Applied Electronics

C7 – Signal Integrity

- Crosstalk
- Techniques to limit crosstalk
- Switching noise
- Bypass Capacitors

Lecture C7: Signal integrity

- Crosstalk
  - Capacitive and inductive couplings
  - Direct and reverse crosstalk
  - Techniques to reduce crosstalk
- Switching noise
  - Ground distribution and power supply
  - Techniques for reducing switching noise
  - Bypass capacitors
- References
  - D. Del Corso: Telecommunication Electronics: Ch. 5.2.10

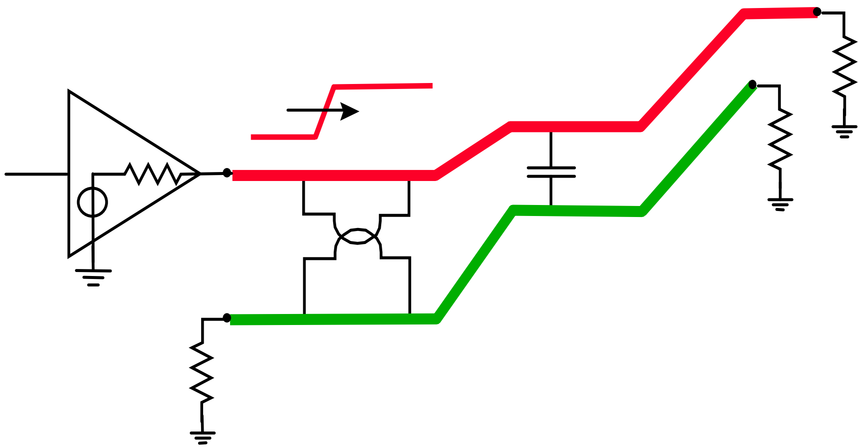
Crosstalk

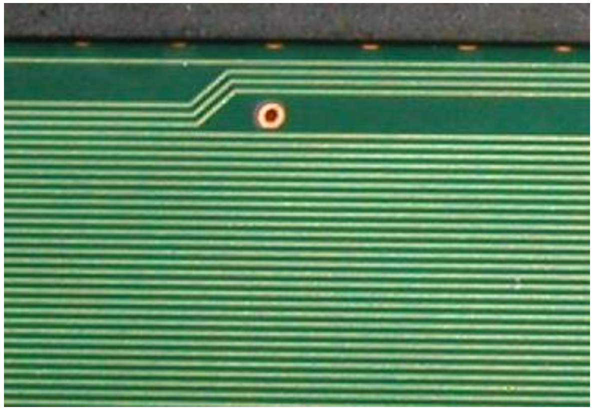
- Crosstalk
  - ♦ Signal passing between two “channels”
    - Separated by space, time, encodings, ...
- Between different conductors:
  - ♦ Inductive and capacitive couplings (rarely resistive)
- On the same conductor (GND, signals, supply)
  - ♦ Coupling for common traces
  - ♦ Power impulse currents disturb the signals
- In time domain
  - ♦ “Code” in symbols → Intersymbol Interference (ISI)

Coupling between conductors

Adjacent conductors have

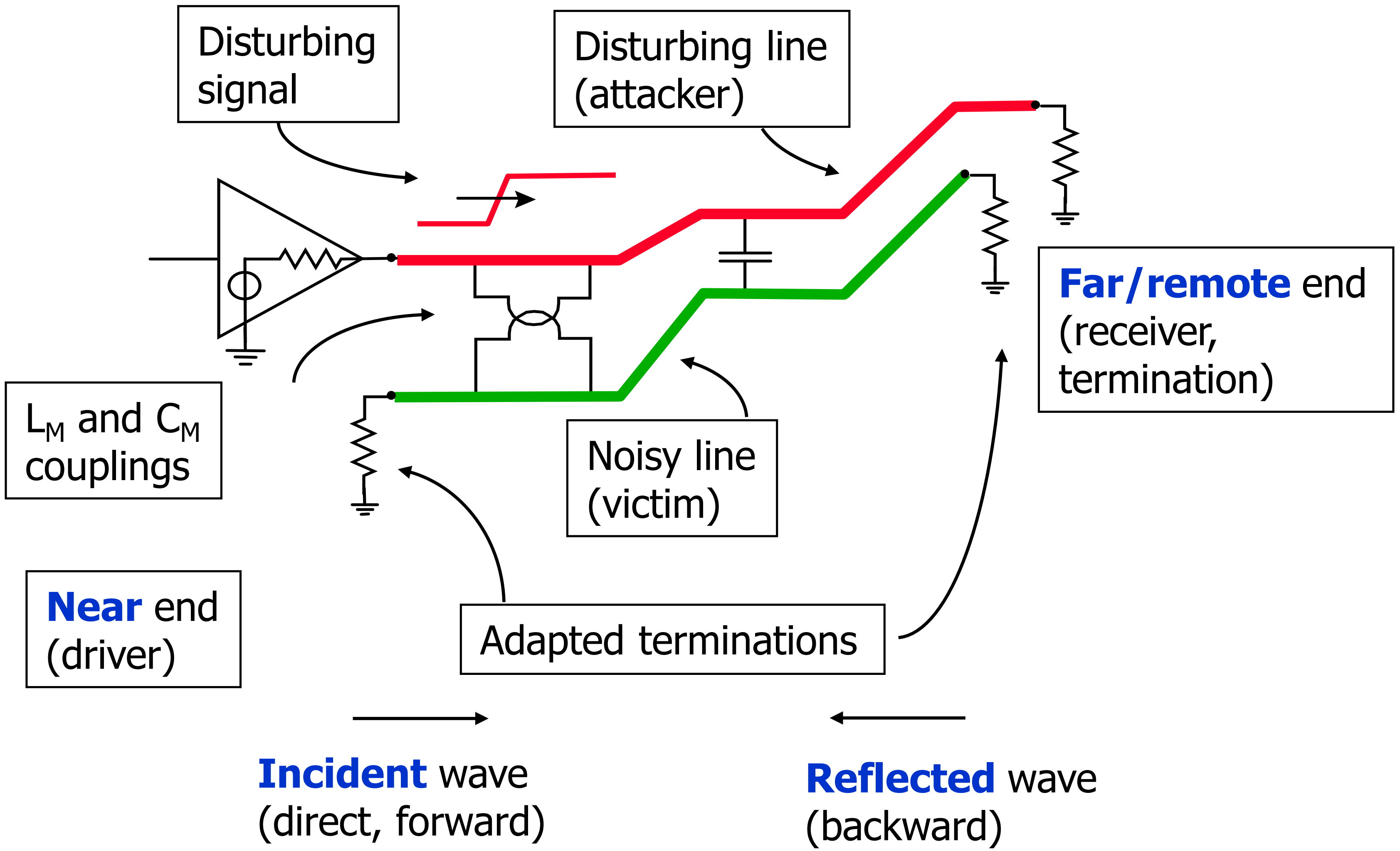
- Inductive couplings
  - L_M – mutual inductance
- Capacitive couplings
  - C_M – mutual capacitance





