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Article

The Need to Reinforce the Teaching of Basic Descriptive Statistics Required in Reporting Quantitative Laboratory Results: Diagnose of Common Students' Misconceptions

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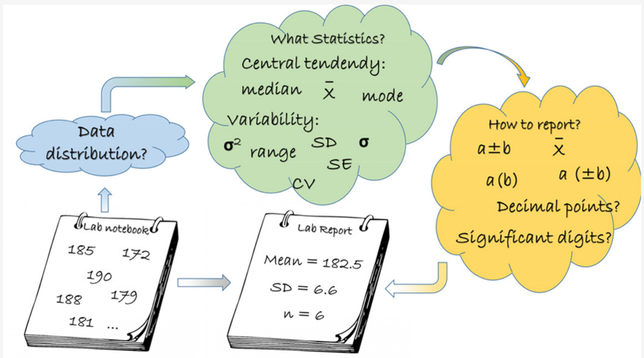
ABSTRACT: Descriptive statistics involves summarizing and organizing data so that they can be easily understood. Even though these are basic and simple concepts, many applied science students have misconceptions about their use in applied experiments in the laboratory. Students usually receive limited or no training in how to understand the meaning of the results obtained from statistical calculations, which leads students, and often even researchers, to assume that statistics are just the ability to count and use formulas with an appropriate software. In this study, students were interviewed after doing an exercise devoted to calculating the descriptive statistics required for some experimental results obtained in the laboratory. This has allowed us to find out the most common misconceptions held by students and has helped to develop a methodology to reinforce descriptive statistics concepts within laboratory lessons, which has been demonstrated to be helpful for students to improve the required descriptive statistical skills in scientific degrees.



KEYWORDS: *Audience: First-Year Undergraduate, General, Second-Year Undergraduate, Domain: Interdisciplinary, Pedagogy: Communication, Writing, Misconceptions, Discrepant Event, Topic: Chemometrics*

The main purpose of a laboratory report is to summarize and disseminate the data obtained within a set of experiments.[1] The design of most quantitative laboratory lessons in chemistry degrees requires students to report the description of the data they have obtained from the analysis of independent replicates of a sample.[2−9] Students must learn during their training that before trying to draw any conclusion from their experimental results, they should begin by calculating the appropriate descriptive statistics of a data set, which will allow them to summarize and describe the characteristics of the data set and to understand the data better. They must also understand that "descriptive statistics do not allow us to make conclusions beyond the data we have analyzed or reach conclusions regarding any hypotheses we have made".[10] It is also important that students learn that when a quantitative result is reported, it is necessary to determine how precisely it must be specified (i.e., how reliable the results are).

Inferential statistics should not be applied at this preliminary stage as inference is required for calculating estimates about populations, which allow to make generalizations about the populations (not the sample), and in testing hypotheses. Despite the difference between descriptive and inferential statistics being simple from a theoretical point of view, practically all undergraduates and even some researchers have difficulty differentiating between them in the evaluation of their experimental data and in understanding when one or the other must be applied. One clear example is the common misconception found in many research articles that standard error (SE, many times called SEM, standard error of the mean) is appropriate to express variability in a set of results when in fact standard deviation (SD) should be used.[11−16] The SE is an inferential statistic that measures the uncertainty in an estimate (usually the sample mean), but it tells us nothing about sample dispersion and, therefore, should not be used as an indicator of the variability between observations.

■ PROBLEMS OF POOR STATISTICAL REPORTING

In the 1960s, Yates and Healy in a discussion of statistical misconceptions held by many scientists and the need to reform the teaching of statistics in science degrees wrote "it is depressing to find how much good biological work is in danger of being wasted through incompetent and misleading anal-

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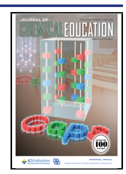

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ysis".[17] Despite the time elapsed, articles today in many scientific fields still contain errors in the application, analysis, interpretation, and reporting of statistics, and studies with major errors in these respects continue to pass editorial and peer review.[11,18] The IUPAC has also reported that the value of much published work on chemical analysis is diminished by the lack of a generally accepted system of reporting numerical results.[19]

