LETTER TO THE EDITOR

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Reply to comment on 'Resistance of a digital voltmeter: teaching creative thinking through an inquiry-based lab'

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First, we thank Gingl and Mingesz for reading our article and providing comments and suggestions. Although their error analysis is interesting [1], it is based on assumptions and on what our reported values might suggest. Even though in our article we showed one value for the voltage and one value for the current, we carefully selected the values consistent with the *I* versus *V* slope. The main point of our article is to challenge students to be creative, not to reveal to instructors how to perform experiments. The inquiry-based electronics experiment we proposed is intended to let students be creative and learn for themselves the conditions under which the use of a voltmeter will have measurable effects on the current in the circuit. As we stated, 'The idea is to observe how the measurement of the voltage affects the current in the circuit' [2]. Therefore, it was natural to mention Method 2 in which current is measured as a function of voltage. We mentioned this method without instructing one how to collect data points because we want students to be creative and come up with their own methods. We gave no details on how we performed measurements and we did not discuss experimental uncertainties.

We agree with Gingl and Mingesz that our two different methods have different uncertainties. However, their comment is based on an incorrect interpretation of our experiment. They say, 'The authors' observations could suggest that the accuracy is almost the same for the two methods (they obtained 10.0 MΩ and 10.1 MΩ), however, it is not the same'. They used this as the basis of their comment, but this is not something that we suggested. The reason we reported two close numbers from two different methods was not to suggest that they are equally accurate. However, we did put our methods on the test numerous times and observed that they give very consistent results with good accuracy, and that is what we suggested.

Since the instrument specifications from the manufacturer's manual are wide enough to allow for manufacturing and component tolerances, we took an empirical approach to finding uncertainties. The measurements performed with one DMM are typically very precise. To test how accurate they are, we used many different DMMs and below we will provide more details regarding the methods mentioned in our article [2].

Method 1 revisited

Method 1 was a direct measurement of the internal resistance of our DVMs and we reported the average value, $R_{\mathrm{DVM}} = 10.0\,\mathrm{M\Omega}$. We were very careful with the number of significant figures we presented. Namely, the DMMs show at least one more digit that we did not specify (see figure 1). The resistance of our BK 2831D DMMs was

Figure 1. Direct measurement of resistances of DVMs. DVMs may be turned off as long as the buttons are set for voltage measurements.

measured using multiple hand-held DMMs (different models and manufacturers), and one representative resistance reading is now displayed in the upper panel of figure 1.

One can also measure this internal resistance with better resolution, as displayed in the lower panel of figure 1. Regardless, hundreds of measurements using different DMMs suggest that measured uncertainty (9.98 MΩ $< R_{\mathrm{DVM}} <$ 10.05 MΩ) can be much smaller than suggested by Gingl and Mingesz (9.75 MΩ $< R_{\mathrm{DVM}} <$ 10.25 MΩ) based on manufacturer's specifications. Our previously reported value for R_{DVM} of 10.0 MΩ is consistent with our observations. Similarly, Gingl and Mingesz assign the uncertainty to our color-code resistor. Their uncertainty, again from manufacturer's specifications, is much larger than the uncertainty we found empirically.

Let us now revisit Method 2, and this time let us first use the $R_{\mathrm{DVM}} =$ 10.0 MΩ (the average obtained from different measurements) to determine the resistance of the color-code resistors. At the end we will use one known resistance in order to obtain the R_{DVM} value.

Method 2 revisited

We will now display results obtained for different color-code resistors using different DMMs. We vary the voltage on the power supply (Keithley 2110) from about 5.00 V up to 30.00 V (figure 2), and we record both the current and the voltage. Voltage was recorded on the DVM whose resistance is 10.0 MΩ. The total resistance (R_{DVM} plus resistance of a color-code resistor) is obtained as the inverse of the slope. The color-code resistance is then calculated using equation (1). Figure 2 displays how current changes as a function of applied voltage. The difference between the two panels is in the current meter used (see the text within each panel). Numerous other measurements on various different DMMs were performed with very similar results (data not shown).

$$R = \frac{R_{\mathrm{DVM}} R_{\mathrm{tot}}}{R_{\mathrm{DVM}} - R_{\mathrm{tot}}}. \qquad (1)$$

We use $R_{\mathrm{DVM}} =$ 10.0 MΩ (note number of significant figures) along with the total resistance from the linear fit (inverse of the slope) for determination of the 'unknown' resistance of the color code resistor using equation (1). The measurements displayed in Figure 2 were performed using two different hand-held DMMs and they reveal values of 10.48 MΩ and 10.42 MΩ, in very good agreement with the values obtained from direct measurements (10.25 MΩ–10.45 MΩ).

Figure 3 displays results obtained from 10 different and randomly selected DMMs to determine the internal resistance of the DVM, R_{DVM}. The total of 211 data points (about 21 each) in the 9.00–30.00 V range is displayed. The resistance of the resistor used was measured to be 15.2 MΩ (15.10 MΩ–15.30 MΩ). The value of R_{DVM} is obtained from equation (2).

