Transfer of learning from classical mechanics to electricity and magnetism. Part 1

Transferencia de conocimientos de mecánica clásica a electricidad y magnetismo. Parte 1

*María D. González Quezada, *Sergio Flores García,*
Osiel Ramírez Sandoval, Víctor Carrillo Saucedo,
Juan E. Chávez Pierce, Luis L. Alfaro Avena

ABSTRACT

We have conducted an investigation to know in what extent students transfer knowledge acquired in classical mechanics courses to electricity and magnetism courses in introductory courses of physics. We have analyzed the students' responses to one selected pair of questions in the MEAT (Mechanics and electrostatics assessment tool (Gonzalez,2013). The first part of this investigation consisted in to probe the efficiency of the *escalator* and *transfer* diagrams, developed as instruments to measure gain in mechanics and transfer of concepts from mechanics to electrostatics respectively. Comparison of pre- and post students' performance on the mechanics questions of the MEAT, using the e*scalator* diagrams is a measure of the degree to which the exposure to the underlying ideas in a new context help to solidify the concepts first introduced in mechanics. Comparison of paired questions using the *transfer* diagrams is a measure of the degree to which students have *transferred* their understanding of mechanics into analogous concepts in E&M.

Keywords: Physics, electrostatics, Newtonian mechanics, knowledge of transfer of transfer

RESUMEN

Hemos realizado una investigación para conocer en que medida, los estudiantes en cursos introductorios de física transfieren conocimientos de mecánica clásica a electrostática. Analizamos las respuestas de los estudiantes a una pregunta seleccionada del MEAT (Mechanics and electrostatics assessment tool) (Gonzalez, 2013). La primera parte de esta investigación consistió en probar la eficiencia de dos instrumentos diseñados para medir ganancia en mecánica clásica y transferencia de conceptos de mecánica clásica a electrostática. La comparación del desempeño de los estudiantes en el pre-examen y el post-examen, utilizando el diagrama *escalador*, nos permiten saber en qué medida la exposición de conceptos en un nuevo contexto fortalecen los conceptos presentados previamente en el curso de mecánica clásica. La comparación de pares de preguntas usando el diagrama de *transferencia* es una medida del grado en el cual los estudiantes transfieren su entendimiento de mecánica clásica a conceptos análogos en electricidad y magnetismo.

* Universidad Autónoma de Ciudad Juárez,*seflores@uacj.mx*

Palabras Clave: Física, mecánica newtoniana y transferencia de conocimientos

Fecha de aceptación: 07.04.2015 Aprobado: 22.06.2015

Introduction

Transfer of learning has been considered as the ultimate goal in education (Lupart, Marini & McKeough, 1995). Our expectations, as educators and researchers, are students to show evidence of transfer in several contexts: from their home to school, from one course to another, and from school to their daily life. The success of people in their workplaces depends in the ability to apply their previous knowledge to solve new problems they encounter in a new and different context.

Transfer of learning has been defined as: "A situation where information learned at one time influences performance on information encountered at a later time" (Dufresne, Mestre & Royer, 2005), "applying that one has learned in one situation to a different situation" (Rebello et al, 2004), and "the degree to which a behavior will be repeated in a new situation" (Detterman, 1993). Processes of learning and the *transfer of learning* are central to understanding how people develop important competencies. It is important to understand the kind of learning experiences that lead to transfer (Cocking & Bransford, 1999). We will define transfer of learning as an individual and internal process that occurs when previous experiences are used to solve new problems in a different context.

The traditional sequence of topics in introductory physics is to some degree predicated on the assumption that the topics that are covered earlier form a basis for later topics, and that students who are successful in earlier courses will be able to use what was learned in those courses later on in a slightly different form or in a different context. Instruction often proceeds by analogy, and instructors assume that students will see how previously learned ideas transfer to new topics in the same way that the instructors do. For example, when instructors introduce electric potential difference, they usually remind students about what they had learned about work in mechanics, and electric potential difference is then defined in terms of the work done by the electric field. Success of this instructional strategy depends first on students' understanding of mechanical work, and additionally on their recognizing how electric potential difference is analogous to gravitational or mechanical potential difference. Similarly, understanding superposition of fields and forces in electrostatics presupposes an understanding of superposition of forces in the more familiar context of mechanics.

