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Designing a teaching sequence for electrostatics at undergraduate level by using educational reconstruction

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Abstract

Building up a comprehension of electrostatics and especially Gauss's law depends on understanding the concept of an electric field. Previous studies demonstrate several learning problems that occur in relation to electrostatics, and the concept of an electric field is one of them. By eliciting information about a student's thinking, it is possible to address the common denominators that form the main obstacles to learning the scientific content of electrostatics. Physics theory at university level is traditionally presented in an abstract and compact form as a result of the evolution of its theory. In this study we approach the problems involved in the teaching and learning of electrostatics by applying the method of educational reconstruction in order to devise more effective teaching. In doing so, we hope to improve students' performance in their adoption of the electrostatics content aimed at in the course**.**

Keywords: Undergraduate, electromagnetics, electric field concept.

Resumen

La comprensión de la electrostática y especialmente, la ley de Gauss dependen de la comprensión del concepto de campo eléctrico. Estudios anteriores demuestran varios problemas del aprendizaje que ocurren en relación a la electrostática, y el concepto de campo eléctrico es uno de ellos. Mediante la obtención de información sobre el pensamiento del estudiante, es posible hacer frente a los denominadores comunes que constituyen los principales obstáculos para el aprendizaje del contenido científico de la electrostática. La teoría de la física a nivel universitario es tradicionalmente presentada en una forma abstracta y compacta, como resultado de la evolución de su teoría. En este estudio nos acercamos a los problemas de la enseñanza y el aprendizaje de la electrostática mediante la aplicación del método de reconstrucción educacional con el fin de diseñar una enseñanza más eficaz. Al hacerlo, esperamos mejorar el rendimiento de los estudiantes en su adopción de los contenidos destinados a la electrostática en el curso.

Palabras clave: Pregrado, electromagnetismo, concepto de campo eléctrico.

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I. INTRODUCTION

An introductory electromagnetics course will generally cover the domain of the integrally formed Maxwell's equations in addition to the basic theory of electric circuits and electromagnetic waves. Learning Gauss's law involves understanding its relationship to the integral calculus of vector fields and their physical interpretation, which is also the case with the other Maxwell's equations. Thus, the concept of an electric field plays a key role in understanding Gauss's law in particular, and thus also electric potential, capacitance, and current.

The reasons suggested for learning difficulties in electrostatics include misconceptions about electric field lines and the electric field vector. In addition, students have difficulties with the graphic representation and interpretation of electric field lines [1]. The electric field vector becomes difficult in a physical context because undergraduate students understand mathematics as mechanical method, not as constructive thinking [2]. Learning Gauss's law requires them to gain an understanding both of electric field and of vector calculus in a physical context, which makes it difficult [3]. Students seem to understand the Coulombian electric force as a vector, for example, in the simple case of two point charges, i.e., in a one-dimensional case. Problems arise, however, when the electric field vector is introduced to describe an arbitrary empty point in a 3D space in the proximity of punctual or continuous charge distribution [4] [5]. Students learning electromagnetics also fail to move their thinking on from the force concept to the theoretically superior field concept [6].

Several instructional approaches to overcoming difficulties involved in learning electrostatics have been reported previously. One of them is an "oriented research activity" that regards secondary-level students as "junior researchers". They investigate problems – in small groups

– related to selected topics such as the nature of electricity, electrical forces, and fields. The idea is to provide secondary students with the possibility, under guidance of a teacher, of themselves formulating the desired concepts of the basics of electricity [7]. Another example of a teaching intervention at undergraduate level is to introduce Gauss's law later, after the students have learned about the supportive concepts in the field of electricity. Traditionally, at undergraduate level Gauss's law is introduced at an early stage of the course, prior to the concepts of potential, capacitance, and current [8].

