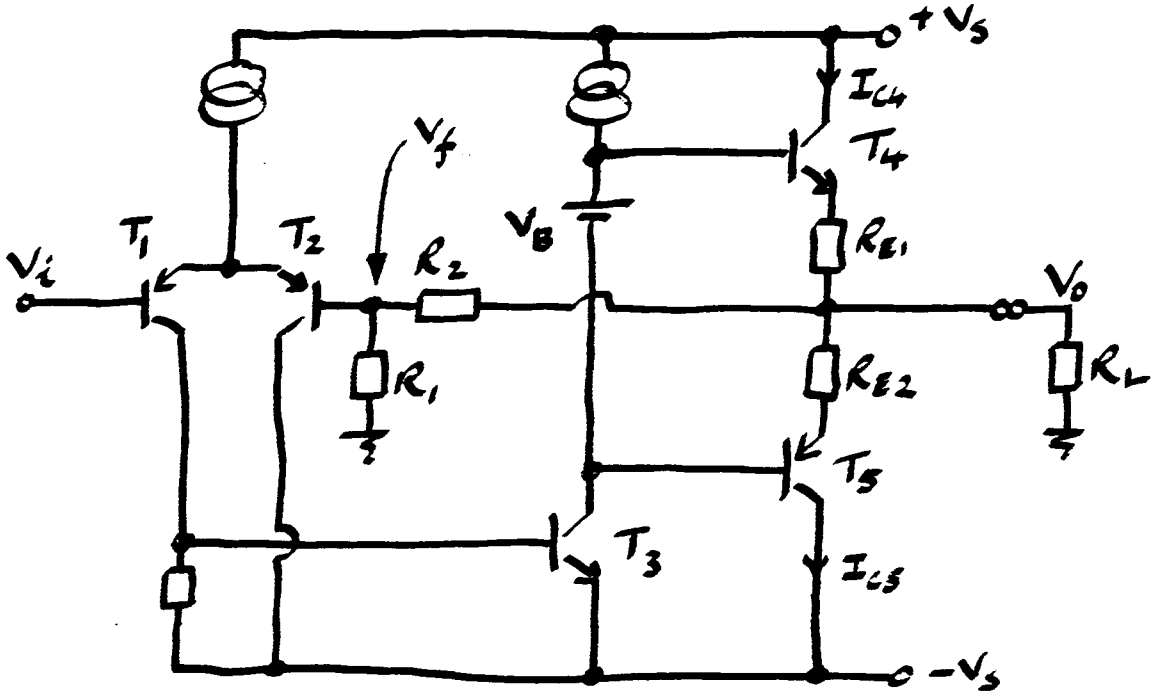
Power Amplifiers

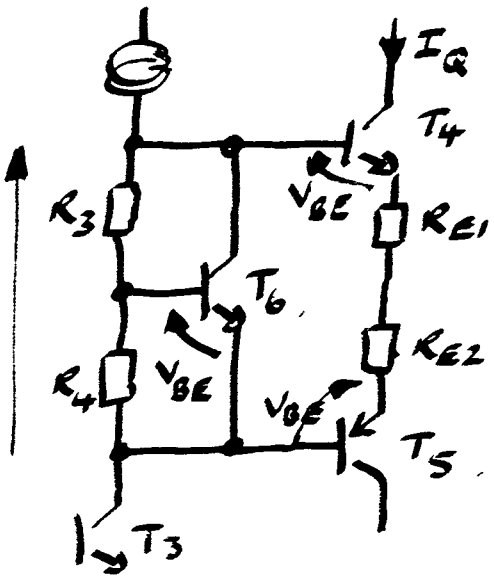
- typical circuit topology .....



