# ECE341
# Electromagnetic Fields

Gong Gu

# Introduction: Why EM Fields?

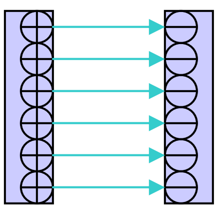
The electromagnetic force is one of the four fundamental forces of Nature.
(What are the other three?)
Charged particles interact by the EM force, via EM fields.
But why do we (electrical engineers) care?

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

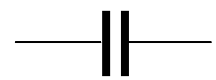
**Inside the black boxes:**

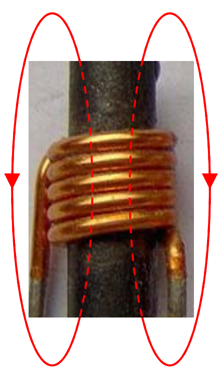
$J = en\mu E$ $\quad V \propto E,\ J = \sigma E = I/A$ $\quad$  $\quad I = V/R$

Velocity $\propto$ Force? What about Newton's laws?



$Q \equiv Cv = CEd$

$dv/dt \rightarrow dQ/dt \rightarrow i$ $\quad$  $\quad i = C\, dv/dt$



$B \propto i$

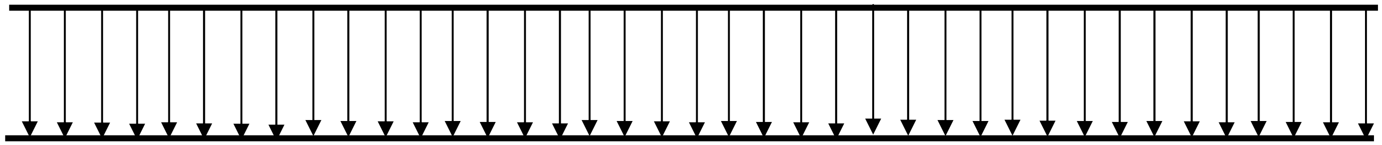
$di/dt \rightarrow dB/dt \rightarrow E \rightarrow v$ $\quad$  $\quad v = L\, di/dt$

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

"Lumped" components when dimensions << wavelength

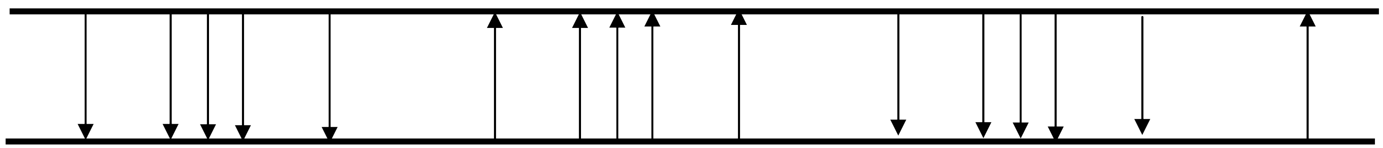
Simplest example: a pair of wires (considered ideal wires)
(the term “transmission line” is a bit confusing)

Length << $\lambda$



Changing electric field induces magnetic field, changing magnetic field induces electric field. Therefore waves.

Length ~ $\lambda$



Voltage along a cable can vary!

| $f$ | $\lambda$ | 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 | |

microwave

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

This course is about electromagnetics (EM), the foundation of Electrical and Computer Engineering, or, how electricity ***<u>really</u>*** 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.

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

Recommended reference book:
Ramo *et al*, *Fields and Waves in Communication Electronics*

**Homework**
To be finished at the start of class on certain days, indicated in the schedule

**Tests and Quizzes**
***Partially*** reflect homework and are certification that you learned what you should from the homework and study. Two major tests, on the days indicated in the schedule. Random in-class quizzes. No make-ups.

