PART 2 – Fundamental Concepts

Signal Integrity (SI), Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC)

References

- [1] C. R. Paul, "Introduction to electromagnetic compatibility", John-Wiley & Sons, 1992. – For good theoretical coverage of electromagnetic principle and in-depth discussion of electromagnetic compatability (EMC) design. (2nd edition 2006 is available)
- [2] H. W. Johnson, M. Graham, "High-speed digital design – A handbook of black magic", Prentice-Hall, 1993. – A classic and practical book referred to by practitioners of high-speed digital design, includes discussion on printed circuit board layout.
- [3] S. Ramo, J.R. Whinnery, T.D. Van Duzer, "Field and waves in communication electronics" 3rd edition, 1994 John-Wiley & Sons. – A more in-depth coverage of electromagnetic theory, wave propagation, relationship between circuit and field theory.
- [4] L. Besser, R. Gilmore, "Practical RF circuit design for modern wireless systems – Volume 1, Passive circuits and systems", Artech House, 2003. – A special chapter is dedicated to the similarities and differences of RF and high-speed digital designs.
- [5] T. Granberg, "Handbook of digital techniques for high-speed design", Prentice-Hall, 2004. – Lots of detail on state-of-the-art signaling technologies.

Other references:

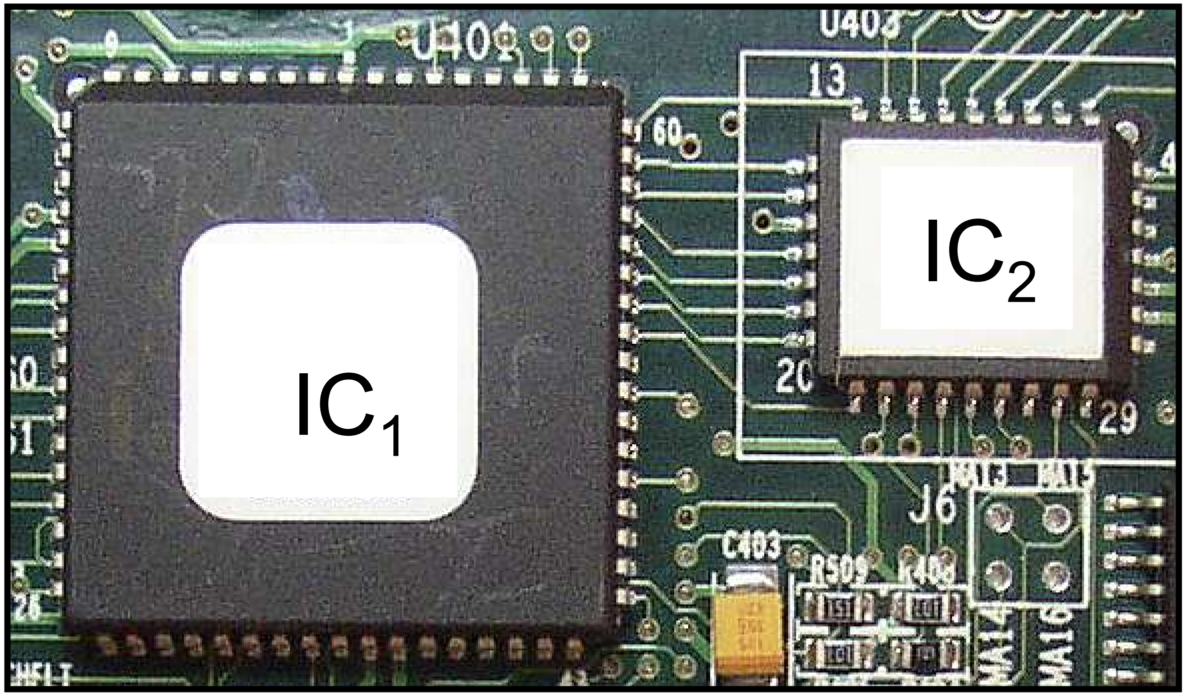
•E. Bogatin, "Signal integrity – simplified", Prentice-Hall, 2003.

•D. Brooks, "Signal integrity issues and printed circuit board design" , Prentice-Hall, 2003.

2.1 – Problem Statement

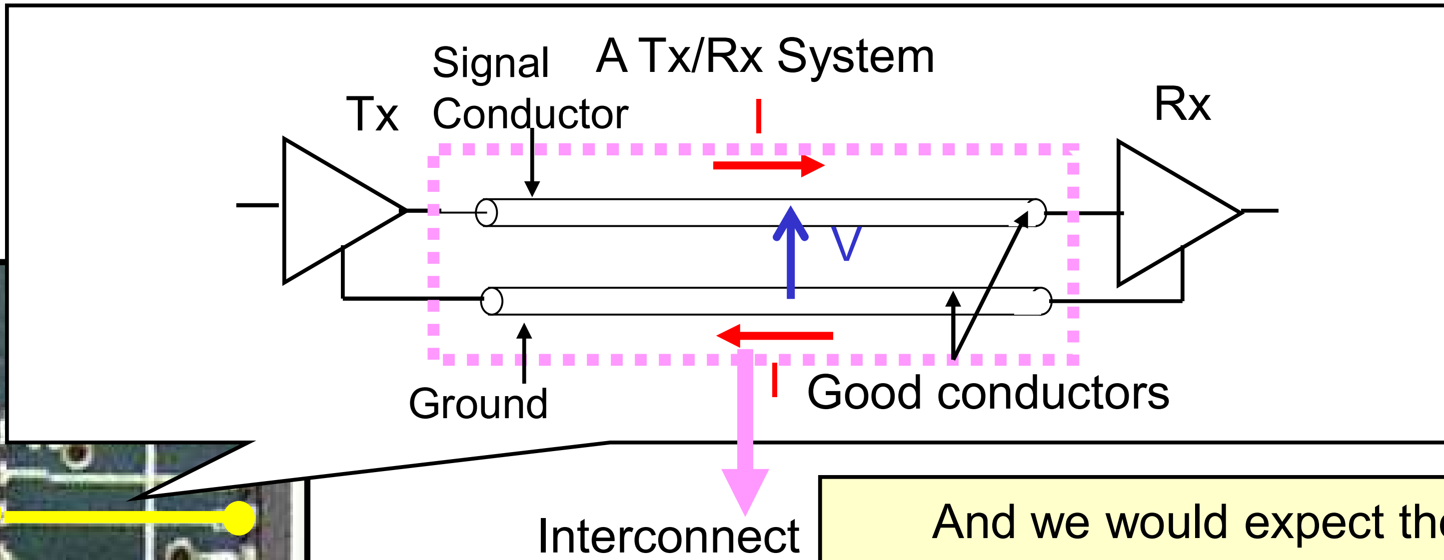
Example 1.1 - Transmit and Receive System

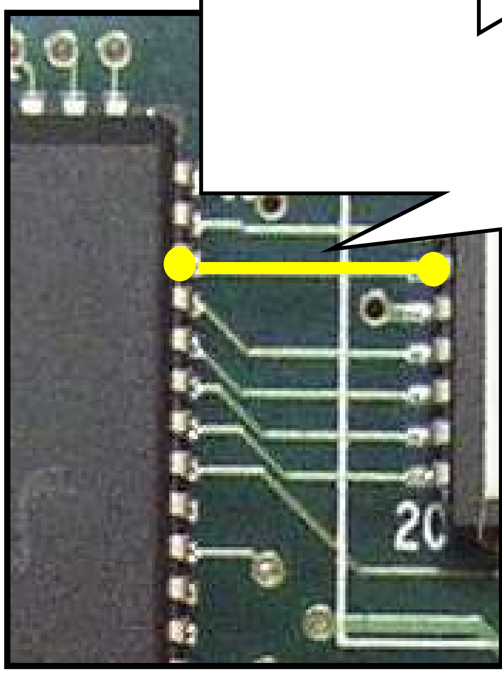
- Consider a simple case of two integrated circuits (ICs) being connected by conducting traces on a PCB.
- Binary digital data is being send between the ICs.



Example 1.1 Cont…

- Each trace connecting two pins is considered as a transmit (Tx) and receive (Rx) system, a single-ended system to be exact for this example.

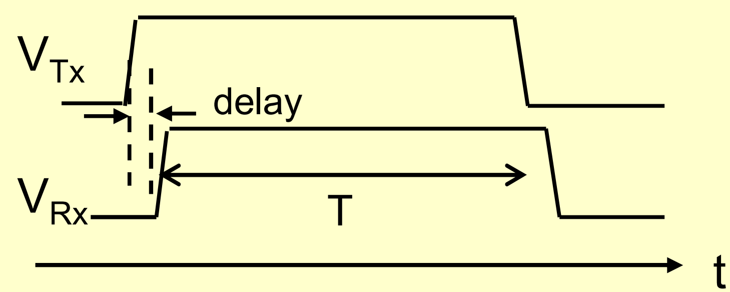




T = Unit interval or pulse width

1/T = bit-rate

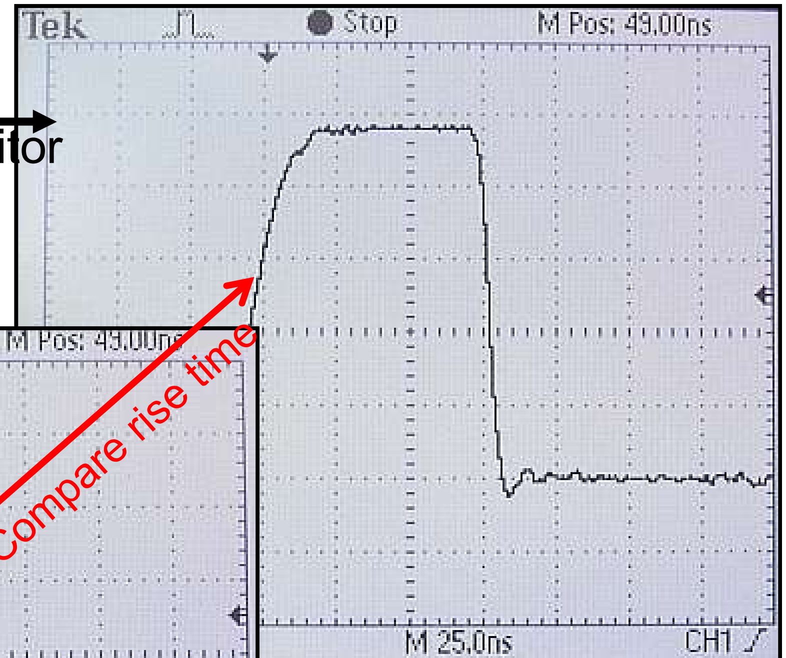
And we would expect the following voltage waveforms…



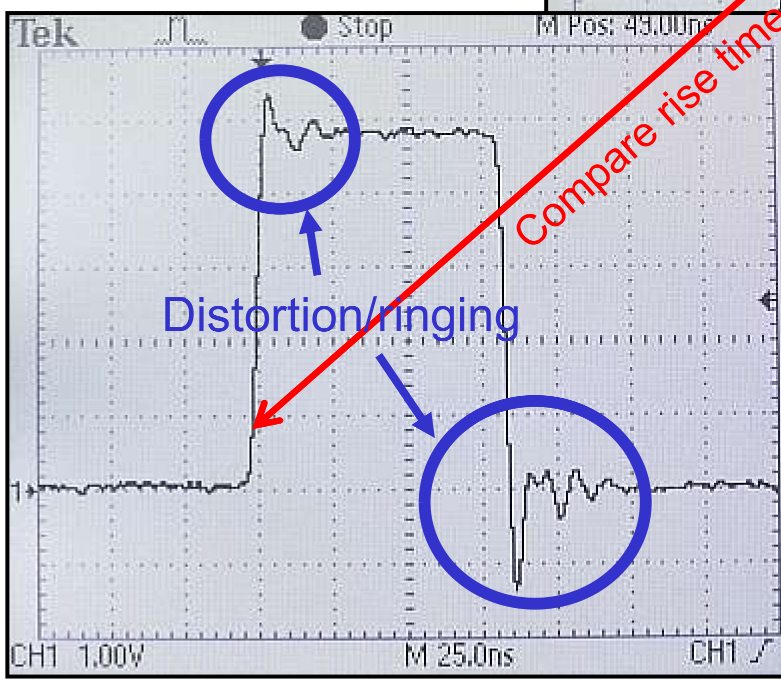
Example 1.1 Cont…

- However things does not always turn up as expected.
- At low bit-rate or slew-rate:

Slew rate is reduced by adding a 22pF capacitor on the driver pin



- At higher slew-rate:

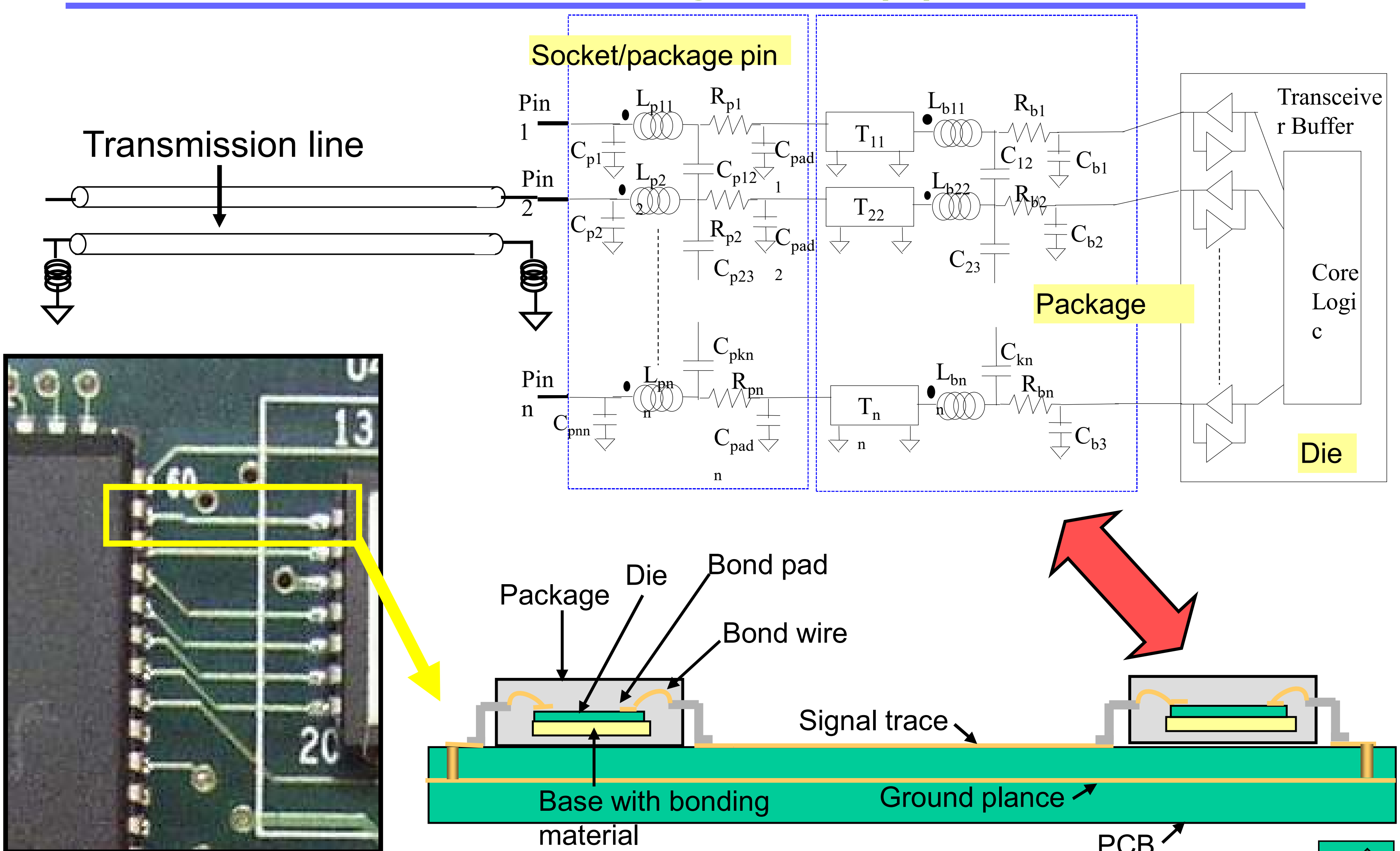


Voltage measured across a copper trace and GND plane via high bandwidth passive probe.

Example 1.1 Cont…

- The distortion of the signal waveform is due to a number of causes.
- The presence of stray inductance (L), and capacitance (C) results in storage of electrical energy and subsequent release into the circuits, which may cause damped oscillation of the voltage observed.
- The parasitic RLC occurs due to the nature of electrical current flow and the interaction of the EM fields with the electric charge.
- The 'obstacle' encountered by the electrical charges from the semiconductor die to the package pin, propagation or transmission line effect on the trace, coupling or interference to adjacent conductors and even radiation from the conducting trace.
- Typically the longer the physical length of the trace and the higher the frequency, the more severe will be the distortion to the electrical signal waveform.
- We will discuss this more thoroughly in **Part 3**.

