2026aug01

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er 5 : Electric Charge and Electric Fields in the Electrostatic ~~Limit~~ limit (the sources of the electric field are at rest or can be approximated as being at rest)

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Introduction, Overview, Preview of Some Aspects, And Context in Which Aspects are Embedd

5.1 Classical Electromagnetism (E&M) (or Classical Electrodynamics) and Touching on Many Other Topics of the Course

{usual shorthand

a) The basics of (Classical) E&M were presented in the 19th and early 20th centuries. Of course, there was a long history of developments and discoveries going back to classical Antiquity and developments in techniques and applications continue.

b) A logical/mathematical presentation of E&M would start with

We will NOT do this since NOT educational goo and NOT everyone has had Vector calculu but this is an over and as we go through the course we intro bit

Maxwell's equations (a fundamental axiom of classical E+M) (1st order partial DEs)

Vacuum form in SI (MKS) units (G-519)

$$\nabla \cdot \underset{\sim}{E} = \frac{\rho}{\varepsilon_0}$$ {Gauss' law differential form

$$\nabla \cdot \underset{\sim}{B} = 0$$ {Gauss's law for magnetism differential form

$$\nabla \times \underset{\sim}{E} = -\frac{\partial \underset{\sim}{B}}{\partial t}$$ {Faraday's law of induction differential form aka Maxwell-Faraday eqn.

$$\nabla \times \underset{\sim}{B} = \mu_0 \left(\underset{\sim}{J} + \varepsilon_0 \frac{\partial \underset{\sim}{E}}{\partial t} \right)$$ Ampère-Maxwell law.

4 partial vector differential equations

The interaction between E and B makes them dynamic equations even though they are 1st order

ρ is electric charge density

$\underset{\sim}{J}$ is electric current density (a vector)

Note, squiggle under = vector in my handwritten notes. It is a common, but not universal formalism

approa as th textb de

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$\underset{\sim}{E}$ is electric field
the cause of the
electrostatic
or Coulomb force

$\underset{\sim}{B}$ is magnetic field
the cause of the
magnetic force

(Why B not M? Some historical reason)

ε_0 vacuum permitivity
μ_0 vacuum permeability
} constants we will deal with later

→ Recall differential equations (DEs)

tell how things change
with respect to other things.
Hence, they contain derivatives.

Most physical laws are formulated
in terms of DEs.

For physical law DEs tell you
what is true at every point
in spacetime (within their
realm of applicability

ou
hich
ou always
leed
oundary
nditions
hich
an
ncluded
nitial
onditions

which may be large or small,
— and for Maxwell's equations
it's very large).

However, you have to
connect the spacetime dots
to solve for a system
and gets its behavior.
This requires imposing
boundary conditions
(including initial conditions).

d) Maxwell's equations tell you
E-field and B-field
evolve in response
to electric charge and current
and to themselves.

However, you also need
to know

how matter (which carries charge and current) responds to E + B-fields.

This response is specified by the Lorentz force (G-198)

$$\underset{\sim}{F}_L = q(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B})$$

point charge

particle velocity

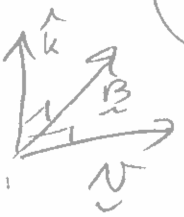
vector (cross product)

A second fundamental axiom of classical E+M in the nonrelativistic limit when relative velocities $v \ll c$

Recall your vector (cross) product behavior

$\underset{\sim}{v} \times \underset{\sim}{B} = vB\sin\theta\,\hat{k}$

and the right-hand rule.



The magnetic part of the Lorentz force is velocity dependent

Recall in the classical limit (i.e., the Newtonian physics limit)

$$\underset{\sim}{F}_{net} = m\underset{\sim}{a}$$

for a point mass relative to an inertial frame

If only the Lorentz force acts $\underset{\sim}{F}_{net} = \underset{\sim}{F}_L$,

and $m\underset{\sim}{a} = q(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B})$

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Actually, there is an important complication, we do NOT treat in this course beyond mentioning.

An accelerating charge radiates electromagnetic radiation (EMR) and this causing the charge to lose energy and decelerate relative to an inertial frame (G-432-43
There is a sort of "friction" called the radiation reaction force.
(G-434)

In general an E+M system can be complex:
— changing E+B-fields
— accelerating charge

which we usually treat as negligible in this course except when w discuss EMR

All things interacting requiring an overall self-consistent solution — but

But in this course, we consider relatively simple systems.

this true in all complex physical systems

2-05008

e) Electric Field, Magnetic Field, the Electromagnetic Field

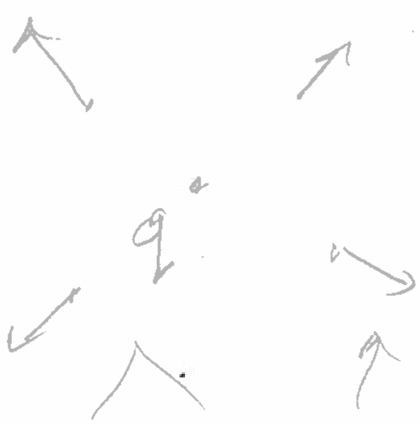
Now it seems there are two distinct fields; E-fields and B-fields.

However, they are really two manifestations of the same thing the electromagnetic field.

To illustrate the point.

A: charge a rest causes an E-field

But a moving charge causes an E-field and a B-field.



charge

representative E-field vectors
— they have direction in real space but their size is their strength in an abstract space

<u>But</u> if you move with a moving charge, you see only an E-field.

So E-field & B-field mix their identities depending on motion of source and observer.

<u>But</u> it's still true E-field and B-fields seem very distinct in most <u>manifestations</u> and we will NOT in this course go into a general treatment of the special relativistic transformations.

f) <u>Electromagnetic Radiation (EMR)</u>

One of Maxwell's discoveries in the 19th century was that you can derive from Maxwell's equations separate wave equations for E-fields and B-fields, but they are implicitly coupled by Maxwell's equations.

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As a preview in vector form

$$\nabla^2 \underset{\sim}{E} = \frac{1}{(1/\sqrt{\varepsilon_0 \mu_0})^2} \frac{\partial^2 E}{\partial t^2}, \quad \nabla^2 \underset{\sim}{B} = \frac{1}{(1/\sqrt{\varepsilon_0 \mu_0})^2} \frac{\partial^2 B}{\partial t^2}$$

and for 1-d for plane waves

ie E- d B-fields /c NOT dependent id both are eeded for e pagating MR

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{(1/\sqrt{\varepsilon_0 \mu_0})^2} \frac{\partial^2 E}{\partial t^2}, \quad \frac{\partial^2 B}{\partial t} = \frac{1}{(1/\sqrt{\varepsilon_0 \mu_0})^2} \frac{\partial^2 B}{\partial t^2}$$

These are, in fact, the standard linear wave equation (Textbook Vol. 1 p. 764)

and $v = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = c = 2.99\,792\,458 \times 10^8\,\mathrm{m/s}$

The phase velocity the velocity of wave propagation not the speed of oscillation

Vacuum speed of light speed relative to all inertial frames. It is frame invariant which is an axiom of special relativity

Note ε_0 and μ_0 are constants set by electromagnetic phenomena NOT light observations.

What Maxwell conjectured was light was a self-propagated electromagnetic.

It needs both E- & B-fields to self propagate.

EMR can be created and destroyed by electric charge, but is independent of charge as it propagates.

Light can travel across the observable universe long after its source has been destroyed, long before it sink has come into existence.

Maxwell's conjecture was verified by the discovery of radio waves by Heinrich Hertz (1857-1894) in 1887.

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So Maxwell's equations united electricity, magnetism, and optics as one physical field.

Note geometrical optics is a simple limit of E & M optics (called physical optics)

which we cover later in textbook Vol 3 Ch. 2

Geometrical optics ignores the wave nature of light and treats light as rays.

EMR's existence also verified that E- & B-fields are real physical things in space, NOT just imaginary aids to calculating forces.

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9) Classical Electromagnetism + Special Relativity

In the 19th century, when it was recognized that light was a wave phenomenon obeying Maxwell's equations the idea was there had to be a medium for light and the name given to this unnoticeable medium was the luminiferous ether and Maxwell's equations applied relative to this medium.

But by the end of 19th century this medium had not been found anywhere

Einstein (the ideal Einstein of explication and not complicated historical person) strongly came to believe

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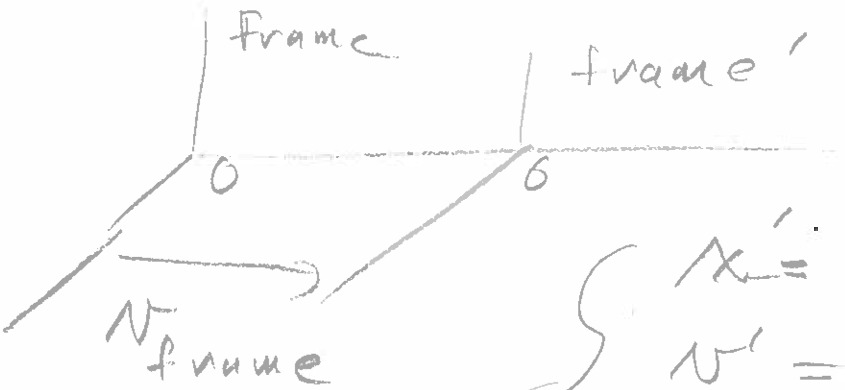
that Maxwell's equations applied relative to all inertial frames and in vacuum.

The waves were just ~~of~~ the E- & B-fields themselves and NOT in any medium.

But Maxwell's equations were NOT inertial ~~frame~~ invariant under the Galilean transformations

$$\underset{\sim}{F}_{net} = m\underset{\sim}{a}$$
$$\underset{\sim}{F}_{net} = m\underset{\sim}{a}'$$

The 2nd law has same formula in the unprimed and the primed frame



$\vec{v}$

$$x' = x - v_{frame}t$$
$$v' = v - v_{frame}$$
$$a' = a$$

simple Galilean transformations

<u>But</u> Maxwell's Equations
were already known to be
invariant under the
Lorentz transformations.

the formulae stayed the same
and $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ was the invariant light measured by all observers

Einstein argued that
Maxwell's equations were correct
and the Lorentz transformations
were correct physical laws

and <u>Newtonian physics</u>
was only asymptotically correct
in the low relative velocity limit;
i.e., when $v_{relative} \ll c$

and this is true
and special relativity was
discovered in essentials
in 1905.

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We will NOT write the Maxwell equations in explicit special relativity form, but we will return to special relativity in Textbook Vol 3, Ch05

h) Fields, Vector Fields, + Field Theory

In physics, a field is any quantity with a value at any point in spacetime ~~within~~ their realm of application.

Scalar fields just have a magnitude: e.g., temperature, pressure.

Vector Fields have magnitude and a direction: e.g., velocity field in a fluid, E-field, B-field.

Tensor Fields Let's NOT go into them here explicitly.

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Only certain fields have their own intrinsic dynamics and the electromagnetic field is the prime example and dynamics are described by Maxwell's equations.

What of the gravitational field.

There is No DE for the Newtonian gravitational field d.e's

For Newtonian gravity, I believe most people would say that field theory is NOT applicable. For one thing pure Newtonian gravity does NOT predict gravitational waves.

It just is where-ever matter tells it to be.

Now general relativity (which is our best theory gravity) is a field theory → a tensor field theory and it does predict gravitational waves which have been directly observed since 2015 (Wik) and predicted by Einstein & Rosen 1936.

shift a mass

and its gravitational field just moves with the mass.

12_05018 General relativity is well beyond the scope of this course.

1) Quantum Electrodynamics (QED)
(of which I know almost nothing)

QED is the relativistic quantum mechanical version of electromagnetism. Quantum mechanics (QM) is the theory of microscopic particles.

