Whiteboard: 1/60, f4.5, iso 640, EV+1.3, Auto Focus, H4n **INPUT** @ **95%** gain.
BBB 1/60, f6.7, iso 640, **WB Use Grey Card**, Manual Audio at level 11, focal length ½ way to ∞. H4n **INPUT** @ **95%** gain.
BBB Check Horizontal Level & Billy's Lights!! Middle line at bottom 1/3 of desk & remember Billy and Bo chair locations!
Electric Charges and Electric Fields - Review for AP Physics C: Electricity and Magnetism **Switch audio to 96kHz!!**

Mr.p: (60 seconds of listening for this group of videos)

Mr.p: Good morning. Before we begin reviewing the entire AP Physics C: Electricity and Magnetism curriculum, I think it is important to identify a basic difference between the AP Physics C: Mechanics and the AP Physics C: Electricity and Magnetism curricula. [♪ Flipping Physics ♪]

- Bobby: Are we really going over all of AP

Physics C: Electricity and Magnetism today?

- Bo: Uh, no. He said, “begin reviewing”. I think we are only reviewing electric charges and fields today.
- Bobby: Oh good. All of AP Physics C: Electricity and Magnetism would be a lot.
- Bo and Billy: Yeah.

Mr.p: Okay, … mechanics tends to feel a lot more tangible to my students than electricity and magnetism. You can see projectile motion. You can feel an impact force when an object runs into you. You can feel rotational inertia change as you change the mass distribution of an object. You can feel a change in angular velocity as you change your rotational inertia while spinning. You can feel conservation of linear momentum when you catch something. However, it is much more difficult to visualize electric and magnetic fields. You cannot really see current moving through wires. You have to visualize gaussian surfaces.

- Billy: And you can actually see the mass in an oscillating mass-spring system moving back and forth in simple harmonic motion which makes it so you can visualize the kinetic and elastic potential energies, however, in an inductor-capacitor circuit, you cannot see the moving electrons causing the energy to be stored in the electric field in the capacitor and the magnetic field in the inductor.

- Bobby: Yeah, mechanics is a lot more tangible than electricity and magnetism.
- Bo: Sure.

Mr.p: Exactly. This makes it so, typically, my students tend to struggle a bit more at the beginning to understand electricity and magnetism than they do mechanics. I do want to make it clear though that, after students have spent time learning and the visualization of electricity and magnetism concepts, typically they feel that these two curricula end up being about the same level of difficulty. … Electricity and magnetism does take a bit of time to get used to though.

- Bo: Yeah, I agree with that.
- Bobby: Totally.

- Billy: I love electricity and magnetism!
- Bo: Right.
- Bobby: But do you love it more than mechanics?
- Billy: I love them both.
- Bobby: Yep.
- Bo: Of course.

Mr.p: Alright. Here we go. Billy, please tell me about electric charge.

- Billy: Okay. … Uh, electric charge is a fundamental property of all matter. … The charge carriers are protons and electrons where protons have a positive charge and electrons have a negative charge. … Both protons and electrons have the same magnitude charge called the elementary charge. … The symbol for the elementary charge is a lowercase e and it has a magnitude of 1.60 times 10 to the negative 19 coulombs. … That is the elementary charge because it is the absolute value of the charge on both a proton and an electron. But, again, the proton has a positive charge and an electron has a negative charge. … The symbol for coulombs is a capital C. … coulombs are not a base SI unit. I always found it weird that amperes are a base SI unit instead of coulombs, but they are.

