TSEK03: Radio Frequency Integrated Circuits (RFIC)

Lecture 1b, 2: Noise

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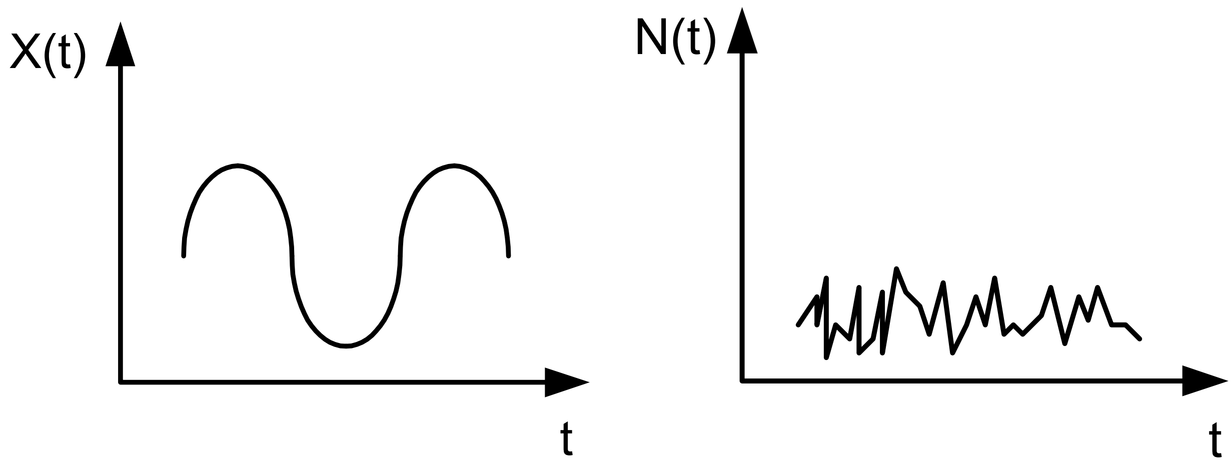
Overview

- Razavi: Chapter 2.3, pp. 35-58.
- Lee: Chapter 11, pp. 334-362.

- Noise: Sources of noise, noise spectrum, thermal noise, 1/f (flicker) noise.
- Calculations: Noise in circuits and noise calculation, noise factor/figure, Friis' equation for cascaded noisy circuits blocks.

2.3 Noise

- What is noise? Typically, it is known as “everything except signal”:



- It affects the sensitivity of communication systems
- There are different types of noise (e.g. thermal noise, shot noise, flicker noise, etc.)

This is strictly not noise!

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A Methodology to Predict the Impact of Substrate Noise in Analog/RF Systems

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Gerd Vandersteen, *Member, IEEE*, and Yves Rolain, *Fellow, IEEE*

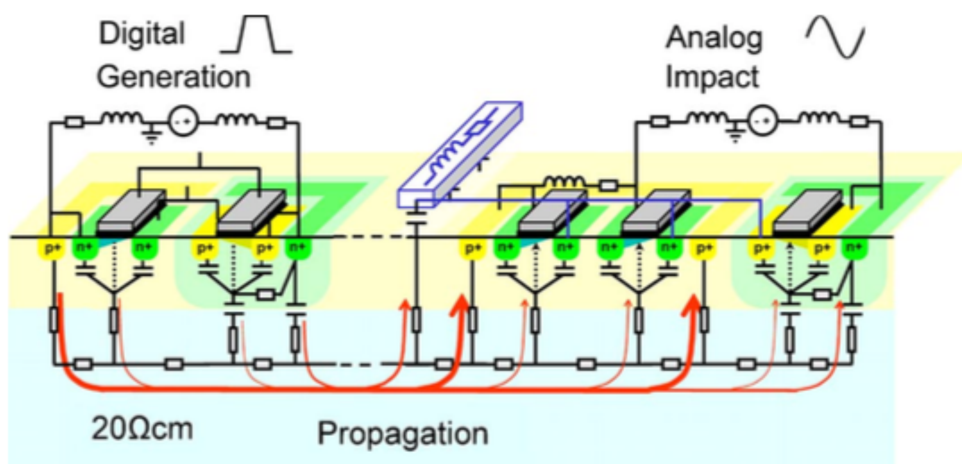
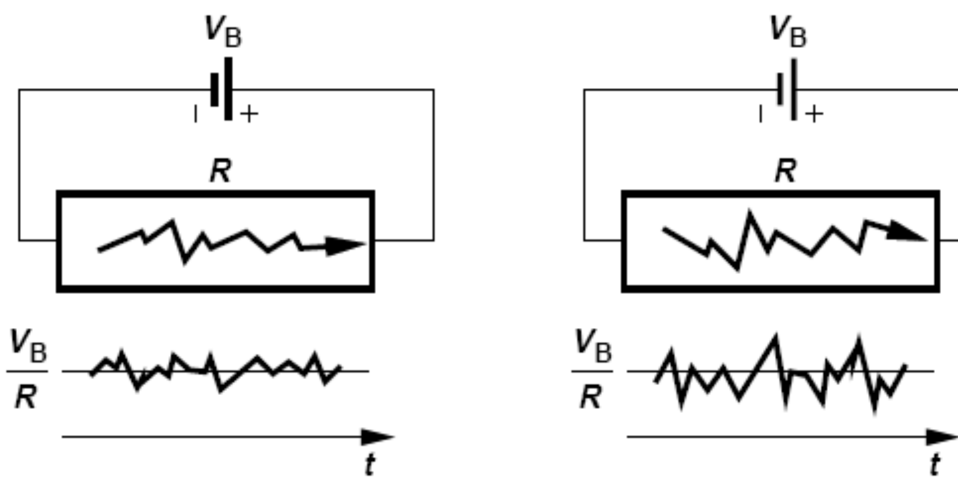


Fig. 1. Switching activity of the digital circuits degrades the performance of the analog circuits through the common substrate.

