Aims
In studying this chapter you should aim to understand the basic concepts of electric charge and field and their connections. Most of the material provides illustrations which should help you to acquire that understanding. To test whether you have understood the concepts see if you can describe and explain the applications in your own words.

Minimum learning goals
When you have finished studying this chapter you should be able to do all of the following.

1. Explain, interpret and use the terms:
   - electric charge, coulomb, electron, electronic charge, conservation of charge, ion, electrostatic force, permittivity, permittivity of free space, conduction, electric field, field lines, field strength, uniform field, surface charge density, electrical shielding.

2. Describe a number of processes by which electric charges can be separated.

3. Describe the qualitative features of the interactions of static charges.

4. State and apply the relation between electric force and electric field.

5. Describe and explain examples of applications and hazards of electrostatic phenomena.

6. (a) Sketch electrostatic field-line diagrams for systems with simple conductor shapes including parallel plates, concentric cylinders, isolated sphere, parallel cylinders.
   (b) Interpret given field-line diagrams in terms of magnitude and direction of the field.

7. State and apply the relation between the surface change density and electric field at the surface of a conductor.

8. Describe and discuss principles and examples of electrostatic shielding.

CONCEPT DIAGRAM

[Diagram showing the concepts and their connections]
1-1 INTRODUCTION

The natural world provides precious few clues to the ubiquity of electromagnetism. The properties of rubbed amber and the magnetism of lodestone were little more than curiosities until the 17th century. The elucidation of the nature of lightning and the recognition of light as electromagnetic radiation were even more recent. Yet our world is governed by electromagnetic interactions. All chemical bonds, the strength and weakness of materials, light, the influences that form and control living things are all aspects of electromagnetism. Indeed, only three other types of fundamental force are known: the weak force, the strong force and gravity.

Of these forces the first two, which are purely nuclear forces, are effective only over distances of less than \(10^{-12}\) m - that is smaller than an atom. They are associated with radioactivity, but otherwise are of no consequence in chemistry and biology. Gravity is such a feeble force that it matters only in interactions involving bodies of ‘astronomical’ mass and is negligible in interactions between small things. Apart from the earth's gravitational pull, every force that you experience is electromagnetic in nature.

Electromagnetic force is associated with a fundamental property of matter - electric charge. No process is known which creates or destroys even the minutest amount of charge. This is formally stated as the law of charge conservation: electric charge can not be created or destroyed.

The SI unit of electric charge is the coulomb, symbol C. The magnitude of the charge on a single electron is a commonly used quantity in atomic physics. It is

\[ e = 1.6 \times 10^{-19} \text{ C}. \]

Thus

\[ 1 \text{ C} = 6.2 \times 10^{18} e. \]

The charge on an electron is \(-e\), and on a proton, \(+e\).

1-2 ELECTRIC CHARGE

Why study electrostatics?

Electrostatics is the basis of industrial processes such as electrostatic spray painting, and xerography, and of the unintentional build-up of electrostatic charge which can trigger explosions and fires in, for example, grain silos and operating theatres.

We study electrostatic phenomena in this course not simply to understand the applications of static charge, or the hazards they present, but because the ideas are applicable in other branches of electricity, and the electrical aspects of other sciences. The theory of electrostatics, electric charge, field and potential apply in more complex situations involving currents and magnetic fields.

Isolated electric charges and atomic structure

Demonstration

Isolated electric charges, such as those obtained by running a comb through your hair, can be detected with a field mill, an instrument which measures the charge induced on an internal sensing electrode. A field mill shows that the positive charge on the comb is balanced by a negative charge left behind on the hair.

Electrostatic phenomena are a consequence of the atomic nature of matter. All atoms are built up from three types of fundamental particles, protons, neutrons, and electrons, the properties of which are given in table 1.1. The nucleus of an atom consists of a number of protons and neutrons tightly bound together and surrounded by a cloud of electrons. The number of electrons in the
electron cloud is equal to the number of protons in the nucleus. Since the charges of the proton and electron are exactly equal in magnitude and opposite in sign, atoms are electrically neutral. Atoms may gain or lose electrons, thus becoming ions.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>$m_p$</td>
<td>$+e$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.01 m_p$</td>
<td>0</td>
</tr>
<tr>
<td>Electron</td>
<td>$\frac{1}{1840} m_p$</td>
<td>$-e$</td>
</tr>
</tbody>
</table>

Table 1.1 The fundamental particles of atomic physics

Atoms combine to form molecules, which in turn combine to form bulk material. The normal state of matter is electric neutrality: matter normally contains equal numbers of protons and electrons, and has no net charge. Electrostatic effects occur when this exact balance of positive and negative charges is disturbed, leaving a net charge of one sign on the body - i.e. electrostatic effects occur when electrical charges are separated.

