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The kickstart of the age of the Earth race: revisiting the experiment of the Comte de Buffon at school

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Abstract

In this work, the first experiment ever done to determine the age of the Earth is revisited. The benefits of its application at primary and secondary school levels are presented and discussed. In particular, emphasis is placed on the advantage of facing students with the challenges that scientists have had to overcome during the past three centuries to reach our present knowledge in contrast to the mere transmission of the latest facts.

1. Introduction

In *Demon Haunted World: Science as a candle in the dark* [1], Carl Sagan discusses the benefits of letting children learn '*how we know*' as early as possible, and proposes the implementation of learning schemes that incorporate hands-on experiences to gain a vivid perspective of the scientific method. This represents a constructive alternative to the simple memorization of authoritative pronouncements and procedures that introduce the scientific method in terms of a number of rigid steps that need to be followed. The main shortcoming of the latter is that the historical development and the evolution of novel ideas, via their generation and evaluation in an overall critical thinking procedure, do not permeate the students' conception of science. In consequence, and despite the increasing amount of initiatives to improve science education worldwide, many students walk towards their adult phase retaining a spontaneous geniality conception of science.

Nowadays, there seems to be general agreement among science education researchers that long-lasting learning is associated with an active role performed by students [2, 3]. The main challenge of this perspective, though, lies in the way it is put into practice [4]. In this sense, joint efforts from scientists and educators are needed to delineate learning schemes not only rich in concepts but also in scientific competences [5].

Among other topics, one that clearly reflects these statements is the determination of the age of the Earth. By 1650, Archbishop Ussher gave the first number based on biblical chronology. Taking the death of the Babylonian king Nabucodonosor in 562 BC, a historical fact registered in the Bible for which precise dates were known at that time, he counted back the 139 generations mentioned in the Old Testament to provide October 22, 4004 BC as the birth date for the Earth.

During the second half of the XVIII century, Georges Louis Lecrerc, also known as Comte de Buffon, decided to put into practice a thought experiment initially proposed by Sir Isaac Newton in the previous century. By assuming an initial Earth consisting of melting iron and by studying the cooling time of iron spheres of different radii, he obtained a linear dependence between these variables which allowed a direct extrapolation to the Earth's radius. The figure obtained by Comte de Buffon for the age of the Earth of 74832 years was very far from the presently accepted value but represents the first attempt to face the problem from a scientific point of view. The advance of thermodynamics during the XIX century, and in particular the work of William Thomson (later known as Lord Kelvin), provided a more complex description of all possible mechanisms mediating the Earth's cooling. Kelvin also started to consider an initial molten Earth that cooled down to form a solid crust but still retained a hot core. Moreover, he proposed that most of the Earth's heat originated in gravitational contraction. Admitting to large uncertainties in heat conductivities, specific heat capacities of rocks, and the latent heat of fusion, his figures for the age of the Earth by 1890 ranged from 20 to 400 million years. Meanwhile, based on their empirical evidence, geologists and biologists (who relied on geochronology to date their fossils) had serious concerns about these values since they presented a very short-lived Earth. However, the tool they had at hand, sedimentation rates, can be strongly affected by climatic factors like floods, rendering the estimation of a precise figure difficult. As a result, a strong debate took place for nearly 50 years [6, 7].

Drastic change took place in 1896 when Henri Becquerel discovered radioactivity. Two years later, Marie and Pierre Curie detected the radiactive elements polonium and radium. A new source of heat for the Earth had been discovered and had to be incorporated into physical models. The XX century saw a continuous refinement of radioactive dating techniques. In 1956, Clair Patterson dated the lead content in several meteorites which led to the presently accepted value of 4.55×10^9 years for the age of the Earth [8].

This work presents an activity designed to highlight the first idea pushed by humanity in order to determine the age of the Earth by scientific means. The focus is on letting primary and secondary school stage students explore by themselves the experience performed by Comte de Buffon and analyze the benefits and limitations of extrapolation procedures at an early stage. Activities are conceived in order to use their respective mathematical backgrounds as potential tools, allowing in this sense for an interdisciplinary approach to the topic.

The present activity stems from a new design of the natural sciences curricula for primary school which is being developed in a joint collaboration between scientists of the Physics and Chemistry departments at the Universidad Nacional del Sur and the staff of educators at Colegio Victoria Ocampo in Bahía Blanca, Argentina. This project has been endorsed by the Regulatory Education Board of the Province of Buenos Aires, Argentina.

In the next section, we present the physical background of the experiment. In section 3, we present the experiment and discuss the obtained results and suggest implementation schemes for primary and secondary school. In section 4 conclusions are drawn.