**Lab** (2 or 3 TBD)
Completion of all labs is required for course completion

**Grade**
Test 1: 20%; Test 2: 20%; Quizzes: 10%
Lab: 15%;
Final exam: 35%

## 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.

## Website

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

## Extra project for Honors class ECE347

## Tips

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

- Don't overload your schedule with courses and/or work;
- Aim toward becoming a good engineer;
- **Don't miss classes (and the quizzes)**;
- **See lab as an inquiry - not following a cook book**;
- 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 some 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 you irreplaceable by machines)

AlphaGo defeated best human players

A plumber working in my basement

Computers recognize cats

Human babies recognize cats

## 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 machine)
- Pursue true understanding, not mimicking
- When you understand the why, the how will come to you naturally

- Class is long; will try not to bore you (but you need to put down your phones)
- Frequent, random in-class quizzes to keep you engaged

- Not easy to fail

**Overview of course**

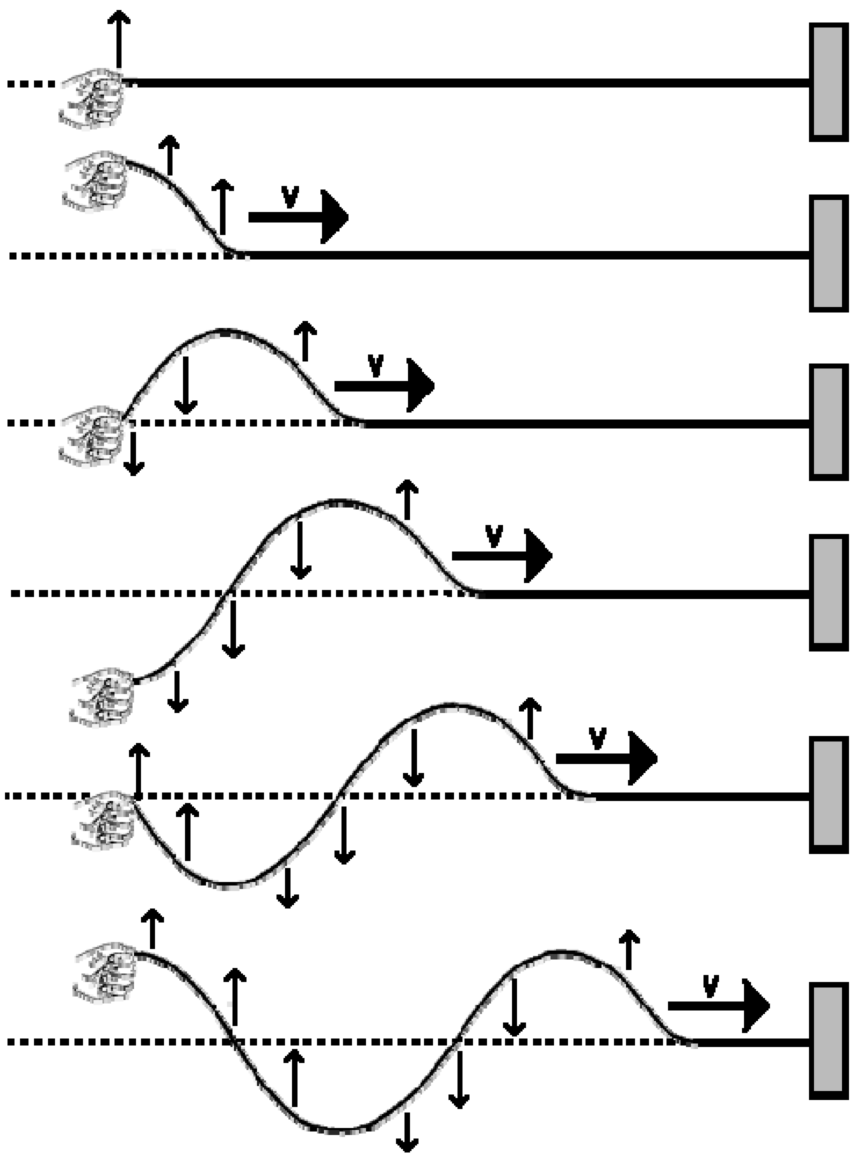
- General concept of waves
- Transmission line theory derived from circuit theory
  (Yes, it works.)
- Electrostatics
  (We start to discuss the “real” EM theory.)
- Magnetostatics
- Dynamic fields
  (Nothing in the world is “static”.)
- EM plane waves
  (The simplest EM waves. You get a sense how waves arise from dynamic fields)