The problem of poor statistical reporting is long-standing and, surprisingly, most mistakes seem to be in the use of basic rather than advanced statistical methods.[18,20,21] This may be due to shortcomings in the cursory education in statistics typically received at undergraduate level in experimental science degrees.[22] It has to be taken into account that the concepts related to descriptive statistics are usually introduced in secondary school courses.[23,24] This introductory lessons are largely descriptive, explaining the concepts from a general point of view, and students are usually only taught about the definitions and the mathematical formulas required to obtain a numerical result,[24] but receive limited practice in understanding their meaning in applied laboratory experiments because the topics explained do not usually address the specific needs of the applied science degrees (e.g., to work with small data sets and the inherent variability associated with laboratory measurements),[25,26] which will allow students to deal correctly with experimental data sets in a rational manner.[23,24] As a result, students assume that statistics is just the ability to count and use formulas with an appropriate software.[24] Unfortunately, during undergraduate formation, these concepts are usually taken for granted and, therefore, neglected rather than being emphasized and reinforced.[24,27] Another common problem is that most lecturers in nonstatistics degrees have not received a specific preparation in statistics and, therefore, can share some of the common reasoning biases and widespread misconceptions about statistics.[28] It has to be taken into account that although many scientists not needing to be experts in statistics, they should understand the principles of sound research methods.[29] The process of scientific discovery does require a good understanding of basic concepts in statistics, and misconceptions usually derive from incorrect statements about them.[30]

In general, there is a need to reinforce basic statistics for many science undergraduates, which has already been reported that can help students developing those skills required in analyzing results of laboratory measurements.[24,31] As in the construction of a building, it is important to have good and strong foundations in descriptive statistics before advancing. The main objective of this study is to demonstrate that many students have significant misconceptions about descriptive statistics. These misconceptions can be solved by applying, within laboratory lessons, a reinforcement methodology that allows students to develop the statistical skills required with their experimental results and to understand why the chosen statistics are the most appropriate for a specific set of data. It will help students obtain a better understanding of this topic and make proper decisions in reporting their experimental results.

BASIC DESCRIPTIVE STATISTICS CONCEPTS FOR APPLIED LABORATORY EXPERIMENTS

The first thing to be introduced is that descriptive statistics are divided into three main categories: measures of distribution, measures of central tendency, and measures of variability (precision) (Figure 1). However, the distribution is usually not taken into account in the case of chemistry lessons dealing with the need to teach students descriptive statistics, and many

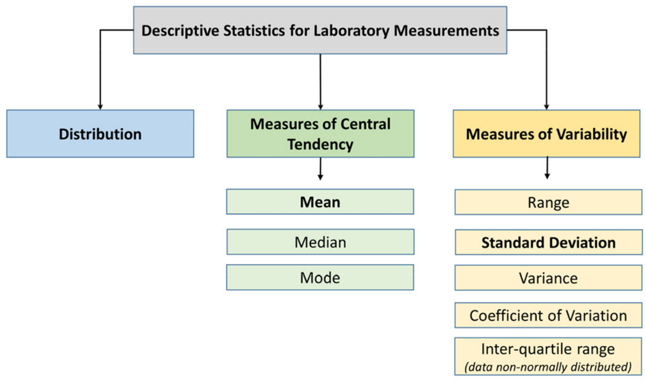

Figure 1. Scheme showing the descriptive statistics that should be introduced to students. In bold are marked the statistics for the central tendency and variability assuming a normal distribution.

authors usually only consider the measures of central tendency and variability that corresponds to normal distributions,[2−9] without explaining to the students the criteria that justify the assumption of this distribution with small data sets. In these conditions, the mean and the sample SD are taken as the only descriptive statistics to be explained. Unfortunately, this can easily lead students to calculate in all their experiments these two statistics simply by repetition, without really knowing whether these are the most appropriate, taking into account the type of experiment performed and the results obtained.

