Solving Your IC Package SI and SSN Problems: ICEMAX And It's Applications

Xin Wu, Ph.D
ICE Electronic Division
Fluent Inc.
Austin, TX
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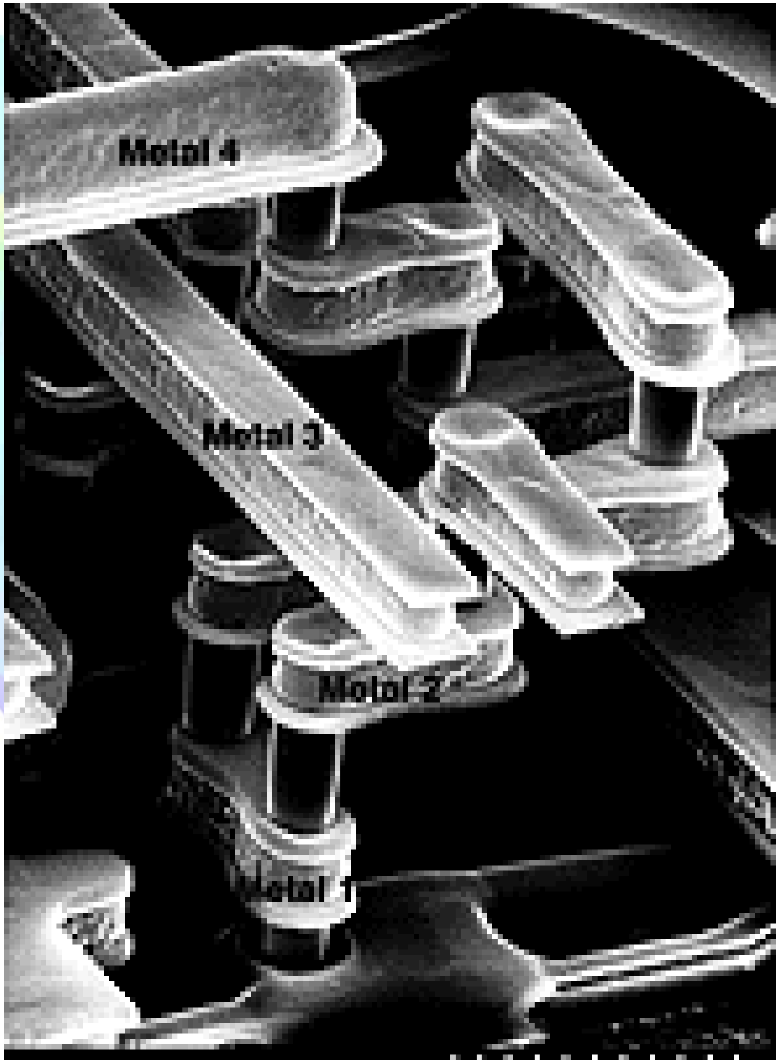
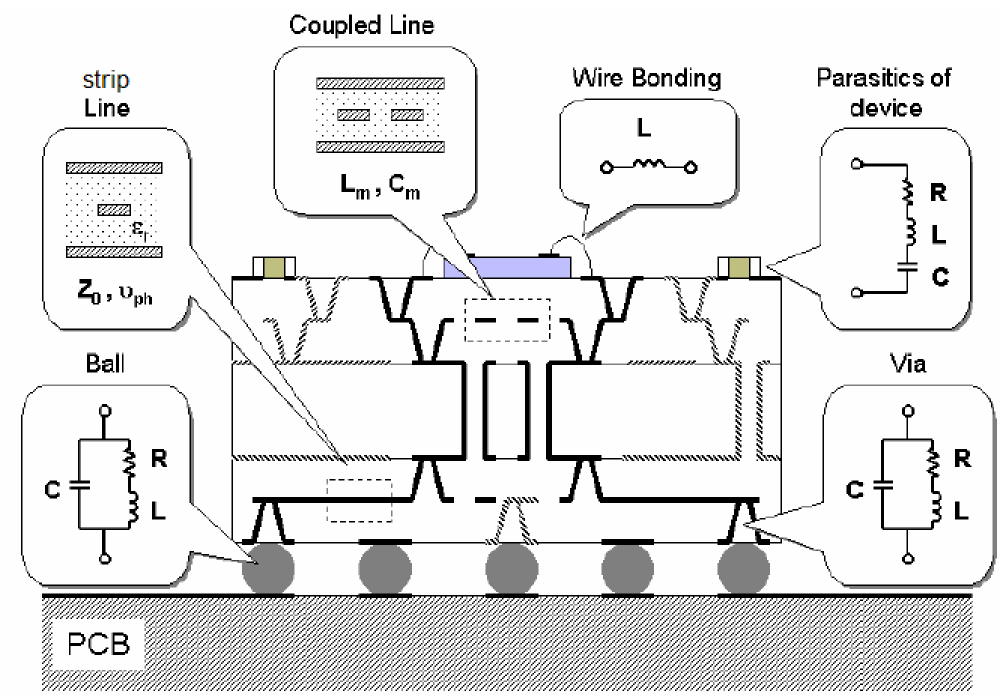
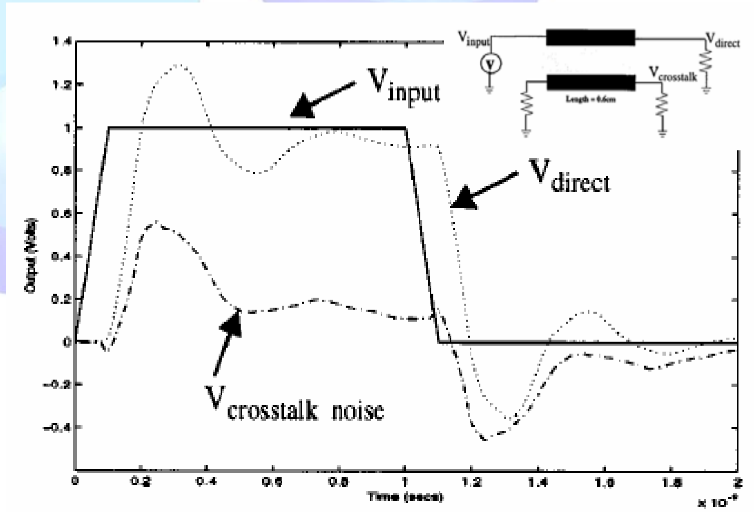
Package Parasitics

- Wires/traces are not ideal. Parasitics:
  - Resistance
  - Capacitance
  - Inductance
- Why do we care?
  - Impact on delay
  - noise
  - Power dissipation
  - power distribution