Separation of electric charges
Charge can be separated by various means. Here are some examples.

- Contact of dissimilar materials is followed by physical separation (combing hair).
- The belt of a Van de Graaff generator carries charge. Here also dissimilar materials (the belt and the pulley) are contacted, and separated. Charge is drawn off the belt, and stored on the dome.
- In a battery charge is separated by chemical means.
- Diffusion of charge occurs in living cells. Ions of one sign of charge can move more readily through the permeable wall of a cell, than those of the other sign.
- Charge is separated by convection in thunderclouds.

All charge separation involves the expenditure of energy. The energy is released, for example in a spark, when the charged particles recombine.

1.3 FORCES BETWEEN CHARGED BODIES
Energy must be supplied to separate unlike charges because there is an attractive electrostatic force between the charges. This electrostatic force is one variety of the general electromagnetic force. It is the basic interaction between charged bodies and it is called electrostatic because the other varieties of electromagnetic force appear only when charges move.

Properties of the electrostatic force
Experiments show the following.

- Like charges repel. If you connect somebody to an electrostatic generator their hair will stand up because each hair carries the same sign of charge and the similar charges repel. Likewise, two foam plastic balls fly apart when both are positively charged.
- Unlike charges attract. When opposite charges are transferred to foam plastic balls, the balls are attracted towards each other.
- The magnitude of the electrostatic force between charges increases as their separation decreases.
**Electrostatic force in atomic physics**

The electrostatic force binds electrons and nuclei together to form atoms and the same force holds atoms and molecules together in bulk material. The strength of materials is due entirely to electric forces.

The electrostatic force is so potent that only minute deviations from charge equality can be achieved in practice. For example when a 0.2 kg aluminium plate is charged negatively by attaching it to a 250-volt battery, the charge on the plate is about \(-5 \mu\text{C}\). To make up this huge charge requires that only \(10^{13}\) electrons, or 1 for every \(10^{12}\) of all the \(10^{25}\) electrons on the plate, be added to the plate.

**Electrostatic force in nuclear physics**

The strong repulsive electrostatic force between the protons in the nucleus of an atom tends to break up the nucleus, which is held together by the very strong attractive nuclear forces. The collision of a neutron with a uranium-235 nucleus can break the nucleus into two lighter nuclei. These fragments are no longer held together by the short-range nuclear force, but move rapidly apart due to the repulsive electrostatic force between the protons in each nucleus. Thus the release of energy in nuclear fission is mediated by electrostatic forces.

### 1.4 ELECTRIC FIELDS

Electric field is an idea introduced to describe electric forces. In the TV lecture the dome of a charged Van de Graaff generator attracts charged droplets of water. This situation can be described by saying that the charge on the dome of the generator sets up an intense electric field, and the charged drops ‘feel’ a force when they are in the space occupied by that field.

A field is something that is defined at all points in a region of space. A familiar example is the gravitational field of the earth, which is often called the acceleration due to gravity \((g)\). Another example is the velocity of water in a river which has different magnitudes and directions at different places. Examples to be considered in this unit are electric field, electrostatic potential and magnetic field. An electric field is said to exist at a point in space if a charged particle placed at that point experiences a force that would not be felt by an uncharged particle. We have already seen that a possible explanation for such a force could be the presence of another charged body - but that is not the only thing that can create an electric field. Instead of describing the interaction of charged particles directly in terms of forces it is more fruitful to use a new kind of description involving electric fields. The two descriptions are visualised and compared in figure 1.1.

![Figure 1.1 The concept of electric field](image)

The diagram on the left represents the description of an interaction in terms of forces. On the right we separate the interaction into two parts.
The value of an electric field $E$ can be defined in terms of the force $F$ experienced by a particle with a small charge $q$:

$$F = qE.$$ ... (1.1)

Both $F$ and $E$ are vector quantities - they have both magnitude and direction.* In this definition the magnitude of the force is equal to $qE$ and the direction of the field is equal to the direction of the force on a positively charged particle. The force on a negative particle is opposite to the field direction. We say that an electric field is uniform when neither its magnitude nor its direction changes from one point to another.