This problem was observed in a laboratory subject where students had to determine the theobromine content in commercial chocolate bar samples, and each student analyzed a different brand of 80% dark chocolate ($n = 28$). In this case, the number of samples measured allowed for the analysis of the population distribution. The histogram (Figure 2) obtained

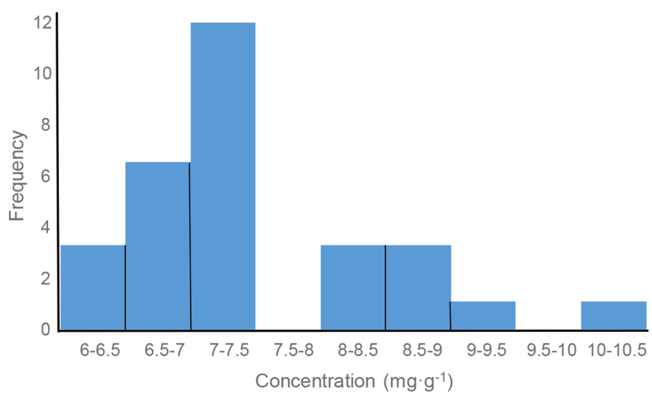

Figure 2. Histogram obtained from students' results in the analysis of 28 samples of commercial 80% dark chocolate bars.

from the results reported by students behaves as a right-skewed distribution (non-normal). The Shapiro−Wilk test was also performed and confirmed that these results were not normally distributed (p = 0.002). However, all students calculated the mean (7.46 $mg{\cdot}g^{-1}$) and the SD (0.93 $mg{\cdot}g^{-1}$) as descriptive statistics for these results, when the median (7.12 $mg{\cdot}g^{-1}$) and the interquartile range (IQR = 1.3 $mg{\cdot}g^{-1}$) should be reported because the data are non-normal.

The most common situation in quantitative laboratory experiments performed by students only requires analysis of a reduced number of replicates of the assessed sample (usually only two or three). Mitschele assessed different descriptive

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statistics for small data sets ($n \leq 5$) and demonstrated that, in this situation, the most adequate measure for the central tendency was always the arithmetic mean, regardless of whether some skewed data was present, whereas the best choice for the variability was the sample SD,[32] which are the two statistics to be considered for normal distributions. Therefore, it should be explained to students that when the number of replicates analyzed is small, the most common situation is to assume a normal distribution, which simplifies the selection of descriptive statistics. However, for large data sets, it is required to perform a preliminary evaluation of the distribution of the data to assess whether normal distribution can be assumed. This is very important as the descriptive statistics to be chosen with non-normally distributed data should be the median and the percentiles (or the IQR), because means and standard deviations are highly influenced by extreme values.[33]

Once the distribution is determined, or correctly assumed, the most basic concept that students must acquire is that only reporting a measure of the central tendency does not provide all information that is essential in learning about a data set.[34] With laboratory results, a mean value without information regarding sample dispersion is usually worthless, and proper conclusions can only be drawn once the mean and its variability are known. As an example, in a laboratory lesson the results from two students analyzing five replicates each of the same sample with the same method were: Student 1: 0.35, 0.38, 0.40, 0.42, and 0.45 mM; Student 2: 0.23, 0.32, 0.42, 0.50, and 0.55 mM (we assume there were no systematic errors, and the Grubbs' test for outliers confirmed that no single data can be considered an outlier, $p > 0.05$). Despite both students obtaining the same mean (0.40 mM), which was taken by students as perfect results, their variabilities were different ($SD_1 = 0.038$ mM, $SD_2 = 0.13$ mM). After an F-test, it was seen that both students had obtained significantly different precision in their measurements ($p = 0.035$). Therefore, it was possible to conclude that Student 2 needed more practice to improve his or her laboratory skills.

