PHYS-379: NOISE FUNDAMENTALS

USING JOHNSON & SHOT NOISE TO MEASURE

FUNDAMENTAL CONSTANTS OF NATURE

BY Sebastian Grabill, Levi Carr

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ABSTRACT:

Johnson noise and shot noise are two fundamental sources of noise in electronic systems. Our characterization of Johnson noise at 297.6 K (room temperature) was consistent with a linear dependence on resistance and frequency bandwidth given by Nyquist’s formula. From it, we calculate a value for Boltzmann’s constant, *kB* = (1.383 ± 0.003) which is 0.57 error bars from the accepted value of Boltzmann’s constant, *k­B* = 1.380649 (NIST). Using an adjustable incandescent lightbulb and a photodiode to produce an adjustable DC photocurrent, our characterization of shot noise is consistent with theoretical predictions of linear dependence on DC photocurrent and frequency bandwidth. However, our best-constrained value of the fundamental charge, *e* = (3.367± 0.006) C, is too low by a factor of 4.76 and/or 1,067 error bars relative to the accepted value of *e* = 1.602176634 x 10-19 C (NIST).

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# introduction

Electrical noise is ubiquitous to all circuits and there are many mechanisms by which it is introduced. In the United States, energy suppliers produce AC power at 60 Hz; these oscillations are present in circuits connected to a wall outlet. Amplifier circuits are often necessary for detecting faint signals, but slight variations in the temperature or the ambient magnetic field can also introduce an errant signal. Mechanical vibrations might also induce electrical noise into a system. Through the course of our experiment, we found—and eliminated through physical or data analysis means—these sources of extraneous noise. Although electrical noise sources are generally undesirable, certain sources of noise were precisely what we sought in our experiment.

There are two noise sources we are specifically interested in studying: Johnson noise and shot noise. Johnson noise is a thermal noise inherent to any resistive element where collisions stemming from the thermal distribution of electron velocities produce fluctuations in voltage. Shot noise is marked by the fluctuation in current or voltage attributed to the discrete, stochastic arrival of these electric charge carriers. This paper delves into the theoretical foundations of Johnson and shot noise, the experimental techniques utilized for its measurement, and a subsequent analysis of the data acquired with a particular focus on determining Boltzmann’s constant, *kB*, and the elementary charge, *e*.

# theory

## Johnson Noise

Johnson noise was discovered by J. B. Johnson and mathematically formulated by H. Nyquist who showed that the mean squared fluctuations in voltage inherent to a resistor in thermal equilibrium with its surroundings are directly proportional to resistance *R*, temperature *T* (K), and bandwidth D*f* (Hz) (Johnson 1928; Nyquist 1928). Nyquist derived a formula for these fluctuations from transmission line theory:

[1]

This is the baseline thermal noise of a resistor, through which no current needs to be flowing for the noise to exist. Eq. (1) can be rearranged to give Boltzmann’s constant:

[2]

In our experimental setup, we cannot measure directly since the magnitude of the Johnson noise signal is very tiny and must be amplified via low noise amplifiers and voltage squarers—thus introducing unwanted noise into the system. Some noise like 60 Hz noise can be eliminated from the system by adjusting the frequency bandwidth to only permit oscillations above 100 Hz or by changing the resistor source in the low-level electronics (LLE) circuit, but other sources persist. For the persistent sources, we measure the mean squared output—a combination of Johnson noise and amplifier noise—from a digital multimeter (DMM) and apply various signal processing techniques post-measurement. For a time-averaged, squared output from the high-level electronics (HLE), we find:

where is the amplification from the HLE. The expected signal from the HLE (unsquared) is:

where is the desired Johnson noise signal and is the extra noise in the system (amplifier, 60 Hz, etc.). So

However, we assume that Johnson noise and other noise sources do not share an emission mechanism—viz. they are independent of one another. This implies that, averaged over time, the net effect from both terms is negligible and the crossing term, , is 0. Thus, we find:

which gives the mean squared voltage:

[3]

We can easily solve for the Johnson noise term:

[4]

Substituting this expression into our expression for *kB*:

[5]

To determine , we want to minimize the Johnson noise. Practically speaking, we want to use a very small resistor and assume . The runs with the small and large resistors are given in the data tables below (Methods & Data, Data Tables). Additionally, the frequency bandwidth we dial up on the HLE is not strictly what the bandwidth is since the frequency filters are not perfectly square in their corner frequencies (in a transmission efficiency vs frequency plot they appear as trapezoids). As such, tables have been computed for the corrected frequency bandwidth given the dial positions on the HLE; we use the table provided in the TeachSpin lab manual (Table 1-15).

