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La construcción de nociones sobre temas complejos, en estudiantes de educación media: un análisis mediante la Teoría de los campos conceptuales

The Construction of Notions on Complex Subjects, in Students of Secondary Education: An Analysis by Means of the Theory of the Conceptual Fields

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Resumen

En este trabajo se analiza y discute el modo en que estudiantes de 15 años de edad construyen conocimiento cuando se implementa una propuesta didáctica sobre el tema interacciones gravitatorias. La puesta en práctica de esta propuesta se constituyó en el espacio para analizar las acciones y relaciones que configuran la experiencia escolar de un grupo de estudiantes cuando se les ofrecen situaciones especialmente elaboradas sobre la base de los principios organizadores del contenido en cuestión y de las características propias del grupo social involucrado. El estudio de la conceptualización de las nociones sobre interacción gravitatoria se enmarca en la *Teoría de los campos conceptuales*, desarrollada por Gérard Vergnaud. Esta teoría es muy favorable para analizar los sujetos organizan las ideas y de qué forma forma las relacionan para generar nuevos conceptos y representaciones a lo largo del tiempo.

Palabras clave: Enseñanza de las ciencias, actividades de clase, conceptos científicos, formación de conceptos, teoría de los campos conceptuales.

Abstract

In this paper we discuss and analyze the way in which fifteen-years-old students construct their knowledge when they attend classes regarding gravitational interactions topic, in which a didactic strategy has been used. Such a strategy provided a space to analyze the actions and relationships that constitute the educational experience of a group of students, when they face situations specially designed from the organizing principles of the subject matter, as well as from the characteristics of the involved social group. The study of the conceptualization of gravitational interaction was based in Vergnaud's Conceptual Fields Theory. This theory is very favorable to analyze how people organize the ideas and connect ones with others, to generate new concepts and representations through the years.

Key words: Science education, class activities, scientific concepts, concept formation, conceptual fields's theory.

Introduction

Research in science education has, for over two decades, repeatedly come up with examples of the distance between explanations, as expressed by students when referring to a specific phenomenon or event, and the explanation on which consensus exists within the scientific community. The complex nature of any solution to this problem lies in the fact that the problem itself is multi-faceted. Different approaches such as the conceptual change (Posner, Strike, Hewson & Gertzog, 1982; Pozo & Gómez Crespo, 1998), conceptual evolution (Toulmin, 1972), and conceptual profiles (Mortimer, 1994), to name but a few, have been and continue to be used to explain, to model, and even to propose didactic strategies to overcome this situation.

This paper discusses the way in which *Polimodal* students build up their knowledge of gravitational interaction[1] In order to analyse what these constructs are, the *Theory of conceptual fields* (TCF) as developed by Gérard Vergnaud (1990,1996,1998) is employed. A cognitive theory that attempts to unravel the way in which knowledge is generated. The psychological, didactic and epistemological implications that may be derived from this theory reveal a possible pathway towards greater insights into the formation of scientific concepts in the classroom.

The results that are discussed here are the consequence of implementing a teaching strategy on the subject of gravitational interaction. Two key ideas are central to the organization of the proposed strategy:

- A set of disciplinary principles that constitutes the theoretical body of knowledge gravitational interaction.
- A set of situations where subject matter content covers one/some of those principles.[2]

The disciplinary principles that constitute the theoretical body of knowledge of the gravitational interaction were drawn up from a preliminary research work that included interviews with teachers, analysis of textbooks and surveys among students from different academic years (Stipcich & Moreira, 2001, 2002a, 2002b).

These principles, taken into account when designing the situations that would be presented to students, are as follows:

- *Reciprocal nature*: If an object A exerts a force on object B, then, object B will exert a force on object A, regardless of the nature of the two objects, A and B. In terms of forces, we can say that: $|F_{AB}| = |F_{BA}|$
- *Compositional nature*: An object termed A can be subjected simultaneously to different types of interaction, each acting independently from one another.
- *Additive nature*: The total field of force due to all the sources is the sum of the fields due to each source. If F is the field produced by various sources, we can say that:
  $F = F_1 + F_2 + F_3 + ...$

- *Simultaneous nature*: In terms of the action-at-a-distance model, interaction occurs at the same time in the two elements interacting.
- *Instantaneous nature*: In terms of fields of force theory, a finite period of time exists for an object A to interact with another object B.
- *The principle of the independence of the magnitudes of intervening objects*: Interactions are possible between objects at a microscopic, mesocosmic and macroscopic level.
- *The principle of the independence of the dynamic state of the participating objects*: Interactions are equally possible for objects at rest or in movement.
- *The principle of the independence of the distance separating participating objects*: Interaction occurs to objects that are very close as well as to objects that are far away from each other.

