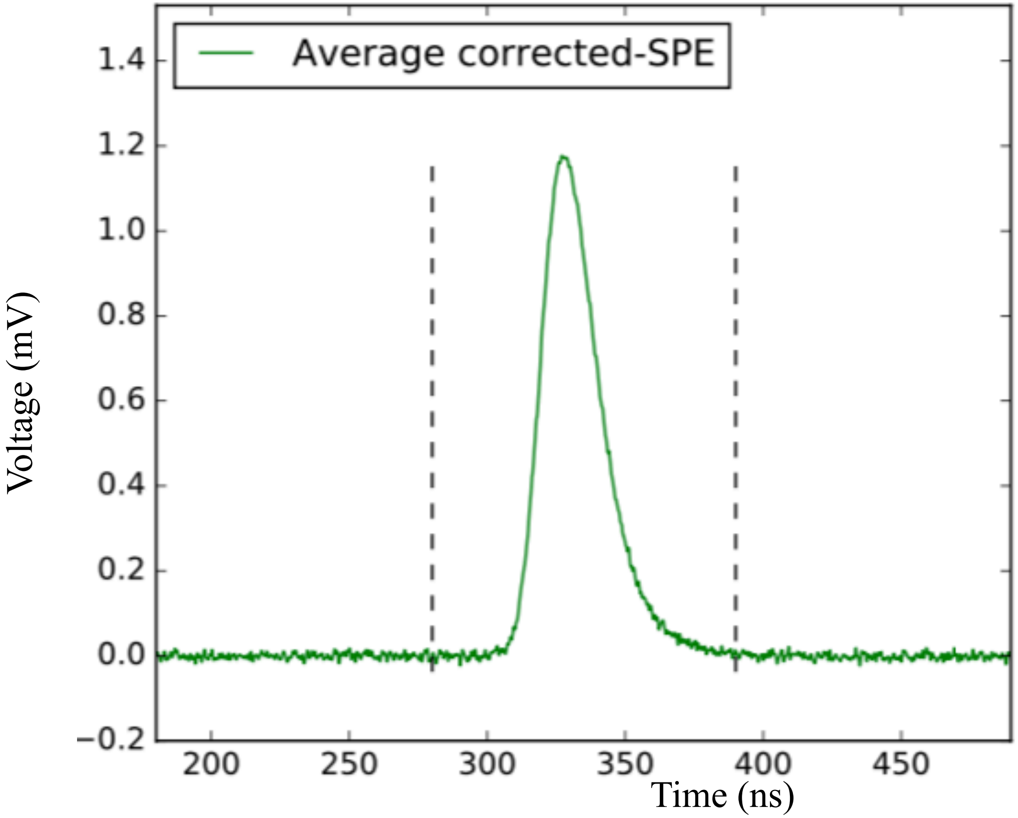
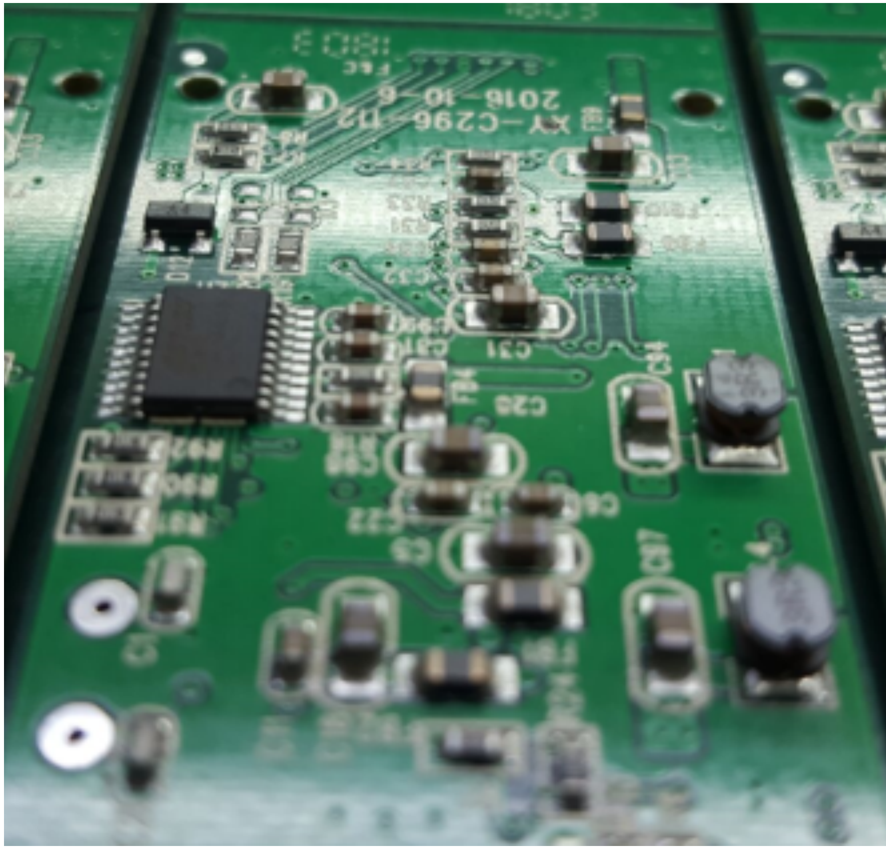
PHYS127AL Lecture 18

David Stuart, UC Santa Barbara

Reducing noise; precision measurements

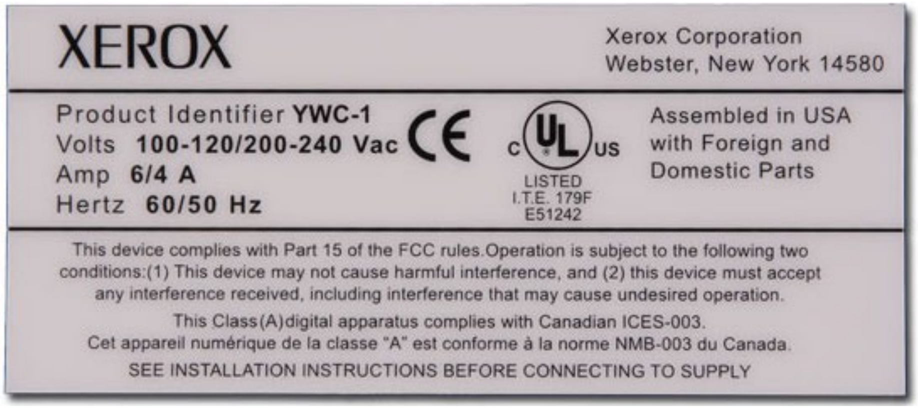




Noise

The term "noise" generically means anything that is not *your* signal.

"I can't hear you over the background noise."



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Other radio stations leaking into our sidebands.

Uncontrolled transmitters, eg microwave ovens overlap WiFi spectrum.

CMB

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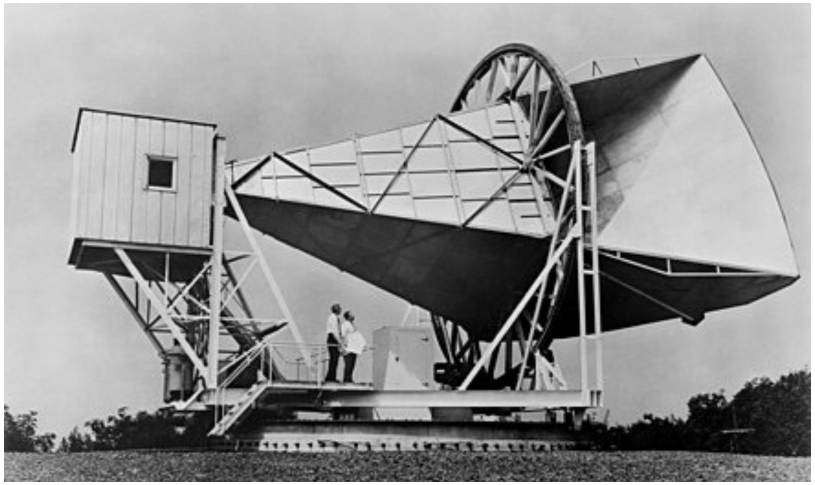

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Rincon Peak Ablaze photo by Mike Eliason / Santa Barbara County Fire Department courtesy of *Noozhawk*

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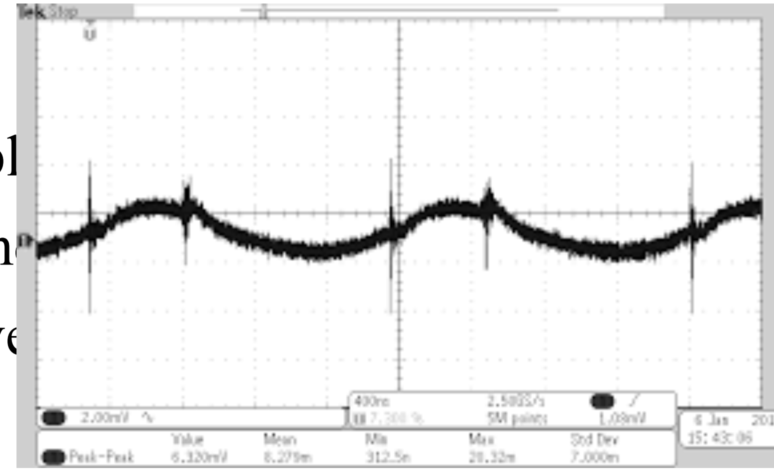

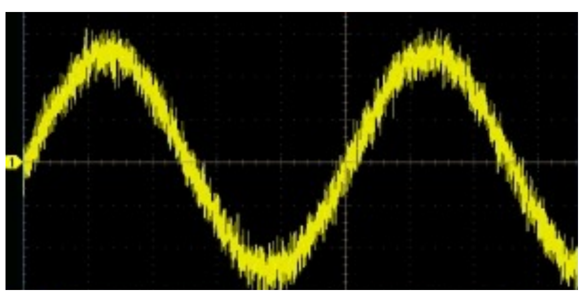

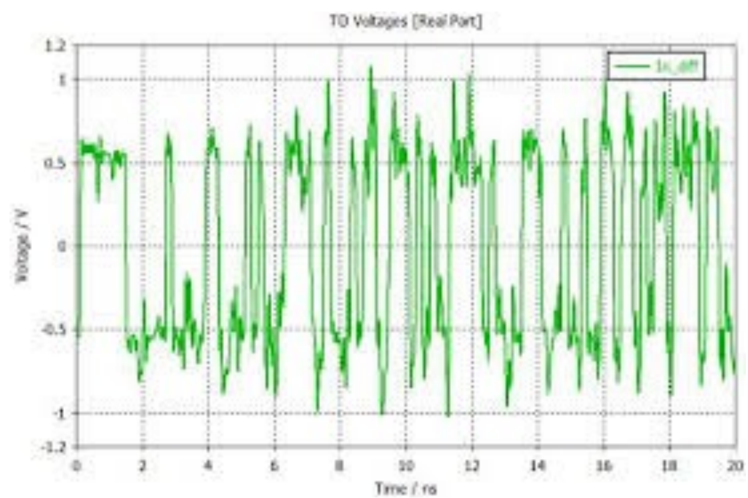

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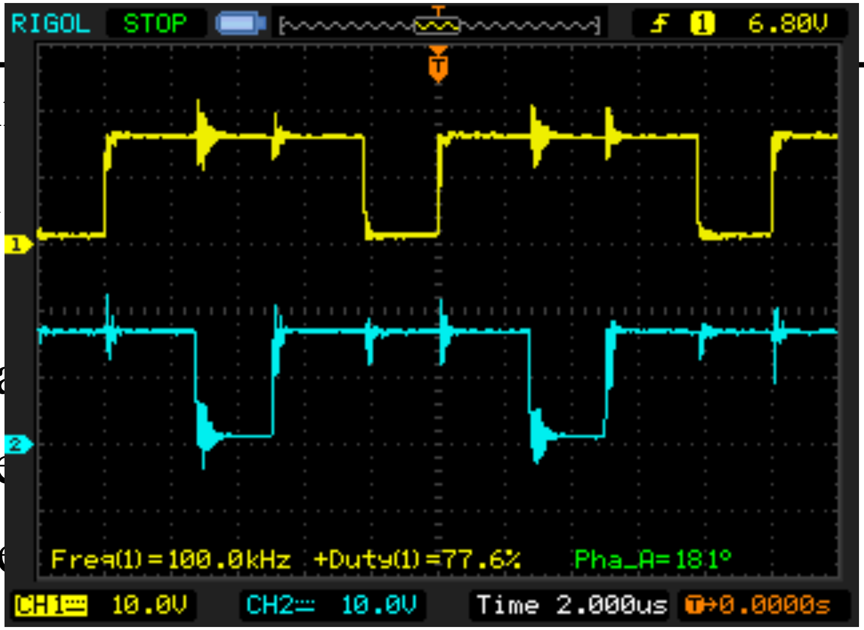
- Capacitive pickup



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"I can't hear you over the background noise."

