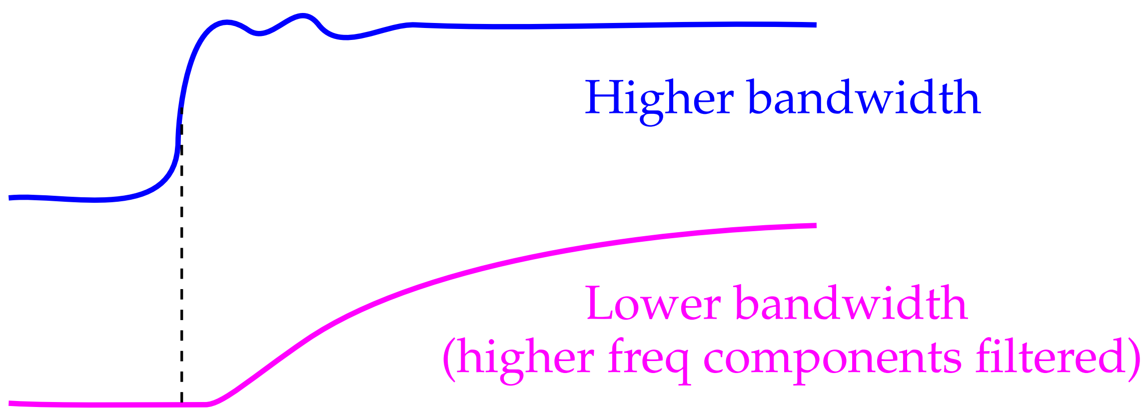
Scope Limitations

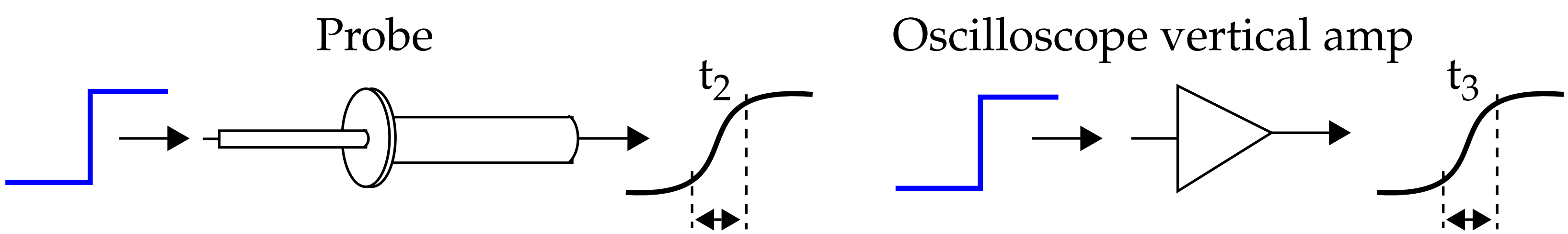
The oscilloscope has three primary limitations:

- Inadequate sensitivity
- Insufficient range
- Limited bandwidth

Limited bandwidth is the most significant limitation.

Both probes measure the same input signal





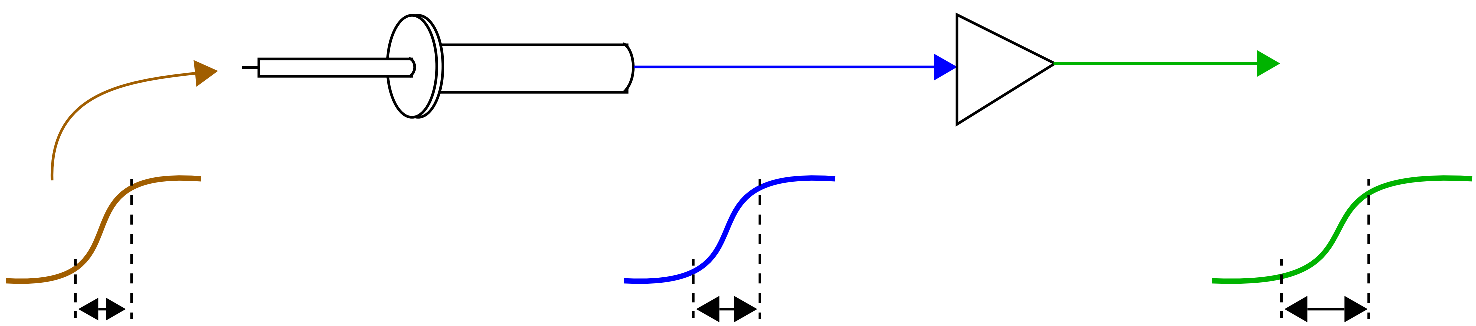
Scope Limitations

Both the probe and vertical amp degrade the rise time.

The degradation in rise time of the combination is given by:

$$T_{\text{rise composite}} = \sqrt{(T_1^2 + T_2^2 + \ldots + T_N^2)}$$

(when impulse response is gaussian)



t_1 $\sqrt{t_1^2 + t_2^2}$ $\sqrt{t_1^2 + t_2^2 + t_3^2}$

input response of probe composite response

Oscilloscope manufacturers commonly quote the *3-dB bandwidth*, F_{3dB}, of probes and vertical amplifiers instead of rise time.