- Bobby: Okay.
- Billy: … Charge is a scalar quantity. …

Charge is quantized. In other words, it comes in discrete quantities in intervals of the elementary charge. … That is actually an equation. The net charge on an object, uppercase Q, equals lowercase n, the integer number of excess positive or negative charges on the object, times lowercase e, the elementary charge. … And n is either positive or negative depending on whether the excess charges are positive or negative. … Quantization of charge means an object will never have, for example, a charge of positive 2.1 times ten to the negative 19 coulombs because that is not an integer multiple of 1.60 times 10 to the negative nineteen coulombs, the elementary charge. … The electric charge on an object is determined by the total number of charge carriers contained in the object. … For example, the electric charge on an object with 4 protons and 6 electrons equals the charge on the protons plus the charge on the electrons or positive 4 times the elementary charge plus negative 6 times the elementary charge, which is negative 2 times the elementary charge. In other words, the net charge on this object is the same as if it contained only 2 electrons, it equals negative 2, the total number of excess electrons, times 1.60 times ten to the negative 19, which is the absolute value of the charge on an electron or the elementary charge, and that works out to be negative 3.20 times 10 to the negative 19 coulombs. … Uh … Many objects we work with will be considered to be point charges even if they are made up of many charge carriers. … And a point charge is a model of a charge where the physical size of the charge, or the charged system, is small enough to be considered to be negligible. … That is all I can think of right now.

- Bobby: You do love this stuff.
- Bo: Yeah.

- Billy: Yeah.

Mr.p: Thank you very much Billy. … Bobby, tell me about the Law of Charges.

Bobby: The Law of Charges. … Well, that states that two charges with opposite signs attract one another and two charges with the same sign repel one another. … That’s it. That’s the law of charges.

Mr.p: Correct. … Bo, Coulomb’s Law, please?

- Bo: … Coulomb’s Law?
- Billy: It is the equation for the electrostatic force between two charged objects.

- Bo: Oh, right. I forgot that is called Coulomb’s Law. … That is … The electrostatic force, which is a vector, equals coulomb’s constant, lowercase k, times charge 1 times charge 2 all divided by the square of r, the distance between centers of charge of the two charges, all times unit vector r, which is directed from one charge to the other.
- Bobby: That is not the equation for Coulomb’s Law that is on the AP Physics C equation sheet.
- Bo: Okay, then take the absolute value of

both sides and the unit vector disappears because it has a value of one.

- Bobby: That is still not the equation for Coulomb's Law that is on the AP Physics C equation sheet.
- Bo: … Then what is on the equation sheet?
- Bobby: Instead of Coulomb's constant it's one over the quantity four pi times epsilon naught. What is that?
- Billy: Lowercase epsilon naught stands for the permittivity of free space and Coulomb's constant equals one divided by the quantity

four pi times the permittivity of free space.

- Bobby: Oh yeah. That’s right. Thanks.
- Bo: Yeah.
- Billy: You are welcome.
- Bo: But what is “the permittivity of free space”?

$$\vec{F}_e = k\frac{(q_1)(q_2)}{r^2}\hat{r} \text{ or } \left|\vec{F}_e\right| = k\left|\frac{q_1 q_2}{r^2}\right| \text{ or } \left|\vec{F}_e\right| = \left(\frac{1}{4\pi\varepsilon_0}\right)\left|\frac{q_1 q_2}{r^2}\right| \ \& \ k = \frac{1}{4\pi\varepsilon_0}$$

{switch perspective}

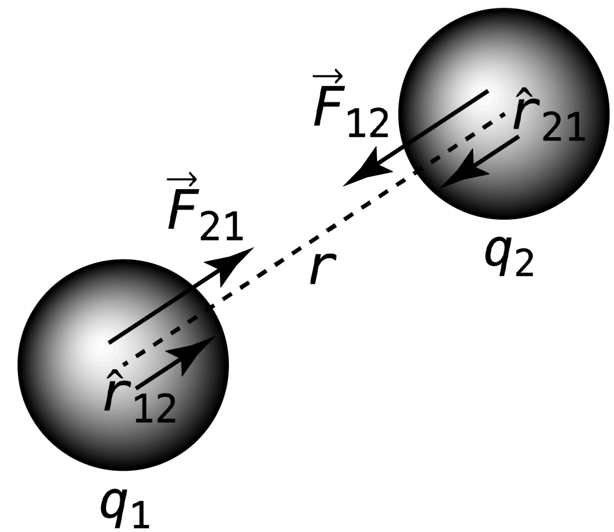
- Mr.p: Lowercase epsilon naught is the permittivity of free space or vacuum permittivity and it equals 8.85 times ten to the negative 12 coulombs squared divided by newtons times meters squared. … We will better define it when we get to capacitors and dielectrics.