The SI unit of electric field is called the volt per metre (symbol V.m$^{-1}$) which is equivalent to a newton per coulomb (N.C$^{-1}$).

### 1.5 FIELD LINES

A neat way of mapping a two-dimensional slice through a magnetic field is to float some grass seeds or some other kinds of small elongated objects on the surface of a liquid. The electric field causes the seeds to align themselves with the field's direction. An equivalent way of visualising a field in three-dimensions would be to imagine lots of tiny arrows, each one showing the direction of the field at the chosen place. There is, however, another way of visualising electric fields (and other vector fields) - field lines. Field lines are continuous directed lines drawn so that at any point on a line the direction of the line (its tangent) shows the direction of the field. Field line diagrams are also three-dimensional so it is not always possible to represent them accurately on flat diagrams. Figures 1.2 and 1.4 are examples where we can draw a two-dimensional picture because they represent situations which have the same configuration in all cross-sections.

Electrostatic field lines start on positively charged surfaces and end on negative charge (figures 1.2, 1.4). If you have an ‘isolated’ charged body the field lines go out to ‘infinity’ as though they are looking for the other sign of the separated charge (figure 1.8).

![Figure 1.2](image-url) Field lines for two oppositely charged parallel cylinders

Not only do field line diagrams represent the field direction in a visually obvious way; the spacing of the lines also represents the magnitude of the field. The field is strongest where the lines are closest together.

* In printed material vectors are indicated by bold-face symbols, such as $E$. In manuscript we usually put a tilde (~) under the symbol (e.g. $\tilde{E}$) or an arrow above it (e.g. $\vec{E}$). The magnitude of a vector is indicated by using the same symbol without bold-face or by omitting the tilde or the arrow. Occasionally a component of a vector is indicated in the same way as a magnitude; the context usually makes it clear which is meant.
1-6 ELECTRIC FIELD AND CHARGE

Conductors with static charges
An electrical conductor is an object through which electrons or ions can move about relatively freely. Metals make good conductors. If a net charge is placed on a conductor and it is then left alone, the charge very quickly settles down to an equilibrium distribution. There are several interesting things to note about that situation. (See figure 1.3.)

- The net charge is spread out over the surface of the conductor, but not uniformly.
- There is an electric field in the space around the conductor but not inside it.
- At points just outside the surface of the conductor, the electric field and the electric field lines are perpendicular to the surface.

Figure 1.3 Electrostatic field near the surface of a conductor
The charge density varies over the surface. The field near the surface is strongest where the charge density is highest.

Figure 1.4 Electric field between a positively charged cylinder and a nearby plane surface.

We can describe the way that charge spreads out on the surface by specifying the concentration of charge or surface charge density - the charge per surface area. The magnitude \( E \) of the electric field at the surface of a conductor is proportional to the surface charge density \( \sigma \). This relation is usually written as

\[
E = \frac{\sigma}{\varepsilon_0}
\]

where \( \varepsilon_0 \) is a constant representing the permittivity of the medium that surrounds the conductor, and is called the permittivity of free space. Although a vacuum is a pretty rare thing, the permittivity of air is very nearly equal to \( \varepsilon_0 \), so in electrostatics we usually regard air as being equivalent to empty space.
The SI unit of surface charge density is the coulomb per square metre (C.m\(^{-2}\)). The SI unit of permittivity is called the farad per metre, F.m\(^{-1}\), which, in terms of units that you know already, is equivalent to C\(^2\).N\(^{-1}\).m\(^{-2}\). The permittivity of free space is one of the fundamental constants of nature; its value is \(\varepsilon_0 = 8.85 \times 10^{-12} \text{F.m}^{-1}\).

Equation 1.2 (with \(\varepsilon = \varepsilon_0\)) is always true for conductors in a vacuum. It is a consequence of Gauss's law, which is one of the four basic laws of electricity.

**Field lines and electric field strength**

Field line diagrams represent the strength of the field at each point provided that they are correctly drawn. In a correctly drawn field-line diagram each line must begin (and end) on equal amounts of charge. The field lines are also drawn so that the field strength is proportional to the concentration of the lines (figure 1.5).

Think of a small imaginary surface, area \(A\), drawn perpendicular to the field at some place in space. Count the number, \(n\), of field lines that go through the surface. Then the magnitude of the electric field averaged across the surface \(A\) is represented by the number of field lines per area.

\[
E = \frac{n}{A}. \quad \text{... (1.3)}
\]

Thus, as the field lines spread out from a charged body the electric field strength falls off correspondingly.

