Physics 126

P. LeClair

OFFICIAL THINGS

- Dr. Patrick LeClair
  - leclair.homework@gmail.com
  - @pleclair on twitter
  - facebook/google+/etc
  - offices: 2050 Bevill, 323 Gallalee; lab: 1053 Bevill
  - 857-891-4267 (cell)
- Office hours:
  - *MW 1-2pm, F 12-2pm in Gallalee 323*
  - *TuTh 1-3pm in Bevill 2050*
- *other times by appointment*

OFFICIAL THINGS

Lecture/Lab:

- lecture in 329 Gallalee, labs in 112 Gallalee
- M-W 11-12:55

"Recitation":

- F 11-11:55
- usually new material, but time spent on HW

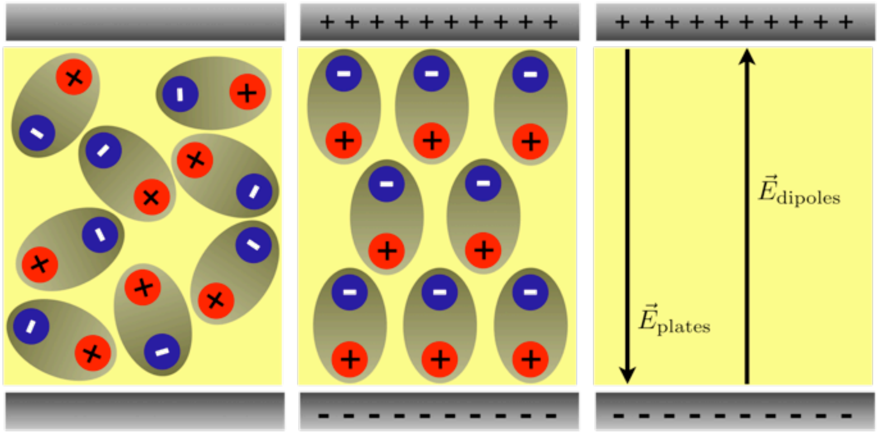
Misc. Format Issues

- lecture and labs will be *somewhat* linked
- labs will mostly be ‘circuits’ and electronics
  - *practical* knowledge more than theory
  - will not bother with the traditional labs

- friday recitations: usually new material
- working in groups is encouraged *for homework*

SOCIAL INTERACTION

- we need you in groups of ~3 for labs to start with
- groups are not assigned ...
  - so long as they remain functional
  - even distribution of workload



Grading and so forth

- labs/exercises 15%
- **homework 25%**

  given weekly via PDF
- quizzes

  maybe. counts with HW
- 4 exams (15% each)

  3 'hour' exams

  comprehensive (takehome) final

Homework

- new set every week, on course blog [pdf]
- problems due a week later (mostly)
- hard copy or email (e.g., scanned, cell pic) are OK

  Gallalee or Bevill mailbox

  at the start of class
- can collaborate - BUT turn in your own
- have to show your work to get credit.

Name & ID ____________________

1.

Find / Given:	**Sketch:**

Relevant equations:	**Symbolic solution:**

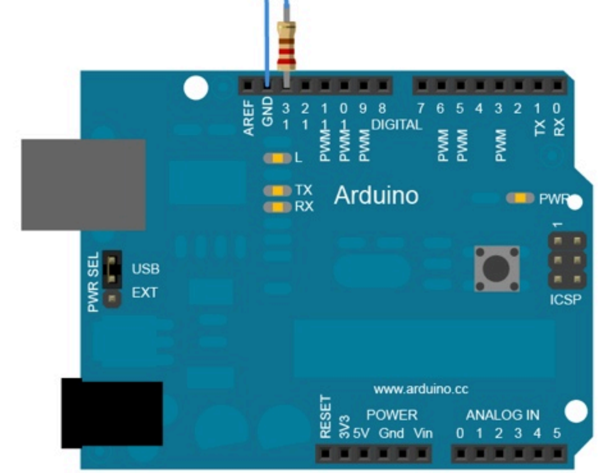
Numeric solution:	**Double Check**	
	Dimensions	Order-of-magnitude

QUIZZES

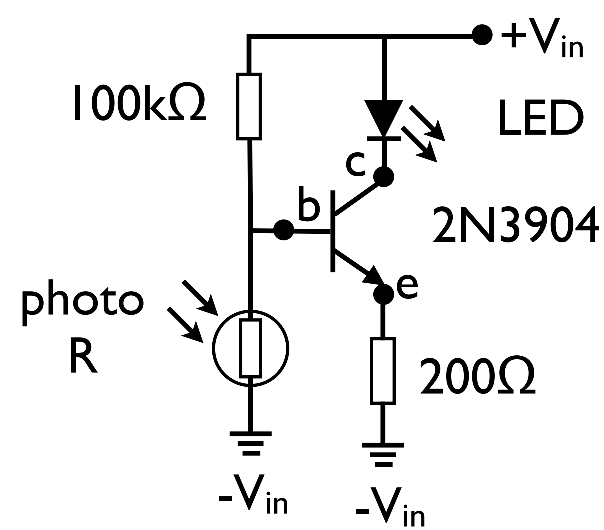
- once and a while, there may be a quiz
- almost the same as current HW problems
- previous lecture’s material
- 5-10 min anticipated

- do the homework & reading, and it will be trivial

LABS / EXERCISES



- labs will be very different ...
  - focus on learning how to build electronic stuff
  - initially: focused labs to learn concepts & practice
  - later: team project
- inquiry-driven: usually no set procedure
- some formal reports, mostly not
- time is always critical …
  - read carefully, work efficiently



STUFF YOU NEED

- textbook (Halliday & Resnick; get a used one)
- calculator
- paper & writing implement
- useful: flash drive, access to a computer you can install stuff on

USEFUL THINGS

Purcell, Edward M. Electricity and Magnetism. In Berkeley Physics Course. 2nd ed. Vol. 2. New York, NY: McGraw-Hill, 1984. ISBN: 9780070049086.

Feynman, Richard P., Robert B. Leighton, and Matthew Sands. The Feynman Lectures on Physics. 2nd ed. Vol. 1-2. Reading, MA: Addison-Wesley, 2005. ISBN: 9780805390452.

Horowitz, Paul and Hill, Winfield. The Art of Electronics 2nd ed. Cambridge University Press, 1989. ISBN: 0521370957

For some material (e.g., optics and circuits) we will make use of supplemental online notes from PH102, which you can find there:

`http://faculty.mint.ua.edu/~pleclair/ph102/Notes/`

have the Feynman lectures in the undergrad lounge ...

SHOWING UP

- no make-up of in-class work or homework

  "acceptable" + documented gets you a BYE

- missing an exam is seriously bad.

  acceptable reason ... makeup or weight final

- lowest single lab, homework are dropped.

- Final is take-home, but you will have questions ...

  so stick around for a bit of finals week

INTERNETS

- we have our own intertubes:
  - http://ph126.blogspot.com/
  - updated very often
  - comments allowed & encouraged
  - rss feed, integrated with twitter (#ua-ph126)
- **google calendar** (you can subscribe)
- **Facebook group** (find each other)
  - can add RSS feed of blog to facebook
- google+, it is the new shiny
- check blog & calendar before class

Quick advertisement:

Phy-EE double major

- Electrical and Computer Engineering majors need as few as 4 additional hours to complete a second major in Physics.
- This combination of fundamental and applied physics can be highly advantageous when the graduate enters the job market.

Today

- Vectors and vector functions
- Laws of E&M in brief
- Charge & electric forces in brief

Our friend the vector

- we will be doing terrible things with them this semester.

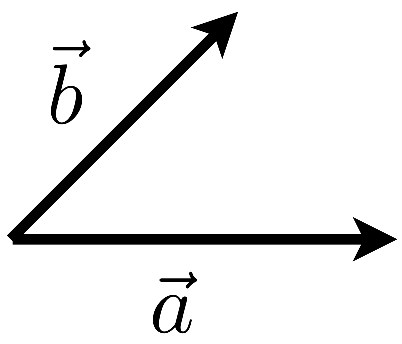
- vector = quantity requiring an arrow to represent
  - *coordinate-free* description
  - described by basis (unit) vectors of a coordinate system

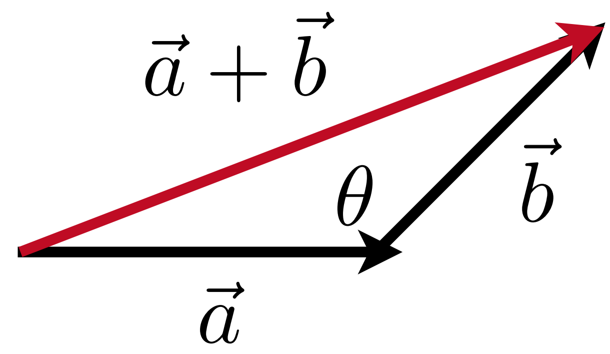
- proper vectors are unchanged by coordinate transformations ...

Adding & subtracting vectors

- commutative, A+B = B+A
- associative, A + (B+C) = (A+B) + C
- subtracting = add negative (reverse direction)

- add head-tail geometrically (law of cosines)
- add by component (using unit vectors)





Geometrically:

$$|\vec{a}+\vec{b}| = |\vec{a}| + |\vec{b}| - 2|\vec{a}||\vec{b}|\cos\theta$$

By components: first choose a basis/coordinate system

$$\vec{a} = a_x\hat{x} + a_y\hat{y} \qquad \vec{b} = b_x\hat{x} + b_y\hat{y}$$

$$\vec{a}+\vec{b} = (a_x + b_x)\,\hat{x} + (a_y + b_y)\,\hat{y}$$

magnitude identical to geometric approach

Scalar multiplication

- Duh, the vector gets longer.
- By component:

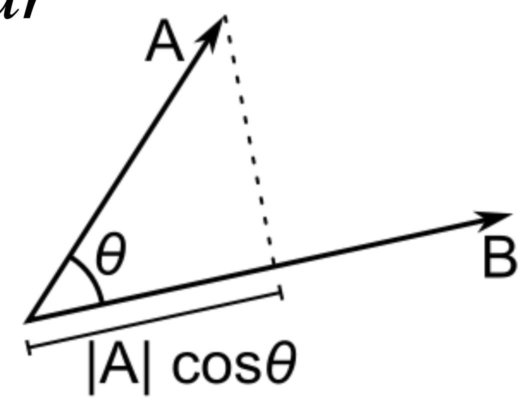
$$c\vec{A} = ca_x\hat{x} + ca_y\hat{y}$$

- Geometrically: the arrow gets *c* times longer
- Distributive.

$$c\left(\vec{A} + \vec{B}\right) = c\vec{A} + c\vec{B}$$

Scalar ("dot") product

- product of vector A and the projection of B onto A
- scalar product of two vectors gives a *scalar*



$$\vec{A} \cdot \vec{B} = a_x b_x + a_y b_y = |\vec{A}||\vec{B}| \cos\theta_{AB}$$

- commutes, distributes

$$\vec{A} \cdot \vec{B} = \vec{B} \cdot \vec{A} \qquad \vec{A} \cdot \left(\vec{B} + \vec{C}\right) = \vec{A} \cdot \vec{B} + \vec{A} \cdot \vec{C}$$

- two vectors are perpendicular if and only if their scalar product is zero

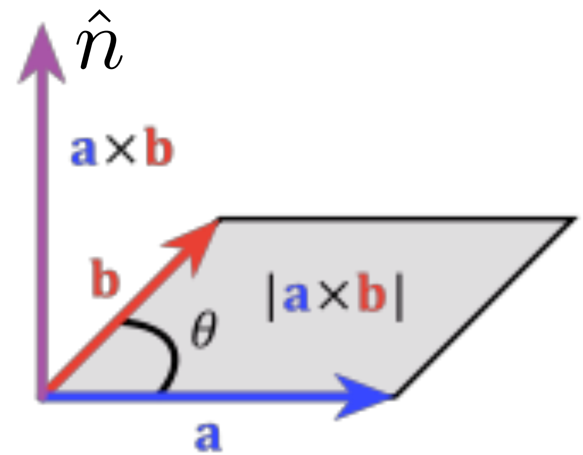
formula	relationship
$\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} = \vec{\mathbf{b}} \cdot \vec{\mathbf{a}}$	commutative
$\vec{\mathbf{a}} \cdot (\vec{\mathbf{b}} + \vec{\mathbf{c}}) = \vec{\mathbf{a}} \cdot \vec{\mathbf{b}} + \vec{\mathbf{a}} \cdot \vec{\mathbf{c}}$	distributive
$\vec{\mathbf{a}} \cdot (r\vec{\mathbf{b}} + \vec{\mathbf{c}}) = r(\vec{\mathbf{a}} \cdot \vec{\mathbf{b}}) + r(\vec{\mathbf{a}} \cdot \vec{\mathbf{c}})$	bilinear
$(c_1\vec{\mathbf{a}}) \cdot (c_2\vec{\mathbf{b}}) = (c_1 c_2)(\vec{\mathbf{a}} \cdot \vec{\mathbf{b}})$	multiplication by scalars
if $\vec{\mathbf{a}} \perp \vec{\mathbf{b}}$, then $\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} = 0$	orthogonality

vector ("cross") product

- product of vector A and B, gives 3rd vector perpendicular to A-B plane

$$|\vec{A} \times \vec{B}| = |\vec{A}||\vec{B}| \sin\theta_{AB}$$

$$\vec{A} \times \vec{B} = \vec{A}\vec{B} \sin\theta_{AB}\,\hat{n}$$



- Distributes, does **NOT** commute

$$\vec{A} \times \left(\vec{B} \times \vec{C}\right) = \left(\vec{A} \times \vec{B}\right) + \left(\vec{A} \times \vec{C}\right)$$

$$\vec{A} \times \vec{B} = -\left(\vec{B} \times \vec{A}\right)$$

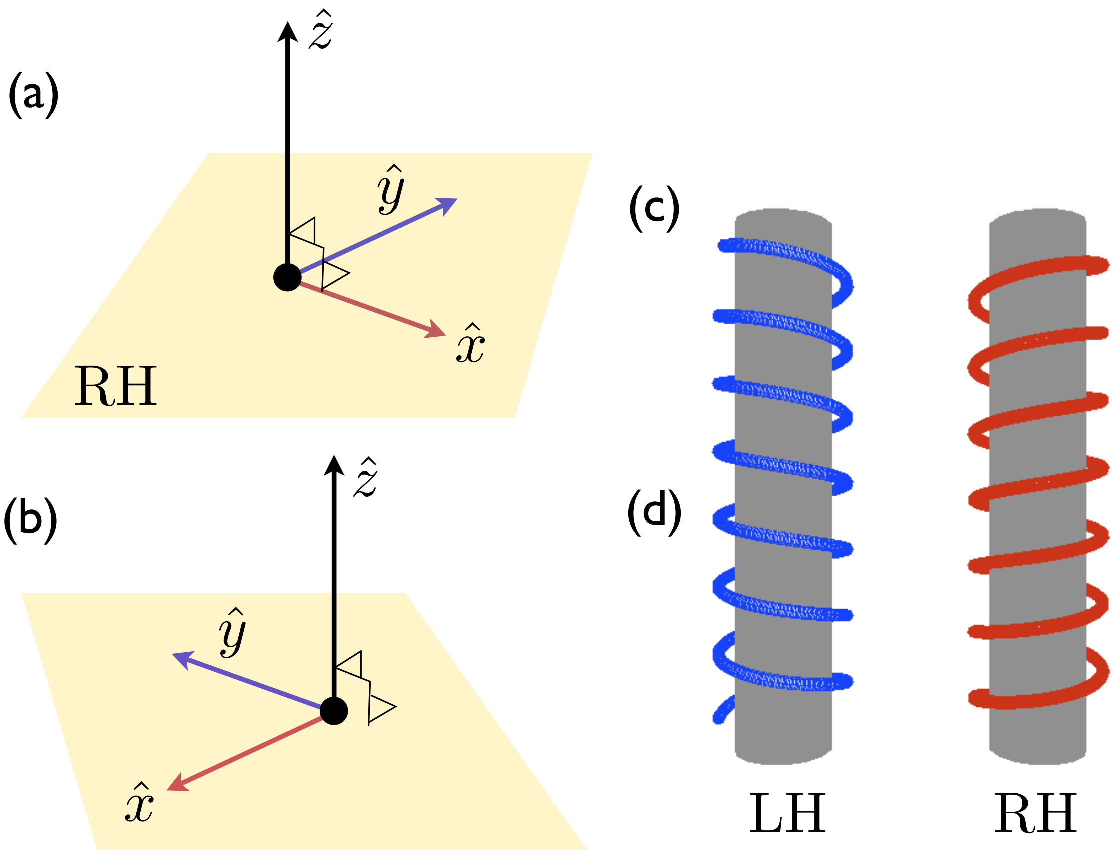
familiarize yourself with these things later ...

