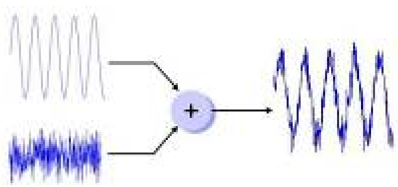
Why study noise?
Noise is one of the two principle limiting factors in the performance of communication systems. The methods by which noise creeps into communication systems and how noise builds and grows once present can help make us more aware of how fragile and carefully designed our systems are.

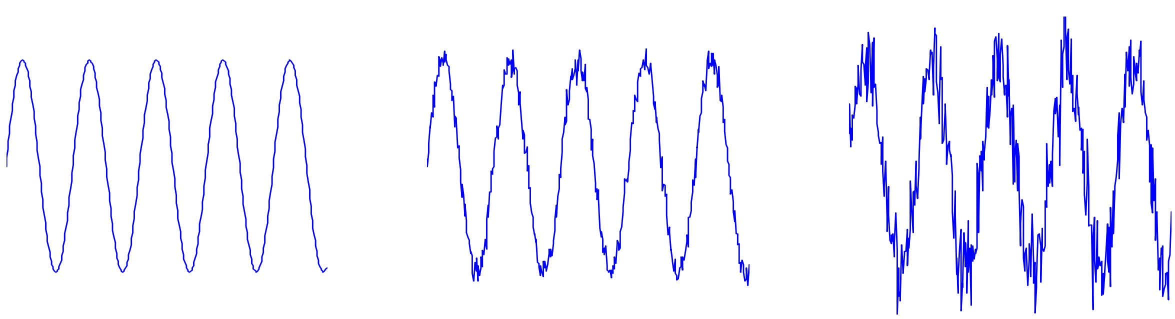
What is noise?

1. The word “noise” has several definitions. List some.

2. In this class we usually think of noise in a negative fashion. What is common about the noise terms listed in #1 that have a negative connotation?

3. **Electrical noise** is any _____________ voltages or currents that end up appearing at the output of a communication system. An example is _________________ that is commonly encountered on broadcast AM radio.





signal without noise   20 dB S/N ratio   10 dB S/N ratio

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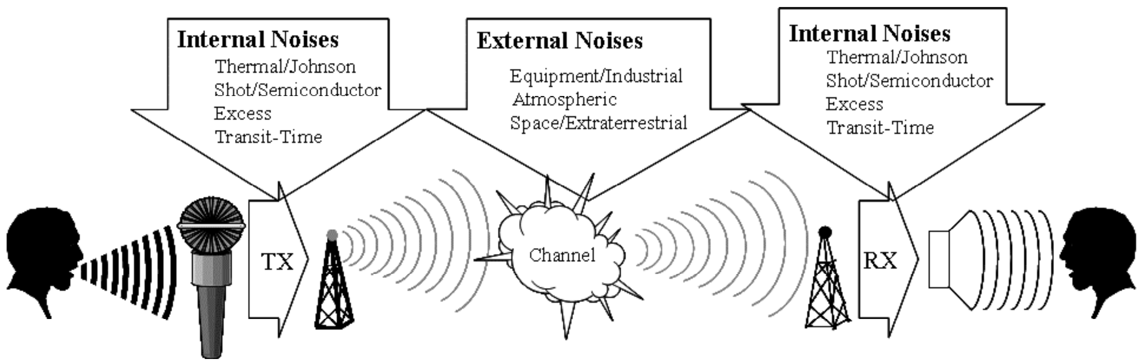
Noise Sources

Noise in electrical communications systems has many sources and can occur anywhere along the communication channel. Moreover noise can come from the physical components of the system itself (internal noise) or be introduced from outside sources (external noise).



4. List some examples of external noise.

Internal noise is a little harder to grasp since it is usually small scale and due to the operation of the device itself. We'll quickly cover four types of internal noise, but only.

Thermal Noise

The first type of internal noise is **thermal noise (**also called **white noise**, **Gaussian noise, Johnson noise**). The random motion of electrons and ions in electrical components causes it. Every time a charged particle moves about, it generates a slight change in voltage (also current). When this happens contrary to our wishes, we call it noise. As the name implies, thermal noise depends on the temperature of the component – the higher the temperature, the more agitated electrons and other particles become and the more random movement and, hence, noise voltage they produce.

