ECE341
Electromagnetic (EM) Fields

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Introduction: Why EM Fields?

The electromagnetic force is one of the four fundamental forces of Nature.
(What are the other three?)

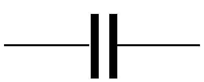
Charged particles interact by the EM force, via EM fields.
(EM forces and EM fields? Shouldn't there be the electric force/field and the magnetic force/field?)

But why do we (electrical engineers) care?

Circuit theory is a simple part of EM (**black boxes: lumped elements**)

$I = V/R$

Resistor: The simplest element. But why $I \propto V$? What are I and V after all?



$i = C\, dv/dt$

Capacitor: The simplest model of the capacitor is a pair of parallel conductor plates. But why $i \propto dv/dt$?

$v = L\, di/dt$

Inductor: The simplest model of the inductor is a conductor coil. But why $v \propto di/dt$?

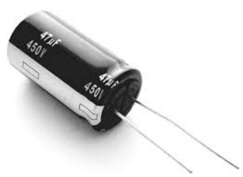
Electrical elements vs. components

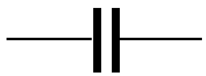
Ideal lumped electrical elements represent real, physical electrical components but they do not exist physically.

Components (physical) | Elements (idealized)

$$I = V/R$$

Resistor: The simplest element.
But why $I \propto V$?
What are I and V after all?





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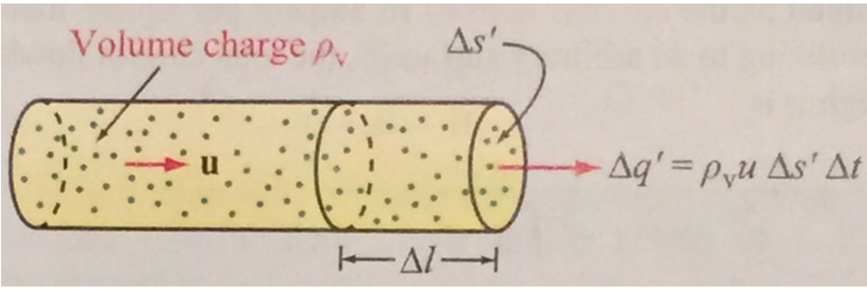
Inside the black boxes:



Conductor w/ mobile charge density ρ_V, or just ρ for short.

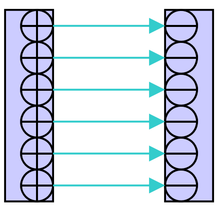
Mobile charges move at an average net velocity **u**.

$$\Delta I = \frac{\Delta q'}{\Delta t} = \rho u \Delta s'$$

Current is charge flow per time.

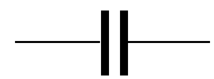
Mobile charges are driven by field *E*. $u \propto E \propto V$ →  $I = V/R$

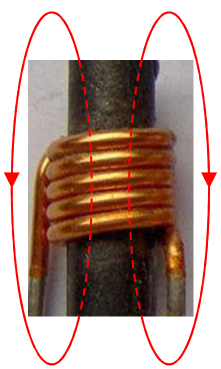
But the force on each charge carrier, $F \propto E$.
Here we are saying $u \propto F$. What about Newton's laws?



$Q \equiv Cv = CEd$
$dv/dt \rightarrow dQ/dt \rightarrow i$

Current is charge flow per time.

→  $i = C \, dv/dt$



$B \propto i$
$di/dt \rightarrow dB/dt \rightarrow E \rightarrow v$

Changing **B** field induces **E**

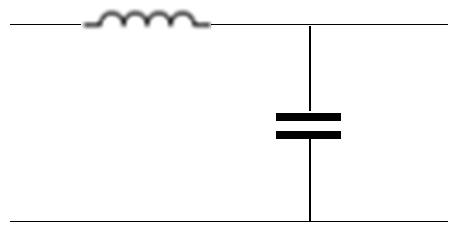
→  $v = L \, di/dt$

Even a wire (or a pair of wires) is an inductor!