Scope Limitations

This conversion technique between 3-dB bandwidth and the 10-90% rise time assumes the frequency response of the probe is *gaussian*:

$$T_{10\text{-}90\%} = \frac{0.338}{F_{3dB}} \quad \text{or} \quad T_{10\text{-}90\%} = \frac{0.361}{F_{RMS}} \quad \text{if RMS bandwidth is given}$$

If you are analyzing low-pass filters (which do not have a gaussian frequency response), the relationship is given as:

$$T_{10\text{-}90\%} = 2.2\frac{L}{R}$$

$$T_{10\text{-}90\%} = 2.2RC$$

$$T_{10\text{-}90\%} = 3.4\sqrt{LC} \quad \text{(for two-pole RLC filter near critically damped)}$$

For example, a 300 MHz probe and scope degrades a 2 ns signal:

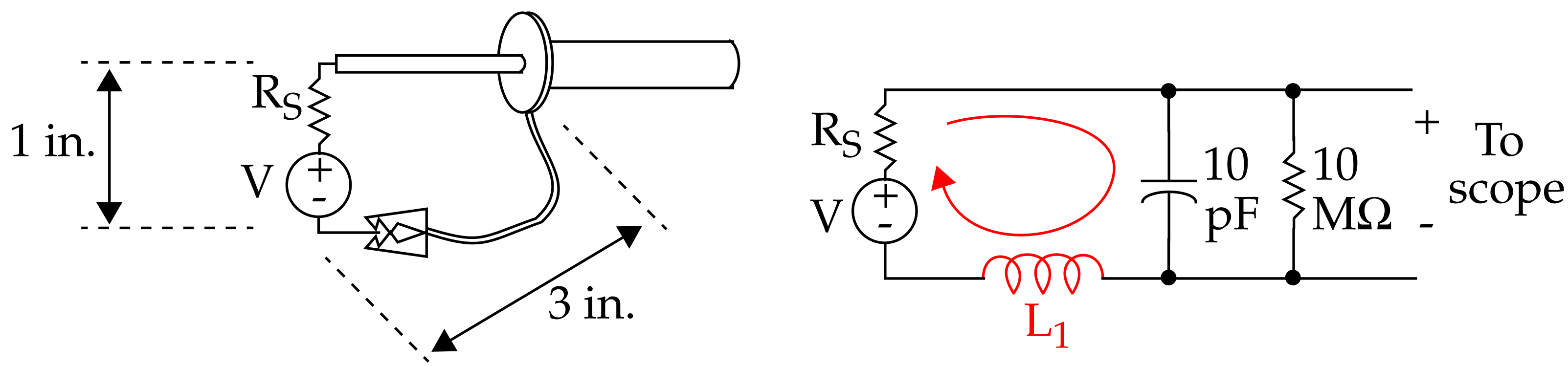
$$\left.\begin{aligned} T_{r\text{scope}} &= 0.338/300\text{MHz} = 1.1ns \\ T_{r\text{probe}} &= 0.338/300\text{MHz} = 1.1ns \end{aligned}\right. \longrightarrow T_{\text{disp}} = \sqrt{1.1^2 + 1.1^2 + 2^2} = 2.5ns$$

Probe Self-Inductance

The *self-inductance* of the ground loop in standard 10:1 probes is the primary factor degrading their performance.

Beware that the manufacturer rates performance with the probe tip and ground connected directly to the circuit (no ground wire).

We more commonly use them as shown:



The 10 pF and 10 MΩ are typical values for scope probes.

L_1 impedes the current on its return to the source.

It adds to the impedance of the probe input and increases the measured rise time.

Probe Self-Inductance

The dimensions of the ground loop are 1 in. + 3 in., made of 24 AWG wire with diameter 0.02 in.

Appendix C of text gives the inductance of a rectangular loop as:

$$L \approx 10.16\left[1\ln\left(\frac{2\times 3}{0.02}\right)+3\ln\left(\frac{2\times 1}{0.02}\right)\right] \approx 200nH$$

The LC time constant of this circuit is:

$$T_{LC} = \sqrt{LC} = \sqrt{10pF \times 200nH} = 1.4ns$$

The 10-90% rise time for a critically damped two-pole circuit of this type:

$$T_{10\text{-}90} = 3.4T_{LC} = 4.8ns$$

The original 300 MHz-rated probe has a rise time of 1.1 ns.

The 3 in. ground wire degrades this to 4.8 ns!

Probe Self-Inductance

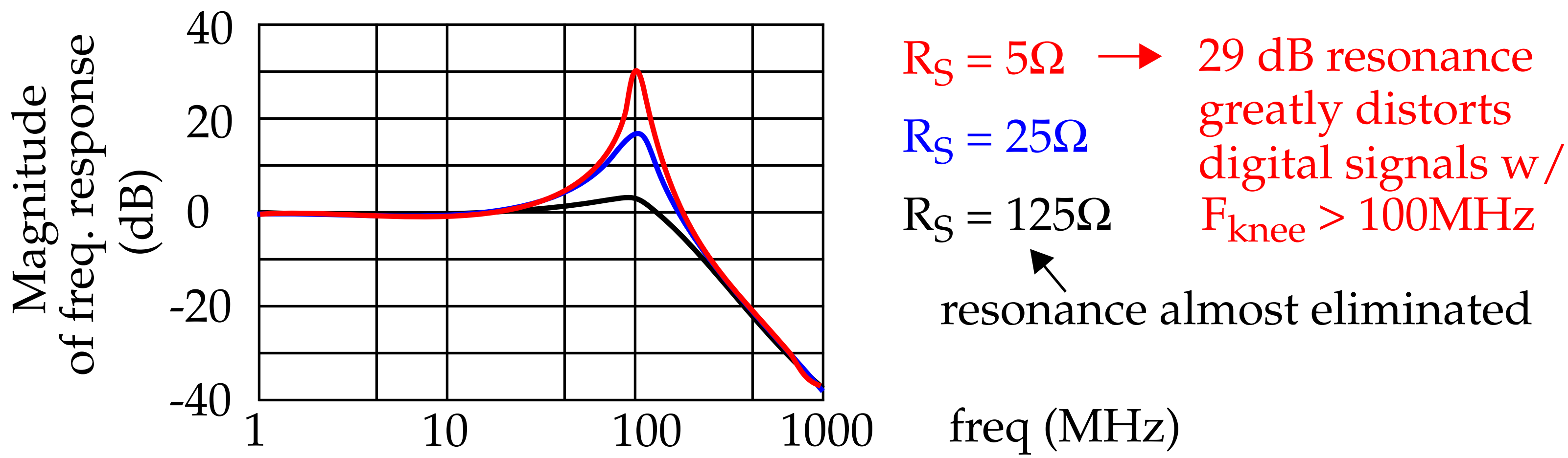
The resistor, R_S, in the previous circuit in series with the source models the output impedance of the driving gate.

