ECE 329 – Fall 2022

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://ursemiconductors.web.illinois.edu**

Introduction to the course

ECE 329 - Fields and Waves I

Instructors:

Section C (10:00am): Professor Xu Chen (xuchen1@illinois.edu)

Section X (12:00pm): Professor Raluca Ilie (rilie@illinois.edu)

Section E (1:00pm): Professor Umberto Ravaioli (ravaioli@illinois.edu)

Teaching Assistants:

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Introduction to the course

EXAMS

Midterm #1 Tuesday, September 20, 2022 (7:00pm - 8:15pm)

Midterm #2 Tuesday, October 18, 2022 (7:00pm - 8:15pm)

Midterm #3 Tuesday, November 15, 2022 (7:00pm - 8:15pm)

Conflict Midterm exams will be scheduled on the same day from 5:30pm to 6:45pm

Final Exam **TBD**

Regular and Conflict final exams will be scheduled on dates and times as assigned by Campus.

In order to sign up for conflict exams, students need to have a valid excuse and obtain approval from the course coordinator (Prof. Ravaioli).

Exam rooms will be posted as soon as scheduling is completed. We do not have an online exam option this semester as we are going back to normal with respect to the pandemic situation.

Stay tuned and engaged, in case the situation changes.

Introduction to the course

Grading Policy

Homework (15%), Midterm 1 (20%), Midterm 2 (20%), Midterm 3 (20%), Final (25%).

Homework will be assigned weekly and will be due on Thursdays at 5:00pm, with electronic submission on Canvas. There will be no extensions granted and late homework submissions will not be accepted. Instead, the two lowest scores will be dropped when computing the final homework grade.

Engagement with the Canvas Discussions board is strongly encouraged. The top 10 (ten) contributors will earn a 1% extra bonus counting toward the final class grade.

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 that rubbed amber attracted small objects.
- **1600** William Gilbert coins the term "***electric***" from the Greek name for amber (ἤλεκτρον).
- **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 $\perp$ 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 (Nobel Prize 1909).

Personal flashback

Villa Griffone – Pontecchio Marconi, Italy

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.


DI QVI MARCONI LANCIÓ
IL PRIMO SEGNALE RADIO
PRIMAVERA MDCCCXCV

Suggested reading on the development of early radio technology and services:

H.G.J. Aitken "**The Continuous Wave: Technology and American Radio 1900-1932**", Princeton University Press, 1985

download pdf from UIUC digital library (JSTOR collection):

https://www-jstor-org.proxy2.library.illinois.edu/stable/j.ctt7zthqr

EM Timeline – 3

- **1895** Wilhelm Röntgen discovers X-rays. (Nobel Prize 1901)
- **1897** Joseph Thomson discovers the electron. (Nobel 1906)
- **1897** Karl Braun invents cathode ray tube (CRT) (Nobel 1909).
- **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) and development of electronics begins
- **1905** Einstein explains thermionic emission.
- **1912** Lee de Forest invents Vacuum Tube Triode amplifier.
- **1919** Edwin Armstrong invents the super-heterodyne radio receiver.
- **1920** Westinghouse starts KDKA commercial radio station in Pittsburgh.
- **1922** First educational radio station WRM (now WILL) at the Electrical Engineering Lab of the University of Illinois in Urbana. Six months later the BBC started operation in England.

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 in Castel Gandolfo (30 km away).
- **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 $\rightarrow$ 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

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

$$\mathbf{B}(\mathbf{r}, t) = (B_x(\mathbf{r}, t), B_y(\mathbf{r}, t), B_z(\mathbf{r}, t))$$

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

$$\varepsilon = \varepsilon_r \, \varepsilon_0 \qquad\qquad \mu = \mu_r \, \mu_0$$

ε_r = **relative permittivity (dielectric constant)**

μ_r = **relative permeability**

In anisotropic media, we have tensors!

$$\varepsilon_r = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \quad ; \quad \mu_r = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix}$$

