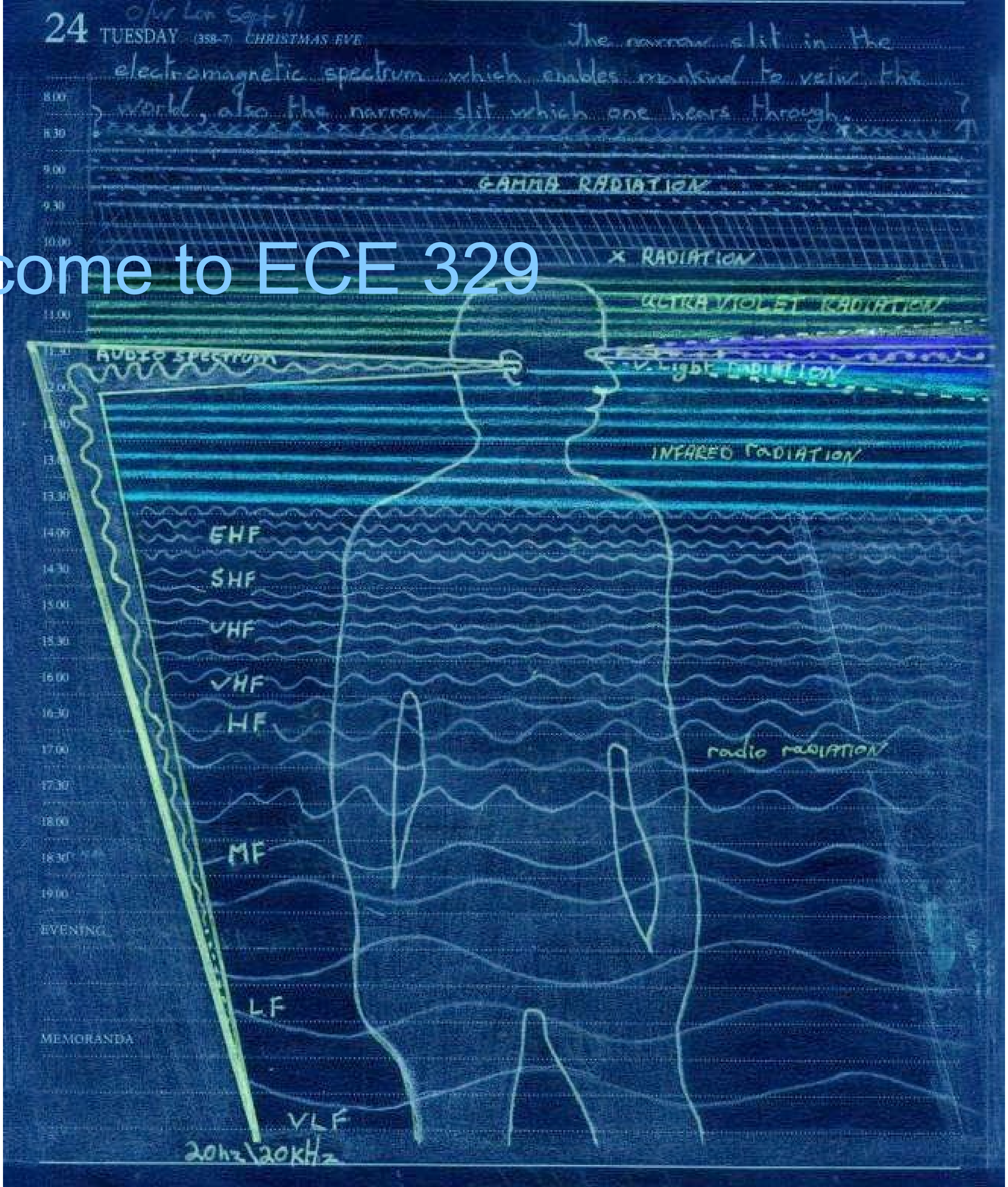
Welcome to ECE 329



History of Electromagnetics

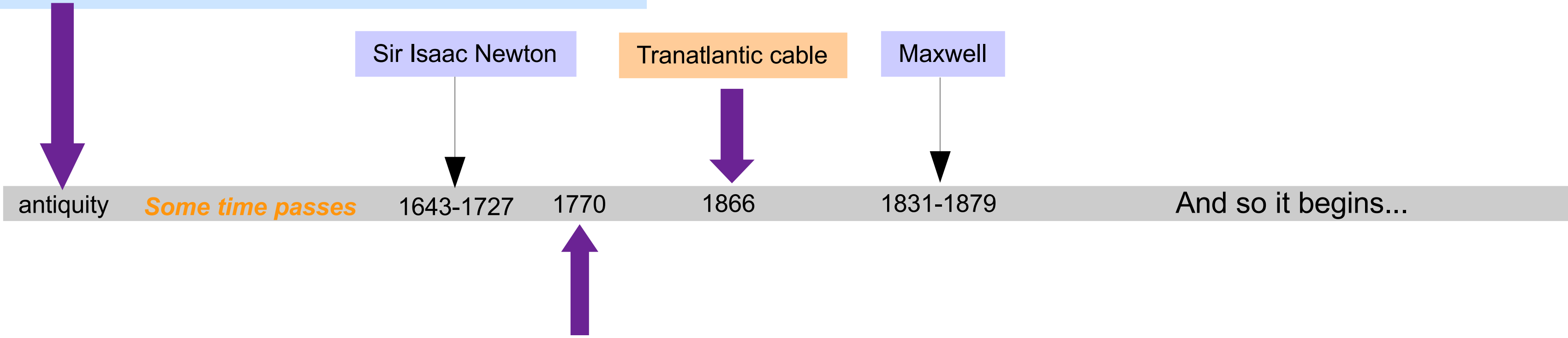
the Reader's Digest version

Electrostatics – static electricity was know as an interesting but mystifying phenomenon of no practical use.

- Lightening
- Amber when rubbed attracted light objects to itself.
- Electrified fish and eels.

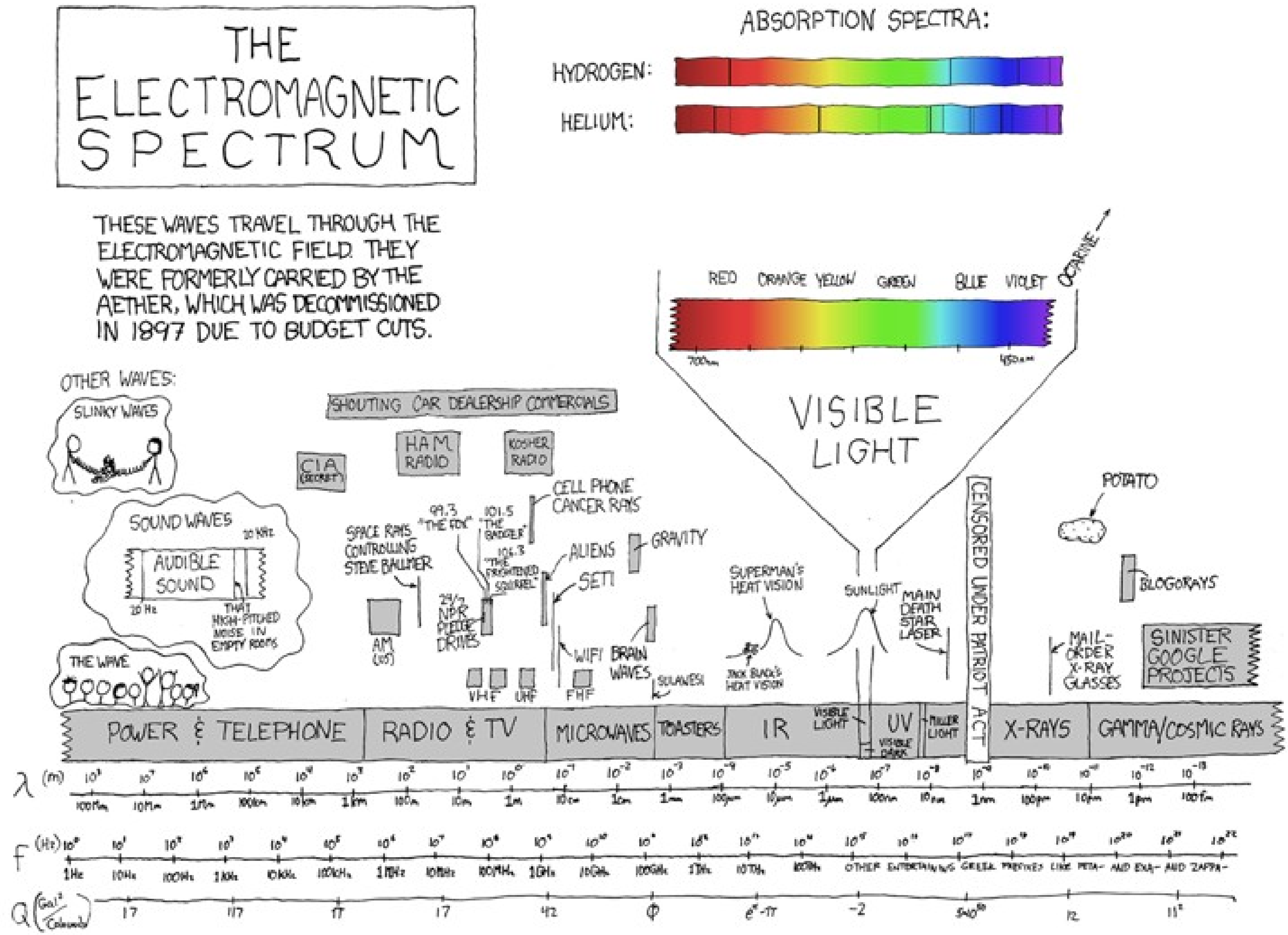
Magnetostatics – the existence of magnetic fields was known only through the behavior of naturally magnetized stones – lodestones. Certainly the Chinese, and perhaps the Central Americans figured out how to utilize the properties to make lodestone.

Light – of all the phenomena, light and its behavior were probably the most understood – lenses have been found that suggest that in the very early years AD the concepts of reflection and refraction were understood and exploited



State-of-the-art: 1770.

- There are two types of electricity (or maybe one that can be added to some materials and taken away from others)
- Electricity is conserved.
- There are insulators in which charge cannot move.
- There are conductors in which it can move freely.
- Equal charges repel each other.
- Opposite charges attract.
- Light reflection and refraction were understood and Sir Isaac Newton had put forth the notion that light was made of very small particles.


THE ELECTROMAGNETIC SPECTRUM
ABSORPTION SPECTRA:
HYDROGEN:
HELIUM:
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.
RED
ORANGE
YELLOW
GREEN
BLUE
VIOLET
OCTARINE
700nm
450nm
VISIBLE LIGHT
OTHER WAVES:
SLINKY WAVES
SOUND WAVES
AUDIBLE SOUND
20 Hz
20 kHz
THAT HIGH-PITCHED NOISE IN EMPTY ROOMS
THE WAVE
SHOUTING CAR DEALERSHIP COMMERCIALS
CIA (SECRET)
HAM RADIO
KOSHER RADIO
CELL PHONE CANCER RAYS
SPACE RAYS CONTROLLING STEVE BALLMER
99.3 "THE FOX"
101.5 "THE BADGER"
AM (US)
ALIENS
GRAVITY
SETI
WIFI
BRAIN WAVES
VHF
UHF
FHF
SUPERMAN'S HEAT VISION
JACK BLACK'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
POWER & TELEPHONE
RADIO & TV
MICROWAVES
TOASTERS
IR
VISIBLE LIGHT
UV
VISIBLE DARK
MILLER LIGHT
X-RAYS
GAMMA/COSMIC RAYS
λ (m)
f (Hz)
1Hz
10Hz
100Hz
1kHz
10kHz
100kHz
1MHz
10MHz
100MHz
1GHz
10GHz
100GHz
1THz
10THz
100THz
OTHER ENTERTAINING GREEK PREFIXES LIKE META- AND EKA- AND ZAPPA-
1km
100m
10m
1m
1cm
1mm
1nm
1pm

QUESTION: How do we even know that electricity exists – or anything else really?

