

# Students' Perception of Vector Representation in the Context of Electric Force and the Role of Simulation in Developing an Understanding

S. Shubha, B. N. Meera

**Abstract**—Physics Education Research (PER) results have shown that students do not achieve the expected level of competency in understanding the concepts of different domains of Physics learning when taught by the traditional teaching methods, the concepts of Electricity and Magnetism (E&M) being one among them. Simulation being one of the valuable instructional tools renders an opportunity to visualize varied experiences with such concepts. Considering the electric force concept which requires extensive use of vector representations, we report here the outcome of the research results pertaining to the student understanding of this concept and the role of simulation in using vector representation. The simulation platform provides a positive impact on the use of vector representation.

The first stage of this study involves eliciting and analyzing student responses to questions that probe their understanding of the concept of electrostatic force and this is followed by four stages of student interviews as they use the interactive simulations of electric force in one dimension. Student responses to the questions are recorded in real time using electronic pad. A validation test interview is conducted to evaluate students' understanding of the electric force concept after using interactive simulation. Results indicate lack of procedural knowledge of the vector representation. The study emphasizes the need for the choice of appropriate simulation and mode of induction for learning.

**Keywords**—Electric Force, Interactive, Representation, Simulation.

## I. INTRODUCTION

PHYSICS Education Research (PER), one of the important facet of Domain Based Education Research, has shown that students do not achieve the expected level of competency in understanding the concepts of different domains of Physics learning when taught by the traditional teaching methods, the concepts of Electricity and Magnetism (E&M) being one among them. Research has also investigated into the effect of role of understanding pedagogy, the use of transformed course and the use of new instructional approaches in the field of E&M for improving student learning [1]-[5].

Investigation of student difficulties related to E&M concepts is important for designing instructional strategies to reduce them. The origin of student difficulties in learning E&M concepts can be due to misconceptions (preconceptions

or alternative conceptions) which may result from previous experience or difficulty of language comprehension and can seriously impede the learning process. Research on the analysis of misconception in the domain of mechanics is prevalent for quite some time [6]-[10] whereas similar detailed studies of misconception in E&M are more recent [11]-[18]. Additional robust understanding of the knowledge base with regard to E&M concepts has been established by standardized concept surveys. The instruments serve to identify common and persistent student difficulties and they have also been powerful tools for supporting curricular reform [19], [2], [13]. Also the mathematical structure of the domain presents difficulties in understanding [20]-[24].

To get a good grasp of functional understanding of concepts and physical processes, learners need a way of experiencing the phenomena which tend to be through normal sensory perception. The use of technology in teaching and learning has recently become an extremely important factor which helps in enhancing the understanding of the abstract or unobservable concepts. Simulation as one of the valuable instructional tool renders an opportunity to visualize varied experiences of the concepts and helps to build the mental model or internal cognitive representation. It also provides an open learning environment to develop a robust conceptual understanding of the physical phenomena by its use of multiple representations (such as verbal, pictorial, graphical, numerical, conceptual...). With the easy access to modern simulation design tools, simulation has become interactive and intuitive. More recent research from the Physics Education Technology (PhET) team has extensively examined the effective way of using simulations as a tool and reported the effectiveness of simulation. The PhET project team creates research-based interactive computer simulations for teaching and learning physics and makes them freely available on the PhET website (<http://phet.colorado.edu>). Simulations can be effective if they are structured, implicitly guiding in developing content knowledge and process skills, as well as in promoting more complicated goals such as inquiry and conceptual understanding [25]. Research studies on how interactive simulation in different domains can be an effective learning tool has been instructive [26]-[32]. The importance of the nature of design of simulation to be of help as a learning tool became more evident as researchers started exploring the features of the simulation which are expected to collaboratively construct knowledge and develop the understanding of subject concepts [33]-[34]. The implicit

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features of simulations should scaffold student to explore along pedagogically prompting useful learning paths and engage in authentic science process skills while simultaneously supporting productive content learning. Implicit scaffolding is meant to allow for intuitive exploration, the feeling that students have independent control over their experience, while both affording and constraining the actions that are productive for learning [33]-[35]. During the process of usage of simulations the nature and the amount of guidance on different levels influences student engagement [25], [30], [35]. Research has established that in completely unguided exploration, students experience difficulties in engaging with it, make false moves and end up in fruitless searching without any productive learning [25], [35]. If completely guided, active engagement is minimal since the learner follows a cookbook, recipe based approach. However, in the gentle guided approach simulations are structured and intuitive. Concepts like field, flux... etc. are difficult to learn as they do not provide real world experiences. These concepts are constructs that are not accessible to learner's intuition and use representational formats with unique features. Simulation when accompanied by appropriate interposed questions can motivate students to engage in inquiry based approach on their own without any external guidance, providing an opportunity to question and clarify the underlying concepts [35].