Classical electromagnetism (E+M) is the macroscopic asymptotic limit of QED.

We'll touch on QM many times

My perspective is that classical E&M is an exact theory in the macroscopic asymptotic limit and NOT just an approximate theory and believe most people agree with this perspective.

Similarily, Newtonian mechanics is an exact theory in the classical limit (i.e., the macroscopic, low-relative velocity, weak gravity field limit).

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To be a bit more general, classical field theory is the macroscopic asymptotic limit of quantum field theory (QFT) (of which I know almost nothing)

Quantum field theory deals with all fundamental forces

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There is no lack of ideas for quantum gravity or TOE, but which if any of those is right, we do NOT know.

At present, it is (or nearly is) impossible to experimentally study gravity at the quantum level.

The gravitational force between atoms is far too weak to measure.

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5.2 Electric Charge

a) Electric charge is a fundamental property of matter

Fundamental means can't be explained any further in the context of some grand theory.

Stuff with rest-mass-energy unlike photons which have mass-energy but no rest-mass-energy to anticipate special relativity and also zero charge

In the case of charge, it is absolutely fundamental to our current knowledge.

A just so.

b) Charge comes in two flavors positive and negative as named by none other than Benjamin Franklin (1706-1790).

Positive and negative makes sense because in many contexts they can cancel each other.

Q or q are common symbols for quantity of charge

Net charge $= Q_+ + Q_-$

is conserved overall in the universe it seems and locally (i.e., in any absolutely enclosing closed surface).

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As far as we can tell, the universe is neutral overall: ie.

$$Q_{+\,universe} + Q_{-\,universe} = 0$$

In fact, most systems on a large enough scale are neutral or asymptotically neutral

Physical context decides on what is a large enough scale.

This tendency to local neutrality is due ~~to the fact~~ unlike charges attract like charge repel.

(Further elucidation p. ______)

Note, net charge is conserved, but positive charge and negative charge are NOT conserved individually.

Equal amounts of positive & negative charge can be created (pair creation) or annihilated (pair annihilation) microscopically (Further elucidation p.)

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c) Charge is Quantized

quanta

i.e., it comes in definite indivisible smallest amounts noticeable at the microscopic scale.

At the macroscopic scale charge can often be treated a continuum like water at the macroscopic scale and not as bunch of H_2O molecules.

Quantum mechanics is called quantum mechanics because many physical entities are quantized — they come is discrete amounts. They do NOT form a continuum like real numbers. But there are continuous entities too.

There are actually two quantizations:

i) First,

a proton (p) and positron (e^+) has $q = e$ (antielectron)

an antiproton ($\bar{p}$) and electron (e^-) has $q = -e$

where e = elementary charge unit

and $e \equiv 1.602\ 176\ 634 \times 10^{-19}$ coulomb (C) $\approx 1.602 \times 10^{-19}$ C

which is exact by definition

The coulomb (C) is the MKS unit of charge

and $1\ C/s = 1$ ampere (amp)

is ~~the~~ familiar unit of electric current

The elementary charge unit is noticeable in many contexts.

Note, there neutral particles: neutrons, neutrinos, photons

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) Second, Guark charge

particle / antiparticle

roton
uud
$2/3 + 2/3 - \frac{1}{3} = 1$

eutron
udd
$\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

$$up(u) = \frac{2}{3}e \ , \ \bar{u} = -\frac{2}{3}e$$

$$down(d) = -\frac{1}{3}e \ , \ \bar{d} = +\frac{1}{3}e$$

other flavors and anti-flavors
have the same set of values.

tons
utrons
e
de
quarks

I do NOT think these charge qualities
can be detected directly

— but maybe in some sense
in a quark-gluon plasma that
the LHC can create
for some tiny fraction of a second.

roton
u u
d

eutron
d d
u

We will not often refer to
quark changes,

l) Note

quantum
mechanical
particles

fundamental particles are
(leptons [electrons, positrons, etc.)
and quarks
and rest-mass-less particles
(photons, gluons)

and composite particles are
(protons, neutrons, nuclei, atoms, molecules, etc.
asymptotically in the unperturbed limit)
are absolutely identical →

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In Way no set of macroscopic objects can be.

This is in principle NOT just in practice.

For example

say you had an electron created in the Big Bang and one created by pair creation a second ago.

There is no way to tell them apart except by tracing their past histories

And if they get close enough to have a joint wave function (a quantum mechanical specification of state), you in principle lose track of which is which and then you don't know which was "old" and which was "young"

Common wave function symbol is capital Greek letter Psi = Ψ.

Wave function are continuous functions, but in many important contexts they form discrete (i.e., quantized) sets of wave functions.

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In fact, quantum mechanical particles have no identity or age.

They are just manifestations of their types.

Why do we belive this?

Quantum mechanics posits this as axiom

an quantum mechanics is the best verified of all physics theories,

It's never wrong.

In applying it you often have to make large approximations because it's a very difficult theory to apply.

Also often you make mistakes in calculation and experiment but no anomaly has ever resisted explanation

All modern electronics, including your phone, verifies quantum mechanics.

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The upshot is that if quantum mechanics (QM) says something is <u>true</u>, we just believe it.

<u>But</u> there are mysteries in QM which we'll mention at appropriate times.

Quantum field theory (QFT) is the special relativistic version of QM.

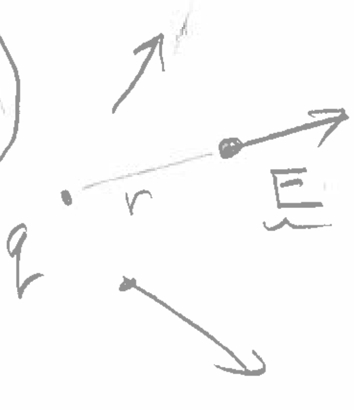
5.3 The Electric Field

(In electrostatics where charges are at rest or can be so approximated G-61 -6)

a) For a (classical) <u>point particle</u> (at an origin of spherical coordinates)

(Coulomb's law for the E-field (G-62 which can be derived from Maxwell's equations (p. 02-05003), but it's beyond our scope to show how.)

$$\underset{\sim}{E}(\underset{\sim}{r}) = \frac{kq}{r^2}\,\hat{r} \begin{cases} \infty & \text{for } r=0 \\ 0 & \text{for } r\to\infty \end{cases}$$



$\Rightarrow$ q is the electric charge of the point particle.

$\Rightarrow$ r is the distance to where the $\underset{\sim}{E}$ is evaluated

$\Rightarrow$ $\hat{r}$ is the radial unit vector

02_05028 $\Rightarrow$ and $k = \frac{1}{4\pi\varepsilon_0} = 8.987\,551\,785\,972(14) \times 10^9 \ \frac{N \cdot m^2}{C^2}$

$\doteq 10^{10}$ MKS units — Newton-meter / Coulomb

is Coulomb's constant

From p. 02_05004, the vacuum permitivity

$$\varepsilon_0 = 8.854\,8188(14) \times 10^{-12} \ \frac{C^2 s^2}{kg\ m^3}$$

$$\doteq 10^{-11} \text{ MKS units}$$

[Note vacuum permitivity in older jargon is the permitivity of free space]

The coulomb (C) is the macroscopic unit of charge (see p. 02_05023) and $1\,C/s = 1$ ampere $= 1$ amp the familiar unit of electric current.

b) Fiducial E-field value

(drop vector squiggle for magnitude)

$$E = \frac{kq}{r^2} \doteq \frac{10^{10} \cdot (1\,C)}{(1\,m)^2} = 10^{10}\ N/C$$

which is an enormous force per coulomb

The electric force on any point charge q is

$$\underset{\sim}{F} = q\underset{\sim}{E}$$

{ Follows from the Lorentz force with $B=0$ (see p. 02_05006).

Fiducial force between point charges of 1 Coulomb each is

$$F = 10^{10}\ N$$

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Ans. In almost all human and other contexts too matter is nearly neutral

All the electrons in hydrogen are balanced by protons.

$\therefore\ q_{net} \triangleq \emptyset$ for most systems.

But in circuits,

we often have currents of order 1 amp = 1 C/s,

and so why so-why do wires NOT have deady strong electric charges?

Ans. Wires are mostly neutral — all the current of free electrons (which are the charge carriers) are flowing through positively charged ions at rest.

Of course 1 amp is a pretty deadly current.

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Recall $1\ N \triangleq 0.224\,81\ lb \triangleq 1/5\ lb$

So actually 1 C of (net) charge is an enormous and dangerous amount of charge <u>in human environments</u>.

<u>Ex.</u> What is the amount of negative charge in 1 kg of hydrogen

$$q = (-e) \cdot N_H = -e \frac{M}{A\,u}$$

M: 1 kg

elementary charge unit

$e = 1.602\,176\,634 \times 10^{-19}\ C$

exact by modern definition (see 02_05023)

atomic weight of H $= 1.0080(20)$ standard

atomic mass unit (AMU) = dalton $= 1.660\,539\,068\,92(52) \times 10^{-27}\ kg$

$$q \triangleq (-1.6 \times 10^{-19}) \left(\frac{1}{1 \cdot 1.7 \times 10^{-27}} \right)$$

$$q = -10^{8}\ C$$

and so why isn't a 1 kg of hydrogen deadly?

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Flowing thru the human body

1 amp even for 10 ms is pretty bad

but 0.5 milliamps is imperceptible even for long times (10s)

(Wik: Electrical injury)

c) Superposition Principle (G-61)

$$\underset{\sim}{E} = \frac{kq}{r^2}\,\hat{r}$$

is the electric field for a point charge everywhere in space when it is at rest or can be approximated as being at rest.

This is the electrostatic limit or the realm of electrostatics.

What if you have multiple charges or a continuum of charge?

system of point charges

dV is differential volume

dq is differential charge

continuum of charge with $dq = \rho dV$

The superposition principle of electromagnetism is that the net electric field $\underset{\sim}{E}(\underset{\sim}{r})$ at some point $\underset{\sim}{r}$ is just the sum of individual E-fields of point charges q_i or differential charges dq.

Note, Maxwell's equations (see p. 02-05003) allow a differential equation solution for E-fields for continuous charge distributions.

Thus

$$\underset{\sim}{E}(\underset{\sim}{r}) = \sum_i \frac{k q_i}{|\underset{\sim}{r} - \underset{\sim}{r}_i'|^2} \hat{r}_i'$$

Note a differential quantity is formally an entity in limiting process; e.g., from calculus

$$\lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt} .$$

where dx and dt are differentials.

In physics, we tend to think of differentials as being small enough for any smallness requirement we put on them is true or more formally asymptotically true.

As here, the differentials have an asymptotically true ratio.

$$\underset{\sim}{E}(\underset{\sim}{r}) = \int \frac{k \rho(\underset{\sim}{r}')}{|\underset{\sim}{r} - \underset{\sim}{r}'|} \hat{r}' \, dr'$$

Note, the superposition principle seems perfectly natural and it is implicit in Maxwell's equations (p. 02-05003), but it did NOT have to hold.

For example say $\underset{\sim}{E}(\underset{\sim}{r}) = \sqrt{\sum_i \left[\frac{kq_i}{|\underset{\sim}{r}-\underset{\sim}{r}_i|^2}\right]^2} \; \frac{\sum_i \hat{r}_i}{N}$

for N point charges,

The superposition principle would NOT hold.

If this were true, reality would be very strange.

d.) Point Particles

Classical point particles do NOT exist,

but they are very useful in introducing concepts and thinking about concepts.

You can think about a classical point particle with charge q_i (a point charge q_i) as representing a differential amount of charge $dq_i = \rho(\underset{\sim}{r}_i)\,dV$ where $\rho(\underset{\sim}{r}_i)$ is charge density and dV is differential volume.

Note the integral and DE solution for E-field will in general be hard and often requires numerical and/or approximate analytic solutions.