2. Theoretical background

In this section, we perform a thermodynamical analysis of the experience performed by Comte de Buffon. Based on the fact that metallic spheres are highly conductive media, their inner temperature T is considered homogeneous provided that the inner heat flow is much larger than the outer heat flow. As a result, the ratio of the outer heat flow to the inner heat flow, a dimenssioneless quantity known as the Biot number, is a very small number [9]. If the spheres are placed in air, convection and radiation are the only mechanisms involved in heat transfer from the object to the surroundings. Thus, the energy rate equation for the system can be expressed as

$$mc\frac{\mathrm{d}T}{\mathrm{d}t} = -\dot{Q}_{\mathrm{conv}} - \dot{Q}_{\mathrm{rad}}. \qquad (1)$$

In this equation, m is the mass of the object, c is the specific heat (assumed constant), $\mathrm{d}T/\mathrm{d}t$ is the variation of temperature due to heat loss, $\dot{Q}_{\mathrm{conv}}$ is the heat flow per second from the object to the surrounding air and $\dot{Q}_{\mathrm{rad}}$ is the net rate of energy gained or lost by the object as a result of radiation.

The convective term is usually parametrized as follows:

$$\dot{Q}_{\mathrm{conv}} = \alpha_{\mathrm{conv}} A \left(T - T_{\mathrm{surr}}\right).$$

Here α_{conv} is the heat-transfer coefficient for convection from the object to the surrounding air, A is the object area and T_{surr} is the surrounding temperature.

For the radiative heat flow, we consider the Stefan–Boltzmann law,

$$\dot{Q}_{\mathrm{rad}} = e\sigma A \left(T^4 - T_{\mathrm{surr}}^4\right)$$

where ε is the emissivity of the object and σ is the Stefan–Boltzmann coefficient.

Keeping in mind that the object is a sphere of volume V and area A, their ratio ${}^{V}\!/_{A} = {}^{r}\!/_{3}$ and equation (1) can be written as a non-linear differential equation:

$$\frac{\rho\, c}{3}\frac{\mathrm{d}T}{\mathrm{d}t^*} = -\alpha_{\mathrm{conv}}\left(T - T_{\mathrm{surr}}\right) - e\sigma\left(T^4 - T_{\mathrm{surr}}^4\right). \qquad (2)$$

Here ρ is the density of the object and t^* is defined such that $\mathrm{d}t^* = \frac{1}{r}\mathrm{d}t$. Equation (2) then provides a unique relation between the object temperature and t^*, without any explicit dependence on the geometry of the body under study. From here we deduce that the time lapse t_{cool} that takes the system to cool down from an initial temperature T_0 to a determinate temperature T_1 increases linearly with the radius of the sphere, as initially suggested by Newton back in the days when caloric theory was in vogue. It should be noted that this result is independent from Newton's law of cooling which can be recovered for small temperature differences after a series expansion of the Stefan–Boltzmann law [8].

3. Revisiting the Comte de Buffon experiment

The setup used for this experience has been conceived to allow primary and secondary students to carry out the whole procedure by themselves. The design of our final setup has been constrained by the need of multiple kits, quick replacement, wide availability, typical school times and safety considerations. It consists of four hollow plastic Christmas baubles filled with water saturated sand with diameters of 5, 6, 7 and 8.5 cm respectively. A hole has been drilled in each of them to allow the introduction of sand and digital thermometers. A black paint finish has been used in the exterior as shown in figure 1.

Once the spheres are completely filled with dry sand at room temperature, warm water at about 75 °C is carefully poured until the water level comes to the top. Supervision by the educators in charge is strongly encouraged at this point to prevent hot water burns. To thoroughly test the physical correspondance between the present experience and that performed by Buffon we have digitally acquired the data provided by a set of eight fast response thermocouples.

In the first instance, we test the thermodynamical properties of our setup as the thermal conductivity k of water-saturated sand is much smaller than that of iron and exhibits a transitory behavior. In figure 2 we show the temperature of the four spheres recorded as a function of time. This time lapse is recorded starting at the instant the warm water is poured into each sphere. In order to check the time at which an homogeneous inner temperature is reached, a set of two thermocouples is used for each sphere. One thermocouple is set at the inner bottom point and the other is set at the center by means of a wooden stick. Readings from both thermocouples tend to agree after a transitory regime with the exception of the smaller sphere considered here for which a small departure between readings stands after 1.7 h. We have corroborated this trend by using a 3 cm diameter bauble (not shown) which was much more difficult to operate due to reduced dimensions.

