Induced charge, polarization, conductors and insulators. Y&F 21.2 covers these topics.

Polarization. A charged Styrofoam cup (negative charge) will pick up neutral bits of paper. Google Images "static charge bits of paper".

How can neutral bodies such as the pieces of paper be attracted to a charged body? The bits of paper are polarized by the field of the cup; the near side of the paper becomes positive, while the far side becomes negative, in equal amounts. The near side is attracted to the cup, the far side is repelled. Since the near side is closer to the cup, the attractive force is stronger that the repulsive force, and the paper is pulled toward the cup, and attaches itself to the cup.

There are two ways to picture what is happening.

1. By Coulomb's law, we say that the negative charge on the cup is attracting positive charge on the paper, and repelling negative charge on the paper.

2. An electric field is created by the cup, the field fills space. The bits of paper are immersed in the field. The field causes positive charges in the paper to move one way and the negative charges to move the other way.

This experiment shows us that charges (electrons) move around inside materials. In some materials the electrons move freely, we call these conductors, they "conduct" electric charge well, and if you apply an external electric field, it is easy to induce electric current, a river of electrons. Metals are conductors. Copper is the best, and is used to make wires for carrying electrical current.

In other materials the electrons barely move, we call these insulators, they do not conduct electric charge very well at all. Plastic, Styrofoam and glass are good insulators, paper is also an insulator. Still, it is possible to make charges move in paper, as you have just seen.

Electrons as (-) charge carriers, "holes" and (+) charge carriers. Let's look closely at what happens during the polarization process.

Place a + charged ball near a neutral piece of paper. An electron located in the 2nd layer of atoms beneath the surface layer is moves to the surface layer, leaving behind a + atom (its missing its electron). An electron hops from the 3rd layer and pops into the hole, leaving behind a + atom. This process continues to the opposite edge of the paper. In effect, the hole has "traveled" from one side of the paper to the other. Even though no + charge particle moved, we think of the hole as a + charge carrier.

The movement of electrons going left is equivalent to holes going right. Electrically, there is no difference. Picture it as combined effect of electrons going left and holes going right as the same time.

In fact later on, when we study electric current, we prefer to say that the current consists of + charge carriers, so that we do not have to both fuss with the – signs of negative charge carriers.

How does the behavior of conductors and insulators differ under the influence of an external electric field? In a perfect conductor, an electron travels from one end of the material to the other. In a perfect insulator, an electron is displaced slightly within an atom.

Why doesn't the electron get pulled out of the paper and into the air?

If the field is strong enough this will happen, we call it an electrical discharge (a spark). For weaker fields the electrons in the paper stop at the boundary of the paper, and go no further.

Removing one electron from the paper is not easy; it is comparable to trying to remove an electron from an atom. Neighboring atoms can pull equally hard on an electron. The atoms are very close to each other and exert very strong electric fields. But an external body (a cup) is much further away.

Picture an atom in the surface of the paper. If you remove one electron from the atom, you leave behind a (+) charged atom that pulls powerfully on the removed electron.

Estimate the field strength near a singly ionized atom (a single electron has been removed)

$$r = 2\text{Å}, \qquad q = e, \qquad E = k\frac{q}{r^2} = 3.6 \times 10^{10}\frac{N}{C}$$

Still, it is possible to cause an electrical discharge using a much weaker field $E \sim 10^4\ N/C$. How? There are several effects, but we will not go into detail now. Suffice to say that the electrons in the paper are in various states of motion (energy), and some are occasionally on the verge of coming loose. Also, ambient light (which is a EM wave) striking the surface of the paper can knock electrons loose. Take PH1130 Modern Physics if you want to know more! We will instead stick to our present topic for now…

FIELD LINES

Sketching field lines, tips and advice. Given a set of charges and conductors of various shapes, sketch the field lines.

For point charges, start by sketching the near field (which is dominated by the local charge):

short arrows pointing out of + charges

short arrows pointing into – charges

make the number of lines proportional to the magnitude of the charge

When sketching more complex configurations, use the simplest configurations as guides: single point charges (+, -), two point charges (+ -, ++, --), a point charge and a plate, etc

For conductors, ask yourself "Is the conductor neutral or charged?" and "What polarization is induced by nearby charges?" The answers to these questions tell you how many little + and – signs to sprinkle over the surface of the conductor, and where to sprinkle them. Then start by sketching:

short arrows perpendicular to the conductor surface that point outward where the conductor is positive, and inward where the conductor is negative.

Remember: no surplus charge remains inside conductors, and there is no field inside conductors.

Extend the field lines. As you extend the lines out from (+) charges, some of the lines will swerve and find their way to nearby (–) charges. Other lines will extend off of your page.

Remember: do not cross the field lines.

Let's work a few examples, apply these techniques, and you will get the hang of it.