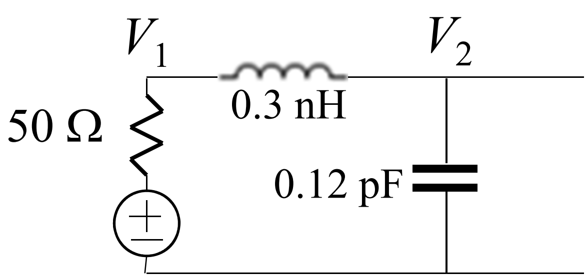
"Lumped" elements when dimensions << wavelength

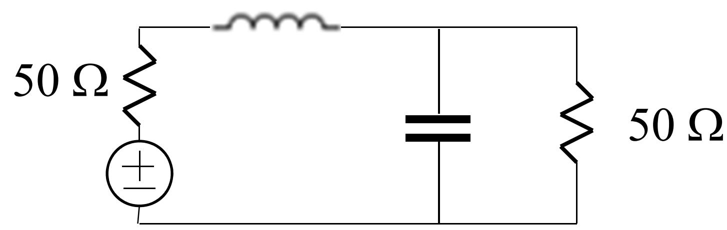
Project

Circuit simulations to transition you from lumped element-based circuit theory



Part 1





Generator: 1 V step, rise time = 0.1 ns. Internal impedance 50 Ω.

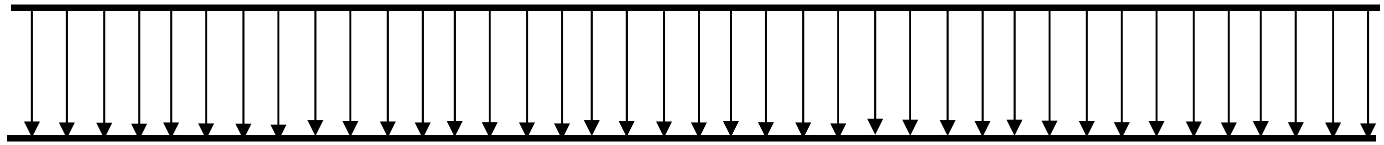
Plot the two voltages V_1 and V_2 for the above two cases.

Hint: You may make mistakes. Do a sanity check by a "back of an envelope" analysis.
At the very least, find out the steady state.
Does the simulation give you more or less what you expect?

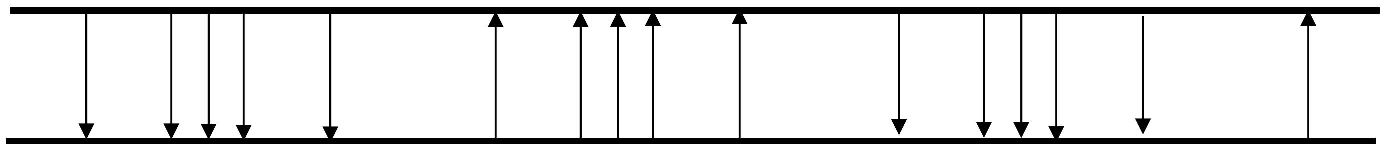
Ongoing project. Stay tuned for next steps.

Simplest example: a pair of wires (considered **ideal** wires)
(the term “transmission line” is a bit confusing)

Length << λ



Length >> λ, say, infinitely long



Voltage along a cable can vary!

f	λ	Comments
60 Hz	5000 km	Power
600 kHz	500 m	Medium wave AM radio
0.3 GHz	1 m	
1.5 GHz	20 cm	CPU clock rate
30 GHz	1 cm	Data communication
300 GHz	1 mm	

(0.3 GHz – 300 GHz: microwave)

$f\lambda = c$,
$c = 3 \times 10^8$ m/s

Here, λ is the wavelength in free space. Wavelength varies in materials.

This course is about electromagnetics (EM), the foundation of Electrical and Computer Engineering, or, how electricity ***really*** works.
-- Look ***into*** the black boxes.

- Circuit theory is a simple model of EM, so it was taught first.
- However there are an increasing number of cases where circuit theory fails (e.g. faster computers, higher communications frequencies, power electronics, power system transients,), and EM must supplement circuit theory. *But, don't worry*…
- Also EM is the basis for many devices (machinery, antennas, etc.), and one of the physical foundations of any active electronic device.
- Serious hazards for electrical and computer engineers in all areas, such as interference and non-ideal behavior of circuit elements, are increasing with the higher frequencies today for Electrical and Computer Engineers in all areas.