But what quantum mechanical point particles?

ndamentally lementary articles n urrent physics, mposite articles re made p of them: e.g., rotons, neutrons, nuclei, toms, olecules,

They may or may not exist in some sense. Leptons (e.g, electrons and positrons) and quarks (see p. 02-05024) may or may not be points in some sense — but only quantum field theorist know (and they aren't telling), but QM particles exist in a continuum superposition of positions

So a point particle electron is "spread out in a "cloud"

For example an isolated electron

$q = -e$

classical picture

There is no sharp edge. The charge density goes to zero as distance increases from cloud center

$$\int \rho_q \, dV = -e$$

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02-0503!

Here $\rho_q = -e|\Psi|^2$ is the charge density and Ψ is the wave function which is intrinsically a complex number function.

Mass density of a particle of mass m is $\rho_m = m|\Psi$

QM seems to be intrinsically a complex number theory. Most people believe if you try to dispense with them, you just use them in another form, (SciAm 2023 April).

The absolute value of Ψ is $|\Psi|^2$ and is called the probability density; but yours truly thinks existence density would be a better name since that is how it is treated in calculations

since composite particles are made of elementary particles, they too exist in a continuum superposition of positions

The idea of a point particle existing in a continuum superposition of positions is just something you get used in quantum mechanics.

The conclusion is that charge effectively is spread into a continuum, but you can treat quantum particles as classical point particles or a continuum averaged over a macroscopic scale if convenient to do so,

5.4 The Electrostatic Force or the Coulomb's Law Force

a) First recall Newton's 2nd Law (AKA f=ma)

$\underset{\sim}{F}_{net} = m \underset{\sim}{a}$ for a classical point particle

System of point particles making up an object at all.

Note $m_i = \rho(\underset{\sim}{r}_i)\,dV$ where $\rho(\underset{\sim}{r}_i)$ is a continuum of density which is actually case for quantum mechanical particles as mentioned on p. 02-05035. But a the macroscopic scale, we usually/always average the quantum mechanical mass density over macroscopic scales.

$$\underset{\sim}{F}_{net} = \underbrace{\sum_i \underset{\sim}{F}_{i\,ext}}_{\text{external forces}} + \underbrace{\sum_{\substack{ij \\ i\neq j}} \underset{\sim}{F}_{ij}}_{\text{internal forces}}$$

But $\sum_{\substack{ij \\ i\neq j}} \underset{\sim}{F}_{ij} = \sum_{\substack{ij \\ i\neq j}} (-\underset{\sim}{F}_{ji})$ by the 3rd Law

$= -\sum_{\substack{ij \\ i\neq j}} \underset{\sim}{F}_{ij}$ by relabeling

$\therefore \sum_{\substack{ij \\ i\neq j}} \underset{\sim}{F}_{ij} = \emptyset$

Note, the 3rd law is actually NOT always valid in the classical limit, but there is always some generalization that is (Goldstein-8), and so we do NOT usually worry about this fine point.

For a system of particles?

$$\underset{\sim}{F}_{i\,ext} = m_i \underset{\sim}{a}_i$$

$$\therefore \quad \underset{\sim}{F}_{net} = \sum_i \underset{\sim}{F}_{i\,ext} = \sum_i m_i \underset{\sim}{a}_i = m\left(\frac{\sum_i m_i a_i}{m}\right)$$

where $m = \sum_i m_i$ is total mass

and $\underset{\sim}{a}_{cm} = \dfrac{\sum m_i \underset{\sim}{a}_i}{m}$ is the center-of-mass acceleration

$$\therefore \quad \underset{\sim}{F}_{net} = m\,\underset{\sim}{a}_{cm}$$

So ~~this~~ form applies to the center-of-mass motion.

To learn about the motions of the parts, you need to consider individual $\underbrace{\underset{\sim}{F}_{i\,ext}}_{\text{external force}}$ and $\underbrace{\underset{\sim}{F}_{ij}}_{\text{internal forces}}$

b) Coulomb's Law for point charges

Recall (~~from~~ p. 02-05006) Lorentz force with $\underset{\sim}{B} = 0$ $\therefore$ $\underset{\sim}{F} = q\underset{\sim}{E}$

Thus, from p. 02-05027, Coulomb's law for E-field, we get the Coulomb's Law ~~for~~ force

$$\underset{\sim}{F}_{ij} = \frac{k q_i q_j}{|\underset{\sim}{r}_i - \underset{\sim}{r}_j|^2}\,\hat{r}_{ij} \quad \left\{ i \longrightarrow j \right.$$

This is what is meant by Coulomb's law (or the electrostatic force law) without qualification.

Force of charge i due E-field of charge j,

Recall from p. 02-05023, $k = \frac{1}{4\pi\varepsilon_0} = 8.987\,551\,785\,972(14) \times 10^9 \doteq 10^{10}$ MKS

02_05038

Note if $q_i q_j > 0$, the force is repulsive

if $q_i q_j < 0$, the force is attractive

Mnemonic "like charges repel"
"unlike charges attract,

Note Coulomb's law is very similar to Newton's law of universal gravitation

$$\underset{\sim}{F}_{ij} = -\frac{G m_i m_j}{|\underset{\sim}{r}_i - \underset{\sim}{r}_j|^2} \hat{r}_{ij}$$

where m_i and m_j are point masses

and $G = 6.67930(15) \times 10^{-11}$ MKS

Points about Coulomb force and Gravity

i) Both depend on particle "charges"

charges q_i for Coulomb's law } masses m_i for grav. law.

But two flavors for charge and likes repel, unlikes attract

One flavor for mass and likes attract,

ii) Both arise from a field

E-field for E&M

Gravitational field $\underset{\sim}{g}$ for grav. force

This means Coulomb's force can be "canceled" but gravity cannot, There is NO antigravity in a straight-forward sense, but $\underset{\sim}{E}$-field obeys E&M dynamics as expressed by Maxwell's equations (p 02.0500 (which is relativistically correct)

and Newtonian gravity (classical gravity) does NOT have a complete dynamics (and is NOT relativistically correct)

General relativity (GR) which is a relativistic theory of gravity does have a complete dynamics expressed by Einstein's field equations and the geodesic equations (Which is well beyond the scope of this course)

iii) They are both long range inverse-square law forces.

iv) The great similarities of E&M and gravity led Einstein to pursue what he called a unified field theory for the last 30 years or so of his life. The unified field theory would unite E&M and gravity

He did find various versions, but we now believe they are all wrong because his approach was wrong — he avoided all quantum mechanics.

The unification of E&M, nuclear weak force, and nuclear strong force in the standard model of particle physics is a quantum field theory and the expectation is a quantum gravity (of which GR is the macroscopic limit) will eventually be united with the other forces. (Maybe the expectation is wrong).

d) Coulomb Force & Gravity Force Strength Comparison

Two Fiducial Cases

i) $\frac{F_g}{F_E} = \frac{G m_1 m_2}{k q_1 q_2} = \frac{G}{k}\frac{(1\,kg)^2}{(1\,C)^2} \approx \frac{10^{-10}}{10^{10}} = 10^{-20}$

Recall 1C is an enormous net charge in the human context (see p. 02-05629)

& ii) e^- electron · ~1Å · p proton for Hydrogen atom

$\frac{F_g}{F_E} = \frac{G}{k}\frac{10^{-30} \cdot 10^{-27}}{10^{-19} \cdot 10^{-19}} \approx 10^{-20}\, 10^{-19} \approx 10^{-39}$

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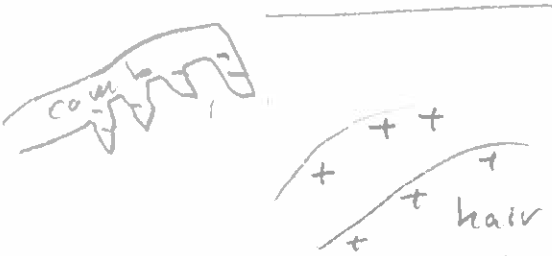
You can see in a sense gravity is a very weak force.

Atoms, molecules, human scale rigid solids are held together by the electrostatic force NOT gravity which at the microscopic scale must be quantum gravity but at that scale gravity is unmeasurable.

Gravity between kilogram masses can be measured in the lab (and has been done since the Cavendish experiment of 1797-1798 (wiki)), but between atoms it's still immeasurably small, which one reason we don't have an establish quantum gravity theory now.

e) Demonstration of Weakness of Gravity

Need bits of paper and Comb

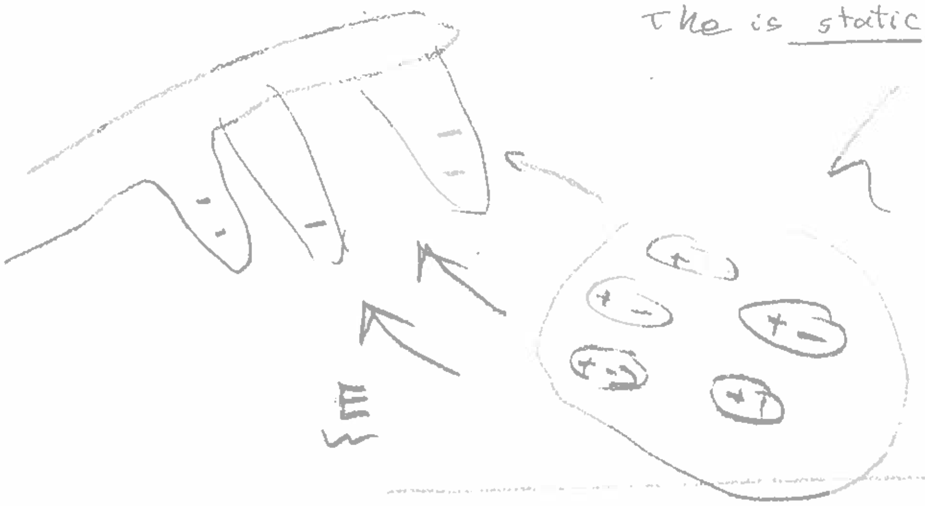


Some kind of rubbing action between materials causes kinetic energy to separate charge and create non-neutrality in combs and hair

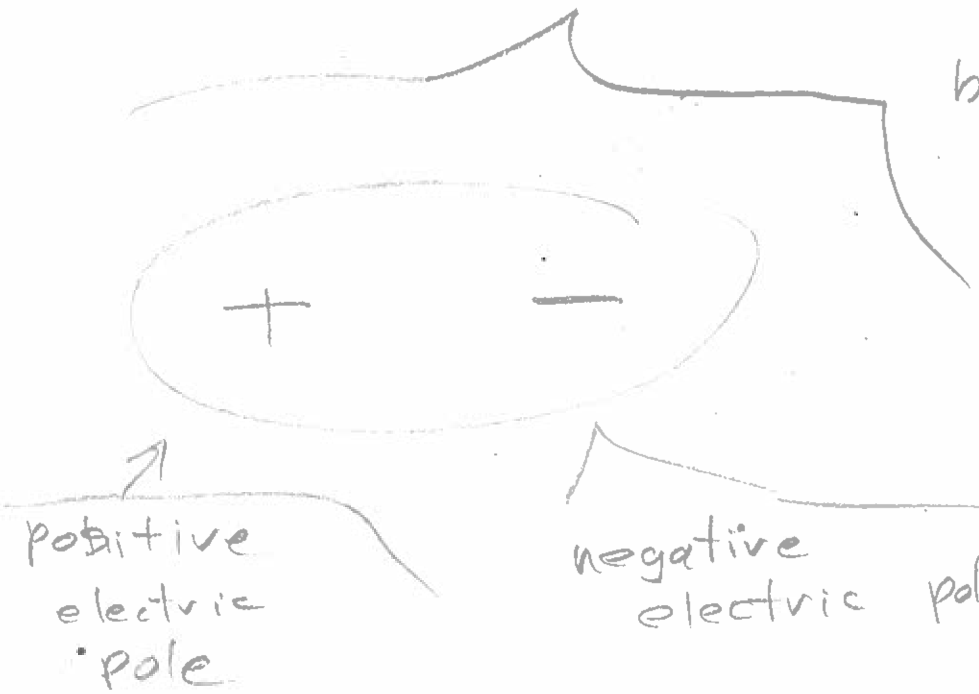
02-05042

- electrons flow onto comb surface and it becomes negatively charge (Google AI)

and they can't quickly discharge since the comb is NOT a conductor.
The is static. Static electricity.