Examples:

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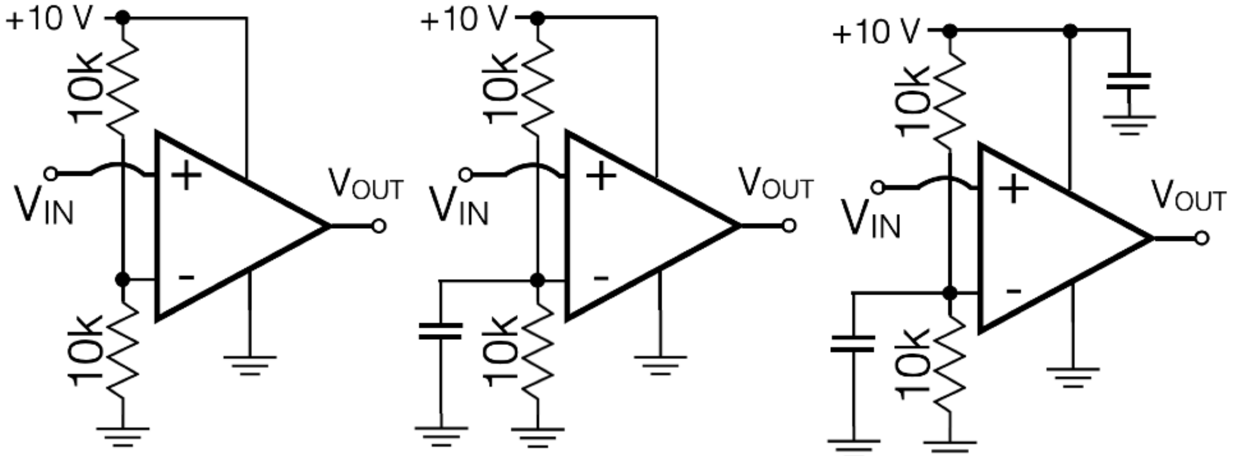
- Pickup: RF and line-noise
- Capacitive pickup
- Power supply bounce
- Power supply sag



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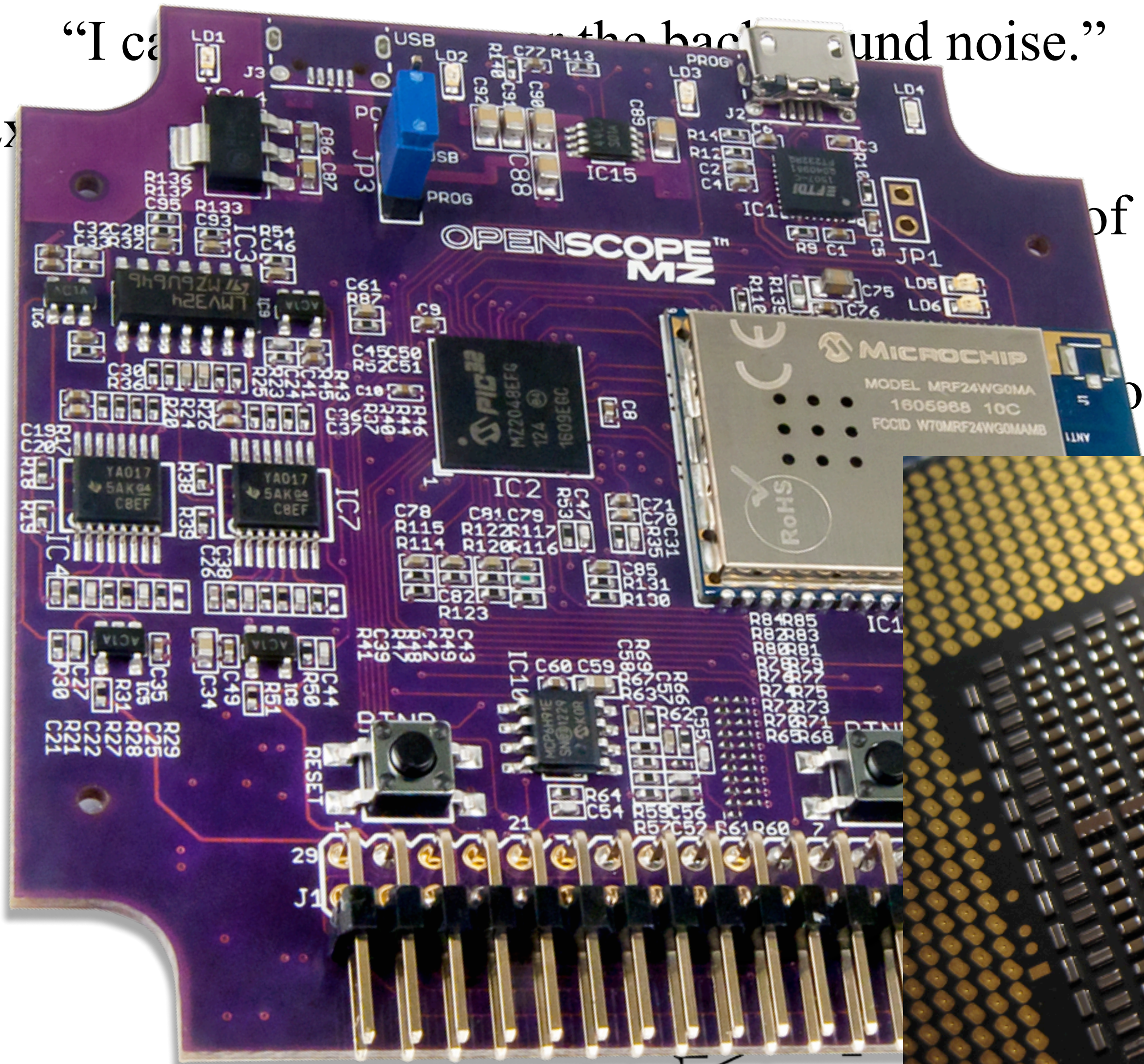
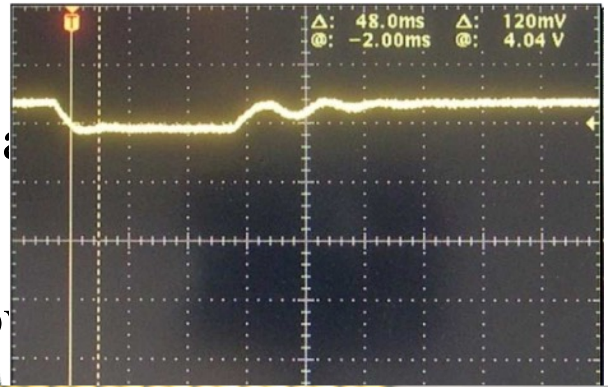
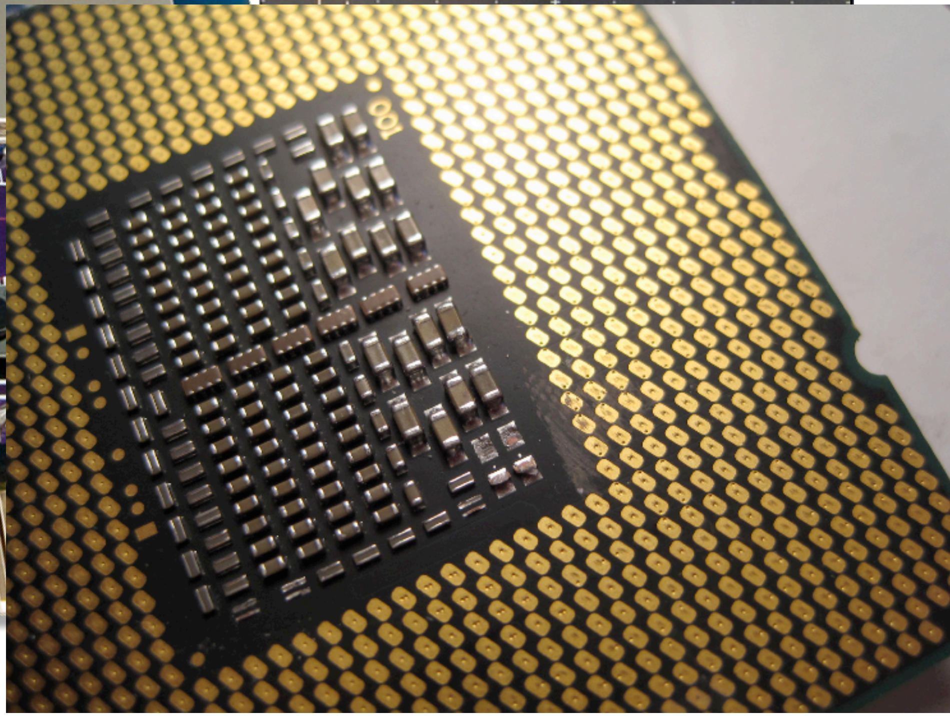






Thermal Noise

There are also thermal noise effects.

Johnson noise is thermal fluctuations that generate RMS current.

That becomes a voltage across a resistor.

Spectral *density* is

$$\overline{v_n^2} = 4k_{\mathrm{B}}TR$$

So RMS noise in a frequency range is

$$v_n = \sqrt{\overline{v_n^2}}\sqrt{\Delta f} = \sqrt{4k_{\mathrm{B}}TR\Delta f}$$

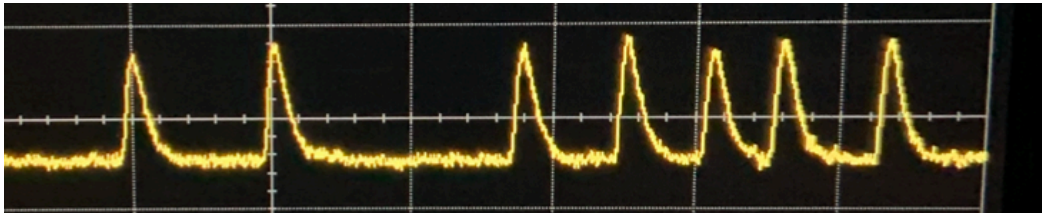
At room temperature, this is a few μV per 10kHz per kΩ.

Using a 10 MΩ input resistor adds a significant, O(10 mV), noise source, so it is best to avoid very large resistors.

Shot Noise

At very low currents, the motion of individual electrons matters.

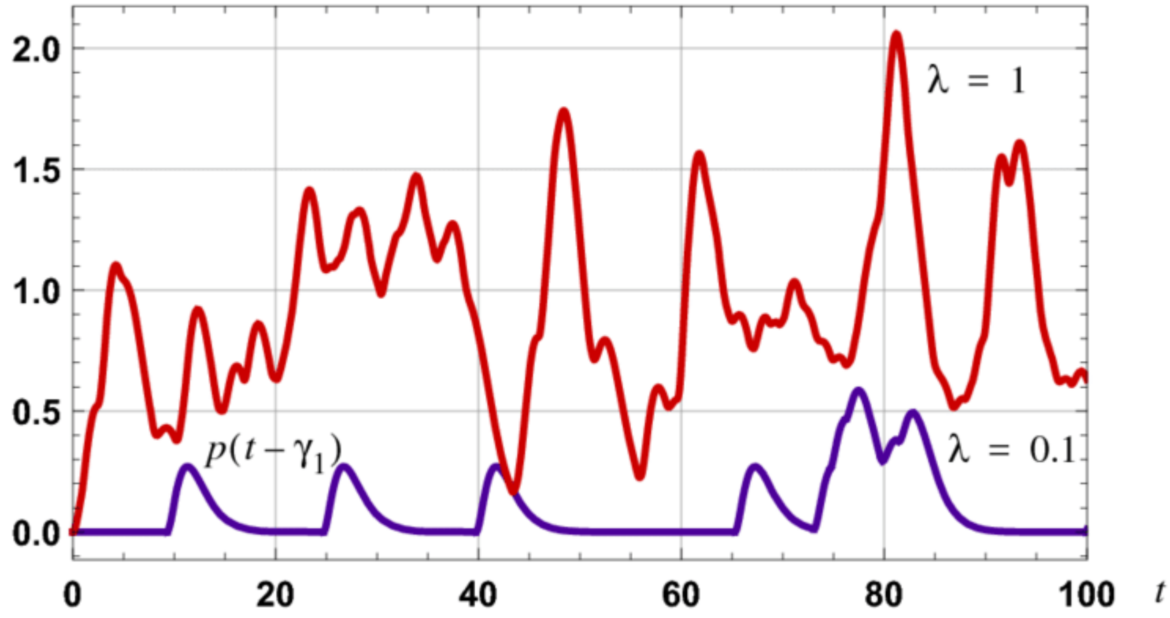
Similarly with low light levels.



