Noise

Types of Noise

Voltage Noise - Fluctuations in voltage

Current Noise - Fluctuations in current

Flicker Noise - Low frequency circuit noise

Interference - External noise

Interference

- High frequency pick up is common in power connections
  May be eliminated with low-pass filters - “surge suppressors”

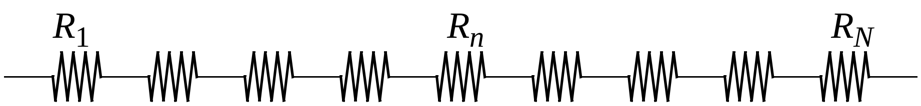
- Capacitive coupling picks up large fluctuations from nearby circuits
  Move components apart or near to a large ground - “ground plane”
  Add metal shielding
  Lower impedance of inputs where possible

- Inductive coupling picks up nearby large fields, especially 60 Hz
  Keep loops small, twist wire pairs together
  Add high pass filters if appropriate

- RF (radio frequency) coupling can be picked up and amplified by resonant circuits
  Shield cables, and keep unshielded leads short

Thermal (Johnson) Noise

- Fluctuations of electrons in a resistor of the order kT
- Appears in any resistive element, including transistors
- Treat a resistor as a number of small resistors in series



$$R = \sum_{n=1}^{N} R_n$$

- The energy associated with a resistive element $e(\Delta V_n) = kT$.
- Energy is also power expended in a time interval τ:

$$e(\Delta V_n) = \frac{(\Delta V_n)^2}{R_n}\tau = kT$$

- Solving for ΔV_n in terms of Δf:

$$\Delta V_n = \sqrt{R_n kT(\Delta f)}$$

- The total voltage fluctuation is a sum of the small fluctuations

$$(\Delta V)^2 = \sum_{n=1}^{N} (\Delta V_n)^2 = \sum_{n=1}^{N} R_n kT(\Delta f) = RkT(\Delta f)$$

- A better approximation gives:

$$\Delta V = \sqrt{4RkT(\Delta f)}$$

Shot (Current) Noise

- Due to statistical fluctuations in current across a junction
- Current in a short time τ is:

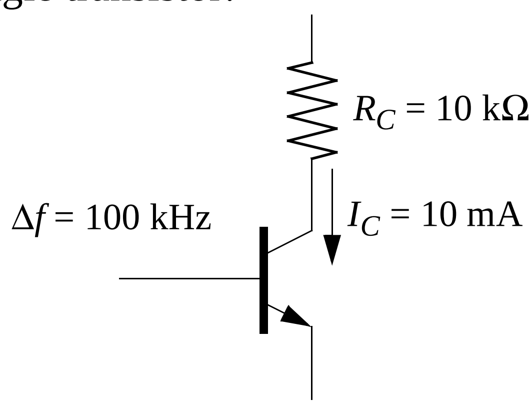
$$I = \frac{ne}{\tau} = ne(\Delta f)$$

A wide band of frequency (Δ*f*) is equivalent to a short time

- Fluctuations in the number of electrons varies as the square root of *n*
- The fluctuation in current is:

$$|\Delta I| = \sqrt{2n}e(\Delta f) = \sqrt{2eI(\Delta f)}$$

- Shot noise in a single transistor:



$$\Delta I = \sqrt{2eI(\Delta f)} = 0.018\mu\dot{A}$$

$$\Delta V = 0.18m\dot{V}$$

1/f (Flicker) Noise

- Shot and Johnson noise are white noise
- Uniform power with frequency: Power proportional to V^2 = constant.
- At very high frquencies quantum effects reduce the noise.

- Flicker noise is inversely proportional to frequency, only shows up at low frequency (typically 100 Hz or less)
- Flicker noise appears in resistors and transistors due to surface effects.

  For example, changes in the base region of a transistor will cause changes in the minority combination rate.

  Other effect include carrier diffusion and thermal noise.
- Flicker noise has been measured at extremely low frequencies, but must eventually stop so that the power does not become infinite at 0 frequency.

Noise Measurement

Signal-to-Noise Ratio

- Unit of gain: decibel (dB)

  For measures of voltage and current, $A_{dB} = 20 \log_{10} A$

  For measures of power = V*I = V^2/R, $A_{dB} = 10 \log_{10} A$
- Signal-to-noise uses the decibel scale for power,

  $S/N = 10 \log_{10} (P_{signal}/P_{noise}) = 10 \log_{10} (V^2_s / V^2_n)$
- Useful rules:

  A factor of 10 is a 10 dB measure

  A factor of 2 is about a 3 dB measure

  0 dB is equal signal and noise
- The bandwidth used in the calculation matters:

  If the signal only covers bandwidth Δf, with an S/N = A, the noise is

  $$(\Delta V)^2 = 4RkT(\Delta f)$$

  If S/N is measured with $2\Delta f$, the signal is the same but the noise is

  $$(\Delta V)^2 = 4RkT(2\Delta f)$$

  a factor 2 greater, so S/N drops by 3 dB

Noise Figure

- The *noise figure* (F) meaures the increase in noise from an amplifier.

$$F = 10\log\frac{S/N_{out}}{S/N_{in}}$$

- Assume a source impedance R_s:

$$F = 10\log\frac{4kTR_s + v_n^2}{4kTR_s} = 10\log\left(1 + \frac{v_n^2}{4kTR_s}\right)$$