2.3.1 Noise

- The average current remains equal to V_B/R but the instantaneous current displays random values.

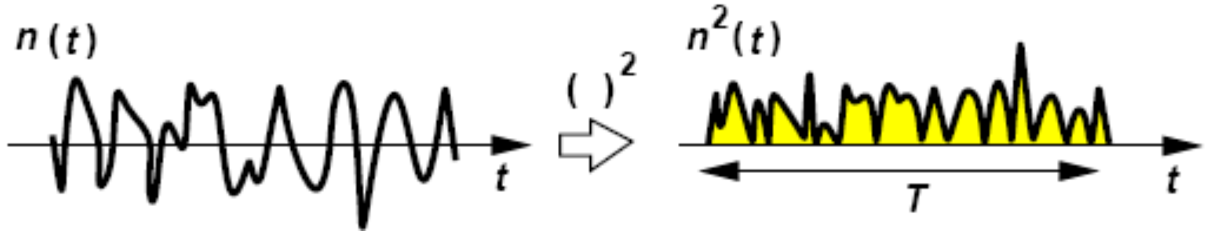


Lower temperature

Higher temperature

2.3.1 Noise

- Average noise power:

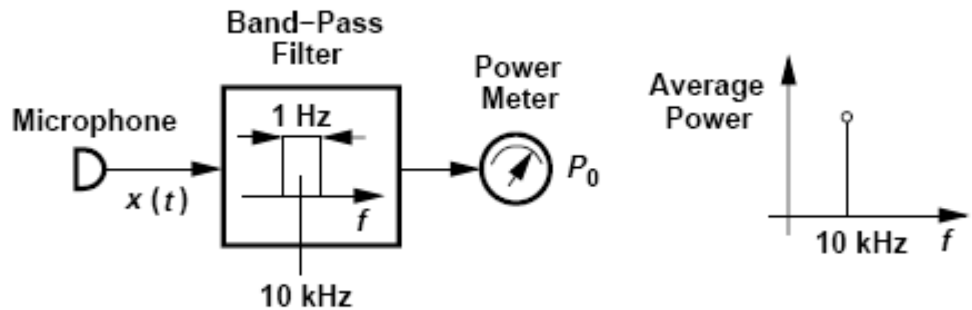


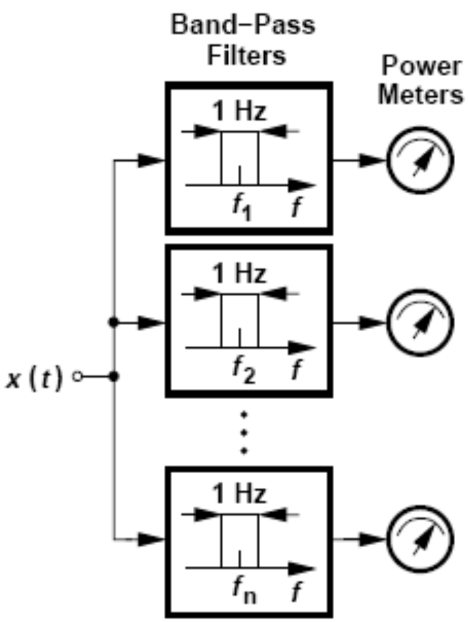
$$P_n = \lim_{T\to\infty} \frac{1}{T} \int_0^T n^2(t)dt$$

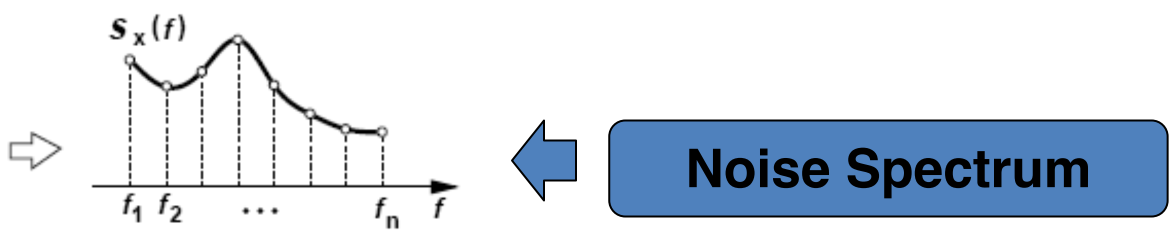
- T must be long enough to accommodate several cycles of the lowest frequency.

2.3.2 Noise Spectrum

- To measure the signal's frequency content at 10 kHz, we need to filter out the remainder of the spectrum and measure the average power of the 10-kHz component.