The present study was initiated to understand the augmented difficulty experienced in some Physics courses. The origin of the difficulties may be because of improper or incomplete functional understanding of the core elementary concepts previously learnt. The main focus of this research work is to evaluate the effect of interactive simulations for learning in the context of the electric force concept. We report here the outcome of the research results obtained by studying the learner's experiences as they use simulations. To do this, we have carefully chosen from existing ones, but not really designed any. We have adopted the Gentle Guidance (GG) style in the study, which directs a student's interaction through the simulation.

## II. PRE-INVESTIGATION STUDIES

The first stage of this study involved eliciting student responses to questions that probe their understanding of the concepts of E&M. The test comprises of 70 post-graduate students answering ten questions on force, field and flux concepts related to both electric and magnetic phenomena. A few questions from CSEM [13] have been used and few were carefully designed addressing specific aspects of verbal and vector form representations. The first five questions were based on electric force and electric field's concepts, next three questions were framed on electric flux and the last two questions were on the magnetic field concept. In this study, the responses to two questions related to concept of electric force are analyzed.

The questions that deal with the concept of electric force are given below

*Q1. Two identical point charges  $+q_1$  and  $+q_2$  are separated by a distance 'x' as shown in Fig. 1.*

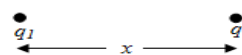


Fig. 1 Two identical point charges

- i. Choose the correct pair of force vectors from Table I which represents the direction of electrostatic force on  $q_1$  (due to  $q_2$ ) and on  $q_2$  (due to  $q_1$ ).

TABLE I  
DIRECTION OF FORCE VECTORS

Options	Force on $q_1$	Force on $q_2$
a)	$\rightarrow$	$\rightarrow$
b)	$\rightarrow$	$\leftarrow$
c)	$\leftarrow$	$\leftarrow$
d)	$\leftarrow$	$\rightarrow$
e)	$\rightarrow$	$\rightarrow$
f)	$\rightarrow$	$\leftarrow$
g)	$\rightarrow$	$\leftarrow$
h)	$\rightarrow$	$\rightarrow$

Note: Use Fig. 2, for answering ii, iii & iv.

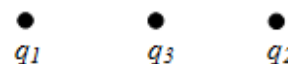


Fig. 2 Three point charges

- ii. Indicate the direction of force on  $q_1$  due to  $q_2$  after introducing another negative charge  $q_3$  of same magnitude is placed midway between  $q_1$  and  $q_2$ .
- iii. Indicate the direction of the net force on  $q_1$  when another negative charge  $q_3$  of the same magnitude is placed midway between  $q_1$  and  $q_2$ .
- iv. Find the net force on  $q_3$ .

The question addresses elementary understanding of the vector representation of electrostatic force.  $Q1(i)$  is in MCQ (Multiple Choice Question) format and probes the students' ability to recognize the nature (attractive/repulsive), direction (arrowhead), magnitude (length) of the electric force and their ability to use vector representation of the relevant forces.

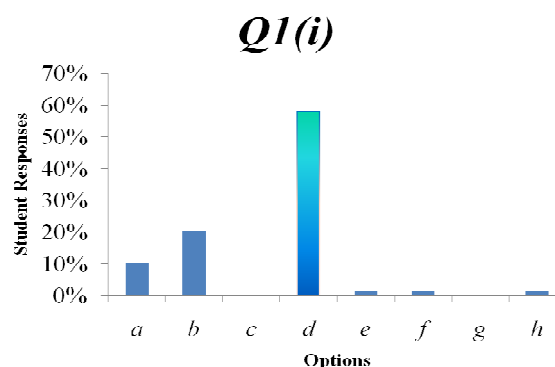


Fig. 3 Student responses for  $Q1(i)$

Fig. 3 shows the responses of students. Nearly 60% of the students responded suitably indicating their correct understanding of the Coulomb's law. The incorrect responses may reflect their poor understanding of the implications of

Coulomb's law or the lack of procedural knowledge while representing force vectors. Since, MCQ format gives limited perception of the nature of understanding, the responses to the remaining questions that are in an illustrated form is expected to be more useful.

Responses to  $Q1(ii)$ ,  $(iii)$  and  $(iv)$  display interesting but distressing features. 34% of the students have not attempted to answer the questions  $Q1(ii)$ ,  $(iii)$  and  $(iv)$ . Among those who have attempted, only 63% of them have made an attempt to draw the vectors. Fig. 4 shows a collection of some of the responses. Most of the diagrams indicate a fuzzy thinking and make no physics sense and provide no clear picture of their conceptual and procedural understanding.  $Q1(ii)$  tests the often explored conceptual inference on the effect on  $q_1$  due to  $q_2$  by the presence of  $q_3$ . Indeed  $Q1(iii)$  and  $(iv)$  necessitates the use of the superposition principle in addition to the resultant vector evaluation. The students' confusion regarding vector representation is real.

