Addressing undergraduate students’ difficulty in learning the Generalized Work-Energy Principle in introductory Mechanic

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Abstract. In this contribution, we report the implementation and evaluation of an interactive Teaching Learning Sequence (TLS) introducing the concepts of Work, energy and the relations between them. The sequence has been designed with the Design Based Research (DBR) methodology. In order to analyse the effectiveness of the Sequence for students to be able to achieve the set learning goals, a pre-post test was designed. We was given the questionnaires, over two academic years (14/15 and 16/17), to about 170 students who attended the introductory physics course for the first engineering degree. Our findings show that the majority of experimental students’ progress from particular cases of the relation between work and energy towards an explanatory general relation between work and energy. We discuss implications of our findings in relation to teaching work and energy in introductory physics courses.

1. Introduction
One of the greatest challenges in physics teaching revolves around helping students to build scientific models that they can use to understand natural phenomena. The challenge is particularly serious for scientific areas where phenomena are complex and a large quantity of prior information has built up. For most topics, there is widespread agreement on what appropriate comprehension of the topic might entail at the different stages of the education process. This is not the case for energy [1]. A representative example of one of these areas in physics is the Generalized Principle of Work and Energy (GPWE) in Mechanics [2]. Some studies show that the students do not establish the field of validity of the Kinetic Energy Theorem as a specific case of GWEP. [3,4,5]. Moreover, students’ difficulties identifying the energy being transferred by means of work and/or heat and the variations in the different forms of energy in the system (kinetic, potential or internal) are detected [6,7].

Prior studies indicated that some teaching approaches propose introducing the First Principle of Thermodynamics working from the kinetic energy theorem W=ΔK [8]. The theorem is expanded for the case where conservative forces are acting so that the total energy of the particles is the sum of the kinetic energy and the potential energy. Consequently, the equation for the kinetic energy theorem becomes ΔU + ΔK= W, and in the absence of work due to external forces on the system ΔU + ΔK= 0. This expression is not the energy conservation principle, but a derivation of the principles of dynamics, which can be applied to mechanical systems in the absence of work from non-conservative forces [9, 10]. When there are forces such as friction, conceptual difficulties emerge between the...
meanings of the “work” concept [11, 12]. Some textbooks usually define the work from the force of friction as \( W = -f_k d \) (1), where \( f_k \) is the force of kinetic friction on the block and \( d \) is the distance through which the block moves relative to the surface. This definition does not usually explain why work is now defined in terms of a distance rather than a displacement. The equation (1) generates a disconnection with earlier discussions on work in which work was calculated by means of displacement. A conceptually more fruitful approach that is proposed in this work is to consider that the product \( f_k d \) represents the contribution of the increase in the system’s internal energy: \( + f_k d = \Delta E_{\text{int}} \), the quantity \( f_k d \) tells us the variation of energy inside the block and the surface area as a system. Research also indicated other teaching approaches, proposing to present the concept of energy as “the capacity to do work” [13], are limited in some cases by the mechanics as, by stating the second principle of thermodynamics, it can be seen that not all the energy is capable of being transformed into work [14]. Consequently, if this type of representation is used in Mechanics, it is necessary to explicitly narrow down its field of validity.

In our study, we suggest a way of avoiding the disadvantages mentioned in order to maintain a strong, natural connection between the concepts of energy and work and the Generalized Work-Energy Principle (GWEP) in mechanics. We propose an approach that, from the outset, works from the fact that the first principle of energy demonstrates that the energy variation in a system is equal to the balance of energy transferred between the system and its surroundings [15, 16, 17]. This system is chosen arbitrarily but the first principle of energy is always met, independently of the chosen system: \( \Delta E_{\text{system}} = \text{Quantity of energy transferred between system-surroundings} \) (\( \Delta T_{s-e} \)).

The purposes of this study were therefore to investigate university introductory physics courses students’ conceptual understanding and the performance of GPWE and, examine the effect of a TLS based on a conceptual structure that present from the beginning the relation of work and energy by \( \Delta E_{\text{system}} = \Delta T_{s-e} \) and then, analyse particular cases such as the Kinetic energy theorem. Our research questions, then, are:

1. How effective is the TLS based in conceptual learning and analysis construction of \( \Delta E_{\text{system}} = \Delta T_{s-e} \) compared with the traditional model bases in a succession of particular cases?
2. How does the new approach allow students to overcome the difficulties identified by research in traditional learning?

