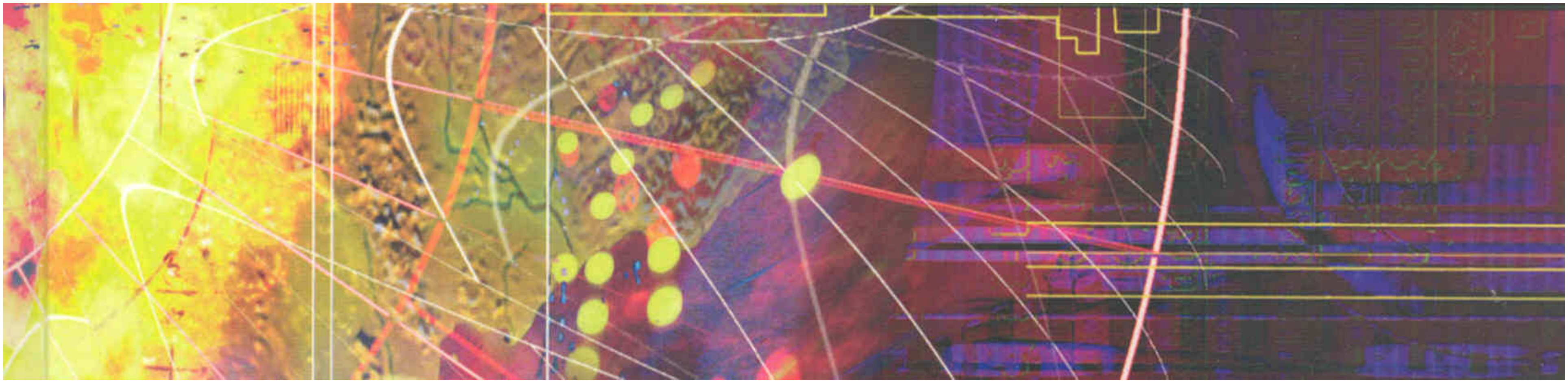


EE302 Lesson 3: Noise

Why study noise?

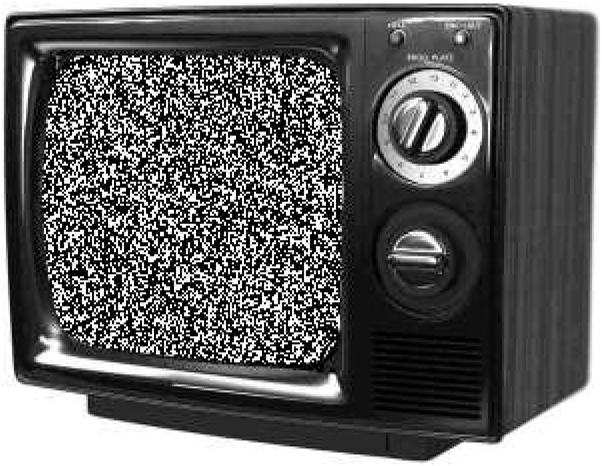
WYPR-FM 88.1 MHz
Transmitted power 15,500 W

~19 orders of magnitude

Received power
~0.00000000000001 W

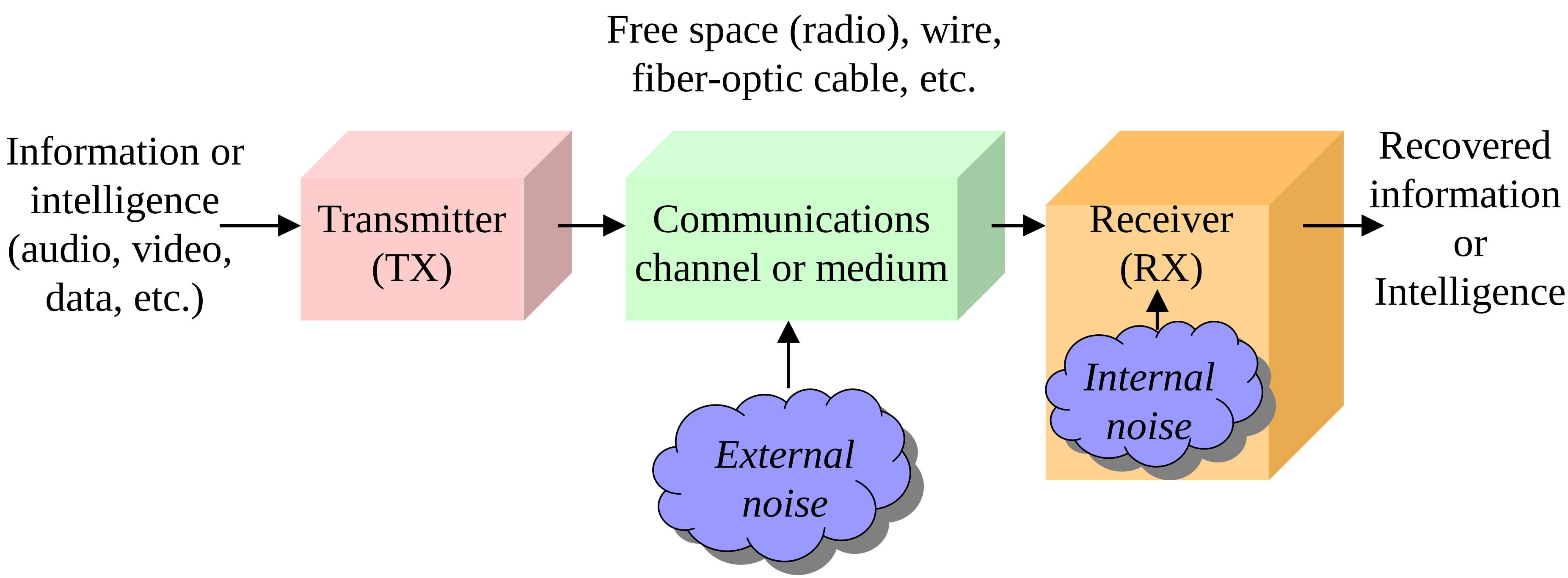
Why study noise?