Maxwell's Equations for free space

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

$$\nabla \times \vec{B}(t) = \underbrace{\mu_0 \, \varepsilon_0}_{\frac{1}{c^2}} \frac{\partial \vec{E}(t)}{\partial t} + \mu_0 \vec{J}$$

Static Regimes – Fields do not vary in time

ELECTROSTATICS

- **The electric charges do not change position in time.**
- **Therefore, ρ, 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 ρ 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**

$$\left|\frac{\partial \vec{D}(t)}{\partial t}\right| << \left|\vec{J}(t)\right|$$

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

$$g = 6.673 \times 10^{-11}\ \mathrm{Nm^2/kg^2}$$

electron-proton

$$F_{g_{ep}} = g\frac{m_e m_p}{r^2} = 1.0167349 \times 10^{-49}\mathrm{N}$$

electron-electron

$$F_{g_{ee}} = g\frac{m_e m_e}{r^2} = 5.5373 \times 10^{-53}\mathrm{N}$$

- **Electrostatic forces**

Assume again distance $r = 10\text{Å}$

$$k = 1/(4\pi\varepsilon_0) \approx 8.9876 \times 10^9\ \mathrm{Nm^2/C^2}$$

$$F_{C_{ep}} = -k\frac{q^2}{r^2} \approx -2.30708943 \times 10^{-10}\mathrm{N}$$

$$F_{C_{ee}} = k\frac{q^2}{r^2} \approx 2.30708943 \times 10^{-10}\mathrm{N}$$

(negative sign corresponds to attractive force)

Note:

$$c = \frac{1}{\sqrt{\mu_o \epsilon_o}} \approx 3 \times 10^8 \, \frac{\mathrm{m}}{\mathrm{s}}$$

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

$$c = 299{,}792{,}458 \ \mathrm{m/s}$$

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 3×10^8 will generally suffice.

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

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

Lorentz Force

$$\boldsymbol{F} = q\,[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}]$$

$$\boldsymbol{F} = \overset{\text{electric force}}{q\,\boldsymbol{E}} + \underbrace{\overset{\text{magnetic force}}{q\boldsymbol{v} \times \boldsymbol{B}}}_{\perp \text{ to } \boldsymbol{v}}$$

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

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$\perp$ to $\boldsymbol{v}$

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

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 = 6kV.

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 = 6kV.

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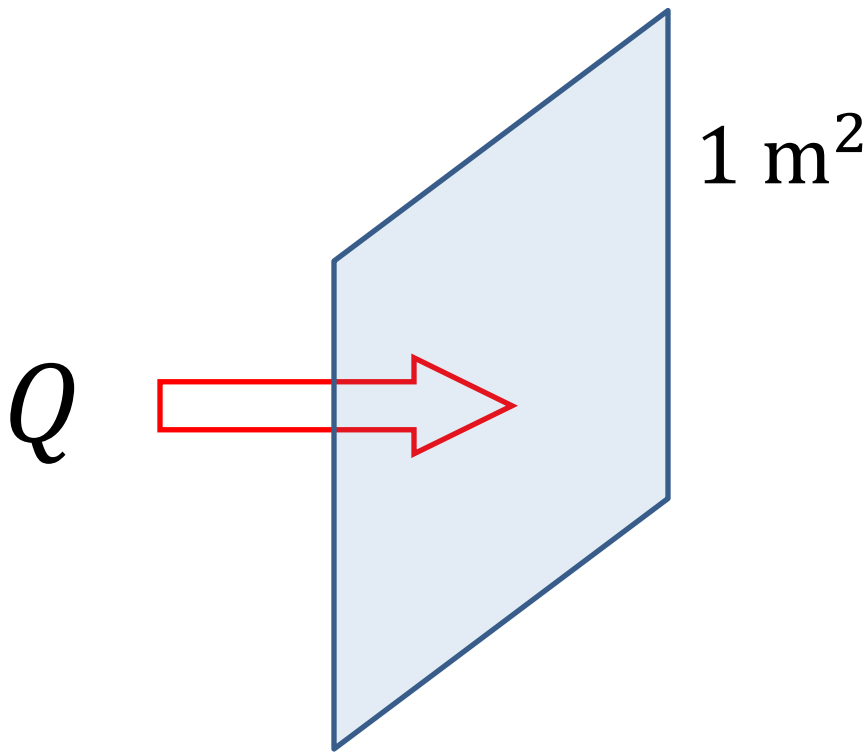
$$v \approx 45{,}941{,}095 \text{ [m/s]}$$

