ECE 105: Introduction to Electrical Engineering

Lecture 19

Noise

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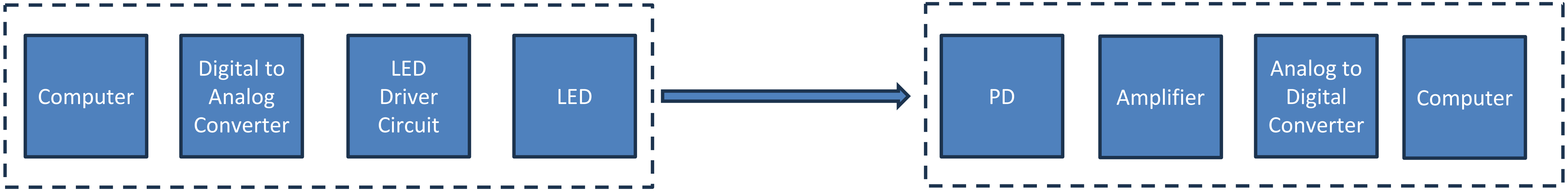
Let’s talk about a real world system



Let’s imagine a system where we would like to send information from one place to another using light.

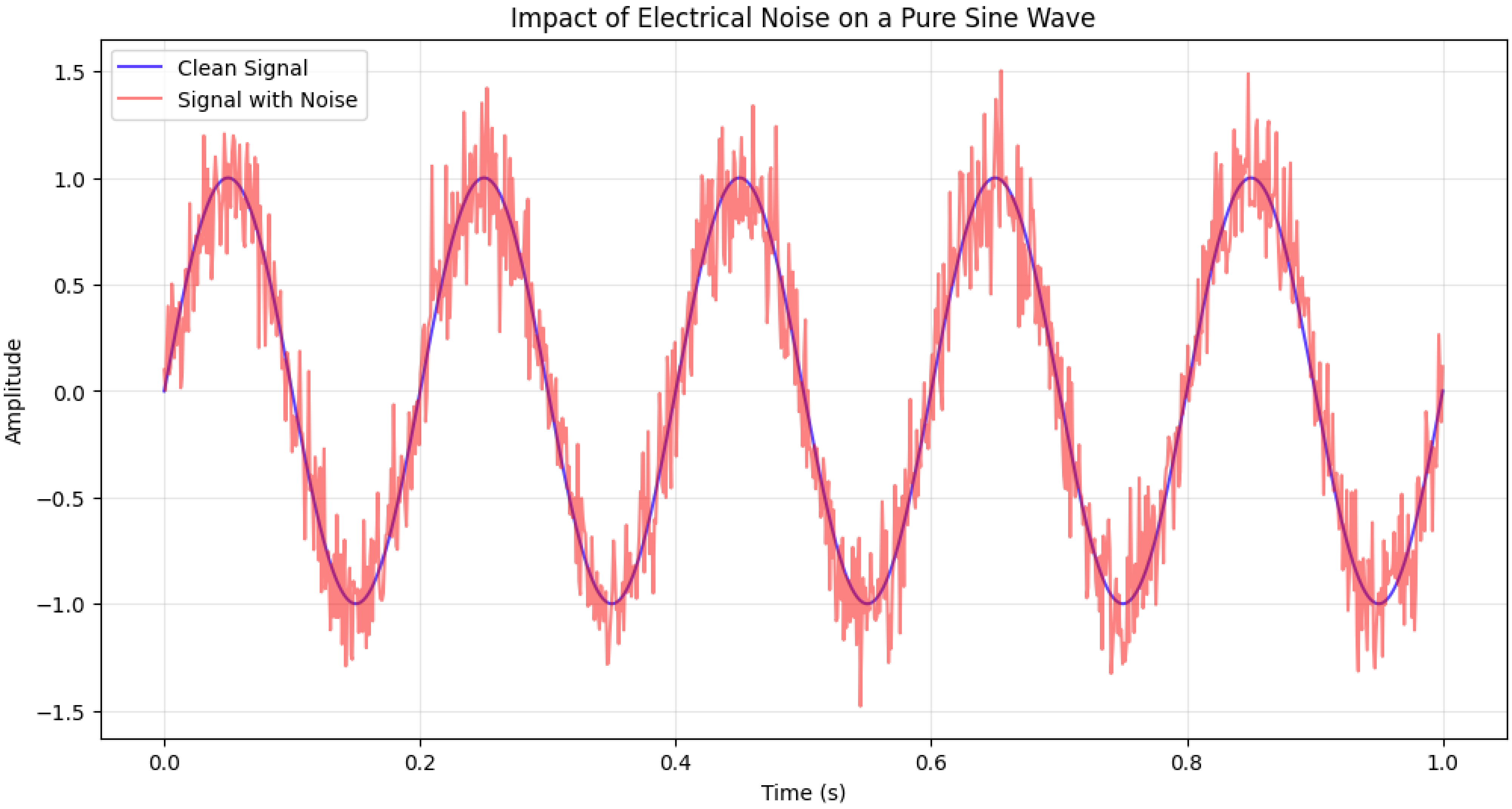
Seems easy, right? We just flash an LED, detect those flashes, and then we are done.

But how much data could we send with such a signal?

What components would we need?

How can we accomplish this?

What is noise?



Types of Noise

- Noise refers to anything that you don't want in your signal
- It can have many different sources and many different resulting affects on your system

- At the component level, here are a few fundamental mechanisms of noise:
- Thermal Noise (Johnson-Nyquist): Arises from the random motion of charge carriers in resistive materials.
- Flicker Noise: Generally related to defects and impurities
- Shot Noise: Arises from the discrete nature of charge carriers

Thermal Noise

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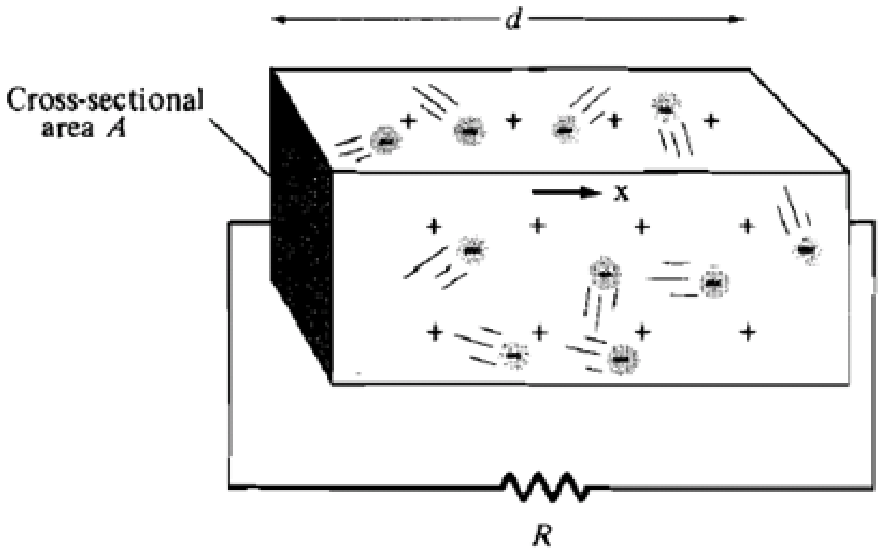


- **Fluctuation in the voltage across a dissipative circuit element (resistor)**
- **Caused by thermal motion of charged carriers**

Equivalent mean square noise voltage: $v_N^2 = 4k_B TR\Delta\nu$

Equivalent mean square noise current: $$i_N^2 = \frac{4k_B T\,\Delta\nu}{R}$$

Shot Noise

Shot noise is caused by the random arrival of charge carriers (e.g., electrons or holes) at a potential barrier or through a quantum tunneling process. Unlike thermal noise, which depends on temperature, shot noise arises solely due to the quantization of charge.

