Intrinsic Noise Sources, Noise Factor

Choose yourself and new technologies

References

Basic:

Ott H. W., *Electromagnetic Compatibility Engineering*, Wiley, Hoboken, NJ, 2009

Additional:

Williams T., *EMC for Product Designers*, Elsevier-Newnes, 4-th ed., Oxford, 2007

Source of illustrative materials

All the illustrative materials have been taken from:

Ott H. W., *Electromagnetic Compatibility Engineering*, Wiley, Hoboken, NJ, 2009

Intrinsic Noise Sources

This lecture covers the two most important intrinsic noise sources: thermal noise and shot noise.

THERMAL NOISE

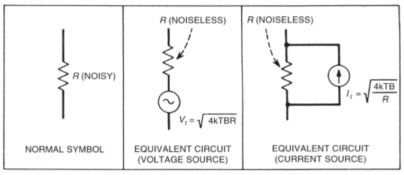
Thermal noise comes from thermal agitation of electrons **within a resistance**, and it sets a lower limit on the noise present in a circuit.
The open-circuit rms noise voltage produced by a resistance is [Nyquist]

$$V_t = \sqrt{4KTBR}$$

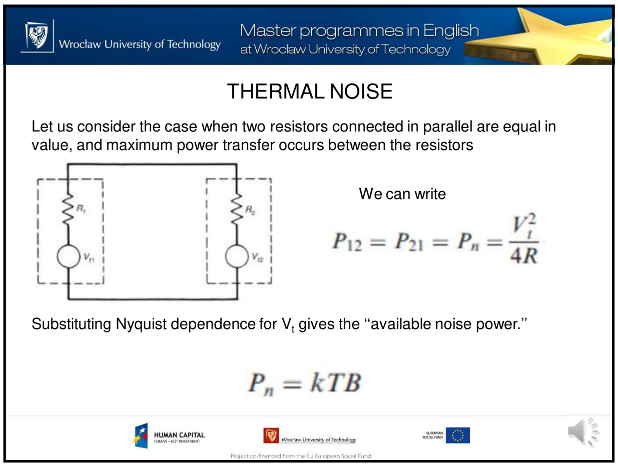
where
K = Boltzmann's constant (1.38 10^{-23} joules/K)
T = absolute temperature (K)
B = noise bandwidth (Hz)
R = resistance (Ω)

THERMAL NOISE

Thermal noise in a resistor can be represented in an equivalent circuit as a voltage source or a current source .



Electric circuit elements can produce thermal noise only if they can dissipate energy. Therefore, **a reactance cannot produce thermal noise.**



THERMAL NOISE

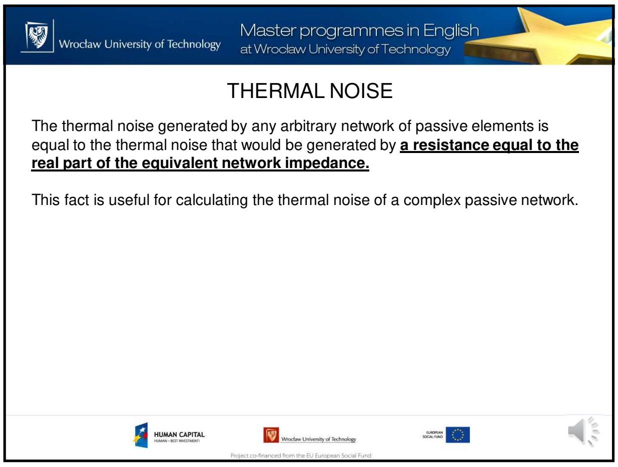
Let us consider the case when two resistors connected in parallel are equal in value, and maximum power transfer occurs between the resistors

We can write

$$P_{12} = P_{21} = P_n = \frac{V_t^2}{4R}$$

Substituting Nyquist dependence for V_t gives the "available noise power."