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

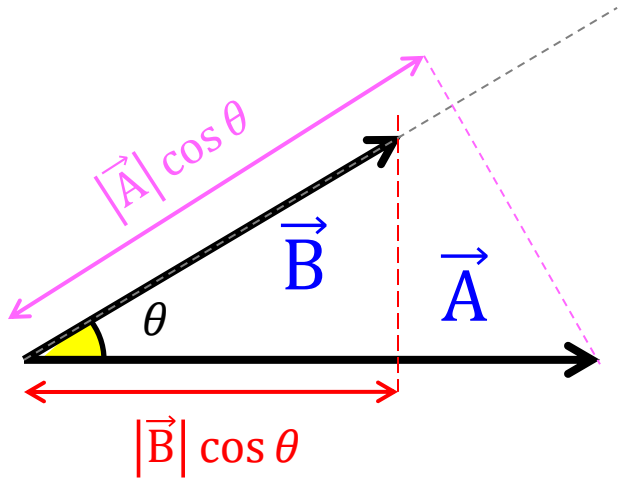


Current density is measured in units of A/m^2

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

Review

Dot product is commutative and distributive

$$\mathbf{A} \cdot \mathbf{B} = \mathbf{B} \cdot \mathbf{A},$$

(commutative property)

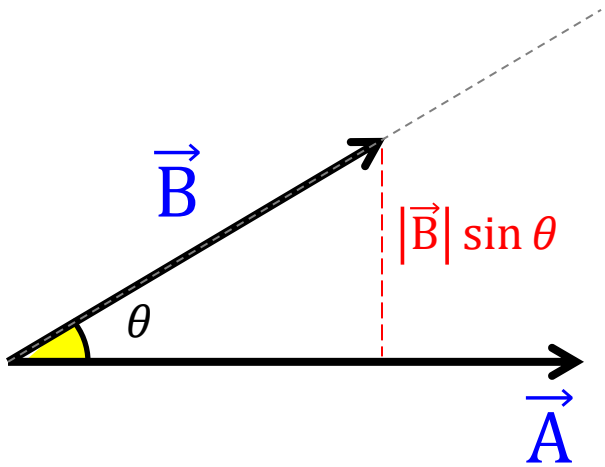
$$\mathbf{A} \cdot (\mathbf{B} + \mathbf{C}) = \mathbf{A} \cdot \mathbf{B} + \mathbf{A} \cdot \mathbf{C},$$

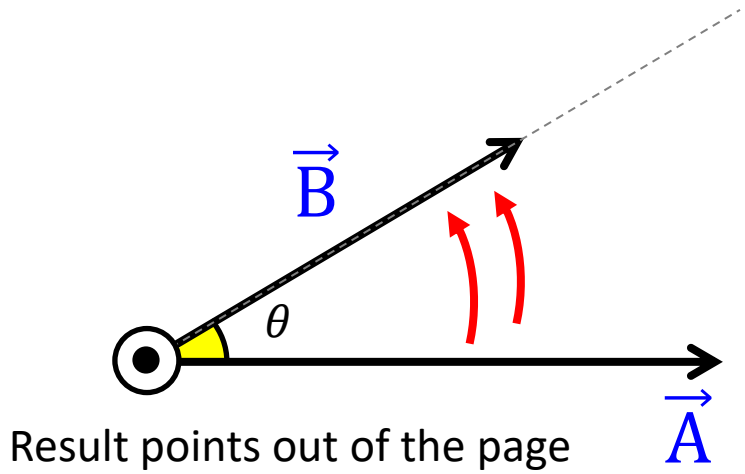
(distributive property)