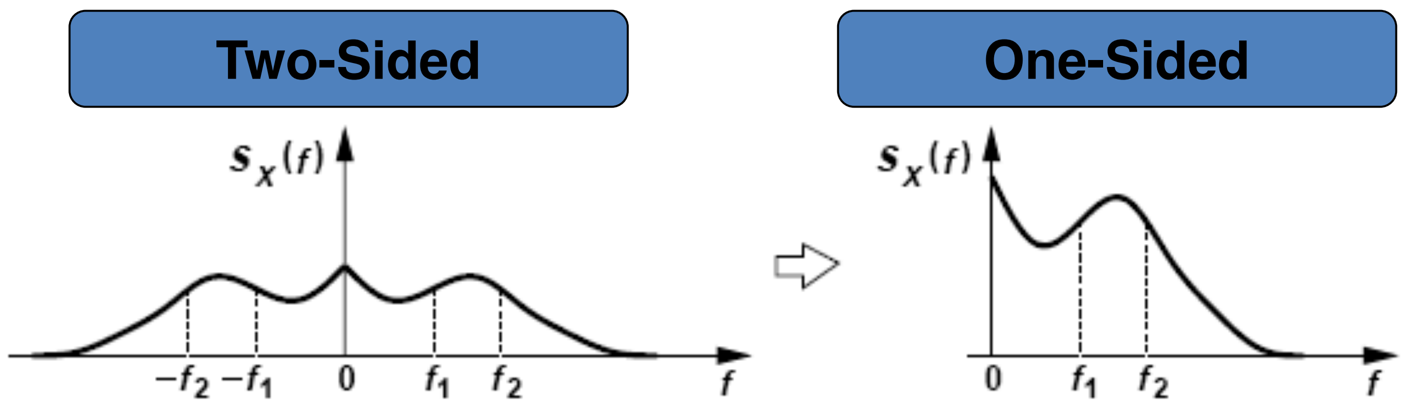


Power Spectral Density (PSD)

- Power Spectral Density (PSD) is the $S_x(f)$.
- Total area under $S_x(f)$ represents the average power carried by $x(t)$.

$$\int_0^{\infty} S_x(f)\,df = \lim_{T\to\infty}\frac{1}{T}\int_0^T x^2(t)\,dt$$

- Two-sided spectrum is scaled down vertically by factor of 2.



Thermal Noise

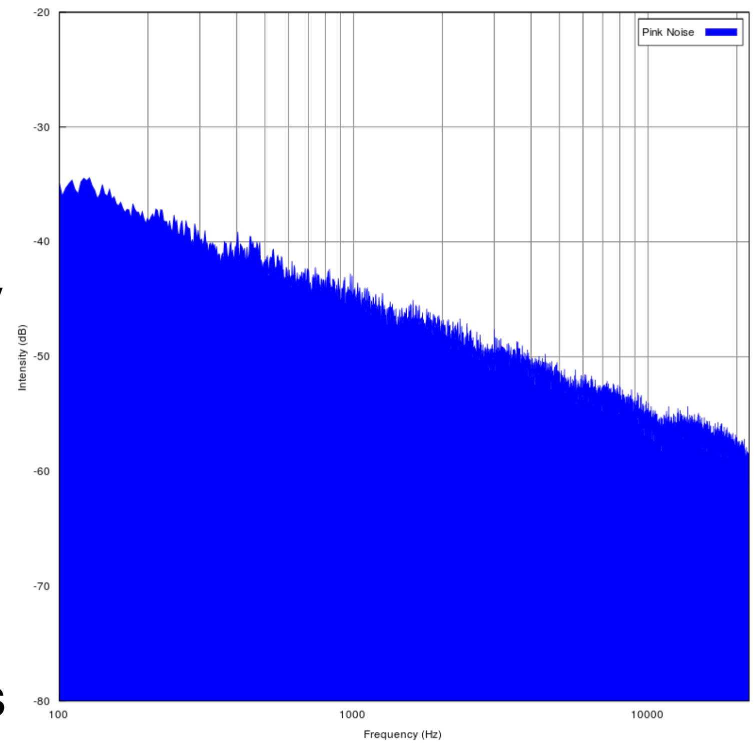
- Charge carriers, which are thermally affected generate a random varying current. It produces a random voltage which is called "thermal noise".
- Thermal noise power is proportional to *T [K].* The one-sided PSD of a resistor is given by:

$$S_v(f) = 4kTR \quad (k\text{=1.38E-23 J/K}) \quad [\text{V}^2/\text{Hz}]$$

- It is independent of frequency, because it is considered as "white" noise (noise power is the same over any given absolute bandwidth).

Pink noise

- Pink noise (Wikipedia): Pink noise or 1⁄f noise is a signal or process with a frequency spectrum such that the power spectral density (energy or power per frequency interval) is inversely proportional to the frequency of the signal. Pink noise is the most common signal in biological systems. …
- The term **flicker noise** is sometimes used to refer to pink noise, although this is more properly applied only to its occurrence in electronic devices.