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

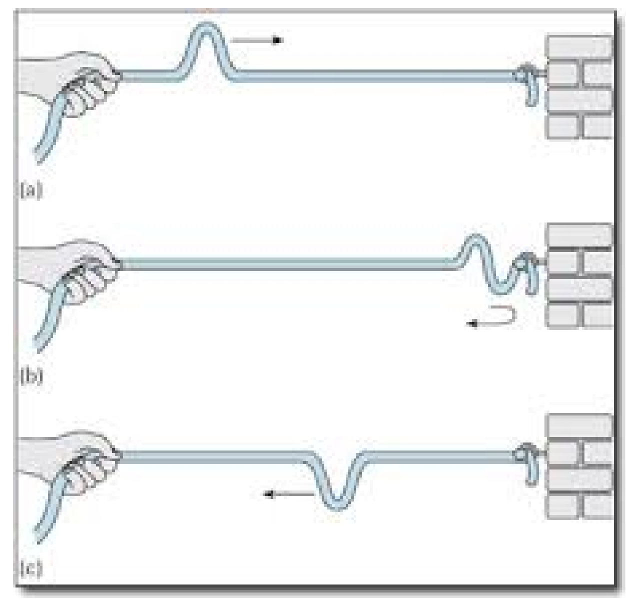
- ECE 443 - Antenna Systems Engineering
- ECE 444 - Microwave Circuits
- Graduate courses: ECE 541, 545, 546, 547

# Traveling Waves

A traveling wave is the propagation of motion (disturbance) in a medium.