The product of the component of the average field perpendicular to the surface and the surface area is called the flux of the field through the surface. So the number of field lines through a surface represents the flux of the electric field through that surface.

In principle once a charge distribution is known the electric field can be deduced and vice versa. In practice such calculations can usually be done only numerically (by computer) except for simple geometries. Calculations of the relationship between electric field and charge distribution are vital in many branches of science and technology. Examples range from the study of ion diffusion in living cells, through the design of electrical equipment, to the investigation of thunderstorms.

For highly symmetrical conductors accurate field-line diagrams are fairly easy to draw. Some examples are given in figures 1.6, 1.7 and 1.8.

**Figure 1.5** Field strength and concentration of field lines

**Figure 1.6** Field lines for parallel plates

The fringing field at the ends of the plates can be ignored if the plate area is large, or if the plates are close together.
1-7  ELECTROSTATICS IN INDUSTRY AND COMMERCE

Electrostatic spray painting
If a surface to be coated is charged, say negatively, then the corresponding electric field will be directed inwards towards the surface. Positively charged droplets of paint from the sprayer are then driven towards the surface by the forces that they experience in this electric field (or, if you like, the positively charged droplets are attracted to the negatively charged surface).

Electrostatic precipitators
In electrostatic dust precipitators a large negative charge is maintained on spiral wire electrodes, which are arranged between positively charged plates. Negative ions (O$_2^-$, N$_2^-$ etc.) are formed at the wire and the exhaust gases pass between the wires and the plates. The negative ions collide with the dust particles, giving them a negative charge. This negatively charged dust is then driven by the electrostatic field to the positive plate, to which it adheres until collected. Electrostatic precipitators are routinely used in coal-fired power stations; they remove over 95% of the light fly ash from the exhaust gases.

Xerography
In a photocopier an image of the document is formed on a charged plate of selenium - a photoconductive material. Light reflected from the white areas of the document discharges the illuminated areas of the plate, leaving a charge-image of the document. Charged particles of black printing ink are then attracted to the charged image. Finally, the ink is transferred by direct contact to the sheet of oppositely charged copy paper.

1-8  ELECTRICAL SHIELDING
Michael Faraday discovered that inside a closed metal room no electrical effects from outside influences could be detected, no matter how violent the electrical activities outside. As he put it:

‘I went into the cube and lived in it, and using lighted candles, electrometers, and all other tests of electrical states, I could not find the least influence upon them ... though all the time the outside of the cube was powerfully charged, and large sparks and brushes were darting off from every part of its surface.’

[From M. Faraday (1849), Experimental Researches in Electricity para. 1174.]

Demonstration
Faraday’s demonstration is repeated in the TV lecture where one lecturer stands inside a wire mesh cage. A potential difference of 40 kV is established between plates on each side of the
cage; the cage rises to a voltage of about 20 kV. Despite the intense electric fields that exist outside the cage, the lecturer is quite safe inside the cage. Indeed, no electric field can be detected inside.

When a hollow conductor is placed in an electric field, charge is redistributed very rapidly over the surface so that the field lines end on surface charges (figure 1.9).

![Figure 1.9 Surface charges on a hollow conductor in an electric field](image)

There is no field within the conducting walls, and hence there is no field inside the hollow space. Of course charge, inside the hollow conductor, can be separated to give an electric field inside the conductor. The point is that no external electric field can influence the electrical conditions inside the conductor. The inside of the conductor is shielded from outside influences. In practice shielding is never absolutely effective, but it can reach 99.99% effectiveness even with mesh rather than continuous metal. Attention must be paid to the integrity of joins, to doors and to the entry of cables. In the TV lecture, it is shown that the field inside the cage, as measured by the field mill, is hundreds of times less inside the cage than outside. Note that a battery operated field mill was used to avoid the problems of bringing in power leads while maintaining complete shielding.

For successful shielding of experimental apparatus, the whole apparatus including signal and power leads, must all be totally within the same shielded space. Provided that the shield encloses the entire experiment it may be any shape. A mesh shield will also protect apparatus from changing fields of electromagnetic radiation, as long as the mesh size is very much smaller than the wavelength of the radiation. In the TV lecture, it is demonstrated that the mesh cage effectively screens broadcast band radio signals (about 300 m wavelength), but not light (500 nm).