- T_1 + T_2 form a "differential amplifier" or "long tailed pair". It behaves like the differential input of an op-amp ($V_i \equiv v^+$ and $V_f \equiv v^-$) and as in the case of the op-amp, because the open loop amplifier gain is high, $V_i \approx V_f$. The gain of this first stage is typically between 2 and 10 V/V.
- T_3 is a common emitter voltage gain stage. A high voltage gain is obtained by providing T_3 with a high impedance collector load, hence the current source in the collector circuit. The gain of this stage is typically between 5000 and 20000 V/V.
- V_B is a floating voltage source which interacts with the base-emitter junctions of T_4 + T_5, and their associated resistors R_{E1} + R_{E2}, to control the bias current through the output stage, and hence control crossover effects.
- T_4 + T_5 are output emitter followers. T_4 does the work (ie supplies the current) on positive output half cycles whilst T_5 deals with the negative half cycles. In this way, the load is driven by a low output impedance in both polarities of output voltage.

The bias control circuit in a little more detail is....

V_B is set by a circuit known as a "V_{BE} multiplier" – a very common arrangement in both power amplifier and op-amp output stage biassing.



T_6 always conducts so V_{BE6} will be more or less constant

$$\therefore I_{R4} = \frac{V_{BE6}}{R_4}$$

and $I_{R3} \approx I_{R4}$ if I_{B6} is negligible

$$\therefore V_{R3} = I_{R3}R_3 = I_{R4}R_3 = \frac{V_{BE6}}{R_4} \cdot R_3$$

$$\text{and } V_B = V_{R3} + V_{R4} = \frac{V_{BE6}R_3}{R_4} + V_{BE6} = V_{BE6}\left[\frac{R_3 + R_4}{R_4}\right]$$

this is the factor that multiplies V_{BE6}

The quiescent output current, I_Q is controlled by R_{E1} – R_{E2} since the voltage across $R_{E1} + R_{E2}$ is controlled by V_B .....

$$V_B = V_{BE4} + I_Q R_{E1} + I_Q R_{E2} + V_{BE5}$$

$$= I_Q(R_{E1} + R_{E2}) + 2V_{BE}$$

$$\text{or } I_Q = \frac{V_B - 2V_{BE}}{R_{E1} + R_{E2}}$$

= "Quiescent" or "no signal" bias current through the output stage.

Note that if the transistors heated up, I_Q would tend to increase since $V_B - 2V_{BE}$ would increase. If R_{E1} and R_{E2} do not exist, the value of I_Q is uncontrolled and increases in temperature lead to increases in I_Q which lead to further increases in temperature..... and so on. The process is known as "thermal runaway" and is usually destructive.

The presence of R_{E1} + R_{E2} limit thermal runaway to manageable proportions by their negative feedback action and the effects of temperature changes on I_Q can be almost eliminated by making sure that V_{BE6} (the V_{BE} that controls V_B) accurately tracks V_{BE4} and V_{BE5} in temperature.

Amplifier Classes

An amplifier with a circuit shape as shown on page ① is often referred to as "push pull" or "double ended". Single ended amplifiers were used in the days of valves but are almost unheard of in transistor circuitry. The following comments apply to push-pull amplifiers unless otherwise stated.....

The class of amplifier describes either the way it is biased or the way it works. There are four main classes:-

Class A, Class B, Class C } These three describe different output stage bias conditions for the output circuit of page 1.

Class D. This is a completely different type of amplifier.

