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Didactic Implications Resulting from Students' Ideas about Energy: an Approach to Mechanical, Thermal and Electrical Phenomena

Dimitris Koliopoulos and Konstantinos Ravanis
dkoliop@upatras.gr; ravanis@upatras.gr

Department of Early Childhood Education, University of Patras, Greece

ABSTRACT

In this article we study lower secondary education students' mental representations about energy and we discuss the didactical implications on designing physics curriculums' content. Firstly, we present a review of the bibliography concerning students' mental representations when they describe and interpret mechanical, thermal and electrical phenomena. This review directly relates students' representations about energy with the relevant phenomenological field where they are developed. Following this, we investigate how Greek students use the energy concept in order to simultaneously describe and interpret a mechanical, a thermal and an electrical phenomenon. Our empirical research results in combination with results previously known in bibliography, show that lower secondary education students are able to spontaneously derive energetical reasoning within the scientific framework, either in mono-phenomenological situations (mainly in electrical and thermal phenomena) or in multi-phenomenological situations, when they activate linear casual reasoning. Finally, we propose new approaches in physics curriculum that would exceed the traditional formalist introduction of energy as a concept-product of the mechanical work and the empirical approaches that indiscriminately use all phenomenological fields, in order to introduce energy as a unified trans- phenomenological concept.

INTRODUCTION

Energy is a fundamental scientific concept. According to Feynman the energy concept is based on the principle of its conservation, and this principle "... is very abstract because is a mathematical one. It suggests the existe-nce of a numerical quantity, called energy, which remains unchanged during the vari-ous changes nature is undergoing" (Feynman et al., 1969). According to Theobald "scientists became conscious that the energy concept and the notion of its conservation could be used to link physical systems with prima facie very diverse characteristics" (Theobald, 1965). The trans-phenomenological character of energy is clearly shown through the principle of equivalence that, historically, has been expressed by the equivalence of work and heat.

Nevertheless, energy is not a homogeneous concept, which had acquired various epistemological profiles (Bachelard, 1940). In the context of Classical

Physics, the analysis of university textbooks shows that energy is not restricted to a par-ticular application field, since it is a fundamental concept in order to interpret all natural interactions. Various scientific models have been formed, closely related to the corresponding phenomenological domains, within which energy gains a conceptual autonomy (Baltas, 1990). One might distinguish three such models namely the "Force-particle", the "Thermodynamic" and the "Field" one (Koliopoulos, 1997). Mechanical and electrical phenomena constitute privileged physical systems to apply the "Force-particle" model and the "Field" model respectively. Thermal phenomena usually are described within "Thermodynamic" model constituting a trans-phenomenological application field.

They are its multi-phenomenological and trans-phenomenological characters that make energy a fundamental physical concept, and constitute a considerable problem in Physics teaching (Koliopoulos & Tiberghien, 1986). The unique way the energy concept appears in various forms, in several subject areas through diverse conceptual models makes its adaptation very difficult when teaching Physics in primary and secondary education schools, where it is necessary to use approaches of very different levels of abstraction.

The whole research community in Science Education has admitted that it is necessary to study students' mental representations in the perspective of their oriented transformation, in order to accomplish any didactic attempt successfully. A series of research studies have shown that students' mental representations about energy are inconsistent with the conceptual representations accepted by scientists (Solomon, 1992; Driver et al., 1994; Koliopoulos & Tiberghien, 1986). The inconsistencies observed concern

a) students' conceptual meaning about energy, when they use it spontaneously

b) how students use the energy conservation principle and the energy transformation and transfer procedures, when they describe or explain physical phenomena.

The above classical studies do not directly or systematically relate students' mental representations to the various domains in Physics.

In this article we try to reveal this relation by studying students' mental representations about energy when they express their ideas regarding mechanical, thermal and electrical phenomena. These domains constitute subjects of science curriculum for both primary and secondary education. They are usually covered in the above order, in order to introduce and apply the energy concept, in various physical situations. We think that the results of our analysis can be used complementary to those of the classical surveys and reveal a new dimension of the problem, such as the general use of pre-energetical mental representations based on linear causal reasoning (Tiberghien, 1988). Afterwards, we present research results concerning students' ideas about energy when they try to describe mechanical, thermal or electrical phenomena using everyday language. Finally, we discuss the implications of our analysis about science curriculum transformations as far as concerning the energy concept.