Signal Integrity and Power Concerns in Package



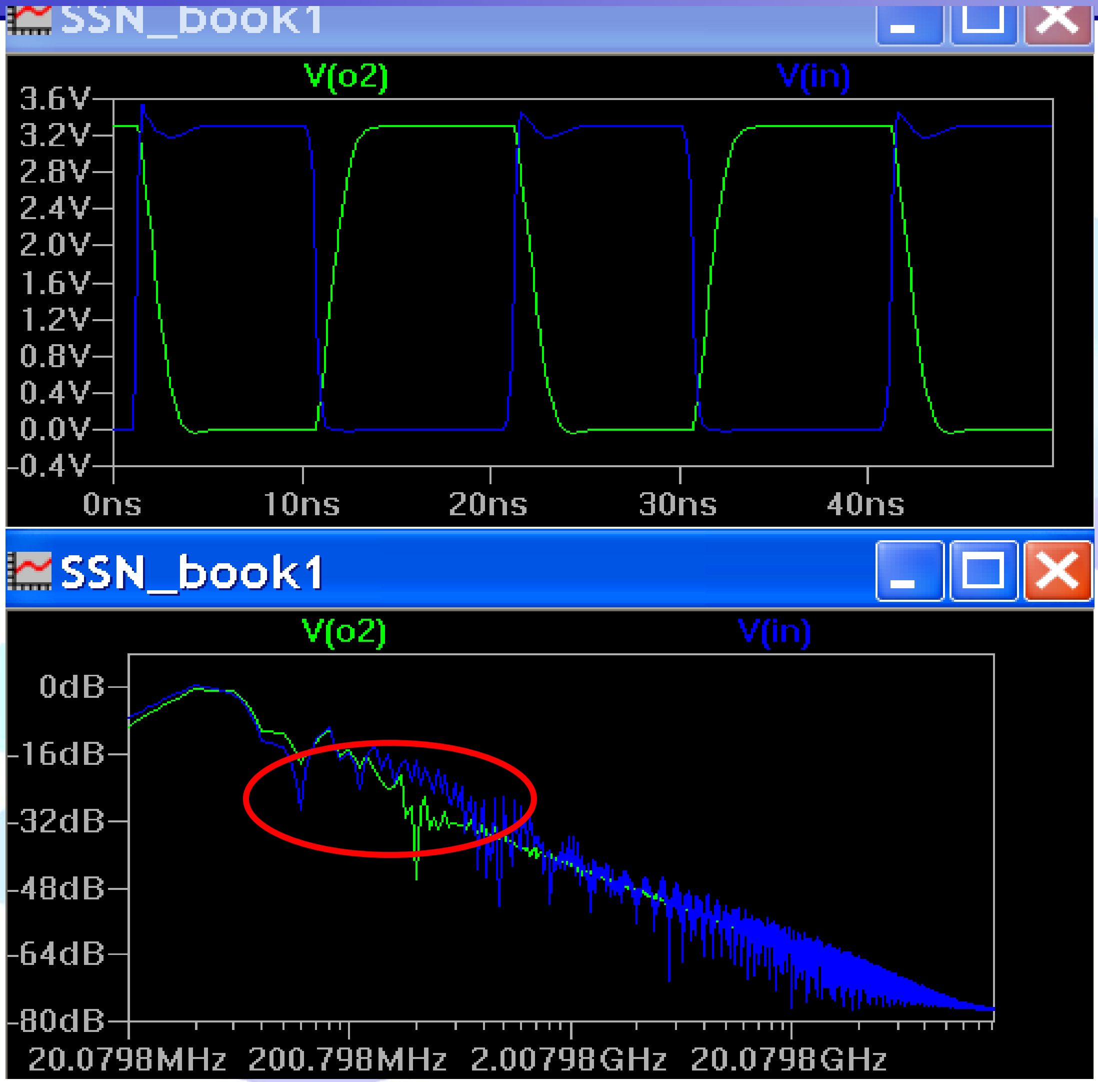


***Attenuation, dispersion and Delay*: propagation in medium, dielectric loss, conductor loss, skin effects**

***Ringing*: impedance discontinuity**

***Crosstalk*: energy coupling**

Distorted Signal Power Spectrum…



Outline

- Theoretical background of ICEMAX
  - Quasi-static solver: why and how it works?
  - PEEC vs. Non-PEEC model
  - Numerical techniques: Finite Volume Method
- ICEMAX Critical Settings
  - Grounding vs. Non-grounding
  - Lumped vs. Distributed
  - Meshing setting
- Working with gerber files/CAD files and run ICEMAX – Project Demo
  - How to export Gerber file from package design?
  - Cadence Import
- Deliver SI and SSN analysis with ICEMAX results
  - Crosstalk analysis
  - SSN analysis

When Quasi-static Fails?

Q: How long does light take from my nose to reach my eye?

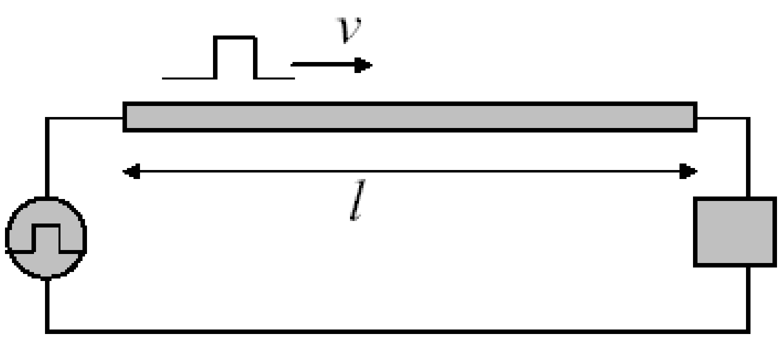
A:

c=3 x10[8]m/s=30cm/ns, L=6cm

t=L/c=6/30=0.2ns=200ps #

Q: The clock cycle of a 2GHz Pentium IV?

A: 500ps



Unequal potential on the conductor!

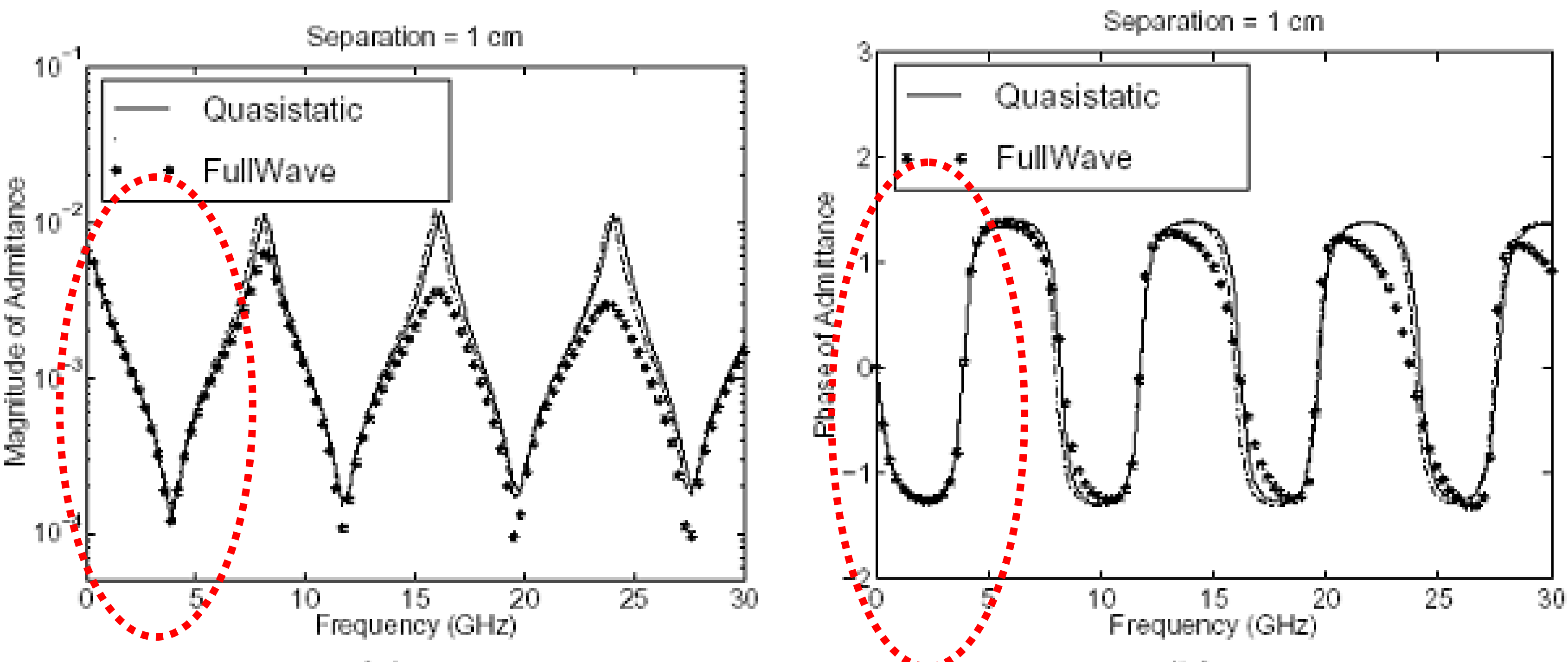
If $t_{tof} > \sim 0.5 t_r$ (rule in digital)

(where $t_{tof} = l/v$, *called time-of-flight*) or

$l > \sim\lambda/10$ (λ: wavelength)

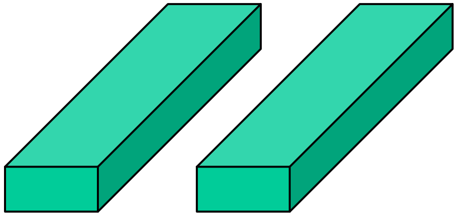
Transmission line effect is important!!

Quasi-static vs. Full-wave



(a) (b)

Magnitude and phase for a two conductor consisted transmission line with high resistivity (sigma=5.8E7 s/m), 1cm long, separated by 1 cm.