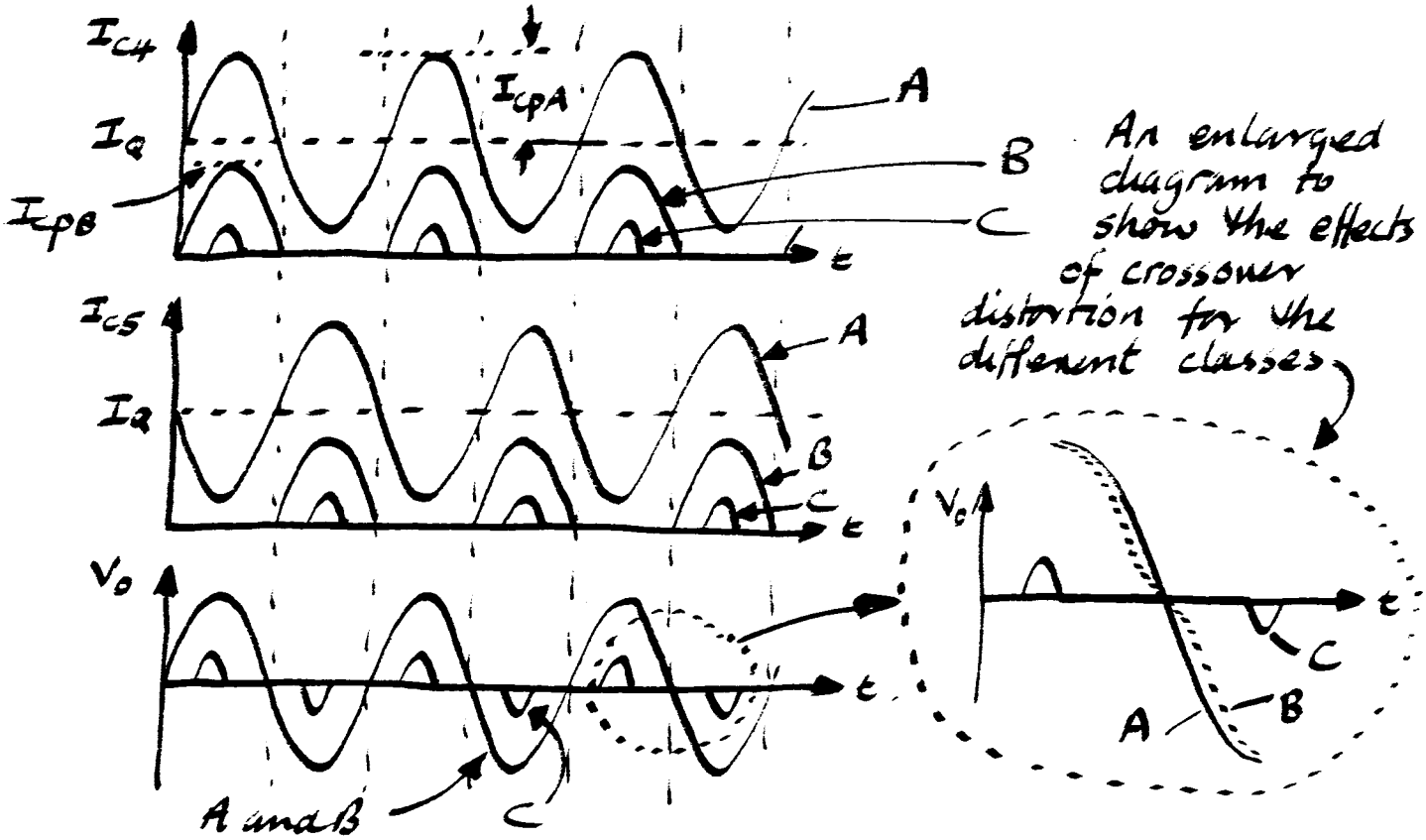
Class A. Both output devices are biased so that they are active throughout a signal cycle.
- Very good linearity
- Very poor efficiency.

Class B The output devices are never on together and never off together – ie top transistor does the +ve half cycles and bottom transistor the -ve ones.
- good linearity
- good efficiency

Class C. The output transistors are both off for most of a signal cycle.
- poor linearity because of extreme crossover distortion
- excellent efficiency
- only useful for RF circuits.

Class D. This is a completely different approach to amplification involving switching transistors and pulse width modulation.
- reasonable linearity
- excellent efficiency.

There are also a number of intermediate classes between A and B which have various ranges of input signal for which both transistors conduct. Such intermediate classes (usually called AB) operate at Class A for low level signals and approach Class B for large amplitude signals.
The collector currents and output voltage for the three amplifier classes A, B and C are....