Example 2.15

A resistor of value R_1 generates a noise voltage whose one-sided PSD is given by

$$S_v(f) = 4kTR_1$$

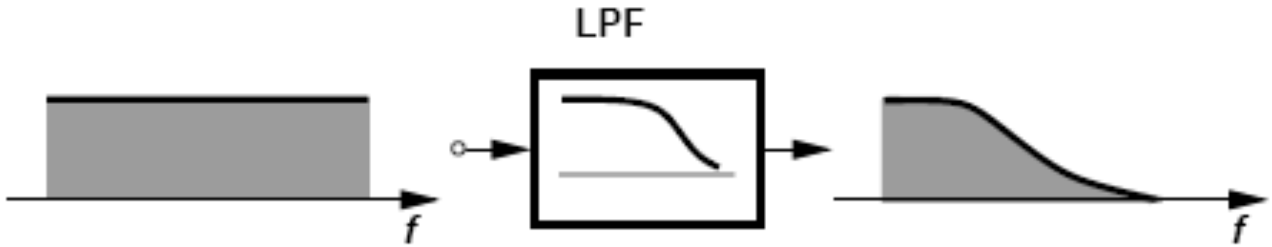
(a) What is the total average power carried by the noise voltage?

(b) What is the dimension of $S_v(f)$?

(c) Calculate the noise voltage for a 50-Ω resistor in 1 Hz at room temperature.

Effect of Transfer Function on Noise

- Effect of a low-pass filter on white noise:



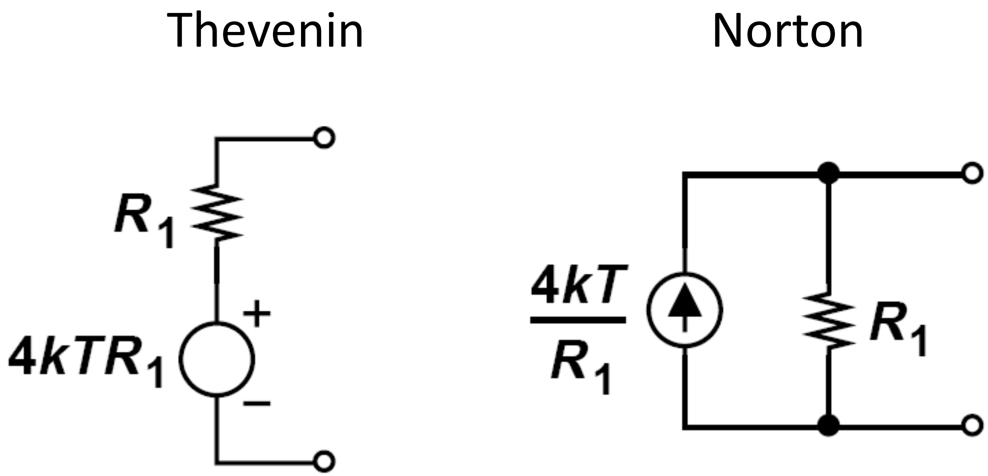
- Generally, with a transfer function H(s):

$$S_y(f) = S_x(f)|H(f)|^2$$

- Define PSD to allow many of the frequency-domain operations used with deterministic signals to be applied to random signals as well.

2.3.4 Device Noise

- Resistor thermal noise (PSD) models:

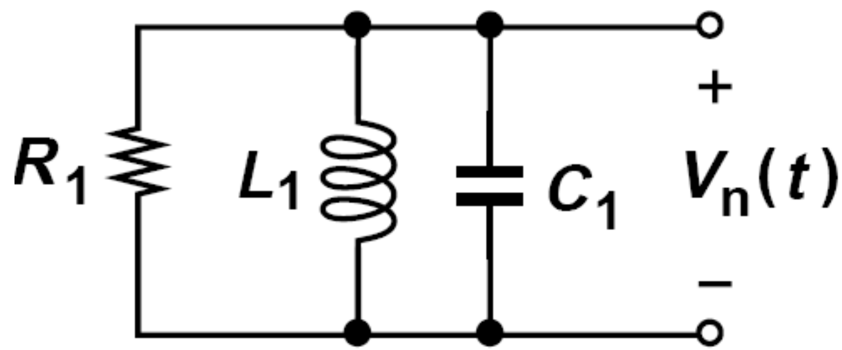


$$\overline{V_n^2} = 4kTR_1 \qquad \overline{I_n^2} = \frac{\overline{V_n^2}}{R_1^2} = 4kT/R_1$$

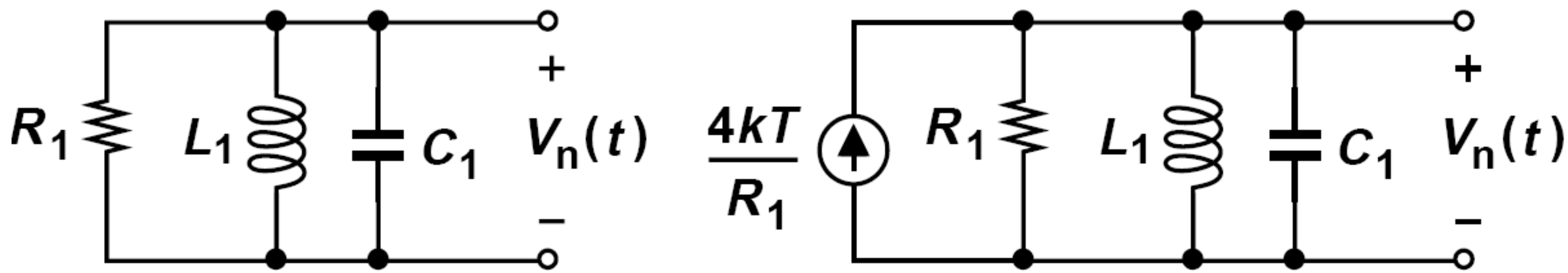
- Polarity of the sources is unimportant but must be kept same throughout the calculations