- **Bo: (sure)**
- Mr.p: And, to be clear, F sub e is the electrostatic force on each of the interacting charged particles. Lowercase k is the Coulomb constant which equals 8.99 times 10 to the 9^{th} newtons times meters over coulombs squared. Q 1 and q 2 are the charges on the two interacting charged particles and r is the distance between the

centers of charge of the two charges as Bo pointed out.

- **Bo: (thank you)**
- Mr.p: … Notice that, in the vector equation form of Coulomb's Law, if the two charges have the same sign, the force is positive and repulsive, which follows the law of charges. And if the two charges have opposite signs, the force is negative and attractive, which again, follows the law of charges. … $\vec{F}_{12} = k\frac{(q_1)(q_2)}{r^2}\hat{r}_{12}$ Realize, this means the

electrostatic force from charge 1 on charge 2 uses the unit vector from object 1 to object 2 as I have shown in the illustration. … And, of course, the electrostatic force from charge 2 on charge one uses the unit vector from charge 2 to charge 1. … Alright, the scalar version of Coulomb's Law, clearly has no direction, because it is a scalar. … Now, I do want to point out that, according to AP Physics C: Electricity and



Magnetism guidelines, you will only be expected to calculate electrostatic forces between four or fewer charged objects or systems. However, you may be required to analyze more than four charged objects in situations which have high symmetry. So, please keep that in mind. … Also, the reality is that electrostatic forces, which can be determined using Coulomb’s Law, cause many of the forces which we work with on a macroscopic level. For example, force normal, forces of static and kinetic friction, and the force of tension. There are just too many microscopic electrostatic forces to reasonably calculate every interaction to find the macroscopic outcome. Therefore, we model the net force caused by all of these microscopic electrostatic forces as these macroscopic forces. … Alright, Bobby, please discuss the similarities and differences between Coulomb's Law and Newton's Universal Law of Gravitation.

{switch perspective}

- BBB: The Big G Equation!

- **Mr.p: (Yes, the Big G Equation. … Bobby?)**
- Bobby: Okay. Newton's Universal Law of Gravitation states that the force of gravity between two masses equals the universal gravitational constant, Big G, times mass 1 times mass 2 all divided by the square of r, the distance between centers of mass of the two masses.
- Billy: On the AP C Equation Sheet it's the absolute value of the vector force of gravity.
- Bobby: Sure, … But that is the same thing as what I just said.

- Billy: Yeah.
- Bobby: … Okay. So, similarities and differences between Coulomb’s Law and Newton’s Universal Law of Gravitation. … Well, the variable r is very similar, it is the distance between the centers of charge or the center of mass. … The electrostatic forces can be attractive or repulsive, however, gravitational forces can only be attractive. … And, the Coulomb constant is much, much larger than the gravitational constant.
- Billy: Big G is not really that big.

- Bobby: Yeah. Big G, the gravitational constant, is only 6.67 times ten to the **negative** 11 newtons times meters squared over kilograms squared, while the Coulomb constant is 8.99 times 10 to the 9th newtons times meters squared over Coulombs squared. Yeah, the Coulomb constant is a much, much larger number than the gravitational constant. That means, when two objects have both mass and electric charge, most often the electric force is so much larger than the gravitational force that the gravitational force is negligible.

- Billy: Yeah, poor big G.
- Bo: Right.

Mr.p: However, it is important to remember that when we are considering large scale objects like like people, planes, pineapples, planets, and Prii

- Bo: Prii?
- Billy: Toyota had a news conference in 2011 to announce that the preferred plural of Prius is Prii.
- Bo: That is perfectly predictable.

