High School Students' Understandings and Representations of the Electric Field

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Abstract

This study investigates the understandings and representations of the electric field expressed by Chinese high school students ages 15 to 16 who have not yet received high school–level physics instruction. The literature has reported students' ideas of the electric field post-instruction as indicated by their performance on textbook-style questionnaires. However, by relying on measures such as questionnaires, previous research has inadequately captured the thinking process that led students to answer questions in the ways that they did. The present study portrays the beginning of this process by closely examining students' understandings pre-instruction. The participants in this study were asked to engage in a lesson that included informal group tasks that involved playing a Web-based hockey game that replicated an electric field and drawing comic strips that used charges as characters. The lesson was videotaped, students' work was collected, and three students were interviewed afterward to ascertain more detail about their work. I identified nine ideas related to the electric field that students spontaneously leveraged, even though they had yet to receive formal instruction on the topic. In this paper, I will discuss my findings in comparison with previous research claims.

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Introduction

The electric field is a concept that is typically introduced in high school physics. Studies that have investigated high school and college students' understandings of the electric field (e.g., Furio & Guisasola, 1998; Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001; Tornkvist, Pettersson, & Transtromer, 1993; Viennot & Rainson, 1992) have documented ideas prevalently held by students: for example, big charges exert stronger forces (Maloney et al., 2001); field lines are the moving trajectories of charges (Tornkvist et al., 1993); and electric forces act at a distance rather than through a medium (Furio & Guisasola, 1998). Among the researchers who have explored students' understandings, some, such as Maloney et al. (2001), have called for further investigation of where these ideas come from and whether they are rooted in common sense much in the same way that students studying mechanics tend to think "force implies motion." The present study will address this question by investigating students' ideas of the electric field before they formally learn about it.

The methods primarily adopted in previous studies consist of questionnaires and interviews containing formal textbook-style questions (e.g., Furio & Guisasola, 1998; Maloney, et al., 2001; Tornkvist, et al., 1993; Viennot & Rainson, 1992). As Maloney et al. (2001) pointed out, it was difficult to know how students actually interpreted the questions on the tests; specifically, students might not interpret the vocabulary in the same way the designers of the survey did.

In contrast, an informal task that draws upon the connection between students' everyday experiences and the targeted disciplinary content area allows students to produce their own ideas and representations prior to formal instruction (e.g., diSessa, Hammer, Sherin, & Kolpakowski, 1991; Penner, Giles, Lehrer, & Schauble, 1997). These ideas and representations can be useful resources for the students' future learning experiences and are also important artifacts that help researchers and educators better understand student thinking (Hammer, Elby, Scherr, & Redish, 2005). As part of the present study, an activity was conducted in which students were engaged in such informal tasks—using their commonsense ideas as starting points and having fewer constraints—in the hope of extending previous research findings and gaining insight into student learning.

The ideas that students begin with deserve a close examination because those ideas contribute crucially to how students learn in a formal setting, a process in which students build newer understandings upon previous ones. Only when we know more about students' pre-instructional conceptions can we possibly unpack their thinking process, a task that is important but inadequately addressed in the literature.

Therefore, the question guiding this research study is: What ideas of the electric field do high school students express as they produce representations of it in an informal context before they receive formal instruction? In this paper, I will explore the ideas students expressed and will compare the findings with previous research claims.

Background

In high school and introductory college level physics instruction, the electric field is presented as an unseen entity generated by electric charges (called source charges). The electric field permeates a space. When a test charge is put in this space, it bears an electric force that comes from the source charges throughout the electric field, which acts as a medium between the source charges and the test charge.

The electric field has strength and direction. These features can be represented mathematically through algebraic formulas as well as through geometric shapes. The electric field line is one of the canonical geometric representations. A picture of electric field lines resembles a wind map, in which vectors indicate the direction of the wind. Figure 1 features some examples of electric field lines. The positive and negative signs in the pictures indicate the source charges that generate the electric field. The lines with arrows are canonical electric field lines showing the electric field vector throughout the space.

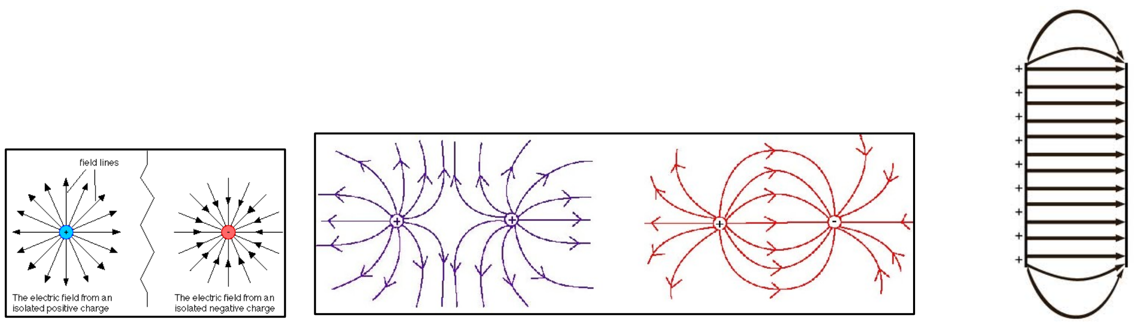


Figure 1. Examples of electric field lines.

Since the early 1990s, scholars have been looking at students' understandings of the electric field from various perspectives. The main effort has been to identify students' learning difficulties and speculate about possible reasons for these difficulties from curricular and pedagogical standpoints.

In the following of this section, I will review the literature on students' understandings about the concept of the electric field. When I review studies, I will point out their research method, because my method is different from previous studies and therefore contributes to this field. When I described their results, I summarize their main findings and bring forth claims that will relate to my findings presented later in the results section of this paper.

Galilli (1995) examined high school students' conceptions of electromagnetism by administering a paper-and-pencil test. He argued that as students learned mechanics, force was the key concept underlying the content area, and field was hardly mentioned. However, when they studied electromagnetism later on, field became a central concept. In mechanics, objects are interacting directly with each other. In electromagnetism, field is a necessary media for the interaction of charges. According to Galilli, students might misinterpret the nature of force interactions and work-energy conservation in the presence of an electromagnetic field because they had previously learned to interpret them differently in mechanics.

Eylon and Ganiel (1990), and later Thacker, Ganiel, and Boys (1999), conducted studies with university students, and the results suggested a gap between students' understandings of electric circuits and those of electrostatics. This gap, the authors proposed, might result from different conceptions the students had between the macro and micro levels of electric phenomena. The former involves numerous charges performing collectively, while the latter deals with interactions among a handful of individual charges.

Viennot and Rainson (1992) interpreted Eylon and Ganiel's findings (1990) as "amply show[ing] students' difficulties in seeing the role of electric field in the interplay of the different elements of circuits," thus motivating them to explore students' reasoning about the electric field. They decided to focus on the principle of superposition of electric fields: whether the students applied the principle of superposition properly and, if not, what were the common obstacles that prevented students to appropriately use the principle. Viennot and Rainson administered a questionnaire that required written explanations. When discussing the results of their study, they said that they confirmed one of the findings of Rozier and Viennot's study (1991), in which the authors investigated students' reasoning with regard to thermodynamics: students use linear causal reasoning to solve a problem involving the simultaneous influence of several factors; in doing so, students generate story-like comments indicating that they conceive the phenomenon as a "successive" sequence of events. In order to illustrate this reasoning, Viennot and Rainson provided the following example: "A charge is placed somewhere, then the insulator gets polarized, and then there is a field created at point M” (p. 479). However, neither one of these studies explicitly addressed whether students who were solving problems involving multiple source charges thought that these charges exert forces simultaneously on the test charge, a basic idea of the superposition of static electric fields.

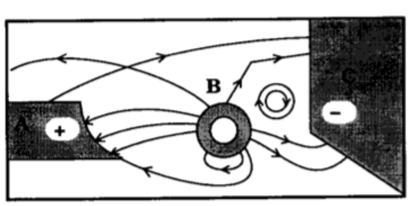
The studies mentioned above related students’ ideas of the electric field to what those students had learned when studying different areas of physics. Other researchers have examined students’ ideas in relation to their ideas of general mathematics concepts. For example, Allain and Beichner (2004) studied college students’ conceptions of the electric potential. They speculated that students’ performance on field-and-potential physics questions should correlate to their performance on rate-of-change mathematics questions because the electric field is the spatial rate of change, or gradient, of the electric potential. The authors developed a questionnaire that contained both types of questions. The results indicated a pattern: the students who answered the electric-potential questions wrong also answered the rate-of-change questions wrong. The authors then suggested that curricula designers should take that correlation into account and therefore approach the concept of electric potential by first reviewing the concept of rate of change and bridge it to electric potential by first using easier rate-of-change situations, such as the gradient of a hill, and graduating toward harder electric potential applications.

Still more scholars have been interested in viewing students’ ideas of the electric field from a cognitive perspective. Greca and Moreira (1997) observed college students’ performance in physics classrooms and on labs, homework, and exams. From their observations, the authors inferred whether the students understood concepts concerning the electric field as interrelated in comprehensible conceptual models when they solved problems. The authors suggested that students worked mostly with propositions—definitions, formulas, etc.—that they manipulated routinely to solve the problems; students did not usually construct operational mental models, nor did they interpret the definitions and formulas according to mental models.

However, at the same time, these researchers pointed out a wide range of student performance. According to the authors, some students in the study constructed mental models and thus had a better understanding of the concepts learned, while some students did not construct mental models at all and thus had little understanding of the concepts. Between these two ends of the spectrum, there were many students who constructed incomplete mental models and understood the concepts only partially. Identifying this range, Greca and Moreira suggested that we should not treat a large group of students as an undifferentiated class of novices, but should recognize that a substantial difference exists among them.

Furio and Guisasola (1998) applied a questionnaire to investigate high school and college students' understandings of the electric field. They came to the conclusion that students' ideas reflected the ontological and epistemological beliefs they held about electrostatic interactions. The authors reviewed the history of electromagnetism and compared students' epistemologies with the evolving epistemology throughout the history of science. They suggested that students usually understood electric interaction as acting at a distance: two charges separated in space can exert forces on each other simultaneously with no medium in between them. This idea, according to Furio and Guisasola, was undergirded by Newtonian cosmology, which suggests that "forces are considered particular aspects of material interactions without procedural explanation" (p. 515). The action-at-a-distance idea prevailed when Coulomb generalized the law of charge interactions in the late 1700s. After Faraday and Maxwell constructed the field theory of electromagnetism in the 1800s, electric interaction was explained as a contiguous force, transmitting through a medium—the electric field—between charges. This field point of view is grounded in what they call Cartesian cosmology, which states that, “forces happen by means of the vortexes or whirls that emanate from corporeous matter” (p. 515). The authors argued that most students adopted a Newtonian cosmology viewpoint rather than that of Cartesian cosmology. Therefore, they saw electric interaction as an action at a distance instead of a contiguous force, and because they were under the sway of this viewpoint, they continued to experience difficulties in understanding the electric field.

Studies have also focused specifically on students’ use of electric field lines. For example, Tornkvist, Pettersson, and Transtromer (1993) gave a paper-and-pencil test to college students as they learned about the electric field. The authors asked students to find the errors in the field lines of a diagram consisting of charged conductors and corresponding field lines in that space (see Figure 2-1). In addition, the authors carried out interviewed with students, trying to capture their interpretations of different types of representations related to the electric field, especially vector representations: field lines, force vectors, velocity vectors, trajectories, etc. During the interview, they presented students with nine printed diagrams of canonical field lines. The interview questions centered on the concepts of electric field strength, electric forces, and the charge’s velocity and trajectory in each of the situations depicted in the diagram. (For example, students were asked to show the forces and trajectories of a test charge at a given point p in a given field represented by the canonical field lines in Figure 2-2.)



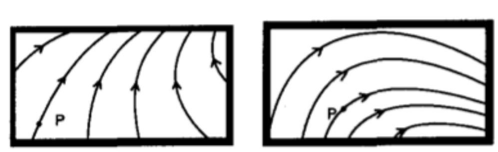


Figure 2. Electric field lines presented to students in Tornkvist et al.'s study (1993). Left: Figure 2-1. The error-finding task. Right: Figure 2-2. Examples of the tasks administered during the interview.

Based on a quantitative analysis of students' responses categorized as right or wrong, the researchers concluded that students usually did not grasp the hierarchical relation between different concepts and representations: charge display determines field lines, which determines force vector, which determines velocity vector, which determines trajectory of a test charge. As a result, students confused field lines with other types of representations, such as force vectors, velocity vectors, and trajectories.