A screened room is a normal feature of any electrophysiology laboratory, where tiny voltages are measured. In other situations screening may be necessary because the external fields are so strong. In plasma physics experiments, for example, huge electrical energy is used to form the plasma so the apparatus which makes sensitive measurements of the electrical properties of the plasma must be thoroughly shielded.

![Figure 1.10 Screening an experiment](image)

If the screen is in two or more disconnected parts, it is ineffective.
1-9 THE FUNDAMENTAL LAWS OF ELECTROSTATICS

Traditional courses on electrostatics start with the inverse square law for the force between two point charges \( q_1 \) and \( q_2 \), Coulomb's law:

\[
F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}
\]

where \( r \) is the distance between the charges, and the force acts along a line joining the charges.

The corresponding expression which gives the magnitude of the radial electric field of a point charge, \( q \), (or of a uniformly charged sphere) is

\[
E = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2}
\]

where \( r \) is the distance from the charge (or the centre of the sphere) and the electric field is in a radial direction.

While this law is of fundamental importance in physics, it is not used in this form either in the later development of electromagnetism, or in the life sciences. Consequently we have based this course on a much more useful law which is equivalent to Coulomb's law: Gauss's law. Although we have not formally stated Gauss's law (it is rather abstract mathematically) we have used two aspects of it.

i) The field near a conducting surface is proportional to the surface charge density (eqn 1.2).

ii) At any place the electric field strength is proportional to the areal density of field lines (eqn 1.3).

Field Lines and Gauss's law

Like many very basic physical laws, Gauss's law appears in many guises, which may be very mathematical. The formal statement of Gauss's law is: ‘The total flux of electric field through any simple connected closed surface is equal to the total charge enclosed by that surface, divided by \( \varepsilon_0 \),’ (Flux is a product of field strength and area of an imaginary surface drawn perpendicular to the field.)

We can also express Gauss's law in terms of field lines: ‘The total number of field lines passing outward through any closed surface is proportional to the total charge enclosed within the surface.’ This statement implies that field lines originate on charges. Field lines passing out of the surface add to the number of lines; those passing into the surface subtract from the number of lines.

Superposition

We have assumed, correctly, that electric fields are additive. Physical quantities which behave additively, like fields, are said to obey the principle of superposition. This is not a trivial statement because there are some quantities, such as intensity of coherent waves and the effects of drug dosages, which do not behave additively. Physical quantities which do obey the superposition principle include force, mass, energy, electric field, magnetic field and electrostatic potential.

Electric dipoles

A pair of oppositely charged particles is often called a dipole. The electric field produced by a dipole is like that shown in figure 1.2. One way of describing the properties of a dipole is to specify its dipole moment, which is defined as the product of the magnitude of the charge and the separation between the particles: \( p = qd \).
1-10 ELECTROSTATIC DEFLECTION

A good example of the force experienced by a charge in an electric field is provided by the technique of electrostatic deflection. Consider an electron of mass $m$ and horizontal velocity $v$ entering a region of vertical (upward) electric field $E$ in a vacuum (figure 1.11).

The electron will undergo an acceleration of magnitude $eE/m$. Since the electron's charge is negative the direction of this acceleration is opposite to the direction of the field. The component of velocity parallel to the field increases in magnitude while the component perpendicular to the field remains constant. The result is a motion in which the path bends rapidly toward the (negative) field direction. The path is like that of a projectile which is thrown with an initial horizontal velocity and bent downwards by the earth's gravitational field.

**Note**

To analyse the motion, use two components. Displacement component $x$ is perpendicular to the field, to the right in figure 1.11, and component $y$ is parallel to the field lines (up). Since a typical electrostatic force is so strong compared with gravity, we leave gravity out of the analysis.

The $x$-component of the motion is force free, so the component of velocity $v_x$ maintains a constant value $v$ and the horizontal displacement in a time interval $t$ is

$$x = vt.$$  

The component of motion parallel to the field is affected by a constant force component $F_y = -eE$. This force produces a constant acceleration component $a_y$ given by the equation of motion, $F_y = ma_y$. To find the velocity component, integrate (find the area under) the acceleration-time graph. That gives

$$v_y = a_y t$$

Then you draw another graph, the velocity time graph, to find $y$. The result is

$$y = \frac{1}{2} \frac{E}{m} t^2.$$  

To find an equation for the shape of the path, eliminate the time from the equations for $x$ and $y$.

$$y = \frac{1}{2} \frac{E}{m} \frac{1}{v^2} x^2.$$  

The electron thus follows a parabolic path in the field.