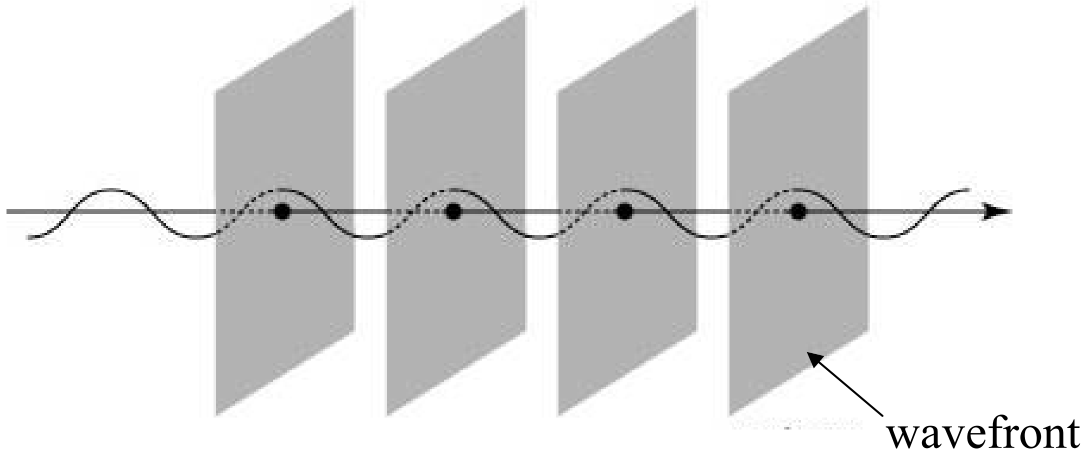

The one-dimensional (1D) case



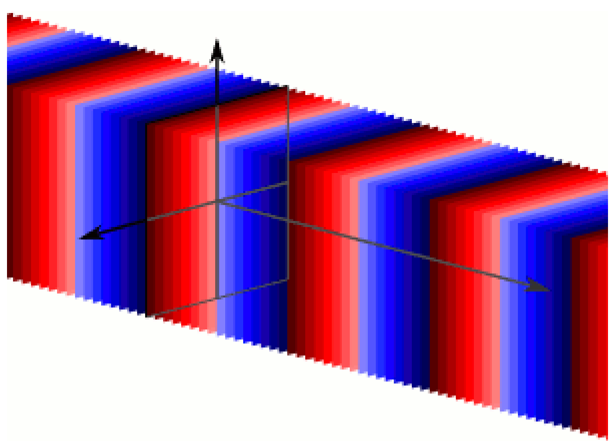
Reflection

# Traveling Wave in Higher Dimensions

Plane waves in 3D

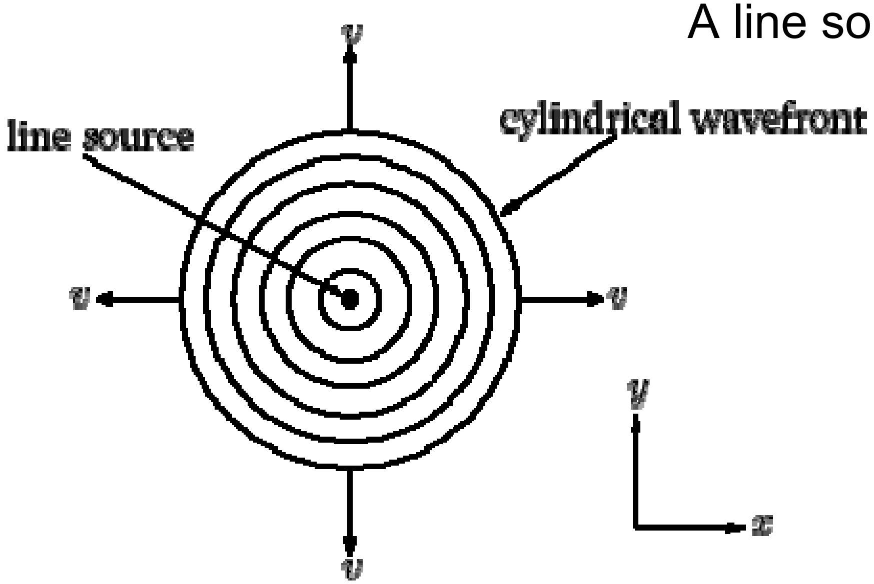



Example: sound waves



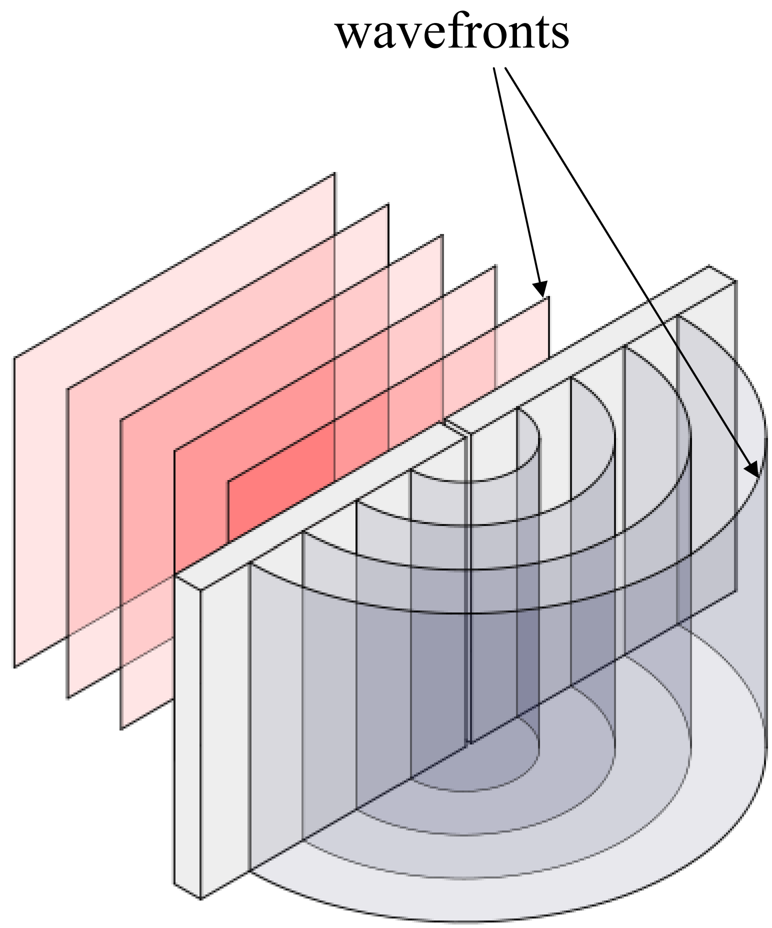
Watch animation: http://en.wikipedia.org/wiki/Plane_wave

A line source makes a cylindrical wave.