Counting N individual events in a time Δt has fluctuations of $\sqrt{N}$.

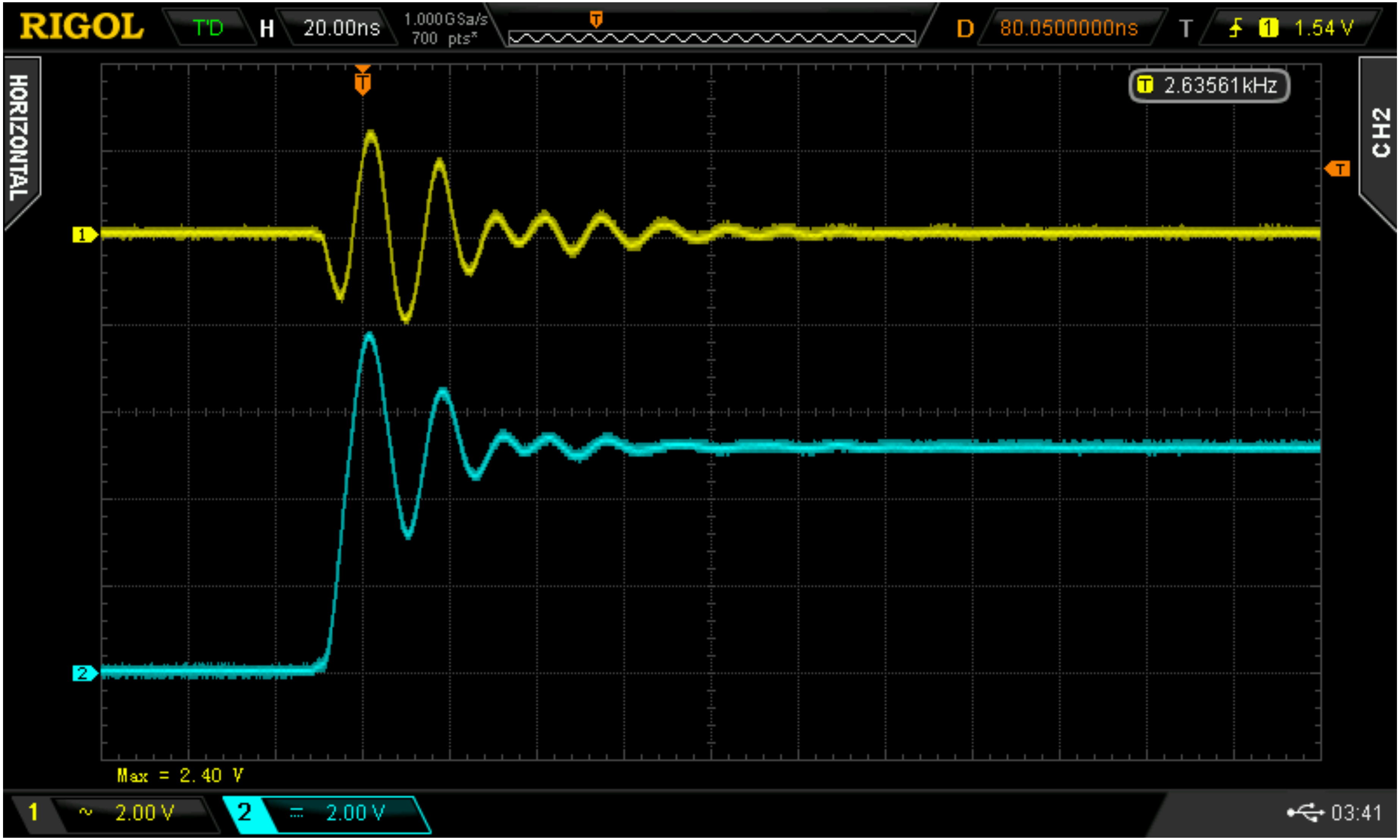
The fractional uncertainty, $\sqrt{N}/N$, reduces at higher currents, but it can dominate for small N.

Best to avoid small I, e.g., i = 10% of I is less noisy if I is larger.



Unwanted oscillations

Often, noise problems are self induced, e.g., unwanted oscillations.

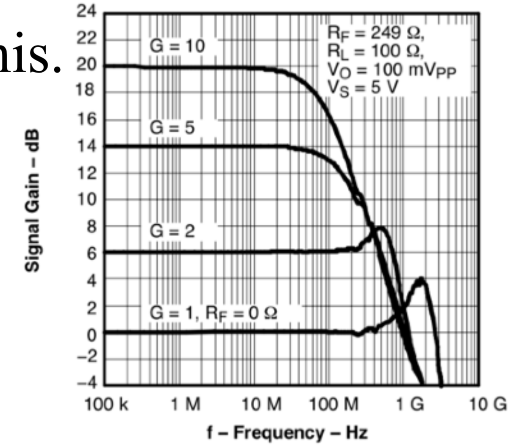


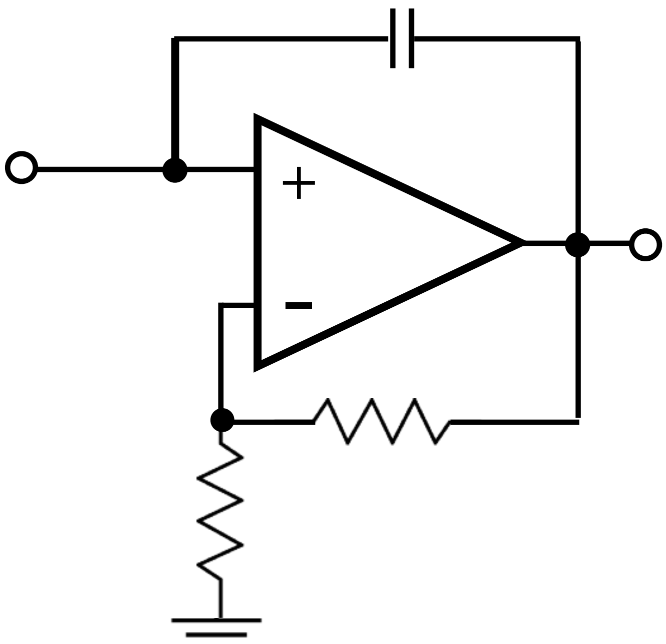
Unwanted oscillations

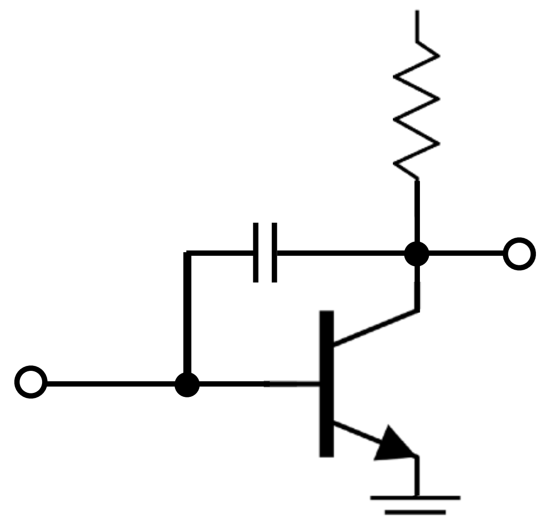
Often, noise problems are self induced, e.g., unwanted oscillations.

Positive feedback through parasitic capacitance can cause this.

- Minimize parasitic capacitance
- Roll off high-frequency gain







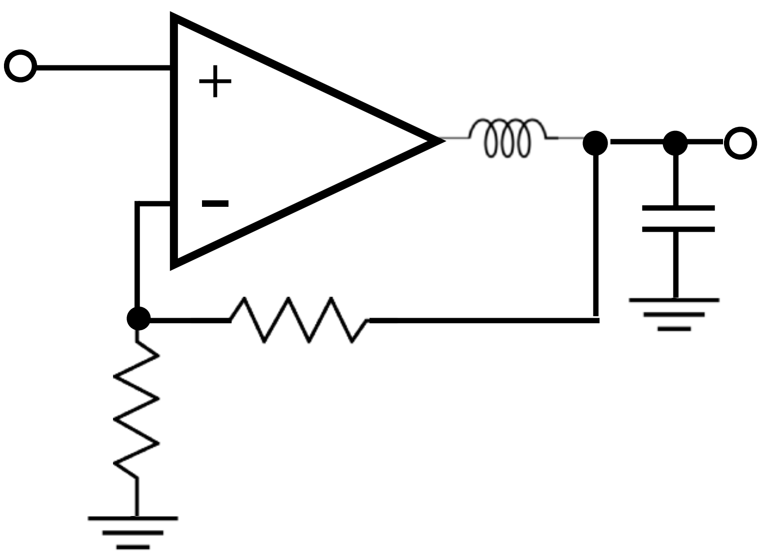
Unwanted oscillations

Often, noise problems are self induced, e.g., unwanted oscillations.

Parasitic inductance and capacitance can cause resonant oscillation.

Parasitic inductance from thin wires

Capacitance from cables.

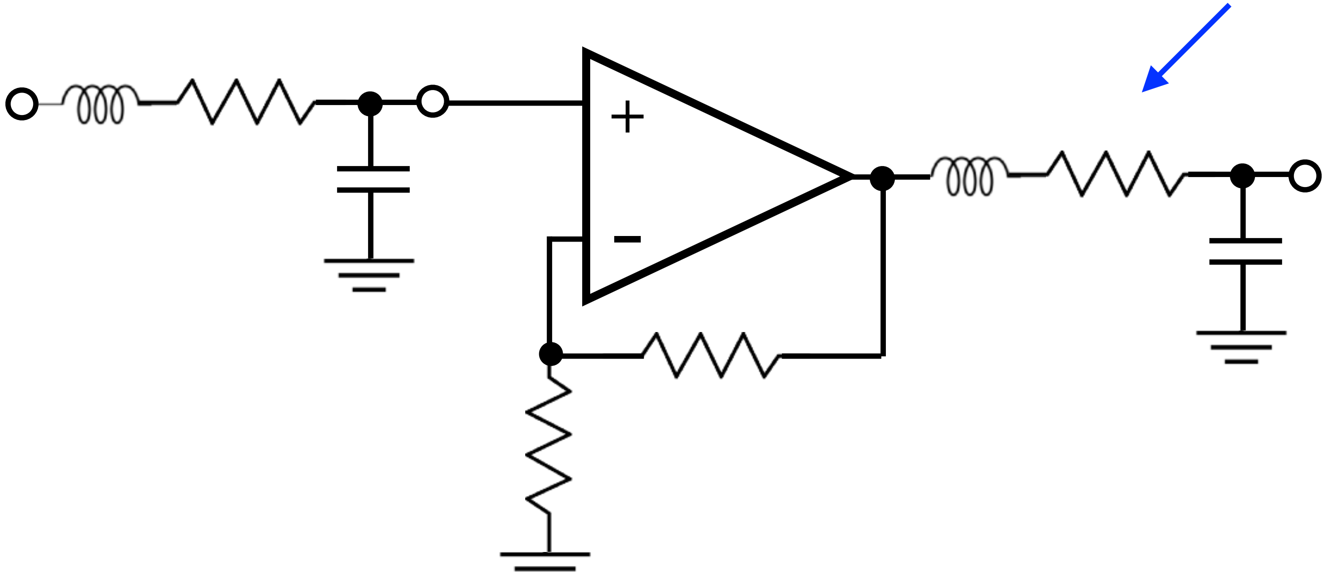


Parasitics

There are always stray (aka parasitic) contributions to capacitance, inductance, and resistance.

A simple non-inverting amp isn't so simple.

A wire is really an LRC.