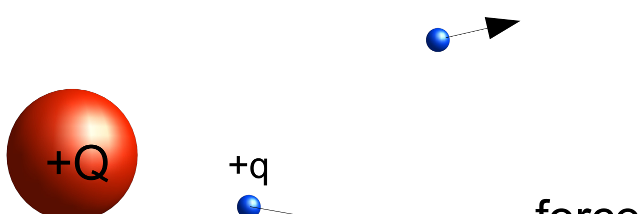
The answer to this question is at the heart of understanding electromagetics and all of physics really.

Answer: We know about our world because we can observe the effects of the existence of – say other matter or charged particles. From direct experience we know that gravity exists because everything that we drop is always pulled downward. In the case of electric phenomena we know how charged particles affect each other through experimentation. The simple law that we will learn is one of 2 fundamental pieces of evidence that constitutes all of electromagnetics.

INTERACTION between CHARGES

Charges exert a force on one another according to these observation:

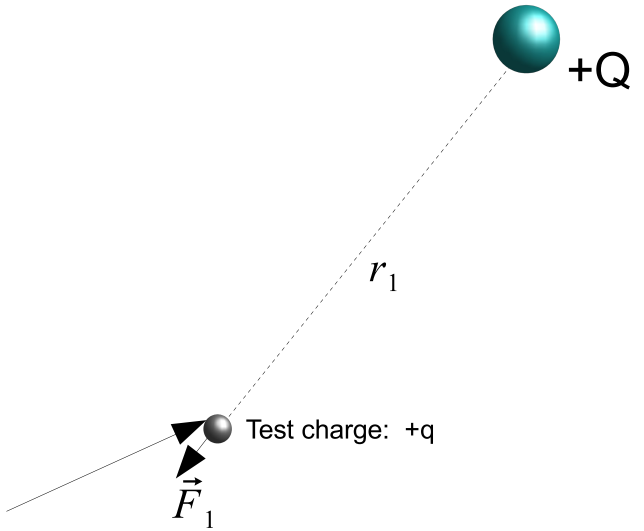
- *magnitude of the force is proportional to the magnitude of both charges*
- *magnitude of the force is inversely proportional to the square of the distance between them*
- *direction of the force lies along the direction of a line connecting the charges. Like charges repel, unlike attract.*



MATH Concepts -

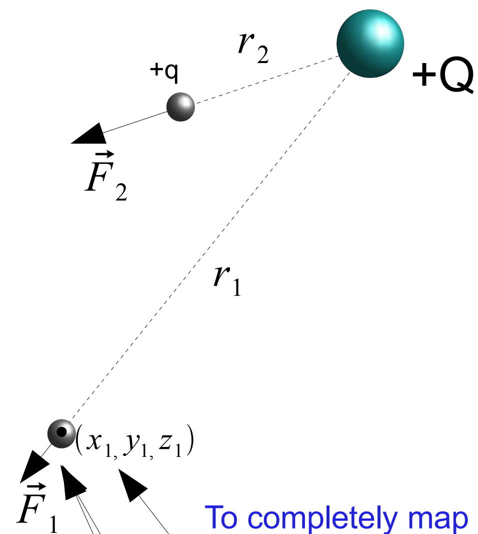
- coordinate systems
- vector notation
- fields

Mapping the influence of a charged particle:



A test charge is put in the vicinity of the charge. By moving the charge and measuring the force at each point a map can be created.

Mapping the influence of a charged particle:



To completely map the influence of Q at a point several pieces of information are needed:

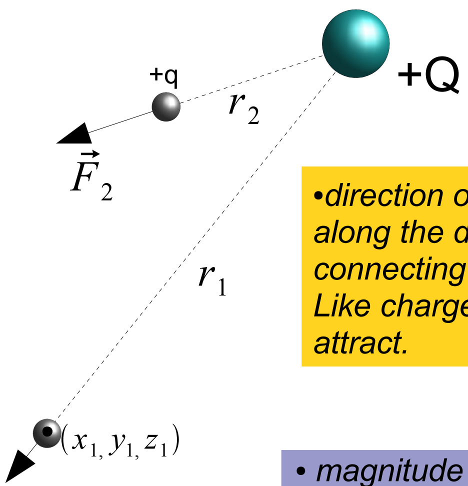
i) Label to specify the point in 3D space that the measurement was made.

ii) Label to specify where the charge resides.

ii) method of specifying the strength of the force (length of arrow)

Iii) method of specifying the direction of the force (direction arrow points)

Mapping the influence of a charged particle:



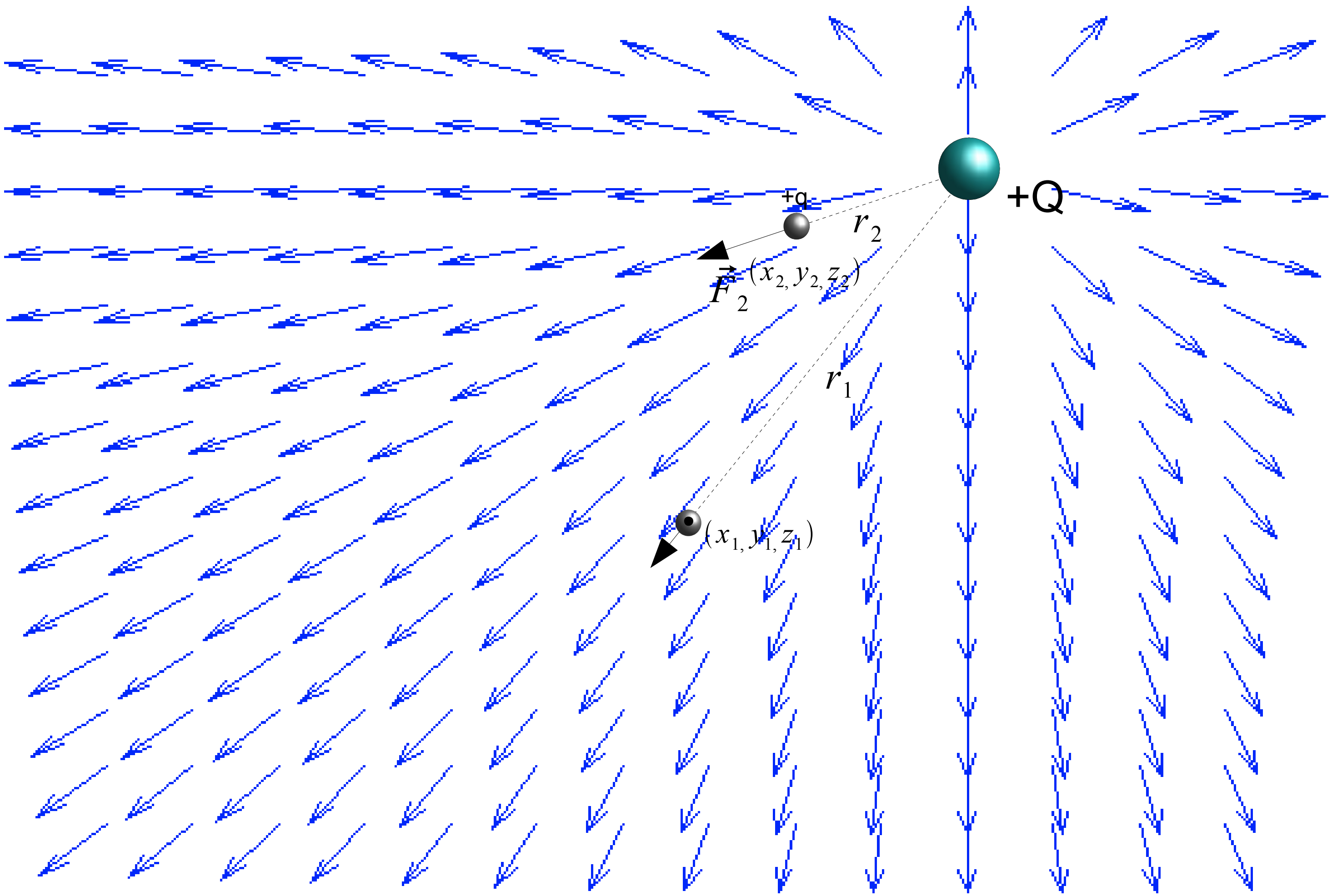
$$|\vec{F}_1| = \frac{Qq}{4\pi\epsilon_o r_1^2}$$

•direction of the force lies along the direction of a line connecting the charges. Like charges repel, unlike attract.

• magnitude of the force is proportional to the magnitude of both charges

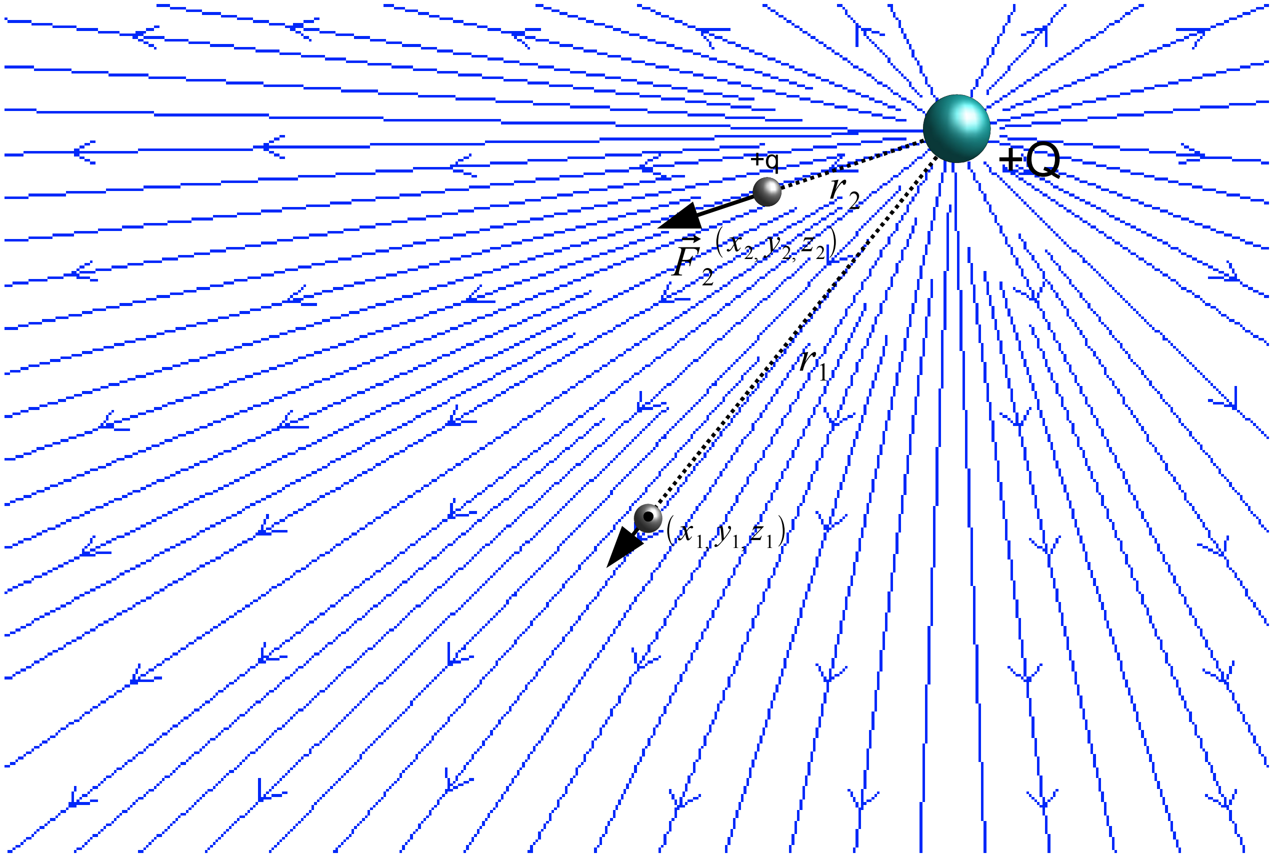
• magnitude of the force is inversely proportional to the square of the distance between them

