Integrating didactical strategies to facilitate meaningful learning in introductory college physics

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Abstract

Research Questions: This research was organized in three studies, in which the first one attempted to answer the following research questions: 1) How to integrate in a didactical proposal situations of Physics applied to Engineering, the Potentially Meaningful Teaching Units (PMTUs), and the Project Method so that this integration could work towards facilitating the meaningful learning of physics concepts? 2) What problem-situations can help engineering students to give meaning to physics concepts of Thermodynamics? 3) The learning of concepts of physics that may derive from the implementation of this proposal can be considered meaningful? 4) How to integrate college Physics with high school Physics? Research methodology: qualitative and quantitative methods were triangulated, and research instruments were validated and tested for their reliability. The qualitative methodology chosen for this research was ethnographic [1], while the quantitative one was based on descriptive and inferential statistics [2]. Data gathering used a quasi-experimental design for time equivalent samples [3]. Some research findings: based on the research questions, a proposal was applied for integrating the Project Method [4] and the PMTUs [5], which were composed of problem-situations [6] that had been proven effective in providing meaning to physical concepts of Thermodynamics. We identified, with the use of various instruments, what can be considered evidences of the occurrence of meaningful learning [7], based on data that arise from the implementation of this proposal; as well as from what seemed to be an improvement for the engineering students about the representation they had of physics, since they started to perceive this discipline as vital to their field of professional practice. From the collected data, we also inferred ways of integrating school and university classes.

Keywords: Engineering, project methods, potentially meaningful teaching units, thermodynamics.

Resumen

Esta investigación fue organizada en tres estudios, de los cuales el primero se ocupó de las siguientes cuestiones de investigación: 1) ¿Cómo integrar en una propuesta didáctica las Unidades de Enseñanza Potencialmente Significativas (UEPS) y el Método de Proyectos, en situaciones de Física aplicada a Ingeniería, de tal manera que esa integración pudiera facilitar el aprendizaje significativo de conceptos físicos? 2) ¿Qué situaciones-problema pueden ayudar a estudiantes de Ingeniería a dar significados a conceptos físicos de la Termodinámica? 3) ¿Puede el aprendizaje de conceptos físicos derivado de esta propuesta, ser considerado significativo? 4) ¿Cómo integrar la Física introductoria universitaria y la Física de secundaria? En la metodología de investigación fueron utilizados métodos cualitativos y cuantitativos; los instrumentos fueron validados y su fidedignidad fue verificada. La metodología cualitativa fue del tipo etnográfico [1], mientras que la cuantitativa fue basada en estadística descriptiva e inferencial [2]. Los datos fueron obtenidos a través de un diseño cuasi-experimental para nuestras equivalentes en el tiempo [3]. Los resultados sugieren que, la integración del Método de Proyectos [4] con las UEPS [5], en las que fueron usadas situaciones-problema [6], fue efectiva para dar significados a conceptos de Termodinámica. Con los varios instrumentos utilizados fueron encontradas evidencias de aprendizaje significativo [7] de parte los alumnos en ese campo conceptual. Asimismo, fueron también obtenidas evidencias de cambio en la representación que tienen estudiantes de Ingeniería respecto a la Física, dado que empezaron a verla como una disciplina vital para su práctica profesional.

Palabras clave: Ingeniería, termodinámica, aprendizaje significativo, método de proyectos.

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I. INTRODUCCIÓN

In many countries, including Brazil, there is a great need of professionals in the area of Engineering, Physics and Medical Physics. According to Jornal Hoje [8], nowadays they are about 38,000 engineers graduate every year. However, to meet the market needs, the 2014 World Cup and the 2016 Olympic Games, this number needs to reach 60,000 per year. As is reported by Telles [9], while in United States, Japan and Germany there are 25 engineers for each 1000 professionally active people, in Brazil there are only six. This is due, in part, to non-contextualized and unattractive teaching, in which students do not see meaning in the physical concepts.

