Welcome to 227 “ELECTROMAGNETISM”

The course Web site: [http://www.physics.rutgers.edu/ugrad/227fall/](http://www.physics.rutgers.edu/ugrad/227fall/)
(also link on Sakai)

Lecturers: Prof. Michael Gershenson, Prof. Vitaly Podzorov

Course administrator: Prof. Roy Montalvo
The last-year lectures are available on our Web page. The finalized slides (with Iclicker questions/answers) will be posted on the Web after each lecture.

I encourage you to look through the lectures and the relevant paragraphs from the textbook *in advance*, before the lecture. This will help you

- to get used to new ideas;
- to check out if the math involved is familiar to you;
- to prepare your questions on the most difficult issues.
Iclickers

During each lecture, several iclicker questions will be asked. Your *correct answers* will be count as an extra credit (extra 2% on top of 100%) towards your course grade. Please **register your Iclicker** as soon as possible.

- Go to http://www.iclicker.com/registration/ (or link from iclicker.com)
- From the drop-down menu below "Which software will your instructor use in class?" Select "iClicker Classic (formerly iClicker 7)".
- From the drop-down menu below "Which Learning Management System does your instructor use?“ Select "My institution does not use an LMS“.
- Enter your first name, last name (NO NICK NAMES, NO ABBREVIATIONS) and your Rutgers 9-digit student ID number, not your SSN, or your NetID.
- Enter your clicker id printed on a tag on the lower rear of the clicker.
- Please copy your id number and keep it in a safe place as it tends to wear off the iclicker back.
- Type the verification number on the screen.
- You will see an on-screen message confirming that registration was successful. Your Rutgers ID is now tied to your unique iclicker ID.
**Homeworks:** one learns most of physics by solving problems, so please take the homework seriously.

If you are observing religious holidays, please complete your MasteringPhysics homework in advance (the deadline is the same for all the students).

Registration:
1. Do not go to masteringphysics.com the course ID will not work. Use the link given on this course website.
2. If you already have a Pearson account linked to this course's book use that account to log in, click enroll in the course and enter the courseID: montalvo44851.
3. If you do not have an account to the course book follow the steps to create a new account then enroll in the course with courseID: montalvo44851.

If you have questions on MasteringPhysics, please e-mail your questions to the course administrator (Prof. Roy Montalvo, rm1255@physics.rutgers.edu) who is in charge of MasteringPhysics.
Invaluable resource (essentially, free tutoring)!

For some of you, talking to your professors/TAs is not easy. Please make any effort to overcome this “potential barrier”! The sooner you start attending office hours the better!

*Important*: you need to formulate your questions before coming to office hours. Remember, the phase like “I don’t understand this...” is not a question, it’s a statement.
Piazza is a free online gathering place where students can ask, answer, and explore 24/7, under the guidance of their instructors.

The main idea: to provide a **discussion forum** for **student-to-student** interaction and learning.

When students post on Piazza, everyone benefits. Students like knowing that others have the same question, and when it's answered on Piazza, it's answered for everybody.
Pre- and Post-Testing (four parts in total)

As part of the pre-testing process in your physics course you are assigned to complete an online survey that will take ~15 minutes to complete. You are expected to take the survey now, and then again at the end of the semester in order to receive credit for having completed the Pre- and Post-testing requirements in this course.

To get this 2% you must complete all 4 parts of this:

• Pre-test which was **administered during this week's recitations (9/5 and 9/6).**

  **Make-up:** NPL-213, Friday 9/15, from 10am-1pm.

• Pre-survey which you will do **online; you must complete this survey by 11:59 pm on Friday, September 15th.**

• Post-test will be administered during recitation at the end of the semester.

• Post-survey will be again on-line, you will receive a link to it at the end of the semester.
Lecture 1. Electric Charge, Coulomb’s Law, Superposition Principle

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Fundamental forces in the macroscopic world

**Enormous range of electromagnetic phenomena (and devices based on them):**

All of them (except interactions of the electromagnetic field with matter) can be described by 4 (!) equations (Maxwell Eqs).

Fundamental goal of the course: to appreciate this unity.
Electric Charge

Electric charge is a physical quantity that characterizes how charged objects participate in electrostatic interactions (compare: mass – the charge for gravitational interactions).

Electric charge properties:

- **It’s a scalar** (remains the same in all ref. frames). Charge comes in two types — positive and negative.

- **It’s quantized** – it’s allowed to be integer multiples of \( \pm e \) (the elementary charge).