In order to help students understand electric field lines, researchers and practitioners have been introducing artifacts that can help students envision these unseen lines. Belcher and Olbert (2003) developed 3-D animations of field lines and suggested that the animations could reinforce the users' insights into the connection between the shape of field lines and their dynamic effects. Shortly thereafter, Dori and Belcher (2005) conducted a long-term study investigating undergraduate students' comprehension of electromagnetism when they were taking a course that employed nontraditional methods. In their class, students were arranged into small groups seated at round tables, and group discussion and experimentation replaced lecturing. The course adopted the 3-D field line animations developed by Belcher and Olbert (2003). To measure the efficacy of the new curriculum in terms of leveraging students' understandings about electromagnetism, Dori and Belcher administered pre- and post-assessment tests, which consisted of conceptual questions from standardized tests. The results showed that the group taking the nontraditional course showed greater conceptual gains than the group taking a more traditional course.

The aforementioned studies explored students' understandings with specific foci. Other researchers have been trying to get a more general overview of students' performance. By administering multiple questionnaires, Sağlam and Millar (2006) found that high school students confused electric and magnetic field effects. Students saw field lines as indicating a "flow" from positive charges to negative charges just like electric current flows from the anode to the cathode; students used cause–effect reasoning in situations where it did not apply; and they had trouble dealing with effects associated with the concept of rate of change. The last result resonates with Allain and Beichner's study (2004).

Maloney, O'Kuma, Hieggelke, and Van Heuvelen (2001), using questionnaires, surveyed students' ideas before and after a college physics course in electromagnetism. They found that some ideas were prevalent and difficult to change among students. For example, they discovered that students believed that larger objects exert larger force. By "larger" they meant "larger charge magnitude" (4Q greater than Q, for instance). Students thought that the forces from 4Q to Q were stronger than the force back from Q to 4Q, an idea that violates Newton's Third Law. When two charges were separated farther, students could not figure out how much the strength of the force had changed. Other findings that resonate with research of Viennot and Rainson (1992) and that of Sağlam and Millar (2006) include: students were confused by the superposition of fields generated by multiple charges; they mistook magnetic field effects for electric field effects; and before instruction, students were apt to make analogies between electric field lines and electric currents.

At the end of their paper, Maloney et al. (2001) suggested that determining the source of students' ideas was difficult. The authors claimed that whether students' ideas came from common sense or some other source required more research. At the same time, the authors raised the issue about the formal language used in the questionnaires. They admitted that many of the questions in the questionnaires they used included physics terms, because they claimed that it would be difficult, if not impossible, to ask about the concept without using that vocabulary. They stated that it was difficult to know how students actually interpreted the questions on the tests, and that students might not interpret the vocabulary in the same way the designers of the survey did. Therefore, the authors speculated that students' seemingly wrong ideas perhaps stemmed from the use of vocabulary and phrases they did not really understand. Maloney et al. hoped that their study could direct research toward students' commonsense conceptions about electromagnetism.

As always, scholars are not content with just examining students' conceptual difficulties. They want to know the reasons for them and find ways to change them. Accordingly, Bagno and Eylon (1997) assessed students' knowledge after a traditional advanced high school course in electromagnetism. They claimed that the study showed deficiencies in students' knowledge in a few areas, one of them being understanding the relationships between the electric field and its sources. They proposed an instructional model that integrated problem solving, conceptual understandings, and construction of the knowledge structure, and then evaluated the effect of this instructional model.

Likewise, previously mentioned studies have proposed myriad methods to address the problems that they had uncovered, from adopting specific instructional tools (e.g., Tornkvist et al., 1993) to fundamentally reforming the curriculum (e.g., Dori & Belcher, 2005). At the same time, researchers have continued to try out new instructional activities underpinned by educational theories such as learning in a context (Finkelstein, 2005) and conceptual change (Başer & Geban, 2007).

Conceptual Framework

Piecing together the research presented in the previous section into a larger mosaic, we can see that so far the literature has: 1) explored students' ideas of the electric field and related topics in physics as well as mathematics; 2) accomplished research objectives by looking at students' answers to textbook-style questions; 3) surveyed students in the course of their learning about the electric field; 4) primarily focused on college students; and 5) mostly emphasized students' learning difficulties or their insubstantial conceptual gains after instruction. This mosaic also reveals holes in the literature. Currently it lacks a wealth of research into how high school students understand the electric field as well as an in-depth perspective of students' comprehension of the electric field pre-instruction as expressed in informal settings.

Drawing upon the constructivist perspective, I view learning as building new understandings upon previous ones. Students' ideas, canonical or noncanonical, are resources they draw upon and use to make sense of the phenomena they encounter (Hammer et al., 2005). If we want to help students build more coherent ideas that are in line with disciplinary understandings, we should first of all attend to their preinstructional ideas and how they express those ideas through their own means. These ideas are best accessed when students engage in informal tasks and are freed from potentially paralyzing formalism inherent in the use of proper terminology and the expectation of correct answers. In this kind of context, students are more likely to make sense of the world than following step-by-step recipes to solve problems (Hammer, 2004).

With this in mind, and as previously stated, in this study I explored the following question: What ideas of the electric field do high school students express as they produce representations of it in an informal context before they receive formal instruction?

Methods

Participants

The participants in this study were ninth graders ages 15 to 16 attending a summer school in China. The school provided summer courses for students preparing for the next year of instruction; in this case, they were preparing to enter high school after finishing their summer school. The students in this study had received no formal instruction on electrostatics but had been exposed to magnetism. They had not systematically studied Newtonian mechanics but had learned how to analyze two balanced forces acting on an object.

The physics course in this program consisted of 12 lessons lasting 90 minutes each. I taught the physics course to three groups of students and implemented my study during lesson 12 for each group. In lessons one to 10, I covered one-dimensional motion. In lesson 11, I very briefly covered force composition. In lesson 12, I conducted the electricity lesson featured in this study.

The Lesson

The goal of Lesson 12, the focus of this study, was to expose students to the phenomenon of electric charge interaction and give them an opportunity to make sense of it through informal activities. The lesson included two open-ended activities. I told the students I was not looking for the right answers, but that the main goal was to discuss ideas with one another; I also informed them that these activities were part of my research project.

I started the lesson by engaging the students in a Web-based computer game called Electric Field Hockey (http://phet.colorado.edu/en/simulation/electric-hockey), which I downloaded from the website produced by PhET, a University of Colorado educational technology group that designs science simulations for classroom use. The game was installed and played on the teacher's computer, which broadcasted its screen through a projector onto the front wall of the classroom. The goal of this activity was to expose the students to simulated electrostatic phenomena—attraction and repulsion between positive and negative charges—and its impact on a test charge's motion.

As shown in the screenshots below (see Figure 3), the game's objective is to make the black hockey puck (positively charged) hit the goal. In the upper right hand corner of the hockey field, charged balls—red positive balls and blue negative balls— are stored in separate boxes according to the type of charge. The charges are depicted as small circles marked with a positive or negative sign. The game requires players to drag and place the charged balls on certain spots in the gray square denoting the hockey field, in order to make the hockey puck move and reach the goal (the blue half-square bracket). The game has four levels of difficulty: the practice level and difficulty Levels 1 through 3. The students were asked to play the two easiest levels in class: the practice level with no barrier in the field and Level 1 with a vertical barrier at the center of the field.

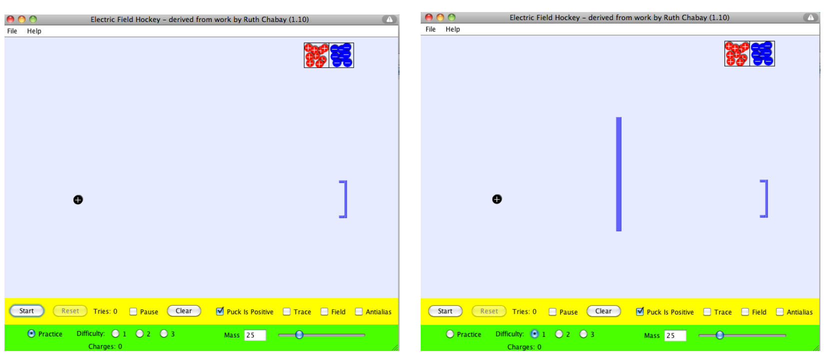


Figure 3. Screenshots of the Electric Field Hockey game. Left: Practice Level. Right: Level 1.

Students were asked to volunteer to play the game on the teacher's computer at the front of the room, as the other students watched and called out suggestions. In the 10 to 15 minutes that I allowed for the activity, five to six students were able to play. I did not intervene during this activity.

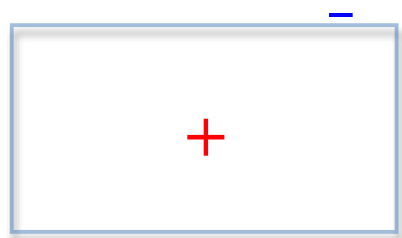
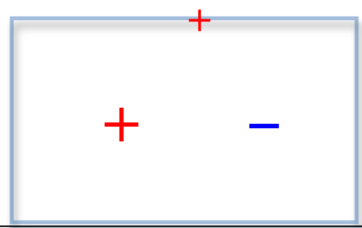
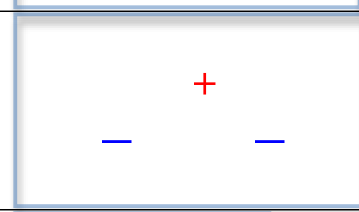
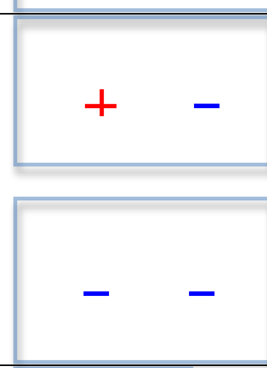
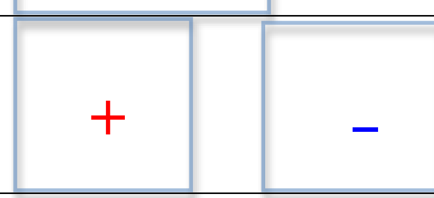
Then students spent the rest of the lesson participating in the second activity: drawing comic strips that showed interactions between positive and negative charges as if they were characters in a cartoon series (the initial scene of each story was described on the worksheet). The charges in the initial scenes were represented very similarly to the ones they had just played with during the hockey game. I chose the comic strip activity because it placed no vocabulary constraint on students. It also served as a way to keep track of students' understandings in a written form that would augment the videotaped recording of the ideas students expressed in class. Finally, I required students to draw multiple frames of the story so that I could capture their ideas about the intermediate steps in the process of charge interaction.

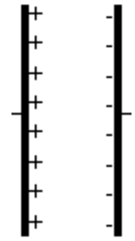
There were five consecutive sections in the comic strip activity. The first three sections concerned charge interactions with the presence of a test charge in each scenario (Sections 1, 2-1, and 2-2). In subsequent sections (Section 3, 4, and 5), the test charge was absent.[1] Sections 1, 2-1, and 2-2 asked students to draw a four-frame story for each scenario. In Section 1, a big charge sits in the room and is immobile. Then a little negative charge comes into the room. The students were asked to draw a story about what happened next. In Section 2-1, a big positive charge and big negative charge sit in the room and are unable to move. And in Section 2-2, two big negative charges sit in the room. In both Sections 2-1 and 2-2 scenarios, a little positive charge comes into the room. Again, students were asked to draw what happened next. Sections 3 and 4 asked students to show the influence the big charges had if a little positive charge were present. Section 3 used the two scenarios of Sections 2-1 and 2-2, and Section 4 put the big

[1] The electric field is formally defined as independent from the test charge. The magnitude of the electric field equals the electric force per unit test charge (in Newton per Coulomb). In addition, the electric field is the same with or without the presence of the test charge. These conventions guided the design of the comic strip activity.

positive charge and the big negative charge into separate rooms. Section 5 asked students to show the influence of charged parallel plates on a test charge (see the summary in Table 1).

Table 1. Comic Strip Activity Tasks

Text	First Scene
Section 1 Draw Something: Draw a four-frame comic telling a story about two characters: Little Positive (P) and Little Negative (N). P is sitting at the center of a room when N comes in through the door. What will happen next? Use four frames to draw at least four scenes of the story. The picture shown could be the first panel, but feel free to draw a picture for the first panel. You are not required to draw every character vividly; the key is to show how and why your characters act the way they do.	
Section 2-1 Draw Something: Draw a four-frame comic telling the stories of two big charges and one little charge. For this first story, there is one Big P, one Big N, and one Little P. Big P and Big N are sitting in the room at a distance. They are fastened to their seats and can't move. Little P comes into the room. What will happen next? Explain your story to the class. What do all the things you have drawn mean?	
Section 2-2 Draw Something: Draw a four-frame comic telling stories of two big charges and one little charge. For this second story, both big charges are negative, while the little charge is positive. What will happen when the little charge enters the room? Explain your story to the class.	
Section 3 Draw Something: Now what if we take away the Little Positive charge from the previous two pictures? Can you find a way to show the influence they have on the little positive charge?	
Section 4 Draw Something: What if we leave only one big charge in the room, P or N? How can you show the influence the big charges (Big Positive or Big Negative) have, respectively, on a Little Positive charge that might come into the room?	

