

EECS 230  
*ENGINEERING ELECTROMAGNETICS*  
*Leland Pierce*

COURSE INTRODUCTION

# Course Objectives

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- To equip EE and CE majors with a fundamental understanding of electromagnetics
- To introduce the student to the engineering applications of electromagnetics
- To help the student develop the **learning skills** and **self discipline** necessary for success as a professional

# What you may expect from me

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1. **Commitment** to help you succeed
2. Good course **organization**
3. Great lab and course **GSI**s

# What I expect from you

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- Taking the course very **seriously**
  - A~18 hrs/wk
  - B~15 hrs/wk
  - C~12 hrs/wk
- Good **organizational skills**, always submitting assignments on time
- Acting with **honesty and integrity**

# EECS 230 Team

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- Course Instructor: Dr. Leland Pierce
- Course GSIs and Lab Instructors:
  - John Le
  - Josey Hanish
  - Majid Aalizadeh

# Course Technical Dimensions

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**Lectures:** 80 minutes, 2/wk, which may include

1. Presentations on various topics
2. Demonstrations /Reviews

**Discussion Session:** 1 /wk on Friday, which may include

1. Solving of selected problems,
2. Answering questions

**Lab Projects (6 sessions)**

1. Prelab: reading and calculating in preparation for In-Lab part
2. In-Lab: 2 to 3-hour experiment
3. Post-Lab Report: Analysis of results

# Course Technical Dimensions

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## Lab Projects (6 sessions)

1. If more than 30 minutes late to a lab: -10% from your grade for that lab.
2. If miss a lab: must make it up.

## Homework:

1. Assigned after each lecture. Due next day: midnight.
2. All content will have been covered in lecture before problems related to that content are assigned

# Course Technical Dimensions

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## Lab Projects (6 sessions)

1. If more than 30 minutes late to a lab: -10% from your grade for that lab.
2. If miss a lab: must make it up.

NOTE: 12PM is noon  
12AM is midnight  
homework is due at midnight

problems related to that content are assigned

# Course A-Z

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All **homeworks** are due by midnight (Ann Arbor time) on the due date.

- a. Answers to HW problems will be made available shortly after that.
- b. HW will be graded and returned to students

**Working Together:** You are encouraged to work with classmates on homework problems. **Do not write anything down.** Later, solve the problem yourself.

**Online Materials:** You may use solutions you found on-line or generated via ChatGPT, etc. **You must not copy/paste these solutions:** instead you must generate your own solution, and you must state on each problem when you used such materials.

# Course A-Z cont.

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**Grading:** NOT on a curve. You will compete against your own potential, not against others.

**When you need help:**

- a) **Lab-related:** Your lab instructor
- b) **Mechanics** ( how to compute a complex number, integrate a function, approach solving a problem, etc): **All GSIs**
- c) **Concepts & Lecture clarifications:** **Dr. Leland Pierce**

# Course A-Z cont.

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## Exam Dates (and alternate)

Exam 1 : Monday Oct 7 (tues 8), 5-6:30PM

Exam 2 : Monday, Nov 11 (tues 12), 5-6:30PM

Final Exam: Monday Dec 16 (tues 17), 8-10AM

## Grading

<b>Labs</b>	<b>25%</b>
<b>Homework</b>	<b>30%</b>
<b>Exam 1</b>	<b>15%</b>
<b>Exam 2</b>	<b>15%</b>
<b>Final</b>	<b>15%</b>

Lowest HW grade will be dropped

# Course A-Z cont.

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## Textbook

Fundamentals of Applied EM, 8e, 2020

by Ulaby and Ravaioli

We will cover most of chapters 1-7.

# Optimum Learning Process

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- **Before Lecture:**

(1) Review material from last class , and look through the slides of coming lecture.

(2) Make sure you have read the book sections assigned on syllabus.

- **In Lecture:**

Take notes and write observations on the PPT slides, do not sit back passively

- **After Lecture:**

within 24 hours: review the lecture, look through book/internet when you have questions. Go to office hours if questions persist.

**Do the homework.**

# Optimum Learning Process

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## Doing the Homework:

- (1) Try to solve each problem without looking at examples in the book.
- (2) If you can't solve it after 10 minutes, then go look in the book.
- (3) Looking on-line for solutions is fine, **after** you've tried to solve it, but don't just copy.
- (4) Compare with the solutions

## Solutions to problems: when the solution is a number:

it is wrong without units (unless it is unitless)

it is wrong if you use  $\pi$ ,  $\sqrt{3}$ , etc: must be decimal number

it is wrong if it has 10 digits: use a reasonable number

if it asks for an EXPRESSION, then don't need numbers/units.

# Optimum Learning Process

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- **Exams:** You get a sheet of paper with anything **handwritten** on it, and your calculator.  
Remember that **homework is practice for the exams**, so don't get help from anything while doing homework that you can't use on an exam.
  
- **Learning: I don't expect you to memorize equations.**  
Instead:
  - \* Understand physics of a problem, and
  - \* Apply relevant modeling techniques.
  - \* Look up eqns as needed.

Fall 2023

Home

Announcements 

Assignments

Discussions

Grades

People

Pages

Files

Syllabus

Outcomes Quizzes Modules 

BigBlueButton

Collaborations

Chat

Engineering Honor  
Code

## EECS 230 001 FA 2023

Jump to Today

 Edit

### Lecture


- T,Th 12:00-1:30PM in G906 Cooley
- Lectures will be held in person, and Lecture notes will be made available. However, lecture recordings will be available.
- There is not a synchronous remote option

I'll try to be at Mujo M-F, 9-5PM

### Office Hours

Leland: Mon, 1-2:50PM, Mujo, or by appointment (email me)

Contact the staff: [eeecs230staff-fall2023@umich.edu](mailto:eeecs230staff-fall2023@umich.edu)

For all the office hours, see Google calendar below. Or add it with [this link](#) .

### EECS 230. Electromagnetics I

*Prerequisite: (MATH 215 and PHYSICS 240; C or better, No OP/F)  
or (Co-requisite: EECS 215; C or better, No OP/F). (4 credits).*

Vector calculus. Electrostatics. Magnetostatics. Time-varying fields: Faraday's Law and displacement current. Maxwell's equations in differential form. Traveling waves and phasors. Uniform plane waves. Reflection and transmission at normal incidence. Transmission lines. Laboratory segment may include experiments with transmission lines, the use of computer-simulation exercises, and classroom demonstrations.

### Additional Information

# Schedule

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Link to detailed schedule on canvas site:

Activities Google Chrome Fri Jul 19 4:25 PM

umich.instructure.com/courses/697901

However, lecture recordings will be made available **only under special circumstances**: email me.

- There is not a synchronous remote option

**Office Hours**

Leland: Mon, 1-3PM, Mujo, or by appointment (email me)

**Contact the staff:** [eeecs230-staff@umich.edu](mailto:eeecs230-staff@umich.edu)

**EECS 230. Electromagnetics I**

*Prerequisite: (MATH 215 and PHYSICS 240; C or better, No OP/F) or (Co-requisite: EECS 215; C or better, No OP/F). (4 credits).*

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**Additional Information**

- [Class Schedule](#) (subject to revisions)
- [Labs](#)
- [Homework](#)
- [Grading](#)
- [Textbook](#)
- [Software](#)
- [Remote Computer/Software Access](#)
- [Other Important Issues](#)

**Lab and Discussion Sections and Instructors**

Session	Time	Location	GSI/IA
...	...	...	...

View Course Stream  
New Announcement  
New Analytics  
View Course Notifications

July 2024

30	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31	1	2	3
4	5	6	7	8	9	10

Assignments are weighted by group:

Group	Weight
Labs	25%
Homework	30%
Exam1	15%
Exam2	15%
Final	15%
Total	100%

# Schedule

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Brings up the spreadsheet of the schedule:

The screenshot shows a Google Chrome browser window displaying a Google Sheets spreadsheet titled "Schedule". The spreadsheet is viewed in a desktop environment with a taskbar on the left showing icons for Chrome, Zoom, and other applications. The browser's address bar shows the URL: [docs.google.com/spreadsheets/d/1\\_B8sxFzMwRMT3fvaMgNOGFY6BPd-S4N/edit?gid=113718061#gid=113718061](https://docs.google.com/spreadsheets/d/1_B8sxFzMwRMT3fvaMgNOGFY6BPd-S4N/edit?gid=113718061#gid=113718061). The spreadsheet has a header row with columns: Week, Lecture Topics, Reading, Lab Topic, HW Due, and Demo. The data is organized into rows for each week, with specific dates, days, and topics listed.

Week	Lecture Topics	Reading	Lab Topic	HW Due	Demo
1	1. Introduction, course logistics, traveling waves	1-1 to 1-5	No Labs		
				1	
2	2. Review of Circuits	1-6, 1-7, Circuits book: chapters 1.2,5,7			
				2	
3	3. Transmission lines 1: Intro	2-1 to 2-2	No Labs		
				3	
4	4. Transmission lines 2: Waves	2-2 to 2-5			
				4	
5	5. Transmission lines 3: Lossless Lines	2-6	No Labs		
				5	
6	6. Transmission lines 4: Wave Impedance	2-7			
				6	
7	7. Transmission lines 5: Special cases, Power Flow	2-8, 2-9	Lab1: measuring xmission lines with a network analyzer		
				7	

# Canvas

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I will not cover everything that's on canvas in lecture.

You should go there and read it.