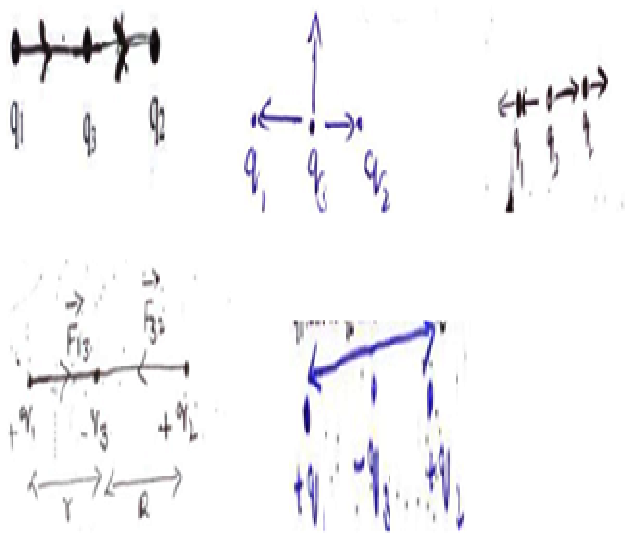


Fig. 4 Responses of vector representation for  $Q1(ii)$ ,  $(iii)$  and  $(iv)$

The other Electric force related question is given below.

$Q2$ . Two unlike point charges are separated by a distance 'x' as shown in Fig. 5. Pick from Table II, in which each pair of arrows describes the relative magnitude and direction of the electric force exerted due to unlike charges.

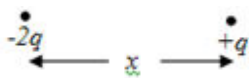


Fig. 5 Two unlike point charges

TABLE II  
DIRECTION OF FORCE VECTORS DUE TO UNLIKE POINT CHARGES

Options	Force on -2q	Force on +q
a)	→	←
b)	→	→
c)	→	←
d)	←	→
e)	←	←

The question  $Q2$  has been used from CSEM [13] and is modified and re framed appropriately. Response to this question is strongly influenced by the ability to understand and apply the action - reaction principle. Fig. 6 shows the responses. 18% of the students have selected the correct response (b). Of the remaining students, 27% of them have selected the wrong option (a) suggesting that students seem to believe "Bigger the charge, bigger the force" idea.

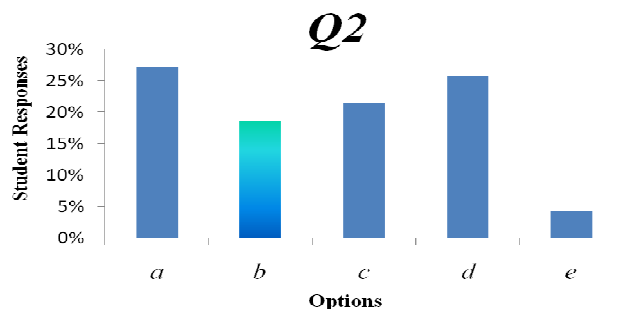


Fig. 6 Student responses for  $Q2$

Force as a Physics concept and its vector property is learnt in the context of mechanics during early instruction days. The concept of force is associated with physical and an experiential attribute. Students also have a fairly good training in dealing with vectors and its mathematical operations while learning mathematics. Despite this, it is intriguing that students' vector representations in the context of the situation presented in question  $Q1(ii)$ ,  $(iii)$  and  $(iv)$  are seriously flawed. Research has established students' experience with vectors [36], [37]. Difficulty to adopt a new representational format is evident. Indeed, this geometrical representation of vectors does not have long term relevance and application. The advanced treatment soon becomes mathematical which really does not require geometrical representation. However, during instruction, the geometrical representation serves as a cognitive bridge between elementary algebraic treatment and dominantly abstract mathematical formulation. The vector representational difficulty is more of an illustration of the reluctance in cognizing a new mode of representation. Research has established similar difficulties in drawing and using graphical representation [38]. Domain specific representational practices are a strong aid for developing understanding and if not learnt correctly, it does nothing to build clarity. The skills required developing a good familiarity and ease to adopt these requires a directed training in procedural understanding. We suggest using simulation as a tool for this. From research on usage of interactive simulation in teaching/learning process in different domains of Physics, it is observed that a simulation enriches student's knowledge through experiences in understanding by visualization and interaction. We selected from the available repository of simulations, one that depicts an explicit treatment of procedural knowledge of vector drawing in a physics context with the example of Electric Force vector in one dimension. We then outline the framework for analyzing data from interviews with students using simulations, followed by the

discussion of the results of the interviews.