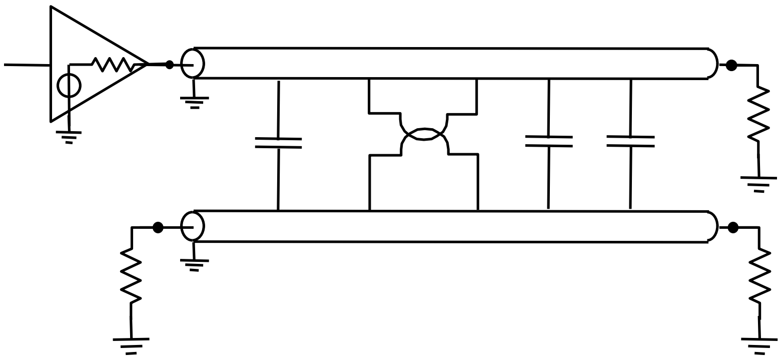
L_M and C_M are distributed over the whole conductor length

Terminology

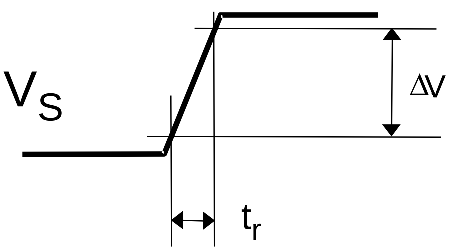


System model and signals

- Line model
  - ♦ Two lines adapted to the driver and the termination, with mutual inductance L_M and mutual capacitance C_M

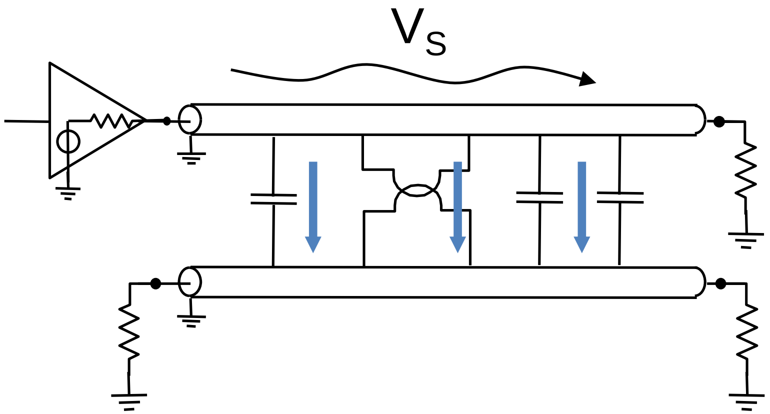


- Disturbing signal (V_S)
  - ♦ Trapezoidal shape (finite dv/dt)



Coupling parameters

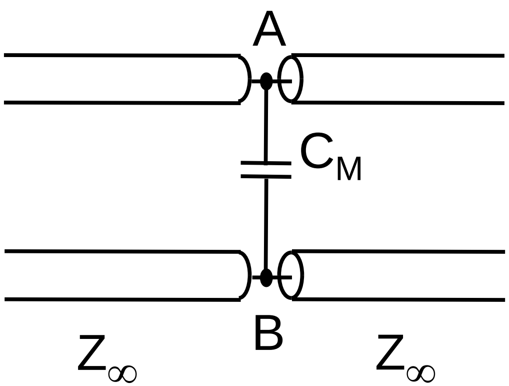
- The V_S signal propagates along the *top line*
- Inductive couplings (L_M) and capacitive (C_M) generate noise in the *bottom line*
- Noise is related to
  - Edge slopes of the disturbing signal (dV_S/dt, dI_S/dt)
  - Mutual inductance L_M
  - Mutual capacitance C_M

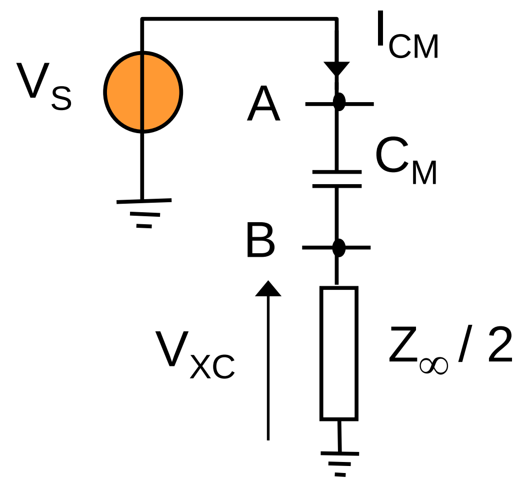


Capacitive coupling model

- Capacitive couplings inject a current I_{CM} that causes a voltage variation proportional to dV_S/dt

$$V_{XC} = Z_\infty / 2\, I_{CM} = Z_\infty / 2\, C_M\, dV_S / dt \quad (V_B \text{ constant})$$

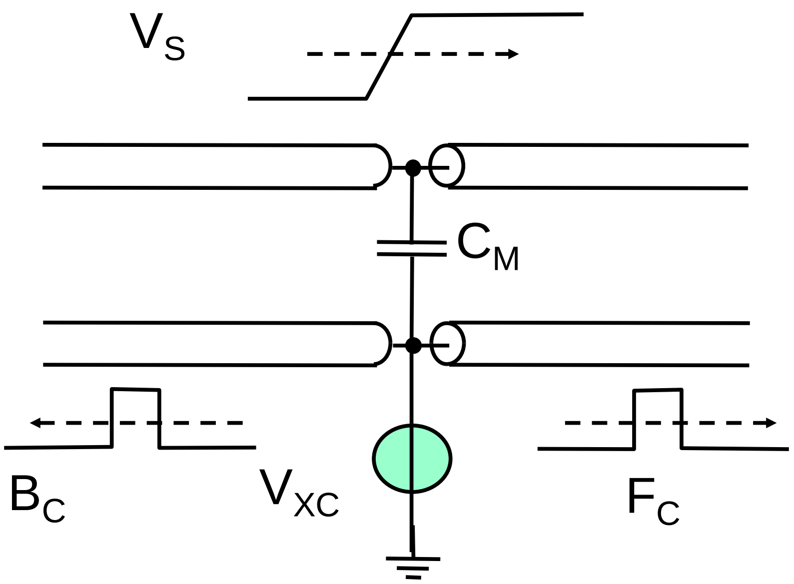




Effect of capacitive coupling

- V_{XC} has the same sign as the disturbing signal
- V_{XC} propagates with the same polarity in both directions