STUDENTS' IDEAS ABOUT ENERGY IN MECHANICAL PHENOMENA

Mechanical phenomena and the "Force-particle" model are considered privileged domains to study the energy concept and particularly to introduce it in science teaching. Early research related to the subject has been performed in the context of Genetic Epistemology. Those researches refer to simple mechanical phenomena that can be explained using the notion of kinetic energy transfer from one body to another. Piaget and De Lannoy (1973) studied students' mental representations about energy transfer between two joined pendulums. They concluded that some students (15-16 years old) could express an energetical conception, according to which the alternative role of the two small pendulum balls led to the notion that they could transfer, not only movement, but also "powers" ("pouvoirs"). According to Piaget's codification for the development levels of thought, these students belonged to the abstract thinking period. A 15 years old child expressed an example of this conception saying that: "The force will be transferred completely by the horizontal string. Forces will be interchanged. That's the way it should be. Transfer will be constant, but not simultaneous" (Piaget and De Lannoy 1973, p. 161).

Grimellini-Tomasini et al. (1993) have shown that many students between 14 and 16 years could not exhibit the abstract thinking period characteristics, while those expressed the energetical conception had use the term "force" to refer to energy. They also observed that 15-16 years old students when working with collision tasks, consider a transfer mechanism in terms of cause to effect, similar to the scientific meaning of the energy transfer. The above belief is mainly derived by everyday experience. A deeper analysis of these notions pointed out also some important diversions; for example, students did not specify any entity describing the state of the system and leading to the balance of a physical quantity.

The problem emerging from the confusion between "force" and "energy" is not always real. Sometimes, students attribute energy like characteristics to the concept "force". For instance, Brook and Driver (1984) stated that many secondary school students use the word force in cases where they should use the concept of kinetic energy. This conception has been observed in students' answers to questions related to the movement of a compact ball placed on a wavy perpendicular rail; pupils had to focus their attention on the "quantity of force" corresponding to the various positions of the ball on the rail. Vosniadou and Ioannidis (1998) found a similar idea in primary and secondary school students; they think that force exists only in moving objects, and only as long as their movement lasts. This conception refers to the "vis viva " and "impetus" concepts found when studying earlier development periods in the history of Physics.

Other studies performed under different conditions also pointed out the problem of the relation between movement and energy. Bliss and Ogborne (1985) found that when 11-13 years old children were asked to pick among pictures representing various natural situations those where energy is used or needed, they mainly choose pictures where activity or movement was shown. In their research with younger and older children. Gilbert and Pope (1982) found that when movement of any kind, or activity is shown in natural situations, many children mentioned the term of energy in their discussion. Quite a few of them considered that energy and activity are the same. Furthermore, children concluded that energy is the result of a force performed on bodies or vice-versa a cause creating forces (Watts, 1983).

STUDENTS' IDEAS ABOUT ENERGY IN THERMAL PHENOMENA

Tiberghien (1984a), has classify the researches dealing with students' ideas about thermal phenomena in three categories, according to the relevant concepts they gave emphasis on:

a) the temperature

b) the heat

c) the relation between temperature, heat and energy.

One of the basic conclusions coming from the results of the above researches is that students, in general, do not differentiate between the concepts of temperature and heat, and attribute properties of one concept to the other and vice-versa. The same problem emerges even after a conventional teaching session (Linn and Songer, 1991). This problem becomes even more complex when younger students are involved.

It has been also observed that many students think that heat has the characteristics of a substance moving towards the bodies heated. More specifically, movement is attributed to an internal force included in heat, or to the properties of an agent (i.e. air) that carries heat from one area to another. The "coldness" concept, in analogy with heat, is often expressed as moving towards bodies that are cooled (Erickson & Tiberghien, 1993). Several researchers observed that students recognize heat as a mediator between a heat source and a heat receptor. However, it has been specified that this conception is expressed only in some special physical phenomena (i.e. when heating a metal rod); in other cases, such as the classification of materials into thermal conductors or insulators, this idea is not generally expressed (Tiberghien, 1983). According to Arnold and Millar (1994), students are not always able to recognize a mediator with energetical properties, in other words they are not always able to proceed to a thorough description of a thermal phenomenon. This happens because they are not often able to discriminate between the boundaries of the physical systems participating in the energy (heat) transfer procedure and the physical reasons causing this transfer. Furthermore, this difficulty prevents students to understand the thermal balance principle, since it constitutes a physical phenomenon requiring a selective application of the energy transfer concept.