formula	relationship
$\vec{\mathbf{a}} \times \vec{\mathbf{b}} = -\vec{\mathbf{b}} \times \vec{\mathbf{a}}$	anticommutative
$\vec{\mathbf{a}} \times \left(\vec{\mathbf{b}} + \vec{\mathbf{c}}\right) = \left(\vec{\mathbf{a}} \times \vec{\mathbf{b}}\right) + (\vec{\mathbf{a}} \times \vec{\mathbf{c}})$	distributive over addition
$(r\vec{\mathbf{a}}) \times \vec{\mathbf{b}} = \vec{\mathbf{a}} \times (r\vec{\mathbf{b}}) = r(\vec{\mathbf{a}} \times \vec{\mathbf{b}})$	compatible with scalar multiplication
$\vec{\mathbf{a}} \times (\vec{\mathbf{b}} \times \vec{\mathbf{c}}) + \vec{\mathbf{b}} \times (\vec{\mathbf{c}} \times \vec{\mathbf{a}}) + \vec{\mathbf{c}} \times (\vec{\mathbf{a}} \times \vec{\mathbf{b}}) = 0$	not associative; obeys Jacobi identity
$\vec{\mathbf{a}} \times (\vec{\mathbf{b}} \times \vec{\mathbf{c}}) = \vec{\mathbf{b}}(\vec{\mathbf{a}} \cdot \vec{\mathbf{b}}) - \vec{\mathbf{c}}(\vec{\mathbf{a}} \cdot \vec{\mathbf{b}})$	triple vector product expansion
$(\vec{\mathbf{a}} \times \vec{\mathbf{b}}) \times \vec{\mathbf{c}} = -\vec{\mathbf{c}} \times (\vec{\mathbf{a}} \times \vec{\mathbf{b}}) = -\vec{\mathbf{a}}(\vec{\mathbf{b}} \cdot \vec{\mathbf{c}}) + \vec{\mathbf{b}}(\vec{\mathbf{a}} \cdot \vec{\mathbf{c}})$	triple vector product expansion
$\vec{\mathbf{a}} \cdot (\vec{\mathbf{b}} \times \vec{\mathbf{c}}) = \vec{\mathbf{b}} \cdot (\vec{\mathbf{c}} \times \vec{\mathbf{a}}) = \vec{\mathbf{c}} \cdot (\vec{\mathbf{a}} \times \vec{\mathbf{b}})$	triple scalar product expansion†
$\lvert\vec{\mathbf{a}} \times \vec{\mathbf{b}}\rvert^2 + \lvert\vec{\mathbf{a}} \cdot \vec{\mathbf{b}}\rvert^2 = \lvert\vec{\mathbf{a}}\rvert^2 \lvert\vec{\mathbf{b}}\rvert^2$	relation between cross and dot product
if $\vec{\mathbf{a}} \times \vec{\mathbf{b}} = \vec{\mathbf{a}} \times \vec{\mathbf{c}}$ then $\vec{\mathbf{b}} = \vec{\mathbf{c}}$ iff $\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} = \vec{\mathbf{a}} \cdot \vec{\mathbf{c}}$	lack of cancellation

vector ("cross") product

- 'perpendicular' direction not unique!

  choice of 'handedness' or chirality. we pick RH.

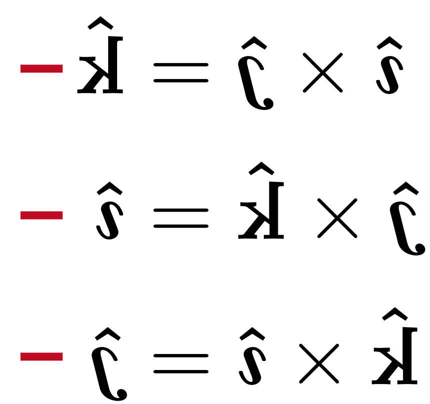


cross products are not the same as their mirror images

$$\hat{\imath} \times \hat{\jmath} = \hat{\mathbf{k}}$$

$$\hat{\jmath} \times \hat{\mathbf{k}} = \hat{\imath}$$

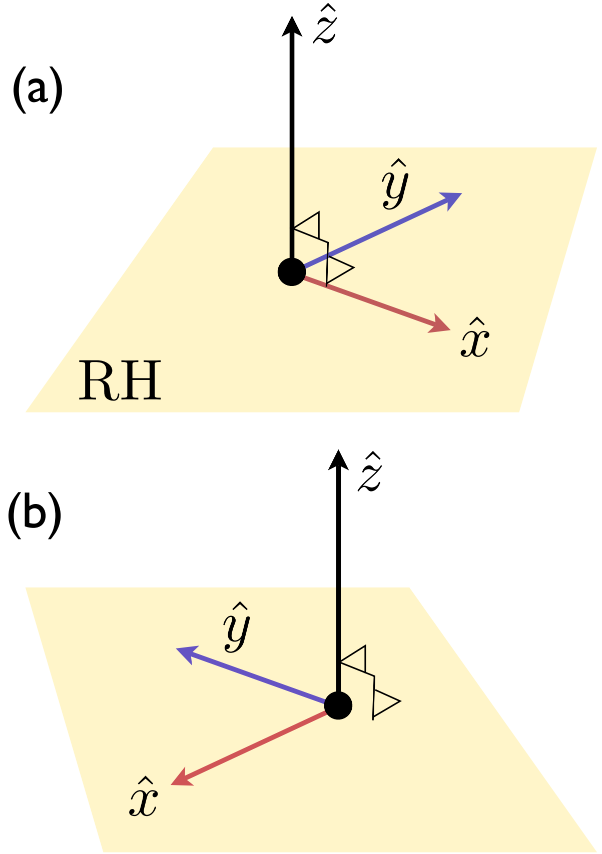
$$\hat{\mathbf{k}} \times \hat{\imath} = \hat{\jmath}$$



- Because of 'handedness' choice, cross products do not transform like true vectors under inversion

e.g., coordinate systems

$$\hat{x} \times \hat{y} = \hat{z}$$



- cannot make RH into LH by proper rot.
- requires an inversion too (mirror flip)
- rotation + sign change required

- lack of invariance under improper rotation makes it a *pseudovector* or *axial vector*
- *i.e.*, you need an axis of rotation to make sense of it.
- *e.g.*, torque, magnetic field

- when we see cross products ...
  - somewhere, there is an axis of rotation
  - the problem is inherently 3D

- cross product of two ‘normal’ polar vectors = axial vector
  - polar = velocity, momentum, force
  - axial = torque, angular momentum, magnetic field

- axial vector = handedness = RH rule required
- axial vector doesn’t change properly in a mirror
  - e.g., angular momentum of car wheels reflected in a mirror

- if there is *no change* when reflected in a mirror ... polar!

(polar) x (polar) = (axial)

$r \times p = L$ (angular momentum)

(axial) x (axial) = (axial)

$\Omega \times L = \tau$ (gyroscope)

(polar) x (axial) = (polar)

$v \times B = F$ (magnetic force)

(any) · (any) = (scalar)

(polar) + (axial) = (neither) !!!

- cyclic permutation encodes chirality ...

$$\vec{\mathbf{c}} = \vec{\mathbf{a}} \times \vec{\mathbf{b}}$$

$$\vec{\mathbf{c}} = \begin{vmatrix} \hat{\boldsymbol{\imath}} & \hat{\boldsymbol{\jmath}} & \hat{\mathbf{k}} \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix} = \begin{vmatrix} a_y & a_z \\ b_y & b_z \end{vmatrix} \hat{\boldsymbol{\imath}} + \begin{vmatrix} a_z & a_x \\ b_z & b_x \end{vmatrix} \hat{\boldsymbol{\jmath}} + \begin{vmatrix} a_x & a_y \\ b_x & b_y \end{vmatrix} \hat{\mathbf{k}}$$

$$= (a_y b_z - a_z b_y)\, \hat{\boldsymbol{\imath}} + (a_z b_x - a_x b_z)\, \hat{\boldsymbol{\jmath}} + (a_x b_y - a_y b_x)\, \hat{\mathbf{k}}$$

- xyz, yzx, zxy = +   yxz, xzy, zyx = -
- know and love this little trick
- note ... one can use the cross product to find the vector normal to a given plane

$$\hat{n} = \frac{\vec{A} \times \vec{B}}{|\vec{A} \times \vec{B}|}$$

Vector triples ... key identities that will come up often.

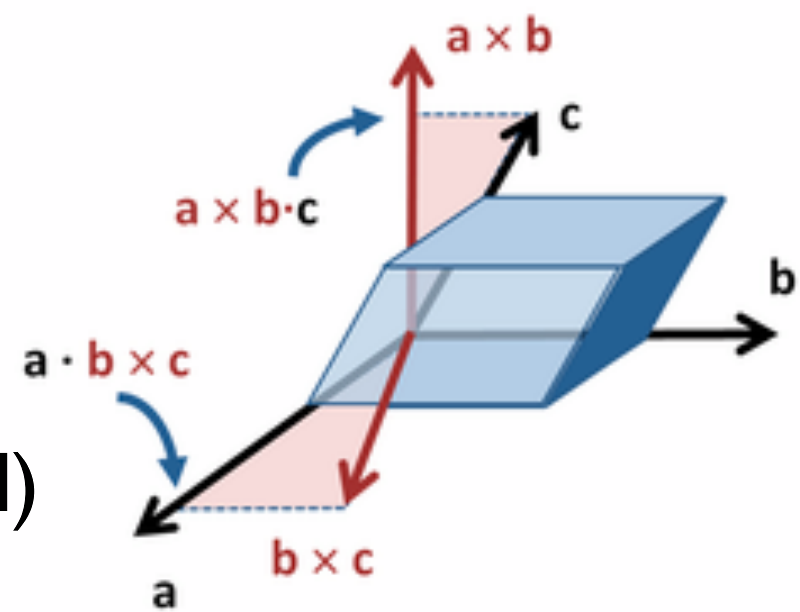
$$\vec{A} \cdot \left(\vec{B} \times \vec{C}\right) = (\text{vec}) \cdot (\text{vec} \times \text{vec}) = \text{vec} \cdot \text{vec} = \text{scalar}$$

$$\vec{A} \cdot \left(\vec{B} \times \vec{C}\right) = \vec{B} \cdot \left(\vec{C} \times \vec{A}\right) = \vec{C} \cdot \left(\vec{A} \times \vec{B}\right)$$

cyclic permutation! break it, and pick up a minus sign

$$\vec{A} \cdot \left(\vec{B} \times \vec{C}\right) = -\vec{B} \cdot \left(\vec{A} \times \vec{C}\right)$$

(also, the volume of a parallelepiped)



component form is nicely simple in matrix notation

$$\vec{\mathbf{A}} \cdot \left(\vec{\mathbf{B}} \times \vec{\mathbf{C}}\right) = \begin{vmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \end{vmatrix} = (a_x b_y c_z - a_x b_z c_y) + (a_y b_z c_x - a_y b_x c_z) + (a_z b_x c_y - a_z b_y c_x)$$

xyz, yzx, zxy = +   yxz, xzy, zyx = -

distributes, associates, etc, and this works too:

$$\vec{A} \cdot \left(\vec{B} \times \vec{C}\right) = \left(\vec{A} \times \vec{B}\right) \cdot \vec{C}$$

this is nonsense though. why?

$$\left(\vec{A} \cdot \vec{B}\right) \times \vec{C}$$

vector triple

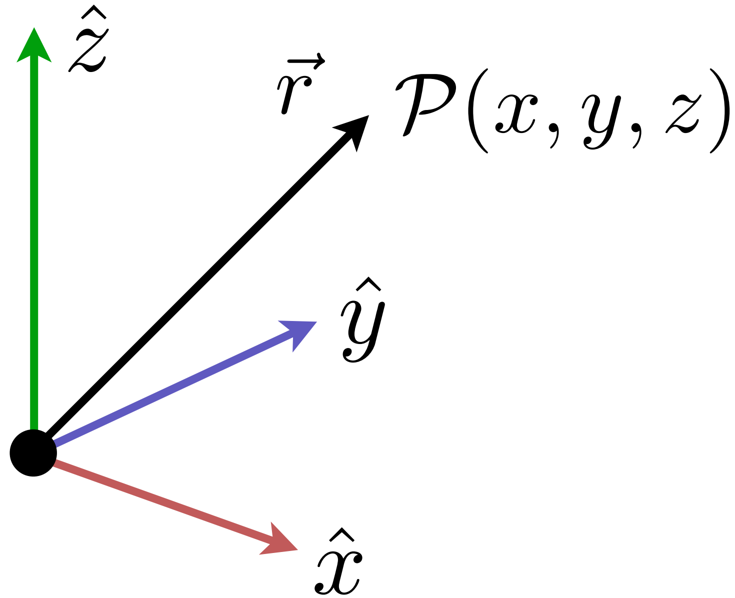
$$\vec{A} \times \left(\vec{B} \times \vec{C}\right) = \vec{B}\left(\vec{A} \cdot \vec{C}\right) - C\left(\vec{A} \cdot \vec{B}\right) \neq \left(\vec{A} \times \vec{B}\right) \times \vec{C}$$

vec scal vec scal

"BAC-CAB" rule

it will come up; this reduction formula is handy

a reminder that X does not commute



$$|\vec{r}|^2 = x^2 + y^2 + z^2 = \vec{r} \cdot \vec{r}$$

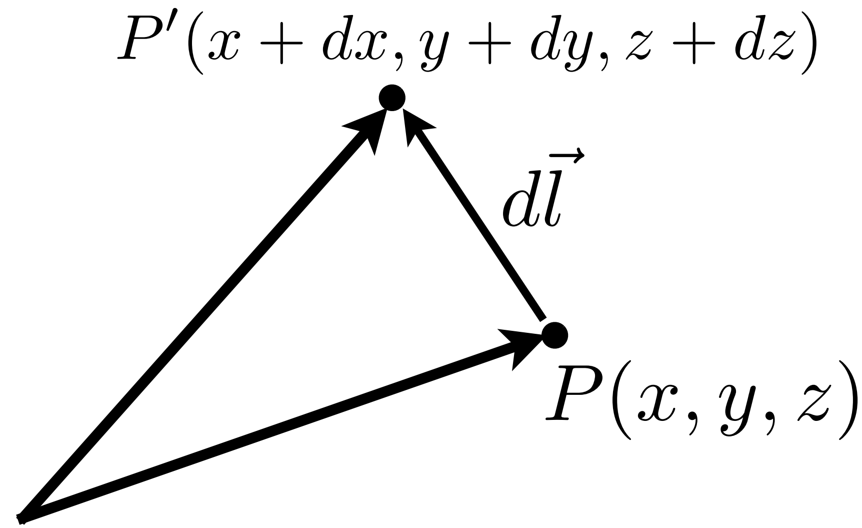
$$\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$$

$$\hat{r} = \frac{\vec{r}}{|\vec{r}|}$$

we remember how to define positions & directions infinitesimal displacements along a path