- Bobby: Perhaps?
- Billy: Possibly.
- Bobby: Potentially.
- Billy: Presumably.
- Bobby: Probably.

{switch perspective}

- Mr.p: {cutting BBB off} When we consider large scale objects like Platypuses,
- **Billy: (or platypi)**
- Mr.p: gravitational forces are large enough to make electric forces negligible because large scale objects are usually nearly electrically

neutral. In other words, their total number of protons and electrons are nearly equal. Which makes their electrostatic force small enough to be negligible. … Now let's talk about the law of conservation of charge. Bo, please?

{switch perspective}

- Bo: The law of conservation of charge … Well, that states that the net charge of an isolated system does not change.
- **Mr.p: (… And, a bit more please.)**
- Bo: … Typically, electrons are the charges which move in a system and, if there is no

way for electrons to leave or enter the system, that is what makes a system an isolated system, then the net charge of the system will not change.

- **Mr.p: (… Again, please keep going. What about charging by friction?)**
- Bo: … Okay. … Charging by friction involves rubbing one object on another object like fur on a balloon, for example. When this happens, electrons move from the fur to the balloon. … The net charge on the balloon-fur system remains the same because the total

number of protons and electrons in the system remains the same. … But, ya know, the two objects in the system have had their net charge change. … The balloon gains negative electrons making the net charge on the balloon more negative. … The fur loses electrons making the net charge on the balloon more positive. That is charging by friction. …

- Billy: … And when you bring two objects close to one another that will cause electrostatic forces between the charges and can change the distribution of the electrons in the objects. This can polarize the objects, however, the net charge on each object will remain the same if electrons are not allowed to flow between the objects.

- Bobby: … When a charged object is brought close to a neutral object, the charged object can rearrange the charges in the neutral object and cause a charge-induced separation of charges in the neutral object.
- Bo: Most often, the way to change the charge of a system is to add or remove

electrons from the system. When that happens, the system is not isolated, and charge is not conserved.

- Billy: Oh, and we should talk about grounding. A “ground” has, relatively speaking, an infinite number of electrons which we can pull from it, or we can give to it. We can “ground” a system by electrically connecting it to the Earth which is a “ground” or a neutrally charged, infinite well of electrons. When we ground a system, the system is not isolated, and charge is not conserved.

Mr.p: Very nice everybody. … Now we need to talk about electric fields. If we were to place a positive test charge in an electric field, it would experience an electrostatic force caused by the interaction of the positive test charge with the electric field. … An electric field is the ratio of the electrostatic force the positive test charge would experience to the charge of the positive test charge. … A positive test charge is a charge which is small enough not to measurably change the electric field it is placed in. … The equation for an electric field is electric field equals electrostatic force divided by positive test charge, where both electric field and electrostatic force are vectors. … Notice this means the units on the electric field are newtons per coulomb. … And please realize electric field is a vector, therefore it has, class, both … $\vec{E} = \frac{\vec{F}_e}{q} \Rightarrow \frac{N}{C}$

BBB: Magnitude and direction.

- Mr.p: Notice the electric field and the electrostatic force experienced by a positive charge in an electric field will be in the same direction.

- **Billy: (Because electric field and electrostatic force are both vectors in that equation and therefore, they have to be in the same direction!)**
- Mr.p: Exactly.

Bo: Hold up! What if the charge we put in the electric field is negative? I don't think the vectors will still be in the same direction.