Finally, we should point out the researches dealing with purely thermodynamic phenomena performed with university students. It has been found that students using linear causal reasoning can hardly make correct approaches when solving thermodynamic problems; indeed they do not consider all the variables contained or/and cannot link with more variables (Rozier, 1987). It would be very interesting to study if primary and secondary school students use also this type of reasoning.

STUDENTS' IDEAS ABOUT ENERGY IN ELECTRICAL PHENOMENA

In the field of electrical phenomena, many researches have found that students, when they observed simple electrical circuits, expressed ideas corresponding to mental representations which involve the energy concept. It has been reported that students attribute properties of energy to "electrical current" (Tiberghien, 1984b). A number of researches have found that pupils express beliefs such as ''a battery contains "something" that is transferred to the lamp, and is "consumed" to give light''. Pupils, usually refer this entity that can be stored, moved and consumed, as electric current (Shipstone and Gunstone, 1985; Psillos et al., 1987).

It has been also shown in a study, concerning upper secondary school students in Greece, that this mental representation is very strong (Psillos et al., 1987). More specifically, students were asked to estimate the readings given by three similar ammeters alternately related with two lamps in a series circuit. Their justifications, even when students gave a correct prediction (i.e. that the readings of the three ammeters would be identical), indicate an energetical notion about electric current ("the three ammeters consume the same amount of current") (Psillos et al., 1987)

However, the use of "modeling analogies" when teaching electricity in primary and lower secondary education can help students differentiate their ideas about electric current and energy. In this framework, Dupin and Joshua (1989) have suggested that a simple electrical circuit can be considered as a hypothetical train moving constantly on a closed circular trajectory, pushed by men while decelerated by a hypothetical brake. This model can help students to discriminate their ideas about movement of bodies and energy consumption (since the correlation between these two notions can lead to the "current consumption" conception) and to identify the role of the battery in the electrical circuit, as the source of energy.

Another research conducted in Greece in secondary education schools (Tiberghien et al., 1995) in the framework of a constructivist teaching project, has showed that students, after their experimental activities, have been guided to conclusions contradictory to their initial predictions. The researchers claim that students' introduction into a domain of knowledge, in a form adaptive to their own level of perception by taking into account the types of causality that are accessible to them, allow them to achieve sufficient conceptions about energy.

STUDENTS' IDEAS ABOUT ENERGY IN A MULTI-PHENOMENOLOGICAL SITUATION

The research presented in this article aimed mainly to investigate in what extent lower secondary education Greek students can express (or apply) the energy concept when they confronted with a multi-phenomenological environment. This constitutes a first attempt to elucidate whether students can use the concept of energy as a "unifying language" to describe and interpret different phenomenological situations.

A total of 61 students, aged between 13 and 14 years, participated in the research. The subjects here were coming from typical public schools in the city of Athens, Greece. No educational intervention took place before the research. Students were asked to fill in a questionnaire, where the term "energy" was not included. The questionnaire included three tasks corresponding to the following phenomena presented to the students:

a) A ball is freely falling to the ground, where it collides with another ball (mechanical phenomenon)

b) A lamp connected with a battery is shining (electrical phenomenon)

c) An amount of water is heated using a gas burner (thermal phenomenon).

We have selected the above physical situations because they constitute typical examples presented in textbooks or in the classroom, and students are familiar with them.

The research took place in two phases. In the first phase students had to explain the presented phenomena. In the second phase, they were asked to state whether they believed there was a common explanation for the pairs of the above situations: a/b, a/c and b/c.

A first reading of their answers to the questions related to the two tasks, has to be done in the perspective under which circumstances the students refer to energy in order to describe or explain the physical phenomena. The answer to this question is given in Table 1 that corresponds to the first phase of the questionnaire and Table 2, which corresponds to the second phase.

