Expt. #11: Electric Field Lines and Equipotential Lines

Aim: Mapping of equipotential lines and field lines for three given electrode configurations

Apparatus: DC power supply, Multimeter, various electrodes, (semi-)conducting paper, carbon paper, arrangements to fix electrodes and papers etc.

Attention: Stock of special (semi-) conducting paper is limited. So, we have to take a small piece (may be 5"x4") and use the same piece of paper multiple times (at least 10 times) by many groups.

Useful concepts and definitions:

Concept of Field: The concept of ***field*** is introduced to describe forces exerted between objects that are separated in space, and not in contact with each other, sometimes referred to as "action-at-a-distance". We say that one object creates a field in the surrounding space, and that the second object experiences a force because of the field. The field represents the strength and direction of the force. For example, at any point in space the gravitational field of the earth represents the gravitation force exerted by the earth on a hypothetical unit test mass located at that point.

Electric Field: Electric field represents the electric force exerted by other charges on a hypothetical ***unit*** test charge. It is a vector quantity, having a magnitude and a direction. Electric field $\vec{E} = \vec{F}/q$, where $\vec{F}$ is the electric force experienced by a test charge q (it should be so small as not to disturb the original electric field that we want to measure). Direction of electric field is given by the direction of the force that a positive test charge will experience. ***SI unit of electric field is Newton/Coulomb. It can be expressed in other unit as well.***

Field lines: Electric fields are often visualized by drawing imaginary lines with an arrow. A test particles placed at a point in the electric field (which we are mapping) would have moved along one of these lines passing through that point. Listed below are some interesting properties of electric field lines:

1. A field line starts either at infinity or at a positive charge.
2. A field lines ends either at infinity or a negative charge.
3. Electric field vector is tangential to the field line at any point in space.
4. Electric field lines arrowheads point from positive charge to negative charge.
5. The number of filed lines that leaves a positive charge or that ends on a negative charge is proportional to the magnitude of the charge.
6. The denser the electric field lines in a region, the stronger the electric field is in that region.
7. No two filed lines can cross each other. (***Can you argue why it is so***?)
8. The electric field lines are perpendicular to the equipotential lines (defined shortly).

Experimentally, it is not easy to measure electric field at different point in space and to draw field lines. To be able to do this, you have to move with a tiny test charge (negligibly small, so that it does not alter the electric field that we want to measure) at different points and measure electric force on it! Therefore, one uses another concept of electric potential and equipotential lines to interpret about electric fields.

Electric Potential: The electric potential (or just the potential) at any point is the electric potential energy per unit charge at that point. More useful concept is to define potential difference between two pints (say, A and B) in terms of work done in moving a unit test charge from point A to point B in the electric field. It is known that a charge experience a force in an electric field. So, to move a charge from one point to other in an electric field one must do some work against the electric force. Work done can be negative or positive depending whether the charge is moved in the direction of force or against it. Potential at a point is usually defined with respect to a reference point whose potential is taken to be zero (the point is usually known as ground). If an infinitesimally small work ΔW is required to move an infinitesimally small test charge ΔQ in an electric field $\vec{E}$ from a point A to a point B separated by an infinitesimally small distance $\overrightarrow{\Delta l}$ against the electric force $\vec{F}$, then the potential difference ΔV between A and B is given by $\Delta V = -\frac{\Delta W}{\Delta Q} = -\frac{\vec{F}\bullet\vec{\Delta l}}{\Delta Q} = -\vec{E}\bullet\vec{\Delta l}$. Using some vector algebra, it can be shown that $\vec{E} = -\vec{\nabla}V$. This gives another way of defining electric field: Magnitude of electric field is given by the highest rate of change of potential with distance away from the point in question and it has the opposite direction to the highest rate of change of potential with distance. ***SI unit of potential is Joul/Coulomb, also known as volt. SI unit of electric field also can be expressed in terms of volt as volt/meter.***

$$\left[\frac{Newtons}{Coulomb} = \frac{Newtons\ .\ m}{Coulomb\ .\ m} = \frac{Joules}{Coulomb\ .\ m} = \frac{Volts}{m}\right]$$

Equipotential lines: (Line of equal potential!) It is the line for which potential is same at every point on the line. Imagine that you are taking a test charge in a path which is perpendicular to the local electric field. Then you do not have to do any work because force will be perpendicular to the trajectory. Then, there will be no potential difference between any two points on the path. So, this path will construct an equipotential line. Actually, in 3-dimensional space one could construct equipotential surfaces. But in this experiment we shall restrict ourselves to the 2-dimentional projection which will be equipotential lines.