Map of the force that a test charge feels in the vicinity of charge +Q



Map of the force that a test charge feels in the vicinity of charge +Q

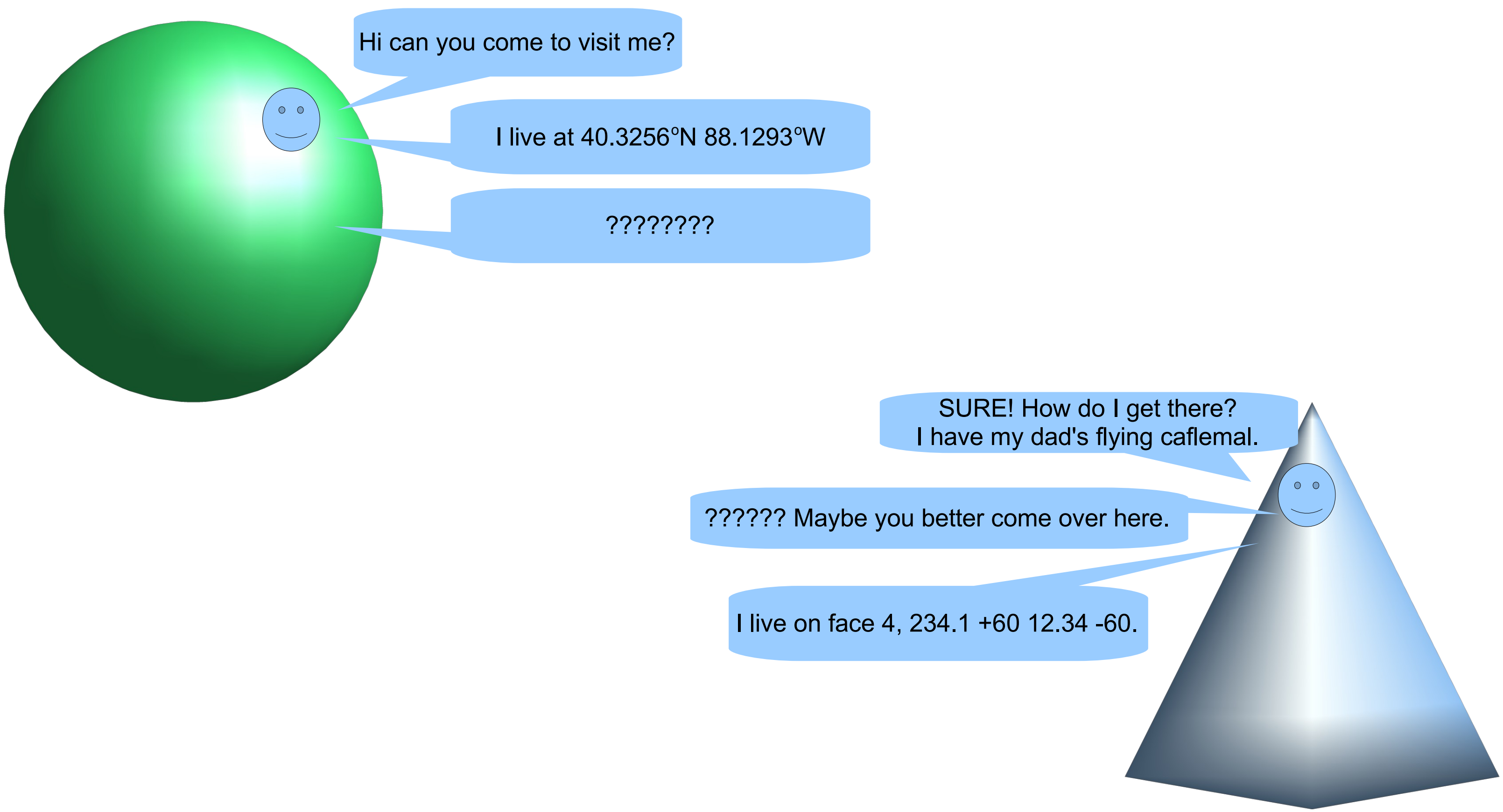
FIELD LINES



To description of how +Q influences the test charge q at all points in space mathematically we need to find suitable operators and a geometry that fits our problems.

STEP 1: DEFINE A COORDINATE SYSTEM

- specify origin
- define method of specifying a point
- define a method of specifying a vector



COORDINATE SYSTEMS

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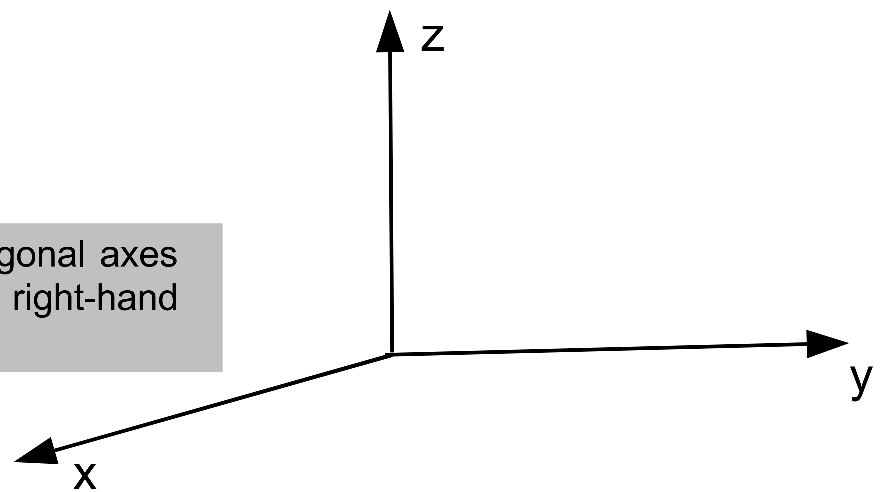

3 mutually orthogonal axes following the right-hand convention

Rene Descarte invented what is now called the Cartesian Coordinate system, named in his honor. This achievement happened around 1637...

Without this innovation, the complex mathematics needed to quantify physical concepts would be impossibly difficult. Consider trying to describe quantitatively, using only words and some hand drawn figure how light behaves when going through a lens, for example.

COORDINATE SYSTEMS

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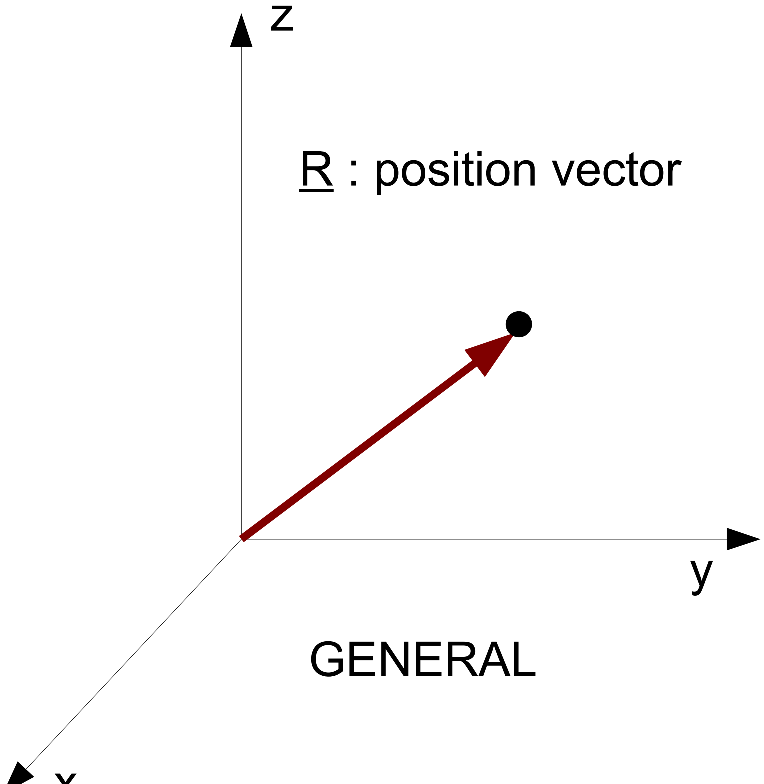

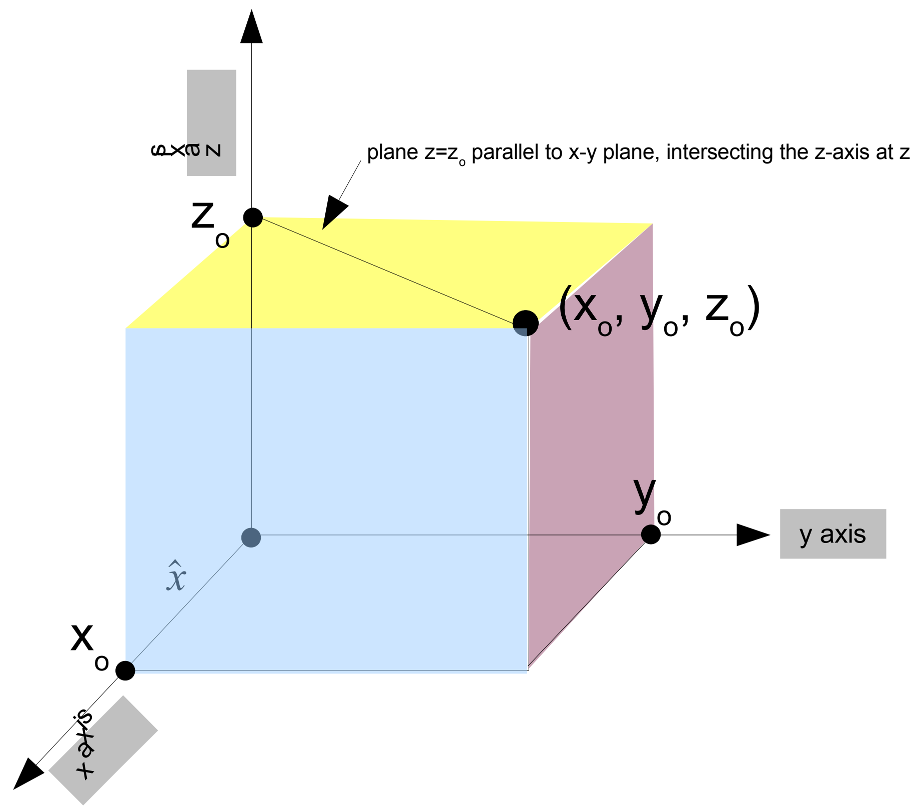

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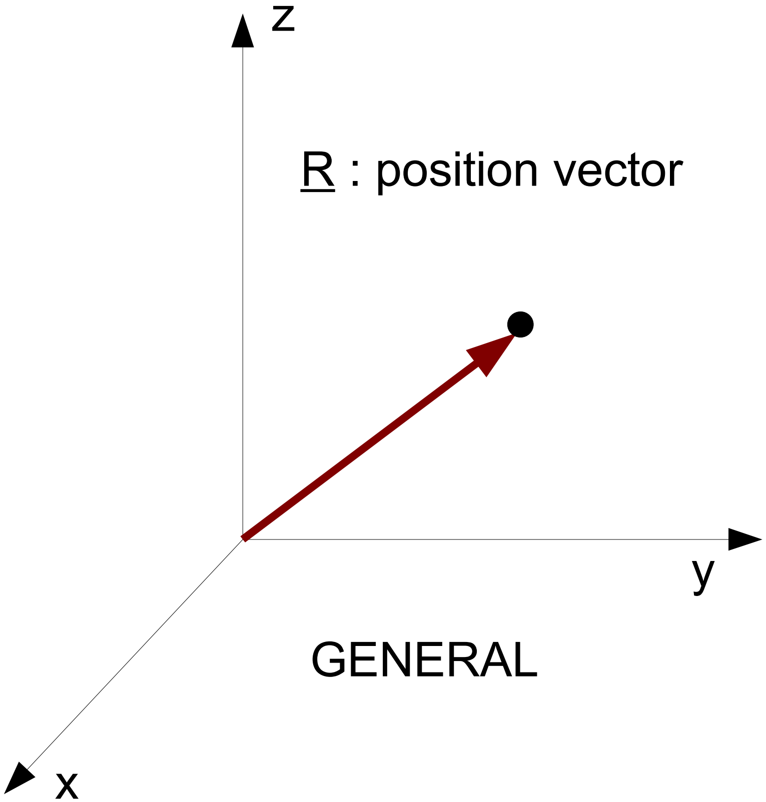

