Physics 121 - Electricity and Magnetism
Lecture 04 - Gauss' Law
Y&F Chapter 22 Sec. 1 - 5

- **Flux Definition (gravitational example)**
- **Gaussian Surfaces**
- **Flux Examples**
- **Flux of an Electric Field**
- **Gauss' Law**
- **Gauss' Law Near a Dipole**
- **A Charged, Isolated Conductor**
- **Spherical Symmetry: Conducting Shell with Charge Inside**
- **Cylindrical Symmetry: Infinite Line of Charge**
- **Field near an infinite Non-Conducting Sheet of Charge**
- **Field near an infinite Conducting Sheet of Charge**
- **Conducting and Non-conducting Plate Examples**
- **Proof of Shell Theorem using Gauss Law**
- **Examples**
- **Summary**

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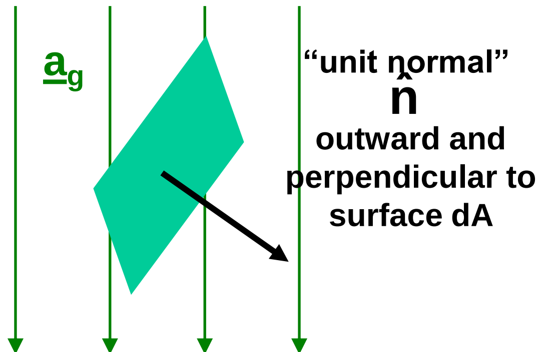
Flux (symbol F) is basically a vector field magnitude x area

Applies to flow of mass or fluid volume, gravitational, electric, magnetic field

Define: dF$_g$ is differential flux of gravitational field $\underline{a}_g$ crossing vector area d$\underline{A}$



$$\Delta\Phi_g \equiv \text{ flux of } \vec{a}_g \text{ through } \Delta\vec{A}$$

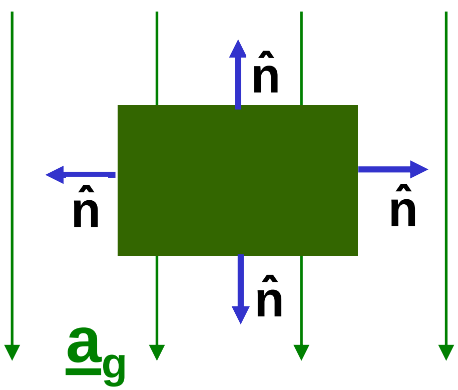
$$= \vec{a}_g \circ \hat{n}\Delta A \text{ (a scalar)}$$

Flux through a closed or open surface S:

calculate "surface integral" of field over S

$$\Phi_S \equiv \int_S d\Phi = \int_S \vec{a}_g \circ \hat{n}\, dA$$

Evaluate integrand at all points on surface S



EXAMPLE : GRAVITATIONAL FLUX THROUGH A CLOSED IMAGINARY BOX (UNIFORM ACCELERATION FIELD)

- No mass inside the box
- ΔF from each side = 0 since $\underline{a}.\underline{n}$ = 0, ΔF from ends cancels
- TOTAL F = 0
- Example could also apply to fluid flow

What if a mass (flux source) is in the box?

Can field be uniform? Can net flux be zero.

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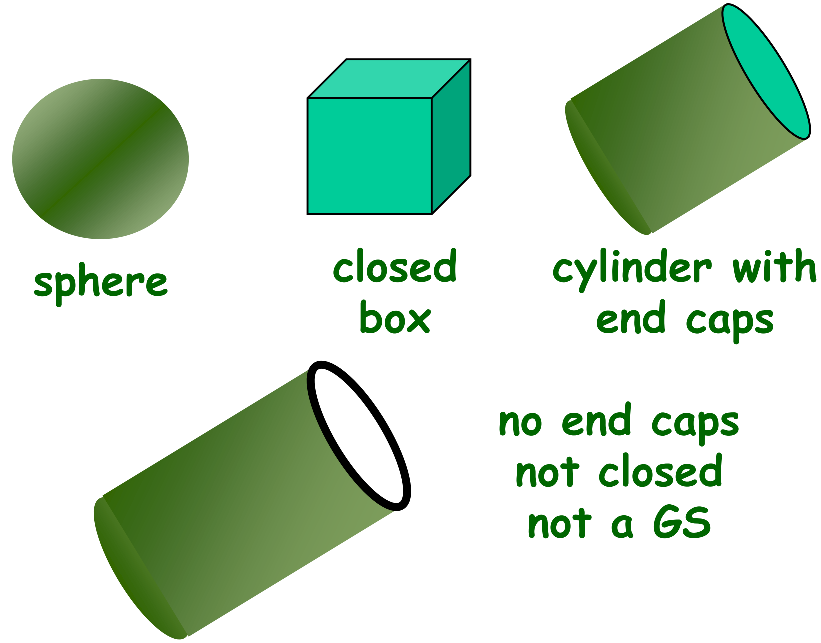
Gauss' Law (Carl Friedrich Gauss (1777-1855)) uses

Gaussian Surfaces: Closed 3D surfaces

- Field lines cross a closed surface:
  - Once (or an odd number of times) for charges that are inside
  - Twice (or an even number of times) for charges that are outside
- Choose surface to match the field's symmetry where possible



The flux of electric field crossing a closed surface equals the net charge inside the surface (times a constant).

Simple example: charge at center of a spherical "Gaussian surface"

$$\text{Flux} \equiv \Phi = \text{Field x Surface Area} = \text{E x S} = \frac{Q}{4\pi\varepsilon_0 R^2} \text{ x } 4\pi R^2 = Q/\varepsilon_0$$

Flux is a SCALAR, Units: Nm^2/C.

Does this apply for non-point charges away from the center of the sphere?

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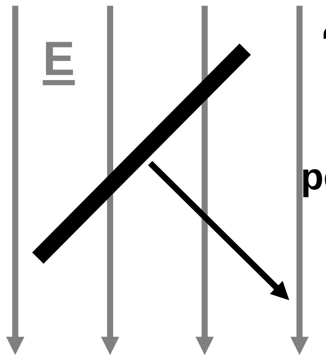
Electric Flux: Integrate electric field over a surface

Definition: differential flux of E crossing dA (area vector)



"unit normal" $\hat{n}$ outward and perpendicular to surface dA

$$\Delta\vec{A} \equiv \hat{n}\Delta A$$

Divide up some surface S into tiny chunks of dA each and consider one of them

$$\Delta\Phi_E \equiv \text{flux of } \vec{E} \text{ through } \Delta\vec{A}$$

$$\equiv \vec{E} \circ \hat{n}\Delta A \quad \text{(a scalar)}$$

Flux through a closed or open surface S: Integrate on S

$$\Phi_E \equiv \oint_S d\Phi_E = \oint_S \vec{E} \circ \hat{n}\, dA$$

To do this: evaluate integrand at all points on surface S

Gauss' Law: The flux through a closed surface S depends only on the net enclosed charge, not on the details of S or anything else.