$$(x, y, z) \to (x + dx, y + dy, z + dz)$$

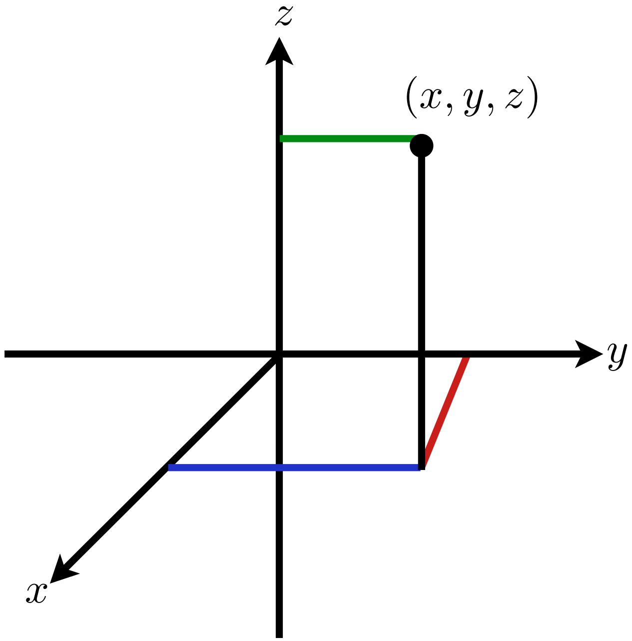
described by a infinitesimal vector



$$d\vec{l} = dx\,\hat{x} + dy\,\hat{y} + dz\,\hat{z}$$

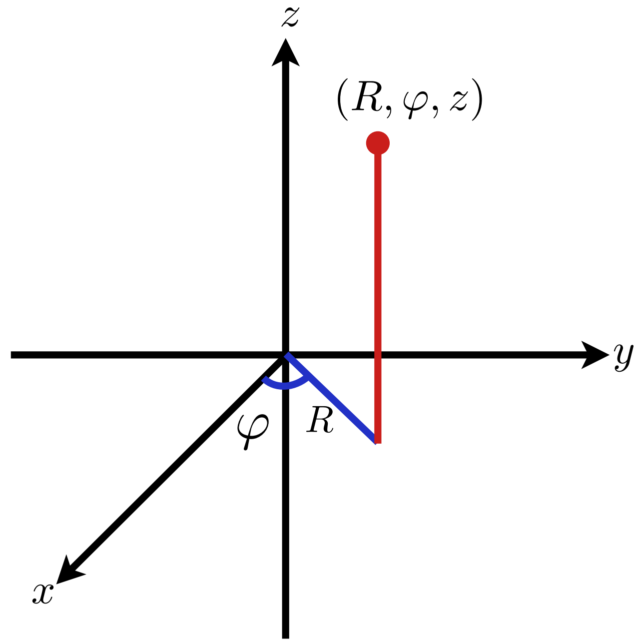
depends on coordinate system

$$d\vec{l} = dr\,\hat{r} + r\sin\theta\,d\theta\,\hat{\theta} + r\,dr\,d\theta\,\hat{\varphi}$$ (spherical)



cartesian

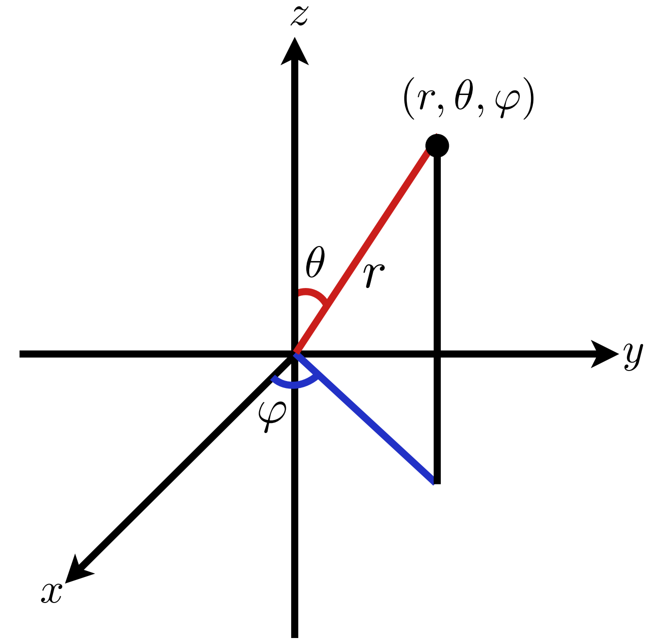
x,y,z



cylindrical

R,φ,z

s,φ,z



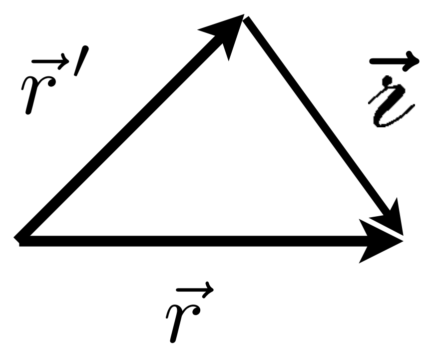
spherical

r,θ,φ

in E&M, we often have a SOURCE point and a FIELD point

we are interested in quantities depending on their separation

(where stuff is)



(where you are)

$$\vec{\mathscr{r}} = \vec{\mathbf{r}} - \vec{\mathbf{r}}'$$

separation vector

(between you & stuff)

like in physics 1: the origin can be in an arbitrary place

you are interested in how far you are from stuff

r = from origin to you

r’ = from origin to stuff

difference = from stuff to you!

we need two new concepts to deal with vector fields.

but only two!

(1) Flux

(2) Circulation

Flux?

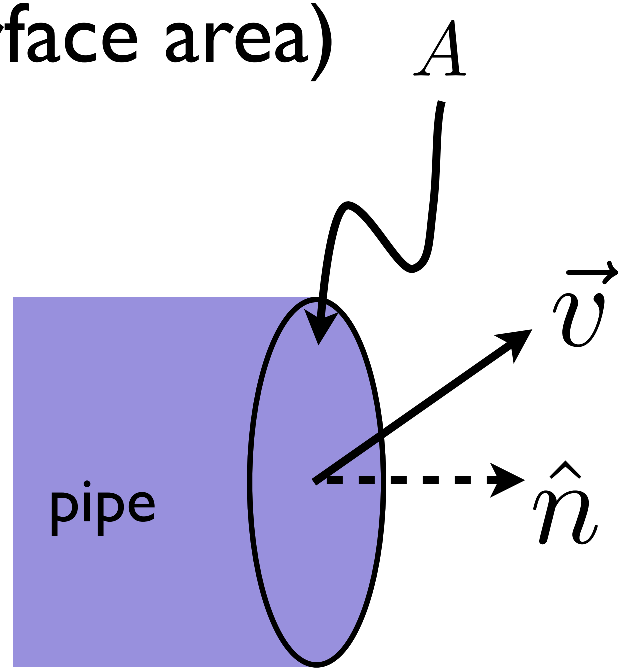
basically, the net flow of a quantity through a region

e.g., liquid flux: liters/sec through a pipe of diameter *d*

Need to define a flow and a surface!

(Flux) = (average normal component)(surface area)

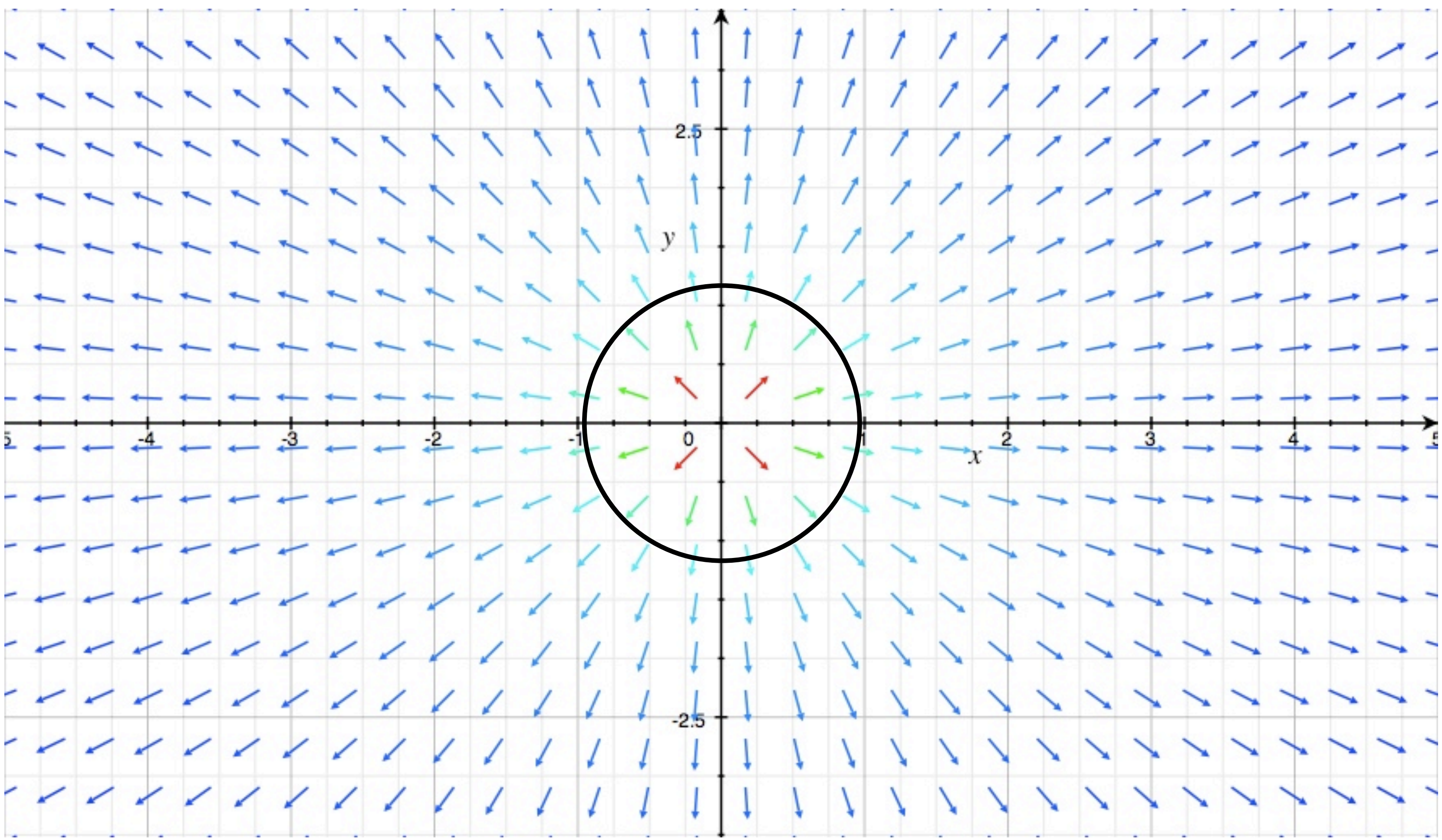
$$\Phi_{\text{water}} = (\rho \vec{v} \cdot \hat{n})\, A$$

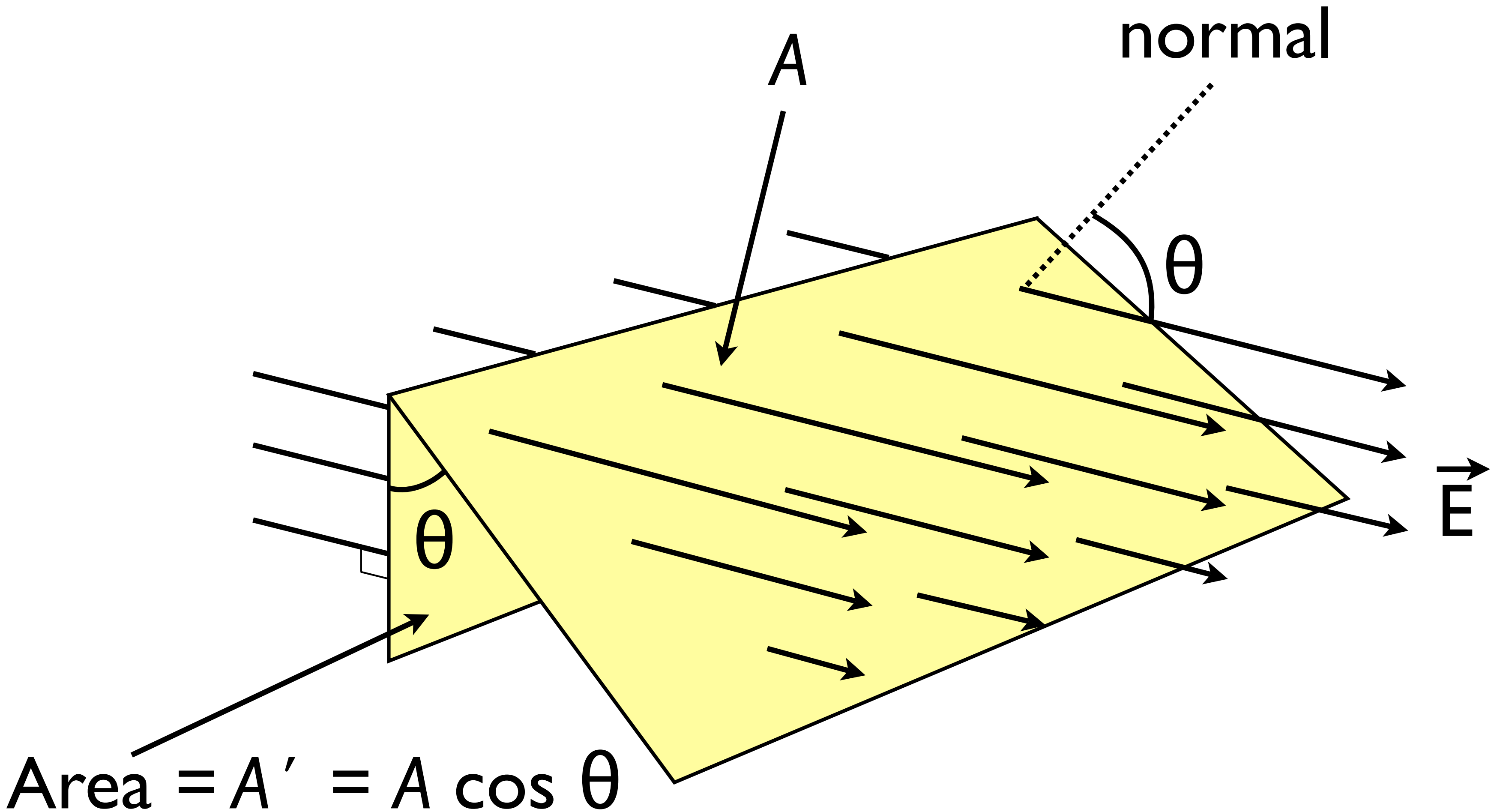


net flux through a *closed* region:
must be a source or sink inside!

Net flux through circle - more arrows leave than enter

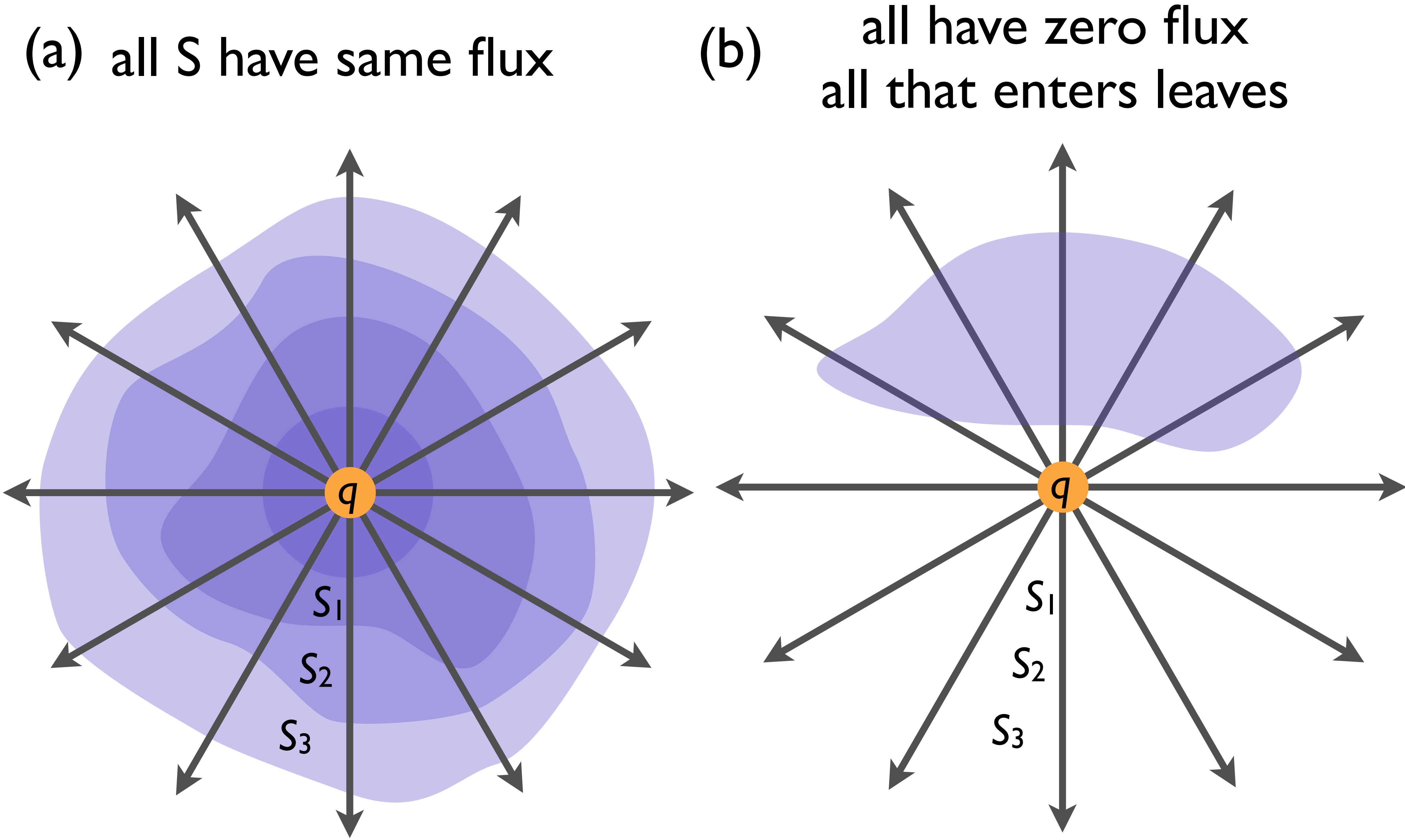
$$\vec{F} = \frac{\hat{r}}{r^2}$$





both surfaces have the same flux!

net ‘flow’ of a vector field out of a closed region



Circulation?