For TTL and high performance CMOS, it's about 30 Ω, while ECL (silicon or GaAs) it's about 10 Ω.

The Q (resonance) of the LC circuit is dramatically affected by this resistance:

$$Q \approx \frac{\sqrt{L/C}}{R_S}$$

Here, Q is the ratio of energy stored in the loop/energy lost per radian during resonant decay, i.e. high Q circuits ring for a long period after excitation.



Probe Self-Inductance

This graph also shows that signals with F_{knee} < 100MHz will exhibit no *artificial* ringing/overshoot under this probe configuration.

With a 100 MHz limitation, the rise time is constrained:

$$\text{Rise time} > \frac{0.5}{100MHz} = 5ns$$

Note that Q and rise time of the probe are separate issues.

Rise time performance depends only on L and C while Q also incorporates R_S, the output resistance of the driver.

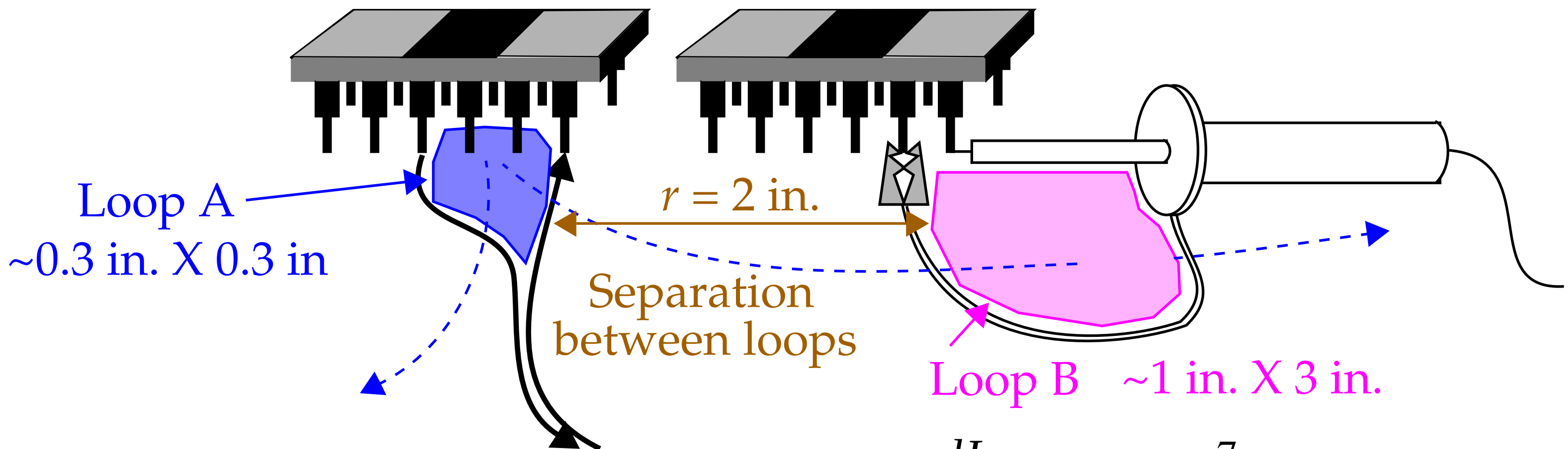
There is no way of curing the probe inductance problem by using a bigger wire.

In general, inductance is roughly proportional to loop area and wire length.

Attachment to the CUT without the ground wire and plastic clip can significantly improve the results (see text for an example).

Inductive Coupling

Any ground wire loop also picks up noise that masquerades as noise present in the signal itself.



$$\frac{dI}{dt} = 7.0 \times 10^7 A/s$$

Mutual inductance using formula from Appendix C:

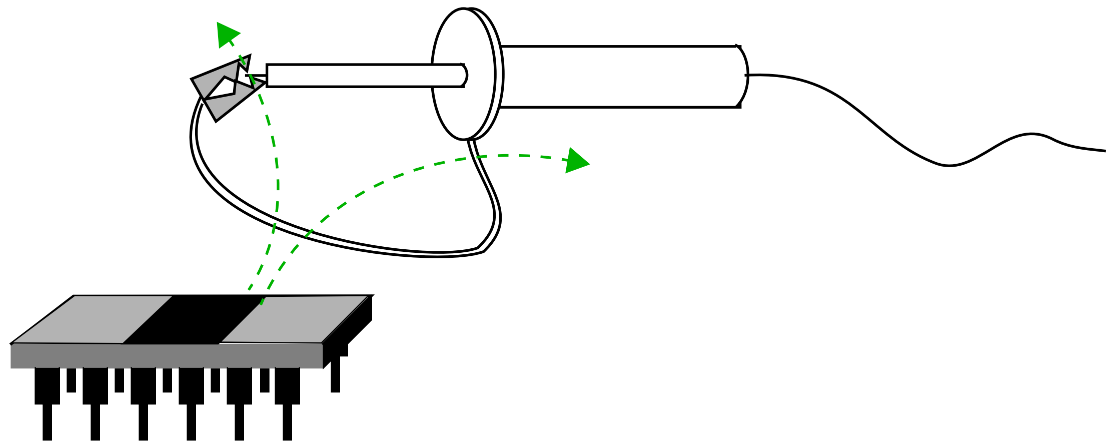
$$L_M = 5.08\frac{A_1 A_2}{r^3} = 5.08\frac{(0.3 \times 0.3)(1 \times 3)}{2^3} = 0.17nH$$

This generates, in this case, only a small noise voltage in loop B:

$$V_{\text{noise}} = L_M\frac{dI}{dt} = 0.17nH \times 7.0 \times 10^7 V/s = 12mV$$

Probe Loading

Another experiment to evaluate inductive coupling:



Turning the loop perpendicular to the magnetic field lines reduces the coupled signal.

