EELE 461/561 – Digital System Design

Module #5 – Crosstalk

- **Topics**
  1. Near-End and Far-End Crosstalk
  2. Simultaneous Switching Noise
- **Textbook Reading Assignments**
  1. 10.1-10.12, 10.18
- **What you should be able to do after this module**
  1. Calculate NEXT & FEXT
  2. Calculate ground bounce
  3. Use a modern CAD tool to extract crosstalk parameters for an interconnect structure

Crosstalk

- **Crosstalk**

  - Crosstalk (or X-talk) is when the switching on one signal causes noise on an adjacent line.

  - The Crosstalk can be due to Electric or Magnetic Field lines interacting with a neighboring line.

  - The term Crosstalk comes from the early analog phone lines where you could actually hear voices from neighboring lines due to EM coupling.

  - Cross talk is due to the capacitance and inductance between conductors, which we call:

    "Mutual Capacitance" (C_M)
    "Mutual Inductance" (L_M)

- **Superposition**

  - Crosstalk is based on the principle of Superposition where:

    1) Multiple signals can exist on the same line without interacting or effecting each other.

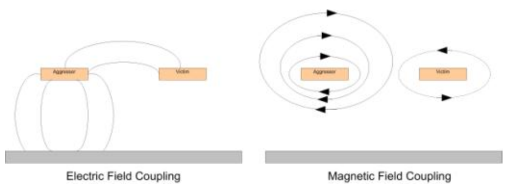
    2) An arbitrary signal can be coupled onto a line independent of what may already exist on that line.

Crosstalk

- **Crosstalk Terminology**

  - We call the switching signal the "Aggressor"

  - We call the line receiving the noise the "Victim"



Crosstalk

- **Crosstalk Classes**

  - There are two main classes of X-talk

    1) Signal X-talk

    - When C_M and L_M produce X-talk noise on the same order of magnitude
    - When the <u>signal path</u> is the reason for the X-talk
    - This is what we see on PCB's and on-chip traces

    2) Switching Noise

    - When the return path is highly inductive and the inductive noise dominates
    - When the inductance in the <u>return path</u> is the reason for the X-talk
    - This is what we see on packages and in connectors
    - This is also called:

      "Ground Bounce / Power Supply Droop"
      "Simultaneous Switching Noise (SSN)"
      "Simultaneous Switching Output (SSO) Noise"

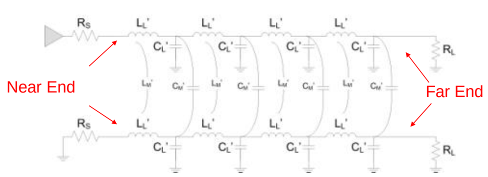
Crosstalk

- **Crosstalk Location**

  - There are two locations where we observe and define X-talk

    <u>Near End</u> - the location closest to the driving source resistor

    <u>Far End</u> - the location closest to the receiving termination resistor



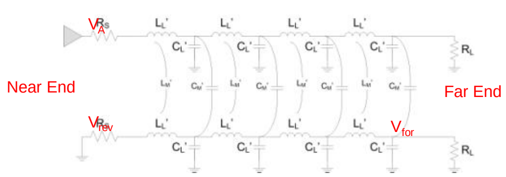
Crosstalk

- **Crosstalk Definitions**

  - We define parameters for X-talk based on a double terminated system.

    <u>NEXT</u> - Near End Crosstalk Coefficient (V_{rev}/V_A)

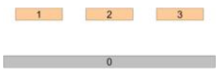
    <u>FEXT</u> - Far End Crosstalk Coefficient (V_{for}/V_A)



Crosstalk

- **SPICE Matrixes**

  - There can be multiple signal lines in a system
  - To keep track of their LC values, we use a matrix
  - Each signal is given an index, where ground is "0"
  - We define C_{11} as the self capacitance of signal 1 (and also for C22, C33, etc…)
  - We define C_{12} as the mutual capacitance between signals 1 and 2 (and also for C13, C23, etc.…)
  - In this system, C_{12} and C_{21} are equal
  - We then put all the values in a Matrix for easy record keeping
  - We do the same for the Inductances



