2. Noise Models
In the above sections, the various physical sources of noise in electronic circuits were described.

In this section, these sources of noise are brought together to form the small-signal equivalent circuits:

- resistors (already discussed)
- diodes,
- bipolar (BJT) and
- field-effect (FET) transistors and
- linear IC (OpAmp)
Resistors

- Noise can be modelled as
  - a Thevenin equivalent voltage source or
  - a Norton equivalent current source.

- The noise contributed by the resistor is modeled by the source, thus the resistor is considered noiseless.
It is important to note that noise sources:
- Do not have polarity
- Do not add algebraically, but as RMS sums

If the sources are not correlated, then:

$$v_{n,\text{total}} = v_{n1} + v_{n2} = 4kTBR_1 + 4kTBR_2$$

$$v_n \text{ (rms)} = \sqrt{v_n^2} = \sqrt{v_{n1}^2 + v_{n1}^2} = \sqrt{4kTBR_1 + 4kTBR_1}$$
If the sources are correlated (derived from the same physical noise source), then there is an additional term: $C$ can vary between $-1$ and $1$.

$$v_n^2 = v_{n1}^2 + v_{n1}^2 + 2Cv_{n1}v_{n2}$$

$$v_n(rms) = \sqrt{v_n^2} = \sqrt{v_{n1}^2 + v_{n1}^2 + 2Cv_{n1}v_{n2}}$$
Thermal Noise Power

- The available noise power can be calculated from the RMS noise voltage or current:

\[ P_{no} = \frac{E_{no}^2}{R_L} = \frac{(E_t / 2)^2}{R_S} = kTB \]

- That is, the available noise power from the source is
  - independent of resistance
  - proportional to temperature
  - proportional to bandwidth
  - has no frequency dependence

- \( P = 4 \times 10^{-21} \) watts in a 1 Hz bandwidth at the standard noise room temperature of 290 K.
Can a resistor produce infinite noise voltage?

\[ v_n^2 \equiv v_t^2 = 4kT \cdot R \cdot B \]

Therefore \[ v_t^2 \to \infty \] when \( B \to \infty \)

Equivalent circuit for noisy resistor always have some shunt. Therefore

\[ |V_{no}| = |V_{no}| \frac{1}{\sqrt{1 + \omega^2 C^2 R^2}} \]

To find the noise power

\[ \overline{v_{no}^2} = \int_0^\infty |V_{no}|^2 \, dt = \frac{kT}{C} \]

Therefore total noise power is independent of \( R \) !!!
The equivalent circuit for a junction diode was considered briefly in the consideration of shot noise.

The basic equivalent circuit of diode (discussed) can be made complete by adding series resistance $r_s$, as shown.

Since $r_s$ is a physical resistor due to the resistivity of the silicon, it exhibits thermal noise.

Experimentally it has been found that any flicker noise present can be represented by a current generator in shunt with $r_d$, and this is conveniently combined with the shot-noise
In a BJT in the forward-active region, minority carriers diffuse and drift across the base region to be collected at the collector-base junction.

Minority carriers entering the collector-base depletion region are accelerated by the field existing there and swept across this region to the collector.

The time of arrival at the collector-base junction of the diffusing (or drifting) carriers is a purely random process, and thus the transistor collector current consists of a series of random current pulses.
Consequently, collector current $I_c$ shows *full shot noise*, and this is represented by a shot noise current generator $i_c^2$ from collector to emitter as shown in the equivalent circuit of BJT.

$$i_c^2 = 2qI_C \cdot B$$
Base current $I_B$ in a transistor is due to recombination in the base and to carrier injection from the base into the emitter.

All of these are independent random processes, and thus $I_B$ also shows full shot noise.

Flicker noise and burst noise in a BJT have been found experimentally. This is represented by shot noise current generator

$$ \bar{i}_b^2 = 2qI_B \cdot B + K_1 \frac{I_b^\alpha}{f} B + K_2 \frac{I_b^c}{1+(f/f_c)^2} B $$
Transistor base resistor $r_b$ is a physical resistor and thus has thermal noise.

