Deviation from the mean in teaching uncertainties

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Deviation from the mean in teaching uncertainties

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Abstract
In this work we present two simple and interactive web-based activities for introducing students to the concepts of uncertainties in measurements. These activities are based on the real-time construction of histograms from students measurements and their subsequent analysis through an active and dynamic approach.

1. Summary

We present two quite simple, but instructional and real-time, activities that aid in introducing students to the concepts related to uncertainties in direct measurements in a *hands-on* approach. As is well known, this topic is particularly important in general physics courses and has been revisited many times [1–5], however, students find these lessons boring [3]. In this context, the approach described here has shown to motivate students and make them curious about uncertainties, since they feel actively involved during the development of the proposed experiences. These activities are based on the real-time construction of histograms and their subsequent analysis to shine light on the characteristics of the measurement process.

2. Background of experiences

The first requisite of the proposed experiences is to select a physical quantity to be measured directly and easily. The second requisite is that the selected quantity should be measured each by a single student (ideally at the same time, so as not to take up too much lesson time). In this context we have found the period of a simple pendulum to be a good candidate, but there might be others as useful as this one. Once the physical quantity to be massively measured by students has been chosen we need a measurement instrument. For time measurements (as for the pendulum's period, which we adopt here) smartphones are difficult to beat, since we can be almost completely sure that all students will have one at hand.

The last and important requirement is a real-time platform allowing one to register each single measurement performed by students in an efficient manner. If smartphones are used as measuring instruments, we have found Google® Forms to be a great ally for this task [6]. These web-based forms can be easily constructed *ad hoc* and accessed through smartphones. Moreover, these forms are automatically linked to a Google® Docs spreadsheet, which we will exploit for our experience. A simple form, as that shown in figure 1(a), with a single text field to introduce the measured value is more than enough, and real-time construction of a histogram from the registered values is straightforward. In figure 1(b) we show a screenshot of the spreadsheet containing real data ($n = 20$) collected during the experience and the obtained histogram.

We must say something regarding the nature of the measurement process and how to deal with some deviations of these experiences with respect to theoretical aspects. A set of n measurements of some

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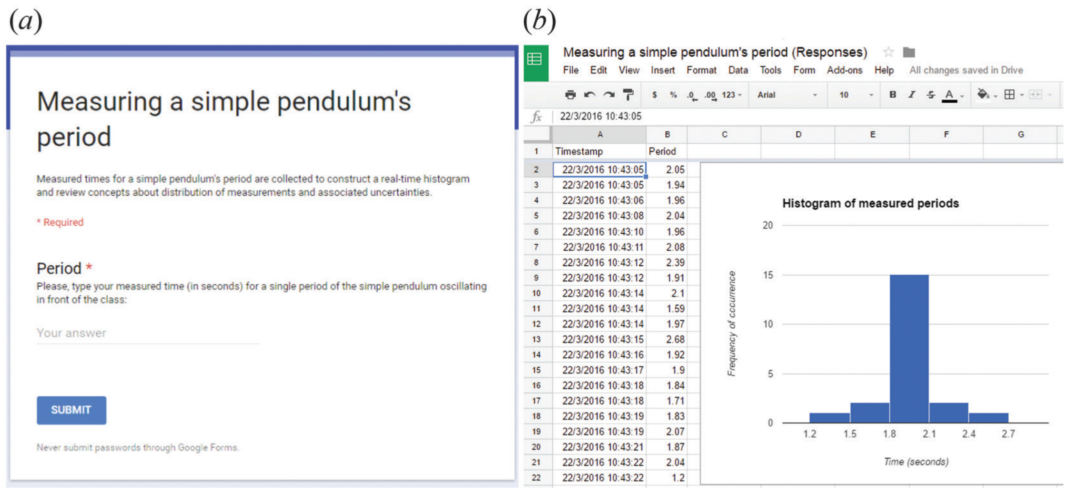

Figure 1. Screenshot of (a) a simple *ad hoc* web form created for students to introduce their single results of a direct measurement and (b) the linked spreadsheet used to show the construction of the histogram in real time.