- Noise is one of the two principle limiting factors in the performance of communication systems.
- **Electrical noise** is any undesired voltages or currents that end up appearing at the receiver output. An example is **static** that is commonly encountered on broadcast AM radio.

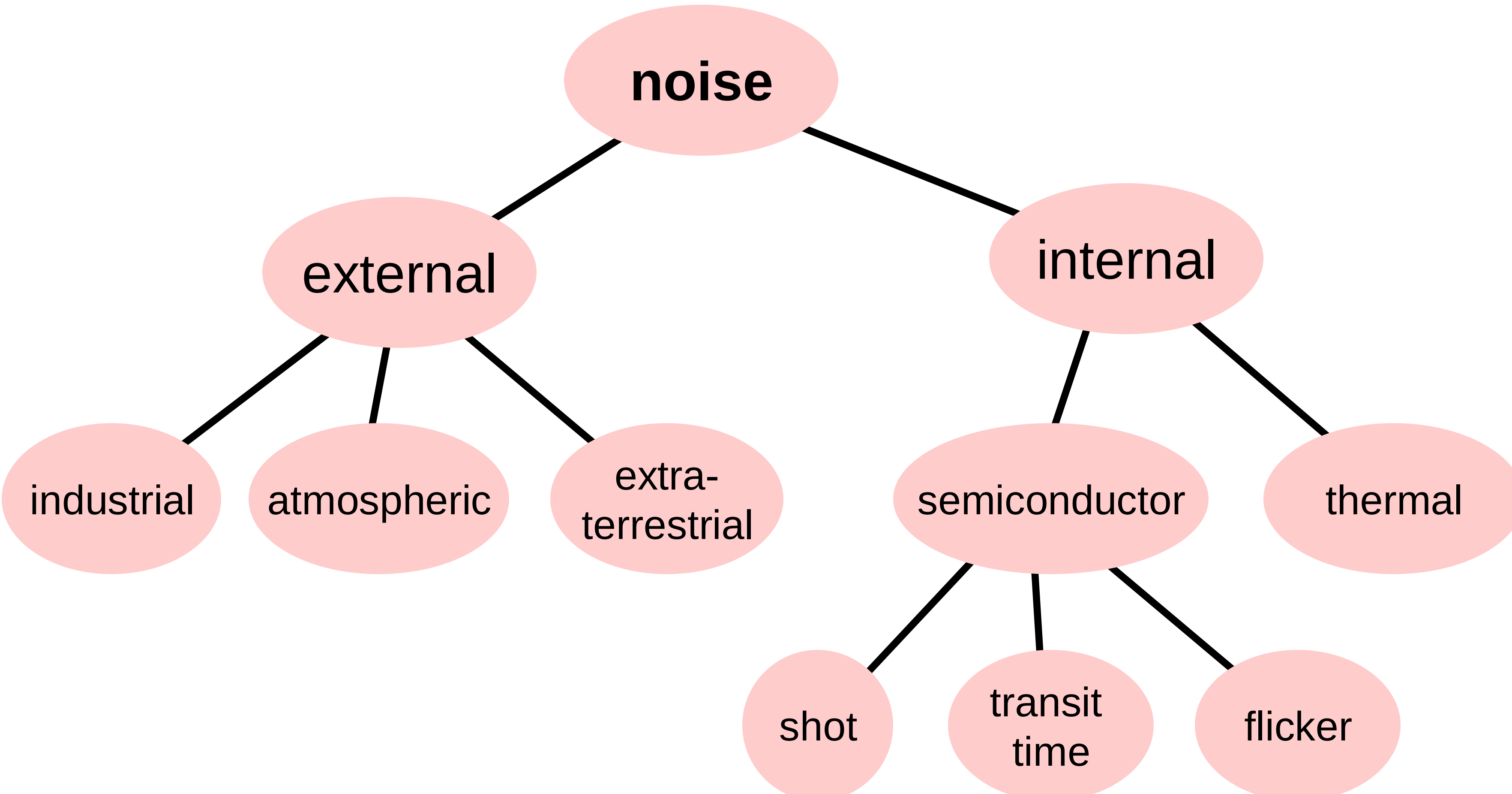


Types of noise

- Noise is divided into two broad categories:
  - **External noise** is noise introduced in the transmission channel.
  - **Internal noise** is noise introduced inside the receiver itself.

