BYOD for Physics Lab: studying Newton's Law of cooling with a smartphone

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ABSTRACT

In this paper we discuss a simple and inexpensive method to introduce students to Newton's law of cooling using only their smartphones, according to the Bring-Your-Own-Device philosophy. A popular experiment in basic thermodynamics, both at a high-school and at University level, is the determination of the specific heat of solids and liquids using a water calorimeter, resourcing in many cases to a mercury thermometer. With our approach the analogical instrument is quickly turned into a digital device by analyzing the movement of the mercury with a video tracker. Thus, using very simple labware and the students' smartphones or tablets, it is possible to observe the decay behavior of the temperature of a liquid left to cool at room temperature. The dependence of the time constant with the mass and surface of the liquid can be easily probed, and the results of the different groups in the classroom can be brought together to observe the linear dependence[1].

CCS CONCEPTS

- **Social and professional topics → Computing education → K-12 education**
- **Applied computing → Physical sciences and engineering → Physics**
- **Human-centered computing → Ubiquitous and mobile computing → Ubiquitous and mobile devices → Smartphones**
- **Applied computing → Education → Computer-assisted instruction**

KEYWORDS

Smartphone; computer skills; heat transfer; high-school students; Newton's law of cooling; Physics; thermometer.

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1 INTRODUCTION

STEM education has a remarkable experimental side, which is reflected in laboratory activities both at a high school and at a university level. Such practical experiences are even part of the contents of the national examinations that are compulsory for admission to university in some countries (e.g., Portugal). However, in many schools, students only learn about those experiments through textbooks, without any hands-on sessions during the entire school year. This raises questions about why is the teaching of aforementioned subjects in high-school or in the first year of engineering degrees so theoretical? Why it is so difficult to do lab classes during the school year? O Livro Branco da Física e da Química [8], compiled in Portugal, showed that only 27% of the teachers performed practical/experimental activities in class, essentially focused on the verification of laws or theories with little participation of the students. Methodologies and teaching materials were little diversified and restricted to textbook and blackboard. The evaluation was done mainly from written tests. Lack of resources or facilities was mainly the cause. Similar reasons were adduced in a study in the USA [12].

In this paper we provide a way out when resources are scarce by showing that a smartphone can easily be used to convert an old mercury thermometer into a digital one, through *time-lapse* tracking [11], and study, for instance, Newton's cooling law

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(through *the cooling of warmed water in a natural convection environment, using different water masses and geometries*).

Most teenagers in developed-countries own a smartphone and bring it with them to the classroom, and such a high-tech object is of great use in the lab. The two mobile apps involved are freely available and can be installed in seconds. The equipment used in this experiment is also extremely cheap: a boiler, some beakers, a ruler, a scale and a thermometer. The smartphone autonomously records a time-lapse set of photos [13] that are then analyzed and processed using VidAnalysis Free app [19].

2 CONTEXT

Although in most cases teachers discourage students from bringing or making use of their portable devices, it should be the opposite! Even in companies, the bring your own device (BYOD) philosophy is gaining momentum and employees are now allowed to bring personally-owned devices (laptops, tablets, and smartphones) to their workplace due to perceived productivity gains and cost savings. The same can be applied to the classroom: if one allows the use of the smartphone as an instrument, then 30 instruments (one for each student) become readily available, each of them with over 20 potential sensors.

Experiments making use of the smartphones sensors have been described before [1; 3; 5; 6], mostly analyzing movement by measuring the acceleration or speed of an object. The speed can be retrieved by analyzing –frame by frame– the position of the object recorded in a video, making use of the slow-motion capabilities of high-end mobile phone cameras. In the proposed experiment the approach is different, since we take advantage of a time-lapse app, compatible even with low-end smartphones, with lower shutter speeds, to study events that occur over long periods of time.