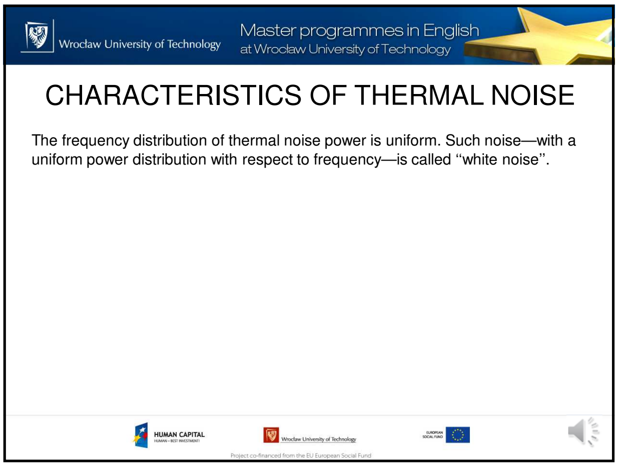
$$P_n = kTB$$



THERMAL NOISE

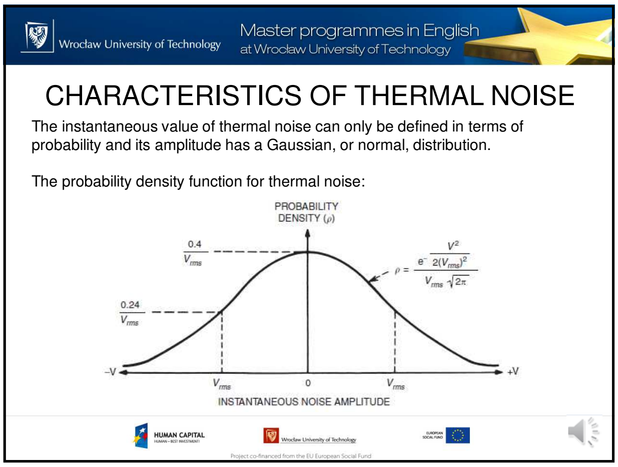
The thermal noise generated by any arbitrary network of passive elements is equal to the thermal noise that would be generated by **a resistance equal to the real part of the equivalent network impedance.**

This fact is useful for calculating the thermal noise of a complex passive network.



CHARACTERISTICS OF THERMAL NOISE

The frequency distribution of thermal noise power is uniform. Such noise—with a uniform power distribution with respect to frequency—is called "white noise".

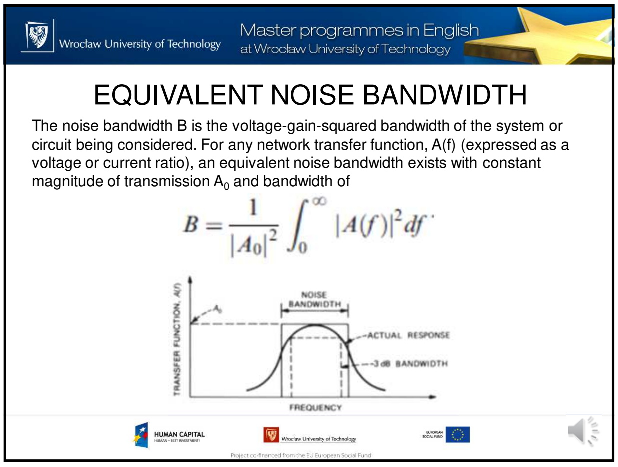


CHARACTERISTICS OF THERMAL NOISE

The instantaneous value of thermal noise can only be defined in terms of probability and its amplitude has a Gaussian, or normal, distribution.

The probability density function for thermal noise:

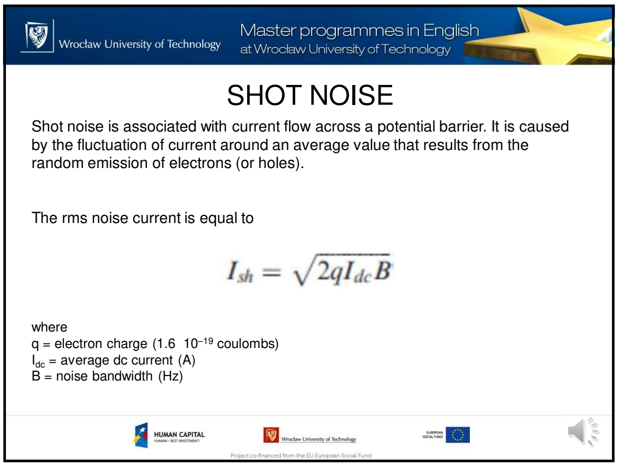
$$\rho = \frac{e^{-\frac{V^2}{2(V_{rms})^2}}}{V_{rms}\sqrt{2\pi}}$$



