Analysis of the learning of electrostatic concepts in pre-service physics teachers

N Garrido, V López, R Pintó

1CRECIM - Centre de Recerca per a l'Educació Científica i Matemàtica, UAB - Universitat Autònoma de Barcelona, Campus UAB, Edifici GL, 304, 08193, Bellaterra, Barcelona, Spain
2Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, 9170124, Estación Central, Santiago, Chile

Abstract. The objective of this work is to analyze the explanations of pre-service physics teachers, when they experience with different electrostatic phenomena included in a teaching and learning sequence (TLS). This TLS was designed for students to use the model of distribution and interaction between electric charges at first, for then promote that they explain certain more complex phenomena with the electric field model. The results show a significant improvement of the students’ explanations throughout the TLS due to several factors, including the teacher’s role.

1. Introduction
This research is framed within an electromagnetism course in the 3rd year of the Physics and Mathematics Teacher Training Program at the University of Santiago de Chile (USACH), in which Chilean pre-service teachers learn about two scientific models for their prospective teaching activity: the model of distribution and interaction of electric charges (addressed to 13-year-old students), and the model of electric field (addressed to 17-year-old students). Along the course, students deal with different everyday-life electrification phenomena (such as attracting pieces of paper using a charged dielectric stick) and they also use different electrostatic laboratory devices, such as electroscopes and Van de Graaff generators. After some years of implementing the course, there emerged a need to better understand why some students had difficulties to understand complex models such as Gauss’s Law, so we decided to go into much more detail in students understanding of electric charges and electrization phenomena.

2. Theoretical framework
2.1 The school model of distribution and interaction between electric charges
Despite the polysemy of the word “model” and its several meanings found in literature, scientific models can be understood as representations of real or conjectured systems. They are characterized by a set of objects with their outstanding properties and by a set of statements that declare the behaviours of these objects and allow descriptions, explanations, and predictions [1] [2]. In science education, a school science model can be understood as a scientific model that has been didactically transposed to facilitate the understanding of a specific group of students [3] [4]. The aim of introducing the perspective of models in pre-service teachers is making them able to construct scientific explanations based on theories and ideas accepted by the scientific community, allowing them to interpret everyday life phenomena [5].
One of the scientific school models expected to be learn in the USACH electrostatic course is the **electrostatic model of distribution and interaction between electric charges**, which can be summarized by a set of statements:

1. Matter is electric because it has positive and negative charges.
2. If a body has more positive than negative charges, it is positively charged, and if it has more negative charges, it is negatively charged.
3. Neutral bodies have the same number of positive and negative charges.
4. The charges of the same sign are repelled and those of opposite sign are attracted.
5. The magnitude of the repulsion or attraction forces between two bodies depends both on the number of charges and on the separation distance between them.
6. The net charge within an isolated system is always constant.
7. In dielectric materials, the movement of charges is very reduced. Dielectric bodies can be partially charged, and they are spontaneously discharged very slowly if they are not isolated.
8. In conducting materials, the movement of charges is feasible throughout its surface and, therefore, it discharges immediately if it is not isolated.

*According to this model, materials are divided between dielectrics and conductors, while other more complex electric behaviour, such as semiconductor materials, are not considered.*

Based on these statements, “electrization” can be understood as the process in which the positive and negative charges of a body or part of it are imbalanced. This electrization can be produced if positive or negative charges are transferred from one body to another, and also if positive and negative charges reorder inside one single body. The combination of electric materials and electrization mechanisms, allows distinguishing between 4 methods, summarized in table 1.

|          | Dielectric material | Conducting material |
|----------|---------------------|---------------------|
| Transfer of charges | Electrization by friction | Electrization by conduction |
| Reorder of charges | Electrization by polarization | Electrization by induction |

That is, transfer of charges can take place when there is friction between two bodies, in which one body becomes positive and the other becomes negative (electrification by friction), and it can also take place when a charged body gets into physical contact with another one (electrification by conduction), since some of the charges move from one body to the other. In contrast, when a charged body is set close to a neutral one, a distribution of charges occurs in it, this is called “reordering”. If the neutral object is a dielectric, it will be polarized (electrification by polarization), and if it is a conductor, it will displace the free charges on the surface, as much as the material allows it (electrification by induction).