The "motion" studied in this work is that of the mercury or alcohol inside the thermometer, thus extending the video analysis methodology to Thermodynamics. This allows an easy study of the Newton's law of cooling, since following the temperature of the system with time becomes an automated task, that frees both students and teacher to other tasks. Newton's law of cooling is an empirical formula, first envisioned by Newton and then formulated by Fourier, who wrote down the equation [20]. Newton's law of cooling states that the rate of heat loss of a body is directly proportional to the difference in temperature between the body and its surroundings, provided the temperature difference is small and the nature of the radiating surface remains the same. This leads to an exponential decrease of temperature of the body with time.

It can be used to introduce students to exponential laws, presenting concepts as the decay constant, the half-life or the mean lifetime [2; 7]. Newton's law of cooling also explains the heating curve of a body, that it is often misrepresented in textbooks as a straight line, as O'Connell notes in his paper "Heating Water: Rate Correction Due to Newtonian" [14]. Newton's law is also used in other thermodynamic matters, such as the comparison of the cooling of solids [2], the influence of a finite reservoir of lower temperature surrounding the object [10; 16], modelling the transient temperature distributions of metal rods heated at one side only [15], or the mechanical equivalent of heat from Joule's experiment [4], but its main use in Secondary Education might be in the study of the specific heat of solids and thermal conductivities [9; 17; 18].

Silva, Precker, Silva and Silva [17] have shown that he specific heat of aluminum can be measured resorting to low-cost materials and making use of the Newton's law of cooling. They immersed a set of aluminum coins into warm water (around 60 ºC) and demonstrated that, by following in time the decrease of temperature before and after inserting the aluminum, it was possible, by extrapolation, to find the change in temperature experienced by both water and aluminum and then use the equation of heat balance to determine the specific heat of the metal.

3 METHODOLOGY

3.1 Theoretical background

The Newton's law of cooling states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the surrounding temperature. This implies that the difference between the initial temperature T_0 and the surrounding air temperature T_{amb} drops exponentially, therefore:

$$T(t) = T_0 + (T_{\mathrm{amb}} - T_0) \cdot \exp(-t/\tau) \quad (1)$$

The time constant τ, characteristic for the object under study, can be written as $\tau = (Mc)/(hS)$, with M the mass of the water (or object cooling), c the specific heat, S the surface of the object and h the convective heat transfer parameter, considered constant and depending only on the medium in which the heat is transferred.

Equation 1 corresponds to an approximate relation since some assumptions have to be valid so that the equation holds. For instance, the object has to be characterized by a single temperature, the temperature of the surroundings has to stay constant during the cooling process, and the internal energy source of the object should be only the stored thermal energy. The former assumptions are easy to fulfill experimentally. But two more assumptions are needed:

For small temperature differences ΔT between the object and the surroundings, the radiative heat transfer coefficient must be constant and the convective heat-transfer coefficient must stay approximately constant during the cooling process. The latter requirement is easier to achieve using steady airflow around objects, i.e., for forced convection.

To calculate the exposed surface, we have considered the flask, a cylinder surrounded by air at room temperature. We have heated water in an electric boiler and videotaped its cooling, changing the amount of water, or the dimensions of the flask. The flasks have a printed scale that can be used to find out the amount of water poured in, but a normal glass and a scale can be used to determine the mass of the cooling water. A ruler can be used to measure the height and diameter of the water cylinder. For each experiment the *M/S* ratio was recorded.

The smartphone is then used to videotape the change in temperature over time, with intervals of 30 seconds (or more), a process that may take up to an hour.

3.2 Equipment

The labware required for the experiment is minimum: a water heater, a flask (or a cup), a thermometer and a smartphone, arranged as shown in Figure 1, using a laboratory stand and clamps.

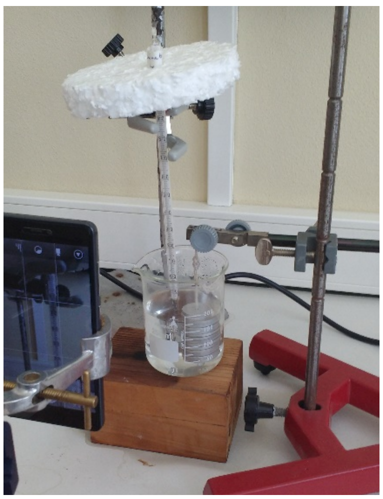

Figure 1: Experimental setup.