Review

Cross product between two vectors is a vector with magnitude

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

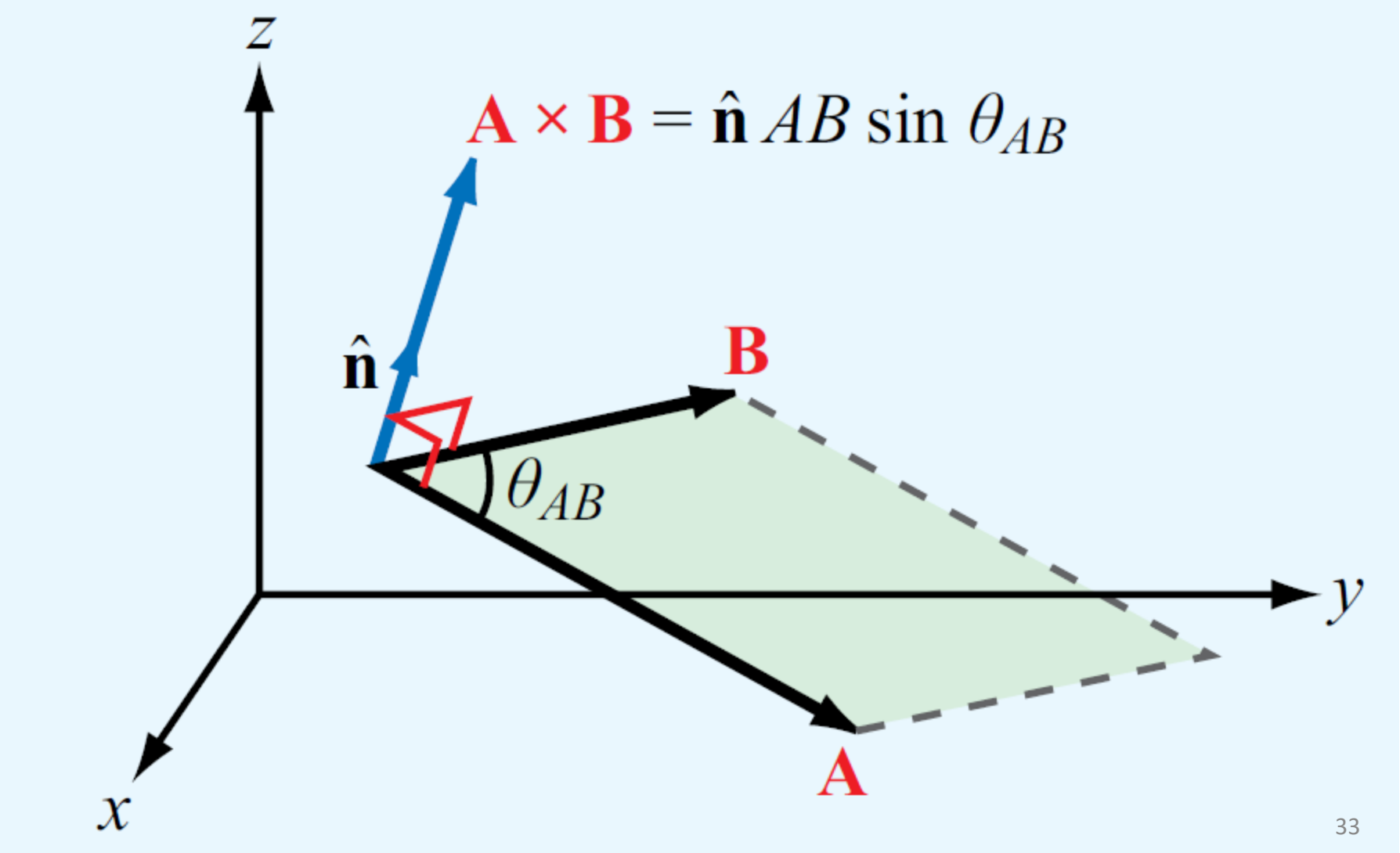




and direction normal to both $\vec{A}$ and $\vec{B}$ pointing as the thumb of the right hand when fingers rotate from $\vec{A}$ to $\vec{B}$