Let's look at a resistive element in a circuit. The noise voltage produced by a resistor *R* over a bandwidth *B* can be calculated with the following equation

$$v_n = 2\sqrt{k_B TRB}$$

Where k_B = Boltzman's constant ($1.38\text{x}10^{-23}$ J/K), T = temperature in Kelvin (K = ºC + 273), B = bandwidth over which the noise is measured (Hz), and R = resistance (ohms, Ω).

The noise power of a resistor is given by

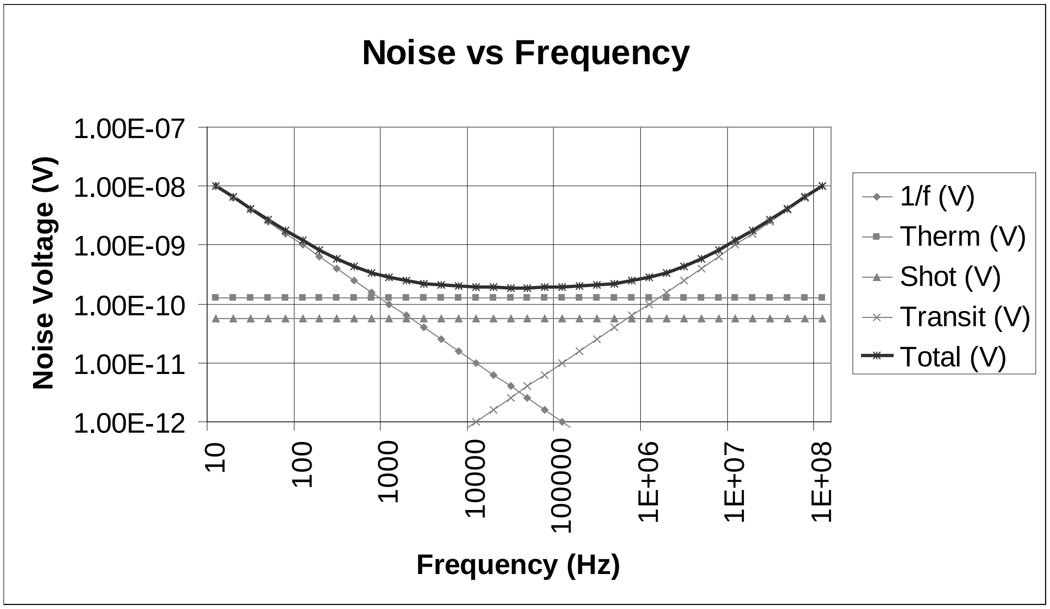
$$P_n = kTB$$

5. Based on the noise voltage equation above, what three things can be done to minimize the noise voltage of an electrical system?

6. The bandwidth of an AM receiver with a 75-Ω input resistance is 10 kHz. The temperature of the receiver is 35°C. What is the noise voltage and noise power of the receiver?

V_n = 112 nV, P_n = 0.042 fW

The other three sources of internal noise originate due to the physical nature of modern day semiconductor devices such as diodes and transistors (most of our electronics today are heavily reliant on semiconductors).



Shot noise

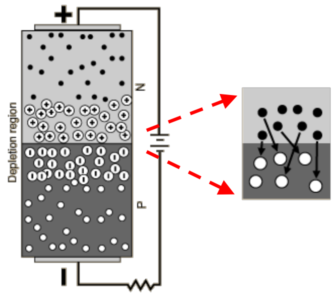
Shot noise, the largest contributor to transistor noise, is due to the random paths of the current carriers flowing in semiconductors.

$I_N = (2qI_0B)^{0.5}$ RMS noise current (A)

$q = 1.6x10^{-19} C / e^-$

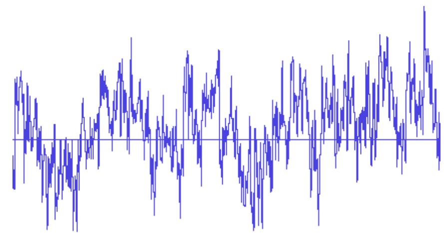
I_0 = DC bias current in Amps

B=Bandwidth over which signal is passed



Transit-time noise
Transit-time noise occurs at high frequencies when "transit time" of charge carriers crossing a semiconductor junction (where one type of semiconductor material meets another) approaches the signal's period. This creates large variations in current flow in transistors, since the electrons may not make it all the way across the junction before being pulled back as the current direction changes. The noise increases rapidly when the device is pushed beyond its cutoff frequency.