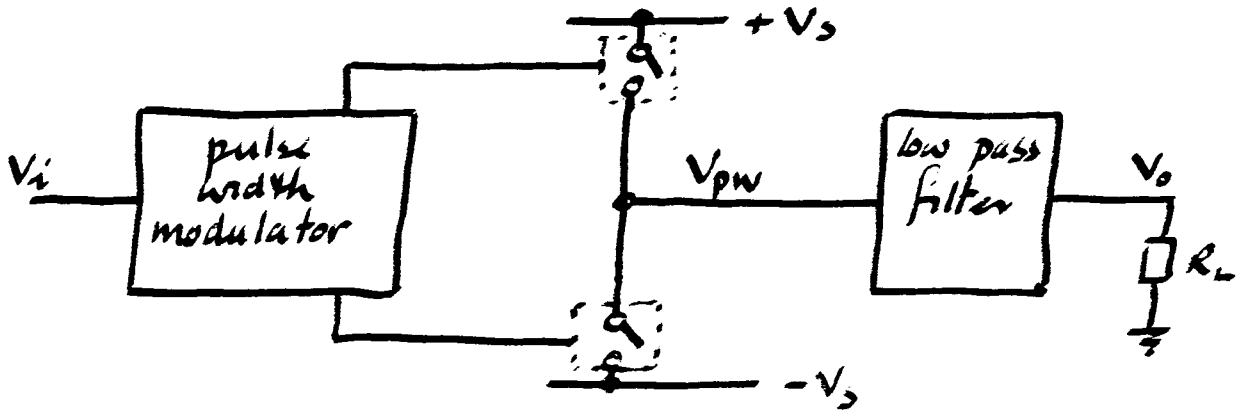
I_{Lpk} for A = $2 \times I_{CPA}$ $\therefore V_{OAp} = 2 I_{CPA} \cdot R_L$

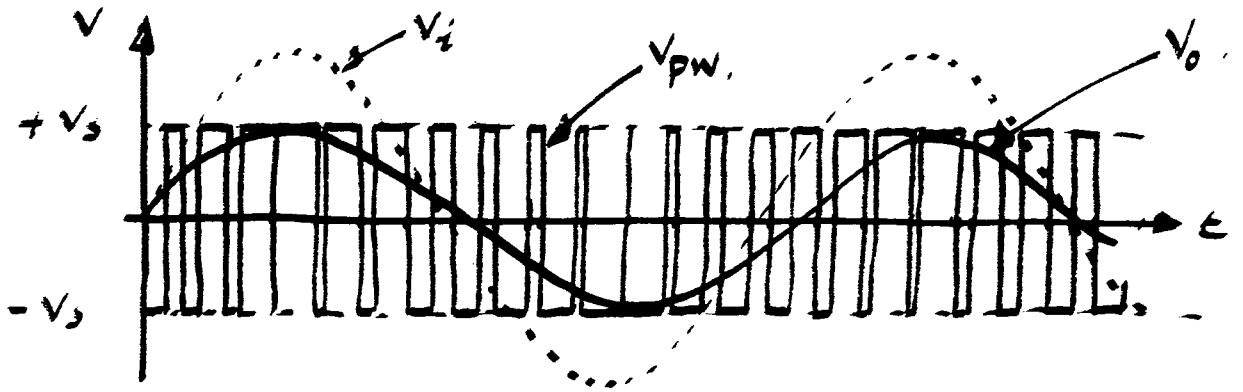
I_{Lpk} for B = I_{CPB} $\therefore V_{OBP} = I_{CPB} \cdot R_L$

I_{Lpk} for C = I_{CPC} $\therefore V_{OCp} = I_{CPC} \cdot R_L$.

Crossover distortion is the non-linearity caused when conduction transfers from the top transistor to the bottom or vice versa.

Class D works by switching between the power supplies at a frequency that is high compared to the maximum frequency of interest. The ratio of high time to low time is varied (pulse width modulation) to vary the average voltage reaching the load.....