3.3 Data collection and data processing

An Android (v5.1.1, Lollipop) smartphone (Moto G 3rd gen, CPU Quad-core 1.4 GHz Cortex-A53, GPU Adreno 306, 8 GB internal storage, 1 GB RAM) with a 13 MP primary camera (f/2.0, autofocus, dual-LED flash) was used in the experiment. Two free apps were installed from Google Play, namely Framelapse-Time Lapse Camera [13] and VidAnalysis Free [19].

The first app lets one shoot time lapse videos, and it ditches simplicity for manual camera settings and controls. The interface looks just like a regular camera app, with all the controls available upfront (there are options to choose the video resolution from a wide range of 144p to 1080p, along with bitrate settings; to select a suitable frame interval speed and to choose custom video duration options; and to adjust white balance setting, camera focus, filter effects, exposure compensation and self-timer options), so the student can have a good control over what he/she is shooting. In our study, a 30 s frame interval and macro auto-focus mode were chosen, leaving all the other options unchanged. Other popular alternatives, such as Microsoft Hyperlapse Mobile or Lapse It-Time Lapse Camera were discarded in this case, because the former only offers video speeds from 1× to 32×, and in the latter most of the features can be only accessed in the Pro version.

The second app (VidAnalysis Free) was used to track the position of mercury in the thermometer. The time-lapse video sequence was loaded from the gallery into the video analysis tool. The app first requires the setting of an axis system and a length scale (indicating the value in degrees between 0 ºC and 90ºC is the recommended approach) before the user can start the tracking of the mercury position through screen touching, frame by frame, generating a position versus time graph (see Figure 2). It should be noted that, if a tablet is available, it would be the most recommendable option at this stage, since the larger screen leads to higher precision when touching on the thermometer positions. When all the frames have been processed, the app shows several graphs and allows to easily export the data into a .csv file.

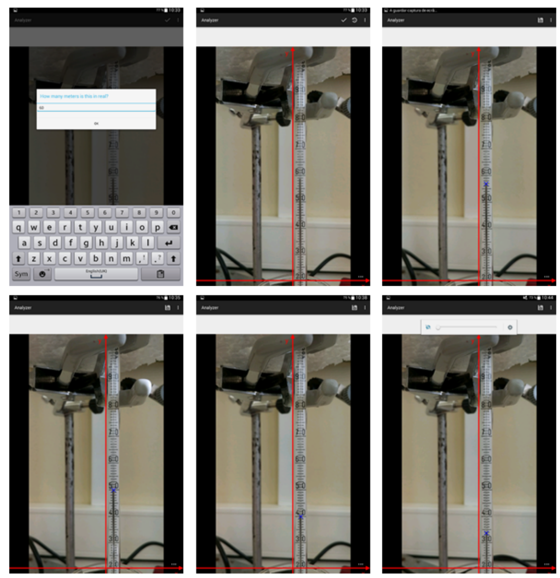

Figure 2: Use of VidAnalysis to track the temperature change: definition of length scale, definition of axes and tracking of temperatures (blue × sign)

The .csv file can then be transferred to a computer to process the data using OpenOffice Calc (or Microsoft Excel) or it can be processed directly in the smartphone using Google Sheets app (other popular free apps cannot open .csv files). Regardless of the chosen procedure, the timescale needs to be updated (using the same interval chosen for the time lapse recording) and an offset in the temperature may need to be added (if the beginning of the length scale was not zero in VidAnalysis). Data plotting results in an exponential decay curve, as indicated above.

The final step involves putting together the τ values obtained by the different groups, plotting them as a function of the *M/S* quotient and fitting them to a straight line.

4. RESULTS

Results obtained using various flask sizes and water volumes are summarized in Table 1.

Table 1: Water mass, flask details and τ values for different experiments.

