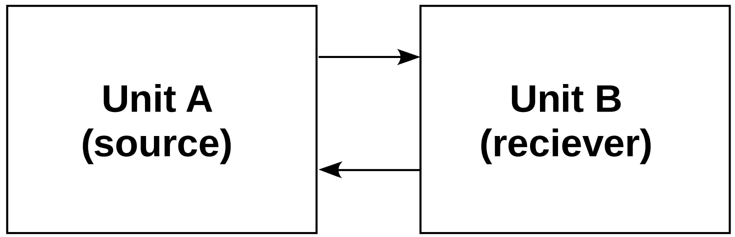
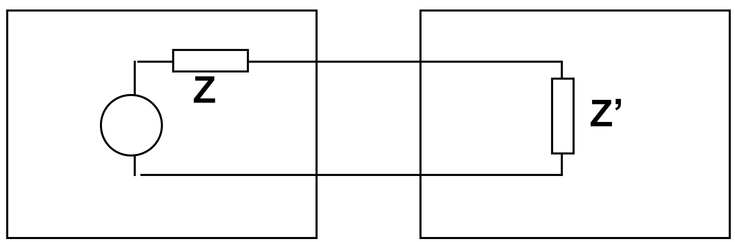
High Speed Signals, Impedances, Reflections and Grounding

Christian Bohm
Stockholm University

Characterize the signal transferred between two modules



Thevenin's theorem tells us that each unit can be modeled by voltage generator in series with an impedance



If we want to maximize the transfer of

Current → |Z'| << |Z|

Voltage → |Z'| >> |Z|

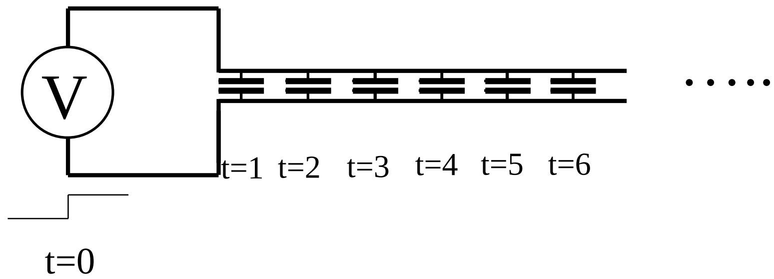
Power → |Z'| = |Z|

This is OK if the signals are slow and the system small

But with high speed signals

we have to consider the finite signal speed.

High speed signal lines are called transmission lines. They are often implemented as coaxial cables.



Infinite length

Each unit length **dx** of the transmission cable must have a capacitance **ΔC/dx**

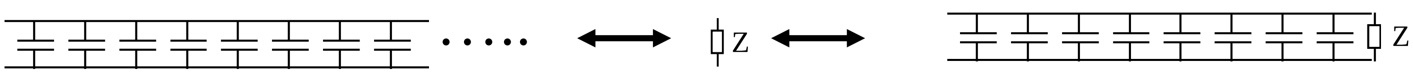
If we generate a **v** pulse at the time **t=0** it will propagate along the transmission line

Each unit time a capacitor is charged with the charge **C·v** (C=Q/V)

Thus we need a constant current i= **C·v /dt**

I.e. the transmission line behaves like an impedance with value **Z=dt/C**

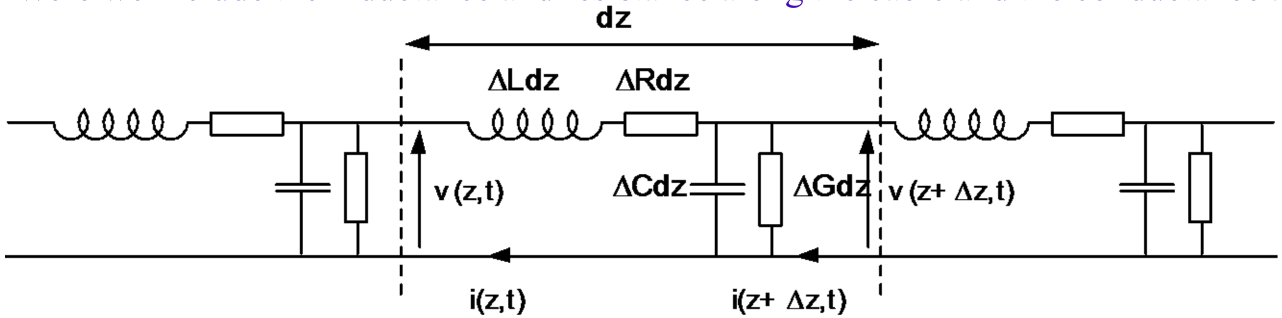
Z is the **characteristic impedance** of the cable



This is called **terminating** the finite transmission line so that it behaves like it was infinite

Let us use a better model

Were we include the inductance and resistance along the cable and the conductance across.