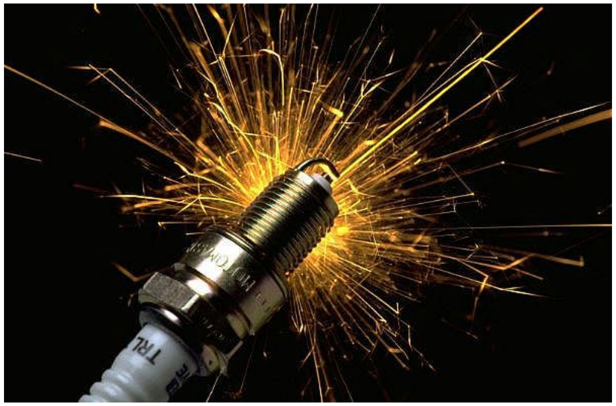


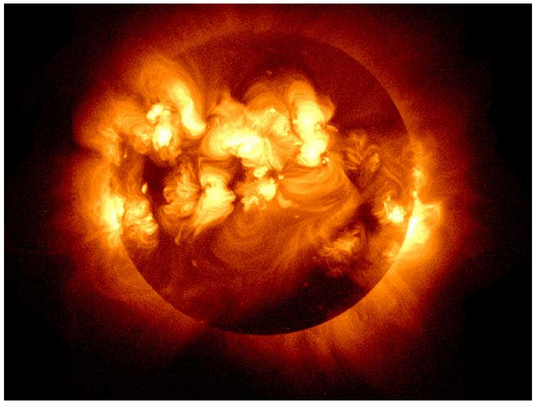
Noise categories



External noise

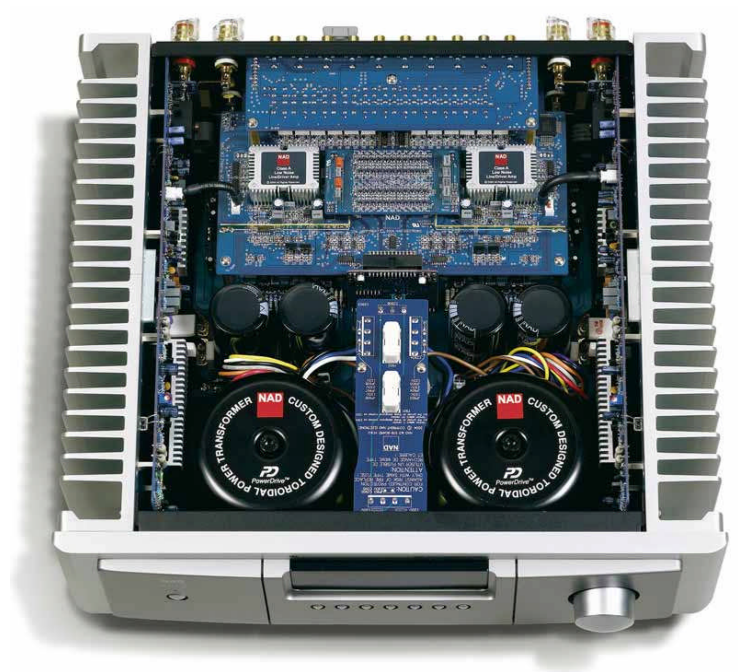
- **Industrial noise** is caused by human made electrical sources (motors, generators, ignition)
- **Atmospheric noise** is due to naturally occurring disturbances in earth's atmosphere such as lightening (< 30 MHz)
- **Extraterrestrial noise** is electrical noise due to solar and cosmic activity (10-1500 MHz)





Internal noise

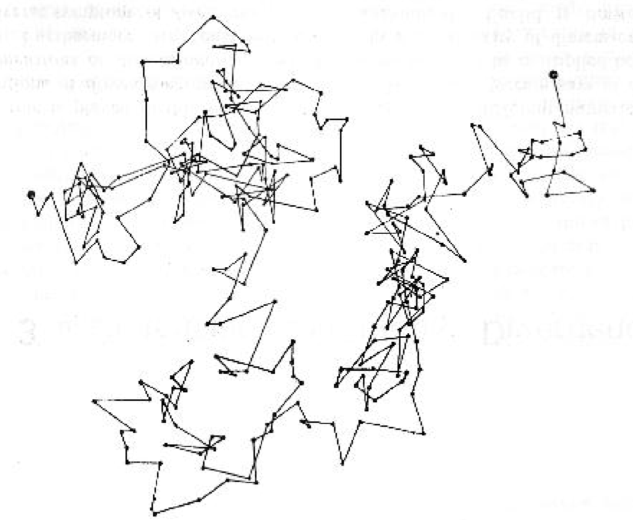
- **Internal noise** is noise introduced inside the receiver.
- Two types of internal noise we will consider
  - Thermal noise
  - Semiconductor noise



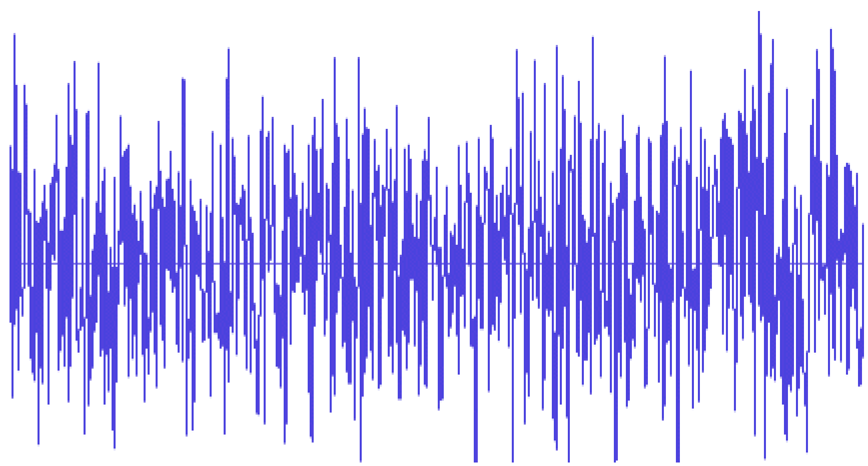
Thermal noise

- Thermal noise is caused by random motion of free electrons and vibrating ions in a conductor.
- Thermal noise is proportional to temperature.