### III. SIMULATION STUDIES

This research work uses Electric Force in One-Dimension interactive simulation [39] developed by Andrew Duffy at Boston University created with Java by using a software tool Easy Java Simulation (EJS) [40]. Fig. 7 shows the design of Electric Force in One-Dimension simulation which makes explicit use of vector representation, and encompasses the features that are of our interest. It deals with the one dimensional vector representation of electric force with built-in implicit scaffoldings as tools in the form of affordances and constraints, thus resulting in any sense making interaction in establishing a conceptual connection.

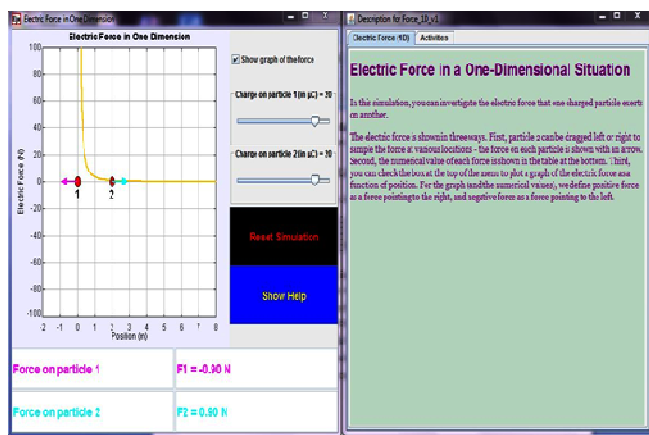


Fig. 7 Screen shot of Electric Force in 1-D Simulation.

### IV. METHODOLOGY

Results of pre-investigation studies have depicted representative aspects that need additional investigation for validation. Detailed student interviews were conducted with specific learning activities while using interactive simulations for a total number of twelve students. The students chosen for this part of the study had not participated in the earlier pre-investigation studies. The activities are conducted in four different stages. In the first stage, ten students are presented with two driving questions to answer before they interact with the simulation. These driving questions help to set up a framework about the concept in the mind of the learner [25], [35]. It also helps, to some extent, to recognize the student's initial understanding of the concept. During our interaction with the students, we did realize a reluctance to adapt to the simulation experience if they were not exposed to preliminary thinking. This response to the question also provides us a basis for validation at a later stage. The second stage is an unguided exploration of the simulation. The students were asked to interact with the simulation on their own. This enables the learner to a self-driven exploration of the concept at their own pace. With undirected exploration, students often interact with the simulation in an arbitrary manner. Having created a framework by posing the driving questions, it was expected that the unguided exploration of simulation would progress in

a direction to evolve answers to those questions - which was not so. In the third stage, adopting a gently guided interview style, the activity of exploring the simulation is accompanied by questions framed on specific aspects pertinent with the features of the simulation. The questions posed were not merely direct functional questions, but ones which require active engagement.

#### A. Stage 1: Driving Questions

In the first stage of the interview, students are given two driving questions and asked to answer them in written form before they are exposed to the simulation interactions. These questions provide concept framing effect by orienting student thoughts on the topic to be explored and also provide a glimpse of their prevalent understanding. The questions are listed below.

1. State the law of force for point charges.
2. Consider two identical charged particles  $q_1$  and  $q_2$  which are separated by a distance 'x'.
  - a) Represent the relevant forces pictorially in Fig. 8.

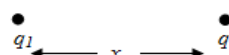


Fig. 8 Two identical point charges are separated by a distance 'x'

- b) Displace the charged particle  $+q_1$  towards  $+q_2$  as shown in Fig. 9.

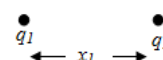


Fig. 9 Two identical point charges ( $x_1 < x$ )

Now, represent the relevant forces diagrammatically.

Question 1 was framed to discern the following three specific aspects: whether the student identifies the law of force between the point charges as Coulomb's law (CL); whether the student chooses to state the law verbally or in a mathematical form; whether the student does use the vector notation on appropriate physical quantities.

Analysis of responses to driving question 1 indicate that all students do recognize the law of point charges correctly as "Coulomb's law" though only five among them explicitly stated the name of the law. All students, except one who stated the law only verbally, did state the law both in verbal and mathematical form. Among them, barring three students, remaining students did so correctly. However, it is interesting to note that six students resorted to the simplistic mathematical

statement of the law  $F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$  rather than the complete vector form as  $\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$  (or equally well as  $\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^3} \vec{r}$ ).

