PAPER

Phys. Educ. **55** (2020) 025013 (7pp) iopscience.org/ped

# Do powerbanks deliver what they advertise? Measuring voltage, current, power, energy and charge of powerbanks with an Arduino

**Christoph Holz and Alexander Pusch**

Institut für Didaktik der Physik, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str.10, D-48149 Münster, Germany

E-mail: christoph.holz@wwu.de and alexander.pusch@wwu.de

**Abstract**

Powerbanks differ in the amount of energy they can store. Usually this capacity (in a colloquial sense) of the powerbanks is stated in the form of charge in mAh for effective advertising. From a physical point of view, shouldn't the energy that a powerbank can provide be of interest? For students, charging smartphones with power banks is commonplace—but the terms voltage, current, power, charge and energy are often not understood clearly. Since misunderstandings can also be expected on this subject, a more detailed analysis of the characteristics of powerbanks provides an opportunity for a context- and life-oriented physics education. In combination with microcontrollers such as the Arduino, simple, inexpensive computer-based experiments and measurements are possible. In this article we present a measurement circuit (see figure 1) for the Arduino, with which series of measurements on the characteristics of various powerbanks can be recorded and evaluated during discharge. Example measurements of various powerbanks are shown and discussed.

## Introduction

Smartphones are often one of the most important everyday items for students and using them is a very popular leisure activity. A problem with modern smartphones which is still not solved is their comparatively short battery life. A common solution is using powerbanks to recharge smartphones on the go, which can sometimes be fully done several times over. Powerbanks provide a voltage of about 5 V with varying maximum currents (smartphones are built to charge with up to 1 A or 2 A). An important characteristic in which powerbanks differ from one another is their maximum of stored energy and with it the total energy that can be put to charging a smartphone. During a charging-process powerbanks behave quite different to, for example, alkaline-manganese batteries: charging electronics are put in place to ensure a steady voltage (around 5 V) compatible with the to be charged devices instead of a declining battery voltage. With too little charge left the charging current will be disabled entirely in order to protect the batteries.

 

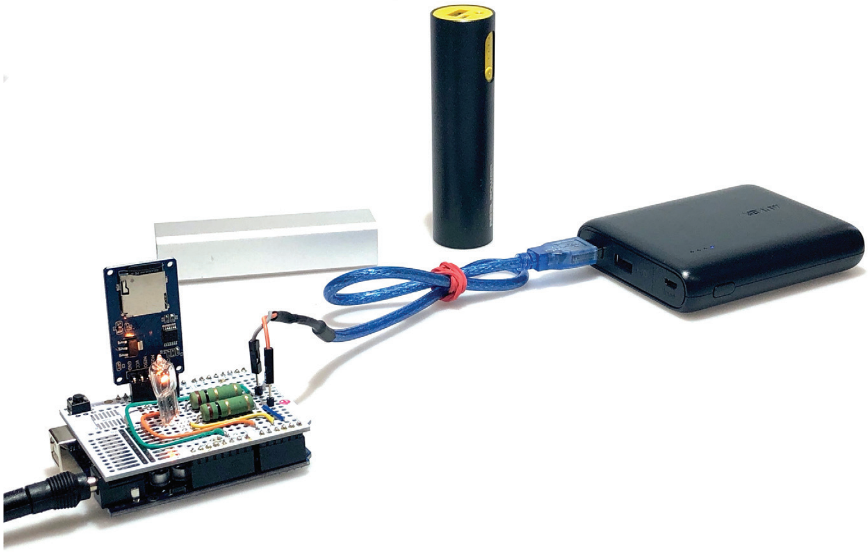

**Figure 1.** Set-up for measuring physical characteristics of various powerbanks with an Arduino. All calculations are done via Arduino and the data is written on an SD card.