## Shot Noise

In contrast to Johnson Noise and thermal fluctuations, shot noise is due to charge quantization. This noise is observed within electric currents due to the grain-like nature of flowing charges with random fluctuations about their average DC values. Even if a DC photocurrent appears steady, there is a mean-squared noise we can attribute to the effect of electrons arriving randomly clustered or spread out. At a given point in the circuit at any given time interval, the expected standard deviation in arrival times goes as electrons.[[1]](#footnote-1) For a given DC current, the larger the fundamental charge, *e*, the larger the expected RMS fluctuations in the total current. Thus, by measuring the fluctuations in the total current, shot noise makes possible the measurement of the magnitude of the fundamental charge by a simple noise measurement.

A formula can be derived to represent the mean-squared noise in the total current, from the definitions of current packets and statistical fluctuations within packets (Schottky 1918):

[5]

where D*f* is defined the same as for Johnson Noise. The average DC photocurrent (A), and bandwidth D*f* (Hz), vary linearly with respect to the mean square photocurrent fluctuations . From this linear relationship, it will be easy to produce a value for the fundamental charge *e*.

We use a dimmable, incandescent lightbulb to produce (what we reasonably assume to be) uncorrelated photons and use a photodiode to measure DC photocurrent fluctuations containing shot noise, . Substituting this and an expression for the DC photocurrent in terms of the output voltage and resistance across the system (Ohm’s law) into Schottky’s formula we obtain:

[6]

where is the DMM reading, G2 is a component of the system gain (see Methods & Data), and Rf is a resistor that moderates the voltage drop when converting current to frequency. Similar to the use of the low resistance resistor to measure the approximate amplifier noise, we measure the output when no photocurrent is passed through the system (the lightbulb is dark) and take this to be the amplifier noise. The measured amplifier noise is subtracted from the DMM output to isolate the shot noise signal. We obtain a value for the electron by applying the formula for noise power spectral density:

[7a]

or equivalently:

[7b]

After substituting the previous formula, we can solve for *e,* giving:

. [8]

As with the Johnson noise experiment, the bandwidth D*f* values are found from a correction table in the TeachSpin lab manual (Table 1-15).

# methods & data

## Equipment

All data collection is done using the TeachSpin Noise Fundamentals Apparatus. This modular device is composed of several parts working in series. First, the noise sources and general configuration are contained within the Low-Level Electronics (LLE). Within the LLE, we can vary resistance—which we assume is the sole source of the Johnson noise—and the temperature of the resistor via a liquid nitrogen (LN2) dewar. The output is amplified by an amount specified in the TeachSpin manual and then passed to the High-Level Electronics (HLE) where it goes through a high/low-pass frequency filter, a second gain module (G2), and a voltage squarer. The outgoing signal for all experiments is time-averaged over 1 second, then sent in parallel to a DMM and an oscilloscope. It should be noted that this is mean-square error, not RMS error.

A table with electrical equipment

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*Figure 1. An image of the experimental setup. The LLE are contained in the black-sided box and the HLE are contained in the brown-sided box. The oscilloscope can be seen off to the right and is used by us to detect and discover external sources of noise. The DMM took all data labeled “Raw Voltage” in the data tables (below).*

As described in Theory, the signal sent to the DMM is a combination of the desired noise source and the extraneous noise sources. Over the course of the experiment, we identified 60 Hz noise and mechanical vibration noise using the oscilloscope. 60 Hz noise would be large amplitude, periodic signals occurring when the horizontal divisions on the oscilloscope were set to considerable fractions of 60 cycles/s. Electrical noise induced by mechanical vibrations would present themselves as spikes in the magnitude of the noise baseline which would take a few seconds to settle back down.