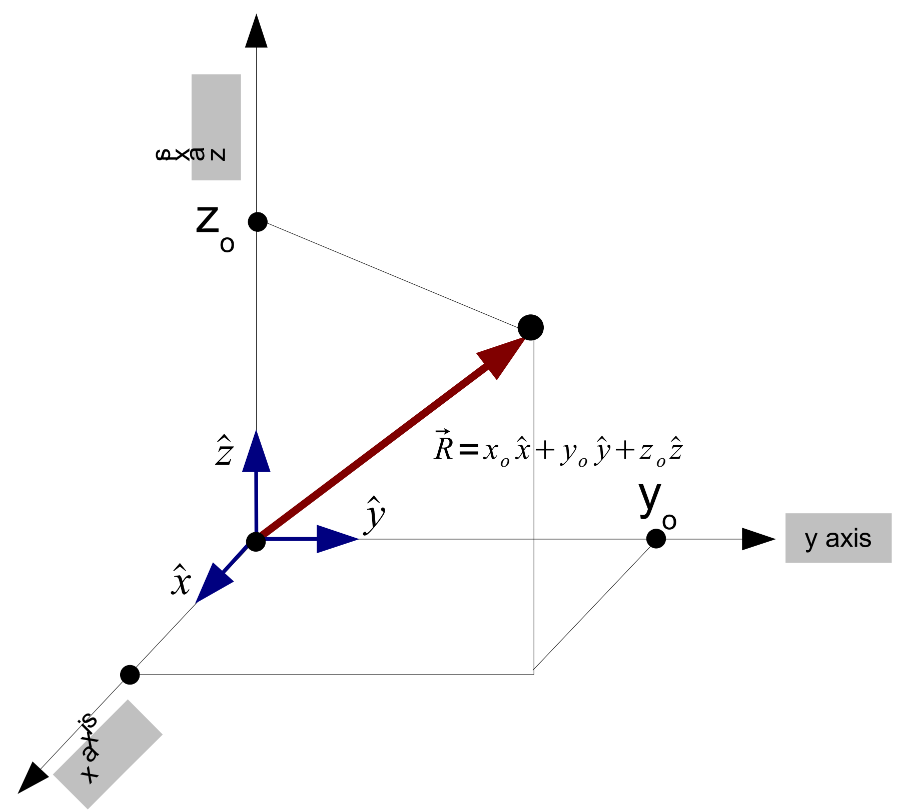

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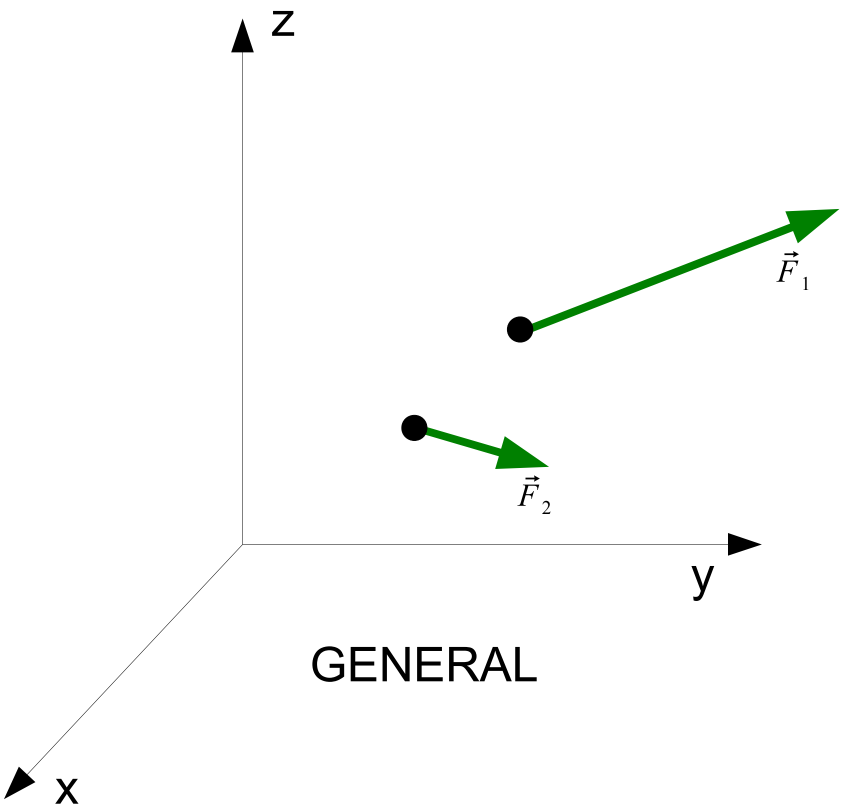