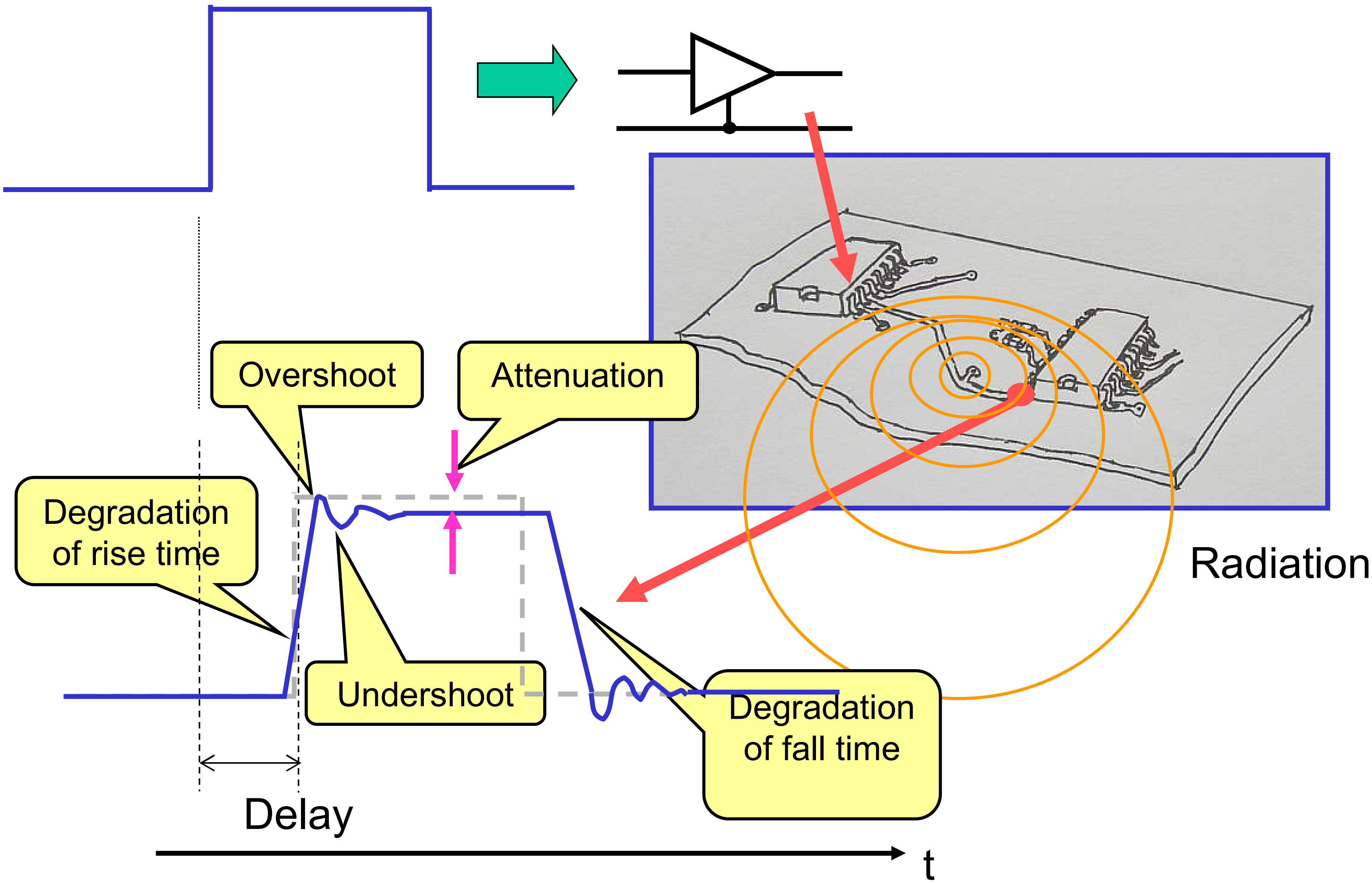
A More Realistic Model for Transmit and Receive System (1)



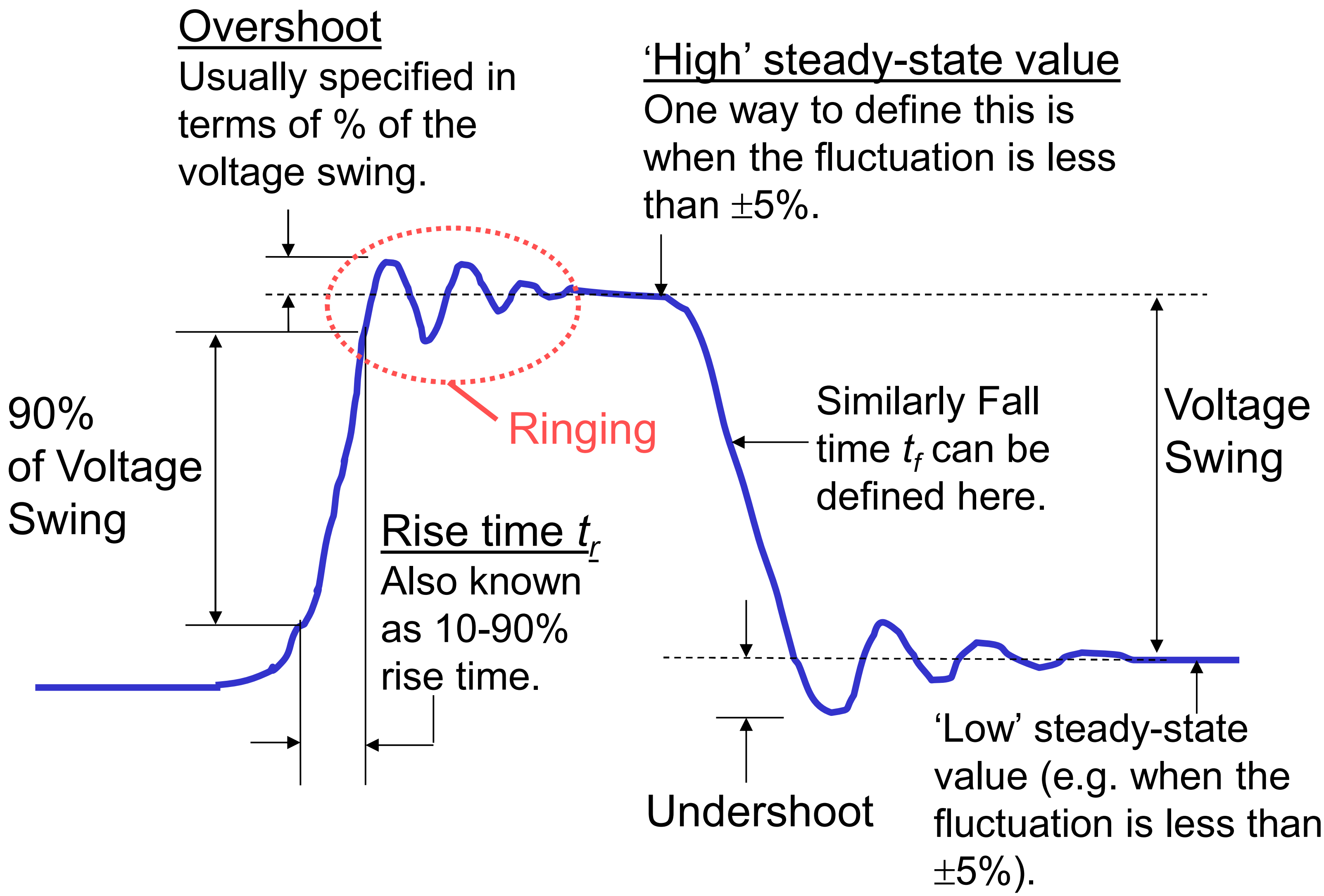
A More Realistic Model for Transmit and Receive System (2)

- The parasitic L, C and R elements are very small, in terms of nH, pF and mΩ.
- At low operating frequency their effect to electrical signals can be safely ignored.
- Thus we do not have much of an issue at low frequency from interconnection.

Distortion of Digital Signal Waveforms

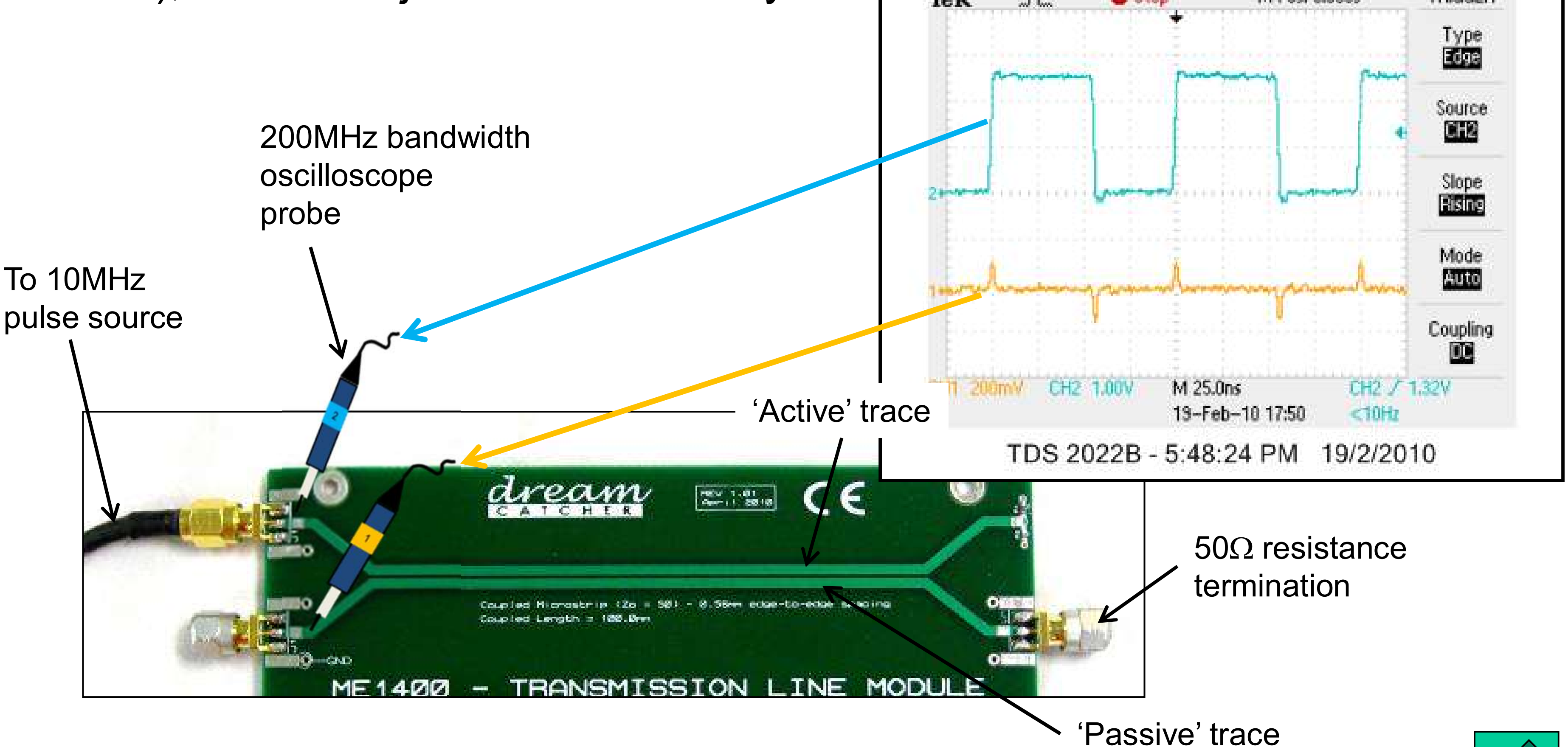


Characterization of Practical Digital Signal Waveforms



Example 1.2 - Electromagnetic Interference

- As another example consider the PCB below with two parallel traces.
- Here a pulse source is driving a PCB trace (this is actually a microstrip line), with an adjacent trace nearby.



Example 1.2 Cont…

- We observe that voltages appear on both ends of the adjacent trace when the signal on the 'active' trace changes from low-to-high and high-to-low.
- The voltages that appear on the adjacent trace is due to a phenomena known as electromagnetic interference (EMI). Energy is coupled from one conductor to another by the action of electromagnetic fields.
- This will be elaborated later in this part and also in **Part 3**.

PCB Design Considerations (1)

- From these two examples, we can imagine the issues facing the circuit and board designers for a complex and compact digital PCB with tens of different components, hundred of traces and many conducting layers.
- Here we only illustrate signal propagation effect and EM field coupling. There are also other mechanisms of EMI such as radiation coupling, impedance coupling etc.
- Thus the possibility of a prototype failure to work properly for is high.
- Proper design techniques and good understanding of interference model is required to ensure the smooth transition from circuit design to first prototype and final product.
- Good understandings of electromagnetic (EM) principles, circuit theories, signal analysis, analog and digital electronics are needed.

PCB Design Considerations (2)

- Analog and digital simulation tools are used to verify system performance in terms of signal integrity, noise margin, interconnection bandwidth, bit-error rate during circuit design and PCB layout to ensure first-time-working prototypes, or at least cut down on design iteration cycles and save cost/time!
- Typical simulation tools are circuit and electromagnetic field simulators.
- To successfully utilize simulation tools, good electrical models will also have to be derived for various PCB structures.

High-Speed PCB Design Techniques

- Proper component placement, component selection, PCB layout, grounding and fabrication approaches can help to reduce the distortion, or 'damage' to the integrity of the signal, through propagation effects and electromagnetic interference.
- **These approaches are collectively called High-Speed or High-Frequency PCB Design Techniques** (again to emphasize that we will define what is high-speed later in this part)**.**
- Here we will not focus much on the IC/component package design and circuit design techniques.

This is usually called High-speed digital design

2.2 – Review of Sinusoidal Signal, Phasor and Wave

Sinusoidal Periodic Signal – Magnitude, Frequency and Phase (1)

- In engineering we usually deal with periodic signals that changes with time in a sinusoidal fashion. This is because many non-sinusoidal signals can be expressed as a combination of sinusoidal components by the use of Fourier Series (for periodic signal) and Fourier Transform (for non-periodic signal).
- Consider a periodic sinusoidal voltage signal $v_1(t)$:

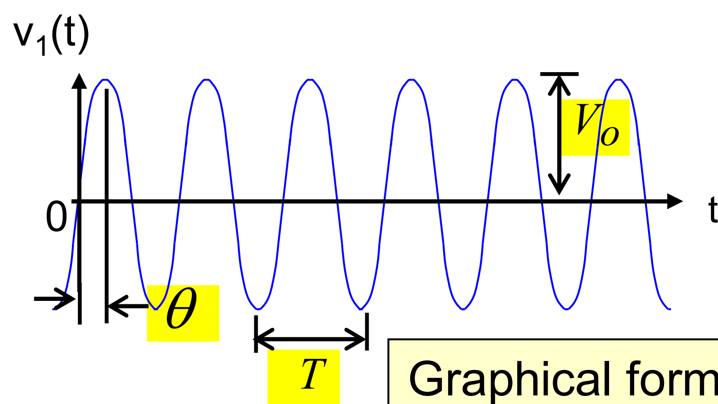
Frequency (radian/sec)

$$v_1(t) = V_o \cos(\underbrace{\omega t + \theta}_{\text{Phase (radian)}})$$

Magnitude (volts)

Excess Phase

Expression form (function of time *t*)



Graphical form

Sinusoidal Periodic Signal – Magnitude, Frequency and Phase (2)

Extra

- Thus we see that 3 parameters are needed to sufficiently describe a sinusoidal signal – frequency (f), magnitude (V_o) and excess phase (θ) (sometimes also called the phase shift).
- Of these, the magnitude and excess phase usually carry more information about the signal.
- In most linear system, if the source frequency is f_o, then we know that the frequency everywhere in the system will also be f_o. However the magnitude and excess phase of the voltage and current signals can vary from point to point.
- This prompt the introduction of a more compact representation of sinusoidal signals without f, called the voltage and current phasors.
- Whenever there is no ambiguity, it is a usual practice to refer the excess phase as the phase of the signal.

Extra

Phasor (1)

- A sinusoidal signal can be expressed in complex exponent form:

$e^{j\alpha} = \cos\alpha + j\sin\alpha$

Euler's formula $j = \sqrt{-1}$

$$\xrightarrow{\alpha = \omega t + \theta} \quad V_o e^{j(\omega t+\theta)} = \underbrace{V_o \cos(\omega t + \theta)}_{\text{Real}} + \underbrace{jV_o \sin(\omega t + \theta)}_{\text{Imaginary}}$$

- Thus $v_1(t) = V_o \cos(\omega t + \theta)$ can be written as:

Both can depend on frequency ω

$$v_1(t) = \mathrm{Re}\left\{V_o e^{j(\omega t+\theta)}\right\} = \mathrm{Re}\left\{V_o e^{j\theta} e^{j\omega t}\right\} \Leftrightarrow V_1(\omega) = \boxed{V_o e^{j\theta}}$$

Phasor

Take magnitude and excess phase, form complex exponent, which we call Phasor.

- The term $V_1 = V_o e^{j\theta}$ is called the phasor, or the time-harmonic form.
- As a convention we normally use small letter to represent time-domain signal, and the capital letter to represent the phasor.

$$\underset{\text{signal}}{v_1(t)} \rightleftarrows \underset{\text{phasor}}{V_1(\omega)}$$

Example 2.1

Extra

- Given a phasor, we can obtain the time-domain form as follows:
  - Multiply the phasor with $e^{j\omega t}$.
  - Take the real part of the product.
- To get back the time-domain form from a phasor, we just reverse the process.
- Example:

Time-domain form of a current

$$i(t) = 0.25\cos\left(2\pi\left(2.0\times10^{6}\right)t + 0.125\pi\right)$$

$$f = 2.0\times10^{6} = 2\,MHz \qquad \theta = 0.125\pi$$

Phasor $I = 0.25e^{j0.125\pi}$

To get back the time-domain form

$$i(t) = \mathrm{Re}\left\{ Ie^{j2\pi\left(2.0\times10^{6}\right)t} \right\}$$

$$= 0.25\cos\left(2\pi\left(2.0\times10^{6}\right)t + 0.125\pi\right)$$

Wave Function (1)

Extra

- We have seen that using the concept of phasor a sinusoidal voltage waveform can be represented as follows:

$$v(t) = V_o \cos(\omega t + \theta) \iff \mathrm{V} = V_o e^{j\theta}$$

- Generally the amplitude and phase depend on frequency. This describes a waveform typically found in electronic circuits.

$$v(t,\omega) = V_o(\omega)\cos(\omega t + \theta(\omega)) \iff \mathrm{V}(\omega) = V_o(\omega)e^{j\theta(\omega)}$$

- We can generalize the expression of sinusoidal even further, by letting the phase θ depends on position:

$$v(t,\omega,z) = V_o(\omega)\cos(\omega t + \theta(\omega,z)) \iff \mathrm{V}(\omega,z) = V_o(\omega)e^{j\theta(\omega,z)}$$

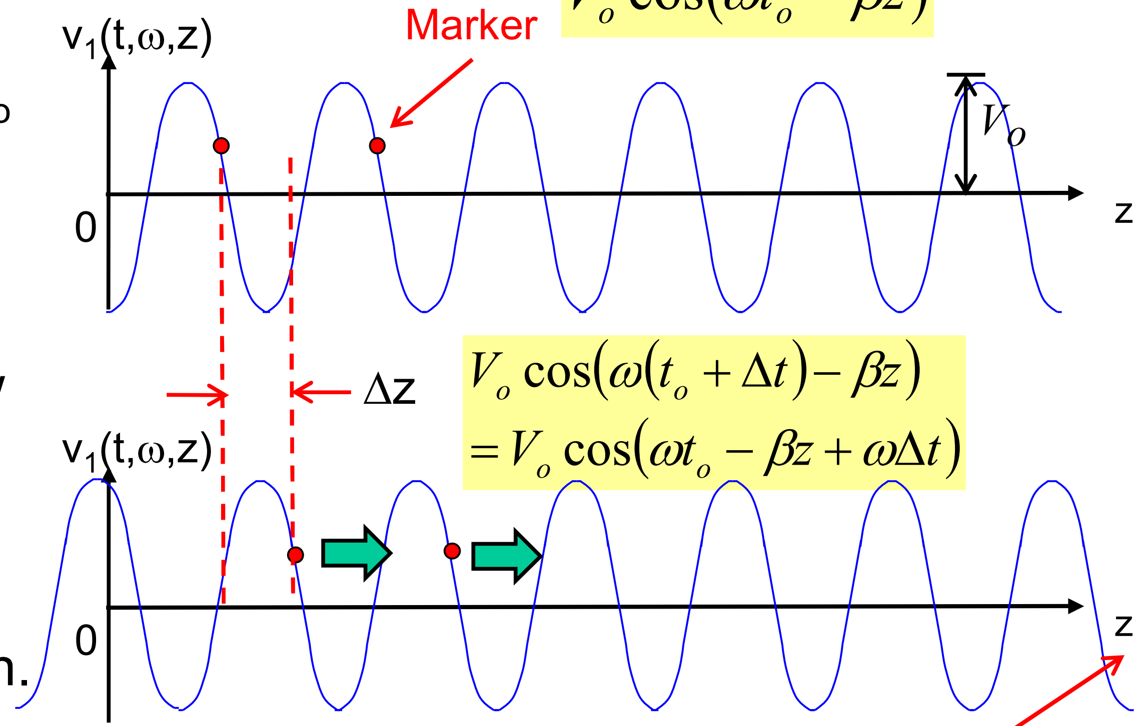
- The third form, for $v(t, \omega, z)$ or $\mathrm{V}(\omega, z)$, is called a Wave Function, as physically it describes a traveling sinusoidal voltage wave along the z direction in space.