# Is it Right?

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Checking your answers is a requirement for all engineers. Many techniques are possible: you choose:

**1. Process: carefully follow a solution process that shows every step.**

- Convert all given quantities to MKS units

- Write generic governing equations

- Solve for the unknowns, usually symbolically

- Plug in values, with units. simplify

- Are the resulting units correct?

  - If not: check units, step-by-step

  - If yes: check algebra and numbers, step-by-step

# Is it Right?

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## 2. Estimate answer

Don't do detailed calculations in your head.

Convert values to simpler ones, then do calcs on paper

Make sure to get the right SIGN

Does the answer make sense?

## 3. Use a different process (for all or part of a problem)

Do you get the same answer?

## 4. Type into your calculator twice

To avoid typos. also check if using degrees or radians.

Beware of arc-tangent.

# Is it Right?

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## 5. Plug answer into original formulas:

Do you get the given values of parameters?

## 6. Check with computer (for homework only)

Write a code using Matlab or Python

Use a circuit simulator (Pspice, ...)

Ask ChatGPT, ... (however: it only gets ~80% correct)

## 7. Discuss with other students (for homework only).

**After** discussing, go back and re-do the problem.

# Is it Right?

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**8. The more you do "in your head":**

**The more mistakes you make.**

**Especially when it comes to SIGNS**

# What are you learning?

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## 1. Certain equations you'll use over-and-over.

Become memorized through repetition: **don't *try* to memorize them.**

Most equations are too detailed or situation-specific to remember.

## 2. Solution procedures

For different kinds of problems, there are different solution procedures.

These should be remembered, mostly through repetition.

# What are you learning?

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## 3. Physical concepts

Physical models and ideas behind the parameters used:  
charge, forces, fields, current, voltage, ...

# What are you learning?

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## 4. Assumptions made when deriving an equation.

For most derived equations: **don't memorize them.**

Instead, **remember the process used for deriving them,** along with the **simplifying assumptions made,** and re-derive when needed.

Especially important: if the situation has changed from that in class:

Now the assumptions we can make are different:  
invalidating the previous solution.

**HAVING CHANGED ASSUMPTIONS IS A COMMON SITUATION**

# Example 1

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$$V = IR$$

Is this always true? ...

# Example 2

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$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 R^2}$$

Is this always true?

# Answers

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Often, you will be asked for a **numerical answer**.

These answers are **correct**: 0.5,  $1.2 \times 10^3$ , 100mV

These answers are **incorrect**:

0.528364095068      too many significant figures.  
should be 0.53

$1/2$       this is an expression. should be 0.5

$\sqrt{3}$       this is an expression. should be 1.73

$\pi$       this is an expression. should be 3.14

# Answers

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If your previous physics classes have not covered the idea of Significant Figures, for this class just use the rule to provide no more than 4 Significant Figures.

Why?

Providing more Significant Figures implies that you have knowledge of the quantity to a certain high precision.

For example:

$x = 1.23456789012$  meters

implies you know the value of  $x$  to within  $10^{-11}$  meters.

Which is very unlikely.

Same goes for Voltage, Current, Resistance.

# Example 3

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The value of resistors is marked on them using a striped color-code.

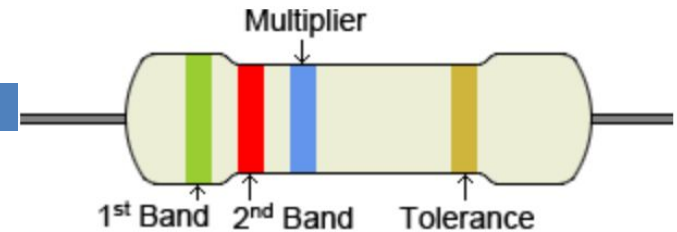
An extra stripe is used to provide the "Tolerance".

Most resistors used in the lab for this class have a Tolerance of 1%

So for a 1 K $\Omega$  resistor the uncertainty is 10 $\Omega$

So write the value as 1.0 K $\Omega$ ,

do not write as: 1.00000000 K $\Omega$



Color	1 <sup>st</sup> , 2 <sup>nd</sup> Band Significant Figures	Multiplier	Tolerance
Black	0	$\times 1$	
Brown	1	$\times 10$	$\pm 1\%$ (F)
Red	2	$\times 100$	$\pm 2\%$ (G)
Orange	3	$\times 1\text{K}$	$\pm 0.05\%$ (W)
Yellow	4	$\times 10\text{K}$	$\pm 0.02\%$ (P)
Green	5	$\times 100\text{K}$	$\pm 0.5\%$ (D)
Blue	6	$\times 1\text{M}$	$\pm 0.25\%$ (C)
Violet	7	$\times 10\text{M}$	$\pm 0.1\%$ (B)
Grey	8	$\times 100\text{M}$	$\pm 0.01\%$ (L)
White	9	$\times 1\text{G}$	
Gold		$\times 0.1$	$\pm 5\%$ (J)
Silver		$\times 0.01$	$\pm 10\%$ (K)

(calculator.net)

# Example 3

32

The value of resistors is marked on them using a striped color-code.

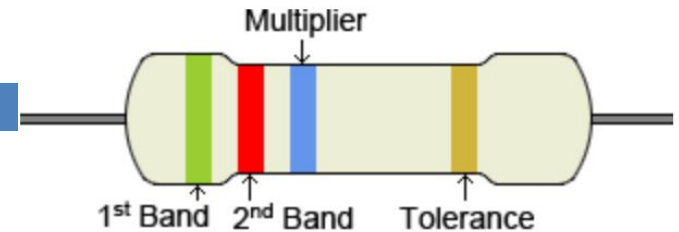
An extra stripe is used to provide the "Tolerance".

What tolerance is this resistor?

So for a 1 K $\Omega$  resistor the uncertainty is 10 $\Omega$

So write the value as 1.0 K $\Omega$ ,

do not write as: 1.00000000 K $\Omega$



Color	1 <sup>st</sup> , 2 <sup>nd</sup> Band Significant Figures	Multiplier	Tolerance
Black	0	$\times 1$	
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White	9	$\times 1G$	
Gold		$\times 0.1$	$\pm 5\%$ (J)
Silver		$\times 0.01$	$\pm 10\%$ (K)

(calculator.net)

# Answers

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If an answer should have **units**:

The answer is wrong if the units are missing.

The answer is wrong if it has the wrong units.

Note that units are only relevant when there are numbers involved.

**Expressions:** can be just symbols

or a combination of symbols AND numbers

each number must have units

# Example 4

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Correct mixed expression/numbers:

$$V(t) = 1.5V \cos [ (1 \text{ rad/sec})t + 1.5 \text{ rad} ]$$

incorrect:

$$V(t) = 1.5 \cos(t+1.5) \text{ Volts}$$

$$V(t) = 1.5V \cos(t+1.5)$$

$$V(t) = 1.5V \cos(t+1.5\text{rad})$$

# Example 5

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Correct mixed expression/numbers:

$$V(t) = 1.5V \cos [ \omega t + \phi ]$$

$$V(t) = 1.5 \cos [ \omega t + \phi ] \text{ Volts}$$

$$V(t) = A \cos [ \omega t + \phi ]$$

Note: The book does not always follow this rule.

# Answers

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## Why numbers and not expressions?

As engineers we depend on our experience and intuition to get to the right answer quickly.

" $29\pi$  milli-amps" for a current does not really give us a sense for magnitude:

"91 milli-amps" does

You may often give expressions as answers in math courses.

**This is not a math course: time to form a new habit.**

# Answers

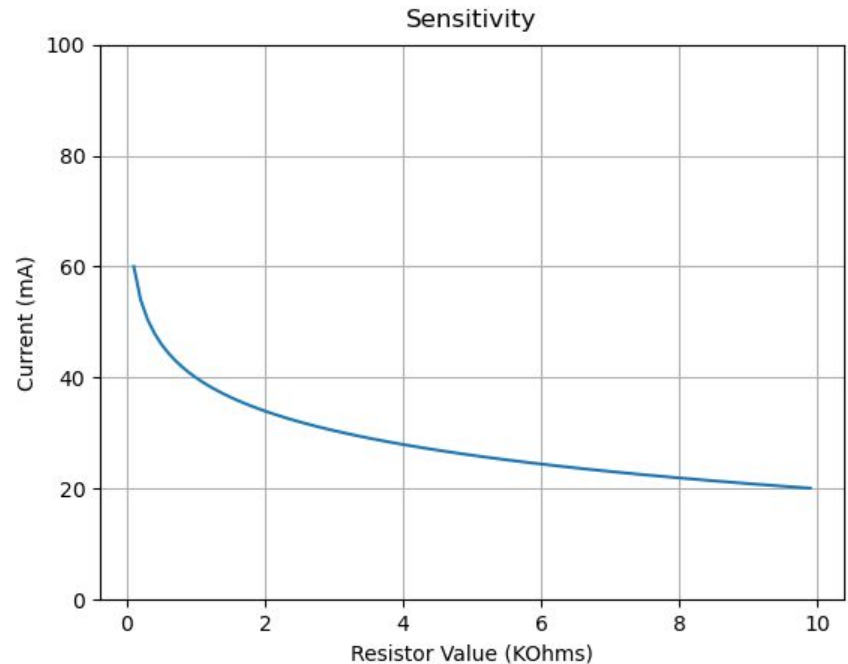
37

In advanced classes we tend to use expressions only.