Paper also Not a conductor and stays neutral, but it molecules become polarized by the E-field



Since the E-field falls off with distance (the inverse-square law in action), the +ve pole more attracted than the -ve pole repeled.

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The upshot is a net attraction of the paper bits to the comb

And this net attraction largely cancels the gravity of the whole Earth.

Other than lightning and electric fish, the oldest known electrical phenomena, but still poorly known. In fact elektron is the Greek word for amber which was noted for static electric properties (wiki: electricity)

, The creation of static electricity is called the triboelectric effect or triboelectric charging and it is an immensely complicated effect And to this day is still needing more elucidation (see Ahart, J. 2026mar18, Nature).

By complex surface interactions, the kinetic energy of rubbing overcomes small scale attraction and move charge from one surface to another

f) Electrostatic Force and Small Scale Structure

Atoms, molecules, and ions cannot exactly neutralize.

Quantum Mechanics forbids electrons and protons from exactly overlapping and in most contexts from combining to make neutrons.

02-05044

So on small scales the electrostatic force is very strong and holds atoms, molecules, ions, and rigid solids together in a way determined by quantum mechanics.

Also the electrostatic force plus QM makes atoms, molecules, and ions strongly incompressible

Thus, the strong ~~pressure~~ force resisting the compression of solids and liquids

But because of the strong tendency to neutralization on the macroscopic scale in many contexts the electrostatic force at the macroscopic scale just appears as a contact force with special cases being

- Normal force
- friction
- viscosity in fluids
- tension
- pressure force
- etc.

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So the long-range inverse-square law nature of the Coulomb force is only apparent in relatively few contexts

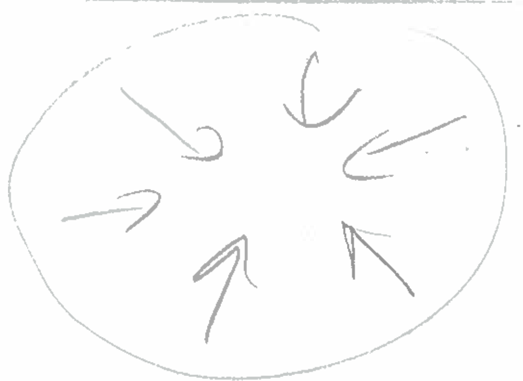
But the electrostatic force dominates small scale structure:

, objects up to small asteroids

9) Medium Scale? large asteroids, planets, stars, pressure-supported astro-bodies

A combination of gravity and pressure force (a special case of electrostatic force)

Pressure-Supported Astro-Body



- gravity pulls in
- pressure pushes out

and there is hydrostatic equilibrium

What of Mountains?

The pressure force is strong enough to support huge columns
But it's isotropic, and so mountains slump.

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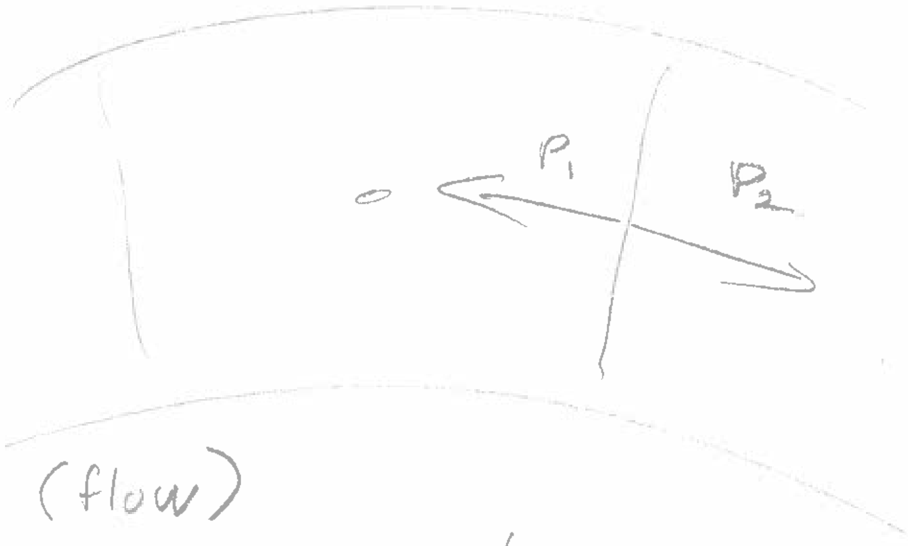
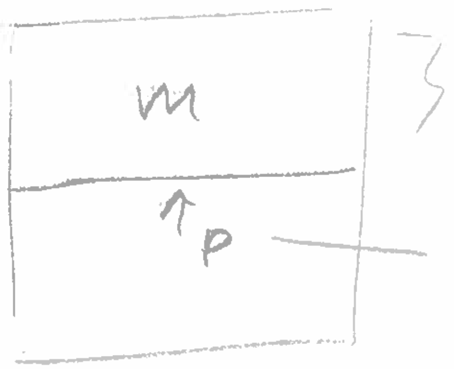
But

column of air or column of Earth's interior



can't slump (flow) because the pressure force in the nonradial direction is equal.



Pressure decreasing going upward because less mass to support.

Note: rigid solid bonds will break or plastically deform if pressure force gets too strong.

Plastic deformation = slow flow

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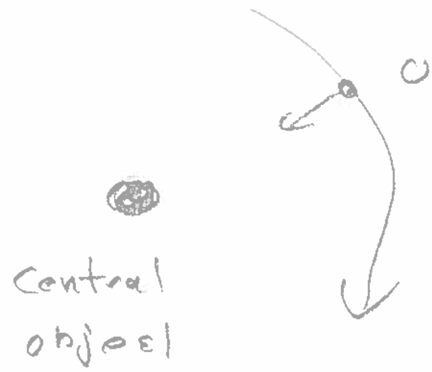
h) Large Scale Structure

Cannot be <u>static</u>

planetary systems
star clusters
galaxies
galaxy cluster

held up by a combination of gravity pulling in and 'macroscopic' kinetic energy resisting.

<u>Orbital systems with central objects</u>



The orbiting object is in perpetual free-fall toward the center, but keeps missing because it has a sideways motion (i.e., angular momentum)

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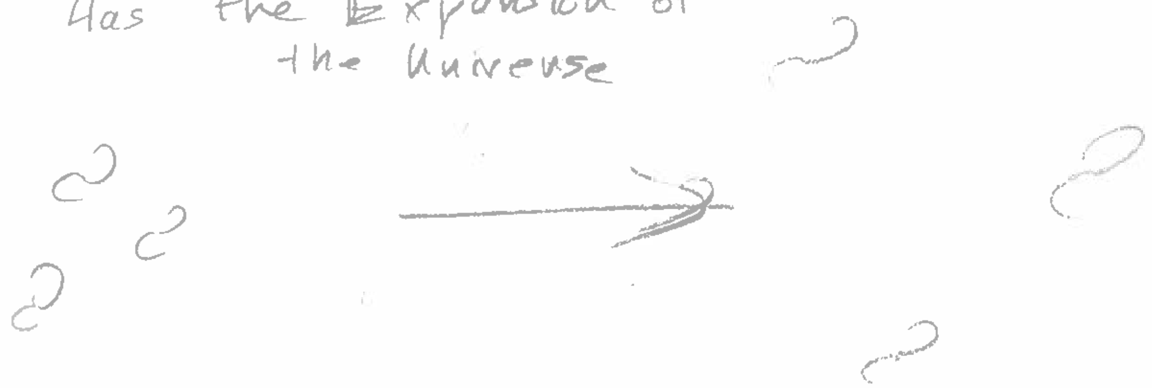
Clusters of stars and galaxies tend to have chaotic orbits determind by interior mass to any radius R from the center of Mass

Observable Universe as a whole

Has the Expansion of the Universe



Distance between bound systems grow by a cosmic scale factor $a(t)$

$$r(t) = a(t)\, r_0$$

with $a(t = \text{cosmic present}) = 1$ by convention.

We live at cosmic present, and so we set $a(t = \text{cosmic present}) = 1$

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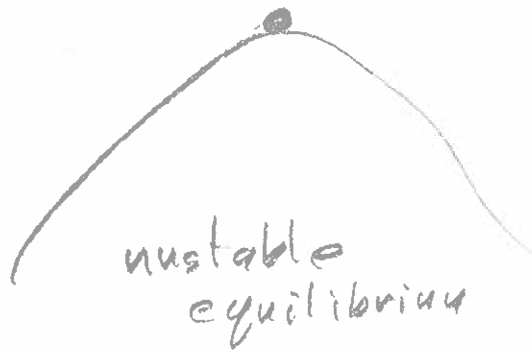
The evolution of a(t) is determined by a combination of gravity, kinetic energy and dark energy (as it usually called) all in a GR sense.

a(t) can only increase or decrease except by fine-tuning to be static, but that is an unstable equilibrium.



At present a(t) is increasing and rate of growth accelerating due to dark energy or so it seems.

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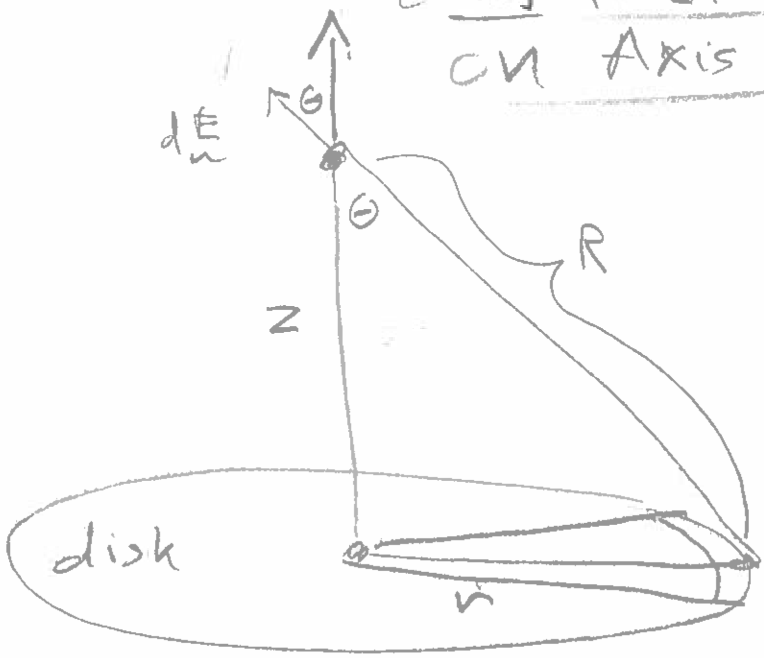
5.5 Analytic Calculation for An Electric Field of a Uniformly Charged Circular Disk on Axis of Symmetry



In electrostatics,

$\Rightarrow \rho$ is used for volume charge density

$$\rho = \frac{Q}{\text{Volume}}$$

$\Rightarrow \sigma$ for surface charge density

$$\sigma = \frac{Q}{\text{Area}}$$

$\lambda = \frac{Q}{\text{length}}$: line charge density

(Just conventions that NOT everyone obeys all the time)

By symmetry at z on axis, only the z-component of the electric field is nonzero

$$\therefore \underbrace{dE_z}_{\text{z-component of electric field}} = dE\cos\theta$$

$$= \frac{k\,dQ\cos\theta}{R^2} = \frac{k\,\sigma(r\,d\phi)\,dr\cos\theta}{R^2}$$

dQ is differential charge
$r\,d\phi$ is differential azimuthal length
dr is differential radial length

For complex charge distributions, the differentials get replaced by small bits

$dr \to \Delta r$ and $d\phi \to \Delta\phi$

and you do numerical integration by sums OR some kind of approximation (e.g., importantly multipole expansion series which we might briefly describe later (G-145)),

But here, high symmetry, allows analytic integration (antidifferentiation)

$$E_z = k\sigma \int_0^{2\pi} d\phi \int_0^{r} \frac{r'dr'}{R^2} \underbrace{\frac{z}{R}}_{\cos\Theta}$$

$$R = \sqrt{z^2 + r'^2}$$

$$= 2\pi k \sigma z \int_0^{r} \frac{r'dr'}{(z^2 + r'^2)^{3/2}}$$

students do the integral for yourselves.