Electromagnetics involves very abstract ideas that cannot be arrived at without formal instruction. Normally speaking, factual knowledge about electromagnetism is relatively easy to learn, but it is much more difficult to achieve a deep understanding. Students, for example, can present the idea of the "right-hand rule", but apart from a naive graphic representation they can make no meaningful use of it [4]. Even if the content of electrostatics is to some extent new for the students, they still possess numerous preconceptions about electricity. Although inaccurate from a scientific perspective, these preconceptions remain the foundation on which we have to construct proper comprehension [9].

The goal of this study was to design a teaching sequence that would help students to achieve an understanding of the basic qualitative ideas that underlie the facts and formulas. In addition, the aim of the teaching intervention was to help students use the concepts of electric field and Gauss's law as powerful tools for thinking and problem-solving. For this reason the highly abstract content of electrostatics must be optimized for learning to occur. Our intention was to integrate the student's preconceptions into meaningful and accurate agreement with the scientific facts [10]. The practical study and teaching took place at the University of Kuopio, Finland, where the audience was made up of first-year students taking an introductory course in electromagnetics based on the textbook "University Physics with Modern Physics", 12th ed., by Hugh D. Young and Rodger Freedman [11].

Based on the preceding paragraphs describing the physical theory of electromagnetics, learning difficulties, and our own view of learning we posed the following research questions:

1. *How can we design effective teaching in electrostatics that takes into account the structure of physics, the student's conceptions, and the teacher's views?*
2. *What impact will the teaching that we design have on the student's understanding?*

The first question deals with designing a new instructional approach to teaching the topics of electric field and Gauss's law. The basis of the question resides in a combination of the structure of physics, learning goals, student's preconceptions and learning problems, and also the teacher's view of the domain.

The impact of the sequence designed has also been studied on a small scale. The emphasis of the present study has been placed on the use of the primary method of educational reconstruction in designing the sequence, and the result of the learning outcome presented here should be regarded as preliminary.

II. METHOD

In this study we utilize the model of *Educational Reconstruction* presented by Reinders Duit and Harald Gropengießer. Typical of the educational reconstruction is that it emphasizes the close connection that exists between the theoretical and practical aspects of designing teaching sequences in physics [12].

The learning outcome was tested by analyzing the students' answers to the final exam questions, which had been designed for this purpose.

The model of the educational reconstruction is based on three main components, which together constitute a cyclic process. The main components and a résumé of contents are illustrated in Figure 1 and described in detail in the subsequent paragraphs.

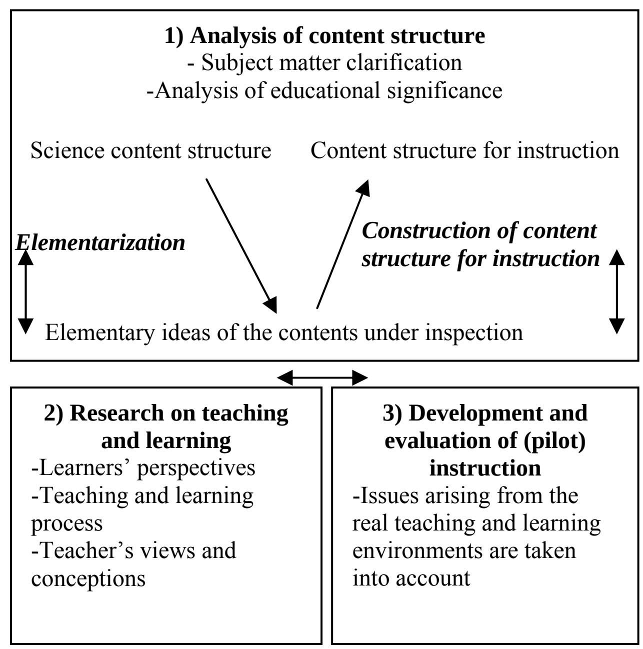

FIGURE 1. The Model of Educational Reconstruction [10].