V_{XC} pulse width is equal to the rise time of V_S



Overall effect C_M and L_M

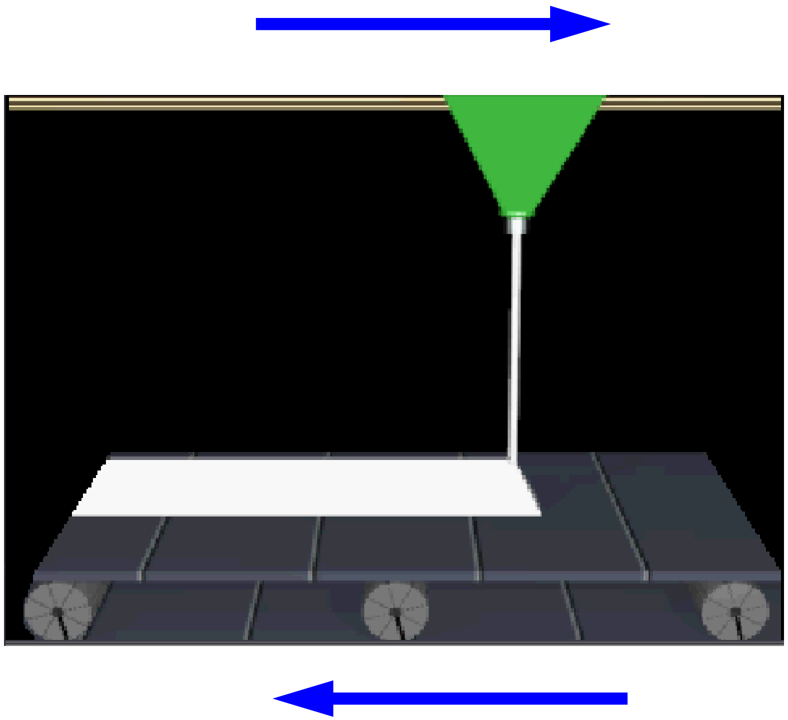
- Inductive coupling (L_M): V_{X_L} is similar to V_{X_C}
  - Total noise: sum of the two effects
- Progressive wave (V_P) towards the termination, $\rightarrow$
  - $V_\mathrm{P} = \left(V_{X_C} - V_{X_L}\right)/2$
- Regressive wave (V_R) towards the driver, $\leftarrow$
  - $V_\mathrm{R} = \left(V_{X_C} + V_{X_L}\right)/2$
- V_{X_L} and V_{X_C} have opposite signs in progressive wave
  - The two contributions can compensate each other
- Equal propagation speed
  - Equal to the propagation speed of electromagnetic waves in that conductor

Sum of noise

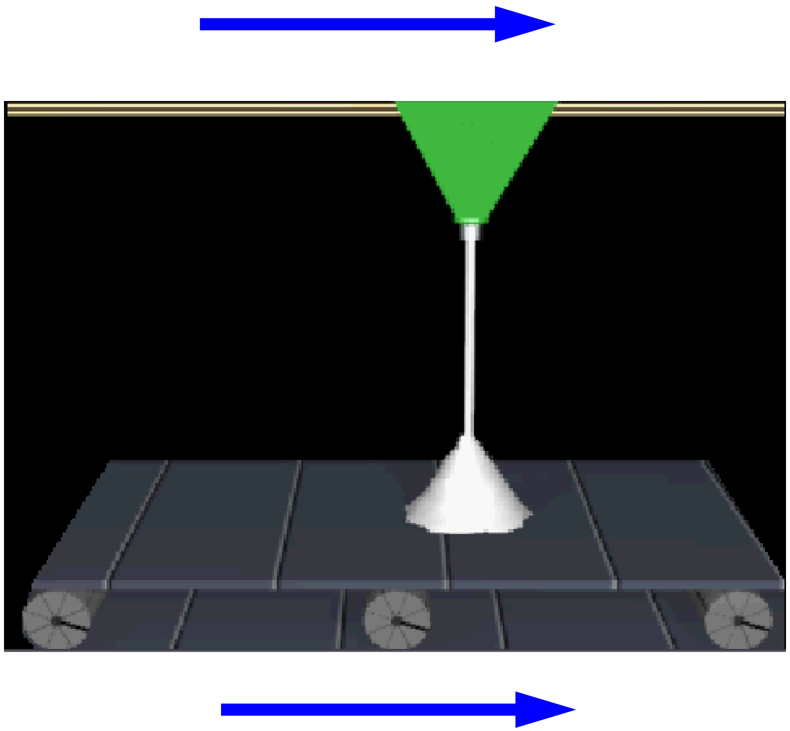
- Same speed as the noise signal, so ...
- Noise that propagate towards the termination
  - ♦ Direct crosstalk →
    - Sum of noise generated as the step propagates
      (the induced noise and its “source” move at the same speed)
    - Total noise of constant width (t_r), variable amplitude depending on the position along the line and the length of the adjacent track
- Noise that propagates to the driver
  - ♦ Reverse crosstalk ←
    - The additional noise generated merge over time
      (the amplitudes do not add up)
    - Total noise has constant amplitude, variable duration depending on the line position and the length of the adjacent track (max 2 t_P)

Mechanical analogy

- Hopper and conveyor belt



(Reverse crosstalk)



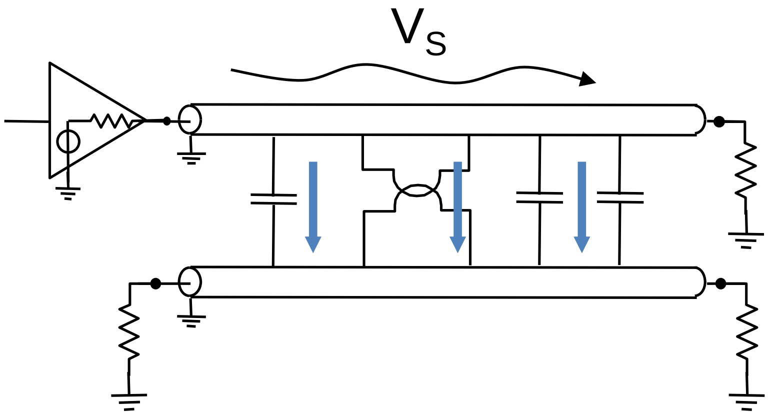
(Direct crosstalk)

Observable signals

- Direct crosstalk
  - ♦ Conveyor belt and hopper move in the same direction
    - Cumulus cone: height gradually increasing
  - ♦ Constant duration, t_r
  - ♦ Variable amplitude with the position: max at the far end
- Reverse crosstalk
  - ♦ Conveyor belt and hopper move in opposite directions
    - Strip heap: constant height, increasing length
  - ♦ Constant amplitude
  - ♦ Variable duration with position: max ($2\ t_P$) to the driver
- On the line always appears the sum of the two

Coupling parameters

- The V_S signal propagates along the top line
- Inductive couplings (L_M) and capacitive (C_M) generate noise in the lower line



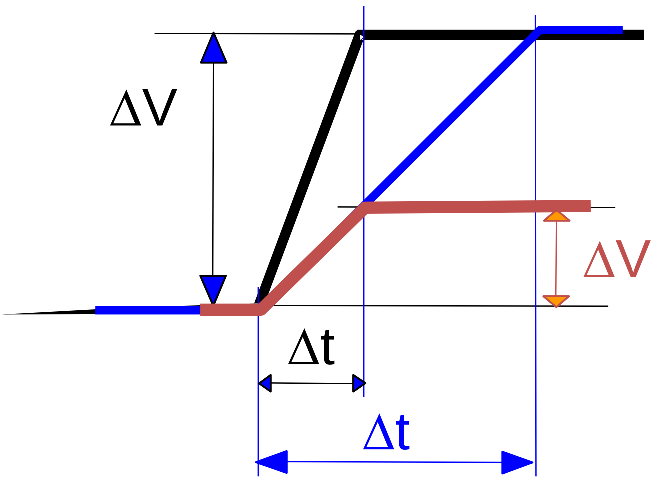
- Noise is related to
  - Slope of the noise edge (dV_S/dt, dI_S/dt)
  - Mutual inductance L_M
  - Mutual capacitance C_M