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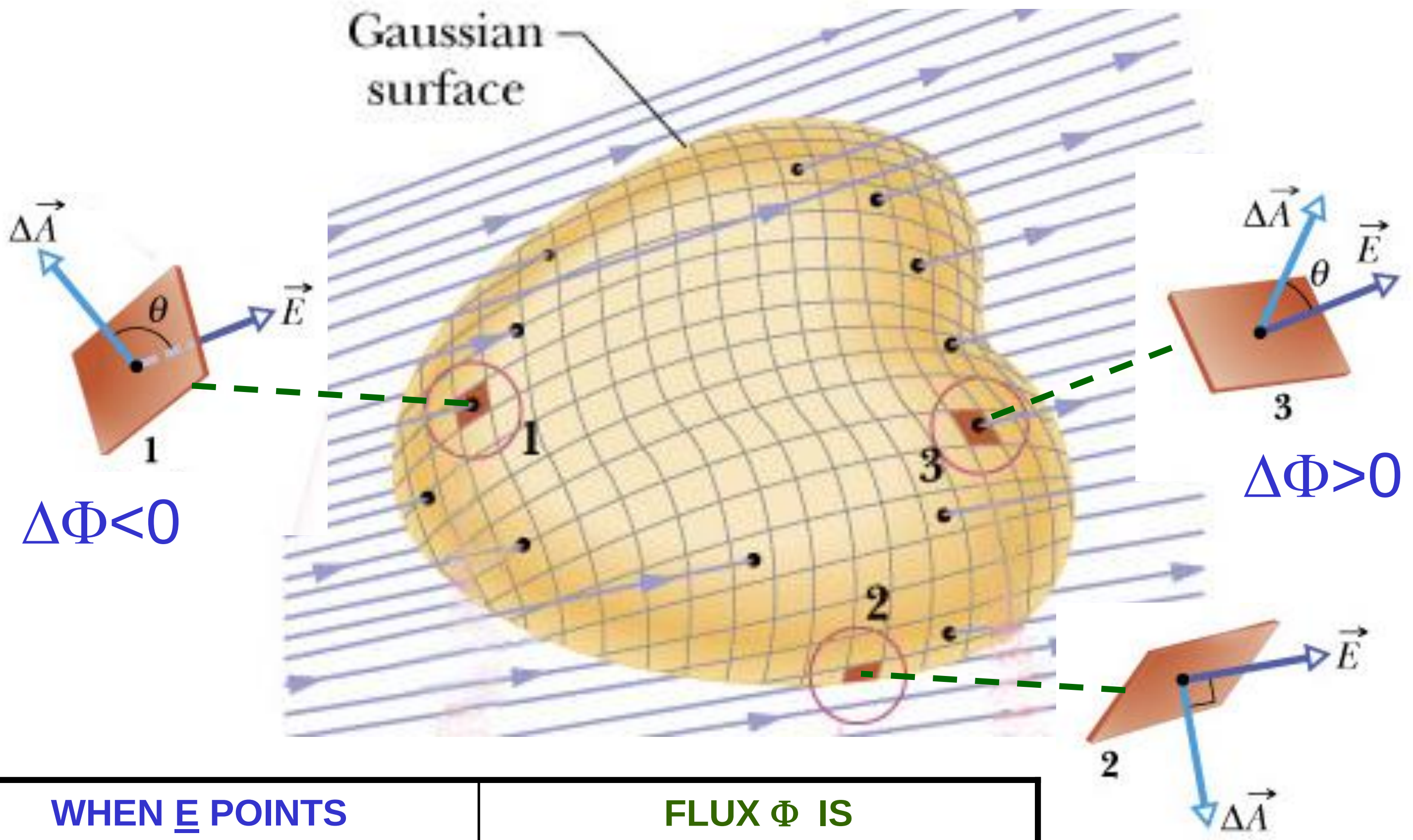
ΔΦ depends on the angle between the field and chunks of area

$$\Delta\Phi = \vec{E} \circ \hat{n}\Delta A = EA\cos(\theta)$$

$$\Delta\vec{A} = \hat{n}\Delta A$$
$$\hat{n} \equiv \text{outward unit vector}$$



ΔΦ=0

WHEN E POINTS	FLUX Φ IS
from inside to outside of surface	E.n > 0 POSITIVE
from outside to inside of surface	E.n < 0 NEGATIVE
tangent to surface	E.n = 0 ZERO

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Evaluating flux through closed or open surfaces

Special case: field is constant across pieces of the surface

$$\Delta\Phi_E \equiv \vec{E} \circ \hat{n}\Delta A \quad \text{(a scalar)}$$

Units of Φ are : Nm^2/C

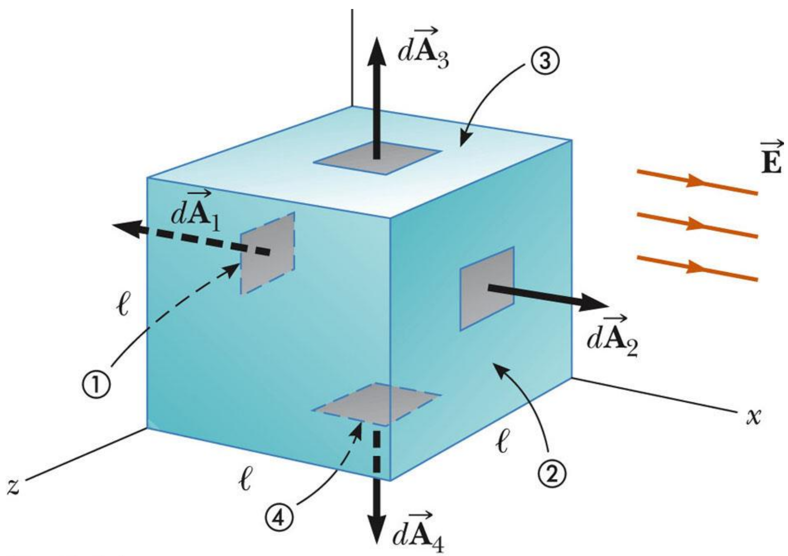
SUM ΔF FROM SMALL CHUNKS OF SURFACE ΔA

$$\Phi_E \equiv \sum_{\text{small areas}} \Delta\Phi_E = \sum_{\text{small areas}} \vec{E} \circ \hat{n}\Delta A$$

EXAMPLE: Flux through a cube

Assume:

- Uniform E field everywhere
- Directed along x-axis
- Cube faces normal to axes
- Each side has area l^2



- **Field lines cut through two surface areas and are tangent to the other four surface areas**
- **For side 1, $\Phi = -E\ell^2$**
- **For side 2, $\Phi = +E\ell^2$**
- **For the other four sides, $\Phi = 0$**
- **Therefore, $\Phi_{total} = 0$**

$$\therefore \Phi_E = \sum_{i=1,6} \Delta\Phi_i = 0$$

- What if the cube is oriented obliquely??
- How would flux differ if net charge is inside??

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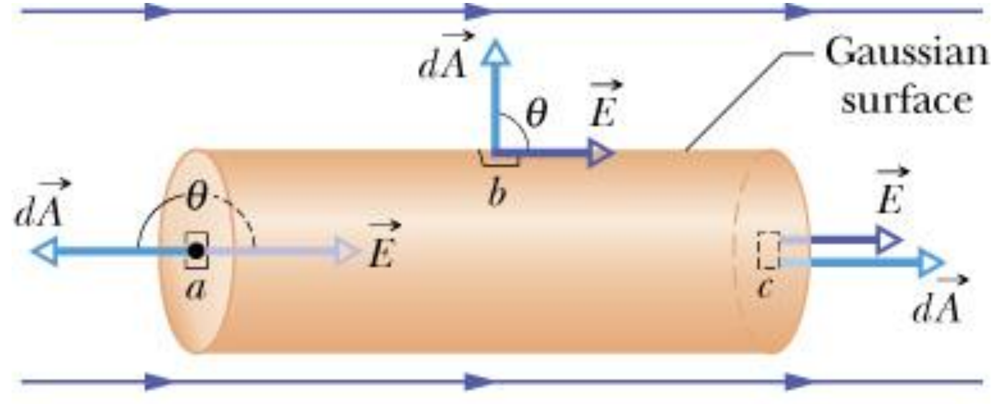
Flux of a uniform electric field through a cylinder

- Closed Gaussian surface
- Uniform E means zero enclosed charge
- Calculate flux directly
- Symmetry axis along E
- Break into areas a, b, c



$$\Phi_{tot} = \int_{a,b,c} \vec{E} \circ d\vec{A} = \Phi_a + \Phi_b + \Phi_c$$

Cap a: $\vec{E} \circ \hat{n} = -E, \ \cos(\theta) = -1 \quad \therefore \ \Phi_a = -E \int_{cap\,a} dA = -E A_{cap}$

Cap c: $\vec{E} \circ \hat{n} = +E, \ \cos(\theta) = +1 \quad \therefore \ \Phi_c = +E \int_{cap\,c} dA = +E A_{cap}$

Area b: $\vec{E} \circ \hat{n} = 0, \ \vec{E} \perp \vec{A}$ everywhere on b $\quad \therefore \ \Phi_b = 0$

$$\therefore \ \Phi_{tot} = 0$$

What if E is not parallel to cylinder axis:

- Geometry is more complicated...but...
- $Q_{inside} = 0$ so $\Phi = 0$ still !!