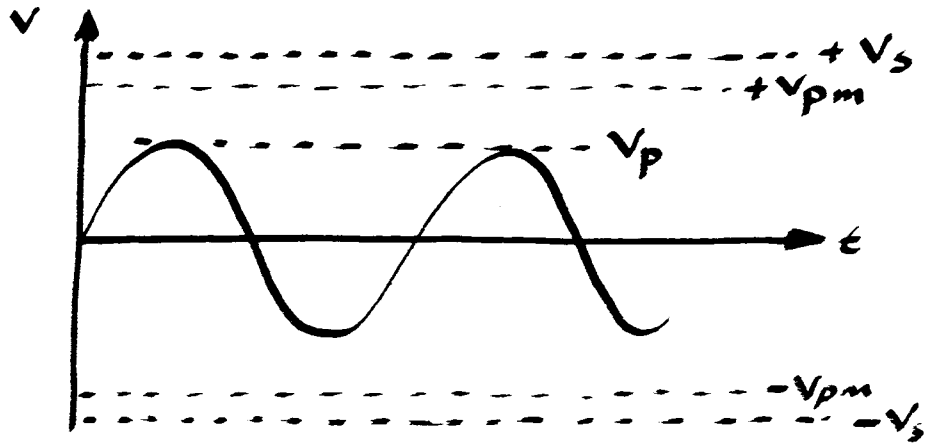


Note: V_i is not drawn to scale – usually $V_i \ll V_s$.

This type of amplifier is very efficient because the output transistors are either on (ie large I_c but small voltage drop) or off (ie large voltage drop but small I_c) so the VI product for the output devices is always small.

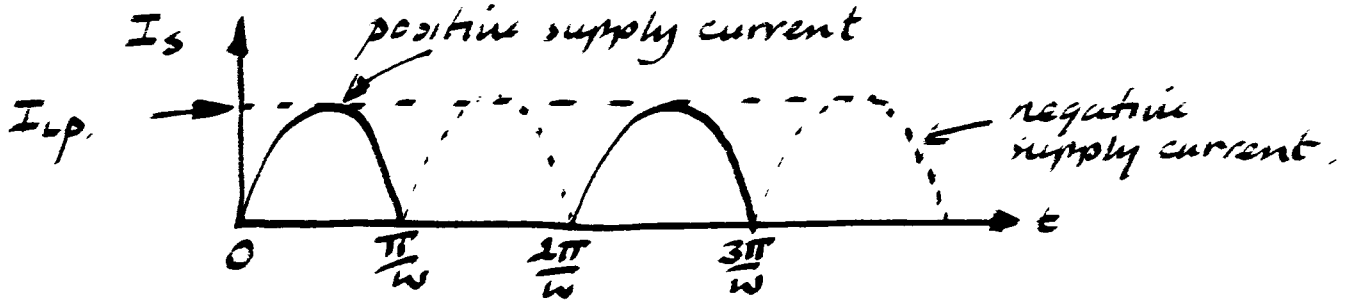
Power Dissipation in Class B Amplifiers.

- Class B commonest – usually with a very small I_Q (making it class A for very small signals). The I_Q is usually sufficiently small to have a negligible effect on power dissipation in the output devices.



V_s = supply voltage

V_{pm} = max value of peak load voltage that the amplifier can support. Sometimes $V_{pm} \approx V_s$.



To find power dissipated in T_4 .....

$$V_{C4} = V_s$$

$$V_{E4} \approx V_L = V_p \sin \omega t$$

∴ voltage drop across T_4 is

$$V_{CE4} = V_{C4} - V_{E4} = V_s - V_p \sin \omega t$$

I_{C4} = positive supply current

$= I_{Lp} \sin \omega t$ for $t = 0$ to π/ω

$= 0$ for $t = \pi/\omega$ to $2\pi/\omega$.

$$P_D = \frac{1}{T}\int_0^T V(t)\,I(t)\,dt \qquad \text{(1)}$$

$$= \frac{1}{2\pi/\omega}\int_0^{\pi/\omega}(V_s - V_p \sin\omega t)(I_{Lp}\sin\omega t)\,dt$$

note that the integral is performed over 0 to π/ω. Between $2\pi/\omega$ and π/ω, $I(t) = 0$ so it is pointless to integrate that bit..... but the averaging is still over a cycle, hence the $1/2\pi/\omega$ before the integral.