The teaching strategy was put into practice in such a way as to facilitate, for research purposes, the analysis of the actions and the relations that define the school experience of a group of students in which knowledge is constructed when situations are presented to them that are based on the above-mentioned principles.[3]

Theoretical framework

As it has been pointed out in the introduction, even though it is a cognitive theory, the adoption of TCF is based on the fact that its assumptions guide teaching decisions, and it is structured around appropriately explained epistemological assumptions.

If we were to offer an overview of TCF, we would have to start by defining it as a pragmatic theory that considers acquired knowledge as a function of the situations and of the actions undertaken by individuals in those situations. It is here that the notion of representation, developed by the theory, assumes importance. Representation is assumed to be a dynamic process that reproduces the structural form of the action (Vergnaud, 1998).

In order to study the way in which scientific knowledge is constructed, making use of the representations that the subjects themselves elaborate, those same representations have to be able to capture the relationships established in the action, as the majority of scientific concepts are interrelated. The notion of representation used in TCF is an alternative to the semiotic triangle, which many authors have used to describe concepts.[4] In the case of TCF, representation arises from the convergence of two elements: actions and language.

The incorporation of action and language into the notion of representation assumes that the latter has components in physical and social reality. The object of Vergnaud's research (1996) is the subject in a situation: the way in which subjects organize their behaviour, and the way in which they conceptualise in face of that situation.

Central to TCF is the concept of *scheme*, which coordinates the observable aspects of a subject's activity with mental aspects of representation. This is a concept inherited from Piaget which Vergnaud (1990) reworks by adopting the idea that a scheme does not correspond to a logical form, but that it is subsidiary to the content with which it is interacting. Vergnaud considers that the scheme is the lynchpin that makes it possible to think through the process of adapting cognitive structures.

The scheme is defined as the invariant organization of behaviour for a certain class of situations (Vergnaud, 1990, 1998). It is seen as a complete functional dynamic used to understand relationships between action and language.

Schemes form part of all possible modes of behaviour, including very different competences such as gestures, intellectual activities, affect, linguistic behaviours (Vergnaud, 1996). Schemes do not constitute elementary units but, on the contrary, are composed of four ingredients (Vergnaud, 1990):

1. *Goals and anticipations*: The goals of possible objectives to be achieved with the schemes that are at stake.
2. *Operational invariants*: The knowledge content of the schemes.
3. *Rules-of-action*: The rules that generate the sequence of actions to be taken. They are "if...then" types of rules that decide the search for information and monitor the results of the action. These rules contain the operational invariants that the subject uses in the action.
4. *Inference possibilities*: Allowing the rules and expected outcomes to be decided based on the information available to the subject.

The content of the schemes that are at stake are found within the operational invariants. Vergnaud defines two types of operational invariants(Vergnaud 1996):

1. *Theorems-in-action*: Propositions that the subject holds to be true in relation to the real world.
2. *Concepts-in-action*: A category of thought considered as relevant or a predicate assumed to be pertinent for a particular statement.

Concepts-in-action are essential components of theorems-in-action, but are different. There are no theorems-in-action without concepts-in-action but concepts-in-action make sense by themselves, in the absence of theorems-in-action. There is a dialectical relationship between them.

As stated before, the schemes that students develop are conditioned by the problematic situations they have to deal with. As a result, another key concept in TCF is that of the situation. It is the situation that constitutes the starting point in a particular conceptual field.[5] It is on the basis of the situations that the processes of cognitive functioning and development may be studied.