Model for transmission lines

Kirchoff's laws -->

$$v(z,t) + \Delta L \cdot dz \cdot \frac{\partial i(z,t)}{\partial t} + \Delta R \cdot dz \cdot i(z,t) - v(z+dz,t) = 0$$

and

$$i(z,t) + \Delta C \cdot dz \cdot \frac{\partial v(z,t)}{\partial t} + \Delta G \cdot dz \cdot v(z,t) - i(z+dz,t) = 0$$

ΔL, ΔR, ΔC and ΔG are the inductance, resistance, capacitance and conductance per unit length of the cable.

After Taylor expansion of i(z+dz,t) and v(z+dz,t) -->

$$\frac{\partial v(z,t)}{\partial z} - \Delta L \cdot \frac{\partial i(z,t)}{\partial t} - \Delta R \cdot i(z,t) = 0$$

and

$$\frac{\partial i(z,t)}{\partial z} - \Delta C \cdot \frac{\partial v(z,t)}{\partial t} - \Delta G \cdot v(z,t) = 0$$

Derivation --> $$\frac{\partial^2 v(z,t)}{\partial z^2} - \Delta L \cdot \frac{\partial^2 i(z,t)}{\partial t \cdot \partial z} - \Delta R \cdot \frac{\partial i(z,t)}{\partial z} = 0$$

$$\frac{\partial^2 i(z,t)}{\partial z^2} - \Delta C \cdot \frac{\partial^2 v(z,t)}{\partial t \cdot \partial z} - \Delta G \cdot \frac{\partial v(z,t)}{\partial z} = 0$$

$$\frac{\partial^2 v(z,t)}{\partial t \cdot \partial z} - \Delta L \cdot \frac{\partial^2 i(z,t)}{\partial t^2} - \Delta R \cdot \frac{\partial i(z,t)}{\partial t} = 0$$

$$\frac{\partial^2 i(z,t)}{\partial t \cdot \partial z} - \Delta C \cdot \frac{\partial^2 v(z,t)}{\partial t^2} - \Delta G \cdot \frac{\partial v(z,t)}{\partial t} = 0$$

--> $$\frac{\partial^2 v(z,t)}{\partial z^2} - (\Delta L \Delta G + \Delta R \Delta C) \cdot \frac{\partial v(z,t)}{\partial t} - \Delta L \Delta C \cdot \frac{\partial^2 v(z,t)}{\partial t^2} - \Delta R \Delta G \cdot v(z,t) = 0$$

$$\frac{\partial^2 i(z,t)}{\partial z^2} - (\Delta L \Delta G + \Delta R \Delta C) \cdot \frac{\partial i(z,t)}{\partial t} - \Delta L \Delta C \cdot \frac{\partial^2 i(z,t)}{\partial t^2} - \Delta R \Delta G \cdot i(z,t) = 0$$

Loss less transmission lines, i.e. ΔR and ΔG = 0 --> wave equations with the **speed**

$$1/\sqrt{\Delta L \Delta C}$$

For each solution i(z,t) there is a solution v(z,t)=Z_o·i(z,t)
If the transmission line is loss less Z_0, the **characteristic impedance**, is:

$$Z_0 = \frac{v(z,t)}{i(z,t)} = \sqrt{\frac{\Delta L}{\Delta C}}$$

Thus if the lines are loss less (ΔR and ΔG = 0) → speed and impedance independent of frequency, no signal distorsion.