Note, for equal input and output impedance: $4RkT(\Delta f) \Rightarrow RkT(\Delta f)$

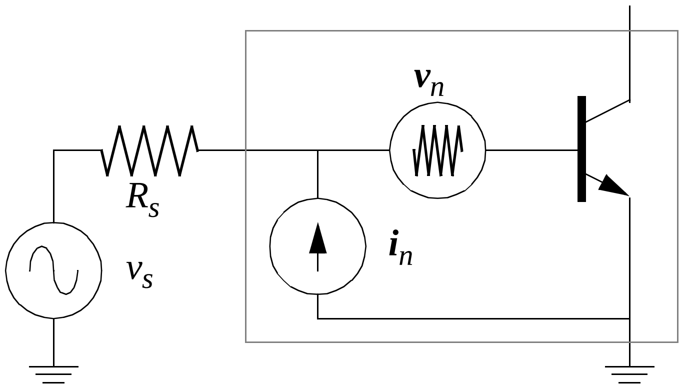
- To convert from F to S/N:

$$S/N = 10\log\frac{v_s^2}{v_n^2} = 10\log\left(\frac{v_s^2}{4kTR_s}\frac{4kTR_s}{v_n^2}\right) = 10\log\left(\frac{v_s^2}{4kTR_s}\right) - F$$

F is measured at R_S, and V_n is sufficiently large.

Bipolar Transistor Amplifier Noise

- A transistor can be replaced by a current and voltage noise source



- The voltage and current noise are listed per unit bandwidth:

  $\boldsymbol{v}_n^2 = v_n^2 / \Delta f$, so the units are V/Hz$^{1/2}$ and A/Hz$^{1/2}$

- The voltage noise is from Johnson noise in the base and shot noise in the base-emitter junction, with negligible flicker noise:

$$\tilde{v}_n^2 = 4kTr_b + \frac{2(kT)^2}{eI_C}$$

- The current noise is due to shot noise in the base current and a little flicker noise in the base:

$$\tilde{i}_n^2 = 2eI_B = 2eI_C/\beta$$

  This noise forms a voltage across the source impedance.

$$\tilde{v}_{ntot}^2 = \tilde{v}_n^2 + \tilde{i}_n^2 R_s^2 = 4kTr_b + \frac{2(kT)^2}{eI_C} + 2eI_C R_s^2/\beta$$

Noise Rejection

Amplifier Impedance Matching

- The amplifier noise figure depends on source resistance

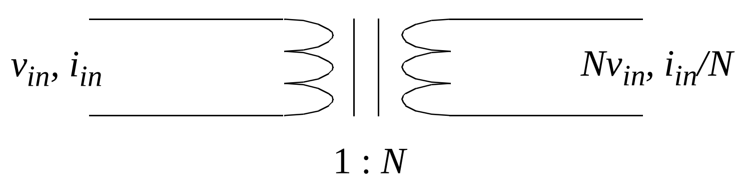
$$F = 10\log\left(1 + \frac{\tilde{v}_n^2 + \tilde{i}_n^2 R_s^2}{4kTR_s}\right)$$

- This reaches a minimum when $\frac{dF}{dR_s} = 0$:

$$0 = \frac{d}{dR_s}\left[10\log\left(1 + \frac{\tilde{v}_n^2 + \tilde{i}_n^2 R_s^2}{4kTR_s}\right)\right] = \tilde{i}_n^2 R_s^2 - \tilde{v}_n^2$$

$$R_s = \tilde{v}_n / \tilde{i}_n$$

- A transformer changes the impedance of a source



$$Z_{out} = \frac{v_{out}}{i_{out}} = \frac{Nv_{in}}{i_{in}/N} = N^2 Z_{in}$$

- With a transformer noise is minimized at:

$$N^2 R_s = \tilde{v}_n / \tilde{i}_n$$

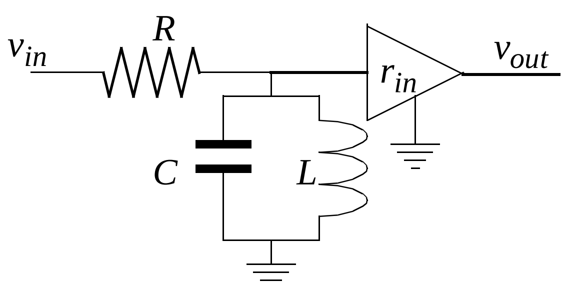
$$N = \sqrt{\tilde{v}_n / (\tilde{i}_n R_s)}$$

Bandwidth Selection

- Noise depends on the bandwidth and this should be restricted to the signal only.
- An RC filter at both frequency ends will reduce the noise outside the signal range.
- For a high pass filter at f_1 and low pass filter at f_2 gives:

$$\Delta f = \frac{\pi}{2} \frac{f_2^2}{(f_1 + f_2)}$$

- A bandpass RLC filter is better for selecting a frequency range



- The resonant frequency, Q and noise bandwidth are related:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$Q = 2\pi f_0 (R \parallel r_{in}) C$$

$$\Delta f = \frac{\pi f_0}{2Q} = \frac{1}{4(R \parallel r_{in}) C}$$