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Flux of an Electric Field

4-1: Which of the following figures correctly shows a positive electric flux out of a surface element?

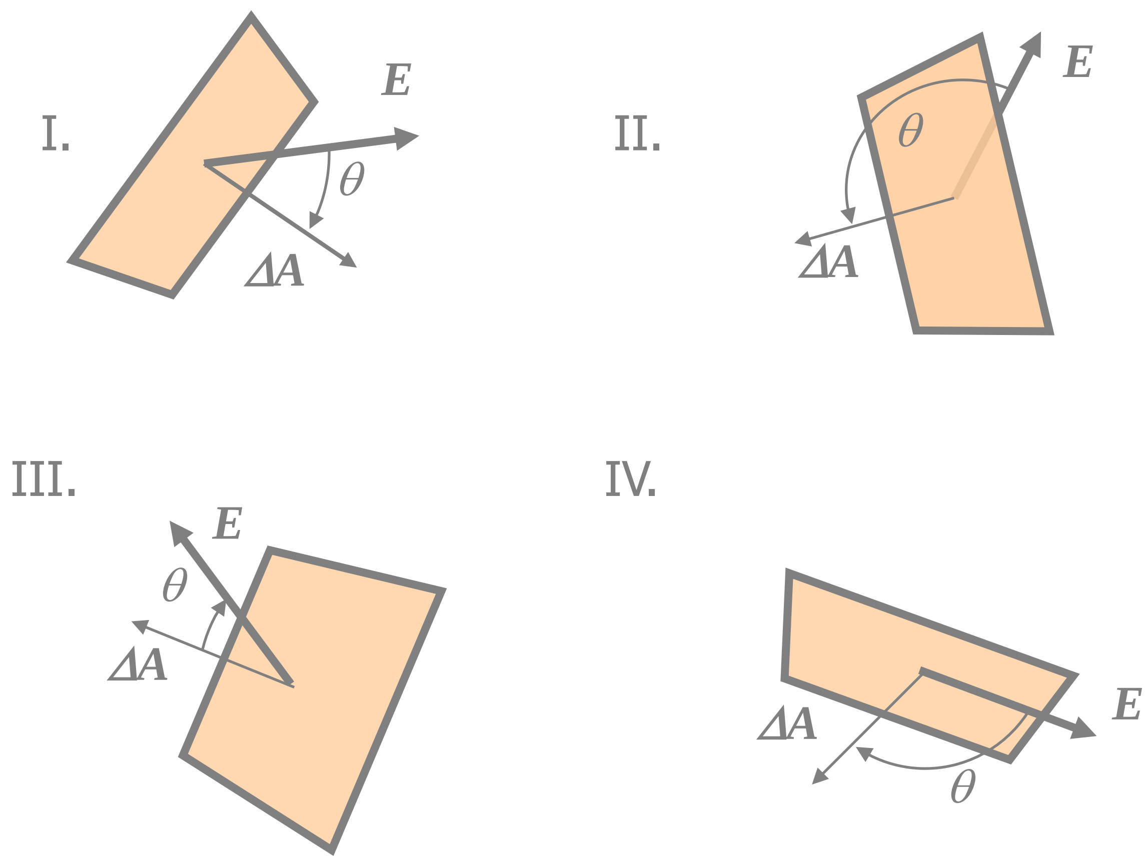
A. I.

B. II.

C. III.

D. IV.

E. I and III.



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Statement of Gauss' Law

Let Q_{enc} be the NET charge enclosed by a (closed) Gaussian surface S. The net flux Φ through the surface is Q_{enc}/ε_0

$$\Phi = \oint_{\text{Surface}} \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0} \qquad Q_{enc} = \varepsilon_0 \Phi$$

- Does not depend on the shape of the surface.
- Charge outside the surface S can be ignored.
- Surface integral yields 0 if $\underline{E}$ = 0 everywhere on surface

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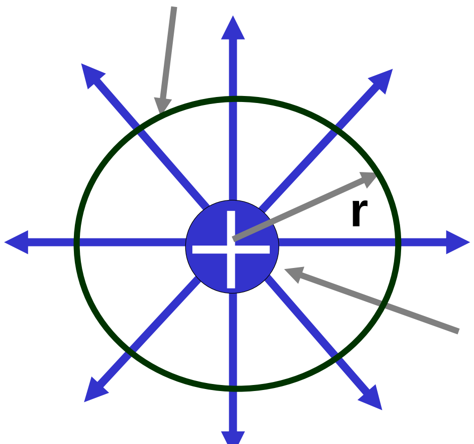
Example: Derive Coulomb's Law from Gauss' Law

Assume a point charge at center of a spherical Gaussian surface

$$\vec{E} \cdot d\vec{A} = E\, dA$$



$\vec{E} \circ d\vec{A}$ is always just $E dA$ because $\vec{E}$ and $\hat{n}$ are always radial

$$\Phi = E\oint_S dA = E \times 4\pi r^2 = \frac{Q_{enc}}{\varepsilon_0}$$

$$\therefore E(r) = \frac{Q_{enc}}{4\pi\varepsilon_0 r^2}$$

Coulomb's Law

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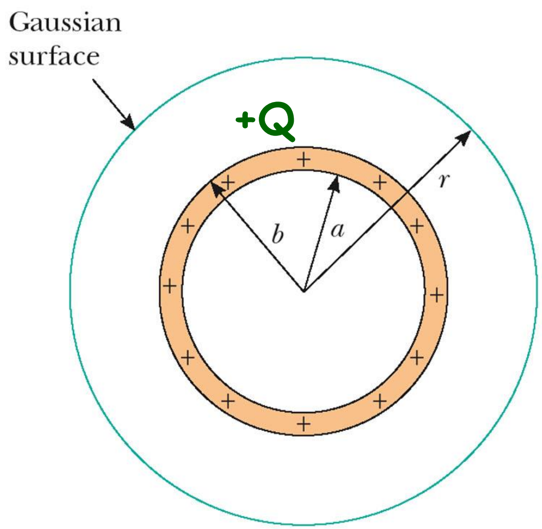
Spherical Shells of Charge

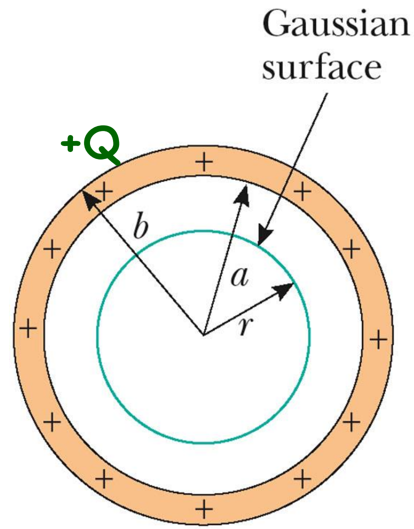


spherically symmetric

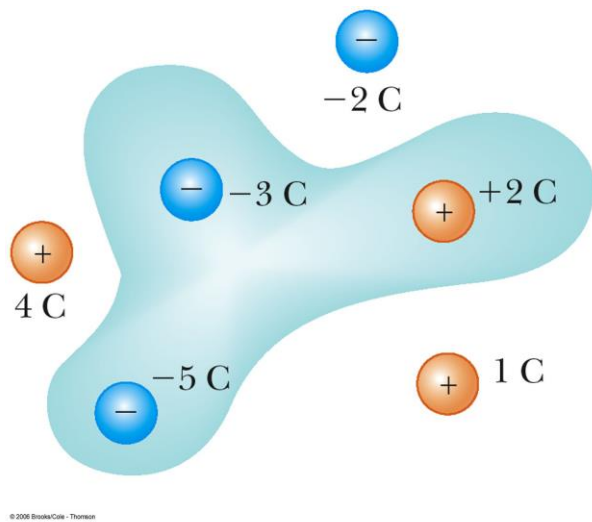
Shell Theorem

$$\Phi = \oint_S \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

What are the fields on the Gaussian surfaces?



