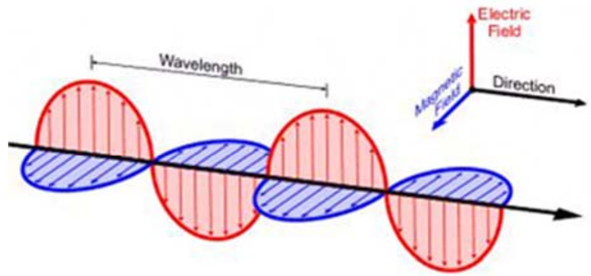
Lecture (01)
Introduction

By:

Dr. Ahmed ElShafee

What is Electromagnetism (EM)?

- The study of electric charges at rest and in motion



Why to study EM?

- To understand the natural EM phenomena

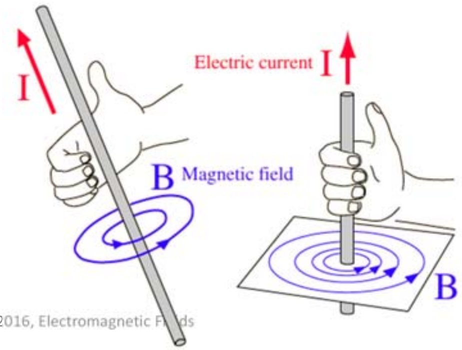
E.g. The "blue" sky (EM wave scattering), the

- lightening (discharge)
- To create EM devices to facilitate (and complicate) our lives

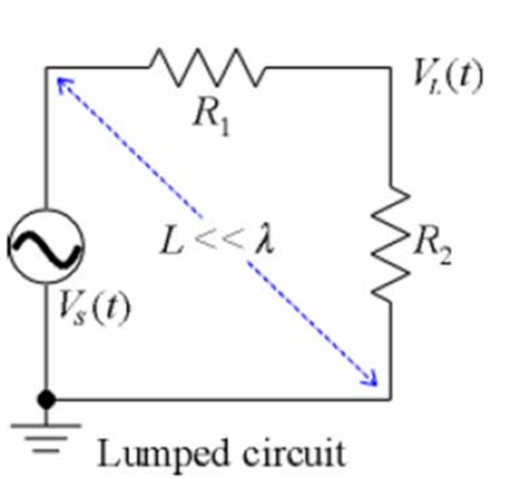
E.g. The compass, motors, memories, solar cells