METHODOLOGY TO ASSESS COMMON STUDENTS' MISCONCEPTIONS

As Lötz wrote, "instead of harassing students with a wealth of statistical theory and test, it is probably wiser to limit the discussion to the basic statistical tasks such as the calculation and proper interpretation of the mean and standard deviation of a collection of data".[3] In general, there is a consensus about the importance of applying some practiced-oriented introduction to the analysis and interpretation of results obtained from real experimental data,[2−9,24,31] also in high school laboratories.[35]

To have detailed information about the level of comprehension of our students about descriptive statistics, during the 2021/22 academic year, 72 junior students were required to pass a final written test regarding a laboratory subject on quantitative analysis. It should be taken into account that this subject was held during the third university year of the students, after having taken different laboratory subjects, where they had also done quantitative analyses, and after having taken a theoretical subject devoted to "applied statistics for scientists". After reviewing the summaries of these previous subjects, it was expected that these students would have a good background in basic statistical skills applied to the laboratory. For this reason, they did not receive any reinforcement about the use of descriptive statistics before they performed the test. It was scheduled after finishing all of their lab experiments and after the presentation of their final reports. In this assessment, students were questioned on how the final result obtained from the analysis of five replicates of a sample should be reported (Box 1). The raw data given were full precision results without taking into account experimental precision and significant digits for each individual measurement. Students were allowed to perform their calculations with the help of scientific calculators. After the correction of the test, students were interviewed to find out the reasons behind their answers.

Box 1. Exercise delivered to students about the use of descriptive statistics with experimental results

Five independent replicated analyses of the same sample were performed in the laboratory, and the experimental concentrations obtained for each replicate were: 29.2496, 30.6243, 28.6186, 31.8754, and 31.1321 mg·L^{-1}

- How many and what statistics do you consider that are required to summarize the raw data obtained?
- Perform the corresponding calculations and write the results obtained (you must write in your answer the formula/s used).

RESULTS

In their answers, all students calculated the arithmetic mean of the results (mean = 30.3 mg·L^{-1}) as the measure of the central tendency, which seemed to confirm that this statistic is an easy concept to understand, as was found in other studies.[21] However, when they were asked why they had not taken into account other statistics (e.g., the median), they were unable to give an answer other than that they had always calculated the mean only in their laboratory experiments.

With regard to the variability of experimental results, only 59 students (82%) reported a statistic for this, and the remaining 18% were not at all concerned about this. The most surprising result was observed when the variability statistic of those students who reported precision was assessed. From the 59 students that reported a statistic for variability, one (2%) calculated the range (eq 1):

$$\text{range} = (x_{i,\max} - x_{i,\min}) \tag{1}$$

and the other 58 (98%) wrote in their answers that they had calculated the SD. However, only 33 students (56%) had correctly calculated the sample SD (eq 2, SD = 1.34 mg·L^{-1}) as the statistic for measuring the variability of replicates:

$$\text{SD} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(n - 1)}} \tag{2}$$

12 students (20%) had calculated the population standard deviation, σ (eq 3, $\sigma = 1.20$ mg·L^{-1}):

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}} \tag{3}$$

four (7%) the population variance, σ^2 (eq 4, $\sigma^2 = 1.44$):

$$\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{n} \tag{4}$$

three (5%) the standard error, SE (eq 5, SE = 0.60 mg·L^{-1}):

$$\text{SE} = \frac{\text{SD}}{\sqrt{n}} \tag{5}$$

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and six (10%) made incorrect calculations, such as,

$$\mathrm{SD} = \frac{\sum (x_i - \bar{x})^2}{(n - 1)} \quad (6)$$

$$\mathrm{SD} = \sqrt{\frac{\sum x_i^2}{(n - 1)}} \quad (7)$$

$$\mathrm{SD} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{\bar{x}}} \quad (8)$$

■ DISCUSSION

The answers given by students with respect to the calculation of the mean as the only descriptive statistic for the central tendency in all types of experimental results confirmed the hypothesis that students tend to calculate the mean only by repetition. None of the students interviewed had previously considered the distribution of their data, and none of them knew about the importance of the distribution when selecting the statistics to be calculated.