2. Theoretical background
This study describes a part of a sequence for teaching GPWE in the introductory physics course for the first engineering degree. In this study, we construct the sequence within the framework of a research and development process [18]. We present a part our design and evaluation process as an implementation of Design Based Research (from now on, “DBR”) methodology [10]. DBR methodology typically consists of cycles of three steps each: design, teaching experiment and retrospective analysis and evaluation [19]. In particular, we use the six phases that Easterday, Lewis, and Gerber [20] propose for DBR methodology. In section II, we present the first four phases: identifying syllabus aims by educational level (“focus” phase); identifying prior research related to possible learning difficulties and feasible teaching strategies to overcome them (“understand” phase); defining specific learning aims (“define” phase) and teaching strategies (“conceive” phase). The last two phases, implementing the TLS (build) and its assessment (test), are presented in section III, including redesigning the first version of the TLS depending on the assessment results from the first implementation, plus data corresponding to the two subsequent implementations. DBR is a widely used approach for tackling informed research designed in science education [21].

3. Context and designing TLS
We start by presenting the context for which the TLS is designed and discussions on the epistemological and educational arguments around the topic in question.
We construct the design of the TLS within the context of a transformed calculus-based physics course for first-year engineering and science degree students at the University of the Basque Country (UPV/EHU). At UPV-EHU, the Mechanics syllabus is taught during the fall semester. The traditional course format is two hours per week of lectures, and a problem session lasting an hour and a half a week, with an enrolment of 60–70 students. The Mechanics syllabus for the topic of work and energy incorporates elements included in the course textbook [22]: work, kinetic energy, potential energy, and conservation of energy. In traditional courses, students do not normally have the chance to participate actively and are limited to taking notes from the teacher’s explanations, both in lectures and in problem sessions. We adopt the same syllabus (factual knowledge) but, as we will explain, we will organize the contents differently.

The definition of learning objectives shares the contemporary idea upheld by the epistemology of Physics that considers that the concepts of work, energy and their relations present the following key ideas:

K1. The concept of work depends on the concept of force and a considerable effort must be made to differentiate the scientific concept of work from the everyday meaning of the word. Work is defined as the scalar product between two vectoral magnitudes.

K2. Work is a way of changing a system’s energy and what is indicated as work in the equations corresponds to the quantity of this change.

K3. Detailed analysis is required of processes where work is involved. It should be taken into account that whilst the energy is associated with systems, work is defined in the transformations of the energies involved, therefore there is little point in associating it with a system.

K4. Energy is defined as a property of a system in a specific condition (a property of the system’s state), not a material substance, or the “capacity” of a system to perform work. Energy is considered as a magnitude associated with a system that can take different forms and that can be transformed and transferred.

K5. The relations between work and energy are established as a natural extension of the energy balance in a system and from the meaning of work as a quantity of transformed energy.

From the Key ideas, we will define a set of research-based learning objective (Define phase), i.e., justified by the disciplinary epistemological evidence and avoiding definitions based on the designers’ idiosyncrasies or traditional curricular choices. In this study, we only present the learning objectives related to the 4 and 5 key ideas (see table 1)

| Epistemology of Physics | Learning indicators |
|-------------------------|---------------------|
| - Key idea K4           | O.3. Knowing how to define the system, the three different forms of energy that can vary in the system (kinetic energy, potential energy, internal energy) and the concepts implicated in the different types of energy transfer between a system and its surroundings (work, heat) \( (\Delta E_{\text{system}} = \Delta E_{\text{ext}}) \). Recognizing that the kinetic energy theorem is a specific case of the generalized principle of work and energy. |
| - Key idea K5           | O.4. Knowing how to apply the generalized principle of work and energy \( (\Delta K + \Delta U + \Delta E_{\text{int}} = W_{\text{ext}} + Q + \text{other energy transfers}) \) in different situations in Mechanics. |
Moving from the defined learning aims to propose learning activities; we consider the gap between students’ ideas showed in previous studies (see introduction) and learning objectives. The size of the gap they need to bridge to attain meaningful learning, as expressed by the indicators, will determine the strategies to be used in each case.