$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$\begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix}$$

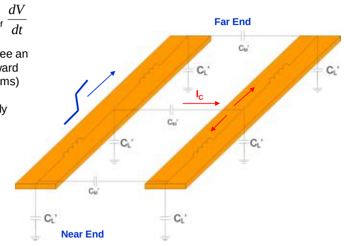
Crosstalk

- **Capacitive Crosstalk**

  - As the Aggressor Edge propagates down the line, it will inject current into the Victim line through the Mutual Capacitance following:

$$I_C = C_M \frac{dV}{dt}$$

  - As the current is injected, it will see an equal impedance in both the forward and reverse directions (i.e., 50ohms)
  - As a result, the current will equally split and half will travel forward and half will travel backwards



Crosstalk

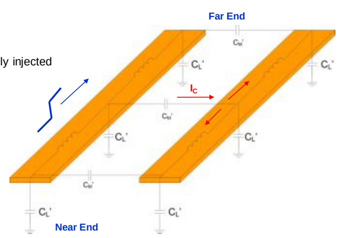
- **Capacitive Crosstalk**

  - The total amount of current injected at any given time is related to the *spatial extent* of the risetime
  - This can be described using the *per unit length* value for Mutual Capacitance (C_M')

$$C_M = C_M' \cdot \Delta x$$
$$C_M = C_M' (vel \cdot t_{rise})$$

  - The total amount of instantaneously injected current is then described by:

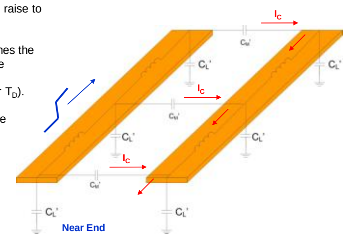
$$I_C = C_M \frac{dV}{dt}$$
$$I_C = C_M' \cdot (vel \cdot t_{rise}) \cdot \left(\frac{V}{t_{rise}}\right)$$
$$I_C = C_M' \cdot vel \cdot V$$



Crosstalk

- **Capacitive Crosstalk (Near End)**

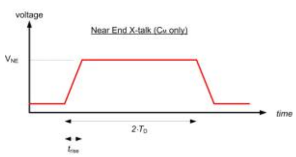
  - Half of the current injected into the victim as the incidence voltage step travels down the aggressor travels back to the Near End.
  - At any given time, only a fixed amount of current will be observed at the Near End
  - This means the Near End voltage will raise to a fixed value and remain there.
  - At the point the aggressor edge reaches the end of the line (T_D), the injected noise on the victim still needs to travel back to the Near-End (taking another T_D).
  - This means the fixed noise level at the Near End will remain for $2 \cdot T_D$



Crosstalk

- **Capacitive Crosstalk (Near End)**

  - This gives a voltage profile at the near-end as follows:



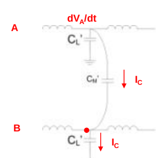
  - The maximum amount of current injected is reduced by a factor of 1/2 to account for the injected energy splitting in both the forward & reverse directions.
  - This current is further reduced by an additional factor of 1/2 to account for the energy being spread out over $2 \cdot T_D$

$$I_C = \left(\frac{1}{2}\right) \cdot \left(\frac{1}{2}\right) \cdot C_M' \cdot vel \cdot V = \left(\frac{1}{4}\right) \cdot C_M' \cdot vel \cdot V$$

Crosstalk

- **Capacitive Crosstalk (Near End)**

  - We can convert this into a ratio of Voltages by looking at KCL at an arbitrary point of injection.



  - a dV/dt occurs on the aggressor node which is seen across the C_L of the aggressor and C_M of the victim.