Section 5 Based on what you have drawn before, how can you show the influence the two charged plates have on a little positive charge that moves between the plates? Why is this true?	

Student worksheets were handed out in packets to each individual student right after they had finished playing the Electric Field Hockey game. When drawing the comic strips, students worked on the tasks sequentially and individually. I walked around and looked at student work. After most students finished each section, I called on a few students to present their work in front of the whole class. When choosing students, I purposely looked for diverse representations that I had noticed among the students' work.

Data Collection

I taught this lesson with three groups of students (92 students in total), videotaped the three iterations of the lesson, and collected student work from all the three groups. After reviewing the work of these 92 students, I decided to focus my post-class interview on students who used arrow diagrams in their work, ascertaining the ideas they expressed by drawing this representation. I made this decision because 1) arrow diagrams were common among the work turned in by all three groups of students; 2) the canonical representation of the electric field consists of arrow diagrams (see Figures 1 and 2); and 3) previous studies (Sağlam & Millar, 2006; Tornkvist, Pettersson, & Transtromer, 1993) claimed that students had difficulties with field lines and other vector representations such as velocity, trajectory, and electric current. Starting with probing students' use of arrow diagrams, which were prevalent, resemble canonical representations, and have been a focus of previous studies, I hoped to explore the ideas of the electric field that students had represented in their drawings.

I carried out post-class interviews individually with three students from the same group who had included arrow diagrams throughout their work. The interviews were videotaped and conducted in Chinese. Each interview was videotaped with two cameras, one focused on the student's face and the other on his or her hands and written work. During the interviews, I asked each student to explain his or her classwork in detail. They were allowed to change their original answers if they came up with new ideas. During the interview, each of them added new ideas to their work in response to my questions, which asked them to elaborate their answers. At times, the questions I asked reflected my interests, rather than the students'. For example, when they explained their work to me, usually it was not totally clear to me whether the arrow diagram they had drawn represented a force, a movement, or both. When I noticed this, I would ask about it, "Does this represent the [charge's] movement or the force?" Table 2 provides an overview of the time frames of the lesson and the interviews.

Table 2. Lesson and Interview Time Frames

The Lesson (90 minutes, including a 10-minute break)		**Post-class Individual Interviews**
Electric Field Hockey activity	Comic strip activity	Explanation of comic strips
10 minutes	70 minutes	45 minutes per student

Analysis

The analysis in this paper draws data entirely from the post-class interviews, which exclusively addressed students' work for the comic strip activity. With the goal of making sense of each individual's understandings of the electric field and comparing them with students' ideas reported in the literature, I first transcribed the videos of all three interviews and translated them into English. When translating the transcripts into English, I made every attempt to keep the meanings as close as possible to the students' ideas as originally expressed in Chinese.

After transcribing, I carried out a line-by-line inspection of the interview transcripts. Considering my main focus on students' use of arrow diagrams, I flagged students' ideas when they: 1) pointed with their fingers to the arrows they had drawn in their work and explained their work; 2) responded to my questions about the meaning of the arrow diagrams in their work; 3) mentioned ideas that related to the arrow diagrams such as force directions and/or moving directions. In addition, I also flagged the ideas they expressed that had been addressed in the literature, such as the relation between force magnitude and charge size. Finally, I flagged emerging themes in students' explanations that reflected their ideas of the electric field, even though they had not been addressed in the literature, such as the description of opposite charges attracting and like charges repelling. My research question focused on high school students' ideas and representations pre-instruction when they were engaged in an informal comic strips activity. The analysis described above allowed me to ascertain their ideas that were related to the arrow diagrams they had produced, and starting from there, also to keep track of other ideas students' expressed that were relevant in the literature and other themes that emerged in their explanations.

I constructed three case studies, one for each student. In each case, I put together the student's drawings along with his or her transcript related to the drawing he or she had produced (shown later in the results section). By doing this, I was able to construct a relatively complete picture for each student about his or her ideas reflected in the drawings and interview transcripts. Then I carried out a *cross-case synthesis* (Yin, 2006) bearing in mind particular ideas that were identified in one or more students' cases. For this purpose, I carried out a cross-student analysis focused on the written work and oral explanations that were centered on a particular idea of the electric field. For each idea, I drew evidence from the three students' written work and/or explanations, and organized the evidence under each idea. Lastly, I compared these ideas with the claims made in previous study findings, and categorized them as “not addressed by,” “contrast with,” and “similar to” previous research claims (shown later in the results section).

Results

To provide adequate context for the individual interviews that are the focus of this study, I will first describe the Electric Field Hockey game that was played at the beginning of the class, which served to introduce students to the phenomenon before participating in the comic strip activity. Essentially, in all three groups, the students performed similarly during the hockey game activity. So although the description below mainly characterizes what happened with one group (from which the interviewed students were drawn), it also represents what occurred with the other two groups.

Description of Students Engaged in the Electric Field Hockey Game

Students played the Electric Field Hockey game for about 10 minutes. Figure 4 shows screenshots of the game that exemplify students’ approach to the game.

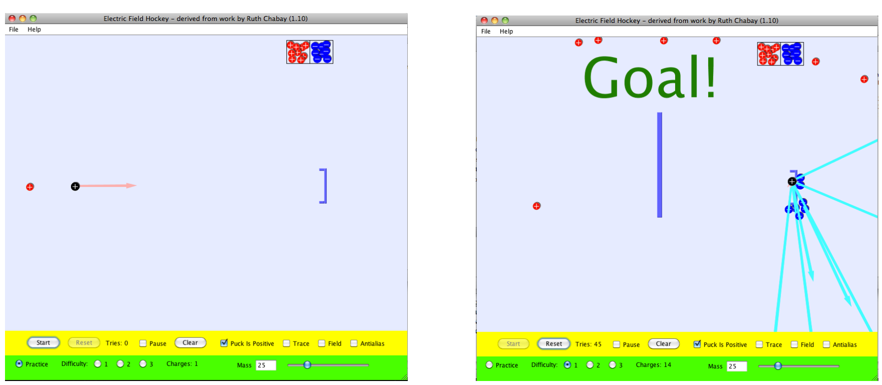


Figure 4. Reproduced screenshots of students playing the Electric Field Hockey game. Left: While playing the Practice Level, a student placed a positive charge to the left of the puck to make it move. The puck then hit the goal. Right: When playing Level 1, students placed many charges in different places. The puck moved around the barrier and hit the goal.

When playing Level 1, which had a vertical barrier in the middle of the field (see Figure 4, right), students tried a variety of different strategies to arrange the charged balls in the field in order to make the puck go along a curve, get around the barrier, and arrive at the goal. They talked a lot about the attraction and repulsion among the balls and the hockey puck, the number of balls they wanted to place on the field, the positions in which to put the balls, and the distance between the charged balls and the hockey puck. They spent nine minutes playing this level (whereas they played the practice level for only one minute) but were not able to complete it before it was time to move on to the comic strip activity. Some of the students returned to Level 1 during the break between the two halves of the 90-minute lesson and passed this level. They shouted out with joy when they finally made the puck hit the goal and heard the congratulating sound played on the computer. These students kept the charged balls at the places that had successfully made the hockey puck arrive at the goal and wanted to show what they had done to the whole class. At the beginning of the second half of the lesson, I projected the computer screen onto the front wall. The whole group watched as one student hit the Start button at the bottom, and then the hockey puck moved in a curve and arrived at the goal. The whole glass hoorayed when watching the puck hit the goal.

A feature of the Electric Field Hockey game might have had an effect on students' comic strips and their use of arrow diagrams, my analytical focus in this study. As shown in the screenshots, when the charged balls were placed in the field, arrows connected to the hockey puck appeared automatically (see Figure 4, left hand side). These arrows represent the electric forces that acted on the puck.[2] However, I never addressed these arrow diagrams that they saw on the screen, and they never asked about them.

[2] The length of each arrow represents the magnitude of the corresponding force; the arrowhead represents the force direction; and the color of each arrow denotes the source of the force (a red arrow means the force came from a

Students' Productions and Explanations for the Comic Strip Activity

Now I will present the comic strips produced by the three students interviewed—Xinmiao, Mandi, and Guanhua. I interviewed them individually on different days after the summer session they had attended had ended.

As I present their work and explanations, I will primarily focus on their original classwork and the first explanation of the work that they gave in the interview. I will also provide the new representations they produced during the interview for cases in which they made revisions to their work during the interview as a result of our conversation and new insights they developed.

For each student, I will show his or her work and explanations in table form. In each table, the first column lists the sections. The student's work is presented in the second column, and the explanations are given in the third. The transcripts of the students' explanations were edited to remove words such as "um" and "like." Following each table, I will summarize the student's ideas about the electric field exhibited in his or her written work and explanations. (Appendixes A to C provide the photocopies of the three students' work.)

Xinmiao's Work

Xinmiao, a quiet boy in class, was the first student I interviewed. Table 3 shows Xinmiao's work. The black marks in his work were added during the interview because at some points he wanted to make the drawings darker (such as in Section 2-1), and other times, when he tried to recall what he did in class by re-reading the task, he realized that he had misunderstood the task requirement in class and thus redid the task during the interview (such as in Section 2-2).

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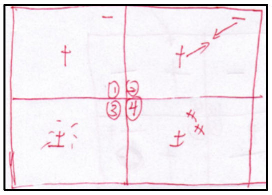
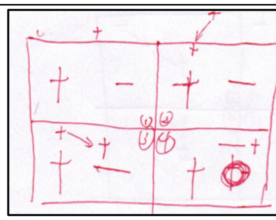
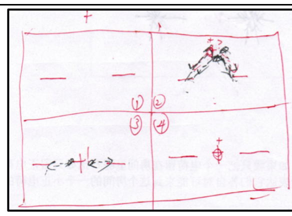
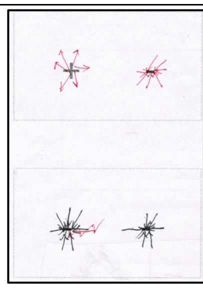
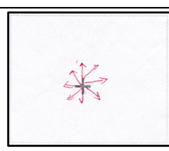
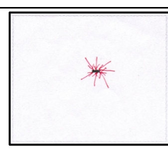
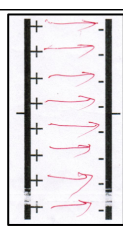
positive charge and a blue arrow means the force was generated by a negative charge). When the charged balls are far away, such as the positive balls in Figure 4, right hand side, the forces from them are very weak and the arrows corresponding to these forces cannot be seen.

Table 3. Xinmiao's work

	Student Work	Explanations
Section 1		Xinmiao said: *When the two charges met, they were attracted to and moved toward each other and combined into a new thing.* He said the fourth frame told nothing more. He just repeated the third frame because the task required him to draw a four-frame comic strip.
Section 2-1		He explained: *The little positive charge came into the room and saw two charges. It looked for a big charge to combine with. It first went to the big positive charge but could not combine with it. It then moved to the big negative charge and combined with it.* He drew a new comic strip during the interview when I asked him what he would have done if I had not required him to fill out four frames. (See Figure 5.)
Section 2-2		He explained: *The little positive charge saw both big negative charges attracting it, and it could combine with either of them. It did not know where to go. The two big negative charges' attracting forces were the same and thus balanced, so the little positive charge stayed in the middle.* Again, he said the fourth frame was a repeat of the third frame, and I did not need to look at it.
Section 3		He said that his drawing meant that a big positive charge could repulse a little positive charge, a big negative charge could attract a little positive charge, and this impact on the little positive charge was in all directions. Although the little positive charge was not represented in the pictures, he did not have trouble imagining one that could show up anywhere around the big charges.
Section 4	 	He claimed that this section was the same as Section 3, only that in Section 3, the big charges also attracted or repulsed each other because they were in the same room, although showing that was not a requirement of the task.
Section 5		In class, Xinmiao was called out to present this piece of work to the whole group. He said then that he could not articulate why he had drawn these red parallel arrow lines. During the interview, he said that the lines meant that the positive charges on the left plate were attracted to the negative charges on the right plate.

Xinmiao expressed the idea that *positive charges attract and negative charges repulse*. In Sections 1 and 2, he used arrows to show the intended and actual directions of the little charge under the influence of the big charges. He also referred often to the idea that *two opposite charges ought to be combined*. He said explicitly that it was bad if the opposite charges did not combine.