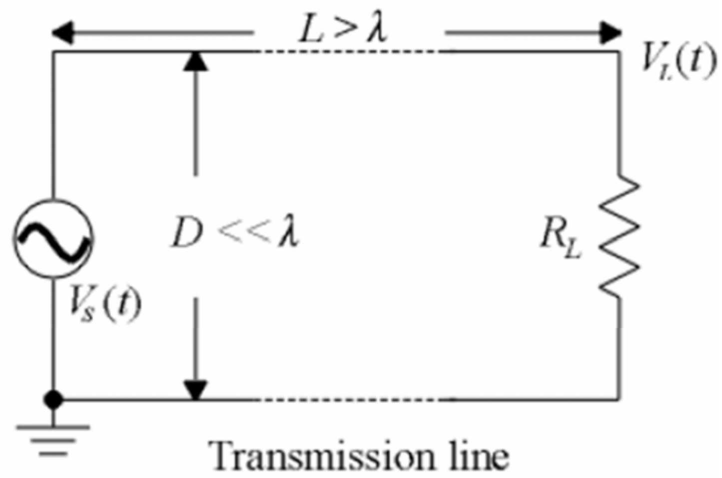
Overview of EM

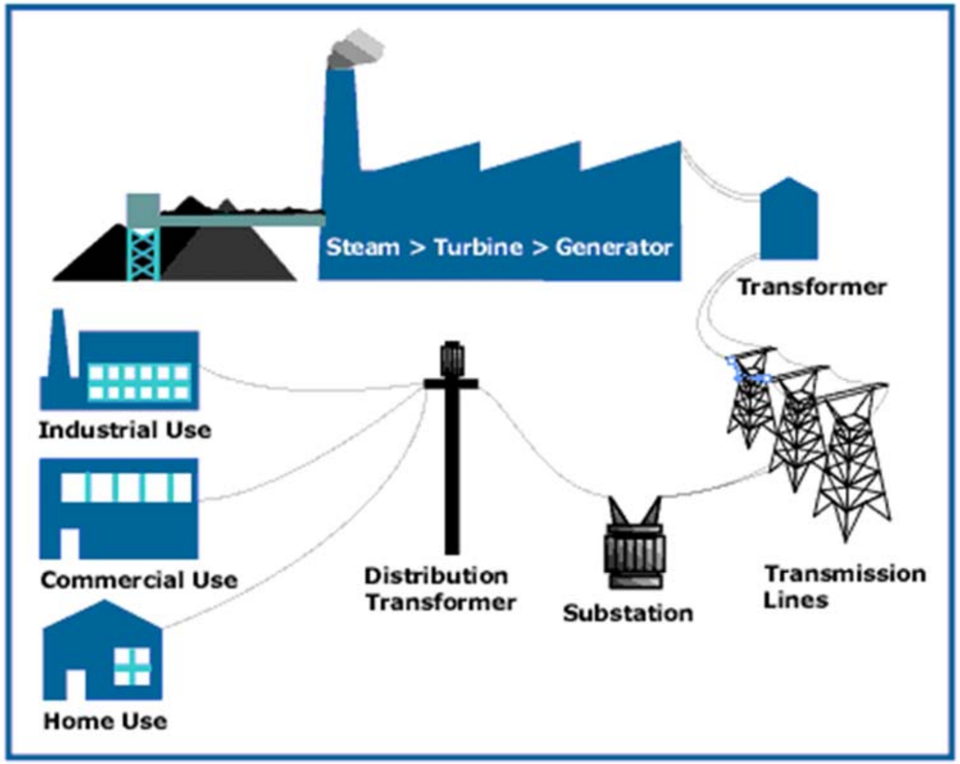
- Electric charges establish electric fields
- Moving charges become electric currents and create magnetic fields
- Timing-varying charges and currents cause the coupling between electric and magnetic fields such that they behave like "waves"

