ECE 329 – Fall 2021

Prof. Ravaioli – Office: 2062 ECEB

Section E – 1:00pm

Lecture 1
Introduction to the course

• Course website
  https://courses.engr.illinois.edu/ece329/

• Course administration will be on Canvas
  https://canvas.illinois.edu/

• Lecture Slides of Section “E” posted at:
  https://urseminar.web.illinois.edu
# Introduction to the course

## Instructors

<table>
<thead>
<tr>
<th>Instructor</th>
<th>Prof. Xu Chen (Coordinator)</th>
<th>Prof. Umberto Ravaiolì</th>
<th>Prof. Lara Waldrop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
<td>C</td>
<td>E</td>
<td>X</td>
</tr>
<tr>
<td><strong>Lecture</strong></td>
<td>MWF 10:00-10:50am ECEB 1013</td>
<td>MWF 1:00-1:50pm ECEB 1015</td>
<td>MWF 2:00-2:50pm Zoom</td>
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<td><strong>Email</strong></td>
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<td><a href="mailto:lwaldrop@illinois.edu">lwaldrop@illinois.edu</a></td>
</tr>
<tr>
<td><strong>Office Hours</strong></td>
<td>Wed. 4-5pm ECEB 5040</td>
<td>Wed. 3-4pm ECEB 2062</td>
<td>Thu. 11am-noon Zoom</td>
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</tbody>
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## Teaching Assistants

<table>
<thead>
<tr>
<th>TA</th>
<th>Victor Shangguan (Head TA)</th>
<th>Robert Irvin</th>
<th>Andrew Page</th>
<th>Dufei Wu</th>
</tr>
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<tr>
<td><strong>Office Hour</strong></td>
<td>Mon. 3-5pm ECEB 3034</td>
<td>Mon. 11am-1pm Tue. 2-4pm ECEB 3034</td>
<td>Tue. 4-6pm ECEB 3034</td>
<td>Mon. 8-10pm Zoom</td>
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Introduction to the course

Exam schedule

- Exam 1 Sep. 23 Thu 7:00-8:15pm
- Exam 2 Oct. 21 Thu 7:00-8:15pm
- Exam 3 Nov. 18 Thu 7:00-8:15pm
- Final Exam date and time TBD
- Midterms are 75 minutes long.
- Conflicts for midterms will be 5:30-6:45pm the same day. You need a valid excuse to sign up for conflict exams.

The exams will be in person, except for students who are attending the semester remotely and have requested permission to take an online version of exams (details TBD).

There will not be accommodation for time-zone differences for students taking the course remotely.

Arrangements may change, depending on the pandemic situation. Stay tuned and engaged.
Introduction to the course

IMPORTANT: If you have not done so already respond to the brief questionnaire

https://forms.illinois.edu/sec/927042887

We need your input to finalize the organizational details

For general questions on the course, DO NOT contact directly by e-mail the instructors or the TA’s, because response is likely to be very slow.

DIRECT GENERAL QUESTIONS ON THE COURSE TO THE CLASS ADDRESS: ece-329-fall21-group@office365.illinois.edu

For questions of a personal nature, contact me instead.
Introduction to the course

Grade Breakdown

<table>
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<tr>
<th>Grade Breakdown</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Participation</td>
<td>1%</td>
</tr>
<tr>
<td>Homework</td>
<td>14%</td>
</tr>
<tr>
<td>Midterm exam(3)</td>
<td>20%</td>
</tr>
<tr>
<td>Final Exam</td>
<td>25%</td>
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</tbody>
</table>

Participation
To receive the full 1% participation credit, you must:
Consistently attend your in-person lecture
OR Consistently attend the 2pm Zoom lecture
AND Actively participate in office hours or Canvas discussion board

Note that watching the Zoom lecture recordings without attending the live lectures will not earn you participation credit
Introduction to the course

You Are Special!