Probes **load** a circuit and change the generated signal.

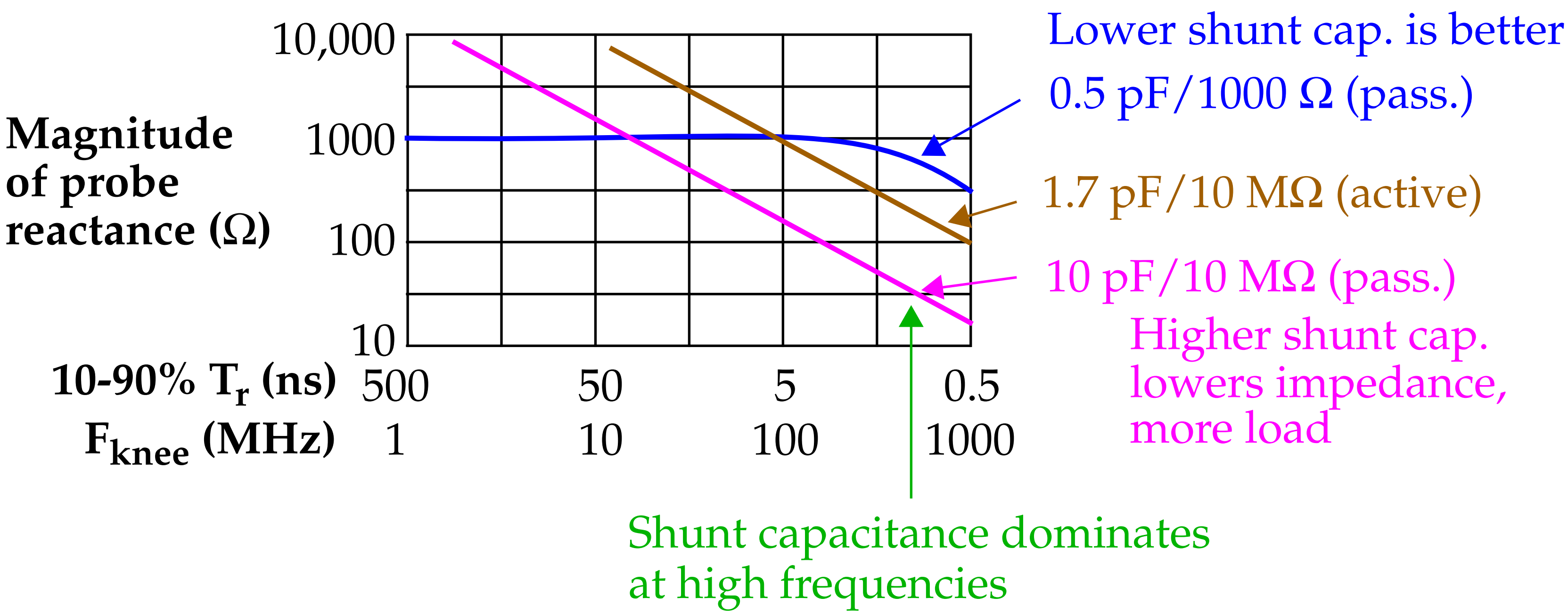
Their effect depends on the relative values of the *circuit's source impedance* with the *scope's input impedance* at the knee frequency.

Higher probe shunt capacitances reduce the impedance (adds more load), under a given impedance mode, e.g., 1 MΩ.

Probe Loading

If we want to probe to have no more than a 10% effect on the CUT's signal, then probe impedance needs to be 10X **larger** than the CUT's src impedance.

Probe input impedance for some common probe types:



Under the assumption that the *source impedance* is between 10 - 75 Ω, it's clear that the 10 pF probe fails for any rise time less than 5 ns.

Text gives example.