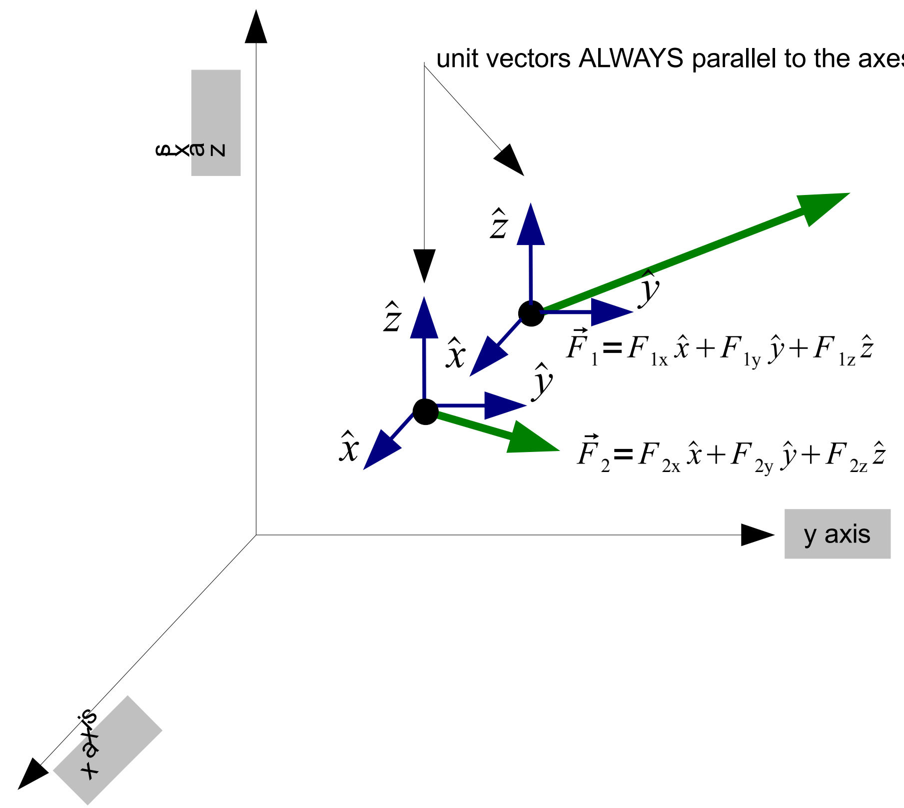

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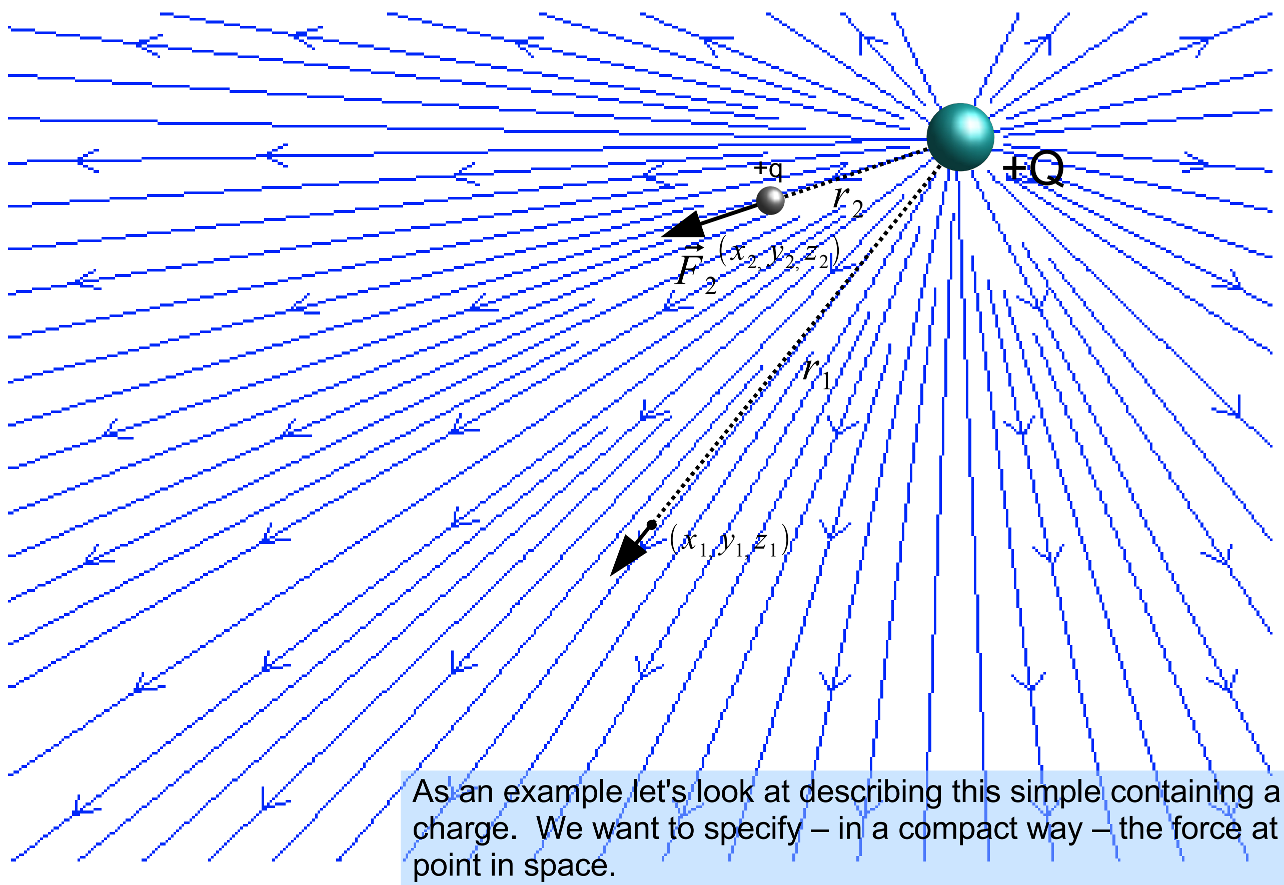
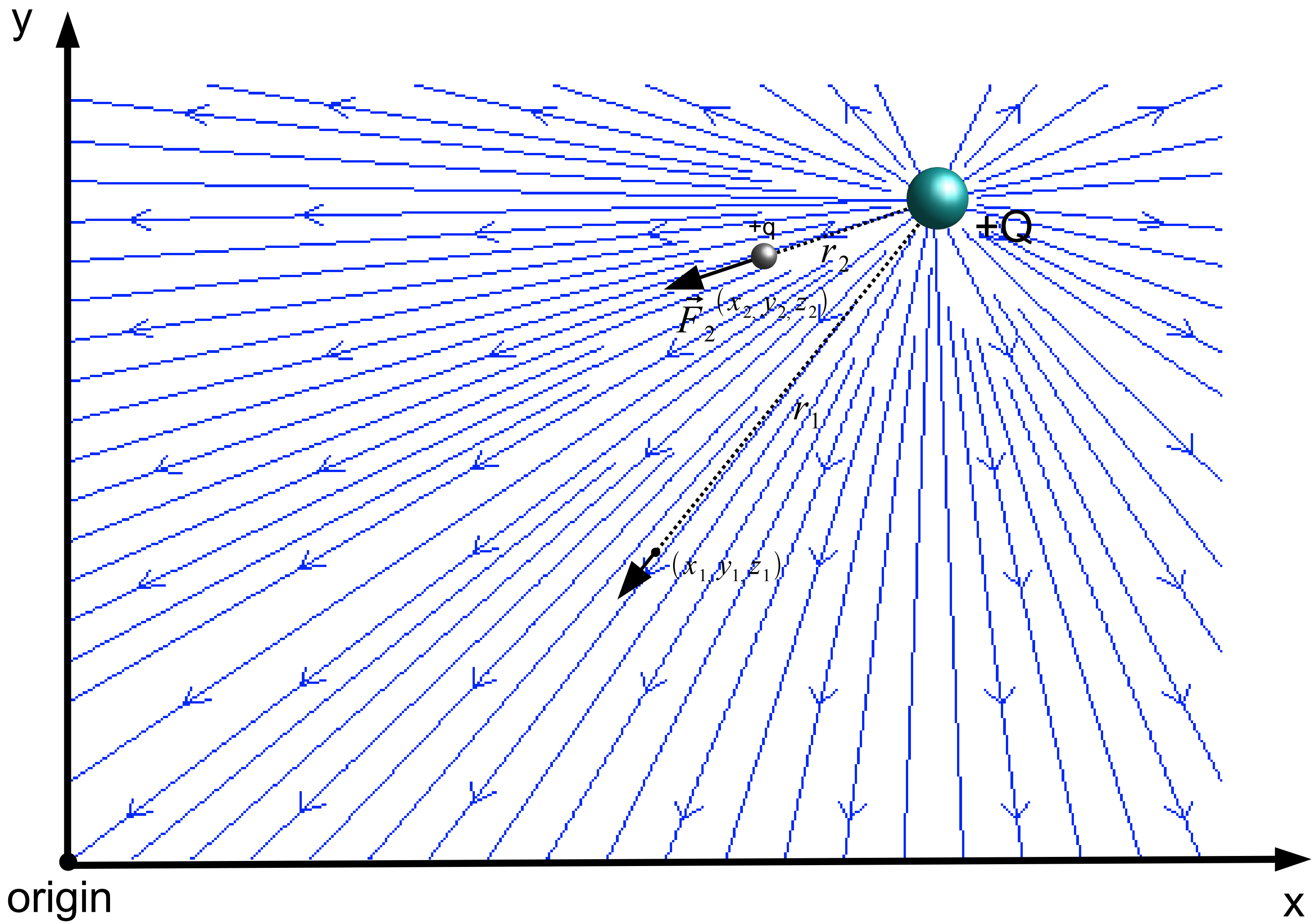


As an example let's look at describing this simple containing a single charge. We want to specify – in a compact way – the force at each point in space.

COORDINATE SYSTEMS

- specify origin
- define method of specifying a point
- define a method of specifying a vector



COORDINATE SYSTEMS

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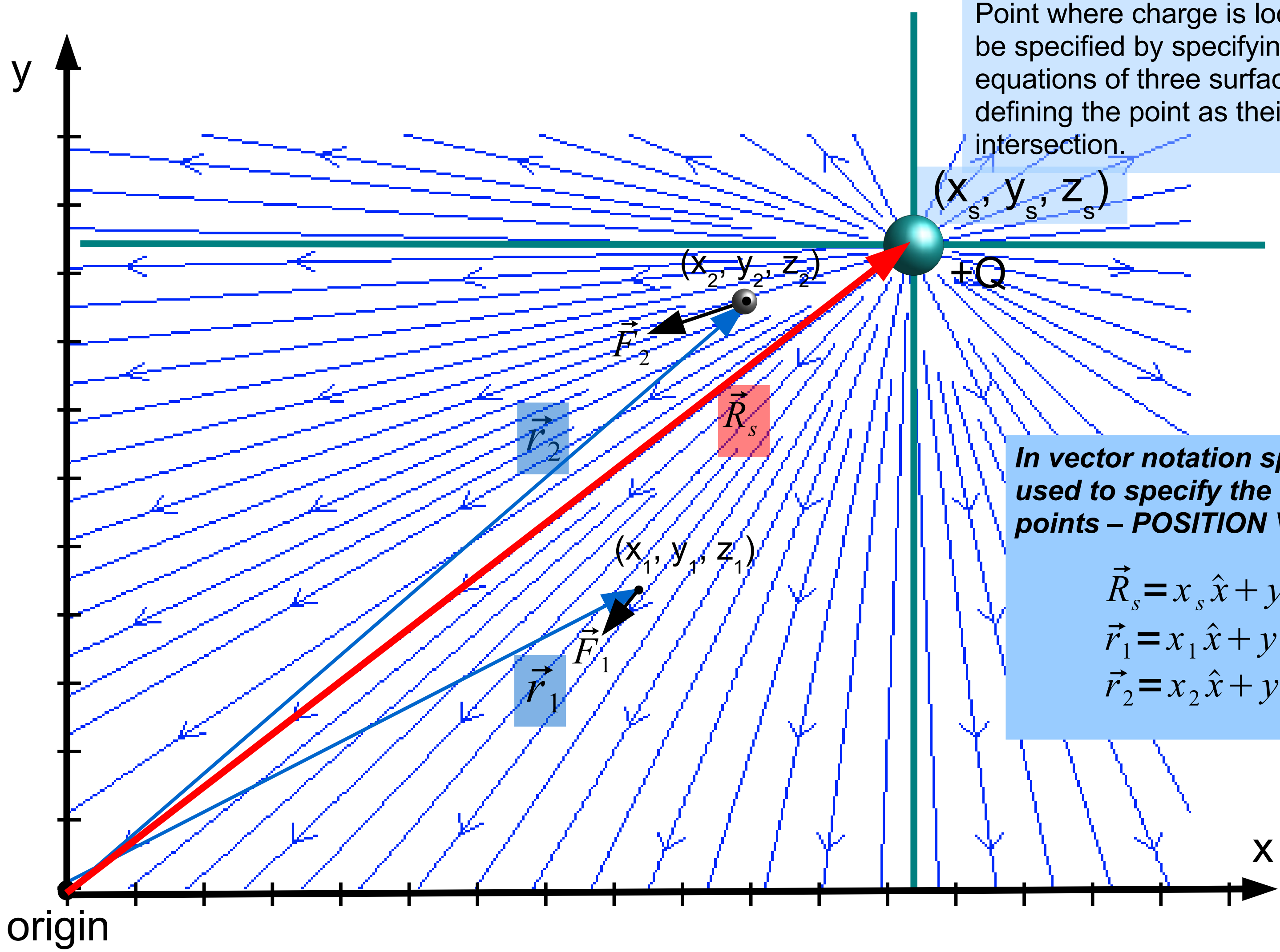


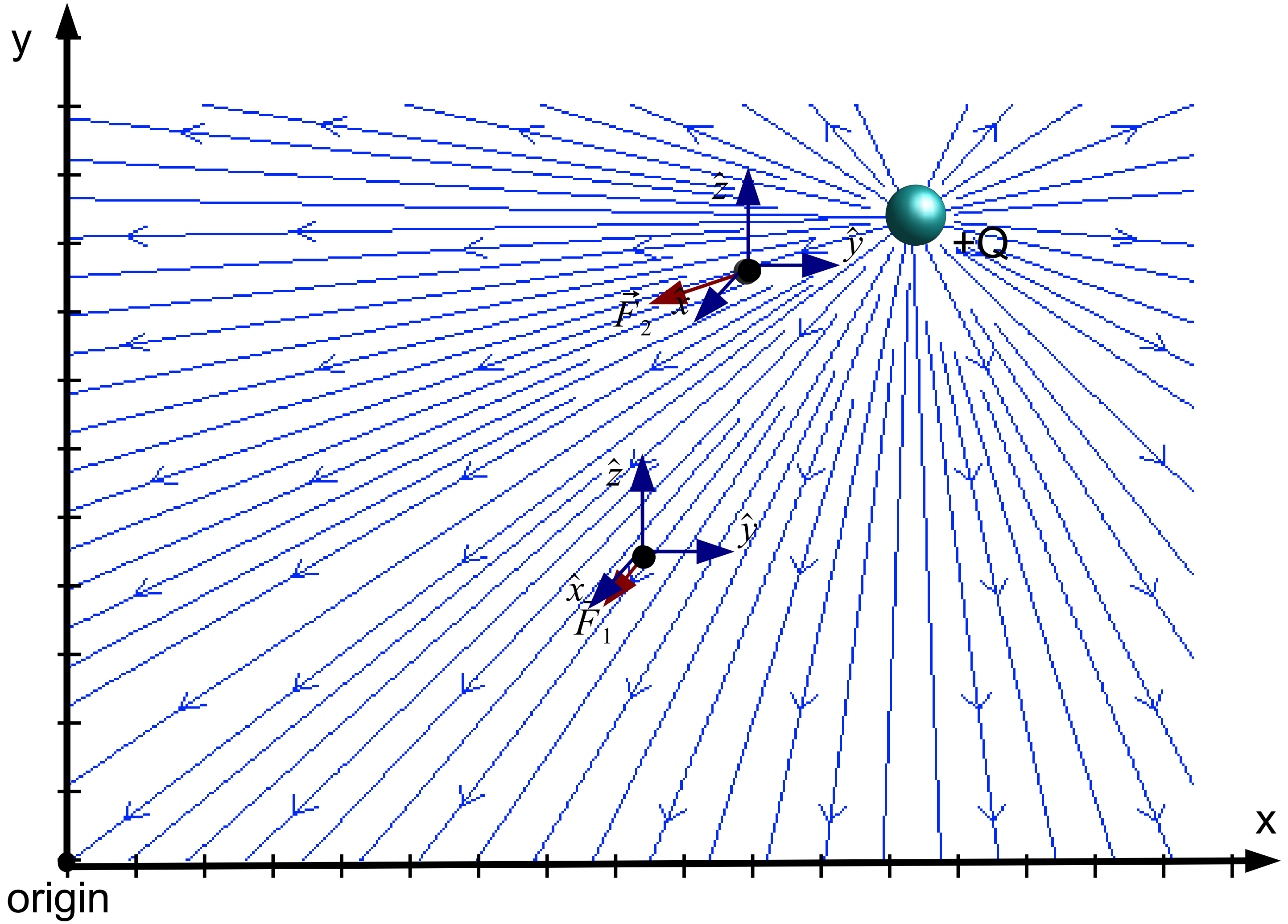
Point where charge is located can be specified by specifying the equations of three surfaces, defining the point as their intersection.