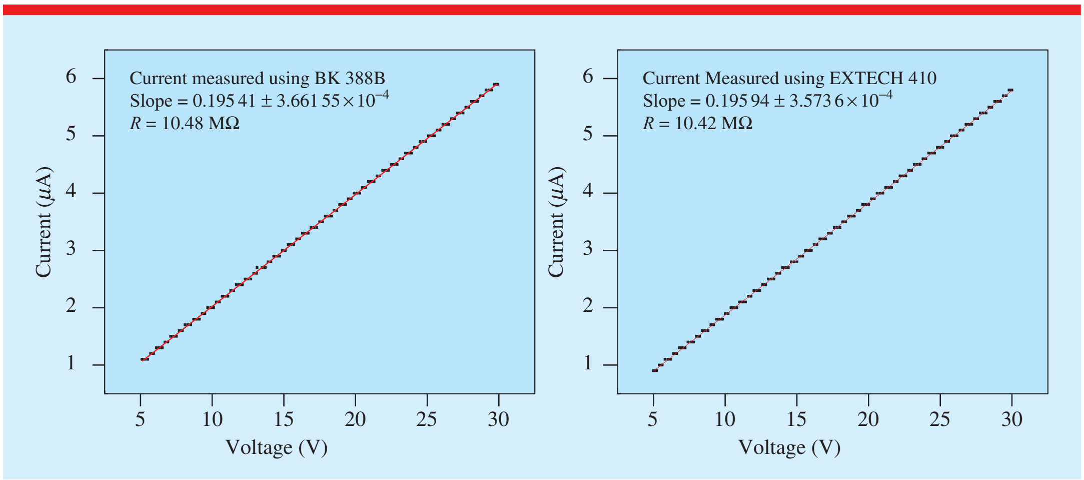

Figure 2. Current versus voltage plots. Left panel shows the current measurements using BK 388B. The right panel shows the results when EXTECH 410 was used. The slope values and errors are specified in each panel. The slope corresponds to the inverse of R_{tot}. The value of R was then calculated using equation (1) and is displayed inside the panels.

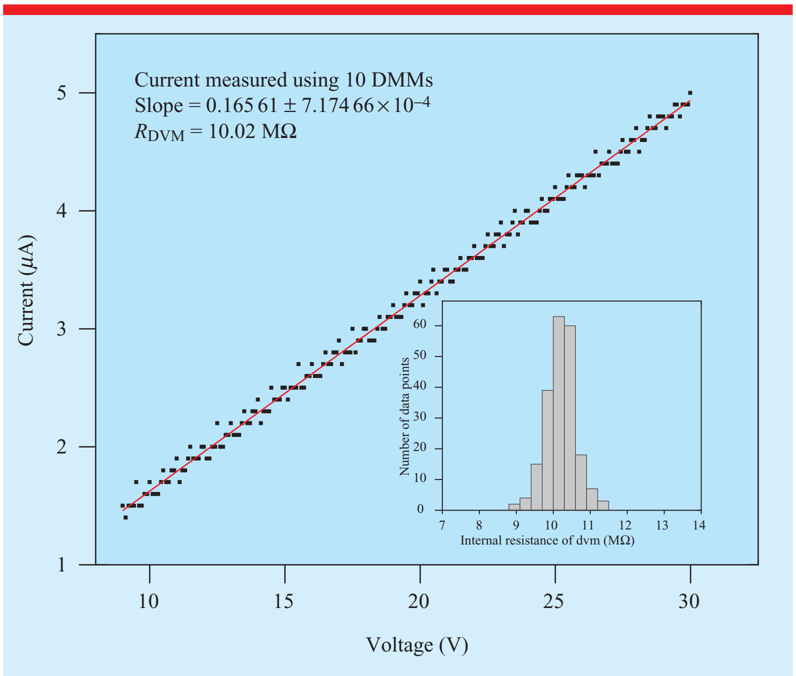

Figure 3. Current versus voltage plot with results from ten different DMMs. This time a 15.2 MΩ resistor was used with the voltage in the 9.00–30.00 V range. The data suggest $R_{\text{DVM}} = 10.02$ MΩ (or 10.0 MΩ).

$$R_{\text{DVM}} = \frac{RR_{\text{tot}}}{R - R_{\text{tot}}}. \tag{2}$$

To measure current, we used DMMs 2 *BK 388B* (10.1 MΩ & 10.2 MΩ), 2 *EXTECH 410* (10.0 MΩ & 10.0 MΩ), 2 *EXTECH MN16A* (10.1 MΩ & 9.85 MΩ), 2 BK *2831E* (10.1 MΩ & 9.85 MΩ), and 2 *GDM-8034* (9.93 MΩ & 10.1 MΩ). The values for R_{DVM}, obtained from slopes and equation (2), are given in parentheses. When data from all 10 measurements are plotted in the same graph, the agreement with Method 1 is excellent.

Namely, $R_{\mathrm{DVM}} = 10.0\ \mathrm{M}\Omega$ is obtained from both methods. The inset of Figure 3 shows how the resistance values obtained from individual measurements scatter.

Even though in our article we reported one value for the voltage and one value for the current, we did not measure only once nor did we propose a single measurement. If one wants to use Method 2, one should get the total resistance from I versus V slope, as we have presented in this replay. Our numerous plots reveal that even 20-to-30 data points give very good results. However, the more data points the better. Although our two methods have different uncertainties, they both can reveal, with very good accuracy, the resistance of a DVM.

Perhaps we should have mentioned that the resistance in Method 2 should be extracted from the slope in the I versus V plot (common approach to finding resistance), but our article [2] should be viewed more as the proposition of an activity than as the detailed description of methods. We only mentioned the two methods as examples of what could be considered as creative approaches to finding the value of the internal resistance of a DMM. We did not provide detailed instructions on how teachers should implement our methods, nor did we instruct students how to measure R_{DVM}. We challenged students to be creative. If instructors want to use our methods in a traditional lab format, in which students are instructed on how to run a laboratory activity, they should then ask students to extract the total resistance from the plot (inverse of the slope) and then use equation (1) or (2) to find the resistance of an unknown resistor or DVM, respectively. Our empirical approach suggests that both methods are relatively accurate. The Method 3 [1] is very elegant, but since it is frequently used it was not given as an example in our article [2]. Our idea was not to list as many methods as we could but instead to suggest to instructors to use this activity to stimulate students' creativity.

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