All of the students that answered the exercise had previously calculated both the mean and sample SD for their analyses in their final laboratory reports, handed in before the exercise, but now 18% did not calculate any statistic for the variability. After interviewing them, it was found that, in many cases, they had performed SD calculations in their reports only because it was written in the laboratory procedures that this statistic had to be calculated, without taking into account how it must be calculated with small data sets. From the students who calculated a statistic for precision in the exercise, only 56% were able to make this calculation correctly. A common explanation given by students was that they normally carry out statistical calculations in the laboratory using spreadsheets, usually with Excel applying the function "STDEV.S" (the old function "STDEV" still exists for compatibility purposes).[24,36−39] However, many could not remember the mathematical formula for this statistical calculation. It was also found that a large proportion of students did not know why scientific calculators have two options for the calculation of the standard deviation, one using $(n - 1)$ in the denominator (sample SD, eq 2) and another using n (population SD, eq 3), which allows us to conclude that a part of the correct results given by students in the test were done so purely by chance. Some of the students acknowledged that they had randomly chosen one of the two options without knowing the difference. This confusion between the sample and population SD can also be found in some articles. As an example, Volmer et al. calculated for some of the data they reported the population SD whereas, in other cases, they calculated the sample SD.[40]

Another common misconception found during the interviews was that students usually said that the most important statistic is the mean, and they considered that precision was only required to demonstrate that the experimental results had less than a predetermined percentage of error or relative standard deviation. It was found that students do not correctly understand that the SD is a descriptive statistic, which generally does not indicate right or wrong, and a low SD is not necessarily more desirable since it is only a measure of the average distance between each quantity and the calculated mean, which, in the case of laboratory measurements, depends on many factors, such as the homogeneity of the sample, the laboratory method applied in the measurements, the experimenter skills, the instrumentation and materials used, and others.

It was also found that those students that calculated the SE had performed this calculation because it made data less variable. This misconception can also be observed in some research articles.[10] Different studies have assessed the inappropriate reporting of the SE for descriptive statistics in published articles in biomedical journals, and found that 64% (from 450 articles evaluated)[14] and 23% (n = 860)[12] of the revised articles failed reporting the SE instead the sample SD.

Proposed Methodology for Reinforcing Descriptive Statistics

The findings obtained during the revision of students' answers confirmed the hypothesis regarding misconceptions and problems with descriptive statistics for many students, when they have to apply them to experimental results. As a consequence, a teaching methodology was developed to reinforce these concepts to students during laboratory lessons. A methodology similar to that proposed by Eierman to develop skills in analyzing numerical results of laboratory measurements was applied.[31] However, instead of explaining students directly which are the two most common statistics used with experimental results, the methodology applied makes special emphasis on showing the reasoning that justifies the use of one or another statistic:

1. At the beginning of a laboratory subject, students are first reinforced in a seminar about the basics of descriptive statistics. It is explained in the seminar the required statistical reasoning to determine what statistics are more appropriate taking into account the experimental measurements performed and the distribution of the data. Students are also explained about the differences between descriptive and inferential statistics and why the SE tells us nothing about the sample precision.
2. Students must apply the concepts reinforced to the experimental results that they will obtain during each laboratory session, to do their own calculations, and to decide what to report and how. At the end of each session, students have to show the results obtained and their calculations to the instructor, explaining why the chosen statistics are adequate to describe the experiment performed, and the criteria they had used to report their results. Feedback is given by the instructor on what students did and did not, and how successfully they were.

Students are also explained the most recommended procedures about how to write the calculated statistics in their final reports (Boxes 2 and 3), taking into account the calculated precision for their experimental results.

Box 2. Summary of the most common descriptive statistics usually required to summarize the results obtained from small data sets of replicate analyses of laboratory samples

Three parameters/statistics should always be determined to summarize the results obtained in the laboratory:

- A measure of the central tendency
- A measure of the precision
- The sample size: Number of replicates measured

When reporting descriptive statistics, it is not recommended to use the shorthand form $a \pm b$.

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Box 3. How to write the descriptive statistics measured in the final report?

The number of significant digits in the SD is the limiting factor:

- First, take the SD value and write it with a maximum of two significant digits (e.g., SD = 0.15 mg·L^{-1})
- Second, write the mean value with the same number of decimal places as reported in the SD value (e.g., if SD = 0.15 mg·L^{-1}, the mean must be reported until the second decimal place: 25.02 mg·L^{-1})

Take into account that the number of significant digits when writing the mean values may change for every analysis, depending on the precision obtained for each analysis.