Example 2.16

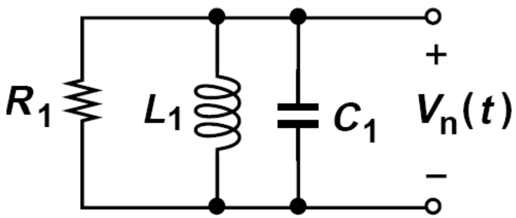
- Sketch the PSD of the noise voltage measured across the parallel RLC tank depicted in figure below.

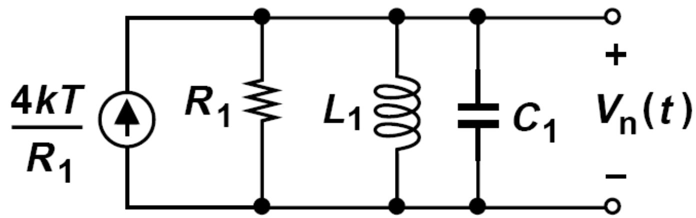


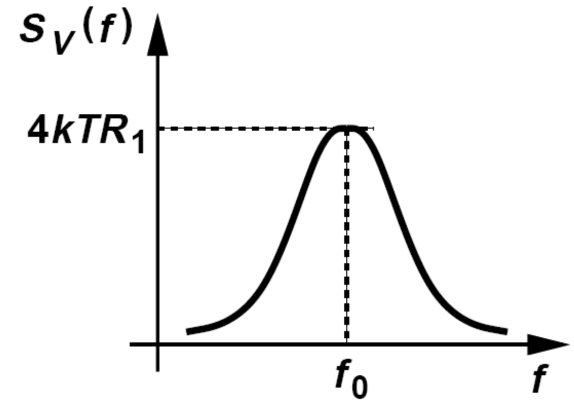
Example 2.16 (cont)



Example 2.16 (cont)







Thermal Noise

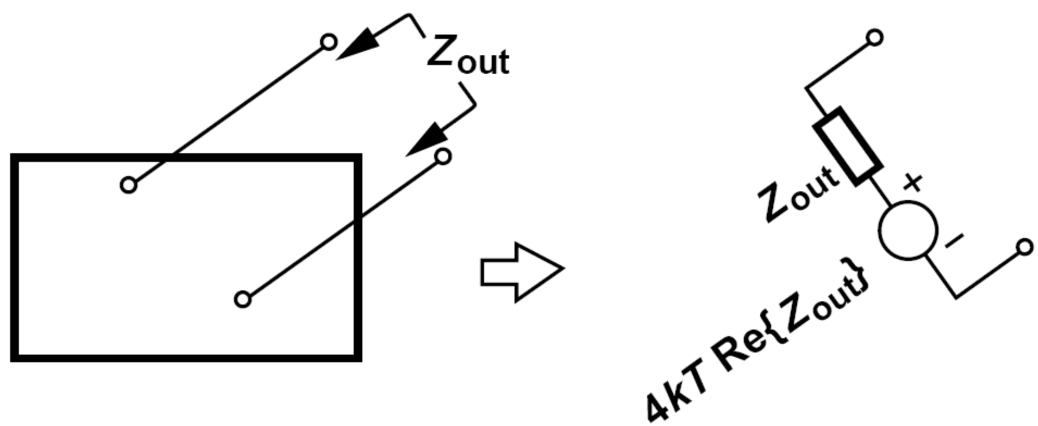
- Example (homework!): Calculate the equivalent noise voltage of two parallel and two series resistors, R_1 and R_2.

- Answers:
  - Parallel: $\overline{V_{np}^2} = 4kT(R_1 \parallel R_2)$
  - Series: $\overline{V_{ns}^2} = 4kT(R_1 + R_2)$

- Tip: One combination is suitable for analysis with Norton models, one with Thevenin.

A Theorem about Lossy Circuit

- If a passive circuit dissipates energy, then it must contain a physical resistance and must therefore produce thermal noise. We loosely say "lossy circuits are noisy."
- If the real part of the impedance seen between two terminals of a passive (reciprocal) network is equal to *Re{Zout}*, then the PSD of the thermal noise seen between these terminals is given by *4kTRe{Zout}*



Noise in MOSFETs

- Thermal noise of MOS transistors operating in the saturation region is approximated by a current source tied between the source and drain terminals, or can be modeled by a voltage source in series with gate.