Collector series resistor $r_c$ also shows thermal noise, but since this is in series with the high-impedance collector node, this noise is negligible and is usually not included in the model.

\[ \overline{v_b^2} = 4kTB \]
All Contributions

- **Shot noise** in collector current $I_c$, \[ \bar{v}_{c}^2 = 2qI_c \cdot B \]
- **Shot, Flicker noise and burst noise** in Base current $I_B$
  \[ \bar{i}_{b}^2 = 2qI_B \cdot B + K_1 \frac{I_b^\alpha}{B} B + K_2 \frac{I_b^c}{1+(f/f_c)^2} B \]
- **Thermal noise** in base resistor $r_b$.
  \[ \bar{v}_{b}^2 = 4kTB \]
The base-current noise spectrum can be plotted where burst noise has been neglected for simplicity.

The shot noise and flicker noise asymptotes meet at a frequency $f_a$, which is called the flicker noise "corner" frequency.

- In some transistors using careful processing, $f_a$ can be as low as 100 Hz.
- In other transistors $f_a$ can be as high as 10 MHz.
In FET the resistive channel joining source and drain, so that the drain current is controlled by the gate-source voltage.

Since the channel material is resistive, it exhibits thermal noise, and this is the major source of noise in FETs. This noise source can be represented by a noise-current generator $i_D^2$ from drain to source in the FET small-signal equivalent circuit.
Flicker noise in the FET is also found experimentally to be represented by a drain-source current generator,

\[ \overline{i_d^2} = 4kT \left( \frac{2}{3} g_m \right) + K_2 \frac{I_a}{f} B \]

The other source of noise in FETs is shot noise generated by the gate leakage current and is usually very small. It becomes significant only when the driving-source impedance connected to the FET gate is very large.

\[ \overline{i_g^2} = 2qI_G \cdot B \]
Consider the noise performance of the simple transistor stage with the ac schematic shown below.

Consider the noise performance of the simple transistor stage with the ac schematic shown below.
In this equivalent circuit the external input signal $v_i$, has been ignored so that output signal $v_o$ is due to noise generators only. $C_\mu$ is assumed small and is neglected. Output resistance $r_o$ is also neglected. The transistor noise generators are as described previously and in addition:

$$\bar{v}_s^2 = 4kTR_S B$$

$$\bar{i_i}^2 = 4kT \frac{1}{R_L} B$$

The total output noise can be calculated by considering each noise source in turn and performing the calculation as if each noise source were a sinusoid with rms value equal to that of the noise source being considered.
BJT noise performance

- The spectral density of the noise generator is equal:

\[
\frac{\overline{v_o^2}}{B} = g_m^2 R_L^2 \frac{|Z|^2}{|Z + r_b + R_s|^2} \left[4kT(R_s + r_b) + (R_s + r_b)^2 2qI_B\right] +
\]

\[+ R_L^2 \left(\frac{4kT}{R_L} + 2qI_C\right) \text{ where } Z = r_\pi \left|\frac{1}{j\omega C_\pi}\right|
\]

- Substituting for Z gives:

\[
\frac{\overline{v_o^2}}{B} = g_m^2 R_L^2 \frac{r_\pi^2}{(r_\pi + r_b + R_s)^2} \cdot \frac{1}{1+\left(f/f_1\right)^2} \left[4kT(R_s + r_b) + (R_s + r_b)^2 2qI_B\right] +
\]

\[+ R_L^2 \left(\frac{4kT}{R_L} + 2qI_C\right) \text{ where } f_1 = \frac{1}{2\pi\left[r_\pi(r_b + R_s)\right]C_\pi}
\]
The output noise-voltage spectral density has a frequency-dependent part and a constant part.

The frequency dependence arises because the gain of the stage begins to fall above frequency $f_1$, and noise due to generators $v_s$, $v_b$, and $i_b$, which appears amplified, also begins to fall.

The constant term is due to noise generators $i_l$ and $i_c$

Assuming $I_C=100 \, \mu A$, $R_s=500 \, \Omega$, $R_L=5 \, k\Omega$, $\beta=100$, $C_\pi=10 \, pF$, $r_b=200\Omega$