One student did make a feeble attempt to incorporate the vector notation by writing  $F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$ . Two students used

$F = \frac{q}{r}$  equation, whereas one of them did state the law in the

verbal form correctly. The mention of a ‘point charge’ in the question probably influenced one student as reflected by the statement “.....  $F = \frac{q}{r}$ , point charge is nothing but very small point; hence the point charge does not have a separation distance”. The student who gave only the verbal statement of the law stated that the law is true for equal magnitude charges alone! Our own research supports learner’s tendency to remember the name of a law, but not the statement with all the involved physics subtleties [41].

Question 2(a) is intended to probe the ability of the student to represent the electric force as a vector on the point charges. Their difficulties to represent physical quantities as vectors are evident in our preliminary investigation. All the ten students, except one, did attempt to represent force vectors. Among them, three could make the vector representation correctly on point charges. The remaining six incorrectly depicted electric force vectors are shown in the Fig. 10. A flawed vector representation indicating a weak procedural understanding is indeed evident. The results support the observations of the preliminary investigations.

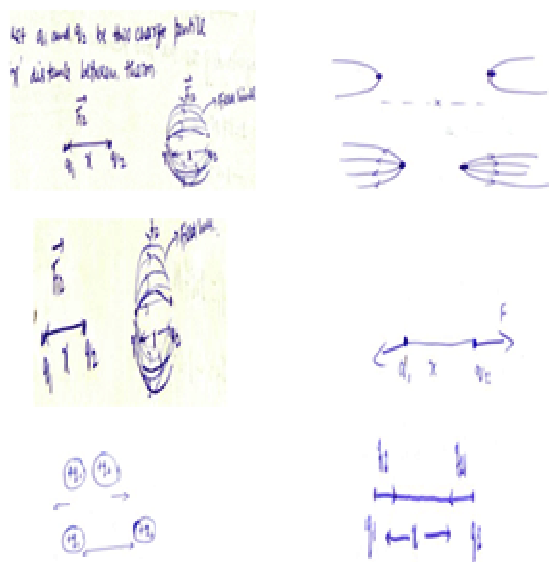


Fig. 10 Student responses for driving question 2(a)

Driving question 2 (b) is framed with a purpose of knowing whether the student represents the increased electric force vector using a longer arrow. On reading the question, every student did make an attempt to represent the electric force in the vector form. But, none of them could make the vector depiction correctly with an increase in the length of the vector (representing the increasing magnitude). The significant observation is that, even though three students, who made a correct representation in driving question 2 (a), failed to make the correct representation in this question.

#### B. Stage 2: Unguided Exploration Activity

After answering the driving questions, students were taken to the second stage of the interview: *Unguided exploration*.

This stage has the following purpose. Some of our students were first time users of simulation platform. One of the advantages of the unguided exploration activity is that students do become familiar with the basic operations of the simulation and our analysis of data at a later stage does not get entangled with familiarity issues. In addition to providing unguided exploration activity to familiarize students, they were asked to identify and list the variable controls and their range of values, thus ensuring the unfamiliarity of using simulation not interfere with their learning. The responses indicate that the choice of tasks while using the simulation was driven mostly by the design features rather than the physical aspects that were posed in their driving question. An analysis of the responses indicates that no pattern of their thinking process is the guiding factor while using the simulation. Thus, their tasks reflected sense making interaction in a very limited manner. Though the analysis of the data from this stage did not provide a concrete understanding of the learners’ thinking profile, it provides a reliable platform for the next stage in building up a familiarity in the use of simulation. Students who did not get involved during the interaction were simply “giving up and moving on” to different elements of the simulation mostly in a random fashion.

#### C. Stage 3: Gentle Guidance (GG) Activity

In this part of the study, the mode of investigation is driven by the carefully-designed activity combined with seven questions/activities with specific objectives. As already mentioned, all twelve students have been considered for this activity. Indeed the GG activity limits the independent exploration of the simulation elements. Analysis is through the verbalizations and interactions made as they are recorded throughout the exploration. The associated questions/activities were designed with an intention of providing pathways for the student to develop a robust thinking pattern.

The activities provided to the student while using simulation are listed below.

1. Fix the charge on  $q_1$  as  $-15 \mu\text{C}$  and decrease the charge on  $q_2$ . Observe the variation in the length of the vectors representing the two forces. Comment.
2. Fix the position of  $q_1$  and drag  $q_2$  to left or right to various locations. Observe the variation in the length of the vectors representing the two forces. Comment.
3. Now, vary the charge on  $q_1$  by a factor of 2. Observe and compare the magnitude of the two forces. Also note down the magnitude of the two forces. (The small window below gives the magnitude of the two forces  $F_{12}$  and  $F_{21}$ ). Comment.
4. Similarly, vary the charge on  $q_2$  by a factor of 2. Observe and compare the magnitude of two forces. Comment.
5. When the distance between the charged particles is doubled, observe what happens to the magnitude of two forces? Comment.
6. From the above observations, identify and formulate the nature of law of force in terms of charges and distance.