In order to reduce this problem, we sought in the research that originated this paper, to evaluate a didactic proposal composed by: physical situations [6] applied to Engineering, Potentially Meaningful Teaching Units [5] and the Project Methods [4], in a way that such an integration could facilitate the occurrence of Meaningful Learning [7] of thermodynamics concepts applied to Engineering, both critically and actively. The way we have chosen to integrate the PMTUs, the problem-situations, and the Project Method is detailed in Methodology of Classes.

The comprehension of physical applications to Medicine, as, for example, seen in Parisoto's master's research [10], is potentially helpful for Meaningful Learning (ML), once it seems to promote the interaction with other ideas that compose the learner's mental representations. The same was identified regarding applications to Engineering.

In the development of the PhD project that followed the master's research, two PMTUs were carried out covering contents of Thermodynamics using Engineering situations.

This was done so as to identify which content (s) of this area can serve as a link for the Teaching of Modern Physics [11]. This will be used for situations related to Medicine, more specifically to the Interaction of Radiation with Matter.

Thus, the study starts with Classical Physics (Physics II), continuing with the teaching of Modern Physics (Physics IV), as suggested in Toulmin [12] and Paulo [13]. The pilot study was guided by the following questions that, since the approach is qualitative and quantitative, could be modified along the research process:

1) How to integrate, in a didactic proposal, physical situations applied to Engineering, the PMTUs, and the Project Method, so that this integration can facilitate Meaningful Learning (ML) of Thermodynamics concepts?

2) Which problem-situations of Engineering may give/add meaning to physical concepts of Thermodynamics?

3) What content of Thermodynamics can be used as input to the teaching of the interaction of radiation with matter?

4) What problem-situations of Thermodynamics can give/add meaning to concepts that involve the Interaction of Radiation with matter applied to Medicine?

5) What previous knowledge do students bring to classes of Physics that might be used to teach concepts of physics applied to Engineering?

6) Is the learning of physics concepts meaningful, considering the application of the proposal?

7) What is necessary to change in the research to help students learn meaningfully concepts that they have not learned in the pilot study?

II. THEORETICAL FRAMEWORK

The theoretical foundation of this research comprises the Theory of Meaningful Learning (TML) [7], the Conceptual Fields Theory [6], The Project Method [4], the Potentially Meaningful Teaching Units [5], and Toulmin's Epistemology [12]. These bibliographic references were just mentioned here, due to limited space. A detailed description can be found in Parisoto [14].

III. METHODOLOGY OF CLASSES

The school year began with a work agreement contract [14].

Afterwards, classes started, bringing together a number of different activities, such as computer simulations [15], resolution of problem situations [6], the drawing of concept maps [16], lecturing [7]. Before and after these activities students responded to problem situations (Table 1), in order to attempt at to identifying the students' existing prior knowledge and at teaching them accordingly, as well as to find what kind of knowledge students had that could stand for evidence of meaningful learning. At the end of the semester, projects [4] developed by the students were presented, as the example shown in section Example of a project that presented evidence of meaningful learning.

IV. BACKGROUND

The research was carried out in Physics II, with two Engineering groups: one of Production Engineering and the other Environmental Engineering, each group with, respectively, 51 and 45 students. These were evening courses that took place at a Community University in Rio Grande do Sul, Brazil. Each group, then, had a 60 hour-course. There was a 3 hour-meeting once week for each group.

V. EXAMPLE OF PROJECT THAT PRESENTED EVIDENCE OF MEANINGFUL LEARNING

Students numbered by 37 and 45 developed a project and a work agreement contract entitled "Self-sustainable and Planned City". They were concerned, mainly, in identifying sustainable materials and bad conductors of heat so as to reduce the flow of thermal energy and to improve thermal comfort inside the buildings. To do so, they used computational and mathematical tools and, as requested, they related Physics to the future course that they would take.