## Data Collection

We used the oscilloscope primarily for signal diagnostics, but the DMM is where the data collection took place. To get consistent data, we roughly followed this procedure:

1. Adjust the parameters to the experiment controls of interest. In the Johnson noise experiment, this was either D*f* or resistance. In the shot noise experiment, this was D*f* or DC photocurrent.
2. Watch the output from the DMM settle into a consistent range of fluctuations.
   1. Mentally track what values occur and when they occur; note where the approximate center is based on this tracking. Approximately 20 s was sufficient to establish a good baseline. This can be automated in future experiments.
   2. Coincidentally monitor external vibrations. Slight vibrations from chairs shuffling on the floor above, bumping the table, or even speaking can cause uncharacteristically high voltage readings that require step 2) to be repeated.
3. Use the “mental tracking” from step 2) to select the value that the voltage seems to fluctuate around.
4. Double-check that the experimental parameters did not change over the course of the experiment; repeat the procedure if they did.

The results of our data collection efforts are given below in the tables and graphically in the “Analysis” section.

## Noise Reduction

We want to characterize a specific type of noise, and there is some irony in trying to isolate noise-free noise. We empirically identified that the LLE module was the most susceptible to the influence of external noise sources such as vibrations or induced 60 Hz oscillations from the wall power supply. We discovered that the pre-installed resistors were very susceptible to 60 Hz noise when the high-pass filter was set to 30 Hz or 10 Hz (thus allowing 60 Hz to propagate). We dealt with the 60 Hz noise by changing where the resistor was located within the LLE. We do not know why the built-in resistors exhibited 60 Hz noise but those slotted into external resistor slots in the LLE did not. In some experiments, 60 Hz noise was identified regardless of resistor position, so we restricted the frequency bandpass to only allow signals with oscillations above 100 Hz; this was effective. Mechanical vibrations—such as talking or tapping the surface supporting the LLE (i.e., the bench)—also produced large fluctuations in the outgoing signal for reasons we cannot fully explain. To address mechanical vibrations, we ultimately placed the LLE on a shelf above the HLE so that there was less coupling between it and the vibrating wall and/or vibrating researchers. However, most data were taken with the LLE on the bench and the researchers actively monitoring noise sources.

## Data Tables: Johnson Noise

For all Johnson noise experiments, we used precision resistors with resistance uncertainty, (where R is the advertised value of the resistor) inserted into the external resistor slot in the LLE circuitry. In the 77 K experiment, precision resistors were used in the dewar probe.

**Table 1: Johnson noise at room temperature while varying resistance.**

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Here, we vary the resistance of the circuit while holding the frequency bandwidth, D*f*, constant. “Raw Output” is the DMM reading, and “Inferred Total Noise” is the noise figure we calculate using eq. [3]. We assume that the Johnson noise produced by the 1 Ω resistor is negligible so that only amplifier noise is present. Thus, Johnson noise is calculated by subtracting the inferred total signal from the “Inferred Total Noise” for the 1 Ω resistor (which is why there is no Johnson noise for the 1 Ω resistor). “g1” is the initial amplification from the LLE quoted in the TeachSpin lab manual page 1-15 for this experiment’s configuration.

**Table 2: Johnson noise at room temperature while varying frequency bandwidth**

A screenshot of a table

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Here, the frequency bandwidth of the circuit is varied while resistance is held constant. We use a 10 kW resistor at room temperature (297.6 K). The “inferred total noise” has both the amplifier and Johnson noise in it. To isolate the Johnson noise, we repeat the experiment with the same conditions, but we make the resistance very small (see Table 3). Since the low- and high-pass filters do not have perfectly square “corners” at their corner frequencies, we reference Table 1-15 in the TeachSpin lab manual to find the corrections in D*f* for each combination of high-pass and low-pass filters; these are given in the “corrected deltaF” column.

**Table 3: Amplifier noise dependence on frequency bandwidth for room temperature**

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This is associated with Table 2. We made a mistake here by adjusting the HLE gain in between trials. The HLE amplifier adds a significant contribution to the total amplifier noise, and if adds different amounts of noise when it is set at 4000 or 8000, this should result in a constant shift on every data point of the derived Johnson noise. Fortunately, a constant offset should produce the same slope as without the offset and our value for *kB* should be unaffected so long as the amplifier noise as a function of frequency bandwidth varies similarly for 8000 as for 4000.