This way, we can easily write a simple computer program to plot the results in various scenarios.

For example, determining the sensitivity of the current to the value of a particular resistor.

For now, numbers-as-answers is meant to keep things simple and practical.



# Overview and Applications

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## Major Topics/Applications of Electromagnetics

High-Frequency Circuits

Waves Travelling on Cables

Optimum Power Transfer

Derivation of KVL, KCL

Behavior of Materials:

Conductors

Insulators

How to design sensors/actuators

Capacitive

Inductive

Electromagnets

RFID

Transformers

Generators

Motors

Wireless Power Transfer

Internet of Things

Waves

Radio transmitters

Radio Receivers

Wireless Propagation

Cell Phones

Radar

Optics

Antennas

# Overview and Applications

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## Major Application Areas

Communications  
Sensing/Interface  
Smart Cities  
Power



# Overview and Applications

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## Major Application Areas

### Communications:

cell phones (\$500 Billion/year)

radio, tv, cable (\$400 Billion/year)

internet (\$6,000 Billion/year)

radar (\$30 Billion/year)

fiber optics, lasers (\$25 Billion/year)

antennas (\$20 Billion/year)



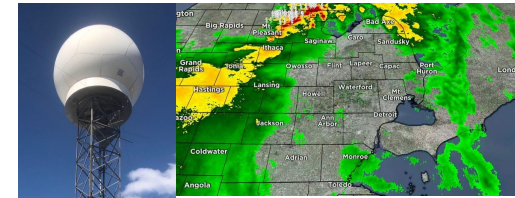
# Overview and Applications

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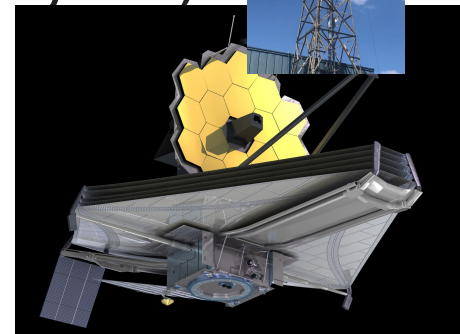
## Major Application Areas

### Sensing/Interface

- Medical Imaging (\$38 Billion/year)
- Remote Sensing (\$18 Billion/year)
- Doppler weather radar (\$34 Billion/year)
- James Webb Telescope (\$10 Billion)
- capacitive touch-pads (\$0.3 Billion/year)
- LCD (\$107 Billion/year)
- Bar-code readers (\$7 Billion/year)
- UAV (\$23 Billion/year)



(clickondetroit.com)



# Overview and Applications

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## Major Application Areas

### Smart Cities

Smart/Electric cars (\$0.01 Billion/yea

Smart Power Grid (\$43 Billion/year)

Internet of Things (\$320 Billion/year)

RFID (\$11 Billion/year)

Wireless Power Transfer (\$7 Billion/year)

Air Cleaners (\$14 Billion/year)



# Overview and Applications

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## Major Application Areas

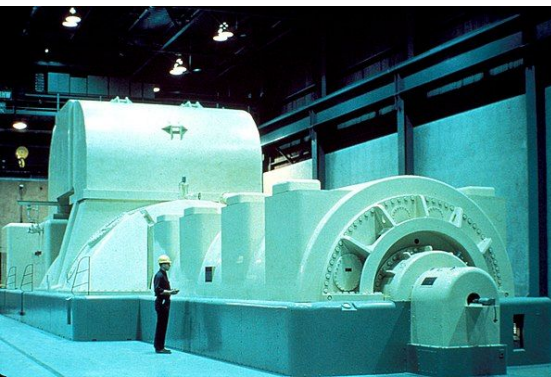
### Power:

Generators (\$6 Billion/year)

Wind Turbines (\$53 Billion/year)

Motors (\$120 Billion/year)

Solar (\$370 Billion/year)



# Overview and Applications

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**Many of these come down to having these:**

**Transmitter**

**and/or**

**Receiver**

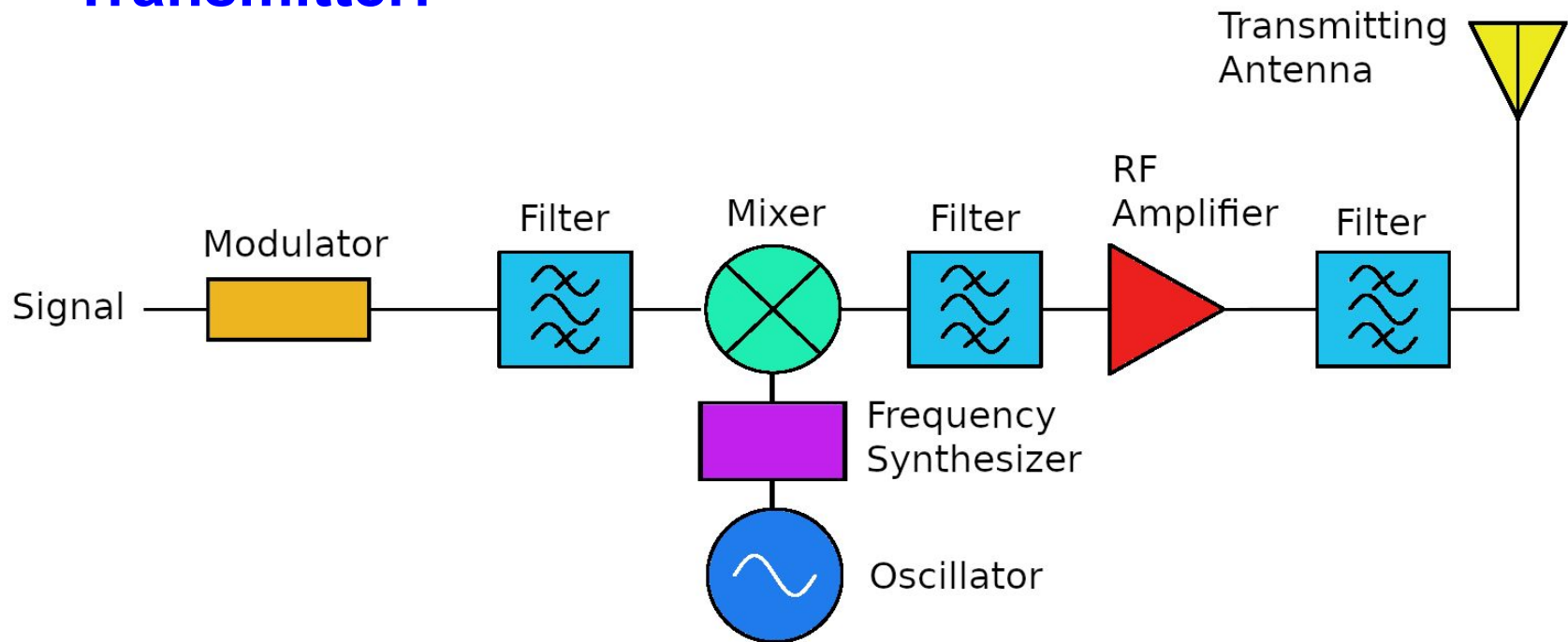
**and**

**Antennas**

# Overview and Applications

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## Transmitter:



# Overview and Applications

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## Transmitter:

**Modulator:** Many: Amplitude modulation (AM),  
Frequency modulation (FM), Phase Shift Keying (PSK)

**Filter:** Learned about these in EECS215, but different at RF

**Mixer:** Generates signals at sum and difference frequencies

**Amplifier:** Similar to OpAmp, but specialized for GHz frequencies

**Oscillator:** Special, high-performance oscillating voltage source,  
available in just a few frequencies

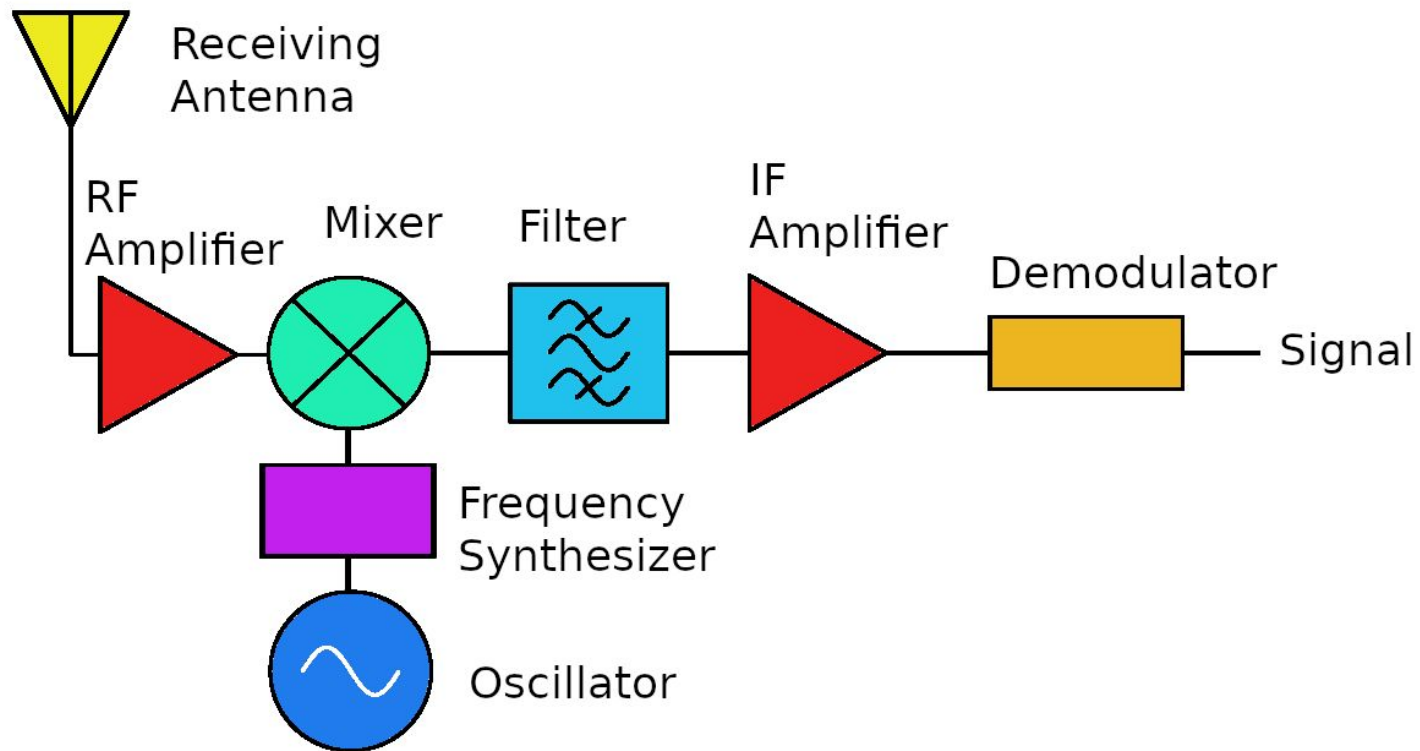
**Freq Synthesizer:** Generate desired frequency from the oscillator,  
usually a multiplier