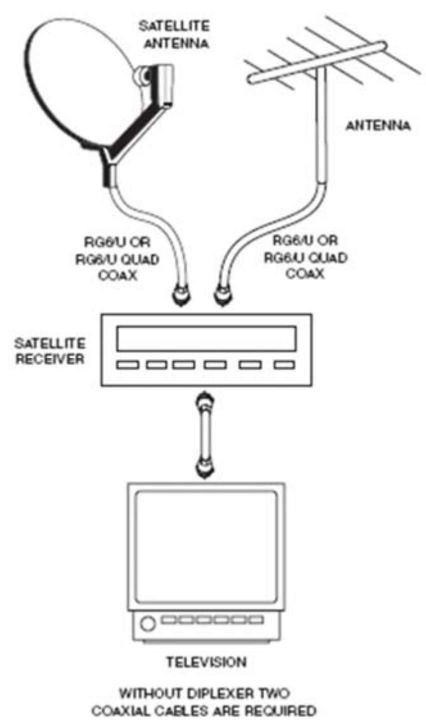


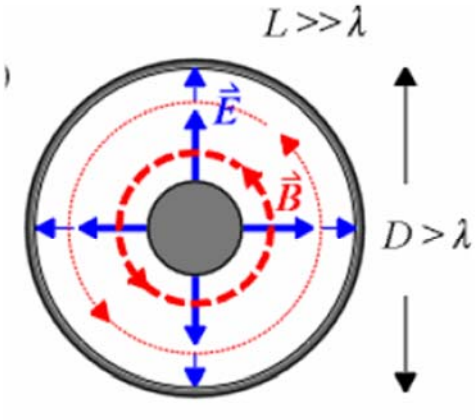
Types of EM problems











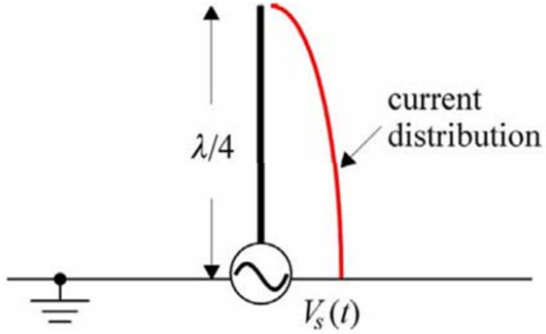
Waveguide (cross-section)

Analysis of EM problems

Conditions	Theory	Unknowns	Math tool	Description
L<<λ	Lumped circuits Kirchhoff's laws	*V* (*t*) , *I* (*t*)	Ordinary differential equations (ODEs)	All points react to the source instantly
L>λ, *D*<<λ	Transmission lines Kirchhoff's laws	*V* (*z*,*t*) , *I* (*z*,*t*)	Partial differential equations (PDEs)	Delay along the longitudinal (*z*) direction exists
L>>λ, *D*>λ	Waveguides Maxwell's equations	E(x,y,z,t) H(x,y,z,t)	Full vectorial PDEs	Delay along the longitudinal (*z*), and transversal (*x*,*y*) directions exist

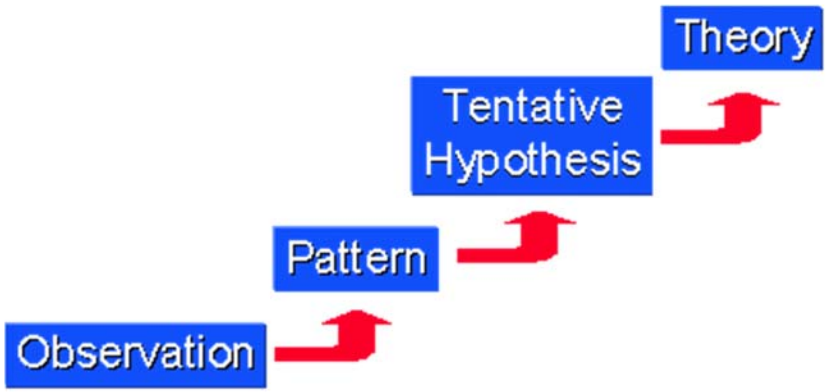
Example

- A quarter-wave monopole antenna) is regarded as an "open circuit" and cannot carry electric current according to the lumped circuit theory.
- However, the EM theory permits it carrying spatially nonuniform currents

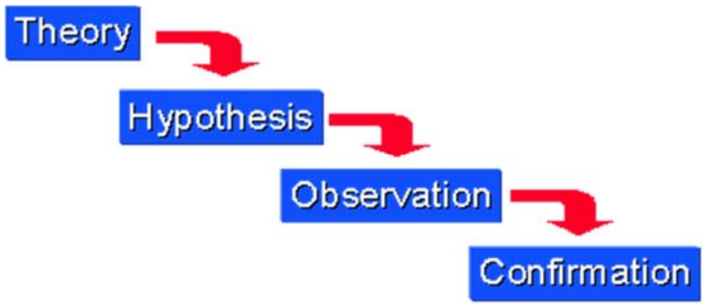


EM Model

- Inductive approach:
- Starting with observations of experiments, inferring laws and theorems (from particular phenomena to general principles)



- **Deductive approach: (ours)**
- Starting with fundamental postulates, deriving particular laws and theorems, which can be verified by experiments