The capacity (colloquially used) of a powerbank and smartphone batteries is usually indicated in form of charge in mAh while from a physics perspective especially the energy stored by a powerbank seems to be of most interest. In case of a powerbank both indicators can however be used analogous, if only theoretically: as long as a constant voltage $U$ is put out, the energy $E = U \cdot I \cdot t$ will be proportional to the charge $Q = I \cdot t$. A more close look to the indicated characteristics however shows that they sometimes can be made out a little 'imprecise'. One of our tested devices for example has their maximum capacity indicated as a current in form of ampere (see figure 2).

Recharging smartphones with powerbanks is commonplace for students, physics terms like voltage, current, power, charge and energy however are not and are often times not clearly distinguished. Moreover while dealing with this content misconceptions are to be expected (e.g. Wilhelm and Hopf 2019). Therefore a more detailed analysis of characteristics of powerbanks provides an opportunity for a context- and life-oriented physics education. In combination with microcontrollers such as arduinos (see Pusch 2019) simple and cost-effective experiments with computer-aided measurements are possible.

In this article we describe such a measuring setup via Arduino (figure 1) able to make long-term measurements of powerbanks while discharging. The focus in the design of this experimental setup lies in its usefulness in a science classroom and its ability to target several different school science and math topics. We show and discuss measurement series of characteristics of several powerbanks.

## How to measure voltage and current with Arduinos?

Arduinos such as the affordable and popular model UNO R3 are able to measure DC voltages between 0 V and 5 V at six analog inputs with a resolution of $\frac{5\text{ V}}{1023\text{ steps}}$, therefore in about 5 mV steps.

Currents cannot be measured directly via arduino, but for example with external modules. These modules however are intended for measuring currents in the range of several ampere and above. They give very low precision at low currents suitable for use in schools. External modules are therefore not suitable for our purpose. There is however a more simple and school-related way by measuring the voltage drop over a known resistor. Via Ohm's law the current can then be calculated. Figure 3 shows the resulting circuit diagram of our measurement setup. A small light bulb is used as a load to drain the powerbank, its resistance does not have to be known. The lamp was chosen as it can be easily distinguished from the resistors (for measuring the load) and it offers the possibility

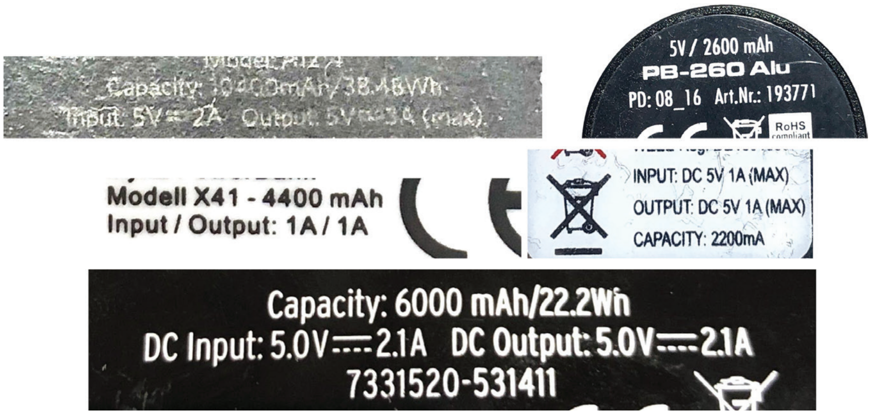


**Figure 2.** Manufacturer specifications of tested powerbanks. Which one will be the 'best'? Do they deliver what is promised?

of visually recognizing the energy transformation. It thereby can be recognized when the powerbank's energy is drained and the measurement can be stopped. Between measurement point 1 (MP1) and ground (GND) the voltage drop over the known resistance is measured. In our case a 1 Ω resistor is used so that the measured voltage is equal to the current of the serial circuit.

The total voltage drop of the circuit could be measured between MP3 and GND, but often times powerbanks have a voltage output slightly higher than 5 V. Since arduinos can only measure up to 5 V this would skew the measurements. This is why a third resistance, this one equal to the known resistance, is connected in series. Now the total voltage of a powerbank with voltages above 5 V can be measured and calculated via Kirchhoff's voltage law: by choosing a third resistance equal to the first one, the total voltage (MP3 to GND) is equal to the sum of the voltages MP1 to GND and MP2 to GND.