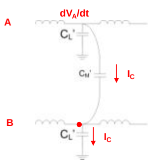
(NOTE: we assume that the victim line is at 0volts for our derivation)

Crosstalk

- **Capacitive Crosstalk (Near End)**

- this change in voltage causes a current to flow through C_M given by:

$$I_{C_M} = C_M \cdot \frac{dV}{dt} = C_M \cdot \frac{(0.8) \cdot V_A}{t_{rise}}$$



- when this current reaches the victim line and evaluate KCL, it instantaneously sees opens in the directions of the Inductors due to their high impedances at AC. As a result 100% of the current flows into C_L of the victim.

$$I_{C_M} = I_{C_L}$$

- This current in C_L then creates a dV/dt given by:

$$I_{C_L} = C_L \cdot \frac{dV}{dt} = C_L \cdot \frac{(0.8) \cdot V_B}{t_{rise}}$$

Crosstalk

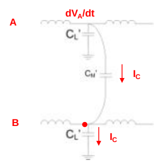
- **Capacitive Crosstalk (Near End)**

- we can now relate the magnitude of the voltage observed on the aggressor (V_A) to the voltage on the aggressor (V_B)

$$I_{C_M} = I_{C_L}$$

$$C_M \cdot \frac{(0.8) \cdot V_A}{t_{rise}} = C_L \cdot \frac{(0.8) \cdot V_B}{t_{rise}}$$

$$\frac{V_B}{V_A} = \frac{C_M}{C_L}$$



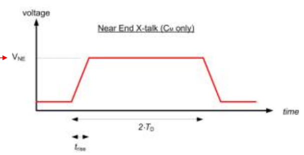
- this is the total voltage created at the injection point prior to the inductors beginning to conduct and allowing the current to flow in both the forward and reverse directions.

Crosstalk

- **Capacitive Crosstalk (Near End)**

- we now apply our 1/4 factor to come up with our final expression for the magnitude of the capacitively coupled voltage observed at the Near-End

$$\left(\frac{V_{NE}}{V_A}\right)_{C_M} = \frac{1}{4} \cdot \left(\frac{C_M}{C_L}\right)$$

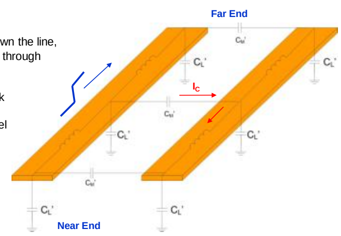


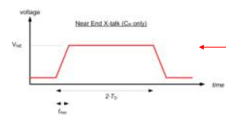
Crosstalk

- **Capacitive Crosstalk**

- As the Aggressor edge propagates down the line, it will inject current into the Victim line through the Mutual Capacitance

- We've derived the Near End Cross-talk due to Mutual Capacitance and saw that the voltage rises to a constant level and remains there for $2 \cdot T_D$





$$\left(\frac{V_{NE}}{V_A}\right)_{C_M} = \frac{1}{4} \cdot \left(\frac{C_M}{C_L}\right)$$

Crosstalk

- **Capacitive Crosstalk (Far End)**

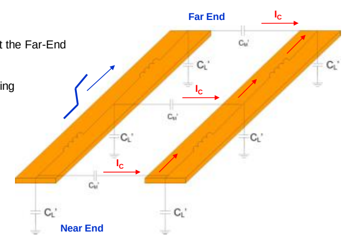
- Now we look at the Noise observed at the Far-End of the Victim line.

- This noise is due to the forward traveling current that is injected through C_M.

$$I_C = C_M \frac{dV}{dt}$$

$$I_C = C_M' \cdot (vel \cdot t_{rise}) \cdot \left(\frac{V}{t_{rise}}\right)$$

$$I_C = C_M' \cdot vel \cdot V$$



- 1/2 of this current travels forward toward the Far-End.

- The current noise is not seen until the Aggressor incident wave reaches the Far-End

Crosstalk

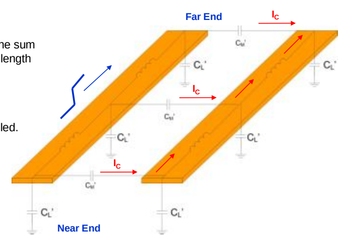
- **Capacitive Crosstalk (Far End)**

- The net voltage at the far end will be the sum of all of the injected current along the length of the coupled line.

