Determination of the Gain in Learning the Free-Fall Motion of Bodies by Applying the Resource of Previous Concepts

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***Abstract*—**In this paper, we analyzed the different didactic proposals for teaching about the free fall motion of bodies available online. An important aspect was the interpretation of the direction and sense of the acceleration of gravity and of the falling velocity of a body, which is why we found different applications of the Cartesian reference system used and also different graphical presentations of the velocity as a function of time and of the distance traveled vertically by the body in the period of time that it was dropped from a height h_0. In this framework, a survey of previous concepts was applied to a voluntary group of first-year university students of an Engineering degree before and after the development of the class of the subject in question. Then, Hake's index (0.52) was determined, which resulted in an average learning gain from the meaningful use of the reference system and the respective graphs of velocity versus time and height versus time.

***Keywords*—**Didactic gain, free–fall, physics teaching, previous knowledge.

I. Introduction

IN the reviews of scientific works and university texts on the subject of the free fall motion of bodies, the analysis of the different didactic proposals for teaching about this motion was observed. In this sense, Rodríguez et al. [1] considered that the use of information and communication technologies, as well as active learning, facilitated the motivation and good academic performance of students evaluated in this area. Rubio et al. [2] used the GeoGebra resource to simulate the free fall motion of bodies and to motivate students who had to use additional mathematical concepts for the construction of the simulation of the aforementioned motion.

Sánchez [3] provided a series of considerations to be taken into account in teaching the motion of a body in free fall. He included conceptual aspects and those relevant to obtain a better conceptual understanding through the use of simulation with Modellus software. And the authors Amadeu and Leal [4] also used simulation software, but added didactic strategies to the teaching process to learn about prior ideas of the topic and then applied the same strategies of prior knowledge to assess the meaningful learning of their students.

In another order, Montero et al. [5] applied different experimental techniques to perform the free fall motion of bodies using the Tracker program and the Python language. However, these authors did not comment on the use of the reference system to be used for the study of the motion under study. However, Forero et al. [6] provided interesting questions on the use of a reference system for the study of a body in motion in free fall.

Regarding university physics textbooks, for example, University Physics [7] provided a significant commentary on the use of the reference system in the free fall motion of bodies. Similarly, Physics [8] explained that it was possible to select the reference system according to the convenience to be used in each problem. In this framework, the motion of bodies in free fall is a uniformly accelerated rectilinear motion. We understand by free fall of a body when it descends on the surface of the Earth under the action of the Earth's gravity and does not experience or is not considered or is negligible air resistance in its straight trajectory.

A first approach to the study of bodies that descended in the bosom of a fluid and disregarding the air resistance on the body when it is very small, then in that situation it was necessary to make use of a reference system for any analysis of the motion of the object. And in this situation of free fall motion, an inertial or non-inertial reference system could be applied.

In the case of classical physics, a reference system for the motion in question constituted a system accelerated by the force of gravity, so a non-inertial reference system was available. But in relativistic mechanics the reference system was inertial because it was not accelerated in space-time. In this contextualization, this work analyzed the case of the free fall motion of a body in a non-inertial reference frame. Therefore, the acceleration acquired by the body in its fall was due only to gravity, regardless of its mass.

Taking into account that the semi-axis y has positive upward direction and that the acceleration of gravity has opposite direction, then $g = -9.8\ m/s^2$ was considered. That is to say that the minus sign represented the sense of the vector magnitude.

The velocity reached by the body for a time t is equal to the initial velocity it had for a time t0 plus the acceleration by the time increment, then:

$$v = v_0 - g.t;\ t_0 = 0 \qquad (1)$$

In the case that the body is dropped, its $v_0 = 0$, therefore (1) remained:

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$$v = -g.t \quad (2)$$

From the mathematical point of view in expression (2), the minus sign represented a line with a negative slope, but it would mean that the velocity decreased as time went by. But physically, the minus sign indicated the direction of the velocity in the reference system that was used, because the velocity of a body in free fall increased. In summary, the velocity was considered negative in the vertical downward direction with respect to the position of the object. And in that sense, the position of the object was determined as follows:

$$y = y_0 + v_0.t - \frac{1}{2}.g.t^2;\ t_0 = 0$$

For the simplest case:

$$y_0 = 0; v_0 = 0 \Rightarrow y = -\frac{1}{2}.g.t^2 \quad (3)$$

Since the free fall motion of the bodies is vertical with increasing velocity, (3) could be rewritten as a function of the height (h), i.e.:

$$y = h_0 - \frac{1}{2}.g.t^2;\ v_0 = 0 \quad (4)$$

Being h_0 the initial height of fall of the body and considering to have as initial data the height and the acceleration of gravity, it remained to determine the time of fall, the distance traveled and the velocity for a time t. However, for first year university students, the analysis of motion in its simplest expression may not be so easy, due to the difficulty in the use of the reference system, i.e., to locate the origin of coordinates and the body together or the body at a height h from the origin of coordinates.