Keep an eye on crosstalk

- Crosstalk is related to
  - Speed of the edges of the noise signal (dv/dt)
  - L and C couplings
  - Noise margin of the receiver
- To reduce the crosstalk
  - Slow down the driver edges on the noisy lines
  - Reduce C_M and L_M
  - Use differential signals
- To reduce the effects of crosstalk
  - Filter the receivers of the line affected by noise
  - Error Detection and Correction Techniques (EDC/ECC)

Reduce the slope of the fronts

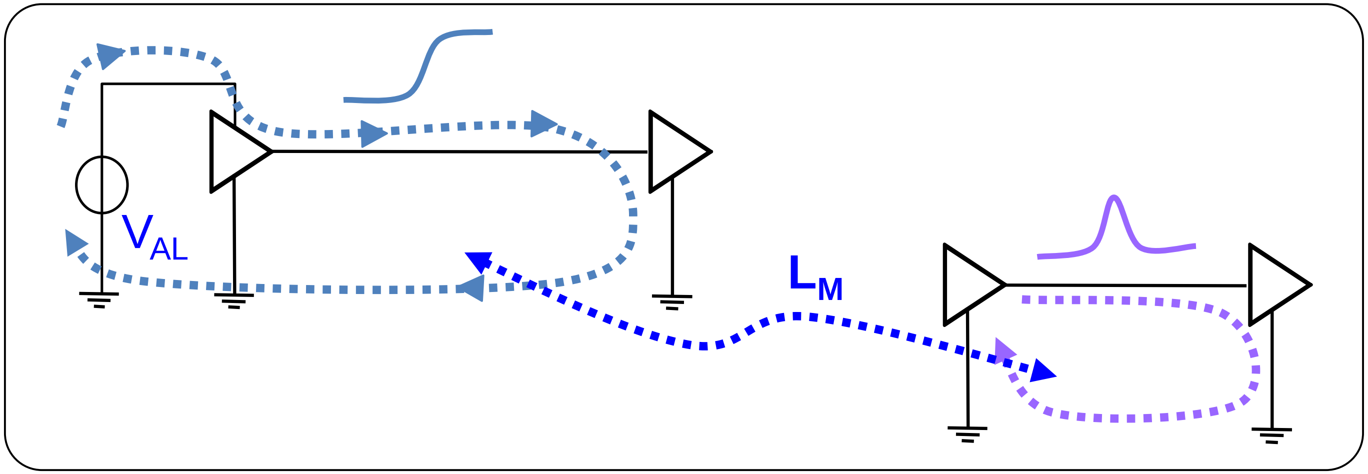
- Slope = dv/dt = ΔV/Δt
- Reduce ΔV
  - ♦ Transceiver family with low voltage range
  - ♦ Differential signals with compensating opposite effects (LVDS)



- Increase Δt
  - ♦ Use slower logic (still compatible with the specifications)
  - ♦ Slower is always good: it reduces consumption and noise

Inductive couplings

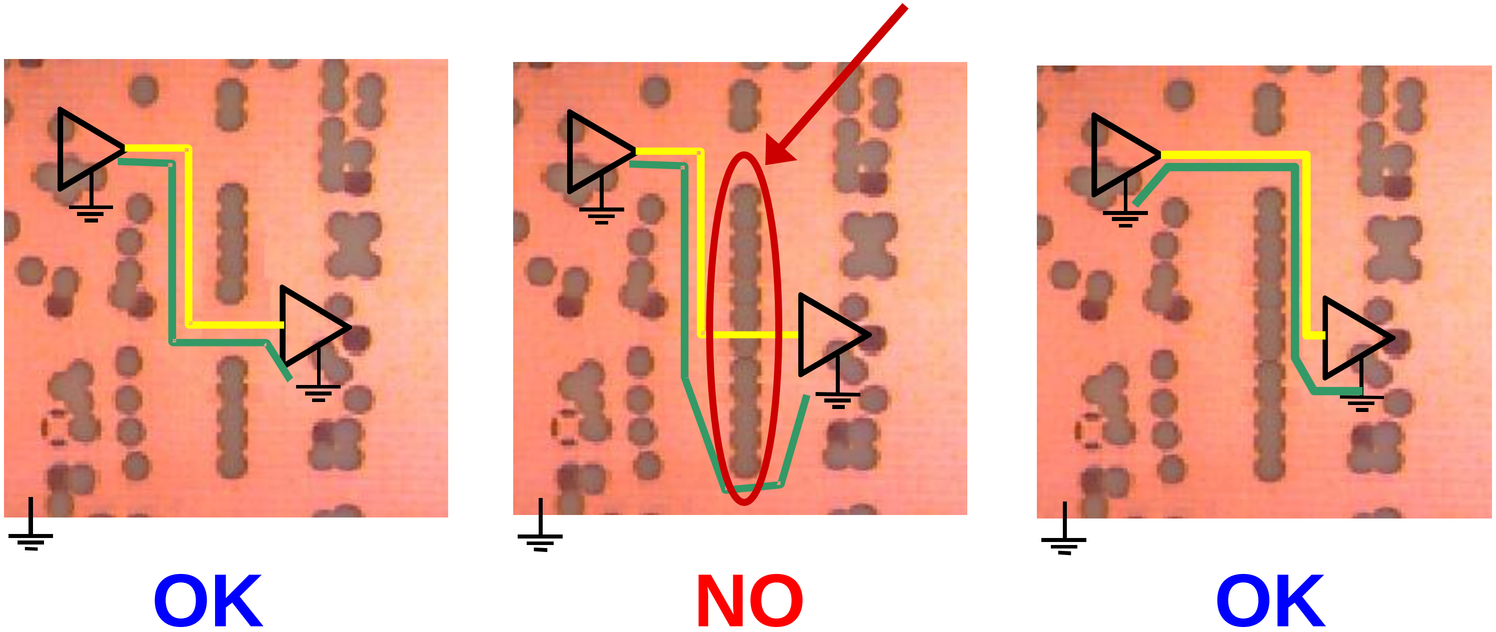
- The signal and return current go through one loop



- The mutual inductance L_M between two loops depends on distance, embedded area, materials, ...
- To reduce L_M avoid wide and embedded loops
  - Keep close the signal and return (ground) tracks