In vector notation special vectors are used to specify the location of single points – POSITION Vectors

$$\vec{R}_s = x_s\hat{x} + y_s\hat{y} + z_s\hat{z}$$
$$\vec{r}_1 = x_1\hat{x} + y_1\hat{y} + z_1\hat{z}$$
$$\vec{r}_2 = x_2\hat{x} + y_2\hat{y} + z_2\hat{z}$$

COORDINATE SYSTEMS

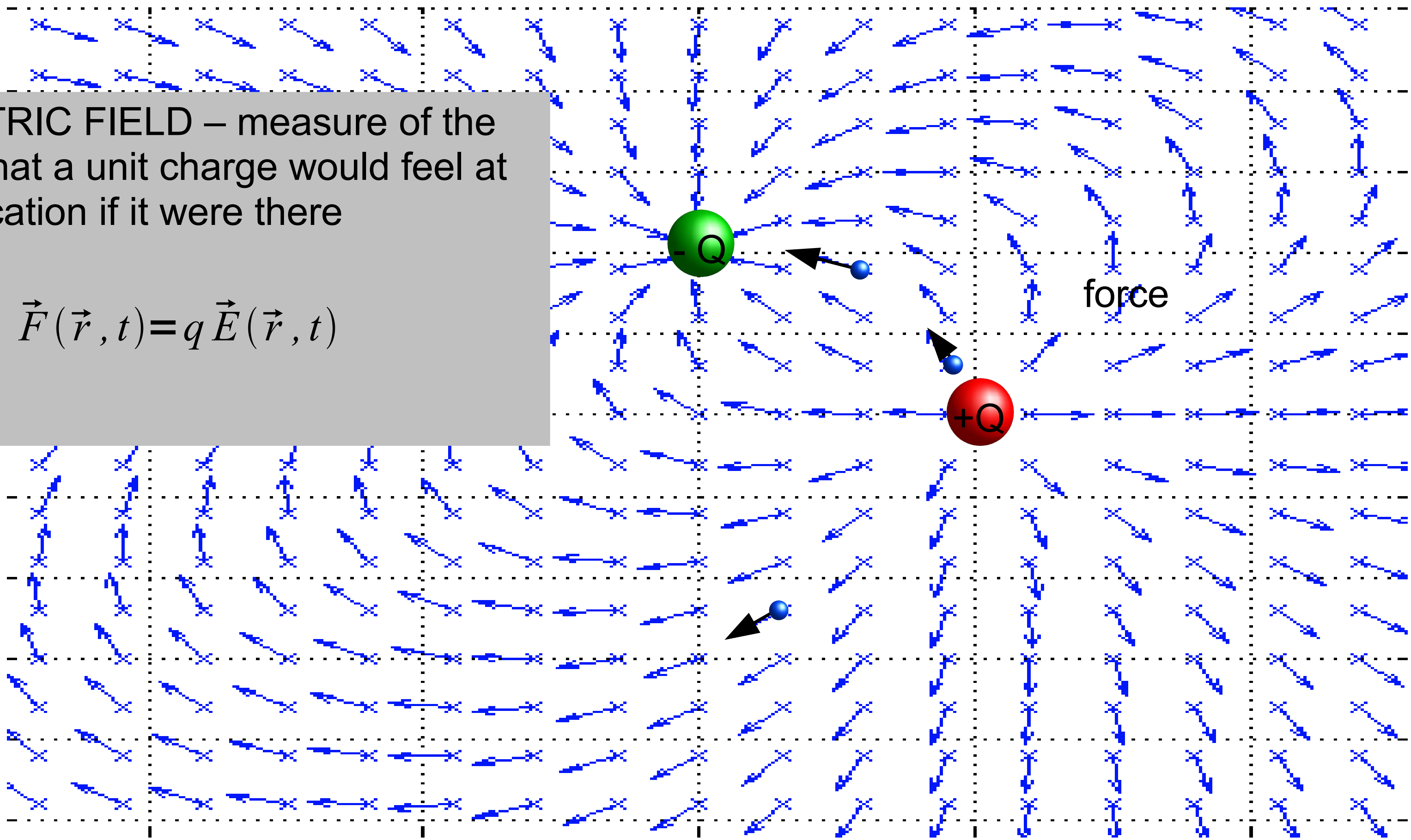
- specify origin
- define method of specifying a point
- define a method of specifying a vector



FIELDS

ELECTRIC FIELD – measure of the force that a unit charge would feel at any location if it were there

$$\vec{F}(\vec{r},t) = q\,\vec{E}(\vec{r},t)$$



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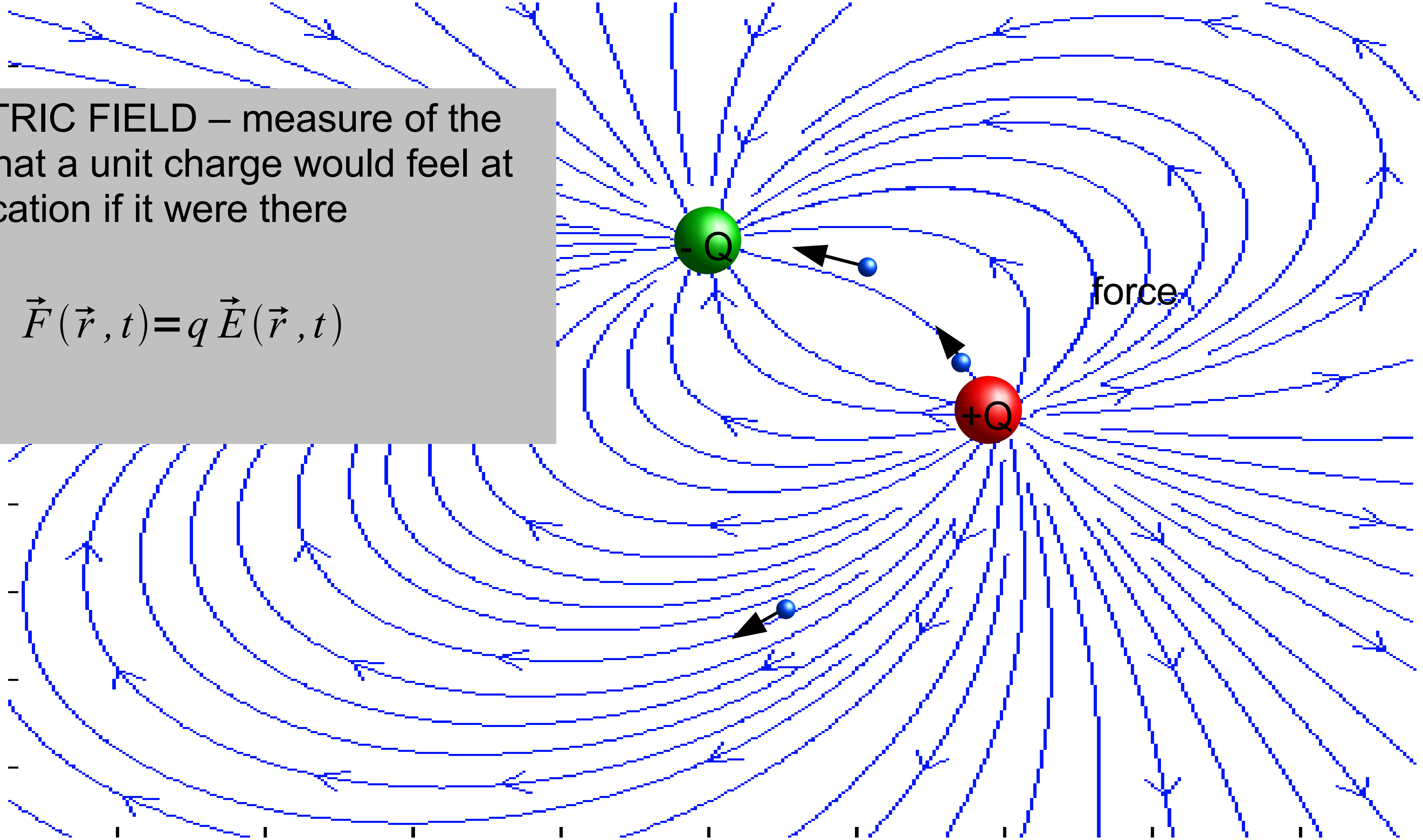


Maxwell equations in integral and differential form

MATH Concepts -

- vector products

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\oint\!\!\oint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oint\!\!\oint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$

E – electric field
B – magnetic field (well not exactly)

the basis for these equations and all of the interesting phenomena are based on 2 very simple concepts:

i) simple interaction between charged particles
ii) delayed response to change

LORENTZ FORCE

Now that we have some notation and the concept of the definition of a field we can investigate how these 2 simple concepts lead to the equation set that is the basis for electromagnetic analysis.

i) simple interaction between charged particles

LORENTZ FORCE – if a charge particle moves in a space where electric and magnetic fields exist it will feel a force generated by both fields in accordance with the following formula:

$$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

it is clear that, depending on one's frame of reference q, the charge particle experiencing the force may or may not be moving. Forces and charge are both quantities that are invariant under changes in reference frame.

WHAT DOES THIS IMPLY ABOUT E and B?

Units in mksA system:

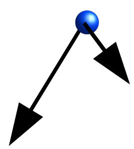
- q[=]C=sA,
- $\mathbf{E}$[=]N/C=V/m,
- $\mathbf{B}$[=]V.s/m^2=Wb/m^2=T,
- ρ[=]C/m^3,
- $\mathbf{J}$[=]A/m^2,

where C, N, V, Wb, and T are abbreviations for *Coulombs*, *Newtons*, *Volts*, *Webers*, and *Teslas*, respectively.

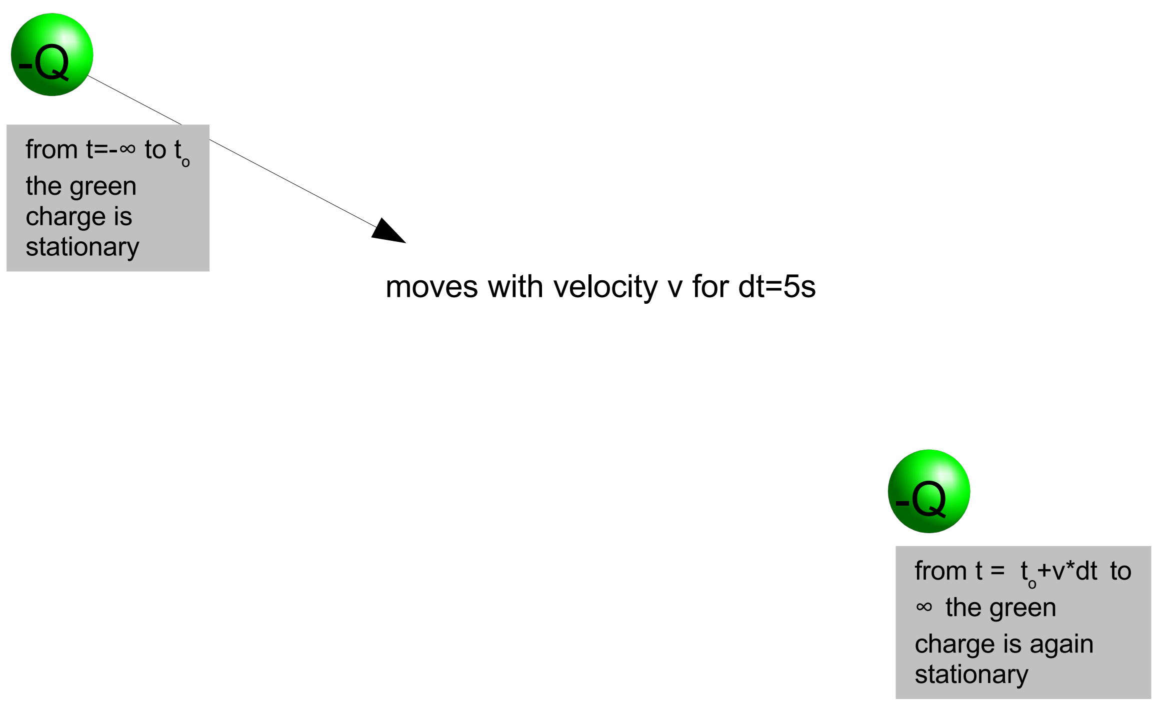
Charge q is quantized in units of $e = 1.602 \times 10^{-19}$ C, a relativistic invariant.