Extra

Wave Function (2)

- Consider a wave function given by: $v_1(t,\omega,z) = V_o \cos(\omega t - \beta z)$
- Here $\theta = -\beta z$ and the waveform on z-axis at t = t_o is plotted below.

$$V_o \cos(\omega t_o - \beta z)$$



$$V_o \cos(\omega(t_o + \Delta t) - \beta z)$$
$$= V_o \cos(\omega t_o - \beta z + \omega \Delta t)$$

- As time increases, the new plot is shown on the right:
- The effect is the waveform moves towards +z direction.
- Using marker and measuring the distance Δz moved, the velocity to is:

$$v_p = \frac{\Delta z}{\Delta t} = \frac{\omega}{\beta}$$

Take note, position NOT time!!!

Wave Function (3)

Extra

- Hence we can conclude that:

$$v(t,\omega,z) = V_o(\omega)\cos\left(\omega t \boxed{- \beta z + \theta_o}\right) \Leftrightarrow \mathrm{V}(\omega,z) = V_o(\omega)e^{-j\beta z}e^{j\theta_o}$$

Describes a waveform that travel in +z direction

The excess phase

- Similarly it is easy to show that:

$$v(t,\omega,z) = V_o(\omega)\cos(\omega t + \beta z + \theta_o) \Leftrightarrow \mathrm{V}(\omega,z) = V_o(\omega)e^{j\beta z}e^{j\theta_o}$$

Describes a waveform that travel in -z direction

- With propagation velocity: $v_p = \frac{\omega}{\beta}$
- The difference between a normal phasor and a phasor for wave function is in the latter, the complex exponent depends on position (*z* in this example).

$$V(\omega) = V_o e^{j\theta}$$

Normal phasor

$$\mathrm{V}(z,\omega) = V_o e^{j\theta}e^{-j\beta z}$$

Wave function phasor

Extra

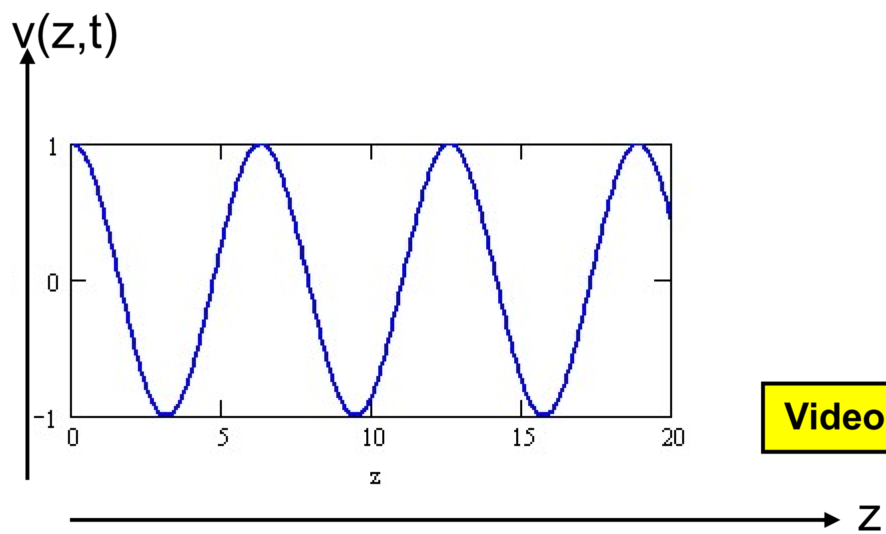
Wave Function (4)

- A sinusoidal wave function example:

$$v(z,t) = V_o \cos\left(2\pi f t - \beta z\right)$$

A sinusoidal wave

$$f = 1.0\text{MHz}\,,\ \ \beta = 1$$



Video

Phase Velocity: $v_p = \frac{\omega}{\beta} = \frac{2\pi f}{\beta}$

wavelength $\lambda = \frac{2\pi}{\beta}$

2.3 – Review of Field Theory and Circuit Theory

Electric Charge and Electromagnetic Fields (1)

- Fundamental to the principle of electric and electronic engineering is the concept of electric charge (q), henceforth called the charge.
- As we have learnt, charge interact with each other via two fundamental forces, electric force and magnetic force.
- Instead of using force, it is more convenient to use the concept of electric field (**E**) and magnetic field (**H**).

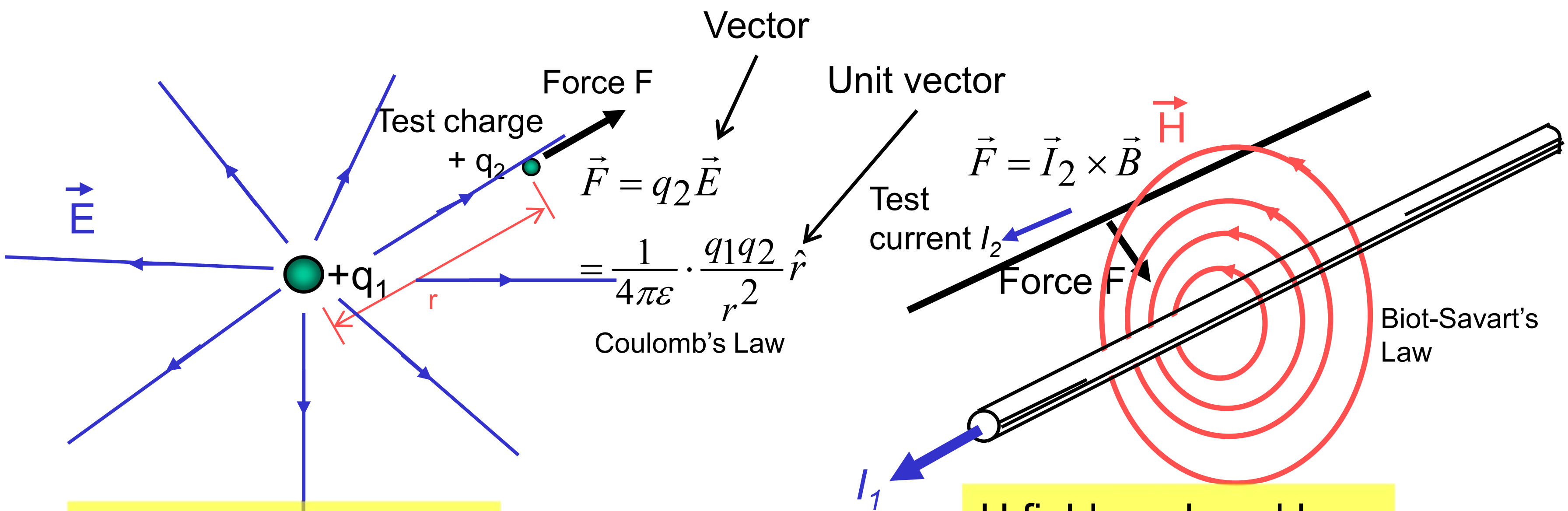
Bold means vector

- A charge creates an **E** field in it's surrounding. Any nearby charge in this **E** field will experience an electric force.
- Similarly a <u>moving</u> charge, which constitute an electric current (I), creates a **H** field in it's surrounding. This **H** field will cause a magnetic force on another <u>moving</u> charge or current.
- Collectively we called the **E** and **H** fields the electromagnetic (EM) fields.

Partial Key Concepts:
- An electric charge cause **E** field, which affect another charge.
- An electric current causes **H** field, which ONLY affect another current.
- Thus charge affects each other via EM fields.

Electric Charge and Electromagnetic Fields (2)

- The following are some diagrams to refresh our memory:



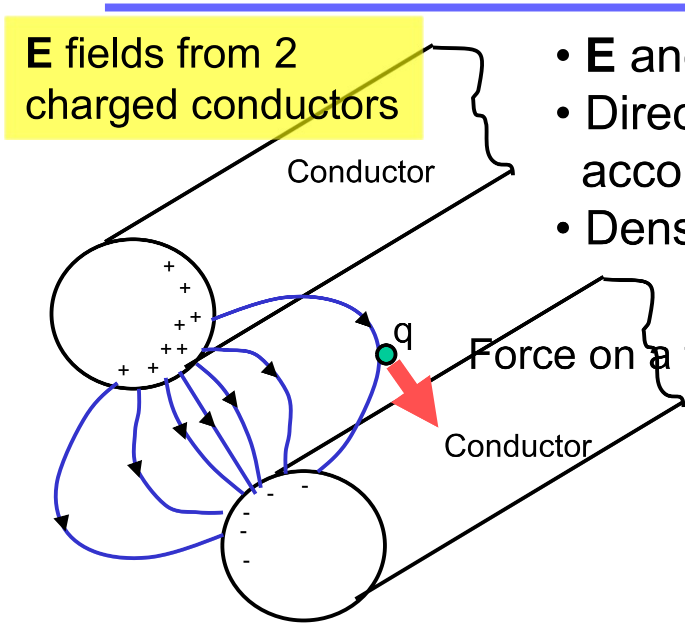
E field produced by a point charge q_1

H field produced by a current I_1

*Actually the magnetic field is **B = µH**, **H** is called the magnetization. However here we prefer to use **H** to refer to the magnetic field.

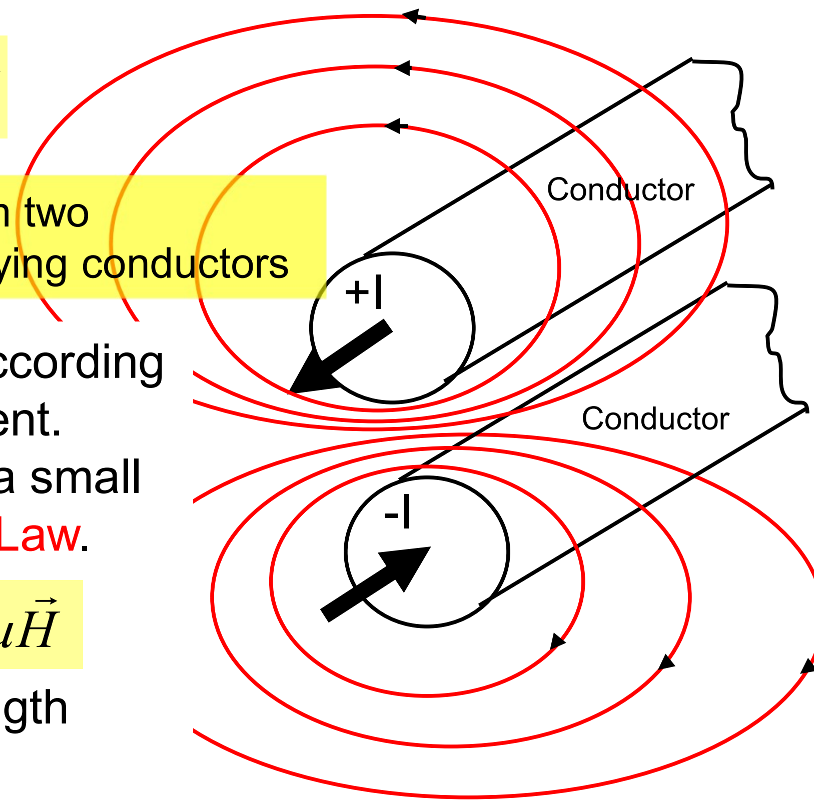
Key Concepts:
- To detect an **E** field we use an electric charge.
- To detect **H** field we use a current loop

Electric Charge and Electromagnetic Fields (3)



$$\vec{F} = \frac{1}{4\pi\varepsilon_o} \cdot \frac{Qq}{r^2}\hat{r}$$

- **E** and **H** fields obey superposition principle.
- Direction indicates force experienced by a small test charge according to Coulomb's Force Law.
- Density of the field lines corresponds to strength of the field.



- **H** or **B** fields, by convention is directed according to the right-hand rule with respect to current.
- Direction indicates force experienced by a small test current according to Lorentz's Force Law.

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right) \qquad \vec{B} = \mu\vec{H}$$

- Density of field lines corresponds to strength of the field.

Electric Charge and Electromagnetic Fields (4)

- In addition to electric charge causing **E** field and moving charge causing **H** field, magnetic field **H** can also be generated (or induced) by time-varying **E** fields (i.e. an **E** field whose direction and magnitude varies with time).
- Similarly **E** field can also be induced by time-varying **H** fields.

Key Concepts – How charge, E and H fields interact:
- An electric charge causes **E** field, which ONLY affect another charge.
- An electric current causes **H** field, which ONLY affect another current.
- **E** field can also be generated when **H** field changes with time.
- **H** field can also be generated when **E** field changes with time.
- Charge affects each other via EM fields.

- As far as we know, the above physical phenomena are Laws of Nature, and can be expressed mathematically as the Maxwell's Equations.
- We have studied this in subjects related to Electromagnetism during our undergraduate days, for instance see [3].

Maxwell Equations (Linear Medium) - Time-Domain Form (1)

Extra

Faraday's law

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

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial}{\partial t}\vec{D}$$

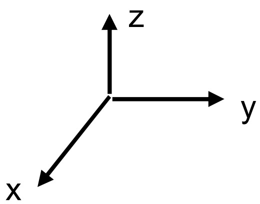
Modified Ampere's law

$$\nabla \cdot \vec{D} = \rho_v$$

Gauss's law

$$\nabla \cdot \vec{B} = 0$$

No name, but can be called Gauss's law for magnetic field



Each parameter depends on 4 independent variables

Where:

$$\vec{E} = E_x(x,y,z,t)\hat{x} + E_y(x,y,z,t)\hat{y} + E_z(x,y,z,t)\hat{z}$$

$$\vec{H} = H_x(x,y,z,t)\hat{x} + H_y(x,y,z,t)\hat{y} + H_z(x,y,z,t)\hat{z}$$

$$\vec{J} = J_x(x,y,z,t)\hat{x} + J_y(x,y,z,t)\hat{y} + J_z(x,y,z,t)\hat{z}$$

$$\rho_v = \rho_v(x,y,z,t)$$

Unit vector in x-direction

x component

- **E** – Electric field intensity
- **H** – Auxiliary magnetic field
- **D** – Electric flux
- **B** – Magnetic field intensity
- **J** – Current density
- ρ_v – Volume charge density
- ε_o – permittivity of free space ($\cong 8.85412 \times 10^{-12}$)
- μ_o – permeability of free space ($4\pi \times 10^{-7}$)
- ε_r – relative permittivity
- μ_r – relative permeability

Constitutive relations

$$\boxed{\begin{array}{ll} \vec{B} = \mu\vec{H} & \vec{D} = \varepsilon\vec{E} \\ \mu = \mu_o\mu_r & \varepsilon = \varepsilon_o\varepsilon_r \end{array}}$$

For linear medium

Maxwell Equations (Linear Medium) - Time-Domain Form (2)

Extra

- Maxwell Equations as shown are actually a collection of 4 partial differential equations (PDE) that describe the physical relationship between electromagnetic (EM) fields, current and electric charge.
- The Del operator ∇ is a shorthand for three-dimensional (3D) differentiation:

$$\nabla = \left(\frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y} + \frac{\partial}{\partial z}\hat{z}\right)$$

- For instance consider the 1st and 3rd Maxwell Equations:

Curl

$$\nabla \times \tilde{E} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{vmatrix} = \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right)\hat{x} + \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right)\hat{y} + \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right)\hat{z}$$

$$= -\frac{\partial}{\partial t}\left(B_x x + B_y \hat{y} + B_z \hat{z}\right)$$

Gradient

$$\nabla F = \frac{\partial F}{\partial x}\hat{x} + \frac{\partial F}{\partial y}\hat{y} + \frac{\partial F}{\partial z}\hat{z}$$

$$\nabla \cdot \tilde{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = \frac{\rho}{\varepsilon}$$

Divergence

To truly understands this subject, and also RF/Microwave circuit design, one needs to have a strong grasp of Electromagnetism (EM). Read references [1], [3] or any good book on EM.

Maxwell Equations (Linear Medium) - Time-Harmonic Form (1)

Extra

- For sinusoidal variations with time t, we substitute the phasors for **E**, **H**, **J** and ρ into Maxwell's Equations, the result are Maxwell's Equations in time-harmonic form.

$$\frac{\partial}{\partial t} \rightarrow j\omega$$

$$\nabla \times \vec{E} = -j\omega\vec{B}$$

$$\nabla \times \vec{H} = \vec{J} + j\omega\vec{D}$$

$$\nabla \cdot \vec{D} = \rho_V$$

$$\nabla \cdot \vec{B} = 0$$

Each parameter depends on 3 independent variables

Where:

$$\vec{E} = E_X(x,y,z)\hat{x} + E_Y(x,y,z)\hat{y} + E_Z(x,y,z)\hat{z}$$

$$\vec{H} = H_X(x,y,z)\hat{x} + H_Y(x,y,z)\hat{y} + H_Z(x,y,z)\hat{z}$$

$$\vec{J} = J_X(x,y,z)\hat{x} + J_Y(x,y,z)\hat{y} + J_Z(x,y,z)\hat{z}$$

$$\rho_V = \rho_V(x,y,z)$$

E – Electric field intensity
H – Auxiliary magnetic field
D – Electric flux
B – Magnetic field intensity
J – Current density
ρ_V- Volume charge density
ε_o – permittivity of free space ($\cong 8.85412 \times 10^{-12}$)
μ_o – permeability of free space ($4\pi \times 10^{-7}$)
ε_r – relative permittivity
μ_r – relative permeability

Constitutive relations

$$\vec{B} = \mu\vec{H} \qquad \vec{D} = \varepsilon\vec{E}$$

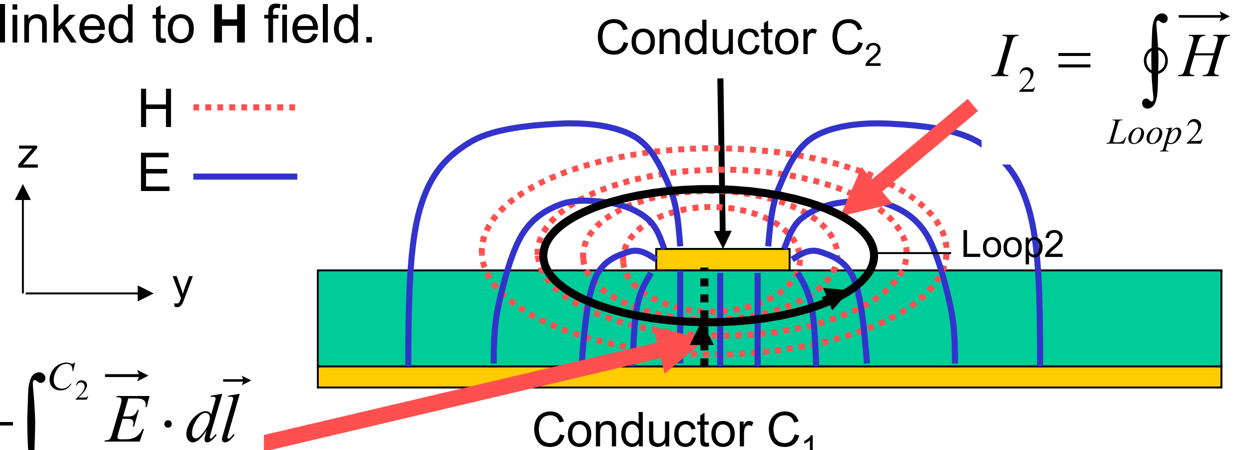
$$\mu = \mu_o\mu_r \qquad \varepsilon = \varepsilon_o\varepsilon_r$$

For linear medium

Electronic System (1)

- **We observe that in order to make our electronic or electrical systems work, we essentially control electric charges.**
- The accumulation and flow of charge run electric motors, actuators, powers electronic displays, transducers, sensors and perform various electronic computations via the operation of diodes and transistors.
- Of course it is difficult to work with charge and EM fields. The EM fields being vectors in 3D, are difficult to measure, visualize and control.
- Thus secondary quantities, like electric potential or voltage (*V*) and electric current (*I*), which are 1D, are introduced. Essentially *V* is linked to **E** field, and *I*, is linked to **H** field.

$$I_2 = \oint_{Loop2} \vec{H} \cdot d\vec{l}$$



Electric potential is the energy needed to bring 1 Coulomb of charge from one location to another.