After a previous implementation of the TLS for a year, we refined the sequence in accordance with the first results obtained. Changes were made in two areas: i) reduction in the number of activities and, reformulation of some activities to adapt them to the learning goals; ii) change in the order of presentation for the program contents. The order of presenting the contents in the second version of the TLS, applied during the 2015/16 and 2016/17 academic years, from the outset presents the relations between work and energy variation as the generalized principle of work and energy that is always met regardless of the chosen system: \( \Delta E_{\text{system}} = \Delta T_{s-e} \). From the outset, the GWEP is specified as \( \Delta K + \Delta U + \Delta E_{\text{int}} = W_{\text{ext}} \) and different specific cases are analyzed such as when there is only a variation in kinetic energy in the system (kinetic energy theorem) or there are only variations in kinetic and potential energy (mechanical energy principle) with no dissipative forces. The new order for content presentation for the TLS is: I) Calculating and using work; II) Relation between work and energy variation for a system. Generalized Principle of work and energy; III) Specific cases. IV) Conservation of energy. In Table II we only present the sequence of activities for the objectives 3 and 4.

The TLS contains each activity with the corresponding comment, that compiles the guidelines for the teacher. These comments are used to make a guide in an attempt to develop the TLS according to the objectives, following the activities that are necessary to develop the TLS correctly and giving some freedom to the teachers in the complementary activities. The teaching strategies are based on active methodologies, meaning the activities are carried out in small groups of three or four students where they discuss the activity and propose an answer, either by means of “clicking” (Personal Response Systems), worksheets or, in the case of problem-solving, by pooling questions that guide the solving process [23]. The teacher guides the discussion on the answers in the full group and directs the learning so that the students can build the right meanings.

| Driving problems | Learning indicators | Strategies to foster learning | TLS2. Activities and comments Implementation and re-design |
|------------------|---------------------|------------------------------|----------------------------------------------------------|
| How can the relations i.2, i.3, i.4 between work and energy variation be quantified? | a.- Familiarizing students with analysis of the phenomena that shows relations between work and energy: Defining system; Force diagrams; Defining work that is external and internal to the system | Activities to analyze the relations \( \Delta E_{\text{system}} = \Delta T_{s-e} \) (implement strategies a and b): A.10 to A.12. | Scenarios to analyze the PGTE (implement strategy c): A.13 to A.17 |
|                  | b.- Organizing empirical information and proposing hypotheses on the relation between work and energy |                             |                                                          |
|                  | c.- Applying the generalized principle of work and energy in different scenarios |                             |                                                          |
Regarding the design of the activities we modified traditional way of questions or problems so that students are able to think about the aim of the task (metacognitive difficulty). An example of modifying activity A.11 is given below (see table 3) in an attempt to overcome the students’ metacognitive difficulties and focus their work on the learning objectives.

**Table 3.** Students' metacognitive difficulties encountered when implementing the TLS and its re-design

| Activity 11 (version 1) | Activity 11 (version 2) |
|------------------------|------------------------|
| A baseball player throws a 0.15 Kg ball at a speed of 30m/s. | A baseball player throws a 0.15 Kg. ball at a speed of 30m/s. |

Find: a) the work done on the ball during the pitch; b) the change in the energy of the ball.

Typical students' answers to the activity A.11, gathered from their workbook during the implementation of version 1 of the activity showed that they did not achieve a clear understanding of the aim of the activity. An example is the following:

"W= ΔK, so the kinetic energy of the ball is ½ mv² =2,25J"

In these typical answers, students solve the question using an equation, in a correct or incorrect way, but without defining the ball-system and without analyzing the forces acting and the processes of work and energy change. These elements were included in the objective of A.11, but students did not consider them. So, we decided to redesign the activity by setting the students a more specific task in a worksheet (see the second column of Table IV). The corresponding modification of the activity was to make the objective more explicit by adding a worktable. This change leads to students focusing on the objective when answering the question. An example of a typical student’s answer is the following:

"The system is the" ball "and therefore we only consider the forces that act on the ball. We take the ball as the initial situation in the player's resting hand and consider a horizontal movement until the

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"The system is the" ball "and therefore we only consider the forces that act on the ball. We take the ball as the initial situation in the player's resting hand and consider a horizontal movement until the
final situation that the ball will leave the hand of the player. If the system is the ball, there is no potential energy and we only consider the variation of the kinetic energy (there is no variation of internal energy) We can calculate the work as the variation of the ball's kinetic energy: 

\[ W = \frac{1}{2} m v^2 = 2.25 \text{J}. \]

It is necessary to emphasize that the great majority of students obtain a correct numerical answer to A.11 in both versions. However, the way of approaching and solving the problem is radically different. In version 2, students have to think about the system and the different concepts that appear in the activity. This prepares students for their own problem-solving skills that will be needed to tackle not-so-simple activities.

