TeachSpin's Noise Fundamentals
A Conceptual Introduction to the Experiment

Just as a weed is an unwanted plant, a noise, ordinarily speaking, is an unwanted sound. In the fields of physics, electrical engineering, and many other places, we extend the definition of 'noise' beyond acoustics to the general field of information. Since almost any signal that's a function of time can be translated into a voltage, we will often use the concept of a voltage signal. We'll call it a 'noisy signal' if, in addition to the voltage we expect or wish to see, there is unwanted, typically (but not always) a randomly-fluctuating, voltage. Surprisingly, the noise signal is sometimes not only wanted, but is the *essence* of the measurement.

The noise that TeachSpin's Noise Fundamentals investigates is 'fundamental noise', noise that is intrinsic and inevitable because of the physical nature of an apparatus. We'll observe noise that arises from the Second Law of Thermodynamics, and from the quantization of electrical charge. Physicists and electrical engineers know these as Johnson and shot noise respectively. Noise sources like these display the characteristics of non-periodic, unpredictable, random waveforms, but nevertheless conforming, in their statistical properties, to universal laws. Both noise sources are described as Gaussian white noise, which turns out to be two distinct properties.

Fundamental noise is especially worthy of study, for at least two reasons. The *first* reason is that fundamental noise sets a lower limit for many sorts of physical measurement. In many cases in research and technology, it often defines what is possible within the limits of physical law. In particular, fundamental noise can and does set limits to the rate of data-transfer in a host of contexts in communication.

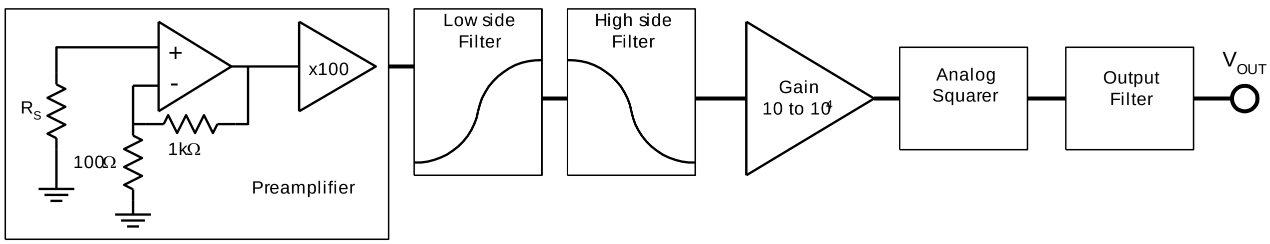
The *second* reason we care about noise is that noise can be used to measure the values of some fundamental constants. Boltzmann's constant k_B can be determined from the voltage or Johnson noise of resistors and the magnitude of the electron charge, e, can be determined from the shot noise of a photocurrent. But measurement of 'fundamental noise' requires some interesting experimental techniques and also entails conceptual challenges. One of these challenges is to recognize that mean-square value, not amplitude, is the proper measure of noise; another is that the bandwidth or Δf of the electronic processing equipment is an essential factor in the result.

The TeachSpin Noise Fundamentals apparatus, includes everything needed to establish the vocabulary, and the facts, about Johnson noise. This noise that is born in resistors, either at room temperature in the electronics package, or in samples within a variable-temperature probe unit, first reaches a wide-band pre-amplifier, and then a combination of filter and gain stages in the main electronics unit. The filter stages are fully adjustable, and their use makes it possible to verify the Δf - or bandwidth - dependence of the results. Student measurements then lead to the Boltzmann constant using the equation:

$$\langle V_J^2(t) \rangle = 4\, k_B\, R\, T\, \Delta f \ .$$

Holding the temperature constant they can work at room temperature varying Δf. The temperature probe used to study temperature dependence is designed to cover the 77 – 350 K range, using liquid nitrogen and a heater unit, and it comes complete with a Dewar and temperature measurement and control capability.

The block diagram below shows the path of the signal from the resistor being studied.



A central part of the electronics is a real-time analog-multiplier module used to form the square-of-noise signal, so that ultimately an ordinary multimeter can be used to establish the mean-square measure of a noise waveform. Another feature of the electronics is the attention paid to the precision and accuracy of the entire noise-measuring electronic chain, and to the calibration procedures which can (optionally) validate that accuracy. One of the investigations open to students is the distinction between the separate noise contributions of the resistor-under-test and the first-stage amplifier at the input of the pre-amplifier.

The electronic units also include all that is needed to produce, instead of Johnson noise, the shot noise exhibited by (certain kinds of) currents. In particular, this apparatus uses a solid-state photodiode, illuminated by thermal light, to produce a current (variable from 10^{-8} to 10^{-4} A or beyond) which exhibits 'full shot noise', ie. the fluctuations implicit in photons individually creating charge carriers in the photodiode. Both the dc value i_{dc}, and the ac fluctuations $\langle i_n^2 \rangle$, in this photocurrent are accessible to students, through the re-configuration of the pre-amplifier's first stage as a current-to-voltage converter.
Shot noise data are used to measure of the charge on the electron to an accuracy of better than 3%. The equation is:

$$\langle i_n^2 \rangle = 2\, e\, i_{dc}\, \Delta f.$$

Finding the value of *e* from noise is a far different experience than watching falling droplets!

TeachSpin's electronic units have also addressed the non-trivial issues (such as power supply, shielding from interference, and ground loops) which so often bedevil low-level measurements. The pre-amplifier unit is modular in organization, and its interior is uniquely fully-accessible to student re-configuration, providing (if desired) the basis for instruction in low-level techniques in electronics. The instrument's Manual gives detailed instructions for the standard, and a host of optional, projects in noise and its measurement. There is sufficient attention paid to those curious noise units, V^2/Hz and even $V/\sqrt{Hz}$, and there are optional sections describing in detail the use of Fourier-transform methods for understanding the spectra of noise.