4-2: What is the flux through the Gaussian surface below?



A. zero
B. -6 C./e_0
C. -3 C./e_0
D. +3 C./e_0
E. not enough info

$$\Phi = \oint_S \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

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Flux through surfaces near a dipole

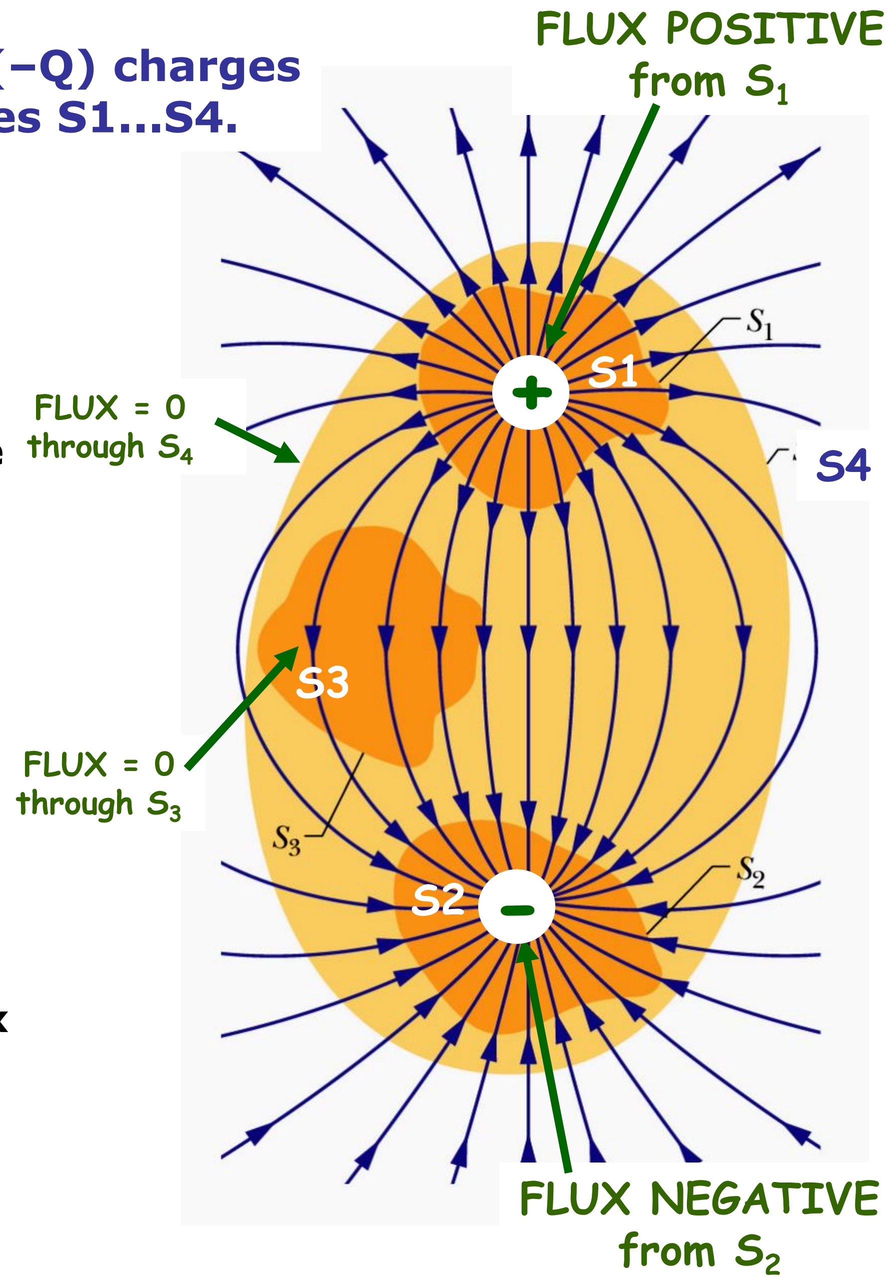
- **Equal positive (+Q) and negative (–Q) charges**
- **Consider Gaussian (closed) surfaces S1…S4.**

- **Surface S_1 encloses only the positive charge. The field is everywhere outward. Positive flux.** $F = +Q/e_0$

- **Surface S_2 encloses only the negative charge. The field is everywhere inward. Negative flux.** $F = -Q/e_0$

- **Surface S_3 encloses no charges. Net flux through the surface is zero. The flux is negative at the upper part, and positive at the lower part, but these cancel.** $F = 0$

- **Surface S_4 encloses both charges. Zero net charge enclosed, so equal flux enters and leaves, zero net flux through the surface.** $F = 0$



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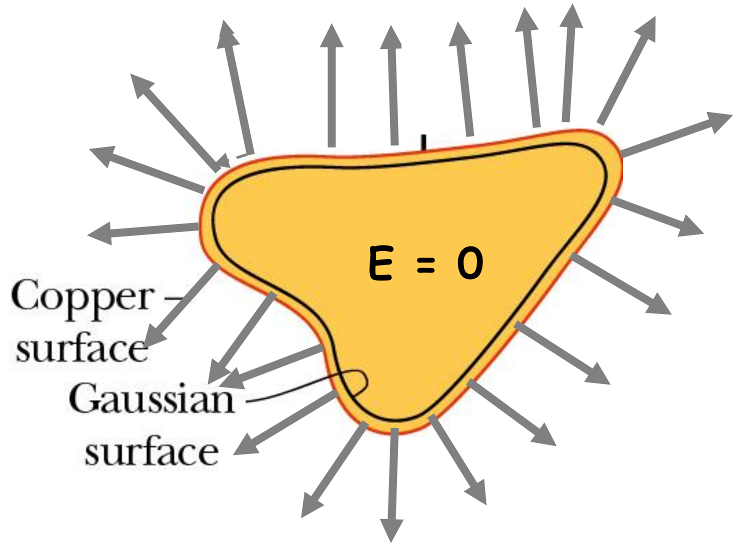
Where does net charge reside on an isolated conductor?

- Place net charge Q initially in the interior of a conductor
- Charges are free to move, but can not leak off

$$\vec{F} = Q\vec{E}$$

- At equilibrium E = 0 everywhere inside a conductor
- Charge flows until E = 0 at every interior point



- Choose Gaussian surface as shown: E = 0 everywhere on it
- Use Gauss' Law!

$$\Phi = \oint_{\text{Surface}} \vec{E} \circ d\vec{A} = 0 = \frac{Q_{enc}}{\varepsilon_0} \Rightarrow Q_{enc} = 0$$

- The only place where un-screened charge can end up is on the outside surface of the conductor
- E at the surface is everywhere normal to it; if E had a component parallel to the surface, charges would move to screen it out.

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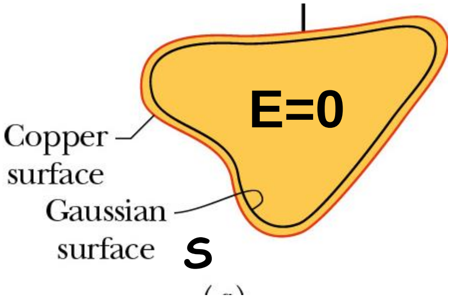
Gauss's Law: net charge on an isolated conductor...
...moves to the outside surface

$$\Phi = \oint_{\text{Surface}} \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

1: SOLID CONDUCTOR WITH EXCESS NET CHARGE ON IT

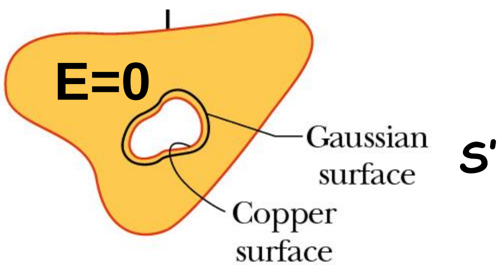


- Choose Gaussian surface S just inside the surface
- E=0 at every point in the metal, including on S
- Gauss' Law says:

$$\Phi_S = 0 = \frac{Q_{enc}}{\varepsilon_0} \quad \therefore Q_{enc} = 0$$

All net charge on a conductor moves to the outer surface

2. HOLLOW CONDUCTOR WITH A NET CHARGE, NO CHARGE IN CAVITY



- Choose Gaussian surface S' just outside the cavity
- E=0 everywhere within the metal, including S'
- Gauss' Law says:

$$\Phi_{S'} = 0 = \frac{Q_{enc}}{\varepsilon_0} \quad \therefore Q_{enc} = 0$$

There is zero net charge on the inner surface: all net charge is on outer surface

Does the charge density have to be zero at each point on the inner surface?