By multiplication of the momentary total voltage $U_{\mathrm{tot},i}$ and current $I_i$ the momentary power $P_i$ for measurement $i$ is calculated (see table 1 for an overview over the various calculations). Numerical integration over the time results in the Energy $E = \sum_i \Delta E_i = \sum_i P_i \Delta t_i$ . In this equation $\Delta t_i = t_i - t_{i-1}$ describes the time difference between the momentary measurement $i$ and the preceding measurement $i-1$. This numerical integration is easily realizable in the program code of the arduino since it consists of a simple addition in each measurement loop. Calculating the charge (in Coulomb) is done in an analogous way, by numerical integration of the momentary currents $I_i$. This results in $Q = \sum_i \Delta Q_i = \sum_i I_i \Delta t_i$. Division of this value by 3.6 results in the charge with the unit mAh, which is usually used in manufacturers specifications of powerbanks.

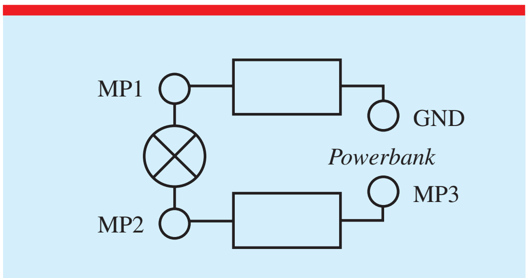


**Figure 3.** Circuit diagram of the measurement circuit. Voltages of the three measurement points (MP) to ground (GND) can be measured.

All of the measured and calculated values could be read out via serial monitor of a connected computer, but for long-term measurements the values are also written on an SD card which can be read out afterwards (figure 4 shows an example of a measurement)[1]. From thereon they can be analyzed and visualized in typical spreadsheet applications without further postprocessing. The program code as well as measurement data of several powerbanks and an alkaline-manganese-battery are available under http://physikkommunizieren.de/powerbank.

[1] Having a computer connected to the arduino while measuring can influence the voltage reference of the arduino which in turn lessens the accuracy of the measurements. This can be avoided by writing the data on an SD card as well as disconnecting the computer and instead connecting a power supply.

**Table 1.** How are energy and charge calculated from the measured values? Overview over measured and calculated values.

| Measured values | labels (for measurement $i$) | Calculated values | labels (for measurement $i$) |
|---|---|---|---|
| Voltage MP1 to GND | $U_{1,i}$ | Current | $I_i = U_{1,i} \ / \ R_{\text{measure}}$ |
| Voltage MP2 to GND | $U_{2,i}$ | Total voltage | $U_{\text{tots},i} = U_{1,i} + U_{2,i}$ |
| System time when starting measurement $i$ | $t_i$ | Time interval of measurement | $\Delta t_i = t_i - t_{i-1}$ |
| | | Power | $P_i = U_{\text{tot},i} \cdot I_i$ |
| | | Output energy in interval of measurement | $\Delta E_i = P_i \ \Delta t_i$ |
| | | Output charge in interval of measurement | $\Delta Q_i = I_i \ \Delta t_i$ |

## Implementations of the circuit

The given circuit can for example be realized on a breadboard or on 'Prototype-boards' (a board that can be directly plugged on top of the Arduino, see figure 5). An advantage of the latter being that all of the cables are firmly soldered, hindering unplanned short-circuits or changes of the circuit while in use.

When the only teaching goal is measurement of powerbanks' specification a realization of these measurements without Arduino and the programming thereof is also feasable. This is possible as long as voltage and current can be measured over a long timespan (depending on the powerbank 48 h and more). Using other devices the shown circuit is not necessary since currents can be directly measured and there is no 5 V limit. While this is a technically much simpler way of measuring a powerbanks specifications, it excludes many learning opportunities that are available in measuring via Arduino such as applying Ohm's law and Kirchhoff's voltage law as well as gaining programming and mathematical skills. An alternative measurement like this was for example done by using a Cassy-module to successfully reproduce the voltage–time-graph seen in figure 6.