physical quantity should be ideally performed by a single operator, under the same conditions and with the same instrument, while here a set of n students (operators) will perform a single measurement of that quantity with different instruments. Moreover, most probably in this case, students will not measure the period of exactly the same oscillation of all those the pendulum performs during the measurement process and reaction times of all them also differ. Therefore, the conditions are not the same for each student's measurement and the resulting n values are by far not equivalent to the theoretically expected n values (i.e. measured by the same operator, under the same conditions and with the same instrument). However, this can be a strength if one considers that the employed methodology (i.e. many operators, measuring with different instruments) reduces systematic errors (e.g. reaction time becomes random) and, therefore, improves the measurement process. Despite the influence of all these aspects, which are briefly addressed and discussed with students prior to the experiences, the achievable results are really useful from a didactic and pedagogical viewpoint since students get down to work in an active learning environment that helps them shine a light on the usually obscure realm of measurement's uncertainties in the physics laboratory.

3. First experience: real-time histogram construction from single measurements

A simple pendulum is located in front of the class and set to oscillate with a small amplitude. Students are asked to use their smartphone's chronometers to measure just one period (T) of the oscillation. Then they access the form to enter their measurements and observe how the empty histogram projected on the screen starts to grow. Once everybody is done, the characteristics of the obtained histogram are highlighted and discussed. Concepts such as *mean value*, *standard deviation* or criteria for *data rejection* can be fruitfully and visually addressed in this way.

In figure 2(a) we show a complete histogram obtained during a real class with $n = 53$ students. The shape of the obtained distribution was quite similar to a Gaussian one (shown superimposed on the graph) and the real-time nature of the experience really motivated students. Exploiting the statistical tools provided by the spreadsheet, we calculated right on the way the *mean value* and the *standard deviation* (σ_{n-1}) of the resulting distribution, obtaining a value $T = (1.91 \pm 0.28)$ s. The concept of *standard deviation of the mean* (also called *standard uncertainty* or *standard error*), which in general is obscure and difficult for students to understand, was introduced here and discussed with the class. This value ($=\sigma_{n-1}/\sqrt{n}$) yielded $T = (1.91 \pm 0.04)$ s. The concept of *standard deviation of the mean* is reviewed during the second experience detailed in the next section.

It is worth noting that data acquisition during this experience lasted only around 4 min, while students were able to dynamically see how the histogram was constructed. We arranged the 3D graph presented in figure 2(b) to show the histogram's time evolution (time axis not to scale).

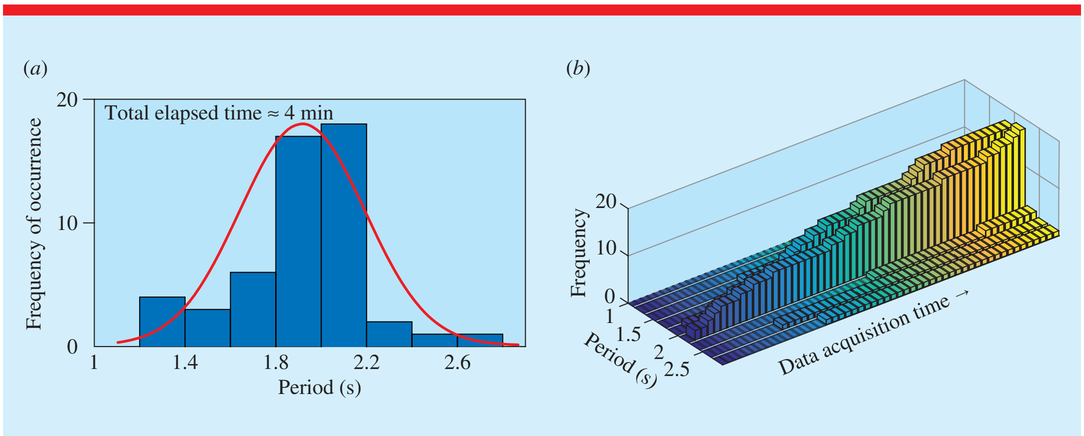

Figure 2. (a) Complete histogram of a simple pendulum's period obtained during a real class with $n = 53$ students (Gaussian fitting superimposed on the graph); (b) time evolution of the histogram (time axis not to scale).