There are a number of electrical concepts that are usually introduced in analogy to mechanics concepts, for example:

- The concept of charge density is analogous to the mass concept. Both are ratios relating charge or mass to volume and do not depend on the size of the object
- The application of Newton's third law for E&M follows from similar application in mechanics. The interaction between charges is similar to the interaction between objects exerting gravitational, normal, or friction forces.
- Electrical and gravitational fields are both conservative. Just as the work done on an object in a gravitational field is independent of the path taken by the object, the electric potential difference between points in a uniform electric field will not depend on the path.

Motivation for study

One of the most prominent outcomes of physics education research is the awareness that while our students may be developing proficiency in solving standard problems in physics, this proficiency doesn't necessarily coincide with an increased conceptual understanding of the material (Kanim, 1999). The primary bearer of this bad news has been the Force Concept Inventory (Hestenes, Swackhamer & Wells, 1992), a 30-question multiple-choice diagnostic about concepts in introductory mechanics. For most instructors, the questions seem obvious and almost trivial, and it is disconcerting that students struggle with them even though they know how to use associated equations to solve problems that seem more challenging. The Force Concept Inventory (FCI) was developed on the basis of reported research results of specific student difficulties that are common in mechanics, and many of the distractors on the inventory reflect misconceptions that are often strongly held by many students about force and motion.

Student gains on the Force Concept Inventory are now the most often reported measures of instructional effectiveness in introductory physics (Dahan, Dehid, Lasry & Reshef, 2011), (Bao y Redish, 2006), (Coletta y Philips, 2005).

The success of the Force Concept Inventory has led to multiple attempts to write a similar diagnostic for the second semester Electricity and Magnetism course, including the Brief Electricity and

Magnetism Assessment BEMA (Coletta & Philips, 2006), the Conceptual Survey of Electricity, Magnetism CSEM (Hieggelke, Maloney, O'Kuma &Van Heuvelen, 2001), the Diagnostic Exam for Electricity and Magnetism DEEM (Marx & Wilson, 1998), and others. None of these have had anywhere near the impact that the Force Concept Inventory has had. Since there is not as strong a research base on student understanding of E&M as there is of student understanding of mechanics, it might be that the questions are not as good at highlighting student difficulties.

Design of instrument

The purpose to write a diagnostic for the Electricity and Magnetism course was to obtain a measurement tool that was *not* a concept inventory. The diagnostic, called the MEAT (Mechanics and Electrostatics Assessment Tool) was predicated on the following assumptions:

First, unlike mechanics, students do not tend to have strongly held misconceptions about electricity and magnetism. Young adults have already developed their own set of rules for how force and motion works based on a lifetime of interacting with objects and observing their motion. The misconceptions that are so prevalent in mechanics occur because these rules are not the same as the rules of physics. In contrast, students have very little concrete experience with electric and magnetic phenomena, and so the incorrect ideas about these topics are less likely to be strongly held, and many responses to diagnostic questions about E&M are more likely to be invented "on the fly" in response to the question asked (Maloney, 1995), (Harrington, 1995). As a result, when students are interviewed about E&M, their responses don't as commonly fall into the kinds of predictable categories that lead to appropriate distractors on multiple-choice diagnostics. Second, success in the second semester course depends less on 'overcoming' misconceptions and more strongly on what students learned in mechanics and on their ability to map the ideas introduced in the first semester course onto the new and unfamiliar context of E&M.

Rather than giving students a diagnostic that assesses their pre-course understanding of E&M, then, the core of the MEAT pre-test is a 12-question measure of students' conceptual understanding of some aspects of mechanics. There are additional questions on the pretest that are attempts to measure a few documented E&M misconceptions, and of students' understanding of vectors (Kanim, 1999) (Flores, 2006). The MEAT post-test asks the same questions at the end of the semester about mechanics, and then asks 12 *paired* questions in E&M.

The paired questions probe the same physics concept in both mechanics and electrostatics contexts, and are formulated as a measure of *targeted transfer*. The question in the mechanics context is considered the *source* and the question in the E&M context is the *target*. The 12 pairs of questions are distributed as follows: 1 pair about mass density and charge density; 2 pairs about vector superposition in mechanics and electrostatics contexts (tension and net force); 1 pair about Newton's 3rd law; 1 pair about Newton's 2nd law; 1 pair about energy conservation; 2 pairs about uniform, conservative fields; 1 pair about work as a dot product; 2 pairs about acceleration-electric field and velocity-electric potential graphs; and 1 about kinematics. The paired questions anticipate the analogous reasoning that textbooks and instructors use in teaching E&M.