It is better to use the forms: Mean (SD, n) or Mean ($\pm$SD, n).

LEARNING ASSESSMENT

The proposed reinforcement methodology was applied during the 2022/23 academic year in a quantitative laboratory subject for junior students. Two groups of students were evaluated. A first group (n = 39) was composed of students that followed the proposed methodology. A second control group (n = 20) included students that did not receive the reinforcement. At the end of the term, during the final written assessment of the subject, all these students were set the same question as the example described in Box 1 (changing the set of raw data).

In the case of students receiving the reinforcement about descriptive statistics, all of them had now clear that it was necessary to calculate a statistic for both the central tendency and the variability of the data set. Moreover, all explained correctly that the arithmetic mean and the SD can be used with the set of data assessed. However, five students (13%) still calculated the population SD (eq 3) instead of the sample SD (eq 2), but nobody tried to calculate the SE for descriptive analysis. The final reports of the reinforced group were also assessed (see Supporting Information for specific results reported by students), and the same error as observed in the written exercise was observed, with five students reporting the population SD for variability.

In the control group, results similar to those obtained in the example explained in the results section were obtained. Seven students (35%) did not calculate any statistic for the precision, and when variability was calculated, the previously described misconception between sample and population SD was observed.

These results confirm that the reinforcement of descriptive statistics does lead to a better understanding of these concepts. Moreover, the statistical skills required can be acquired in a relatively simple way once these concepts are reinforced and applied within laboratory experiments. However, in a few cases it is necessary to keep on this point. It has been reported that misconceptions take part in the generation of new knowledge and, consequently, once an incorrect concept is learned, it can be difficult to replace.[41] Therefore, some students who have misconceptions may have difficulties to overcome them and may require time to solve them.[42] As indicated, these were junior students, and at this level of their formation, they may have acquired misconceptions and used them for a long time. It has been reported that the longer a misconception remain unchallenged the more likely it is to become entrenched, and some students may retain for a long time their misguided beliefs.[41] Moreover, despite common misconceptions can be identified, each student is different, with individual and specific misunderstandings.[41] For this reason, the National Research Council suggested that to break down students' misconceptions, it is required to revisit common misconceptions as often as we can and to assess and reassess the validity of students concepts.[43] Therefore, it is expected that these descriptive statistical concepts will probably be easily adsorbed if they are reinforced right in the beginning of their training. Eierman also found in its similar methodology for developing skills in analyzing numerical results that a clear progress was obtained, but there was a significant number of students that were not able to reach the required level only practicing these concepts in one laboratory subject and they needed more practice.[31]

CONCLUSIONS

The main finding obtained from this study is that many experimental science students have some misconceptions about how to apply descriptive statistics and need to reinforce these concepts and to practice descriptive statistics calculations when applied to experimental laboratory results to reach the minimum data analysis skills, in a way similar to what happens with basic laboratory skills. The specific conditions of each applied experiment have to be known and taken into account when statistical calculations are performed, which is not always as simple as might be expected from the general and theoretical concepts that are explained in general lectures. Moreover, students must learn to apply statistical criteria when selecting the type of calculation to be made rather than applying one equation only by replication.

The results obtained confirm that reinforcing these basic concepts during their application to experimental results helps students to reach a better general understanding of them, of their meaning when applied to experimental results, and of why it is so important to determine one value for the central tendency and another for the variability with experimental results. Moreover, it is recommended that this reinforcement should start from the beginning of their undergraduate formation. In this study, some misconceptions were difficult to solve for some students, probably because the methodology was tested with junior students, which have already acquired some incorrect habits that become difficult to change and solve at this time.

Although the conclusions obtained in this study are not based on general evidence but rather are the result of the findings obtained from our students, it can be expected that the misconceptions and limitations found are relatively common and that the same or similar misconceptions will be present in other students. It should be noted that many of the misconceptions found in our students can also be observed in published scientific studies.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00394.

Results written in final reports by those students that received the reinforcement methodology (PDF, DOCX)

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Notes

The author declares no competing financial interest.

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