72_05052

$$\int_0^r \frac{r'dr'}{(z^2+r'^2)^{3/2}} = \frac{1}{-1/2}\frac{1}{2}\left(z^2+r'^2\right)^{-\frac{1}{2}}\Big|_0^r$$

$$= -\frac{1}{\sqrt{z^2+r^2}} + \frac{1}{z}$$

$$\therefore E_z = 2\pi k\sigma z\left(\frac{1}{z} - \frac{1}{\sqrt{z^2+r^2}}\right)$$

$$= 2\pi k\sigma \left[1 - \frac{z}{\sqrt{z^2+r^2}}\right]$$ in general

for $z << r$

$$1 - \frac{z}{r} + \frac{1}{2}\left(\frac{z}{r}\right)^3$$

$$\frac{z}{\sqrt{z^2+r^2}} = \frac{z/r}{\sqrt{1+(z/r)^2}}$$

$$\simeq \frac{z}{r}\left(1 - \frac{1}{2}\left(\frac{z}{r}\right)^2\right)$$

$$\simeq \frac{z}{r} - \frac{1}{2}\left(\frac{z}{r}\right)^3$$

to 3rd order

for $z = 0$

$$1$$

for $z >> r$

$$\frac{1}{2}\left(\frac{r}{z}\right)^2$$

$$\frac{1}{\sqrt{1+(r/z)^2}}$$

$$= 1 - \frac{1}{2}\left(\frac{r}{z}\right)^2$$

to 2nd order

and so

$$E_z = \frac{k\pi r^2\sigma}{z^2}$$

$$= \frac{kQ}{z^2}$$

where $Q = \pi r^2\sigma$ is the total charge and this like a point charge

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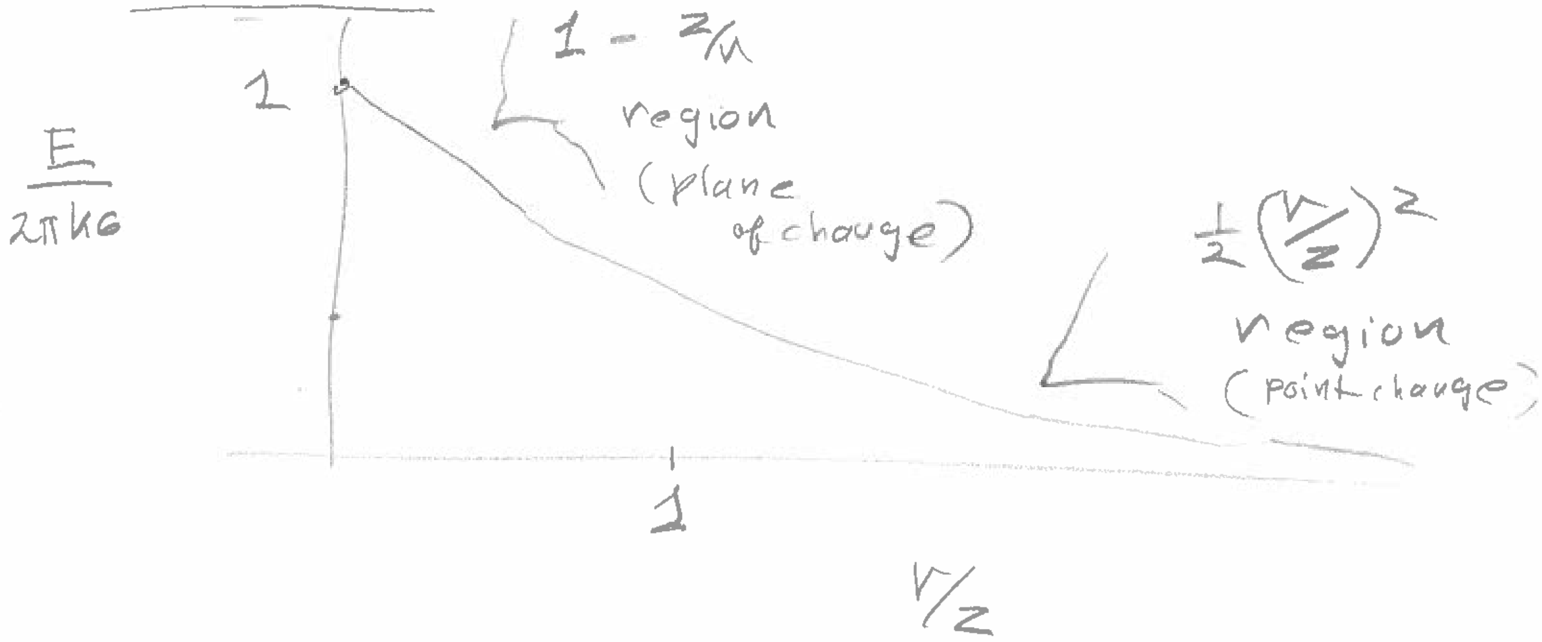
Plot of E_z



Actually for small z/r

$$E \doteq 2\pi k\sigma \left[1 - \frac{z}{r} + \frac{1}{2}\left(\frac{z}{r}\right)^3\right]$$

and as $r \to \infty$, one obtains the E-field for an infinite plane of charge

where $\underset{\sim}{E} = 2\pi k\sigma \, \hat{z}$

the E-field is indepeudent of distance z

and by symmetry there is only a nonzero z component

72-05054

5.6 Electric Field Lines

a) Any vector field can be visualized in terms of field lines.

At every point in space there is a vector value

Vectors point in real space but their length is in their own abstract space: e.g., velocity space, E-field strength space,

You can only draw a represontative set of vector since they form a continuum. The set is a visualization.

But you can a line through a continuum of points at every point in the direction of the field. These are field lines.

The best known are
streamlines for fluid velocity field
E-field lines for the electric field
B-field lines for the magnetic field

Mostly field lines are
a very useful visualization tool,
You can think of special cases where
they are physically realized.

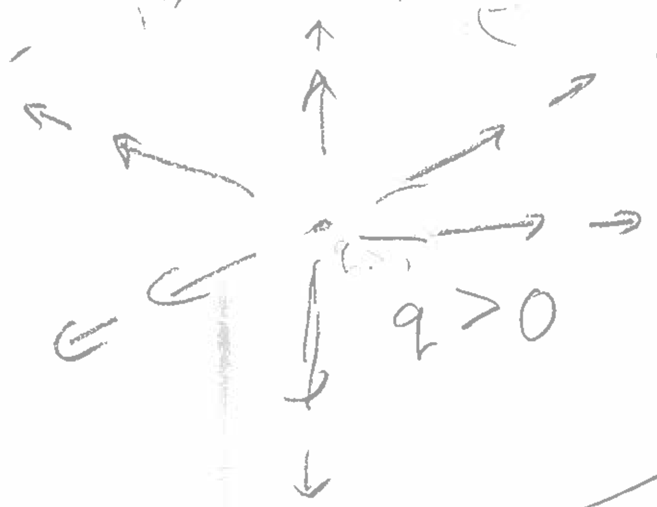
Michael Faraday
(1791 → 1867) was
invented them
as a visualization
tool.

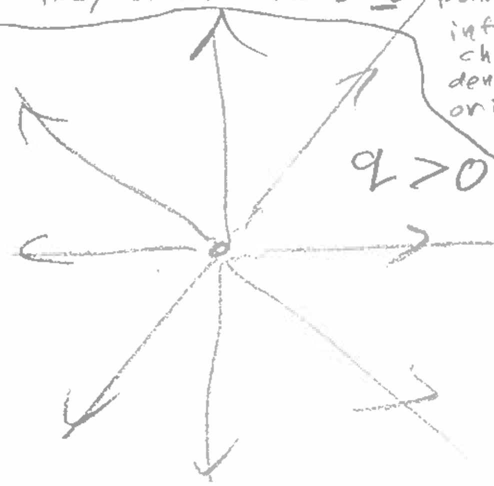
Now for some examples

b) Classical Point Particles

i) Classical Point charges

For classical point charges $\underset{\sim}{E} = \infty$
at the charge. A limit for concentrated cha
Quantum mechanical point particles are in
a continuum superposition of positions, and so
even if they exist, there is no point of
infinite
charge
density
or infinite
field

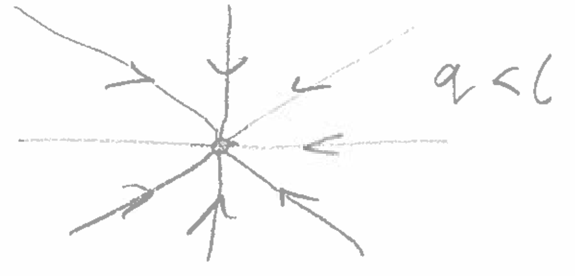




the field lines
extend to infinity

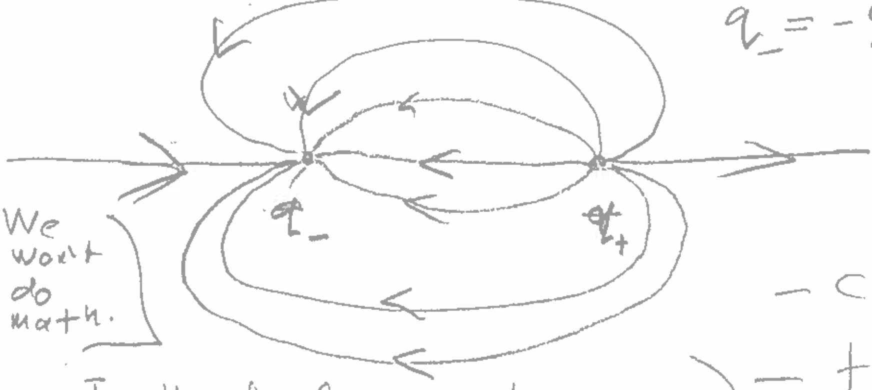
Note spherical symmetry
is implied. The drawing
is a cross-section

For $q < 0$, the
field lines point inward



c) Electric dipole

made of point charges
where
$q_- = -q_+$



We
won't
do
math.

– Cylindrical symmetry implied
– the field lines must begin
and end on a charge
OR extend to infinity
for electrostatics,

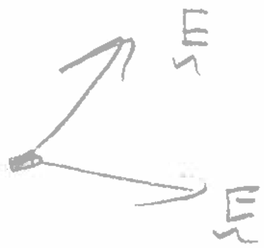
In the far field limit,
$\underset{\sim}{E} \sim \frac{1}{r^3}$ from the center
not as $\sim 1/r^2$ and $\underset{\sim}{E}$ has directional
dependence

How do we know this — that field lines must start/end on charge or extend to infinity?

d) <u>A tricky point</u>

i) Note, E-field lines <u>cannot</u> intersect, except where $\underset{\sim}{E} = 0$.

<u>Why?</u>



Because the field would point in multiple directions at one point which violates a <u>basic axiom</u> of classical E&M that the E-field is a vector field. This <u>axiom</u> is just an implied part of Maxwell's equations (see p. 05-05003).

ii) Note again <u>classical point particles</u> are an idealization.