One of the students was taking Computer Engineering, and then he built a virtual city and an experiment that virtually measured temperature fluctuations through a wall. Student 45 was studying to become a Production Engineer, and in this profession one of the main goals is cutting cost.

He was working in rice planting, whose peels are disposed off, and with this in mind he came up with a way to use such material in constructions, in order to improve thermal comfort. Another material he used was tire rubber, which is usually neither recycled nor reused.

The students planned the whole city aiming at sustainability, Thermodynamics and their course. On their first 26 pages, they described the city they had planned. On page 27, they discussed whether the investment in sustainable construction could be profitable, and they concluded that each dollar invested in sustainable buildings would become increasingly worth in fifteen to twenty years.

On page 28, they started to describe two experimental procedures (real and virtual). The first was related to the expansion of materials. The students wanted to determine what would be the temperature fluctuation a 100 meter building, with a steel structure, would bear if it had a 10 centimeter maximum clear width. In this calculation, they considered the coefficient of volumetric expansion, transforming it into to the linear coefficient, thus, demonstrating that they knew when to use one or the other and how to transform both. In the presentation, they calculated how much space would be necessary between two columns, if the temperature fluctuation were 40ºC, which they did it correctly.

Afterwards, they described the second experiment, which was supposed to identify what sort of material offers a better insulation (the rice peel and/or the tire rubber). Considering the calculation they had developed, the experimental activities and the computer simulations presented, students concluded that rubber can be a better insulation than rice peel. However, this might stand as a good option to improve thermal comfort in constructions. That research is shown in more details in another paper [17].

VI. SUMARY OF RESULTS FOUND IN THE PILOT STUDY

This paper describes the synthesis of findings of an ethnographic and exploratory study, grounded in conceptions of qualitative research, advocated by [1, 18]. In the next implementations, quantitative analysis will also be used.

In this section, we present research questions we sought to answer in this first implementation as well as a synthesis of the attained responses. Finally, we present perspectives for further research.

The work was divided into development and research. In the first one, two PMTUs were built as integrated to the Project Method and to the Problem-Situations, which, as mentioned before, were applied in two Engineering groups, Production and Environmental, which had, each one, 60 hours of class. *The four first questions are related to the developmental part and not so much to research. The last five, as it will be seen, concern research.*

To answer the *first research question* ("How to integrate, in a didactic proposal, situations of Physics applied to Engineering, the PMTUs, and the Project Method, so that the integration can facilitate the Meaningful Learning (ML) of concepts of Thermodynamics?"), lessons were planned according to the theoretical and epistemological references, and such planning was validated by three physics professors of the Federal University of Rio Grande do Sul (UFRGS), Brazil. The problem situations (Table I), related to Engineering, were applied in the second and sixth stages of PMTU. The Project Method permeated both PMTUs starting in the first class, with the organization of the activity, and reaching its peak in the last two classes with the presentation and discussion of final projects developed by students.

Details the planning of lessons can be found in Parisoto [14].

Table I presents a synthesis that can answer the *second research question*: "What problem situations, from Engineering, may give/add more meaning to physical concepts of Thermodynamics*?"*

TABLE I. Problem situations used in two PMTUs and the concepts involved.

Problem situations	Concepts involved
Let's suppose you are an engineer and need to choose the parameters you will use to make the electrical connection of a city: a) Which variables, related to Ther-modynamics, would you consider? b) Which thoughts, related to Thermo-dynamics would you have? Use Mathematics to support your ideas. c) Give a numerical example. Consider that the city has well-defined stations.	Length, area, volume, linear coefficient of expansion, superficial and volumetric, variation, thermal equilibrium, cold, hot, temperature and heat.
a) Create your thermo-metric scale, b) Represent it and also on a Celsius temperature scale, c) Transform a temperature from its scale to ºC.	Temperature, variation and liquid expansion.
A potato is on a table, outside, on a sunny day: a) How would you cook it the fastest way possible, using only solar energy? b) If instead of potato we had ice, what would happen to its temperature, and what sort of thermal processes would occur until it became steam? c) If we wanted it to evaporate faster, what could we do?	Thermal capacity, a-mount of heat: sensitive and latent, specific heat and mass.
Explain considering the ways of spreading heat: a) How does a thermos flask work? b) How does sea breeze happen during the day and during the night? c) How does solar radiation reach the Earth? d) Why in cold days there are more respiratory problems because of pollution?	Convection, irradiation and conduction.