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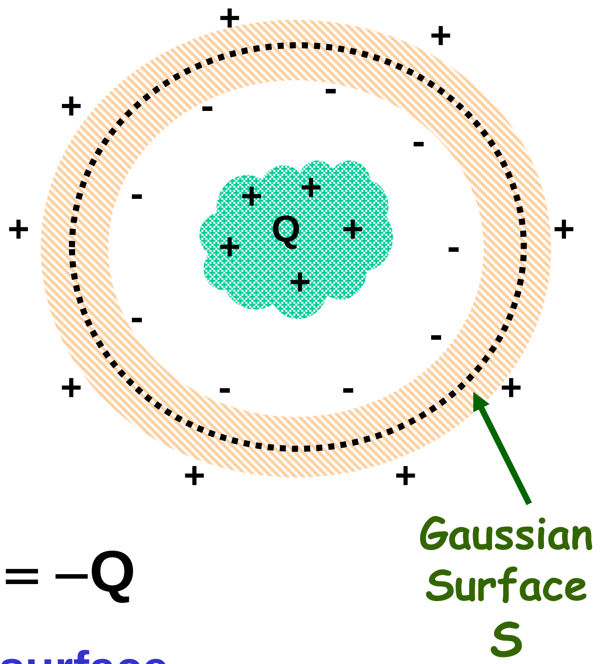
Charge inside a conducting spherical shell

- Electrically neutral shell
- Arbitrary charge distribution +Q in cavity
- Choose Gaussian surface S <u>completely within</u> the conductor



$$\Phi_S = \oint_S \vec{E} \circ d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$$

- <u>E</u> = 0 everywhere on S, so $\Phi_S = 0$ and $q_{enc} = 0$
- Negative charge Q_{inner} is induced on inner surface, distributed so that E = 0 in the metal, hence…

$$q_{enc} = 0 = +Q + Q_{inner} \quad \Rightarrow \quad Q_{inner} = -Q$$

- The shell is neutral, so +Q must appear on the outer surface

OUTSIDE:

- Choose another spherical Gaussian surface S' outside the shell
- Gauss Law:

$$\Phi = \frac{q'_{enc}}{\varepsilon_0} = \frac{+Q}{\varepsilon_0} = 4\pi r^2 E(r) \quad \Rightarrow \quad E(r) = \frac{Q}{4\pi\varepsilon_0 r^2}$$ radially outward

Whatever the inside distribution may be, outside the shell it is shielded and the field looks like that of a point charge at the center
For a spherical shell, +Q outside is uniform, o/w E inside could not = 0

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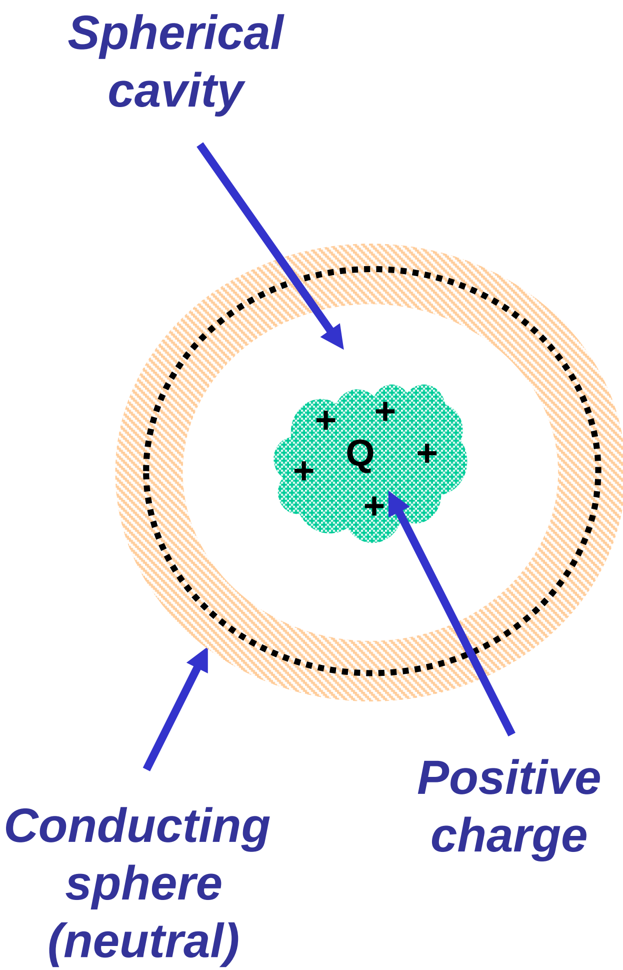
Conducting spherical shell with charge inside



4-3: Place a charge inside a cavity in an isolated conductor. Which statement is true?

A. E field is still zero in the cavity.
B. E field is not zero in the cavity, but it is zero in the conductor.
C. E field is zero outside the conducting sphere.
D. E field is the same as if the conductor were not there (i.e. radial outward everywhere).
E. E field is zero in the conductor, and negative (radially inward) outside the conducting sphere.

$$\Phi = \oint_S \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

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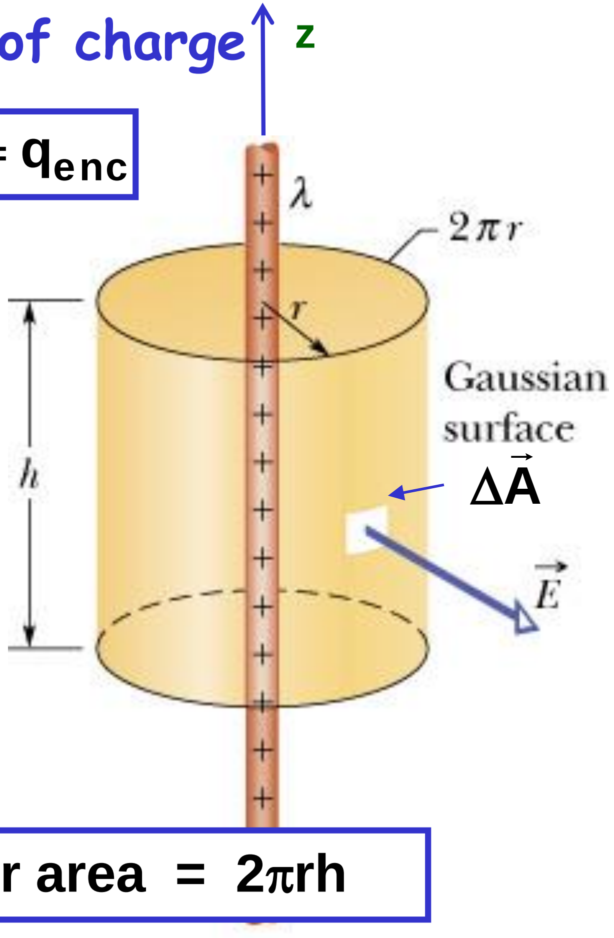
Example: Use Gauss' Law to find the electric field at a distance r from an infinitely long (thin) line of charge

$\lambda h = q_{enc}$



- Cylindrical symmetry around z-axis
- Uniform charge per unit length l
- Every point on the infinite line has the identical surroundings, so….
  - E is radial, by symmetry
  - E has the same value everywhere on any concentric cylindrical surface
  - Flux through end caps = 0 as E is perpendicular to DA
- E on cylinder is parallel to unit vector for DA

$$\therefore \quad \Phi = \oint_S \vec{E} \circ d\vec{A} = 2\pi r h E = \frac{\lambda h}{\varepsilon_0}$$

Cylinder area = $2\pi rh$

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0 r}$$

radiallyoutward

- No integration needed now due to Gauss Law
- Good approximation for finite line of charge when r << L, far from the ends.