EQUIVALENT NOISE BANDWIDTH

The noise bandwidth B is the voltage-gain-squared bandwidth of the system or circuit being considered. For any network transfer function, A(f) (expressed as a voltage or current ratio), an equivalent noise bandwidth exists with constant magnitude of transmission A_0 and bandwidth of

$$B = \frac{1}{|A_0|^2}\int_0^{\infty} |A(f)|^2 df$$



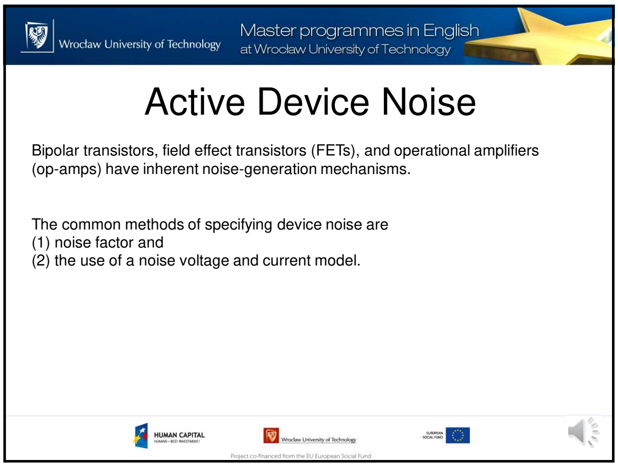
SHOT NOISE

Shot noise is associated with current flow across a potential barrier. It is caused by the fluctuation of current around an average value that results from the random emission of electrons (or holes).

The rms noise current is equal to

$$I_{sh} = \sqrt{2qI_{dc}B}$$

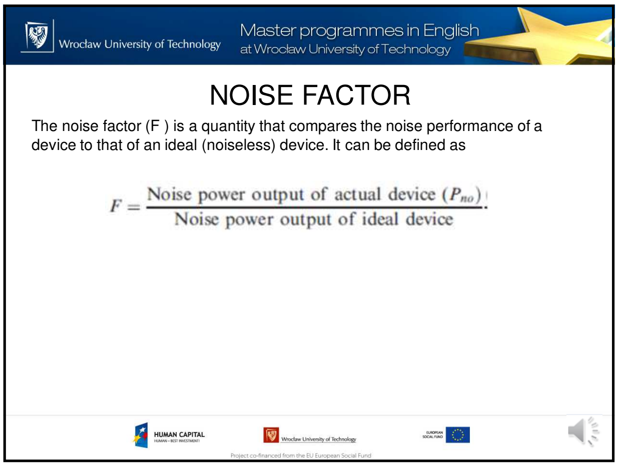
where
q = electron charge ($1.6\ 10^{-19}$ coulombs)
I_{dc} = average dc current (A)
B = noise bandwidth (Hz)



Active Device Noise

Bipolar transistors, field effect transistors (FETs), and operational amplifiers (op-amps) have inherent noise-generation mechanisms.

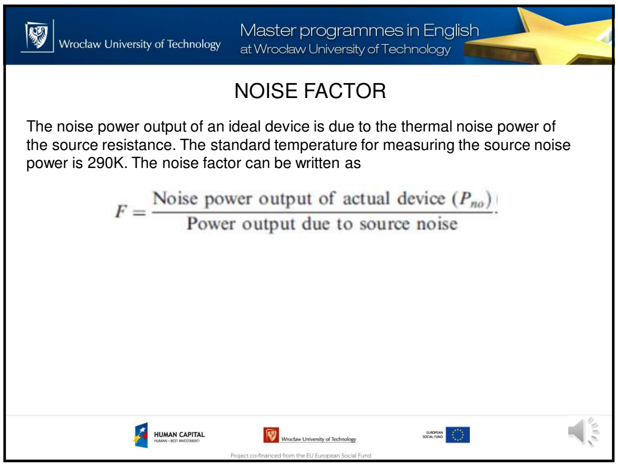
The common methods of specifying device noise are
(1) noise factor and
(2) the use of a noise voltage and current model.