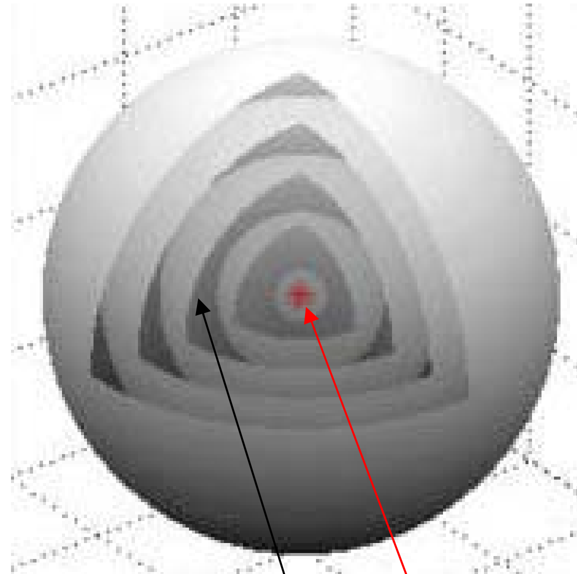

Cylindrical wave (3D; top view)

Water surface wave (2D)
(Circular wave)




Make a cylindrical wave from a plane wave

A point source makes a spherical wave.

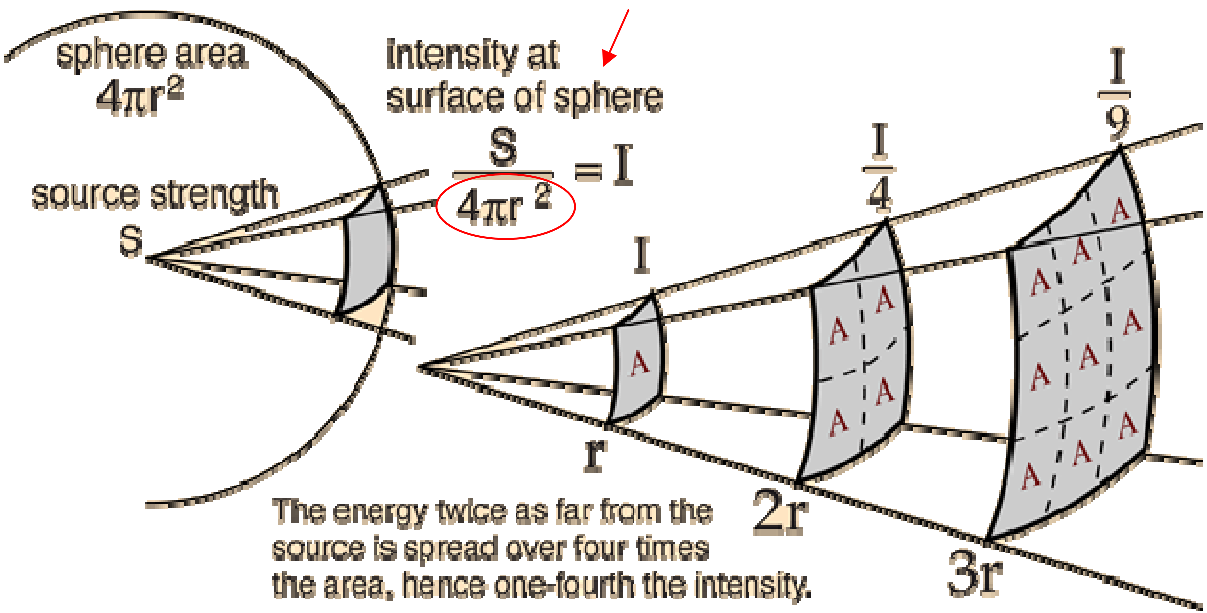


Point source

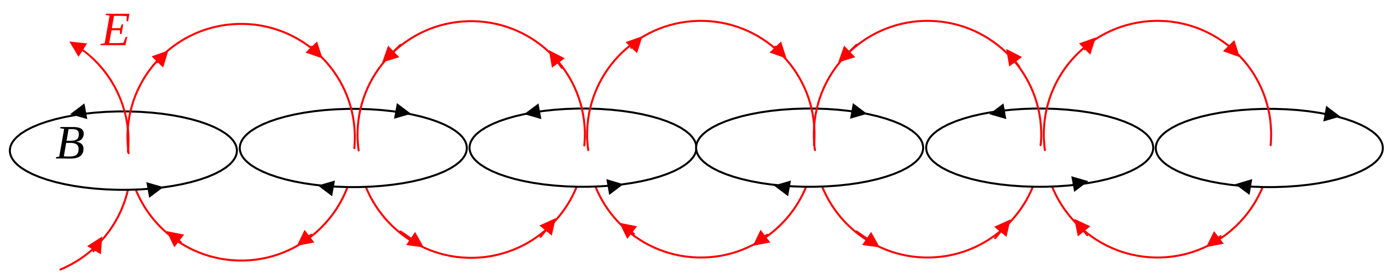
wavefronts

Intensity is energy carried per time per area, i.e., power delivered per area

Conservation of energy



# Electromagnetic Wave




Somehow start with a changing electric field $E$, say $E \propto \sin\omega t$