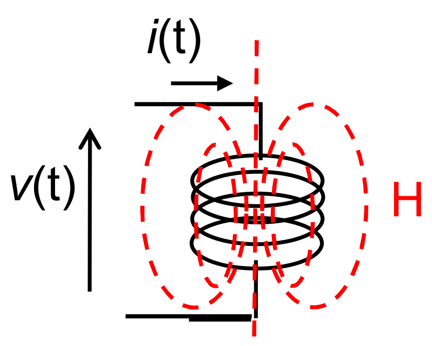
$$V_{21} = -\int_{C_1}^{C_2} \vec{E} \cdot d\vec{l}$$

Electronic System (2)

- We can measure *V* and *I* with oscilloscopes, voltmeter and current probes, and from them infer the relative properties of **E** and **H** field in an electronic system.
- Area with high charge concentration usually have high **E** field intensity, hence high voltage *V*, and vice versa.
- Similarly a conductor with a large current *I* flowing tells us that the surrounding must contain high **H** field intensity, and vice versa.
- For digital and analog electronics, usually it is the voltage *V* at various locations in the circuit which we interpret as our ‘signals’ (NOTE: for RF/microwave circuits typically the signal refers to power).
- Typically voltage changes with time, e.g. *v*(t). Thus there will be constant movement of charge throughout our circuit, e.g. there are currents flowing.

Electronic System (3)

- How do we control the accumulation and flow of charge then?
- We use components like resistor, capacitor, inductor, PN junction, BJT, FET etc., in conjunction with Kirchoff voltage and current laws to control where the charge will flow and accumulate.
- Since it is the EM fields which provide the force to move charge, these components actually control the EM fields and its interaction with charge.
- Example: Consider an inductor, this is a component which concentrate the **H** field, and use it to induce an **E** field by virtue of Faraday's Law. This results in the following V-I relationship:



$$v(t) = L\frac{di(t)}{dt}$$

In a similar manner we see that capacitor is a component which concentrate **E** field and promotes accumulation of charge.

Electronic System (4)

- Some further examples:
- Logic gates and flip-flops – These are solid state switches using PN juctions and FET or BJT, which transfer charge from one location to another location (e.g. an input voltage results in an output voltage along certain direction).

- Amplifiers – This is a collection of resistors, capacitors and BJTs or FETs, such that a small accumulation of charge at one location (e.g. small voltage at the input) results in large accumulation of charge at another location (e.g. large voltage at the output).

Conclusion

- Our present electronic technology depends on controlling THREE fundamental parameters: electric charge and EM fields, subject to Maxwell's Equations.
- Usually it is more convenient to work with V and I, which relate to EM fields.
- By manipulating voltage V and current I at strategic locations in our system, we indirectly control the EM fields and charge behavior in the system, hence making the system functions properly.
- Lumped components such as resistor, capacitor, inductor, diode, BJT, FET, and distributed components such as transmission line are used to 'manipulate' the V and I of the system by linking them up to form electrical circuits.
- This short discussion aims to provide a 'glimpse' of the close relationship between EM fields, charge and circuit quantities such as V, I, R (resistance), L (inductance) and C (capacitance).

Field and Circuit Theory

- The analysis of the interaction between charge and EM fields via Maxwell's Equations is called Field Theory.
- The analysis of the interaction between V, I and related parameters such as R, L, C is called Circuit Theory.
- As this short discussion shows, there is a close relationship between Field Theory and Circuit Theory.

Key Concepts:
- Field Theory and Circuit Theory are closely related.
- It is easier to work with Circuit Theory in system design and analysis, e.g. *V* and *I* versus **E** and **H**.
- However Field Theory provides a more complete description of the system operation.

Field Theory vs Circuit Theory

Extra

- Field Theory is the basic physical laws that describe the interaction between EM fields, electric charges and current.
- Circuit Theory is derived from Field Theory under low-frequency or quasi-static conditions.

$$\boxed{\nabla \times \vec{E} = -j\omega\mu\vec{H}}$$

$$\nabla \times \vec{B} = \mu\vec{J} + j\omega\mu\varepsilon\vec{E}$$

$$\nabla \cdot \boxed{\vec{E}} = \frac{\rho}{\varepsilon}$$

$$\nabla \cdot \boxed{\vec{B}} = 0$$

$$\boxed{\nabla \cdot \vec{J} = -\frac{d\rho}{dt}}$$

Field Theory

Concern with E & H fields, current and charge.

Under Low Frequency (quasi-Static) Approx.

$$\sum_i V_i = 0$$

$$\sum_i I_i = 0$$

$$V_{21} = -\int_{C_1}^{C_2} \vec{E} \cdot d\vec{l}$$

$$I = \oint_{C_1 \text{ or } C_2} \vec{H} \cdot d\vec{l}$$

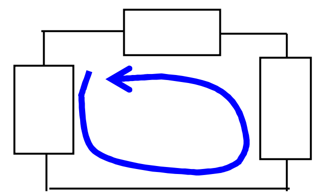
Circuit Theory

Concerns with voltage, current and RLC parameters.

See Chapter 4, book by S. Ramo, J.R. Whinnery, T.D. Van Duzer, "Field and waves in communication electronics". 1994 John-Wiley & Sons.

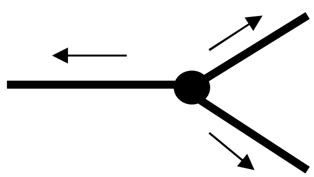
Circuit Theory

- Circuit Theory contains TWO important law, as opposed to the 4 Maxwell's Equations in Field Theory.
- Kirchoff Voltage Law (KVL) - potential difference around a closed loop is 0.

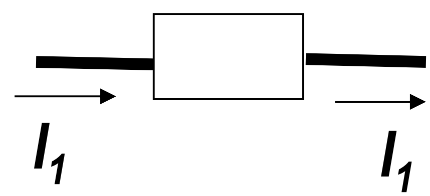


$$\sum_i V_i = 0$$

- Kirchoff Current Law (KCL)- conservation of electric charge, total current from a node is 0.



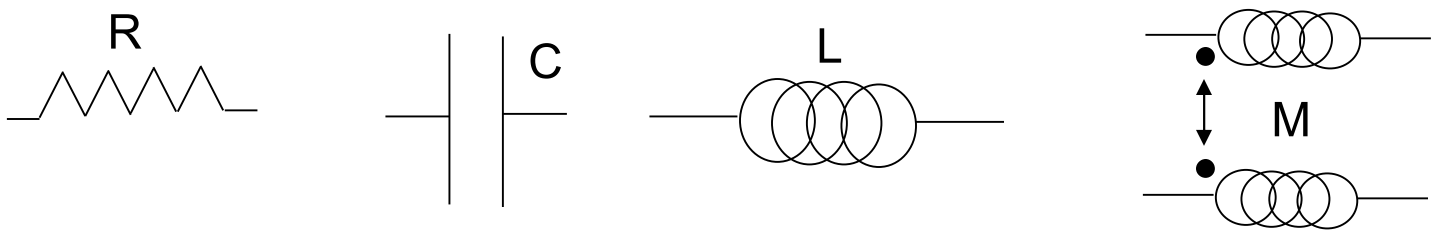
$$\sum_i I_i = 0$$

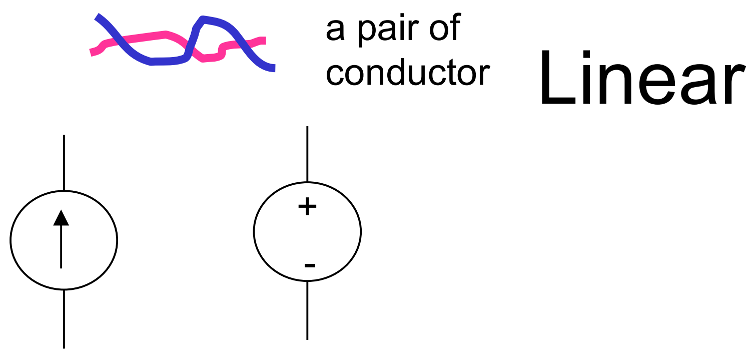


$I_1 = I_2$

2.4 - Lumped Vs Distributed Components

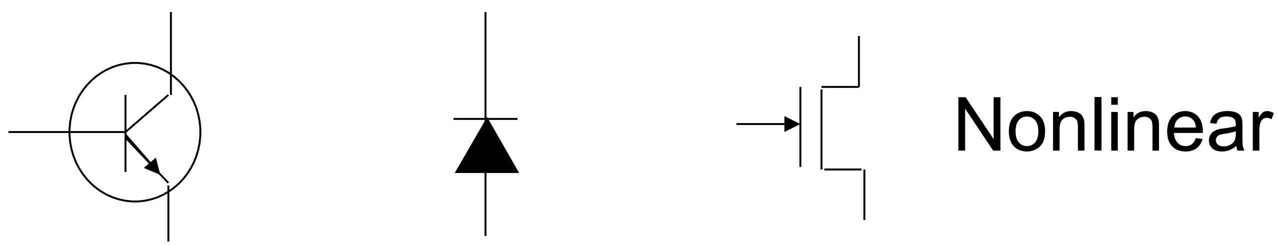
Lumped Elements (1)



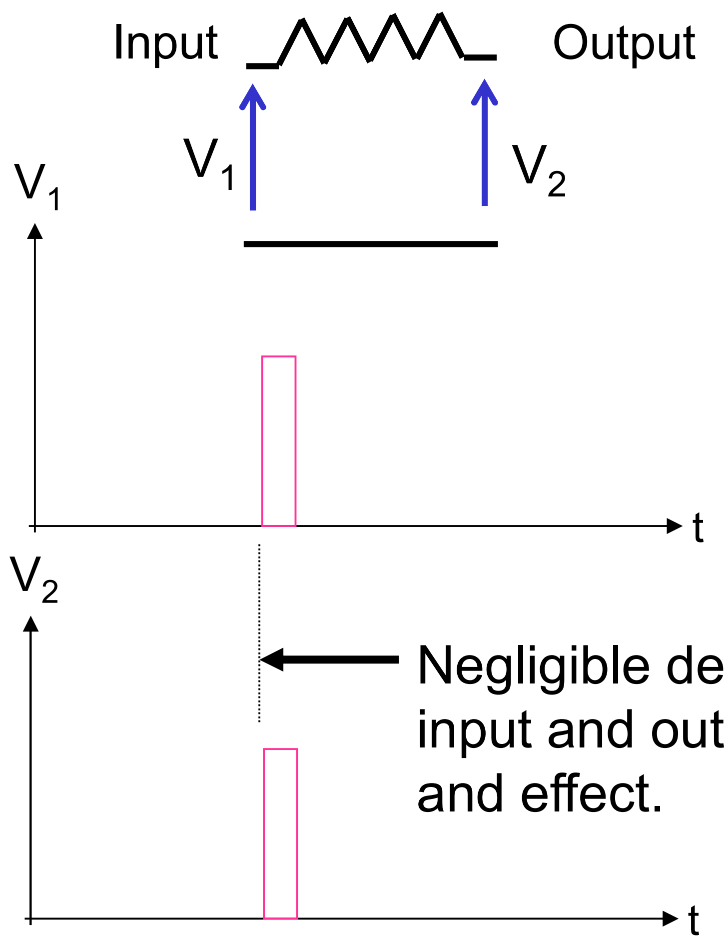


Key characteristics:

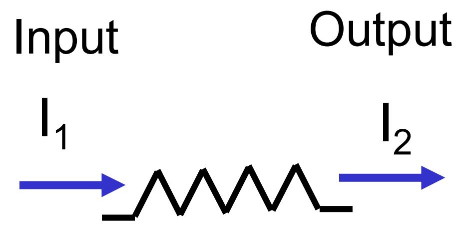
- Elements relates to voltage and current.
- Negligible delay between cause and effect.
- Total input and output current are equal.
- *V* and *I* depend on **time** only.



Lumped Elements (2)



Negligible delay between input and output, e.g. cause and effect.

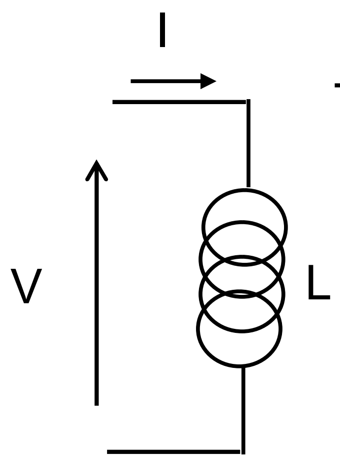


Input and output currents are similar at any instant in time.

Extra

Lumped Elements (3)

- Example of lumped components:

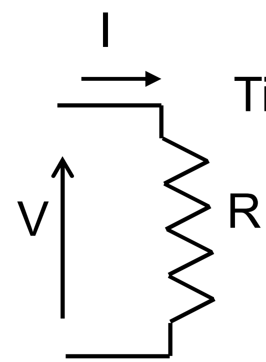


Time-Domain

$$v(t) = L\frac{di(t)}{dt}$$

Frequency -Domain

$$V(\omega) = j\omega L I(\omega)$$

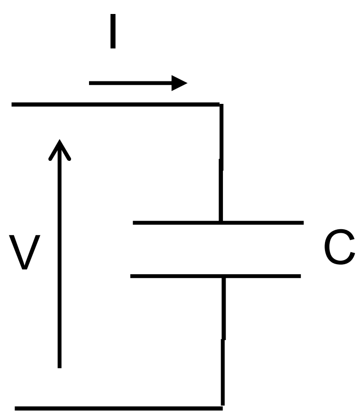


Time-Domain

$$v(t) = Ri(t)$$

Frequency -Domain

$$V(\omega) = RI(\omega)$$



$$v(t) = \frac{1}{C}\int_0^t i(\tau)d\tau$$

or

$$i(t) = C\frac{dv(t)}{dt}$$

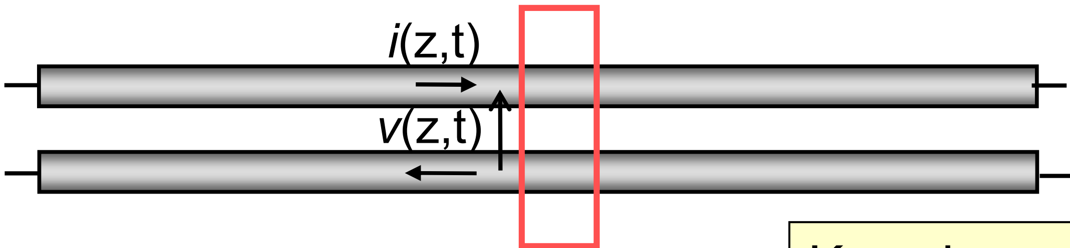
Voltage phasor

Current phasor

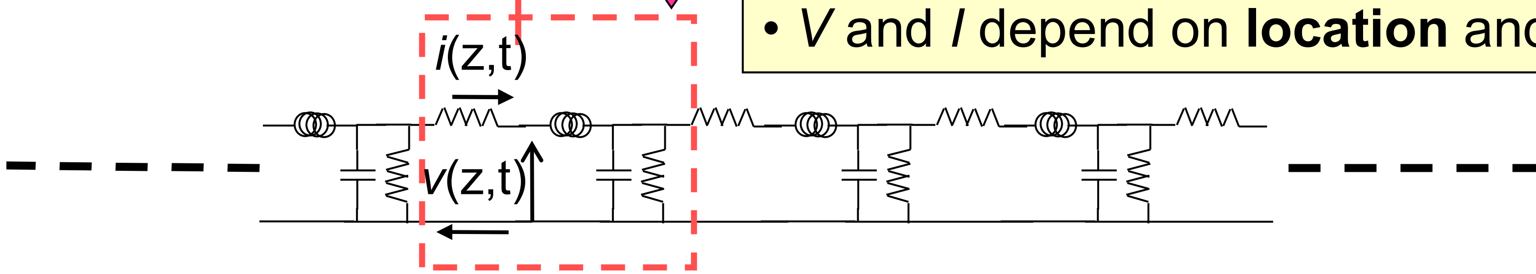
$$V(\omega) = \frac{1}{j\omega C} I(\omega)$$

Make sure you know what
is the 'meaning' of this statement

Distributed Elements (1)

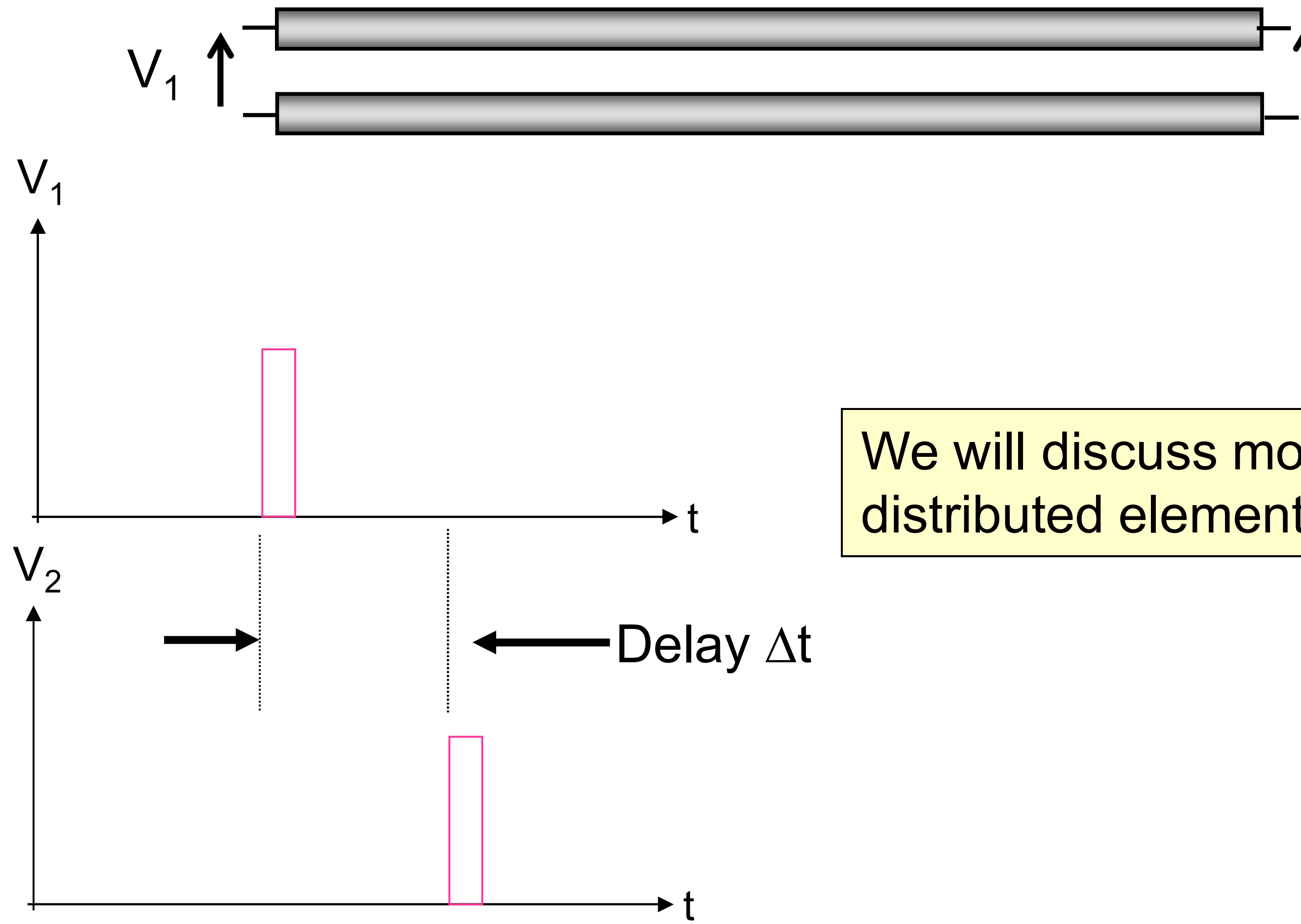


Transmission Line…
- Linear
- Nonlinear



Key characteristics:
- Elements can relate to voltage and current.
- Significant delay between cause and effect.
- *V* and *I* depend on **location** and **time**.