While for the teacher it would be a matter of didactic strategy to develop the conceptual explanation and the respective practices of development of the exercise models that he would offer to his students, the young people do not necessarily assign significance to the importance of the reference system and the free fall movement that a descending body would experience. That is to say, the interpretations of the graphs of height versus time and speed versus time which would be easier for the students to anchor the concepts with significance.

Therefore, in this work, the objective was to measure the didactic gain in learning the free fall motion of bodies through the application of prior knowledge and to provide recommendations to improve the teaching of Physics.

II. Methodology

The work was developed considering the following criteria: 10 student volunteers with grades higher than 6, 10 students volunteers with grades equal to 6, and 10 student volunteers with grades lower than 6. The numerical grade was the passing grade of the exams at the university where the present work was carried out. Therefore, according to the criteria, a sample (n) of 30 volunteer students, who studied Biological Physics in the Zootechnical Engineering course at the National University of Formosa, should have been taken into account.

The student sample is shown in Table I. In it, it was possible to observe the variation in the number of students who studied between the years 2018 to 2022 inclusive and the total number of students for the period analyzed. On the other hand, following the sample criterion, the sample size was also calculated online, also obtaining the same value of the sample n, with an error (e) = 10%, i.e., with the error made, the confidence level or degree of probability of the estimate made was 95% and the average population: 42 volunteer students. The study was conducted over five consecutive years, testing 30 student volunteers per year.

TABLE I
NUMBER OF STUDENTS PER YEAR

Years	Quantity
2018	56
2019	31
2020	54
2021	41
2022	30
Total	212

The prior knowledge questionnaire was included in the annex. It consisted of statements such as the position of a body, the choice of the reference system, some characteristics of the free fall motion of bodies and the possibility of simulating such motion. The answers to these statements allowed us to know the value given by the students to each item.

The rating scale for the 10 statements was the Likert scale with five options. The test was applied before the class corresponding to the subject of free fall motion of bodies and then at the end of the subject the same questionnaire of previous knowledge was applied again.

The thematic core of the class was to analyze the applicability of the reference system, for this the didactic methodology was a body located at a height (h) above the ground, then:

a) The origin of coordinates of the reference frame at the initial position of the body, to measure how far the body moves away from the starting point, the upward direction was taken as positive. The initial velocity (v_0) and the initial coordinate (y_0) are both zero. The acceleration of gravity is vertical downward, in the direction of the semi-axis y negative, so the value of $-g = -9.8\ m/s^2$. The value of v_y is also negative, because the positive semi-axis y was upward. In this criterion the direction of the acceleration of gravity was not changed, it is still downward.
b) The origin of coordinates of the reference system at h = 0 m and the positive direction of the semi-axis y downward. Then the initial height h_0 had a negative value, while the acceleration of gravity is positive, because its direction is downward. At the instant the body reaches the ground, the value of the velocity was positive downward.

In this framework, the graphs of $h = f(t)$ and $v = f(t)$. Moreover, in both situations the choice of the origin of coordinates did not affect the numerical results, only the correct interpretation of positions and signs of the variables velocity, height and acceleration of gravity.

Regarding the analysis of the prior knowledge questionnaire, the data were processed and the averages of the percentage of correct answers obtained before and after the planned class were calculated, in order to subsequently calculate Hake's index [9], i.e., the normalized didactic gain (g), useful for situations where didactic strategies with alternative and/or innovative methodologies were applied.

The measure of gain comprised three scales: g ≥ 0.7 high index; 0.3 < g < 0.7 medium index and g ≤ 0.3 low index. Its analytical expression was:

$$g = \frac{\overline{P_{final}} - \overline{P_{inicial}}}{100 - \overline{P_{inicial}}} \quad (5)$$

$\overline{P_{final}}$ = average of the final percentage of correct answers. $\overline{P_{inicial}}$ = average percentage of correct answers at the beginning.

The use of normalized gain was to avoid comparing students with very heterogeneous knowledge levels.

III. Results

The study found that the application of the prior concepts resource improved the learning gain related to the free-fall motion of bodies. Calculation of Hake's index resulted in a mean gain of 0.52, indicating a significant improvement. The study also provided data on prior knowledge in physics learning.

First, the minimum and maximum global scores were determined, and these values made it possible to determine the maximum and minimum limits to be expected from the processing of data in each questionnaire applied.

The minimum score was 2.10 and the maximum score was 4.90. The average of the corresponding correct scores was calculated before the development of the class and presented in Table II. The values were above the minimum score of 2.10. Table III shows the average of the correct results of previous knowledge after the class. It should be noted that the values found were also above the minimum score and below the maximum score stipulated.

TABLE II
Average Number of Correct Results before the Class

Average	16.40

TABLE III
Average Number of Correct Results after the Class

Average	60.10

The prior knowledge referred to the value that the students gave to the use of a reference system; the arbitrary choice; the application of the origin of coordinates in the initial position of the body to measure how far it moves away from the origin of the system, in a positive or negative sense (items 3 and 4 of the applied questionnaire); and, the concepts of position and trajectory of a body in free fall motion (items 1 and 9 respectively).