The changing electric field induces a magnetic field, $B \propto \dfrac{\partial E}{\partial t} \propto \cos\omega t$

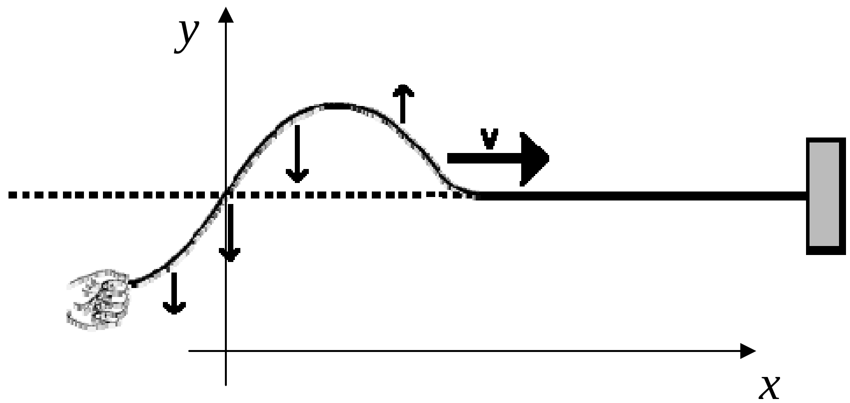
If the induced magnetic field is changing with time, it will in turn induce an electric field

$$E \propto \frac{\partial B}{\partial t} \propto \sin\omega t$$

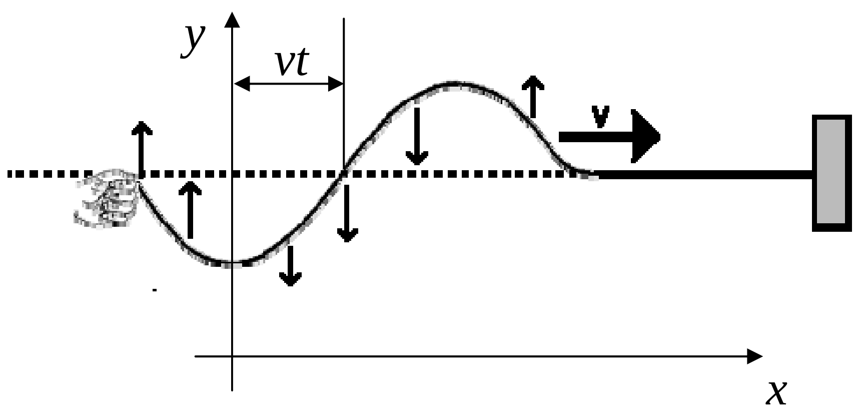
And so on and so on....
Just as the mechanical wave on a string.

# Mathematical Expression of theTraveling Wave

A traveling wave is the propagation of motion (disturbance) in a medium.