- The TOTAL amount of current that is injected through C_M is proportional to the total length that the lines are coupled.

$$I_{C_{tot}} = C_M \frac{dV}{dt}$$

$$I_{C_{tot}} = C_M' \cdot (length) \cdot \left(\frac{0.8 \cdot V_A}{t_{rise}}\right)$$



Crosstalk

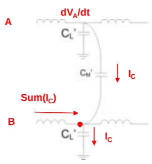
- **Capacitive Crosstalk (Far End)**

  - All of the current that is injected into the victim line will add together and be injected into the last C_L segment of the Victim at the Far-End

  - The current in the last segment is described as:

$$I_{C_L} = C_L^{'} \cdot \Delta x \cdot \frac{dV}{dt}$$

$$I_{C_L} = C_L^{'} \cdot (vel \cdot t_{rise}) \cdot \frac{(0.8) \cdot V_B}{t_{rise}}$$



Crosstalk

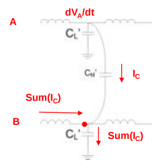
- **Capacitive Crosstalk (Far End)**

  - We can now relate the total current injected along the line to the voltage induced at the Far-End using:

$$I_{C_M} = I_{C_L}$$

$$C_M^{'} \cdot (length) \cdot \left(\frac{0.8 \cdot V_A}{t_{rise}}\right) = C_L^{'} \cdot (vel \cdot t_{rise}) \cdot \frac{(0.8) \cdot V_B}{t_{rise}}$$

$$\left(\frac{V_B}{V_A}\right)_{FE} = \left(\frac{length}{vel \cdot t_{rise}}\right) \cdot \left(\frac{C_M}{C_L}\right)$$

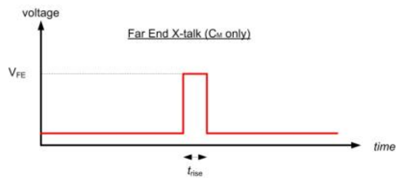


Crosstalk

- **Capacitive Crosstalk (Far End)**

  - We now apply our factor of 1/2 to account for the forward and reverse traveling current and we get:

$$\left(\frac{V_{FE}}{V_A}\right)_{C_M} = \frac{1}{2} \cdot \left(\frac{length}{vel \cdot t_{rise}}\right) \cdot \left(\frac{C_M}{C_L}\right)$$



NOTE: The magnitude of FE X-talk can get very large because it is proportional to coupled length and inversely proportional to t_{rise}

Crosstalk

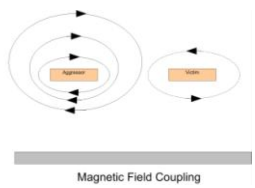
- **Inductive Crosstalk**

  - Magnetic Fields exist as the current travels down the Aggressor line.

  - These B-field lines induce B-field lines around the Victim line, which in turn creates current.

  - The direction of the B-field lines in the Aggressor follow the Right-Hand-Rule.

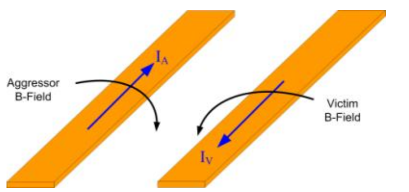
  - The direction of the B-field lines in the Victim are opposite of the Aggressor.



Crosstalk

- **Inductive Crosstalk**

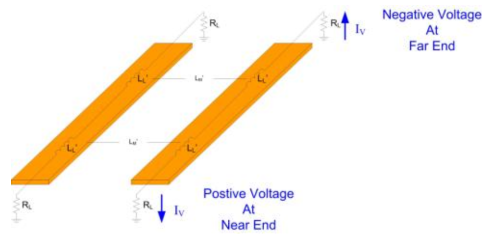
  - The B-Field lines induced on the Victim create a current that flows in the opposite direction of the Aggressor current.



Crosstalk

- **Inductive Crosstalk**

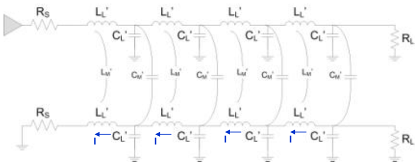
  - The direction of the induced current creates a Negative Voltage at the Far-End and a Positive Voltage at the Near-End as it flows through the termination impedances.