Component **1)** of the analysis of the content structure concerns the physical theory of the electrostatics in our case. The aim of this elementarization is to find the central principles and theoretical nodal points that are relevant to the domain of the designed teaching. Influenced by the main components **2)** and **3)**, the elementarization reshapes the material to construct the content structure that can be used in the actual teaching. The process of elementarization provides the essential basis of the whole cycle of the educational reconstruction. We present here the key questions used in the educational analyses used when we utilize the concept of educational reconstruction [13]:

a) *What is the general idea that is represented by the contents of the immediate topic of interest? Which basic phenomena or basic principles and which general laws can be addressed in an exemplary way as a result of dealing with the content?*
b) *What is the significance of the immediate content or the experiences, knowledge, abilities, and skills that will developed by dealing with the course content in the students' actual intellectual lives? What significance should the content have, from a pedagogical point of view?*
c) *What is the significance of the content for the students' future lives?*
d) *What is the structure of the content when viewed from the pedagogical perspectives outlined in questions 1 to 3?*
e) *What are the particular cases, phenomena, and situations that help to make the structure of the specific content interesting, worth questioning, accessible, and understandable for students?*

The empirical research **2)** consists of the preconceptions subjected to study, of analysis of the teaching material, and of teachers' views and conceptions. In connection with our project, other results were already available concerning commonly held preconceptions about electric force and electric field. In the main, we were influenced by students' vague understanding of the conceptual, graphic, and mathematical representation of electric field as a vector field in general. Emphasizing the electric field aspect was essential, since the concepts in electrostatics are generally field-related.

However, the students' previous educational level –at secondary school – provides no significant instruction concerning Gauss's law. Hence, in this respect its influence on the teacher's construction of the content structure of his/her teaching depends purely on the individual teacher's point of view.

The development and evaluation of the teaching **3)** will be carried out based on the information obtained partly from the students' conceptions and partly from the goals of the teaching. The fine-grain design can be understood as a practical, detailed outcome of the result from the first main course component. The outcome of this component in particular is closely related to the answer to the key question e).

Students' performance at the end of the course was measured by means of final exam questions designed precisely for this purpose to give information on the way in which the students' applied their concepts in their problem-solving.

III. RESULTS

The sequence of the educational reconstruction was the same as that presented in the methods described above. The actual work done and the results obtained can be represented by the sequence: elementarization ➔ construction of the content structure of the instruction ➔ fine-grain design of the teaching sequence. The process that aims at the fine-grain design can be regarded as a pilot instruction since this was being conducted for the first time.

A. Educational reconstruction

In the case of electrostatics, the elementarization was based on answering the key questions a), b), and c) of the first main component. The general idea of electrostatic theory is to introduce the first four steps of electrostatics and their dependence in increasing hierarchical order: Step 1) electric force (Coulombian force); Step 2) Coulombian electric field; Step 3) electric flux; and Step 4) Gauss's law (and Maxwell's electric field).

These steps can be found arranged in this sequence in the majority of university-level textbooks. From a pedagogical perspective, however, the significance of the four steps is that they represent a deep grasp of the relation between force and field. In addition, it is important for the learner to understand how the field is derived from the force, and how the force and field are connected with each other. The concept of flux depends on the concept of electric field and surface – both treated as vectors. Furthermore, it is important for the learner to understand the relationship between the total electric flux through a closed surface and the enclosed charges, all of which forms the conceptual basis for Gauss's law. The mathematical representation of Gauss's law is meaningful only if the preceding concepts are understood correctly.

The significance of understanding the electric field and Gauss's law for a student's future learning is quite profound. The course of fundamental electromagnetics will be followed by other courses, such as electromagnetic field theory, optics, electronics, and various courses in technology, in which the correct treatment of the electrostatic phenomena and principles are essential.

After completion of this analysis we are able to respond more precisely to key question d). The goal of the teaching sequence in the present study is Gauss's law. Steps 1)-3) can be regarded as supportive steps towards an understanding of the conceptual underpinning of Gauss's law.

The concept of the construction of the content structure as an aspect of instruction is not to re-invent physics. Rather, this approach can be described as reshaping the analysis of elementarization as a set of practical guidelines for teaching that takes into account both students' (and teachers') conceptions and potential learning problems, too.