Random electron motion due to heat



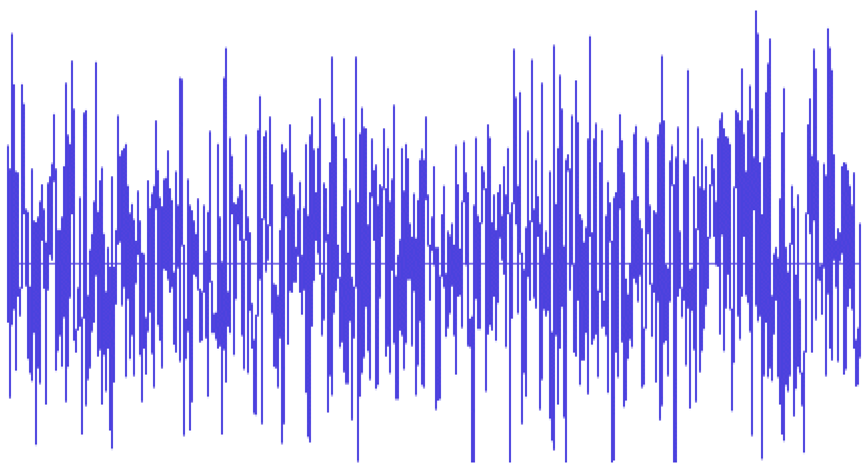
Thermal noise voltage as a function of time



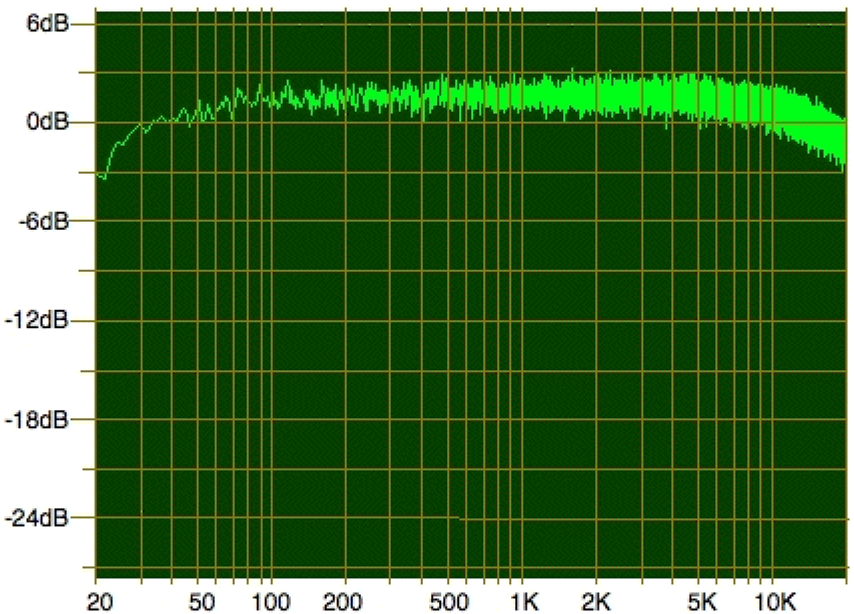
Thermal noise

- Thermal noise is also termed **white** noise or Gaussian noise.
  - Just as white light contains all frequencies, white noise contains an equal weighting of all frequencies.

Thermal noise voltage as a function of time



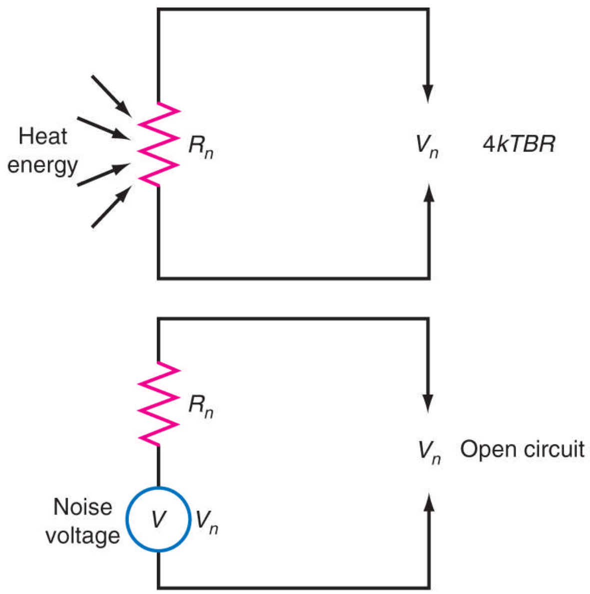
Frequency spectrum of thermal noise



Frequency (Hz)

Thermal noise voltage

- The noise voltage produced by a resistor R over a bandwidth B can be calculated



$$v_n = \sqrt{4kTBR}$$

where $v_n =$ rms noise voltage

$k =$ Boltzman's constant $(1.38 \times 10^{-23}$ J/K$)$

$T =$ temperature, K (°C + 273)

$B =$ bandwidth, Hz

$R =$ resistance, Ω

Example Problem 1

The bandwidth of a receiver with a 75-Ω input resistance is 6 MHz. If the temperature is 29°C, what is the input thermal noise voltage?