Just what you think it is: is the field 'swirling' at all?
Does it circulate?
Given some loop, is there net rotation?

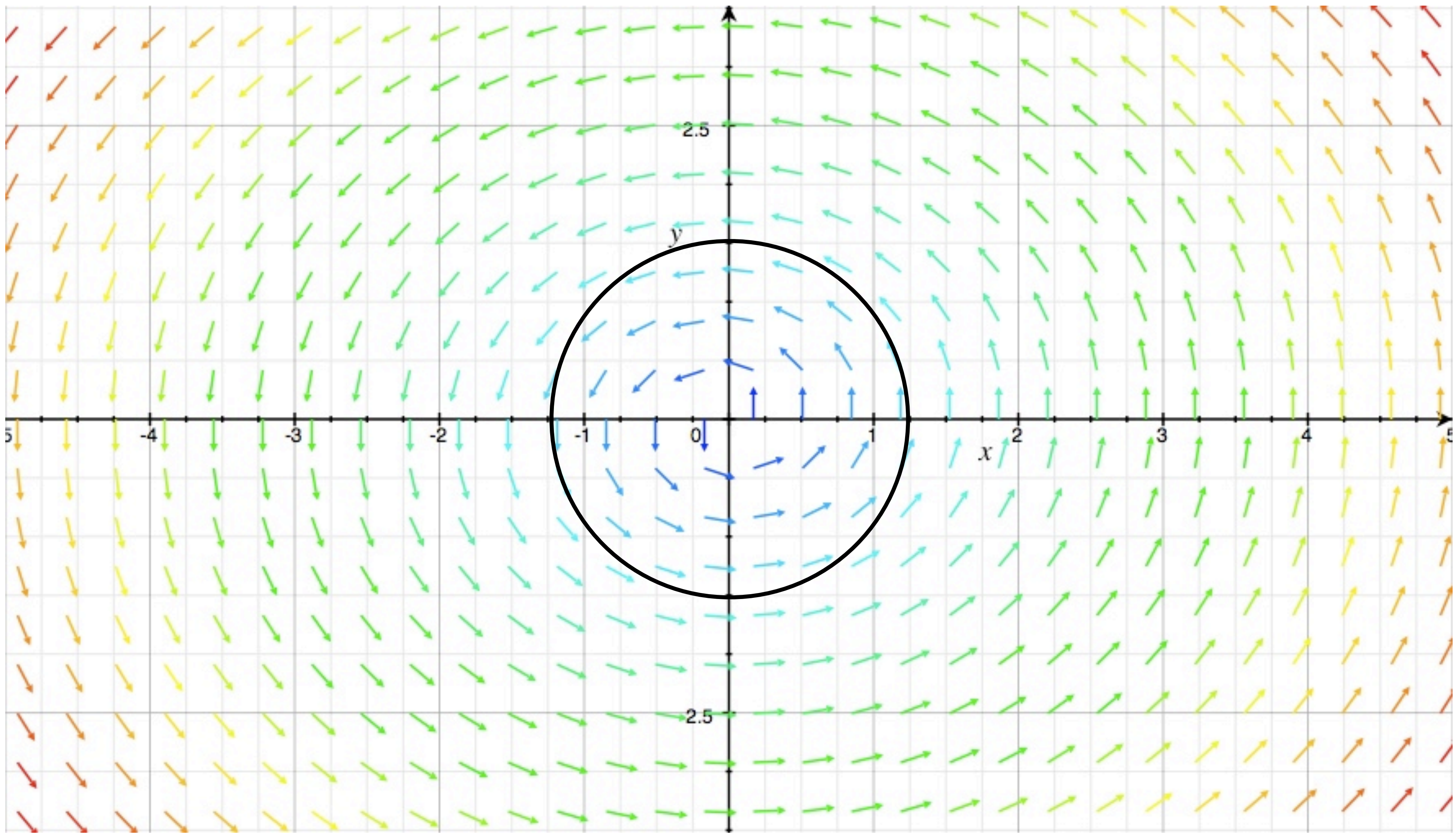
E.g., stirred pot
    there is no net flux
    there *is* a *circulation*

circulation = (average tangential speed around a loop)(circumference)

pick a loop in the field, and find the average tangential velocity
if it is nonzero, the field circulates!

net CCW tangential velocity
angular velocity about z axis

$$\vec{F}(x,y) = -y\hat{x} + x\hat{y}$$



E&M: all about flux and circulation of E & B

$$\text{(flux of E through a closed surface)} = \frac{\text{(net charge inside)}}{\epsilon_o}$$

$$\text{(flux of B through any closed surface)} = 0$$

given a curve C bounding a surface S:

$$\text{(circulation of E around C)} = \frac{d}{dt}\text{(flux of B through S)}$$

$$c^2\text{(circulation of B around C)} = \frac{d}{dt}\text{(flux of E through S)} + \frac{\text{(flux of electric current through S)}}{\epsilon_o}$$

So how to do this quantitatively?

We need vector derivatives for that.
Later.

The laws of classical physics, in brief

1. Motion

$$\frac{d\vec{p}}{dt} = \vec{F} \qquad \text{where} \qquad \vec{p} = \frac{m\vec{v}}{\sqrt{1 - v^2/c^2}}$$

Newton, with Einstein's modification

2. Gravitation

$$\vec{F} = -G\frac{m_1 m_2}{r^2}\,\hat{r}_{12}$$

3. Conservation of charge

$$\vec{\nabla} \cdot \vec{j} = -\frac{d\rho}{dt}$$

(flux of current through closed surface) = - (rate of change of charge inside)

any conservation of stuff:

(net flow of stuff out of a region) =
(rate at which amount of stuff inside region changes)

4. Maxwell's equations

$$\vec{\nabla} \cdot \vec{\mathbf{E}} = \frac{\rho}{\epsilon_r \epsilon_0}$$

(flux of E thru closed surface) = (charge inside)

$$\vec{\nabla} \cdot \vec{\mathbf{B}} = 0$$

(flux of B thru closed surface) = 0

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

(circulating E) = (time varying B)

(line integral of E around loop) = -(change of B flux through loop)

$$\epsilon_0 c^2 \vec{\nabla} \times \vec{\mathbf{B}} = \vec{\mathbf{j}} + \epsilon_r \frac{\partial \vec{\mathbf{E}}}{\partial t}$$

(circulating B) = (time varying E)

(integral of B around loop) = (current through loop) + (change of E flux through loop)

4. Maxwell's equations (alt)

$$\vec{\boldsymbol{\nabla}} \cdot \vec{\mathbf{E}} = \frac{\rho}{\epsilon_r \epsilon_0}$$

Gauss: electric charge = source of electric fields

$$\vec{\boldsymbol{\nabla}} \cdot \vec{\mathbf{B}} = 0$$

There are no magnetic charges

$$\vec{\boldsymbol{\nabla}} \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

Faraday: time-varying B makes a circulating E

$$\epsilon_0 c^2 \vec{\boldsymbol{\nabla}} \times \vec{\mathbf{B}} = \vec{\mathbf{j}} + \epsilon_r \frac{\partial \vec{\mathbf{E}}}{\partial t}$$

Ampere: currents and time-varying E make B

5. Force law

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

And that's all of it!

Of course, the solutions are tougher ...
but we have a whole semester for that.

electrostatics

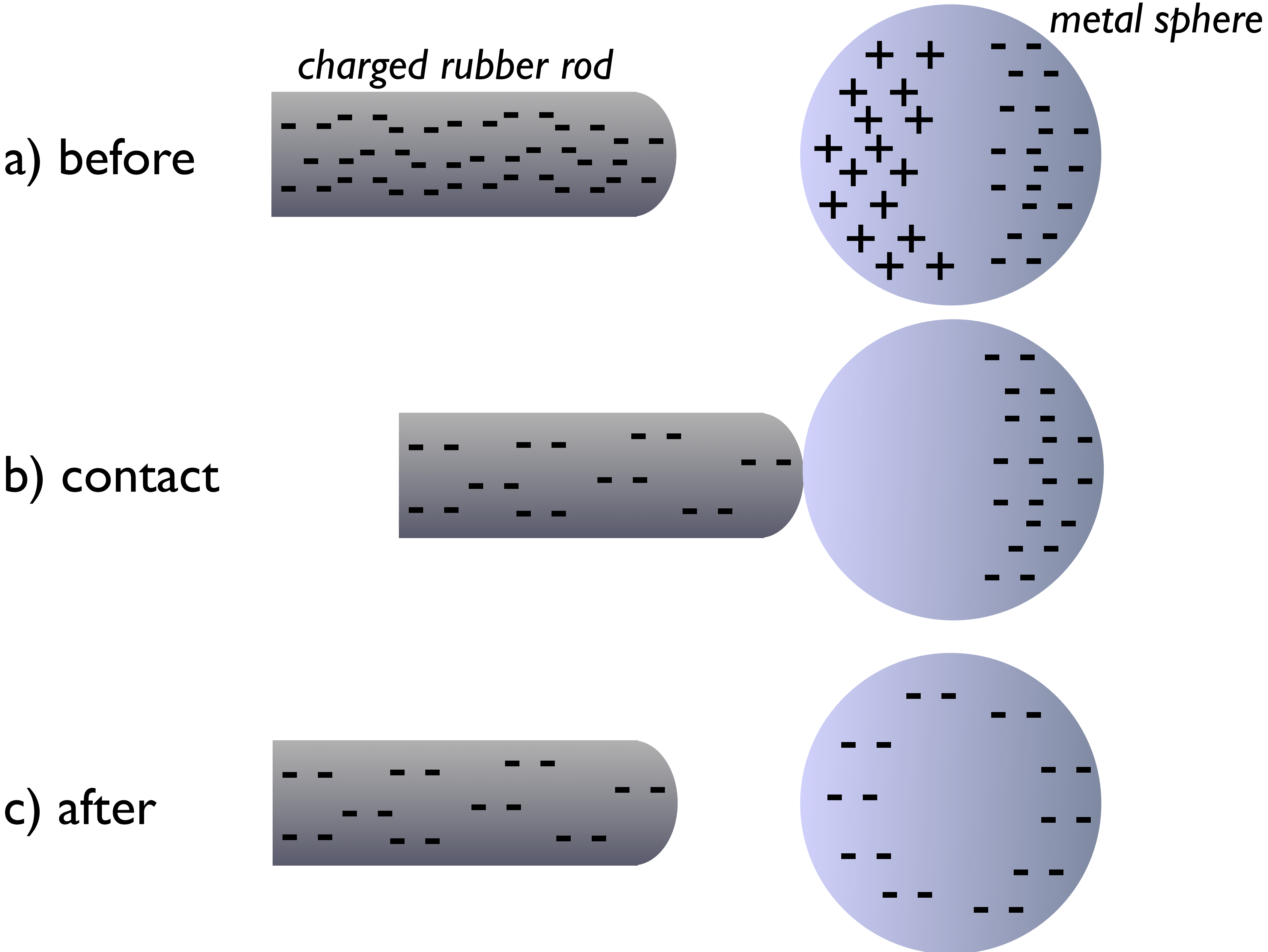
or, electric forces when nothing is moving.

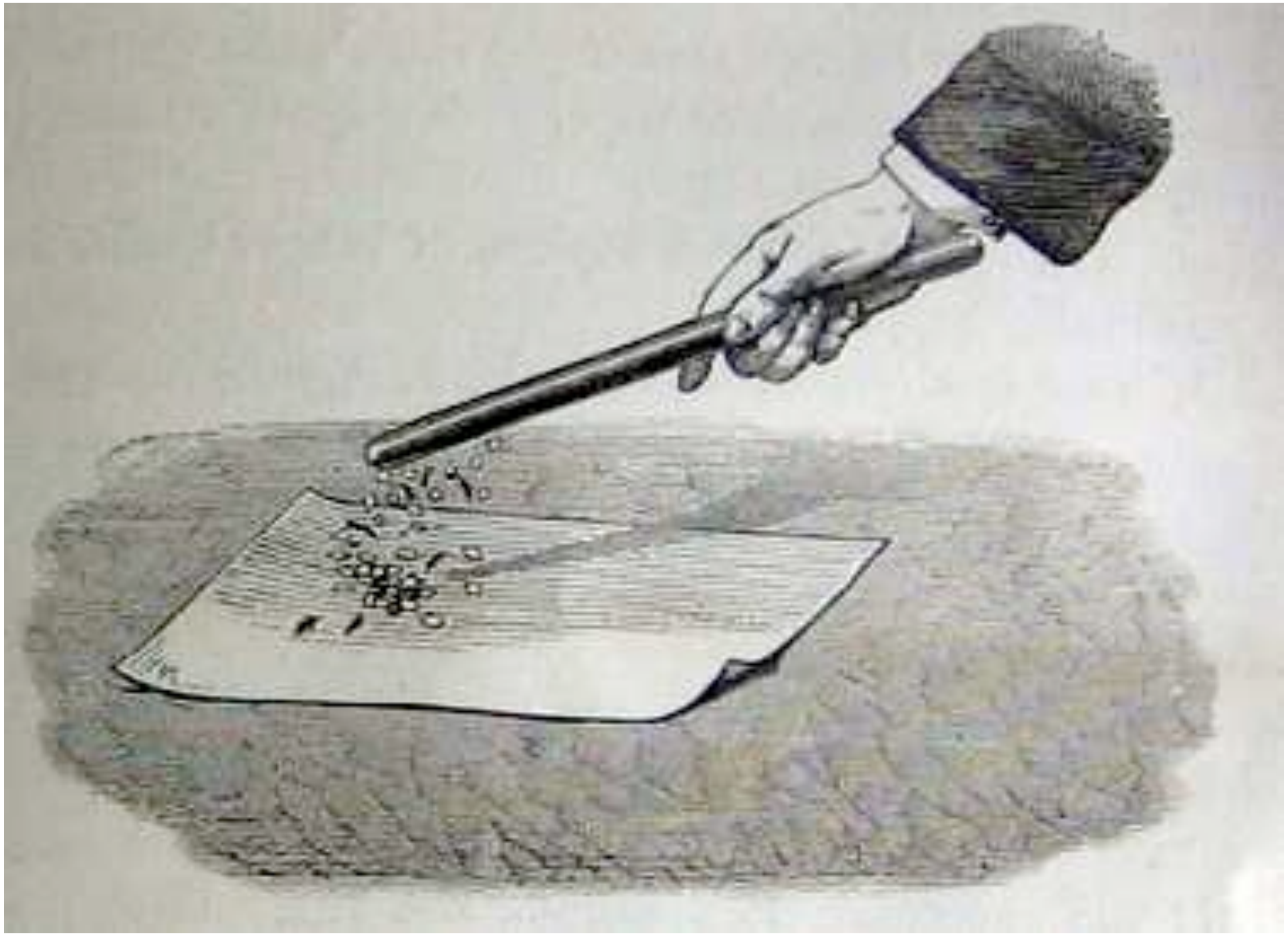
Summarizing the properties of charge:

1. Charge is quantized in units of $|e| = 1.6 \times 10^{-19}$ C
2. Electrons carry one unit of negative charge, $-e$
3. Protons carry one unit positive charge, $+e$
4. Objects become charged be gaining or losing electrons, not protons
5. Electric charge is always conserved

Table 3.1: *Properties of electrons, protons, and neutrons*

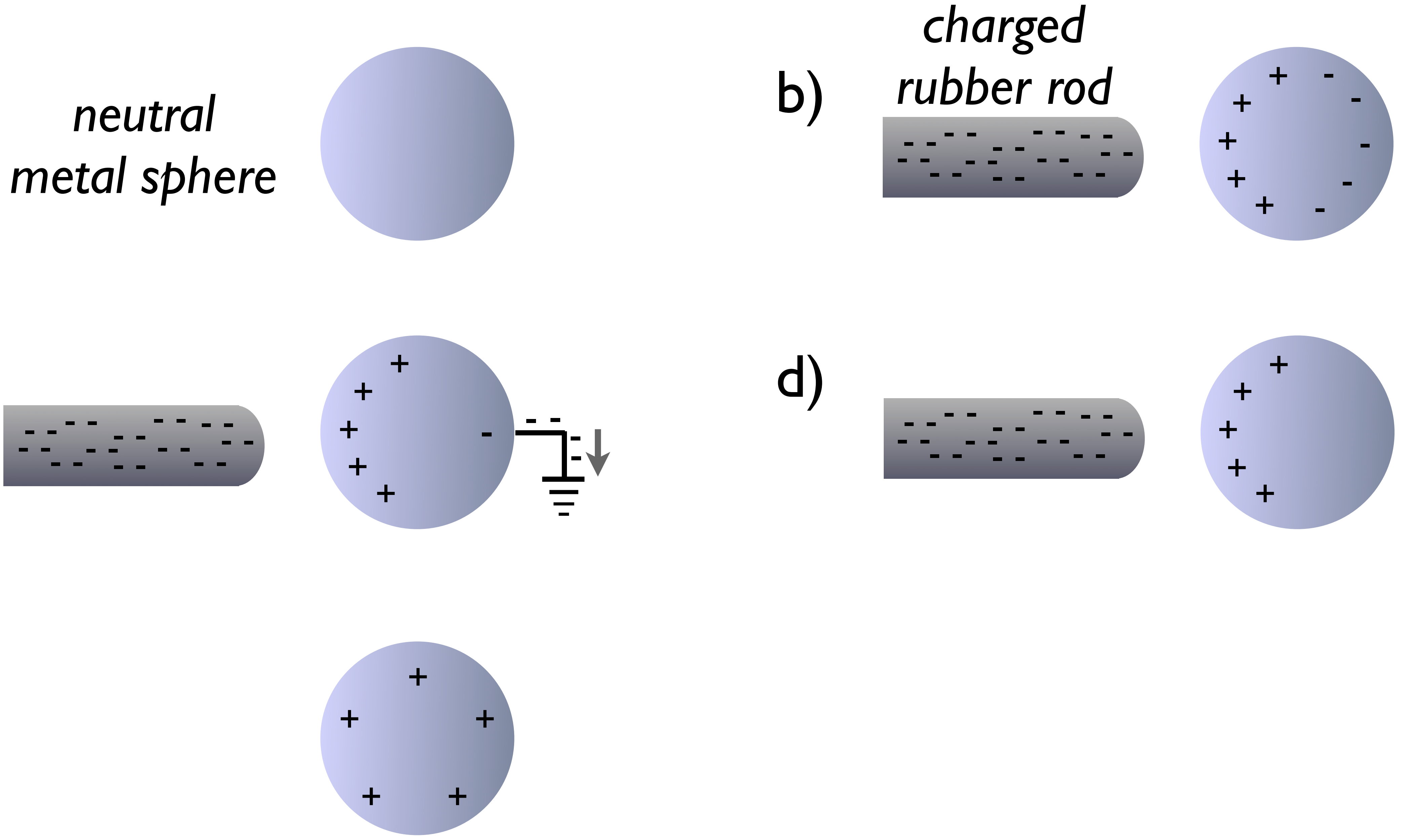
Particle	**Charge [C]**	$[e]$	**Mass [kg]**
electron (e^-)	-1.60×10^{-19}	-1	9.11×10^{-31}
proton (p^+)	$+1.60\times10^{-19}$	$+1$	1.67×10^{-27}
neutron (n^0)	0	0	1.67×10^{-27}


metal sphere
charged rubber rod
a) before
b) contact
c) after

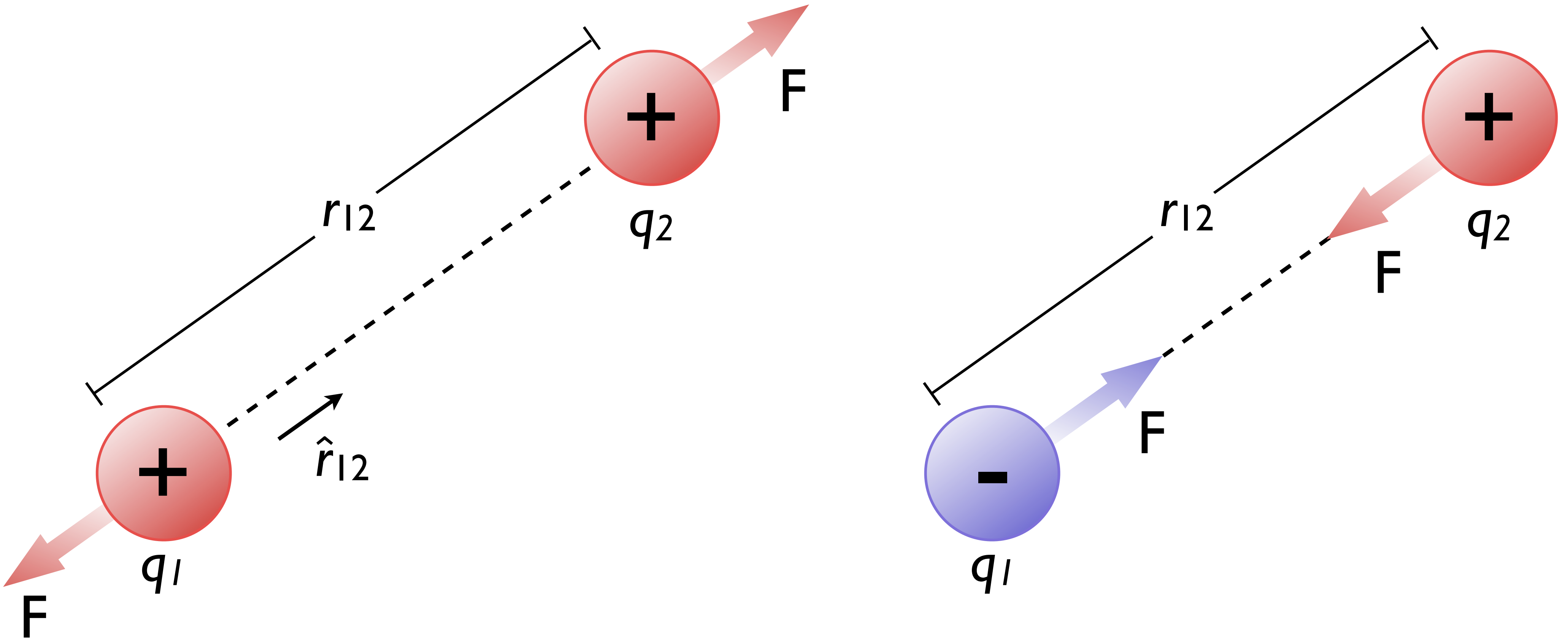


"Little pieces of tissue paper (or light grains of sawdust) are attracted by a glass rod rubbed with a silk handkerchief (or by a piece of sealing wax or a rubber comb rubbed with flannel)."

- from a random 1902 science book

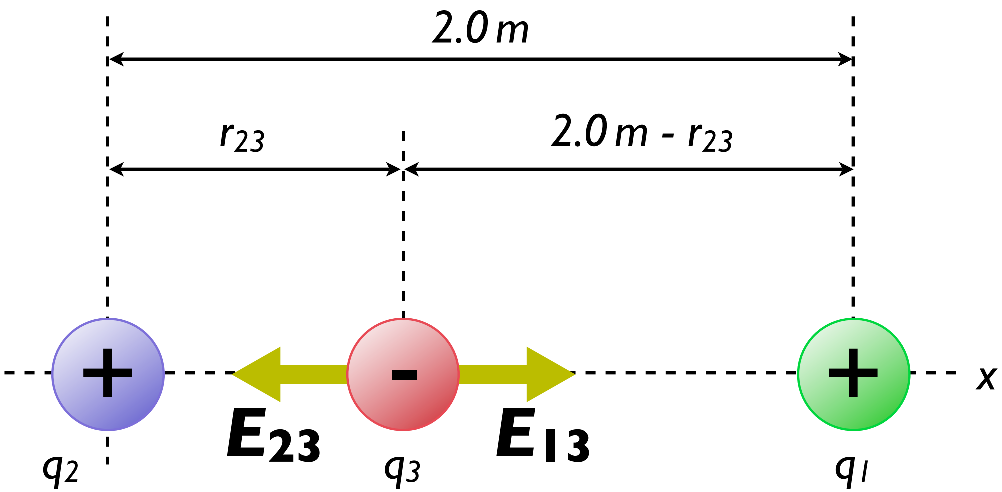


neutral
metal sphere
b)
charged
rubber rod
d)



F
r_{12}
q_2
$\hat{r}_{12}$
q_1
F
F
r_{12}
q_2
F
F
q_1

2. Three point charges lie along the x axis, as shown at left. A positive charge $q_1 = 15\,\mu\text{C}$ is at $x = 2\,\text{m}$, and a positive charge of $q_2 = 6\,\mu\text{C}$ is at the origin. Where must a *negative* charge q_3 be placed on the x-axis **between the two positive charges** such that the resulting electric force on it is zero?



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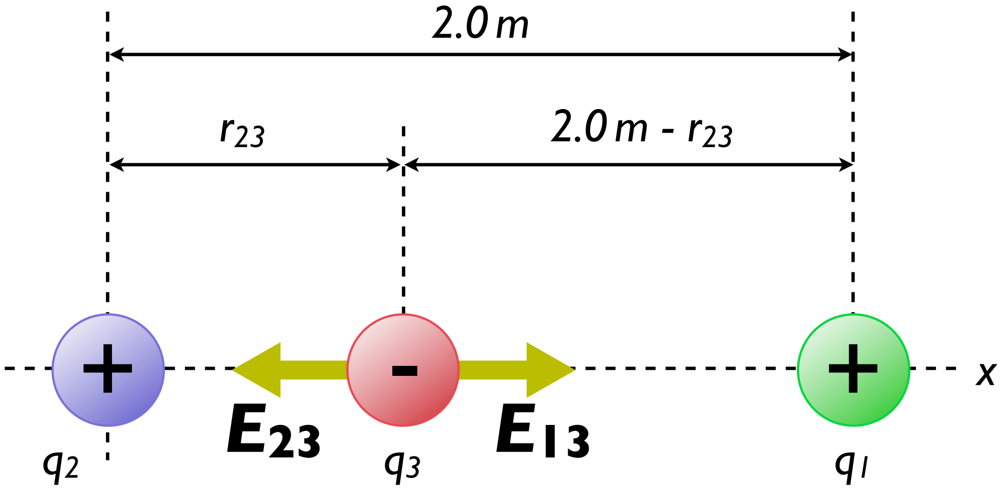
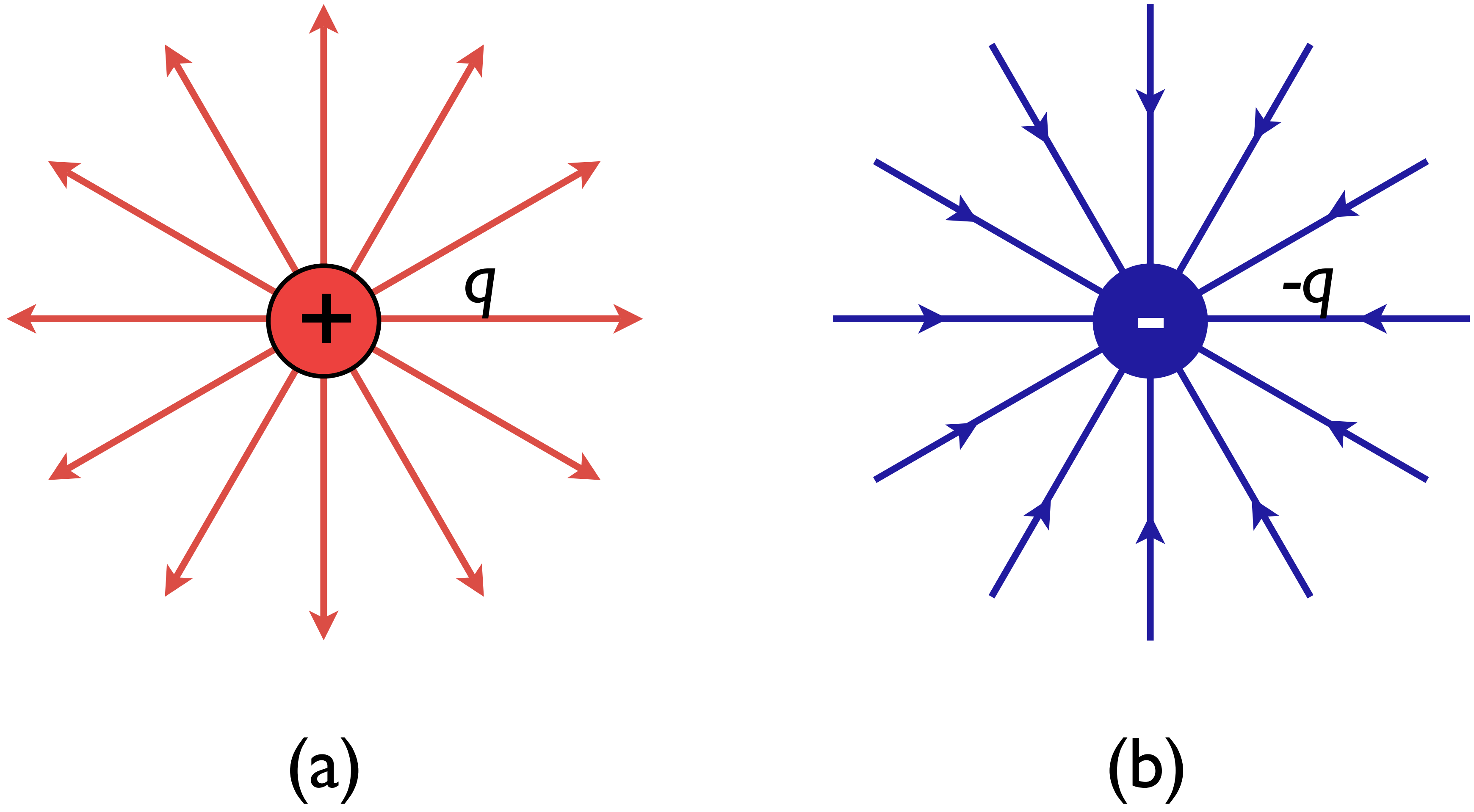