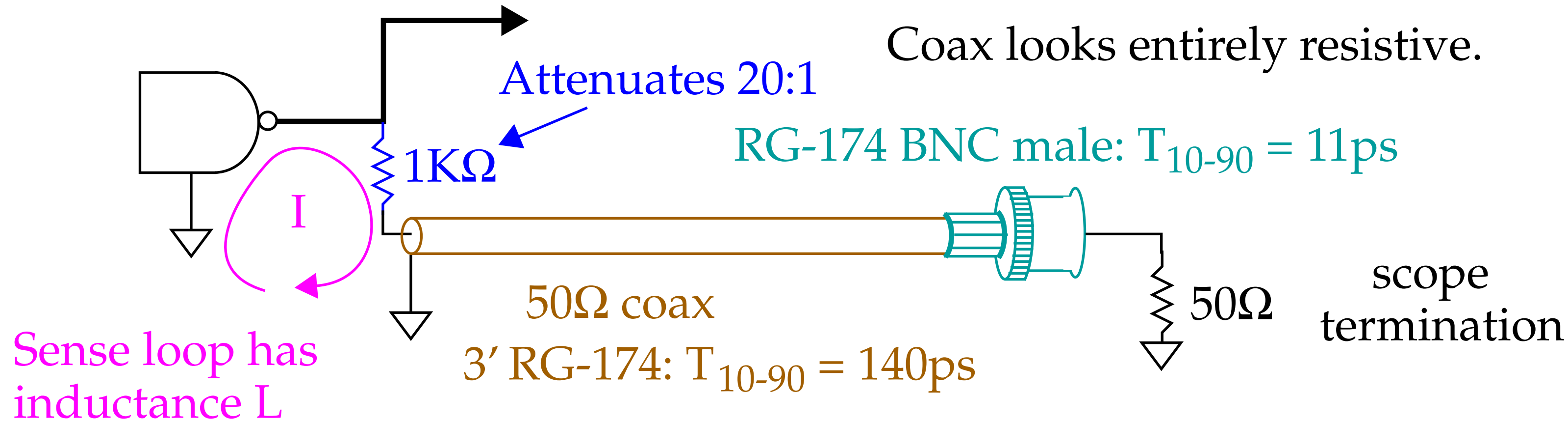
Special Probe Fixtures

Common probes in digital labs have 10-pF cap. loads and use a 3- to 6-in. ground wire.

With such high ground loop inductance and shunt cap, not much hope in measuring a 2-ns rising edge.

Solutions:

- Lab (shop) built 21:1 probe



$$T_{10\text{-}90} = 2.2L/R = 2.2L/1050$$

Signal and GND of coax is soldered at CUT.

Voltage divisor at scope reduce amplitude by 50/(50+1000) = 0.048.

Special Probe Fixtures

- Lab (shop) built 21:1 probe (cont)

  The probe's rise time is fast because:

  - DC impedance is 1050 Ω instead of 50 Ω.
  - Shunt cap of 1/4 W 1000 Ω resistor is 0.5 pF.

  Three factors that play a role in the probe's 10-90% rise time:

  - Rise time of BNC
  - Rise time of coax
  - Rise time of sense loop

  BNC jack introduces series inductance (0.5 nH) into the 50 Ω cable at the point where the shield spreads out away from the center conductor.

  The coax *rise time* is proportional to the **square** of its length.

  The inductance and rise time of the *sense loop* is related to the loop diameter -- smaller is better, of course (see text for numbers).

Special Probe Fixtures

- Lab (shop) built 21:1 probe (cont)

  For example:

  RG-174 BNC connector T_{BNC} = 11 ps

  6′ of RG-174 coax T_{coax} = 394 ps

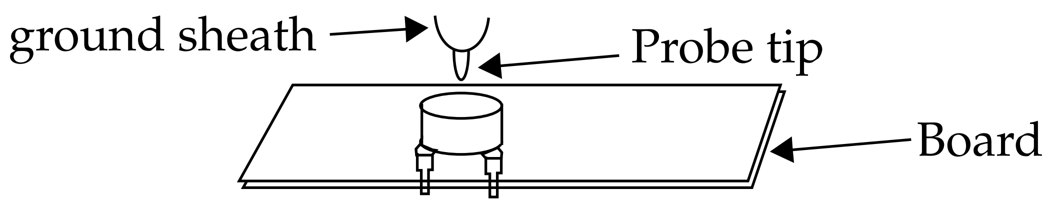
  0.5-in. probe sense loop T_{loop} = 60 ps

$$T_{\text{composite}} = \sqrt{T_{BNC}^2 + T_{\text{coax}}^2 + T_{\text{loop}}^2} = 399\,ps$$

- Low-inductance GND loop fixtures:

  Disassembling the probe exposes its ground sheath, which extends out to the end of the probe tip

  It electrostatically shields the probe tip and reduces sensing loop diameter.