Crosstalk

- **Inductive Crosstalk (Near End)**

  - Just as in Near-End Capacitive X-talk, the currents that are induced by the inductive coupling will travel back to the Source (or Near End) over a time span of $2 \cdot T_D$



Crosstalk

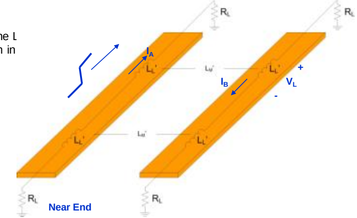
- **Inductive Crosstalk (Near End)**

  - The current that flows through the self inductance of the Aggressor line causes a voltage on the Victim line as follows:

$$V_M = L_M \cdot \frac{dI_A}{dt}$$

  - This voltage appears across the L inductance of the Victim which in causes a current to flow:

$$V_L = L_L \cdot \frac{dI_B}{dt}$$



Crosstalk

- **Inductive Crosstalk (Near End)**

  - Since the coupled voltage (V_M) is the same as the Victim line voltage (V_L) which creates the current, we can relate the currents of the Aggressor and Victim.

$$V_M = V_L$$

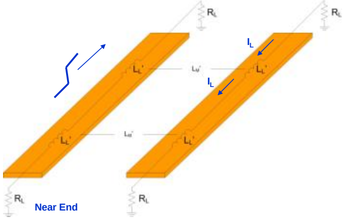
$$L_M \cdot \frac{dI_A}{dt} = L_L \cdot \frac{dI_B}{dt}$$

$$L_M \cdot \frac{I_A}{t_{rise}} = L_L \cdot \frac{I_B}{t_{rise}}$$

  - This can be converted to voltage by multiplying the current by the impedance (which is the same in both lines):

$$L_M \cdot \frac{I_A \cdot Z}{t_{rise}} = L_L \cdot \frac{I_B \cdot Z}{t_{rise}}$$

$$L_M \cdot \frac{V_A}{t_{rise}} = L_L \cdot \frac{V_B}{t_{rise}}$$



Crosstalk

- **Inductive Crosstalk (Near End)**

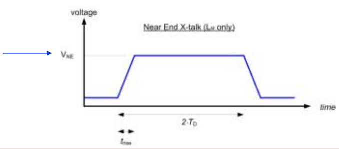
  - Now we have a relationship between the Aggressor and Near-End Victim Voltages:

$$L_M \cdot \frac{V_A}{t_{rise}} = L_L \cdot \frac{V_B}{t_{rise}}$$

$$\frac{L_M}{L_L} = \frac{V_B}{V_A}$$

  - We now apply a factor of 1/2 for the forward/reverse traveling current and 1/2 to account for the energy being split out over $2 \cdot T_D$

$$\left(\frac{V_{NE}}{V_A}\right)_{L_M} = \frac{1}{4} \cdot \left(\frac{L_M}{L_L}\right)$$



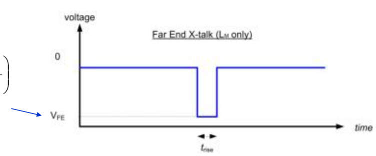
Crosstalk

- **Inductive Crosstalk (Far End)**

  - The exact derivation is applied to the Far-End inductive Xtalk to derive the maximum amount of noise due to Inductive coupling.

  - The only difference is that the magnitude of the Far-End noise is **NEGATIVE**.

$$\left(\frac{V_{FE}}{V_A}\right)_{L_M} = -\frac{1}{2} \cdot \left(\frac{length}{vel \cdot t_{rise}}\right) \cdot \left(\frac{L_M}{L_L}\right)$$



Crosstalk

- **NEXT**

  - We can combine all of the coupling at the Near-End to come up with the

    Near End Crosstalk Coefficient (NEXT)

$$NEXT = \left(\frac{V_{NE}}{V_A}\right) = \frac{1}{4} \cdot \left(\frac{C_M}{C_L} + \frac{L_M}{L_L}\right) = k_b$$

  - We define k_b *as the Backward Coefficient* which is only in terms of intrinsic values.