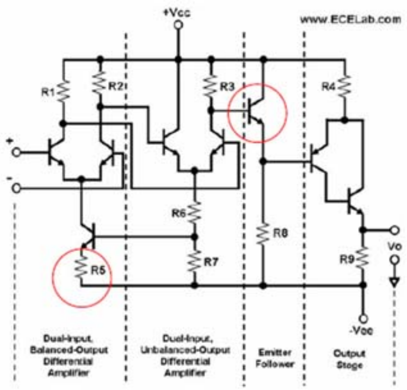
Defining the basic quantities

- Electric charge q (e =1.6×10^{-19} C),
  - volume charge density ρ (C/m3)
- Current I (C/s, or A),
  - volume current density (A/m2)
- Electric field intensity E (V/m): Electric force on a unit charge
- Electric flux density D (C/m2): measure of the **Electric** Field due to some charge, experienced over a Unit surface area i.e. 1 square units.

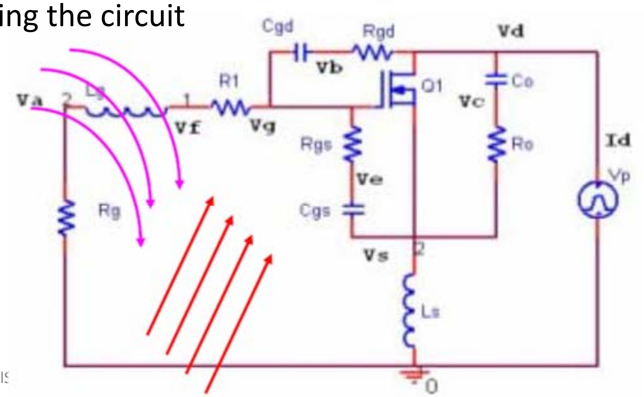
Transmission Lines Fundamentals

Why discussing transmission lines?

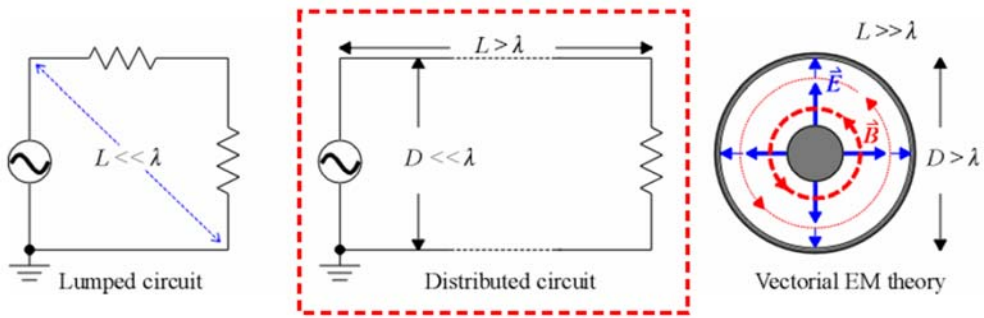
- The rapid development of electronic technology in the 20th century lies on the employment of simple but powerful tool called (lumped) circuit theory to accurately predict the performance of sophisticated electrical circuits.
- Circuit theory considers the effects of **lumped** elements (R, C, L, dependent sources) connected in series and/or parallel, while the conducting wires play no role (space-independent v, i).



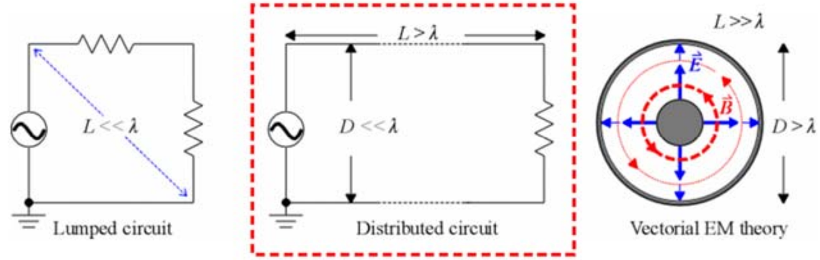
- In fact, elements and wires provide a framework over which electric charges move, setting up electric and magnetic (vector) fields and determining the circuit behaviors.