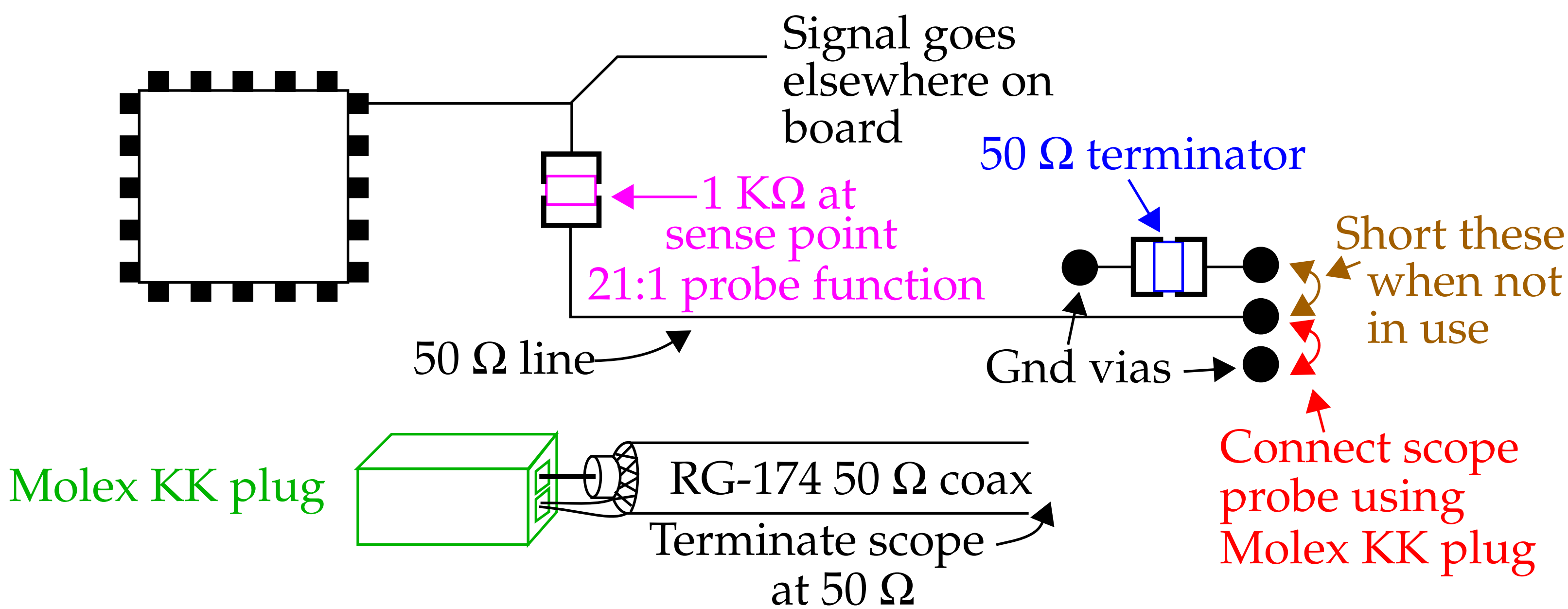
Special Probe Fixtures

- Embedded fixtures for probing:

  Embedded probes can leave the circuit under test in the same condition with and w/o taking the measurements.

  From our previous analysis, for a circuit driving a 3 ns edge, a scope probe with 10 pF looks like 100 Ω.

  Embedded probing fixture typically have only about 1 pF.



Special Probe Fixtures

- Embedded fixtures for probing:

  The test trace provides a constant resistive load of 1050 Ω.

  Many options exist for connecting the test point to the scope, e.g. square posts or BNCs

    PC-mounted BNCs consume a lot of board area.

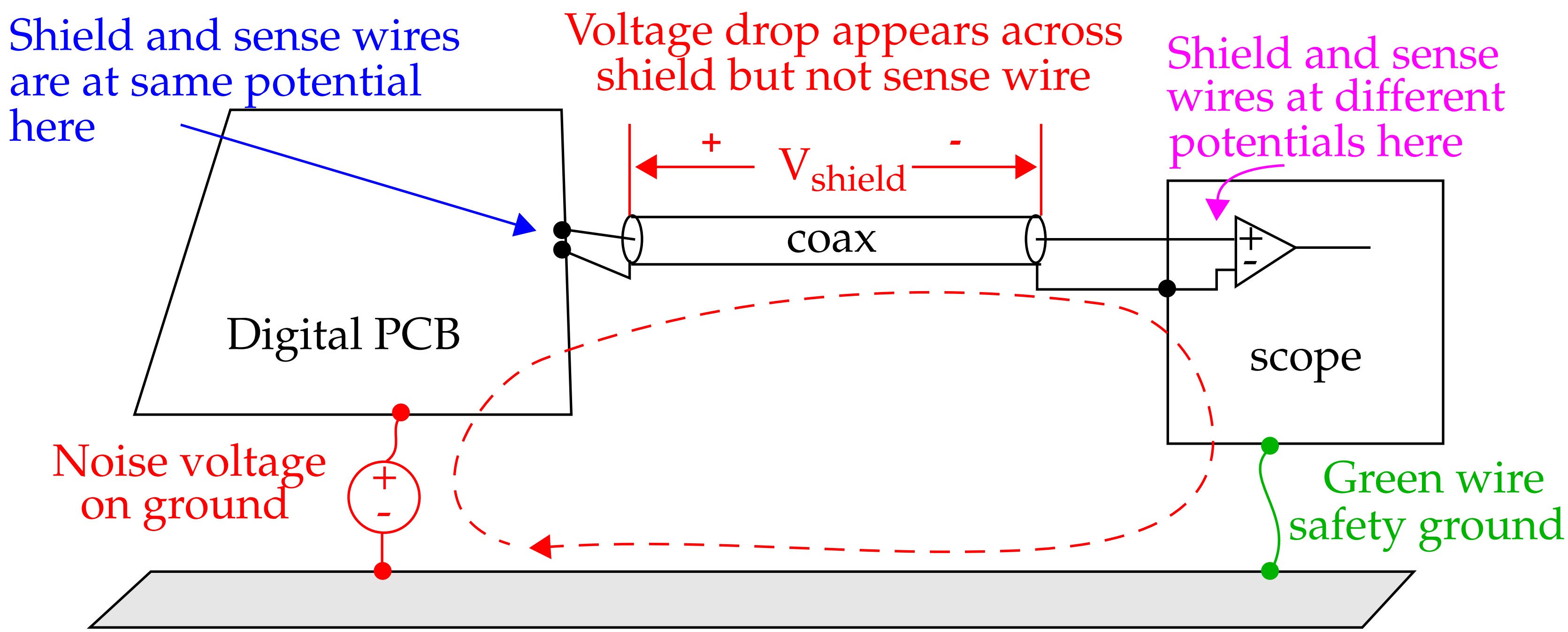
  The author prefers MOLEX/WALDOM KK series terminal housing.

    Loop inductance is about 10 nH, yielding a $T_{10\text{-}90}$ of 220 ps when used in series with the 50 Ω cable.

    Keeping the MOLEX very close to the 1000 Ω sense resistor reduces $T_{10\text{-}90}$ to 25 ps.

Avoiding Pickup from Probe Shield Currents

Scope probes have two wires, the *sense* wire and a *shield* wire.



Normally, we consider only that the scope responds to voltages on the *sense* wire.

Here, we consider how the scope responds to voltages on the *shield* wire.

Any (DC or AC) voltage difference between the board's ground and the scope's chassis ground causes current to flow in the *shield* wire.

Avoiding Pickup from Probe Shield Currents

Shield current causes a voltage drop, V_{shield}, across the shield wire's resistance, R_{shield}.

The *sense* wire carries no current and therefore has no voltage drop.