Mathematic background of ICEMAX

- Quasi-static electromagnetics
  - Displacement current being ignored

$$\nabla \cdot D = 0$$

$$\nabla \cdot B = 0$$

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

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

$$D = \varepsilon E$$

$$B = \mu H$$

$$J = \sigma E$$

$\frac{\partial D}{\partial t} \rightarrow 0$ **Negligibly Small Displacement Current**

If ignoring the displacement current, Ampere's Law becomes an equation which describes the H-field and conduction current.

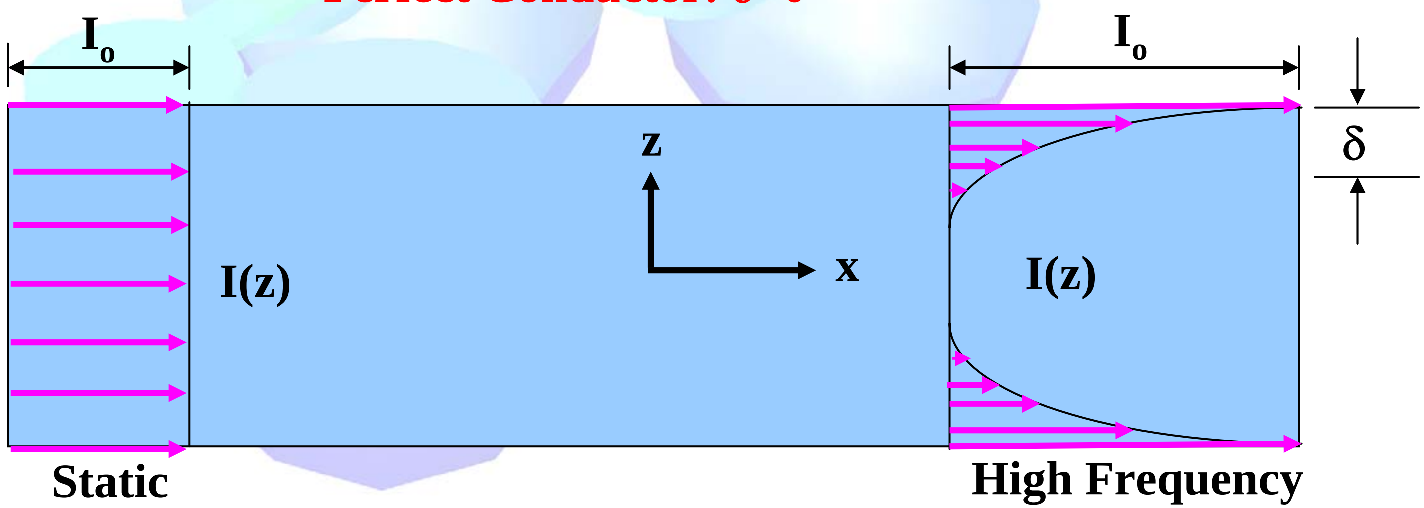
Skin Effects and Conduction Current

$$I(z) = I_o \cdot e^{-(z-z_o)/\delta}$$

$$\delta = \sqrt{\frac{1}{\pi\mu\sigma f}}$$

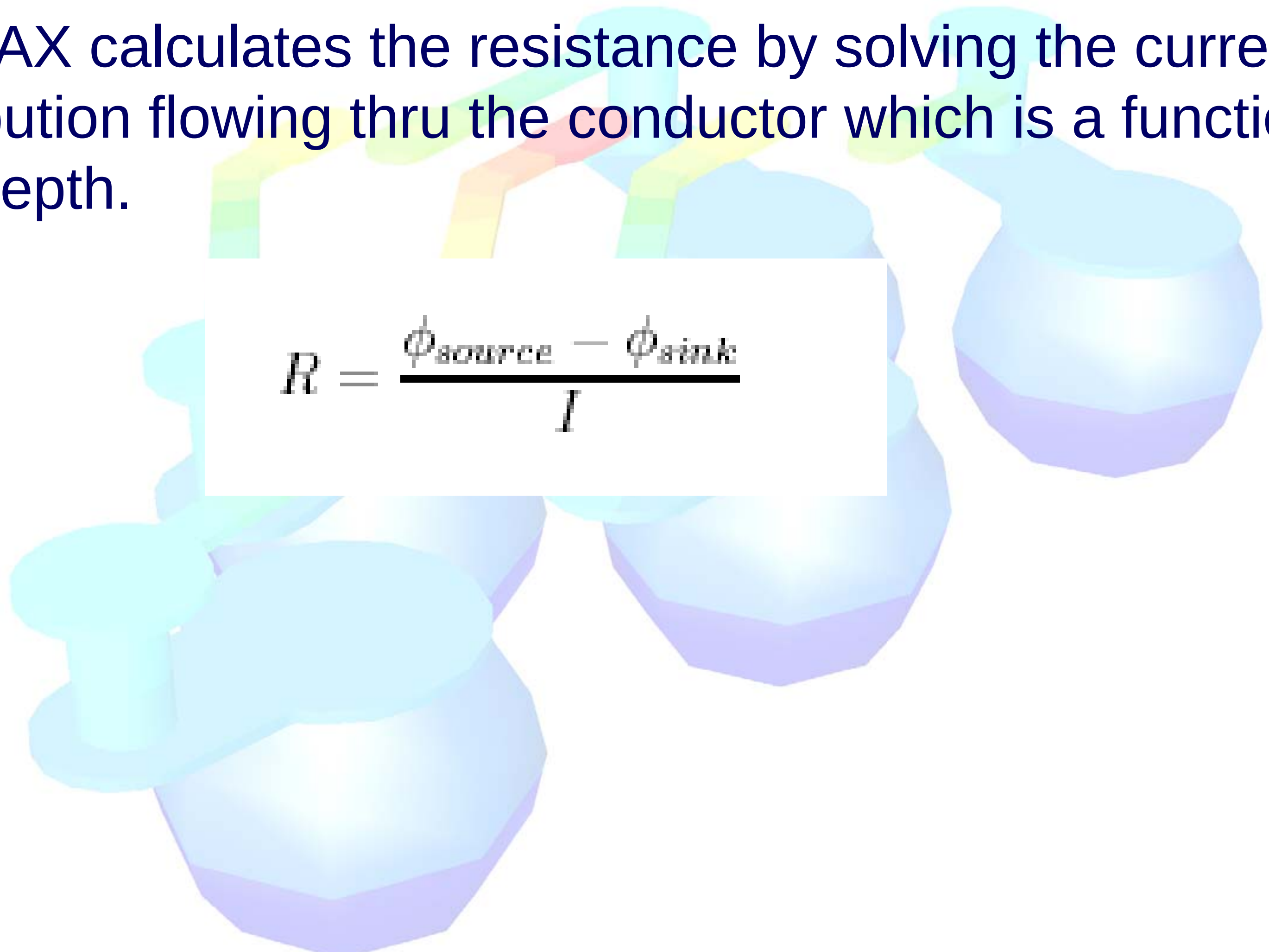
Copper	ρ=1/σ=1.68×10⁻⁸ Ω•m
f (Hz)	**δ (μm)**
10^4	652.0
10^6	65.2
10^8	6.5
10^9	2.1
10^{10}	0.65

Perfect Conductor: δ=0



Resistance Calculation

- ICEMAX calculates the resistance by solving the current distribution flowing thru the conductor which is a function of skin depth.