Distributed Elements (2)



We will discuss more about distributed elements in Part 3

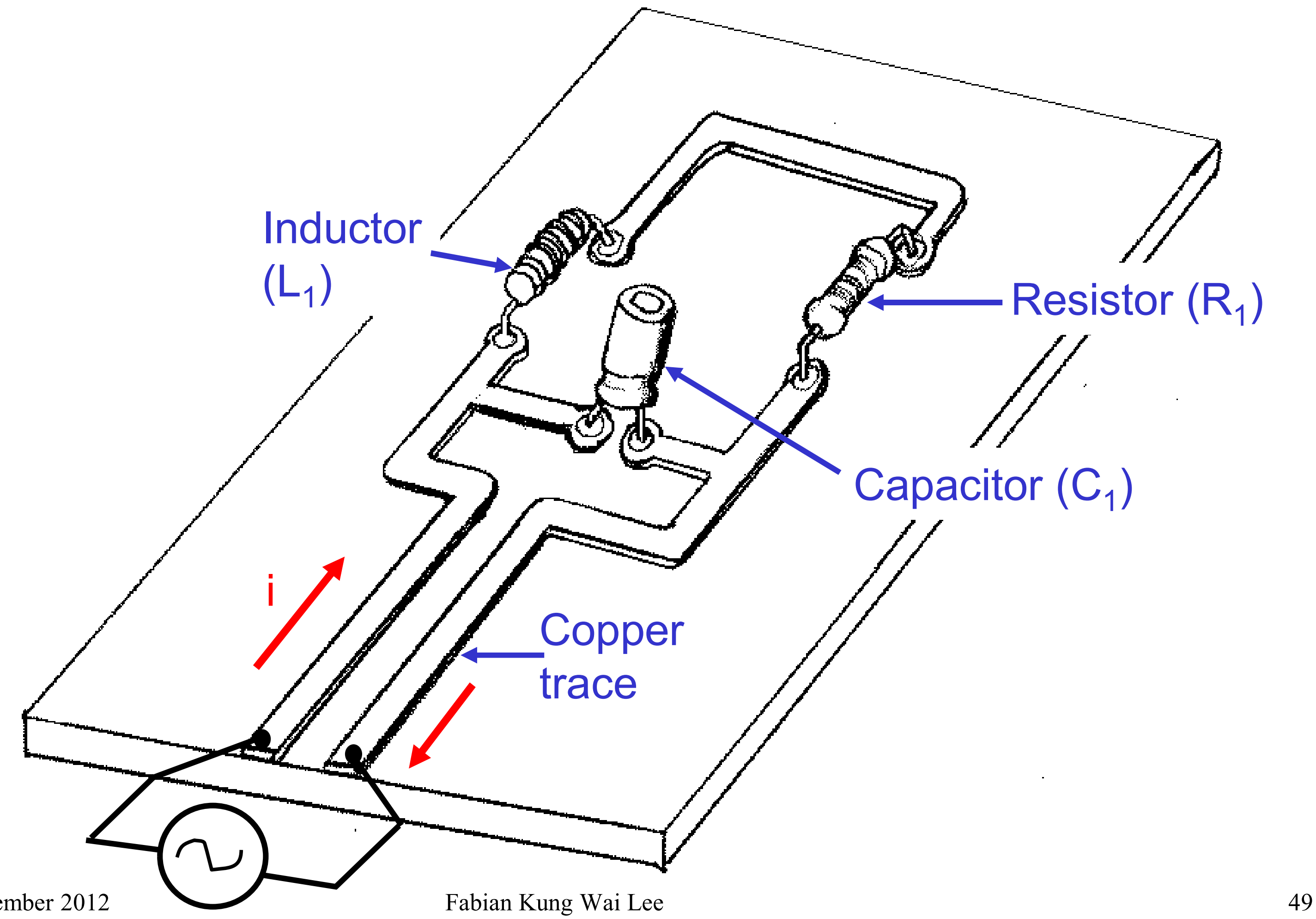
The limit of Lump Circuit

- All real components are distributed by nature, i.e. if you put an input (voltage or current) at one end, the output will only appear after a short delay.
- In cases where the delay is negligible, we can consider the component to be lumped.
- For instance if a component is driven by a periodic signal at 100MHz, the period is thus 10 nanoseconds (ns). If the component delay is less than 0.5 ns, we can assume it to be lumped and can model it's input-output relationship by a combination of suitable lumped elements.

Transition From Lumped To Distributed Circuit

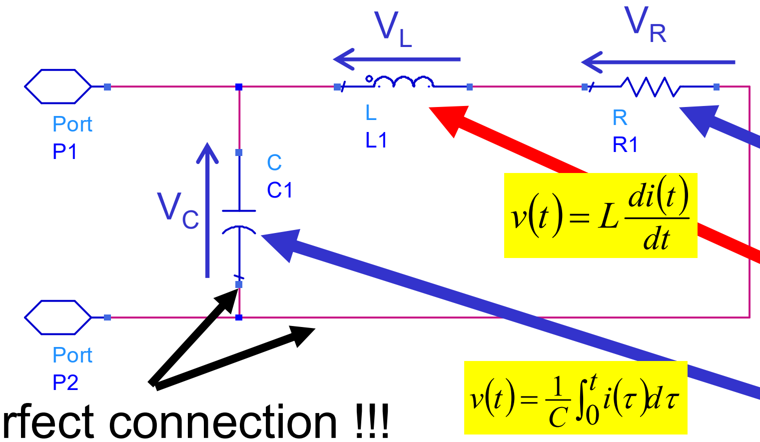
Extra

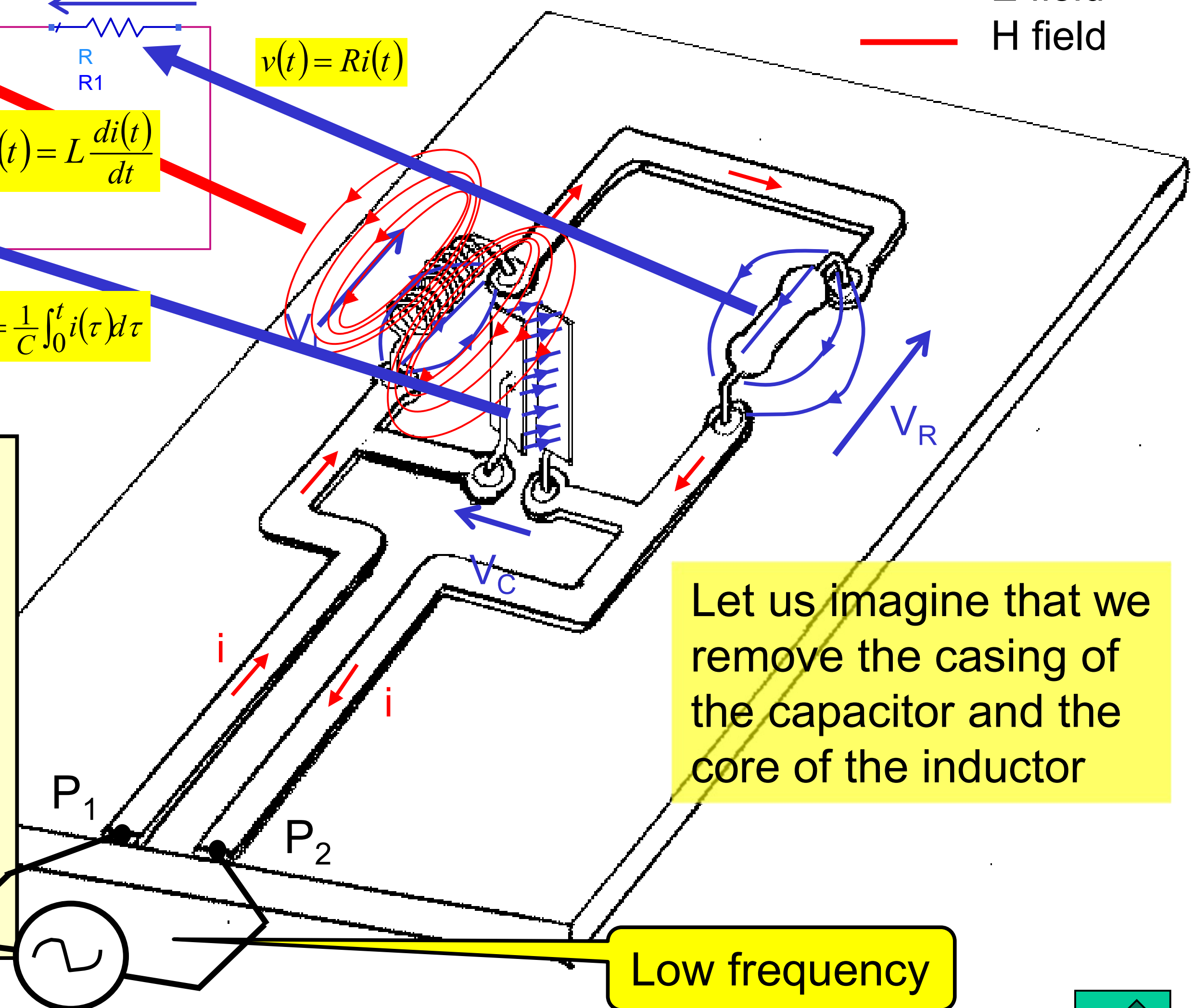
- Consider a simple circuit built on a single-sided printed circuit board (PCB):



Low-Frequency Condition

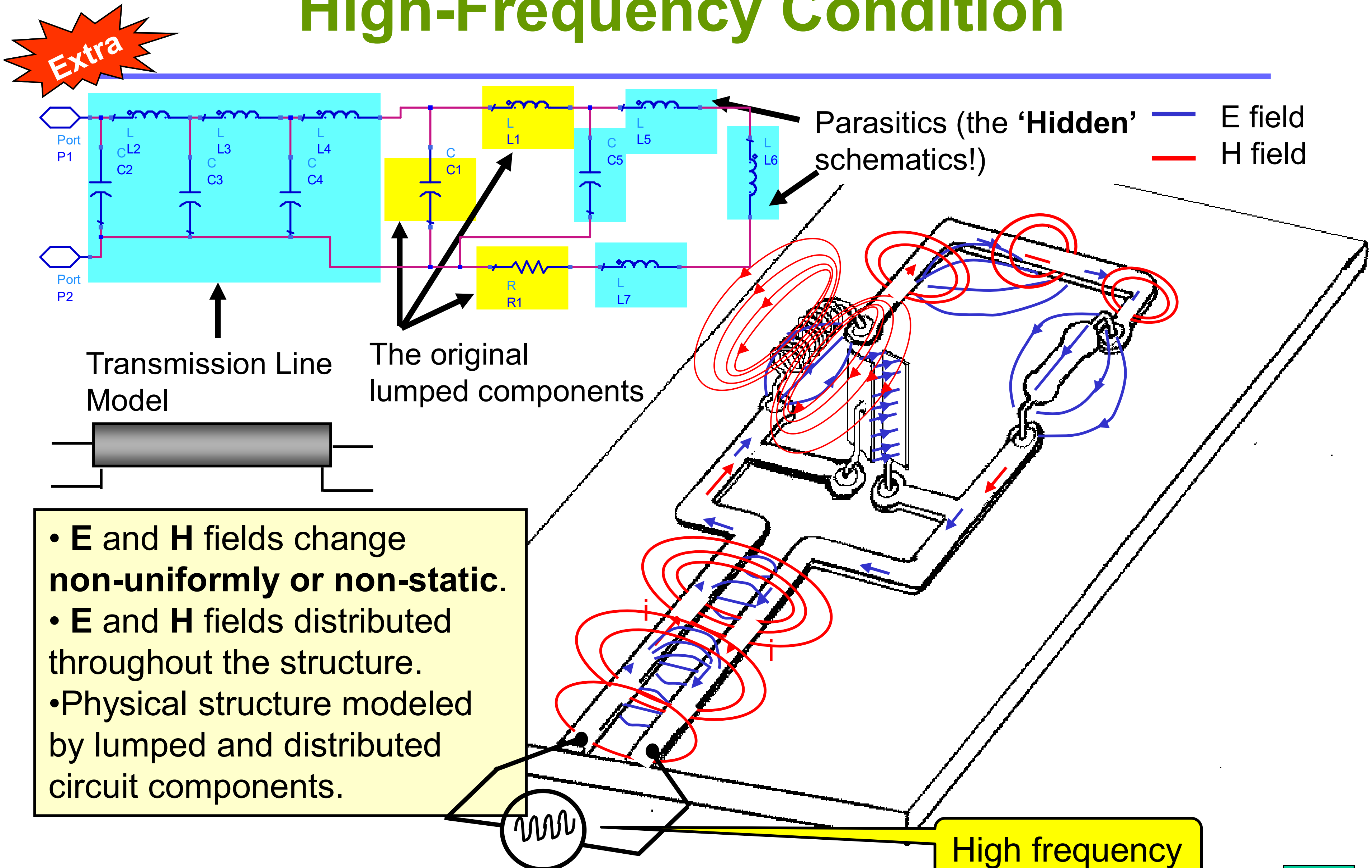
Extra





- **E** and **H** fields change **uniformly or static**.
- **E** and **H** fields concentrate mostly on the components.
- Fields are weak around the copper traces.
- Physical structure modeled by lumped circuit components.

High-Frequency Condition

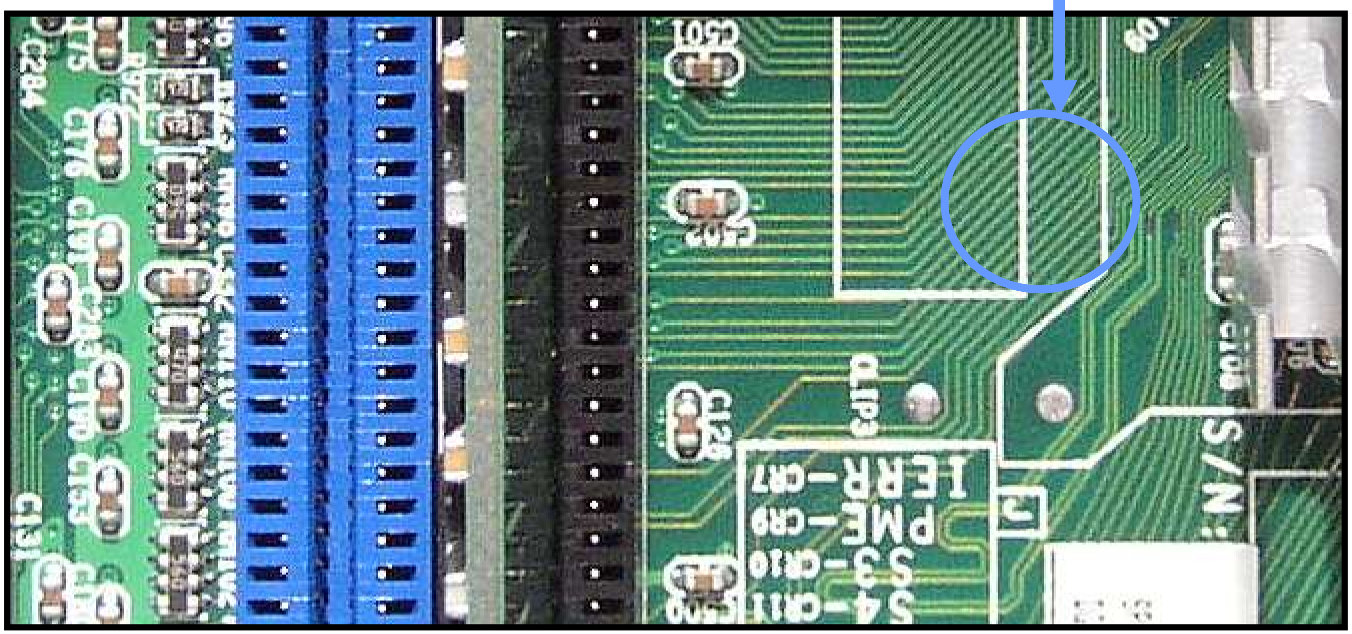


- **E** and **H** fields change **non-uniformly or non-static**.
- **E** and **H** fields distributed throughout the structure.
- Physical structure modeled by lumped and distributed circuit components.