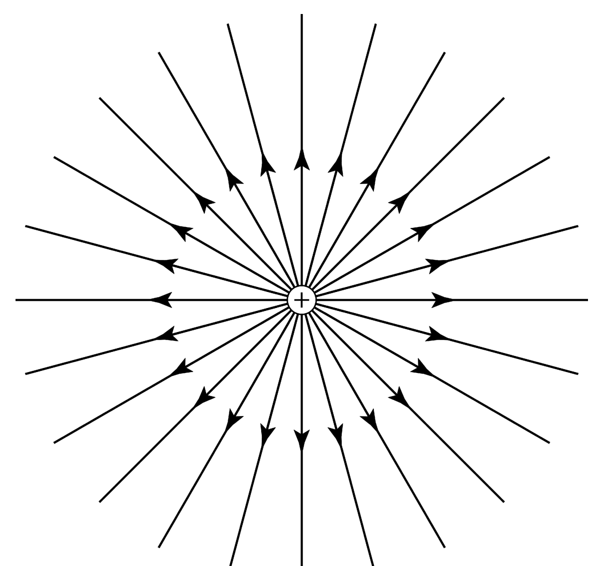
Mr.p: Good point, Bo. Looking at the equation, how do you think using a negative charge changes the direction of the force experienced by the charge?

- Bo: Uh, well … when the charge is negative in the equation … oh, I get it. That makes the force experienced by the negative charge and the direction of the electric field opposite in direction because of the negative in the equation. That totally makes sense.
- Bobby: Sure, but why do we always use a positive test charge and not a negative test charge.

Mr.p: The reason we use a positive test charge is just convention. That is how all electric fields are defined, using a positive test charge … Okay, Bobby, please tell me what the electric field map looks like around a single, isolated, positive point charge.

- Bobby: Well, let's start with the electric field due to a single, isolated, positive point charge. … When we take a positive test charge and place it near the positive point charge, according to the law of charges, because both charges are positive and therefore have the same sign, the positive test charge will be repelled from the positive point charge. That means, no matter where we place the positive test charge, it will experience an electrostatic force radially outward from the positive point charge. … Also, we know that, according to Coulomb's Law, the magnitude of the force will decrease as the positive test charge gets farther from the positive point charge. … Therefore, the electric field which surrounds a positive point charge is always directed outward away from the positive point charge and decreases in magnitude as we get farther from the positive point charge.

- Bo: We can determine the equation for that electric field by plugging the electrostatic force equation into the electric field equation, using lowercase q for the positive test charge and uppercase Q for the positive point charge. We get that the electric field which surrounds the positive point charge equals the Coulomb constant times the point

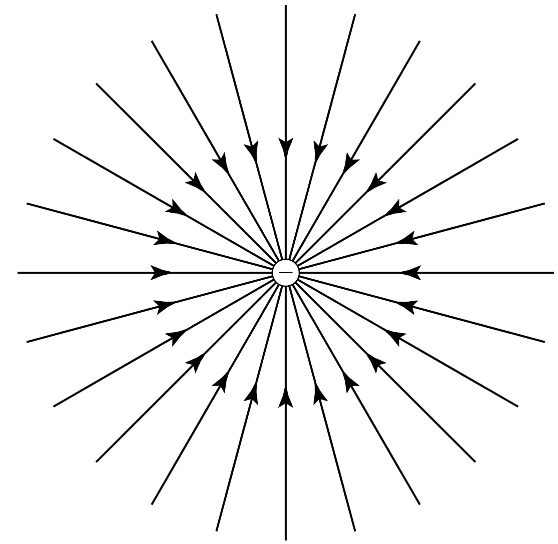


charge all over the square of r, which is the distance between centers of charge … actually, no, r is the distance from the center of the positive point charge to the location of the positive test charge or the location we are defining the electric field. That equation matches the diagram Bobby drew, correct, mr.p?

$$\vec{E} = \frac{\vec{F}_e}{q} \Rightarrow E_{\text{point charge}} = \frac{\frac{kqQ}{r^2}}{q} = \frac{kQ}{r^2}$$

Mr.p: Absolutely Bo, well done. … And Bo, what does the electric field around a negative point charge look like?