NOISE FACTOR

The noise factor (F) is a quantity that compares the noise performance of a device to that of an ideal (noiseless) device. It can be defined as

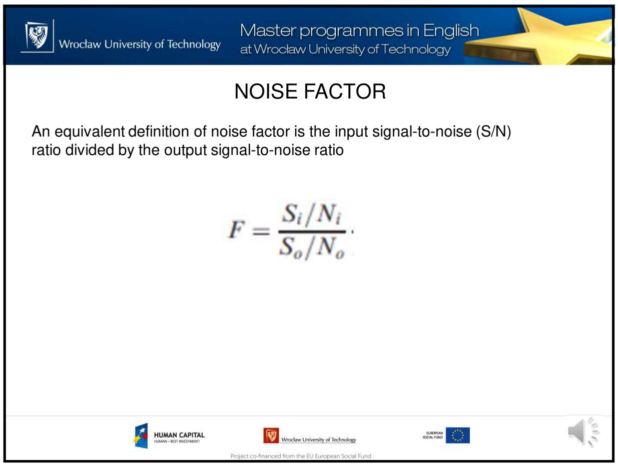
$$F = \frac{\text{Noise power output of actual device } (P_{no})}{\text{Noise power output of ideal device}}$$



NOISE FACTOR

The noise power output of an ideal device is due to the thermal noise power of the source resistance. The standard temperature for measuring the source noise power is 290K. The noise factor can be written as

$$F = \frac{\text{Noise power output of actual device } (P_{no})}{\text{Power output due to source noise}}$$



NOISE FACTOR

An equivalent definition of noise factor is the input signal-to-noise (S/N) ratio divided by the output signal-to-noise ratio

$$F = \frac{S_i/N_i}{S_o/N_o}.$$

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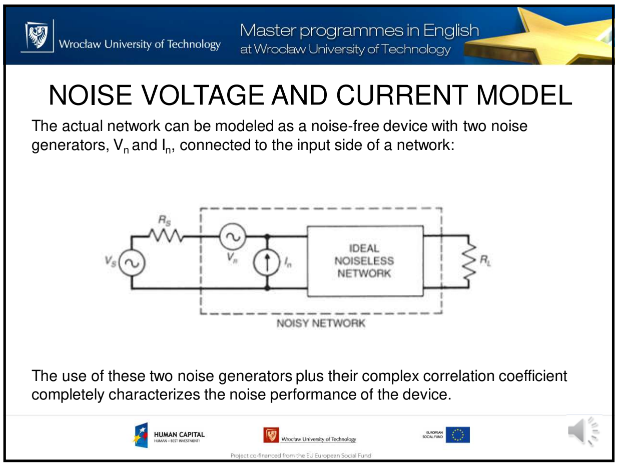

NOISE VOLTAGE AND CURRENT MODEL

The actual network can be modeled as a noise-free device with two noise generators, V_n and I_n, connected to the input side of a network:

The use of these two noise generators plus their complex correlation coefficient completely characterizes the noise performance of the device.

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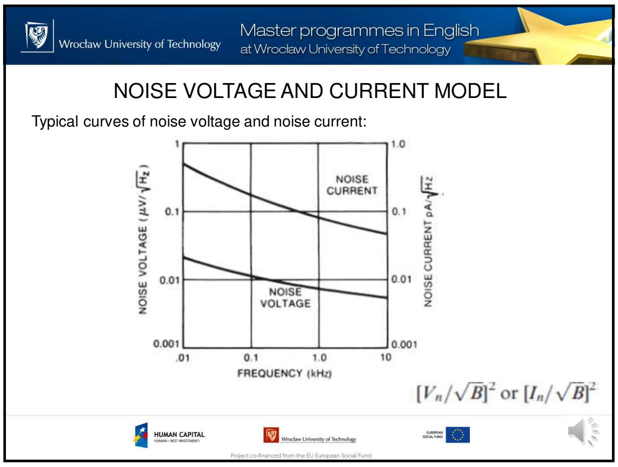

NOISE VOLTAGE AND CURRENT MODEL

Typical curves of noise voltage and noise current:

$[V_n/\sqrt{B}]^2$ or $[I_n/\sqrt{B}]^2$

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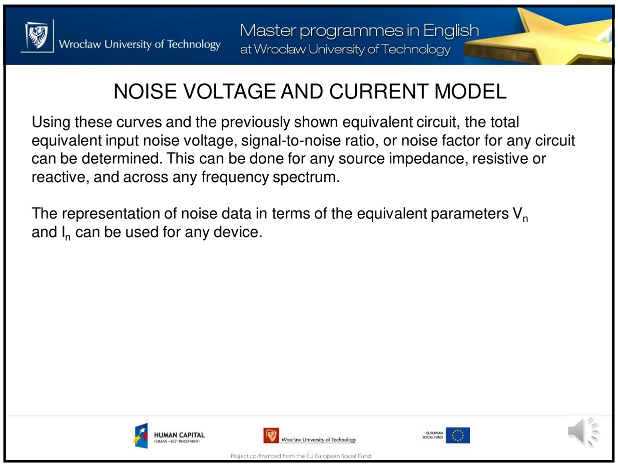

NOISE VOLTAGE AND CURRENT MODEL

Using these curves and the previously shown equivalent circuit, the total equivalent input noise voltage, signal-to-noise ratio, or noise factor for any circuit can be determined. This can be done for any source impedance, resistive or reactive, and across any frequency spectrum.

The representation of noise data in terms of the equivalent parameters V_n and I_n can be used for any device.

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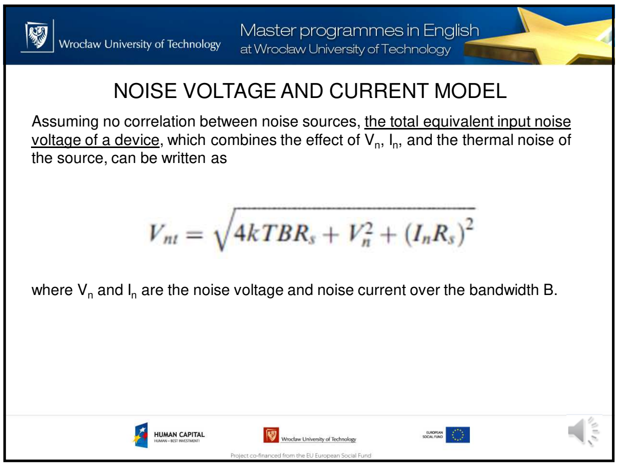

NOISE VOLTAGE AND CURRENT MODEL

Assuming no correlation between noise sources, the total equivalent input noise voltage of a device, which combines the effect of V_n, I_n, and the thermal noise of the source, can be written as

$$V_{nt} = \sqrt{4kTBR_s + V_n^2 + (I_nR_s)^2}$$

where V_n and I_n are the noise voltage and noise current over the bandwidth B.

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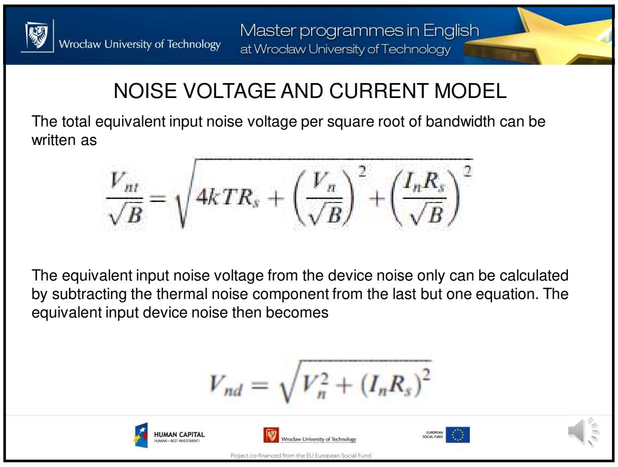

NOISE VOLTAGE AND CURRENT MODEL

The total equivalent input noise voltage per square root of bandwidth can be written as

$$\frac{V_{nt}}{\sqrt{B}} = \sqrt{4kTR_s + \left(\frac{V_n}{\sqrt{B}}\right)^2 + \left(\frac{I_nR_s}{\sqrt{B}}\right)^2}$$