If the lines are not loss less then:

$$v = \frac{1}{\sqrt{(\Delta R/\omega + j\Delta L)\cdot(\Delta G/\omega + j\Delta C)}}$$

and

$$Z_0 = \frac{v(z,t)}{i(z,t)} = \sqrt{\frac{\Delta R + j\omega\Delta L}{\Delta G + j\omega\Delta C}}$$

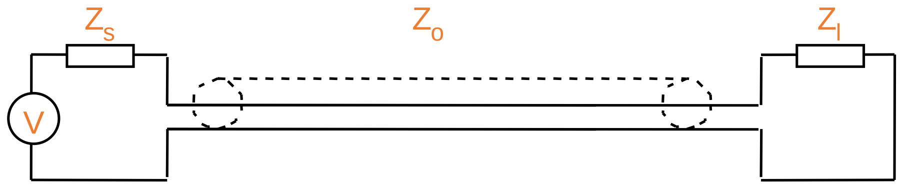
This solution you get by assuming $v=Z_o \cdot i$ and $i=\exp(-j\omega(t-z/v))$

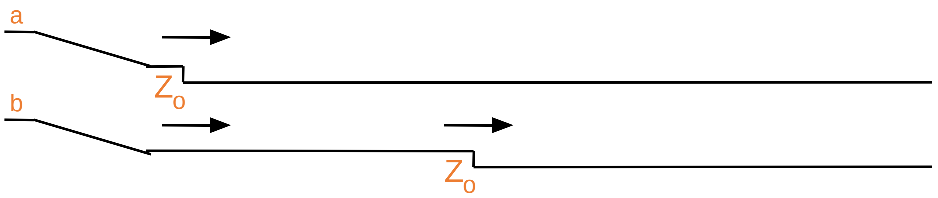
The frequency dependence means that the different frequency components are differently attenuated and move at different speed - (dispersion). →
The pulse **deforms as it passes long distances**.

In coaxial cables the size of the **loss** is connected with the **quality** of the cable.
In general thicker cables give less losses.

The properties of cables can also be affected by external conditions such as **bending**.

Reflection in the transmission line.



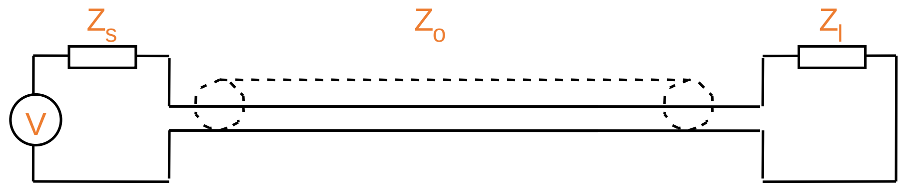


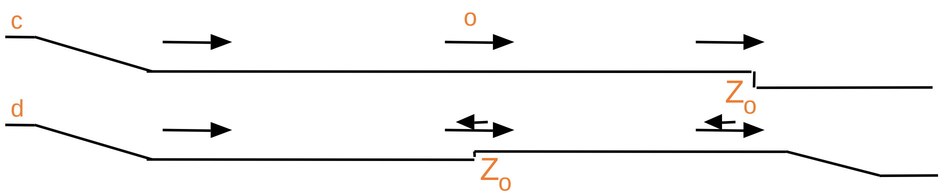
The wave front moves with the speed $1/\sqrt{\Delta L \Delta C}$

After the wave front the current is initially constant, i.e. the current needed to charge the cable after the wave front.

$$dq = i \cdot dt = u(z,t) \cdot \Delta C \cdot dz = u(z,t) \cdot \Delta C \cdot dt / \sqrt{\Delta L \Delta C} =$$
$$= u(z,t) \cdot dt / \sqrt{\Delta L / \Delta C} = u(z,t) \cdot dt / Z_o$$

The cable continues to behave as if has **the impedance Z_o**





When the pulse reaches the far end of the cable, to the load impedance Z_l, the current will split and the voltage level change to drive new currents.

Part of the current will pass the termination resistance and the other reflect back.
The reflected current combines with the original current.