A common feature to all bauble sizes explored is that temperature readings from the thermocouples located at the center of the spheres decrease monotonically, while those located at the bottom follow an increasing behavior at short times, reach a maximum value and finally exhibit a monotonically decreasing behavior.

Provided that our main objective is to prove that cooling times increase linearly with the sphere radius, and considering that this result does not depend on the temperature interval considered, we have concentrated on the 35 °C–30 °C range, which is feasible in terms of school times, is burn-risk free, and assures that the obtained measurements are meaningful in thermodynamical terms provided that the inner temperature can be considered approximately uniform.

Figure 3 shows the registered cooling time for the thermocouple located at the center of each sphere as a function of its diameter. The least-squares fitting procedure shows that the recorded data follow a perfect linear relationship. The explicit expression is given by t_{cool} (h) $= -0.303$ (h) $+ 0.126$ (h cm^{-1}) $* \, d$(cm). The surrounding temperature at the time our measurement took place was $T_{\text{surr}} = 24.9$ °C.

It should be noted that that the present setup allows an extrapolation towards larger but not smaller radii, provided that the linear extrapolation predicts $t_{\text{cool}} = 0\,\text{h}$ for $d = 2.48\,\text{cm}$.

3.1. Primary school (ages 6–11)

For sixth-graders (~11 years old) we encourage educators to bring to class graph paper with Cartesian axes for t_{cool} and d with numeric legends already marked on them. In addition, measured cooling times should be expressed in hours (up to two digits) to ease the registration of the resulting ordinate pairs on graph paper with millimeter divisions.

Digital probe cooking thermometers are expected to be used in the classroom instead of the present set of thermocouples. Since one probe is expected to be used per bauble, the main challenge for the educator in charge of the activity is to determine the optimal temperature range for their setup. Based on the physical trends shown in figure 2, we focus on the smallest bauble (the one that cools faster), locate the thermocouple at the inner bottom point, and take as our upper temperature T_0 the temperature reading at $t_0 = 5t_{\max}$, $t_{\max}$ being the time at which the maximum temperature is reached at that specific point. In our case, $t_{\max} = 270\,\text{s}$, $t_0 = 1350\,\text{s}$ and $T_0 = 35$ °C. The final temperature T_1 is arbitrarily considered 5 °C below T_0 to avoid pushing the temperature readings extremely close to T_{surr} which would involve a prohibitive amount of time.

The proposed activities for this level are:

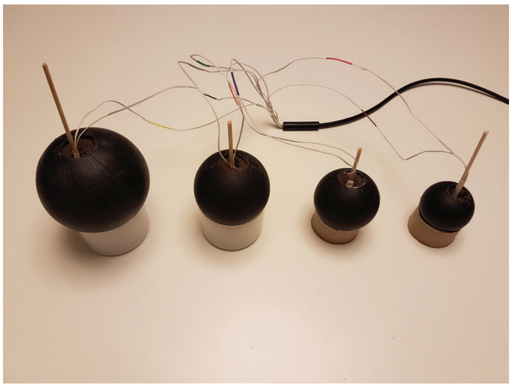

Figure 1. Experimental setup employed of four plastic Christmas baubles filled with saturated sand.

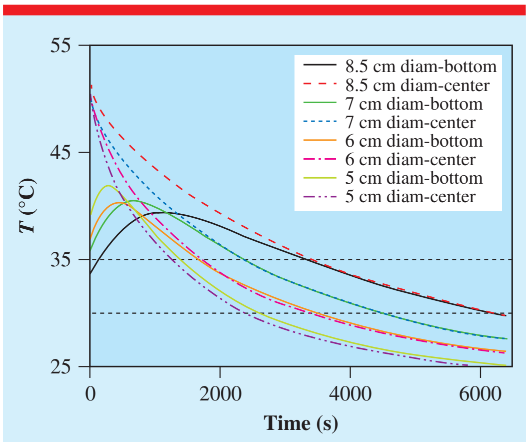

Figure 2. Temperature of the spheres as a function of time. Measurements with the present setup are considered meaningful in temperature ranges at which readings from the thermocouples at the bottom and the center of the baubles are in agreement.

- The direct measurement of the diameters of spheres by means of calibers or their perimeter with measuring tapes. The latter is a viable option only if the concept of perimeter has been previously introduced and can be used to obtain the radii of the spheres.
- The direct measurement of cooling time (in seconds) for the baubles to go from T_0 to T_1 by means of digital chronometers.
- The conversion of time readings from seconds to hours.
- The registration of cooling time (in hours) for the different diameters/radii (in cm) in the graph paper.
- The graphical interpolation of points by means of a ruler (i.e. drawing of a line providing the closest visual agreement to all registered points).