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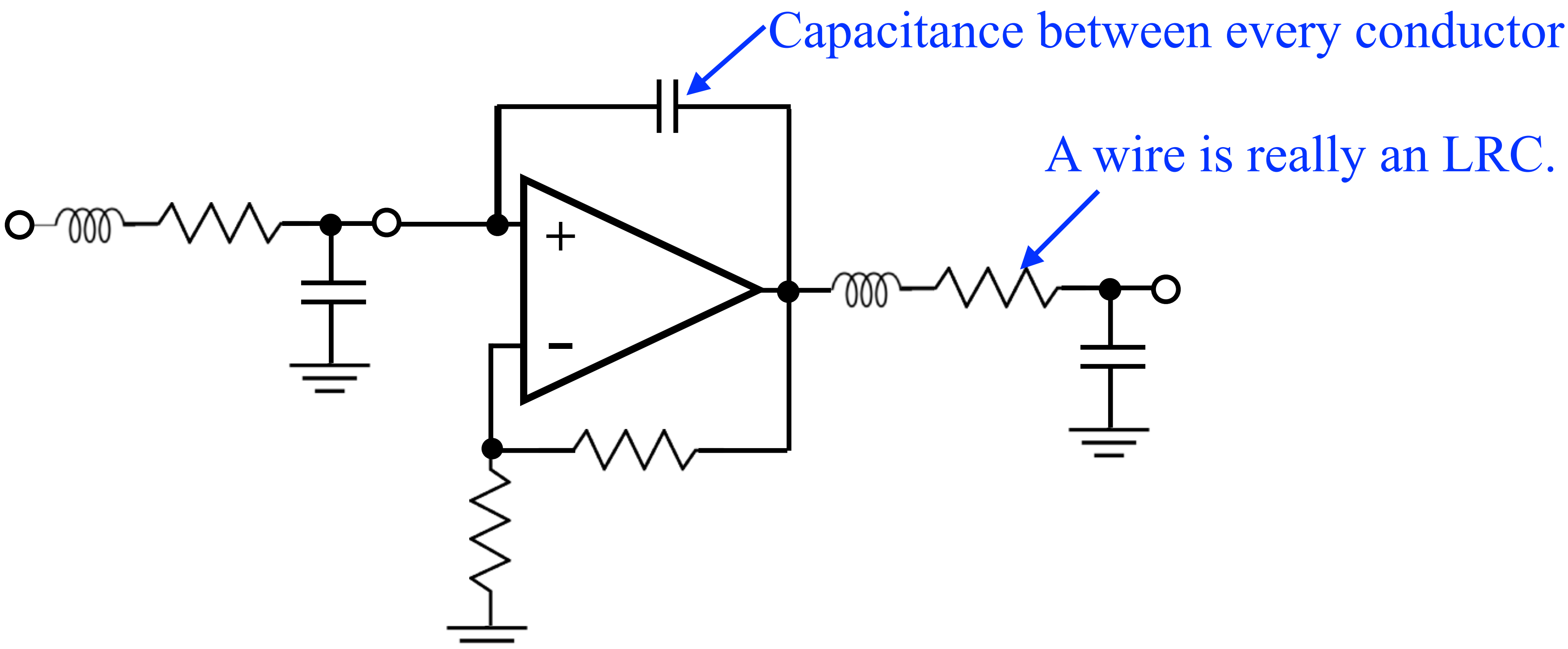

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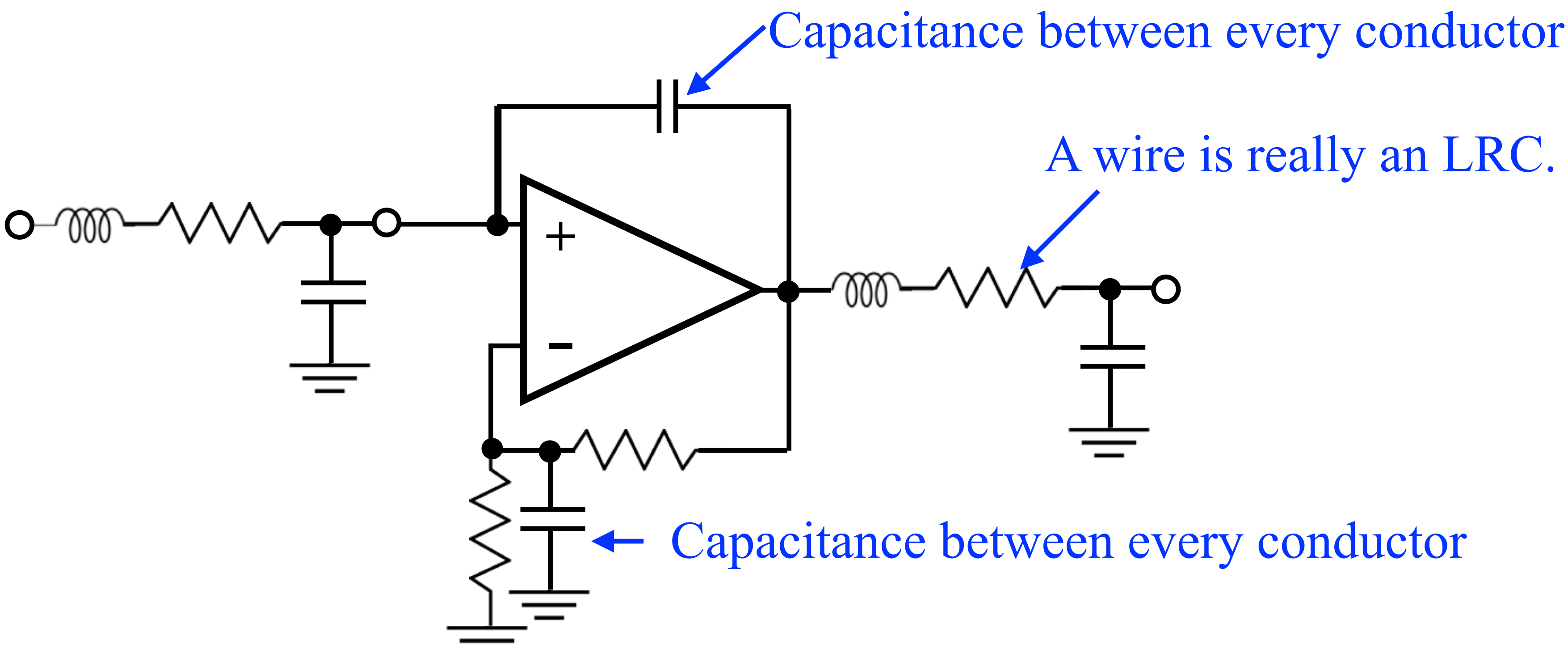

Parasitics

You'd like to keep the values for these parasitic contributions small.

Small capacitance means only impact is at very high frequency where the op-amp is already designed to roll-off the gain.

Small inductance and capacitance puts resonance at high $\omega = 1/\sqrt{LC}$ where gain is low.

Small capacitive coupling minimizes differentiator pickup: $V_{out} = -RC\, dV_{in}/dt$

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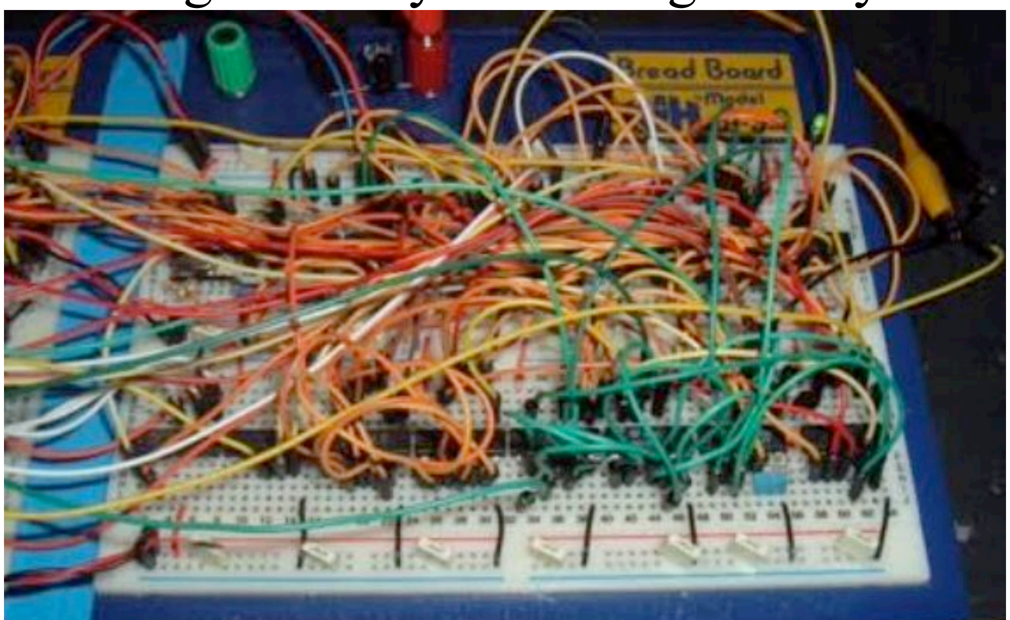
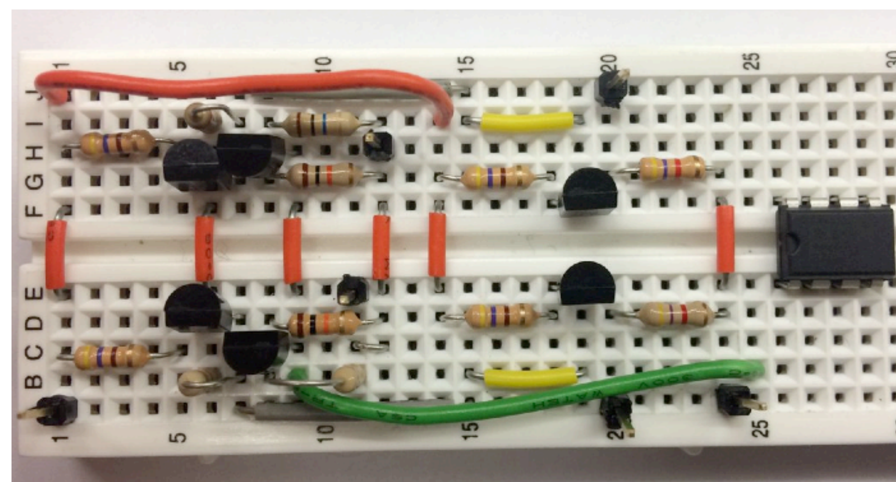
You'd like for them to at least be stable so the circuit doesn't go from working to fatally oscillating when you breath on it.

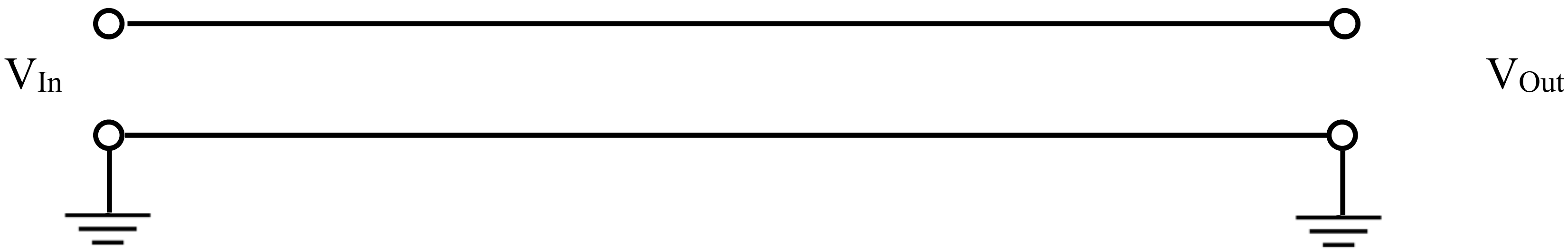


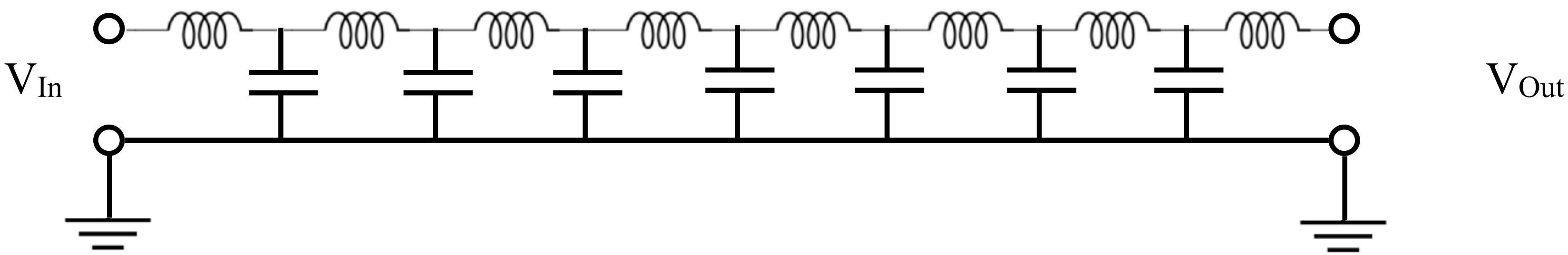


Transmission lines

At high frequencies, you have to think about wires as a transmission line.

Signals travel at some speed, as E and B vary.





A voltage pulse travels at a speed set by the L and C per length, i.e., the characteristic impedance of the transmission line. This is like an index of refraction. Reflections will occur at changes in impedance.