The size and polarity of the reflected current depend on the size of the load impedance.
$Z_l = Z_o$ will not lead to reflection.

$$i = i_r + i_l \Rightarrow \frac{u}{Z_o} = \frac{du}{Z_o} + \frac{du + u}{Z_l} \Rightarrow du = \frac{Z_l - Z_o}{Z_l + Z_o} u$$

$$i = i_r + i_l \Rightarrow \frac{u}{Z_o} = \frac{du}{Z_o} + \frac{du + u}{Z_l} \Rightarrow du = \frac{Z_l - Z_o}{Z_l + Z_o} u$$

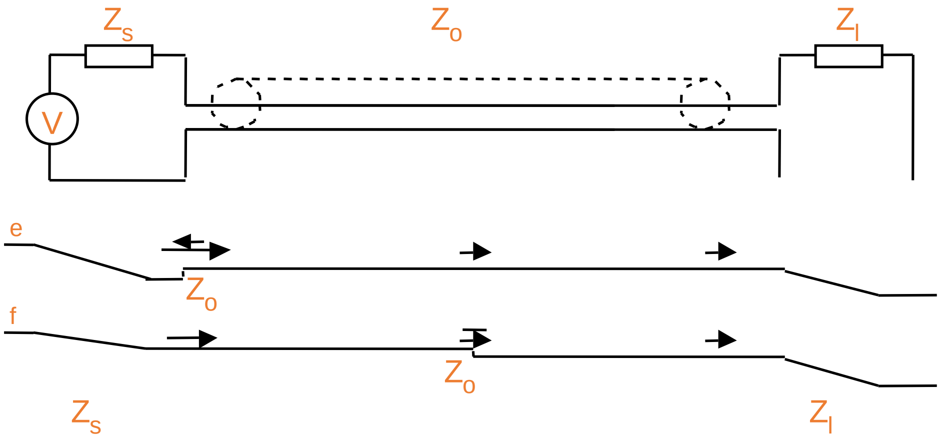
If $Z_l = Z_o$ then du = 0 and nothing changes, the same voltage level and the same current continues to flow through the termination. The cable is well terminated.

If $Z_l = \infty$ the reflected current will suffice to charge the capacitances to v and move the positive wave front back with the speed, where it cancels the incoming current.

No current flows anymore, which is natural since the current path is actually broken. It just took the circuit some time to realize this.

In the end you get the level you would have had directly if the signal speed was infinite

If $Z_l = 0$ the voltage –u is reflected back. This means that the return current i will discharge the capacitance and move the negative wave front back with the speed $1/\sqrt{\Delta L \Delta C}$



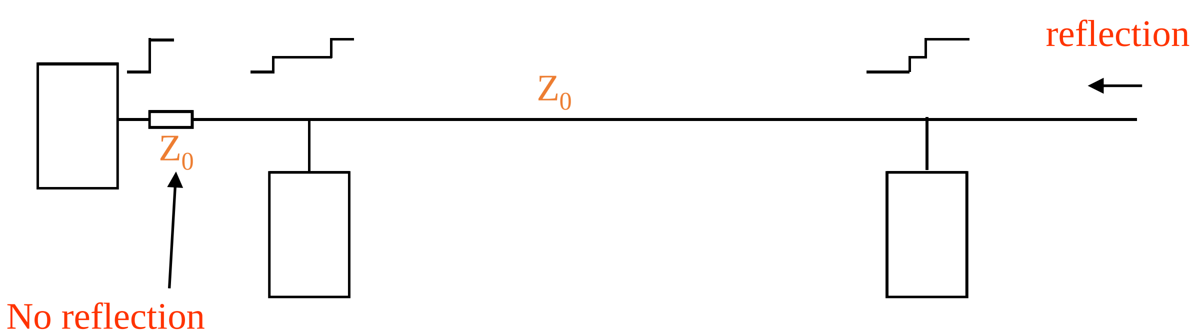
If Z_s is not equal to Z_o --> a new reflexion occurs when the reflected pulse reaches the beginning of the cable.

Multiple reflexions of this type are called **ringings**, exponentially reduced oscillations that occur at each state charge at the output

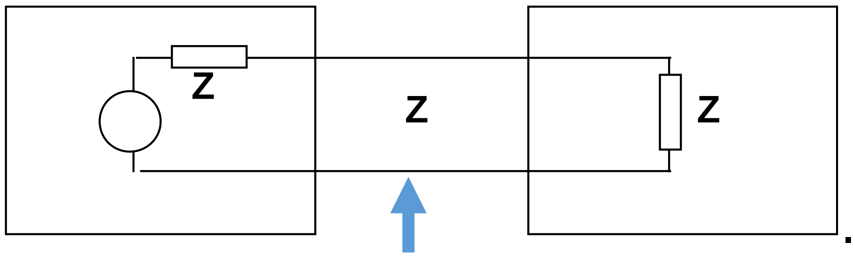
To eliminate effects of this type of long signal lines for fast signal communication the end points must be loaded (**terminated**) with impedances that are tuned to the characteristic impedance.