Key Characteristics:

- It is independent of temperature.
- It is proportional to the average current and depends on the bandwidth of observation.
- It is most commonly observed in **semiconductor junctions**, **vacuum diodes**, and **photodetectors**.

$$\overline{i_n^2} = 2qI\Delta f$$

Where:

- q: Elementary charge
- I: Average direct current
- Δf: Bandwidth

Shot Noise

•**Proportional to Current:**
Shot noise increases linearly with the current III. Systems with higher currents generate more shot noise.

•**Statistical Nature:**
Shot noise is inherently random and follows a Poisson distribution because it is governed by the discrete and independent arrival of charge carriers.

•**Independence from Temperature:**
Unlike thermal noise, shot noise does not depend on the ambient temperature, making it a fundamental noise source.

•**Quantum Nature:**
Shot noise is a direct consequence of the quantized nature of charge, highlighting its quantum mechanical origin.

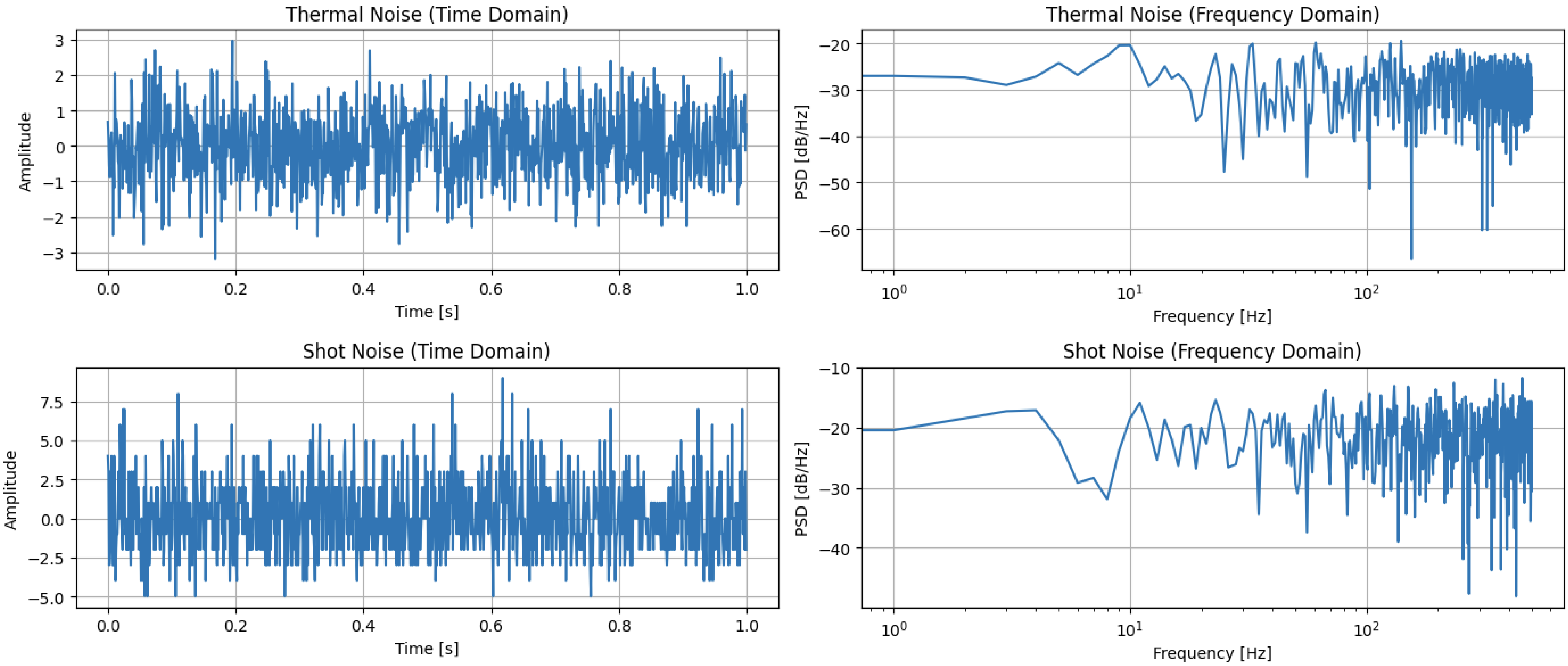
Flicker Noise

Definition:
Flicker noise, also known as 1/f1/f1/f noise, is a type of electrical noise that is dominant at low frequencies. It is caused by imperfections and defects in materials or processes and is observed in electronic devices like resistors, transistors, and semiconductors.

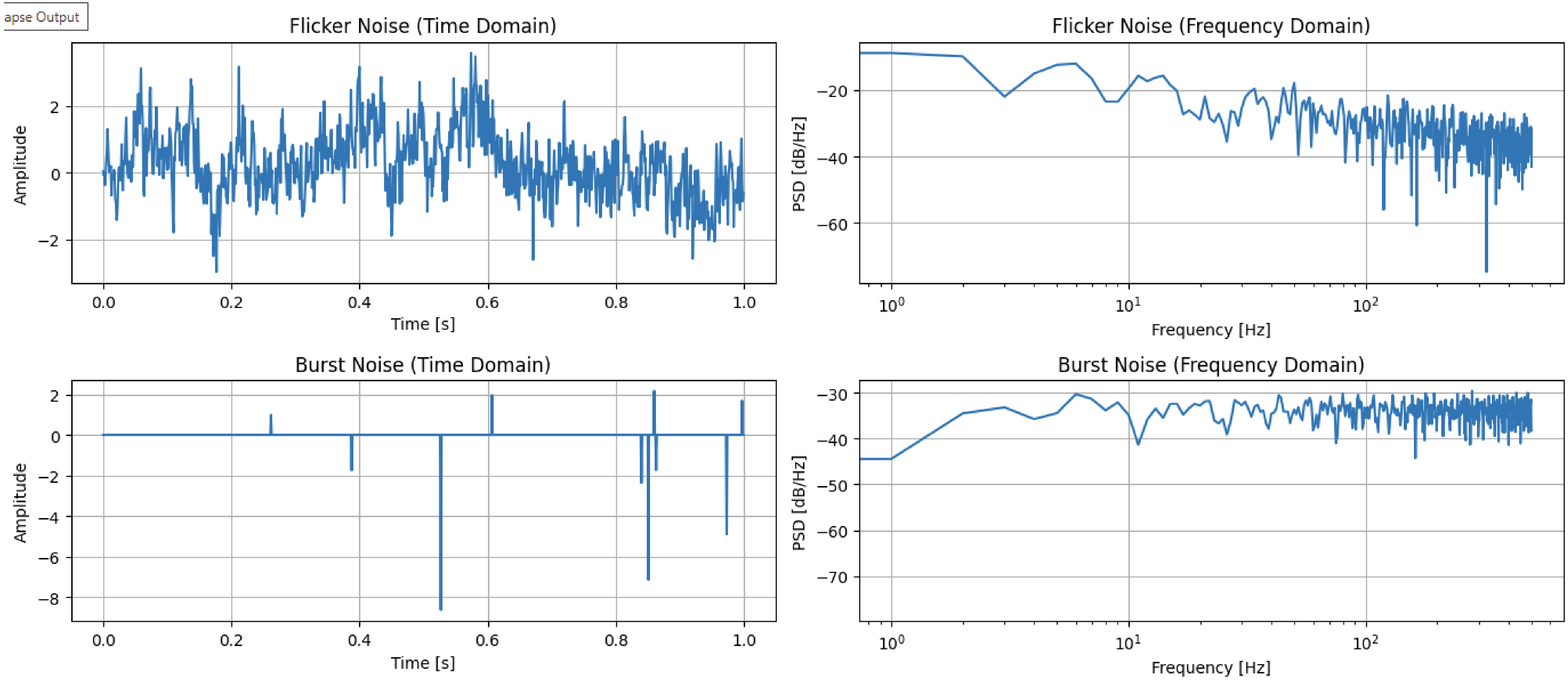
Key Characteristics:

- **Frequency Dependence:**
The power spectral density (PSD) decreases as the frequency increases, following a $1/f^{\alpha}$ relationship where α is typically between 0.8 and 1.2.
- **Low-Frequency Dominance:**
Flicker noise is most prominent at lower frequencies and becomes negligible at higher frequencies.
- **Material-Dependent:**
It arises from defects, impurities, and surface traps in materials.