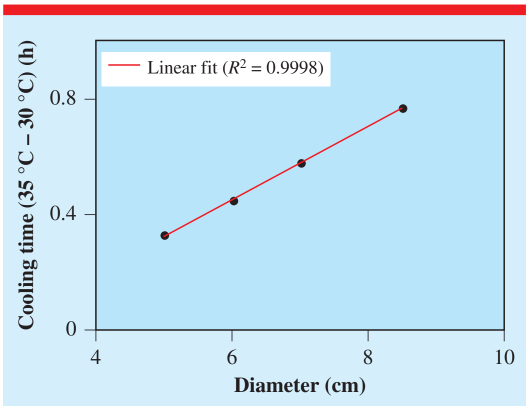

Figure 3. Cooling time interval needed for the system to go from 35 °C to 30 °C as a function of the diameter of the spheres.

Table 1. Cooling times corresponding to the temperature interval 35 °C–30 °C as a function of the diameter of the spheres. $T_{\mathrm{surr}} = 24.9$ °C.

Diameter (cm)	Cooling-time (h)
5	0.33
6	0.45
7	0.58
8.5	0.77

- A graphical extrapolation to a larger *d*-value that fits into the graph paper legends.
- The determination of the extrapolated cooling-time from this graphical representation.

The result of the proposed classroom sequence for the present data (see table 1) is depicted in figure 4. We have included the result of our graphical extrapolation for the cooling time corresponding to a sphere with a diameter of 15 cm which is about 1.59 h. The extrapolation to the Earth's diameter is not feasible at this level and is not our objective. Instead, the focus is on understanding the overall underlying procedure for the first approach to the problem.

3.2. Secondary school (ages 12–17)

For this level, the line equation can be estimated from the graphical interpolation. The graph paper can be replaced by spreadsheets. With this tool at hand, the extrapolation to diameter sizes which largely exceed the range used in the graph paper (or spreadsheet) is feasible and turns the extrapolation procedure into a simple mathematical exercise. For the present set of data, our least-squares fitting procedure predicts that it would take 18667 years for an Earth consisting of water-saturated sand to cool down from 35 °C to 30 °C.

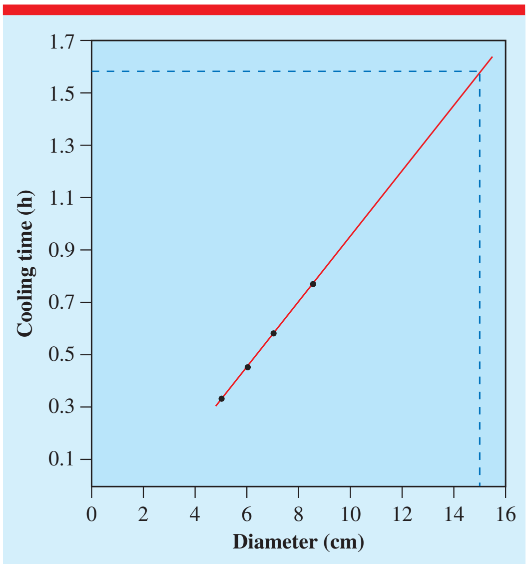

Figure 4. Graphical extrapolation procedure proposed for primary school applied to the present set of data. The graph paper grid lines have been omitted for visualization purposes.

Another point worth exploring at this level is the introduction of the 'physical model' as a simplified representation of reality for which the validity range needs to be determined. For instance, the present linear behavior seems to be representative of what has been observed for the spheres radii explored, and it can in principle be extrapolated for larger spheres but it would certainly fail for smaller radii.

4. Conclusions

In this work we have presented an activity based on the Comte de Buffon's experiment specially designed for primary and secondary school levels. The purpose of the activity is twofold. On the one hand, it allows an overview of the time lapse that it took humanity to figure out the age of the Earth, and the evolution of ideas, disputes and scientific advances that improved our knowledge in the meantime. On the other hand, it lets students experience by themselves all the stages of the first experiment ever tried to determine the age of the Earth. In fact, this experience can be used to highlight the fact that complex questions on nature are frequently tackled in an initial approach by invoking simple physical models which, as in the present case, can be simple enough to allow their exploration in the classroom context. In addition, this experience gets students familiar with the extrapolation procedure in a very early stage of their instruction.

Even though the proposed setup is a risk-free adaptation of that employed by the Comte de Buffon, we have checked that at the temperature range explored it can be considered conceptually correct from the thermodynamical point of view. In this sense, all the main ingredients of Buffon's procedure and analysis remain intact and will hopefully provide a memorable experience for students to recall in future years.

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