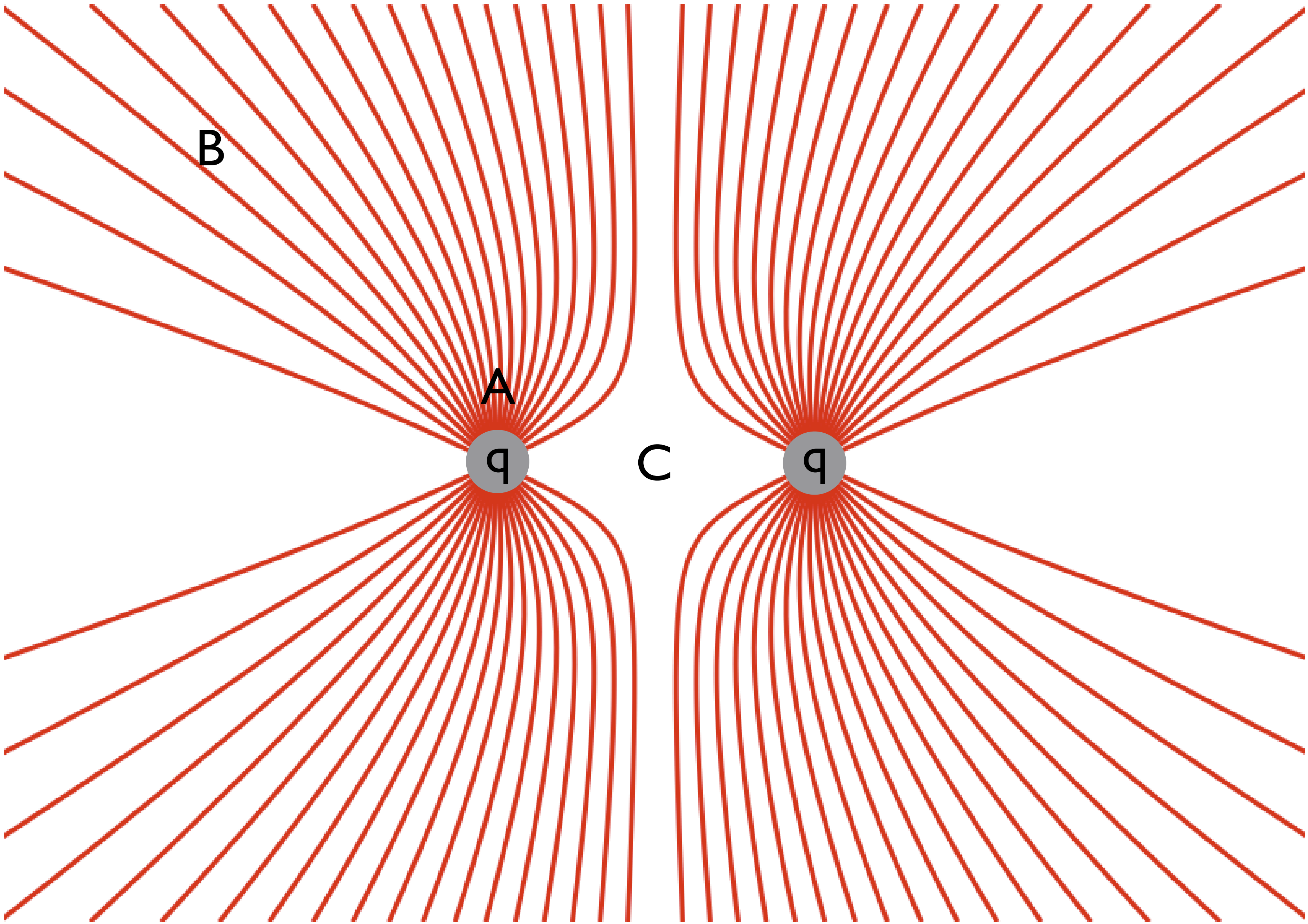
~ 0.77m from q_2

or

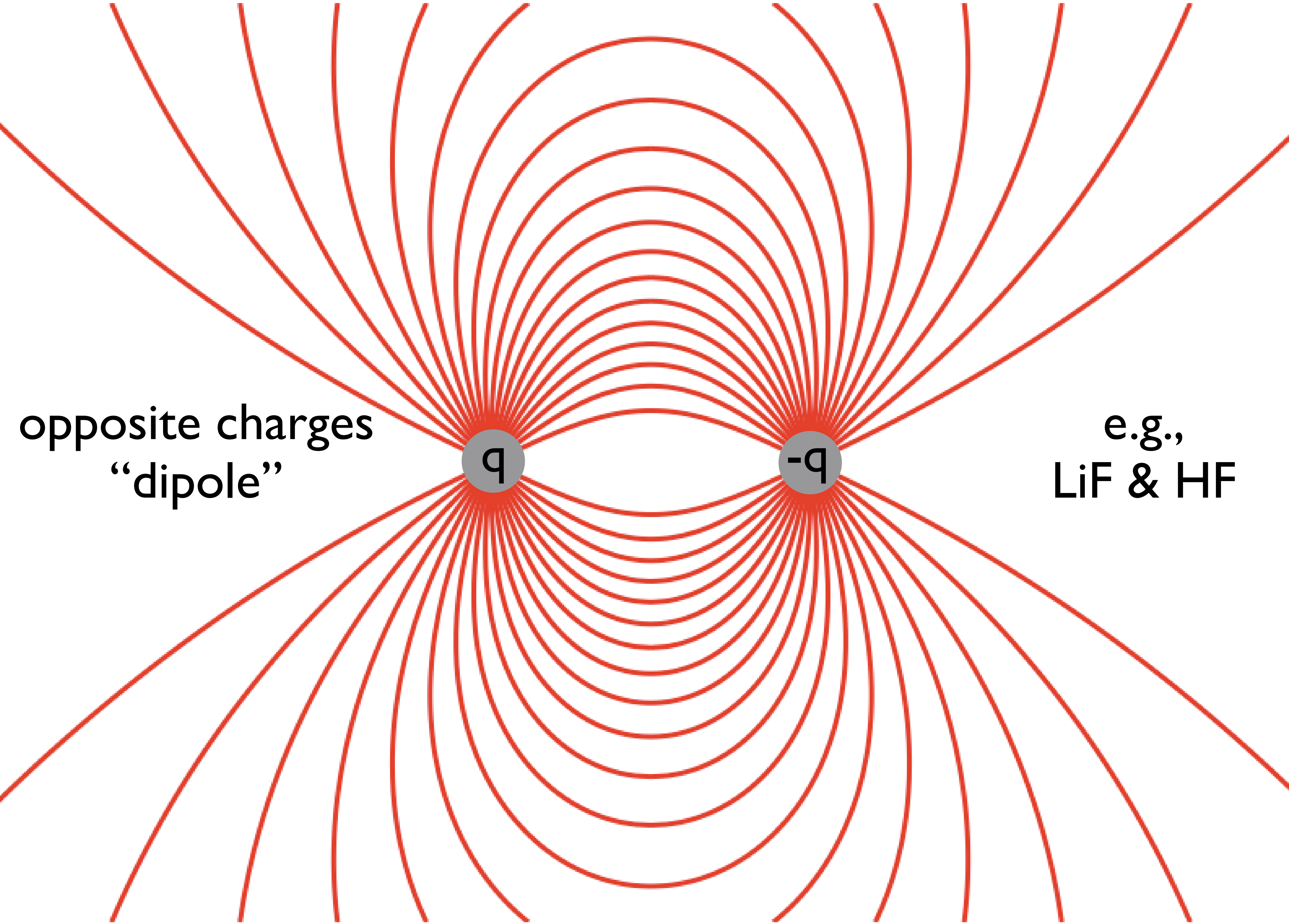
~ 1.23m from q_1

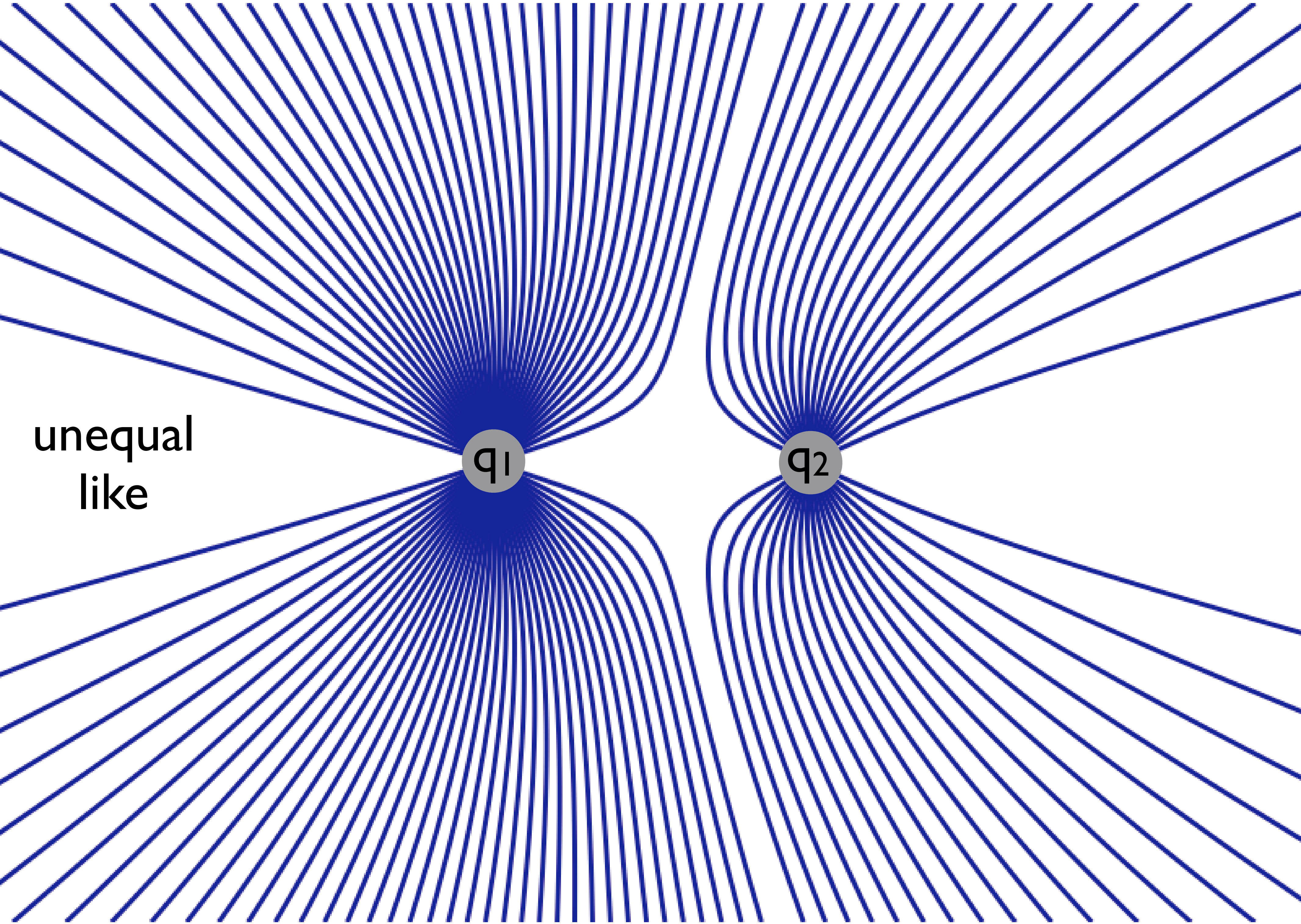

+
q
(a)
-
-q
(b)