- A full vector analysis based on Maxwell's equations is most complete.
- The theory of **distributed** circuits (transmission lines) bridges circuit theory and Maxwell's equations.



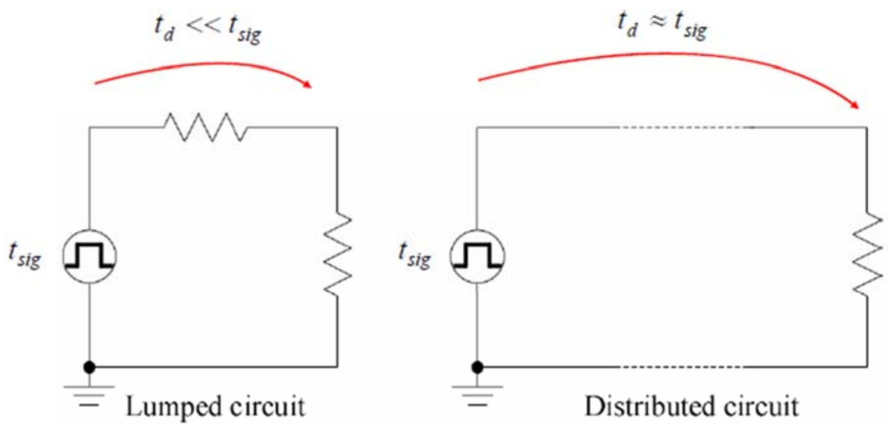
- On the one hand, it can describe some wave properties (wavelength, phase velocity, reflection, …) that are absent in circuit theory but critical in power transmission and current integrated circuits.
- On the other hand, it deals with scalar quantities (v, i) as in circuit theory (but with one extra spatial variable z), free of complicated vector analysis.



Criteria to consider distributed circuits

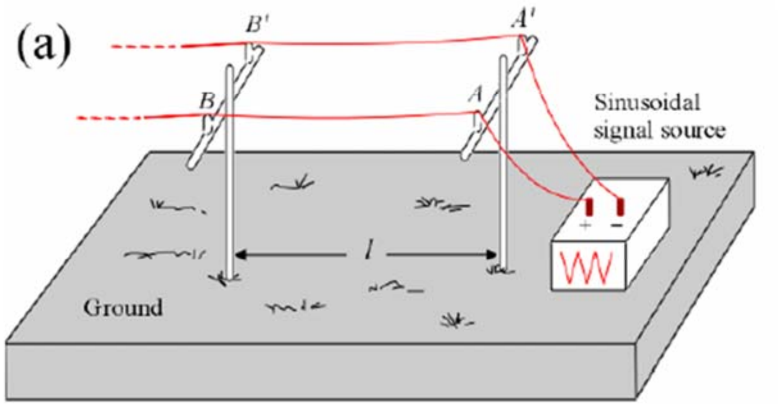
- The central difference between lumped and distributed circuit theories is the latter considers time delay $d\,t$ when signal (v, i) travels from one point to another
- The signal travels with velocity $v = c\ n$, where c is the light velocity in vacuum, n is the refractive index of the medium where EM fields exist.

- Distributed circuit theory matters when t_d is comparable or longer than the t_{sig} "signal time scale".