With both the *shield* and *sense* wires touching ground on the PCB, the *shield* current causes the scope to display a voltage difference even though there isn't one.

Shield voltage is proportional to R_{shield} and not to shield inductance.

The *shield* and *sense* wire are magnetically coupled, i.e., any changing magnetic field encircles both wires inducing identical voltages.

Shield voltage is easy to observe:

- Connect the probes ground and tip together.
- Move the probe near an operating circuit without touching anything.

  Voltage variations result from magnetic pickup in the probe's sense loop.
- Cover the end of the probe with aluminum foil, shorting the tip and ground sheath (to eliminate magnetic pickup) and contact the PCB's ground.

Avoiding Pickup from Probe Shield Currents

There are nine ways to attack shield noise:

- Lower R_{shield}.

  Not possible with stock probes. For shop build, use larger coax, i.e. RG-178 -> RG-58 -> RG-8.

- Add a shunt impedance between the board's and the scope's gr ound.

  This diverts shield current through the shunt wire.

  For high frequency apps, attaching a ground wire between board and scope with low enough inductance to make a difference is hard.

  Since inductance varies as the logarithm of diameter, the shunt wire will necessarily have to be much *shorter* to make a difference.

- Turn off the circuit board or sections of it.

  Although not always possible, this is a good test to determine if the board is generating the *shield* current or some other source.

Avoiding Pickup from Probe Shield Currents

- Put a big inductance in series with the shield.

  Wrap the probe wire 5 or 10 times through a big high-frequency magnetic core (raises the inductance of the probe's shield).

  Works well for noise in range 100 KHz to 10 MHz

    Below 100 KHz, you'll need a very large inductor to make any difference

    Above 10 MHz, the effectiveness of the magnetic core deteriorates.

- Redesign the board to reduce radiated fields.

  Change a 2-layer board to a 4-layer with **solid** ground planes.

- Disconnect the scope's safety ground.

  Obviously, this is dangerous.

  It breaks the probe shield's ground loop but is not effective for high-speed digital logic (only for frequencies, e.g., < 10 MHz).

Avoiding Pickup from Probe Shield Currents

- Use a *triaxial* shield on the probe.

  The triaxial shield is connected to the scope's chassis on one end and the PCB's ground on the other (same point as probe's ground).

  At high frequencies, most of the shield current diverts (because of the skin effect) to the outer ground.

  Triaxial shield can be made from aluminum foil or a stripped out RG-8 (see text for how to make your own 21:1 triax probe).

  Works well if the length of the exposed probe is minimized to reduce magnetic noise coupling into the triax shield/probe point loop.

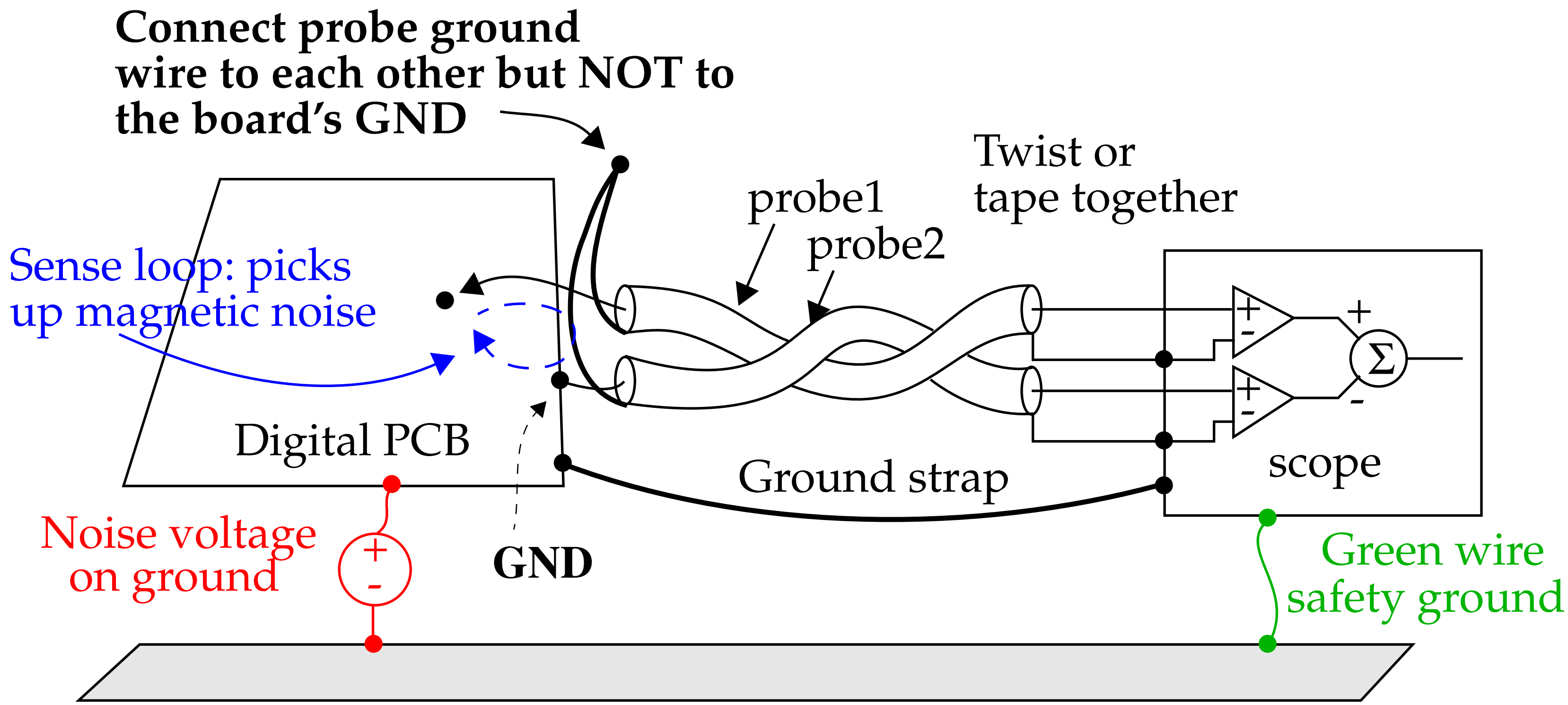
- Use a 1:1 probe instead of a 10:1 probe.