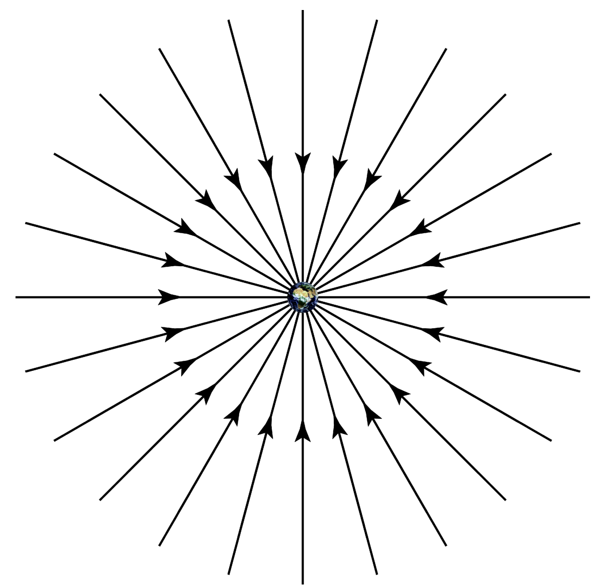
Bo: … Well, … it ends up being the same equation only capital Q, the charge of the point charge, is negative. That means all the field lines go toward the negative point charge. … It's almost the same as for the positive point charge, only all the arrows point radially inward toward the negative point charge because the law of charges says the positive test charge will be attracted to the negative



point charge, because the two have opposite charge signs.

- Mr.p: Correct Bo, thanks. Now …
- **Bobby: (mr.p)**
- Mr.p: Yes, Bobby?

{switch perspective}



- Bobby: That looks a lot like the gravitational field which exists around a planet, right?
- **Mr.p: (Yes Bobby, that is correct.)**
- Bobby: Why?

Mr.p: (Fair question.) Remember that the gravitational field equals the force of gravity divided by a test mass. … And we can substitute Newton's Universal Law of Gravitation in for the force of gravity, using lowercase m for the mass of the test mass and uppercase M for the mass of the point mass. … And we get that the gravitational field around a point mass equals the gravitational constant times the mass of the point mass divided by the square of r, the distance from the center of the point mass to the location of the test mass or the location of the gravitational field.

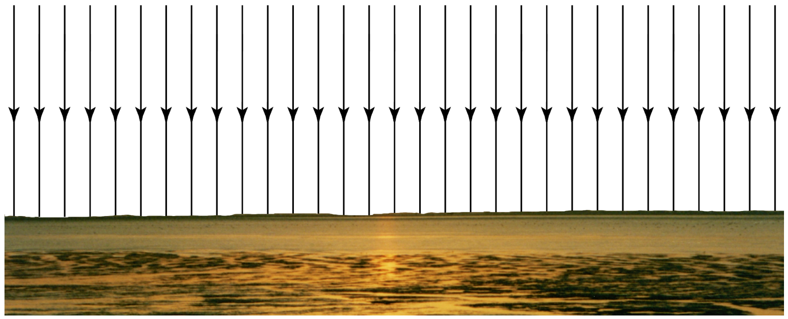
$$g = \frac{F_g}{m} \Rightarrow g_{\text{point mass}} = \frac{\frac{GmM}{r^2}}{m} = \frac{GM}{r^2}$$

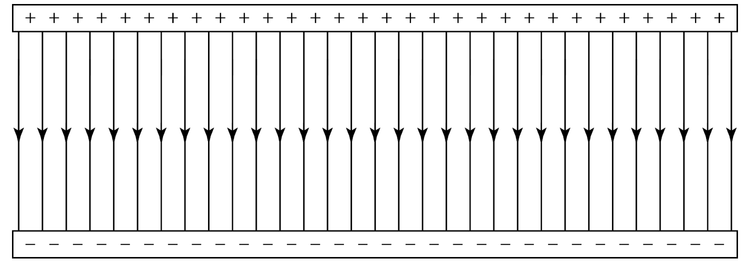
- Billy: And that equation is similar to the equation for the electric field around a point charge, which is why the gravitational field around a planet and the electric field around a negative point charge look the same.
- Bobby: … How come we can treat a planet as a point mass?
- Bo: When we get far enough away from a

planet, we can treat a planet as a point mass like we do here.