e) Where would you place the devices for cooling and heating a house (use what we have learned about density and convection)?	
Based on what has been studied until now: a) How would you design a house in the state of Pará (in the north of Brazil) so that you would not have to cool it during the Summer and would not have to heat during the Winter? Justify your answer using what you know of Thermo-dynamics. Use at least three ideas; b) For this purpose, would it be better to use wood or brick? See the chart of thermal conduction. c) Which are the differences between regu-lar and compound walls?	Convection, irradiation and conduction.
How does a gasoline engine motor work?	Pressure, strength, area, volume, temperature, molar mass, mass, molecules, atoms, displacement, work, adiabatic, isovolumetric, isothermic, isobaric, degrees of freedom, internal energy, atomic ray, triple point, critical point, the relative humidity of the air and specific heat.
a) In the case of ideal gases, equation of state of ideal gas called "Clapeyron Equation" (PiVi = nRT) is used. Based on this equation, how would you make, mathematically, to reach the "Van der Waals Equation"? b) What variables, which have not been taken into conside-ration in the ideal gases, should be considered in real gases?	Pressure, strength, area, volume, temperature, molar mass, mass, molecules, atoms, dis-placement, work, adia-batic, isovolumetric, iso-thermic, isobaric, de-grees of freedom, inter-nal energy, atomic ray, triple point, critic point, the relative humidity of the air and specific heat.
"The inside of a tank wagon was washed with steam by a cleaning crew at dusk. As the service had not been finished at the end of the working day, they closed the wagon tightly and left it overnight. When they returned the next morning, they discovered that something had sma-shed the car, in spite of its extremely resistant steel walls, as if some giant creature from a science fiction movie had stepped on the wagon" [19]. Explain how the tank wagon had been smashed during the night. Use the relationship among pressure, work, volume and temperature. Show the differences if real and ideal gases can be taken in consideration.	Adiabatic, isovolume-tric, isothermic, isoba-ric, area, pressure, strength, volume, tem-perature, work, internal energy, rotation, trans-lation, binding energy, amount of heat.
How to enhance performance of a refrigerator and a boiler? Provide at least three arguments based on Thermodynamics.	Performance, entropy, energy, thermal equi-librium, temperature, work, internal energy, heat, hot, cold, varia-tion, amount of heat, adiabatic, isothermic and volume.

The contents of Thermodynamics that are to be used as an input for teaching the interaction of radiation with matter (*third research question*) are the *forms of heat spread*.

Various analogies might be established between the two contents, considering classical Physics to teach modern Physics. It may be possible to ask questions such as: 1) What would happen to a person, if electromagnetic radiation with an infrared wavelength incided upon him/her? And if electromagnetic radiation with X-rays and gamma rays wavelength were incided upon him/her? 2) Which kinds of exams/or medical treatments are to be used in each of these situations? 3) What are the ways you can protect yourself from these types of radiation? 4) What are the diseases that can be caused by exposure to these types of electromagnetic radiation?

Thus, the problem situation of Thermodynamics that can provide meaning to concepts related to interaction of radiation with matter applied to medicine (*fourth research question*) is: Based on what has been studied until now a) How would you design a house in the state of Pará (northern Brazil), so that in the Summer you do not have to cool it down and in Winter you do not have to use heat?