The situations that the subject faces are not to be understood in terms of didactic situations. They should be seen more as tasks. All complex situations can be analysed as a combination of tasks the nature of which it is important to understand. The difficulty of a task is not a result of adding together the difficulties of each of the sub-tasks by which it is formed. However, the performance of each sub-task affects the global performance (Vergnaud, 1990). As Frachi has stated: “A situation may be thought of as a particular complex of objects, properties and relations in a defined time and space, involving the subject and their actions”. (Franchi, 1999, p.158).

Situations are responsible for the sense attributed to a particular concept (Barais & Vergnaud, 1990). Nonetheless, it must be made clear that the sense is neither in the situations nor in the concept, but in the relation that the subject establishes with that situation. Clearly, the relation that the subject establishes when faced with a situation is mediated by schemes. It is, therefore, the operational invariants contained in the subject's schemes that are responsible for the meaning attributed to the situation.

Each conceptual domain may be approached through a large number of situations, in such a way that the meaning of a particular concept will arise from the different schemes that the subject is capable of bringing to bear on a variety of situations in which that concept plays a role.

In this investigation, the notion of *situation* is given a wide-range meaning, forming part of a teaching event and involving psychological components. An event in the teaching process is understood as a defined *space* during the lesson, in which both teachers and pupils dedicate time to a specially designed activity that is based on previous studies and has a defined purpose. The activity may be presented orally or in writing (a question or a problem) and simply consists of the intention (oral or written) of what will be the situation. The situation itself consists of the pupils' response to the situation as well as the teacher's own deliberate interventions to assist them in making the concepts more accessible. The situation, in this study, is what the teacher and pupils do in response to the activity at any particular moment in the classroom. As interest is centred on the way in which students conceptualise the notion of interaction, the analysis is focused on the indicators of the actions of the students, but that does not imply that the teacher's interventions are ignored. The situation has an important function in educational research since it is the space in which the conditions for learning and teaching are recreated according to a preset plan. Note that the situation is considered a construct for the educational research process, in similar terms to the way in which a psychologist would treat the processes recreated by a patient.

Methodological framework

This research may be classified as a study of ethnographical nature, since it attempts to conduct research into actions and relations that define the school experiences of a group of pupils in which the subject matter is gravitational interaction. To study the actions and relations that take place in school experience in their actual context (the classroom) is, in a way, to study the culture of the classroom. Bearing this in mind, it was decided to conduct participant observation in all classes that involved further development of the subject matter on gravitational interaction.

To seek to understand, through participant observation, the way in which pupils might be constructing knowledge, means it is necessary to record the interpretations expressed by the students. Relevant aspects of these interpretations that involve the subjects' internal states may be inferred by assessing the language used in the different interventions that they make in the classroom. It was therefore decided to make audio records of the oral conversations produced during the classes, at the same time as collecting some examples of individual written works.

The subject matter being studied requires a methodological approach that considers the following two steps:

1. Set down a description of the dimensions used to analyse the classroom situation, collecting information that allows the entire picture to emerge; those dimensions account for the dynamism of the actions that are developed in the class.
2. Insert in this framework the thematic relations that are to be specifically identified.

This means that the analysis has a dual purpose: being both dynamic and synoptic (Lemke, 1997). The first is related to what an event means to whoever is observing it. That is to say, it is the appraisal that is made of what is said and what is done at any given moment in this case, in the physics class. The synoptic variant is the overall vision of all the actions and discourse that occur at any other time and which are "looked at" as a sequence of actions tending towards an end.

Content analysis is used to carry forward an analysis that successfully incorporates what happened before. It basically consists of a set of systematic procedures and objectives that are intended to describe the content of the messages. This might be an analysis of what is signified, which is to say, a thematic analysis, or the analysis of the signifiers:

> To have recourse to these tools for meticulous documentary research is to stand firmly among the ranks of those who, from Durkheim to Bourdieu, and Bachelard, wish to say no to the illusory transparency of social facts, rejecting or trying to move away from the dangers of spontaneous understanding (Bardin, 1986, p. 21).