Really we have regions of continuum of electric charge which the quantum mechanical view

So a point charge

q • is really a clump of charge: q

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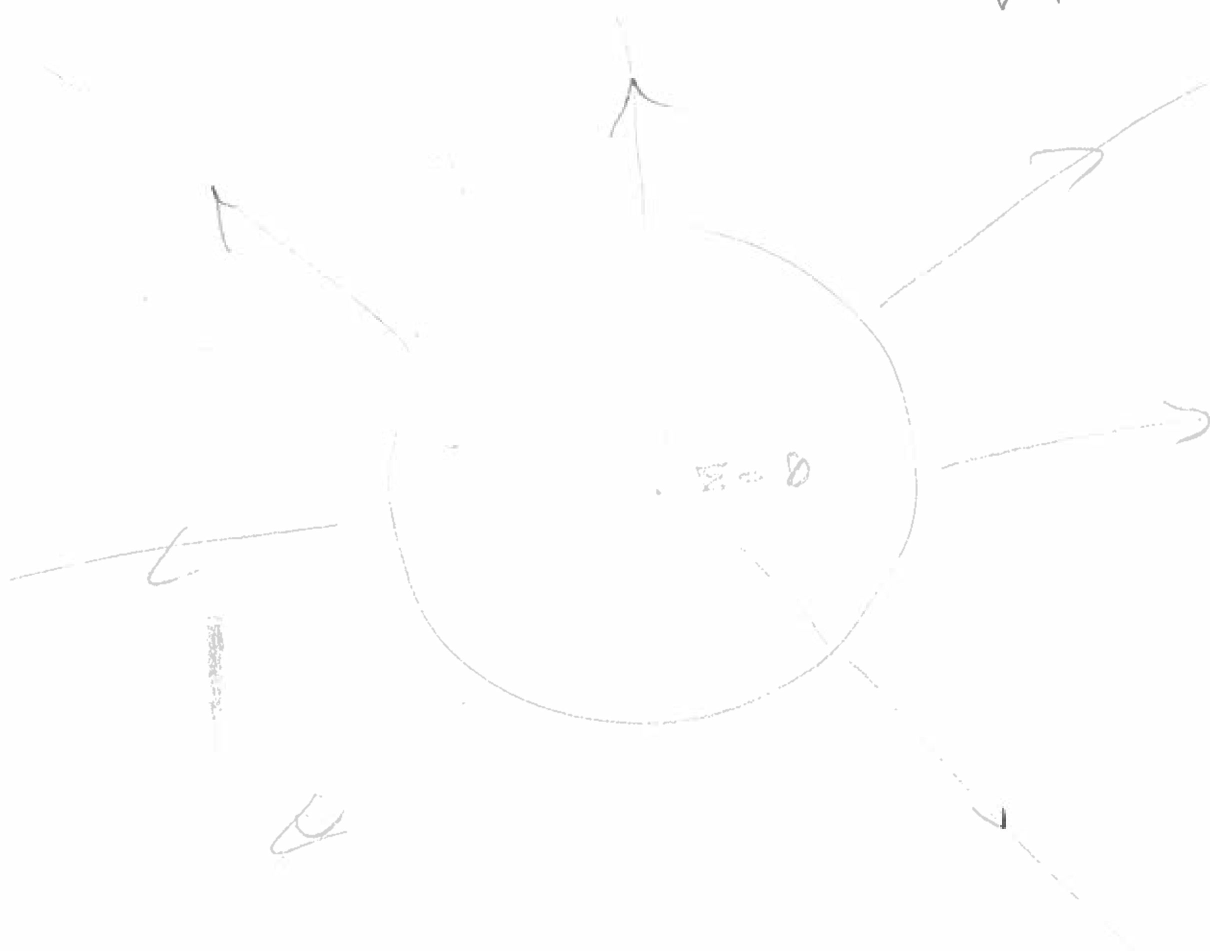
iii) Imagine a small spherically symmetric charge distribution of positive charge



from outside
the field lines begin
at a point-like source;
But inside the field lines
begin at the center
where $\underset{\sim}{E} = 0$ by symmetry

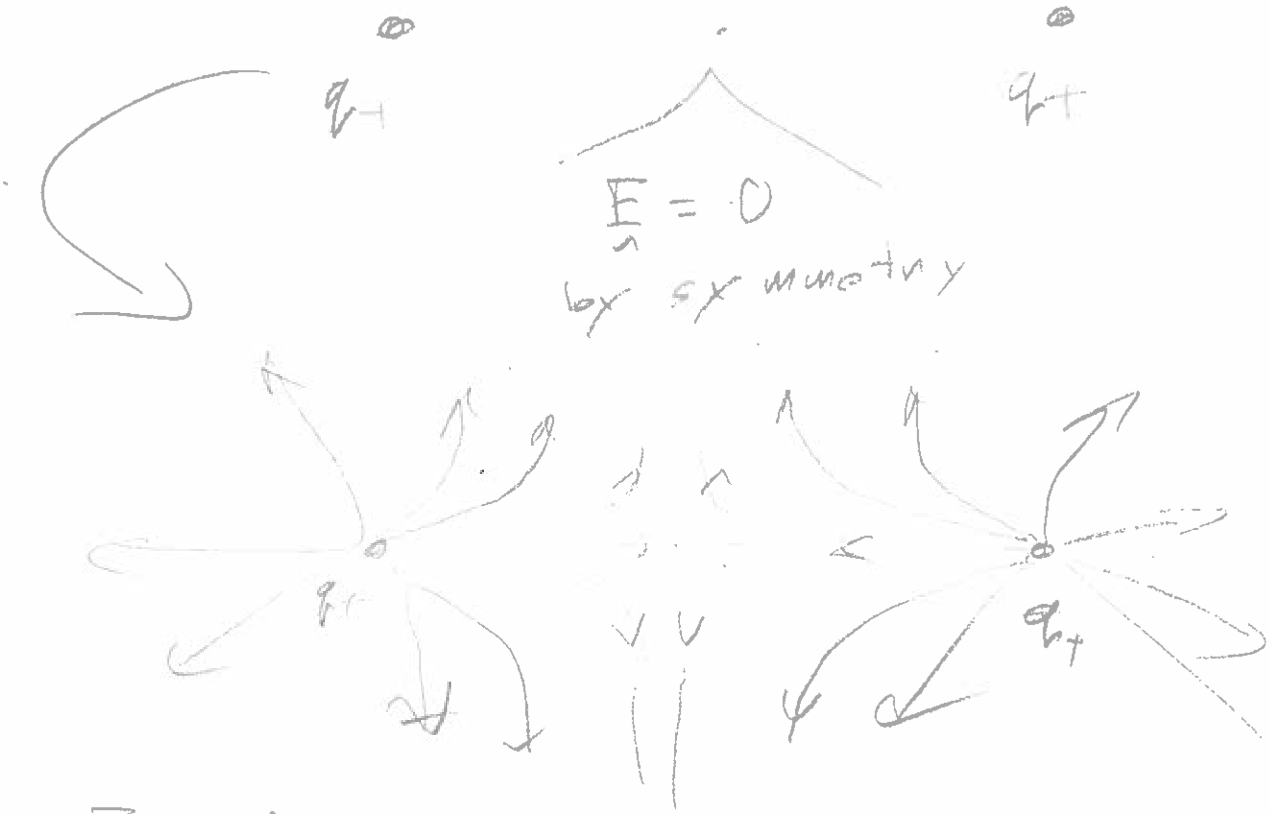
Google AI seems to agree if you interrogate it for enough.

In the classical continuum picture, I think field lines always end on $\underset{\sim}{E} \neq 0$ points.
For the classical point, line, plane of charge, they end on those.
The quantum electrodynamics is fuzzy to me, but probably it's a fuzzy end.

2_05058

iv) <u>However</u> the classical point charges as start/end of $\underline{E}$-field lines is a useful picture.

v) Note, $\underline{E} = 0$ points can happen where there is no start/end of E-field lines, except in one direction.
Consider two positive point particles



In far field limit, the two point charges asymptotically appear as a single point charge of charge $2q_+$.
We won't do the math proof here, but it is physically intuitively reasonable.

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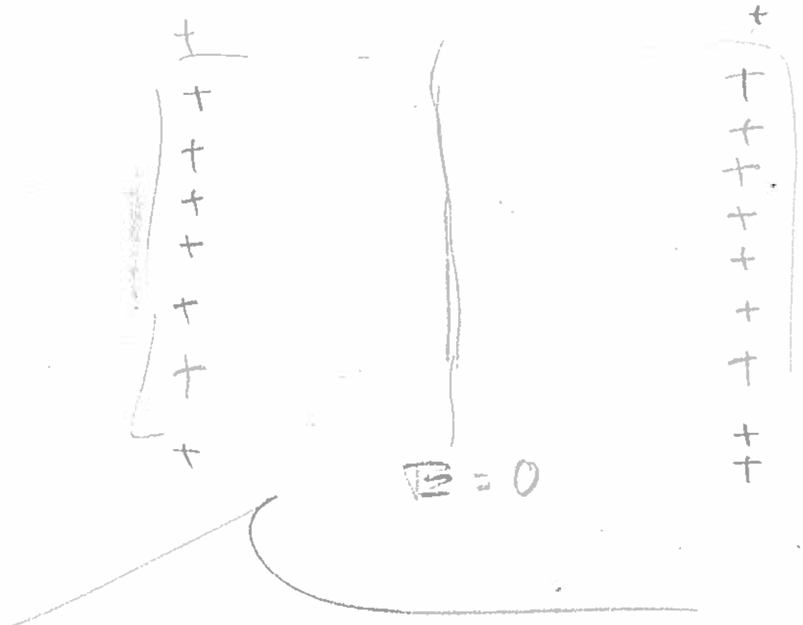
vi) In general clump of continuum charge?

Not a conductor

There might be multiple points of $\underline{E} = 0$



Note, this description is still at the macroscopic scale where we are averaging over field variations at the atomic and nuclear scale quantum vacuum scale (where the E-field is never zero and has no fixed directi