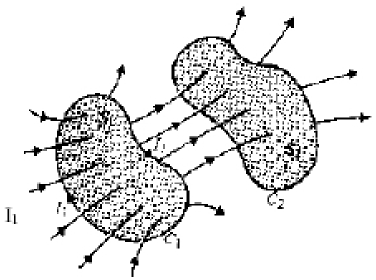
$$R = \frac{\phi_{source} - \phi_{sink}}{I}$$

Inductance: I

Faraday's Law

$$\oint_C \vec{E}\cdot d\vec{l} = -\int_S \frac{\partial \vec{B}}{\partial t}\cdot d\vec{s} \Rightarrow V = -\frac{d\Phi}{dt}$$

$\Phi = \iint_S \vec{B}\cdot d\vec{s} = LI$ =magnetic flux cross surface S



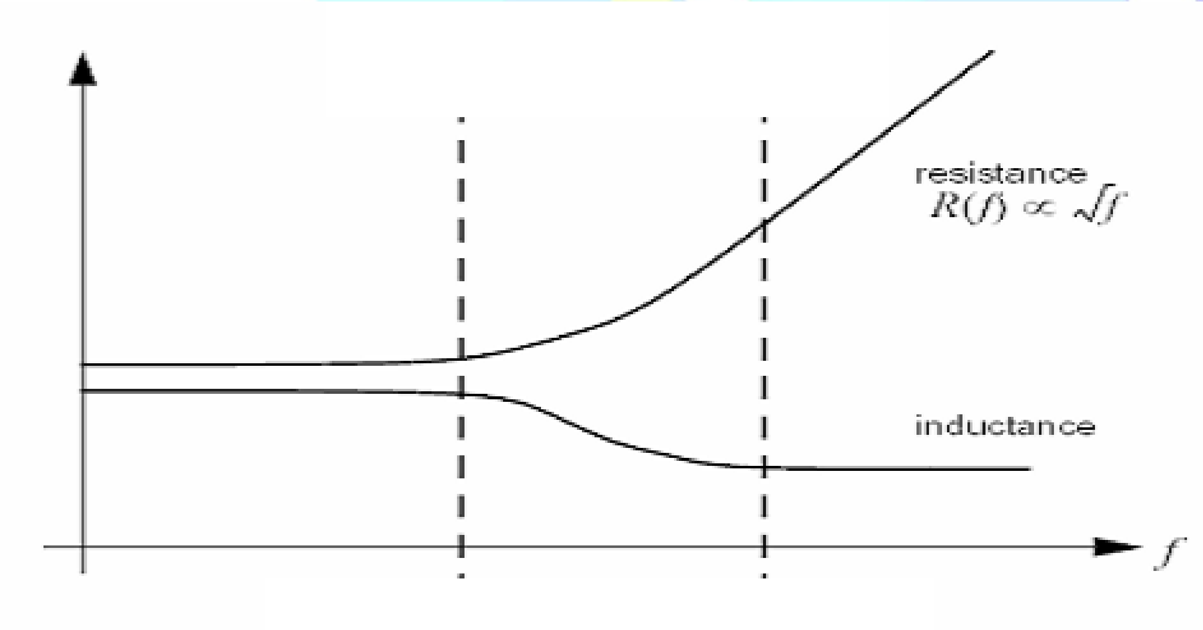
Mutual flux:

$$\Phi_{12} = \int_{S_2} \vec{B}_1 \cdot d\vec{s}_2 = L_{12} I_1$$

$$L = \frac{d\Phi}{dI}$$

Inductance: II

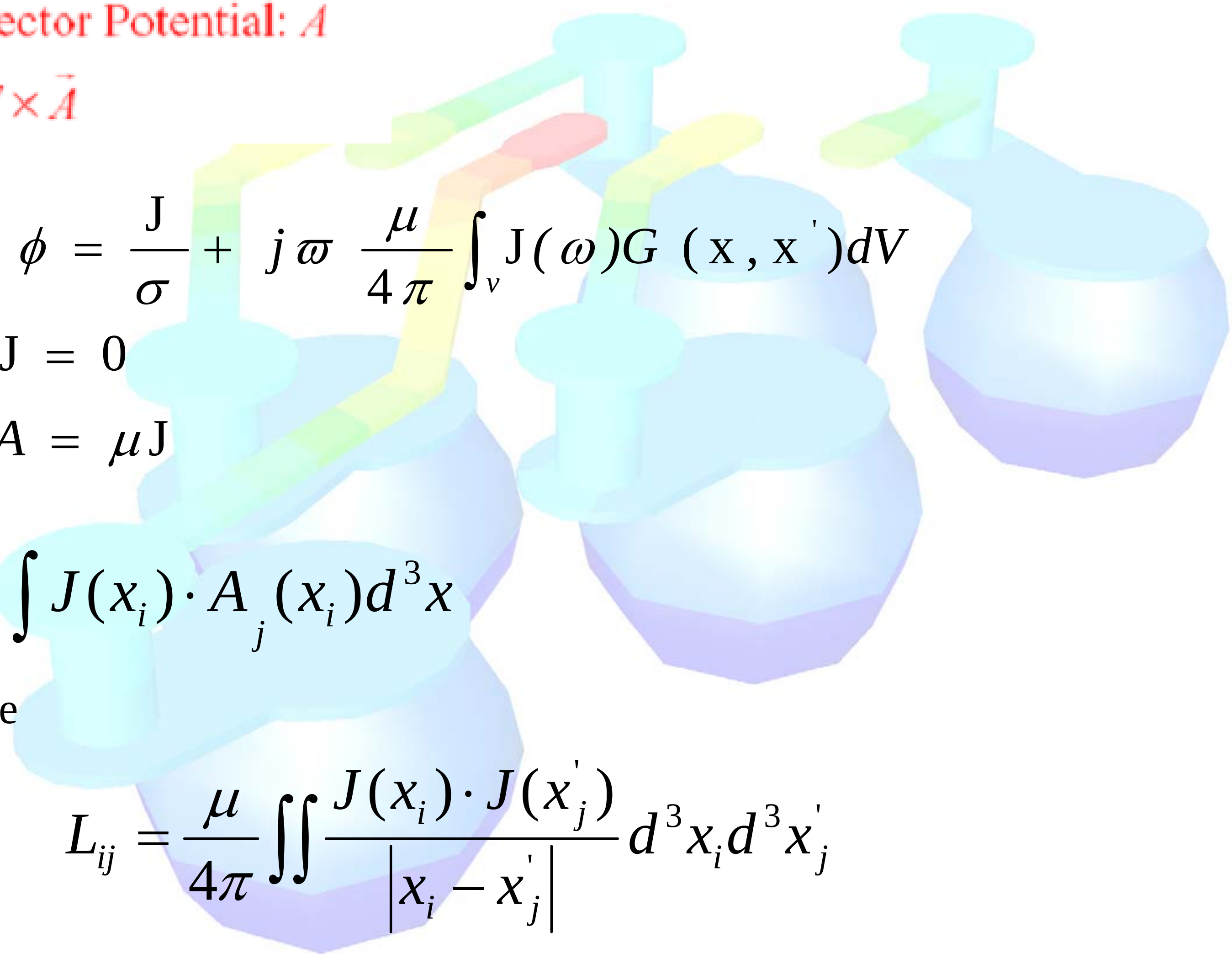
- Inductance
  - Total inductance including internal inductance and external inductance
  - Internal inductance changes due to skin effects
  - External inductance doesn't change w.r.t frequency



Inductance Calculation

Magnetic Vector Potential: $\vec{A}$

$$\vec{B} = \nabla \times \vec{A}$$



$$\begin{cases} -\nabla\phi = \dfrac{J}{\sigma} + j\varpi\dfrac{\mu}{4\pi}\int_v J(\omega)G(x,x')dV \\ \nabla\cdot J = 0 \\ \nabla^2 A = \mu J \end{cases}$$