7. Set the charge on  $q_1$  and  $q_2$  as  $+15 \mu\text{C}$  and  $-15 \mu\text{C}$  and fix the distance between two charges as 2 units respectively. Reverse the sign on one of the charges? Observe and comment on the magnitude and the direction of the two forces.

Activities 1 and 2 intend to bring to focus relevant features of the simulation. It provides a qualitative understanding of the force dependence on charge and distance in terms of pictorial vector representation. Since, pre-investigation results showed that representation of force vectors were faulty, explicit instruction on the procedure for drawing vectors was given at the beginning of the gently guided simulation. The majority of students noted the vector length changes as charge and distance varied, though some recorded the direct proportionality with charge and inverse variation with distance erroneously showing the difficulty is translating and expressing proportionality behavior. All twelve students interacted with charge control slider (to change the charge) and the click and drag tool (to change separation). A student who chose to represent the observation vectorially indicated the vector as a line joining the point charges. Even though the simulation changed the vector lengths equally as the charge / distance was changed it did not get translated into  $|\vec{F}_{12}| = |\vec{F}_{21}|$  conceptually by most of the students.

Activities 3 and 4 draw attention of the student to the quantitative dependence of force on a charge. The simulation has a window that displays the magnitude of force and the question did bring the attention to this aspect. Out of twelve, nine students noted the numerical values of  $F_{21}$  and five identified magnitudes of forces as equal and opposite, i.e.,  $\vec{F}_{12} = -\vec{F}_{21}$ . Among the twelve students, seven students did double  $q_1$  &  $q_2$  ratio by a factor of two. Five of them have mentioned that there is an increase in the electric force with the increase in the charge quantity. Among them, one student recognized that, with doubling of charge quantity, there is an increase in the electric force by the same ratio by comparing the numerical values ( $\vec{F}_{12}$  and  $\vec{F}_{21}$ ). Two students have shown two times increase in force by using a longer arrow. The remaining five students did not increase charges by a factor of two. Two students have arbitrarily changed the charge and separation. One student merely made an observation of increase of electric force though did not change charge by a factor of two. Remaining three students have wrongly interpreted factor of two as increment of two.

Activity 5 was framed to check the student understanding of quantitative aspects of variation of electric force with an inverse square variation of distance. All twelve students, except one, have interacted and interpreted correctly. Among them, four students have noted the numerical value of the forces  $\vec{F}_{12}$  and  $\vec{F}_{21}$ . Interesting detectable betterment in reasoning was accomplished by six students. They verbally did verify with the numerical values by doubling the distance between the charge particles, and also did verify that there will be a decrease in the magnitude of the electric force by a factor of four. Four students supported it by the mathematical

statement. Of the remaining, five students have mentioned in a simplistic verbal statement that a decrease in the magnitude of the electric force results by doubling the distance between the charged particles.

Activity 6 is framed to help student cast empirical results in the form of a physical law. All twelve students identified and represented the law of force mathematically, except one, who did it verbally. Out of eleven, seven students have identified and also mentioned the name of the law of force as "Coulomb's Law" and made a simplistic mathematical statement of the law  $F \propto \frac{q_1 q_2}{r^2}$  and two students have corroborated with Newton's law of action of forces. Of the remaining eleven, four students did a frail attempt to build a mathematical statement by using vector notation in different forms such as  $F_{12} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}^2} \hat{r}$  or  $F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$  or

$$|\vec{F}| \propto \frac{q_1 q_2}{r^2} \text{ or } \vec{F} \propto \frac{q_1 q_2}{r^2} \cdot$$

Activity 7 was formed to investigate the student's ability extend their understanding in an altered context. Out of twelve, except two, ten students have identified the direction of force correctly. And six of them verbally mentioned that the magnitude of the forces remains same but the arrow head direction becomes exactly opposite (i.e., attractive to repulsive). Of the remaining four, two students have correctly explained with a schematic representation on the point charges, and the other two students have noted the numerical values before and after the reversing the sign on one of the point charges.

#### D. Stage 4: Validation Test

There was a noticeable improvement in the usage of simulation as the learner progressed from one question to the other. In order to validate learning gain we presented students with three problems. Five students were presented with these problems along with unguided and GG activity (immediate response group) and five were given these after a gap of six months from the time they had used simulation (delayed response group). The questions are given below.

