DESIGN WITH DISCRETE TRANSISTORS.

Notes and jottings on audio design with discrete transistors. Thank you to all of those who have sent encouraging feedback!

Diagrams are scaled down for convenience. Use "view image" or "save image" on browser to get full-size version.

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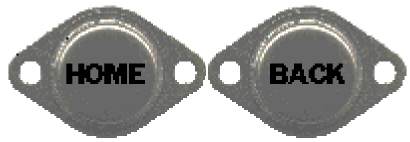


to The Institute

CONTENTS.

INTRODUCTION.

This discourse deals with small-signal design using discrete transistors, specifically BJT's. It is not an exhaustive guide, but concentrates on audio issues, and so many things found in standard textbooks are skated over. It does however give information that I do not think appears anywhere else, mainly on the distortion behaviour of various configurations.
Some of this information may seem pretty much historical. That doesn't mean we should throw it away. You never know when you might need it...

Circuitry made with discrete transistors is not obsolete. It is appropriate when:

1. **A load must be driven to higher voltages than the opamp can sustain between the supply rails.**
2. **A load requires more drive current, because of its low impedance, than an opamp can provide without overheating or current-limiting; eg any audio power amplifier**
3. **The best possible noise performance is required. Discrete bipolar transistors can outperform opamps, particularly with low source resistances, say 500 Ohms or less. The commonest examples are moving-coil head amps and microphone preamplifiers.**

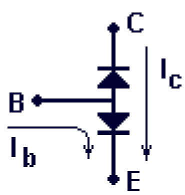
HOW TRANSISTORS WORK.

BIPOLAR JUNCTION TRANSISTORS. (BJTs)
It has taken a little while to put this section together; describing bipolar transistor operation in a short space is not so easy.

There is one thing to get straight first. The transistor is a voltage-operated device. What counts is the base-emitter voltage, or Vbe. Certainly a BJT needs base current to flow for it to operate, but this is really an annoying imperfection rather than the basis of operation. I appreciate this may take some digesting; far too many textbooks say something like "a small current flowing into the base controls a much larger current flowing into the collector". There is no prize for locating the source of this quotation. In fact the only truly current-operated amplifying device that comes to mind is the Hall-effect multiplier, and you don't come across those every day. I've certainly never seen one.

Transistor operation is thus: if the base is open-circuit, then no collector current flows, as the collector-base junction is effectively a reverse-biased diode. There is a little leakage through from the collector to the emitter, but with modern silicon BJTs you can usually ignore it.

When the base is forward biased by taking it about 600 mV above the emitter, charge carriers are launched into the base region. Since the base region is narrow, only a small proportion of these carriers are snared and become the base current. The vast majority shoot through into the collector, to form the collector current Ic.



$$I_c = I_s \cdot \left[e^{\left(\frac{V_{be}}{V_t}\right)} - 1 \right]$$

where $V_t = \frac{k \cdot T}{q}$ = 26 mV at 25 C

T= abs temp

$q := 1.6022 \cdot 10^{-19} \cdot coul$ $\quad k := 1.381 \cdot 10^{-23} \cdot \frac{joule}{K}$

Fig 0: Current flow through a bipolar transistor, and the fundamental transistor equation.

T is the absolute temperature in Kelvin.
q is the charge on an electron.
k is the Boltzmann constant (NOT the Stefan-Boltzmann constant, which is quite different)

THE TRANSISTOR LAW. ***(in preparation)***
Every transistor obeys it with startling accuracy over nine or ten decades of Ic, which is a pretty broad hint that we are looking at the fundamental mechanism. In contrast, beta varies with Ic, temperature, and just about everything else. The collector current is to a first approximation independent of collector voltage- in other words it is a current-source output. The qualifications to this are:
1: This only holds for Vce above, say, 2 Volts.
2: It is not a perfect current-source; even with a high Vce, Ic remains a weak function of Vce. This is called Early Effect, after Dr Early, and has nothing to do with timing or punctuality. The same effect when the transistor is operated in reverse mode- a perversion that will not concern us here- has sometimes been called Late Effect. Ho ho :(

BETA.
Beta is not a fundamental property of a BJT. Never design circuits that depend on beta. Unless of course you're making a transistor tester...

Here are some of the factors that affect beta. This should convince you that it is a shifty and untrustworthy parameter.

- **Beta varies with Ic.**
  First it rises as Ic increases, usually reaching a broad peak, then it falls off as Ic continues to increase.
- **Beta increases with temperature. This seems to be very little known. Most things, like leakage currents, get worse as temperature increases, so this makes a nice change.**
- **Beta is lower for high-current BJT types.**
- **Beta is lower for high Vceo BJT types.**
- **Beta varies widely between nominally identical examples of the same transistor type.**

A good refutation of the beta-centric view of BJTs is given in "Analogue Design: The Current-Mode Approach" Chapter 2, by Barrie Gilbert. Highly recommended: ISBN 0 86341 215 7.