Sample	M (g)	Flask radius (cm)	Flask height (cm)	S (cm^2)	M/S	τ
#1	47	2.05	3.5	71.49	0.657	$1.58 \cdot 10^3$
#2	71	2.05	5.15	92.74	0.766	$1.93 \cdot 10^3$
#3	97	2.05	7	116.57	0.832	$2.38 \cdot 10^3$
#4	95	2.8	4.2	123.15	0.771	$1.93 \cdot 10^3$
#5	139	2.8	6	154.82	0.898	$2.55 \cdot 10^3$
#6	175	3.4	5.8	196.54	0.890	$2.32 \cdot 10^3$
#7	191	3.4	6.3	207.22	0.922	$2.51 \cdot 10^3$

If the characteristic (response) time values are then plotted as a function of M/S, the different experiments can be fitted to a straight line ($y = 3693.7x - 855.76$) with R^2=0.93, as shown in Figure 3.

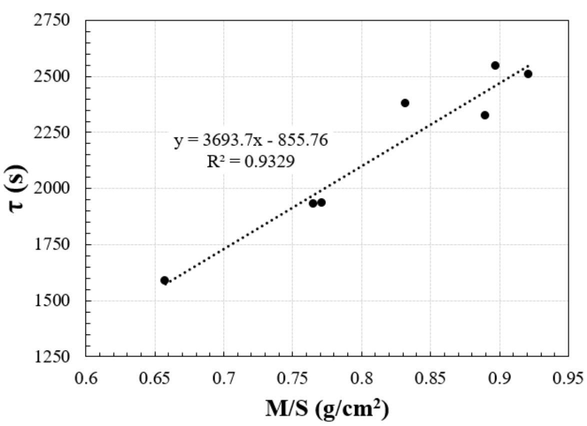

Figure 3: Plot of the characteristic time values *vs.* the *M/S* quotient for different water masses and flask sizes.

4.1 Further analysis and alternative procedures

An interesting extension of the experiment would consist in using other liquids (e.g., alcohol or kerosene, see Figure 4) to highlight the differences in their response times associated to their different specific heats. Given the difficulty in determining h (the convective heat transfer parameter), obtaining their actual specific heat values could be complicated, but a comparative analysis with water is straightforward.

The same recording and analysis procedure could also be used to determine the specific heat of different metals, as in the paper by Silva, Precker, Silva and Silva [17]: if a piece of metal at room temperature is plunged into hot water, there will be a sharp transition in the temperature decay curve, and it is possible to determine the value of c from it.

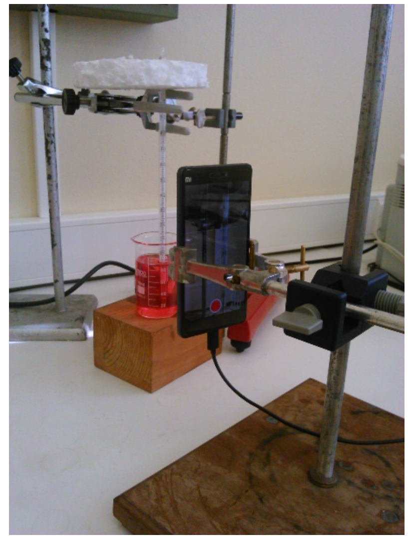

Figure 4: Experiment with kerosene.

5 CONCLUSIONS

We have shown how a smartphone's camera with a time-lapse app and a video analysis app that run on Android OS can be used to track the change in temperature of a liquid in a simple and inexpensive way, providing high-school students with a valuable insight into motions that do not belong to the realm of kinematics.

The proposed novel experiment makes use of common lab or household ware and transforms a slow experiment into an automated data collection. The analysis of the data with a video tracker immediately outputs the data in a digital form, that can be easily manipulated with a spreadsheet if more calculations are intended. We propose a collective effort with many groups working simultaneously to extract the variation of the time constant of the temperature decay, changing the mass and surface of the water.

The experiment is not only extremely easy to perform but can also be easily upgraded to fit the syllabus of the Physics current high-school courses, just as the measurement of the specific heat of some metals (aluminum, copper, lead, etc.).

The proposed activity is oriented towards the students' preferences, provided that 2 out of 3 students prefer to use their own mobile device for learning.

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