$$I_{Lp} = V_p/R_L$$

$$\text{so } P_D = \frac{\omega}{2\pi}\int_0^{\pi/\omega}(V_s - V_p\sin\omega t)\left(\frac{V_p}{R_L}\sin\omega t\right)dt$$

$$= \frac{\omega}{2\pi}\int_0^{\pi/\omega}\frac{V_s V_p \sin\omega t}{R_L}\,dt - \frac{\omega}{2\pi}\int_0^{\pi/\omega}\frac{V_p^2}{R_L}\sin^2\omega t\,dt.$$

$$= \frac{V_s V_p}{\pi R_L} - \frac{V_p^2}{4R_L} \qquad \text{(2)}$$

This is the difference between a linear and a quadratic term and so will have a maximum value somewhere.....

$$\frac{dP_D}{dV_p} = \frac{V_s}{\pi R_L} - \frac{2V_p}{4R_L} = 0 \text{ for max}$$

ie P_D max when $V_p = \frac{2V_s}{\pi}$

$\therefore$ max P_D is....

$$P_{DM} = \frac{V_s\left(\frac{2V_s}{\pi}\right)}{\pi R_L} - \frac{\left(\frac{2V_s}{\pi}\right)^2}{4R_L} = \frac{2V_s^2}{\pi^2 R_L} - \frac{4V_s^2}{4\pi^2 R_L}$$

$$= \underline{\underline{\frac{V_s^2}{\pi^2 R_L}}}.$$

Note that this is the power dissipated per transistor because the $V(t)$ and $I(t)$ used to evaluate it related to one transistor.

The power dissipated in T_5 is the same as that dissipated in T_4 because of the symmetry of the circuit, ie the waveforms across + through the transistors are identical except for a phase shift. Note that the idea of r.m.s. is inappropriate in this sort of power calculation.

An alternative way of finding P_D

The previous derivation of dissipated power was based on the power integral of equation ①, the classical way of calculating power dissipation. An alternative is to use arguments based on energy conservation.....

Power in = Power out

↑ Total power supplied by the supplies $\pm V_s$

↖ Power Dissipated plus power delivered to load.

ie $P_S = P_D + P_L$

$$P_S = \frac{1}{T}\int_0^T V(t)\, I(t)\, dt$$

$$= V_S \cdot \frac{1}{T}\int_0^{T_0} I(t)\, dt$$

$$= V_S \cdot I_{AVE}$$

$$= V_S \, I_{P/\pi}$$

$$= \frac{V_S V_P}{\pi R_L} \text{ per supply}$$

and since there are two supplies...

$$P_S = \frac{2V_S V_P}{\pi R_L}$$

?

$$P_L = \frac{V_{r.m.s}^2}{R_L}$$

$$= \frac{V_P^2}{2R_L}$$

Note that r.m.s can be used here because the waveform is sinusoidal and the load is a linear resistor.

hence $$\frac{2V_S V_P}{\pi R_L} = P_D + \frac{V_P^2}{2R_L}$$

or $$P_D = \frac{2V_S V_P}{\pi R_L} - \frac{V_P^2}{2R_L}$$

This is the same as equation (2) in the previous derivation except that P_D is now the total dissipation — hardly surprising since P_S is the total power supplied and P_L is the total load power.

Proceeding as before gives:-

$$P_{DM} = \frac{2V_S^2}{\pi^2 R_L} \quad \text{for both devices}$$

(ie $V_S^2/\pi^2 R_L$ per device).

NOTES - Max dissipation does not necessarily occur at max power output.
- These relationships are different for different waveshapes
- Heatsink requirements must be specified on basis of maximum power dissipation.

Choosing a value for V_S

Supply voltage V_S depends on:

- required maximum output power
- load resistance
- waveform of interest (eg Sinusoid, triangle, etc)
- minimum voltage difference between V_S and the maximum peak output voltage, V_{pm}.

If V_S is bigger than it needs to be, energy will be wasted.

Let maximum load power required = P_{Lm}
load resistance = R_L
$(V_S - V_{pm})$ = V_{DIFF}
waveshape = sinusoid

$$P_{Lm} = \frac{V_{r.m.s.\,max}^2}{R_L} = \frac{V_{pm}^2}{2R_L}$$

$$\therefore V_{pm} = \pm\sqrt{2R_L P_{Lm}}$$

$$\therefore V_S = \pm\left[\sqrt{2R_L P_{Lm}} + V_{DIFF}\right]$$

$$\approx \pm\sqrt{2R_L P_{Lm}} \text{ if } V_{DIFF} = 0, \text{ ie if the output devices work normally to } V_{CE} = 0.$$

Defining the peak and average current that the supply must be capable of delivering.