The equivalent input noise voltage from the device noise only can be calculated by subtracting the thermal noise component from the last but one equation. The equivalent input device noise then becomes

$$V_{nd} = \sqrt{V_n^2 + (I_nR_s)^2}$$

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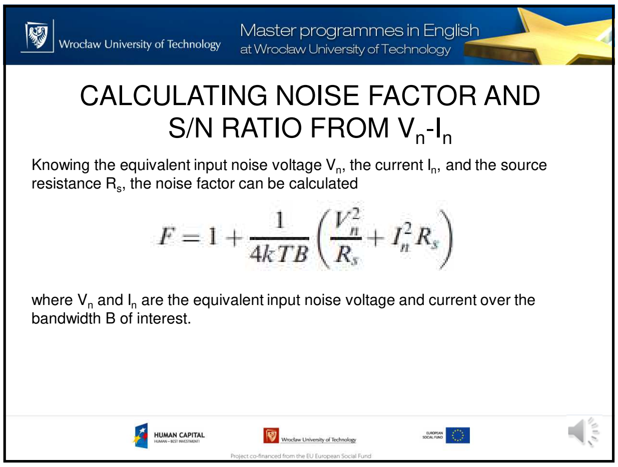
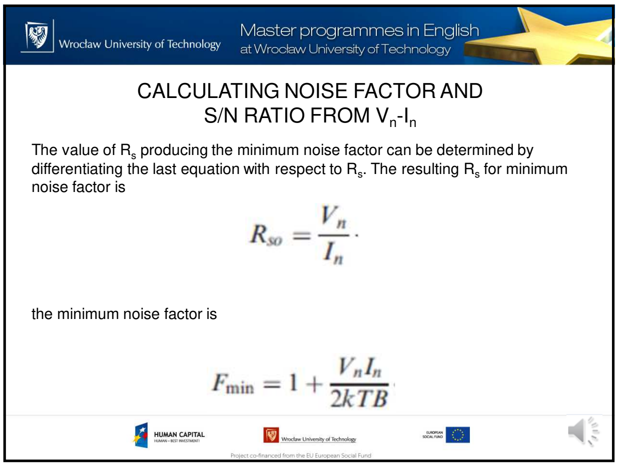


CALCULATING NOISE FACTOR AND S/N RATIO FROM V_n-I_n

Knowing the equivalent input noise voltage V_n, the current I_n, and the source resistance R_s, the noise factor can be calculated

$$F = 1 + \frac{1}{4kTB}\left(\frac{V_n^2}{R_s} + I_n^2 R_s\right)$$

where V_n and I_n are the equivalent input noise voltage and current over the bandwidth B of interest.



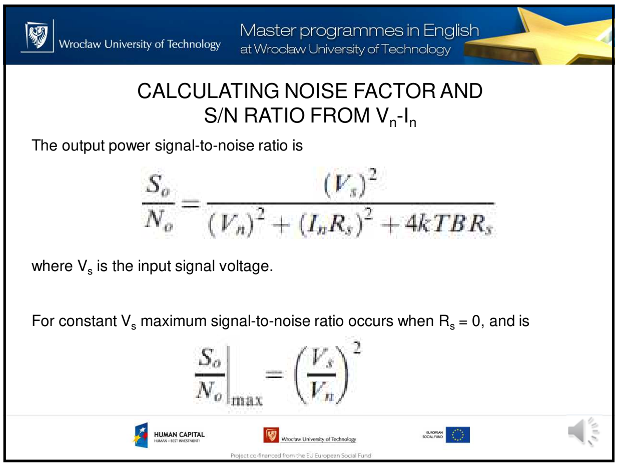
CALCULATING NOISE FACTOR AND S/N RATIO FROM V_n-I_n

The value of R_s producing the minimum noise factor can be determined by differentiating the last equation with respect to R_s. The resulting R_s for minimum noise factor is

$$R_{so} = \frac{V_n}{I_n}.$$

the minimum noise factor is

$$F_{\min} = 1 + \frac{V_n I_n}{2kTB}$$



CALCULATING NOISE FACTOR AND S/N RATIO FROM V_n-I_n

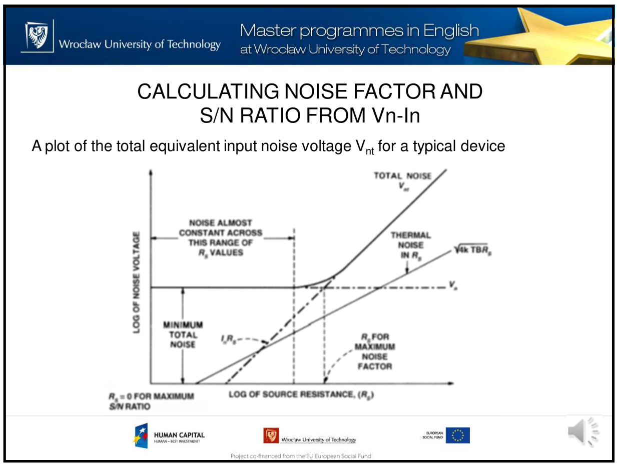
The output power signal-to-noise ratio is

$$\frac{S_o}{N_o} = \frac{(V_s)^2}{(V_n)^2 + (I_n R_s)^2 + 4kTBR_s}$$

where V_s is the input signal voltage.