At time 0,
$y = f(x)$




At time $t$,
$y = f(x-vt)$

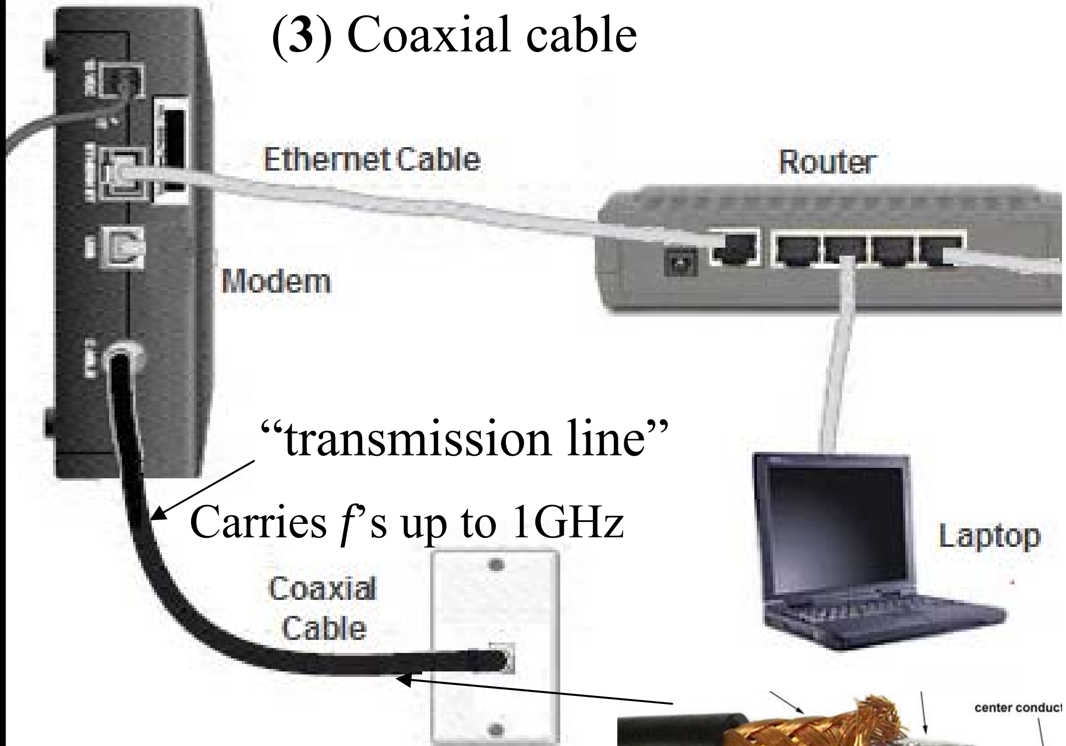
This is the general expression of Traveling waves.

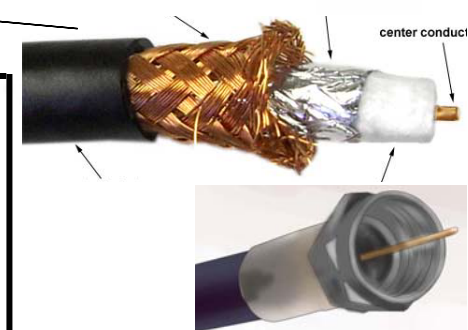
Questions:
What kind of wave does $y = f(x+vt)$ stand for?
What about $y = f(vt-x)$

Question:
For the string, you ***see*** the displacement is different at each point (**1**).
If you measure the instantaneous $v$ between the two wires in a "transmission" line at two locations 1 ft apart, will the two $v$'s be different? Answer for both cases (**2**,**3**). If yes, how can a wire sustain the voltage difference?

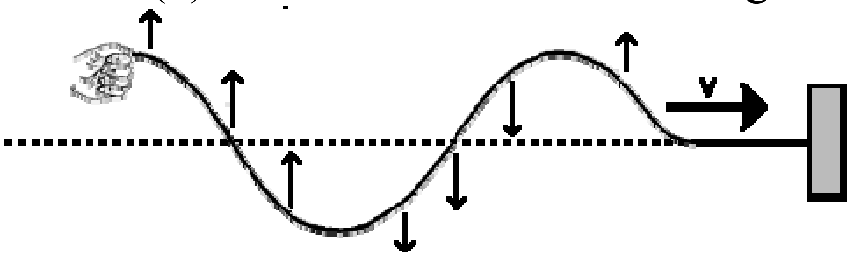
voltage

## (**3**) Coaxial cable




## (**1**) Mechanical wave on a string




## (**2**) Power transmission line