**Table 4: Johnson noise at liquid nitrogen temperature while varying frequency bandwidth**

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Like Table 2, the frequency bandwidth of the circuit is varied while resistance is held constant. We use a 10 kW resistor at liquid nitrogen (LN2) temperature (77.08 K). The “inferred total noise” has both the amplifier and Johnson noise in it. To isolate the Johnson noise, we repeat the experiment with the same conditions but make the resistance very small (see Table 5). Since the frequency bandwidth does not have perfectly square corner frequencies, we reference table \*\* in the TeachSpin lab manual to find the corrections for our particular arrangement; these are given in the “corrected deltaF” column.

**Table 5: Amplifier noise dependence on frequency bandwidth at LN2 temperature**

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This is associated with Table 4. We made a mistake here by adjusting the HLE gain in between trials. The HLE amplifier adds a significant contribution to the total amplifier noise, and if adds different amounts of noise when it is set at 4000 or 8000, this should result in a constant shift on every data point of the derived Johnson noise. Fortunately, a constant offset should produce the same slope as without the offset and our value for *kB* should be unaffected so long as the amplifier noise as a function of frequency bandwidth varies similarly for 8000 as for 4000.

## Data Tables: Shot Noise

The Johnson noise source was removed from the LLE circuitry prior to the shot noise experiment. A resistor within the linear regime found in the Johnson noise vs resistance experiment was placed in the LLE to create a transimpedance amplifier that turns the photocurrent into a voltage. We placed an adjustable brightness lightbulb (adjusted via a variable voltage control) at one end of a small tube in the LLE. At the other end of the tube, we placed a photodiode AC coupled to a low-noise, 100-gain amplifier. The photodiode was also DC-coupled to a 1 kW resistor to monitor the DC photocurrent. The outgoing signal was sent to the HLE for frequency bandpass, amplification, and subsequent squaring.

**Table 6: Shot noise with a varied DC photocurrent**

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Here, shot noise is measured with DC photocurrent varied and frequency bandwidth fixed. This was done with a 10 kW resistor since the 10 kW resistances worked well in our Johnson noise experiments. Similar to Johnson noise, the corrected bandwidth was used. To subtract off Johnson and amplifier noise, the voltage was lowered as far as the LLE would allow (< 0.01 V), and the voltage was recorded. Since we do not have a changing bandwidth, we both expect and see that the voltage with the light powered “off” is constant. The mean squared photocurrent fluctuations were computed according to eq. [6]

**Table 7: Shot noise with a varied frequency bandwidth**

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Here, shot noise is measured with frequency bandwidth varied and DC photocurrent fixed. This was done with a 10 kW resistor since the 10 kW resistances worked well in our Johnson noise experiments. Similar to Johnson noise, the corrected bandwidth was used. To subtract off Johnson and amplifier noise, the voltage across the light bulb was lowered as far as the LLE would allow (< 0.01 V) thereby eliminating and allowing us to measure the extraneous noise. Since we have a changing bandwidth in this case, we both expect and see that the noise voltage with the light powered “off” is directly proportional to the bandwidth. The mean squared photocurrent fluctuations were computed according to eq. [6].

# Analysis

## Johnson Noise

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*Figure 2. Plot of Johnson noise vs. log resistance. Resistance error bars can be seen but the Johnson noise error bars are too small to see. There is an approximately linear regime for this data from 100 Hz to 10000 Hz which we fit with a linear trendline (appears exponential with the semi-log vertical axis). The data in this region are highly linearly correlated with an r2 = 0.99999. The slope of our line of best fit, m = (2.014 ± 0.005) . We assume* D*f = 110961 ± 4438 Hz (from Table 1-15 in the TeachSpin manual), and temperature T = 297.6 ± 0.2 K.*

A graph of a person with a red line

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*Figure 3. Plot of Johnson noise vs. corrected frequency bandwidth. The bandwidth error bars can be seen but the Johnson noise error bars are too small to see. The data are highly correlated with a linear model with an r2 = 0.99997. From the slope, m = (1.646 ± 0.003) We assume resistance R = 10000 ± 10 W and temperature T = 297.6 ± 0.2 K.*

