I. INTRODUCTION

Ohm's Law, $V = IR$, states that the voltage drop V across a resistor is proportional to the current I passing through the resistor [1]. The proportionality constant, R, is known as the *resistance* and is determined by both material properties (the intrinsic resistivity) and geometry (length and cross-sectional area of the active material). This law is one of many with a similar form, "potential drop" $\propto$ "current," that include Fourier's law of heat conduction (temperature gradient $\propto$ heat current) and Fick's law of diffusion (chemical-potential gradient $\propto$ mass current) [2]. All of these laws are expected to hold when "close enough" to equilibrium – that is, when the currents that pass are "small enough." However, it is not obvious just what "small enough" means in practice, nor what happens if the required conditions are not met. In this study, we examine this question in the context of Ohm's law, by measuring the electrical resistance of a lamp as the current through it is increased. The drastic change in temperature of the bulb's filament – from room temperature with no current to white-hot at full current – leads one to anticipate that out-of-equilibrium effects will be important. For comparison, we also look at an ordinary metal-film resistor.

II. PROCEDURE

In order to examine Ohm's Law, we need a setup that allows us to vary the current passing through the studied resistor. Here, we rely on a voltage divider, hooked up to a data acquisition device, or DAQ [3]. In Fig. 1, the top resistor R_1 is an ordinary carbon resistor with a nominal resistance of 221 Ω, as measured by a digital multimeter [4]. We used the DAQ to measure the voltage drop across this resistor and converted it to a current using Ohm's law and the nominal resistance of the carbon resistor. The lower resistor, R_2 in the figure, was either a lamp [5] or a metal-film resistor, as discussed below.

We controlled the current through the lamp by setting an overall voltage across the circuit. The current was controlled by our computer, using one of the DAQ's analog out circuits to control the analog input of a Xantrex analog-programmable power supply [6]. The power supply had an internal gain of 6, so that the maximum voltage of the DAQ, 5 V, corresponded

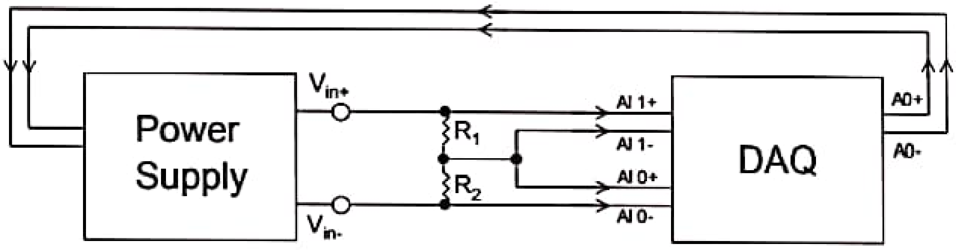

FIG. 1: Schematic of the experimental setup, showing the voltage divider, with R_1 the reference resistor and R_2 either the lamp or metal-film resistor. Connections to the voltage inputs of the DAQ and the analog output that controls the power supply are also shown.

to 30 V on the power supply. We wrote several different but similar programs in National Instruments LabVIEW [7] to measure the response of the lamp under different conditions. The recorded data were graphed and analyzed using the Igor-Pro software package [8].

In initial work, we used a knob control to set (and change) the current through the lamp. Qualitatively, we noticed that the voltage measured across the bulb drifted after changing the current. We confirmed this by taking a time series of the bulb voltage while making small step increases or decreases to the current through the bulb (Fig. 2). We see that the temperature relaxes to the new steady-state value as the current is either increased or decreased. In Fig. 2, we have fit an exponential curve to one of the segments and found a decay constant of roughly 0.9 s (0.8884 ± 0.0005 s). (Exponential cooling and heating curves are typical of systems described by Newton's law of cooling, where the relaxation rate to the current equilibrium is proportional to the distance from equilibrium [9].) Since the relaxation time is just under 1 s, we expect that waiting 10 s should be sufficient for transient effects to relax.

We looked at the question of drift in a slightly different way, as well. In the measurement of IV curves (current-voltage), we stepped through a series of currents, with a set time between each measurement. At the end of that time, 100 points were collected at 1 kHz. Fig. 3a shows one such measurement taken 1 s after changing the current. One can easily see the drift superimposed on top of statistical fluctuations. Fig. 3c shows similar data collected 10 s after changing the current. No drift is discernible. (However, quantization