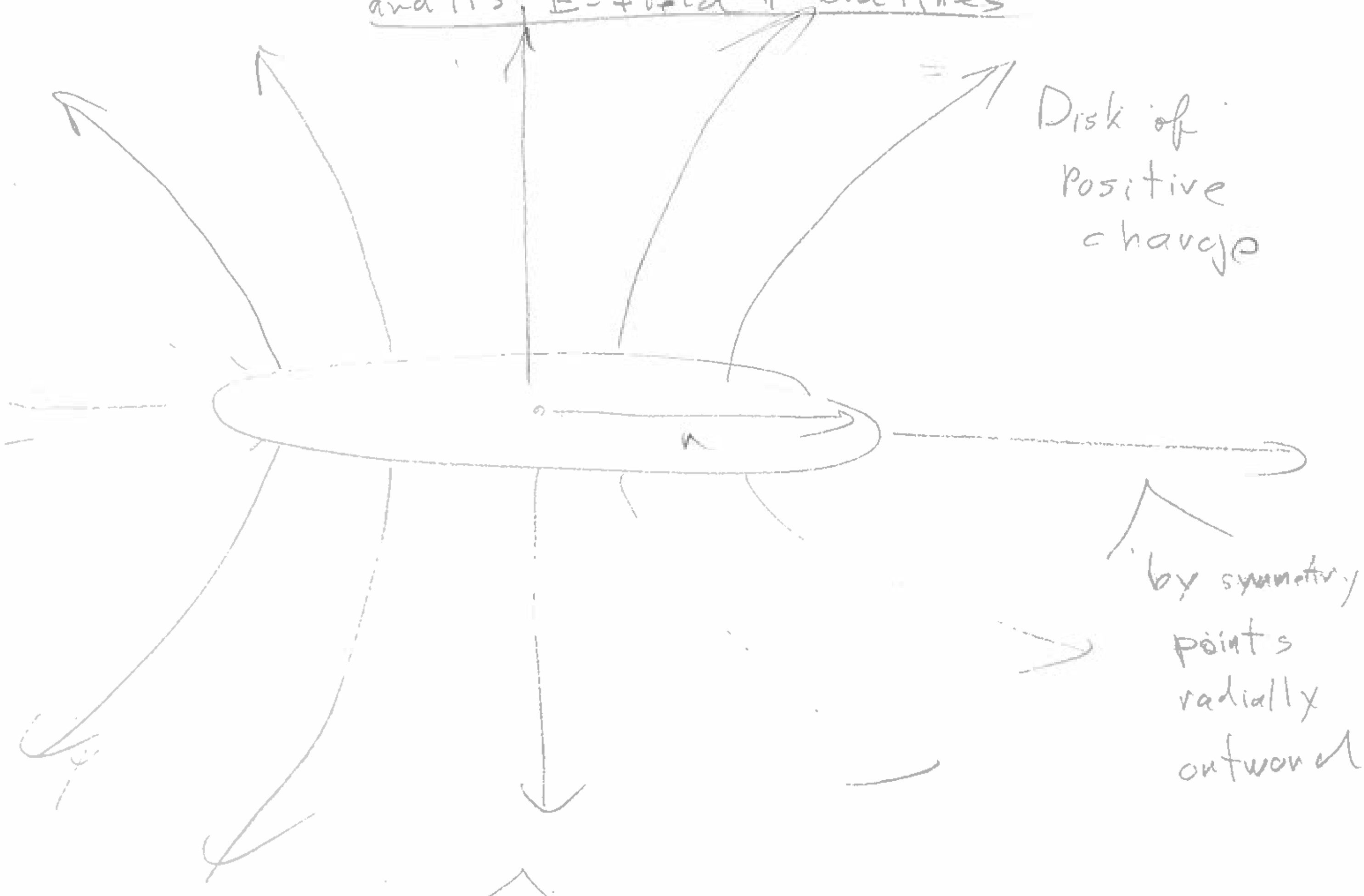
At atomic scale maybe there are E = 0 points above the vacuum level.

NOT a conductor.

Conductors are important special case, we consider in Chapter 6. On Gauss' Law

vii) Actually at the quantum field level there is always a vacuum zero point (i.e., non zero) E&M field, but that is well beyond our scope

e) Disk of charge (see p. 02_05050)
and its E-field Fieldlines



on Axis of symmetry

$$\underset{\sim}{E} = \begin{cases} 2\pi k\sigma\left[1 - \frac{z}{\sqrt{z^2+r^2}}\right]\hat{z} & \text{(see p. 02\_05052)} \\ 2\pi k\sigma\,\hat{z} & \text{for } z/r \ll 1 \\ \frac{kQ}{z^2}\,\hat{z} & \text{for } z/r \gg 1 \\ & \text{where } Q = \pi r^2\sigma \end{cases}$$

In far field limit in all directions

$$\underset{\sim}{E} = \frac{kQ^2}{r^2}\hat{R}$$

unit vector pointing radially outward from center of disk.

physically intuitively reasonable, but to be sure it needs a proof we will not give here.

For an infinite plane of charge

$$\underset{\sim}{E} = 2\pi k\sigma\hat{z}$$ for all space, No distance dependence.

z

We prove this ideal limit case in Chapter 6 on Gauss' law

f) Electric Field Line Loops

On p. 02_05055, we said E-field lines extend to infinity or start/end on classical point charge which must be qualilified to points of $\underset{\sim}{E}=0$ in the true classical continuum picture, But this is the electrostatic case where $\underline{E}$-fields are generated by static electric charge (static in the inertial frame of observation).

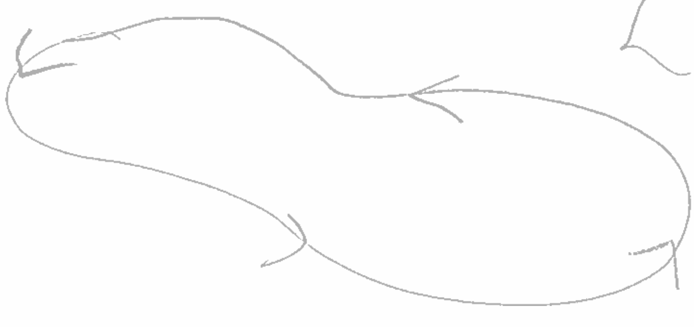
However, E-fields can also be created by time varying B-fields, as shown by the Maxwell equation the Maxwell-Faraday equation

or Faraday's law of induction differential form
(see p. 05-05003)

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

curl of $\underline{E}$ for those familiar with vector calculus

The equation can be read as a time varying magnetic field generates an electric with a structure where the E-field lines are loops



The E-field lines in this case form loops

And such E-fields
can drive currents and this
is what goes on in electric generators.
A time varying B-field drives
an electrical current.
This is the basics of
thermo, hydro, nuclear electric power.

9) <u>Visual Tool</u>
E-field field lines can often be
estimated qualitatively using
only qualitative concepts,
And that's we've done in
this section (<u>5.6</u> starting p. 02_05054),
We get more practice with
them and B-field field lines too
as we cover more of classical E+M.

22_05064

5.7 Electric Dipoles

a) We already consider the point - charge electric dipole on AG2_05055.

$q_- = -q_+$ and so overall neutral

Asymptotically close to each point charge, the E-field looks like a point charge E-field

$$\underset{\sim}{E} = \frac{kq_-}{r^2}\hat{r}$$

where $\underset{\sim}{r}$ is radius from q_-

$$E = \frac{kq_+}{r^2}\hat{r}$$

where r is radius from q_+

In the far field (asymptotic) limit

$$\underset{\sim}{E}(\underset{\sim}{r}) = k\left[\frac{3(\underset{\sim}{p}\cdot\hat{r})\hat{r} - \underset{\sim}{p}}{r^3}\right] \qquad |\underset{\sim}{r}| >> |\underset{\sim}{d}|$$

(wiki: electric dipole moment)

where $\underset{\sim}{r}$ is radius from the center

$q_+ \longrightarrow q_-$

$\underset{\sim}{d}$ is the charge separation vector and $\underset{\sim}{p} = q_+ \underset{\sim}{s}$ is the dipole moment (vector)

just the positive charge

$\underset{\sim}{s}$ displacement vector from negative to positive charge

For a physical dipole, q_+ and $\underset{\sim}{s}$ are finite.

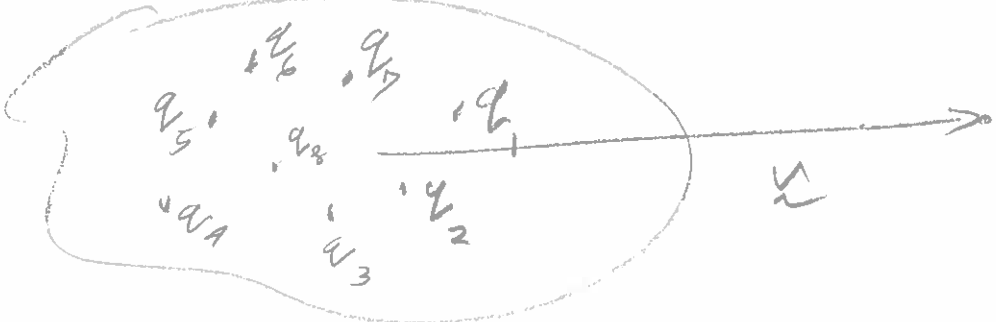
An ideal dipole has $q_+ \to \infty$ and $\underset{\sim}{s} \to 0$ in such a way that $\underset{\sim}{p}$ stays finite (G-150)

For an ideal dipole, $\underset{\sim}{E}(\underset{\sim}{r})$ given on p. 02-05064 is exact. (G-150)

b) Now our dipole formula $\underset{\sim}{p} = q_+ \underset{\sim}{s}$ can be to any set of localizable point charges and any localizable continuum of charge.

12_05066

Localizable in this context means you can put the charge within a finite closed surface



When you are sufficiently far away from the charge distribution, you can expand the field in a multipole expansion series (6-145)

$$\underset{\sim}{E} = O\left(\frac{1}{r^2}\right) + O\left(\frac{1}{r^3}\right) + O\left(\frac{1}{r^4}\right) + O\left(\frac{1}{r^5}\right) + \ldots$$

monopole term — Zero if total charge is zero

dipole term

quadrupole term

octopole term

etc.

Infact quantum mechanical particles (e.g., electrons, protons) can be treated as classical point particles in many cases since only the monopole is important in those cases

It is well beyond our scope to cover multipole expansion but we should keep in mind that it can be done.

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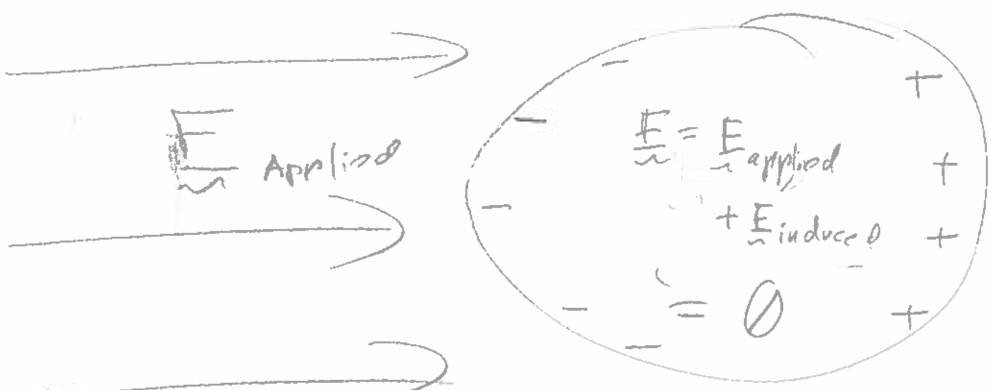
5.8 Polarization of Bulk Materials

Mostly Thinking of Insulators
Leaving Conductors Mostly
for Chapter C

a) Conductor Thinking of Solid Metals



Overall Sample polarized under applied E-field.

The negative charge are attracted
The positiv charge is repeled.

Positive charge repeled in field directiu

Negative charge attrac in the opposite directiu

In metals the free electrons
(negative charge mobile charge carriers
$q = -e = -1.602\ 176\ 634 \times 10^{-19}\,C$
exact by definition)
move
and the free positive charge is
absense of electrons,
All such free charge is on the surfure

02_05068

Ideally all free charge is on the surface in electrostatic cases and inside $\underline{E} = 0$

This is macroscopic $\underline{E}$

At the microscopic level the E-field has all kinds of variations over the ions.