Carefully read through the web site and all instructions for homeworks and exams to understand our policies. We understand that occasionally you may have an accident (late homework, forgot to sign up for conflict on time, etc). We are willing to bend the rules and give you special treatment once this semester, but we want to ensure we treat all students equally special. Hence, a “You Are Special” credit will be deposited on your gradebook at the beginning of the semester. When you require special treatment outside of the rules, you may redeem this credit.
Introduction to the course

If you have time and interest, consider registering for this companion enrichment course:

ECE 398
Special Topics in ECE

- Course in Catalog
- List of Terms offered
- PDF
- Register for Classes

**Course Details:**
- **Code:** ECE 398
- **Title:** Special Topics in ECE
- **Fall 2021 All Classes**
- **Availability:** Open
- **Credit:** 1 hours
- **Section Title:** Fields and Waves VR Lab
- **Date Range:** Meets 08/23/21-12/08/21
- **Part of Term:** 1

**Section Info:**
This course is designed to be taken concurrently with ECE 329 “Fields and Waves I”, to strengthen the students' understanding of the concepts in electromagnetism and their applications, through a combination of customized Virtual Reality (VR) experiences and computer simulations using Mathematica. Topics include static and quasi-static electric fields, polarization, static and quasi-static magnetic fields, dynamic fields and Maxwell's equations, wave solutions of Maxwell's equations in free space and homogeneous media, time- and frequency-domain analysis of waves in transmission line circuits, and Smith Chart analysis. Prerequisites: Concurrent enrollment in ECE 329.
Introduction to the course

• **ECE 329** assumes knowledge of
  – **PHYS 212** (Electromagnetic Fields)
  – **MATH 241** (Mathematics of Vector Calculus)
  – **ECE 210** (Lumped circuits, Time-domain, Frequency-domain, Phasors)

• Follow on course is **ECE 350**
Introduction to the course

• Topics to be covered
  – Electrostatics = Static electric fields
  – Magnetostatics = Constant currents and static magnetic fields
  – Time-varying fields described by the complete set of Maxwell’s equations
  – Plane waves solutions of Maxwell’s equations
  – Waves in Transmission Lines (distributed circuits)
EM Timeline – 1

• **BC** – The ancient philosophers knew that magnetite minerals attracted iron and rubbed amber attracted small objects.
• **1600** William Gilbert coins the term “electric” from the Greek name for amber (ἠλεκτρον).
• **1671** Isaac Newton demonstrates that white light is a mixture of all colors.
• **1733** Charles-François du Fay discovers that electric charges are of two forms (like charges repel each other, unlike charges attract each other)
• **1745** Pieter van Musschenbroek invents the Leyden jar, the first electrical capacitor.
• **1752** Benjamin Franklin invents the lightning rod.
• **1785** Charles-Augustin de Coulomb formulates the force between electrical charges.
• **1800** Alessandro Volta invents the electric battery.
• **1820** Hans Christian Oersted discovers that the electric current in a wire orients a compass needle ⊥ to the wire.
EM Timeline – 2

• **1820** André-Marie Ampère notes that wires with parallel currents attract each other and with opposite currents repel each other.

• **1820** Jean-Baptiste Biot and Félix Savart formulate the law relating current in a wire with induced magnetic field.

• **1827** Georg Simon Ohm formulates the law relating electric potential to current and resistance.

• **1831** Michael Faraday discovers that a changing magnetic field causes an electromotive force.

• **1835** Carl Friedrich Gauss’ law relates the electric flux through a closed surface to the enclosed electric charge.

• **1873** James Clerk Maxwell publishes his treatise containing Maxwell’s equations.

• **1887** Heinrich Hertz generates radio waves demonstrating that they share the same properties as light.

• **1888** Nikola Tesla invents the alternating current motor.

• **1895** Guglielmo Marconi invents the wireless telegraph demonstrating transmission of information via radio.
Personal flashback
Villa Griffone – Pontecchio Marconi, Italy

the famous window

Location of the first wireless telegraph radio experiment by Marconi, now remodeled as Telecommunications Laboratories of the University of Bologna, museum, and headquarters of the Marconi Foundation. I worked there 1979-1982 for my dissertations on fiber optics and on microwaves in plasma physics, and for various professional projects.
Suggested reading on the development of early radio technology and services:


download pdf from UIUC digital library (JSTOR collection):
https://www-jstor-org.proxy2.library.illinois.edu/stable/j.ctt7zthqre
EM Timeline – 3

- **1895** Wilhelm Röntgen discovers X-rays.
- **1897** Joseph Thomson discovers the electron.
- **1897** Karl Braun invents the cathode ray tube (CRT).
- **1902** Reginald Fessenden invents amplitude modulation (AM) for telephone; **1906** first AM radio transmission.
- **1904** John Fleming realizes the vacuum tube diode (using the Edison effect).
- **1905** Einstein explains thermionic emission.
- **1912** Lee de Forest invents Vacuum Tube Triode amplifier.
- **1919** Edwin Armstrong invents the superheterodyne radio receiver.
- **1920** Westinghouse starts KDKA commercial radio station in Pittsburgh.
EM Timeline – 4