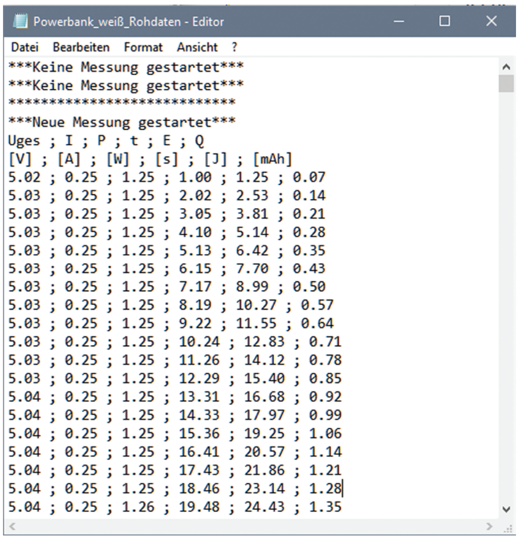
```
Powerbank_weiß_Rohdaten - Editor
Datei  Bearbeiten  Format  Ansicht  ?
***Keine Messung gestartet***
***Keine Messung gestartet***
****************************
***Neue Messung gestartet***
Uges ; I ; P ; t ; E ; Q
[V] ; [A] ; [W] ; [s] ; [J] ; [mAh]
5.02 ; 0.25 ; 1.25 ; 1.00 ; 1.25 ; 0.07
5.03 ; 0.25 ; 1.25 ; 2.02 ; 2.53 ; 0.14
5.03 ; 0.25 ; 1.25 ; 3.05 ; 3.81 ; 0.21
5.03 ; 0.25 ; 1.25 ; 4.10 ; 5.14 ; 0.28
5.03 ; 0.25 ; 1.25 ; 5.13 ; 6.42 ; 0.35
5.03 ; 0.25 ; 1.25 ; 6.15 ; 7.70 ; 0.43
5.03 ; 0.25 ; 1.25 ; 7.17 ; 8.99 ; 0.50
5.03 ; 0.25 ; 1.25 ; 8.19 ; 10.27 ; 0.57
5.03 ; 0.25 ; 1.25 ; 9.22 ; 11.55 ; 0.64
5.03 ; 0.25 ; 1.25 ; 10.24 ; 12.83 ; 0.71
5.03 ; 0.25 ; 1.25 ; 11.26 ; 14.12 ; 0.78
5.03 ; 0.25 ; 1.25 ; 12.29 ; 15.40 ; 0.85
5.04 ; 0.25 ; 1.25 ; 13.31 ; 16.68 ; 0.92
5.04 ; 0.25 ; 1.25 ; 14.33 ; 17.97 ; 0.99
5.04 ; 0.25 ; 1.25 ; 15.36 ; 19.25 ; 1.06
5.04 ; 0.25 ; 1.25 ; 16.41 ; 20.57 ; 1.14
5.04 ; 0.25 ; 1.25 ; 17.43 ; 21.86 ; 1.21
5.04 ; 0.25 ; 1.25 ; 18.46 ; 23.14 ; 1.28
5.04 ; 0.25 ; 1.26 ; 19.48 ; 24.43 ; 1.35
```

**Figure 4.** Start of the textfile of a measurement example.

## Do powerbanks deliver what they promise?

Looking at the voltage–time-graphs while discharging the powerbanks some abnormalities can be found. With some powerbanks the voltage output fluctuates in timespans of several hours, for example between 5,12 V and 5,05 V (figure 6, compare to figure 7). By the end of this discharge the frequency of these sawtooth shaped ramps increases rapidly until the voltage suddenly drops to 0 V. This can be traced back to the charging electronics. These convert the initial voltage of several parallely connected lithium batteries of a maximum of about 3,7 V (Brown *et al* 2011) up to a voltage around 5 V. The discharge curve of an alkaline-manganese battery (figure 8) shows an ordinary discharge without such electronics.