- A. Two point charges which are separated by a distance 'x'. Draw the relevant electric force vectors on both the point charges in Fig. 11.

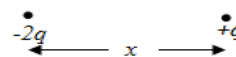


Fig. 11 Two unlike point charges are separated by distance 'x'

- B. Two point charges of  $+20 \times 10^{-6} \text{C}$  and  $-1.7 \times 10^{-6} \text{C}$  are separated by a distance of 2 m. Calculate the magnitude of the force on each charge and verify the result.
- C. In Fig. 12, three charged particles are arranged horizontally. Draw the relevant electric force vectors and net electric force vector on the central charge  $q_2$  due to the charges  $-q_1$  and  $q_3$  respectively.

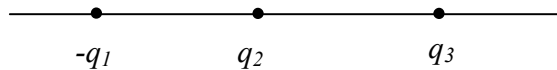


Fig. 12 Three point charges ( $-q_1$ ,  $q_2$  &  $q_3$ ) arranged horizontally

In addition  $Q1(i)$  and  $Q2$  (used in pre-investigation studies) which are in the MCQ format were also given. It is important to note that these questions require students to identify the appropriate vectors rather than draw them.

As mentioned earlier ten students have answered these questions. For  $Q1(i)$  eight students, of which five were from the immediate response group and three from the delayed response group, identified the vectors correctly indicating a clear effect of the usage of simulation. Of those who answered incorrectly selected the option (b). The next question  $Q2$  is in MCQ form and requires identification of the appropriate vectors. In response to  $Q2$ , three students have chosen the correct pair of vectors, i.e., option (b). Of those, two students were from the immediate response group and another one from the delayed response group. Dominant incorrect response (from five students) is an unequal vector lengths suggesting  $F_{12} \neq F_{21}$ .

This is then followed by  $Q(A)$  that require students to draw the vectors. In response to  $Q(A)$ , four students have drawn the force vectors with equal magnitude and shown the arrow head direction correctly. Among them, three students are from the immediate response group and one is from the delayed response group.

In the numerical question (B), except one, all have solved the problem and found the solution correctly and among them four students have verified the answer by noting the magnitudes of the forces from the simulation and also highlighted that ( $F_{12} = F_{21}$ ). One student who solved incorrectly is the one took the test after six months.

Question (C) is intended to inspect the procedural knowledge in drawing the vectors by applying the superposition principle for three point charges. It checks whether students' will be able to extend from two point charges to multiple charges in one dimension. The delayed response group was not presented with this question. Five students of the immediate response group were presented with the question. Two students have depicted the individual relevant force vectors correctly and one has mentioned verbally that net electric force on central charge particle  $+q_2$  as  $F_{12} + F_{23}$ . The remaining three students have made the same error in drawing the vector as a line joining the point charges as in the previous questions, within them one has given the mathematical expression for net electric force on  $q_2$  is the sum of forces due to charge particles  $-q_1$  and  $q_3$  thus showing a clear inability to transfer the learning from a known context to an unknown.

## V. DISCUSSION

As discussed earlier, the present research effort is an attempt to cognize the student learning difficulties in understanding elementary fundamental concepts like electric force which may provide pointers for influencing learning in

advanced courses like electrodynamics. The preliminary investigations were intended to obtain an insight into the understanding of the concept. The most interesting inference is their difficulty to represent vectors, with the majority using faulty vector conventions. This is despite the fact that all or most of the students did possess the working knowledge of vectors in mathematics. This may be because of continuous usage of equation format rather than pictorial form in the prior learning stage. Learning physics involves adhering to procedures that are exact. Representations of students depict a clear failure to use appropriate procedures. This basic error definitely propagates when situations with unequal or more than two charges are presented. Their favorable response to  $Q1(i)$  that required only identifying a correct pair of vectors show an intuitive, correct understanding, but their vector representations in  $Q1(ii)$  and (iii) which involved drawing of these vectors shows a lack of procedural knowledge. Unless instruction specifically addresses this requirement of exactness of procedure, the lacunae in learning shall persist. A similar lack of procedural knowledge shows up in the Coulomb's law representation in their response to driving question  $Q1$ . Paying attention to the vector nature of physical quantity, understanding the notation of meaning of unit vector would possibly avoid errors. Faulty representation of vectors continued to dominate their vector drawings in the response to driving question  $Q2(a)$ . This lack of knowing how to draw vectors influenced the response to driving question  $Q2(b)$  also. The implication of the relative change of the length of the vector as charge separation decrease did escape them.