$$L_{ij} = \int J(x_i)\cdot A_j(x_i)d^3x$$

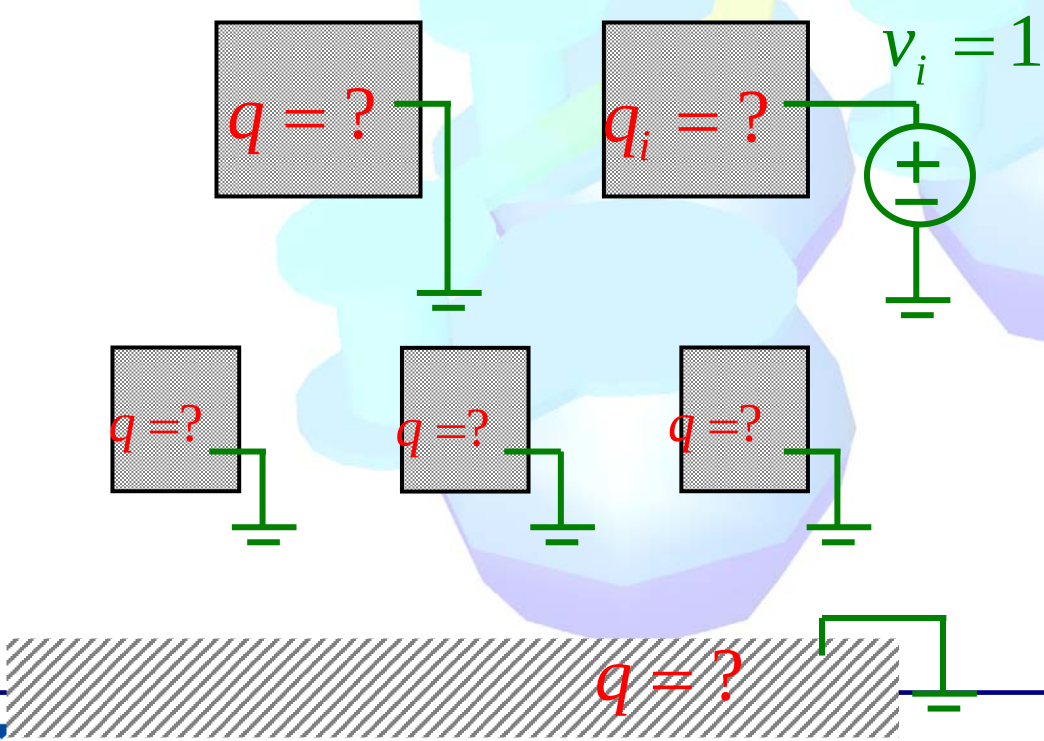
Infinite space

$$L_{ij} = \frac{\mu}{4\pi}\iint \frac{J(x_i)\cdot J(x_j^{'})}{\left|x_i - x_j^{'}\right|} d^3x_i d^3x_j^{'}$$

Capacitance Extraction
Solution Procedure

- For i = 1 to N,
  - apply one volt to conductor i and ground all the others
  - solve the electrostatic problem and find the resulting vector of charges on all conductors
  - that is the i-th column of the conductance matrix

$$\nabla^2 \phi = \frac{\rho}{\varepsilon}$$



$$\begin{bmatrix} \vdots & C_{1,i} & \vdots & \vdots \\ & C_{2,i} & & \\ & \vdots & & \\ & C_{N,i} & & \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ \vdots \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_N \end{bmatrix}$$

$$q_j = C_{ij} = -\oint \epsilon \nabla \Phi \cdot \vec{n} dA$$

Partial Inductance and PEEC

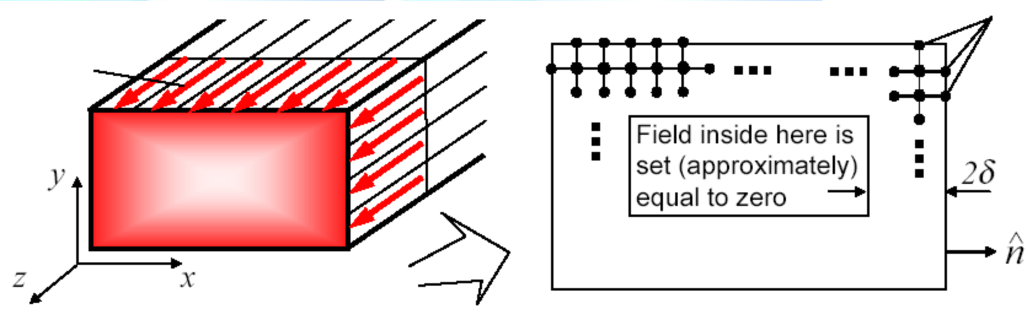
- PEEC = Partial Equivalent Element Circuit
- A loop can be broken into smaller sections
- Inductances can be computed for each section
- The loop can be re-generated with the partial inductances
- And the loop inductance can be calculated
- This is ***purely*** for calculation purposes

$$L = L_1 + L_2 - 2M$$

Quiz: How much is the inductance of a typical bondwire??

PEEC : I

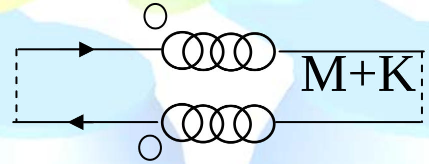
- Pros and Cons
  - Without prior knowledge of the return path, a current loop can be reconstructed
  - Can exactly evaluate the skin-depth effects by discretizing the conductors as a combination of many thin-wires (filaments)
  - Good for rectangular dominated geometry due to the filaments discretization (good applications: on-chip parasitic modeling)



  - High-cost, not feasible for high-end package extraction

PEEC: Non-uniqueness of PEEC

Loop of Wire

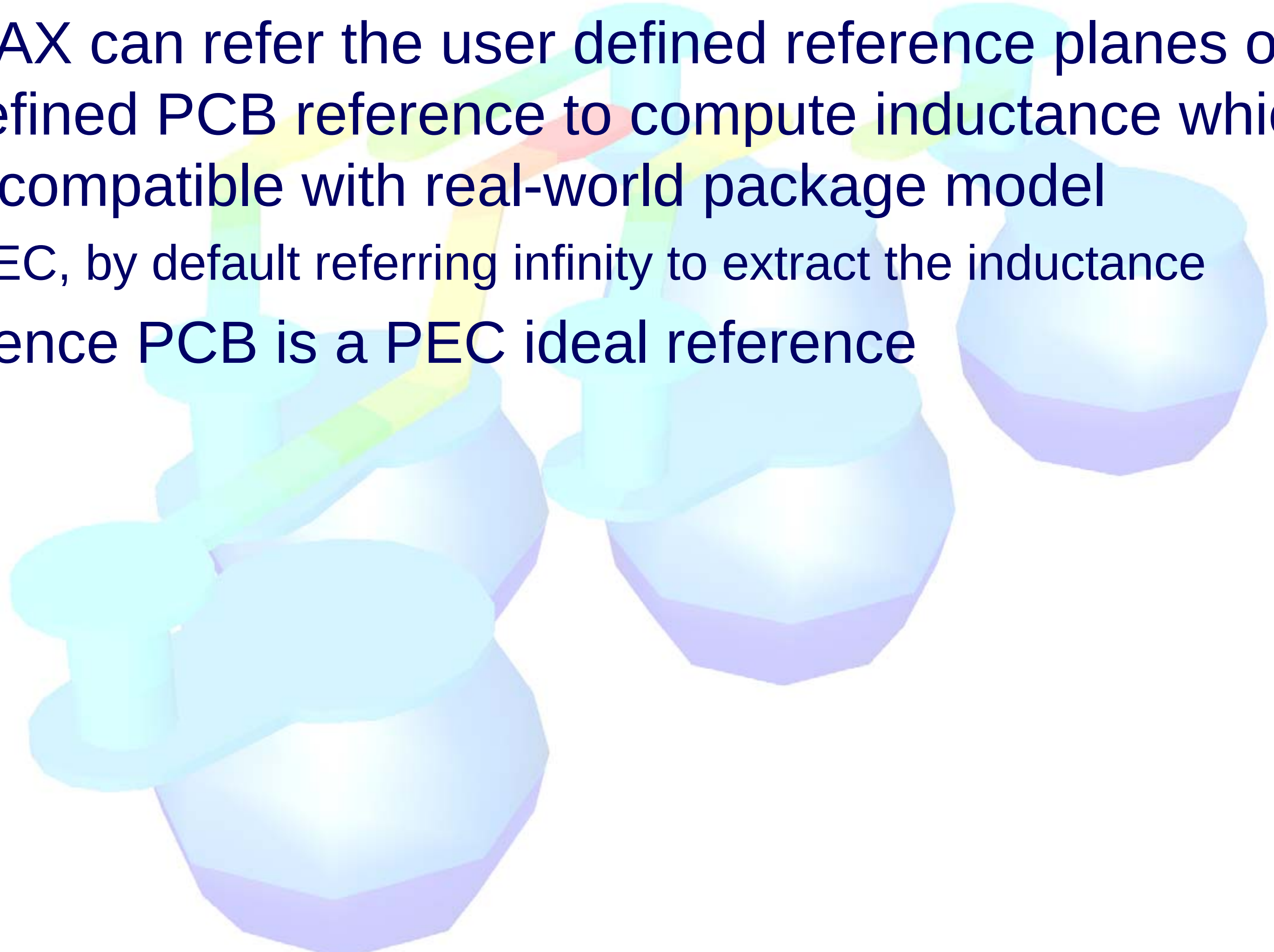


$$L = (L_1 + K) + (L_2 + K) - 2(M + K)$$

If a constant is added to the self and mutual inductance, loop inductance does not change.
However, ***loop inductance*** is always unique.