**Antenna:** Many kinds, based on application

# Overview and Applications

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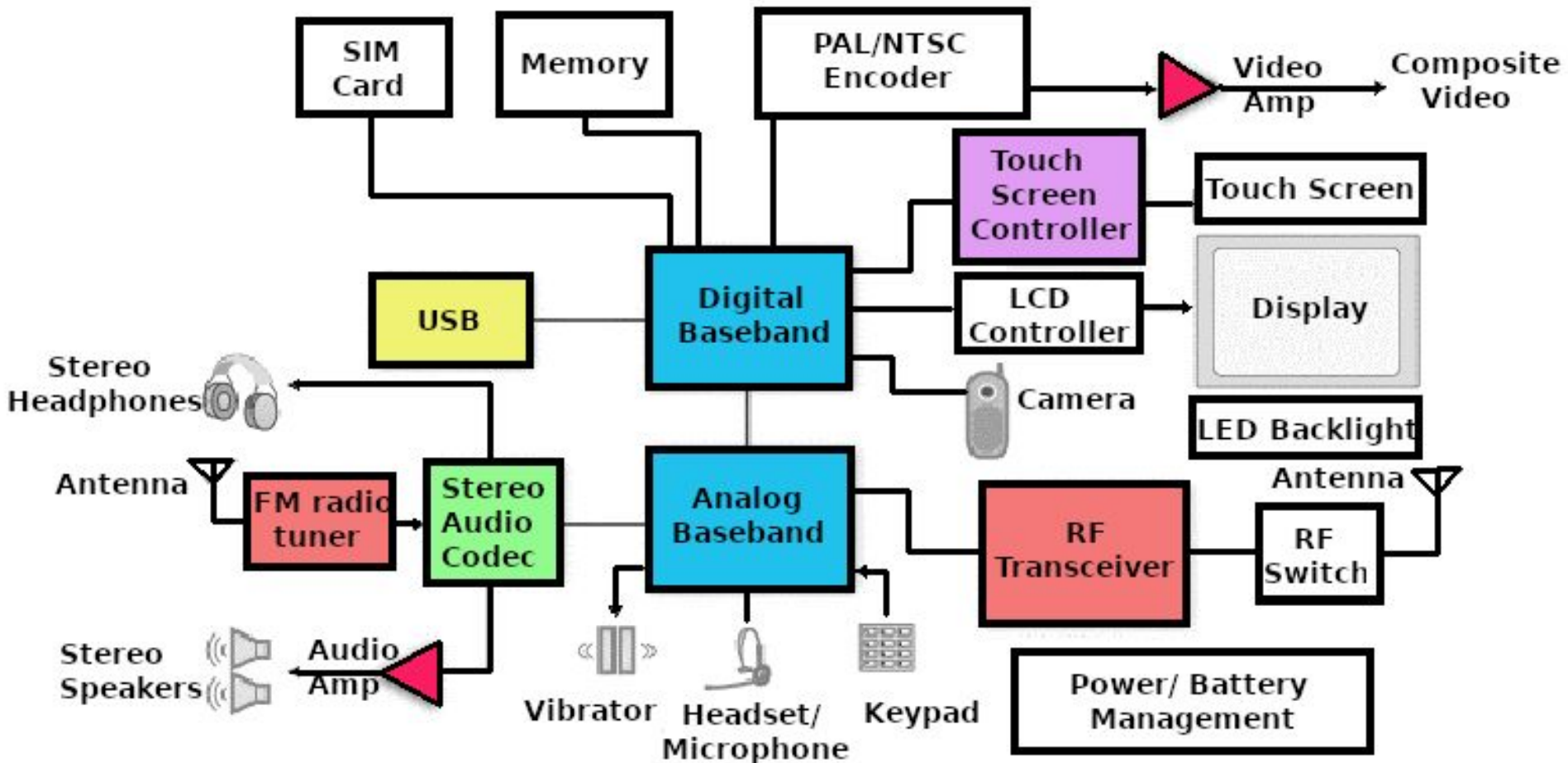
## Receiver:



# Overview and Applications

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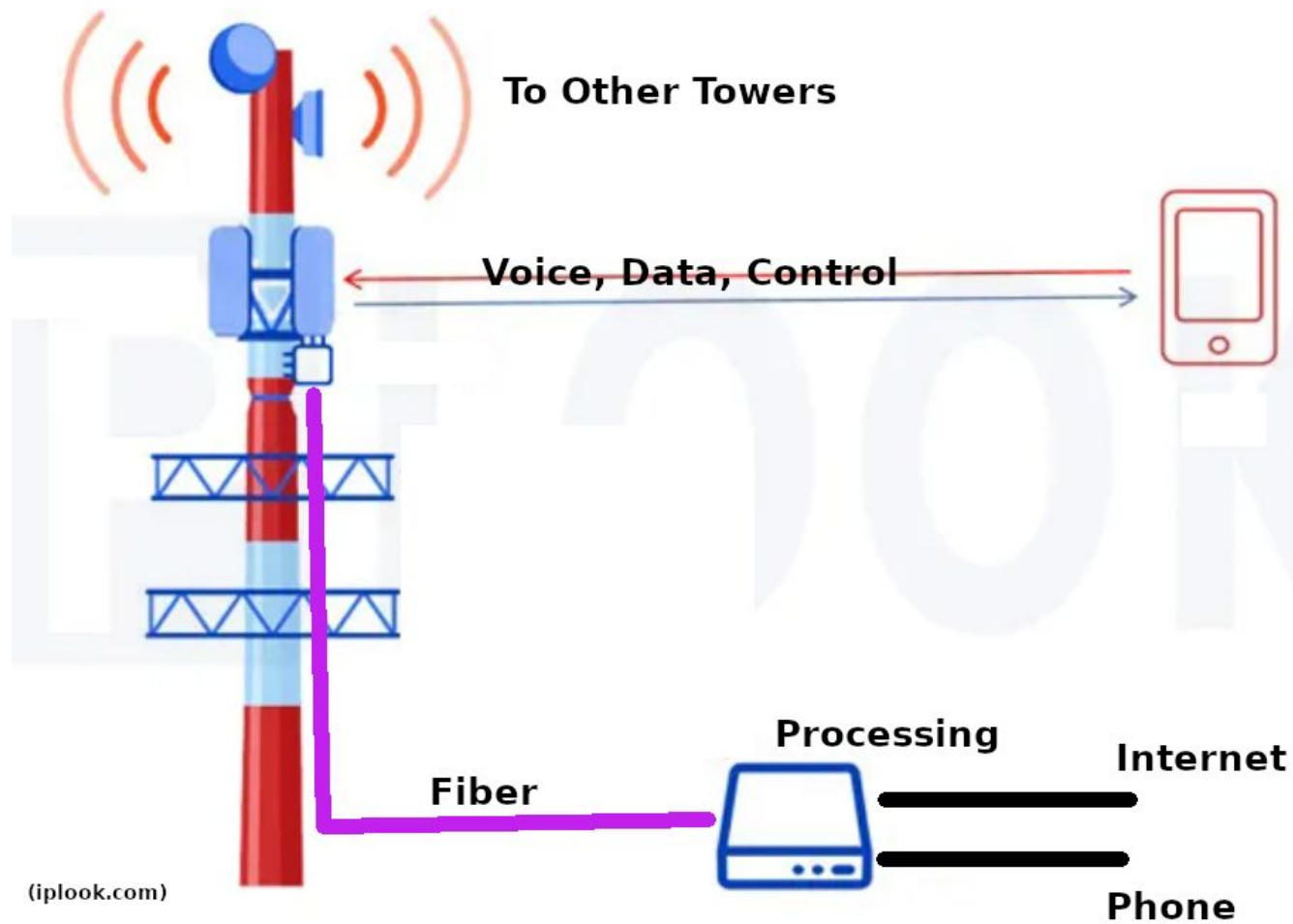
## Cell Phone: Functional Block Diagram



# Overview and Applications

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## Cell Phone: Single Cell



# Relevant EECS Classes

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**411/413: RF circuits**

**330/430/455: Wireless circuits, systems**

**525: Advanced RF circuits**

**531: Antenna Design**

**532/632: Remote Sensing**

# Overview and Applications

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## EECS 230 Class Overview

Ch1: Travelling Waves

Ch2: High-Frequency Waves

Travelling on Cables

Reflection

Standing Waves

Optimum Power Transfer

Ch 4: Electric Fields

Capacitors

Sensors

Ch 5: Magnetic Fields

Inductors

RFID

Ch 6: Electromagnetic Fields

Motors/Generators

Transformers

Wireless Power Transfer

Chs 7,8: Wave Propagation

Plane waves, reflection, refraction

# 1-2 Dimensions, Units

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**Table 1-1** Fundamental SI units.