Excess (Flicker) noise
Flicker noise results from minute variations in resistance in semiconductor material. Flicker noise increases as frequencies decrease. It is ________________ proportional to frequency and sometimes referred to as $1/f$ noise. Flicker noise is also found in resistors and conductors.



To combat flicker noise, choose high quality resistors OR higher operating frequencies where this is not a factor.

Signal-to-noise Ratio (SNR)
To quantify the effect of noise on a signal, we use the signal-to-noise (S/N) ratio or SNR.

7. Write a definition of SNR in your own terms.

8. A strong signal and weak noise results in a ___________ S/N ratio. A weak signal and

   strong noise results in a ___________ S/N ratio.

When the SNR is low, engineers may give the SNR in power ratios. More commonly, however, the SNR is given in decibels (dB). To avoid confusion, we will always express SNR as a power ratio. We have to be careful about calculating SNR from voltage ratios.

9. Fill in the blanks below.

   SNR in dB in reference to power: SNR_{dB} = _______ log SNR

   SNR in dB in reference to voltage: SNR_{dB} = _______ $\log\left({}^{V_{signal}}/_{V_{noise}}\right)$

10. The signal input to the RF amplifier in an AM radio has an amplitude of 3.0 μV. The RMS noise voltage entering the amplifier is 0.2 μV. What is the SNR as a ratio and in dB at the input to the RF amplifier?

SNR =23.5 dB = 225

Noise Ratio (NR)

Oftentimes engineers are interested in how the SNR changes from the input to the output of a device such as an amplifier. One way to represent this SNR change is the **noise ratio (NR)** The NR is simply the ratio of SNR at the input over the SNR at the output.

NR =

11. Your iPod changes its digitally stored music into voltages using a digital-to-analog converter (DAC). The voltages coming out of the DAC are boosted using an amplifier based on your volume control settings and then delivered to your headphones for your listening enjoyment. Say that the signal voltage at the input of the headphones is 75mV and the noise voltage is 0.63mV. At the output of the digital-to-analog converter the voltage SNR is 43.52dB. What is the SNR at the headphones? What is the NR of the amplifier?

SNR = 41.5 dB, NR =1.26

Noise Figure (NF)

The noise figure (NF) is the NR expressed in decibels.

NF =

12. What is the NF of your iPod in problem #11?

NF = 2 dB

13. Rework problem #11, but put all units into decibels first.

Same answers, hopefully

14. What's the relationship between $SNR_{in,dB}$, $SNR_{out,dB}$, and NF? Adjust the NF equation accordingly.

15. If $SNR_{out} = SNR_{in}$, what is the NR and NF?

16. What does it mean for the NR to be less than 1 (the NF to be negative)?

17. Do you think it's possible for the NR to be less than 1 (the NF to be negative)? Why?

Noise in Cascaded Stages (Systems)

The total noise performance of any multi-stage system (such as cascaded amplifiers) depends upon the gain and noise ratio of each stage. Even though gains multiply when cascaded, noise is added at each stage and compounds as it is amplified. Therefore, you cannot simply multiply noise as you do gains to find the overall noise in a system. You must do something different.

In fact you must use **Friis's Formula** to find the total noise performance of multiple stages:

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

where A_i and NR_i are the power gain and noise ratio of the ith stage.

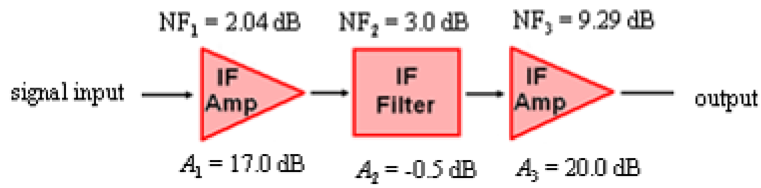
18. Take a close look at Friis's formula. The noise factor of which stage matters the most? Why?

The first – the noise it produces is amplified by each subsequent amplifier

19. Based on #17, in a series of amplifiers, where should you place the least noisy amplifier? Where should the noisiest one go?

Least noisy (meaning expensive) at the beginning of the chain.

20. The gain of the three stages of the IF filter/amplifier combo shown below are 17.0 dB, -0.5 dB, and 20 dB. The noise figures associated with these stages are 2.04 dB, 3.0 dB, and 9.29 dB, respectively. What is the overall NR and NF for this cascade of components? What is the total gain for this circuit?



NR_{total} = 1.8, NF_{total} = 2.5 dB, G_{total} = 36.5 dB