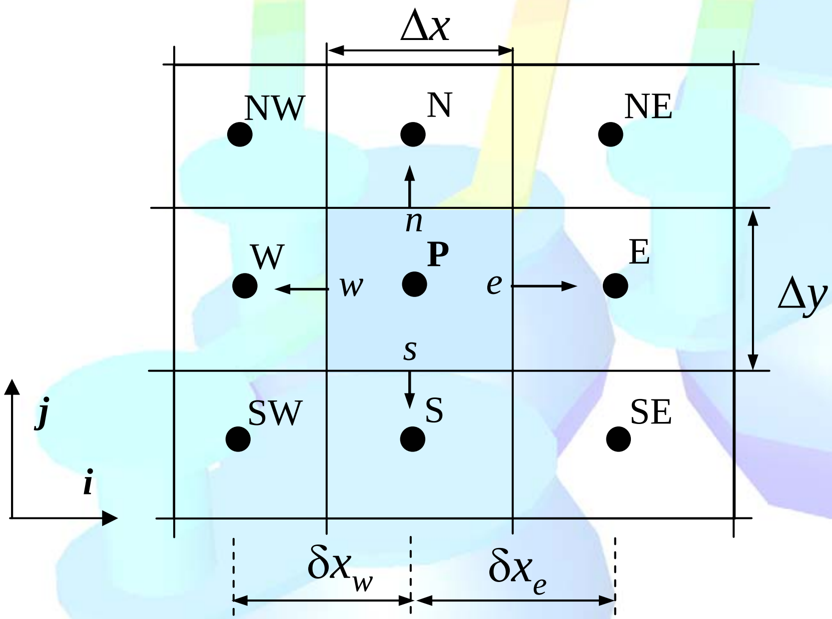
How ICEMAX Deals with Inductance

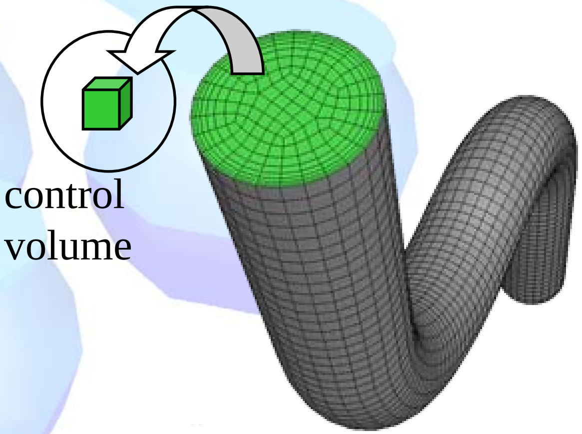
- ICEMAX can refer the user defined reference planes or/and the defined PCB reference to compute inductance which is more compatible with real-world package model
  - PEEC, by default referring infinity to extract the inductance
- Reference PCB is a PEC ideal reference



Numerical Tech – Finite Volume Method Overview

- **Finite volume method**
  - Domain is discretized into a finite set of control volumes or cells



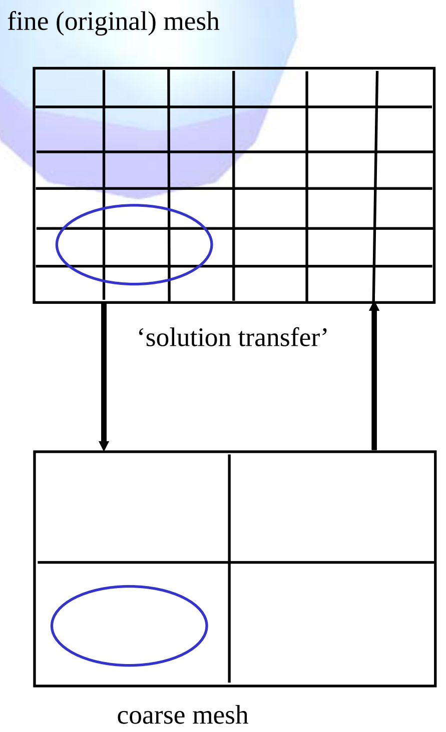


$$a_p\phi_p + \sum_{nb} a_{nb}\phi_{nb} = b_p$$

- The net flux through the control volume boundary is the sum of integrals over the four control volume faces (six in 3D).

Numerical Tech – Finite Volume Meshing

- Multigrid Acceleration
  - The Multigrid solver accelerates convergence by using solutions on coarse meshes as the starting point for solutions on finer meshes
    - Influence of boundaries and far-away points are more easily transmitted to interior of coarse mesh than fine mesh
    - Coarse mesh defined from original mesh
      - Multiple coarse mesh levels can be created
      - Final solution is for original mesh
  - Accelerates convergence for problems with
    - Large number of cells
    - Large cell aspect ratios
    - Large differences in properties



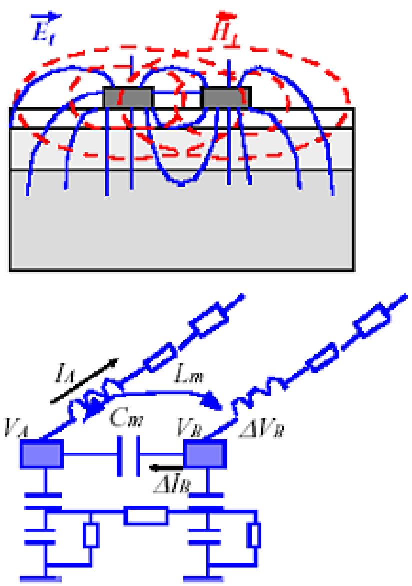
ICEMAX Critical Settings

- Grounding vs. Non-grouding G/P
  - Exclude G/P will ignore the ground/power plane nets while treating them as a non-ideal reference planes for signal nets.
  - Include G/P
    - IF the ground plane filter (which is based on how many solderballs are connected to the ground/power planes) setting is greater than the actual solderballs that the planes have, any ground/power nets will be treated as signal nets, thus the PEEC-like (referring to PCB) inductance will be calculated.
    - IF the ground plane filter setting is less than the actual solderballs that the planes have, any ground/power nets will be treated as a reference for signal nets, however, the self value of ground/power nets will be reported separately.
- Lumped vs. Distributed
  - Lumped setting reports any net as a single series RLC circuit
  - Distributed model either reports a model with respect to geometry discontinuities or an averaged distribution of the total RLC value
- Meshing settings

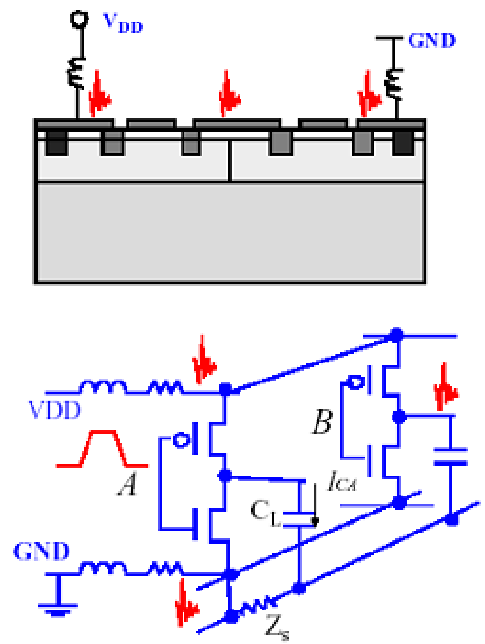
Applications of ICEMAX: Crosstalk

- Crosstalk
  - Two contributions: capacitive coupling and inductive coupling
  - The mutual capacitance and the mutual inductance plays important role