Our measurements of voltage and current with the subsequent calculation of put out energy and charge of several powerbanks results in the values seen in table 2. It is noteworthy that some manufacturers specifications do not differ too much from the measured values while others deviate strongly.

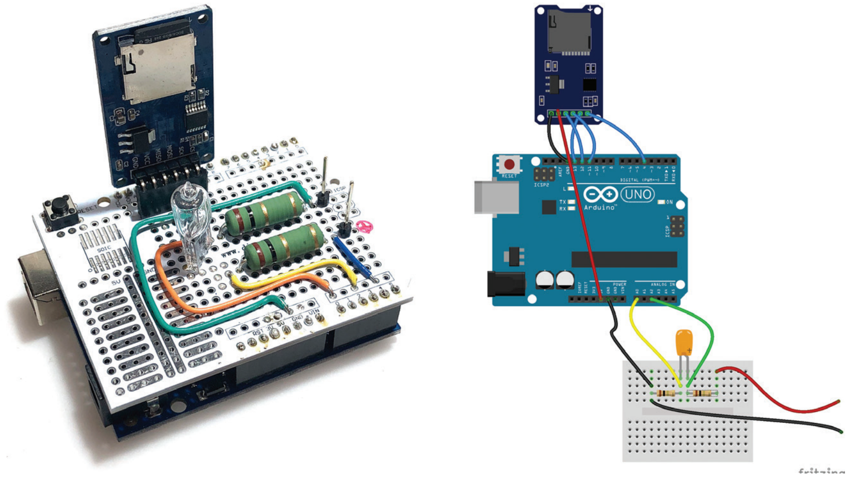


**Figure 5.** (left) Measurement circuit on a prototype-board. The same circuit can also be realized on breadboards (right).

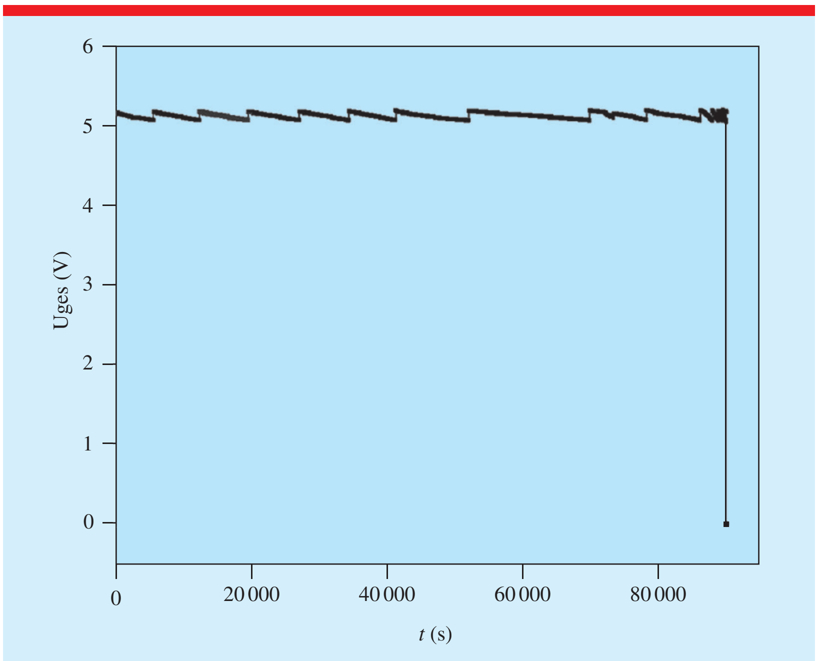


**Figure 6.** Voltage-time graph of the Li-ion powerbank with 11000 mAh indicated. The charging electronics are clearly visible as sawtooth type fluctuation.