![Figure 1. Attraction between a charged stick and pieces of paper. Left: Photo of the phenomena. Right: Representation of charges involved in the interaction.](image)

By combining these four electrization mechanisms, many electrostatic phenomena can be explained, such as the attraction of small pieces of paper by a charged dielectric stick (figure 1), or the
behavior of electrosopes (figure 2). In figure 1, the stick has been charged by friction, and then it is approached to the pieces of paper. The paper is a dielectric material, so it does not allow the charges to move across it, but slight displacements of the dipole charges are produced. The force of attraction is greater than the force of repulsion on the opposite charges, so if this difference between the two forces exceeds the weight of the pieces of paper, they are lifted, getting stuck to the stick. In figure 2, the behaviour of the electroscope is different depending on whether it is neutral (all the charges are homogeneously distributed around the body) or it has been electrized by induction or by conduction.

2.2. Students’ difficulties in the understanding of electrostatics
Many difficulties related to students’ understanding of electrostatic concepts can be identified in the literature. Their understanding is usually affected by the density of concepts needed to understand electrical phenomena [6] [7]. Some of the most common difficulties are the idea that neutral bodies have no charge, the idea that friction between two dielectric bodies “creates” new electric charges, and the problems to understand how the charge is distributed in dielectric materials and conductors. In addition, spontaneous ideas of students and their similarities to the models that had historically emerged during the development of the theory can be observed [8]. This shows that simple phenomena of electrification by friction and induction are interpreted by students according to conceptual stages, including creationist approach (electricity appears in a body when it is rubbed), halo-effect approach (electricity acts around charged bodies), electric fluid approach (electricity is an electric fluid that acts by contact) and electric induction approach (electricity is a group of charges that acts at a distance). Finally, Vercellati and Michelini’s [9] findings show that confusion between physics domains (force, energy, electricity and magnetism) occurs when students explain the electrostatic phenomena using the idea of magnetic force.

2.3. Transfer of knowledge from one electrostatic phenomenon to another
Gick and Holyoak (1987) [10] define the transfer of skills as a process that implies a change in the development of a task resulting from the performance of a different task. The transfer is close if it is applied in a type of task which is similar to the previous one and in the same area of knowledge. Instead, the transfer is distant, if it is applied in a task of another type and area. At the same time, the transfer can be "low-road" when it is an automated process because of the repeated practice of the same task, or "high-road" when it depends on the student performing a deliberate process of abstraction of a principle. The specialized literature on the subject has constantly raised the question of whether it is possible to transfer the so-called 'cognitive skills', such as problem solving, critical thinking, meta-cognition and communication, considering that they are skills applicable to any discipline [11].

Through a review of 700 researches on the development of cognitive abilities in higher education students, Billing [11] identifies the conditions which foster the transfer of reasoning skills and problem solving skills: (a) learning self-monitoring principles, concepts and practices, (b) using various examples and potential applications in which the students discover the underlying explanations, (c) feedback on the performance, (d) an appropriate social space that stimulates the elaboration of students explanations, and (e) showing students similarities between different situations.
3. Research questions
Considering the model of distribution and interaction of charges previously defined, and also students’ difficulties in the understanding of electrostatics, and the conditions that foster the transfer of knowledge from one electrostatic phenomenon to another, we wonder:

- 1. How do pre-service physics teachers explain the different existing electrification mechanisms using their ideas about charge distribution and interaction?
- 2. How do these explanations evolve along a teaching-learning sequence in which students have to transfer their knowledge from one phenomenon to another?

4. Methodology
In order to analyze the pre-service physics teachers’ ideas about charge distribution and interaction, and their evolution when transferring them from one electrostatic phenomenon to another, an instructional sequence was designed, in which students were asked to explain different phenomenon several times by drawing and writing. This instructional sequence was implemented in 2016 and 2017, and students’ answers were collected and analyzed, which allowed us to classify them and observe their evolution along the sequence.