LORENTZ FORCE

i) delayed response to change – this is the property that has allowed electromagnetic theory to remain in tact despite upheavals in the approach to physics brought on by the advent of relativity and quantum mechanics.



What happens to the force that this charge feels?



REVIEW Problems
Coordinate systems/vector notation

Find the distance between two points in space.

- adding and subtracting vectors

Find the amount of work needed to move charges in electric and magnetic fields.

- adding and subtracting vectors
- dot (or scalar, or inner) product

Calculate the angular momentum of a rotating charge.

- adding and subtracting vectors
- cross (or vector, or outer) product

REVIEW Problems
Coordinate systems/vector notation

Find the distance between two points in space.

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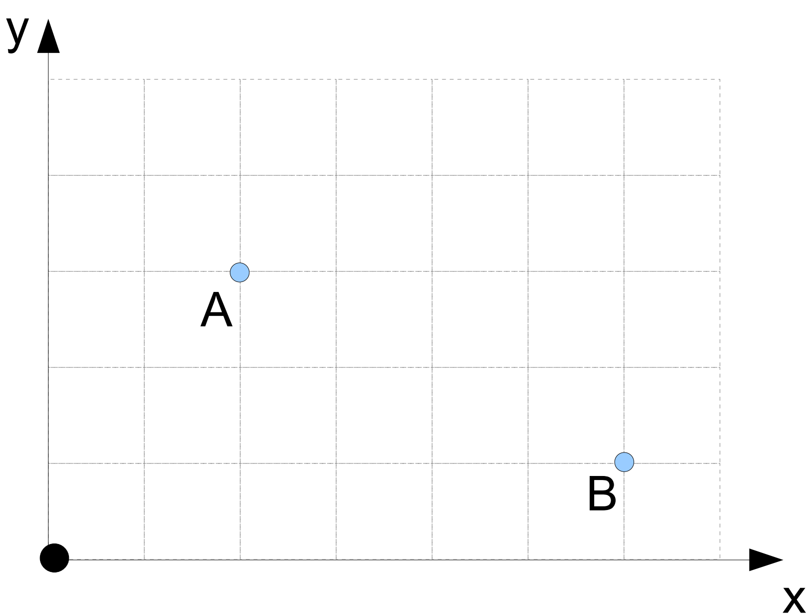
REVIEW Problems
Coordinate systems/vector notation

Find the distance between two points in space.

• adding and subtracting vectors



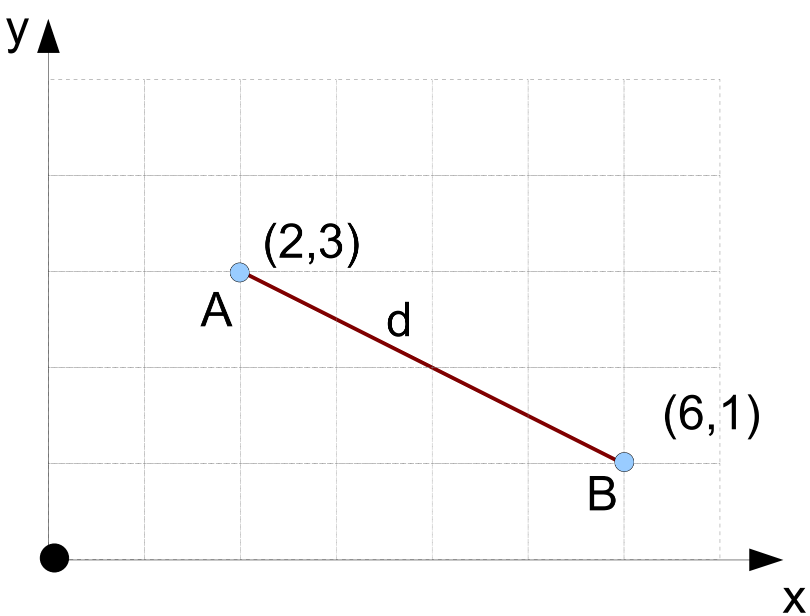
establish coordinate system and units

REVIEW Problems

Coordinate systems/vector notation

Find the distance between two points in space.

• adding and subtracting vectors

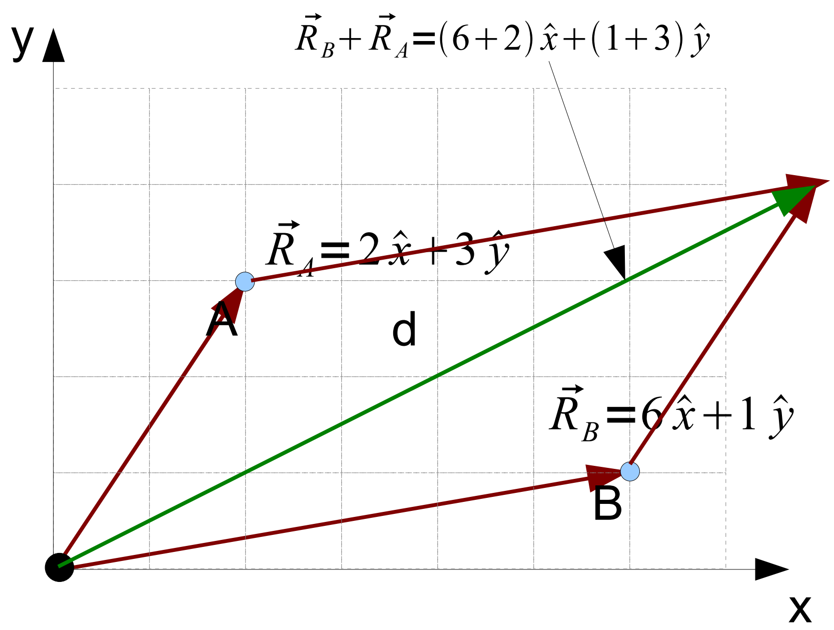


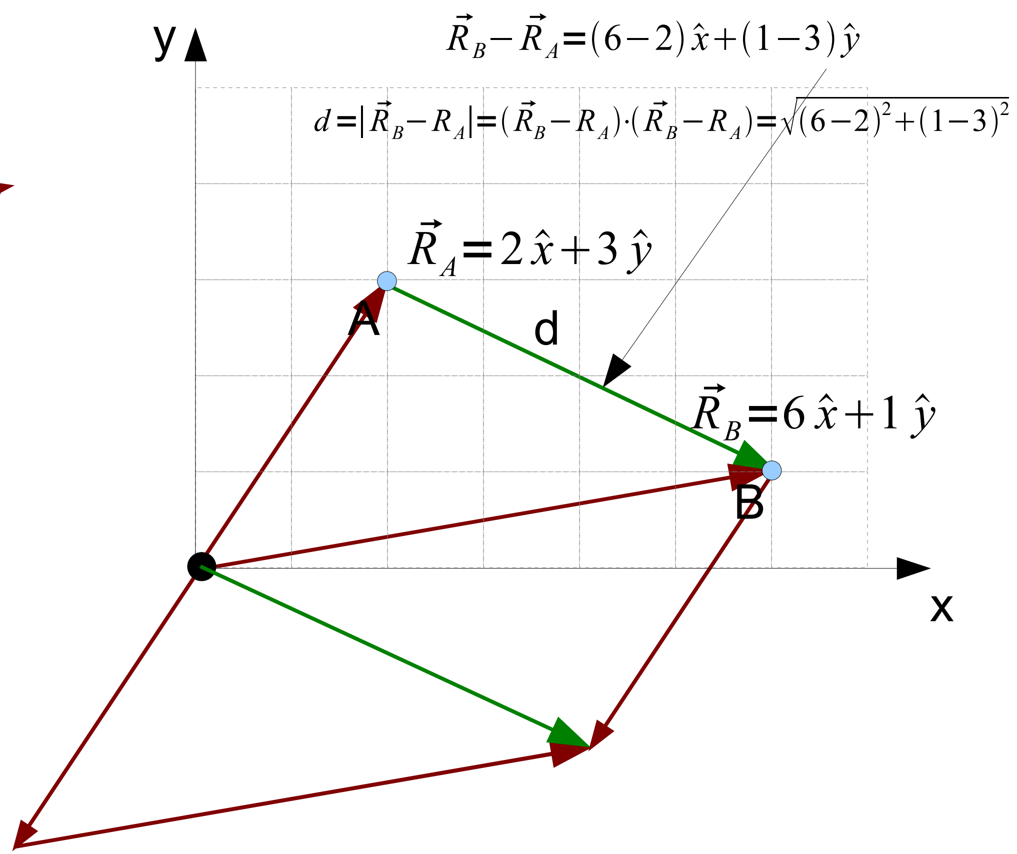
$$d = \sqrt{(2-6)^2 + (3-1)^2}$$

REVIEW Problems
Coordinate systems/vector notation

Find the distance between two points in space.

- adding and subtracting vectors



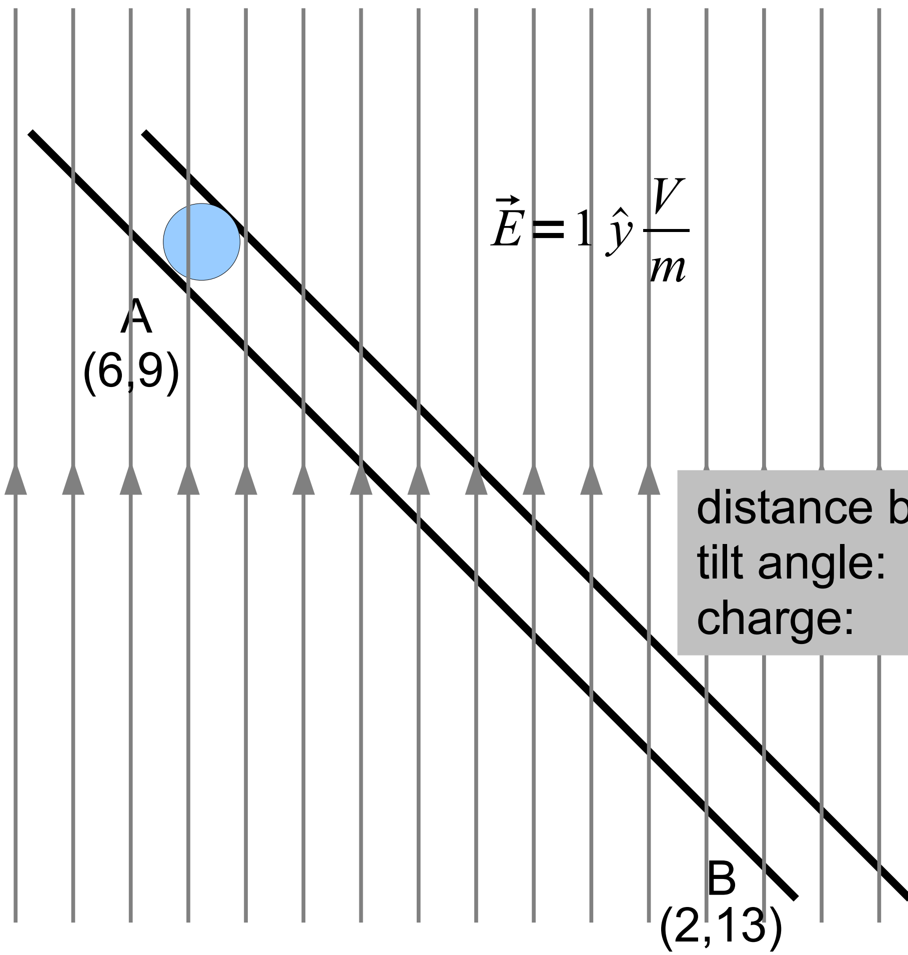


REVIEW Problems

Coordinate systems/vector notation

Find the amount of work needed to move charges in electric and magnetic fields.