Time and Frequency Domain Visualizations



Time and Frequency Domain Visualizations



How do different noise sources add?

When multiple uncorrelated noise sources contribute to the total noise in a system, the **total RMS noise** is calculated using the **root-sum-square (RSS)** method:

$$V_{n_{total}} = \sqrt{V_{n_1}^2 + V_{n_2}^2 + \cdots + V_{n_n}^2}$$

where:

- $V_{n_1}, V_{n_2}, \ldots, V_{n_n}$ are the RMS noise values of individual noise sources.

This summation is based on the principle that the **variances** of uncorrelated random variables can be added together to get the total variance, and then the RMS value is the square root of this variance.

Why Do We Use Quadrature Summation?

- Noise sources are typically random processes that vary both in amplitude and phase.
- Since the different noise sources are **uncorrelated**, they do not reinforce each other directly as coherent signals would.
- Therefore, we must use the **root-sum-square** approach, which combines their powers rather than their amplitudes.

Examples of calculating Noise

Example 1: Thermal Noise and Shot Noise in a Photodetector

Consider a photodetector with two primary noise sources: **thermal noise** from a resistor and **shot noise** from the photodetector current.

1. **Thermal Noise** ($V_{n_{thermal}}$):

$$V_{n_{thermal}} = \sqrt{4k_B T R \Delta f}$$

2. **Shot Noise** ($I_{n_{shot}}$):

$$I_{n_{shot}} = \sqrt{2qI_{ph}\Delta f}$$

   If the shot noise current passes through a transimpedance amplifier with a feedback resistor R_f, it contributes to a voltage noise:

$$V_{n_{shot}} = I_{n_{shot}} \times R_f = R_f \times \sqrt{2qI_{ph}\Delta f}$$

To find the total output noise ($V_{n_{total}}$) of the TIA with both noise components:

$$V_{n_{total}} = \sqrt{V_{n_{thermal}}^2 + V_{n_{shot}}^2}$$

Example of calculating signal to noise ratio (SNR)

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Example 2: Quantization Noise and Thermal Noise in an ADC

Consider an ADC with two primary noise sources: **quantization noise** and **thermal noise** from its analog front end.

1. **Quantization Noise ($V_{n_{quant}}$):**

$$V_{n_{quant}} = \frac{\Delta}{\sqrt{12}}$$

   where $\Delta = \frac{V_{ref}}{2^n}$ is the quantization step size.

2. **Thermal Noise ($V_{n_{thermal}}$):**

$$V_{n_{thermal}} = \sqrt{4k_BTR\Delta f}$$

To calculate the **total RMS noise** of the ADC:

$$V_{n_{total}} = \sqrt{V^2_{n_{quant}} + V^2_{n_{thermal}}}$$

Power perspective of noise addition

Power Summation Approach (Variance Approach)

The quadrature summation of noise RMS values can be understood from the perspective of **noise power.** For a random signal, the power (P) is proportional to the **square of the RMS value.** Thus, the total noise power from multiple uncorrelated sources is:

$$P_{n_{total}} = P_{n_1} + P_{n_2} + \cdots + P_{n_n}$$

Since the power of a noise source is proportional to the square of its RMS value ($P = V_{n_{rms}}^2$), we get:

$$V_{n_{total}}^2 = V_{n_1}^2 + V_{n_2}^2 + \cdots + V_{n_n}^2$$

Taking the square root gives:

$$V_{n_{total}} = \sqrt{V_{n_1}^2 + V_{n_2}^2 + \cdots + V_{n_n}^2}$$

Power perspective of noise addition

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Example: Total Noise in a Photodetector System

Suppose a photodetector system includes:

- **Thermal Noise** from a resistor: $V_{n_{thermal}} = 5\,\mathrm{mV}$
- **Shot Noise** from the photodetector current: $V_{n_{shot}} = 3\,\mathrm{mV}$
- **Amplifier Noise** from the TIA: $V_{n_{amp}} = 2\,\mathrm{mV}$

The total noise RMS value would be:

$$V_{n_{total}} = \sqrt{(5\,\mathrm{mV})^2 + (3\,\mathrm{mV})^2 + (2\,\mathrm{mV})^2}$$

$$V_{n_{total}} = \sqrt{25 + 9 + 4}\,\mathrm{mV} = \sqrt{38}\,\mathrm{mV} \approx 6.16\,\mathrm{mV}$$

How do we calculate Δf

Definition of Bandwidth (Δf)

Bandwidth (Δf) refers to the range of frequencies over which a system, component, or signal operates effectively.

In the context of noise calculations, Δf is the **frequency range** through which noise is filtered or allowed to pass.

The noise power is directly proportional to the bandwidth: as the bandwidth increases, more noise power passes through, and vice versa.

How do we calculate Δf

There are different bandwidths to consider, depending on the context of the system:

Signal Bandwidth

- This is the frequency range over which the actual signal is transmitted or detected.
- If you are analyzing the noise in a communication system, the signal bandwidth is often used as Δf
- **Example**: For a radio signal modulated over a frequency range of 10 kHz, the signal bandwidth is Δf=10 kHz

Amplifier Bandwidth

- In systems where an **amplifier** (e.g., a TIA, voltage amplifier, or operational amplifier) is present, the bandwidth of the amplifier limits the range of frequencies over which noise can be amplified.
- The amplifier bandwidth, typically specified as the **-3 dB bandwidth**, is often used as Δf in noise calculations.
- **Example**: If a transimpedance amplifier (TIA) has a -3 dB bandwidth of 1 MHz, the noise calculation should use Δf=1 MHz

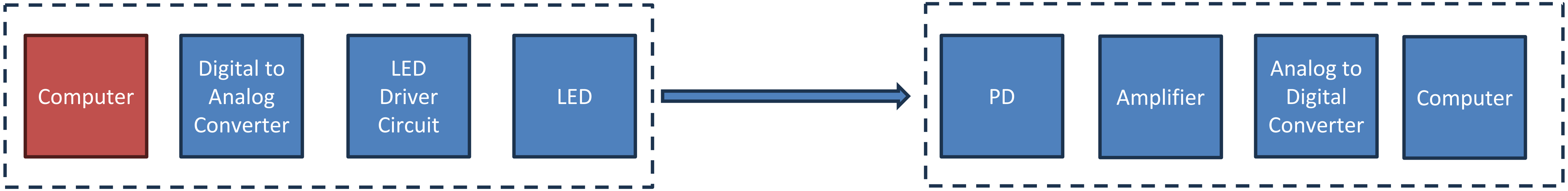
Filter Bandwidth

- If the signal passes through an **electronic filter**, the bandwidth of that filter determines Δf
- Filters are used to limit noise contributions by restricting the frequency range that can pass through.
- **Example**: A low-pass filter with a cutoff frequency of 100 kHz has a bandwidth of Δf=100 kHz

Measurement Instrument Bandwidth

- When using instruments like **oscilloscopes** or **spectrum analyzers**, the measurement device itself has a limited bandwidth, which may affect noise readings.
- The **instrument bandwidth** may be specified and needs to be considered when interpreting noise measurements.
- **Example**: If an oscilloscope has a bandwidth of 20 MHz, then the noise observed on the oscilloscope is limited by Δf=20 MHz\Delta f = 20 \, \text{MHz}Δf=20MHz.

