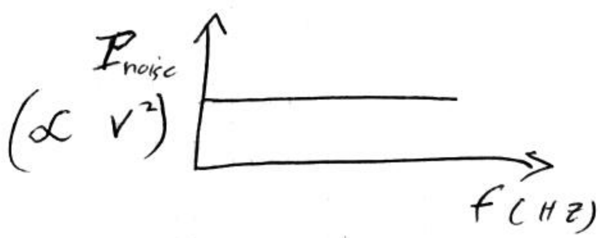
A primer on <u>noise</u> (see Meyer Sec. 6.9, esp pp. 269ff.)

"Ideal" noise is <u>white</u> <u>noise</u> -- constant per unit bandwidth


Plot rms amplitude vs frequency (use narrowband filter or take FFT)




Cannot be set arbitrarily small of course.

1) Even a resistor has "Johnson noise"

Reasoning:


$$\frac{V_{noise}\ (rms)}{\sqrt{\text{bandwidth (Hz)}}} = \sqrt{4kTR}$$

K = Boltzmann's constant, $\sqrt{4kTR}$ = ~~...~~ $1.27\times10^{-4}\sqrt{R}\ \left(\frac{\mu V}{\sqrt{Hz}}\right)$

origin: thermal fluctuations produce noise current & voltage

Ex: 1 MΩ feedback resistor ~~photodiode~~ used at 1 MHz:

$$V_{noise} = (1.27\times10^{-4})(10^3)(10^3)\ \mu V$$
$$= 1.27\times10^2\ \mu V \quad \text{or} \quad 0.127\ mV\ !$$

This is one of the reasons we cannot use huge resistors for photodiode transimpedance amp's. (Another is excessive time constants.)

The distribution of $V_{Johnson}$ is Gaussian, with $V_{rms}$ as already specified.

2) <u>Shot noise</u> exists for any normal current.

Simple physics: The current is comprised of a large but finite number of electrons/s (or holes/s). They arrive randomly in time, leading to a <u>Poisson distribution</u>. For N electrons, std. deviation is $\sqrt{N}$. It follows that

$$\frac{I_{rms}^{shot}}{\sqrt{BW\ (Hz)}} = \sqrt{2e\,I_{avg}}\,.$$

For example, if a detector produces a signal of 1pA and the system bandwidth is 100 kHz,

$$I_{rms}^{shot} = \sqrt{2(1.6\times10^{-19})(10^{-12}A)}\ \ \sqrt{10^5\,Hz}$$
$$= 1.79\times10^{-13}A, \text{ or } 0.18\ pA.$$

This is only slightly smaller than the signal, since 1pA → about 62 electrons in 10 μs, leading to a large statistical uncertainty.

Note that if the current is converted to a voltage $V = IR$, the resistor $R$ should be chosen large enough that the signal voltage exceeds the resistor Johnson noise. If this is not feasible, a different design will be needed (more signal, cooled resistor/amp, restricted bandwidth, etc.)

3) Amplifier noise: For good op amps, $> 1\ nV/\sqrt{Hz}$ of input voltage noise is present, as well as input current noise of $> 0.01\ pA/\sqrt{Hz}$. Specialized transistor designs can do somewhat better.

4) 1/f noise: Typically the noise$/\sqrt{Hz}$ increases at very low frequencies $\sim 1$ Hz. This is caused by a multitude of issues, some rather obscure. It's the reason that frequency-shifting methods such as lock-in amplifiers are widely used for detecting weak signals

There are other less fundamental noise sources too:

- 60 Hz ground loops (or other frequencies): can be resolved by maintaining separate signal and power grounds
- rf pickup
- microphonic noise from moving cables, vibration, ...
- power supply noise feed-through (decoupling capacitors help)

⋮ and others.