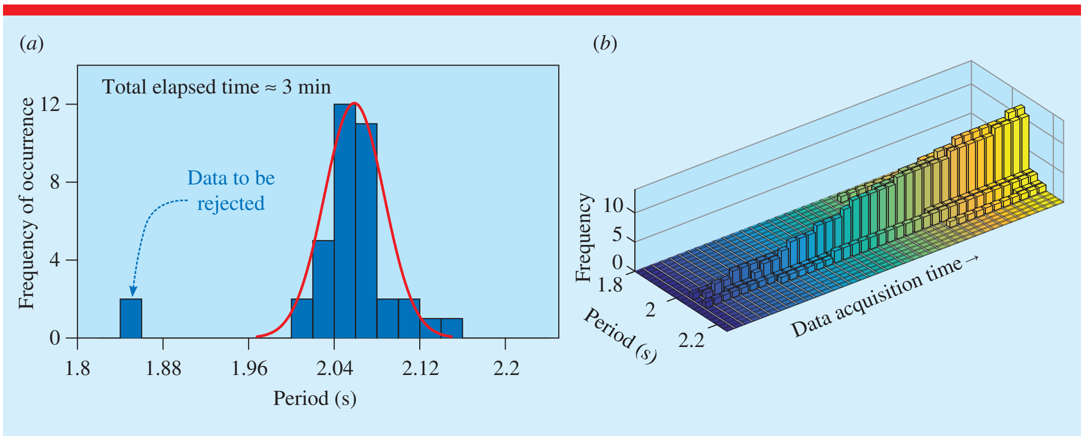

Figure 3. (a) Complete histogram of a simple pendulum's mean period obtained during a real class with $n = 38$ students measuring the mean of ten periods (Gaussian fitting after data rejection, with $n = 36$, is superimposed on the graph); (b) time evolution of the histogram (time axis not to scale).

4. Second experience: real-time histogram construction from mean values

The second experience consisted of each student measuring ten periods and determining a mean value for the pendulum's period. These n values were thus used to construct a new real-time histogram, but now of *mean values*. Subsequently, a debate about the difference between *standard deviation* (σ_{n-1}) and *standard deviation of the mean* (σ_m) was promoted.

From students' measurements ($n = 38$) we obtained the respective histogram with $T = (2.05 \pm 0.05)$ s, shown in figure 3(a). The time evolution of the histogram as data were collected is shown in figure 3(b) (time axis not to scale). As students could clearly observe, the histogram was narrower this time and analysis of data rejection became quite obvious. After rejecting the two average periods below 1.9 s, the resulting period was corrected to $T = (2.06 \pm 0.03)$ s. The Gaussian curve shown in figure 3(a) was obtained after this rejection. Two important and non-trivial facts about uncertainties related to measurements were remarked here, namely: that *not always* by *considerably* increasing the number of measurements one gets a result with *significantly* lower uncertainty and that most mean values obtained by students differ from the resulting average mean values ($T = 2.06$ s) by less than the *standard deviation of the mean* ($\sigma_m = 0.03$ s) obtained by the whole class.

5. Conclusion

The activities described here exploit the use of simple and effective web-based forms, accessible through smartphones, which allows students to observe in real time the construction of histograms of direct measurements made by themselves. In this way, students are actively involved in their own process of learning and motivated to discuss the relevant concepts related to measurements and associated uncertainties, such as Gaussian distribution, mean value, standard deviation, standard deviation of the mean and effectiveness of increasing the number of measurements.

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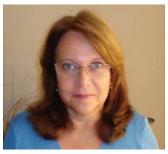

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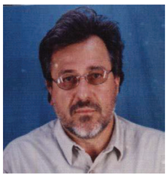

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