If $Z_l = Z_0$ then the transmission line is parallel terminated which means that pulses can not be reflected

If Z_l is missing but Z_s compensated so that it becomes $=Z_0$ the transmission line will be serially terminated and no signals reflected



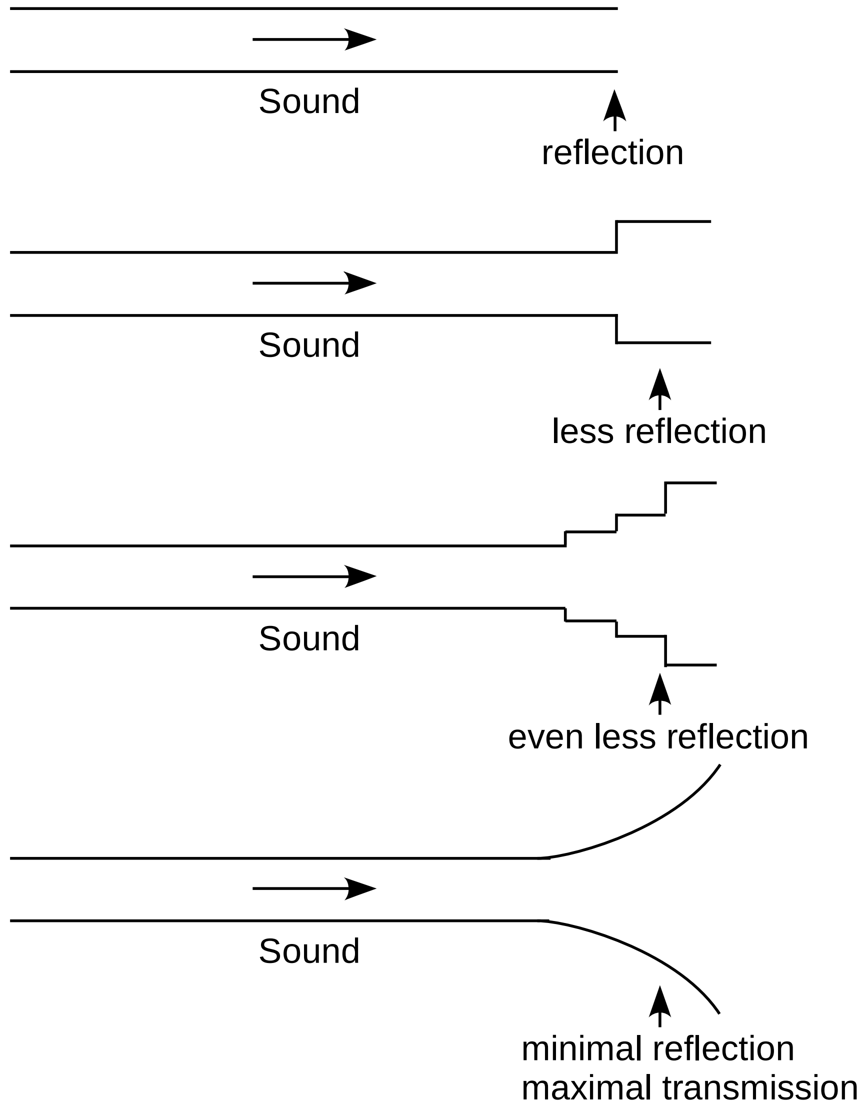
Transferring high-speed signals between two modules



Characteristic impedance

To avoid reflections and to maximize signal transfer the characteristic impedance and the output and input impedances should be the same

Acoustic impedance matching



Standard high-speed connectors

BNC
Old standard

50 Ω coaxial cables with standard connectors are Used in physics experiments

Signal inputs are often Internally terminated with 50Ω

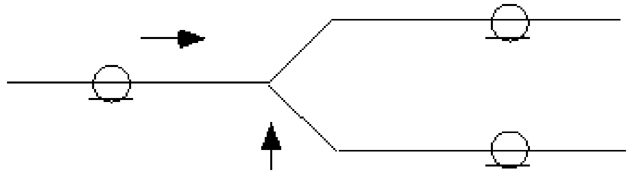
High impedance inputs are not terminated