Potential at a point (with respect to a reference point) can be easily measured using a voltmeter. To draw equipotential lines, one simply needs to locate several points which are at the same potential and then join them to get the trajectory of equal potential or the equipotential lines. Then one can use the properties of field lines listed above to draw the electric field lines.

Example of field lines and equipotential lines for some charge configurations:

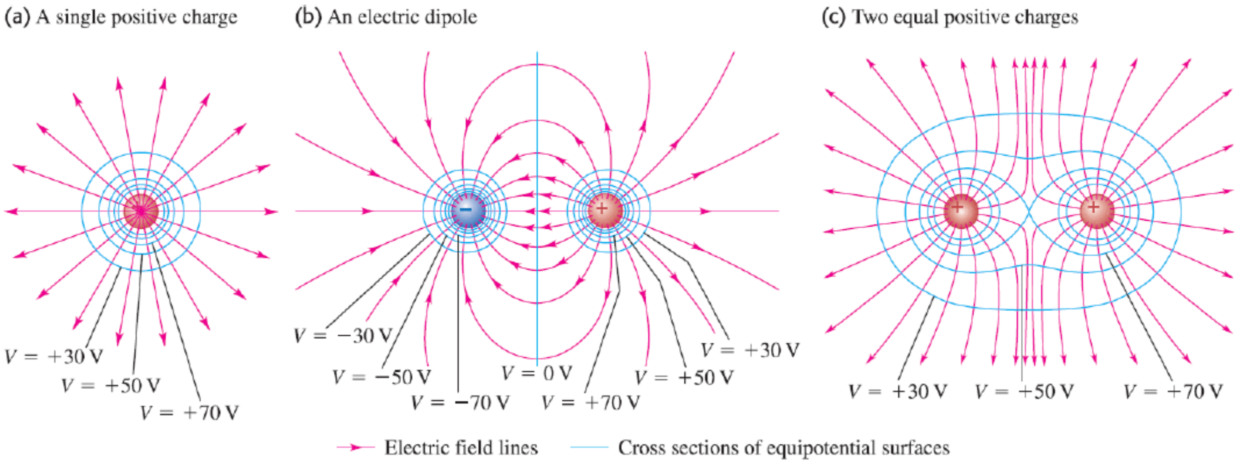

Figure 1: Schematics of field lines and equipotential lines for some charge configurations.

Experimental setup:

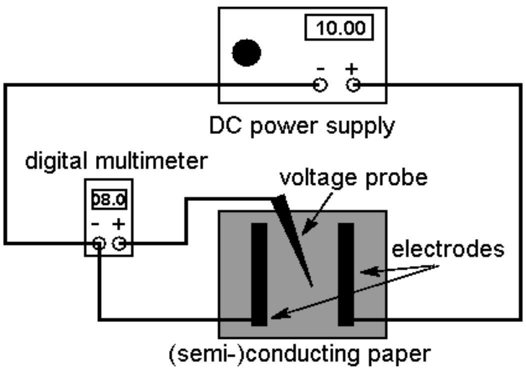

Figure 2: Schematic of experimental

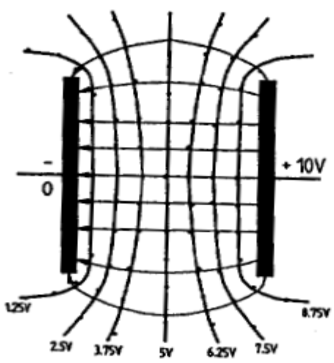

Figure 3: Schematics of expected field lines and equipotential lines.

Why do we need the (semi-)conducting paper? In order to determine the potential difference between a point in the electric field and an electrode (reference point), it would be necessary to place one test lead or probe of a voltmeter on the conductor and one at the point in question. A voltmeter has very large input impedance and it is connected in parallel to the terminals whose potential difference has to be measured. It draws very small current to measure the voltage (potential difference). Figure 4 shows a schematic of voltage measurement by a voltmeter (digital multimeter). Here, R_M (R_P) is the resistance of the multimeter (conducting paper) and I_M (I_P) is the current flowing through multimeter (conducting paper). (1) If we put insulating medium between the electrodes (i.e. $R_P = \infty$) then circuit of the multimeter will be open and both I_M and I_P will be zero. So, multimeter will not be able to measure any voltage. (2) If we put a good conducting medium between electrodes (i.e. $R_P \approx 0$) then the multimeter electrode circuit will be short (i.e. $I_P \to \infty$); we cannot maintain any voltage difference between the electrodes. (3) If we put a weakly conducting (semi-conducting) medium (which conducts, but, of course, it must not conduct nearly as well as the electrodes themselves) in between electrodes (such that $0 \ll R_P \ll R_M$) then a steady state (finite) current I_P will flow

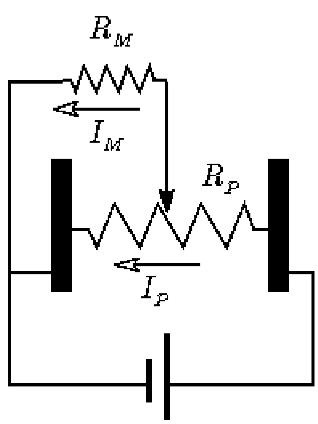

Figure 4: Schematic of voltage measurement with multimeter.