The supply current, I_S, is a half wave rectified version of the load current for each supply as shown on page 6.

The largest peak current I_{Lpm} is given by Ohms law as

$$I_{Lpm} = \frac{V_{pm}}{R_L} \approx \frac{V_S}{R_L} \quad \text{if } V_{DIFF} = 0$$

The average value of a half wave rectified sinusoid with an amplitude I_{Lpm} is:

$$I_{AVE} = \frac{I_{Lpm}}{\pi} = \frac{V_{pm}}{\pi R_L} \approx \frac{V_S}{\pi R_L} \quad \text{if } V_{DIFF} = 0.$$

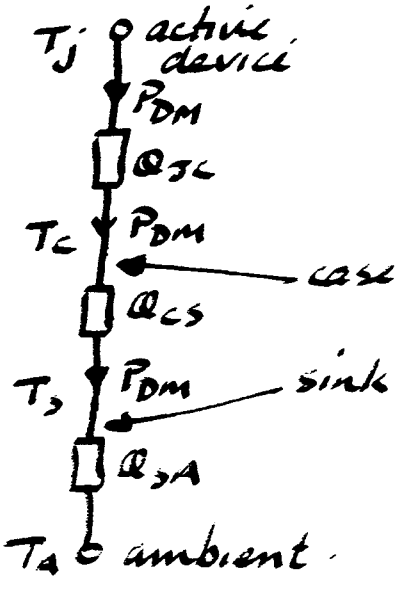
WARNING You need to think carefully for a particular application about which of the peak or the average value is the appropriate one to use. eg if the amplifier works down to dc (0Hz), I_{AVE} is equal to I_{Lpm} under some circumstances.

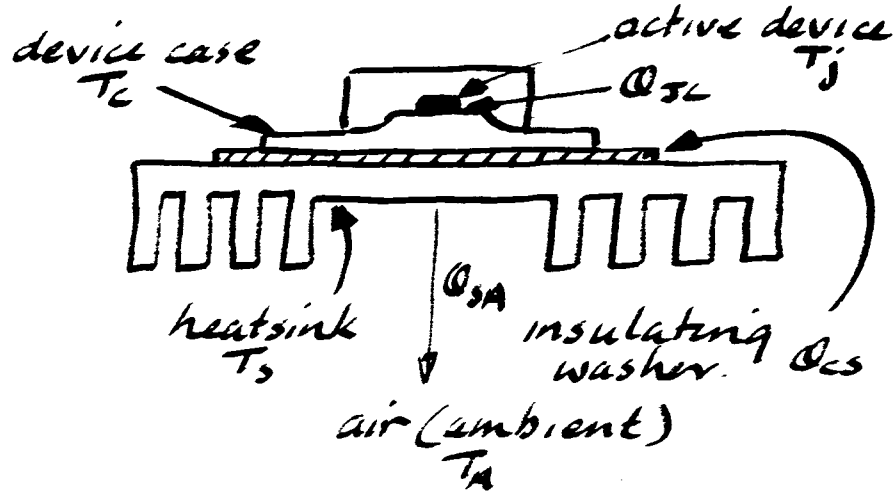
Removing the dissipated thermal energy

- done using a heatsink
- air cooled by convection, forced air (fan) cooled, water cooled, etc depending on amount of power to be removed.
- heatsinks specified by "thermal resistance" which has the units $^{\circ}C/W$

– ie if you know how many watts are passing through a thermal resistance you can easily work out the temperature difference across it.

Thermal Structure of device + heatsink.





T_j = junction temp.
T_C = case temp.
T_S = sink temp.
T_A = ambient temp.

θ_{JC} = junction to case thermal resistance
θ_{CS} = case to sink thermal resistance
θ_{SA} = sink to air (ambient) therm. res.