Crosstalk

- **FEXT**

- We can combine all of the coupling at the Far-End to come up with the

Far End Crosstalk Coefficient (FEXT)

$$FEXT = \left(\frac{V_{FE}}{V_A}\right) = \frac{1}{2}\cdot\left(\frac{length}{vel\cdot t_{rise}}\right)\cdot\left(\frac{C_M}{C_L} - \frac{L_M}{L_L}\right)$$

- We define k_f as the *Forward Coefficient* which is only in terms of intrinsic values.

$$k_f = \frac{1}{2\cdot vel}\cdot\left(\frac{C_M}{C_L} - \frac{L_M}{L_L}\right)$$

where,

$$FEXT = \left(\frac{length}{vel\cdot t_{rise}}\right)\cdot k_f$$

Crosstalk

- **Total X-talk**

- If we look at NEXT, we see that:

$$NEXT = \left(\frac{V_{NE}}{V_A}\right) = \frac{1}{4}\cdot\left(\frac{C_M}{C_L} + \frac{L_M}{L_L}\right) = k_b$$

1) Near End X-talk doesn't depend on risetime
2) Near End X-talk is always positive (for a rising edge on the Aggressor)

- If we look at FEXT, we see that:

$$FEXT = \left(\frac{V_{FE}}{V_A}\right) = \frac{1}{2}\cdot\left(\frac{length}{vel\cdot t_{rise}}\right)\cdot\left(\frac{C_M}{C_L} - \frac{L_M}{L_L}\right)$$

1) Far End X-talk depends on coupled length and t_{rise}
2) FE X-talk can actually **cancel** if the ratios of Capacitance and Inductance are equal

- NOTE: this cancellation occurs if all of the field lines are contained within a homogenous dielectric.

Crosstalk

- **Scaling Near-End X-talk**

- If the coupled length of the T-line is shorter than the risetime, the peak value of NEXT will not reach its maximum value.

- We scale the maximum value that it will reach using:

$$NE_{scaling} = \frac{\text{Length of Coupled Region}}{\text{Length of Risetime}}$$

- Risetime is converted to *Length* using:

$$length_{rise} = vel\cdot t_{rise}$$

Crosstalk

- **Switching Noise**

- We've covered the 1st class of X-talk (Signal X-talk)

- Now we turn to the 2nd class of Crosstalk:

2) Switching Noise

- When the return path is highly inductive and the inductive noise dominates
- When the inductance in the return path is the reason for the X-talk
- This is what we see on packages and in connectors
- This is also called:

"Ground Bounce / Power Supply Droop"

or

"Simultaneous Switching Noise (SSN)"

or

"Simultaneous Switching Output (SSO) Noise"

Crosstalk

- **Switching Noise**

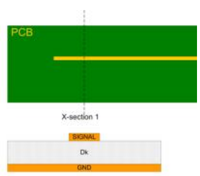
- When we derived the LC model of a transmission line, we assumed that the ground (or return path) was a perfect conductor.

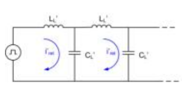
- That allowed us to model the ground with a simple wire.

- This is reasonable in a transmission line when the ground conductor is much larger than the signal conductor.

Ex) PCB trace:

- the signal sees an *infinite* ground plane beneath it.





Crosstalk

- **Switching Noise**

- When the signal travels through connectors or packages, the shape of the return path changes.

- This typically results in a return path with the same geometry as the signal.

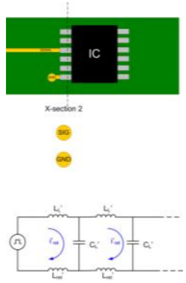
Crosstalk

- **Switching Noise**

  - This means we need to model the return path's electrical properties.

  - The capacitance between the signal and ground is already present in our LC model.