Let’s talk about a real world system



In the computer, we can define a signal as an array of numbers.

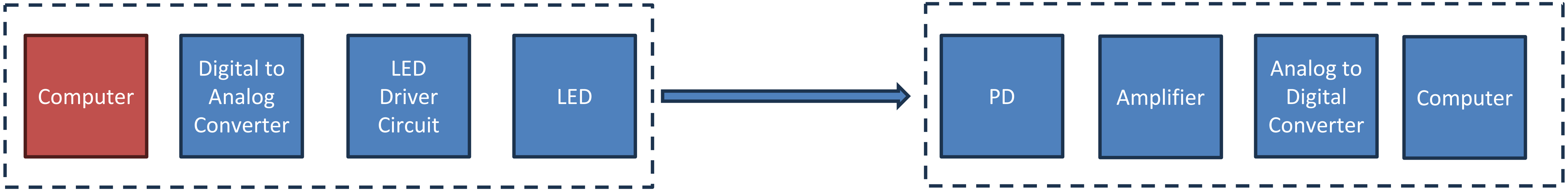
If we wanted to define a sine wave, we could define it as an array of double precision numbers, where each point in the array corresponded to a given time.

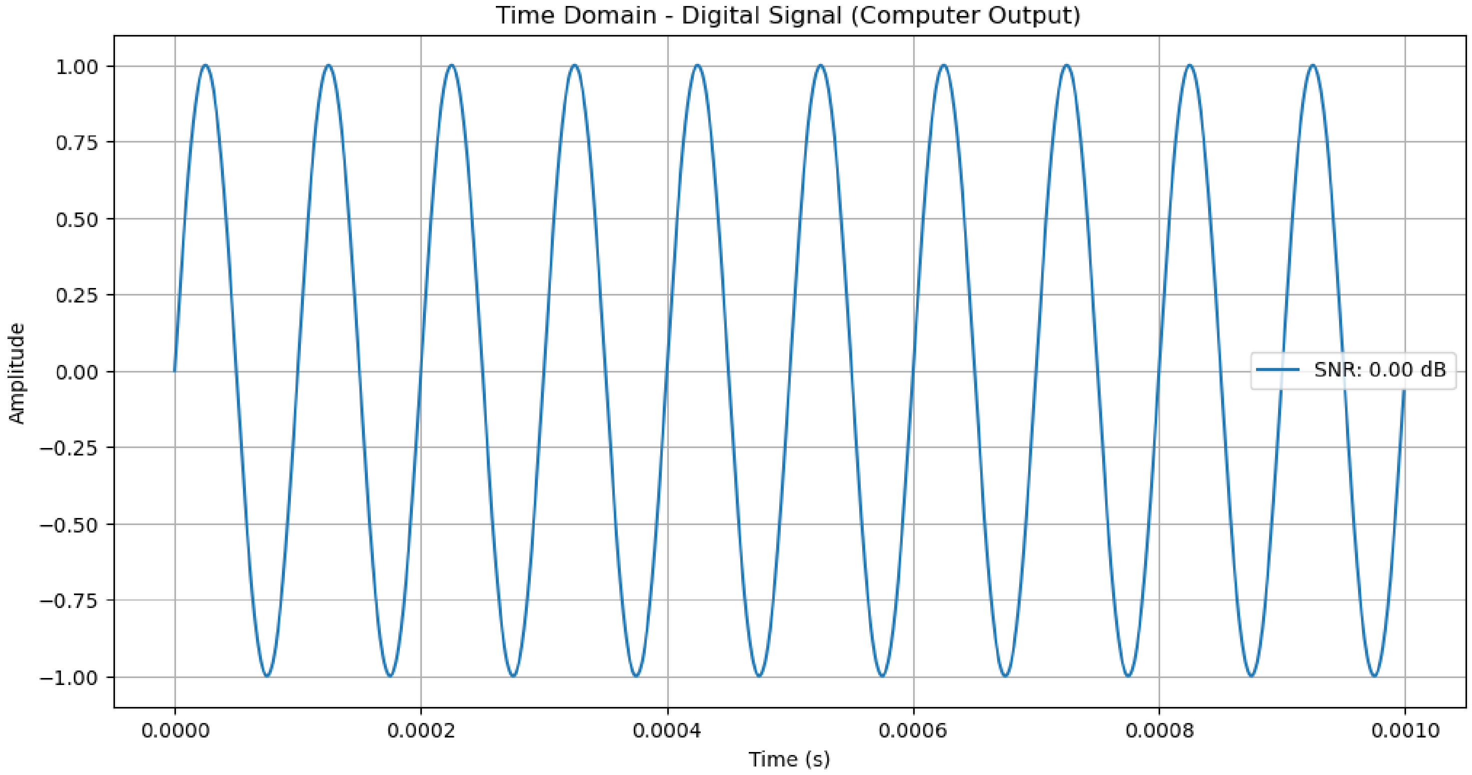
Integers from -2^{53} to 2^{53} (−9,007,199,254,740,992 to 9,007,199,254,740,992) can be exactly represented

We could then take this range, which is 2^{54} and spread our output voltage range across that, giving us a very precise number for each time step.

However, there is still going to be one level per timestep, so there is some level of quantization in both voltage and time

Let’s talk about a real world system





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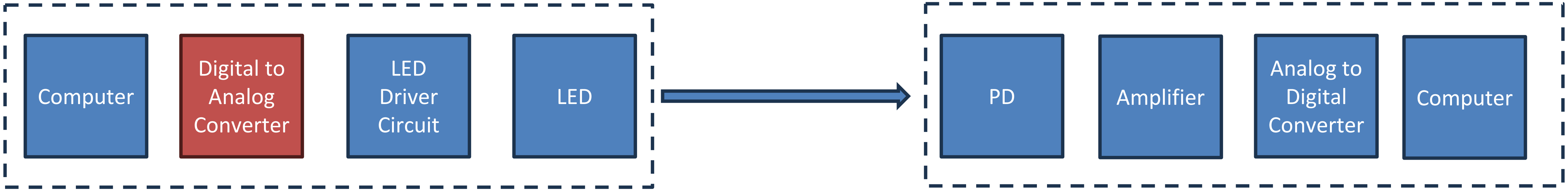


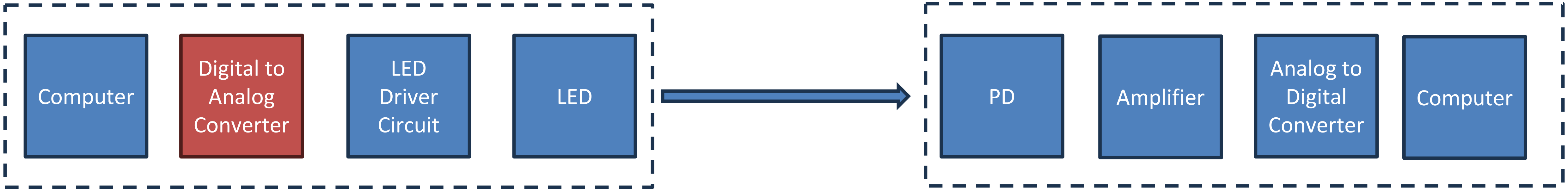
However, we can’t drive an led with a double precision number, that’s just a bunch of 1’s and 0’s

We need to convert those into an actual voltage value to apply to the LED.