4.1. The instructional sequence
In 2015, an instructional sequence was designed on the basis on previous research on students understanding of electrostatic concepts [12]. The sequence followed a step by step structure, combining classroom big-group discussions [13], individual and small-group inquiry and modeling activities [14], and interactive demonstration made by teacher [15]. The aim of the sequence was not to provide students with isolated and cumulative concepts, facts and equations (as it had been done in traditional lectures in the USACH), but to help them to reason about multiple electrostatic phenomenon based on models [16], promoting the development of students’ language and providing them cognitive support in the reasoning process [17].

The central role that the sequence gives to students’ explanations is because they are a daily and essential component in the teaching practice [18] and a fundamental part of the models that the students build. In addition, it is known that novice teachers have difficulties in constructing explanations in the classroom and in getting students to generate explanations [19]. The sequence is strongly supported by a multimodal communication [20] due to the good results shown by Petridou [21] and Taramopoulo [22] regarding the teaching of electrostatics. We consider in the different representations, different levels of analysis: microscopic [21] and macroscopic [23] and combinations between abstract representations and the real phenomenon [22].

| Table 2. Structure of the instructional sequence implemented with pre-service physics teachers. |
|---------------------------------------------------------------|
| **Sessions** | Activities in which the data were collected | Electrization methods involved in the phenomena |
| Session 1: 3 hours | 1. Distance interaction between charges in stick (charged by friction) and little pieces of paper (first explanation) | Friction and Polarization |
|  | 2. Contact interaction between charges in stick, a metal ball and a metal bar (first explanation) | Conduction |
|  | 3. Contact interaction between charges in stick, a metal ball and a metal bar (improved explanation) | Conduction |
|  | 4. Contact interaction between a latex balloon (charged by friction) and the plaster wall (first explanation) | Friction and Polarization |
|  | 5. Distance interaction between charges in stick (charged by friction) and little pieces of paper (improved explanation) | Friction and Polarization |
| Session 2: 3 hours | 6. Distance interaction between a charged resin stick and an electroscope (first explanation) | Induction |
|  | 7. Distance interaction between a charged resin stick and an electroscope (improved explanation) | Induction |
As presented in table 2, students first deal with different simple electrification phenomena in specific contexts to test their models, and then they are faced with more complex phenomena: an electroscope, a Van der Graft generator and a Faraday cage. The sequence also includes the idea of electric field (which cannot be explained with the model of charges previously described), since field-based model is more efficient than force-based model when explaining the Faraday cage phenomenon [7]. However, the analysis of students’ ideas about field-based model goes beyond the study presented in this paper, so it has not been included.

4.2. Data collection and analysis
A total of 50 students of the Physics and Mathematics Teacher Training Program at USACH were enrolled in the Electromagnetism course during 2016 and 2017. All students used their own student portfolio that included all the worksheets provided by teacher. After finishing the sequence, the teacher collected and scanned all the worksheets, and a total of 1000 answers (that is, 20 activities per 50 students) were uploaded to the Atlas.ti software, in which every answer corresponded to an analysis unit, and which could include both written text and drawings.

These 1000 analysis units were qualitatively analyzed following a bottom-up approach and a comparison by contrast technique, assuring the validity of results by triangulation of the analysis. The analysis categories were grouped according to dimensions, which corresponded to the four electrization methods presented in table 1. For each dimension, 4 categories were used:

- Description without explanation (L0), in which the electric phenomena are not explained but only described.
- Confusion between charge transfer and reorder (L1), that is, in which students make explanations that correspond to other electrization methods.
- Explanation with non-consistent aspects (L2), in which students provide explanations that are coherent with the model but include some non-consistent aspects from the physics’ point of view.
Explanations which are consistent with the model (L3), in which students are supposed to understand properly the electrostatic model of distribution and interaction between electric charges.

In the following tables these categories are presented in detail for all the four dimensions.