There are multiple ways that the MEAT can be used and its results analyzed. In absolute terms, the MEAT pretest gives some measure of how much students have understood from the mechanics course, and of how well prepared students are to understand the analogous concepts in E&M. Comparison of pre- and post-performance on the mechanics questions of the MEAT is a measure of the degree to which the exposure to the underlying ideas in a new context help to solidify the concepts first introduced in mechanics. Student performance on the electrostatics questions measures their acquisition of new knowledge as a result of instruction in E&M. Finally, comparison of paired questions is a (perhaps crude) measure of the degree to which students have *transferred* their understanding of mechanics into analogous concepts in E&M.

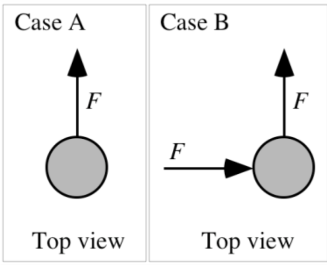
Population description

New Mexico State University is our primary source of data. Almost 40% of students are Hispanic, and three-fourths are from New Mexico. NMSU has an acceptance rate of about 96%, which is one of the highest acceptance rates of colleges and universities nationwide. Introductory physics courses are three 50-minutes lectures and there is no recitation section. There is an associated 1-credit laboratory that is required for some majors. About one-half of the students enrolled in lecture also take the laboratory section.
The course used as information source for this preliminary study was NMSU students taking an introductory calculus-based E&M course.

Experiment description

We selected one pair of questions and administered them to 90 New Mexico State University students in an introductory calculus-based E&M course as part of the first homework. One question of the pair asks students to compare the net mechanical force acting on two different objects based on the free body diagrams of each object (Figure 1 [a]); The paired electrostatics question is to compare the net electrical force on a charge due to different distributions of charges acting on it (Figure 1 [b]).

(a)



A 5-Kilogram mass is placed on a frictionless table, as shown in the top view. In case A it is pulled with a force F as shown. In case B two forces act on the 5-Kilogram mass: A pull with force F just as in case A, and a push of the same magnitude F at a 90° angle.

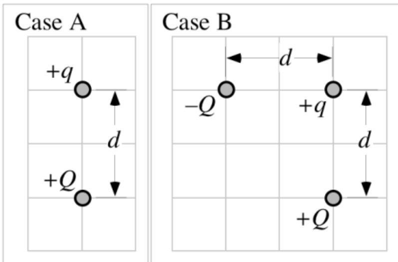
Which of the following statements is true about the magnitude of the net force in case B due to the push and the pull?

(a) The net force in case B is zero.
(b) The net force in case B is less than the net force in case A, but is not zero.
(c) The net force in case B is equal to the net force in case A
(d) The net force in case B is greater than the net force in case B, but not twice as great.
(e) The net force in case B is twice the net force in case A.
(f) There is not enough information to compare the net force in case B to the net force in case A.

Explain or show why you chose the answer that you did

(b)

In case A, a charge +q is placed a distance d from a second charge +Q as shown. Case B is identical to case A, except there is an additional −Q charge placed a distance d to the left of charge +q as shown.



Which of the following statements is true about the magnitude of the net force on charge +q in case B due to both the +Q and the −Q charges?

(a) The net force on +q in case B is zero.
(b) The net force on +q in case B is less than the net force in case A, but is not zero.
(c) The net force on +q in case B is equal to the net force in case A
(d) The net force on +q in case B is greater than the net force in case B, but not twice as great.
(e) The net force on +q in case B is twice the net force in case A.

(f) There is not enough information to compare the net force in case B to the net force in case A.
Explain or show why you chose the answer that you did

Figure 1 Paired question about net force. (a) Mechanics context. (b) Electrostatics context

Results

Using superposition of vectors, the correct answer in both the mechanics and electrostatics contexts is that the net force is greater in case B than in case A. The work of one student is shown in Figure 2.