2.5 – Coupling, EMI, EMC and SI

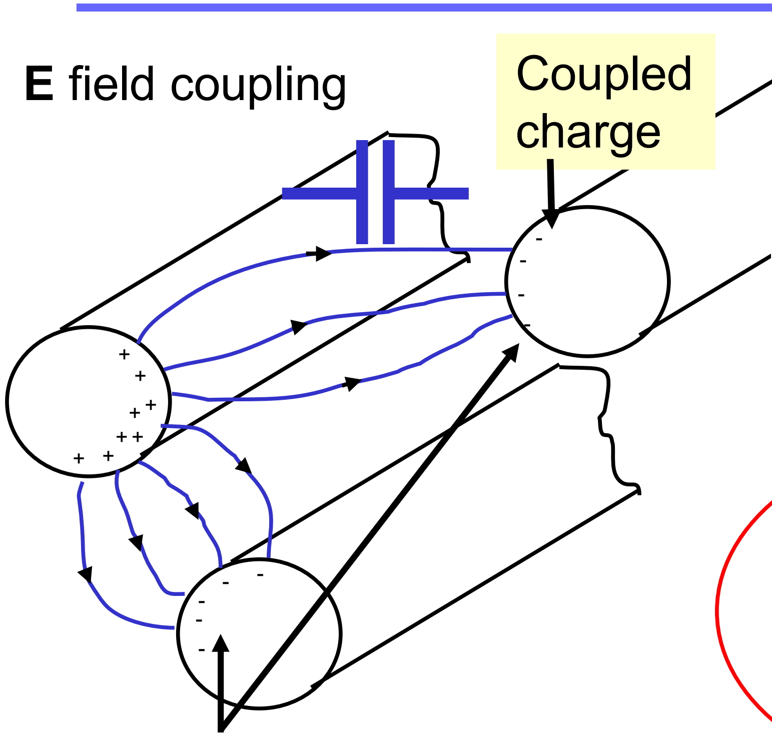
Electrical Interference

- Here we provide a more accurate definition of some terms introduced in Section 2.1 – Problem Statement.
- When two or more conductors are placed close to each other, electrical energy is exchanged between the conductors.
- This electrical energy distribution occurs via electric field (**E**) and magnetic field (**H**) interaction according to Maxwell's Equations, and is usually called Coupling.

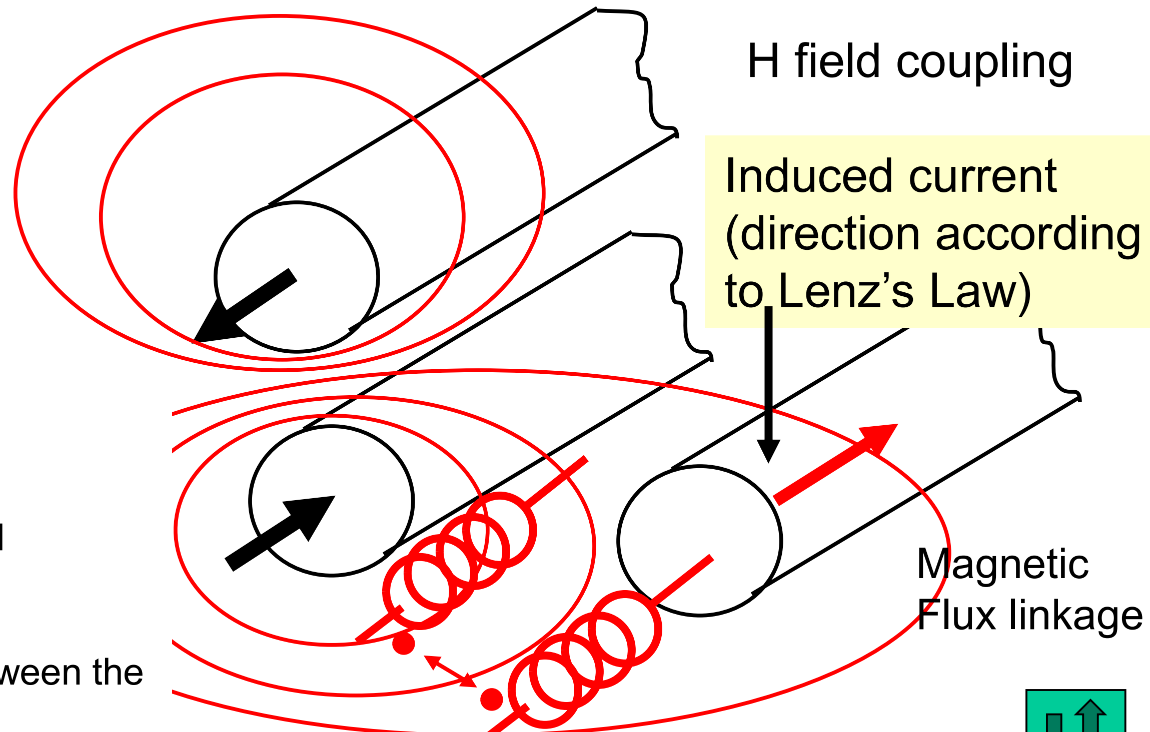


Electric and Magnetic Field Interactions

E field coupling



- A positive charge in one conductor will induced negative charge in adjacent conductors by virtue of **E** field coupling. (we can imagine the positive creates **E** field which repel attract the opposite charge in adjacent conductors.
- This effect can be modeled by mutual capacitance between the conductors.



- The original conducting loop results in a magnetic field **H**. The field 'links' an adjacent conductor.
- As the **H** field changes, current is induced in the adjacent conductor by virtue of Faraday's Law and Lenz's Law.
- This is modeled by mutual inductance between the conductors.

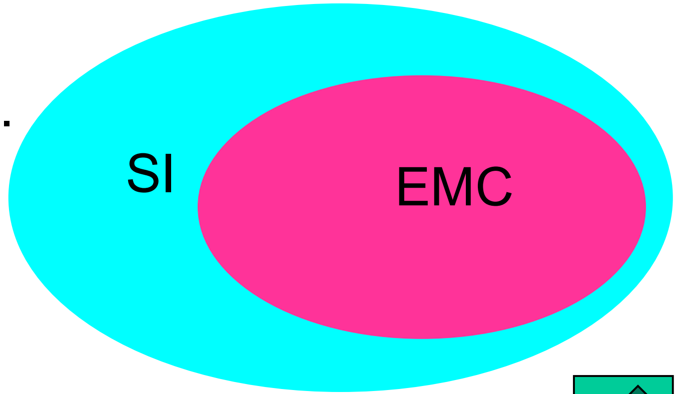
EMI & EMC

- Sometimes this coupling is intentional, e.g. the operation of a transformer, wireless communication system, microwave/RF circuits etc.
- When the coupling is unintentional, it can interfere with the proper functioning of the system. We usually call the coupled signal the noise*.
- This unintentional coupling is termed Electromagnetic Interference (EMI).
- The ability of an electrical system to coexist in its EM environment without suffering or causing degradation and damage is termed Electromagnetic Compatibility (EMC).
- A controlled EMI environment is required for good EMC.

*Note: “Noise” has a different meaning in telecommunication theories.

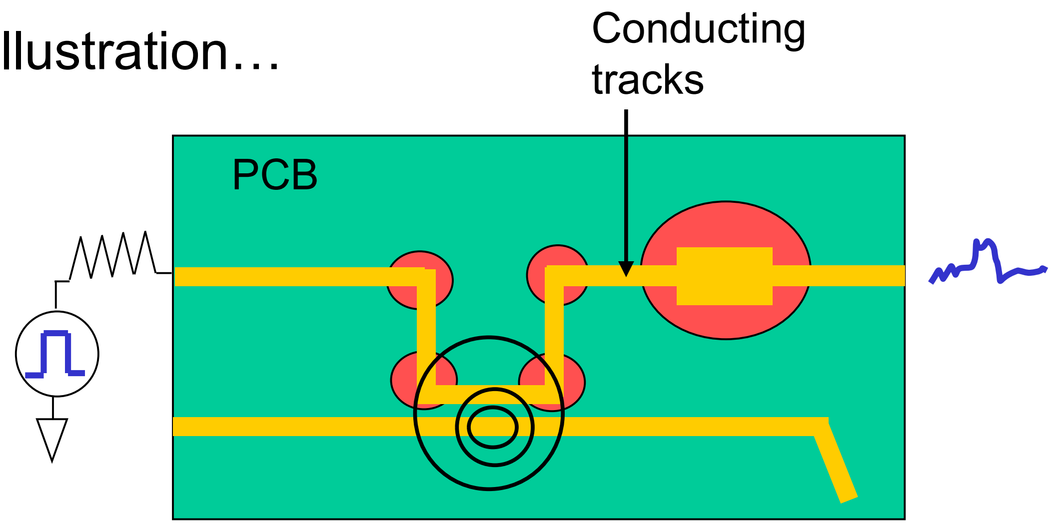
Signal Integrity (SI) (1)

- Signal integrity concerns with the methods and processes of maintaining the quality of electrical signal (usually digital) in an electronic system.
- To maintain signal quality, one has to reduce EMI or unintentional coupling, as this could degrade the signal.
- One also has to ensure that the electrical path from the source to the load (destination) is of optimum condition, we will call this interconnection optimization (IO).
- To main good EMC, one needs to control EMI. However to maintain good SI, one needs to have controlled EMI and good interconnection optimization.
- Thus the concept of SI is a superset of EMC.

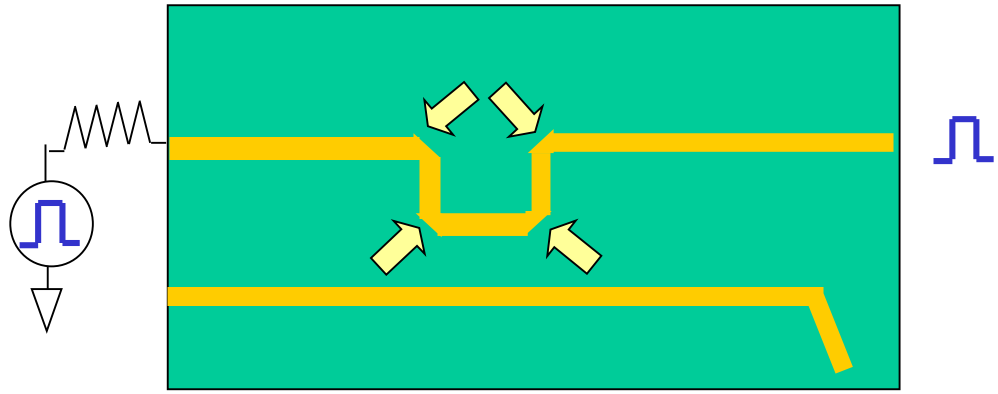


Signal Integrity (2)

An illustration…



EMI & Non-ideal Propagation path



Reduced EMI (greater track separation) and streamlined propagation path – Good SI

Dependence of EMI and SI Effects on Frequency

- Electromagnetic induction effects increase with frequency.
- Since all EMI and SI phenomenons trace their origin to Maxwell's Equations, we expect EMI and SI effects to become more severe for high frequency systems.

Maxwell's Equations

$$\nabla \times \vec{E} = -j\omega\vec{B}$$

$$\nabla \times \vec{H} = \vec{J} + j\omega\vec{D}$$

$$\nabla \cdot \vec{D} = \rho_V$$

$$\nabla \cdot \vec{B} = 0$$

Time varying magnetic field 'induces' electric field

Time varying electric field 'induces' magnetic field

Frequency in rad/s

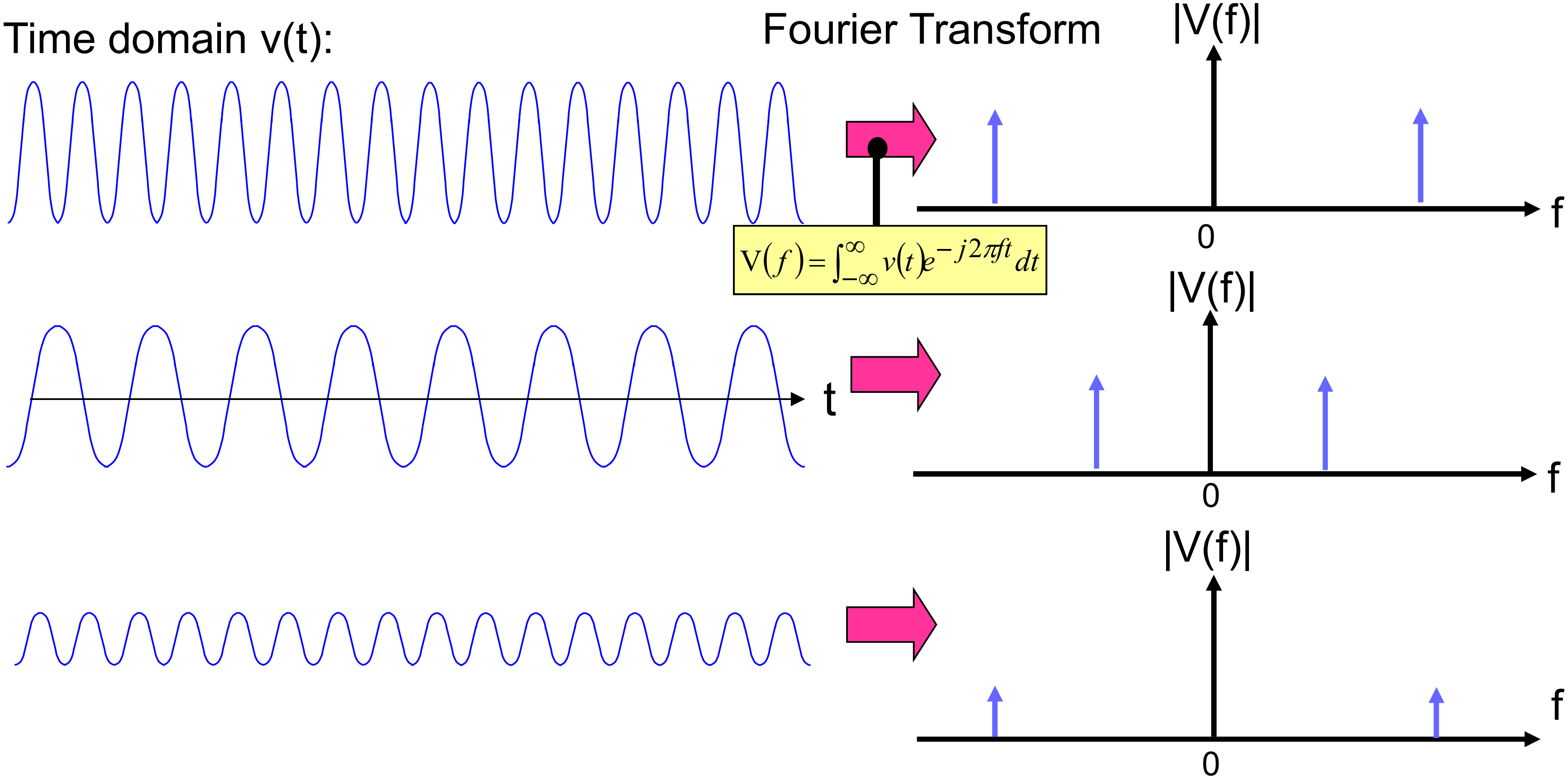
Electromagnetic Interference (EMI) and Signal Integrity (SI) Issues of PCB

A summary of possible issues on HS-PCB:

- Interference/coupling between conductors. EMI
- Ground bounce, simultaneous switching noise. IO
- Reflection in signal. IO
- 'Ringing' in signal. IO
- Degradation of signal rise/fall time. IO EMI
- Excessive attenuation of signal. IO EMI
- False triggering in logic circuits. IO EMI
- Spurious radiation. EMI
- Reliability issues affecting hardware.

2.6 – Time and Frequency Domain Representation of Signals

Time and Frequency Domain Representation of Signals (1)



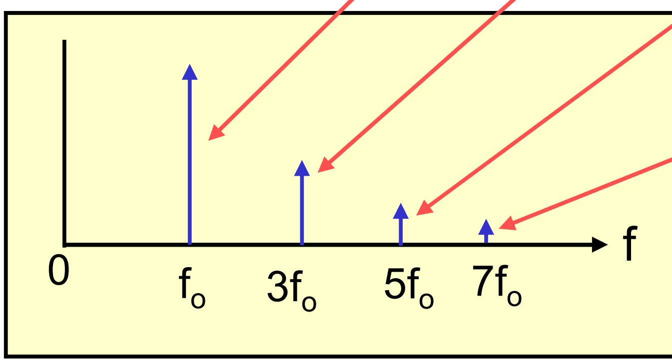
Use Fourier Series for periodic signal and Fourier Transform for aperiodic signal with finite power.

Time and Frequency Domain Representation of Signals (2)

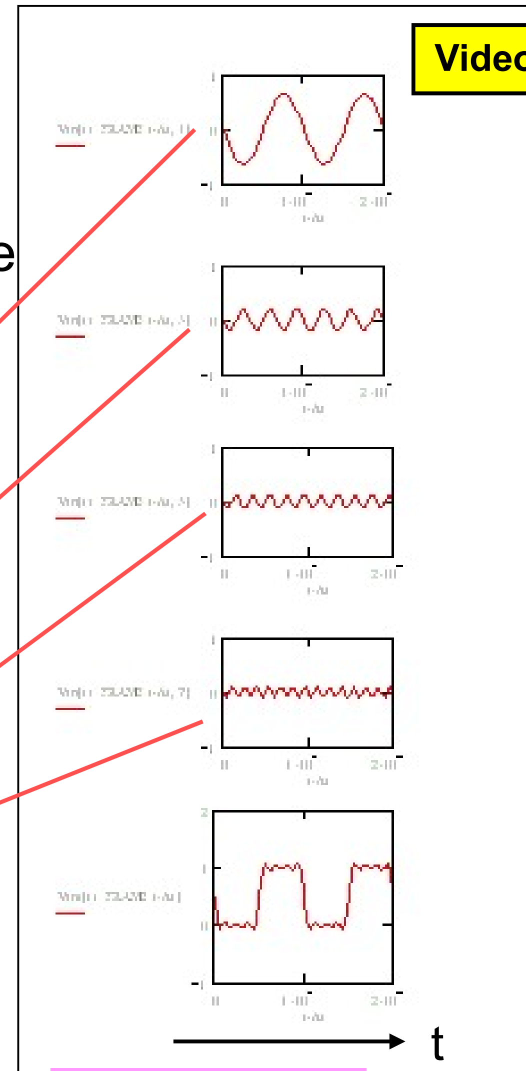
- A non-sinusoidal signal can be constructed from superposition of many sinusoidal components (Fourier series). For periodic signals these components are at discrete frequencies called the fundamental and harmonics.
- For non-periodic signal, the sinusoidal components degenerate into infinitesimal sinusoidal signal across a continuous range of frequency, called a spectrum.

Video

NOTE:
Note that square pulses only contain odd harmonics. Otherwise in general odd and even harmonics are present.