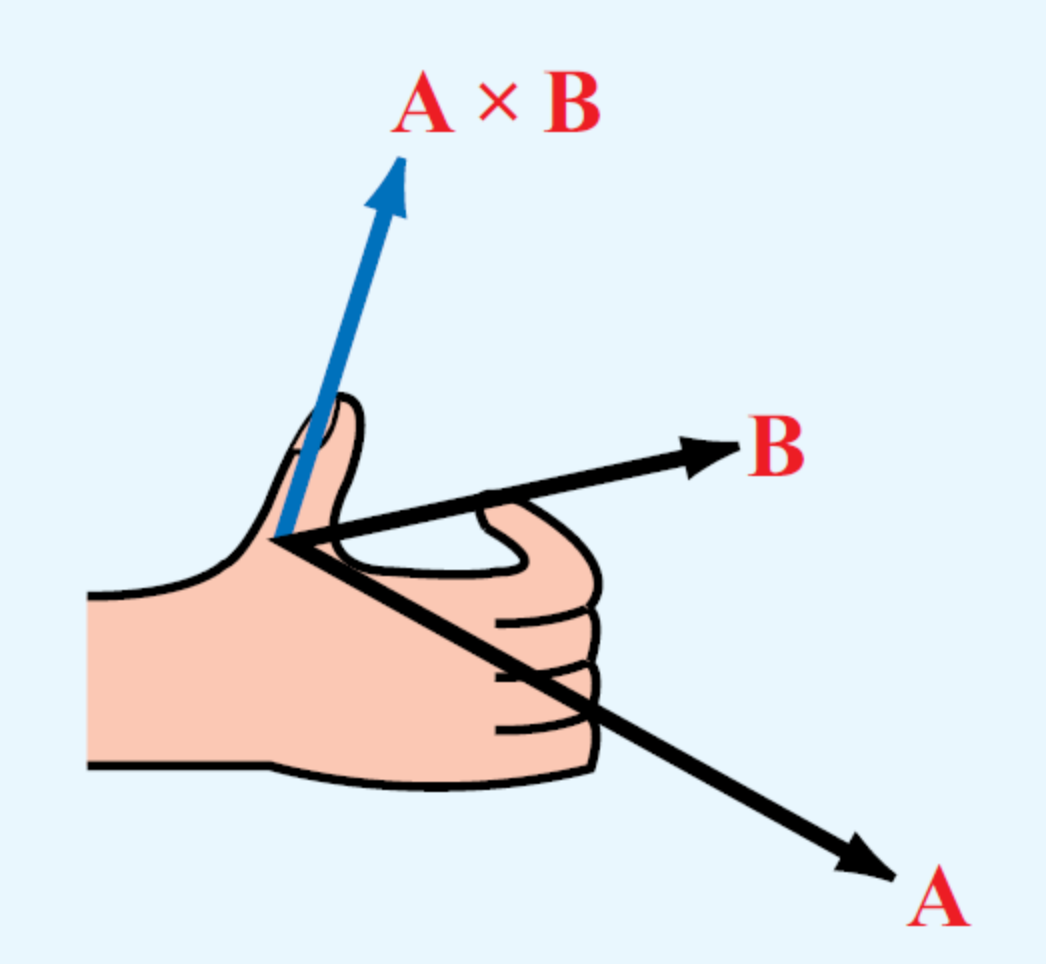
Review

Cross product



Review

Right hand rule



Review

Cross product is anticommutative and distributive

$$\mathbf{A} \times \mathbf{B} = -\mathbf{B} \times \mathbf{A} \quad \text{(anticommutative)}$$

$$\mathbf{A} \times (\mathbf{B} + \mathbf{C}) = \mathbf{A} \times \mathbf{B} + \mathbf{A} \times \mathbf{C}$$

$$\text{(distributive)}$$

Review

Question:

what is the cross product of a vector with itself?