Analysis of the enunciation is used in this research. This technique assumes that communication is a process and does not simply produce static data. In this communicative process, discourse is understood as the word in action. That is to say, the production of an enunciation involves a process in which a meaning is elaborated and transformations are performed. It is not a completed discourse. On the contrary, it is a moment in a process. At that moment, elaboration is both spontaneous and forced by the classroom situation, which implies inconsistencies and a lack of conclusions. In synthesis, it is a dynamic discourse, which is the consequence of a set of thought transformations operating at different levels. An attempt is made to construct a coherent discourse, but attention is paid, at the same time, to the circumstances in which it is produced (Bardin, 1986).

The way the categories of analysis were defined is not discussed here due to restrictions on the length of this paper. Nevertheless, the following section gives examples of the way in which the oral discourse was analysed.

Examples of oral discourse

The following paragraphs present the first situation proposed to the class and the transcription of the audio recording of the expressions used by pupils in their oral discussions of such a situation.

Subsequently, on the basis of the previously explained theoretical and methodological frameworks, it is examined how it is possible to identify the way in which pupils construct knowledge.

As previously mentioned, a situation is much more than a stated intention, as it is presented in the following:

> **Teacher:** We will begin with the contents of this new module (gravitational interactions) by putting forward one of the problems that had to be solved: what is it that makes the planets move?
>
> Daily experience allows us to assume that the movement of a body is the consequence of its interaction with other bodies that surround it. Particularly, in relation to planetary interaction: how is it that the planets move? What are they interacting with?
>
> Some of the first ideas in circulation that attempted to respond to this question were the following:
>
> - Oresme, a bishop who participated in discussions on this problem supported the idea that if other "worlds" existed in the universe, matter situated near to them would be attracted towards their centre.
>
> - Kepler, a mathematician from that time, imagined that the planets were swept along in their orbits due to the influence of the Sun.
>
> - Galileo (the first to practice science, as we understand it today) came to the conclusion that if something moves without anything touching it or disturbing it, it will continue to move indefinitely in a straight line and at a constant speed.

- Another proposal upheld the idea that the planets were kept in orbit because there were angels behind them beating their wings and propelling them on their way.

Which of the ideas that have been put forward is the most acceptable to you? Why?

Are there any other possibilities to explain the movement of the planets? Explain your answer.

This proposal is intended to engage pupils in the analysis of a problem through the formulation of one or more hypotheses. It is understood that these statements may be critically analysed in view of their content and may further develop in relation to the subject matter in question. The following contents were taught over previous courses, and are related to this study:

- Attributes of scientific knowledge.
- The way knowledge is produced in physics.
- Physical system.
- The notion of force between two or more elements.
- Force as a cause of deformations or motional changes (modification of the value of the velocity module or of its direction).
- Force represented by a vector.
- Units in which force is expressed.
- The notion of constant velocity.
- The notion of acceleration as a consequence of net forces greater than zero.
- The weight force as the attraction exercised by the Earth.
- Allusion to the notion of gravity.
- Distinction between weight and mass.

Regarding mathematical contents, direct and inverse proportion, calculations and graphs, and scientific notation, may be mentioned.

The following are some of the interventions recorded during the discussions at a class.[6]

1. **T:** We are now going to discuss what you have thought up to this point. Give us all of your possible answers. It's your turn now. Let's see, over there, Julia.

2. **J:** Yes, we put the one about the influence of the Sun, because it is the most reasonable.

3. **P3:** The solar system was where the planets were. And we think that the centre of.... gravity, no. (she says it in a low tone of voice as if she were taking a risk)

4. **T:** Yes, we'll look at the names later, go on!!

5. **P3:** As if the centre of gravity is the Sun

6. **T:** Good, then, the Sun exercises a force on the planets so that they orbit it.

7. **J:** I think that as the Sun is the biggest in the solar system, it exerts more force on the others.

8. **T:** Tell me how you worked out that the Sun is the biggest.

9. **P3:** Well, because it has more mass.

10. **T:** And, so what...

11. **P3:** Because it's the one that attracts.

In these exchanges, the students opted for Kepler's proposal arguing that the Sun is responsible for the movement and they say it is the centre of gravity. In line 4, the teacher minimizes the importance of identifying the term centre of gravity and tries to redirect the discussion so that the choice of the Sun is justified as being responsible for the movement. As she does not achieve this (pupil 3 gives the same answer in line 5), in line 6 she synthesizes the idea picking up on the students' own words but overlooking the role of the centre of gravity. In line 7, Julia assigns a new property to the Sun, as the biggest element in the system, and as such, it has the possibility of exerting its force over all of the other planets. It is important to note the way in which the teacher in the following line questions her on that decision, which Julia associates with mass.