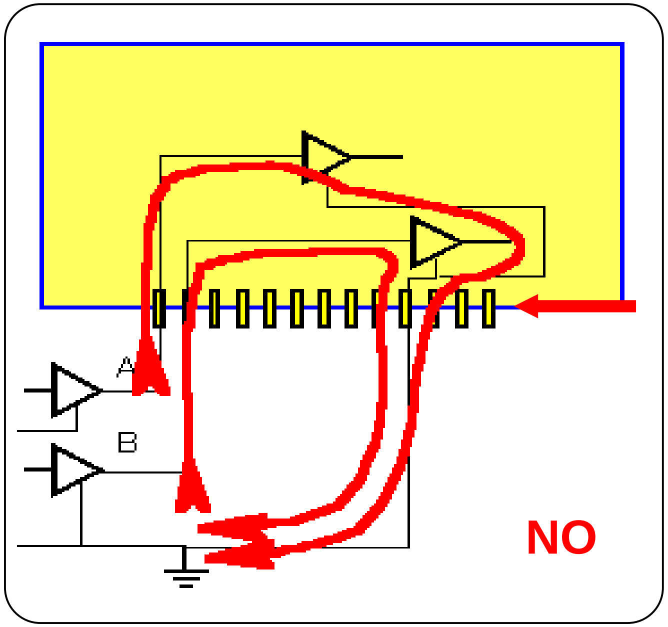
Return currents paths

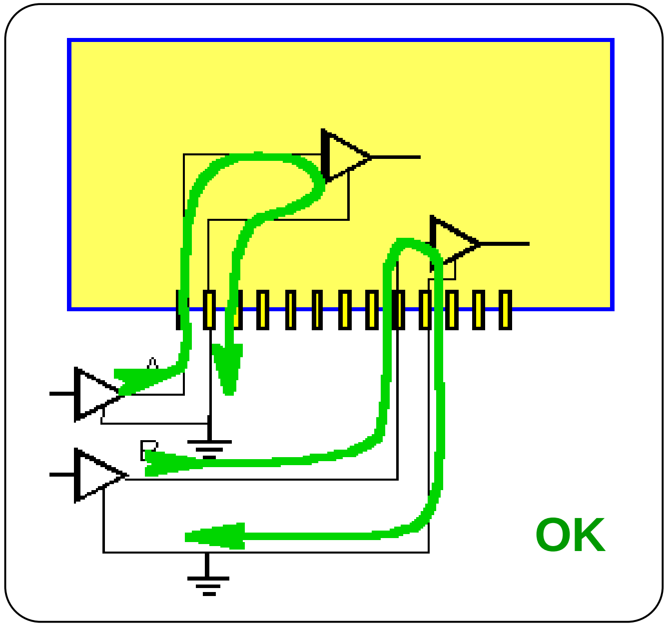
- The return currents follow paths with minimal area
  - Spend less energy to create the magnetic field
- The return currents flow “close” to the signal
  → Continuous ground plane, without cuts



Reduce inductive couplings

- Nested loops include shared ground paths
  - Separate ground connections per signal to avoid inductive couplings (also reduce capacitive couplings)



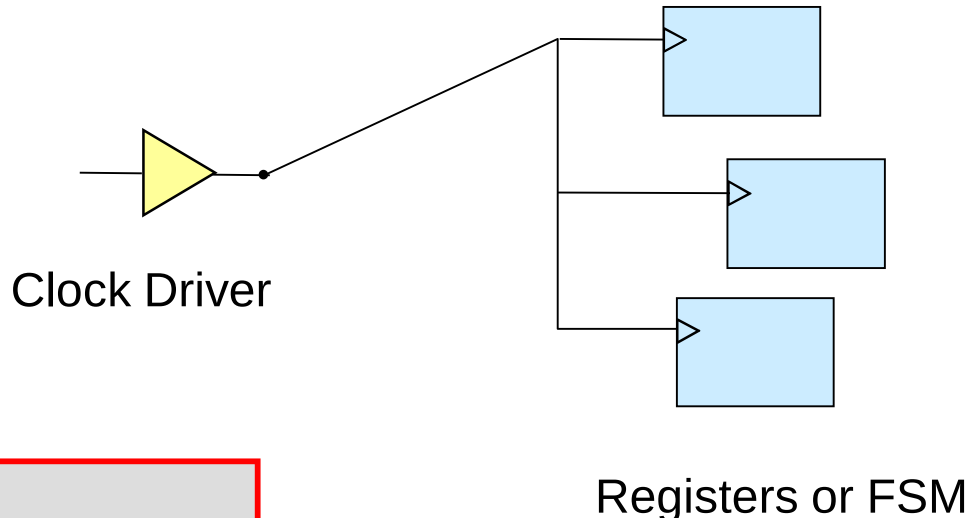


Differential signals

- Advantages
  - Noise is common mode and is strongly rejected
    - Allow to reduce the voltage amplitude of the signal
    - Lower ΔV → lower consumption and interference (crosstalk, EMI)
  - The total current in a differential pair is constant
    - The current is switched from one conductor to the other
    - Constant absorption from the power supply
    - Lower interference (EMI)
- Disadvantages
  - 2 tracks/pins for each signal
  - Require “analog” techniques (differential stages, ...)

Clock distribution

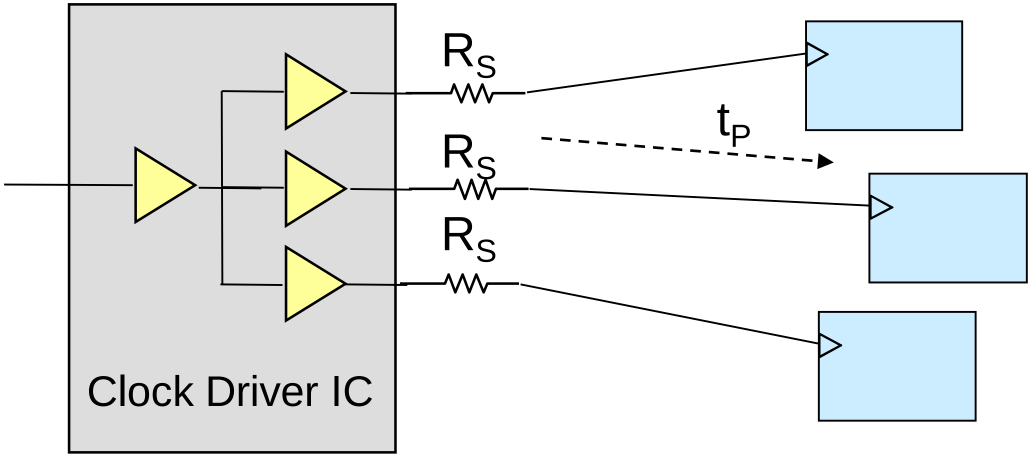
- Multi-point chain connection → high skew
- The clock arrives at different times at the registers



Do not use!