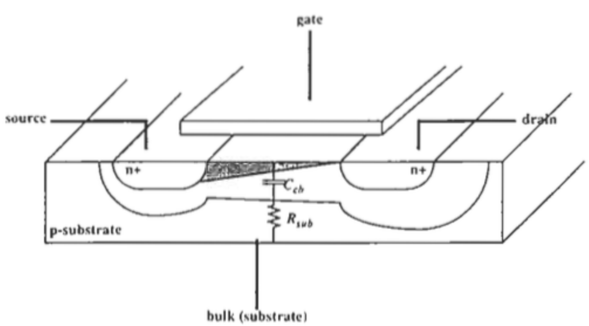
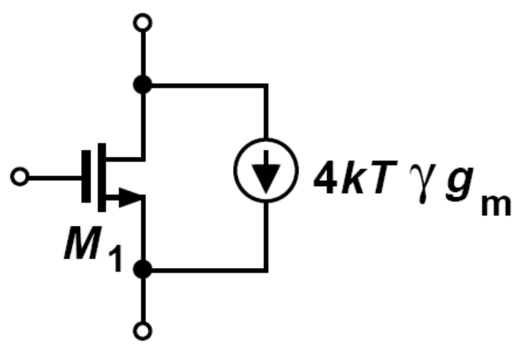
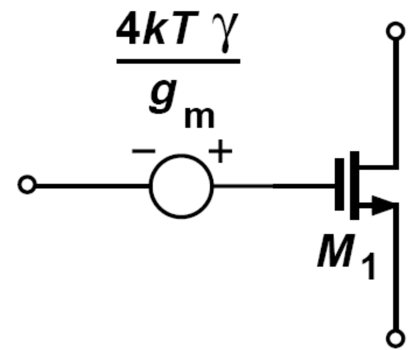


FIGURE 11.3. Simplified illustration of substrate thermal noise.



$$\overline{I_n^2} = 4kT\gamma g_m$$



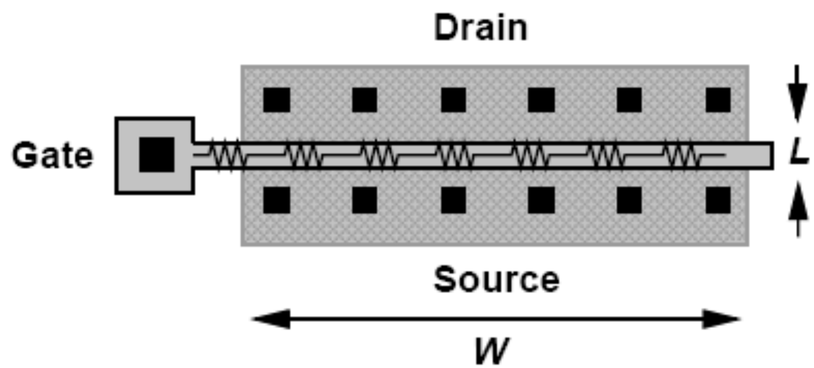
$$\overline{V_n^2} = 4kT\gamma / g_m$$

γ: ”excess noise coefficient”, 2/3 for long channel and up to 2 for short channel devices

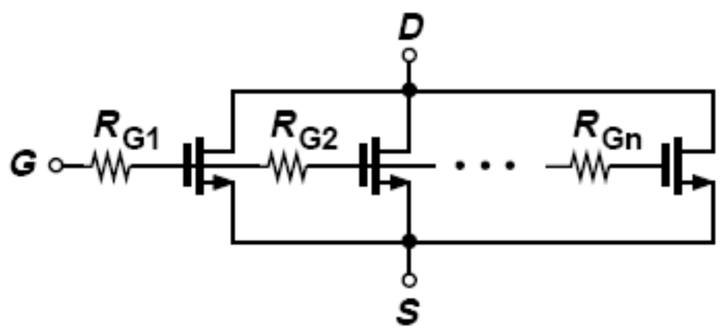
Thermal Noise in MOSFETs

- The gate noise due to gate resistance:

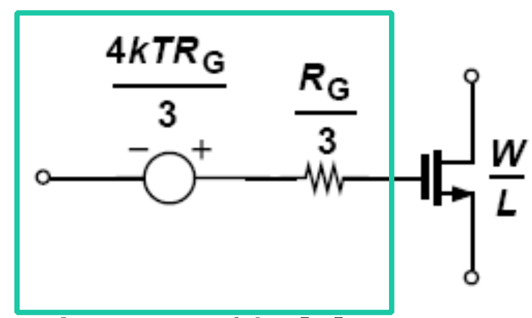
$$R_G = \frac{W}{L} R_{\square}$$



(a)