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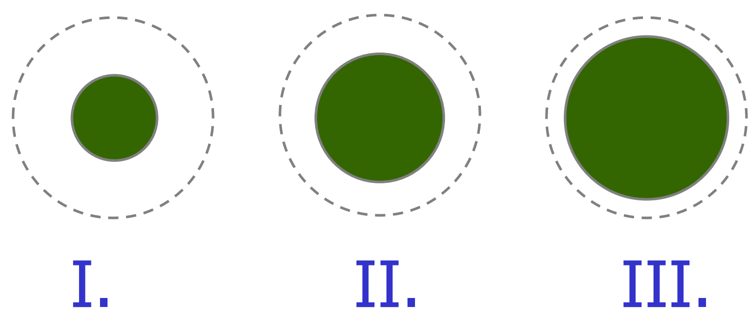
Field Lines and Conductors

4-4: The drawing shows three cylinders in cross-section, each with the same total charge. Each has the same size cylindrical gaussian surface (again shown in cross-section). Rank the three according to the electric field at the gaussian surface, greatest first.

$$\Phi = \oint_S \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

- **A. I, II, III**
- **B. III, II, I**
- **C. All tie.**



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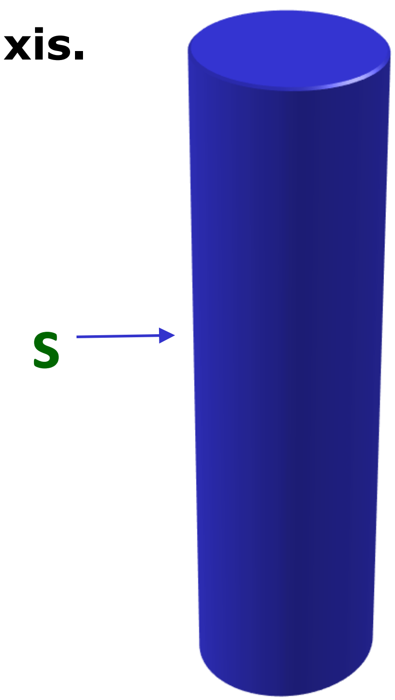
Use symmetry arguments where applicable

4-5: Outside a sphere of charge the electric field is just like that of a point charge of the same total charge, located at its center.

Outside of an infinitely long, uniformly charged conducting cylinder, which statement describes the electric field?

A. **Like that of a point charge at the center of the cylinder.**
B. **Like a circular ring of charge at its center.**
C. **Like an infinite line of charge along the cylinder axis.**
D. **Cannot tell from the information given.**
E. **The field equals zero**



$$\Phi = \oint_S \vec{E} \circ d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

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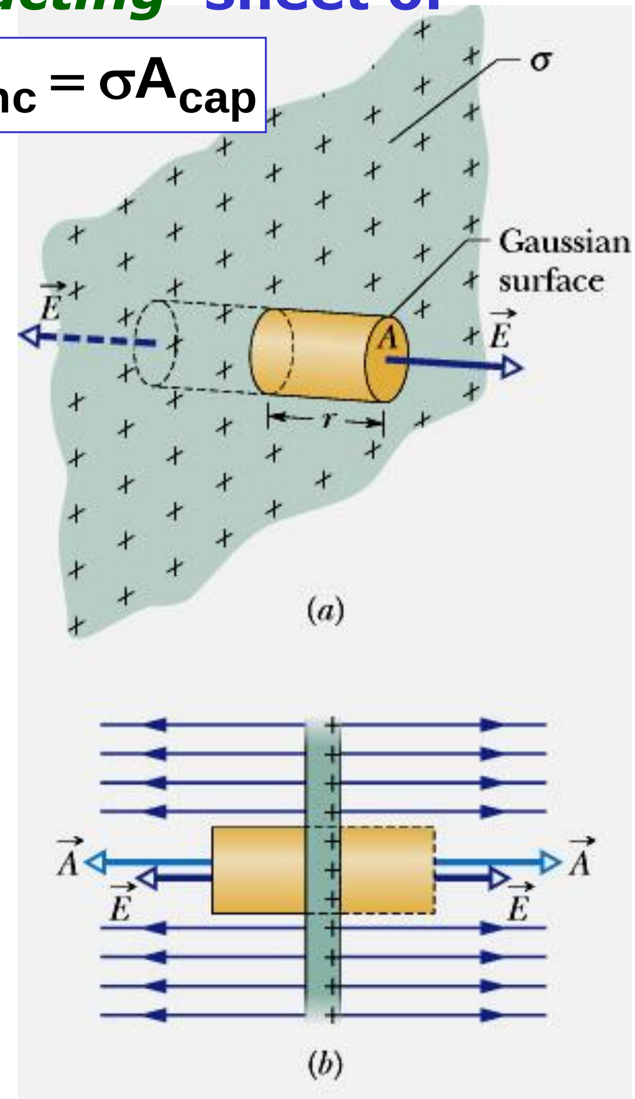
Electric field near an infinite *non-conducting* sheet of charge – using Gauss Law

$$q_{enc} = \sigma A_{cap}$$

- Cylindrical Gaussian Surface penetrating sheet (rectangular OK too)
- Uniform positive charge per unit area s
- E has same value when chosen point moves parallel to the surface
- E points radially away from the sheet (both sides),
- E is perpendicular to cylindrical part of surface Flux through it = 0
- On both end caps E is parallel to A so F = + EA_{cap} on each



$$\Phi = \oint_S \vec{E} \circ d\vec{A} = 2EA_{cap} = \frac{q_{enc}}{\varepsilon_0} = \frac{\sigma A_{cap}}{\varepsilon_0}$$

$$\therefore \quad E = \frac{\sigma}{2\varepsilon_0}$$

- Uniform field – independent of distance from sheet
- Same as earlier result but no integration needed now
- Good approximation for finite sheet when r << L, far from edges.

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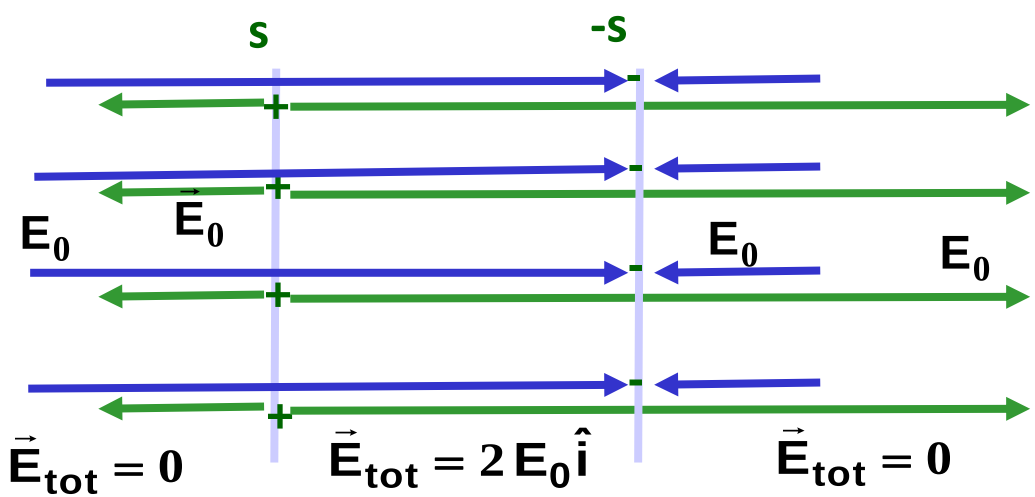
Example: Fields near parallel nonconducting sheets - 1

- Bring two "large" nonconducting sheets of charge close to each other,
- Approximate as infinite sheets
- The charge cannot move, use superposition.
- There is no screening, as there would be in a conductor.
- Each sheet produces a uniform field of magnitude: $E_0 = \frac{\sigma}{2\varepsilon_0}$

Oppositely Charged Plates, same |s|



- Left region: Field due to the positively charged sheet is canceled by the field due to the negatively charged sheet. E_{tot} is zero.
- Right region: Same argument. E_{tot} is zero.
- Between plates: Fields reinforce. E_{tot} and is twice E_0 and to the right.