Distribution with clock driver

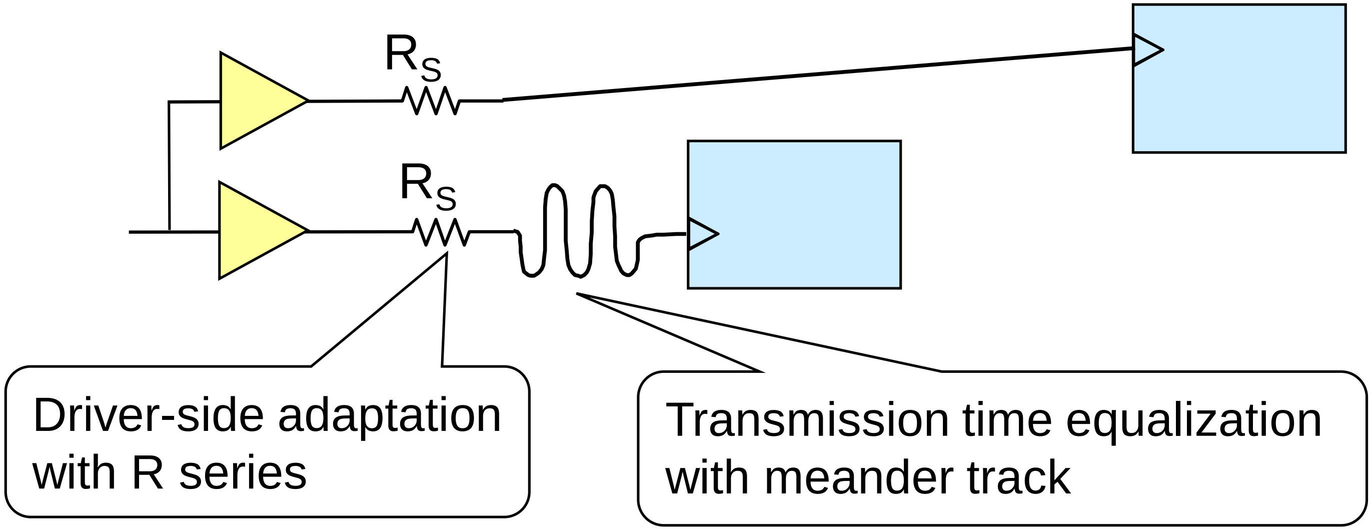
- Separate devices for driving multiple clocks
  - Delays are known and controlled
  - Driver-side adaptation (near end): $R_S = Z_\infty - R_O$
  - Reflection at termination (RWS, reflected wave switching)
  - Maximum transmission time (to the driver) $t_{TXmax} = 2\ t_P$



ALMOST OPTIMAL

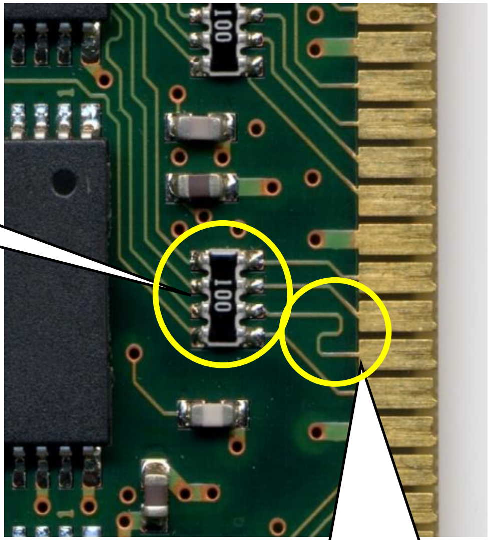
Equalization of delays

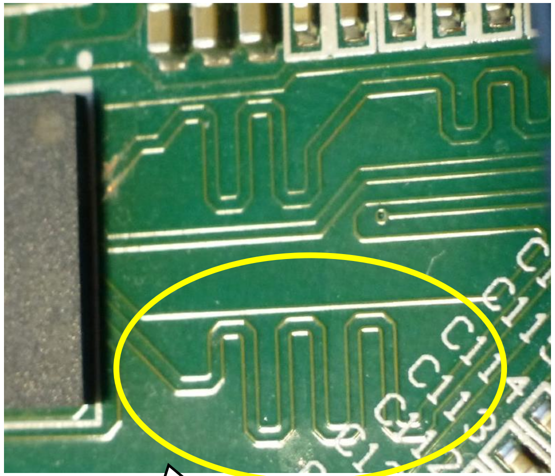
- Use separate devices when driving multiple clocks
  - ♦ Known and controlled delays, driver-side adaptation (near end): Reflected Wave Switching: $t_{TXmax} = 2\ t_P$
- Same length for all paths (use of meanders to equalize the t_P)



PCB examples (memory)

Series **termination** resistances (4)





Meander track to equalize the transmission times

Meander track for differential signals (2 conductors)

- Crosstalk
  - Capacitive and inductive couplings
  - Direct and reverse crosstalk
  - Techniques to limit crosstalk
- Switching noise
  - Ground distribution and power supply
  - Techniques for limiting switching noise
  - Bypass Capacitors

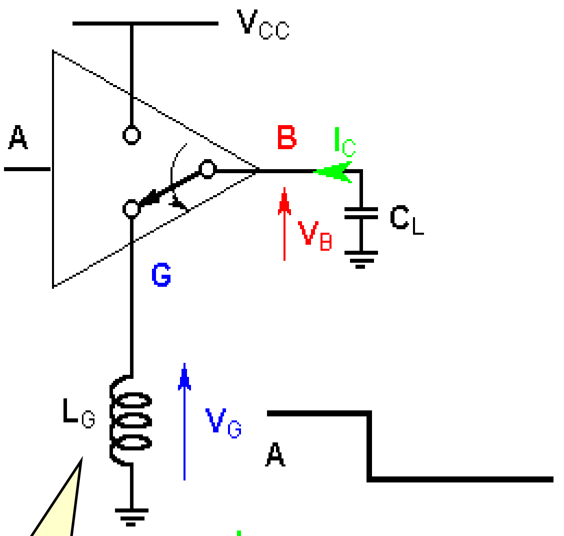
Couplings from common connections

- The currents that supply different parts of the circuit can have common paths
  - Static voltage drop (constant I): $\Delta V = R\,I$
  - Dynamic voltage drop that is caused by changes in the current during switching: $\Delta V = L\,dI/dt$
- Ground bounce
  - Pulsed currents cause shifts of the reference

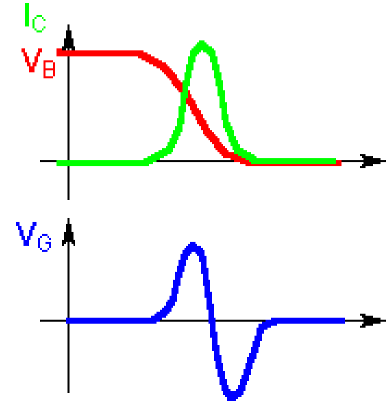
    $\Delta V = L\,dI/dt$; $I = C\,dV/dt$; $\Delta V = L\,C\,d^2V/dt^2$
- Simultaneous switching of several outputs
  - Simultaneous switching noise

Impulsive currents: V_{CC} – GND

- C_L discharge current flows in the GND conductor, and V_G varies
- Ground Bounce
- Ground bounce depends on
  - Load capacitance C_L
  - dV/dt slope of V_B
  - L_G of the GND connection
- For L-H transitions Same effect on V_{CC}
  - V_{CC} Sag or Power Bounce