  The 10:1 does not attenuate the shield voltage effect.

  Rather the attenuation of the logic signals by 10x amplifies makes the noise appear 10 times larger.

Avoiding Pickup from Probe Shield Currents

- Use a differential probe arrangement.



Use the ground strap if the board has no connection to earth GND.

Set the scope to subtract probe2's signal from probe1's signal.

Tie both probes to a common point and adjust gains.

Touch both probes to GND to determine if noise is reduced.

Avoiding Pickup from Probe Shield Currents

- Use a differential probe arrangement (cont.)

  Twist the probe wires and minimize the sense loop -- any magnetic pickup in these loops will induce voltages between the two probes.

  Probes should be the same type and length since imbalances in the frequency response or delay will generate **common-mode** signals.

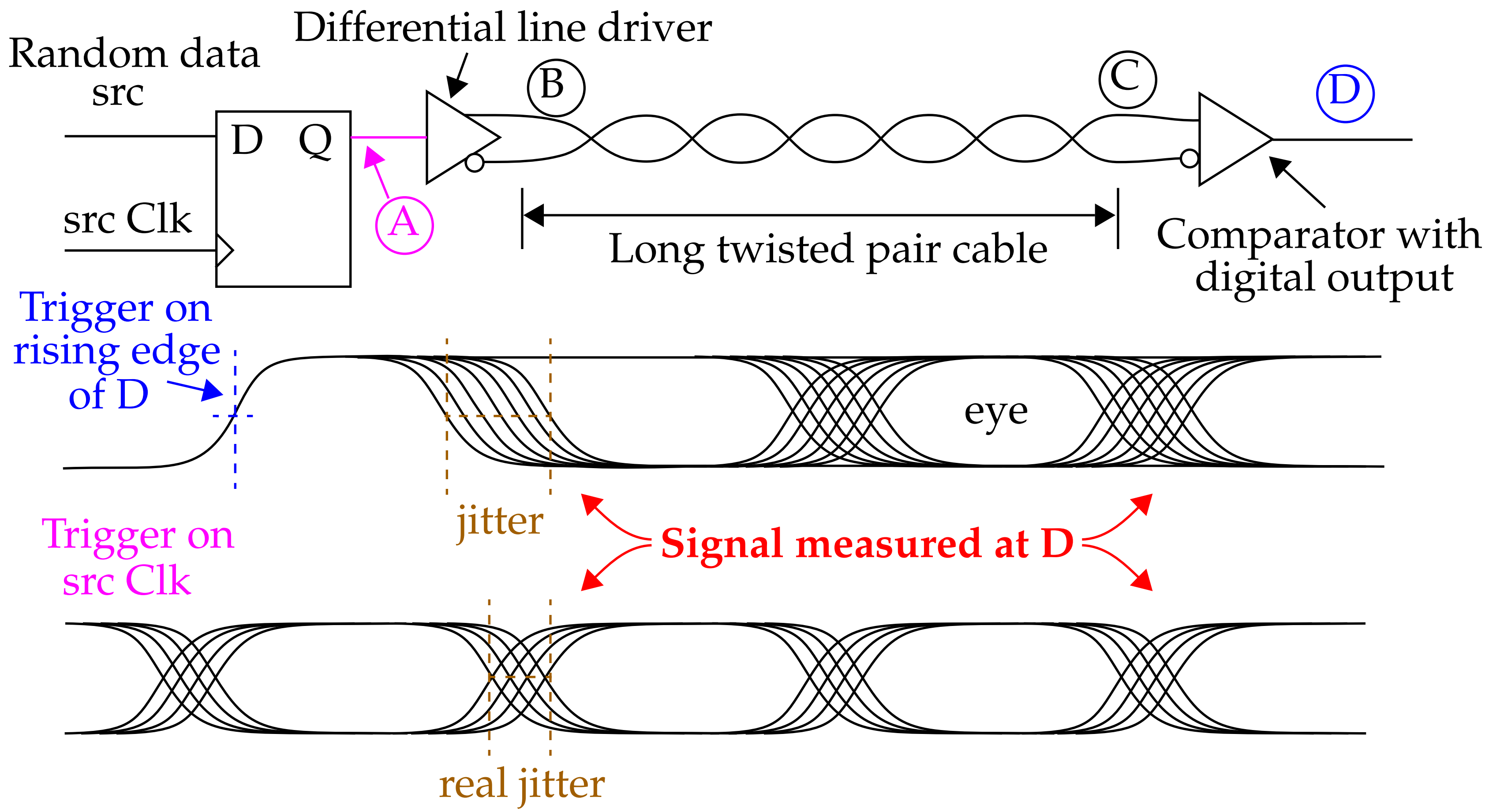
  Beware 10x probes because **common-mode** cancellation is difficult to achieve at high frequencies.

A major benefit of differential probing is the absence of *shield* currents.

  This is likely the only alternative for boards with floating GNDs or GNDs not a true earth GND.

Characterizing Jitter

Intersymbol interference and additive noise adds *jitter* to the signal transmitted to point D over that in the generated signal at point A.



Therefore, to measure the true jitter, it is necessary to use the driver signal at A, otherwise the amount of jitter observed is doubled.