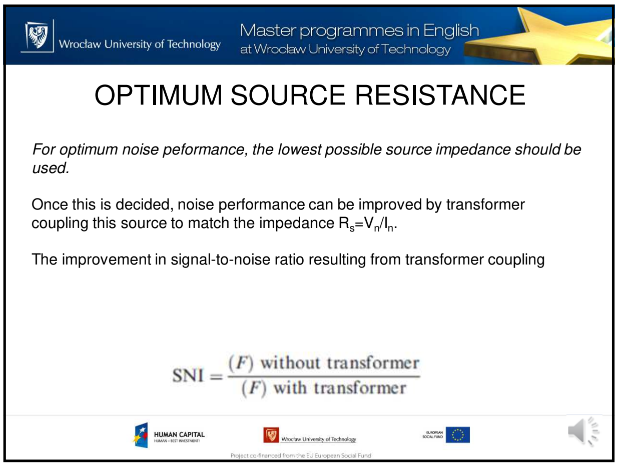
For constant V_s maximum signal-to-noise ratio occurs when R_s = 0, and is

$$\left.\frac{S_o}{N_o}\right|_{\max} = \left(\frac{V_s}{V_n}\right)^2$$



CALCULATING NOISE FACTOR AND S/N RATIO FROM Vn-In

A plot of the total equivalent input noise voltage V_{nt} for a typical device



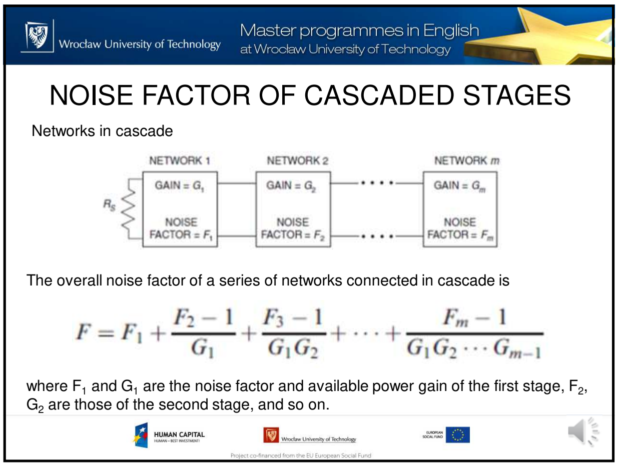
OPTIMUM SOURCE RESISTANCE

For optimum noise peformance, the lowest possible source impedance should be used.

Once this is decided, noise performance can be improved by transformer coupling this source to match the impedance $R_s=V_n/I_n$.

The improvement in signal-to-noise ratio resulting from transformer coupling

$$\mathrm{SNI} = \frac{(F)\ \text{without transformer}}{(F)\ \text{with transformer}}$$



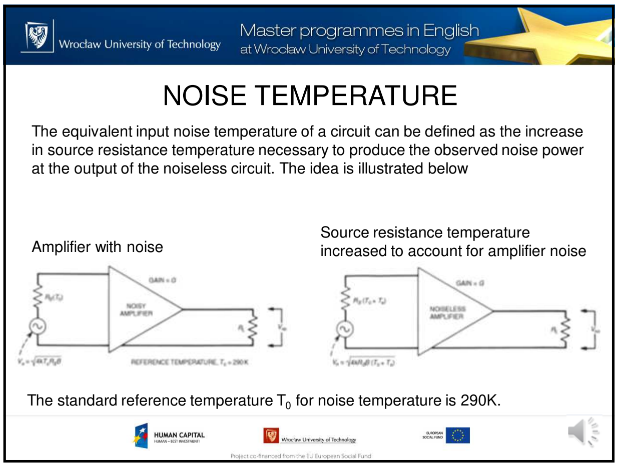
NOISE FACTOR OF CASCADED STAGES

Networks in cascade

The overall noise factor of a series of networks connected in cascade is

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_m - 1}{G_1 G_2 \cdots G_{m-1}}$$

where F_1 and G_1 are the noise factor and available power gain of the first stage, F_2, G_2 are those of the second stage, and so on.