• **1923** Vladimir Zworykin invents television.
• **1926** Transatlantic telephone service between London and New York.
• **1932** Guglielmo Marconi realizes first microwave telephone link, between the Vatican and the Pope’s Summer residence.
• **1933** Edwin Armstrong invents frequency modulation (FM).
• **1935** Regular television transmissions begin in Germany, followed by England (1936) and USA (1939).
• **1935** Robert Watson-Watt invents the Radar.
• **1938** Alec Reeves invents Pulse Code Modulation (PCM).
• **1947** Invention of the transistor by Bardeen, Brattain and Shockley → solid-state electronics development begins.
Vector Fields

Interaction between charged particles is described in terms of electric field and magnetic field.

**Cartesian coordinates**

\[(x, y, z) \equiv \mathbf{r}\]

**Time-dependent fields**

\[
E(\mathbf{r}, t) = (E_x(\mathbf{r}, t), E_y(\mathbf{r}, t), E_z(\mathbf{r}, t))
\]

\[
B(\mathbf{r}, t) = (B_x(\mathbf{r}, t), B_y(\mathbf{r}, t), B_z(\mathbf{r}, t))
\]
Maxwell’s Equations

\[ \nabla \times \vec{E}(t) = -\frac{\partial \vec{B}(t)}{\partial t} \]

\[ \nabla \times \vec{H}(t) = \frac{\partial \vec{D}(t)}{\partial t} + \vec{J} \]

\[ \nabla \cdot \vec{D}(t) = \rho \]

\[ \nabla \cdot \vec{B}(t) = 0 \]

\[ \vec{D}(t) = \varepsilon \vec{E}(t) \]

\[ \vec{B}(t) = \mu \vec{H}(t) \]
In free space

\[ \varepsilon = \varepsilon_0 = 8.854 \times 10^{-12} \text{ [F/m]} \]
\[ \mu = \mu_0 = 4\pi \times 10^{-7} \text{ [H/m]} \]

In a material medium

\[ \varepsilon = \varepsilon_r \varepsilon_0 \quad \mu = \mu_r \mu_0 \]

\( \varepsilon_r = \) relative permittivity (dielectric constant)
\( \mu_r = \) relative permeability

In anisotropic media, we have tensors!

\[
\varepsilon_r = \begin{bmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{bmatrix}
\]
\[
\mu_r = \begin{bmatrix}
\mu_{xx} & \mu_{xy} & \mu_{xz} \\
\mu_{yx} & \mu_{yy} & \mu_{yz} \\
\mu_{zx} & \mu_{zy} & \mu_{zz}
\end{bmatrix}
\]
Maxwell’s Equations for free space

\[ \nabla \times \vec{E}(t) = -\frac{\partial \vec{B}(t)}{\partial t} \]

\[ \nabla \times \vec{B}(t) = \mu_0 \varepsilon_0 \frac{\partial \vec{E}(t)}{\partial t} + \mu_0 \vec{J} \]

\[
\frac{1}{c^2}
\]
Static Regimes – Fields do not vary in time

**ELECTROSTATICS**

- The electric charges do not change position in time.
- Therefore, $\rho$, $E$ and $D$ are constant and there is no magnetic field $H$, since there is no current density $J$.

**MAGNETOSTATICS**

- The charge crossing a given cross-section (current) does not vary in time so that $J$, $H$ and $B$ are constant.
- Although charges are moving, the steady current maintains a constant charge density $\rho$ in space and the electric field $E$ is static.
Time-Varying Fields

LOW FREQUENCY (Slowly-Varying Fields)

• The displacement current is negligible in Maxwell’s equations

\[
\left| \frac{\partial \vec{D}(t)}{\partial t} \right| \ll \left| \vec{J}(t) \right|
\]

HIGH FREQUENCY (Fast-Varying Fields)

The general set of Maxwell’s equations must be considered, with no approximations.
Elementary charged particles

Electromagnetic phenomena at the fundamental level are closely linked to the movement and interaction of charged particles