In Section 2-1, Xinmiao's first frame depicted the moment before the little charge came into the room. The second frame showed what would happen if the little charge went to the big positive charge first. In the third frame, the little positive charge was repulsed by the big positive charge, and in the fourth frame, the little positive charge combined with the big negative charge. He described what he drew, "*First,* the little charge went to the big positive charge but could not combine with it; *then* it came to the big negative charge and combined with it [italics added]."

I asked him to tell me more about why he thought the little positive charge went to the big positive charge first. He said that if the little charge went to the big negative charge first, they would combine directly, and the story would end. However, since he had not addressed the interaction between the little and the big positive charges, the story was "not complete." I asked him what he meant by "not complete." He replied that he needed to fill up all four frames. From this, I infer that he felt the need to present four events in four separate frames.

Because of this obligation to fill four frames throughout Sections 1, 2-1, and 2-2, he drew a repetitive fourth frame for Sections 1 and 2-2 since he had already finished the story in the third frame. For Section 2-1, he was able to tell the story of attraction and repulsion separately in four distinct frames, which made him feel more content than when he repeated what he had drawn for the third frame in the fourth frame, as he had for Sections 1 and 2-2.

Trying to probe his reasoning further, I asked him to redraw this story using as many frames as he liked. In response, his drawing for the first frame showed that from the very beginning, the little positive charge was repulsed by the big positive charge and, at the same time, attracted to the big negative charge (represented by two dashed arrow lines in the top left corner of Figure 5). In the second frame, the little positive charge moved toward the big negative charge due to attraction (shown by the arrow pointing down and right to the big negative charge in the top right corner of Figure 5). As the little positive charge moved, repulsion from the big positive charge still acted upon the little one by changing its direction (shown by the group of arrows pointing right and up, also in the top right corner of Figure 5). The third and last frame was kept the same as what he had done before in class (see the bottom left corner of Figure 5).

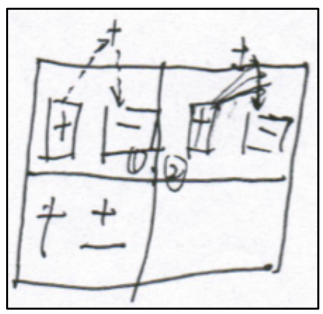


Figure 5. Xinmiao's revised drawing for Section 2-1.

In Section 2-2, he represented attractions from two big negative charges in the same frame. Examining his work for Sections 2-1 and 2-2 provides us with evidence that students can understand that *electric forces act simultaneously when multiple charges are present*. In some cases, as Xinmiao did in Section 2-1, students might draw or refer to the interactions sequentially for reasons other than their understanding of the electric force, such as in response to the structure a particular task requirement (e.g., draw four different scenes in four separate frames).

When Xinmiao explained his drawing for Section 2-1, I asked him another question: "How come the little positive charge knew he would be rejected or accepted by the big charges?"

He thought about it for a while and answered that it was due to the signals the big charges sent out. His response indicates that he believed *electric interactions are contiguous interactions*. According to the literature, even college students think of electric interaction not as a contiguous force, but as an action at a distance (Furio & Guisasola, 1998), which is viewed as a less advanced understanding.

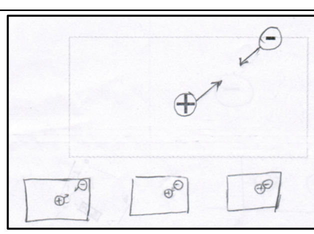
Xinmiao produced groups of arrows in Sections 3 through 5 instead of the single arrows he had produced in Sections 1 and 2. According to his explanation, in Sections 3 and 4 the little charge was no longer present in the frames, therefore he drew a group of arrows indicating that *the attraction or repulsion from a source charge could be in any direction around it depending on where the little charge would be*.

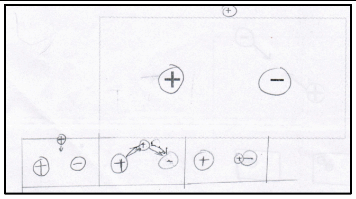
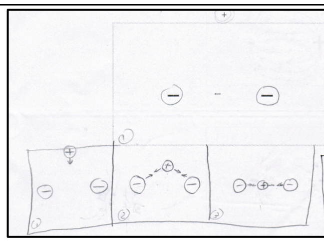
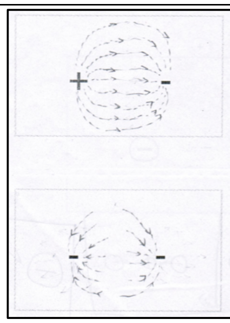
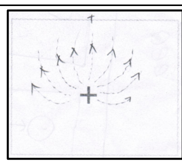
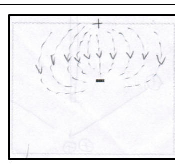
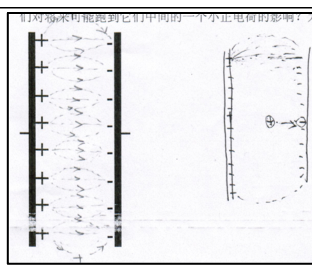
The arrows Xinmiao drew represented mixed meanings regarding the direction of a force and the direction of a charge's motion. The field lines he drew basically represented electric forces on a positive test charge. He was not bothered by using the same representation to describe multiple meanings (although this is usually an issue for the instructor; see Tornkvist et al., 1993).

Mandi's Work

Mandi, a dedicated participant in class, was the second student I interviewed. Table 4 shows her work and her explanations for each section of the activity.

Table 4. Mandi's Work

	Student Work	Explanations
Section 1		Mandi said that the two charges attracted each other and moved to the middle.

Section 2-1		She explained: *"...[A] little charge may not attract as strongly as a big one, or... the strength of attraction [of a big charge] is bigger. ... [W]hen [the little positive charge] comes in, it is immediately repulsed by the big positive charge and attracted to the big negative charge. So the moving trajectory should be...* [gestures a curve from left to right].*"*
Section 2-2		She explained that because the strength of the two negative charges was the same, their attraction to the little positive charge should also be the same. The little positive charge moved to the middle point, where the force was the smallest, and got stuck there.
Section 3		She said that according to magnetic field lines starting from the north pole and ending at the south pole, these electric field lines should start from the positive charge and end at the negative charge. Her lines showed the attraction and/or repulsion to an imagined little positive charge in the middle of the two big charges.
Section 4	 	She said the lines showed the attraction and/or repulsion from the big charges at the center to the little positive charge at the top.
Section 5		She said that the little positive charge in the middle was repulsed by the positive charges on the left plate and attracted to the negative charges on the right plate.

Mandi's and Xinmiao's work for Section 1 look similar. However, their foci of explanation diverged slightly. Xinmiao often emphasized the idea of the *combination of two opposite charges* (both for Sections 1 and 2). Mandi made no mention of the final status (combination or otherwise) of the little charge, although her final frame for Section 1 was similar to what Xinmiao had drawn. She repeatedly emphasized the idea of *attraction and repulsion*. She seemed to pay more attention to the mechanics (attraction and repulsion) than the final status (e.g., the little positive charge should combine with a negative charge, as Xinmiao framed it) of the phenomenon.

Mandi's explanation of her work for Section 2-1 might indicate that she understood that *a bigger charge exerts a stronger force and a smaller charge exerts a weaker force*. It could make sense if she were talking about the forces of two source charges of different magnitude.

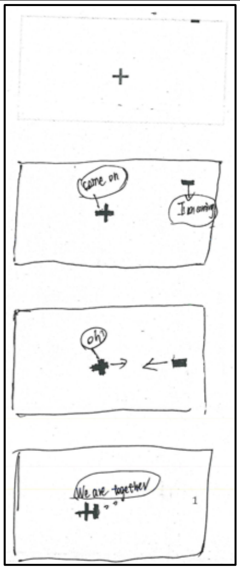
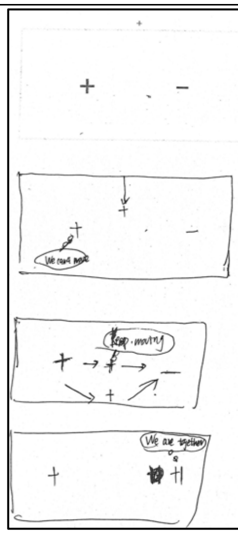
As exhibited in Mandi's drawings and her explanations for Sections 3 through 5, arrow lines *always start from positive charges and end at negative charges* and those lines must be *curves so that they can fill in all of the space.* She said that the lines should *look like magnetic field lines* because *electricity and magnetism are closely related,* that those lines were *not real lines,*[3] and that all these ideas came from what she had learned in middle school. These lines, according to her explanation, represented the attraction and repulsion from the big charges to the little positive charge. She said that the curves also represented the trajectory of the little charge because she had observed during the hockey game that the puck moved along a curve.

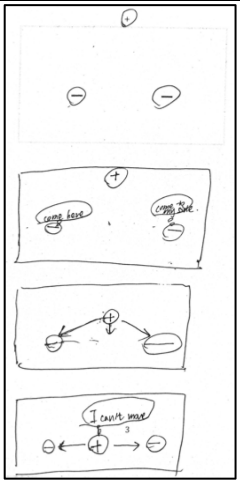
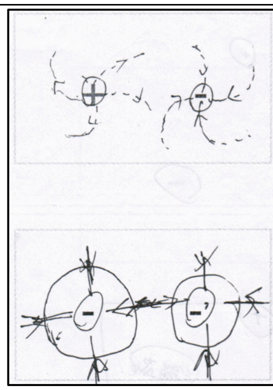
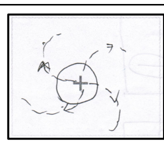
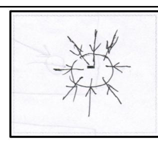
Guanhua's Work

Guanhua was an active boy in class. He was the last student I interviewed. During the interview, his ideas evolved and he added representations, especially during the last section (see Table 5).

[3] I was not sure what she meant by "not real." It could either mean "not physical" or "not visible." I attempted to ask her to say a little more about it. She just repeated that they were "not real." It could be that this description was what she remembered her middle school teacher telling her in class.

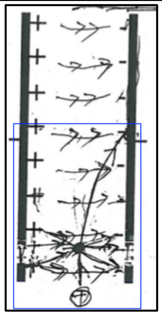
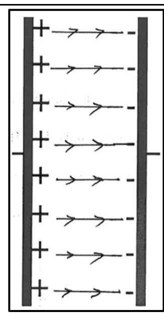
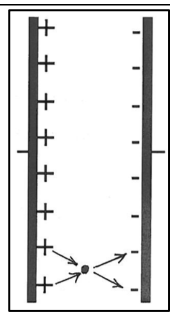
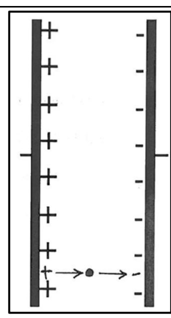
Table 5. Guanhua’s Work

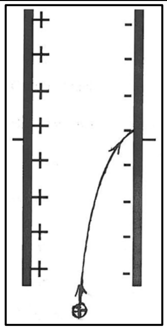
	Student Work	Explanations
Section 1		Guanhua stated that the big positive charge said, *“Come on.”* The little positive came in with an initial *“moving tendency”* pointing down, saying: *“I’m coming.”* When the two charges were located on the same [horizontal] line, they were closest, so the attraction between them was the strongest. The big positive charge said, *“Oh?”* They attracted each other and moved closer and got together, saying, *“We are together.”* He kept bringing up the idea of the *“moving tendency”* of the little positive charge in the following sections. He seemed to be referring to the little positive charge’s initial velocity, because every time he brought up the phrase *moving tendency*, he was talking about the beginning of the story, referring to the arrows attached to the little charge that indicated its initial direction with which it rushed into the frame before interacting with any of the other charges in the room.
Section 2-1		He explained that the little positive came in with an initial moving tendency pointing down. The big positive charge said: *“We can’t move.”* When the three charges were on the same line, the attraction/repulsion between them was the strongest. The big positive charge repulsed the little positive charge, and big negative charge attracted it. The little charge said, *“Keep moving.”* At last, it came closer to the big negative charge and combined with it, saying, *“We are together.”* For the third frame of this section, his original drawing did not have the lower part (the positive sign and two diagonal arrows). During the interview, when he responded to my question about why the charges had to be on the same straight line, he added the lower positive sign and two diagonal arrows in frame three to show that when the little positive charge was not on the same line, the attraction/reaction still acted on it in directions other than the horizontal.