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

Unit of charge: Coulomb

Oil drop experiment 1909

Harvey Fletcher (1884 - 1981)

Robert A. Millikan (1868 - 1953)

Nobel 1923

- **The net charge of any isolated system is conserved** (this doesn’t mean that the number of particles is conserved). The net charge of the Universe = 0. Because the net charge of the Universe is zero, its large-scale structure is shaped by gravitation, not by electromagnetic interactions (which are much stronger).
Coulomb’s Law

\[ \mathbf{F}_{Q-q} \quad \mathbf{F}_{q-Q} \]

(the force that \( Q \) exerts on \( q \))

\[ \hat{x} \rightarrow \text{unit vector along } +x \]


The x-component of \( \mathbf{F}_{q-Q} \) ? (\( \mathbf{F} \cdot \hat{x} \Rightarrow F_x > 0 \) if \( \mathbf{F} \) along \( \hat{x} \), \( F_x < 0 \) if \( \mathbf{F} \) along \( -\hat{x} \)):

A

B

C

D

\[ \hat{x} \rightarrow \text{unit vector along } +x \]
Coulomb’s Law (cont’d)

The force of interaction between two point charges at rest in vacuum is directed along the line connecting the charges, it is proportional to the charges $q_1$ and $q_2$ and inversely proportional to the distance between the charges squared.

Iclicker Question

The Coulomb force is proportional to both $q_1$ and $q_2$. This means:

A. $F_{12} \propto q_1 + q_2$

B. $F_{12} \propto q_1 - q_2$

C. $F_{12} \propto q_1 \times q_2$

D. $F_{12} \propto q_1 / q_2$

E. None of the above
The force of interaction between two \textbf{point} charges \textit{at rest in vacuum} is directed along the line connecting the charges, it is proportional to the charges $q_1$ and $q_2$ and inversely proportional to the distance between the charges squared.

$$F = \frac{1}{4\pi \varepsilon_0} \frac{|q_1 q_2|}{r^2}$$

$\varepsilon_0 \approx 9 \times 10^{-12} \text{C}^2/(Nm^2)$

$$\frac{1}{4\pi \varepsilon_0} \approx 9 \times 10^9 \text{Nm}^2/C^2 \approx 10^{10} \text{Nm}^2/C^2$$

This formulation suggests \textit{instantaneous} interaction ("spooky action at a distance" Einstein). Thus, this law must be modified in electrodynamics.
Electromagnetic interaction is billion-….billion times stronger than the gravitational one. Why do we usually ignore it? Because the matter around us is mostly **uncharged** (almost perfect balance of positive and negative charges).

To appreciate the strength of electric forces, let’s calculate the force of repulsion between two persons with $10^{-9}$ (one part per billion) of their electrons being removed:

\[
\text{force: } F = \frac{1}{4\pi\varepsilon_0} \frac{q_1q_2}{r^2} \approx 10^{10} N m^2/C^2 \frac{10C \times 10C}{(1m)^2} \approx 10^{12} N
\]

- strong enough to lift a $500m \times 500m \times 500m$ lead cube!
Coulomb's Law in the coordinate form

\[ F = \left| \mathbf{F}_{2-1} \right| = \left| \mathbf{F}_{1-2} \right| \]

\[ = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{r_{21}^2} \]

Coulomb's Law in the vector form

\[ \mathbf{F}_{1\rightarrow 2} = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{(\mathbf{r}_2 - \mathbf{r}_1)^2} \frac{\mathbf{r}_2 - \mathbf{r}_1}{|\mathbf{r}_2 - \mathbf{r}_1|} \]

force on \( q_2 \) by \( q_1 \)

unit vector along \( \mathbf{r}_2 - \mathbf{r}_1 \)

If one of the charges is at the origin \( (r_1=0) \):

\[ \mathbf{F}_{1\rightarrow 2} = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{(\mathbf{r}_{12})^2} \mathbf{r}_{12} \]

\[ \mathbf{F}_{2\rightarrow 1} =？ \]
**Superposition Principle**: Interaction between any two charges is completely unaffected by the presence of the other charges.

\[ \vec{F}_{net} = \sum_i \vec{F}_i \]

\[ \vec{F}_{net} = \vec{F}_{2-3} + \vec{F}_{1-3} \]

\[ \approx 0.005N \cdot \hat{x} - 0.005N \cdot \hat{y} \]

\( \hat{x} \) - the unit vector along \( \hat{x} \)

\( \hat{y} \) - the unit vector along \( \hat{y} \)

\[ F = \sqrt{F_x^2 + F_y^2} \approx 0.007N \]
Maxwell Equations are **linear** differential equations; they have solutions which can be added together to form other solutions. This is a reflection of the fact that photons *do not* interact with each other.

One of the consequences: light sabers don’t work as intended 😞.

Foundations of Electrostatics:

**Coulomb’s Law and Superposition Principle.**

**The Main Problem of Electrostatics:**

Given: the charge distribution (charges at rest).

Find: the force on a probe charge everywhere.
Three point charges lie on the x-axis. All three charges have the same magnitude +1C. The positions of the charges are shown on the plot. Find the force exerted on #3 by #1 and #2.

\[ F = k \frac{|q_1q_2|}{r^2} \]

A. \( F = k \frac{1}{2} [N] \)  
B. \( F = k2[N] \)  
C. \( F = k \frac{1}{3} [N] \)  
D. \( F = k \frac{5}{4} [N] \)  
E. \( F = k \frac{3}{2} [N] \)
1. Draw a nice sketch (force diagram) and introduce the coordinate system.

2. Write down what is given and what is to be found (introduce notations).

   Given: ....
   Find: ...