Previous research results concerning problems in learning the topic can be placed in the context of elementarization as in Table I. At this point we also present the elementary ideas concerning the content under examination in the column "Content structure steps".

Previous research has revealed several different learning problems in the general field of electrostatics. The most relevant ones occurring at the nodal points of the developing educational reconstruction are indicated in Table I. These have been are considered mainly in the case of electric force and electric field. The construction of the content structure of flux and Gauss's law, based on students' conceptions, appeared to be unproductive as a result of the students' lack of any previous knowledge in the domain. In consequence, emphasized here more are the teachers' perspectives – a view that is also present in other cases.

Table I. Elementary ideas concerning the construction of the content structure.

Learning problem / issues to be considered	**Content structure step**
Vector algebra is difficult in a physical context [2]. Electric force is difficult in non-symmetric discrete situations. (Teacher's view)	Step 1: Establishing the basis of the Coulombian field concept on the force concept. (Teacher's view)
There is no differentiation between field intensity and electric force. Neglecting the vector character of the electric field [6]. The field intensity is understood as scalar [4].	Step 2: Differentiation between field intensity and electric force. Enhancing the vector character of an electric field. [6]
The concept of flux requires understanding of the vector product of surface and electric field and their integration. (Teacher's view).	Step 3: Representation of the field and surface. Establishing the flux concept in the context of the vector product. (Teacher's view)
Using Gauss's law requires a recognition of the topology and symmetry of the charge distribution, assuming the field and Gauss's surface. (Teacher's view)	Step 4: Combining the concept of flux and enclosed charge in the case of symmetrical charge distributions within Gauss's law. (Teacher's view)

The teacher's view can be arrived at through the experience of teaching the subject for several years. It also originates from its presentation in the textbooks and the teaching aims of the course.

The design of the fine-grain teaching sequence follows quite straightforwardly from the results of the content structure. Based on the content structure and the various steps, a set of 21 tasks were designed. These formed the basis of the teaching intervention. Some of the tasks were carried out as classroom demonstrations, while others were handed over to the students in the during the classes to be solved in groups of three or four.

In addition to the production of our own ideas we made use of several excellent examples taken from Randall D. Knight's Student workbook [13]. In the following sections, examples of each step will be presented. The original tasks are presented in detail in the Appendix.

Step 1 (see tasks 1, 3, and 5 in the Appendix): the idea is to enhance the vector calculus in the case of electric force. The vectors appear as powerful tools especially in cases of non-symmetrical, multiple sources and continuous charge distributions. Another important aspect is to learn how to draw and use the notation of the vector presentation graphically [15].

Step 2 (see tasks 2, 4, and 6 in the Appendix): the example tasks are based on a problem concerning differentiation between electric force and electric field and also the problem of the superposition principle of an electric field (adding up multiple vectors). The tasks involve a repetition of the previous tasks, but without the test charge, and to present the result as the intensity of the electric field (V/m). These tasks are also good for practicing the use of field vector representation and its advantages over field line representation since the field lines are not obvious and are easy to draw and interpret in the case of multiple charges. In addition, the field vectors are the result of the combination of three separate fields of point charges and they thus promote an understanding of the superposition principle [15].

Step 3 (see tasks 7-12 in the Appendix): the concept of flux requires practical exercises concerned with treating both the surface and the electric field as vectors. Combining the graphic and mathematical representation of flux on a closed surface is particularly important for finding the physical interpretation of Gauss's law, which is to be introduced later.

Step 4 (see tasks 13-21 in the Appendix): teaching Gauss's law is emphasized in terms of three sections. In the first section Gauss's law is interpreted as the relation between the whole flux and the enclosed charge, as treated in tasks 13 and 14. The second section is concerned with learning how to use the formula itself to derive electric fields for symmetrical distributions. After finding the symmetry of between the field and the Gaussian surface , the resultant field derivation is quite straightforward. The resulting electric field and the idea of Gauss's law is used in examples 15, 16, and 19-21. The third section involving Gauss's law is based on using it as a problem-solving tool in more general and more complex situations. Examples 17 and 18 are based on the information that there is no net electric field in the conductive material. A Gauss's law interpretation with respect to the conductor can be useful in looking for a solution to the question of the (induced and placed) charges on the surfaces.