The relationships are intuitive and straightforward:

$$T_S = P_{DM}\theta_{SA} + T_A$$

$$T_C = P_{DM}\theta_{CS} + T_S = P_{DM}\theta_{CS} + P_{DM}\theta_{SA} + T_A$$

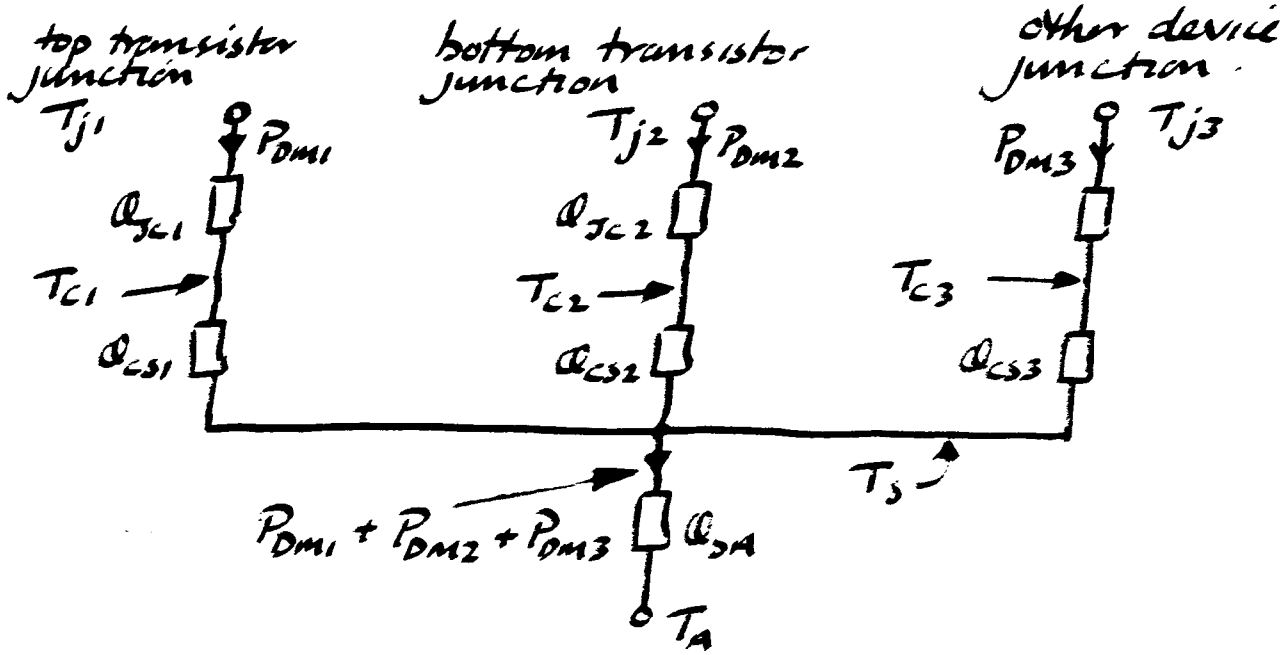
$$T_j = P_{DM}\theta_{JC} + T_C = P_{DM}\theta_{JC} + P_{DM}\theta_{CS} + T_S$$

$$= P_{DM}\theta_{JC} + P_{DM}\theta_{CS} + P_{DM}\theta_{SA} + T_A$$

You must use P_{DM}, the maximum power dissipation, and T_A must be the maximum expected ambient temperature.
The limits are usually T_j (typically 120°C to 150°C – figure given in manufacturers data) and T_S. The limit on T_S is simply to prevent overheating of components near

the heatsink and to prevent burn injuries to operators. (many devices are happy at 100°C, humans, regretfully, are not!)

If there are two (or more) devices mounted on the same heatsink, just extend the model



If T_1 & T_2 are the output stage of a power amplifier, $P_{DM1} = P_{DM2}$.

NOTE An IC amplifier effectively has one junction in thermal terms; T_j is actually the silicon chip temperature. All the power dissipated in the output stage passes through the IC's θ_{JC} and θ_{CS}.

This thermal model works reasonably well for most low and medium frequency devices — transistors, rectifiers, thyristors, triacs IGBTs, power resistors and many more.