<b>Dimension</b>	<b>Unit</b>	<b>Symbol</b>
<b>Length</b>	meter	m
<b>Mass</b>	kilogram	kg
<b>Time</b>	second	s
<b>Electric charge</b>	coulomb	C
<b>Temperature</b>	kelvin	K
<b>Amount of substance</b>	mole	mol
<b>Luminous intensity</b>	candela	cd

# 1-2 Dimensions, Units

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<b>Dimension</b>	<b>Unit</b>	<b>Symbol</b>
<b>Electrical:</b>		
<b>Current</b>	ampere	A
<b>Voltage</b>	volt	V
<b>Resistance</b>	ohm	$\Omega$
<b>Capacitance</b>	farad	F
<b>Inductance</b>	henry	H
<b>Power</b>	watt	W
<b>Frequency</b>	hertz	Hz

# 1-2 Dimensions, Units

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**Table 1-2** Multiple and submultiple prefixes.

Prefix	Symbol	Magnitude
<b>exa</b>	E	$10^{18}$
<b>peta</b>	P	$10^{15}$
<b>tera</b>	T	$10^{12}$
<b>giga</b>	G	$10^9$
<b>mega</b>	M	$10^6$
<b>kilo</b>	k	$10^3$
<b>milli</b>	m	$10^{-3}$
<b>micro</b>	$\mu$	$10^{-6}$
<b>nano</b>	n	$10^{-9}$
<b>pico</b>	p	$10^{-12}$
<b>femto</b>	f	$10^{-15}$
<b>atto</b>	a	$10^{-18}$

# 1-3 Electromagnetic Force

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Only charged particles are affected by the electromagnetic force.

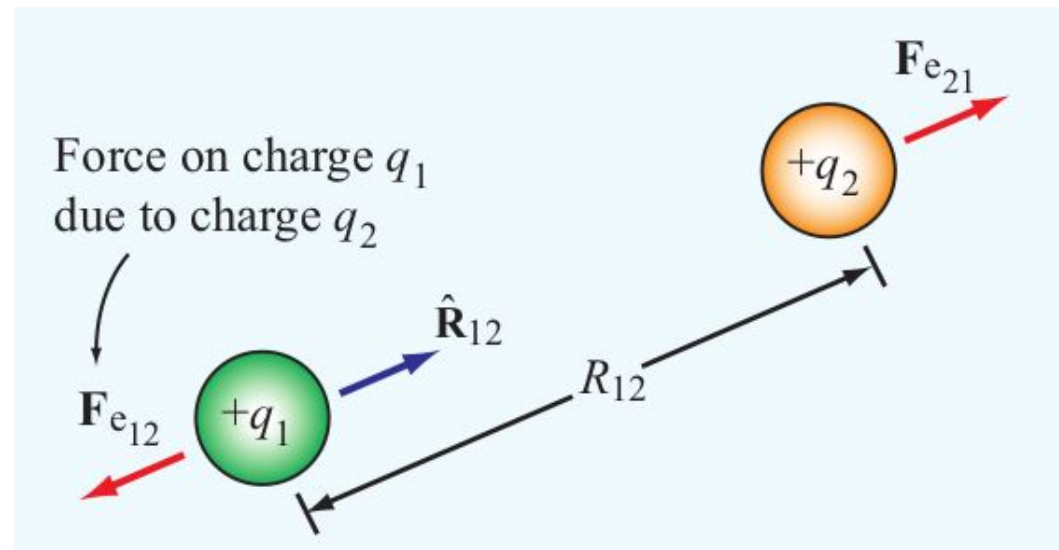
Charge is quantized in multiples of:

$$e = 1.6 \times 10^{-19} \quad (\text{C}).$$

For charges that are not moving, use Coulomb's Law:

in free space:

$$\mathbf{F}_{e_{21}} = \hat{\mathbf{R}}_{12} \frac{q_1 q_2}{4\pi\epsilon_0 R_{12}^2} \quad (\text{N})$$

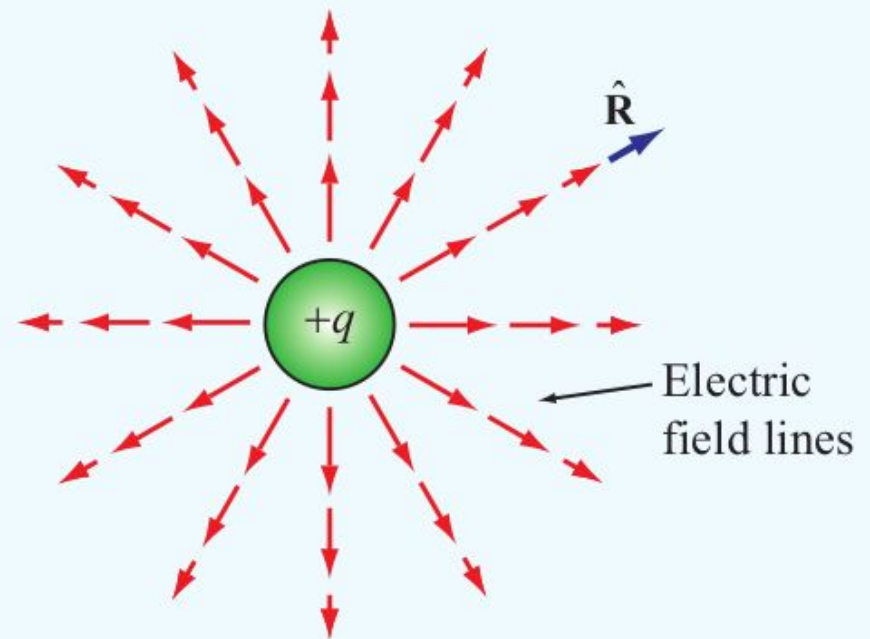


# 1-3 Electric Field

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Electric field due a single charge:  
in free space:

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi\epsilon_0 R^2} \quad (\text{V/m})$$



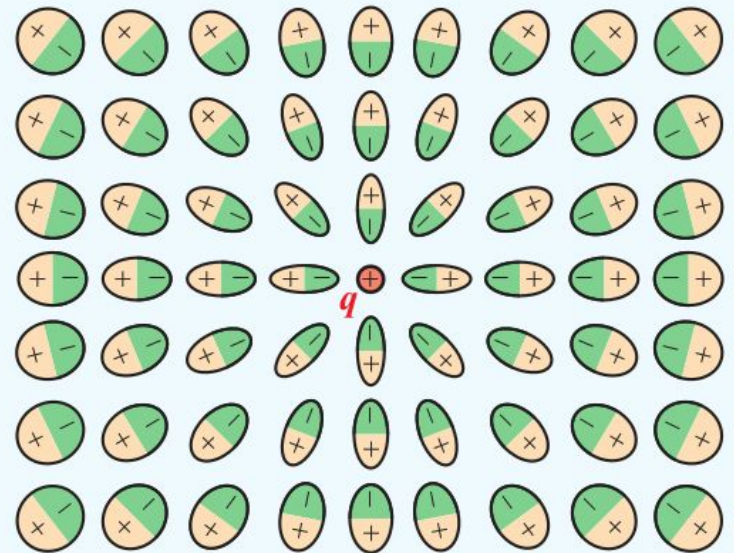
**Figure 1-6** Electric field  $\mathbf{E}$  due to charge  $q$ .

