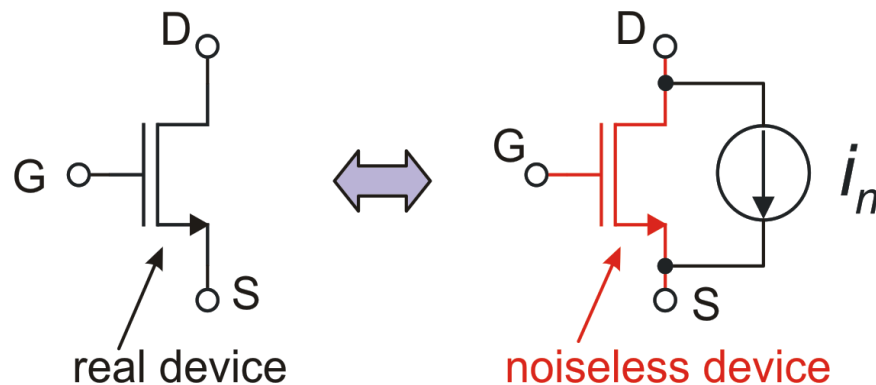


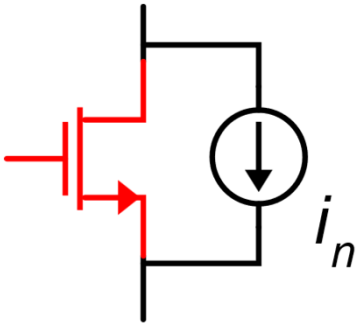
Noise in active devices

MOSFETs



This noise schematization is valid up to a frequency that depends on the process and device length. Generally, for integrated MOSFETs, it is possible to use this single-source model up to frequencies of several hundred MHz

Mosfet Thermal noise



Being frequency independent, thermal noise is the origin of the **broad-band** noise in MOSFETs

$$S_{In-T}(f) = \frac{8}{3} kT g_m \cdot m$$

$$m = 1 + \frac{g_{mB}}{g_m} \quad \text{Typically: } 1 < m < 1.5$$

A more general expression that resembles thermal noise in resistors:

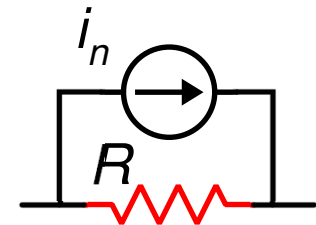
$$S_{In-T}(f) = \gamma_n \underline{4kTg_m}$$

$$\gamma_n = \frac{2}{3} m \approx 1$$

For simplicity, we will use:

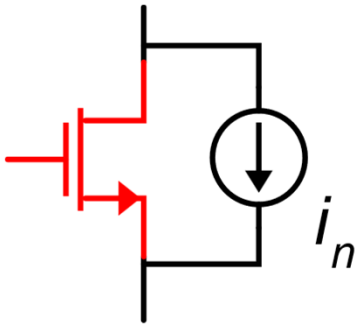
$$S_{In-T}(f) = \frac{8}{3} kT g_m$$

Thermal noise of a resistor:
Equivalent noise current.