EXAMPLES

A point charge near a flat neutral metal surface (identical to a dipole field); try at various distances.

A charged body +Q near a neutral metal surface induces a charge of –Q on the surface.

Two charged bodies near a neutral metal surface.

A charge of +Q near a metal body of charge +2Q.

A charged body near a neutral dielectric (an insulator); metals and insulators behave differently.

A charge near a needle point (see picture of girl in Chap. 22), each hair is like a needle.

A rectangular wire with one side placed in an electric field (this is essentially what a battery does)

Place a charge near a metal body, then attach the metal body to the Earth (we call this grounding). The Earth is large, and the induced charge spreads throughout the Earth. When you disconnect the wire, the metal body is remains charged.

The average field inside a neutral conductor. While the field is strong near an individual electron or proton, the average field strength is zero, since any given point inside the conductor will experience fields in all directions and with varying strengths. Suggested problem 21.49 shows that the field between to charges can be zero, for example.

The field inside a charged conductor, see Y&F 22.5.

If you release charge within a conductor, the charge will quickly spread to the surface. What is the field inside? Zero! For one thing, try sketching field lines inside the conductor and you will see that there is nowhere for them to go. In suggested problem 21.23, four charges placed at the corners of a square, the field at the center of the square is zero. The sum of the fields inside is zero

$$\sum_{n=1}^{N} \vec{E}_n = \vec{E}_1 + \vec{E}_2 + \cdots$$

How long does it take for the charges to move to the surface? Remember the calculation we did for an electron in a field of $E = 100\ N/C$? It took 34 ns for an electron to start from rest, accelerate to 600 km/s and move 1 cm.

If you introduce electric instability, electrostatic conditions (no charges in motion) very quickly return.

You have to be careful with the statement "the electric field inside a conductor is zero". This is not always true, and is only true on average. The correct statement is "the electric field inside a conductor is zero on average under electrostatic conditions".

What about a hollow conductor?

If there is no charge inside the hollow then again, under electrostatic conditions there is no field inside the conductor.

If you place a charge inside the hollow, it will attract opposite charge to the inner wall of the conductor, of equal and opposite amount! The charge can be measured accurately, and such experiments (see Y&F 0g 768) confirmed Gauss' law, which states that the electric flux through a closed surface is proportional to the enclosed charge

$$\Phi = \oint \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0}$$

which, for a spherical surface, leads to Coulomb's law.

We will not study electric flux and Gauss' law, but we will make use of magnetic field flux later on. Here, we simply accept the Law, and note the law can be used to demonstrate that E is zero inside a conductor.

How can you create a uniform electric field? With two parallel metal plates placed close together! Use the Caltech Applet, make two rows of charges to simulate two charged plates. See that the field lines between the plates are roughly parallel.

Let's see why the field is uniform. If you read Y&F 21.1, it will help you understand the following.

Attach a battery across two metal plates of area A, one becomes positively charged $+Q$ while the other becomes negatively charged $-Q$. Since like charges repel, the charge on both plates will spread out evenly over the surface of the plate.

Why the surface? The charges are trying to get as far away from each other as possible.

Why don't the charges leave the plates and jump into the surround space? While a charge moves around within in the metal, it experiences equal tugs from neighboring atoms, and so finds itself moving freely about the "cabin". But a charge "exiting the cabin" would leave behind an oppositely charge atom, which will pull with all its might to keep the charge from leaving.

Why does such a charge distribution produce a uniform field?

Let's pick an arbitrary point in space between the plates, and sketch the electric field vectors created at that point by infinitesimal patches of charge. What we find is that horizontal field components cancel, while vertical components add constructively, ultimately creating a uniform vertical electric field of magnitude

$$\sigma = \frac{Q}{A}, \qquad E = \frac{\sigma}{2\epsilon_0}, \qquad \epsilon_0 = 8.854 \times 10^{-12} \frac{C^2}{Nm^2}, permitivity\ of\ empty\ space$$

where σ is the surface charge density in coulombs per meter squared. See Y&F 21.5 for details. The above formula is exact for infinite plates, and very accurate for plates that are close together.

Let's start with two patches of equal charge on the positive (upper) plate, equidistant from the field point. The patches create electric field vectors $\vec{E}_1$ and $\vec{E}_2$ at the field point. One points down and left, the other points down and right. Their horizontal components cancel, while their vertical components add constructively.

Continue this process for pairs of patches, until you have covered the entire surface of the plate. The resultant field points downward.

Repeat for the negative (lower) plate. Again, the resultant field points down.

Since we are summing over an infinite number of patches, will the sum be infinite? No, because we started with a finite amount of charge on each plate; a finite amount of charge cannot create and infinite field strength. If we divide the charge Q into N equal charges, each of charge Q/N, the total charge is

$$N\left(\frac{Q}{N}\right) = Q$$

Even if $N \to \infty$, we still have a total charge of Q.