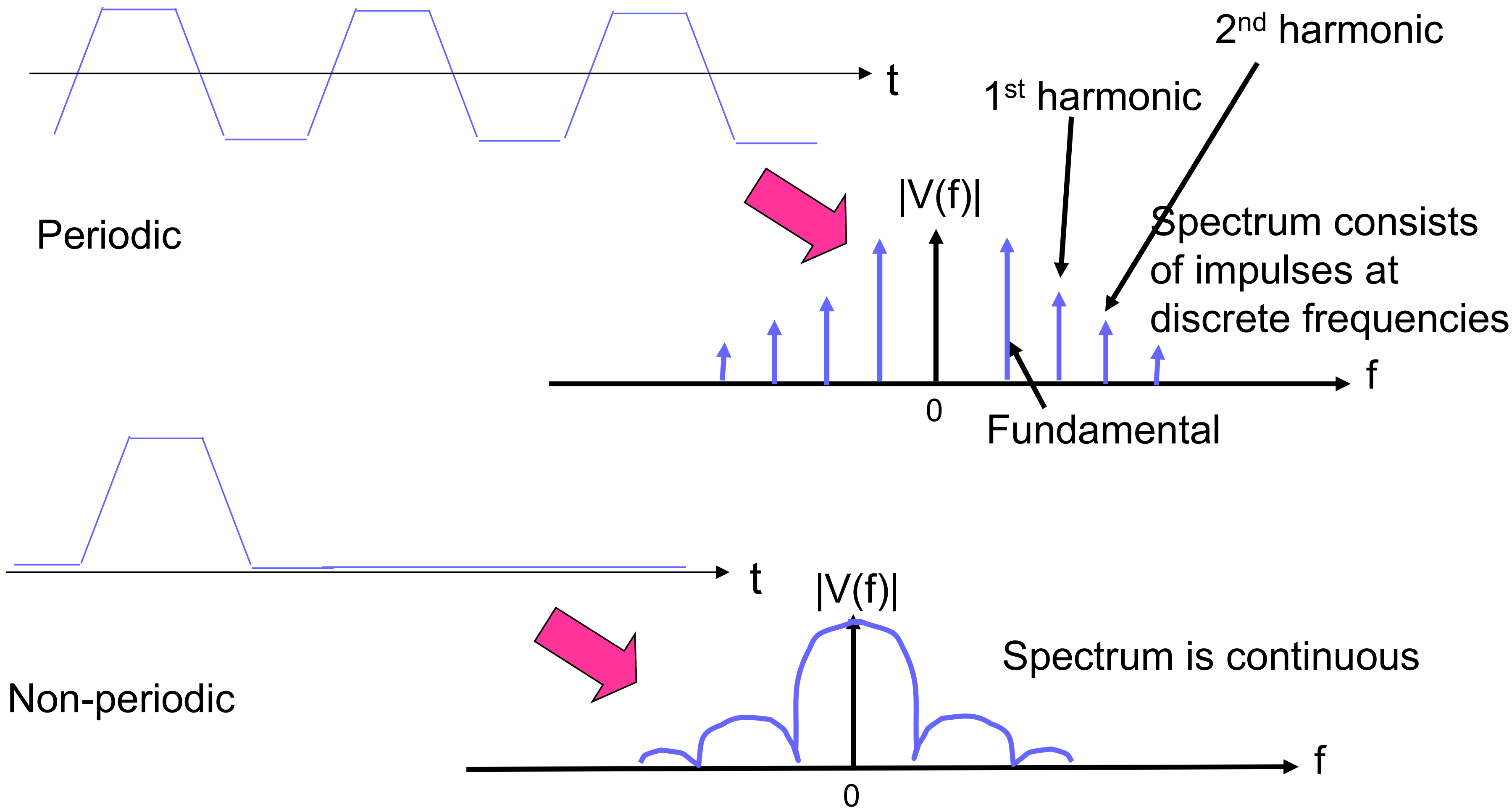


Frequency domain



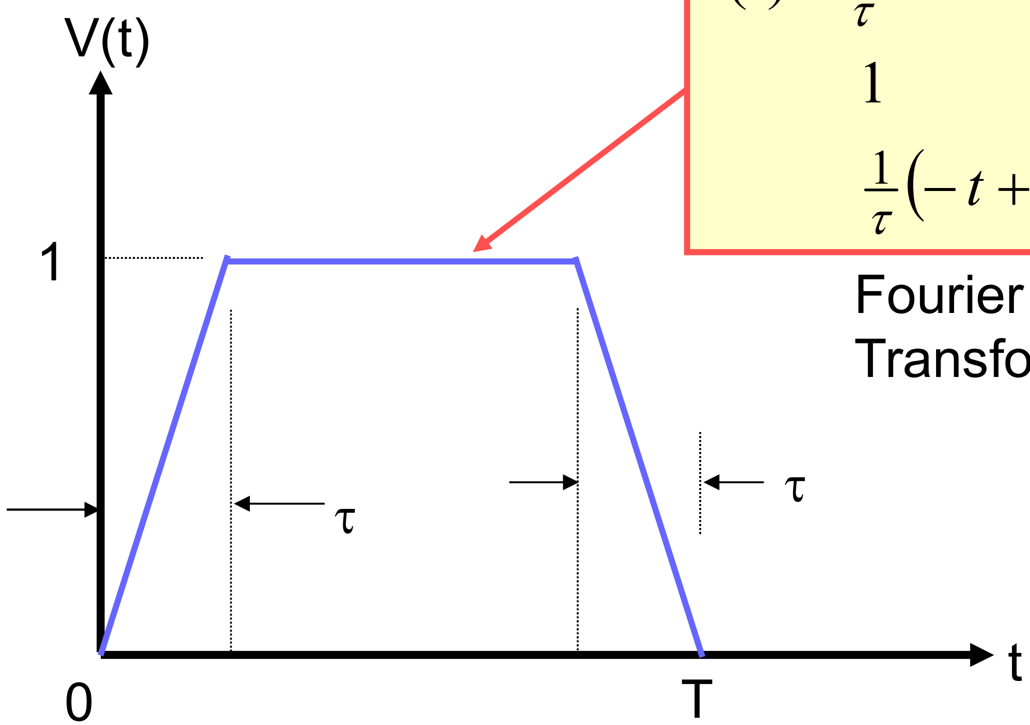
Time domain

Time and Frequency Domain Representation of Signals (3)



Spectrum of a Single Digital Pulse (1)

- Here we will only focus on a single trapezoidal pulse, which is a rough estimate of digital signal waveforms (See [1] for more details).



$$v(t) = \begin{cases} \frac{t}{\tau} & , \quad 0 \le t < \tau \\ 1 & , \quad \tau \le t < (T-\tau) \\ \frac{1}{\tau}(-t+T) & , \quad (T-\tau) \le t < T \end{cases}$$

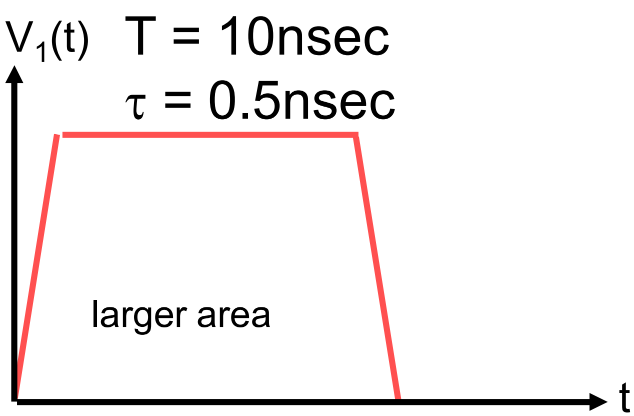
Fourier Transform

$$V(\omega) = \int_{-\infty}^{\infty} v(t) e^{-j\omega t} dt$$

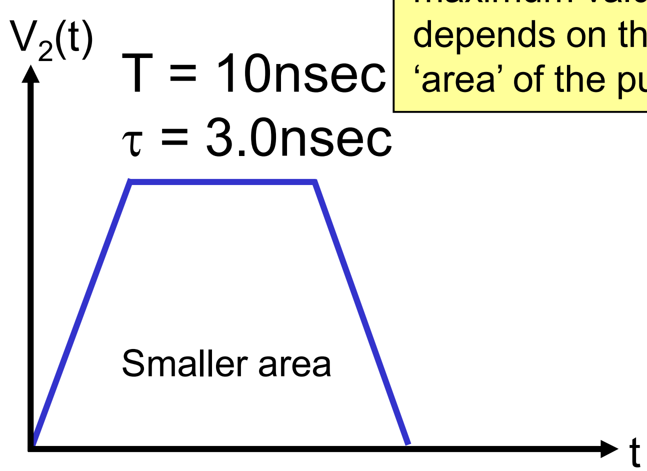
$$V(\omega) = (T-\tau) e^{j\frac{\omega}{2}(T-2\tau)} \cdot \left(\frac{\sin\left(\frac{\omega(T-\tau)}{2}\right)}{\frac{\omega(T-\tau)}{2}} \right) \left(\frac{\sin\left(\frac{\omega\tau}{2}\right)}{\frac{\omega\tau}{2}} \right)$$

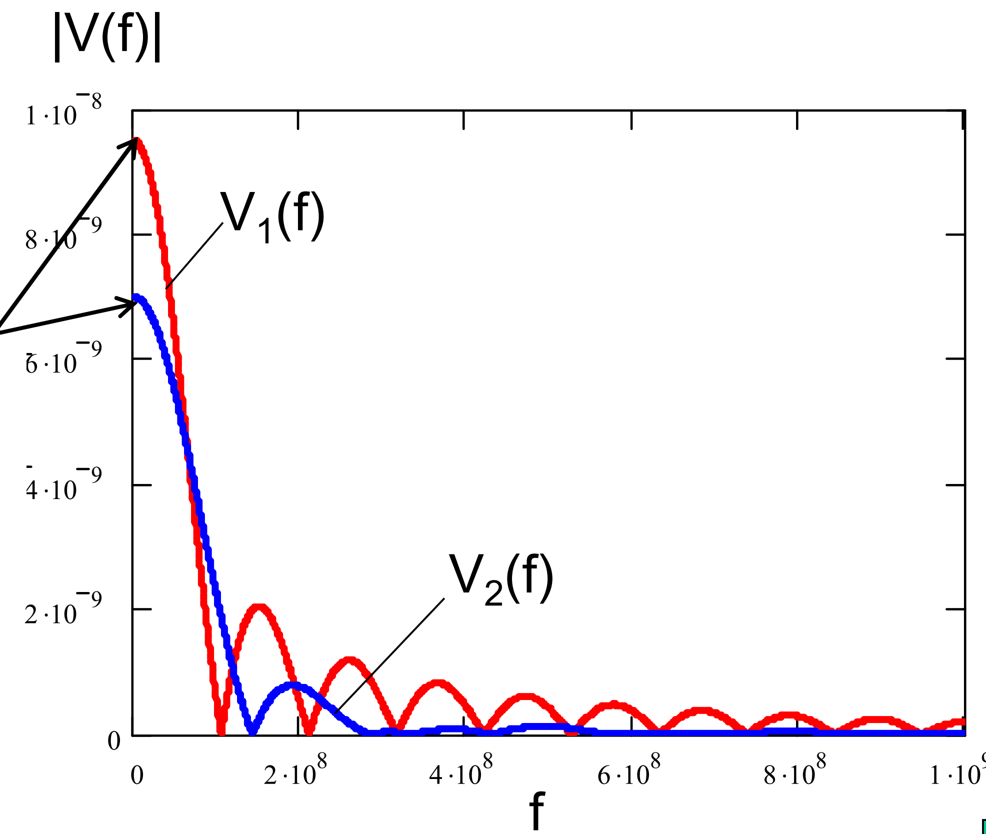
Spectrum of a Single Digital Pulse (2)

Observation: The spectra for pulse with smaller rise/fall time extends further out onto the frequency axis.



Note that the maximum value depends on the 'area' of the pulse



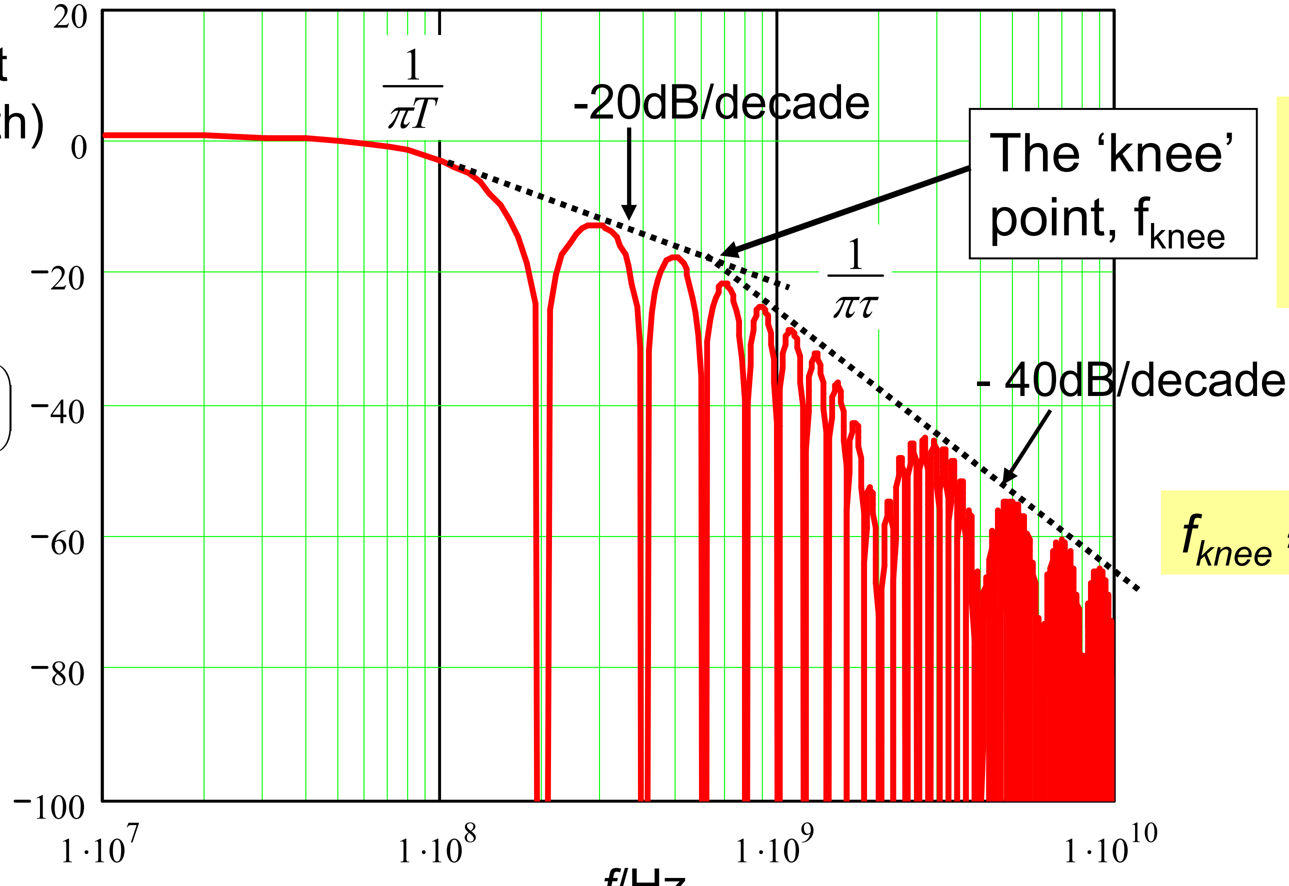


Spectrum of a Single Digital Pulse (3)

- To get an estimate of the bandwidth, we plot the normalized spectrum of the pulse in dB versus *f* in logarithm grid.

Normalized (with respect to pulse width) magnitude in dB scale

$$20\log_{10}\left(\left|\frac{V(f)}{T-\tau}\right|\right)$$

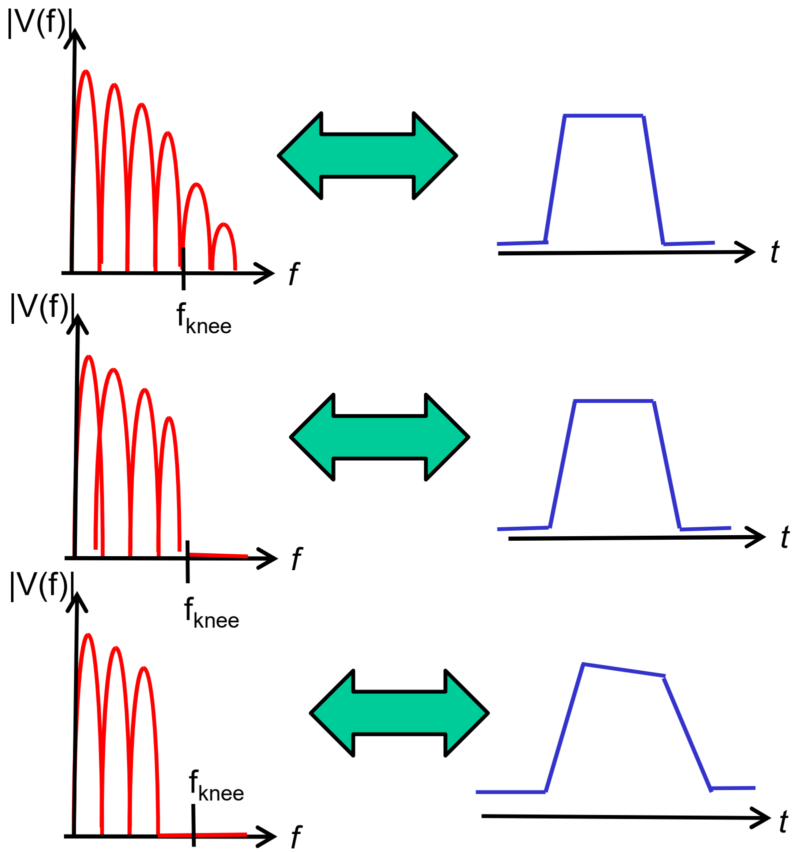


Example:
T = 5.0nsec
τ = 0.5nsec

$f_{knee} \approx$ 700MHz

Bandwidth and Edge-Rate (1)

- *0* to f_{knee} can be taken as the <u>significant spectrum</u> of the digital pulse.
- Elimination of frequency components greater than f_{knee} will only result in negligible distortion on the waveform. This means majority of the pulse energy is concentrated on frequency components less than f_{knee}.



Original spectra.

Removal of components above f_{knee} does not cause significant distortion.

Removal of components below f_{knee} results in significant distortion of the pulse.

Bandwidth and Edge-Rate (2)

- Typically, the bandwidth (BW) of the digital pulse can be approximated by f_{knee}:

$$BW_{pulse} = f_{knee} = \frac{1}{\pi\tau} \cong \frac{0.318}{\tau} \qquad \textbf{\textit{(6.1)}}$$

- From previous slide:

$$BW \cong \frac{1}{\pi \cdot 0.5 \times 10^{-9}} = 636.6\ \mathrm{MHz}$$

See Chapter 7, Paul [1]

Bandwidth and Edge-Rate (3)

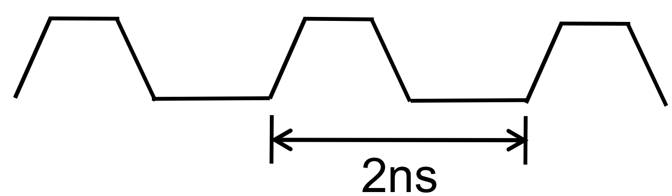
- Thus the conclusions are:
  - BW of digital pulse depends on rise/fall time only.
  - Small rise/fall time, large BW.
  - Small rise/fall time means large dV/dt or dI/dt, i.e. large edge-rate, in other words the 'speed' of the signal is high.
- Thus the rise/fall time of digital pulse determines whether the signal can be considered 'high-speed' or 'low-speed'.
- The rise/fall time also determines the rate-of-change of the electrical signal, usually called the Edge-Rate.

$$\frac{dV}{dt} \quad \frac{dI}{dt} \equiv \text{Edge-rate}$$

High edge-rate, high-speed, needs large bandwidth.
Low edge-rate, low-speed, needs small bandwidth.