“T:s” are used to terminate unterminated inputs

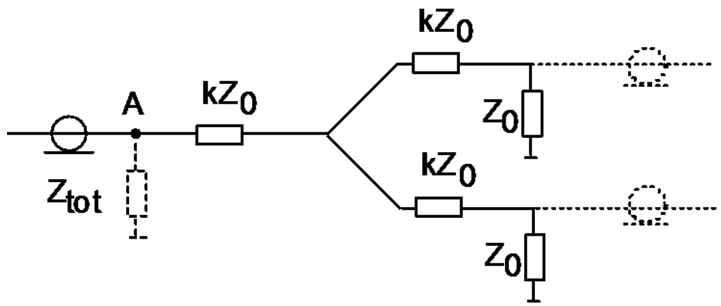
Lemo
New standard
Much smaller

Signal splitting

If we split the signal with a T-junction.



This effect can be eliminated if the connection occurs via 3 suitably chosen resistors.



The total impedance in the point A must be Z_o to eliminate reflections. This implies:

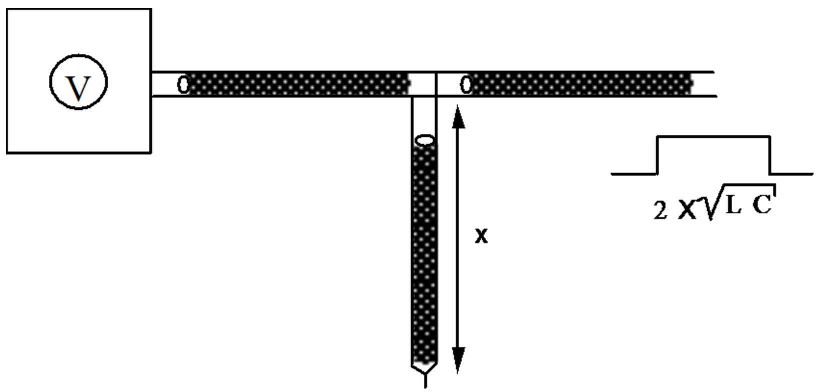
$$Z_{tot} = k \cdot Z_0 + (k \cdot Z_0 + Z_0)/2 = Z_0 \Rightarrow$$
$$\Rightarrow 3k + 1 = 2 \Rightarrow k = 1/3$$

the voltage -->

$$\frac{u_{ut}}{u_{in}} = \frac{i/2 \cdot Z_0}{i \cdot (k \cdot Z_0 + (k \cdot Z_0 + Z_0)/2)} = \frac{1}{3k+1} = 1/2$$

Reflections can be used for signal forming purposes. A T-junction with a shorted cable leads to a short positive pulse with a length corresponding twice the propagation delay when the driving pulse goes high and a similar but negative pulse when the driving pulse goes low.

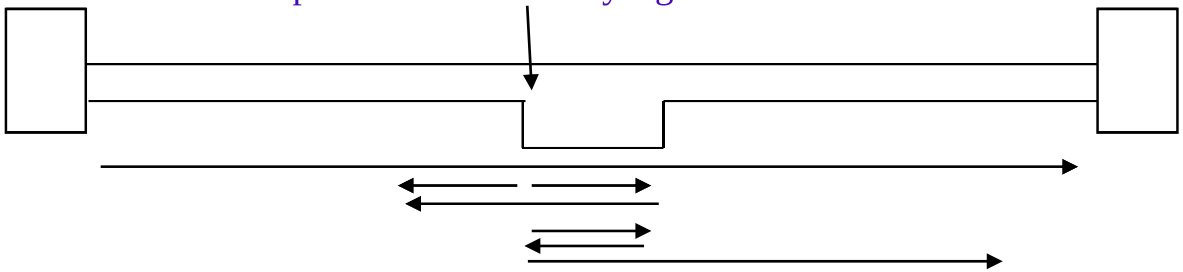
It takes twice the propagation delay for the junction to realize that it is shorted



Pulse clipping.

Impedance variations

Impedance discontinuity e.g. a connector



In practice one must consider the pulse rise time. If it is slow it not so bad

If twice the size of the impedance mismatch is considerably less than the pulse rise time the reflections will be minor since the reflections occur pairwise with opposite polarity

Rule of thumb: If the critical dimensions are less than 1/6 of the distance the pulse moves during a rise time effects due to the finite propagation speed can be disregarded.