Thermal noise design considerations

- Since thermal noise is proportional to resistance, temperature, and bandwidth, receiver designs that reduce these values will have superior performance.

$$v_n = \sqrt{4kTBR}$$

where $v_n =$ rms noise voltage

$k =$ Boltzman's constant (1.38×10^{-23} J/K)

$T =$ temperature, K (°C + 273)

$B =$ bandwidth, Hz

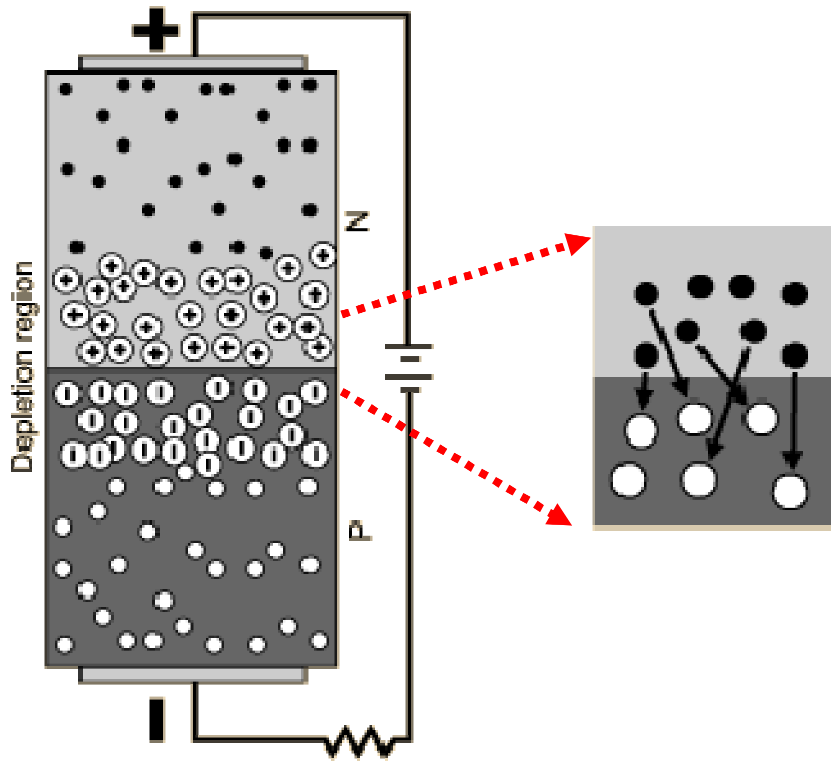
$R =$ resistance, Ω

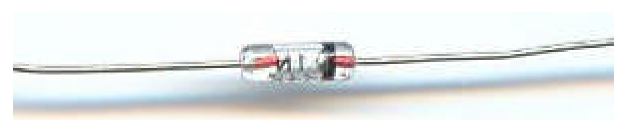
Semiconductor noise

- The other major category of internal noise originates from semiconductor devices such as diodes and transistors.
- Semiconductor noise is comprised of
  - Shot noise
  - Transit-time noise
  - Flicker noise

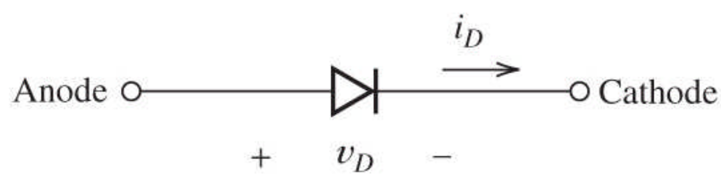
Shot noise

- **Shot noise**, the largest contributor to transistor noise, is due to the random paths of the current carriers flowing in semiconductors.





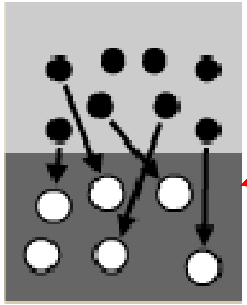
diode



circuit symbol for a diode

Transit-time noise

- **Transit-time noise** occurs at high frequencies when “transit time” of charge carriers crossing the semiconductor’s junction approaches the signal’s period.
- This type noise increases rapidly when operating above the device’s high-frequency cutoff.

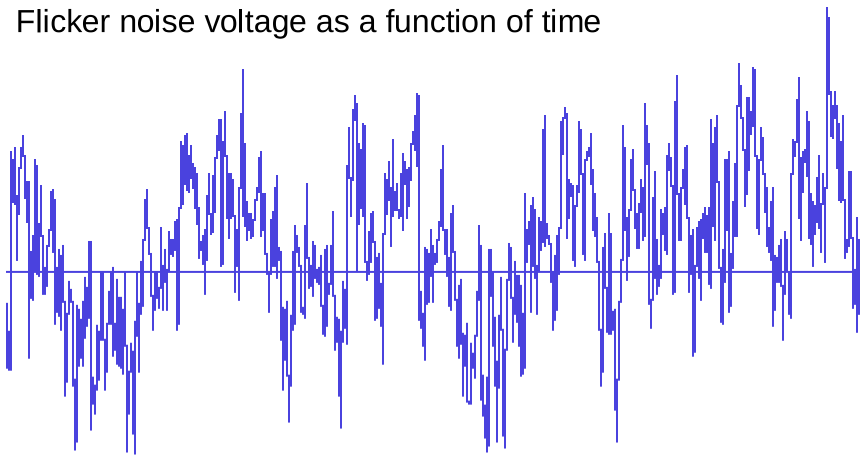


Time required to cross *pn*-junction close to period (*T*) of the signal.