# 1-3 Electric Field

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Electric field due a single charge:  
in a material, characterized  
by dielectric constant  $\epsilon$ :

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi\epsilon R^2} \quad (\text{V/m}).$$

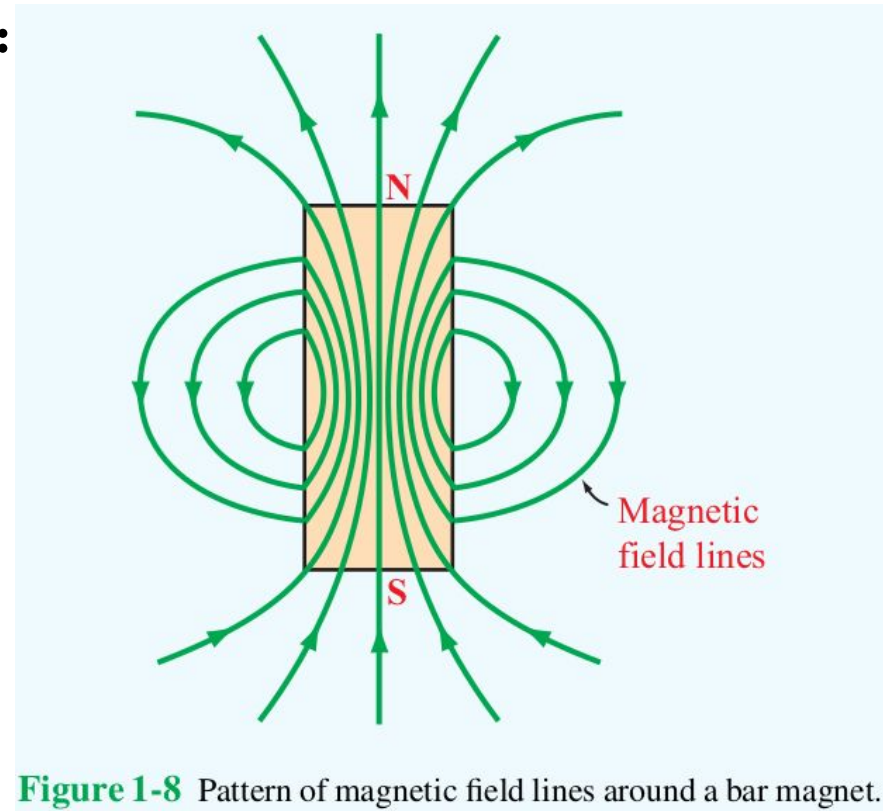


**Figure 1-7** Polarization of the atoms of a dielectric material by a positive charge  $q$ .

# 1-3 Magnetic Field

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Magnetic field of a bar magnet:



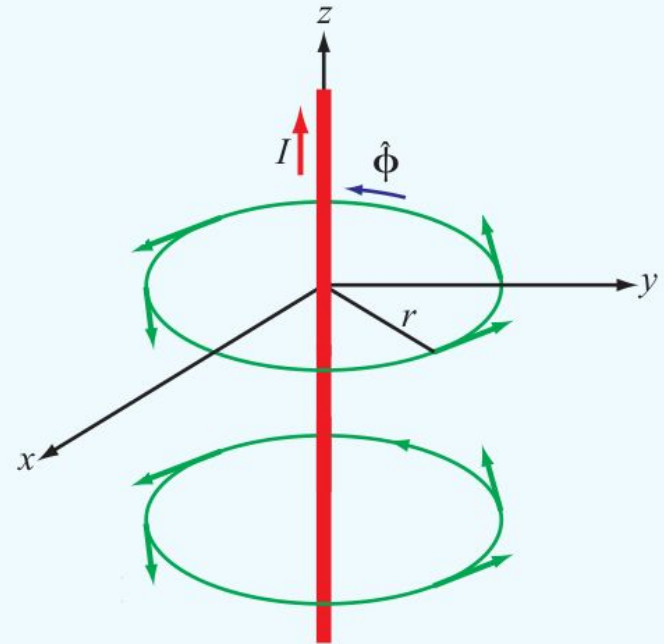
**Figure 1-8** Pattern of magnetic field lines around a bar magnet.

# 1-3 Magnetic Field

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Magnetic field of a line current:

$$\mathbf{H} = \hat{\phi} \frac{I}{2\pi r} \quad (\text{A/m})$$



**Figure 1-9** The magnetic field induced by a steady current flowing in the  $z$  direction.

# 1-3 Electromagnetic Field

## Terminology:

- **Static**—describes a quantity that does not change with time. The term **dc** (i.e., direct current) is often used as a synonym for static to describe not only currents, but other electromagnetic quantities as well.
- **Dynamic**—refers to a quantity that does vary with time, but conveys no specific information about the character of the variation.

# 1-3 Electromagnetic Field

## Terminology:

- ***Periodic***—a quantity is periodic if its waveform repeats itself at a regular interval, namely its period  $T$ . Examples include the sinusoid and the square wave. By application of the Fourier series analysis technique, any periodic waveform can be expressed as the sum of an infinite series of sinusoids.
- ***Sinusoidal***—also called ***ac*** (i.e., alternating current), describes a quantity that varies sinusoidally (or cosinusoidally) with time.

# 1-3 Electromagnetic Field

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Terminology:

**Table 1-3** The three branches of electromagnetics.

Branch	Condition	Field Quantities (Units)
<b>Electrostatics</b>	Stationary charges ( $\partial q/\partial t = 0$ )	Electric field intensity <b>E</b> (V/m) Electric flux density <b>D</b> (C/m <sup>2</sup> ) $\mathbf{D} = \epsilon\mathbf{E}$
<b>Magnetostatics</b>	Steady currents ( $\partial I/\partial t = 0$ )	Magnetic flux density <b>B</b> (T) Magnetic field intensity <b>H</b> (A/m) $\mathbf{B} = \mu\mathbf{H}$
<b>Dynamics</b> (time-varying fields)	Time-varying currents ( $\partial I/\partial t \neq 0$ )	<b>E, D, B, and H</b> ( <b>E, D</b> ) coupled to ( <b>B, H</b> )

# 1-3 Electromagnetic Field

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Terminology:

**Table 1-4** Constitutive parameters of materials.

Parameter	Units	Free-Space Value
<b>Electrical permittivity <math>\epsilon</math></b>	F/m	$\epsilon_0 = 8.854 \times 10^{-12}$ $\approx \frac{1}{36\pi} \times 10^{-9}$
<b>Magnetic permeability <math>\mu</math></b>	H/m	$\mu_0 = 4\pi \times 10^{-7}$
<b>Conductivity <math>\sigma</math></b>	S/m	0

# 1-4 Traveling Waves

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For microwave circuits, we have voltages and currents that are a function of BOTH time and space.

Along a 1-dimensional transmission line this becomes a **traveling wave**:

$$y(x, t) = A \cos \left( \frac{2\pi t}{T} - \frac{2\pi x}{\lambda} + \phi_0 \right)$$

# 1-4 Traveling Waves

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$$y(x, t) = A \cos \left( \frac{2\pi t}{T} - \frac{2\pi x}{\lambda} + \phi_0 \right)$$

A: Amplitude (Volts, or Amps, ....)

T: time period, sec

$\lambda$ : spatial wavelength, m

$\phi_0$ : offset phase, radians

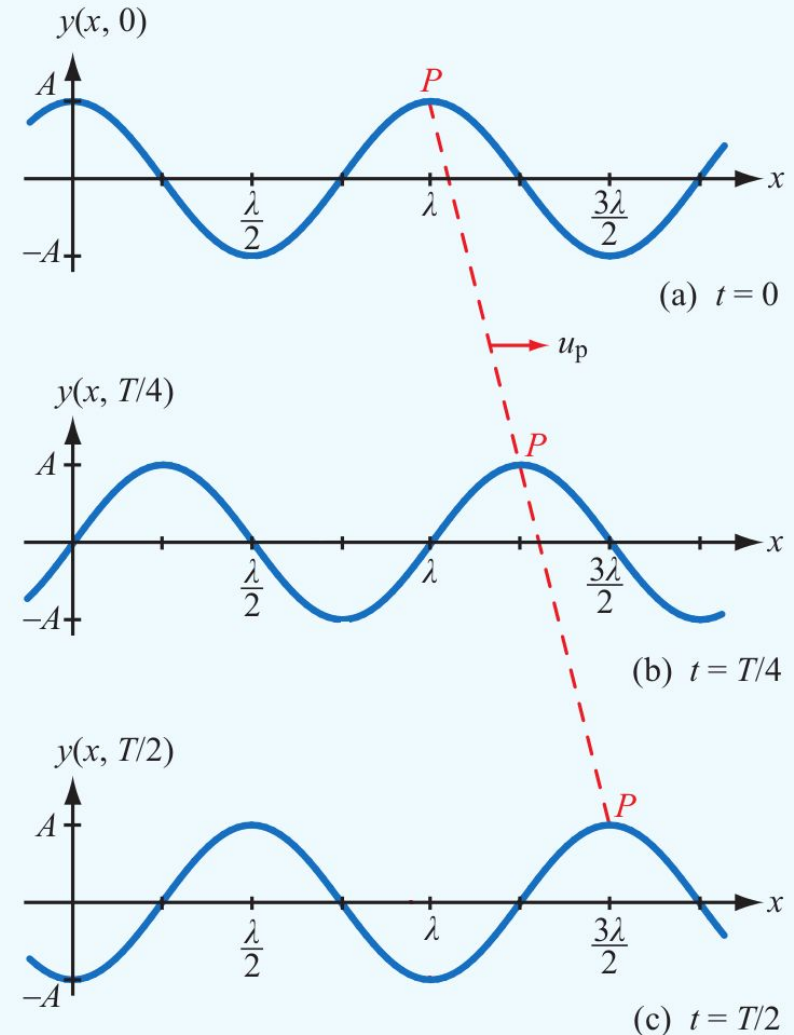
traveling in the +x direction: **how do we know?**

# 1-4 Traveling Waves

66

$$y(x, t) = A \cos \left( \frac{2\pi t}{T} - \frac{2\pi x}{\lambda} + \phi_0 \right)$$

**Phase velocity** of the wave:  
Velocity of a point on the wave  
with the same phase.



# 1-4 Traveling Waves

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$$y(x, t) = A \cos \left( \frac{2\pi t}{T} - \frac{2\pi x}{\lambda} + \phi_0 \right)$$

**Phase velocity** of the wave:

Velocity of a point on the wave with the same phase.