Light moves 3dm in 1ns, signals in a PCB 2dm. The critical distance for 1GHz is about 3cm, but only 3mm for 10GHz

In digital systems the rise time is the critical parameter not the frequency. The rise determines the frequency spectrum.

Connectors do not need to be impedance matched at low frequencies.

At high frequencies everything must be impedance matched.

Return currents

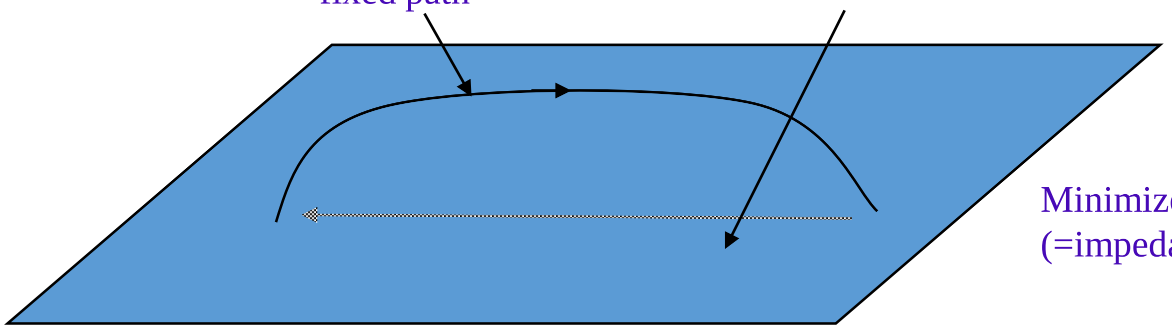
When designing Printed Circuit Boards (PCBs) signals are constrained to follow a fixed path but its return current is free to choose it's own path in a "ground plane" below.

All return currents follow the path of least impedance

Low frequency signals

Signal current following a fixed path

return current following a free path

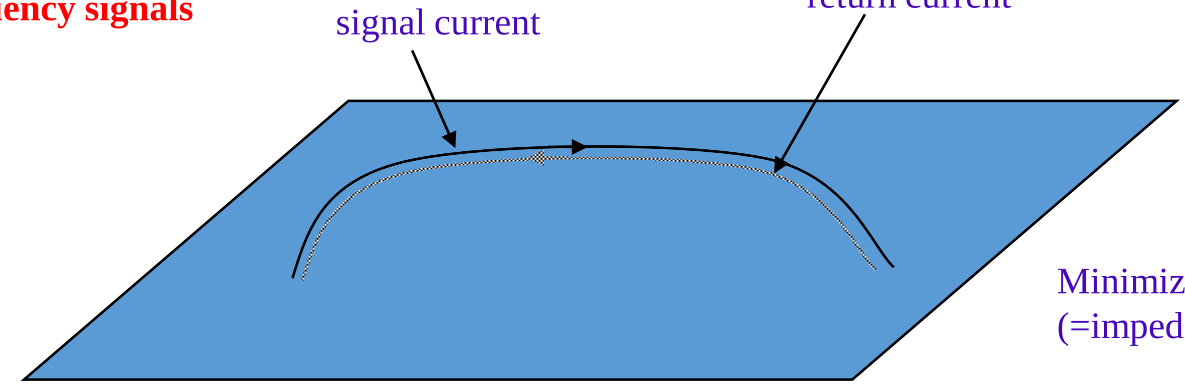


Minimize the resistance (=impedance @ low frequencies)

Low frequency signals

High frequency signal current

return current

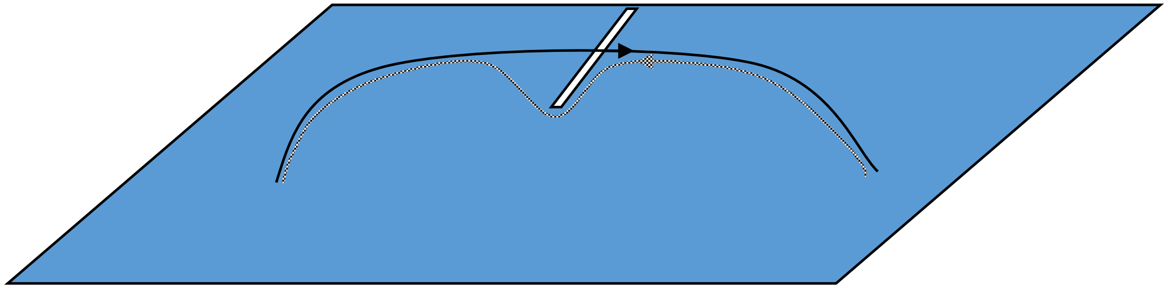


Minimize the inductance (=impedance @ high frequencies)