Boltzmann’s constant is found via eq. [5]. We calculate the uncertainty in Boltzmann’s constant by computing:

Where each δ term is the associated uncertainty. We derive the slope uncertainty, δm, using the standard error computed in Scipy’s “linregress” module (Virtanen et al. 2020). δR = 0.001 ∙ R for all resistors with resistance R per the manufacturer’s standards. For room temperature measurements, we took two desktop thermometers with 0.1 ⁰C precision, averaged them to give the “best temperature” (T = 297.6 K), and took the difference from the average temperature to be the uncertainty in temperature, δT = 0.2 K. We used the DMM uncertainty (0.0001 V) and the gain uncertainty (1% the total gain) to compute error bars in Johnson noise; the frequency bandwidth uncertainty (4% the bandwidth) to compute error bars in corrected frequency bandwidth; and resistor uncertainty(0.1% the resistance) to compute error bars in the resistance.

Boltzmann’s constant is determined by the National Institute of Standards and Technology (NIST) to be *k­B* = 1.380649 x 10-23 J. We use the slope of the least squares regression line and eq. [2] to compute values for Boltzmann’s constant. For our experiment examining Johnson noise vs resistance, we determine *kB* = (1.53 ± 0.06) . This is 2.36 error bars from the accepted value of Boltzmann’s constant. For our experiment examining Johnson noise vs frequency bandwidth at room temperature, we find Boltzmann’s constant, *kB* = (1.383 ± 0.003) . This is 0.57 error bars from the accepted value of Boltzmann’s constant.

*A graph of a person with a red line

Description automatically generatedFigure 4. Plot of Johnson noise vs. corrected frequency bandwidth. Bandwidth error bars can be seen but the Johnson noise error bars are too small to see. The data are highly correlated with a linear model with an r2 = 0.99998. The slope is m = (4.291 ± 0.008) We take resistance R = 10000 ± 10 W and temperature T = 77.08 ± 0.13 K. This value is* ***not*** *within one error bar of the accepted value of Boltzmann’s constant (it is within three).*

At liquid nitrogen (LN2) temperatures, the calculation was more involved. First, we assume that the electronics are in thermal equilibrium with the boiling temperature of LN2 at our location. This is a reasonable assumption as we let the LN2 boil for several minutes before data collection. The boiling point of LN2 is 77.36 K at 1013.25 mbar. We did not record the exact date for our runs, so we used a monthly average pressure to give our “best pressure”. For the month of March 2024, the average pressure in Grand Rapids was 981.37 mbar (Weather Underground). Using the Clausius-Clapeyron equation, we can get a rough estimate of the boiling temperature as a function of pressure. We begin with the full form of the Clausius-Clapeyron equation:

[10]

where L is the latent heat of vaporization for molecular nitrogen, T is the boiling temperature of the nitrogen, and is the change in the volume of gas when one molecule of nitrogen transfers from liquid to gas. For the calculation, we will assume that , and that the ideal gas law holds. These approximations yield:

or

as shown in Kittel & Kroemer (1980). We can easily solve for T as a function of P by integrating both sides:

where *P0* and *T0* are a pair of pressures and temperatures corresponding to a boiling point of nitrogen. Additionally, we transform our calculation to deal with moles of N2. We obtain:

where *L0* is the latent heat of vaporization per mole of molecular nitrogen, *R = NAkB* » 8.31446 J mol-1 K-1 is the gas constant, and *N­A* is Avogadro’s number. Solving for the boiling temperature as a function of local pressure:

[10]

Using P0 = 1013.25 mbar, T0 = 77.36 K, L0 = 5.57E3 J mol-1, and P = 981.37 mbar, we find the boiling temperature for this pressure to be 77.08 K (Lide 2003). Additionally, the temperature corresponding to the March monthly high was 77.18 K and the temperature corresponding to the monthly low was 76.93 K. The difference between the high and low temperature is 0.25 K so we take the variation in temperature, dT, to be 0.125 K.