The TCF makes it possible to identify in these oral interventions the following *concepts-in-action*: mass, solar force, centre of gravity. Likewise, the *theorems-in-action* that might be recognized are: "The centre of gravity of the solar system is the Sun", and "The Sun exerts a force over the planets".

Going even further, it could be said that they had used the following types of *rules of action*: "If a planet (such as the Sun) is the biggest, then its mass is greater", "If its mass is greater, it exerts a greater force".

These rules of action are inferred from line 7 and are specified in lines 9 and 11. Note that they also contain the previously specified concepts-in-action and theorems-in-action. Later on, another group made the following comments:

12. **P4:** We chose or combined the first three. For example, what Kepler said or the first one.

13. **T:** Let's see what the first one says.

14. **P4:** It says that there are other worlds that would attract. And we agree with that.

15. **T:** ¿And which worlds would those be?

16. **P4:** Mars, or others.

17. **T:** Other planets. And, the centre of those planets, what would it feel attracted by?

18. **P4:** We think that there are other worlds but there is no other centre as powerful as the Sun. Then what Kepler said, some things, yes. For example the solar force, no?

19. **T:** ¿The Sun doesn't attract them?

20. **P4:** Yes, it does attract them but not necessarily. It is what has the greatest mass at the moment but if there were a planet that had a greater mass it would be attracted by that planet.

These contributions reaffirm some of the theorems-in-action inferred earlier. For example, in lines 18 and 20 the students represented by the voice of P4 make it quite clear that the Sun exerts a force because, at present, its mass is the greatest. The differentiating feature with regard to the conclusions of the former group is that this could change in the presence of a planet more massive than the Sun.

Further contributions were made by the following group:

21. **P5:** Without the influence of the Sun, the planet continues moving in a straight line.

22. **T:** Go on, Lucía.

23. **L:** Because of what Galileo says, it continues moving in a straight line with the same speed.

24. **T:** Which do you agree with?

25. **P6:** With Lucía. The speed wouldn't change.

26. **T:** Why wouldn't the speed change?

27. **P6:** Because there wouldn't be anything to disturb it.

28. **T:** And what is it that makes the speed of a body change?

29. **P6:** Friction.

30. **T:** Friction?

31. **P7:** A force.

32. **T:** Let's see. What has to be there for the speed to change?

33. **P:** A force.

34. **T:** There has to be a force. It could be friction, but not necessarily.

35. **P8:** It can decrease. (in relation to the speed and the effect of the force)

36. **T:** What other thing could influence the movement of a body?

37. **P9:** Deformation.

38. **T:** And the movement?

39. **P9:** A change of direction.

40. **T:** What would that be like?

41. **P:** And if the Sun wasn't there it would go in a straight line.

42. **T:** So you would agree with Galileo. If no force existed between the Sun and the planet, the planet would continue along a straight line, at a constant speed.

43. **P6:** Because it is moving without anything disturbing it.

44. **T:** So, there would have to be a force attracting the planets that would be in the Sun. That is where you agree with Kepler. If that force didn't exist, the planet would continue at a constant speed and in a straight line, now here you agree with Galileo. In line with the first idea, Tomás proposes that if there were another planet with a bigger mass than the Sun, they would be attracted towards that planet. That is what he suggested.

45. **P7:** Provided that they are at the same distance.

46. **T:** Augustín says that the distance is also important.

47. **T:** What provokes a force?

48. **P:** Change.

49. **T:** A change in what?

50. **P6:** A change in the speed and deformation.

51. **P7:** The speed can decrease or increase.

52. **P9:** Or change direction.

The interesting point in this discussion is that the pupils opt for Kepler's explanation, making use of the contribution made by Galileo. That is to say, they begin by assuming the presence of a force, as if it did not exist the planets could not follow an orbit as they do and would move in a straight line. Also noteworthy is that in line 45 a student introduces distance as a variable that can modify the conditions of the situations that had previously been discussed.