We would use a digital to analog converter (DAC) to do this. This takes in some number of bits, and depending on the values, it outputs the corresponding analog signal

This DAC needs to be able to take an input, and “instantly” change the output analog voltage to reflect that input.

Let’s talk about a real world system



There are a number of noise sources that are relevant:

•**Quantization Noise**: Introduced by the discrete steps used to represent a continuous signal, dependent on DAC resolution.

•**Thermal Noise**: Arises from resistive components, increases with temperature and resistance.

•**Nonlinearity (Distortion Noise)**: Due to imperfections in the DAC's response, results in harmonic distortion.

•**Clock Jitter**: Variations in clock timing, affecting precision especially at higher frequencies.

•**Power Supply Noise**: Coupling from power supply fluctuations into the analog output.

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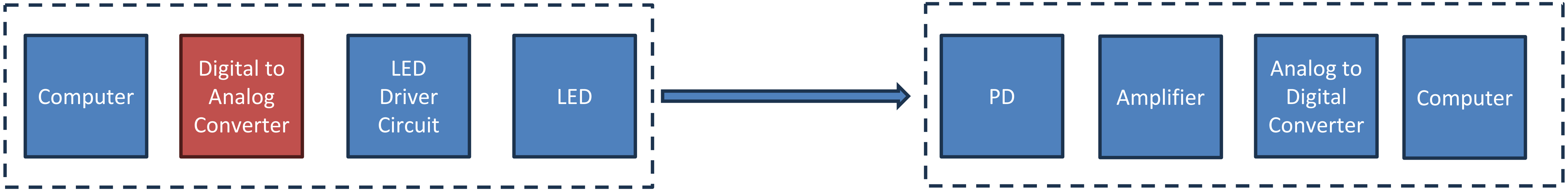
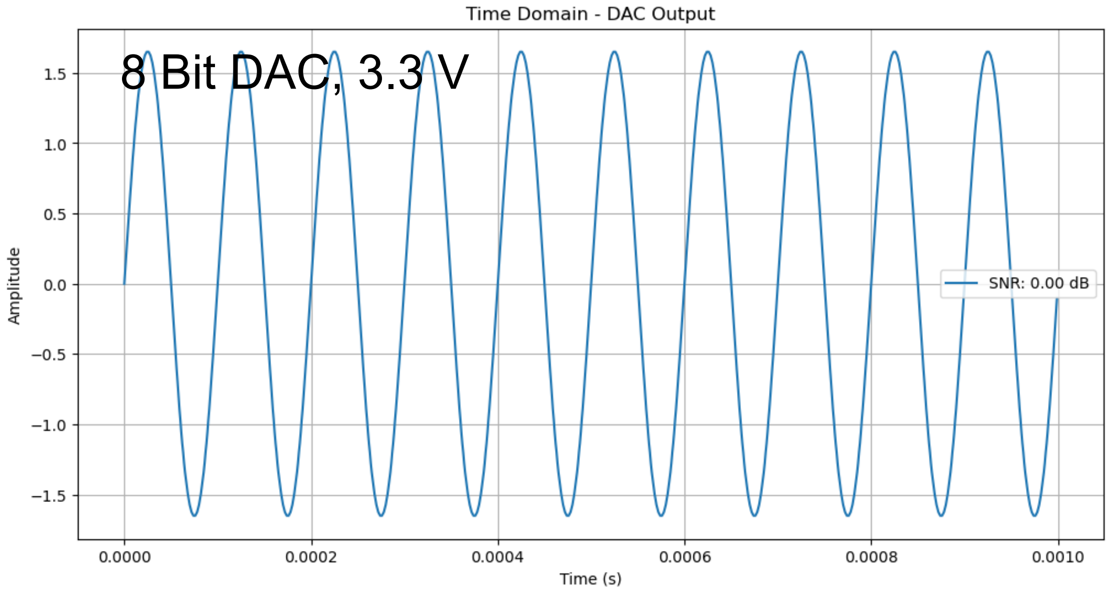
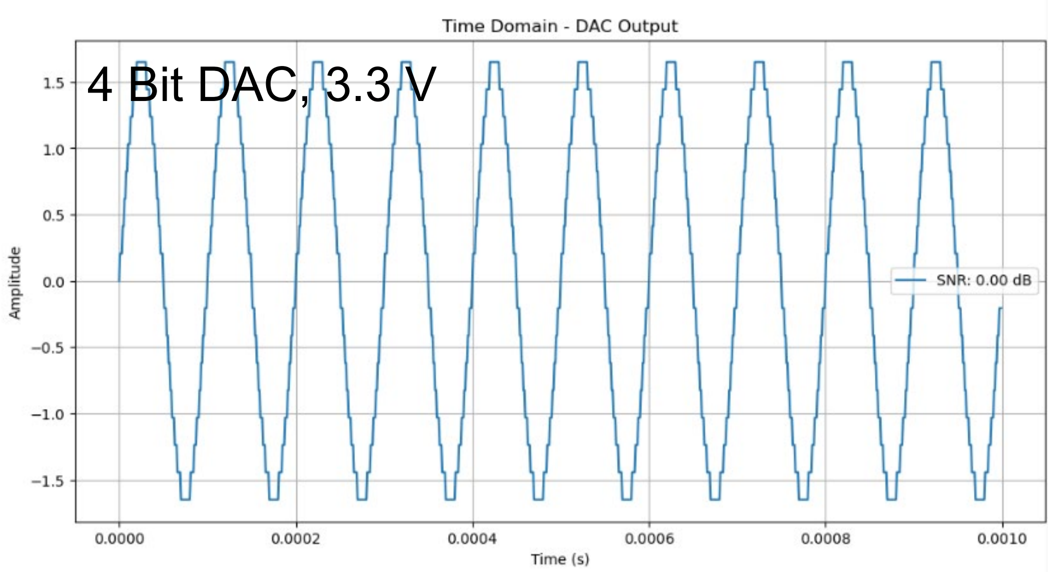


What is the number of bits for a DAC? It defines the number of different output levels it can generate.
A 2 bit DAC would generate 4 values, a 10 bit DAC would generate 1024 values