A detailed description of the teaching sequence designed also provides an answer to key question e), which is required when the model of educational reconstruction is used.

The whole process of using the process of educational reconstruction provides an answer to the first research question. An evaluation of the teaching was made by analyzing the final exam questions that also provided answers to the second research question.

B. The learning outcome from the intervention

Two exams were set during the course, each consisting of 5 questions. The first exam included two questions that were designed specifically for the present study. The first question concerned the electric force resulting from the distribution of point charges. The idea of the question was

to discover whether students had learned to use the physical vectors correctly:
Final exam question 1:

"Three identical +35nC point charges, q_1, q_2, and q_3 are located at P_1=(0, 0) m, P_2=(1, 0) m, and P_3=(0, 1) m. A test charge Q of +1nC is brought to a location P= (1, 1) m. Determine the total electric force acting on the test charge Q."

The correct answer is based on Coulombian force and the superposition principle. The number of students providing an answer to the first question was 35. The answers fell into three categories. The first category (14 students) consisted of answers that were completely correct. The students applied Coulombian force vectors correctly to solve the problem. Some students first calculated the electric field at the location *P* = (1, 1) m and used the relation $F=qE$ in the final stage. The second category (12 students) consisted of conceptually correct answers with some minor errors in the vector calculus. The Coulombian force was handled in terms of vectors and an attempt was made to determine the net force by keeping the vectors in mind. The errors consisted of various minor mistakes in the vector calculus. A typical mistake was that the separate forces were dealt with as vectors, but in the final stage the students added up only the magnitudes of the vectors. The third category (9 students) then consisted of a set of incorrect answers with a common denominator: from the very start, electric force was treated as scalar.

The idea of the second question was to test how the student's applied their understanding of electric field and Gauss's law:

Final exam question 2:

"A spherical conductive shell has radii R_1 = 10cm and R_2 = 15 cm. Inside the shell there is a concentric conductive sphere with radius R = 5 cm. The direction of the 15 000N/C electric field is shown in the image below at distances of 8 cm and 17 cm from the origin. Determine the total amount of the charge in the shell."

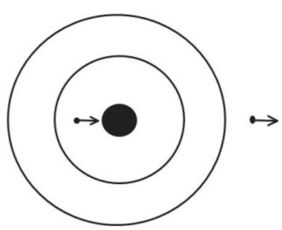

FIGURE 2. Illustration for question 2 of the final exam.

The correct answer is based on the use of Gauss's law of electric fields.

The answers can be placed in three categories. The first consists of correct answers (12 students), while the second consists of partially correct answers (10 students). The most common mistakes were related to the distance function in the Coulombian field or in Gauss's law. Typically, the distance of the field strength was measured from the surface of the objects. The other common mistake was to take only the outer object and its field into consideration by invoking Gauss's law but forgetting that it is valid for the algebraic sum of the charges inside the Gaussian surface. In addition, there were students in this category who misinterpreted the direction of the given fields when otherwise correctly applying the Coulombian field concept. The third category (7 students) made a variety of poor attempts that demonstrated that they did not understand the question at all. In the second and third categories we can see that learning problems were to some extent still present as far as those students were concerned.

To sum up our analysis of the final exam, the number of fully correct answers to both final exam questions (first: 14/35; second: 12/29) indicates that although the tasks were relatively challenging, a certain proportion of the students applied a correct understanding of electric force, electric field, and Gauss's law.