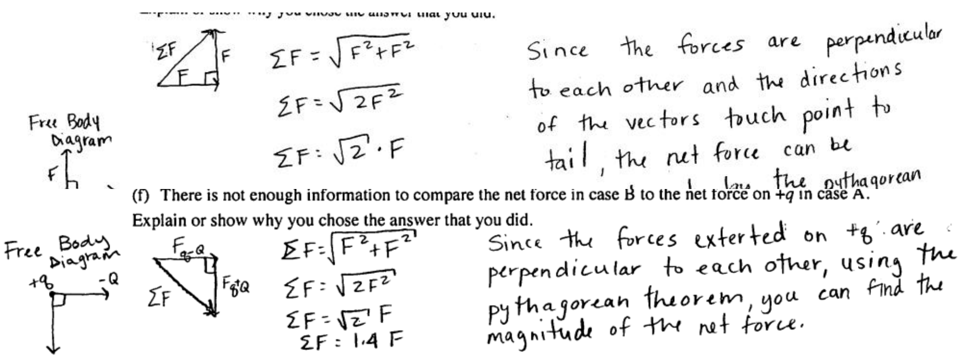


Figure 2 One student adds the forces graphical and analytically in both contexts: the mechanics and the electrostatics

Overall, 79 students (88%) answered correctly in the mechanics context and 75 (83%) in the electrostatics context. The number of students answering correctly in both contexts is 71 (79%) and incorrectly to both contexts 7 (8%). Eight students answering correctly in the mechanics context answered incorrectly in the electrostatics context and four students answering incorrectly in the mechanics context answered correctly to the electrostatics context. Results for this question are shown in the diagram in Figure 3. The top row gives the number of students answering the mechanics question correctly; the bottom row gives the number of students answering incorrectly. The left column gives the number of students answering the electrostatics question correctly; the right column gives the number of students answering incorrectly.

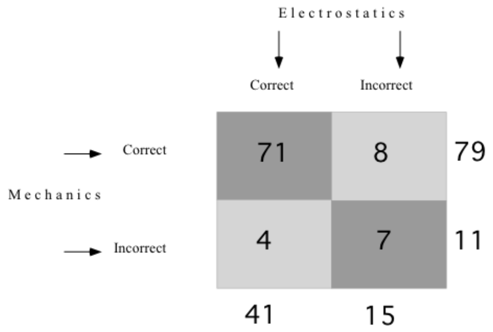


Figure 3 Diagram to represent correlation of mechanics and electrostatics results

The majority of students answering correctly in both contexts used the same reasoning or procedure. Of the 71 students answering correctly in the two contexts, 52 added vectors based on a free-body diagram, and then applied the Pythagorean Theorem. Figure 3 above shows one student drawing a free body diagram and finding the net force adding vectors graphical and analytically in the two contexts.

Another student, following the same procedure, explicitly stated that the reasoning or procedure to answer the question in the electrostatic context was exactly the same as in the mechanics context (Figure 4).

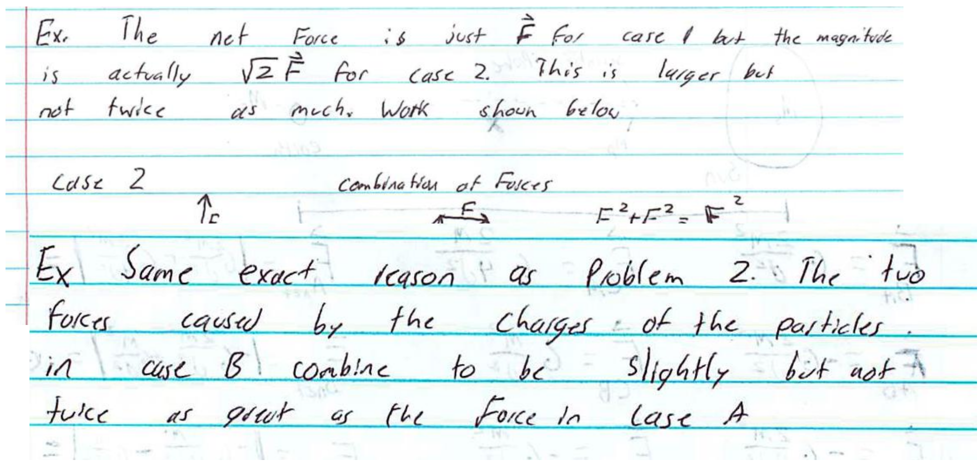
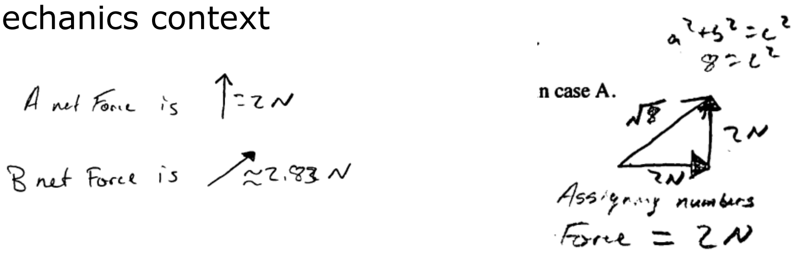


Figure 4 One student stated that the procedure to solve the question in the electrostatics context is the same as in the mechanics context.