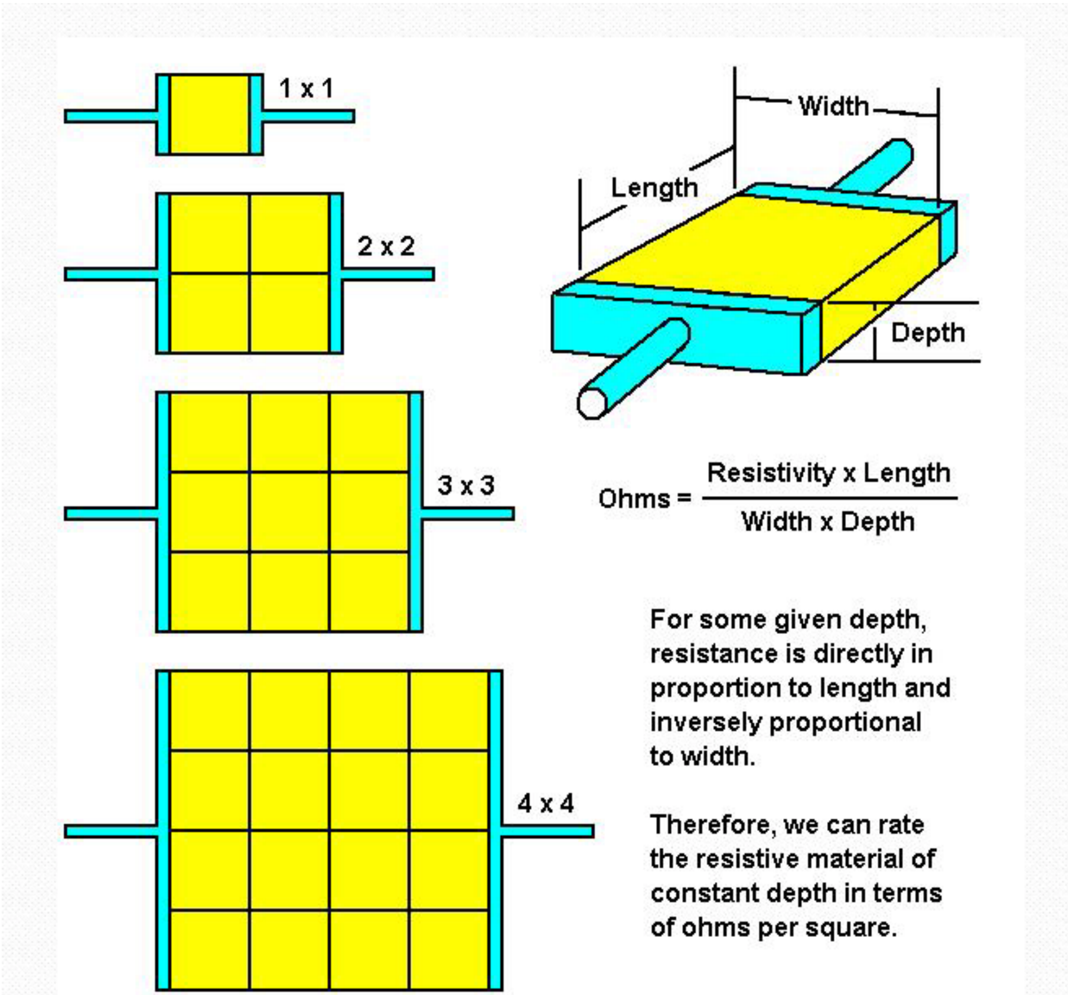


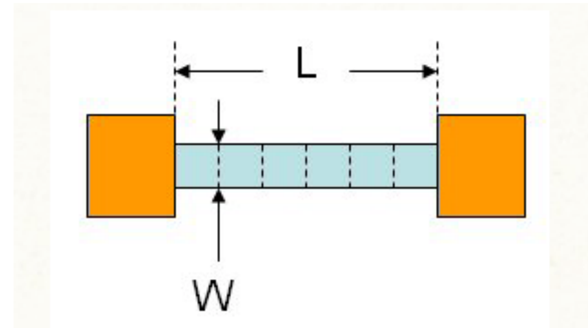
$$R_{G1} + R_{G2} + \cdots + R_{Gn} = R_G$$

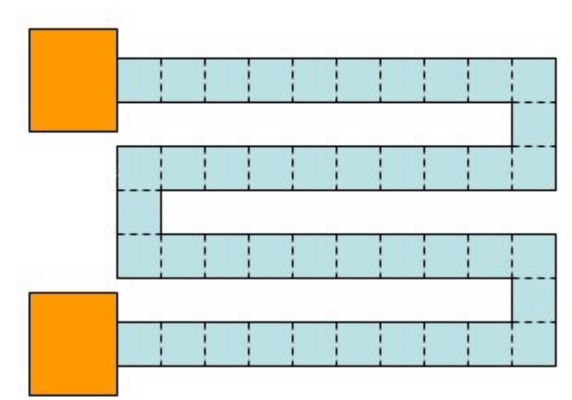


As proved in [6]

Ohms/square? square what?





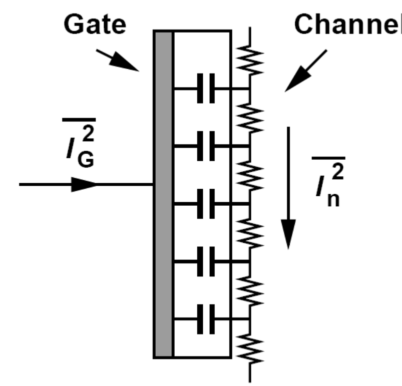


Thermal Noise in MOSFETs

- Good design: Gate noise much less than channel noise

$$4kT\frac{R_G}{3} \ll \frac{4kT\gamma}{g_m}$$

- At very high frequencies thermal noise current flowing through the channel couples to the gate capacitively, ”gate-induced noise current”