Among the *concepts-in-action* that were used, we can highlight: Solar force, velocity, the force of friction, distance, movement.

Analysing the exchanges between successive interventions, it is possible to reconstruct the following *rules of action*:

- **r1:** If there were no solar force, then, the movement of the planet would be in a straight line.
- **r2:** If there were no disturbance (understood as a force) then, the speed would not change.
- **r3:** If a force is applied, the speed could increase or diminish.
- **r4:** If a force is applied the movement (of a planet) changes direction.

Contained in each on of these rules are *theorems-in-action*. Amongst which, the following may be inferred: “The solar force changes the direction of the planet”, “The force provokes changes in the velocity”, “The force causes deformation”, “The distance between the Sun and the planets influences the attraction between both objects”.

Final comments

From the synoptic point of view, mentioned earlier in the methodological framework, it is important to highlight how the different components of the schemes proposed by students can constitute indicators of the way in which they are constructing knowledge.

The notion of a centre of gravity that students had brought up by themselves (lines 3 and 5), even though it was not included in the stated hypotheses, is an item that should be reconsidered. Likewise, in the first group of spoken interventions, there is an implicit association between the size of an element and its mass, an association that should be reviewed in other situations so as to make the necessary distinctions. (Lines 7 and 9).

In the last group of selected spoken interventions, there is a clear need to propose new situations that move the discussion on to the effects of a force on a moving body: The importance of insisting on the vectorial nature of velocity making it quite clear that the module may be constant and nevertheless the direction may be altered, which in student terminology appears under the heading of a “change of direction”.

Some of the questions that follow were advanced with the intention of developing the knowledge at stake in the treatment of the previously mentioned hypotheses:

- Is the tangential velocity of the Earth variable? And, of the Moon? Why?
- Is it possible for the same object to be submitted to more than one force of gravity? Why?

- If all the planets are pushing and pulling each other, is it not contradictory to say that the force that controls the movement of each one is the Sun?
- If there is a force of attraction between all objects, how come we are not pulled towards the buildings surrounding us?

To master a conceptual field, such as in the case of gravitational interactions, is a demanding task. This is a long-drawn-out process that can last several years in which there are successes and misunderstandings. Its correlate is that a concept is not formed within one single situation and, at the same time, a situation is not analysed with one single situation (Vergnaud, 1983). It is also important to note that different conceptual fields can be related to one another increasing the complexity of the operations of thought required to work through them.

The *Theory of conceptual fields* employed here appears to favour the analysis of how ideas, which the subjects have already connected up, are organized, and in what way this generates new concepts and representations over the course of time. Cognitive functioning (ideas or notions, connecting among themselves) is developed to deal with a particular situation and it becomes more powerful as it incorporates new aspects that are brought up by the situation.

Findings such as the ones presented in this paper could assist teachers in designing new situations which, when put into practice, would help students to broaden the scope of their conceptual skills. According to Vergnaud, *conceptualization* is at the heart of cognitive development.

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[1] *Polimodal* refers to the final stage of pre-university education. It involves students between 15 and 18 years-old, and is organized around modules such as social sciences, management, natural sciences, etc. In this research, the selected course is part of the natural sciences module.

[2] The term *situation*, on which details are given later on, is used with the same meaning as in the *Theory of conceptual fields*.

[3] It must be stressed that when we refer to school experience, we are alluding to the way in which knowledge is constructed *at school*.

[4] In the semiotic triangle, it is assumed that the concept of an *object* (situated on the upper vertex of an equilateral triangle) is defined by the *representation* of that object (situated on one of the lower vertices) and by the *symbol* with which it is associated (the element of the third remaining vertex).

[5] Knowledge, for Vergnaud (1982, p. 40), is organised into conceptual fields: “A conceptual field is an informal and heterogenous set of problems, situations, concepts, relations, structures, contents and operations of thought, some connected with others and, probably, interrelated during the acquisition process”.

[6] The letter **T** is used to identify the teacher's lines, whereas **P** followed by a number identifies pupils' participations. In cases where the teacher refers explicitly to the name of a pupil, the initial of the pupil's name is used.