Section 2-2		He said that the little positive charge came in and moved down. When the charges were on the same straight line (he drew this “same straight line” horizontally), the two attracting forces were the strongest, and the two forces were balanced. The little positive was stuck in the middle. The two diagonal arrows in the third frame were not in his original drawing. He added them during the interview when he was trying to analyze whether the two forces were balanced or not. He struggled for a while and decided that they were not.
Section 3		He explained that all the arrows on the lines he drew represented force directions: big positive charges repulsed [a little positive] outward and big negative charges attracted [a little positive] inward. In the upper part, the lines were dotted and curved. The dotted feature showed that the lines were “not real lines.”[4] The curved shape showed that when the little positive charge moved in with a velocity that was not in the “right direction,”[5] its trajectories would not be straight, but curved. In the lower part, the big circles around the big negative charges stood for the range of effects of the attraction from the negative charges.
Section 4	 	His explanation for Section 4 was similar to that for Section 3. During the interview, when he was explaining his work for Sections 3 and 4, he decided to change the straight and solid lines in these two sections into curved and dotted lines because he realized that in these situations, the lines were also “not real” and the trajectories of the little positive charge should also be curved.

[4] When he described the lines as “unreal” or “not real,” he probably meant “not physical” or “unable to be seen.” I asked a follow-up question about what he meant by saying the lines were “unreal,” but he just repeated that they were “not real lines.” As in Mandi’s case,it could also be that he was repeating what he had learned in middle school from his textbook or his teacher, describing the magnetic field lines as being “not real,” but he could not articulate what that meant.

[5] He showed by fingers the horizontal and vertical directions.

Section 5 (Original)		The part I highlighted with the blue square was not part of the work he did in class but added by him during the interview. Below I reproduced his work in several separate rows to illustrate his thinking process.
Section 5 (Reproduced)		He produced this drawing in class. According to his explanation, the parallel lines with arrows pointing to the right meant the positive charges on the left plate were attracted to the negative charges on the right plate. During the interview, he read the requirement of this task again and realized that he had misunderstood it. Then he added other drawings to this section, shown below.
		During the interview, he put a little dot in the middle and drew the four arrows. He explained that when there was a little positive charge in the area between the plates, it was repulsed by the nearby positive charges and attracted to the nearby negative charges. The forces were in *"opposite"* directions so they should be balanced and the little p should stay still. Here he understood a force pointing up and right and a force pointing down and right as in *"opposite"* directions.
		He then added a pair of opposite charges on each plate that were on the same line with the little positive charge and drew the two arrows. *"Because you don't limit the number of the charges,"* he said, *"I can add one more pair. The little positive charge is repulsed by the positive charge [I just added] and attracted by the negative charge [I just added], so it will move."* He was confused by the two contradicting conclusions—the little positive will stay still or move—for a while. Then he recalled that he had learned about the principle of force composition and realized that in the situation of the previous row, the "net force" (he later also called it "the total pushing force" when I asked him to repeat what he had said) should be to the right. He concluded that the little positive charge would definitely move to the right.

		He then added a little positive charge that came in from the bottom with an upward *"moving tendency."* He explained that it kept being pushed to the right along the way after it entered the area between the two plates. As a result, it would move along a curve (he drew the parabola) until it hit the right plate and then continued to move upward and pushed tightly against the plate.

Through the entire interview, Guanhua kept referring that *opposite charges attract and like charges repulse,* as did the other two students. Additionally, Guanhua seemed to have a rather coherent framework to explain these stories: The little charge came in with an initial direction (indicated by a little arrow attached to the little positive charge, pointing down); at that moment, *the little charge was far away from the big charges in the room, their attraction/repulsions were weak*; so the little charge moved according to the initial direction. When the charges lined up, *they were close up and the attraction/repulsion became the strongest*; at that point, the little charge's movement was determined by the attraction/repulsion; the little charge moved accordingly and reached a final state.

In his explanations to his work of Sections 1, 2-1, and 2-2, we see that he had an idea that *electric interactions are weaker when they are farther away, and the interactions are strong when they are close*. He continued to exhibit this idea in his later work for Sections 3 and 4, in which he drew circles around the big charges, denoting that the electric interactions have a range of effect.

An idea that was expressed throughout Guanhua's explanation, but not in Xinmiao's or Mandi's interviews, is that he seemed to like to represent directions—force directions, moving directions, and so forth—in the horizontal direction and the vertical directions and think these directions were in some ways different from diagonal directions. For example, In Sections 1, 2-1, and 2-2, he denoted the little charge's initial velocity in horizontal directions. He then drew all the charges lined up horizontally, in which case the forces' (attraction and repulsion) and the moving directions were all in horizontal directions. Only after I probed about these directions, he shifted to talk about diagonal forces and added to his work the diagonal forces in Section 2-1 and 2-2.

Similarly, in Sections 3 and 4, he kept bring up the difference between the situation that the test charge came from "the right directions" and the situation that the test charge came from "not the right directions." He tried to represent them differently, drawing solid, straight lines when he talked about cases that the test charge moved "in-right-directions" and dashed, curved lines for cases that the test charge moved "not-right-directions." When I asked about what he meant by "the right directions," he showed me that they were horizontal and vertical directions. This idea that direction matters in some ways may have helped him, later in the interview when he talked about Section 5, to think about more complex situations that involve directions of force and motion.

His ideas of the superposition of electric forces evolved while he was explaining his drawings for different sections, in which multiple charges exerted forces on a little charge. He represented forces in the same frame and showed the idea of *forces act simultaneously and collectively determine the little charge's motion*. At the end of the interview, he was able to compose forces from multiple source charges and used that to determine how a test charge moved.

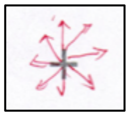
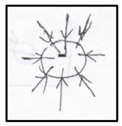
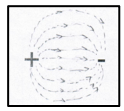
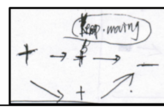
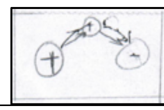
Another idea Guanhua expressed throughout the interview was that of *initial velocity* (he called it "moving tendency"). He began to address and label the initial velocities of the little charges early in Sections 1 and 2. In Sections 3 and 4, he drew arrow lines as curves around the big positive charges and big negative charge because, as he explained, when the direction of the initial velocity of the incoming little positive charge and the direction of the force from the big charges were not on the same line, the little positive charge's trajectory would be a curved line. He initially drew straight lines around some of the big negative charges. After explaining his ideas and thinking about them, he decided to change the straight ones into curves as well. In Section 5, he put together all his ideas and finally analyzed the mechanics of electric charges in a fair amount of detail. He figured out the trajectory of a little charge with an initial velocity rushing into the field between the two plates and drew that as a parabola, which is consistent with the canonical solution. For the first time, he called the parallel arrows between the plates *force lines*.

He figured out that *force lines and moving trajectories are lines with different meanings, although under certain conditions they look the same.* Together with his understanding of superposition of electric forces, he gradually formulated the idea that *when there is no initial velocity, the little charge's trajectory is a straight line and the same as the force line; if there is an initial velocity, the little charge's trajectory is curved and should be thought of as different from the force line, even though the lines look the same*.

Summary of the Three Students Ideas

Overall, we identified nine ideas that Xinmiao, Mandi, and Guanhua spontaneously leveraged in this activity, as shown in Table 6. Three of them (ideas 1-3) are not addressed by the literature, four (ideas 4-7) contrast with what prior studies have reported, and two (ideas 8 and 9) are similar to what prior studies have claimed. Students' ideas identified in this study are listed in column 1. For each idea, evidence from their written work and oral responses is shown in the same row in column 2, and the comparison with literature is in the same row of column 3.

Table 6. Summary of Students' Ideas

Students' Ideas Found in This Study	**Examples of Evidence in Students' Work and Explanations**	**Comparison with Literature**
1. Opposite charges attract and like charges repel.	Mandi: [W]hen [the little positive charge] comes in, it is immediately repulsed by the big positive charge and attracted to the big negative charge.	Literature does not address.
2. Two opposite charges ought to be combined.	Xinmiao: The little positive charge came into the room and saw two charges. It looked for a big charge to combine with.	Literature does not address.
3. The attraction or repulsion from a source charge could be in any direction around it depending on where the little charge is.	All three students drew arrows in all directions.   	Literature does not address.
4. Electric forces act simultaneously when multiple charges are present.	All three students drew two force arrows from different charges in the same frame.   	According to the literature, high school and college students in previous studies had difficulties understanding the superposition of the electric field.
5. Electric interactions are contiguous interactions.	Xinmiao: *The big charges are sending out signals to the little charge [to let it know whether it is gonna be attracted or repelled].*	According to the literature, college students in previous studies understand the electric force as an action at a distance, not as a contiguous force.
6. Strength of electric force depends on the amount of charges and the distance between charges.	Mandi: [A] little charge may not attract as strongly as a big one, or... the strength of attraction [of a big charge] is bigger. Guanhua: *They were the closest, so the attraction between them was the strongest.*	According to the literature, college students in previous studies fail to grasp the relationship between force strength and magnitude of charges and their distance.
7. Force lines and trajectories are different lines but related.	Guanhua: When there is no initial velocity, the little charge's trajectory is a straight line and the same as the force line; if there is an initial velocity, the little charge's trajectory is curved and should be thought of as different from the force line, even though the lines look the same.	According to the literature, college students in previous studies confuse force vectors with velocity vectors and the trajectories of charges.
8. Arrows diagrams had mixed meanings that combined both the direction of the force and of the charge's motion.	All three students said something related to this idea: *They [the arrows] represent attracting forces as well as [the charge's] trajectory.*	Similar to what was reported in previous studies with college students, the students in this study used arrow diagrams to depict force vectors and the trajectories of charges.
9. Arrow lines are like magnetic field lines.	Mandi: *These electric field lines should start from the positive charge and end at the negative charge. They should be curves and fill out the space.*	Similar to what was reported in previous studies with high school and college students, students in this study related electricity with magnetism.

Discussion

For each subtopic that follows, I will compare Xinmiao's, Mandi's, and Guanhua's ideas to what has been reported in the literature. As I stressed earlier, the students in previous studies were older and already taking formal courses in electrostatics at the high school or college level. Xinmiao, Mandi, and Guanhua were younger and they had not received any formal instruction in electrostatics.

As shown in Table 6, ideas 1-3 are basic characteristics of electrostatics: for example, opposite charges attract and like charges repel (idea 1). I speculate that the reason why they are not mentioned much in the literature is that previous studies focus on students' learning difficulties, but so far students have not shown significant difficulties understanding these ideas.

Ideas 4-7 are about features and representations of electrostatics that are more complex than ideas 1-3. Previous studies have emphasized obstacles students have encountered when learning these ideas, and highlighted the incorrect answers or explanations students have produced in the questionnaires administered in their studies. In this study, I recognized students' ability to generate these ideas.

Electric Force Magnitude

In their explanations, the students in this study showed their understandings of the strength of the electric force. Guanhua has asserted that *closer charges have stronger forces* (Table 5, Sections 1, 2-1, and 2-2; and Table 6, idea 6). His ability to figure out the relationship between force strength and charge distance contrasts with Maloney et al.'s findings1 among college students, whom the authors claimed were unable to do it well.

Mandi expressed the idea that *a bigger charge exerts a stronger force* (Table 4, Section 2-1; and Table 6, idea 6), which Maloney et al. concluded as violating Newton's Third Law1.

We argue that this idea by itself does not necessarily violate Newton's Third Law and that Maloney et al.'s conclusion is only valid in certain circumstances. In their study, the question in the assessment asked about the two forces between two charges: the force acted by one charge on the other, and the force acted back. These two forces are equal and opposite, according to Newton's Third Law. If students state that these two forces are of different sizes, the statement does violate Newton's Third Law. In our study, however, the task was not specifically about the force of one charge on the other and the force acted back. When Mandi said that a bigger charge exerts a stronger force, she might have considered, for example, the two charges both as source charges and acting forces on a third test charge, in which case the forces' strength does depend on the amount of the charges and thus her idea would make sense according to the canon.

Superposition of Electric Forces

When dealing with the superposition of electric interactions in an electric field, Xinmiao (Table 3, Section 2-2 and his revision for 2-1), Mandi (Table 4, Sections 2-1 and 2-2), and Guanhua (Table 5, Sections 2-1, 2-2, and 5) analyzed *the forces from multiple charges as acting simultaneously* (Table 6, idea 4). This finding adds to the results from studies about students' ideas of the principle of the superposition of the electric field, and especially speaks to the argument about students' sequential reasoning (Viennot, 1992). Sometimes students may express multiple electric forces as occurring one after another, but at least on some occasions, they do this because of reasons other than due to their understandings of electric forces. Xinmiao drew two events that he thought were happening simultaneously in two successive frames to meet a particular task demand: to fill out four distinct frames for the comic strip. (Table 3, Xinmiao's original work for Section 2-1).