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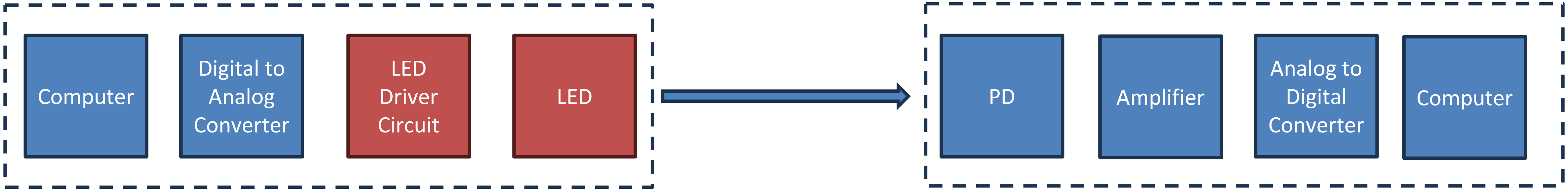
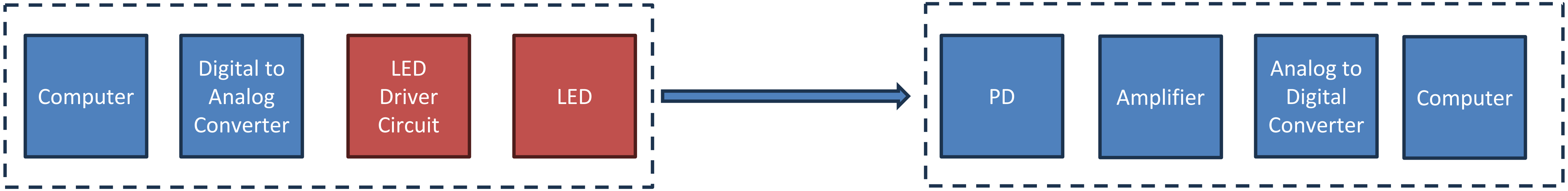
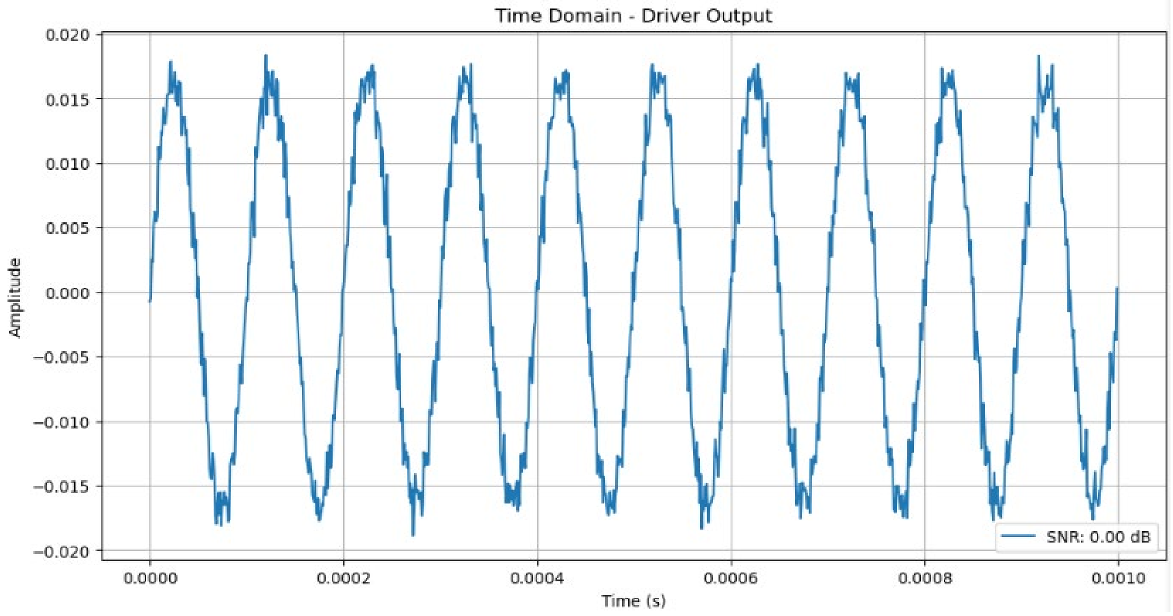


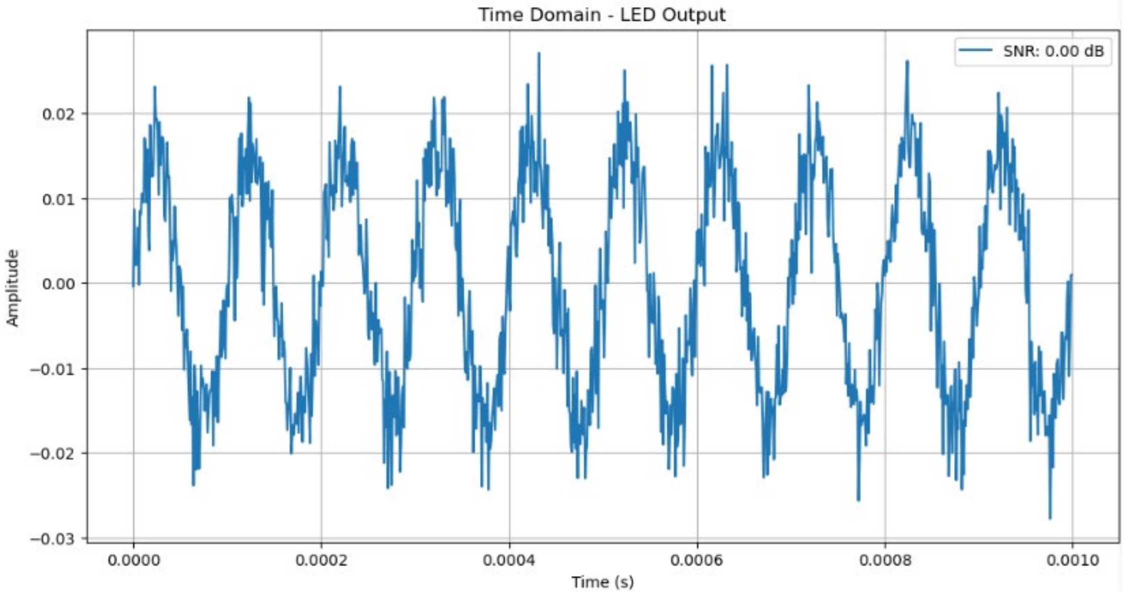
There will be a circuit which drives the LED to the appropriate values, and the LED itself, which will also introduce noise based on the device properties. The key noise components will be:

•**Thermal Noise**:
•Found in the resistive elements of the LED driver circuit.
•It is directly proportional to temperature and resistance.
•**Shot Noise**:
•Found in the LED itself due to the random nature of current flow.
•Proportional to the square root of the average current through the LED.
•**Flicker Noise**:
•Found in driver components due to material imperfections.
•Dominates at low frequencies and adds to the overall noise in the driver stage.

Let’s talk about a real world system







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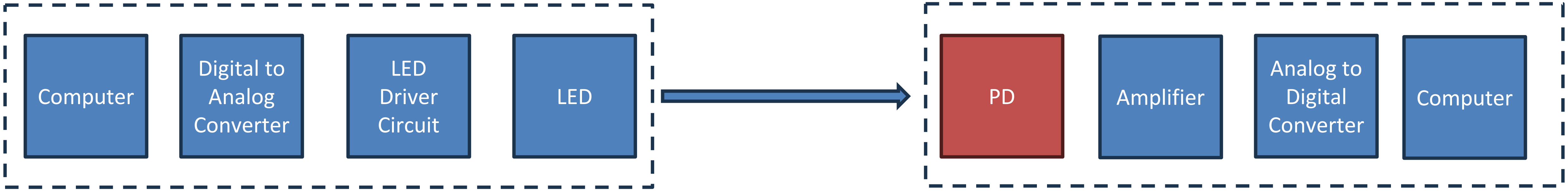
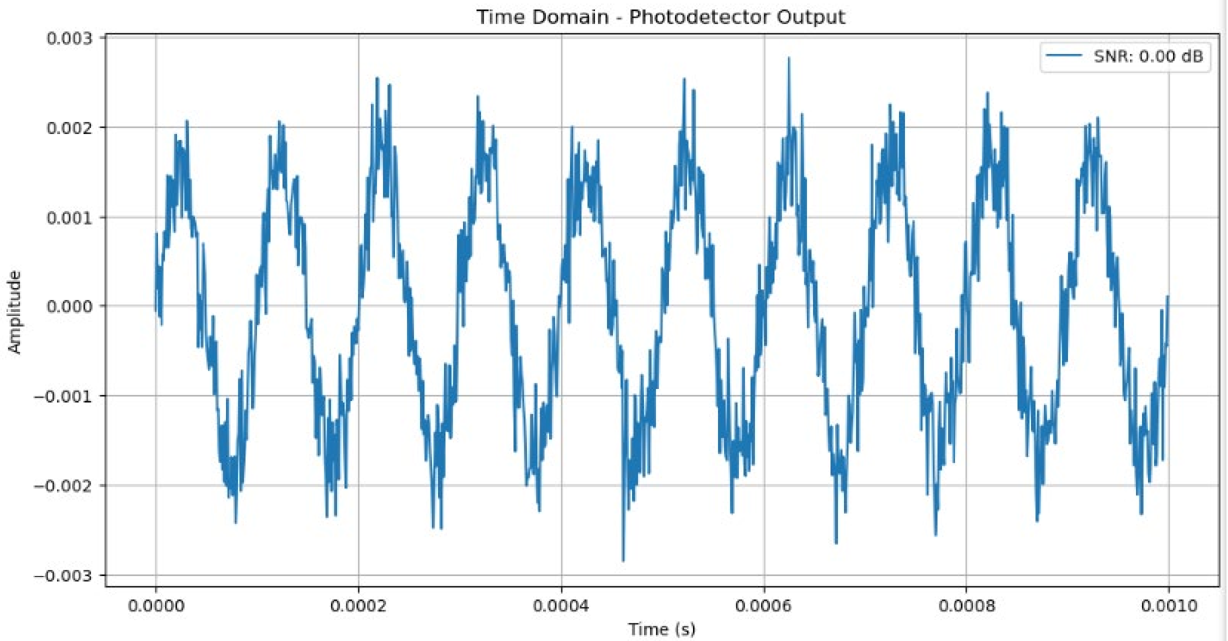