IV. DISCUSSION

As a consequence of the requirement to master new mathematical techniques, simultaneous learning of new physical concepts seems to be difficult for students [16]. The shift from understanding electric force to active use of electric field is not a straightforward process for them. It seems that by taking into account students' preconceptions, their learning problems, and an analysis of the taught subject, it is possible to design a good foundation for an instructional intervention [7]. The method of educational reconstruction to design such an intervention is ideal for undergraduates in the case of electrostatics. The course includes a lot of new physics concepts, such as Gauss's law, that are not taught at the preceding secondary level. Students are unfamiliar with the elements (*i.e.* field, flux, and surface integration) before the start of formal instruction. The physical theory of electrostatics is quite abstract and it is generally presented in a compact form. Thus it provides space for an educational reconstruction that expands and interconnects the essential concepts into a clearer form that reduces or simplifies the theory itself.

In the course of the intervention the teaching methods, *e.g.* group discussions, emphasized the interplay between the students and their instructor. The consensus they reached during these discussions proved to correspond to the scientific aims of the teaching. The discussions also helped the instructor to see what the students had learned and to recognize which were the most difficult topics for them to understand. In the future it would be particularly interesting to analyze in detail the learning process and the group discussions [17].

Chabay's analysis of the learning problems connected with Gauss's law suggests a need to restructure the sequence of the introductory course in such a way that Gauss's law is introduced later in the course [8]. This would be an understandable choice – also from a teacher's perspective – since Gauss's law is indeed difficult for students if presented in the initial stage of a course. Our approach is, however, based on teaching that includes steps towards learning about electric field and Gauss's law at the start of the course. By making this choice we initially consume more time resources as a result of working our way through the various steps, but this will pay back later. Indeed the role played by electric field is essential in making sense of the content of electric potential, capacitance, and current.

Analysis of the final exam questions showed that for some students problems concerning the essence of a physical vector still remain [18]. Nevertheless, in light of our experience it appeared that the large number of acceptable responses to the second exam question testified to effective maturation in students' understanding of Gauss's law and its correct use.

The reasoning and theoretical framework underlying the concepts of electric force, electric field, and flux make Gauss's law more meaningful. In addition, a good comprehension of Gauss's law, and thus a theoretically more powerful concept of electric field, would seem to provide a better background for subsequently studying such subjects as electric potential, capacitance, and current when they are introduced at university level as an outcome from interpretation of electric field. In sum, efforts made to understand Gauss's law and the formation and physical meaning of the surface integral also provides a good background for learning the other Maxwell's equations.

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APPENDIX

1. In the following Figure A1 there is an infinite sheet of charge of $5nC/m^2$. A test charge of 1nC can be placed anywhere. Draw suggestive electric force vectors in the dotted locations acting on the test charge and give the exact value of the force (magnitude and direction) within the locations labeled "P" 1m in distance from the sheet.

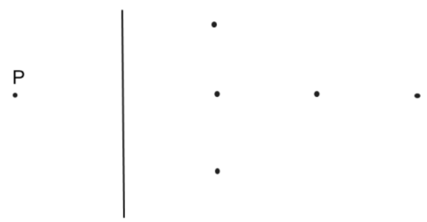

FIGURE A1.

2. With reference to Figure A1, above, draw the electric field vectors within the dotted locations and give the exact value of the electric field (magnitude and direction) in the locations labeled "P" 1m distance from the sheet.

3. In Figure A2 below, there are three fixed-point charges at the corners of a square. A test charge of 1nC can be place anywhere. Draw suggestive electric force vectors within the dotted locations acting on the test charge and give the exact value of the force (magnitude and direction) in the locations labeled "P" at the corner of a 1m-sided square and midway on the lower side.

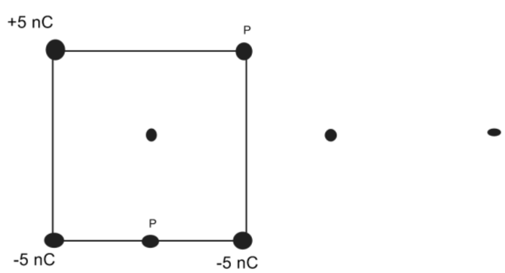

FIGURE A2.