Electric Field Lines

The students in this study produced arrow diagrams that resembled canonical field lines, and the meanings they attributed to these lines included force directions, velocity directions, trajectories, and intentional moving directions. When they explained the meaning of each arrow they had drawn, they were able to articulate it clearly. Therefore, using, say, the same arrow or the same type of arrow diagram to represent both velocity and force directions in their drawings does not mean that they failed to grasp that velocity and force are two different things. In most cases, each student articulated the relationship among charge geometry, electric forces, and trajectories: e.g., source charge distribution determines the electric forces; electric forces determine the trajectory of the movable test charge (Table 6, ideas 3 and 8).

This finding contrasts with Tornkvist and colleagues' claim (1993) that college students confused representations and did not understand the hierarchical relationship among the concepts. The three students in this study were able to articulate their ideas about and discriminate among representations for different vectors (force and velocity) even though they used the same symbols, and when the situation necessitated the differentiation of the representations, they were able to draw different representations for the myriad meanings they wanted to express. In-depth understandings did not necessarily occur when the students first expressed their ideas about the situation; rather, these understandings emerged during the process in which they tried to explain their initial ideas. For example, at the beginning, in Sections 1, 2-1, and 2-2, Guanhua represented the little charge's initial velocity and the charges' interaction in separate frames, which indicated that he had an idea that the velocity and the force are two distinct concepts. However, he did not explicitly analyze the relation between them. In addition, he only drew the situation in which the two electric forces were on the same straight line (Table 5 Sections 2-1 and 2-2). As the interview went on and he tried to explain his understandings, he started to think more about the situations in which the two forces were not on the same straight line (see the drawings he added to Sections 2-1 and 2-2 during the interview). By the end of the interview, when he explained his work for Section 5, he analyzed the superposition of the forces from the multiple charges on the two parallel charged plates, related that to the little charge's velocity direction, and eventually figured out what the little charge's trajectory would be in this situation. His explanation was in line with the canonical descriptions. During the process, he gained the ability to differentiate force lines from trajectories without explicit instruction (see Table 6, idea 7).

By highlighting these results I do not mean to imply that high school students do everything correctly without any instruction. Students in this study did show alternative understandings that were not in line with canonical explanations, as ideas 8 and 9 illustrate. For example, when Mandi drew curved lines in Section 3, the lines she had drawn resembled canonical electric field lines of two source charges (Figure 1, center), which only represent electric forces; and in this case force lines and trajectories cannot possibly be the same. Mandi attributed double meanings—force as well as trajectory directions—to the curved lines. Nevertheless, we should not broadly conclude that students confused representations, but should examine more meticulously the specific situation in which the representations were produced.

Electricity and Magnetism

Mandi understood electricity and magnetism as closely related and, in many respects, similar. She drew field lines that began with a positive charge and ended with a negative charge (see Table 6, idea 9). She did so not because she made an analogy between field lines and electric current that comes out from a positive charge and goes into a negative charge (Sağlam & Millar, 2006). Instead, she drew upon what she had previously learned about magnetism (magnetic field lines begin from the north pole and end at the south pole) and applied it to the informal tasks concerning electricity. From this perspective, when these students connect electricity to magnetism they do so in an attempt to make sense of the task at hand using their own resources (Hammer et al., 2005); the differentiation between electricity and magnetism will emerge when the students encounter other scenarios in which that differentiation becomes necessary. This viewpoint is different from those of other scholars who have taken it to mean that students are apt to confuse magnetism with electricity (Maloney et al., 2001; Sağlam & Millar, 2006).

Future Work and Implications

The aim of the comparisons I have presented is to highlight what these three pre-high school students can do rather than what they cannot. In addition, the study suggests that we need to examine the context in which students produce specific ideas and representations—for example, the way the task is presented to them—and whether and how that context might have affected their ideas. So far, the literature has failed to fully explore student thinking from this angle.

While I presented a fair amount of student ideas in this study, I had access only to their written work and the explanations they gave in the post-class interviews. I did not capture sufficient videos of the three students I interviewed when they were participating in class discussion, so I do not have enough data about what led them to produce these representations and ideas in class and whether any issues related to the class discussion or their peers' presentations in class may have had any effect on their productions. In future studies I will focus more on the classroom discussion so that I can follow the moment-by-moment change in students' ideas and representations to identify their evolution from a more microgenetic perspective.

Taking the stance that learning is building new understandings upon previous ones, a process in which students use resources to make sense of phenomena they encounter (Hammer et al., 2005), one implication of this study is that we should provide students with more opportunities to produce their own representations before teaching them specific conventional representations. When designing curricula, we should give students time to play with and make sense of the graphical representations of field lines, for instance, before we introduce algebraic expressions of electric field strength. (In fact, historically speaking, magnetic field lines were used to describe the field long before the algebraic definition of magnetic field strength was introduced.)

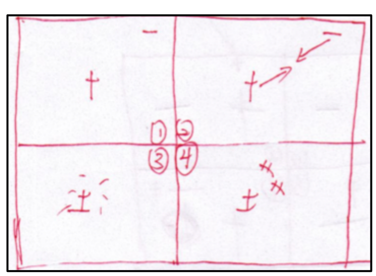
Because this study indicates that students' ideas are context sensitive, and the tasks used in this study were in many senses unique, in future work I plan to conduct an analysis of the specific artifacts used in this study: the Electric Field Hockey game and the comic strip activity. By examining how they could have shaped students' ideas and representations one way or another, I hope to make suggestions regarding the design of artifacts that could scaffold students' thinking.

Appendix A: Xinmiao's Work of Comic Strip Activity (Inserted into an English Version of the Worksheet)

Name: ______ *Date:* _______

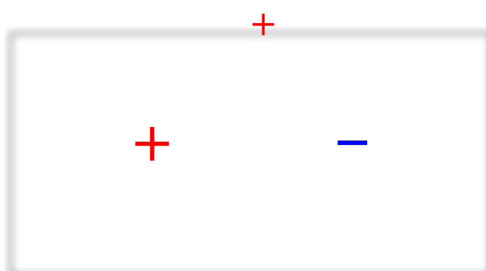
Section 1:

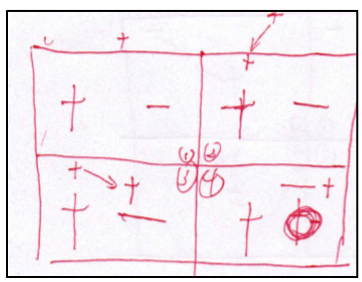
Draw Something: Draw a four-frame comic telling a story about two characters: Little Positive (P) and Little Negative (N). P is sitting at the center of a room when N comes in through the door. What will happen next? Use four frames to draw at least four scenes of the story. The picture shown could be the first panel, but feel free to draw a picture for the first panel. You are not required to draw every character vividly; the key is to show how and why your characters act the way they do.

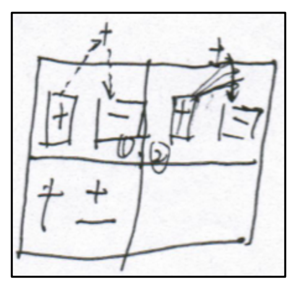


Section 2-1

Draw Something: Draw a four-frame comic telling the stories of two big charges and one little charge. For this first story, there is one Big P, one Big N, and one Little P. Big P and Big N are sitting in the room at a distance. They are fastened to their seats and can't move. Little P comes into the room. What will happen next? Explain your story to the class. What do all the things you have drawn mean?

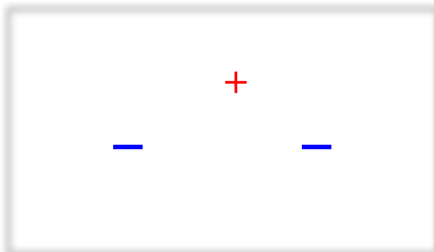


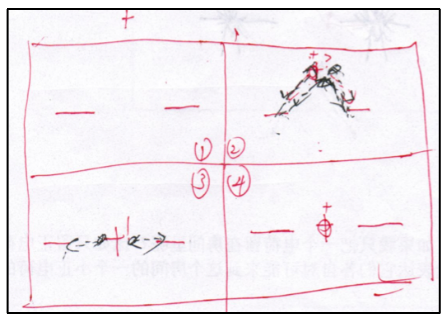




Section 2-2

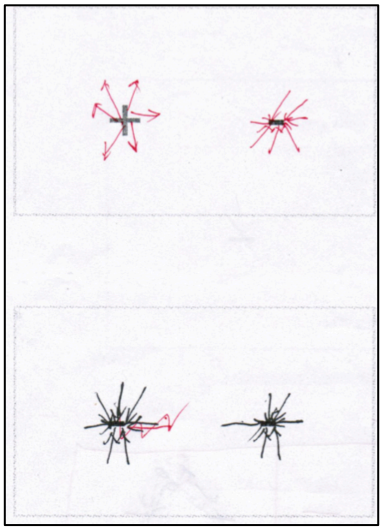
Draw Something: Draw a four-frame comic telling stories of two big charges and one little charge. For this second story, both big charges are negative, while the little charge is positive. What will happen when the little charge enters the room? Explain your story to the class.





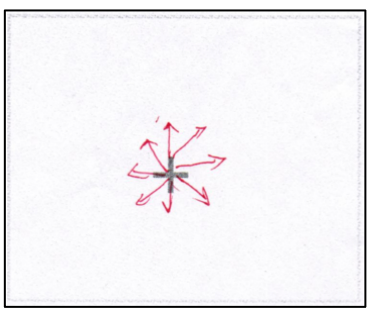
Section 3

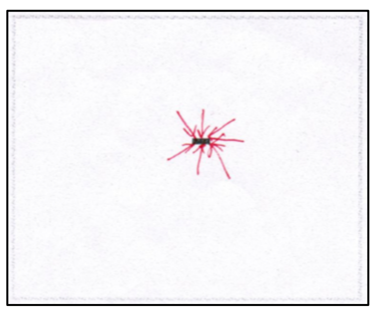
Draw Something: Now what if we take away the little positive charge from the previous two pictures? Can you find a way to show the influence they have on the little positive charge?



Section 4

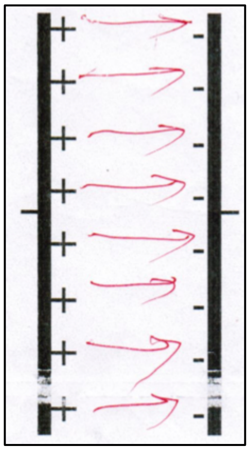
Draw Something: What if we leave only one big charge in the room, P or N? How can you show the influence the big charges (Big Positive or Big Negative) have, respectively, on a little positive charge that might come into the room?



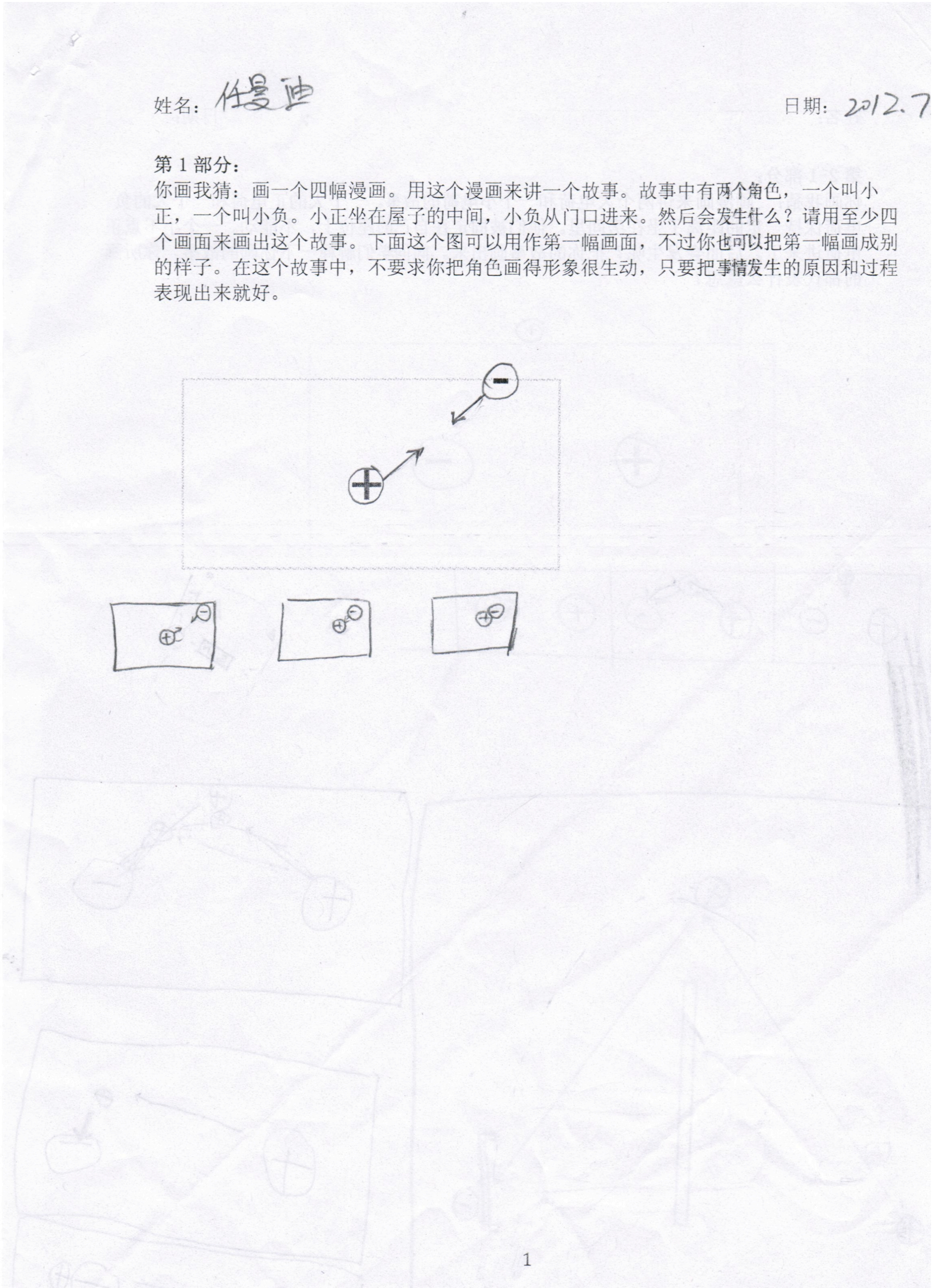


Section 5

Based on what you have drawn before, how can you show the influence the two charged plates have on a little positive charge that moves between the plates? Why is this true?