$$S_{In-R} = 4kT \frac{1}{R} = \underline{4kTG}$$

Mosfet flicker noise



simplified flicker noise expression

$$S_{In-F}(f) = \frac{N_f}{WL} \frac{1}{f} g_m^2$$

Frequently used by designers of analog integrated circuits

N_f is a parameter that depends on the process

N-MOS: N_{fn}

P-MOS: N_{fp}

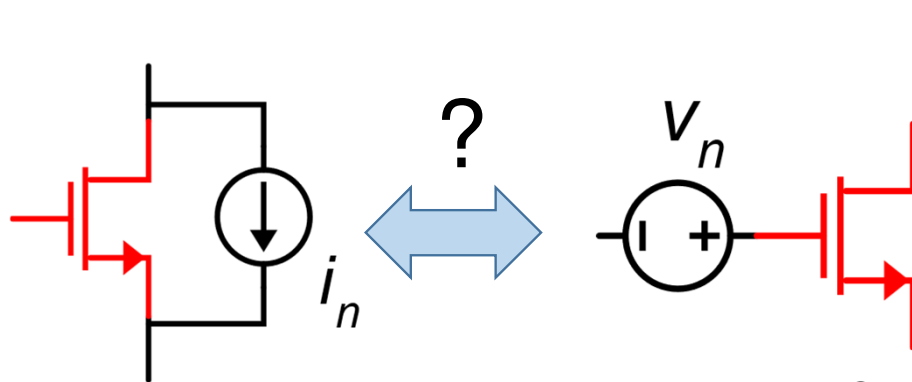
Dimensions of N_f are: $V^2 \cdot (\mu m)^2$

More general expression:

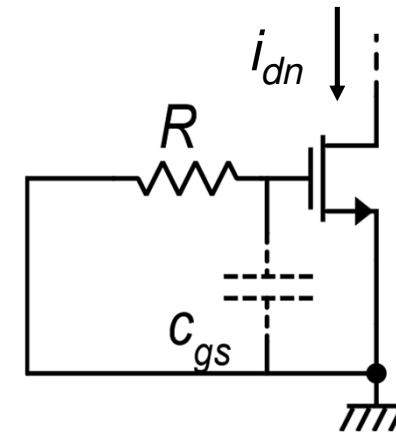
$$S_{In-F}(f) = \frac{k_{fi} I^\alpha}{C_{OX} L_{eff}^2} \frac{1}{f^\gamma}$$

- Can be used in traditional SPICE noise models.
- Too complicated for hand calculations of circuits with a large number of devices
- With $\alpha=1$ and $\gamma=1$, the two expressions give the same dependence of device size and current

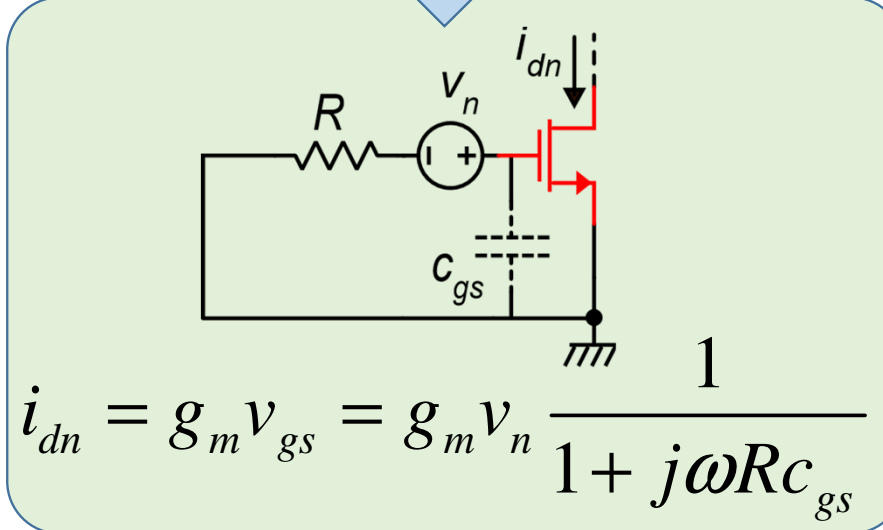
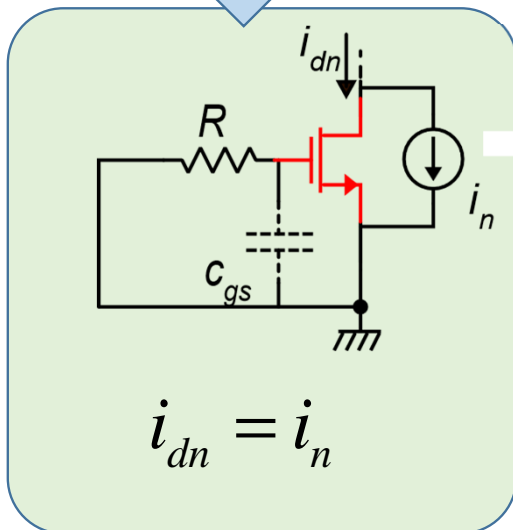
Equivalent gate noise



Are they fully equivalent?