What noise in photodetectors do we see?

•**Shot Noise**:
•Due to the statistical variation in the arrival of photons.
•Significant at low light levels.
•White noise, with uniform power distribution across all frequencies.
•**Thermal Noise**:
•Due to thermal agitation of electrons in resistive components.
•Increases with temperature and resistance.
•Present in the circuit regardless of light exposure.
•**Dark Current Noise**:
•Due to thermally generated carriers in the absence of light.
•Increases with temperature.
•Reduces signal accuracy, especially in low-light applications.
•**Flicker Noise (1/f Noise)**:
•Caused by material imperfections and traps.
•Prominent at low frequencies.
•Inversely proportional to frequency, affecting low-frequency applications.



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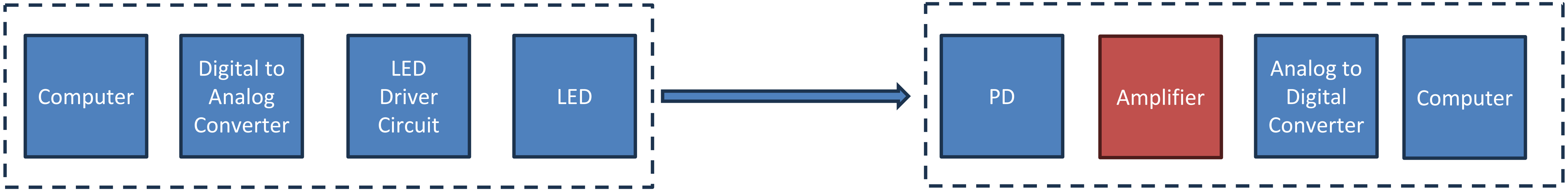


What noise in amplifiers do we see?

•**Thermal Noise from Feedback Resistor**:

•Arises from the feedback resistor.

•Increases with resistance and temperature.

•Affects the output directly as voltage noise.

•**Shot Noise from Photocurrent**:

•Originates from the statistical nature of the current generated by the photodetector.

•Amplified by the TIA, contributing to the output noise.

•**Op-Amp Voltage Noise**:

•Intrinsic noise from the operational amplifier.

•Modeled as a noise voltage at the input.

•Amplified by the gain of the TIA.

•**Op-Amp Current Noise**:

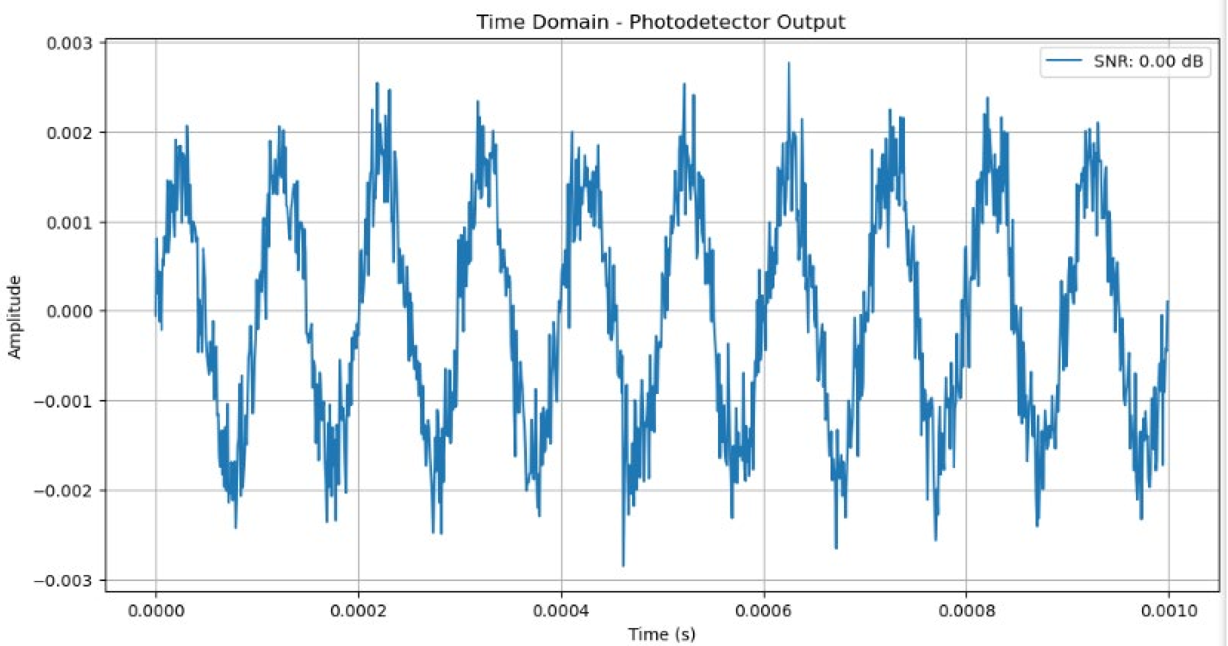
•Due to bias currents of the op-amp transistors.

•Creates additional voltage noise when interacting with the impedance of the circuit.

•**Flicker Noise (1/f Noise)**:

•Low-frequency noise due to imperfections in the op-amp.

•Dominant at low frequencies, decreasing with increasing frequency.