Appendix B: Mandi’s Work for the Comic Strip Activity


姓名：任曼迪　　日期：2012.7

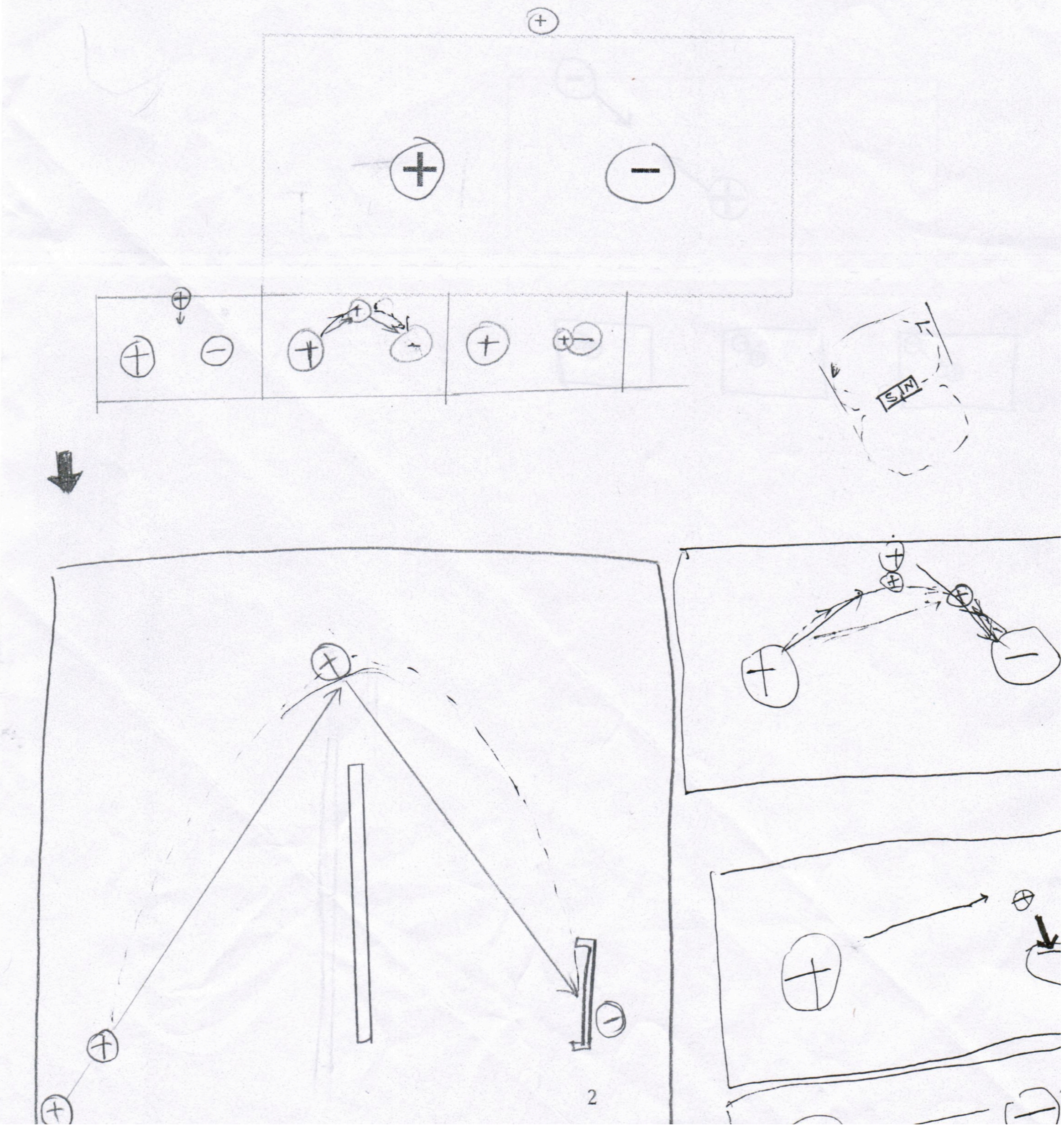
第 1 部分：

你画我猜：画一个四幅漫画。用这个漫画来讲一个故事。故事中有两个角色，一个叫小正，一个叫小负。小正坐在屋子的中间，小负从门口进来。然后会发生什么？请用至少四个画面来画出这个故事。下面这个图可以用作第一幅画面，不过你也可以把第一幅画成别的样子。在这个故事中，不要求你把角色画得形象很生动，只要把事情发生的原因和过程表现出来就好。

1

姓名：　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　日期：

第 2-1 部分：
你画我猜：　画漫画来讲两个大电荷和一个小电荷的故事。一个大的正电荷和一个大的负电荷保持一定的距离了坐在房间里。他们被固定在自己的座位上，不能动。一个小不点正电荷进来了。后面会发生呢？把你的故事画出来。向同学们解释一下你画的故事。你所画的都代表什么意思？

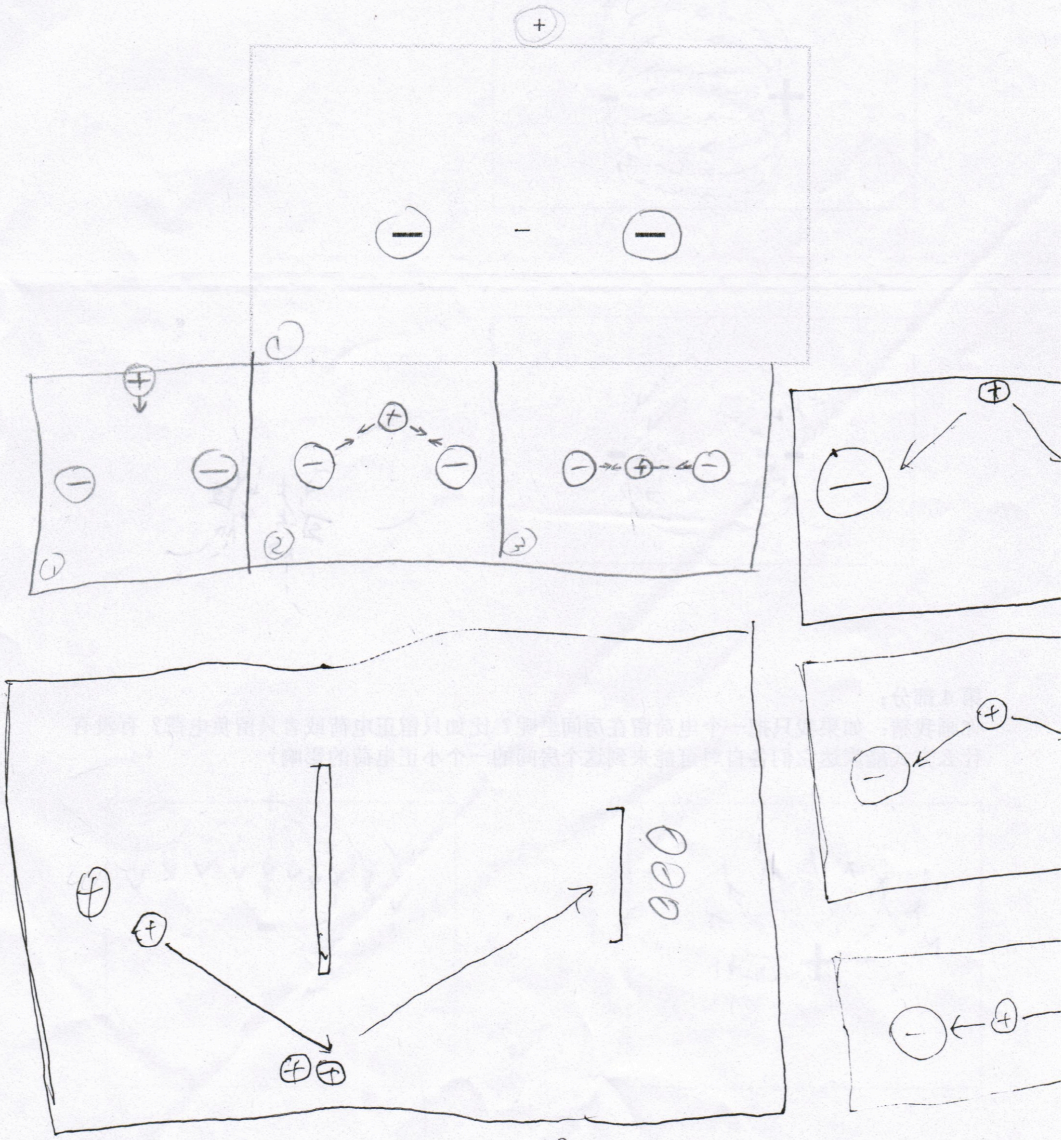


2

姓名：　　　　　　　　　　　　　　　　　　　　　　　　　　　　　日期：

第 2-2 部分：

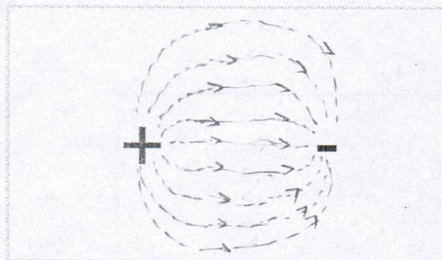
你画我猜：　画漫画来讲两个大电荷和一个小电荷的故事。两个大的电荷都是负的。 他们保持一定的距离了坐在房间里，被固定在自己的座位上，不能动。一个小不点正电荷进来了。接下来会发生呢？把你的故事画出来。向同学们解释一下你画的故事。你所画的都代表什么意思？

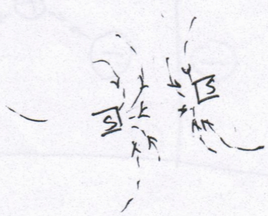


姓名：　　　　　　　　　　　　　　　　　　　　　　　　　　　　日期：

第 3 部分：

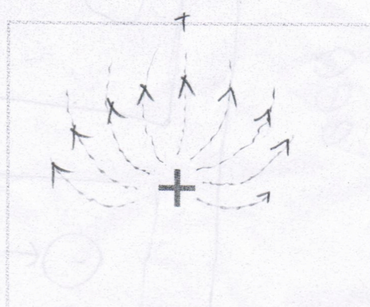
你画我猜：这一次如果我把前面的那个图中的小不点正电荷拿走呢？你可不可以找到一种方式来表达刚才它们对小不点正电荷的影响？