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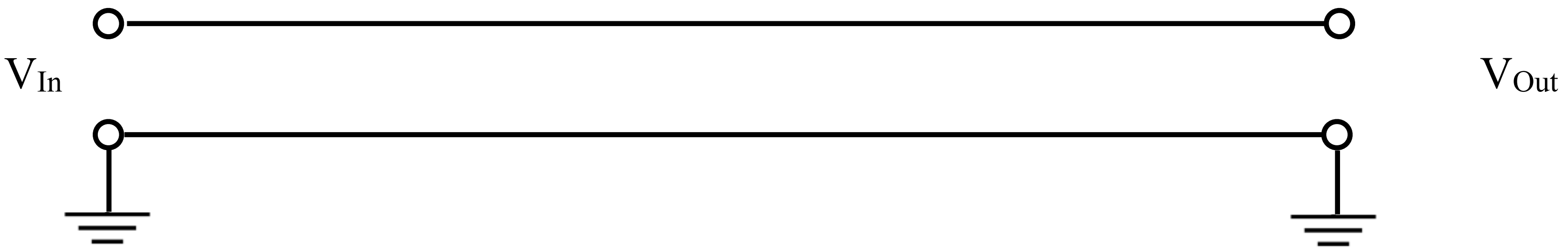

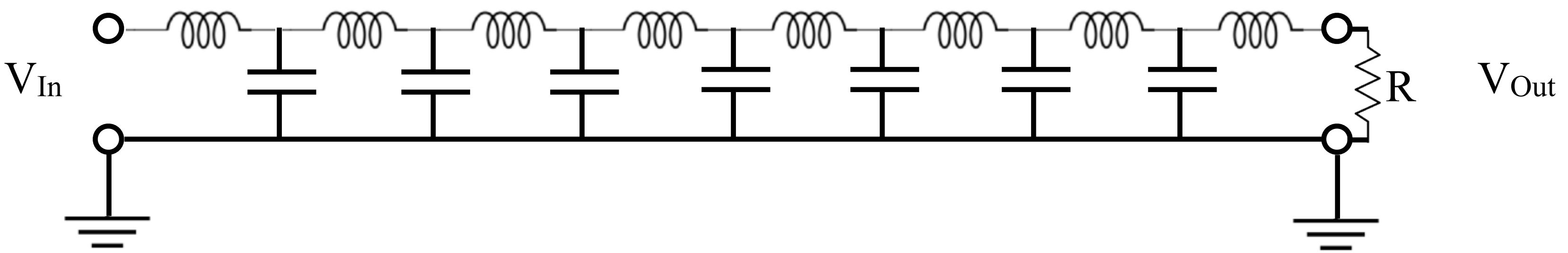

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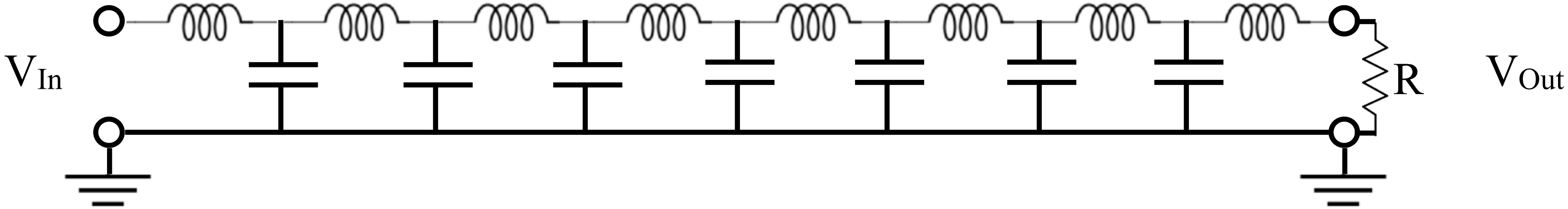
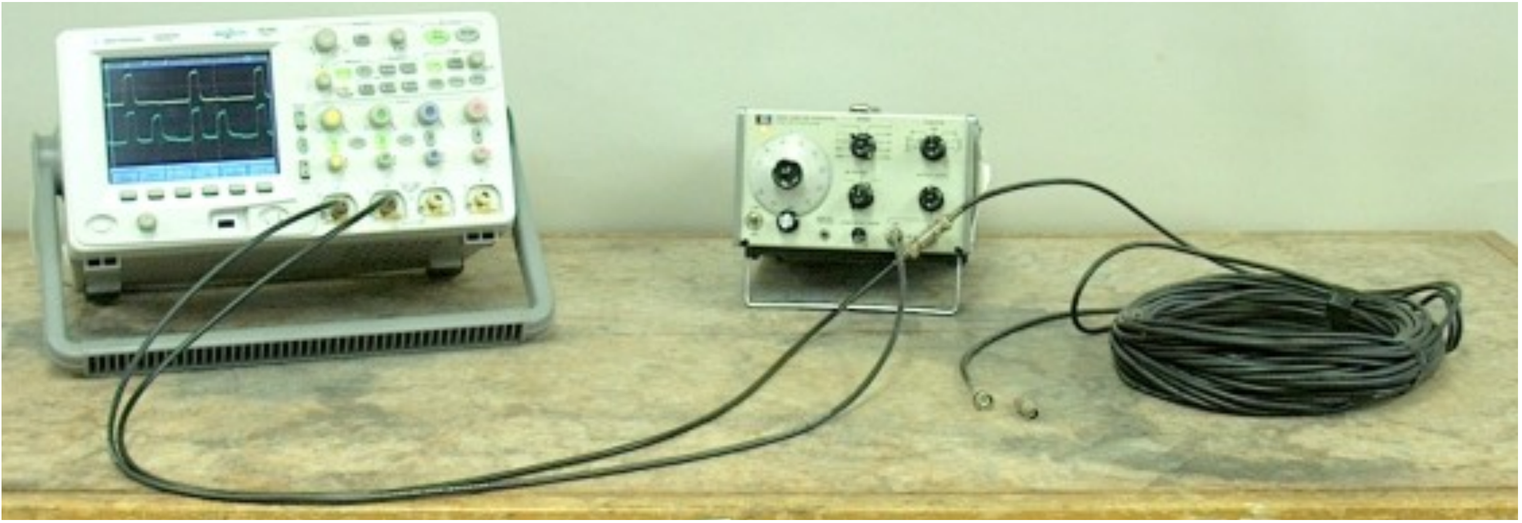
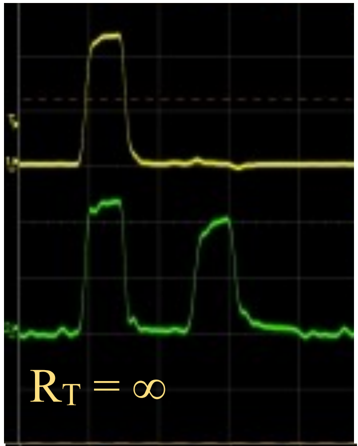




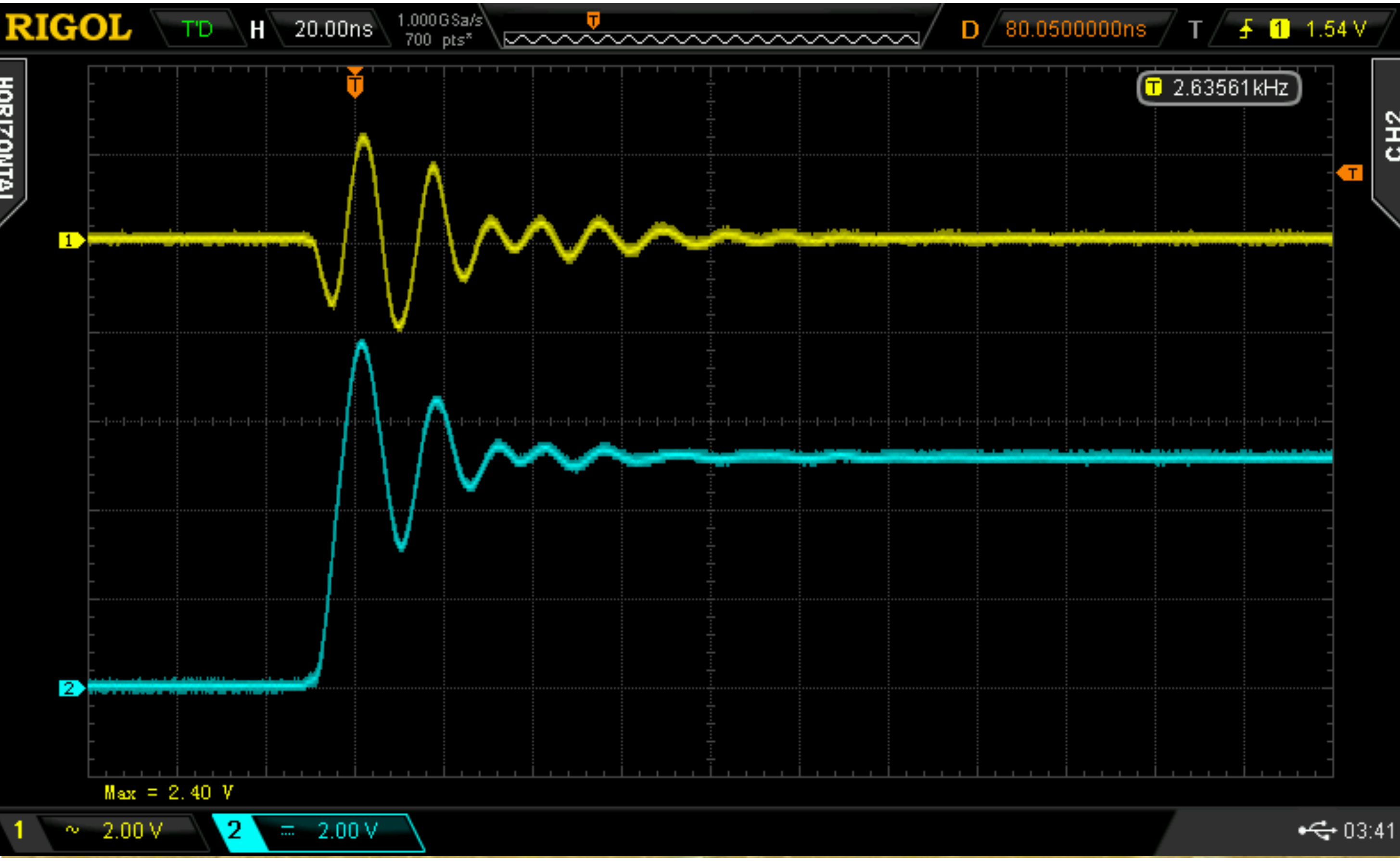


If you had an open or short at the oscilloscope end of the cable, the pulse would reflect there too, and ring back and forth until it dies down. (Note reflected pulse is slightly smaller.)

Need *impedance match* to avoid reflections.

Impedance mis-match reflects signal. (Common physics jargon.)

Transmission lines



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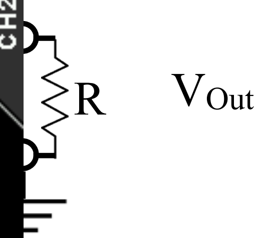

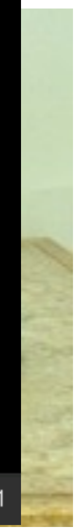

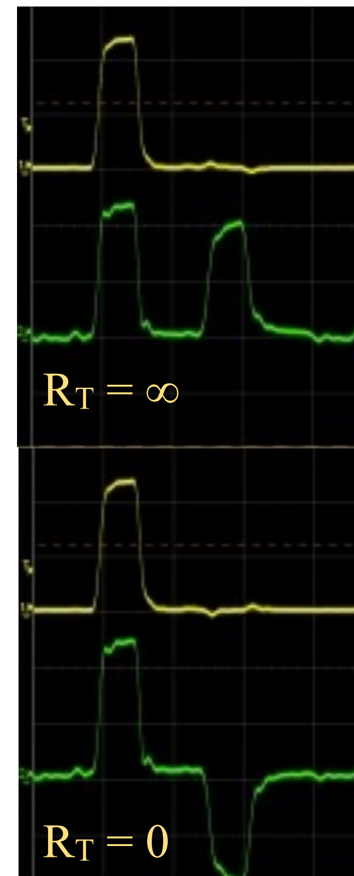

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Cable impedance

Need *impedance match* to avoid reflections.

Most Coaxial cables are 50Ω. Some 75Ω.

Fast oscilloscopes have 50Ω input impedance option.