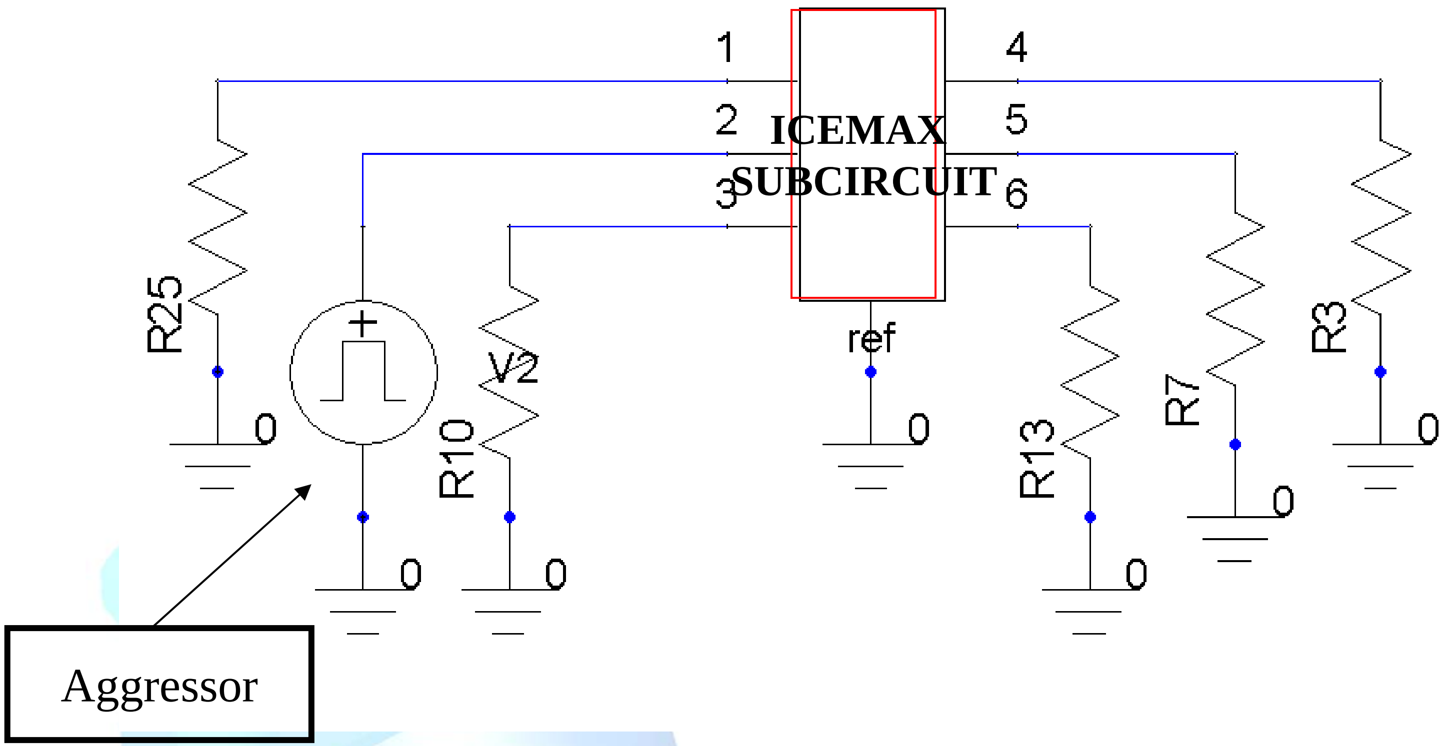
❑ Near Field Coupling



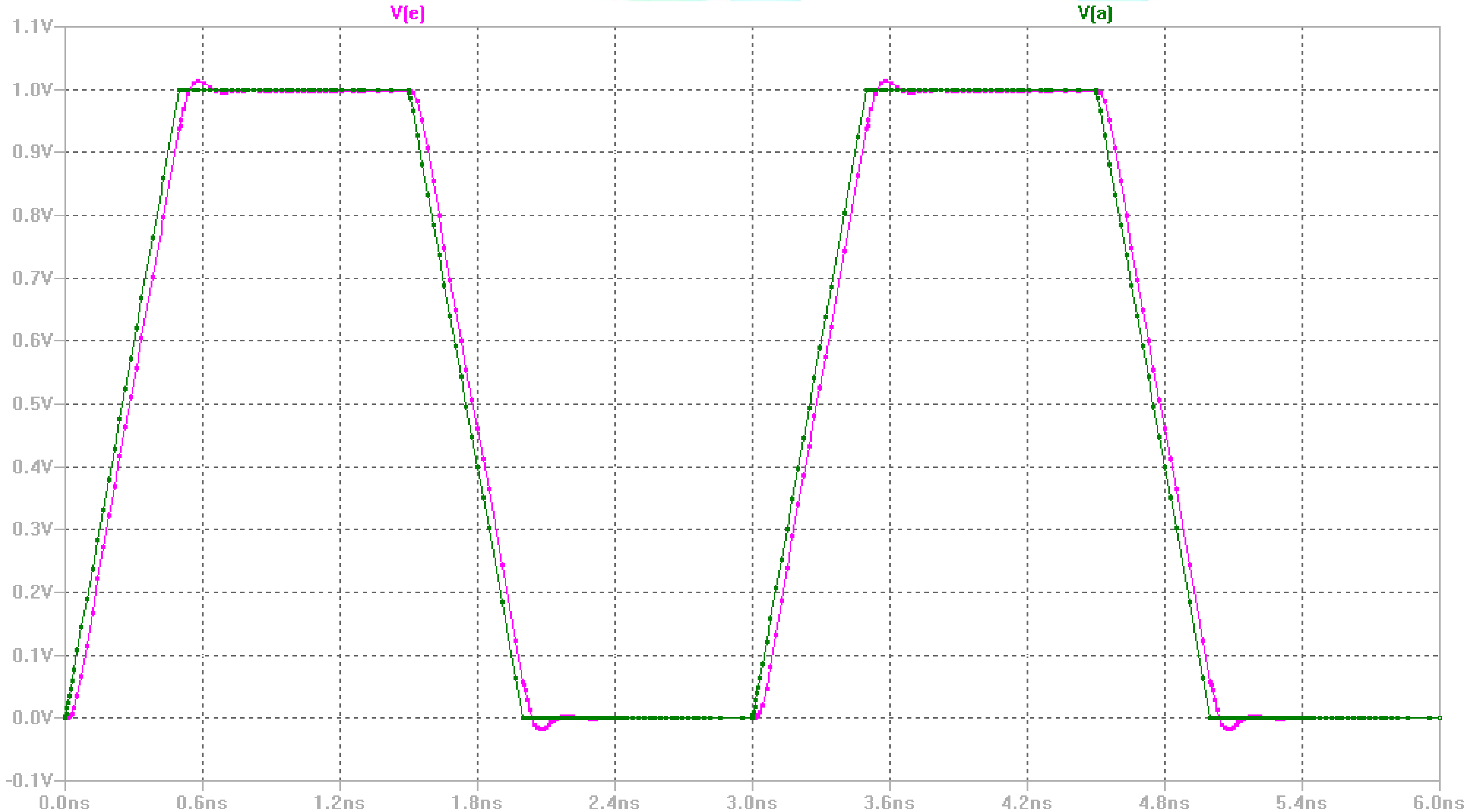
❑ Power/Ground Crosstalk
❑ Signal Return Crosstalk