- adding and subtracting vectors
- dot (or scalar, or inner) product



Find the work needed to move the charge from point A to point B

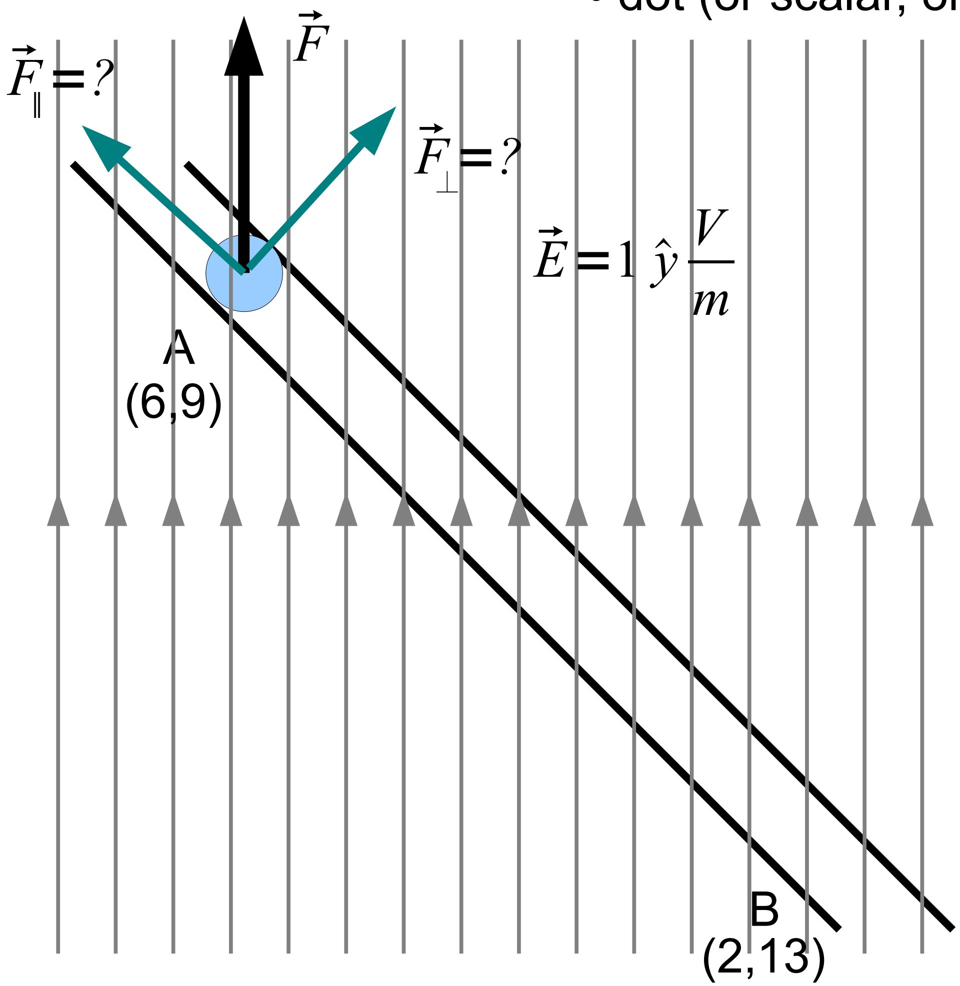
distance between A and B:	d
tilt angle:	θ
charge:	q

REVIEW Problems

Coordinate systems/vector notation

Find the amount of work needed to move charges in electric and magnetic fields.

- adding and subtracting vectors
- dot (or scalar, or inner) product



$$|\vec{F}_{\parallel}|d = work$$

REVIEW Problems
Lorentz Force

calculate the position and velocity of a particle in an electric and/or magnetic field

calculate the electric and magnetic fields present by the motion of charged particles

REVIEW Problems
Lorentz Force

calculate the position and velocity of a particle in an electric and/or magnetic field

$$\vec{F} = m\vec{a} = q\vec{E}$$

$$ma_x = qE_x$$
$$ma_y = qE_y$$
$$ma_z = qE_z$$

REVIEW Problems
Lorentz Force

calculate the position and velocity of a particle in an electric and/or magnetic field

Suppose $E_x = E_o$ and $E_y = E_o$

What do we expect to happen?

$$ma_x = m\frac{dv_x}{dt} = qE_o \quad \text{or} \quad \frac{dv_x}{dt} = \frac{q}{m}E_o$$

this is a simple differential equation that can be solved by simply integrating in time to get -

$$v_x = \frac{q}{m}E_o t + v_o$$

REVIEW Problems
Lorentz Force

$$v_x = \frac{q}{m} E_o t + v_o$$

$$x = \frac{q}{2m} E_o t^2 + v_{ot} + x_o$$

The velocity is shown to increase linearly in time going faster and faster with no limit in the direction of the field – IS THIS CORRECT?

REVIEW Problems

Lorentz Force

calculate the position and velocity of a particle in an electric and/or magnetic field

$$\vec{F} = m\vec{a} = q\vec{E}$$

$$ma_x = qE_x$$

$$ma_y = qE_y$$

$$ma_z = qE_z$$

REVIEW Problems
Lorentz Force

calculate the position and velocity of a particle in an electric and/or magnetic field

Suppose $B_z = B_o$

What do we expect to happen?

$$m\frac{dv_x}{dt} = qB_o v_y$$
$$m\frac{dv_y}{dt} = -qB_o v_x$$

$$\vec{F} = q\,\vec{v} \times \vec{B}$$

this is a simple differential equation set of second order with constant coefficients whose solutions are of the form $v_x = Ae^{st}$

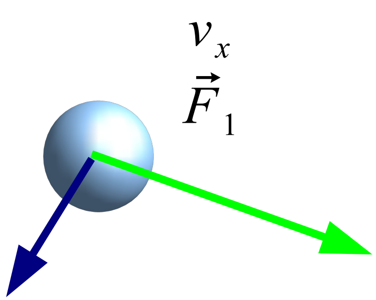
$$\frac{d^2 v_x}{dt^2} + \frac{q^2 B_o^2}{m^2} v_x = 0$$

REVIEW Problems

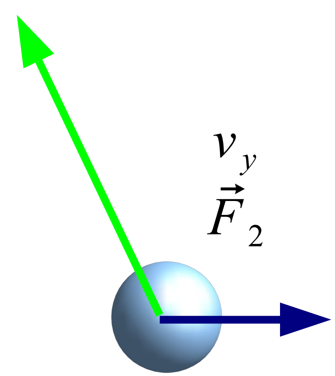
Lorentz Force

calculate the electric and magnetic fields present by the motion of charged particles

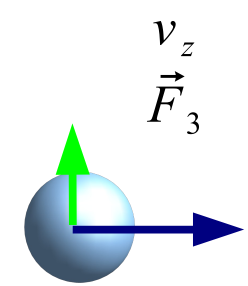
A constant electric field and a constant magnetic field MAY exist – either or both can be present. Suppose you want to know the magnitude and direction of the fields and all you have is a single test charge. What experiment would you perform?



move charge a little bit in the x-direction and measure the force



move charge a little bit in the y-direction and measure the force



move charge a little bit in the z-direction and measure the force

REVIEW Problems

Lorentz Force

$$F_{1x} = qE_x$$
$$F_{1y} = qE_y - q(v_x B_z)$$
$$F_{1z} = qE_z + q(v_x B_y)$$

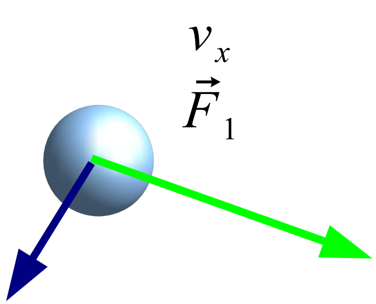
$$F_{2x} = qE_x + q(v_y B_z)$$
$$F_{2y} = qE_y$$
$$F_{2z} = qE_z - q(v_y B_x)$$

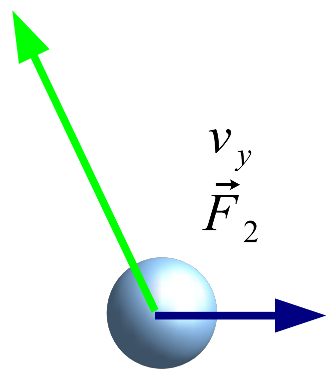
$$F_{3x} = qE_x - q(v_z B_y)$$
$$F_{3y} = qE_y + q(V_z B_x)$$
$$F_{3z} = qE_z$$

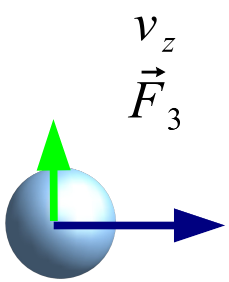
measured quantities

known experiment parameters

desired quantities







move charge a little bit in the x-direction and measure the force

move charge a little bit in the y-direction and measure the force

move charge a little bit in the z-direction and measure the force

REVIEW Problems
Lorentz Force

calculate the electric and magnetic fields present by the motion of charged particles

A constant electric field and a constant magnetic field MAY exist – either or both can be present. Suppose you want to know the magnitude and direction of the fields and all you have is a single test charge. What experiment would you perform?

$$\vec{F}_1 = 0 \quad V_x = 0$$
$$\vec{F}_2 = 0 \quad V_y = 0$$
$$\vec{F}_3 = A\,\hat{z} \quad V_z = 1$$

no information about the magnetic field

$$\vec{F}_1 = 0 \quad V_x = 0$$
$$\vec{F}_2 = 0 \quad V_y = 1$$
$$\vec{F}_3 = A\,\hat{z} \quad V_z = 1$$

$$\vec{F}_1 = 0 \quad V_x = 0$$
$$\vec{F}_2 = 0 \quad V_y = 0$$
$$\vec{F}_3 = A\,\hat{z} \quad V_z = 1$$

some examples – charged particles moving in an antenna

what we know as propagating electromagnetic radiation could be computed this way, but it is completely impossible analytically using these two fundamental properties. It is almost impossible to compute the field of a single moving charge this way, but with perseverience... It was Faraday's and Maxwell's genius – particularly Maxwell to realize that the fields themselves have some very simple properties at a more abstract level which are more amenable to analysis. The sources and fields can be simply connected and – the fields can be substituted for the sources in many cases – radiation is a good example.