Possible reasons lie in the following aspects:

- The usable capacity of a battery depends on the discharge current and the discharge voltage, which is regulated by the charging electronics. Higher discharge currents (e.g. in the so-called 'fast charging') can result in a smaller amount of energy that can be provided. One of the reasons for this lies in the internal resistance of the batteries.
- The maximum capacity of powerbanks may decrease over time of usage.
- The indicated charge usually refers to the total charge of the battery cells. It is not completely emptied to protect the cells (up to 10% of the capacity remain). Likewise,

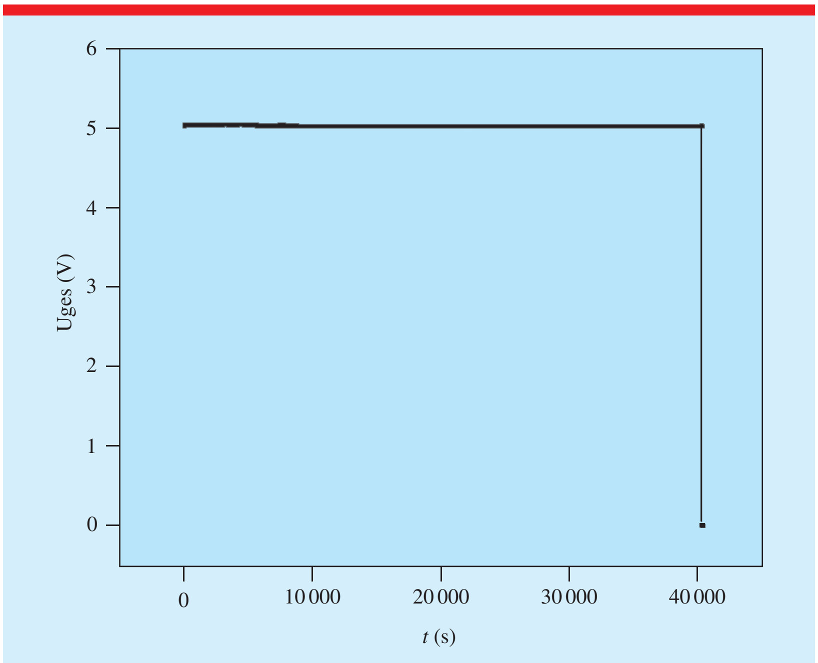


**Figure 7.** Voltage–time graph of the Li-ion powerbank indicated with 4400 mAh. The voltage is mostly constant.

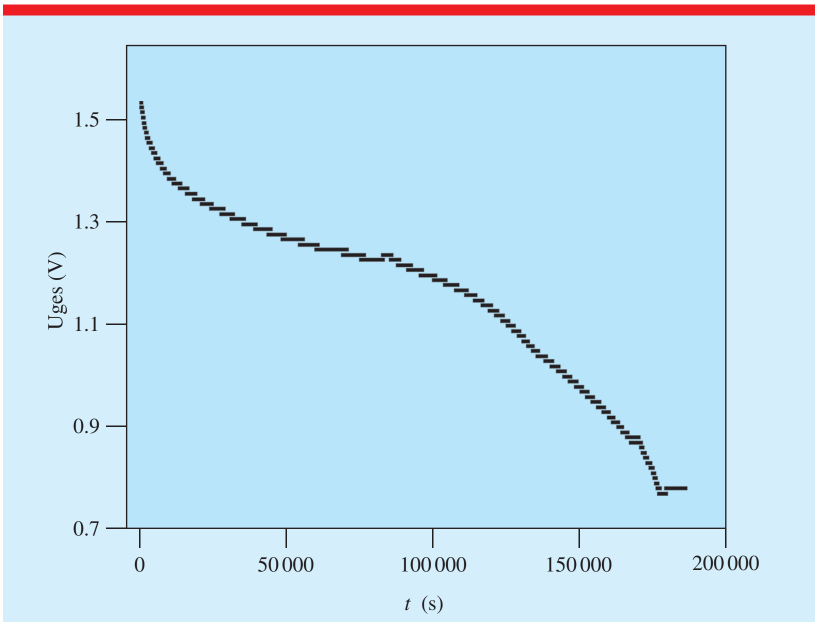


**Figure 8.** Voltage–time-graph of an AA alkaline-mangenese battery. The battery does not have a charging electronic, so the voltage drops while discharging.

the consumption of the charging electronics itself is usually not included.