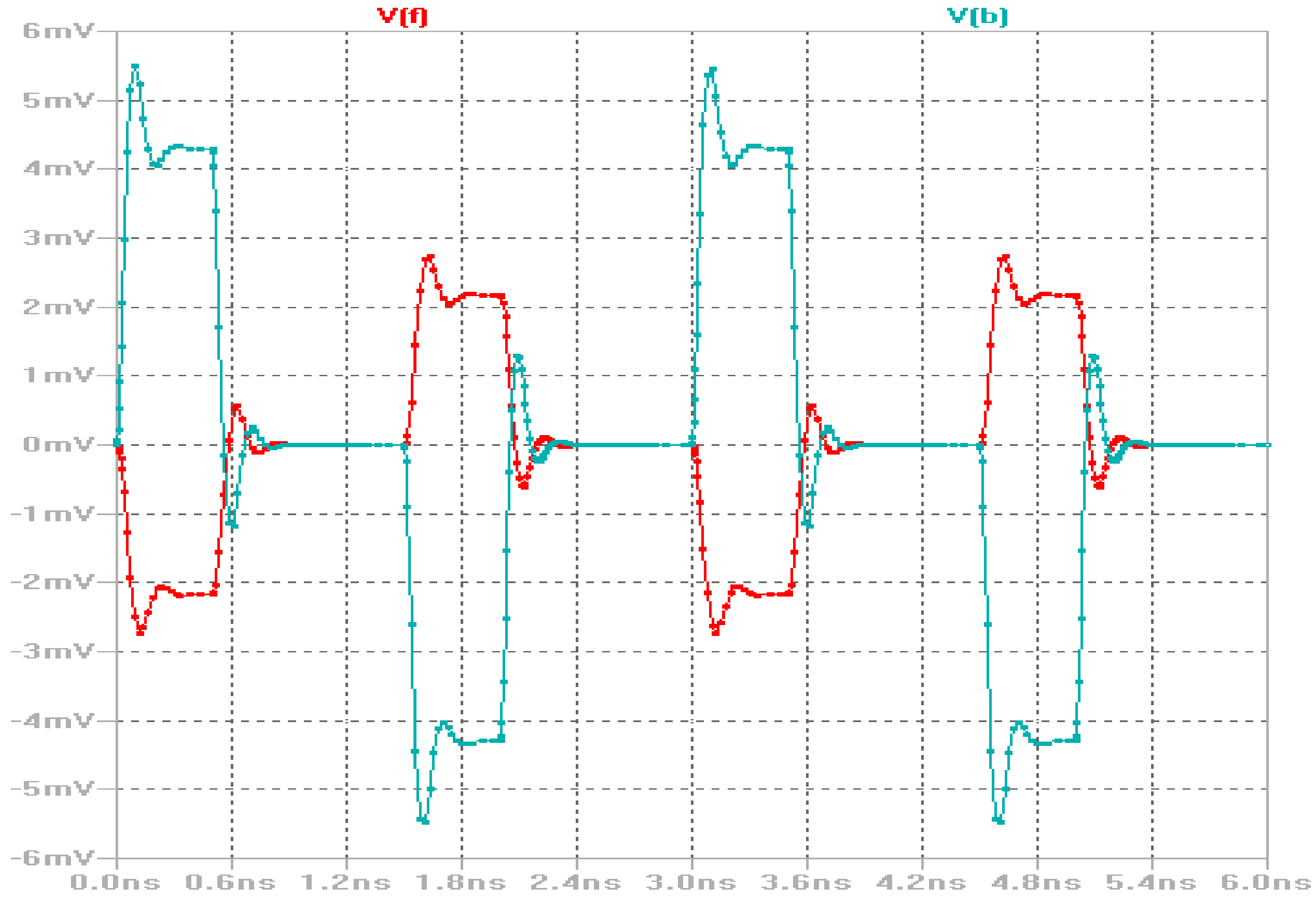
Crosstalk Example: 3 Coupled Nets



Aggressor Input and Output



Victim 1 Near-end and Far-end Crosstalk



icemax

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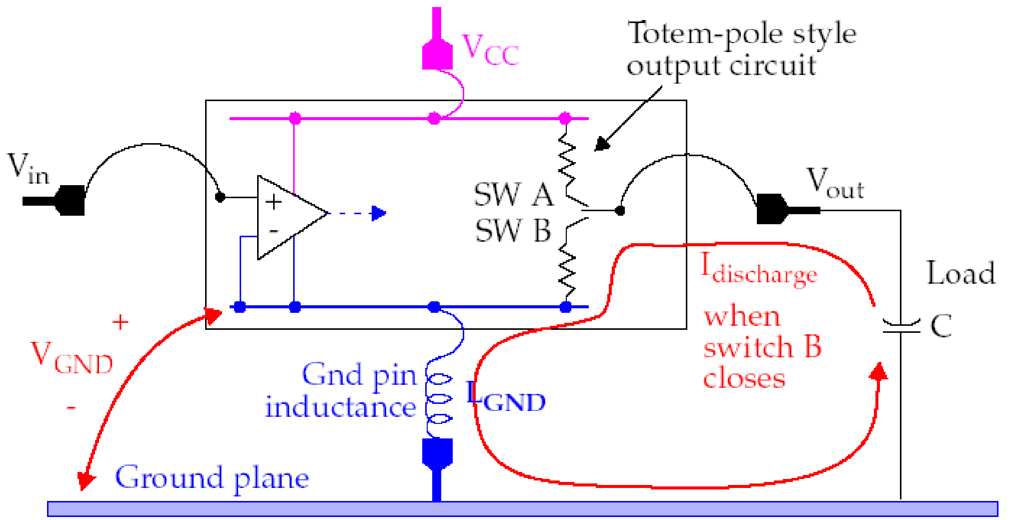
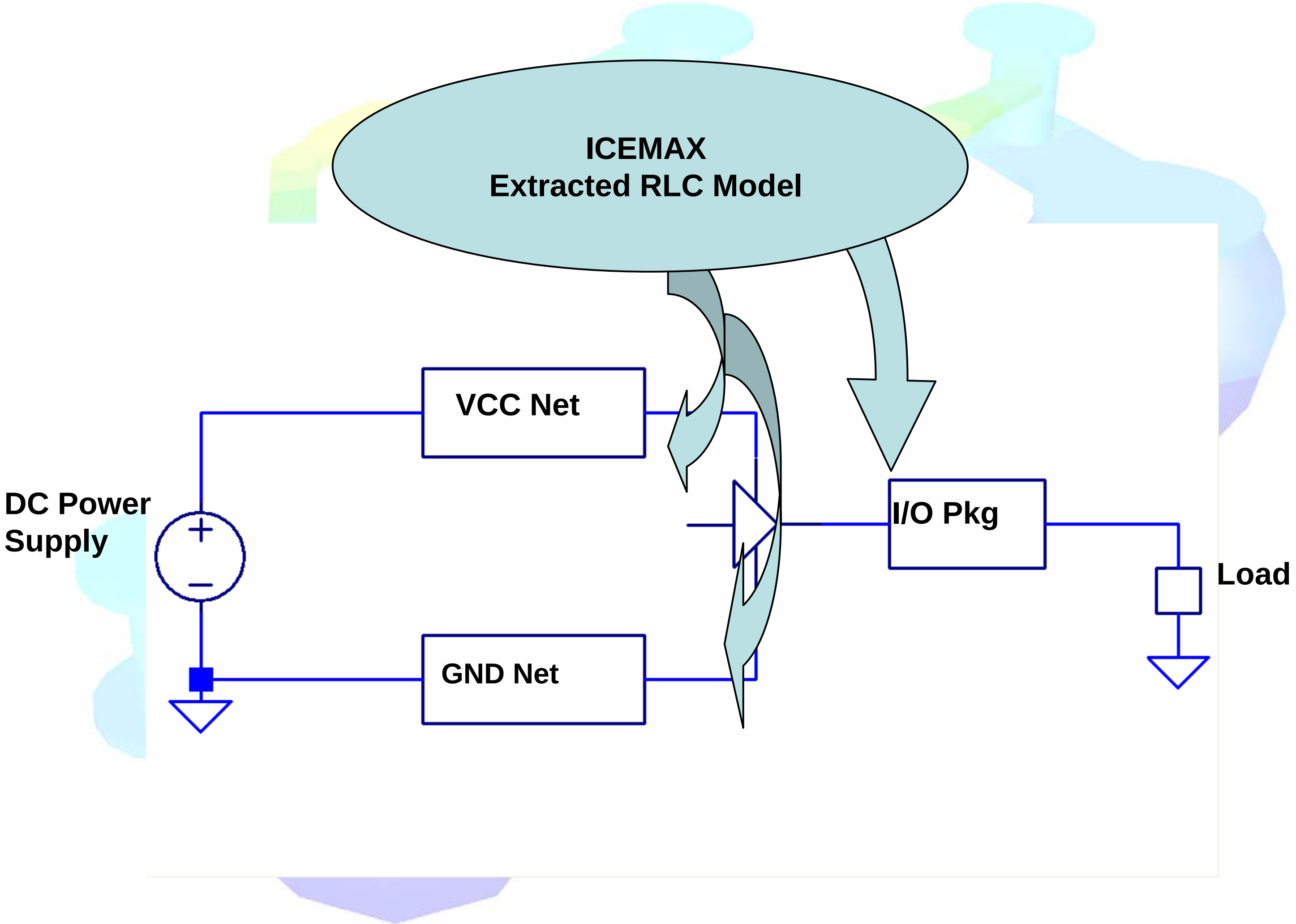
Application Example 2: SSN

- SSN is due to the non-ideal reference plane and ground/power connection effects



$$V_{GND} = L_{GND}\frac{dI_{discharge}}{dt}$$

Using ICEMAX Model for SSN



A Simple SSN Example