SMA

BNC male

BNC female

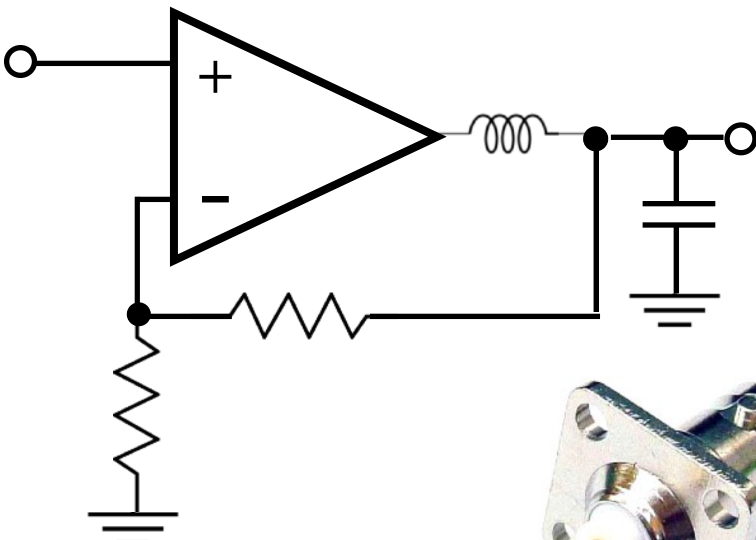
MCX

Unwanted oscillations

Often, noise problems are self induced, e.g., unwanted oscillations.

Parasitic inductance and capacitance can cause resonant oscillation.

- Parasitic inductance from thin wires
- Capacitance from cables.
  - ~ 30 pF/foot



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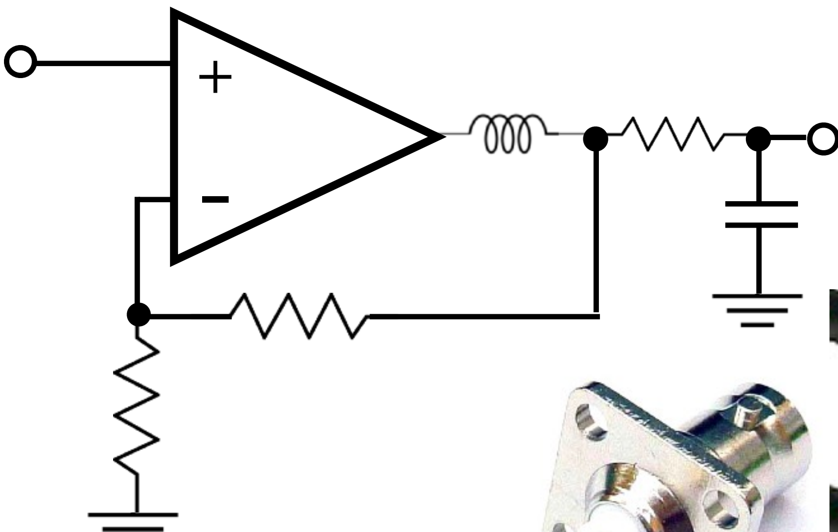
- Suppress resonance with small R.



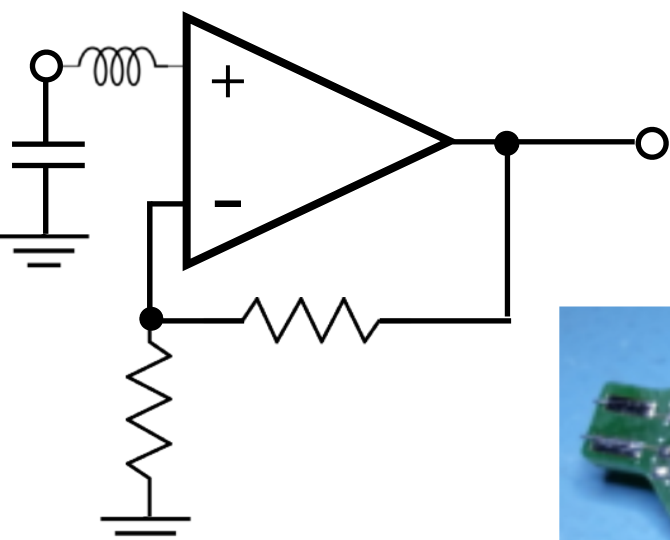
Unwanted oscillations

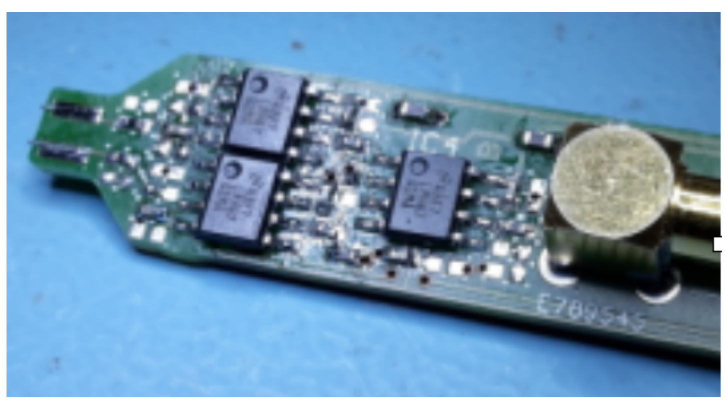
Often, noise problems are self induced, e.g., unwanted oscillations.

Also have parasitic inductance and capacitance at inputs.

Your breadboard wires are long and would cause problems at high frequency

For > 1 GHz, need *differential* scope probes.

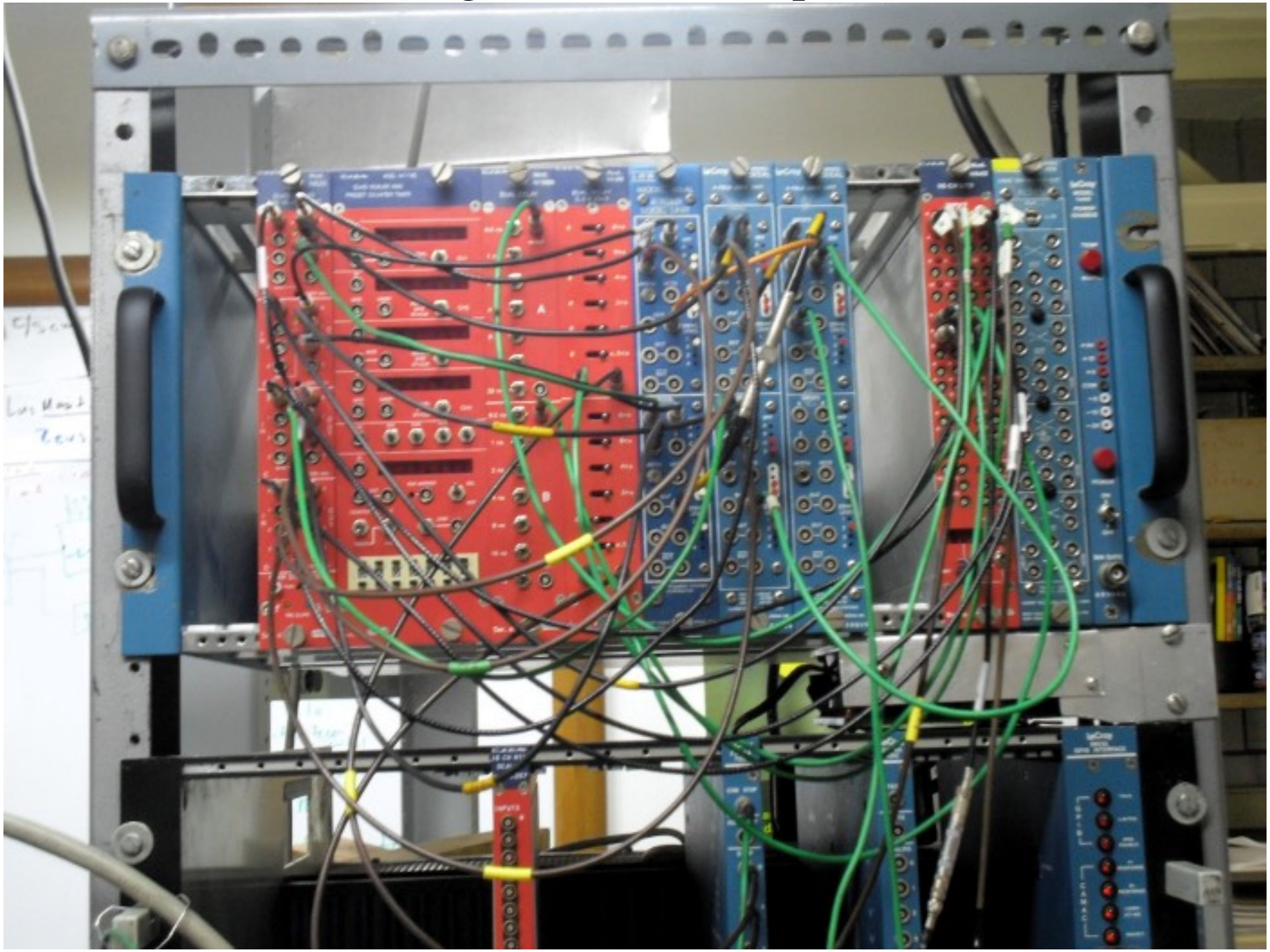




Cable impedance

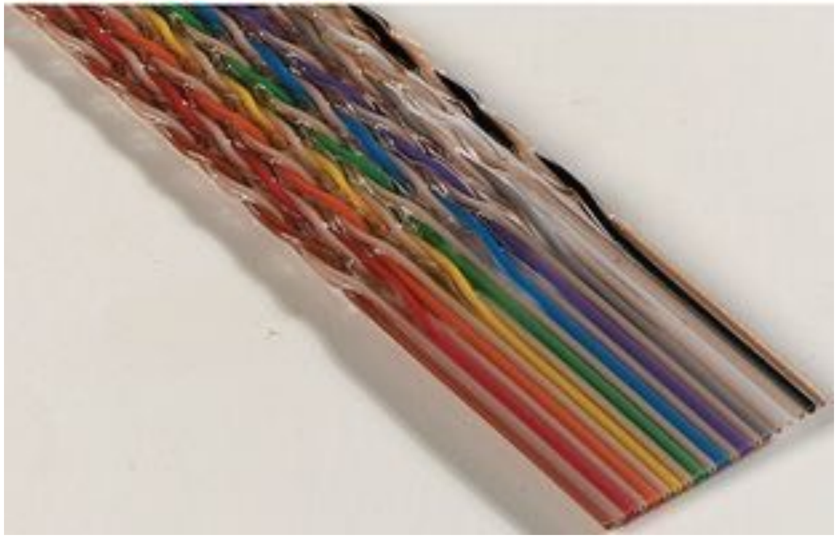
An example logic crate from an experiment. (Similar to breadboard, but fast.)

Cables have labels with the "length" in ns. All inputs have $X_{in}=50\Omega$.



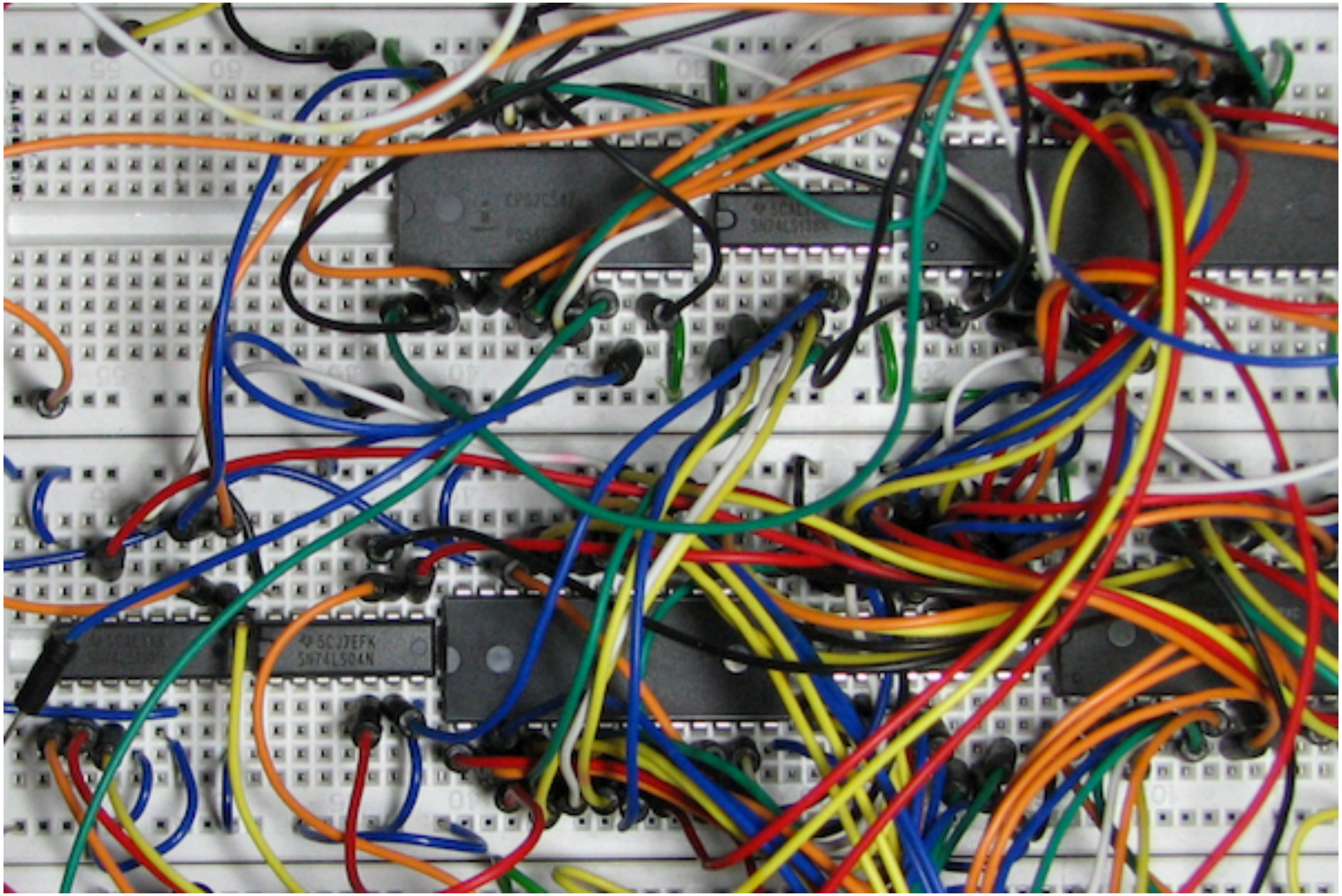
Cable impedance

Twisted pair ribbon cable typically has ~ 100Ω characteristic impedance.