Table 1. Relative frequencies of students' answers (first phase)

	Using the word "energy"	Not using the word "energy"
Mechanical phenomenon	7 %	93 %
Electrical phenomenon	55 %	45 %
Thermal phenomenon	12 %	88 %

Table 2. Relative frequencies of students' answers (second phase)

	Using the word "energy"	Not using the word "energy"	Total
Common explanation (a), (b), (c)	23 %	7 %	30 %
Common explanation (a), (b)	2 %	6 %	8 %
Common explanation (a), (c)	0 %	3 %	3 %
Common explanation (b), (c)	21 %	10 %	31 %
Non common explanation	15 %	13 %	28 %
Total	61 %	39 %	100 %

Table 1 shows that the majority of the students do not referred to energy spontaneously when they gave their explanations to the three phenomena independently. However, in the case of the electrical phenomenon a larger percentage of students (55%) referred to energy. The term "energy" is being used in the second phase, where students were asked to give an explanation common to the three physical phenomena. More specifically, 77% of the students considered that there is a common explanation to the three phenomena were referring to energy (23% of the students in the sample). 68% of the students, who considered that there is a common explanation only between thermal and electrical phenomena, used the term "energy" (21% of the students in the sample).

During the second phase, 61% of students did refer to energy when answering the questionnaire. It is important, however, to see how students used to word "energy"; therefore we will try to analyze their answers farther, in order to obtain a thorough qualitative interpretation of our results.

We can classify students' responses with no reference to energy as follows:

a) Answers where students are restricted to descriptive references to the processes involved. Some characteristic answers of this category are given below:

"When I light the gas burner the fire heats the water"

"I think that the lamp lights up because the two wires are connected with it and also with the two poles of the battery. One pole is positive and the other is negative. If we would connect the lamp only with one pole, it could never light up".

There were a few answers or the above type, which were recorded in the first phase of the research only.

b) Answers where students were referring to the corresponding phenomenological field using the relevant physical concepts such as "force", "heat" and "electricity". Characteristic answers of this type are as following:

"When the gas burner lights up, it produces heat and the water is heated", or

"Ball 1 gets some force while moving on the board. When it contacts with the other ball, it exerts a force that is greater than the friction between the ball and the ground. The result of this is that ball 2 moves."

c) Answers, like the following, were recorded in both phases of the research:

"In all situations there is a kind of transfer. In the first situation there is a force transfer that causes the second ball to move. In the second, there is an electricity transfer that causes the lamp to light up. In the third, there is a heat transfer so that the temperature increases heating the water."

We can also classify students' answers that refer to energy in the following categories:

a) Answers given by a small proportion of students where they use terms like "kinetic energy", "electrical energy" and " thermal energy". It is not clear if those students used the concept of energy meaningfully or their textbooks or even everyday life language influenced them.

b) Answers where energy is understood as an activity that can induce a process (i.e. to turn on a light, to heat an amount of water etc...). The cause of this process can be an action (i.e. electric current) or an object (a battery, a moving ball).

Examples of this type answers are as following:

"The gas burner produces a kind of energy, that is heat. Indeed, when we put the water on the top of the flame produced by the gas burner, the heat is transferred to the water" (first phase) or

"Yes, there is a common explanation to the three physical phenomena, since all three produce some energy. In the first phenomenon, ball 1 induces ball's 2 movement by hitting it with force. In the second phenomenon, battery produces electricity when properly connected to the lamp. In the third phenomenon, the gas burner produces heat warming up the water in the vessel. As we can see from above, we have a word common, that is produces".

c) Answers where energy is considered as a property transferred from one object to the other, which receives it in order to induce a process. It is difficult to exactly designate the meaning of this transfer, since students at this age have usually a poor vocabulary. But it seems that students attribute to this transfer properties of action (force, power) of an object over another (especially when they used the expression "production of energy"). In many cases students gave descriptions or explanations focusing on the transfer of a mediator stored in another object/s. Characteristic answers of this type are:

"The lamp needs a battery that gives energy to light up. Water needs temperature and receives it from the gas burner's flame. In other words, the lamp and the water need to get energy from some other agents" or

"The second ball will move because as the first ball is moving and touches the second ball, some energy is transferred and the second ball moves" or

"In the first case, the two balls are in close contact and ball 1 exerts some force on ball 2. In other words, a force is transferred to the second ball. In the same way, heat is transferred to the water during heating, through the vessel's walls, which are made of a heated material. In the second case, energy is driven from the battery to the lamp through the wire".