- The reference value of the specified charge is usually not the output voltage of 5 V but the internal voltage of the battery cells (up to 3.7 V).

This is especially evident in the powerbanks, where an energy (here in Wh) is indicated. The indication in Wh has much smaller deviations from the measured and calculated value. If the specified charge is referenced to the extractable

**Table 2.** Manufacturer characteristics and measurements of five different powerbanks.

| Type | Charge (manufacturer) | Energy (manufacturer) | Charge (measurement) | Proportion measured to manufacturer | Energy (measurement) |
|---|---|---|---|---|---|
| Lead | 2600 mAh | — | 1470 mAh | 56% | 7,21 Wh |
| Lithium | 2200 mA (sic) | — | 800 mAh | 36% | 3,93 Wh |
| Lithium | 10400 mAh | 36,16 Wh | 6240 mAh | 60% | 32,01 Wh |
| Lithium | 6000 mAh | 22,22 Wh | 4100 mAh | 68% | 20,21 Wh |
| Lithium (factory new) | 4400 mAh | — | 2760 mAh | 63% | 13,85 Wh |

voltage the presumed losses are between 30% and up to 65%. By relating the charge to the voltage of a lithium cell (up to 3.7 V) results in losses between 10% and 50%.

Fast charging with high currents up to 2 A, instead of 300 mA as with our set-up, could result in even lower efficiency. A comparative measurement of the characteristic data by means of an alternative circuit which allows a discharge current of 1 A, however, shows no appreciable differences. The latter was realized via an equivalent circuit with a total resistance of 5 Ω, capable of high power, resulting in a current of about 1 A.

## Discussion

The measurements with our circuit are subject to an uncertainty. Thus, the resolution of the arduino at the analog inputs is 0.005 V, which mainly affects the voltage drop across the 1Ω resistors and the resulting current. Furthermore, the 1Ω resistors can be measured only conditionally, as in a conventional, school-typical measurement by multimeter, the contact points already provide significant resistance. Therefore the specified tolerance of 5% has to be assumed.

In our measurements some powerbanks were analyzed that had already been in use. The capacity of the powerbanks could therefore have subsided. However, comparative measurements with new powerbanks also show comparable deviations. When taking into account the losses described above and the measurement accuracy of our set-up, the charge indicated on the powerbanks is realistic. It is misleading, however, because it does not correspond to the actual utilizable charge or energy.

In summary, the measurement characteristics of powerbanks for physics lessons is an exciting experiment in an everyday context. In addition to the measurement of electrical quantities Kirchhoff's and Ohm's law can be applied. Also simple programming of microcontrollers with related mathematical applications such as numerical integration and even the accuracy of measurements can be addressed.

## ORCID iDs

Christoph Holz https://orcid.org/0000-0002-3539-4164
Alexander Pusch https://orcid.org/0000-0001-5407-8469

*Received 6 November 2019, in final form 2 December 2019*
*Accepted for publication 17 December 2019*
*https://doi.org/10.1088/1361-6552/ab630c*

## References

Brown T L, LeMay H E and Bursten B E 2011 *Chemie Studieren Kompakt* (München: Pearson Deutschland GmbH)

Pusch A 2019 Arduino im Physikunterricht *Phys. J.* **18** 26–9

Wilhelm T and Hopf M 2019 Schülervorstellungen zum elektrischen stromkreis ed H Schecker *et al Schülervorstellungen und Physikunterricht* (Berlin: Springer) pp 116–38

**Christoph Holz** studied physics and mathematics. Since 2016, he has worked at the Institute of Didactics of Physics at the University of Münster. His research interests include teachers handling of uncertain experimental data as well as the use of 3D printing and microcontrollers such as Arduino in physics education.

**Alexander Pusch** is fascinated by the application of physics in technology and the physics behind technological applications and developments as well as their potential for school and university. He is always looking for good and up-to-date experiments. In order to develop these, he often uses modern technologies such as components from the 3D printer or the arduino microcontroller.