Choose a point with phase of zero:

$$\text{phase} = \frac{2\pi}{T}t - \frac{2\pi}{\lambda}x + \phi_0 = 0$$

To solve for  $dx/dt$ , take the time-derivative of the equation:

$$\frac{d}{dt} \left\{ \frac{2\pi}{T}t - \frac{2\pi}{\lambda}x + \phi_0 = 0 \right\}$$

# 1-4 Traveling Waves

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$$\frac{d}{dt} \left\{ \frac{2\pi}{T}t - \frac{2\pi}{\lambda}x + \phi_0 = 0 \right\}$$

$$\frac{2\pi}{T} - \frac{2\pi}{\lambda} \frac{dx}{dt} + 0 = 0$$

$$-\frac{2\pi}{\lambda} \frac{dx}{dt} = -\frac{2\pi}{T}$$

$$\frac{1}{\lambda} \frac{dx}{dt} = \frac{1}{T}$$

$$\frac{dx}{dt} = \frac{\lambda}{T}$$

# 1-4 Traveling Waves

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Since: 
$$\frac{dx}{dt} = \frac{\lambda}{T}$$

The phase velocity is:

$$u_p = \frac{dx}{dt} = \frac{\lambda}{T} \quad (\text{m/s}).$$

Phase velocity of light in vacuum:

$$c = 3 \times 10^8 \text{ m/sec}$$

# 1-4 Traveling Waves

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Because  $f = 1/T$ :  $u_p = f\lambda$

A different parameterization of a traveling-wave:

$$y(x,t) = A \cos \left( 2\pi f t - \frac{2\pi}{\lambda} x \right)$$
$$= A \cos(\omega t - \beta x),$$

**(wave moving along  $+x$  direction)**

$\beta$  is the "phase constant" or "wavenumber", units: rad/m

What are the units of  $\omega$  ?

# 1-4 Traveling Waves

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Since:  $u_p = f \lambda$

and:  $f = \omega / 2\pi$        $\lambda = 2\pi / \beta$

then:

$$u_p = \omega / \beta$$

# 1-4 Traveling Waves

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$$y(x,t) = A \cos(\omega t + \beta x).$$

**(wave moving along  $-x$  direction)**

$$u_p = -\omega / \beta$$

# 1-4 Traveling Waves

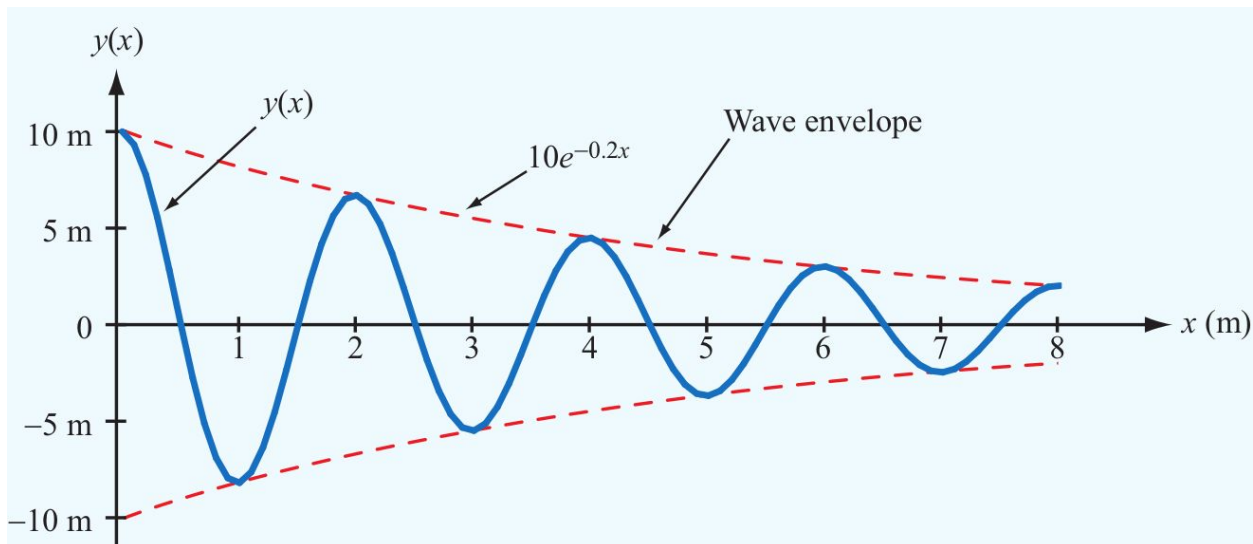
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A "Lossy" medium causes the amplitude of the wave to decrease as a function of distance:

$$y(x,t) = Ae^{-\alpha x} \cos(\omega t - \beta x + \phi_0)$$

$\alpha$  is the "attenuation constant" with units: Np/m

recall that Np or "Nepers" is another dimensionless "unit".



# Example 1-2 Power Loss

74

**Given:** A laser beam propagating through air.

$$E(x,t) = 150e^{-0.03x} \cos(3 \times 10^{15}t - 10^7x) \quad (\text{V/m}),$$

$x$  = distance from source, meters

attenuation due to absorption by atmospheric molecules

**Find:** (a) direction of wave travel

(b) wave velocity

(c) wave amplitude at distance of 200 m

**Solution:**

(a) since the coeffs of  $t$  and  $x$  have opposite signs:

travelling in  $+x$  direction.

# Example 1-2 Power Loss

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**Given:**  $E(x,t) = 150e^{-0.03x} \cos(3 \times 10^{15}t - 10^7x)$  (V/m),

**Solution:**

**(b)** phase velocity is:

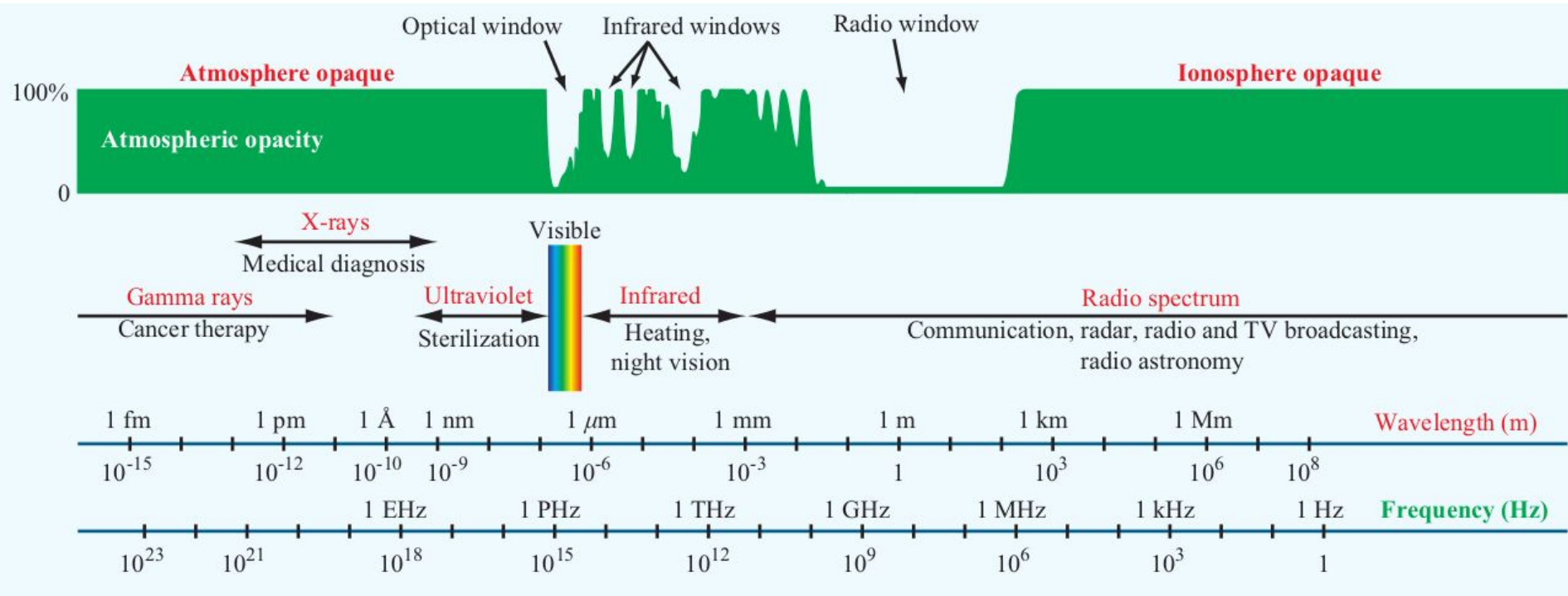
$$u_p = \frac{\omega}{\beta} = \frac{3 \times 10^{15} \text{ rad/sec}}{1 \times 10^7 \text{ rad/m}} = 3 \times 10^8 \text{ m/sec}$$

**(c)** amplitude at  $x=200$  m:

$$\text{Amplitude}(x) = Ae^{-\alpha x} = (150 \text{ V/m})e^{-(0.03\text{Np/m})(200\text{m})} = 0.37 \text{ V/m}$$