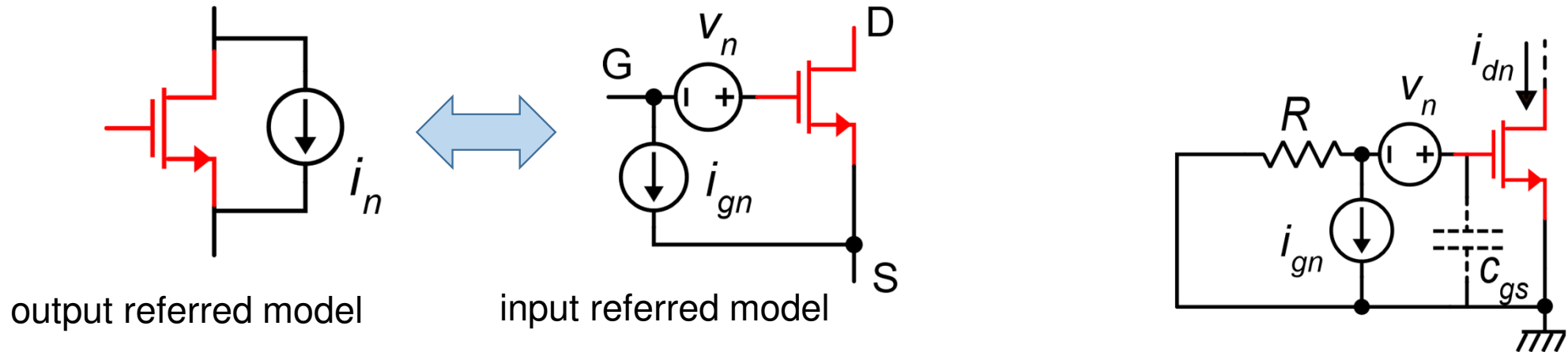


Let us consider a resistive input termination and let us focus on the noise added to the drain current ...



Substituting i_n with a single voltage source in series with the gate gives a contribution that depends on the resistance (R) seen by the gate.

Equivalence between the output referred and input referred noise models



$$i_{dn} = g_m \left(v_n \frac{1}{1 + j\omega R c_{gs}} - i_{gn} \frac{1}{1/R + j\omega c_{gs}} \right) = g_m \left(\frac{v_n - i_{gn} R}{1 + j\omega R c_{gs}} \right)$$

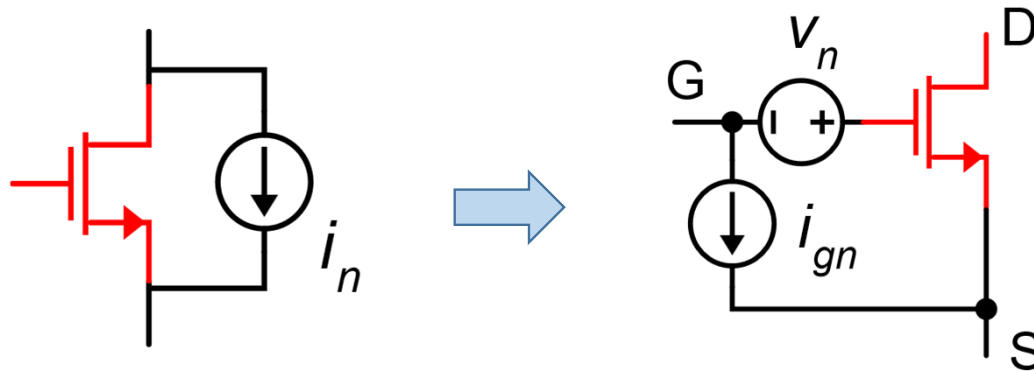
By setting:

$$i_{gn} = -j\omega c_{gs} v_n \quad \Rightarrow \quad i_{dn} = v_n g_m$$

Independent of R, as required for the equivalence with the output referred model.