From the analysis above, we can derive that students do not refer spontaneously to energy in order to express their ideas or justifications about physical phenomena. On the other hand, it seems that they are able to describe various physical phenomena using terms relevant to each phenomenological field, when they asked to give their explanations for each phenomenon independently. Students were able to easily correlate electrical phenomena with energy transfer. At an extent, they could correlate energy with the thermal phenomenon, while they exhibited serious difficulties with the mechanical phenomenon used in our research.

It seems however, that tasks based on comparison between physical phenomena, could facilitate students not only to use the term "energy" in their justifications, but also to express ideas containing energetical notions i.e. ideas that can be considered a priori compatible with elements of scientific knowledge. This is probably due to the fact that linear causal reasoning is activated and related to the word "energy". This relation is established mainly at the action level where energy is shown as a unifying factor between various activities and the relevant mediators (heat, electricity).

DISCUSSION

In this article we have presented a series of critical problems concerning the instructional approach of the energy in various situations. We also have tried to identify the cognitive difficulties and the obstacles encountered by students and their relation to the physical phenomena under study. Evaluating them we can emphasize on ideas that could be used in order to re-examine and dispute students' conceptions usually taken for granted, when teaching energy in primary and secondary schools.

Firstly, a series of researches related to mechanical phenomena have reveal two important points concerning students' ideas about energy: they usually

a) confuse between the concepts of energy and force

b) correlate energy with movement or any action.

Although the first approach constitutes a typical instruction problem concerning the formulation of the solution, the second approach poses a strong cognitive obstacle. Indeed, if energetical reasoning is limited to situations where a distinct movement or activity can be observed, it is very difficult for the students to achieve functional meaning of complicated concepts, like energy storage and transformation.

Furthermore, the approach of the energy conservation, even in very simple systems, constitutes a difficult task; for example, this could be the case of a body hanging vertically by a string and being in equilibrium. Students when linking energy with movement cannot establish a strong mental representation that could help them to understand energy storage. If we cut the string, the body will start falling freely to the ground. Then students are able to recognize energy (even as force) but they cannot connect energy with systems' previous state. Consequently, it is difficult for the students to relate the two situations in terms of conservation and/or transformation of energy; this is due to the fact that students are usually able to recognize energy in the movement phase but not in the state of equilibrium. Therefore, mechanical phenomena cannot provide us with effective tools in order to introduce energy, since they undermine our teaching efforts reinforcing students' cognitive obstacles originating from their life experience.

Introducing energy in the framework of electrical phenomena could provide a reliable instruction choice. We have pointed above that students' pre-energetical mental representations based on linear causal reasoning can be re-organized into an early energetical mental framework using proper teaching interventions. The above statements have led us to consider that electrical circuits offer suitable systems for the introduction of the energy concept, instead of mechanical phenomena, which are conventionally used in physics curriculum. We can derive similar conclusions by observing how students used the energy concept, when they describe and explain thermal phenomena such as heating and cooling.

In spite of all, these mono-phenomenological approaches based on the study of electrical or thermal phenomena, although it seems they can replace the historically privileged domain of mechanical phenomena, minimize the value of the unifying character of the energy concept. A number of teaching interventions based on the constructivist hypothesis for learning attempted to solve this problem (Lemeignan and Weil-Barais, 1993; Koliopoulos and Ravanis, 2000a). These attempts aimed at overcoming the difficulties, originating from introducing energy in isolated cognitive fields. They have designed and tested new instructional interventions based on students' gradual construction of the energy concept, which is accomplished through the properties of storage, transfer, transformation, measure and debit in the form of the unified conceptual framework of the energy chain. The results of our investigation are very supportive to these instructional proposals. We have found that students can spontaneously formulate or make energetical reasoning in the three fields, using qualitative causal descriptions and giving explanations of the relevant physical phenomena. This statement seems to help students organize their representations about energy in terms of the energy chain, i.e. a didactic transposition of the thermodynamic model, which offers structural and semantic compatibility between the students' mental representations and the relevant scientific models (Astolfi and Develay, 1989)

According to the above analysis, we assert that traditional curricula and instruction approaches concerning energy must be revised. These approaches, followed also in Greece, are based to mechanical phenomena in order introduce the energy concept, seems to be accepted mainly for historical reasons while not indicated by research. The main reasons supporting traditional instruction approaches about energy are the following:

- students are familiar with mechanical phenomena because of their every day life experiences
- energy has been historically established as an agent which can produce mechanical work.