Flicker noise

- Flicker noise results from minute variations in resistance in semiconductor material.
- Flicker noise is inversely proportional to frequency and sometimes referred to as $1/f$ noise or pink noise.

Flicker noise voltage as a function of time

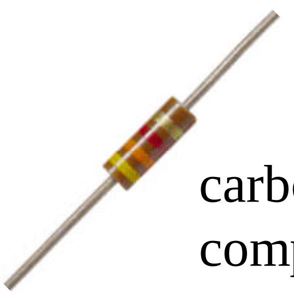


Flicker noise

- Flicker noise is also found in resistors and conductors.

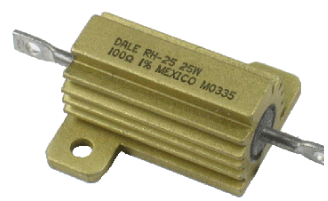
Flicker noise for various types of resistors

Type of resistor	Noise voltage range (μV)
Carbon-composition	0.1-3.0
Carbon-film	0.05-0.3
Metal-film	0.02-0.2
Wire-wound	0.01-0.2



carbon-composition

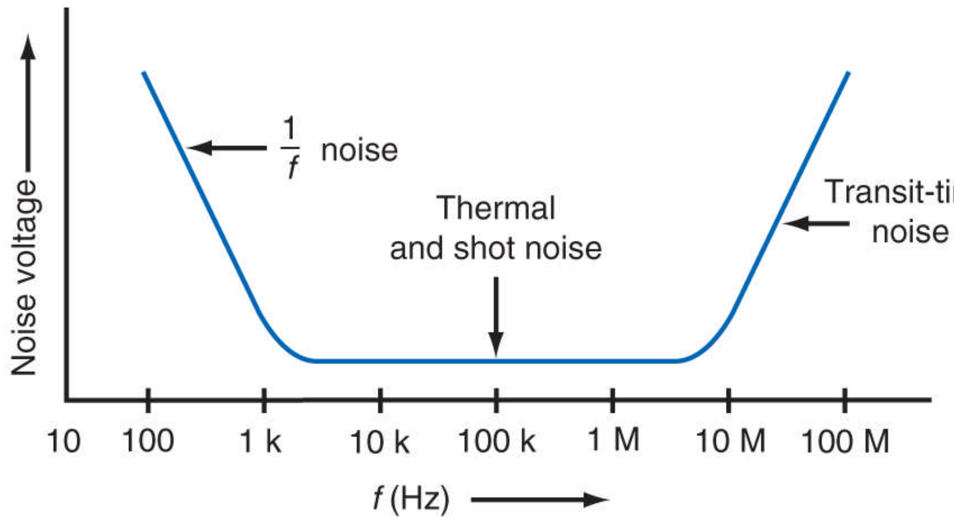
metal-film



wire-wound

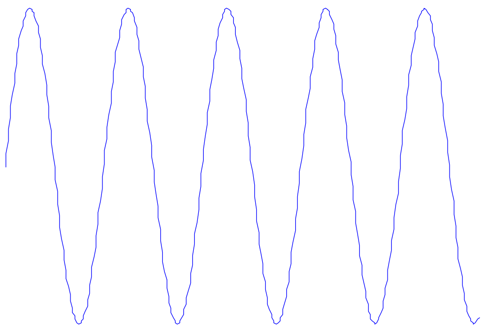
Semiconductor noise

- Total noise voltage of semiconductor devices varies with frequency with different types of noise predominating in different regions.

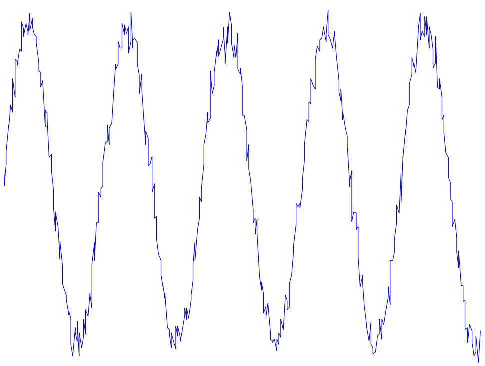


Measuring noise

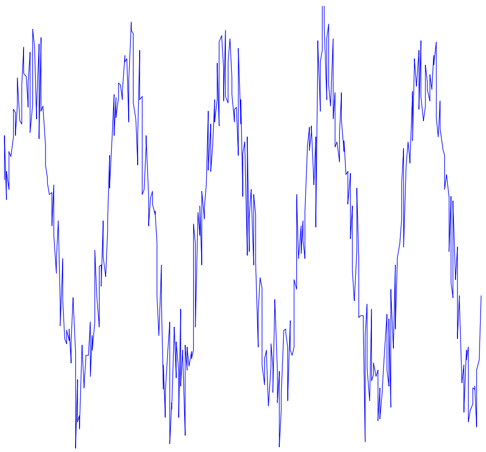
- To quantify the effect of noise on a signal, we use the **signal-to-noise** (S/N) ratio or SNR.
  - A strong signal and weak noise results in a high S/N ratio.
  - A weak signal and strong noise results in a low S/N ratio.