Justify your answers based on your knowledge of Thermodynamics. Use at least three ideas: a) Having in mind this purpose, would it be better to use wood or brick? (See the chart of thermal conduction); b) What are the differences between simple and compound walls?

The *fifth research question* is: What previous knowledge students bring to physics classes that could be used to teach physics concepts applied to Engineering?

According to Ausubel [7], prior knowledge is the most important variable to facilitate meaningful learning; therefore, it must be identified before starting the teaching process. Summing it up, in the pilot study, based on problem situations and mental maps, it was possible to qualitatively verify that most students, when entering the process of instruction, did not have any previous knowledge of Thermodynamics that could have been used as subsumers.

The first problem situation *aimed at identifying which students had any previous knowledge concerning linear expansion*. Some (6) demonstrated that they knew the relationship among linear expansion, the material that constitutes the wire, and the coefficient of linear expansion, but none of them mentioned that variation in wire length is directly proportional to the coefficient of linear expansion.

Six students showed some evidence of knowing that wire length variation was related to its expansion and compression. Some (4) correctly related temperature variation to dilation. Eight students mentioned other variables that are not directly related to Thermodynamics, such as population growth and supply capacity. From the variables that do not need to be considered in the process of linear expansion, some (4) correctly mentioned the coefficient of superficial expansion and volumetric. Among the inadequate prior knowledge related to the context of physics, attention can be called to those presented by four students that have considered the current temperature of the city, or its average, which is incorrect because what should be used is the minimum and maximum temperature of the location. The need to explain students the meaning of idealization was identified, thus, stressing the negotiation of meanings, as suggested by Gowin [20], Vergnaud [6] and Toulmin [12].

The second problem situation *aimed at identifying the previous knowledge students had about thermometric scales*.

Most students (10 out of 14) showed they knew how to represent thermometric scales, interpret them, construct the equation, and, thus, representing them. Only two had formal mistakes. In addition, one did not use the Celsius scale while another student did not present the two scales.

The alternatives a) and d), the third problem situation, *aimed at identifying the previous knowledge students had regarding the processes of heat conduction*. Out of the nine students, two responded that in order to get the ice to evaporate faster, we had to get it close to a thermal conductor, two expressed that solar energy irradiation should be increased, three students said that mechanisms that increased energy absorption should be used, such a wrapping the ice in a dark paper. Three others mentioned that they would use systems to increase the reflection of solar energy in the ice by using mirrors, for example. Two affirmed that they would use refractor systems, such as lamps with water.

One mentioned that he/she would increase the contact area of the ice with the air, dividing it into several parts. One student said he would increase the amount of heat with other sources.

Alternatives b) and c), the third problem situation, *aimed at identifying what previous knowledge students already had about latent and sensible heat*. Of (10) respondents, it can be said that one had some previous knowledge about thermal conductor, irradiation, amount of heat, sensible and latent; two understood about reflection and five about absorption.

Half of the respondents had erroneous prior knowledge about when the temperature remains constant and when it changed.

The fourth problem situation was not answered at the beginning of class, but it was also about conduction of heat, similarly to the fifth problem situation.

The fifth problem situation *aimed at identifying the previous knowledge students had about heat conduction*. Out of the twelve students who responded, seven would design the building considering the position of the sun, the wind, and the breeze; seven considered relevant the question on the material for the house, stating that it had to be made of insulating materials; two would plant a vine on the house walls or plant trees, which in Winter lose their leaves, thus, increasing the amount of sunlight and, therefore, the temperature inside it ,whereas, in the Summer they would be used as thermal insulation that could decrease the inside temperature; seven others emphasized the aspects of house construction, for example, the need of using glass, compound walls, and green roofs.