**Table 3. Categorization of the dimension “Electrization by friction”**

| Category | When can we find it? | Example of student answer |
|----------|----------------------|---------------------------|
| Description without explanation (L0) | Electrization by friction is not explained. It is only said that it allows to charge a body. | “When the comb is exposed to friction, it becomes electrically charged” |
| Confusion between charge transfer and reorder (L1) | Electrization by friction is explained as a reordering of charges, like polarization. |
| Explanation with non-consistent aspects (L2) | Electrization by friction is explained by a transfer of charges between two dielectric bodies, resulting both charged, but as if it were a conducting material. |
| Explanations consistent with the model (L3) | Electrization by friction is explained by a charge transfer from one dielectric to another, resulting both with an excess of opposite charges in the zone exposed to friction. |

**Table 4. Categorization of the dimension “Electrization by polarization”**

| Category | When can we find it? | Example of student answer |
|----------|----------------------|---------------------------|
| Description without explanation (L0) | Polarization is not explained. It is only said that there is a reordering of charges. | “(The polystyrene ball) tends to get stuck to the VDG” |
| Confusion between charge transfer and reorder (L1) | The charges of an excessively charged dielectric material reorder the charges of another neutral dielectric material through contact. | “The balloon moves the charges of the wall when touching it” |
| Explanation with non-consistent aspects (L2) | The charges of an excessively charged dielectric material reorder the charges of another neutral dielectric material due to the sign of the charge of the first material |
| Explanations consistent with the model (L3) | The charges of the external body exert a force of attraction and repulsion over the charges of the neutral dielectric. This produces a reordering of its charges. |

**Table 5. Categorization of the dimension “Electrization by induction”**

| Category | When can we find it? | Example of student answer |
|----------|----------------------|---------------------------|
| Description without explanation (L0) | Induction is not explained. It is only said that there is a reordering and movement of charges. | “The electroscope will move slowly” |
| Confusion between charge transfer and reorder (L1) | The charges of an excessively charged body are transferred to the conductive material at distance. |
Explanations consistent with the model (L3)

The charges of an excessively charged body are transferred to a neutral conductor isolated by contact, leaving the conductor with the same sign of the charge in excess. The charge is uniformly distributed over the surface of the conductive material.

---

**Table 6. Categorization of the dimension “Electrization by conduction”.

| Category                                      | When can we find it?                                                                 | Example of student answer                                                                 |
|-----------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Description without explanation (L0)          | Conduction is not explained. It is only said that if the charged body touches another, the latter obtains the same charge (sign). | “When it (the charged body) gets in contact with another metal bar, it becomes charged with the same charge as the first bar” |
| Confusion between charge transfer and reorder (L1) | The charges of an excessively charged body reorder the charges of the conductive material through contact |                                                                                          |
| Explanation with non-consistent aspects (L2)  | The charges of an excessively charged body are transferred to a neutral conductor isolated by contact, leaving the conductor with the opposite sign of the charge in excess. |                                                                                          |
| Explanations consistent with the model (L3)   | The charges of an excessively charged body are transferred to a neutral conductor, isolated by contact, leaving the conductor with the same sign of the charge in excess. The charge is uniformly distributed over the surface of the conductive material. |                                                                                          |

5. Results and discussion

The graphic of figure 3 summarizes the obtained results, including four graphics corresponding to the four dimensions of analysis (friction, polarization, induction and conduction). The horizontal axis corresponds to the evolution of the instructional sequence, according to the list of 20 activities presented in table 3. So, numbers from 1 to 20 in figure 3 correspond to activities 1 to 20. The values presented in these graphics correspond to the prevalence of the four categories presented above per dimension and per activity. We have used a color code that uses a traffic light metaphor: Description without explanation (L0=Grey); Confusion between charge transfer and reorder (L1=Red); Explanation with non-consistent aspects (L2=Yellow); Explanations consistent with the model (L3=Green). The size of the circles corresponds to the number of students that have been classified in each category for each dimension and for each activity, so the bigger the circle, the more answers were classified as part of that category.

As presented in table 2, each activity concerns only one or two electrization methods (that is, its answers have been analyzed from the corresponding dimensions), so in graphic some empty boxes can be observed, which correspond to the electrization mechanism that intervene in the specific phenomenon.

Based on the proposal made by Hernández, Couso and Pintó [24], we have included straight lines in the graphics, connecting the category with the highest prevalence in each activity. The solid lines correspond to the connection between activities in which students deal with the same electrostatic
phenomenon, while dashed lines correspond to connection between activities concerning different electrostatic phenomenon.

Figure 3. Graphic corresponding to the number of answers classified in each category (L0, L1, L2 and L3) for each dimension (friction, polarization, induction and conduction) and for each activity (from 1 to 20). The quantity of students is represented by the size of the circumferences.