During the same class, we also explained the free fall motion of a body when the slope the $v = f(t)$ was negative. It was emphasized that the acceleration of gravity is negative because it has a downward direction with respect to the semi-axis y and the Cartesian reference system used.

Garduño et al. [10] employed a test on the understanding of free fall motion handling with respect to initial velocity and free fall time, as well as the behavior of gravity acceleration. Similar situation to the questionnaire developed in this work, with item 6 and item 7 for the initial velocity, and item 8 about the constant value of the acceleration of gravity. But they did not work on the importance of the position of the object to fall in free fall and the choice of the reference system to be used.

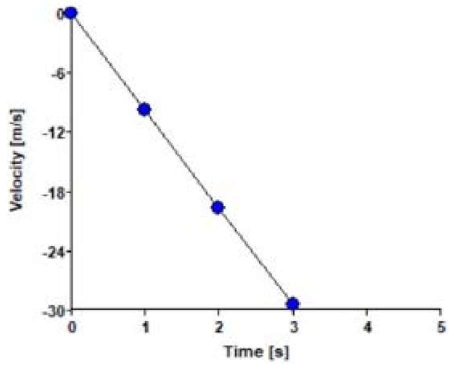

Fig. 1 Velocity as a function of time in free fall

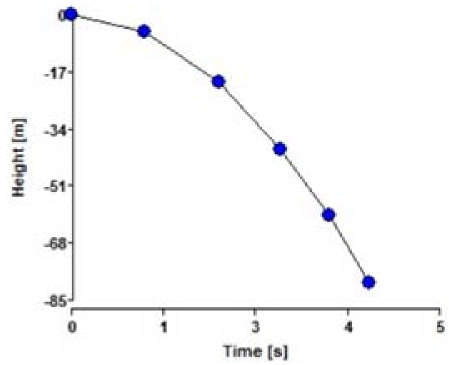

Fig. 2 (a) Height as a function of time in free fall

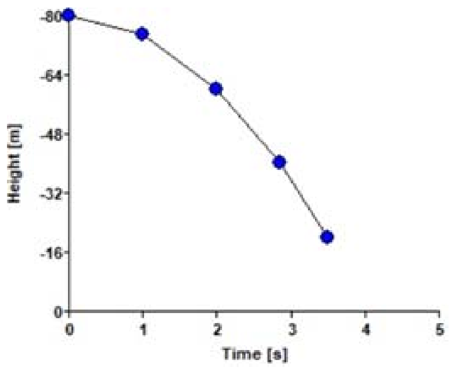

Fig. 2 (b) Height as a function of time in free fall

Figs. 1, 2 (a) and 2 (b) showed the velocity and height for any example. In Figs. 1 and 2 (a) they corresponded to an origin of coordinates at the body that had zero initial velocity and height 0 m. While in Fig. 2 (b), the origin of coordinates was on the ground and the body was at a height of 80 meters and zero initial velocity.

The units of velocity were [m/s]; height [m] and time [s]. The inclusion of the arbitrary application of a reference system allowed the post-class results to improve significantly. In the figures the bodies are allowed to fall freely.

The didactic gain value considered by Hake as acceptable for an innovative and efficient teaching method was 0.52, which was obtained from the calculation with the values expressed in Tables II and III. Therefore, the use of the resource of prior knowledge constituted an alternative to improve the gain in the learning of the free fall motion of bodies.

IV. Conclusions

This work suggests that the use of prior concepts can improve learning outcomes related to the free-fall motion of bodies. The study also provided information on students' attitudes, in the sense that when faced with the resolution of a problematic situation of free fall motion of bodies, they can decide which reference system is convenient to use, which can help to design effective didactic teaching strategies. Even using some software to simulate the motion in question, they will be able to discern about the correct interpretation of the position of the body and that the sign of the acceleration of gravity is correct.

In addition, the study contributes to the theoretical understanding of Physics teaching and provides ideas on teaching strategies based on the use of prior knowledge to obtain a satisfactory didactic gain, the analysis of students' attitudes and motivations, as well as invites to design new Physics teaching lesson plans, using Hake's index as an interesting indicator in the fixation of concepts developed in Physics teaching.

Annex

Previos concepts	1	2	3	4	5
1. The position of a body is the vector that joins the place occupied by the body and the origin of the reference system.					
2. The trajectory is rectilinear when the free fall motion of a body is from a height of 2 meters with respect to the Cartesian coordinate system.					
3. The reference system is a coordinate system for determining the position of a body.					
4. The location of a reference system is completely arbitrary.					
5. A reference system can be inertial or non-inertial.					
6. When we drop a body in free fall it is considered to have no initial velocity.					
7. When in a free fall motion a body is thrown vertically, it falls with initial velocity.					
8. In free fall motion from a height of 2 meters with respect to a reference system the acceleration of gravity is a constant.					
9. For a body in free fall without friction the trajectory is exactly a parabola.					
10. The simulation of the free fall motion of a body is feasible.					

References
1: strongly disagree
2: disagree
3: indifferent
4: agree
5: strongly agree

Fig. 3 Questionnaire of Previous Concepts

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