signal without noise



20 dB S/N ratio

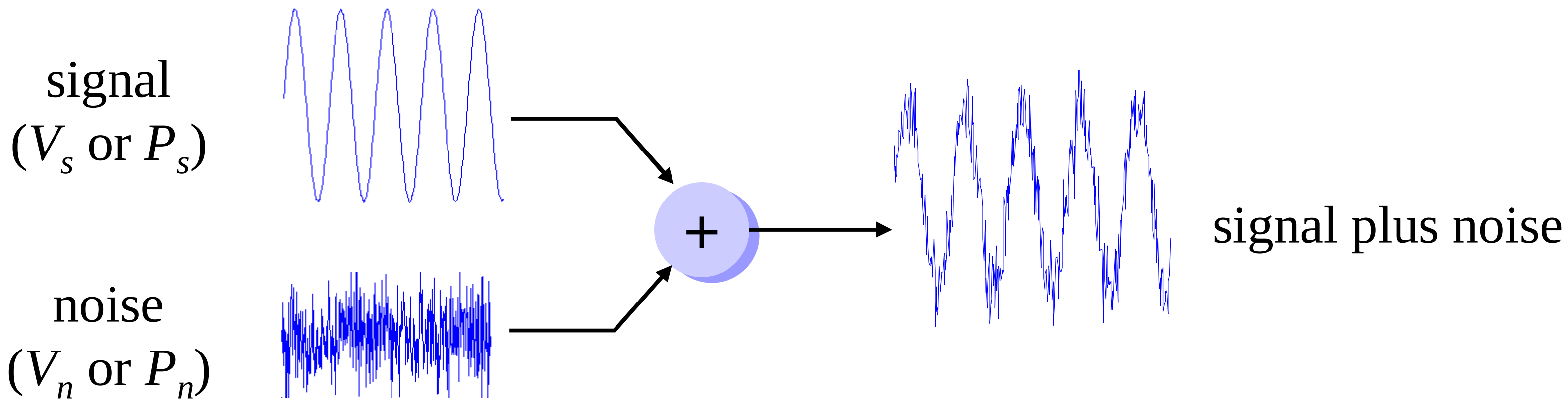


10 dB S/N ratio

Signal-to-noise ratio

- Signal to noise ratio can be expressed in terms of voltage or power.

$$\frac{S}{N} = \frac{V_s}{V_n} \quad \text{or} \quad \frac{S}{N} = \frac{P_s}{P_n} \quad \text{where} \begin{cases} V_s = \text{ signal voltage (rms)} \\ V_n = \text{ noise voltage (rms)} \\ P_s = \text{ signal power (W)} \\ P_n = \text{ noise power (W)} \end{cases}$$



Signal-to-noise (decibels)

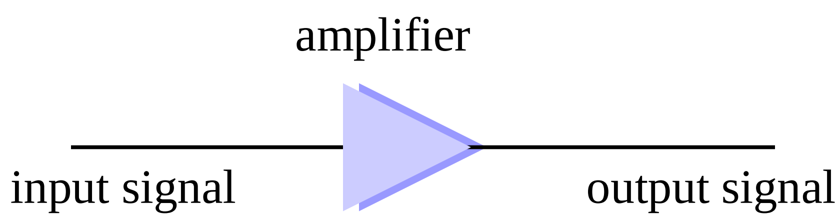
- Signal to noise ratio is most commonly report in decibels

$$S/N \text{ ratio (dB) using voltage: } \text{dB} = 20\log\frac{V_s}{V_n}$$

$$S/N \text{ ratio (dB) using power: } \text{dB} = 10\log\frac{P_s}{P_n}$$

Noise ratio (NR)

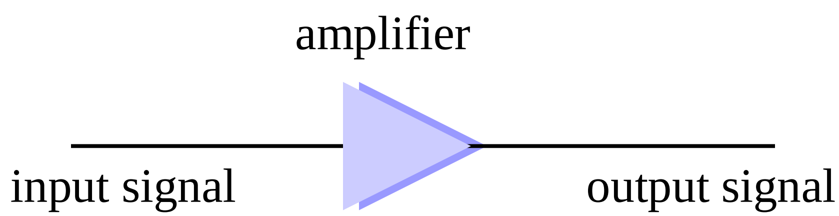
- We often need to quantify how much noise a device adds to a signal as it passes through the device.
- One measure is the **noise ratio** (NR) which is simply the ratio of input S/N to output S/N.



$$\mathrm{NR} = \frac{S/N \text{ input}}{S/N \text{ output}}$$

Noise figure (NF)

- When the noise ratio (NR) is expressed in decibels, it's called the noise figure (NF).
- Since the output S/N ratio will be less than the input, the NR > 1 and NF > 0.
  - For an ideal device, NR = 1.0 and NF = 0 dB.
  - In practice, NF less than 2 dB is excellent.



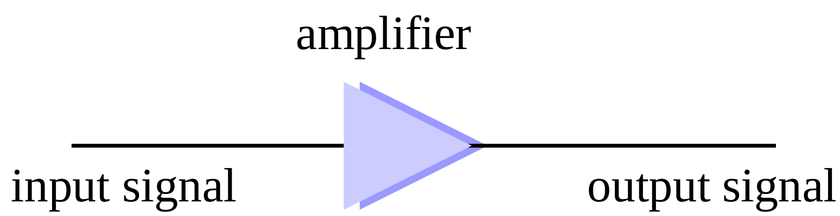
$$NF = 10 \log NR \quad [dB]$$

Example Problem 2

A transistor amplifier has a measured S/N power ratio of 10,000 at its input and 5,624 at its output.