We use the slope of the least squares regression line and eq. [2] to compute values for Boltzmann’s constant. For Johnson noise vs. frequency bandwidth at 77 K, we find Boltzmann’s constant, *kB* = (1.392 ± 0.004) . This is 2.93 error bars from the accepted value of Boltzmann’s constant.

## Shot Noise

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*Figure 5. Plot of shot noise vs. corrected frequency bandwidth. The bandwidth error bars can be seen, but the error bars on the photocurrent fluctuations are too small to see. We take the DC photocurrent as I = 40 mA ± 0.1mA. The data are very highly correlated with a linear model with an r2 =0.99999 which is what we expect from our linear model. The least squares regression line gives the slope, m = (2.693 ± 0.004) , and the y-intercept,*

*b = -2.437, is near zero, which is what we expect from our model.*

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*Figure 6. Plot of shot noise vs DC photocurrent. All points have error bars that are too small to see. We take the corrected bandwidth frequency to be 9900 ± 396 Hz. The data are highly correlated with a linear model with an r2 = 0.99996 which is what we expect from our linear model. The slope, m = (7.4339 ± 0.02) A, and the y-intercept, b = -4.042 , is near zero, which is what we expect from our model.*

The fundamental charge, *e*, is computed using eq. [7a] or eq. [7b], depending on which quantity is held constant. We compute the uncertainty in the fundamental charge by computing:

Where each δ term is the associated uncertainty. We derive the slope uncertainry, δm, using the standard error computed in Scipy’s “linregress” module (Virtanen et al. 2020). The “c” term is a general way of describing the variable held constant. For the trials where frequency is varied, c is the DC photocurrent and δc is the photocurrent uncertainty obtained from the limits of the DMM. For the trials where DC photocurrent is varied, c is the frequency bandwidth and δc is the bandwidth uncertainty (4%; given in the TeachSpin manual). We used the DMM uncertainty (0.0001 V) and the gain uncertainty (1% of the total gain) to compute error bars in shot noise, frequency bandwidth uncertainty (4%; given in the TeachSpin manual) to compute error bars in corrected frequency bandwidth, and the DMM uncertainty (0.1 mA) to compute error bars in DC photocurrent.

The fundamental charge was determined by NIST to be *e* = 1.602176634 x 10-19 C. We use the slope, m, of the least squares regression line, and eqs. [7a] (for a varying frequency bandwidth) or [7b] (for a varying DC photocurrent) to compute the fundamental charge from our data. For shot noise vs. frequency bandwidth, *e* = (3.367± 0.006) C. This is too low by a factor of 4.76 and/or 1,067 error bars. For shot noise vs. DC photocurrent, *e* = (3.7545 ± 0.1506) C. This is also too low by a factor of 4.27 and/or 196 error bars.

Unfortunately, neither of our measurements of shot noise are close to the NIST-reported value of the fundamental charge. Curiously, they are both ~ 5 times too small but very linearly correlated, which suggests there is a systematic error in how our data are taken or a fundamental flaw in our equipment. This is an issue that will need to be addressed in future experiments.

# Conclusion

In summary, our exploration of shot noise and Johnson noise offer valuable insights into electronic systems. For Johnson noise, this was temperature and frequency sensitivity. For shot noise, it was the discrete behavior of electric charge carriers in electronic systems. Through meticulous measurements using the TeachSpin Noise Fundamentals Apparatus, we have obtained precise values for Boltzmann’s constant, *kB*, and the elementary charge, *e*. While we were successfully able to confirm the accepted value of Boltzmann’s constant while varying resistance and temperature, we were not able to confirm the magnitude of the fundamental charge. In future work, groups should examine the source of the systematic error in our shot noise setup which we suspect drove both values to be too low. Additionally, the use of an automated data-taking device would allow for more precise data-taking, although researchers would still need to carefully and actively monitor the environment for sources of extraneous noise.

The understanding gained from this study has promising implications for improving electronic devices from photodetectors to semiconductor technologies. As we refine our experimental techniques and deepen our knowledge, noise continues to be an intriguing and ever-present frontier in electronics and quantum phenomena.

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1. Cf. TeachSpin Noise Fundamentals Manual, ch. 3. [↑](#footnote-ref-1)