4. In Figure A2, above, there are three fixed-point charges at the corners of a square. Draw suggestive electric field vectors within the dotted locations and state the exact value of the field (magnitude and direction) in the locations labeled "P" at the corner of a 1m-sided square and at the mid-point of the lower side.

5. In Figure A3, below, there is a uniformly charged sphere (Q = +5nC). A test charge of 1nC can be placed anywhere. Draw suggestive electric force vectors within the dotted locations and state the exact value of the electric force (magnitude and direction) in the locations labeled "P". What happens if the sphere is a conductor?

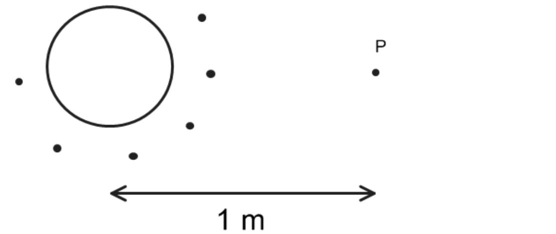

FIGURE A3

6. Consider Figure A3. Draw suggestive electric field vectors within the dotted locations and state the exact value of the electric field (magnitude and direction) in the locations labeled "P". How would your answer change if the sphere were a conductor?

7. State the directions and magnitudes of all of the surface area vectors needed for a sphere at origin, radius = 1m. Use the correct differential notation and unit vectors of the relevant coordinate system.

8. State the directions and magnitudes of all of the surface area vectors needed for the cube illustrated in Figure A4, side = 1m, one corner in the origin. Use the correct differential notation and unit vectors of the relevant coordinate system.

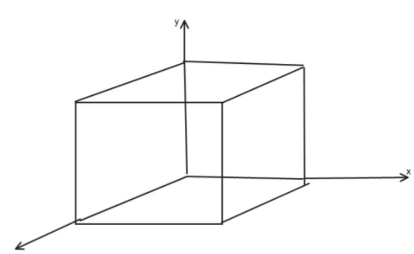

FIGURE A4.

9. Give the directions and magnitudes of all the surface area vectors needed on the following surface in Figure A5 (cylinder, height 1m, radius, 0,5m axis along the z-axis, center at the origin). Use the correct differential notation and unit vectors of a relevant coordinate system.

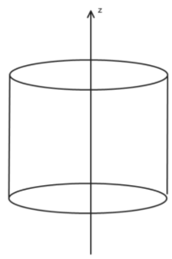

FIGURE A5

10. Draw a surface around and through the infinite sheet of charge (surface charge density $5nC/m^2$) so that the surface is symmetrical with the electric field. Using several examples, show both the electric field vector and the surface vector originating from the same point. Give the result of the dot products in each section of the given surface.

11. Draw a surface around the spherical charge distribution with a charge of +5nC so that the surface is symmetrical with the electric field. Using several examples, show both the electric field vector and the surface vector originating from the same point. Give the result of the dot products in each section of the given surface.

12. In Figure A6 below, there is a hemisphere in an uniform electric field. Is the flux Φ_1 at the circle larger or smaller, than the flux Φ_2 at the hemisphere, or is it the same? Explain [13].