Review

Question:

what is the cross product of a vector with itself?

$$\mathbf{A} \times \mathbf{A} = 0.$$

Review

Relationships between basis vectors of Cartesian coordinates

$$\hat{\mathbf{x}} \times \hat{\mathbf{y}} = \hat{\mathbf{z}}, \qquad \hat{\mathbf{y}} \times \hat{\mathbf{z}} = \hat{\mathbf{x}}, \qquad \hat{\mathbf{z}} \times \hat{\mathbf{x}} = \hat{\mathbf{y}}.$$

(note the cyclic order)

$$\hat{\mathbf{x}} \times \hat{\mathbf{x}} = \hat{\mathbf{y}} \times \hat{\mathbf{y}} = \hat{\mathbf{z}} \times \hat{\mathbf{z}} = 0.$$

Review

By applying all the properties reviewed so far to the cross product of two vectors

$$\mathbf{A} = (A_x, A_y, A_z)$$

$$\mathbf{B} = (B_x, B_y, B_z)$$

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

$$= \hat{\mathbf{x}}(A_y B_z - A_z B_y) + \hat{\mathbf{y}}(A_z B_x - A_x B_z) + \hat{\mathbf{z}}(A_x B_y - A_y B_x)$$

Review

A useful mnemonic trick is to use the fact that the cross product gives the same terms as the determinant of the matrix below

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

$$= \quad A_y B_z \hat{\mathbf{x}} + A_z B_x \hat{\mathbf{y}} + A_x B_y \hat{\mathbf{z}}$$

$$- A_z B_y \hat{\mathbf{x}} - A_x B_z \hat{\mathbf{y}} - A_y B_x \hat{\mathbf{z}}$$

Lorentz Force example

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

$$\mathbf{E} = 5.0\ \hat{\mathbf{y}}\ \frac{\mathrm{V}}{\mathrm{m}} \qquad \mathbf{H} = 5.0\ \hat{\mathbf{z}}\ \frac{\mathrm{A}}{\mathrm{m}}$$

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

<u>Electric Force</u>

$$F_E = q\mathbf{E} = -1.602 \times 10^{-19} \times 5.0 =$$

$$-8.01 \times 10^{-19}\ \hat{\mathbf{y}}\ \mathrm{N}$$

Lorentz Force example

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

$$\mathbf{E} = 5.0\ \hat{\mathbf{y}}\ \frac{\mathrm{V}}{\mathrm{m}} \qquad \mathbf{H} = 5.0\ \hat{\mathbf{z}}\ \frac{\mathrm{A}}{\mathrm{m}}$$