Figure 5: Photograph of experimental setup.

between the electrodes, and there will be a voltage distribution between the electrodes. Also, multimeter circuit will be complete, I_M will be nonzero, but much smaller than I_P. This will allow the multimeter to measure a voltage at any point between electrodes without much disturbing the voltage distribution between electrodes. The black colored paper that you will be using for this experiment has been coated with a black pigment made from fine particles of carbon black. This allows the paper to conduct electricity, much better than an insulator, but not as good as a metallic conductor. Therefore, a two-dimensional electric field will be created when a dc voltage is applied across two metal electrodes that touch the paper. If the ground terminal of the voltmeter is connected to the negative electrode, and the positive meter probe to the other, the meter will read the applied voltage, but if the probe is touched to the paper surrounding the electrodes, a lower potential difference will be read. As an alternative to the paper, one can immerse the electrodes in a tank of dilute salt-water or other mildly conducting solution. One probe of the meter is connected to one electrode and the other measures potentials at various points in the solution without disturbing the electric field appreciably, provided that the current drawn by the voltmeter is small compared to the total current flowing in the vicinity of the point in question.

Experimental Procedure:

1. **You have to draw equipotential lines and electric field lines for 3 different configurations of electrodes. For each configuration you have to draw 5-7 equipotential lines.**
2. Special conducting paper has to be used multiple times. So, do not draw equipotential lines and electric field lines directly on it.
3. You have to use white paper and carbon paper below the conducting paper to get impression of equipotential points on the white paper as explained below.
4. Take white paper, carbon paper and conducting paper, 1 piece each, of size approximately 4 inch by 5 inch and arrange them in the following order on the polycarbonate plate: first white paper, then carbon paper and then conducting paper at the top. **** If there are two partners, then 2 layers of white paper and carbon paper can be put to get data for both partners in one experiment. ****
5. Make the circuit as shown in the figures 2 (schematic) and 5 (actual photo) for one configuration of the electrodes. Electrodes should be uniformly pressed on the conducting paper so that there is good contact between all points of the electrode and conducting paper.
6. Mark the boundary of the electrodes on the conducting paper with a pointer so that its impression is recorded on the white paper below the carbon paper (an empty ball point refill may be used, so that it records the impression on white by pressure on carbon paper but does not write anything on the conducting paper).
7. Apply about 10 volts to the electrodes from the power supply. Measure the actual voltages on the electrodes using the digital multimeter and note it down. ****Before starting experiment learn how to use digital multimeter.****
8. Now touch the multimeter probe on the conducting paper slightly away from the electrode so it reads a voltage which differs by 1-2 volts from that on the electrode. Lightly press the multimeter probe at that point on the conducting paper to make a mark on the white paper below. **DO NOT press to hard. It should make a hole on the conducting paper.**
9. Move the multimeter probe to nearby points to locate another point where you get the same voltage as in the previous point. Press again to mark it. Then move to another point where you get same voltage again, mark it.
10. Repeat this process to mark sufficient number of points of equal voltage so that later on you can join these points to get a smooth equipotential curve. ****Do not try to draw the equipotential line just now. You still have to mark points for other equipotential lines.****
11. Move the multimeter probe to another point slight more away from the electrode where you get another voltage, about 2 volt different from the previous one. Mark points of equal potential for this potential (repeat steps 8-10). Similarly mark points for other equipotential lines. You should draw at least 4 equipotential lines.
12. After you have marked all points for at least 4 equipotential lines, loosen the screws, take out electrodes, and take out white paper.
13. You should now have marks for the boundary of electrodes and several points for different equipotential lines. Draw the boundaries of electrodes by a pencil and write measured voltages at them. Join the respective points of equal potentials to draw (smooth curve) each equipotential line by a pencil. Label each of the equipotential lines by corresponding voltages.
14. Draw uniformly spaced filed lines, perpendicular to the equipotential lines. Use properties of field lines listed earlier as your guide. Put arrow to indicate filed direction.
15. **Repeat the experiment for 2 other configurations of the electrodes.**