Finally, setting: $v_n = \frac{i_n}{g_m} \quad \Rightarrow \quad i_{dn} = i_n$

Equivalence between the output referred and input referred noise models



$$i_n \longrightarrow \begin{cases} v_n = \frac{i_n}{g_m} \\ i_{gn} = -j\omega c_{gs} v_n \end{cases}$$

$(i_n = v_n g_m)$

Note that i_{gn} is dependent on v_n
(they are correlated stochastic processes)

Transformations between drain noise current and gate noise voltage

$$v_n = \frac{i_n}{g_m}$$

$$i_n = v_n g_m$$

$$S_{Vn}(f) = \frac{S_{In}(f)}{g_m^2}$$

$$S_{In}(f) = g_m^2 S_{Vn}(f)$$

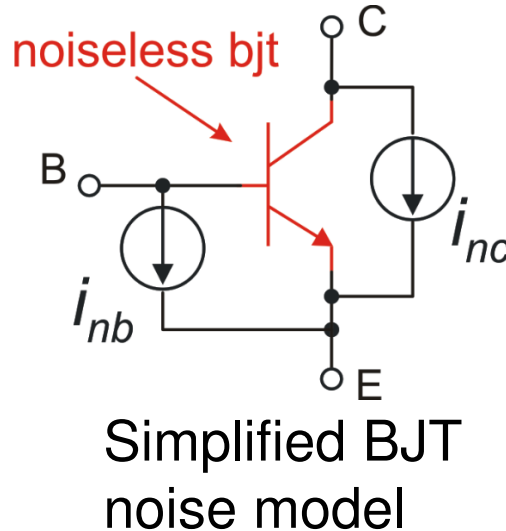
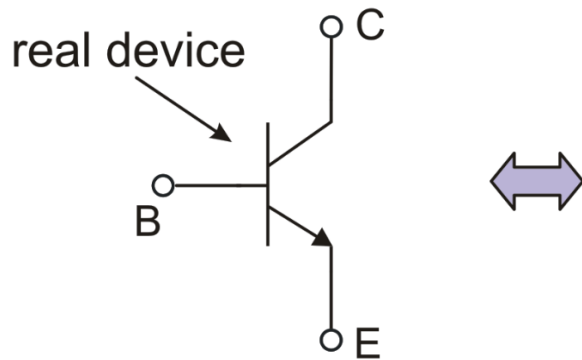
Thermal noise:

$$S_{In-T}(f) = \frac{8}{3} kT g_m \cdot m \quad \Rightarrow \quad S_{Vn-T}(f) = \frac{8}{3} kT m \frac{1}{g_m}$$

Flicker noise:

$$S_{In-F}(f) = \frac{N_f}{WL} \frac{1}{f} g_m^2 \quad \Rightarrow \quad S_{Vn-F}(f) = \frac{N_f}{WL} \frac{1}{f}$$

Noise in BJTs



Since the BJT has a non negligible base current, it is necessary to use **two distinct current noise** sources for the base and the collector

Collector noise current PSD:

$$S_{InC} = 2qI_C$$

Only shot noise (broad-band)

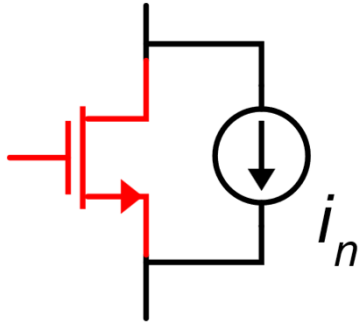
Base noise current PSD:

$$S_{InB} = 2qI_B + k_{fB} \frac{I_B^\alpha}{f}$$

Base shot noise (broad-band)