Periodic Digital Pulses Bandwidth

- For periodic digital pulses such as clock signal, a simple rule-of-thumb is to take a minimum of 5 harmonics.
- For instance if a clock source has a frequency of 600 MHz, with 50% duty cycle, then the bandwidth required to ensure minimal distortion to the clock signal would be 5 x 600 MHz = 3000 MHz.
- Take note that even though we do not consider rise/fall time for periodic signal, the rise/fall time generally is dependent on the frequency too.
- For instance if the clock signal frequency is 500 MHz, then one period is 2ns, with a duty cycle of 50%, the pulse width will be 1ns or less. Naturally the rise/fall time of the clock pulse have to be smaller than 1ns.
- Thus for periodic signal, the higher the frequency, the smaller will be the corresponding rise/fall time.



High-Speed versus High Frequency

- High-speed digital signals typically refer to digital pulses with rise/fall time less than 1.0nsec (sub-nanosecond).

$$\text{Significant frequency} = \frac{1}{\pi \cdot 1.0 \times 10^{-9}} = 318.3MHz$$

- This term is only applicable to digital circuits.
- For analog circuit, for instance for microwave circuits dealing with sinusoidal signals, we only use the term high or low frequency, as the sinusoidal signal usually does not contains much harmonics.

Therefore when a PCB assembly contains digital pulses with < 1.0nsec rise/fall time, and contains some of the characteristics of Slide #16, it is termed 'High-speed PCB'

2.7 – Summary

The Big Picture

- Hopefully by this slide you are able to see connections of the concepts that we have covered.
- EMI and SI effects depends on frequency, the higher the frequency of a sinusoidal signal, the larger are effects such as coupling, propagation, reflections, radiation etc.
- Digital signal with small rise/fall time (e.g. high-speed) has high frequency contents (or Fourier components). These high-frequency components cause the most EMI and SI effects, thus degrading the signals.
- Thus we need to implement some measures to control EMI and SI phenomenon.
- The measures and analysis techniques focusing on PCB are called High-Speed PCB Design.

High-Speed PCB Design in a Nutshell

- High-speed PCB design involves …

Application of knowledge in electromagnetism,
microwave engineering, circuit theory,
signal analysis theory, analog and digital electronics
in solving and preventing SI and EMI/EMC related issues.
Computer simulation and modeling is frequently employed.

Typical analysis tools:

1. Rule-of-thumb.
2. Analytical formula or design equations.
3. Computer modeling or numerical simulation.
4. Measurement.

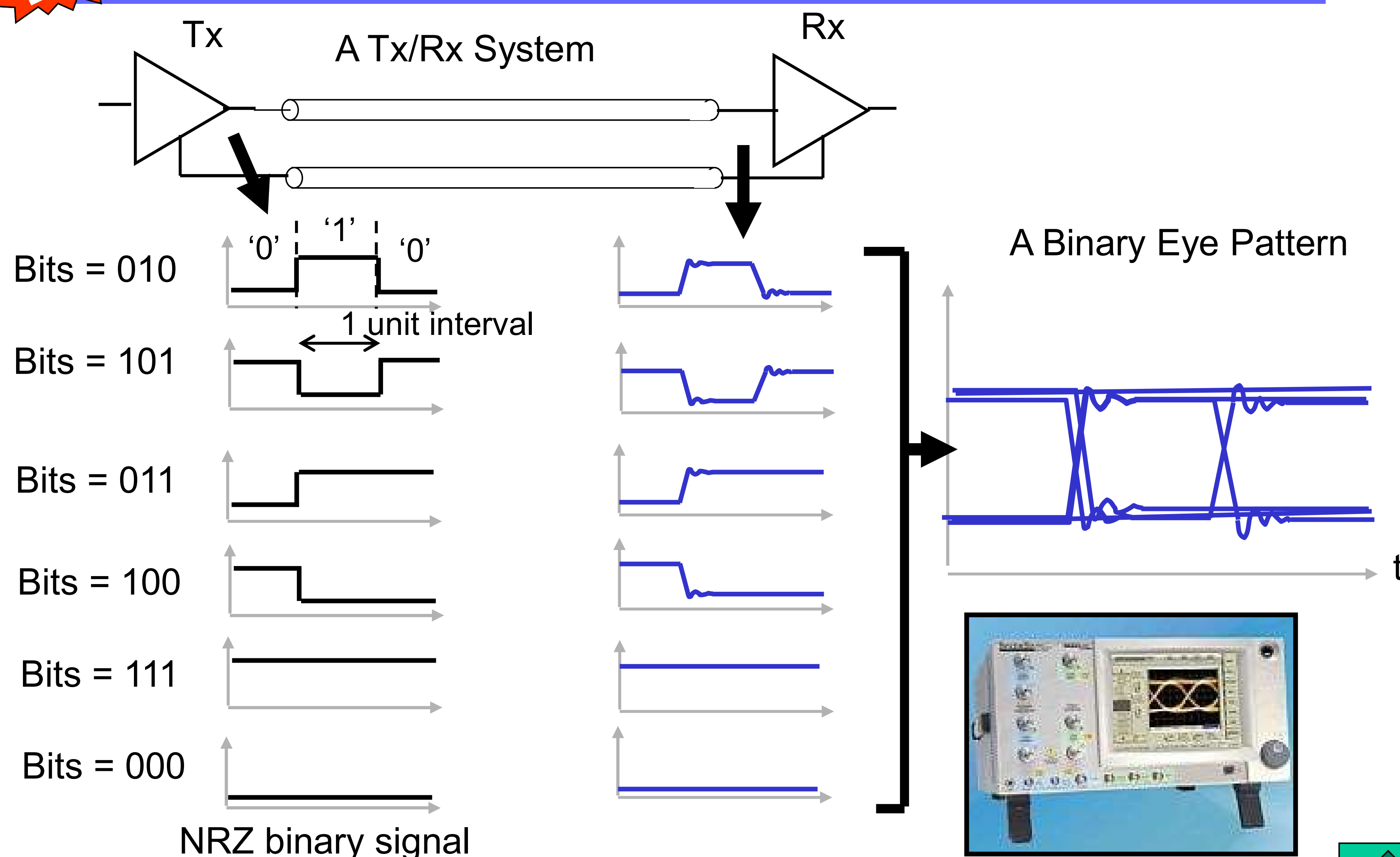
Key Learnings for Part 1 and 2

- Names of various PCB assembly structures.
- Characteristics of modern PCB assembly.
- Electromagnetic fields, Field Theory and Circuit Theory.
- Mechanism of electric interference.
- Definition of EMI, EMC, SI.
- EMI and SI issues on PCB.
- Motivation for reduction of EMI.
- Relation between voltage, current and EM fields (Electric and magnetic fields).
- Concepts of lumped vs distributed circuit elements, when to use lumped and when to use distributed elements.
- Time domain and frequency domain representation of signals.
- Estimation of bandwidth for digital signals.
- Definition for "High-speed" signal, when will the system becomes high-speed.

2.8 – Miscellaneous

Eye Diagram

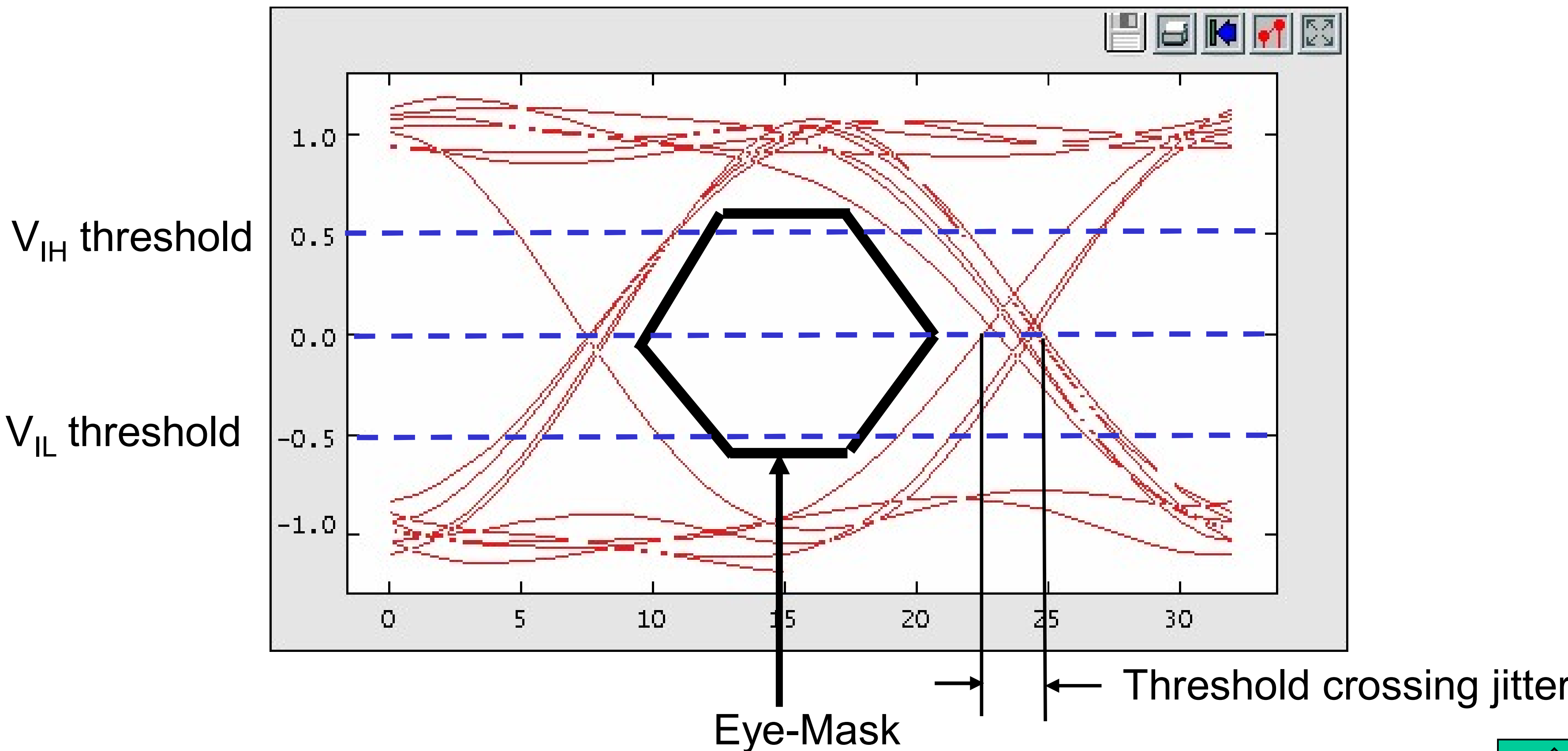
Extra



Eye-Mask and Jitter

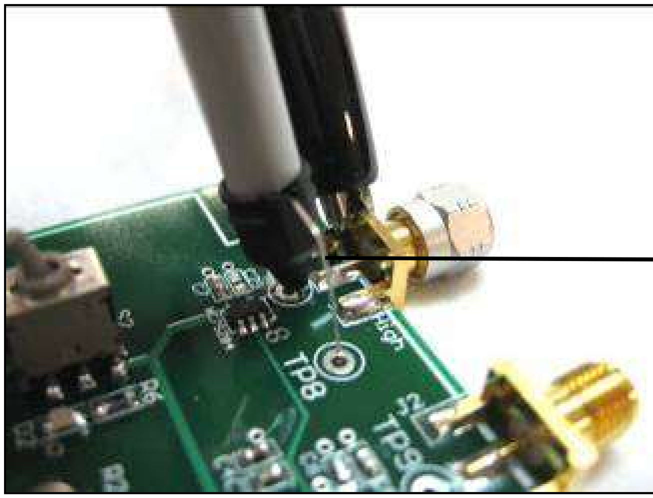
Extra

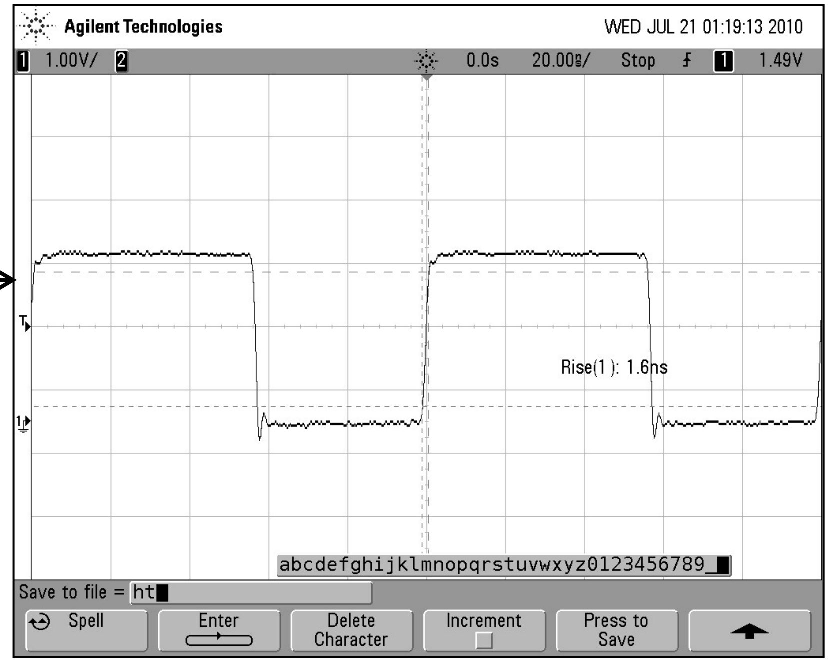
- The opening of the eye-mask indicates 1) The max. bit-rate achievable 2) The optimum level of sampling and 3) The threshold levels.
- Eye diagram can also be generated for multi-level digital signal.



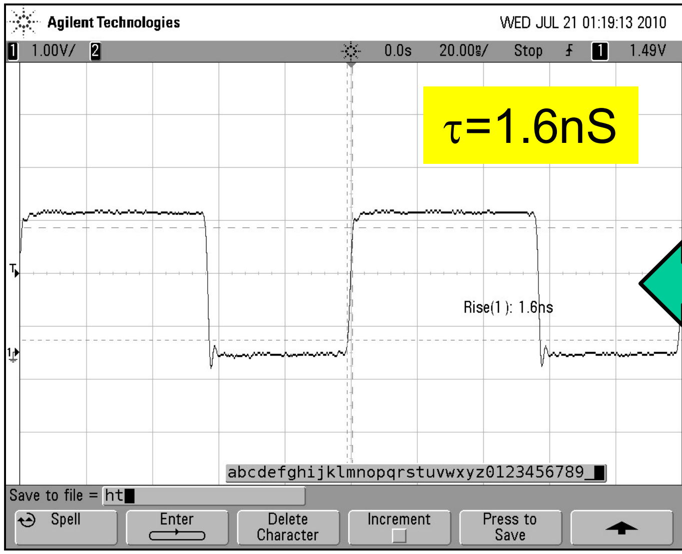
Measured Spectra from Digital Pulses (1)

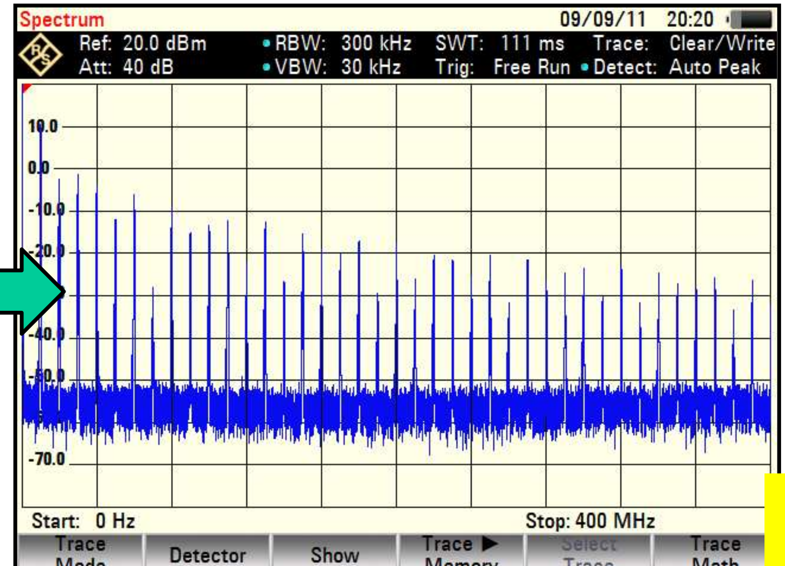
- 10MHz Digital pulse source into 50Ω termination.



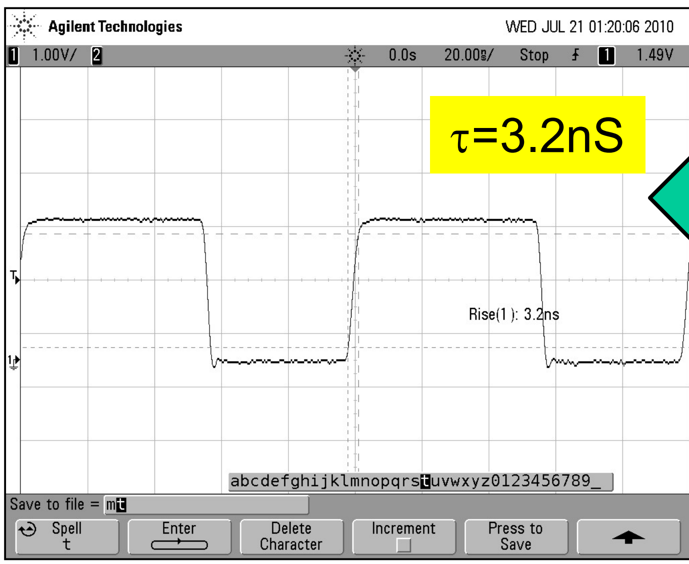


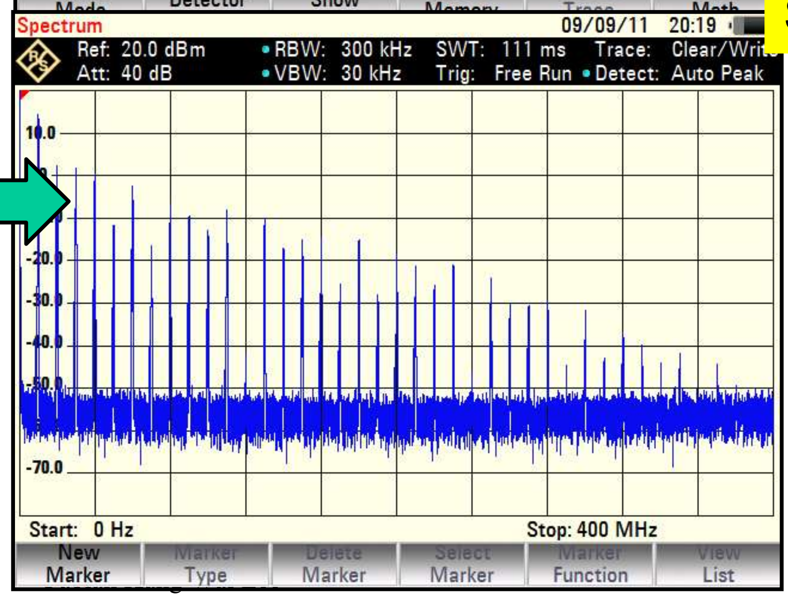
Measured Spectra from Digital Pulses (1)





Start = 100kHz
Stop = 400MHz





Measured Spectra from Digital Pulses (2)