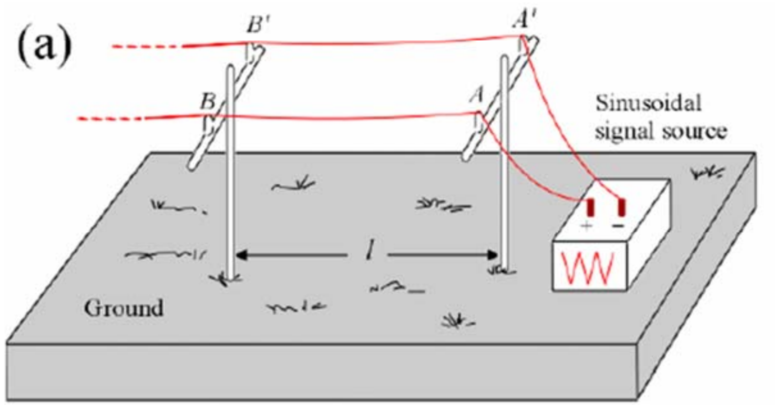
Example

- The Taipower distributes electric power via 60-Hz sinusoidal waves traveling in air (oscillating period T = 1/ 60 sec, $v = c$).
- The source signal $V_{AA'}(t) = V_0 \cos(2\pi \cdot 60 \cdot t)$



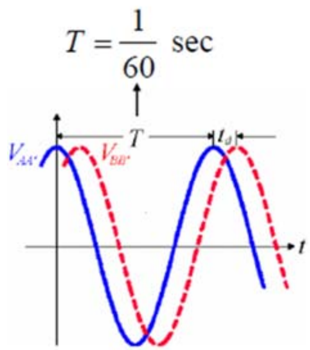
- The load signal $V_{BB'}(t) = V_0 \cos[2\pi \cdot 60 \cdot (t - t_d)]$

$$t_d = l/v$$



- if $t_d > 0.01T$ (rule of thumb), have a "non-negligible" time delay, and (thus lumped circuits model is inadequate)

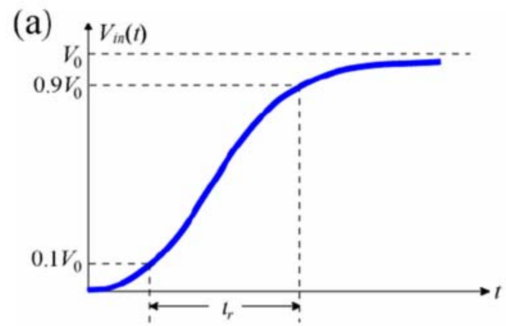
$$t_d = L/V$$
$$t_d > \frac{0.01}{60} = 0.16 \times 10^{-3}$$
$$L = V \times td = 3 \times 10^8 \times 0.16 \times 10^{-3}$$
$$= 48\ km$$



- ⇒ L > 50 km.
- As a result, the operation of the island-wide power system relies on distributed circuit analysis.

Example

- In digital electronic circuits, rise time r t is defined as the duration when the signal changes from 10% to 90% of its final value



- For 1-cm on-chip SiO2 interconnection,

$$V = 0.5\ C$$

$$t_d = \frac{L}{V} = \frac{0.01}{0.5 \times 3 \times 10^8} = 9 = 67\ \times 10^{-12} s = 67\ Ps$$

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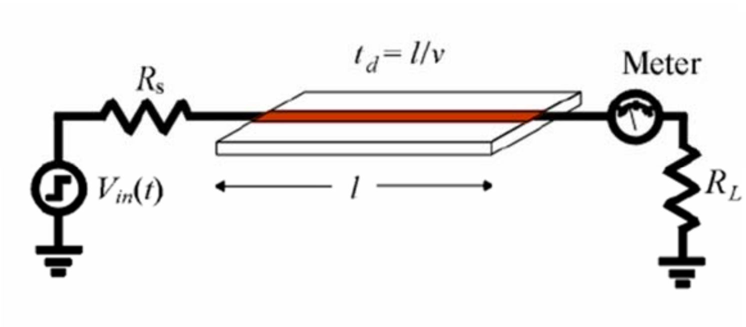

- The source and load signals have a “non-negligible” time delay if ((rule of thumb).)

$$t_r < 2.5\ td\ \cong 167\ Ps$$

- Rise time of CMOS transistors can be as fast as 100 ps, where distributed circuit theory is required