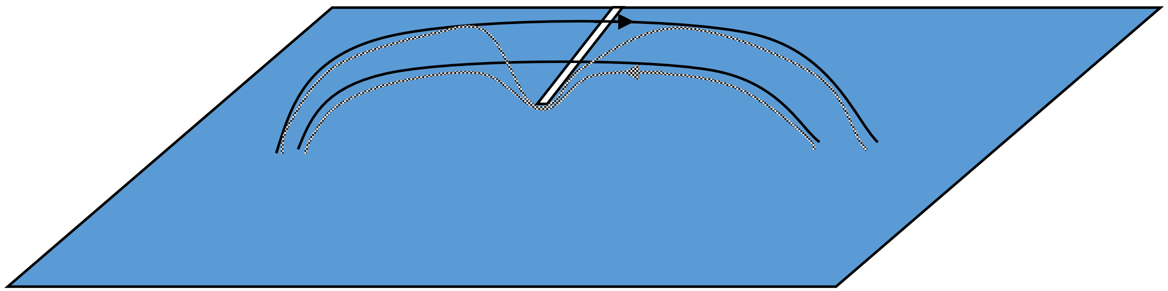
If the width of the trace and the distance between signal and ground plane are constant, the trace will have a very well defined impedance.

Return currents

A obstruction in the ground plane forces the return current to make a detour which affects the impedance



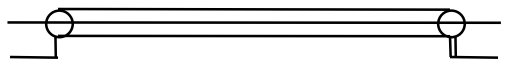
A tear in the ground plane amplifies the coupling (crosstalk) between the currents via their returns



Ground loops

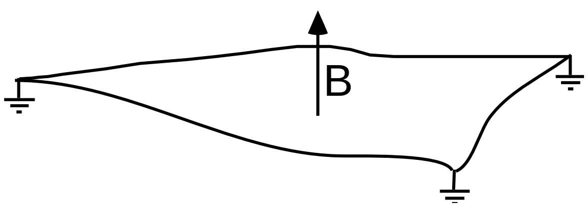
Time varying magnetic fields cause problems via induction in loops

Reduce or cancel the loops



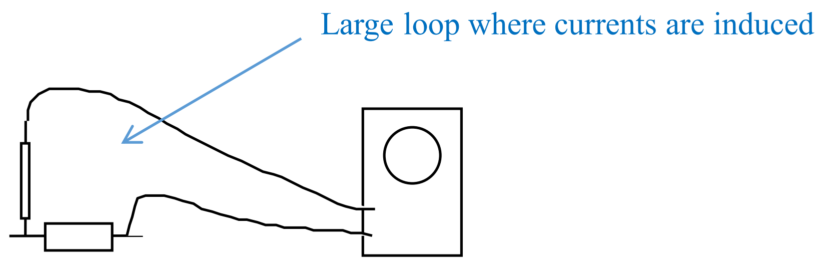
Coaxial cable

Twisted pair cable

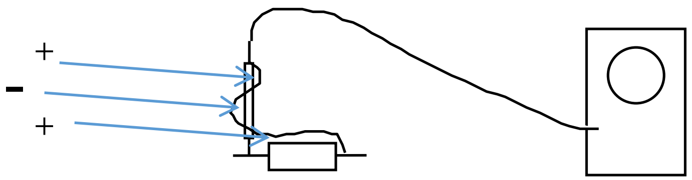


Ground loops should be avoided. Magnetic fields can induce large currents that, in turn, causes voltage variations

Different unit's grounds should be connected in one point
Floating power supplies
Fiber or differential communication



Using a separate ground line when measuring weak currents lead to increased sensitivity to interference.



By using the ground connection on the probe it is possible to reduce the induction sensitive area.

That is all

Thank you for your attention