The situation with two unequal charges, however needs in addition, conceptual understanding. The bigger the charge - larger the force appear as an intuitive idea. However, as one student pointed, writing the mathematical equation show forces are equivalent even though the student may not see Newton's third law in action! Translating mathematical equation into physics understanding is indeed a desirable learning objective. An emphasis on reading the Physics in equations makes students make sense out of mathematics in Physics

As discussed earlier providing the students with driving question and the unguided activity with the simulation has a positive framing effect. Use of simulation being an unfamiliar platform appeared to overwhelm the student and was not productive. For quite a few students, use of any type of simulation was a first time experience.  $Q1$  among the driving question may appear trivial. Understanding the physical situation, identifying the governing law, recognizing the approximations involved in arriving at the law and knowing the limitations of the law are some of the very important objectives of teaching / learning. Students have a tendency to remember the name of the law for example Coulomb's law, Stefan's law.....than recognizing it as a relation between physical quantities. As a consequence, the student is incapable of identifying the applicable physical law in a given context. Indeed the 'point charge' did throw off some students. Our own research which probed into the problem solving process reflected a similar outcome [41]. Students often remembered

that Stefan's law is applicable for black body, but could not use the law in its completeness.

Though the use of simulation as a learning aid has been prevalent for quite some time, incorporating pedagogical objective into the design aspect of simulation is more recent. More so is the importance of method of induction. As discussed earlier the driving question phase was followed by unguided exploration phase. Our own research also proved that completely unguided exploration did produce minimal productive learning. Unless channelized, a novice learner may get lost in unimportant features of the simulation resulting in no learning outcome. The focus of this study is based on the process of learning by using simulation at different levels with and without guidance and observations on the changes in students' conceptual understanding. Visualization and interactivity in a certain way helps in developing conceptual understanding in terms of implicit scaffoldings in the form of affordances and constraints.

Guided activities create directions to make conceptual connections through interaction. As discussed above twelve students were provided with activities while using the simulation. A detailed examination of the students' interaction with simulation, we find that engaged exploration of a simulation occurs only during the gentle guidance. Novice learners do not pick observations relevant in a given context, though experts are at ease to do the same. This was clear when students went through activity 1 and 2 where identifying the equality of magnitude was not explicitly directed in the activity. Activity 3 and 4, which explicitly brings out the magnitude of forces, brought in conceptual understanding of equivalence of forces. However, in activity 5 which involves inverse proportional reasoning there is a betterment of dealing with simulation activity. Activity 6 is a logical conclusion of ideas put forth in activity 1 to 5 that influence in a positive way by the usage of simulation. An important observation by noticing how students interact with simulation is that deducing the law of force was done mostly by quoting from activities 1 to 5 and not by recalling the statement of Coulomb's law. It is observed that there is an improvement in the student observation as they progress from Activity 1 to 6. Activity 7 familiarizes in an altered context which shall have some bearing during the validation test. The validation test intends to test the effect of using simulation and also the retention ability after such an activity.

Simulation used with appropriate guidance can thus foster a logical way of developing concept understanding as it is coupled with intractability and visual inputs. Indeed, simulation is a powerful teaching aid when used appropriately; keeping in mind the way it is used. Simulation because of its visual appeal helps them to internalize the procedural aspect by reinforcing understanding. Interesting is the lack of retention of this learning framework. Retention requires active knowledge construction mechanisms which can be problem solving, learning concepts through demonstration experiments and others. No single teaching aid, not classroom teaching solely, may be sufficient – combining tools with emphasis on

the process of learning which focuses on what needs to be learnt in a given context rather than content may be of use.

## VI. CONCLUSIONS

The present study focuses on understanding student perception of the concept of electric force between charges and investigates the effect of simulation in doing so. An elementary concept is chosen so as to eliminate entanglement with mathematical complexity or bring in a new concept about which learner has no understanding. A pre investigation, study revealed the possible roadblocks, faulty drawing of vectors to represent physical quantities being the primary one. These difficulties influenced learning in several contexts. After presenting students with driving questions so as create a situational familiarity, the students were asked to explore the simulation. Though the unguided exploration resulted in a minimal learning gain, it served to build a familiarity with the simulation which made the gentle guided approach more productive. The activities which accompanied the simulation were prompted by the results of pre investigation studies. A clear enhancement of understanding was evident as students progressed during the use of simulation. The validation question which was given to evaluate the influence of simulation depicted a positive effect. However, retention did seem to be a factor of concern despite the usage of simulation. The findings of the study, however, may be influenced by the use of computers which to some students was an unfamiliar platform. This has been kept to a minimum by allowing students to explore the simulation in an unguided manner prior to actually going into the gentle guidance stage and by not putting a time frame for the completion of the activities. Role of using simulation in understanding concepts like electric field, flux is under progress.

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