Cable impedance

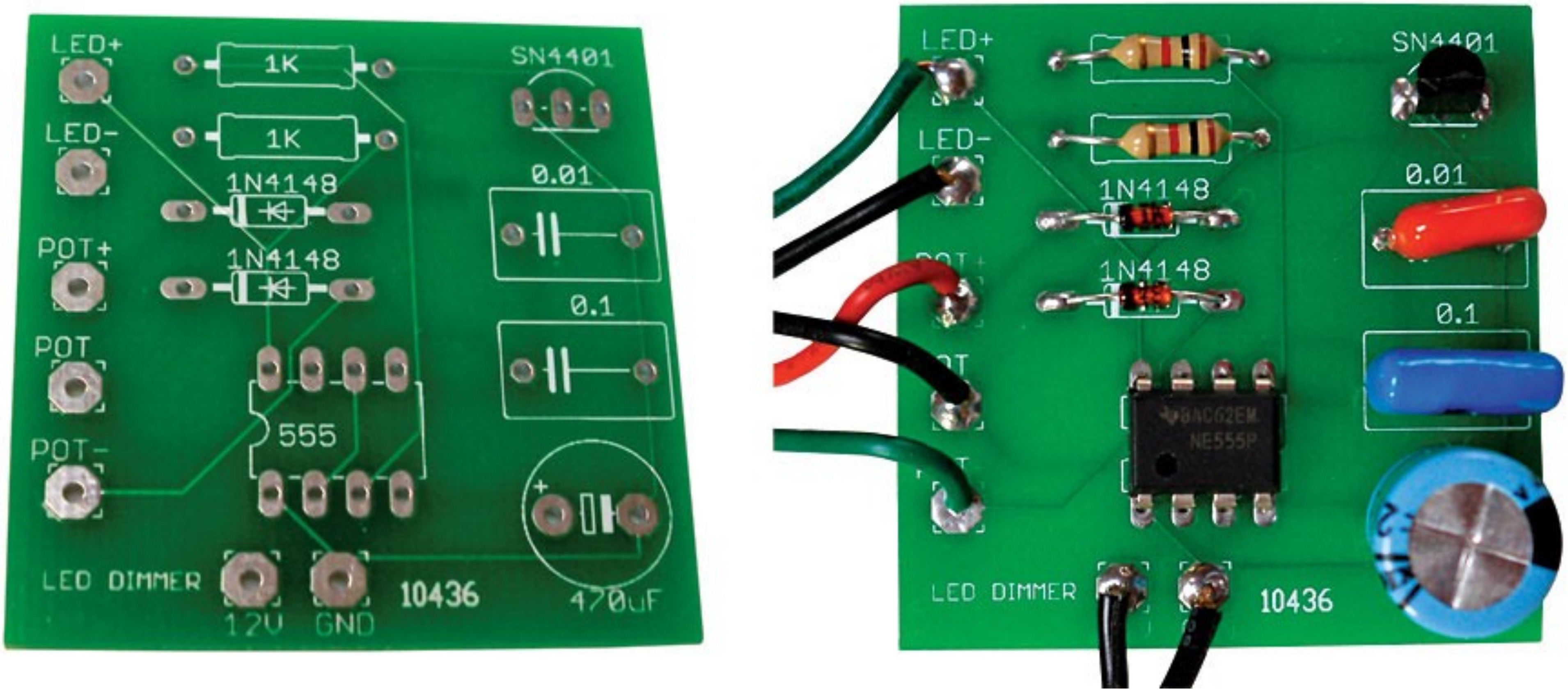
What is the characteristic impedance of these wire connections?



Because of this uncontrolled impedance and parasitics, breadboards are not good for stable, high speed circuits.

PCBs

Printed circuit boards (PCBs) allow robust, stable connections, with controlled impedance for all connections.



Note the 555 timer.

Instead of wires there are metal traces within the board.

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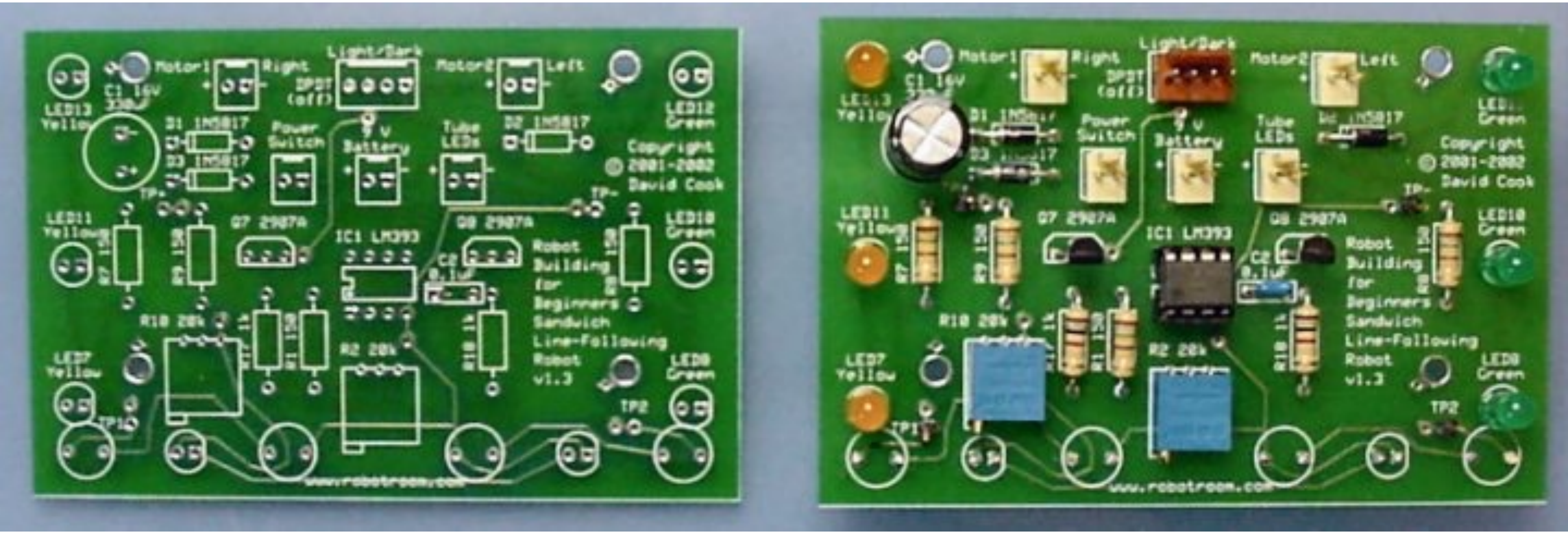


The LM393 IC is a comparator.

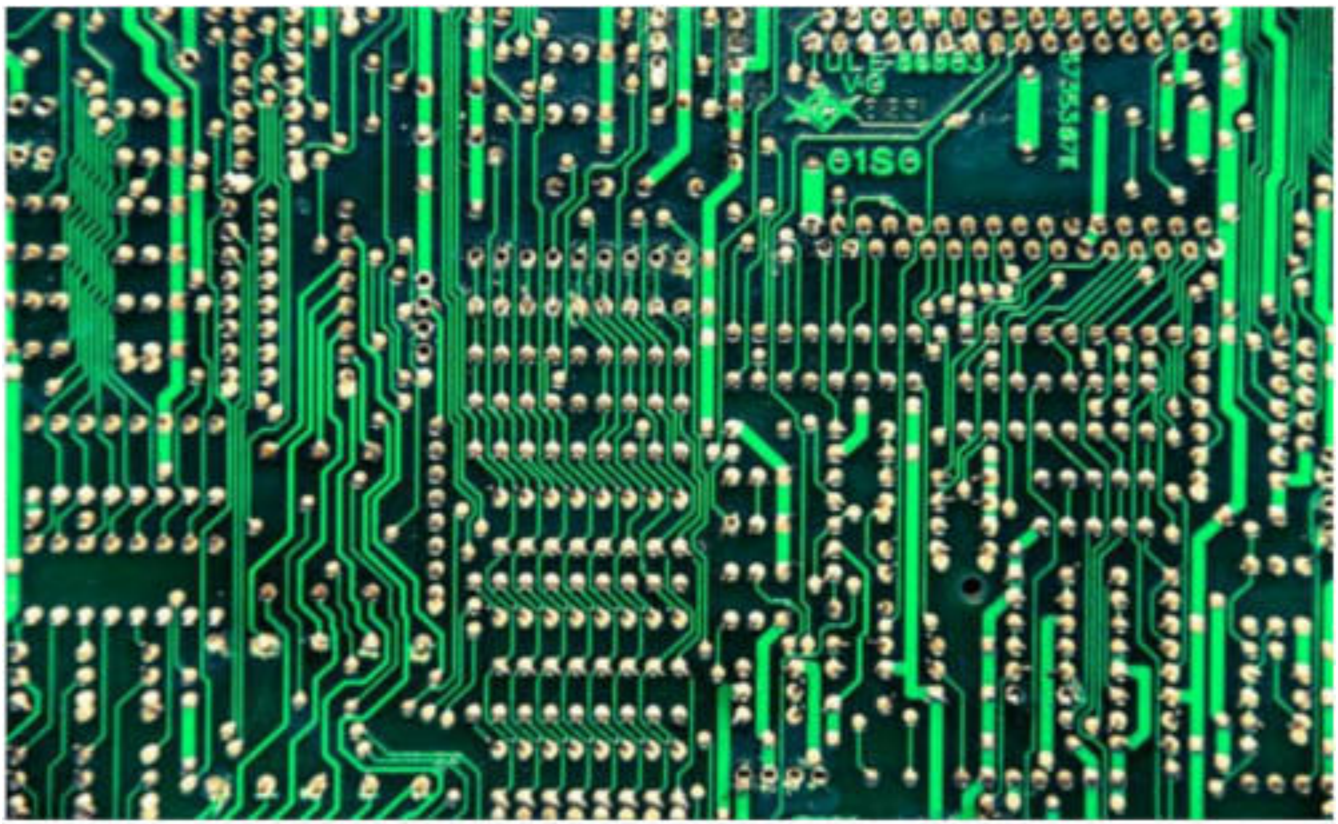
PCBs

Printed circuit boards (PCBs) allow robust, stable connections, with controlled impedance for all connections.

Stable, soldered connections.

Higher density: trace width and spacing can be as small as 0.004”

Traces can have defined impedance and optimized parasitic effects.