Another two students, who answered correctly in the two contexts, assigned values to the forces in the two contexts to perform the sum of vector (Figure 5).

Mechanics context



Electrostatics context

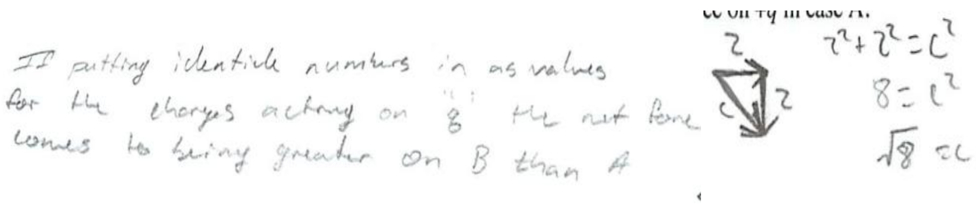


Figure 5 One student assigned values to the forces to calculate the sum of vectors in both contexts: the mechanics and the electrostatics

Four students correctly answering in the two contexts gave an incorrect reasoning. They stated that the net force in case B was greater than the net force in case B because of the number of forces acting on the object. One of these students explained:

> Mechanics context
> *"In case A the net force is equal to the only force acting. Whereas the net force in case B is the resultant of the two forces is greater than the single force acting in case B"*
> Electrostatics context
> *"The net force in case B is greater than the single force acting in case A"*

The rest of the students answering correctly in the two contexts (13) gave different reasoning for each context. For example, the student below is comparing the sum of the forces in the mechanics context, and explaining why he chose the correct option, and why he discarded the other options in the electrostatics context.

> Mechanics context
> *"The magnitude in case A is just F. In B is* $\sqrt{F^2+F^2}$ *, which is larger than F"*

Electrostatics context

"It should not be twice; they should be in a line if that were true. There is no way to be zero. It cannot be the same"

A different behavior was observed in students incorrectly answering in both contexts, where only 2 of 7 students used the same reasoning. One student's answers showing the same incorrect belief in both contexts are shown below.

Mechanics context

"In case A there is only one force acting on the object and case B there is 2 times the amount of force acting on the object meaning the net force in case B will be twice the net force in case A"

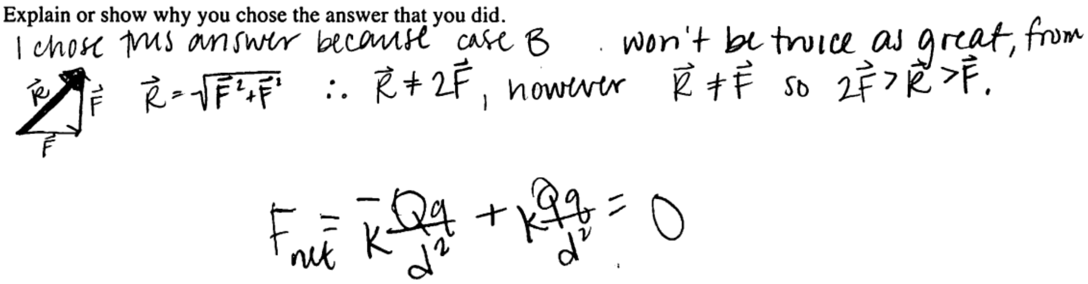
Electrostatics context

"Case B, there are two forces acting on +q one attracting to the left and one pulling upward. Where in case A there is only one force pulling upward."

The high percentage of students giving the same arguments to answer correctly in both contexts (52 of 71) could be an indicator that students are transferring the concepts and procedures. Nevertheless, it is difficult to be completely sure that transfer of knowledge is occurring because it is an individual and complicated mental process. For this study, we will assume, with certain restrictions that students answering correctly in the two contexts are showing evidence of transfer.

On the other hand, we cannot assure that students who answered incorrectly in the two contexts are transferring a misconception or a wrong procedure. The small percentage of students using the same reasoning or procedure of these students (2 of 7) cannot be used as an indicator of evidence of *negative* transfer (i.e. students using a misconception or a wrong procedure in the two contexts).