Read this introduction again at the end of the semester after we have presented all the material. You will have a deeper understanding and a delight from it.

<u>Textbook</u>:

Ulaby *et al*, *Fundamentals of Applied Electromagnetics* (7/E or 6/E)

"Modern" sequence to teach the material: start with transmission lines based on a version of "circuit theory"

Relax the requirement of previous knowledge in physics, and get students into it.

<u>Recommended reference books</u>:

Ramo *et al*, *Fields and Waves in Communication Electronics*

Old school, rigorous.

Start from "true" field theory – Maxwell's equations

A bit hard on today's students, but it's a good thing.

Inan, Inan, and Said, *Engineering Electromagnetics and Waves*

Another modern book in the same sequence as our textbook.

Useful additional insights (one example)

Jackson, *Classical Electrodynamics*

A classic for physicists and microwave, optical engineers

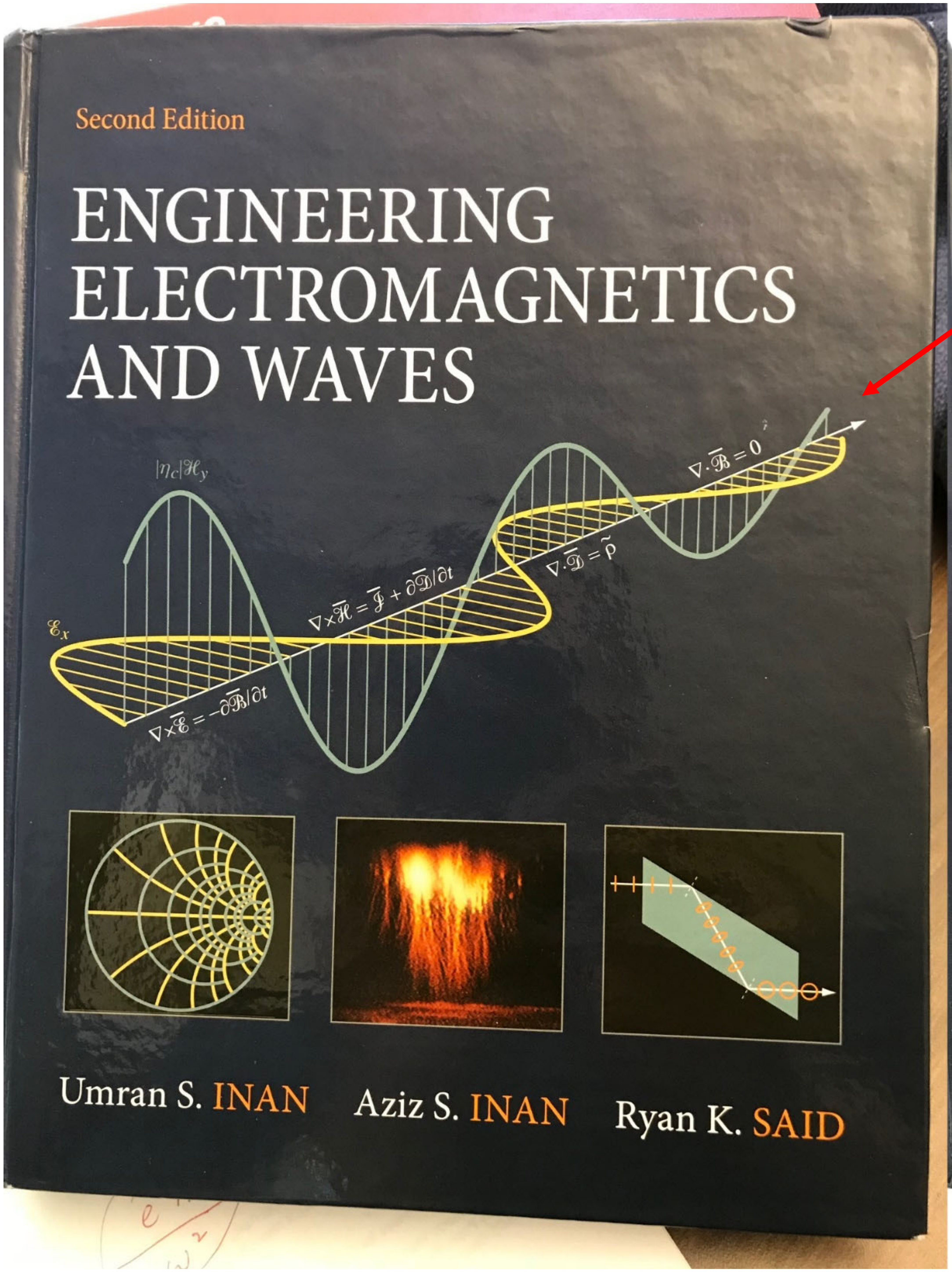
(The word "classical" in the title has a slightly different meaning.)