The peak current is followed by a voltage drop on L_G

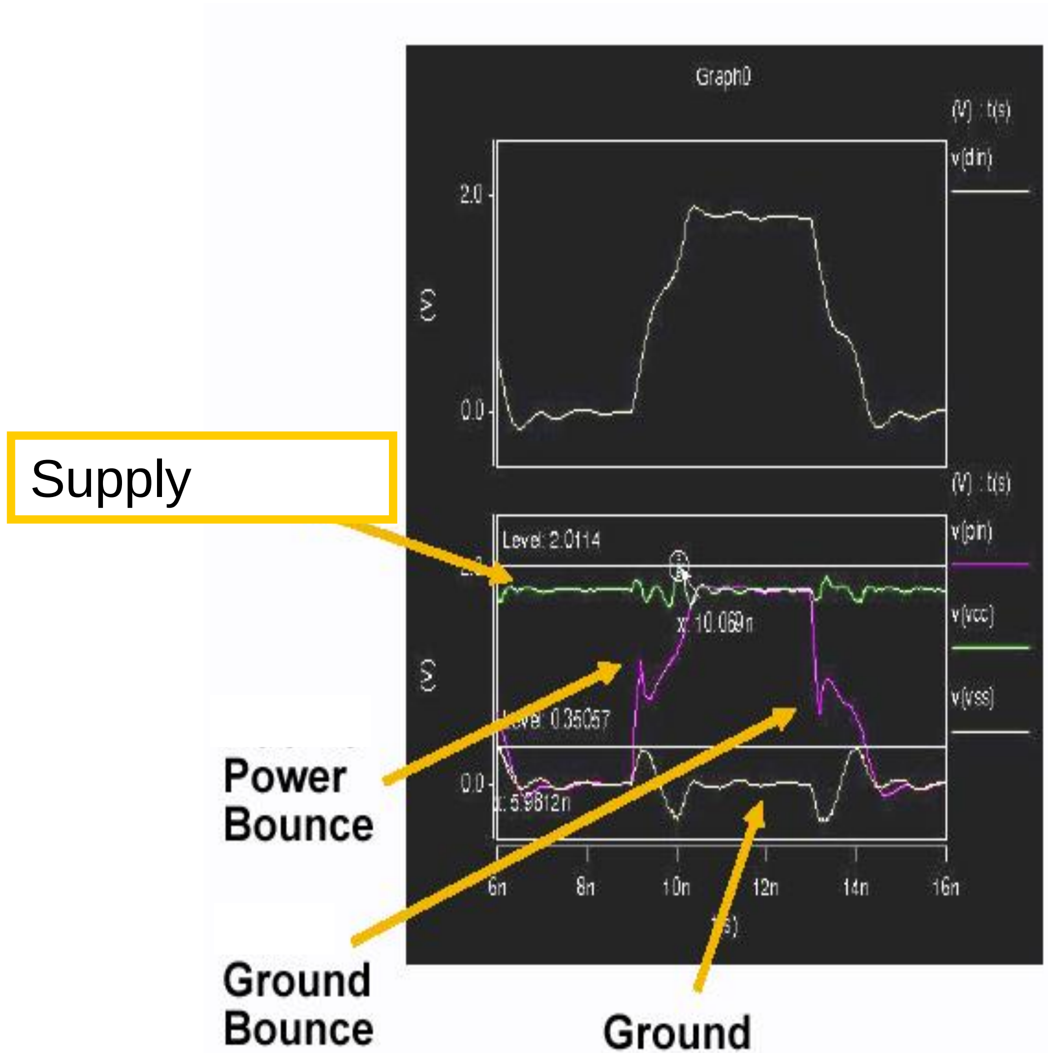


Switching noise

- Ground bounce and switching noise related to
  - Slope of transitions (dV/dt)
  - Charge quantity to be moved (load capacitance C_L)
  - Inductance of the GND and power connections (L_G, L_S)
- Voltage variations on GND and power supplies
  - Concern devices with common ground and power supply
    - Other logic gates of the same component
    - Other neighboring components (same ground and power supply)
  - They cause variations of
    - Actual input voltages
    - Output voltages
  - They can determine oscillations

Effects of ground and power bounce

- Ground bounce
  - It can transform a logical 0 into 1
- Power bounce
  - Similarly, it can turn a 1 into 0
- Both worsen the noise margins



Ground bounce and switching noise

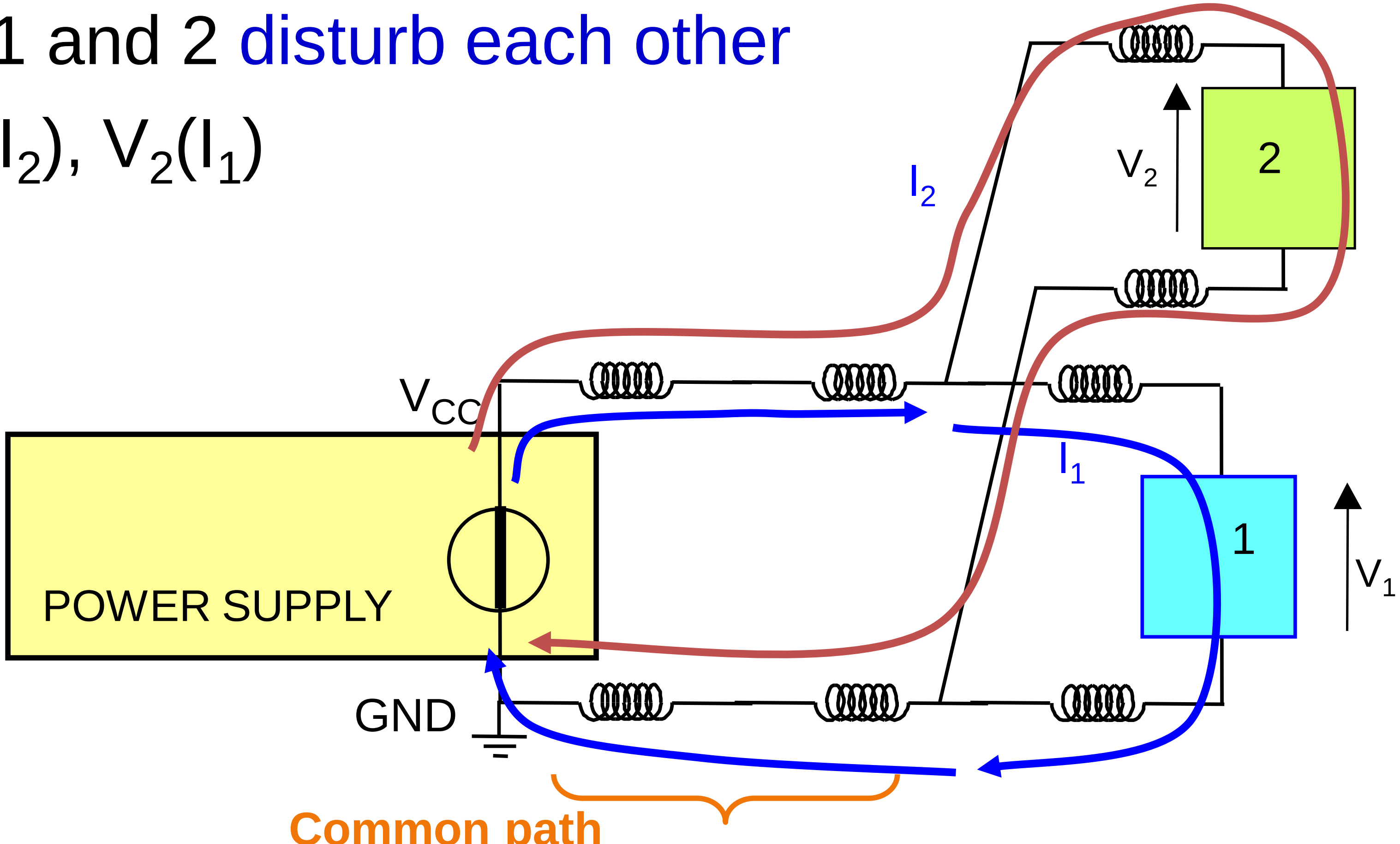
- Switching noise related to # of outputs changing state
  - For each output
    $\Delta V = L\, dI/dt$; $I = C\, dV/dt$; $\Delta V = L\, C\, d^2V/dt^2$
  - Speed of the edges
  - Load capacitance
  - V_{CC} and GND inductance
- Switching noise shifts ground and supply
- Affects other gates of the same integrated circuit
  - Common ground and power supplies
  - Change the input threshold
  - Change the output levels