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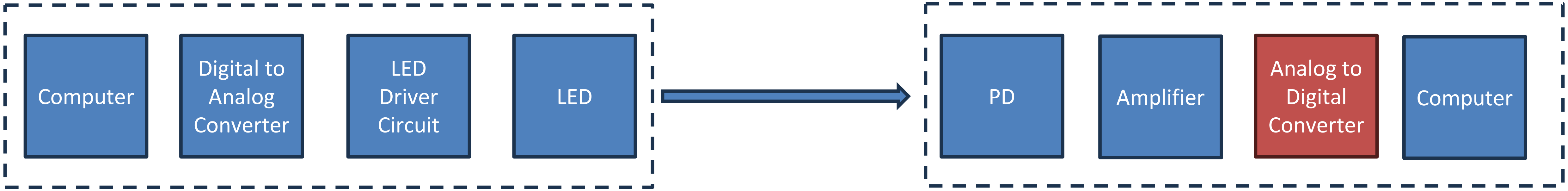
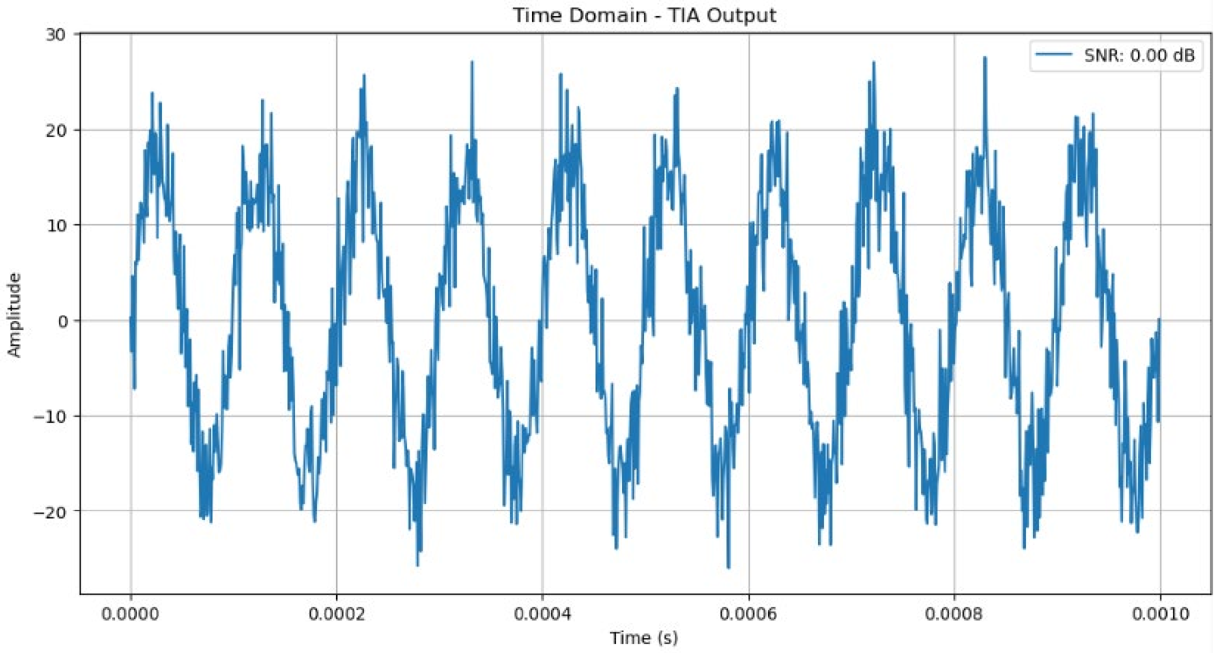


What noise do we see in the ADC?

•**Quantization Noise**:
•**Cause**: Due to approximating a continuous signal with discrete levels.
•**Characteristics**: Inversely proportional to the number of bits. Modeled as white noise.
•**Thermal Noise**:
•**Cause**: Due to resistive elements in the analog front end.
•**Characteristics**: Proportional to temperature and resistance. Sets a noise floor for the ADC.
•**Sampling (Aperture) Jitter**:
•**Cause**: Timing uncertainty during sampling.
•**Characteristics**: Affects high-frequency signals more severely, proportional to input frequency and signal amplitude.
•**Reference Voltage Noise**:
•**Cause**: Noise or fluctuation in the reference voltage.
•**Impact**: Leads to inaccurate conversions if the reference is not stable.
•**Clock Noise**:
•**Cause**: Instability or noise in the sampling clock signal.
•**Impact**: Affects the timing of samples, resulting in inaccuracies.
•**Nonlinearity (Distortion Noise)**:
•**Cause**: Imperfections in the ADC's transfer function.
•**Impact**: Causes harmonic distortion of the signal, seen as additional unwanted frequency components.
•**Flicker Noise (1/f Noise)**:
•**Cause**: Semiconductor imperfections and low-frequency irregularities.
•**Characteristics**: Dominates at low frequencies and can degrade signal quality in low-frequency applications.



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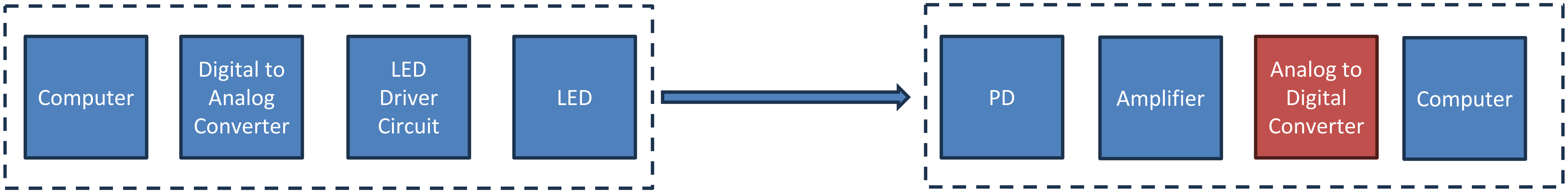

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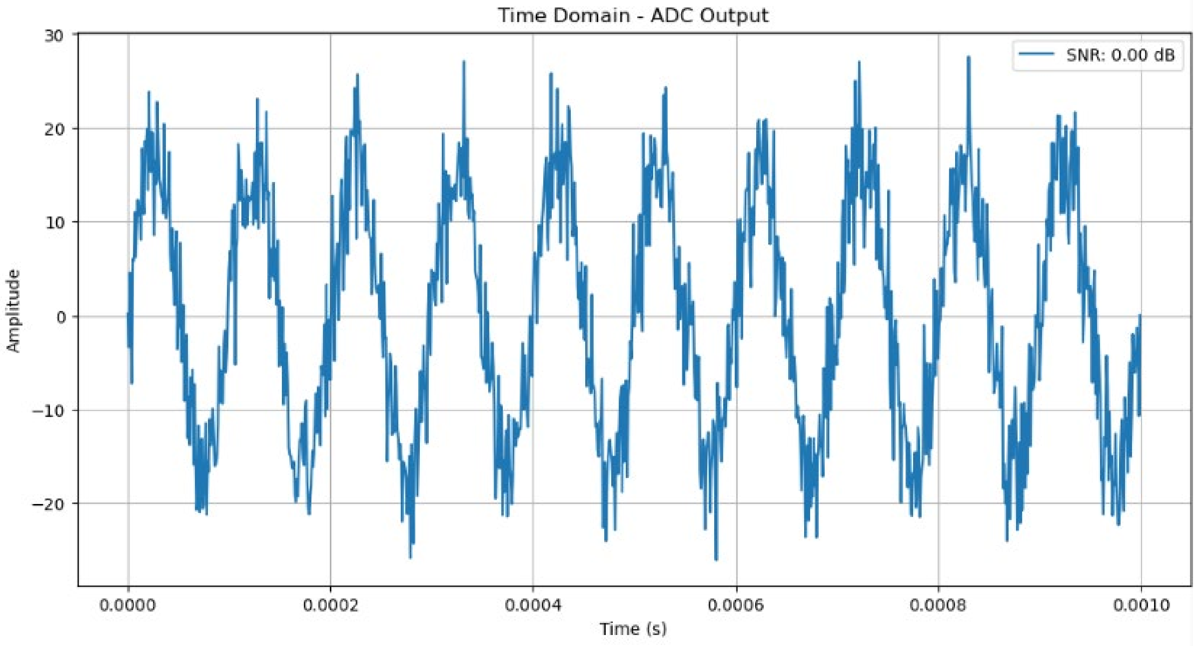

Let's talk about a real world system