Measurement of the Newton’s cooling law time-constant by Arduino: an idea for STEM education in high schools

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Abstract
Commercial electronic measuring devices used in physics usually have high costs. In recent years, thanks to its low cost and the high number of available sensors, the Arduino board has been used for many educational purposes in physics education. In this paper a method to measure the Newton’s cooling law time-constant by the Arduino board is presented.

Keywords: Arduino board, COVID-19, physics teaching, physics education

1. Introduction
Despite laboratory practice being essential for physics, due to lack of time and/or resources, it is often neglected at High School. Many schools do not have adequately equipped laboratories.

During the last few years, many science communicators published educational articles that can easily made by students of High Schools using the Arduino [1] board. Some examples of these articles regard a body in free-fall [2], the time constant of a resistor capacitor (RC) circuit [3], the kinetic friction coefficient [4], and many more.

Arduino is an open source platform made of electronic boards, sensors and expansion boards. With an Arduino, students can acquire additional competences, as for example coding and programming [5, 6]. Original Arduino boards can be bought very cheaply, but there are even cheaper clones available. Both the board and the sensors can be easily bought on-line or in electronics stores [6]. There are also many kits including the board and common sensors available for just 50–60 euro. Thanks to the low cost, the Arduino board and related components can be bought directly by students or by schools to be provided to students.

In this paper we present an Arduino-based experiment on Newton’s cooling law, allowing High School students to replicate it.
It consists of the measurement of the cooling time-constant of a liquid. By doing the experiment, students have the opportunity to show the exponential trend of the cooling law, estimate uncertainties, interpolate data and work with the exponential function. The latter is an important function for physics also describing other physics laws as in the RC circuit.

2. Theory

Newton’s law of cooling (equation (1)) describes the rate at which an exposed body changes temperature by radiation. According to this law, the trends over time of the temperature depends on the initial temperature of the body \( T_0 \) and the environment temperature \( T_{env} \) as:

\[
T(t) = T_{env} + (T_0 - T_{env}) e^{-t/\tau}. \tag{1}
\]

Defining \( m \) and \( c \) as respectively the mass and the specific heat of the body, the time-constant is given by [7, 8]:

\[
\tau \propto mc. \tag{2}
\]

The value of the time constant depends on the composition of the body (and its container) and represents the time after which the temperature difference \( T_0 - T_{env} \) is reduced to approximately 63% of its original value. After 5\( \tau \) we expect that the body reaches room temperature. It is similar to an RC circuit. The exponential dependency of the temperature on the time can be verified and the time-constant \( \tau \) can be estimated measuring the temperatures of body and environment.

3. Experimental setup and procedure

The experimental setup (figure 1) consists of an Arduino UNO R3 board, a temperature sensor DS18B20, a 10 k\( \Omega \) resistor, a room thermometer, a stove, a computer, a breadboard, Dupont cables and a cup. The working range of the DS18B20 is \( (218.15 \text{ K}; 398.15 \text{ K}) \) and the sensitivity is 0.5 K in the range \( (263.15 \text{ K}; 358.15 \text{ K}) \). The resistor, the breadboard and the Dupont cables could be found in a typical Arduino kit. The sensor temperature must be purchased separately.

The temperature sensor is connected to the Arduino by Dupont cables. The sensor has three cables: the first one to be connected to the GND pin of the Arduino, the second one to the \( V_{cc} \) pin (both the 3.3 or 5 V can be used) and the last one to be connected to a digital one. The resistor is inserted between the digital and the \( V_{cc} \) pins as shown in figure 1. Lastly, the Arduino board is connected to the computer for data acquisition by the USB cable. The cup has been filled with a mass \( m = (9.9 \pm 0.1) \times 10^{-2} \text{ kg} \) (the specific heat of water is \( c = 4186 \frac{1}{\text{kg K}} \)) and has been placed on the stove to be heated. The temperature sensor has been inserted in the cup to measure the water temperature during the cooling.

The water has been heated up to \( T_0 = (349.0 \pm 0.5) \text{ K} \), then it has been left cooling up to \( T_f = (300.2 \pm 0.5) \text{ K} \). To measure the temperature, it has been written a sketch (code) for Arduino. The sketch allows the user to measure the temperature over time. Then, values of time and temperature are printed on the terminal to be analysed.

The environment temperature has been measured by the room thermometer to ensure a constant temperature during the experiment.

4. Data analysis and results

From equation (1), by defining

\[
y = \ln \left( \frac{T(t) - T_{env}}{T_0 - T_{env}} \right) \tag{3}
\]

we get:

\[
y = kt \tag{4}
\]

where

\[
k = -\frac{1}{\tau}. \tag{5}
\]

It follows that, to estimate the time-constant \( \tau \) by measured data, we can assume the linear dependency (equation (4)), interpolate data by it (figure 2(a)) and estimate the time-constant as:

\[
\tau = -\frac{1}{k} \tag{6}
\]

The slope \( k \) resulting by interpolation and the estimated \( \tau \) value are given in table 1.

As expected, in figure 2(b) we observe that after 5\( \tau \) the liquid reaches room temperature.
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Figure 1. Experimental setup.

Figure 2. (a) Data interpolation. (b) Cooling trend up the liquid reaches the room temperature.

| Table 1. Fit result slope and obtained τ value. |
|-----------------------------------------------|
| $k \ (s^{-1})$ | $\tau \ (s)$ |
| $(-9.625 \pm 0.01) \times 10^{-4}$ | $1039 \pm 2$ |

5. Conclusions
In this paper a technique has been presented to measure the Newton’s cooling law time-constant by using an Arduino. The article goal is to encourage teachers to propose the experiment to their students in order to carry on laboratory practice even in this pandemic period. In particular we encourage readers to replicate the experiment changing the body (water in this case) and environment conditions in order to estimate the time-constant for several materials and conditions.
Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

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References
[1] Arduino collaboration 2005 (available at: www.arduino.cc/)
[2] Casaburo F 2021 Teaching physics by Arduino during COVID-19 pandemic: the free falling body experiment Phys. Educ. 56 063001
[3] Pereira N S A 2016 Measuring the RC time constant with Arduino Phys. Educ. 51 065007
[4] Çoban A 2020 Determination of kinetic friction coefficient using an Arduino Phys. Educ. 55 063009
[5] Organtini G 2018 Arduino as a tool for physics experiments J. Phys.: Conf. Ser. 1076 012026
[6] Organtini G 2021 Fisica con Arduino (Italy: Zanichelli)
[7] Vollmer M 2009 Newton’s law of cooling revisited Eur. J. Phys. 30 1063–84
[8] Davidzon M I 2012 Newton’s law of cooling and its interpretation Int. J. Heat Mass Transfer 55 5397–402
[9] Lab2Go collaboration (available at: https://web.infn.it/lab2go/)