Reduce switching noise

- Objectives
  - ♦ Create low impedance paths for impulse currents
  - ♦ Current peaks supplied by nearby “charge tanks”
- Decoupling Capacitors (bypass)
  - ♦ Placed close to the ICs that drive low impedance loads
  - ♦ Create low inductance paths for impulse currents
  - ♦ Recharge slowly, without current pulses
- Necessary
  - ♦ Capacitors with low Equivalent Series Resistance (ESR) and low Equivalent Series Inductance (ESL)
  - ♦ Use appropriate layout criteria

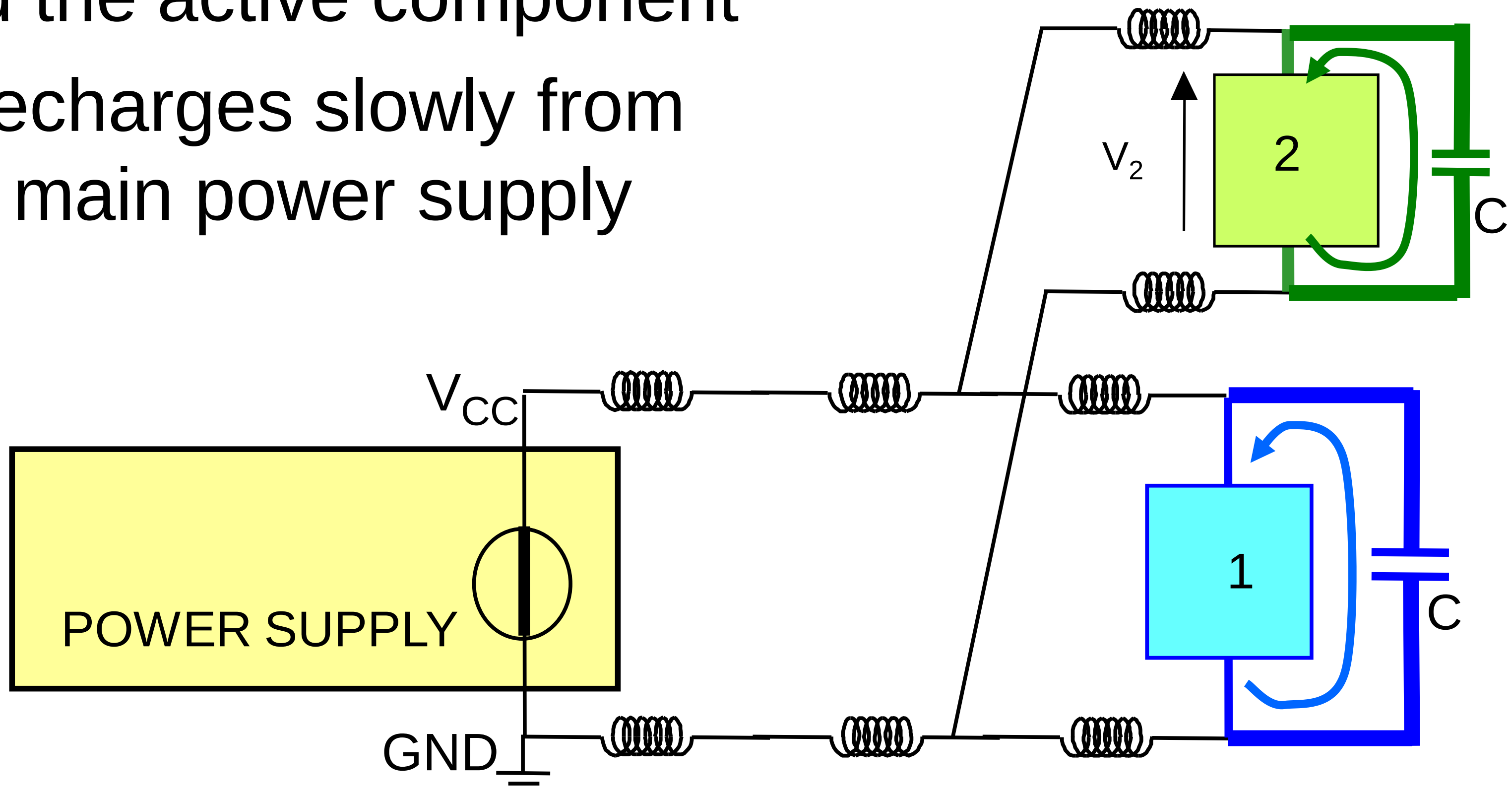
Path of the currents

- All currents come from the power supply, and determine voltage drops on inductances
  → 1 and 2 disturb each other
- $V_1(I_2)$, $V_2(I_1)$



Bypass Capacitors

- Impulse currents are supplied by the capacitors C
- Flow only on low impedance tracks between C and the active component
- C recharges slowly from the main power supply



Value of the bypass capacitors

- Purpose: limit the ripple on power supply and GND
- Q = charge stored in the capacitor
- V = Voltage across the capacitor
  - ΔV = max voltage variation allowed
  - Δt = duration of capacitor supply (ground bounce duration)
  - $\Delta Q = C\ \Delta V$; $I = \Delta Q/\Delta t = C\ \Delta V/\Delta t$
  - $C = I\ \Delta t/\Delta V$
  - Considering the equivalent series resistance of C (ESR)
    $C = I\ \Delta t/(\Delta V - I \cdot ESR)$
- If ESR is high → use several parallel capacitors
  - Multiple bypass C, of different values

Example: Switching noise

- The switching noise depends on the current peak and the inductance of the power supply connection (R series of ideal power supply is ESR = 0 Ω)
- Peak current: I = 0.2 A, triangular, 2 ns duration
  - $dI/dt = 0.2\ A / 2 \cdot 10^{-9}\ s = 0.1 \cdot 10^{9}\ A/s$
- Inductance of the V_{CC} connection: L = 10 nH
  - $\Delta V_{CC} = L\ dI/dt = 10 \cdot 10^{-9}\ H \cdot 0.1 \cdot 10^{9}\ A/s = 1\ V$
- Value of the bypass capacitor to have $\Delta V_{CC} = 0.1\ V$
  - With ESR = 0 Ω: $C = I\ \Delta t/\Delta V = 0.2\ A \cdot 2 \cdot 10^{-9}\ s / 0.1\ V = 4\ nF$
  - With ESR = 3 Ω: the drop on ESR = 0.6 V > $\Delta V_{CC} = 0.1\ V$
    - Impossible! Must use several C in parallel to reduce the ESR

Lecture C7: final questions

- Explain the term “crosstalk”
- What are the effects of inductive and capacitive couplings between the tracks of a printed circuit?
- How do common paths create crosstalk?
- Should you use a slow or a fast logic family To reduce crosstalk interference?
- Recommended topology for clock distribution?
- What are simultaneous switching noise and ground bounce?
- Why are used bypass capacitors on power supplies?