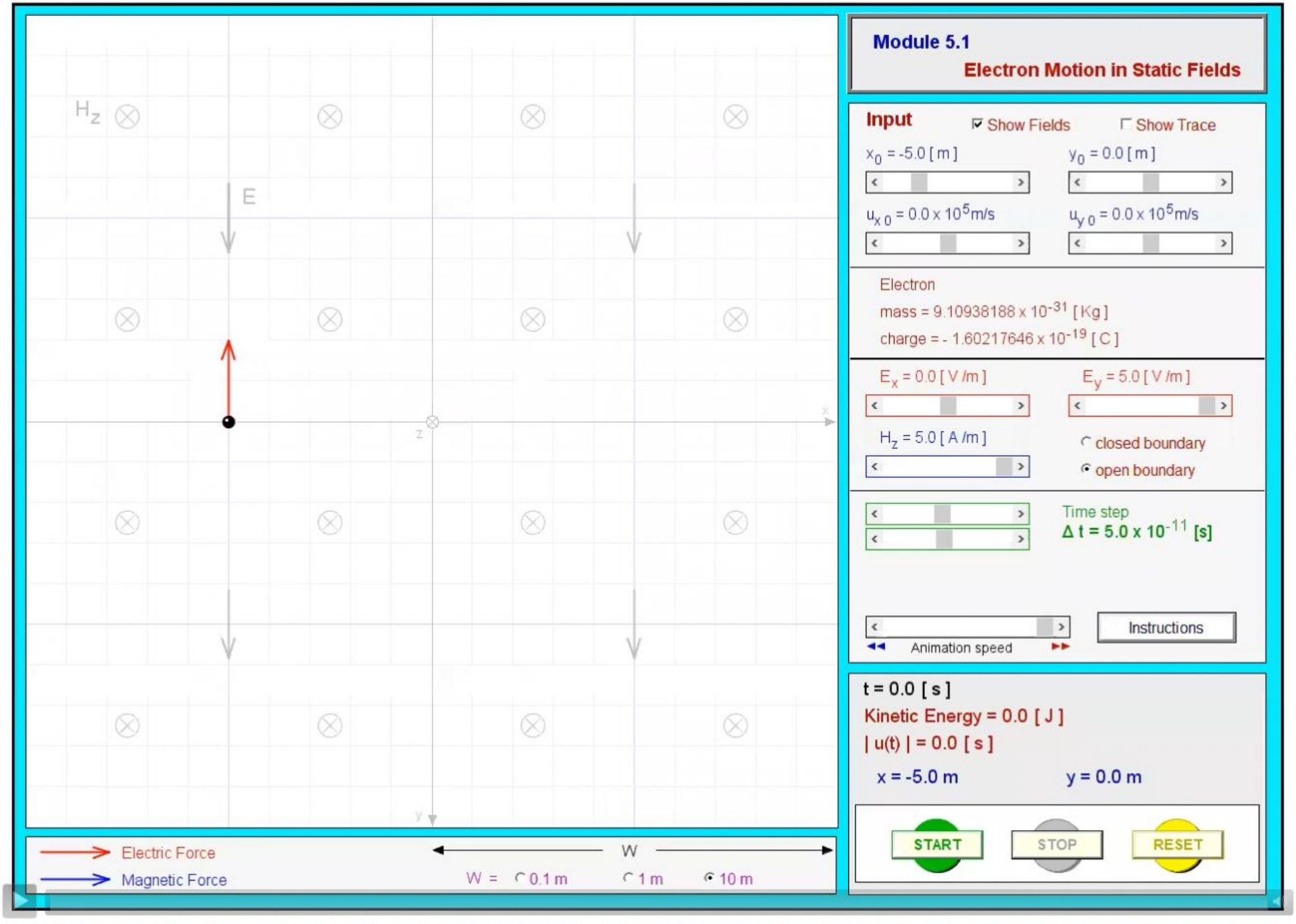
Find the Lorentz force acting on the particle

Magnetic force

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

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

$$= -4.03 \times 10^{-19}\ \hat{\mathbf{y}}\ \mathrm{N}$$


Module 5.1
Electron Motion in Static Fields
Input
Show Fields
Show Trace
x0 = -5.0 [m]
y0 = 0.0 [m]
ux 0 = 0.0 x 10^5 m/s
uy 0 = 0.0 x 10^5 m/s
Electron
mass = 9.10938188 x 10^-31 [Kg]
charge = - 1.60217646 x 10^-19 [C]
Ex = 0.0 [V /m]
Ey = 5.0 [V /m]
Hz = 5.0 [A /m]
closed boundary
open boundary
Time step
Δ t = 5.0 x 10^-11 [s]
Animation speed
Instructions
t = 0.0 [s]
Kinetic Energy = 0.0 [J]
| u(t) | = 0.0 [s]
x = -5.0 m
y = 0.0 m
START
STOP
RESET
Hz
E
x
z
y
Electric Force
Magnetic Force
W
W =
0.1 m
1 m
10 m

Reading Assignments

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

- **Introduction**
- **1) Vector Fields and Lorentz Force**