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NOISE TEMPERATURE

The equivalent input noise temperature of a circuit can be defined as the increase in source resistance temperature necessary to produce the observed noise power at the output of the noiseless circuit. The idea is illustrated below

Amplifier with noise

Source resistance temperature increased to account for amplifier noise

The standard reference temperature T_0 for noise temperature is 290K.

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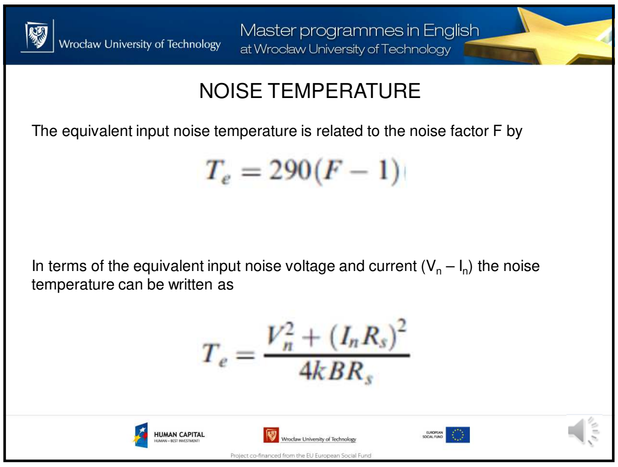

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NOISE TEMPERATURE

The equivalent input noise temperature is related to the noise factor F by

$$T_e = 290(F - 1)$$

In terms of the equivalent input noise voltage and current (V_n – I_n) the noise temperature can be written as

$$T_e = \frac{V_n^2 + (I_n R_s)^2}{4kBR_s}$$

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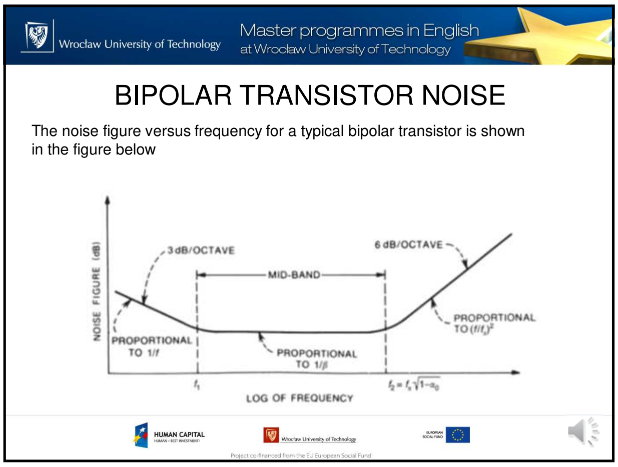

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BIPOLAR TRANSISTOR NOISE

The noise figure versus frequency for a typical bipolar transistor is shown in the figure below

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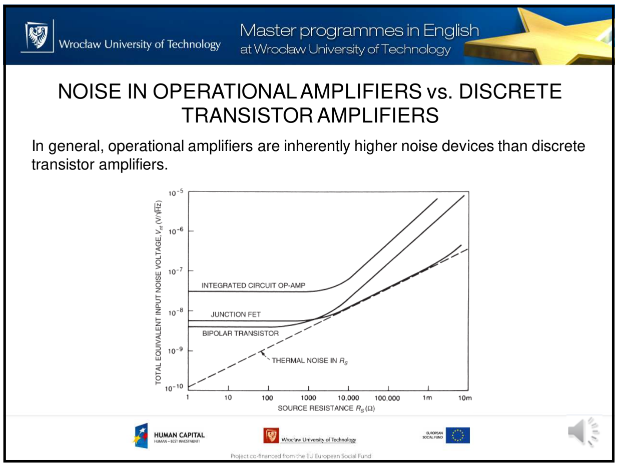

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NOISE IN OPERATIONAL AMPLIFIERS vs. DISCRETE TRANSISTOR AMPLIFIERS

In general, operational amplifiers are inherently higher noise devices than discrete transistor amplifiers.

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Thank you for your attention

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