- G/S/D terminal resistance can be reduced by parallel transistors

Flicker Noise

- Flicker noise or 1/f noise appears at low frequencies. It increases when frequency decreases.
- Flicker noise in MOSFET

$$\overline{V_n^2} = \frac{K}{WLC_{ox}}\frac{1}{f}$$

Transistor width　　Gate length

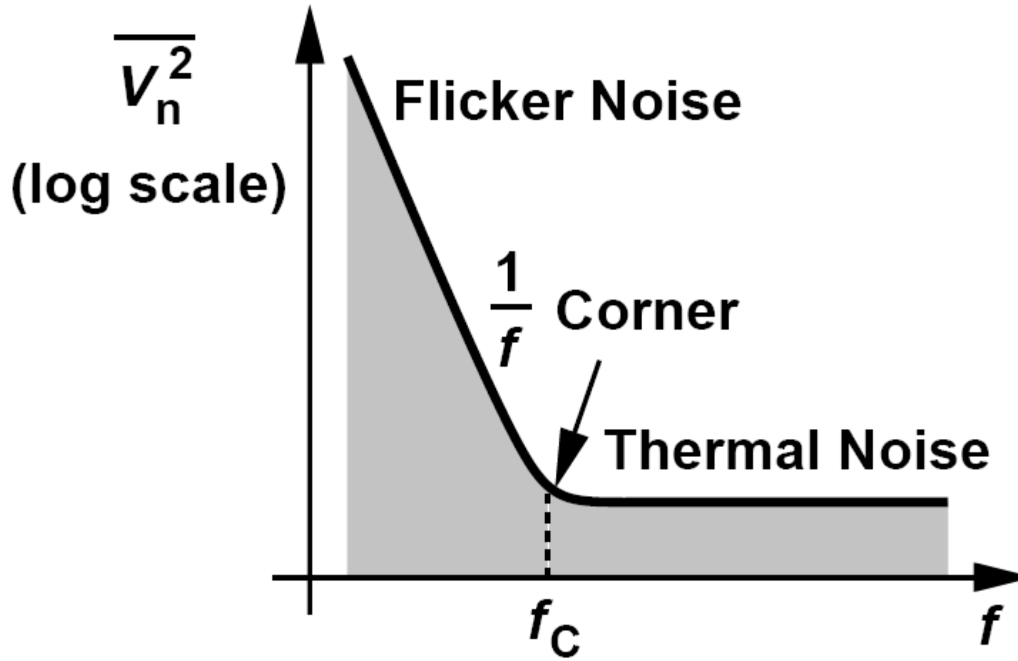
- *K* is a process dependent constant, which is typically lower for PMOS devices than NMOS transistors.

Flicker Noise: corner frequency

$$\overline{V_n^2} = \frac{K}{WLC_{ox}}\frac{1}{f}$$

$$\frac{K}{WLC_{ox}}\frac{1}{f_c}g_m^2 = 4kT\gamma g_m$$

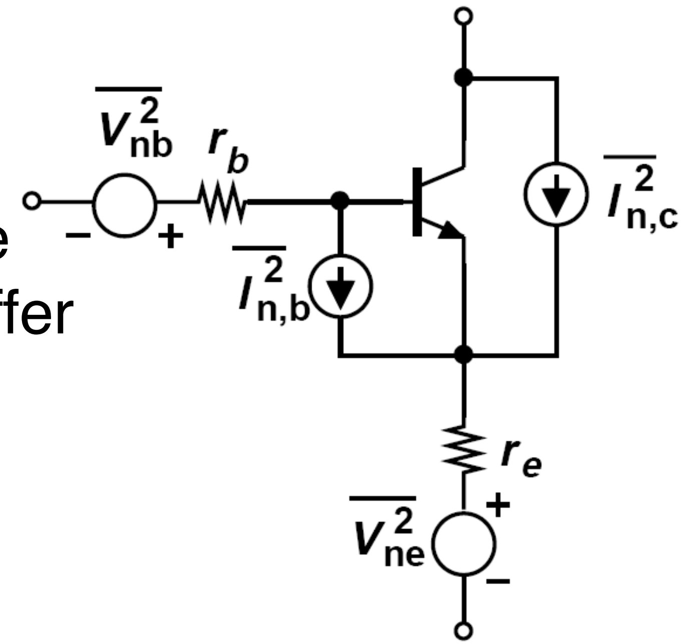
$$f_c = \frac{K}{WLC_{ox}}\frac{g_m}{4kT\gamma}$$



- For CMOS devices, the 1/f noise corner falls in the range of tens or hundreds of MHz in today's MOS technologies.

Noise in Bipolar Transistors

- Bipolar transistors contain physical resistances in their base, emitter, and collector regions, all of which generate thermal noise. Moreover, they also suffer from “shot noise” associated with the transport of carriers across the base-emitter junction.
- In low-noise bipolar circuits, the base resistance thermal noise and the collector current shot noise become dominant. For this reason, wide transistors biased at high current levels are employed.



Noise Temperature

- Sometime you can see the term "Noise Temperature". What is this?

- Definition: "the equivalent temperature of a source impedance into a perfect (noise-free) device that would produce the same added noise".

$$F = 1 + \frac{T_N}{T_{ref}} \Rightarrow T_N = T_{ref}(F - 1) \qquad T_{ref} = 290 \text{ K}$$

- Ex:
  NF=3 dB => T_N = 289 K
  NF=1 dB T_N = 75 K