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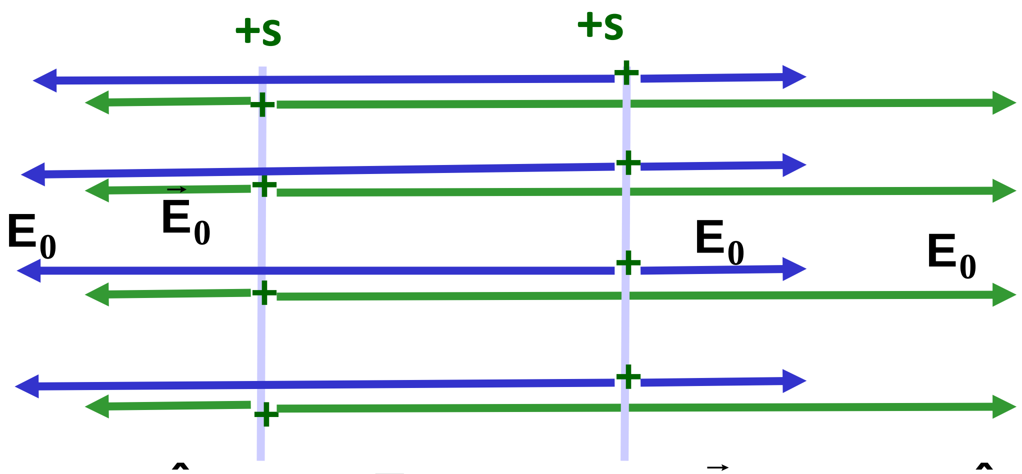
Example: Fields near parallel nonconducting sheets - 2

Positively Charged Plates, same s

$$E_0 = \frac{\sigma}{2\varepsilon_0}$$



$\vec{E}_{tot} = -2\,E_0\,\hat{i}$ $\quad E_{tot} = 0$ $\quad \vec{E}_{tot} = +2\,E_0\,\hat{i}$

- **Now, the fields reinforce to the left and to the right of both plates.**
- **Between plates, the fields cancel.**
- **Signs are reversed for a pair or negatively charged plates**

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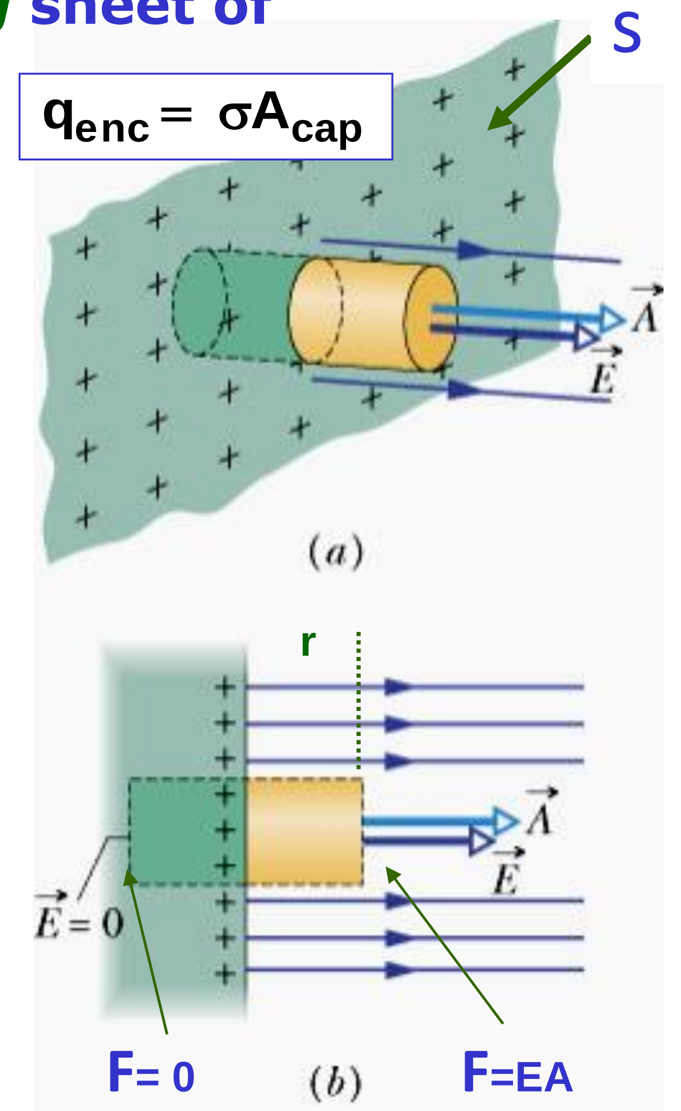
Electric field near an *infinite conducting* sheet of charge – using Gauss' Law



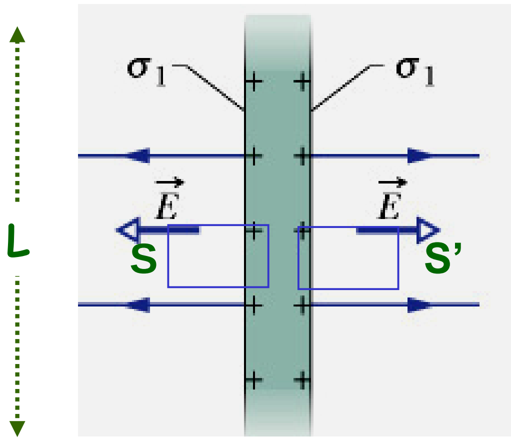
- Uniform charge per unit area s on one face
- Use cylindrical or rectangular Gaussian surface
- End caps just outside and just inside (E = 0)
- E points radially away from sheet outside otherwise current flows (!!)
- Flux through the cylindrical tube = 0
  E normal to surface
- On left cap (inside conductor) E = 0 so F = 0
- On right cap E is parallel to DA so F = EA_{cap}

$$\therefore \quad \Phi = EA_{cap} = \frac{q_{enc}}{\varepsilon_0} = \frac{\sigma A_{cap}}{\varepsilon_0}$$

$$\therefore \quad E = \frac{\sigma}{\varepsilon_0}$$

- Field is twice that for a non-conducting sheet with same s
- Same enclosed charge, same total flux now "squeezed" out the right hand cap, not both
- Otherwise like previous result: uniform, no r dependence, etc.

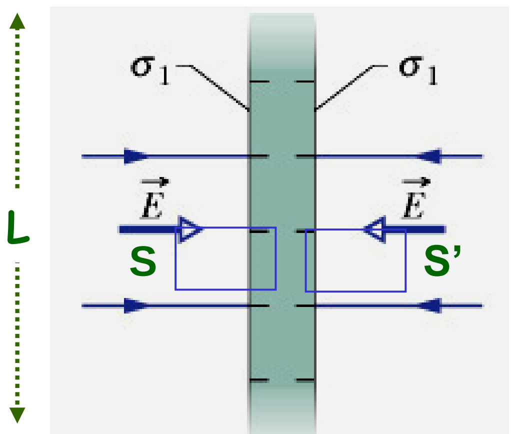
Charge on a finite sized conducting plate in isolation



- E = 0 inside the conductor
- Charge density s_1 is the same on both faces, o/w charges will move to make E = 0 inside
- Cylindrical Gaussian surfaces S, S'
- S → charges distribute on surfaces

or

$$\mathbf{E} = \pm \frac{\sigma_1}{\varepsilon_0}$$



- Same field magnitude on opposite sides, opposite directions
- Same field by replacing each conductor by 2 charged non-conducting sheets alone:
  - cancellation inside conductor
  - reinforcement outside

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Electric field near oppositely charged *conducting* plates (large, but not infinite)