In this study, there were 8 students answering correctly in the mechanics context but incorrectly in the electrostatics context. Many of them performed a sum of vectors to answer in the mechanics context but summed algebraically in the electrostatics context. Figure 6 shows the work done by one of these students.


Explain or show why you chose the answer that you did.

I chose this answer because case B won't be twice as great, from $\vec{R} = \sqrt{F^2+F^2}$ $\therefore$ $\vec{R} \neq 2\vec{F}$, however $\vec{R} \neq \vec{F}$ so $2\vec{F} > \vec{R} > \vec{F}$.

$$F_{net} = -k\frac{Qq}{d^2} + k\frac{Qq}{d^2} = 0$$

Figure 6. An example of a student adding the forces as vectors in the mechanics context, but adding the forces algebraically in the electrostatics context

On the contrary, students who answered incorrectly to the mechanics context and correctly to the electrostatics context (only 4 in this study) summed algebraically in the mechanics context and performed a vector sum in the electrostatics context. The explanation one student gave is shown below.

> Mechanics context
> *"In this case B would double the net force only if both forces are equal."*
> Electrostatics context
> *"…but since case B we have another charge, when we add that force we get a slightly bigger net vector than case A, but will not be double."*

Again, we cannot categorically say that students in these two categories are not transferring concepts and procedures between contexts. However, again with some restrictions, we will assume that students answering correctly in one context and incorrectly in the other context are showing evidence of lack of transfer.

In the second part of this investigation, we will present data obtained from the MEAT according with these assumptions. We will refer to the diagram above as the Transfer diagram. The number in the upper left corner, in dark grey will correspond to students showing evidence of transfer. The numbers in the upper right corner and in the lower left corner, both in light grey, to students showing evidence of lack of transfer.

Similarly, we used The MEAT as a measure of mechanics understanding. Figure 7 show the "escalator" diagram, designed to give a sense of how student performance changed as a result of instruction. Data are shown only for the 55 students who took both pre and post-tests in this preliminary study. The upper part, in dark grey, contains the number of correct answers and the lower part, in light grey, contains the number of incorrect answers. For this question, 41 students answered correctly on the pretest, and 45 answered correctly on the post-test. The arrow in the downward direction and the number 2 beside it tell us the number of students changing from the correct answer on the pretest to an incorrect answer on the post-test. The number 39 in the middle part of the dark grey rectangle, the result of subtracting 2 from 41, represents the number of students answering correctly on both the pretest and the post-test. The arrow in the upward direction and the number 6 beside it tell us the number of students changing from an incorrect answer on the pretest to a correct answer in the post-test [We would like this number to be large!]. In the lower part, in light grey, 14 students answered incorrectly on the pretest. Eight students answered incorrectly on both the pretest and the post-test, and ten students answered incorrectly in the post-test.

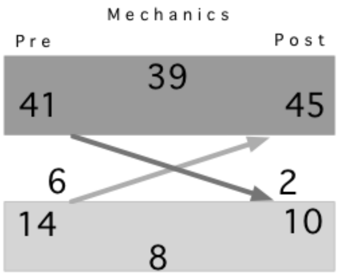


Figure 7. The "escalator" diagram showing student performance for a single question on both the pretest and the post-test.

Conclusions

The results in this preliminary study helped us to determine that we can use the *transfer* diagrams that we elaborated as an instrument to determine at first sight a measure of transfer of knowledge from mechanics to E&M context. The number of students answering correctly in the mechanics context as in the electrostatics context providing a similar reasoning or even explicitly stating that they used the same reasoning or procedure to answer, gave us confidence to state that the students in this category are showing evidence of transfer. Similarly, the explanations provided by students answering correctly to one context and incorrectly to the second context, showed the inconsistency on their answers. This fact allowed us to assume that students show evidence of lack of transfer. However, only few students answering incorrectly to both contexts used the same misconception to answer, not allowing us to state a negative transfer.

The "escalator" diagrams allowed us to see that 41 of 55 students (75%) arrived to the E&M course with a good understanding of the mechanics context, and that this percentage had a light improvement to 45 of 55 students (82%). We found a strong correlation between the "transfer" and "escalator" diagrams. Students need to use their previous mechanics concepts knowledge to be able to transfer them to the new context. Based on these results, the students' performance on mechanics questions on the MEAT, and the degree at which students have *transferred* their understanding of mechanics into analogous concepts in E&M will be measured and analyzed in the second part of this article.

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