# 1-5 Electromagnetic Spectrum

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Gamma Rays

$10^{20}$  Hz

Visible

$10^{15}$  Hz

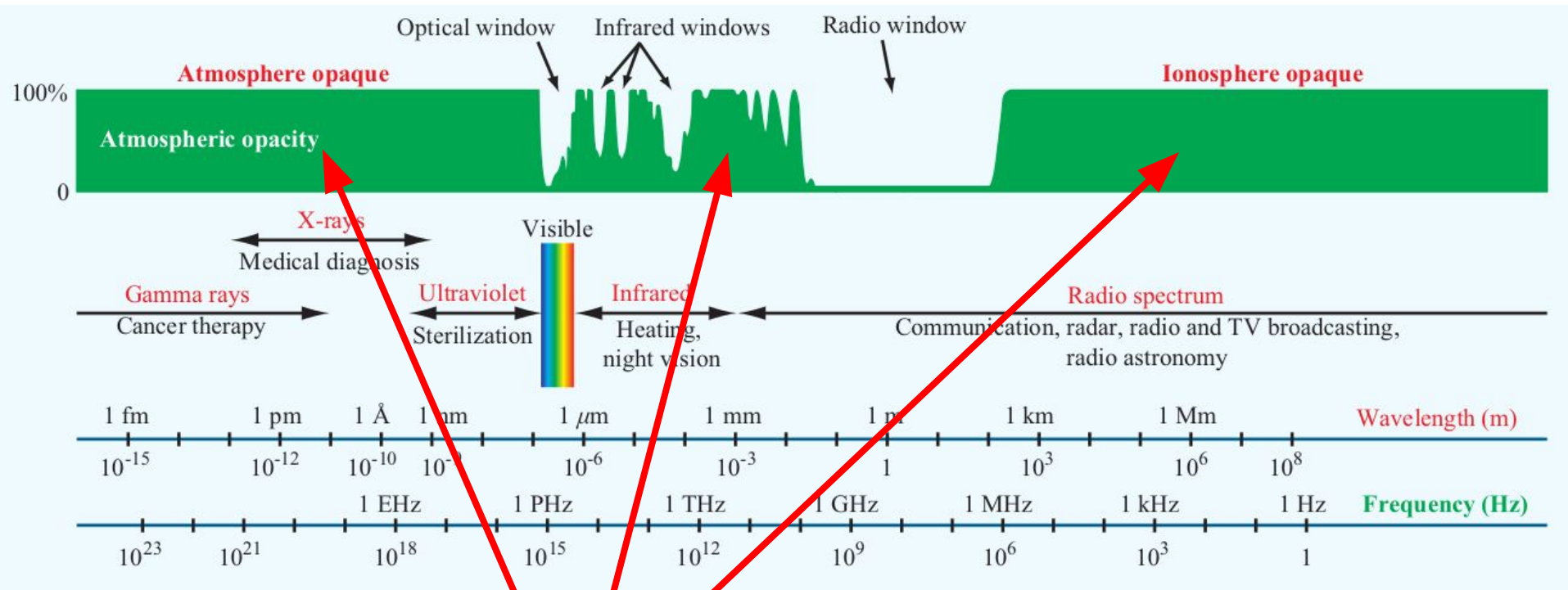
Radio

$10^{10}$  Hz

AC Power

60 Hz

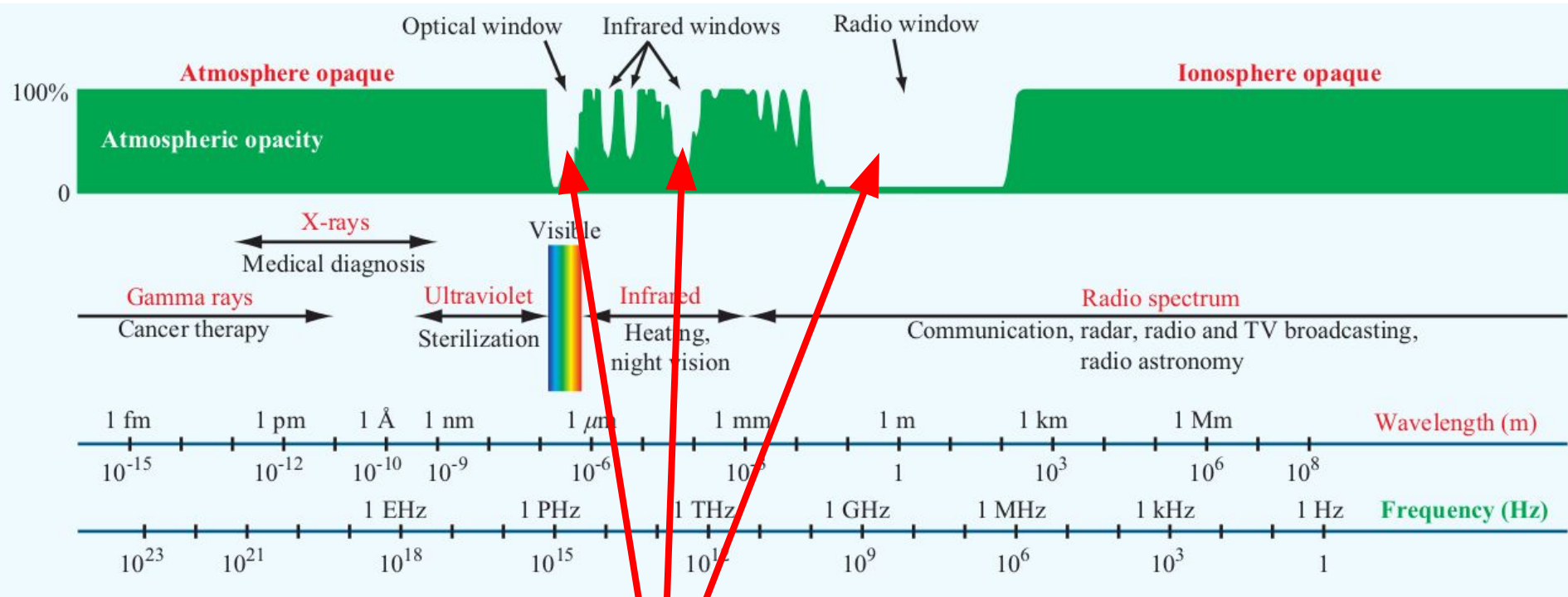
# 1-5 Electromagnetic Spectrum



Atmospheric gases absorb most of radiation

# 1-5 Electromagnetic Spectrum

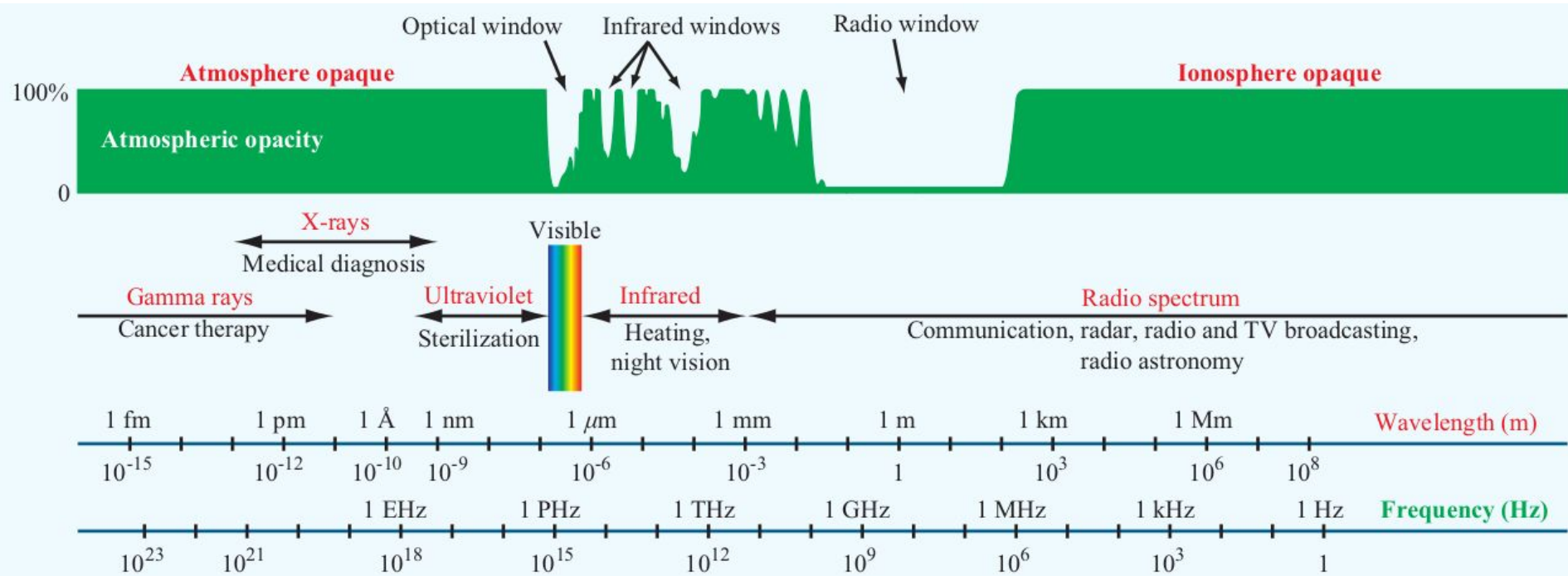
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Atmosphere is clear to these frequencies

# 1-5 Electromagnetic Spectrum

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Can we use the same frequencies for communications on Venus?

# Homework

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**Homework 1 is due tomorrow at midnight.**

**submit to gradescope via the canvas site.**

# Next Time

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## **Review of Circuits:**

you should review Chapters 1,2,5,7 of **Circuits** book,  
and sections 1-6, 1-7 of Electromagnetics book..