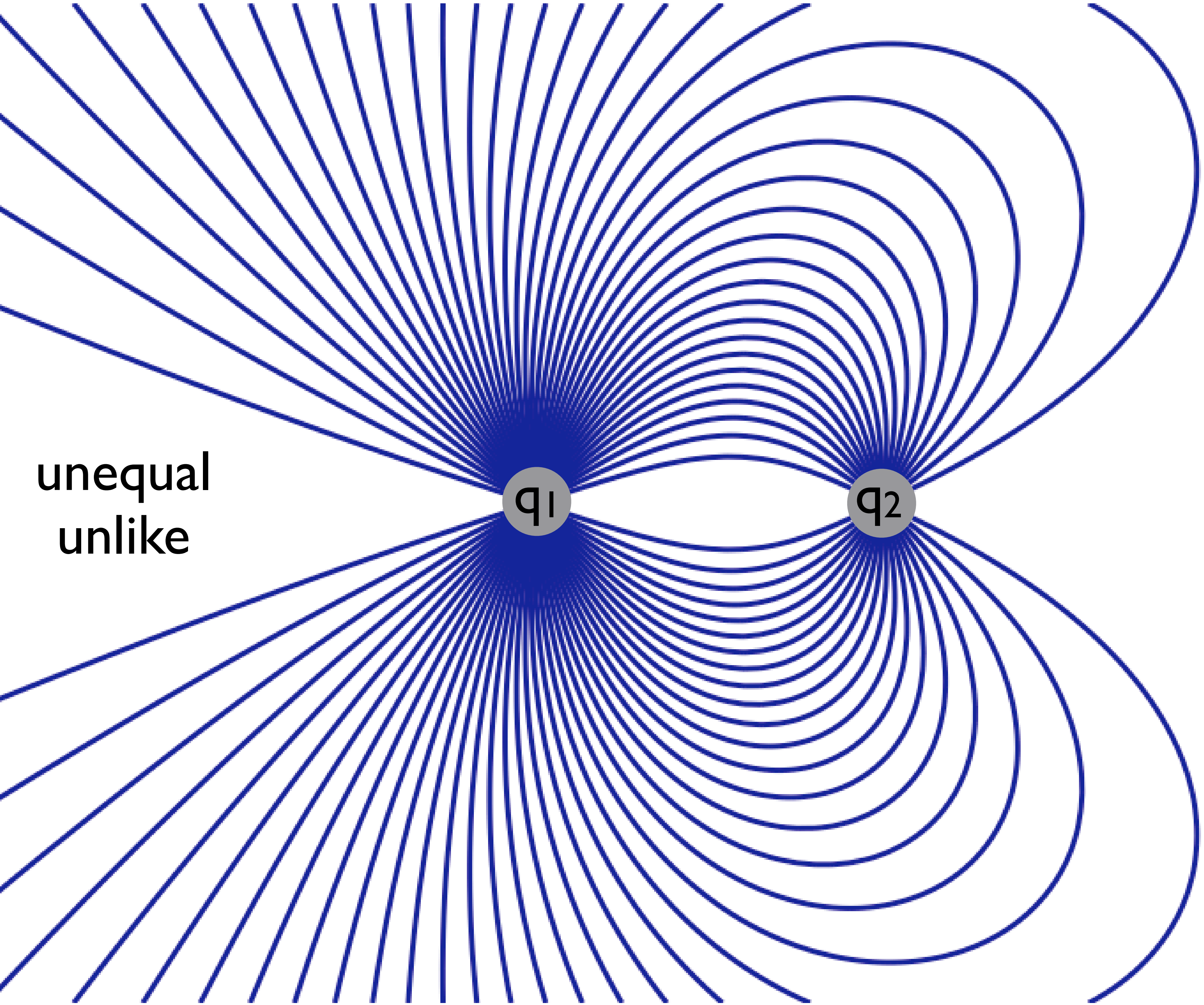
equal charges

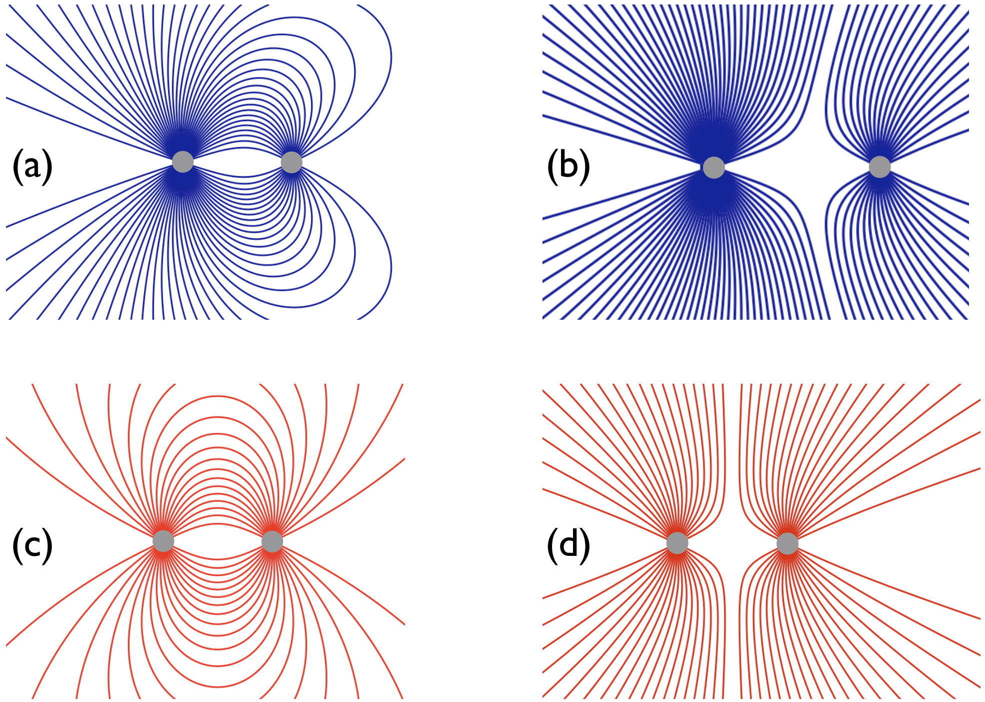


field: A > B > C


opposite charges
“dipole”
q
-q
e.g.,
LiF & HF

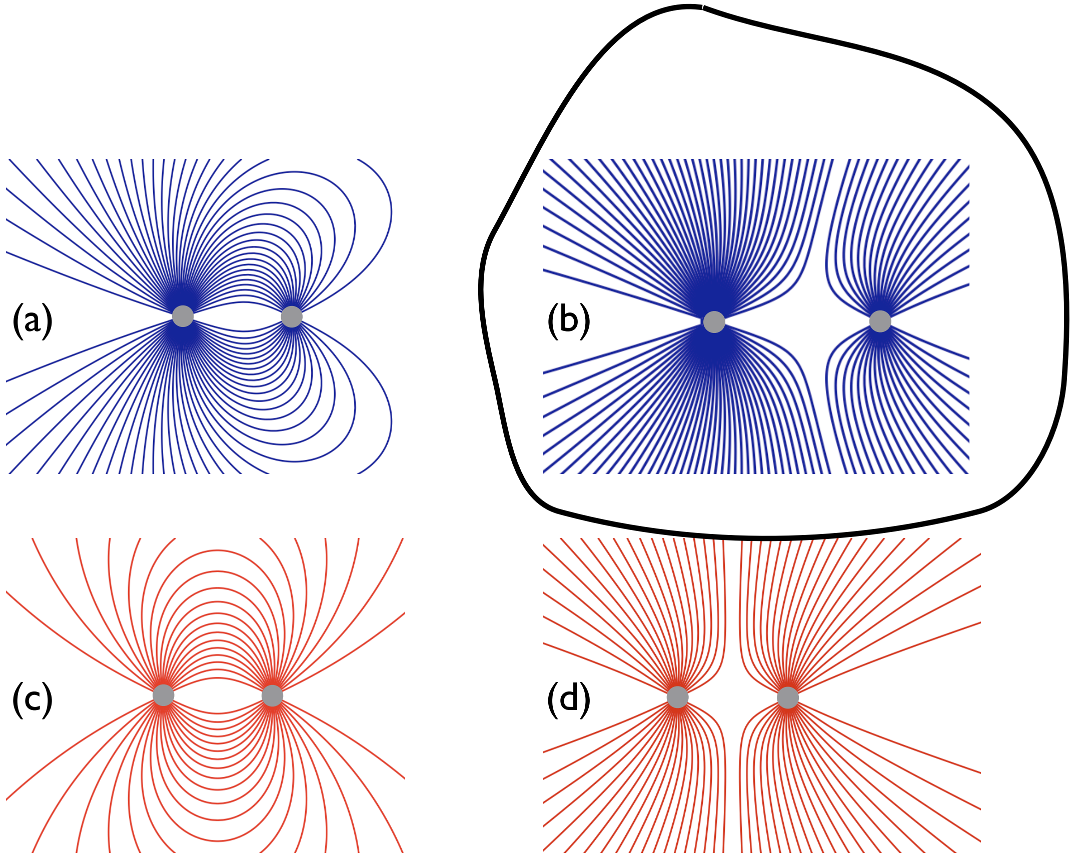

unequal
like
q1
q2


unequal
unlike
q1
q2



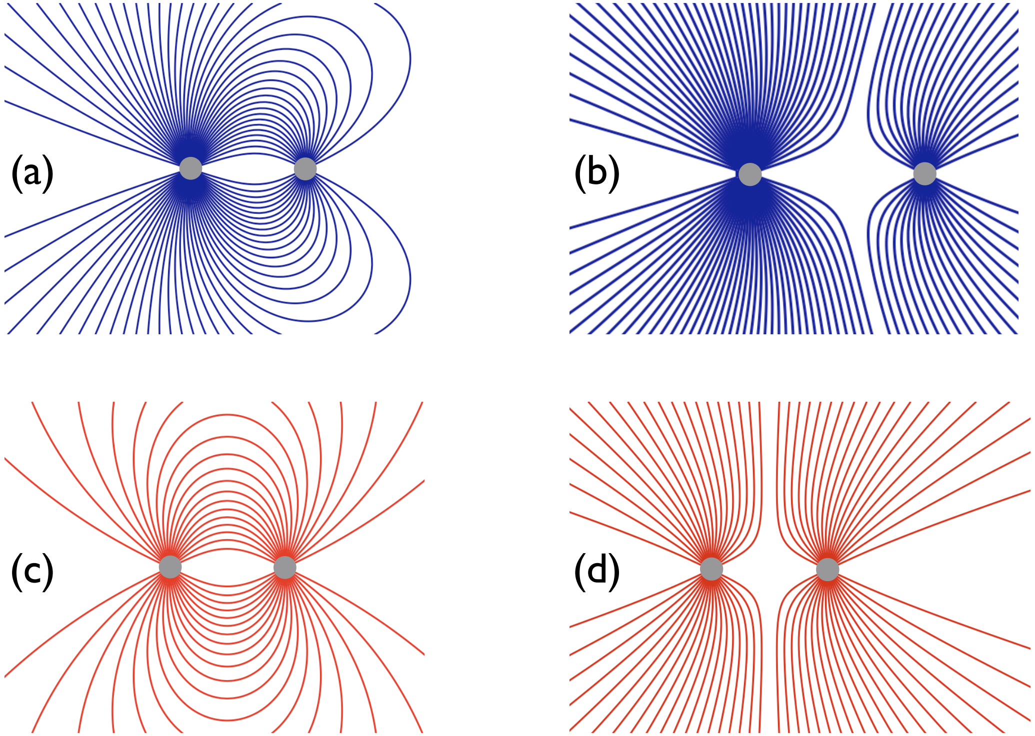
9. Which set of electric field lines could represent the electric field near two charges of the *same sign*, but *different magnitudes*?

- ☐ a
- ☐ b
- ☐ c
- ☐ d



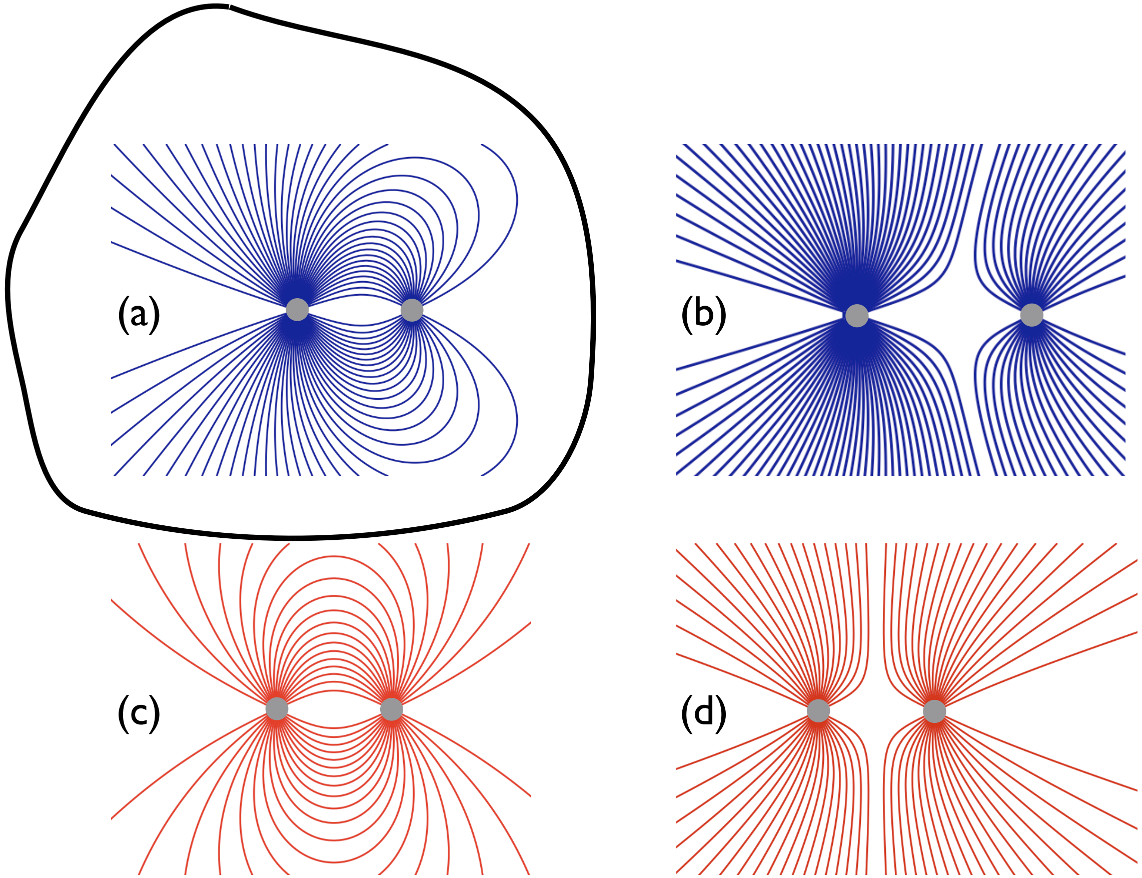
9. Which set of electric field lines could represent the electric field near two charges of the *same sign*, but *different magnitudes*?

- ☐ a
- ☐ b
- ☐ c
- ☐ d



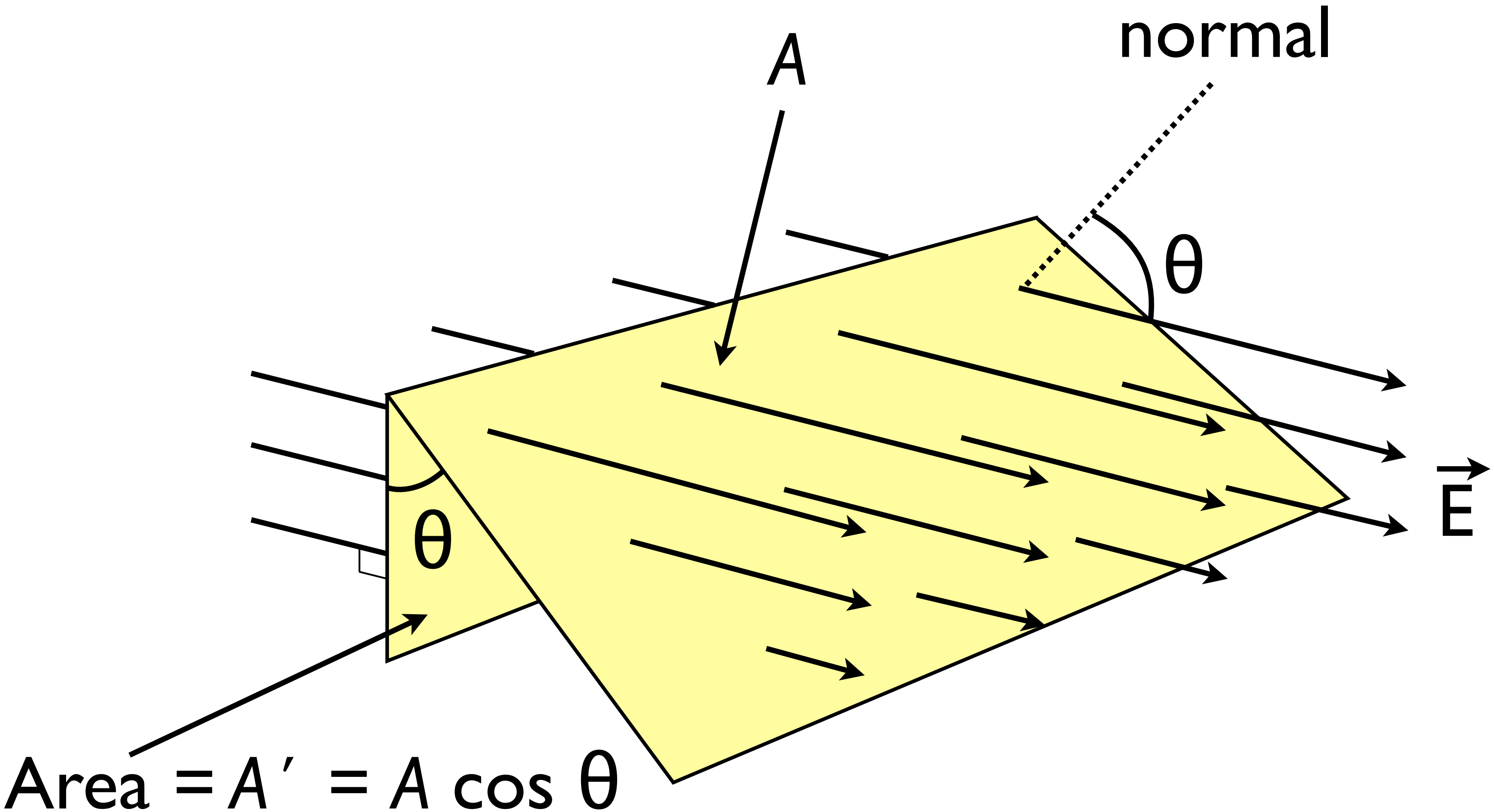
10. Referring again to the figure above, which set of electric field lines could represent the electric field near two charges of *opposite sign* and *different magnitudes*?