These graphics show that there was an overall positive evolution in the quality of the students’ explanations along the sequence. For example, 21 of 50 students moved from an explanation based on the idea that "a charged body can attract other objects" to the idea that "the difference between the magnitude of the force of attraction and repulsion leads to a reordering of the charges of a neutral body, causing its attraction or its reorientation".

At the same time, these graphics allow observing a difference between solid and dashed lines (that is, in those cases in which students remain in the same context and those cases in which students have to transfer their knowledge from one context to another). Students’ explanatory level decreases when there is a change of context (dashed lines), and then it increases again after an activity in which students have to improve their explanation (solid lines). This evolution can be observed in electrization by polarization, when analyzing the change from activity 5 to 14. As presented in table 2, activity 5 concerns the interaction between a resin stick and little pieces of paper, while activity 14 is related with the interaction between a VDG generator and a polystyrene ball. In this case, most of students fail in transferring their knowledge from one context to another. At the same time, we can observe that in activity 15, students’ explanatory level rises again, after students participate in a group discussion and are asked to improve their explanations. Then, in activity 19 the level decreases again when there is a new change of context (now the context is the interaction between an electrode in a bucket and little pieces of thread floating in oil), and it increases again in activity 20, when students are asked to improve their explanations in the same context.

A similar result can be observed when analyzing the answers about electrization by induction: a decrement from activity 8 to 12, and a similar decrease from activity 13 to 16. In both cases, students fail in transferring their knowledge from one context to another, but then they reach higher levels of explanations when they have to improve them after group discussions.

Finally, we can observe that the answers about electrization by friction follow a different pattern than the others. By analyzing students answers, we realize that this is not because of the change of context, but because students must explain two electrization mechanisms at the same time (friction and
polarization, see activities 1, 2 and 5 in table 2), so their efforts are focused on improving the explanations about polarization, leaving the explanations about friction aside.

6. Conclusions

The explanations given by pre-service physics teachers about the existing electrification mechanisms are strongly affected by their ideas about charge distribution and interaction, which are not always consistent with the science school model of distribution and interaction between charges. Despite this model clearly distinguishes between transfer mechanisms (friction and conduction) and reordering mechanisms (polarization and induction), some students tend to confuse these mechanisms, providing wrong explanations about simple electrostatic phenomena. At the same time, other explanations are also affected by other non-consistent ideas, such as that confusions between dielectric and conducting materials, or confusions with the positive / negative sign of charges. These students’ alternative ideas about the behavior of charges and electric materials are coherent with some of the findings presented in the literature [7] [8].

In parallel, most students experience an evolution of their explanations along the instructional sequence. This evolution combines increments of the explanatory level, which is mainly observed when students go into detail about the same phenomenon (that is, the same context), and they are asked to improve their explanations through group discussion, new observations and teacher feedback. The decrease in the explanatory level can be mainly observed when students have to transfer from one context to another. Coinciding with Billing [11], the difficulties to overcome the students’ difficulties to transfer their knowledge and skills from one context to another is still a challenge. For this reason, we can conclude that despite being progressive, the evolution of students’ explanations cannot be understood as a linear process.

Finally, we want to remark that this study has been extremely valuable in the paradigm of research-based design in order to improve the instructional design used in the following courses in USACH. The instructional sequence has been re-designed to improve the scaffolding strategies, such as graphic representations that promote students’ explanations, specific experimental set-up that helps students reasoning and combination of phenomena that allow students to refine their models. With this work, we hope to contribute with strategies that may be beneficial in the future professional performance of the students of the Physics and Mathematics Teacher Training Program, enriching their knowledge so they can explain the electrostatic phenomena with ease, using the models as a reference. This research should also be of help to make them able to carry out a correct didactic transposition for their students, avoiding the difficulties of learning reported in the literature. In this way, they will meet the demands of our national curriculum, which states that teachers must ensure that their students are able to "build explanations about natural phenomena based on principles and scientific evidence" [25].