(a) Calculate the NR.

(b) Calculate the NF.

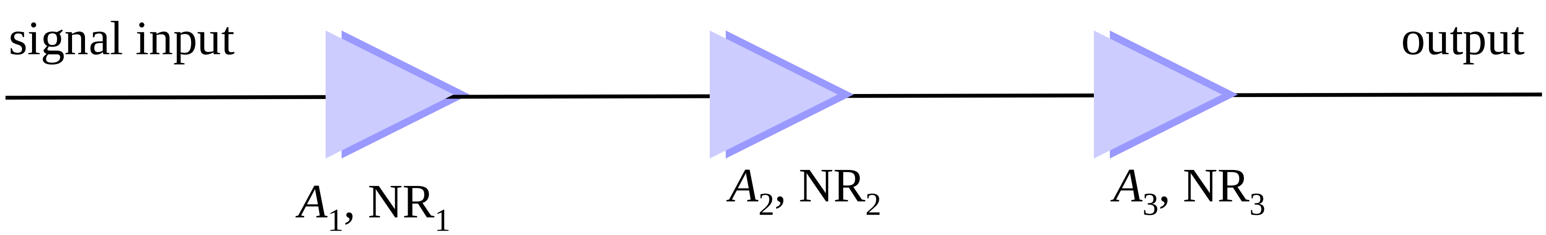


Noise in cascaded stages

- The total noise performance of a cascade of amplifiers depends upon the noise ratio and power gain of each stage.
- The total noise performance of multiple stages is given by Friis' formula

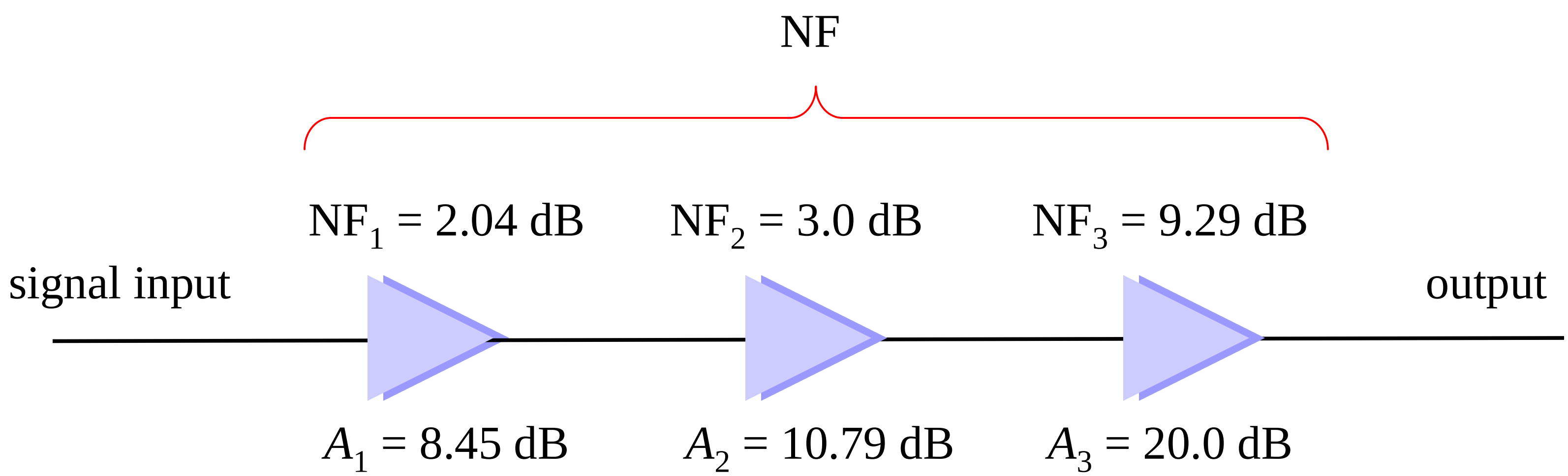
$$\mathrm{NR} = \mathrm{NR}_1 + \frac{\mathrm{NR}_2 - 1}{A_1} + \frac{\mathrm{NR}_3 - 1}{A_1 A_2} + \cdots + \frac{\mathrm{NR}_n - 1}{A_1 A_2 \cdots A_{n-1}}$$

where A_i and NR_i are the power gain and noise ratio of the *i*th stage.



Example Problem 3

The gain of the three stages of an amplifier are 8.45 dB, 10.79 dB, and 20 dB. The noise figures associated with these stages are 2.04 dB, 3.0 dB, and 9.29 dB. What is the overall NR and NF for this cascade of amplifiers?



Implications of Friis' formula

- The total noise performance of a receiver is invariably determined by the very first stage.
- Beyond the first and second stage, noise is no longer a problem.

$$\mathrm{NR} = \mathrm{NR}_1 + \frac{\mathrm{NR}_2 - 1}{A_1} + \frac{\mathrm{NR}_3 - 1}{A_1 A_2} + \cdots + \frac{\mathrm{NR}_n - 1}{A_1 A_2 \cdots A_{n-1}}$$