- ☐ a
- ☐ b
- ☐ c
- ☐ d

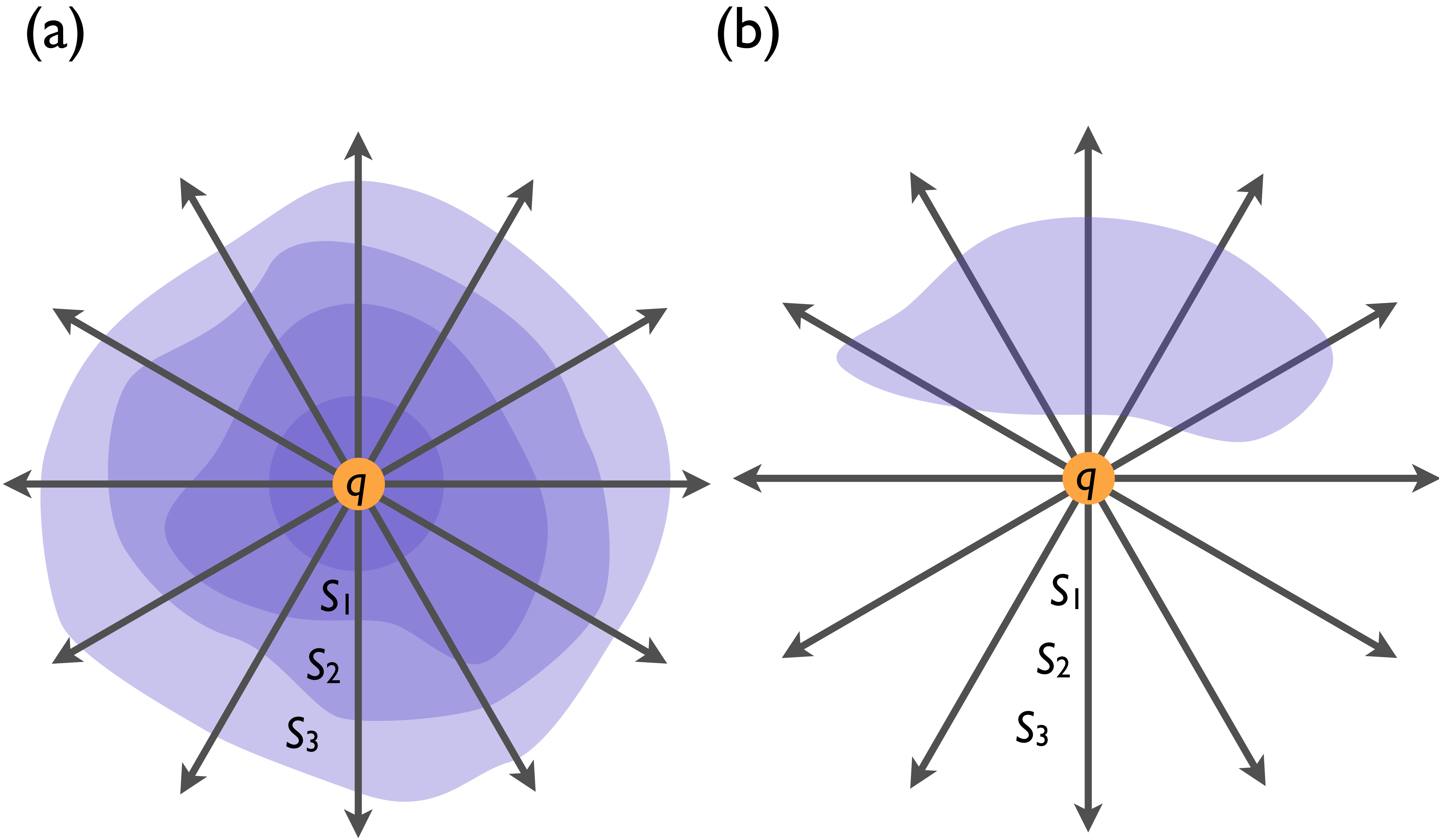


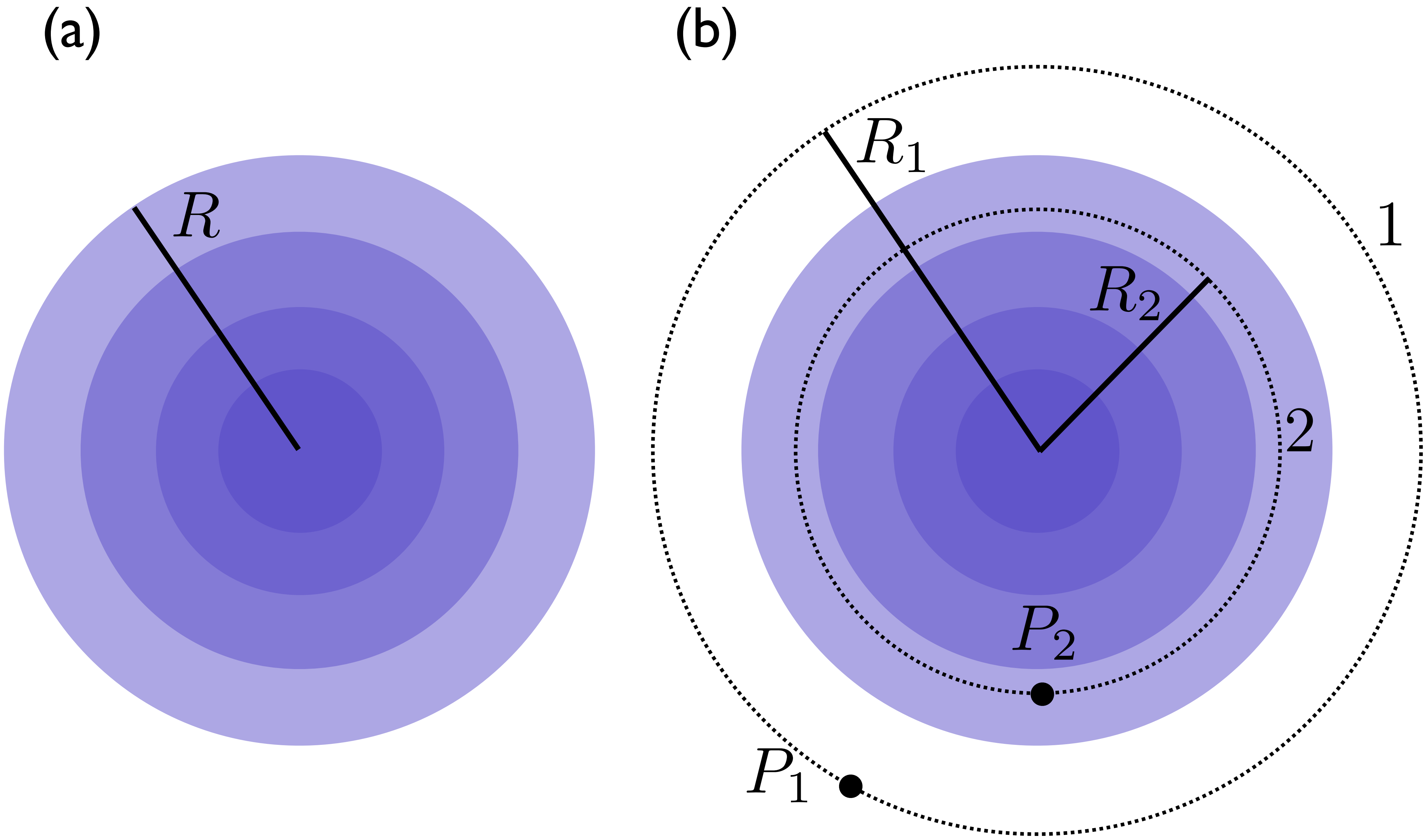
10. Referring again to the figure above, which set of electric field lines could represent the electric field near two charges of *opposite sign* and *different magnitudes*?

- ☐ a
- ☐ b
- ☐ c
- ☐ d

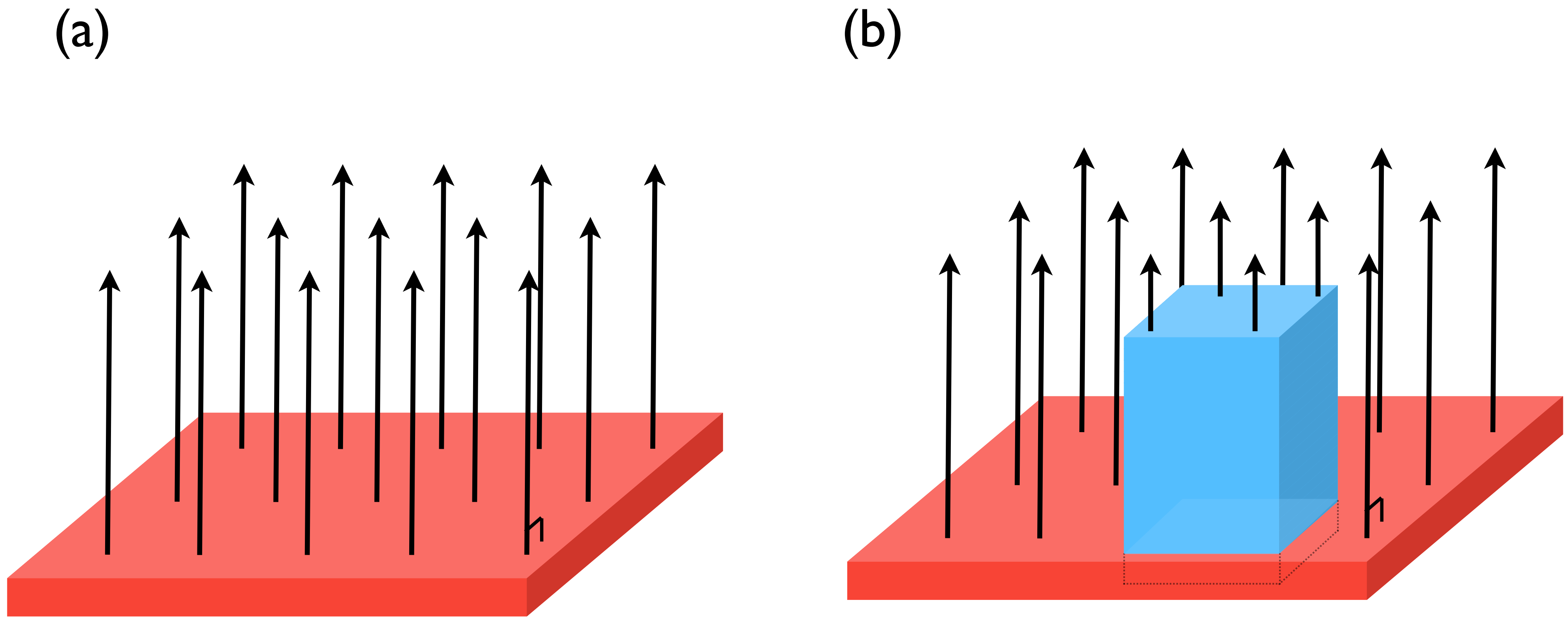


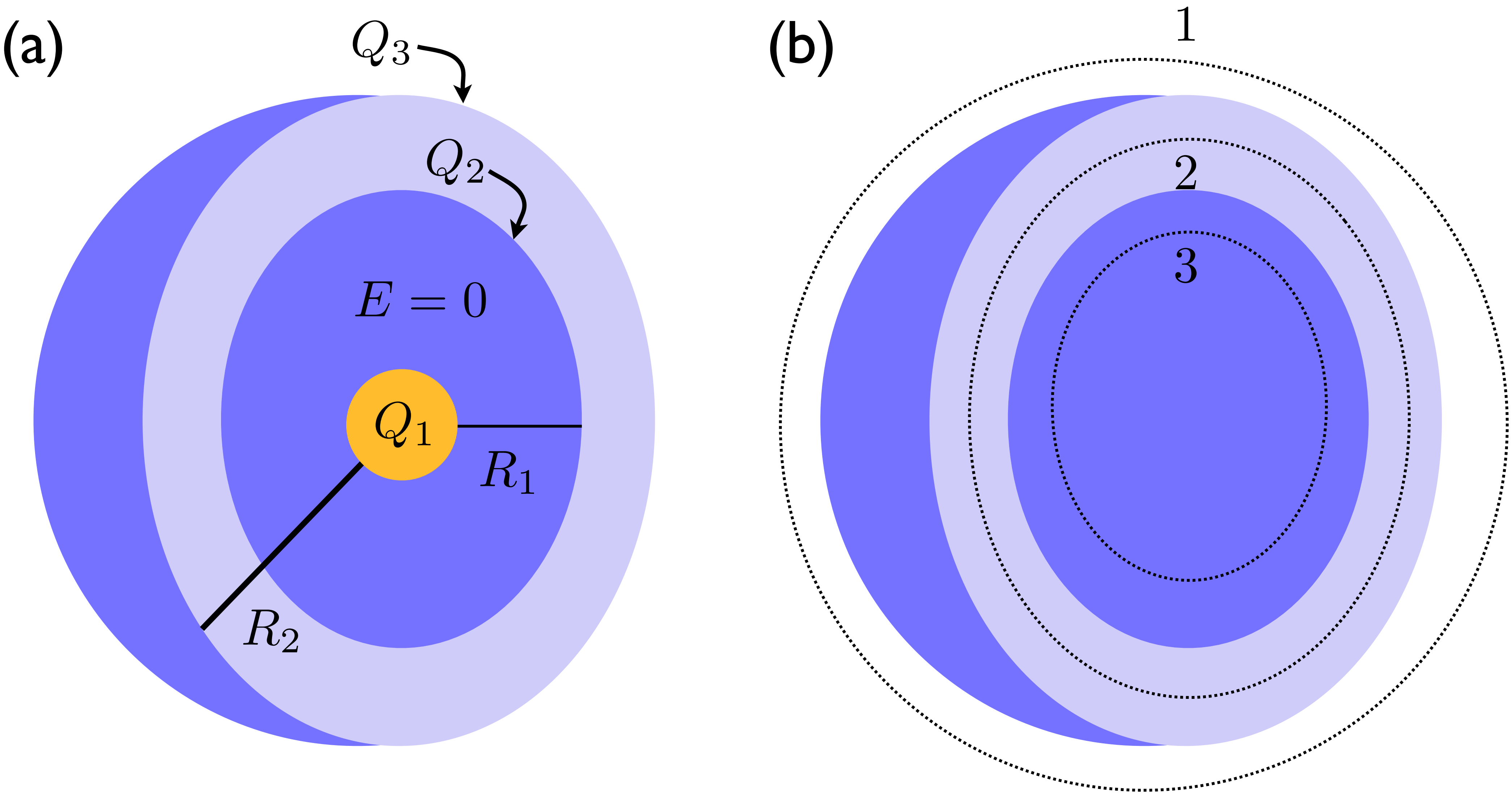
both surfaces have the same flux!

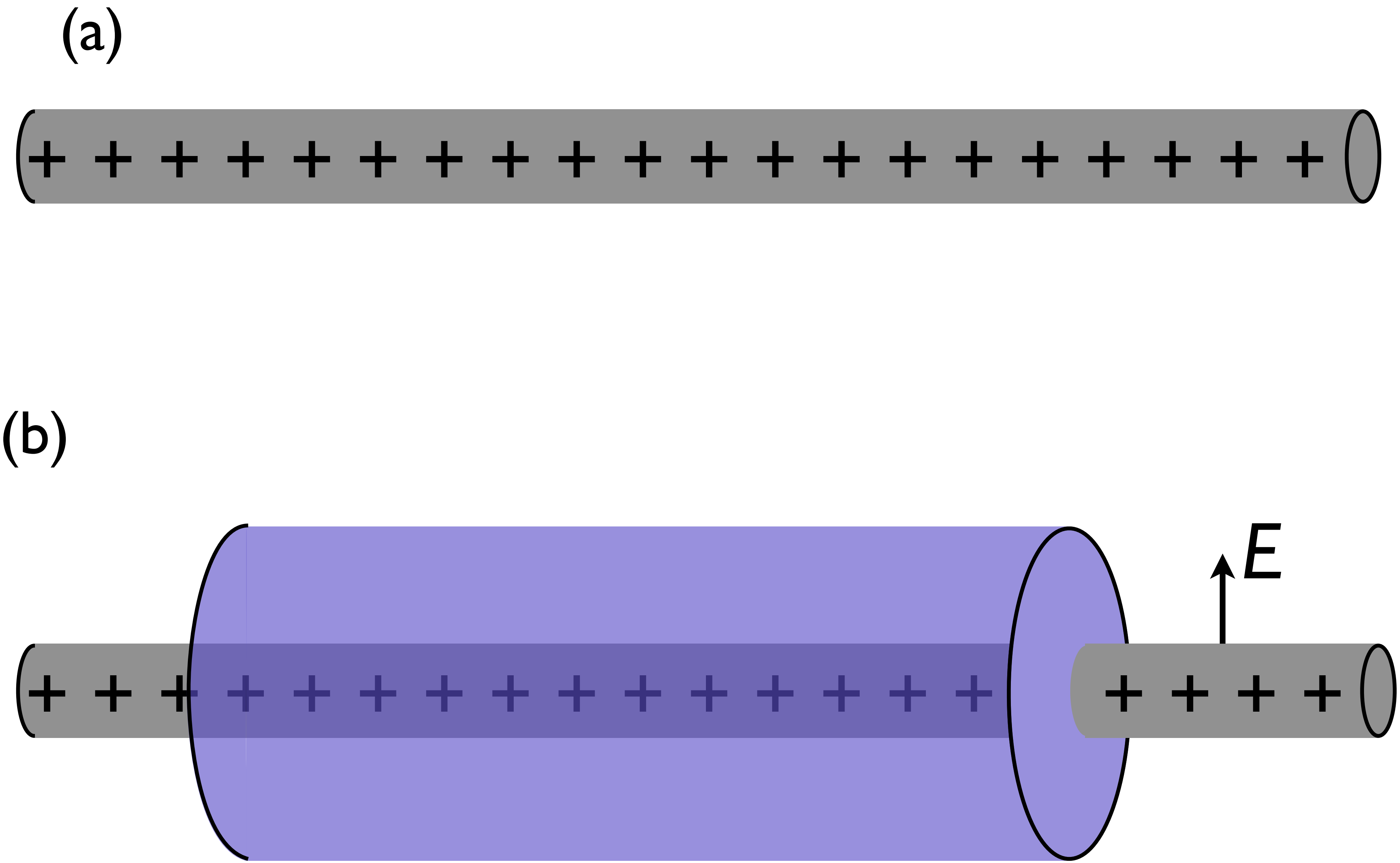

(a)
q
S1
S2
S3
(b)
q
S1
S2
S3



(a)
R
(b)
R1
R2
1
2
P2
P1


(a)
(b)


(a)
Q_3
Q_2
$E = 0$
Q_1
R_1
R_2
(b)
1
2
3


(a)
(b)
E