7. References

[1] Oh PS nd Oh SJ 2011 What teachers of science need to know about models: an overview Int J Sci Educ 33(8) 1109–30
[2] Gutierrez R 2004 La modelización y los procesos de enseñanza/aprendizaje Alambique. 42 8-18
[3] Izquierdo M, Espinet M, García M, Pujol R and Sammartí N 1999 Caracterización y fundamentación de la ciencia escolar Enseñanza de las Ciencias 17 (1) 45-59
[4] Acher A, Arcá M and Sammartí N 2007 Modeling as a teaching learning process for understanding materials: A case study in primary education Science Education 91(3) 398-418
[5] Zangori L and Forbes C 2013 Preservice elementary teachers and explanation construction: Knowledge-for-practice and knowledge-in-practice Science Education 97(2) 310-30
[6] Shipstone D, Rhöneck C, Jung W, Kärqvist C, Dupin J, Johsua S and Licht P 1988 A study of students’ understanding of electricity in five European countries International journal of science education 10(3) 303-16
[7] Guisasola J 1996 Análisis crítico de la enseñanza de la electrostática en el bachillerato y propuesta alternativa de orientación constructivista Universidad del País Vasco 104
[8] Furió C, Guisasola J and Almudí M 2004 Elementary electrostatic phenomena: historical hindrances and students’ difficulties Canadian Journal of Math, Science & Technology Education 4(3) 291-313

[9] Michelin M and Vercellati S 2010 Primary pupils explore the relationship between magnetic fields and electricity In Raine, D., Hurkett, C., Rogers, L., Physics Ed. Community and Cooperation: Selected Contributions from the GIREP-EPEC & PHEC 2009 International Conference, Lulu/The Centre for Interdisciplinary Science Leicester vol. 2, p 162-70).

[10] Gick M L and Holyoak K J 1987 The cognitive basis of knowledge transfer Transfer of learning: Contemporary research and applications 9-46

[11] Billing D 2007 Teaching for transfer of core/key skills in higher education: Cognitive skills

[12] Guisasola J Zubimendi J L Almudí J M and Ceberio M 2008 Difficulties persistent in the learning of electricity: reasoning strategies of the students to explain phenomena of electric charge Enseñanza de las Ciencias 26 177-91

[13] Mercer N 2010 The analysis of classroom talk: Methods and methodologies British journal of educational psychology 80(1) 1-14

[14] Schwarz C V Reiser B J Davis E A Kenyon L Achér A Fortus D and Krajcik J 2009 Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners Journal of Research in Science Teaching 46 632-54

[15] Sokoloff D and Thornton 2004 Interactive Lecture Demonstrations: Active learning in introductory physics (Wiley-VCH New York) p 374

[16] Duschl R, Maeng S and Sezen A 2011 Learning progressions and teaching sequences: a review and analysis Studies in Science Education 47(2) 123-82

[17] Hernández M, Couso D and Pintó R 2015 Analyzing students’ learning progressions throughout a teaching sequence on the acoustic properties of materials with a model-based enquiry approach Journal of Science Education and Technology 24(2) 356-37

[18] Geelan D 2012 Teacher explanations Second International Handbook of Science Education ed B Fraser (The Netherlands: Dordrecht) pp 987-99

[19] Tang K 2016 Constructing scientific explanations through premise-reasoning-outcome (PRO): an exploratory study to scaffold students in structuring giren explanations International Journal of Science Education 38(9) 1415-40

[20] Kress G, Ogborn J and Martins I 1998 A satellite view of language: some lessons from science classrooms Language Awareness 7(2-3) 69-89

[21] Petridou E, Psillos D, Hatzikraniotis E and Viiri J 2009 Design and development of a microscopic model for polarization Physics Education 44(6) 589

[22] Taramopoulos A and Psillos D 2017 Complex phenomena understanding in electricity through dynamically linked concrete and abstract representations Journal of Computer Assisted Learning 33(2) 151-63

[23] Eylon B and Daniel U 1990 Macro-micro relationships: the missing link between electrostatics and electrodynamics in students’ reasoning International Journal of Science Education 12(1) 79-94

[24] Hernández M, Couso D and Pintó R 2012 The analysis of students’ conceptions as a support for designing a teaching/learning sequence on the acoustic properties of materials Journal of Science Education and Technology 21(6) 702-12

[25] Ministerio de Educación 2015 Bases Curriculares 7º básico a 2º medio (Santiago de Chile: Ministerio de Educación)