One of the students considered, erroneously, that one should build a brick house instead of a wooden one for, according to the student, "masonry has a higher heat capacity than wood, so that it heats up less in the summer". As seen in the first test, the thermal conductivity of wood (0.11 to 0.14 J/s/(mK)) is lower than the one for brick (0.40 to 0.80 J/s/(mK)),which is the main constituent of a brick house, therefore, from the point of view of thermal comfort, it is better to build a wooden house. Many students were wrong in choosing between brick and wood for building houses. So, we asked, informally, the reason for the mistake, to which some mentioned that they did not know how to interpret the table and considered the value 0.11 greater than 0.4, which is incorrect. This showed the need to teach them how to interpret tables.

From the collected data, evidence has been found about the existence of an alternative view, in most of the students, according to which anybody that receives thermal energy increases its temperature whereas, if it loses it, temperature decreases.

Next, there was evidence to answer the *sixth research question*: from the implementation of the proposal, can we say that the learning of physics concepts by the students involved in this project is meaningful?

Summing it up, after the process of instruction, students seemed to show evidence of procedural and conceptual meaningful learning, applicable in science, in the following knowledge topics: states of matter, heat, thermal equilibrium, temperature, volume, specific heat, mass, amount of sensible heat, the amount of latent heat, convection, irradiation, conduction, coefficient of linear expansion, coefficient of superficial expansion, coefficient of volumetric variation, length, area and volume.

Most students did not show evidence of meaningful learning in the following knowledge topics: recognition of compound and simple walls, compression of materials, identifying whether it is wood or brick the best thermal insulator, when temperature changes or remains constant in thermal processes. As to applications in science, most students could not relate the types of heat spread to thermo flasks, city pollution, air conditioning, heaters, and sea breeze.

VII. FINAL CONSIDERATIONS

Based on the collected data, it was verified the need to consider the following points:

- to teach students how to interpret tables;
- to different between simple and compound walls;
- when addressing dilation, compression should also be addressed;
- to emphasize when temperature changes or when it remains the same along thermal processes;
- to teach students what idealizations really mean;
- to explain in a more detailed way the following applications of Thermodynamics: thermos, city pollution , air conditioning, heaters, and sea breeze;
- to provide extra points to the grade of any student that solves all problem situations;
- to change the context of the student's project, by replacing the state of Pará with our own state, Rio Grande do Sul. This should be done since contextualization provided by such change would have students concerned not only about reducing the temperature inside the house, but also about increasing it in winter, something that is not necessary in Pará, but in their own context;
- to provide a minimum of concepts for the students to construct their projects and to fulfill their work agreement contracts.

What was found can be used to improve teaching and learning; leading the student to learn and evaluate themselves; to articulate the physics with the students' future profession, decreasing mistakes that are sometimes fatal; to decrease the rate of repetition and dropout. Can also lead to curricular modification [21] that leading the students to improve their procedural knowledge ("How to do something; methods of inquiry, and criteria for using skills", [22]), conceptual knowledge ("Interrelationships among basic elements within a larger structure", [22]); society and engineering applications [5]).

As it is our goal to continue this research, we aim at identifying:

1) What are the operational invariants of students in the area comprised by the proposal?
2) Does the integration among situations of Physics applied to Engineering, the PMTUs and the Project method constitute a better facilitator for the occurrence of meaningful learning than lectures followed by problem solving?
3) How to integrate the situations of Physics applied to Medicine, the PMTUs, and Project Method so as to facilitate ML concepts about the Interaction of Radiation with Matter?
4) What previous knowledge do students bring to physics classes that could be used when teaching concepts of physics applied to Medicine?
5) Is it possible to say that physics concepts have been meaningfully learned through the implementation of the proposal?
6) Do teachers continue using the proposal after they come to the end of this research? If the answer is a negative one, it will be the object of a further research to get an answer to the following question: What could be changed in order to allow the proposal to continue being implemented?

The aim is also to find ways to facilitate the comparison of data presented by the students in the different instruments and to triangulate these data so as to verify the existence of evidence of how evolution occurs in the conceptual field of thermodynamics and radiation interaction with matter throughout the instructional process.

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