Classics are not easy to read.

A different unit system is used, which we engineers may not be used to.

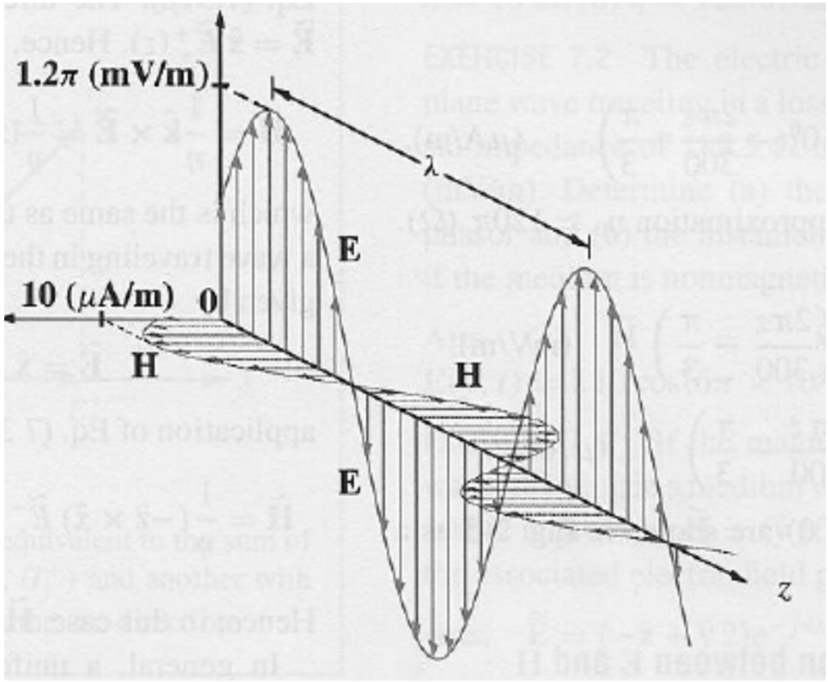
(Some equations look different, unlike elsewhere in physics, where different unit systems give you the same equations but only "different" physical constants.)

Venture into it only if you are really into this field after this course.



Stare at this picture.
See the difference?

The picture we are more "used to":



Requirements & Evaluation

Homework (or, more appropriately, exercises)
To be finished at the start of class on certain days, indicated in the schedule.
Not graded. For your exercise.
Do it first, and then check against my answers online. Not the other way!

Quizzes
Random, in-class or take-home. Graded.

Tests
Partially reflect homework (exercises) or sometimes extend the quizzes, and are certification that you've learned what you should. Two major tests, on the days indicated in the schedule.

Lab (3 labs)
Completion of all labs is required for course completion. Submit report on time.

Grade
Test 1: 15%; Test 2: 20%; Quizzes: 10%
Project: 15%; Lab: 10%
Final exam: 30%

Schedule

The syllabus is online, as well as this introduction presentation and all class notes.

The schedule is subject to changes, so check it often.

Homework may require knowledge not covered in class at the time. Read the book on your own and do it. This is in preparation of the next class.

Website

http://web.eecs.utk.edu/~ggu1/files/UGHome.html

Extra project for Honors class ECE347

Tips

How to do well in this course (and others) and prepare to be a successful engineer:

- Don't overload your schedule with courses and/or work (and other things).
- Aim toward becoming a good engineer.
- **Don't miss classes (and the quizzes)**.
- **See lab as an inquiry - not following a cook book**.
- **Don't just do the project; think and get insight**.
- Study daily, not just the four nights before tests.
- Ask questions, take notes.
- Don't rely on somebody else (*or my answer sheets online*) for homework.
- **Pursue understanding of the principles** - not just memorizing the symbols in homework problems and equations.
- **Try to visualize phenomena - don't just manipulate math symbols**.
- **Relate this material to other courses**.
- Revisit and reinforce the above three during the course, and, in your future study (e.g. read this Introduction again at end of course).
- Read ahead, think in practical terms; see if using the book's CD helps.