- Bobby: Sure. … But have we ever been that far from Earth?
- Bo: Depends how you define “we”.
- Billy: … But if you are actually standing on the surface of a planet, like we are currently on planet Earth, we can consider the gravitational field to be constant and pointed down toward the Earth and that looks just like the electric field that exists between two, large, parallel, oppositely charged plates.

Right mr.p?

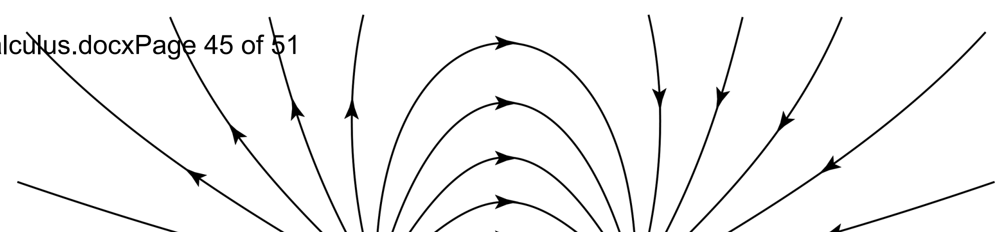




Mr.p: That is a valid point Billy. But please remember that is for an ideal case where the two parallel plates are very large relative to the space between the two plates. In a nonideal case, the two parallel plates will have an electric field which curves a bit near the edges of the plates and there will be some electric field which exists outside the parallel plates.

… Billy, let’s walk through one more electric field map. Please tell me what the electric field map for two point charges, one positive and one negative, which are isolated from all other charges, will look like.

Billy: Okay. A positive and negative point charge are isolated from all other charges … We already know what the electric fields which surround a single positive point charge and a single negative point charge look like, so let’s add those electric fields for each of the charges. … Actually, that’s kind of confusing,



so let’s make the electric field from the positive charge blue and the electric field from the negative charge red. … Because the electric field is a vector, the electric field from both point charges will be the sum of the electric fields for both charges. That means we need to do vector addition of each of those electric fields. So, we can go through and approximate the vector addition of both electric fields and we end up with a net electric field which … looks like it does in the net electric field map you are showing there in black.

Mr.p: Thank you Billy. Please realize electric field maps like this one are simplified models and are vector field maps which show the magnitude and direction of the electric field for an entire region. … You know what, we never actually went over the basics of electric field lines. I think we should do that.

BBB: Yes. Yeah. Yep.

mr.p: Okay. Electric field lines are always in the direction a small, positive, test charge would experience an electrostatic force. … The number of electric field lines per unit area is proportional to electric field strength. In other words, a higher density of electric field lines means a higher electric field strength. … Electric field lines always start on a positive charge and end on a negative charge, unless there is more of one charge than the other, then some of the electric field lines end or start infinitely far away. … Electric field lines always start perpendicular to the surface of the charged objects. … And lastly, electric field lines will never cross. … Okay, now let's talk about conductors versus insulators. … Conductors are materials which allow electrons to move rather easily. This is because conductors have electrons which are loosely bound to their atoms which then allows those electrons to flow. … Some examples of conducting materials are aluminum, stainless-steel, and gold. … Insulators are materials which resist the motion of electrons. Insulators have electrons which are tightly bound to their atoms which does not allow electrons to flow. … Some examples of insulating materials are plastic rubber, glass, and paper. … Semiconductors are materials which are somewhere in between conductors and insulators. … Electrons in semiconductors have some resistance to flow, and the precise resistance to flow is controlled by the composition of the materials, and how the material interacts with the composition of other semiconductors in contact with it. Some examples of semi-conducting materials are silicon, germanium, and gallium arsenide. Some examples of applications of semiconductors are diodes, transistors, amplifiers, solar cells, and light emitting diodes or LED’s. … That concludes my review of Electric Charges and Electric Fields for AP Physics C: Electricity and Magnetism. Next time I’ll be reviewing Electric Flux and Gauss’ Law. … Thank you very much for learning with me today, I enjoy learning with you.