Base flicker noise

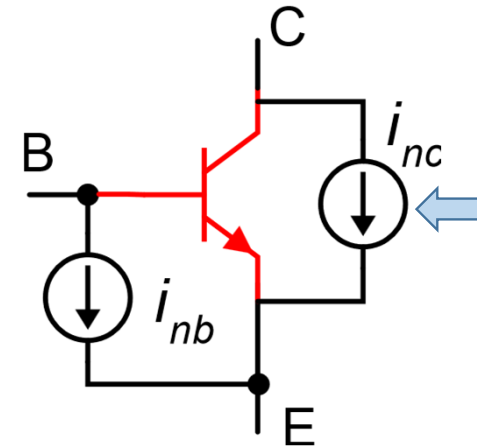
MOSFET vs BJT: Broadband noise



Let us consider only the drain (i_n) and collector (i_{nc}) noise sources.

$$S_{In-T}(f) = \gamma_{n-MOS} 4kTg_m$$

$$\gamma_{n-MOS} = \frac{2}{3}m \approx 1$$



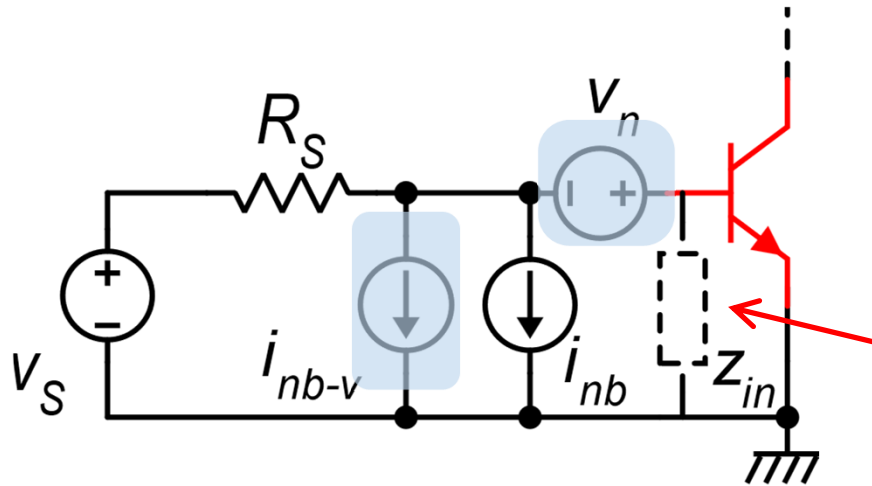
$$S_{InC} = 2qI_C$$

$$g_m = \frac{I_C}{V_T} \Rightarrow I_C = g_m V_T = g_m \frac{kT}{q}$$

$$S_{InC} = 2qg_m \frac{kT}{q} = 2kTg_m$$

$$S_{InC}(f) = \gamma_{n-BJT} 4kTg_m \quad \gamma_{n-BJT} = \frac{1}{2}$$

BJT input referred noise voltage



$$v_n = \frac{i_{nC}}{g_m}$$

$$i_{bn-v} = -\frac{v_n}{z_{in}}$$

$$\frac{1}{z_{in}} \cong \frac{1}{r_{be}} + j\omega c_{be}$$

$$\text{if } |z_{in}| \gg R_S \quad v_{be} \cong v_S + v_n$$

$$\text{BJT:} \quad S_{v_n} = 2kT \frac{1}{g_m} = 2kT \left(\frac{V_T}{I_C} \right)$$

$$\text{MOSFET:} \quad S_{v_{n-th}} \cong 4kT \frac{1}{g_m} = 4kT \frac{V_{TE}}{I_D}$$

In this case, the noise voltage source v_n is the only significant contribution to the input referred noise

Much more noise for the same static current consumption!

The Noise Efficiency Factor (NEF)

Since the single-BJT amplifier offers an excellent trade-off between noise and power consumption, in 1987 M. Steyaert (KU Leuven University) proposed a FOM (figure of merit) called NEF to characterize all voltage amplifiers in terms of noise efficiency

$$NEF = \frac{V_{rms-rti}}{\sqrt{4kT \left(\frac{V_T}{I_{supply}} \right) B \frac{\pi}{2}}}$$

Total *rms* noise of the amplifier under consideration

Effective noise bandwidth and total current consumption of the amplifier under consideration

Denominator = $\sqrt{2} \cdot V_{rms-bjt}$

Input *rms* voltage of a BJT with same current and BW of the amplifier