4. Results on the achieved learning

To see how much students had improved their understanding of relations between work and energy, we used a pre and post-test design. The post-test was given to students from experimental groups and comparison group students under exam conditions and the result was included as a part of the final mark for the subject unit. The scores were compared for each group’s answer category. To decide whether there were any significant differences between the experimental and comparison groups, the chi-square statistic was used for the usual level of confidence of 5% or less [24]. The results tables group together the experimental and comparison data, as there are no significant differences between them in accordance with the chi-squared statistical results. Moreover, to analyze the relevance of the differences between the experimental and control groups, we used the "effect size" statistic. Effect Size is a way of quantifying the size of the difference between two groups [24,25]. In accordance with Black and Harrison [24], “The size of the typical effect in the research being analyzed is between 0.4 and 0.7; a value of 0.4 means that the average student that takes part in the innovation will achieve the same learning as a student in the top 35% of any students not involved in the innovation.”

Pre-test and post-test questions are similar and some of them have been discussed in previous papers on student difficulties concerning relations between work and energy. In this study we present the questions Q2 (for explaining the limits of the Kinetic Energy Theorem validity) and Q4 (for understanding and applying the GWEP: \( \Delta K + \Delta U + \Delta E_{\text{int}} = W_{\text{ext}} \)). The questions Q2 and Q4 are shown in table 4

| Question Q2 | Question Q4 |
|-------------|-------------|
| A student states: "If a work is done on a system, the kinetic energy of the system increases". Do you agree with the student’s reasoning? Justify your answer. | A car moves at constant velocity on a horizontal highway. Is work done on the car? Is there variation of system energy? |

Question Q2 aims to set the field of validity of the kinetic energy theorem, as a specific case of the generalized principle of work and energy. Correct student answers describe the kinetic energy theorem as a specific case or they explain examples that limit its validity. Many of the arguments for answers recognizing the validity limit of the kinetic energy theorem speak only about potential energy and do not mention cases of dissipative forces or the energy conservation principle. As we will show in the next section, a significant percentage of students demonstrate persistent difficulties when establishing the validity limits for the kinetic energy theorem.

Questions Q4 presents a situation for the students to carry out the energy balance in accordance with external work on the system. The students have to define the system and apply the GWEP. Correct answers have to define a system that includes car and the surface of highway, because there is friction...
between both car and surface. This friction is an internal force of the system and contributes to the variation of the internal energy.

Table 5 shows the frequency of correct answers for the questions Q2 and Q4. During the two years of the experiment, the percentages of correct answers in the pre-test did not have statistically significant differences, so we have presented the average percentages in the first column of table 5.

Table 5. Percentages of correct answer for the questions Q2 and Q4.

| Questions | All courses | Post-2015-16 | Post-2016-17 |
|-----------|-------------|--------------|--------------|
|           | Pre (N=257) | C-16 N=115   | E1-TLS2 N=175| C-17 N=115   | E2-TLS2 N=178 |
| Q2        | 22.5        | 39.5         | 74.5         | 34.0         | 72.0          |
| Q3        | 0.0         | 9.0          | 55.5         | 8.0          | 62.0          |

The results from table 5 show a significant improvement in the percentages of correct answers in the experimental group. In addition, the chi-squared statistic for two questions obtains results with $p<<0.0001$. It can be stated that the results depend on the teaching method being used. As we have already indicated to show whether the difference between the experimental and control groups is relevant from an educational point of view, we calculate the size of the effect. In our case, for the learning objectives for the questions Q2 and Q4 the size of the effect in implementing the TLS lies between 0.4 (in Q2) and greater than 0.5 (in Q4), which means a large size of the effect.

5. Conclusions and future work

One of the reasons why the long debate over the decades on the teaching of energy has had little impact in practice is the lack of emphasis on the evaluation of the proposed materials and their effectiveness in understanding students. To progress, we need assessment instruments that, on the one hand, analyze the activities and structure of the materials in relation to the teaching approach that we want to promote. On the other hand, evaluation instruments that ask students to do things that we consider according to the objectives to be learned. The project for which this TLS has been developed, aims to achieve those objectives. It is a large task and it is unlikely that we have achieved it completely. But the results obtained seem to indicate that we are on the right way.

The results in terms of the learning achieved are hopeful and demonstrate a significant statistical improvement and a medium to large size innovation effect (see table V). However, in this paper we only show two questions of the all evaluation of the TLS. In future works we will presents the results for all part of the teaching sequence and the assessment analysis taking into account students’ difficulties. Qualitative analysis of the answers in categories will led us to consider student comprehension difficulties that are demonstrated in some cases.

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