- **Electron**
  
  \[ m_e = 9.10938188 \times 10^{-31} \text{kg} \]
  
  \[ q = -e = -1.602 \times 10^{-19} \text{C} \]

- **Proton**
  
  \[ m_p = 1,836.15266 \ m_e = 1.67262158 \times 10^{-27} \text{kg} \]
  
  \[ q = e = 1.602 \times 10^{-19} \text{C} \]
• **Gravitational forces**

Assume distance \( r = 10\text{Å} \) between particles

\[
g = 6.673 \times 10^{-11} \text{Nm}^2/\text{kg}^2
\]

**electron-proton**

\[
F_{gep} = g \frac{m_e m_p}{r^2} = 1.0167349 \times 10^{-49} \text{N}
\]

**electron-electron**

\[
F_{gee} = g \frac{m_e m_e}{r^2} = 5.5373 \times 10^{-53} \text{N}
\]
• Electrostatic forces

Assume again distance \( r = 10\text{Å} \)

\[
k = \frac{1}{(4\pi \varepsilon_0)} \approx 8.9876 \times 10^9 \text{Nm}^2/\text{C}^2
\]

\[
F_{C_{ep}} = -k \frac{q^2}{r^2} \approx -2.30708943 \times 10^{-10} \text{N}
\]

\[
F_{C_{ee}} = k \frac{q^2}{r^2} \approx 2.30708943 \times 10^{-10} \text{N}
\]

(negative sign corresponds to attractive force)
Note:

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \times 10^8 \text{ m/s} \]

In most cases it is acceptable to use this approximate value for the speed of light in vacuum.

However, keep in mind that since 1983 the International System of Units has adopted an exact value for the speed of light

\[ c = 299,792,458 \text{ m/s} \]

and has redefined the meter as the distance travelled by light in vacuum in \(1/299,792,458\) of a second.

There are certain special cases (e.g., relatively long lossy transmission lines) for which the exact value should be used because the approximation may lead to vastly incorrect results.

For the cases covered by this course, the approximation \(3 \times 10^8\) will generally suffice.
Electromagnetic fields accelerate charged particles according to Newton’s second law of motion ($v \ll c$)

$$m \frac{dv}{dt} = q[E(r, t) + v \times B(r, t)]$$

Lorentz Force

$$F = q \left[ E + v \times B \right]$$

- electric force
- magnetic force

$$F = qE + qv \times B$$

$\perp$ to $v$
Electromagnetic fields accelerate charged particles according to Newton’s second law of motion ($v \ll c$)

\[
m \frac{dv}{dt} = q[E(r,t) + v \times B(r,t)]
\]

Lorentz Force

\[
F = q \left[ E + v \times B \right]
\]

Always remember that for an electron the charge is negative so that forces point in the direction opposite to $E$ and $v \times B$. 

\[
F = qE + qv \times B
\]

\[\perp \text{ to } v\]
What is the velocity reached by an electron in the apparatus used by J.J. Thomson in his famous experiment, for an accelerating voltage $V_0 = 6\text{kV}$.

**Kinetic energy:** \[ |eV_0| = \frac{1}{2} m_0 v^2 \]

\[
1.602 \times 10^{-19} \cdot 6000 = \frac{1}{2} \cdot 9.10938188 \cdot 10^{-31} \cdot v^2
\]

\[ v \approx 45,941,095 \text{ [m/s]} \]

Do we need to worry about relativity?
What is the velocity reached by an electron in the apparatus used by J.J. Thomson in his famous experiment, for an accelerating voltage $V_0 = 6\text{kV}$.

**Kinetic energy:** \[ |eV_0| = \frac{1}{2} m_0 v^2 \]

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\]

\[ v \approx 45,941,095 \text{ [m/s]} \]

relativistic mass \[ m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \approx 1.01194 m_0 \] small mass correction
Definition of current density $J$

Net charge $Q$ crossing a unit area per second

Current density is measured in units of $A/m^2$
Review

**Dot product** between two vectors is a scalar

\[ \vec{A} \cdot \vec{B} = |\vec{A}| |\vec{B}| \cos \theta \]