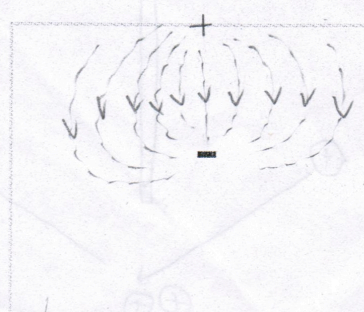




第 4 部分：

你画我猜：如果我只把一个电荷留在房间里呢？比如只留正电荷或者只留负电荷？有没有什么方式能表达它们各自对可能来到这个房间的一个小正电荷的影响？



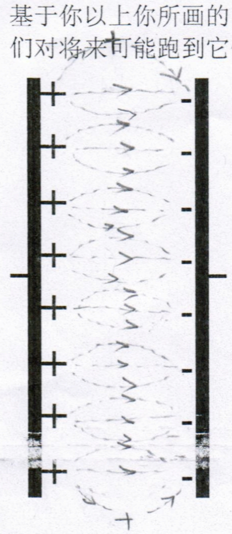


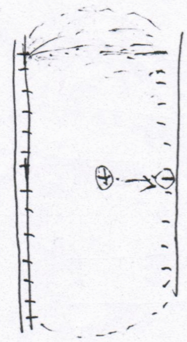
4

姓名： 日期：

引申：

基于你以上你所画的，你觉得在以下这两个带电的平板之间，有没有什么方式可以表达它们对将来可能跑到它们中间的一个小正电荷的影响？为什么？



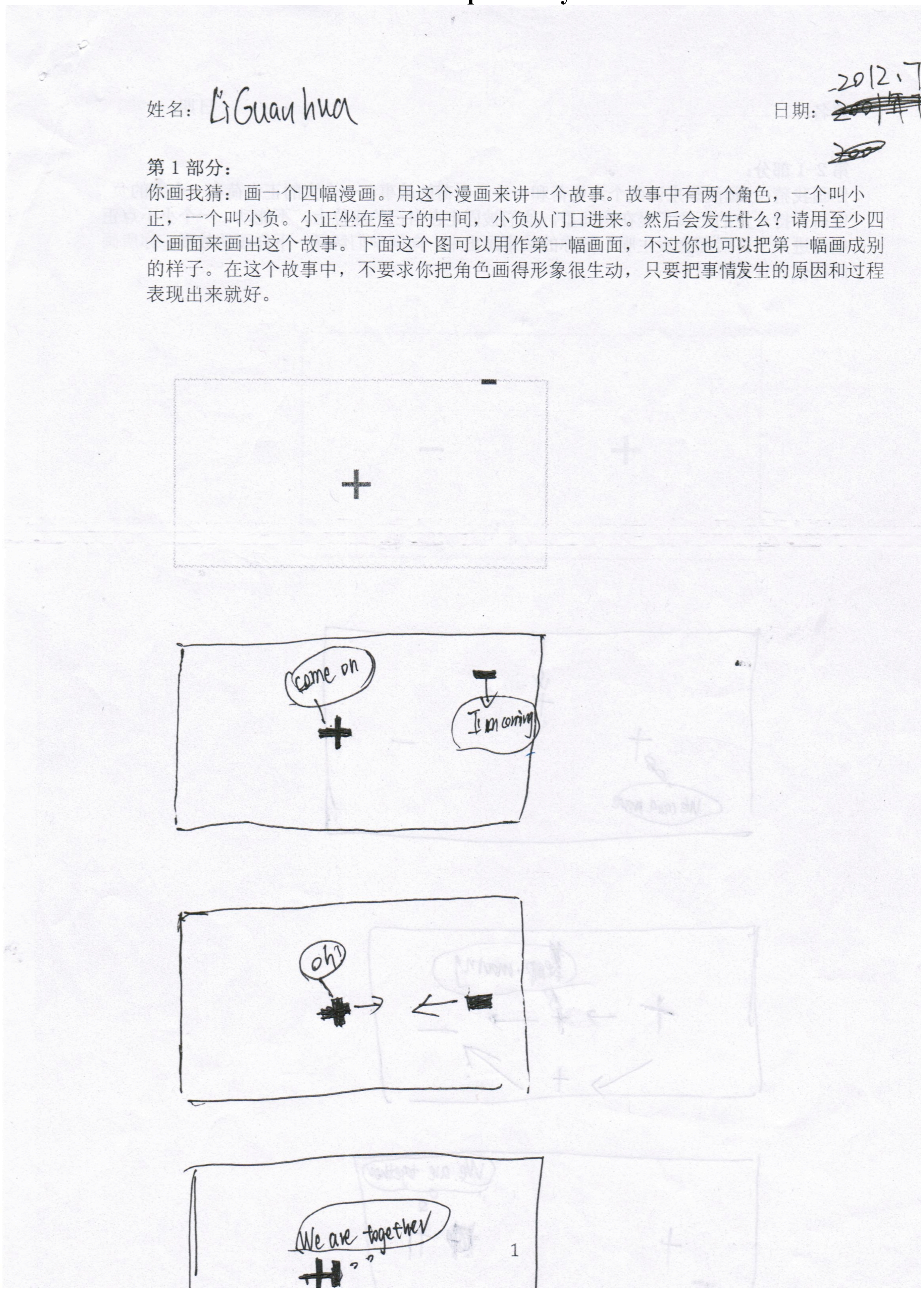


2:00
2:45
2:55
3:40
3:50

Beat

5

Appendix C: Guanhua's Work for the Comic Strip Activity



姓名：Li Guanhua　　　　日期：2012.7

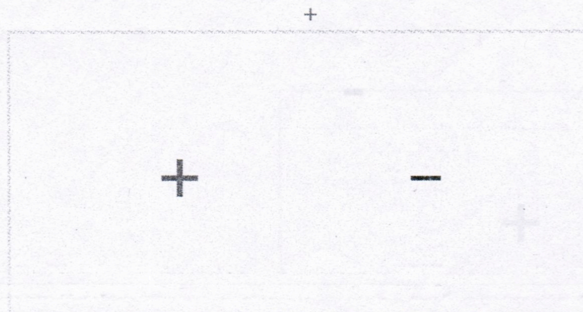
第 1 部分：

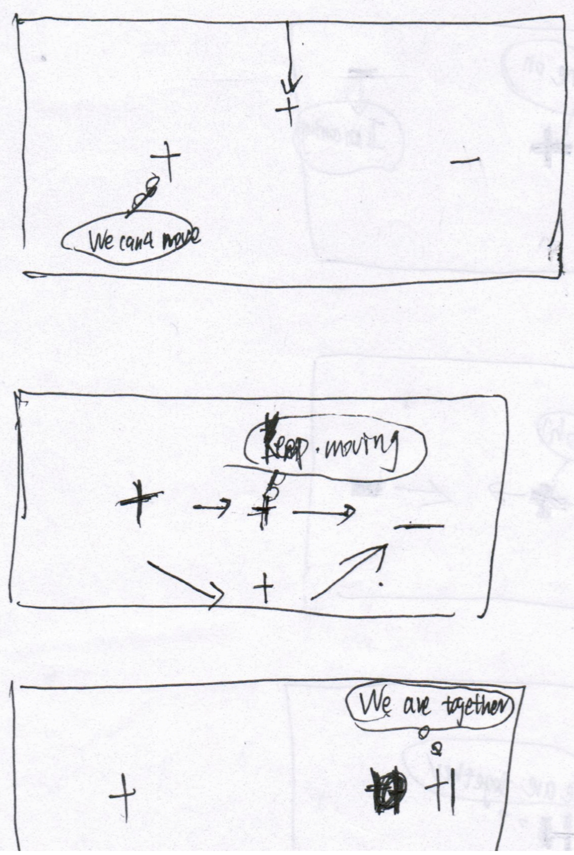
你画我猜：画一个四幅漫画。用这个漫画来讲一个故事。故事中有两个角色，一个叫小正，一个叫小负。小正坐在屋子的中间，小负从门口进来。然后会发生什么？请用至少四个画面来画出这个故事。下面这个图可以用作第一幅画面，不过你也可以把第一幅画成别的样子。在这个故事中，不要求你把角色画得形象很生动，只要把事情发生的原因和过程表现出来就好。

姓名：　　　　　　　　　　　　　　　　　　　　　　　　　　日期：

第 2-1 部分：

你画我猜：　画漫画来讲两个大电荷和一个小电荷的故事。一个大的正电荷和一个大的负电荷保持一定的距离了坐在房间里。他们被固定在自己的座位上，不能动。一个小不点正电荷进来了。后面会发生呢？把你的故事画出来。向同学们解释一下你画的故事。你所画的都代表什么意思？

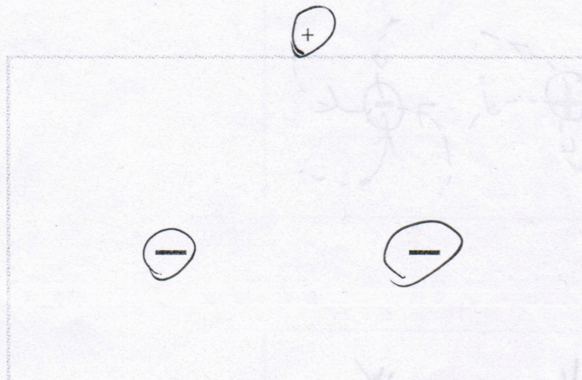


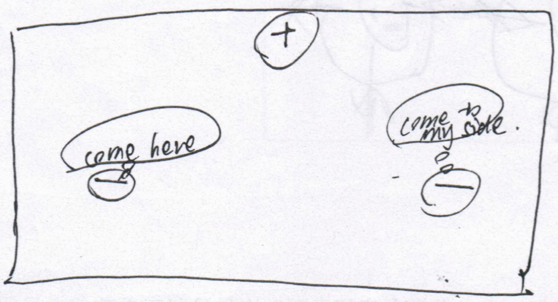


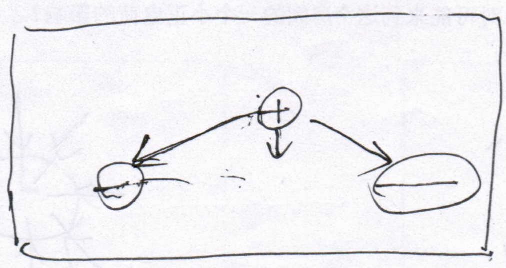
姓名： 日期：

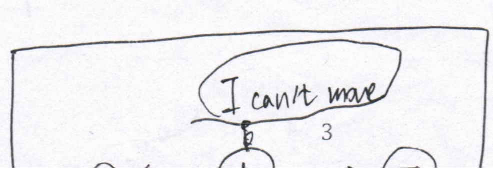
第 2-2 部分：

你画我猜： 画漫画来讲两个大电荷和一个小电荷的故事。两个大的电荷都是负的。 他们保持一定的距离了坐在房间里，被固定在自己的座位上，不能动。一个小不点正电荷进来了。接下来会发生呢？把你的故事画出来。向同学们解释一下你画的故事。你所画的都代表什么意思？









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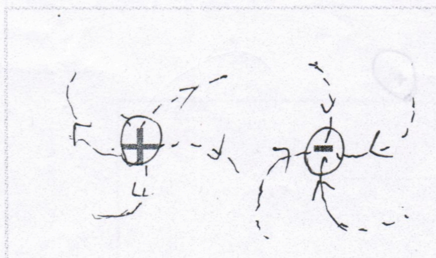
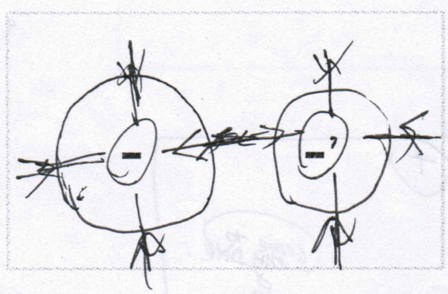
姓名：　　　　　　　　　　　　　　　　　　　　　　　　　　　日期：

第 3 部分：

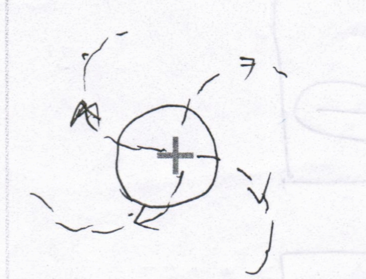
你画我猜：这一次如果我把前面的那个图中的小不点正电荷拿走呢？你可不可以找到一种方式来表达刚才它们对小不点正电荷的影响？

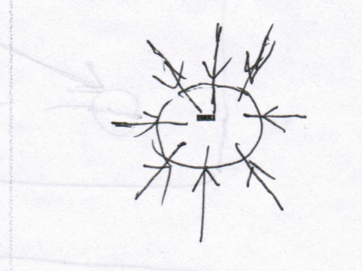




第 4 部分：

你画我猜：如果我只把一个电荷留在房间里呢？比如只留正电荷或者只留负电荷？有没有什么方式能表达它们各自对可能来到这个房间的一个小正电荷的影响？





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姓名：　　　　　　　　　　　　　　　　　　　　　　　　　日期：

引申：

基于你以上你所画的，你觉得在以下这两个带电的平板之间，有没有什么方式可以表达它们对将来可能跑到它们中间的一个小正电荷的影响？为什么？

5

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