3. Analyze the problem:
   - identify concepts (and symmetries);
   - transform concepts into equations;
   - solve the system of equations;
   - analyze the limiting cases, check if the answer makes sense.

4. Plug in numbers.
An **electric dipole** is formed by two charges $+q$ and $-q$ at the distance $d$ apart. Find the force on a probe charge $+q_p$ which is placed at a distance $r$ from the middle of the dipole along the line perpendicular to the dipole axis.

### Step 1: nice sketch and notations

![Sketch of an electric dipole with probe charge](image)

### Step 2: Given: $q$, $q_p$, $d$, $r$. Find: $F_{net}$

### Step 3: analyze the problem

**Concepts**: Coulomb’s law and superposition principle.

**Symmetry**: horizontal components of $F_1$ and $F_2$ compensate each other, we need to consider only vertical components.

\[
F_{net} = F_{++y} + F_{-+y}
\]

\[
F_{++y} = F_{++} \sin \alpha = \frac{1}{4\pi \varepsilon_0} \frac{q_p q}{r^2 + (d/2)^2} \sin \alpha = \frac{1}{4\pi \varepsilon_0} \frac{q_p q}{r^2 + (d/2)^2} \frac{d/2}{\sqrt{r^2 + (d/2)^2}}
\]

\[
F_{net} = F_{++y} + F_{-+y} = \frac{1}{4\pi \varepsilon_0} \frac{q_p q d}{(r^2 + (d/2)^2)^{3/2}}
\]
Electric dipole (cont’d)

Step 4: analyze the answer

\[ F_{\text{net}} = \frac{1}{4\pi\varepsilon_0} \frac{q_p q d}{[r^2 + (d/2)^2]^{3/2}} \rightarrow (r \gg d) \approx \frac{1}{4\pi\varepsilon_0} \frac{q_p q d}{r^3} \]

- at \( r \gg d \), the force decreases with distance faster than that for a point charge. This makes sense because the net charge of the dipole is 0.


Iclicker Question

Correct representation of \( F_y(x) \):

A

B

C

D

E
Electrostatics: Coulomb’s Law + Superposition Principle

The Main Problem of Electrostatics

The charge distribution is given (charges at rest).

Find the force on a probe charge everywhere (or the electric field everywhere).

Appendix I: Four Fundamental Interactions

- **Strong** force: Initially all four forces were equally strong. Present.
- **Electromagnetic** force: Gravity became a distinct force, weaker than the others. Present.
- **Weak** force: The strong force became distinct from the electroweak force. Present.
- **Gravitational** force: The electromagnetic and weak forces became distinct, leaving a total of four forces. Present.

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Appendix II: Electromagnetic Interactions Timeline

- **1830**: Electromagnetic Induction
  - Faraday, Henry
- **1861**: Maxwell Equations
  - Maxwell
- **1887**: Electromagnetic Waves
  - Hertz
- **1905**: Special Theory of Relativity
  - Einstein
- **1950-60**: Quantum Electrodynamics
  - Feynman, Schwinger, Tomonaga

**Feynman**: “It (the Faraday’s discovery which finally resulted in Maxwell equations) transformed the rather dull subject of static fields into a very exciting dynamic subject with an enormous range of wonderful phenomena”.

Faraday’s discovery stimulated the **Second Unification** in physics that united electricity, magnetism, and optics.

**Classical Physics**
- Interactions mediated by classical el.-mag. fields
- E.M. 227

**Quantum Physics**
- Particle-particle interactions mediated by exchange of photons
Can neutral (uncharged) objects participate in el.-mag. interactions?

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The answer is **YES** unless we consider point-like elementary particles with no internal structure (example: neutrino).

*Examples of neutral objects participating in el.-mag. interactions:*

- All macro objects (they can be polarized);
- Neutral atoms (they can be polarized, excited by photons);
- Neutrons (composite particles, contain three charged quarks);
- Etc.
Structure of the Course

**Electromagnetism**

- **E** - electric fields
- **B** – magnetic fields
- **Q** – charges
- **I** – currents
- **Φ** - fluxes

\[
\oint E \cdot dA = \frac{Q}{\varepsilon_0} \\
\oint B \cdot dA = 0 \\
\oint E \cdot ds = -\frac{d\Phi}{dt} \\
\oint B \cdot ds = \mu_0 \varepsilon_0 \frac{d\Phi}{dt} + \mu_0 \mu_0 I
\]

\[
\frac{d}{dt} = 0
\]

**El.-mag. fields generated by alternating currents**

- Ch. 29 - 31

**Electro Magneto**

- Electrostatics

\[
\frac{d}{dt} \neq 0
\]

**Magnetic fields generated by time-independent currents**

- Ch. 27 - 28

**Electrodynamics**

**Electromagnetic Waves**

- Ch. 32
**Electromagnetic Phenomena**

**Enormous range of electromagnetic phenomena:**

All of them (except interactions of the electromagnetic field with matter) can be described using Maxwell Equations.

Fundamental goal of the course: to appreciate this unity.