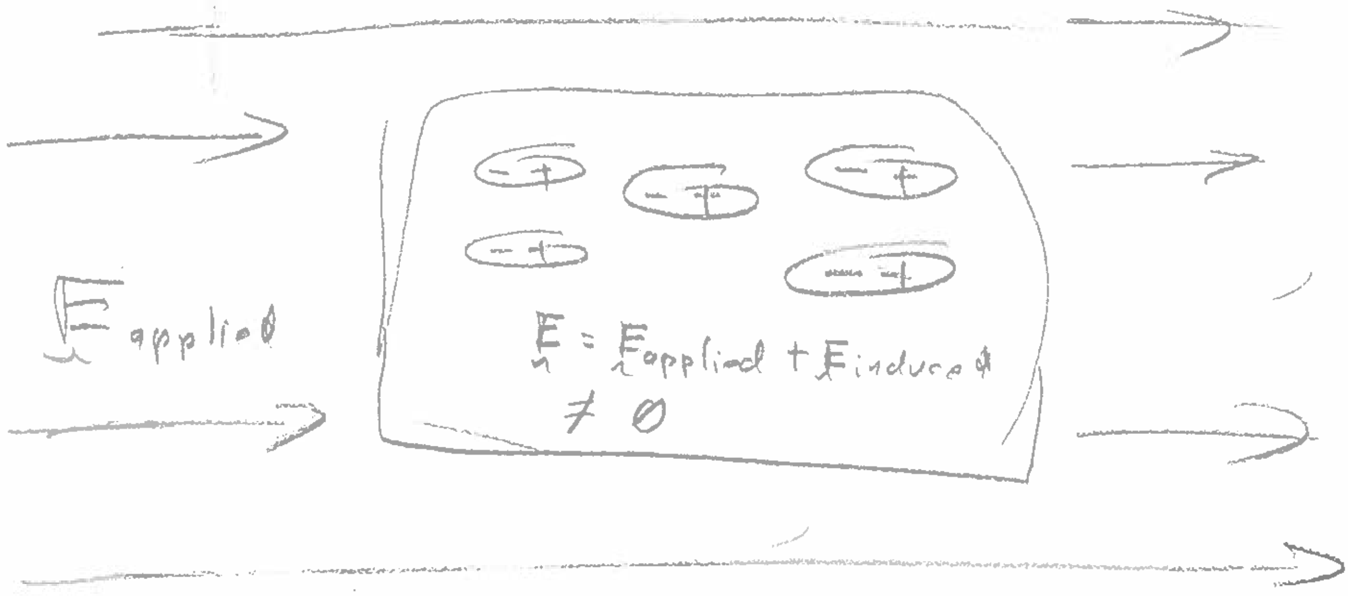
The free electrons are the outermost 1 or 2 valance electrons become unbound to ions in metals, but are still bound inside the metal.

In Chapter 6 we go into a bit more detail about metal conductors

In fluid conductors, positive and negative ions are the charge carriers.

b) Dielectrics

A dielectric is an insulator that can be polarized by an applied E-field and, in fact, all insulators must be dielectric to some degree.



There is NO free charge to move macroscopic distances, but the individual atoms or molecules polarize

Develop an induced dipole moment (see p.02.05065.

or if there are permanently polarized molecule they can align with the applied E-field if free to rotate.

c) Demonstration repeated from p. 02_05041.

There is an attraction of the polarized sample because the positive end of each dipole moment is in a stronger E-field than the negative end.

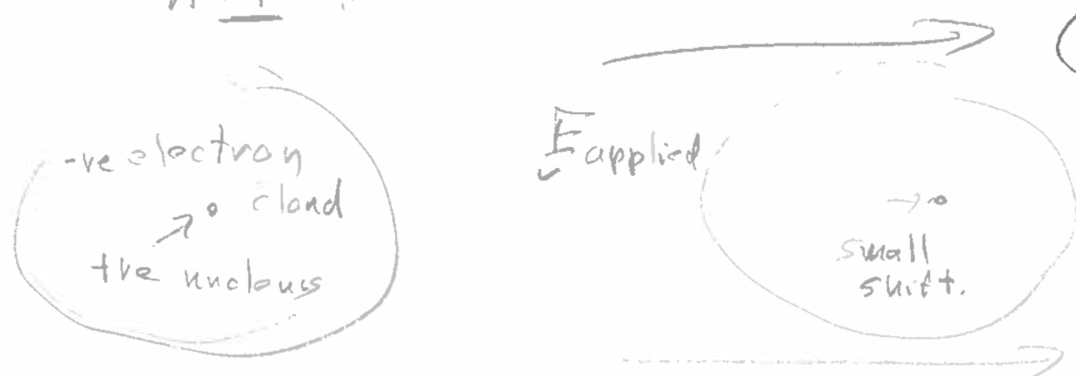
Probably mostly induced polarization since paper molecules NOT free to rotate much.

This is a highly simplified picture of a polarized atom or molecule.

A bit more realistically

(G-159)

Atom & nucleus



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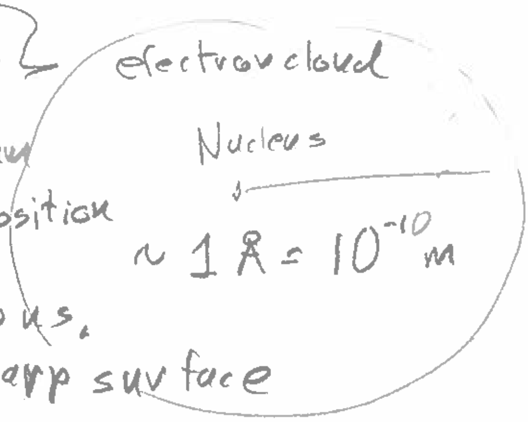
d) Recall

Atom size scale

Electrons in a continuum superposition of positions.

No sharp surface



Nucleus bonded electron cloud by the long-range inverse square law Coulomb force

$$\propto \frac{1}{r^2}$$

which formally only goes to zero at infinity

Nucleus size scale

$\sim 1 \text{ fm} = 10^{-15}$ m

Cloud of protons and neutrons. They exist in a continuum superposition of positions

No sharp surface

Nucleus of +ve protons and neutral neutron bonded together by nuclear strong force.

Very strong since it can overcome the Coulomb force repulsion of protons, but it extends only ~ 1 fm from

)2_05072

) According to Google AI, ground state atoms (atoms in their lowest interna energy state) have no intrinsic polarization.

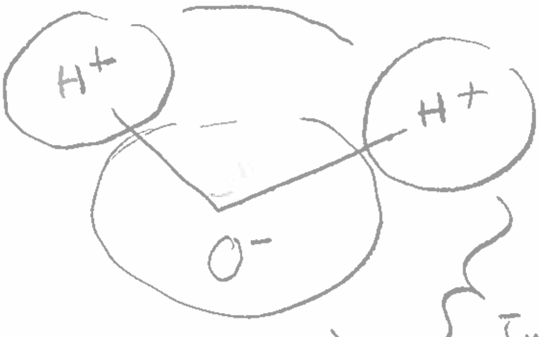
Do NOT have permanent dipole moments

But there can be polar atoms if the atom is an excited state (I'm NOT totally convinced).

Molecules can be polar molecules (i.e., have permanent dipole moments).

An all-important example is the H_2O molecule of water

Angle = 104.45°



Inter-nucleon separation = 0.9584 Å

An overall small charge separation, and so a permanent dipole moment = 1.8546 D

D = debye ≅ 3.33564×10^{-30} C·m ≅ 0.2081943 e·Å unit of dipole moment (Wik)

(Wik G-161)

Why can a small charge separation exist?

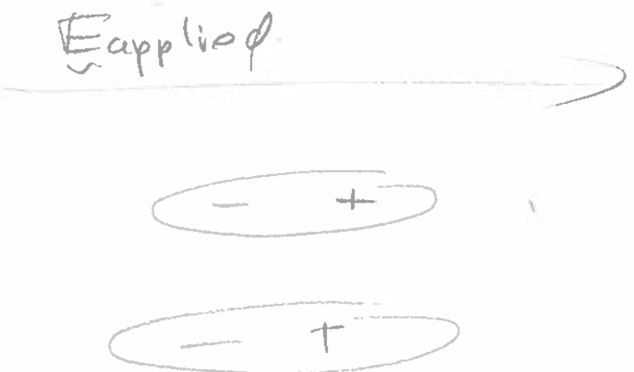
Short answer → Complex quantum mechanics interaction of dynamics and forces

We leave it to chemistry for a longer answer.

All very complex, but it allows complex materials and life as we know it

f) In liquid water

the permanant dipole moments are torqued to align with an applied E-field and some induced polarization can exist too



schematic water molecules

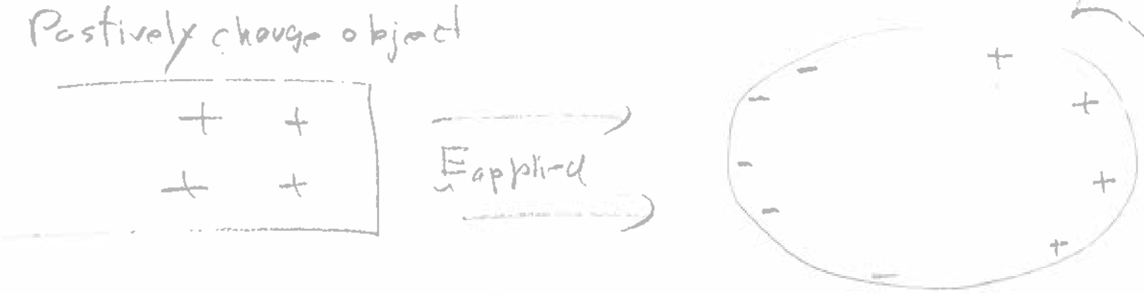
torquing action of $\underset{\sim}{E}_{applied}$ tends to align dipoles (thermal motions try to randomize order)

02-05074

The process is NOT electrostatic.

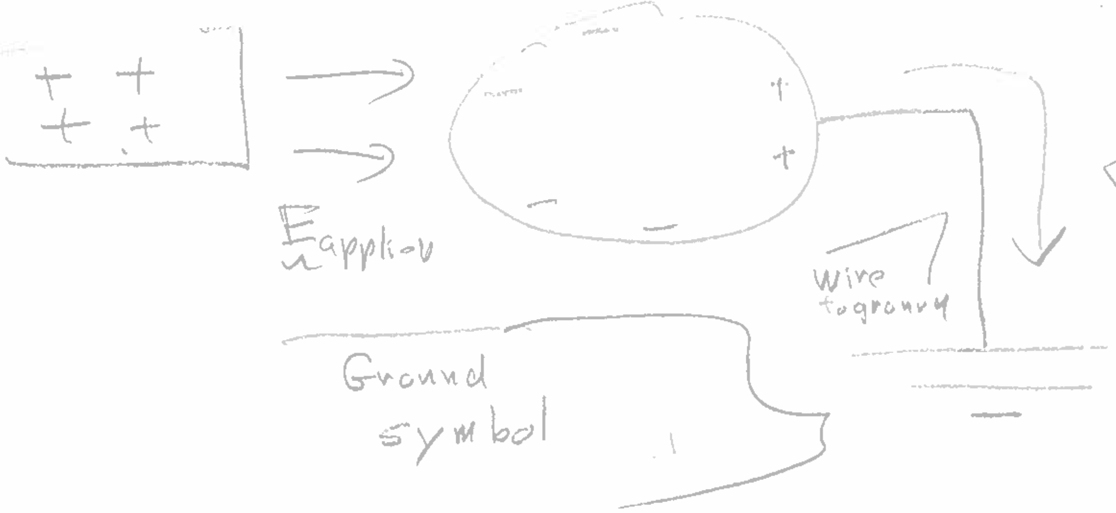
5.9 Charging by Induction

a) Just a short coverage



Isolated metal conductor Polarized by $E_{applied}$.

Recall the separated charge is on the surface



Positive charge flows to ground. Really electrons flow out of ground

If you disconnect the wire,
the conductor stays
negatively charged.

b) Ground is any huge
(effectively infinite) source
of charge.
Ground can just be the physical ground.

As an electrical safety feature
conductive parts of a device
that insulated from current
and charge are grounded.
Thus, if insulation fails
there is a very low resistance
(more generally impedance) path
for current to flow through
(and NOT flow through a human)
and the strong current should cause
the circuit to break by a blown fuse
or circuit breaker of some kind.

02_09076

c) Lightning

- very short coverage of cloud-to-ground lightening

~95 % cases the atmospheric E-field points up and so electrons flow down to ground (Wiki: lightening)

If your hair stands on end, negative charge has been repeled to Ground and the hair strands are mutually repulsive and you are in danger of a lighting strike. Get out of that place.

Take shelter in a closed building or vehicle, Don't touch conductors (Wiki: Lightning strikes)