Projection of one vector onto the other
Dot product is commutative and distributive

\[ A \cdot B = B \cdot A, \quad (\text{commutative property}) \]

\[ A \cdot (B + C) = A \cdot B + A \cdot C, \quad (\text{distributive property}) \]
Cross product between two vectors is a vector with magnitude

$$|\vec{A} \times \vec{B}| = |\vec{A}| \ |\vec{B}| \sin \theta$$

and direction normal to both $\vec{A}$ and $\vec{B}$ pointing as the thumb of the right hand when fingers rotate from $\vec{A}$ to $\vec{B}$.
Cross product

\[ \mathbf{A} \times \mathbf{B} = \hat{n} A B \sin \theta_{AB} \]
Review

Right hand rule
Cross product is anticommutative and distributive

\[ A \times B = -B \times A \quad \text{(anticommutative)} \]

\[ A \times (B + C) = A \times B + A \times C \quad \text{(distributive)} \]
Question:

what is the cross product of a vector with itself?
Question:

what is the cross product of a vector with itself?

\[ A \times A = 0. \]
Review

Relationships between basis vectors of Cartesian coordinates

\[ \hat{x} \times \hat{y} = \hat{z}, \quad \hat{y} \times \hat{z} = \hat{x}, \quad \hat{z} \times \hat{x} = \hat{y}. \]

(note the cyclic order)

\[ \hat{x} \times \hat{x} = \hat{y} \times \hat{y} = \hat{z} \times \hat{z} = 0. \]
By applying all the properties reviewed so far to the cross product of two vectors

\[
\mathbf{A} = (A_x, A_y, A_z) \\
\mathbf{B} = (B_x, B_y, B_z)
\]

\[
\mathbf{A} \times \mathbf{B} = (\hat{x}A_x + \hat{y}A_y + \hat{z}A_z) \times (\hat{x}B_x + \hat{y}B_y + \hat{z}B_z)
\]

\[
= \hat{x}(A_y B_z - A_z B_y) + \hat{y}(A_z B_x - A_x B_z) + \hat{z}(A_x B_y - A_y B_x)
\]
A useful mnemonic trick is to use the fact that the cross product gives the same terms as the determinant of the matrix below

\[
\mathbf{A} \times \mathbf{B} = \det \begin{bmatrix}
\hat{x} & \hat{y} & \hat{z} \\
A_x & A_y & A_z \\
B_x & B_y & B_z
\end{bmatrix}
\]

\[
= A_y B_z \hat{x} + A_z B_x \hat{y} + A_x B_y \hat{z} \\
- A_z B_y \hat{x} - A_x B_z \hat{y} - A_y B_x \hat{z}
\]
Lorentz Force example

At $t = 0$ an electron ($q = -1.602 \times 10^{-19} \text{ C}$) has velocity $v_e = 4.0 \times 10^5 \, \hat{\mathbf{y}} \text{ m/s}$. It is immersed in a space with uniform fields

$$E = 5.0 \, \hat{\mathbf{y}} \, \frac{\text{V}}{\text{m}} \quad H = 5.0 \, \hat{\mathbf{z}} \, \frac{\text{A}}{\text{m}}$$

Find the Lorentz force acting on the particle at $t = 0$.

**Electric Force**

$$F_E = qE = -1.602 \times 10^{-19} \times 5.0 =$$

$$-8.01 \times 10^{-19} \, \hat{\mathbf{y}} \, \text{N}$$
Lorentz Force example

At a given instant, an electron \( (q = -1.602 \times 10^{-19} \text{ C}) \) has with velocity \( v_e = 4.0 \times 10^5 \, \hat{y} \, \text{m/s} \). It is immersed in a space with uniform fields

\[
\mathbf{E} = 5.0 \hat{y} \, \frac{\text{V}}{\text{m}} \quad \mathbf{H} = 5.0 \hat{z} \, \frac{\text{A}}{\text{m}}
\]

Find the Lorentz force acting on the particle

**Magnetic force**

\[
F_H = q \, \mathbf{v} \times \mathbf{B} = q \mu \, \mathbf{v} \times \mathbf{H} = q \mu \, \det \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \\ 0 & 4 \times 10^5 & 0 \\ 0 & 0 & 5.0 \end{bmatrix}
\]

\[
= -1.602 \times 10^{-19} \times 4\pi \times 10^{-7}[4 \times 10^5 \times 5] \, \hat{x}
\]

\[
= -4.03 \times 10^{-19} \, \hat{y} \, \text{N}
\]
Reading Assignments

Prof. Kudeki’s ECE 329 Lecture Notes on Fields and Waves:

• Introduction
• 1) Vector Fields and Lorentz Force