The arguments above, connected to the conventional perception about science instruction, are mainly based to empiricist or intuitive approaches aiming to simplify the subject. We think that it is now time to reconsider and dispute thoroughly this approach because of the great conceptual difficulties encountered by students.

A great number of phenomena or situations treated in physics instruction deal with the trans-phenomenological and unifying nature of energy. This can be accomplished by introducing a series of innovative activities covering various topics and aiming at students' mental construction of the basic characteristics of the concept, such as conservation, transfer and transformation. This approach, based on an innovative proposal about science curricula (Koliopoulos and Tiberghien, 1986), seems to be a promising instruction choice in order to minimize conceptual distance between students' mental representations and scientific models on one hand, and to show the social and cultural sides of the energy concept, on the other (Koliopoulos and Ravanis, 2000b).

In the framework of our results, we have to dismiss the empiricist approach based to many heterogeneous phenomenologi-cal situations in order to introduce some model of energy chain. On the other hand we propose a phenomenological field, based on electrical or/and th-ermal phenomena, which could facilitate perception of the energy representations by students. After understanding the features of this qualitative model of energy, students can be guided to apply it furthermore to mechanical phenomena.

The subject of the energy's didactic transformation, instructional approach and learning procedures constitutes an open research problem in Science Education. Our main objectives are to establish a functional relation between research findings about energy and teaching procedures applied in primary and secondary education schools.

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ΣΥΝΟΨΗ

Διδακτικές Επιπτώσεις των Αντιλήψεων των Μαθητών για την Ενέργεια: μια Προσέγγιση Μηχανικών, Θερμικών και Ηλεκτρικών Φαινομένων

Στην εργασία αυτή μελετώνται οι νοητικές αναπαραστάσεις μαθητών γυμνασίου σχετικά με την έννοια της ενέργειας και συζητούνται οι διδακτικές επιπτώσεις στο σχεδιασμό του περιεχομένου του αναλυτικού προγράμματος φυσικής. Αρχικά, γίνεται μια βιβλιογραφική επισκόπηση των νοητικών αναπαραστάσεων που έχουν οι μαθητές για την έννοια όταν περιγράφουν και ερμηνεύουν μηχανικά, θερμικά και ηλεκτρικά φαινόμενα. Η επισκόπηση αυτή συνδέει άμεσα τις νοητικές αναπαραστάσεις για την ενέργεια με το συγκεκριμένο φαινομενολογικό πεδίου στο οποίο δημιουργούνται. Στη συνέχεια, διερευνάται πως μαθητές του ελληνικού γυμνασίου χρησιμοποίησαν την έννοια της ενέργειας ως ενοποιητική γλώσσα για να περιγράψουν και εξηγήσουν συγχρόνως ένα μηχανικό, ένα θερμικό και ένα ηλεκτρικό φαινόμενο. Τα αποτελέσματα της εμπειρικής αυτής έρευνας, σε συνδυασμό με τα αποτελέσματα της βιβλιογραφικής έρευνας, δείχνουν ότι οι μαθητές γυμνασίου είναι σε θέση να εκφράσουν αυθόρμητα ενεργειακούς συλλογισμούς κατ' αρχήν συμβατούς προς το αποδεκτό επιστημονικό πρότυπο, είτε σε μόνο-φαινομενολογικές (κυρίως σε ηλεκτρικά και θερμικά φαινόμενα) είτε σε πολύ-φαινομενολογικές καταστάσεις, όταν ενεργοποιούν τον λεγόμενο γραμμικό αιτιακό συλλογισμό. Τέλος, προτείνονται νέες προσεγγίσεις του αναλυτικού προγράμματος, οι οποίες υπερβαίνουν αφ' ενός την φορμαλιστική παραδοσιακή προσέγγιση που εισάγει την ενέργεια ως παράγωγη έννοια του μηχανικού έργου αλλά και αφ' ετέρου τις νεώτερες εμπειριστικές προσεγγίσεις που χρησιμοποιούν αδιακρίτως όλα τα φαινομενολογικά πεδία για να εισάγουν την ενέργεια ως ενοποιητική δια-φαινομενολογική έννοια.