yourself how this circuit works. Hint: nearly all of the current flows not in the base path, but from collector to emitter.