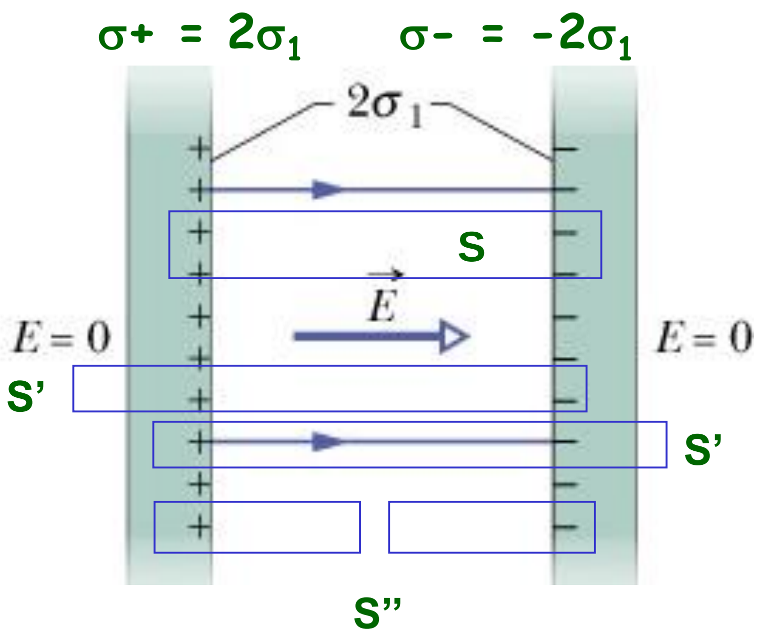
Initially: charge density +/- s_1 on both faces of each plate (neutral)

Then bring plates close to each other.

Free charge moves to make E = 0 within the metal.

All surface charge density ends up on inner faces, zero on outer.

(valid for infinite sheet) $s^{+/-} = +/- \ 2s_1$



- Charge moves by induction to keep E = 0 inside each conductor
- Field between plates remains uniform
- Flux through Gaussian surface S = 0, so $\sigma^- = -\sigma^+$
- Using either S', q_{enc}= 0 so E = 0 outside
- So the charge density = 0 on the outer faces,
- All the net charge density must move to the inner surfaces
- Using either surface S":

$$E_{inside} = \frac{\sigma^{+/-}}{\varepsilon_0} = \pm \frac{2\sigma_1}{\varepsilon_0}$$

- This already counts effects of both plates
- Fields everywhere would be the same if charge distributions were there w/o the conductors.

Parallel plate capacitor

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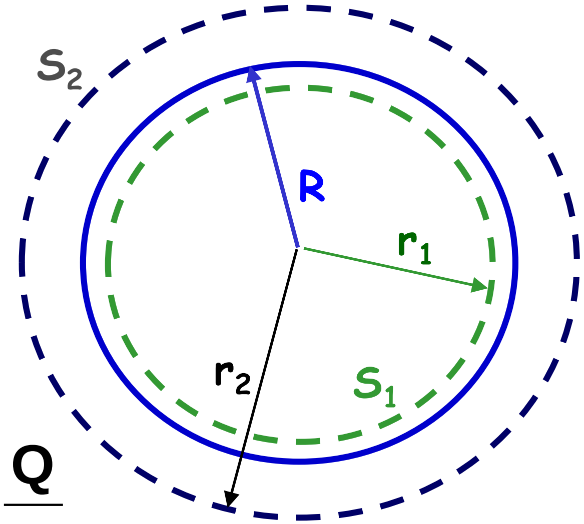
Proof of the Shell Theorem using Gauss' Law (spherical symmetry)



- Hollow shell of charge, net charge Q
- Spherically symmetric surface charge density σ, radius R
- Two spherical Gaussian surfaces:
  - S_1 is just inside shell, $r_1 < R$
  - S_2 is outside shell, $r_2 > R$
- q_{enc} means charge enclosed by S_1 or S_2

OUTSIDE: (on S_2)

$$\Phi_2 = \oint_{S_2} \vec{E} \circ d\vec{A} = 4\pi r_2^2 E_2 = \frac{q_{enc}}{\varepsilon_0} = \frac{Q}{\varepsilon_0}$$

$$\therefore \quad E_2 = \frac{Q}{4\pi\varepsilon_0 r_2^2} \quad \text{for } r_2 > R$$

Shell of charge acts like a point charge at the center of the sphere

INSIDE: (on S_1)

$$\Phi_1 = \oint_{S_1} \vec{E} \circ d\vec{A} = 4\pi r_1^2 E_1 = \frac{q_{enc}}{\varepsilon_0} = 0$$

$$\therefore \quad E_1 = 0 \quad \text{for } r_1 > R$$

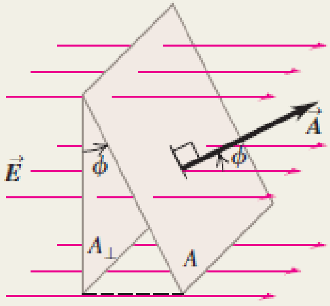
Shell of charge creates zero field inside (anywhere)

At point r inside a spherically symmetric volume (radius R) of charge,
- only the shells of charge with radii smaller than r contribute as point charges
- shells with radius between r and R produce zero field inside.

CHAPTER 22 SUMMARY

Electric flux: Electric flux is a measure of the "flow" of electric field through a surface. It is equal to the product of an area element and the perpendicular component of $\vec{E}$, integrated over a surface. (See Examples 22.1–22.3.)

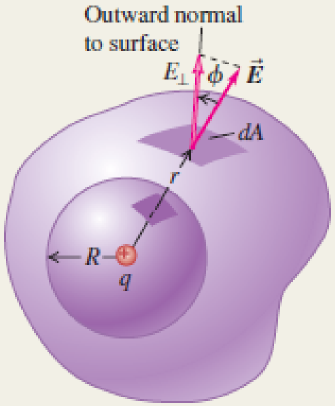
$$\Phi_E = \int E\cos\phi \, dA = \int E_\perp \, dA = \int \vec{E} \cdot d\vec{A} \quad (22.5)$$



Gauss's law: Gauss's law states that the total electric flux through a closed surface, which can be written as the surface integral of the component of $\vec{E}$ normal to the surface, equals a constant times the total charge Q_{encl} enclosed by the surface. Gauss's law is logically equivalent to Coulomb's law, but its use greatly simplifies problems with a high degree of symmetry. (See Examples 22.4–22.10.)

When excess charge is placed on a conductor and is at rest, it resides entirely on the surface, and $\vec{E} = \mathbf{0}$ everywhere in the material of the conductor. (See Examples 22.11–22.13.)

$$\Phi_E = \oint E\cos\phi \, dA = \oint E_\perp \, dA = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{encl}}{\epsilon_0} \quad (22.8), (22.9)$$



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Electric field of various symmetric charge distributions: The following table lists electric fields caused by several symmetric charge distributions. In the table, q, Q, λ, and σ refer to the *magnitudes* of the quantities.

Charge Distribution	Point in Electric Field	Electric Field Magnitude
Single point charge q	Distance r from q	$E = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$
Charge q on surface of conducting sphere with radius R	Outside sphere, $r > R$	$E = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$
	Inside sphere, $r < R$	$E = 0$
Infinite wire, charge per unit length λ	Distance r from wire	$E = \frac{1}{2\pi\epsilon_0}\frac{\lambda}{r}$
Infinite conducting cylinder with radius R, charge per unit length λ	Outside cylinder, $r > R$	$E = \frac{1}{2\pi\epsilon_0}\frac{\lambda}{r}$
	Inside cylinder, $r < R$	$E = 0$
Solid insulating sphere with radius R, charge Q distributed uniformly throughout volume	Outside sphere, $r > R$	$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}$
	Inside sphere, $r < R$	$E = \frac{1}{4\pi\epsilon_0}\frac{Qr}{R^3}$
Infinite sheet of charge with uniform charge per unit area σ	Any point	$E = \frac{\sigma}{2\epsilon_0}$
Two oppositely charged conducting plates with surface charge densities $+\sigma$ and $-\sigma$	Any point between plates	$E = \frac{\sigma}{\epsilon_0}$
Charged conductor	Just outside the conductor	$E = \frac{\sigma}{\epsilon_0}$

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