  - However, we need to add an inductive component into the return path for an accurate model

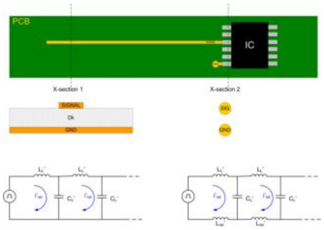


Crosstalk

- **Switching Noise**

  - This geometry change in the conductors results in a highly inductive path that the current needs to flow through.

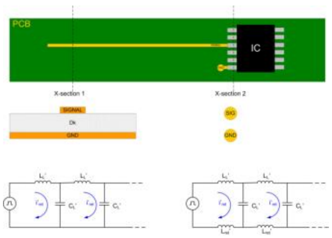
  - In addition, the capacitance typically is reduced due to the surface area of the connector/package being less than in the trace section of the link.



Crosstalk

- **Switching Noise**

  - This inductive interconnect is the source of *Switching Noise*

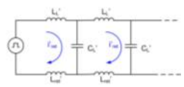


Crosstalk

- **Switching Noise (Ground Bounce)**

  - The return current that passes through the inductive interconnect causes a voltage to form following:

$$V_N = L_{ret} \cdot \frac{dI_A}{dt}$$



  - This voltage changes the ground potential of the integrated circuit relative to the ground of the system which gives the name *Ground Bounce*

Crosstalk

- **Switching Noise (Ground Bounce)**

  - This becomes a more critical problem when signals in packages and connectors share a common return pin.

  - It is cost effective to reduce the pin count of packages/connectors by sharing ground pins.

  - However, the Ground Bounce now becomes proportional to the # of signal lines using that return pin.

$$V_N = \left(L_{ret} \cdot \frac{dI_A}{dt} \right) \cdot (\text{\# of signals})$$

  - This can be related to voltage by using V=IZ

$$V_N = \left(L_{ret} \cdot \frac{0.8 \cdot V_A}{t_{rise} \cdot Z_0} \right) \cdot (\text{\# of signals})$$

Crosstalk

- **Switching Noise (Ground Bounce)**

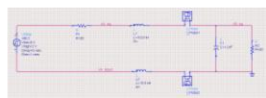
  - ex) L_{ret} = 10nH
    t_{rise}=800ps
    Z_0=50Ω

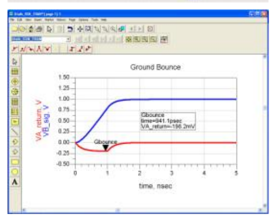
$$V_{Gbounce} = \left(L_{ret} \cdot \frac{0.8 \cdot V_A}{t_{rise} \cdot Z_0} \right) \cdot (\text{\# of signals})$$

$$V_{Gbounce} = \left(10n \cdot \frac{0.8 \cdot 1}{800p \cdot 50} \right) \cdot (1)$$

$$V_{Gbounce} = -0.2v$$

  - a positive dv/dt causes current to flow back to the source. The inductor acts as a passive element in this case so the voltage induced causes the source ground to become negative.





Crosstalk

- **Switching Noise (Mutual Inductance)**

  - there is also mutual inductance that couples between the signal inductance and the return path inductance.

  - in this case, the inductor acts as a voltage source in the return path, which creates a voltage in the opposite polarity as the noise caused by the return current.

  - this actually has the result of *decreasing* the total inductive ground bounce noise and can be a good thing.

  - however, this is a secondary effect compared to the noise generated when multiple signals share a common return path.

Crosstalk

- **Switching Noise (Mutual Inductance)**

  - ex) L_{ret} = 10nH
    L_M=2.5nH
    t_{rise}=800ps
    Z_0=50Ω

$$V_{NM} = \left(L_M \cdot \frac{0.8 \cdot V_A}{t_{rise} \cdot Z_0} \right)$$

$$V_{NM} = \left(2.5n \cdot \frac{0.8 \cdot 1}{800p \cdot 50} \right)$$

$$V_{NM} = +0.05v$$

- Mutual inductive coupling causes the return inductor to act as a voltage source so the resultant voltage is opposite in polarity to the return noise. The total voltage in this case is: -0.2 + 0.05 = -0.15v