Topics off the topic

Artificial intelligence and future engineering jobs
(How to make yourself irreplaceable by machines)

AlphaGo defeated best human players (old news now).
Now there's AlphaGo Zero

A plumber working in my basement

Computers recognize cats

Human babies recognize cats

Recent story:
https://www.theverge.com/2018/8/23/17772376/openai-dota-2-pain-game-human-victory-ai

Humans grab victory in first of three Dota 2 matches against OpenAI

"The bots are still very good at moment-to-moment, but they seem bad on macro-level decisions."

Features of this course

- Not so “structured” as you might expect
- Learn how to define your problems
- Foster curiosity, the habit of thinking (as humans as opposed to machines)
- Pursue true understanding, not mimicking
- When you understand the why, the how will come to you naturally

- Lectures often take different approaches than does the textbook
  - **Review these notes (they are on the website)**

- Class is long; will try not to bore you (but you need to put down your phones)
- The project makes you engaged right from the beginning (before things get busy)
- Frequent, random in-class quizzes to keep you engaged
  - **Again, you need to review the class notes (they are on the website)**

- Not easy to fail

Overview of course

- General concept of waves
- Transmission line theory derived from a form of circuit theory
  (Yes, it works.)
- Electrostatics
  (We start to discuss the "real" EM theory.)
- Magnetostatics
- Dynamic fields
  (Nothing in the world is "static". In general, the dynamic field is not just the same as static fields with time variation, as in "quasi-static" approximation. There is "dynamics," although sometimes the "quasi-static" picture works. BTW, under what condition does the "quasi-static" picture work?)
- EM plane waves
  (The simplest EM waves. You get a sense how waves arise from dynamic fields)

This course is about the ***fundamentals***. More cool stuff (waveguides, antennas, etc.) will be covered in advanced courses (#s may change):

- ECE 443 - Antenna Systems Engineering
- ECE 444 - Microwave Circuits
- Graduate courses: ECE 541, 545, 546, 547

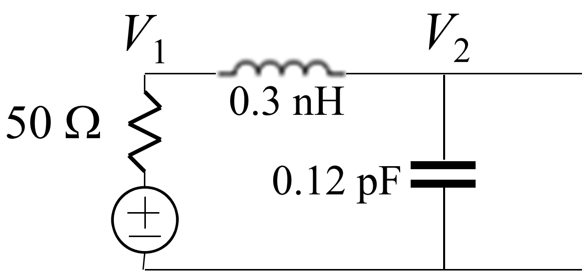
A few more words about the course website

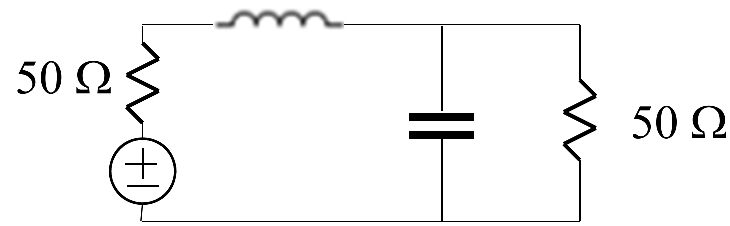
Another way to find/access the course website:
EECS Dept website: https://www.eecs.utk.edu
Click on Academics, choose Course Websites, and you are at
https://www.eecs.utk.edu/academics/course-websites/
Click on ECE 341: Fields

There is a link to the project (a pdf), so that you do not have look for parts of it scattered in class notes.

Project

Part 2





Part 1

Generator: 1 V step, rise time = 0.1 ns. Internal impedance 50 Ω.

Plot the two voltages V_1 and V_2 for the above two cases.

What have you got?

Now, do the same simulations for rise time = 1 ps.
Notice that you might need to set MaxTimeStep & StopTime. Try different values for these and see what difference you make by changing them.
Also, adjust the scales of the plots to show details.
Do not forget to do a sanity check.
Compare the results to those of Part 1. Similarities and differences?
Do the results make sense to you?

Ongoing project. Stay tuned for next steps.