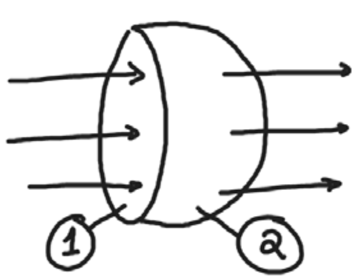

FIGURE A6

13. Is the net electric flux on each of the following closed surfaces, below, positive, negative, or zero? Explain [13].

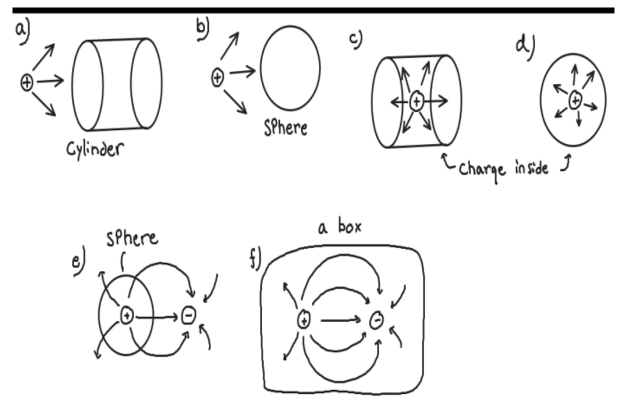

FIGURE A7

14. What is the electric flux on each of these surfaces [13]?

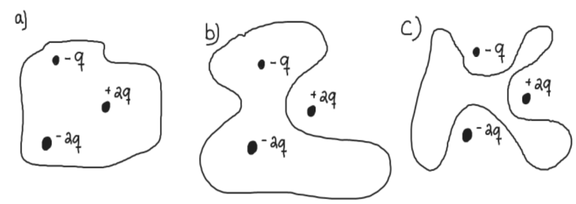

FIGURE A8

15. A charged, spherical balloon expands from its initial size to its final size as shown in the Figure below. Does the electric field at points 1, 2, and 3 increase, does it decrease, or does it stay the same? Explain [13].

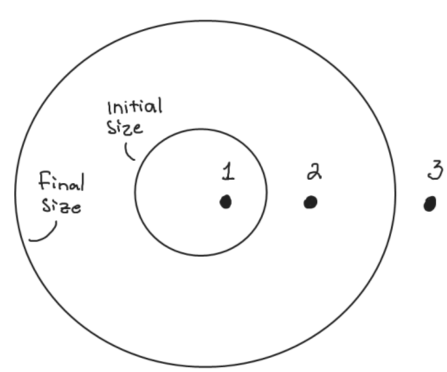

FIGURE A9

16. Two parallel infinite planes of charge have charge densities 2σ and –σ. A Gaussian cylinder with cross section A extends to distance l on either side [13].

    a. Is the **E** perpendicular or parallel to the surface at the top and bottom and on the wall?

    b. Compare the magnitudes of **E** emerging from the top and bottom.

    c. Define the electric fluxes at the top and bottom and on the wall.

    d. Define the quantity of the charge inside the cylinder.

    e. Combine your answers and derive the **E** everywhere by using Gauss's law.

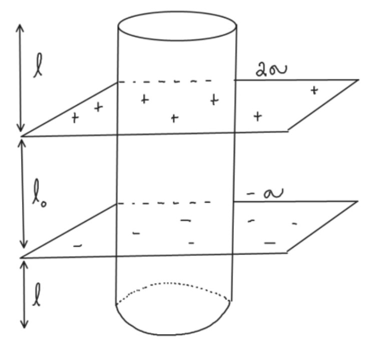

FIGURE A10

17. A +10nC point charge is placed inside the cavity of a conductor. The conductor has no net charge. Determine the total amount of induced surface charges on the inner and outer surface of the conductor. Explain your reasoning based on your interpretation of Gauss's law[13].

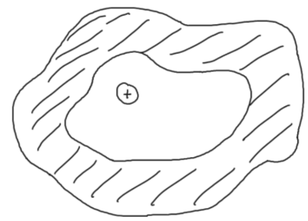

FIGURE A11

18. Repeat previous task no. 17 but with the exception that the conductor has a net charge of -25nC.

19. Draw a surface around and through the infinite sheet of charge with a surface charge density of $5nC/m^2$ so that the surface is symmetrical with the electric field. Calculate the total flux throughout the closed surface and solve the electric field using Gauss's law.

20. Draw a surface around and through the infinite line of charge with a charge density of 5nC/m so that the surface is symmetrical with the electric field. Calculate the total flux throughout the closed surface and solve the electric field using Gauss's law.

21. Draw a surface around the uniform spherical charge distribution with a charge of +5nC so that the surface is symmetrical with the electric field. Calculate the total flux throughout the closed surface and solve the electric field using Gauss's law.