**Demonstration**

The path is demonstrated in the next TV lecture, E2. A special electron beam tube has a longitudinal phosphorescent screen which reveals the path of the ribbon-like electron beam. The vertical $E$ field is produced by putting a high potential between a pair of horizontal plates inside the tube.

Electrostatic deflection of electron beams is used in cathode ray oscilloscope tubes to make electrical measurements. Amplified signals are applied to horizontal and vertical deflector plates inside the tube, both to provide the time base sweep, and to display the signal under investigation.
1-11 **QUESTIONS**

**Q1.1** Why do you think it took people so long to formulate the notion of electric charge, whereas mass has been recognised since antiquity?

**Q1.2** If you pass a comb through your hair and it acquires a charge of \(-0.1\ \mu\text{C}\), how many excess electrons does it carry? What conclusions can you reach by applying the law of conservation of charge to this situation?

**Q1.3** Which of the following effects are fundamentally electric in nature? Discuss each briefly.

1. tension in a spring.
2. gas pressure.
3. ‘crackles’ from some very dry garments when you undress.
4. ‘crackles’ from treading on dry leaves.
5. gravity.
6. nerve conduction.
7. nuclear fission.
8. the aurora.
9. radioactive decay.
10. centrifugal force.
11. the spiral structure of galaxies.
12. moment of inertia.
13. ‘magnetic’ photo albums.

**Q1.4** A charged object, such as the dome of a Van de Graaff generator, is discharged by momentarily touching it with an earth wire. Draw diagrams of the charge and fields involved, and explain what is going on here.

**Q1.5** A spray-painter nozzle normally produces droplets of paint in a cone shaped beam of width 30°. What do you think would be the effect on the beam if each droplet were given a large positive charge as it left the nozzle? Give your reasons. [Hint: remember that the separation of the droplets increases as they move away from the nozzle.]

**Q1.6** A petrol fire at a filling station was allegedly caused by ‘static electricity’. Explain what this claim means, and outline the investigation that a forensic scientist might make to establish whether or not static electricity could have been the cause of the fire.

**Q1.7** A cell membrane has a surface charge density of \(-2.5 \times 10^{-6} \ \text{C.m}^{-2}\) on the inside surface and \(+2.5 \times 10^{-6} \ \text{C.m}^{-2}\) on the outside. The thickness of the membrane is much less than the size of the cell. Ignore any dielectric polarisation effects.

a) Sketch the electric field between these charge layers.

b) Calculate the magnitude of the electric field
   (i) within the cell membrane,
   (ii) inside the body of the cell.

This problem, and other similar problems, will be discussed in later sections of this course.

**Q1.8** In the previous problem, what electric force would be experienced by a singly ionised ion of sugar? Compare this with the gravitational force on the same ion.

Data required:

\[
\begin{align*}
\text{Relative molecular mass of sugar ion} & = 343 \\
\text{Electronic charge} & = 1.6 \times 10^{-19} \ \text{C} \\
\text{Mass of proton} & = 1.67 \times 10^{-27} \ \text{kg} \\
\text{Magnitude of gravitational field} & = 9.8 \ \text{m.s}^{-2}
\end{align*}
\]

**Q1.9** a) Sketch the electric field between two concentric cylinders of radii \(r_1\) and \(r_2\) and length \(h\). The charges \(+Q\) and \(-Q\) on these cylinders are equal in magnitude, but opposite in sign.

b) Obtain an expression for the magnitude of the electric field at a point between these cylinders, at a distance \(r\) from their common axis.

**Q1.10** A 2.0 m long cylinder, 0.50 m in diameter, has a charge of \(2.0 \times 10^{-3} \ \text{C}\) uniformly distributed over its curved surface.

a) Calculate the electric field at the curved surface of the cylinder.

b) What is the electric field 0.75 m from the axis of the cylinder?

**Q1.11** An experiment is planned which involves the measurement of very small potentials from living fish (in water). Indicate how the requirements for thorough electrostatic shielding might influence the choice of equipment and the configuration of the apparatus.

**Q1.12** A one-cent coin and a twenty-cent coin are placed about 10 cm apart on a sheet of glass. The 1 c coin bears a charge of \(+Q\) and the other coin, \(-Q\). Sketch the field lines in the vicinity of the coins. Where will the electric field be strongest?