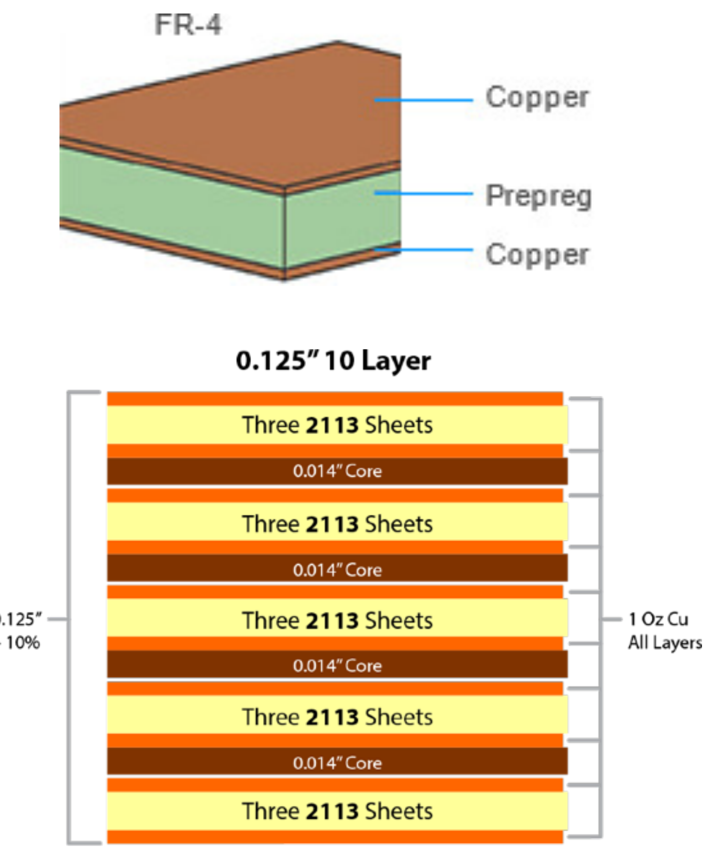
PCBs

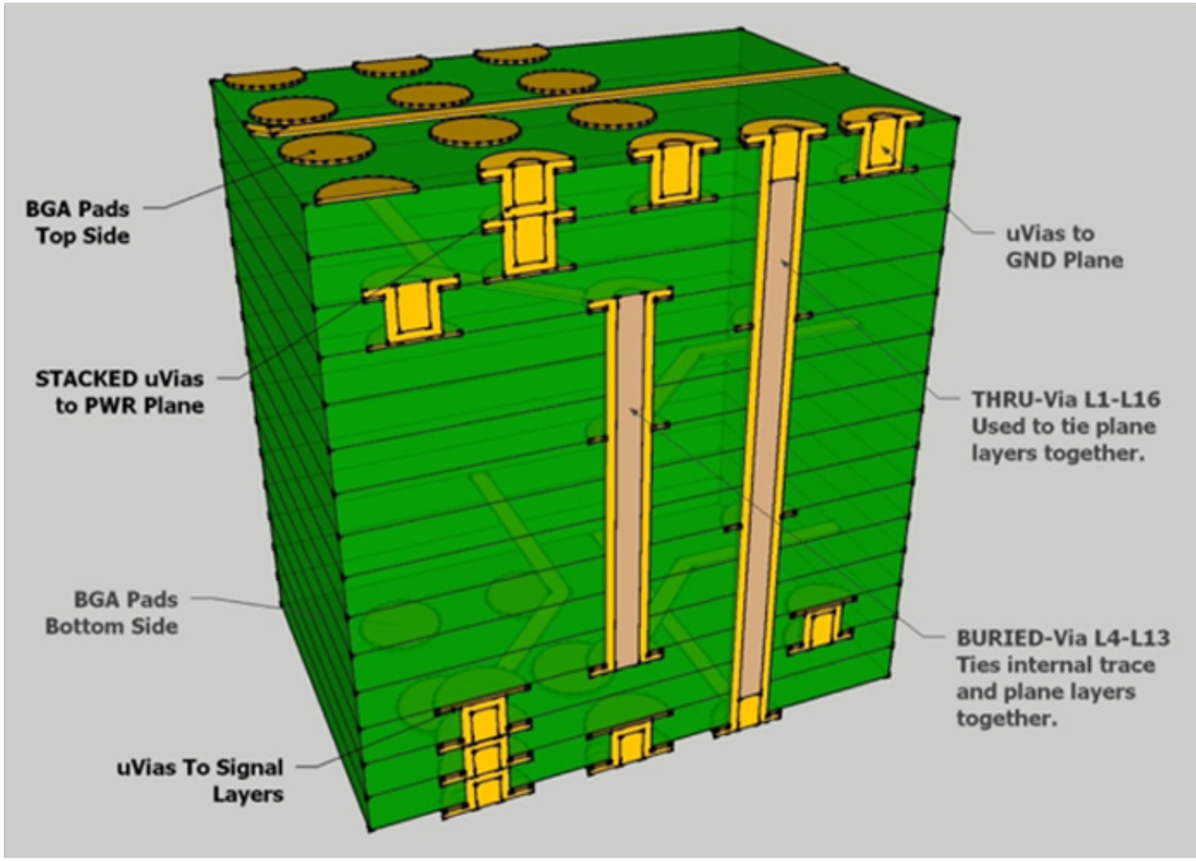
PCBs are copper-clad fiberglass (FR4).

An etch resist is patterned on and the unwanted copper is etched away.

Holes drilled (typically ≥0.2 mm) and copper plated through them for “vias”.

A “solder mask” is deposited, except in regions that should be exposed.

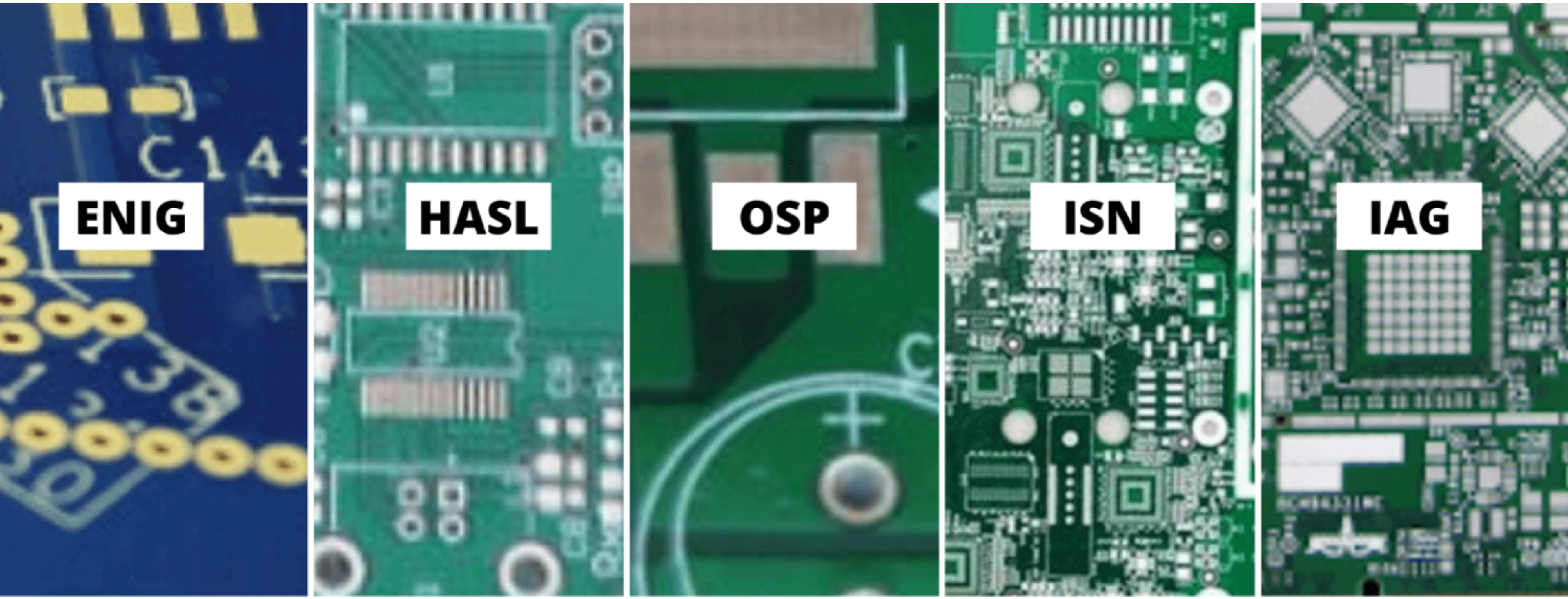




PCBs

A "solder mask" is deposited, except in regions that should be exposed.

Finish surface to protect copper and ease soldering.



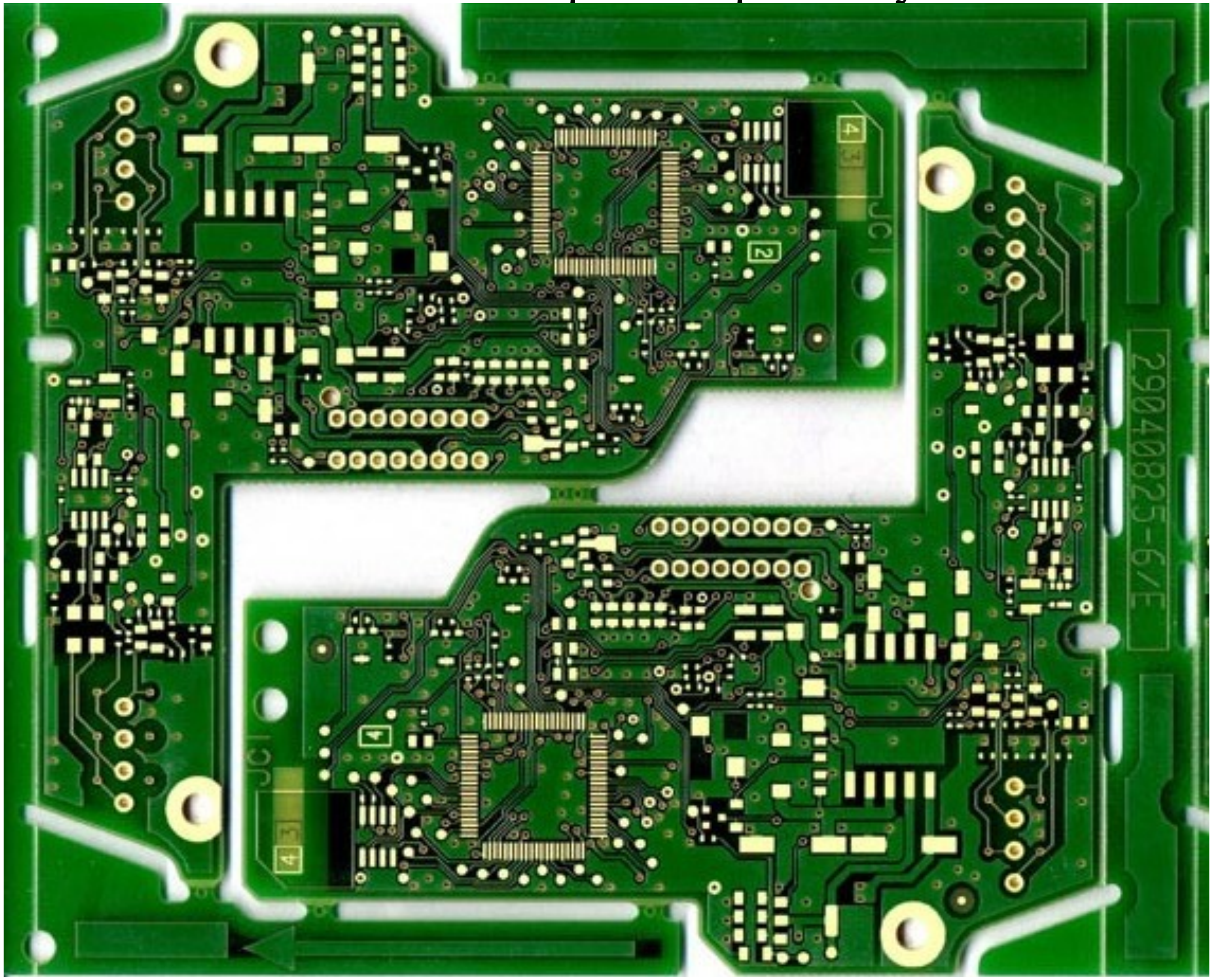
Electroless Nickel Immersion Gold	Hot Air Solder Leveling	Organic Solder Preservative	Immersion Tin	Immersion Silver
Best, expensive	Cheap, coarse			

https://youtu.be/ljOoGyCso8s

PCBs

PCBs are copper-clad fiberglass (FR4).

Cut them into whatever shape is required by mechanics.



PCBs

Whole fabrication process is automated, with standard file formats.

PCBs can be ordered quite cheaply online, <$1/square-inch

For example, see https://jlcpcb.com/ and YouTube videos linked there.

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Assembly can also be automated.

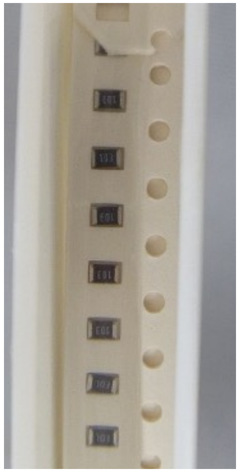
Solder applied with a squeegee and a laser cut stencil.

Components robotically placed on surface with a “Pick-and-place” machine.

Solder melted (“reflowed”) in an oven.

For example, see https://www.youtube.com/watch?v=ylk6VMBLrvM

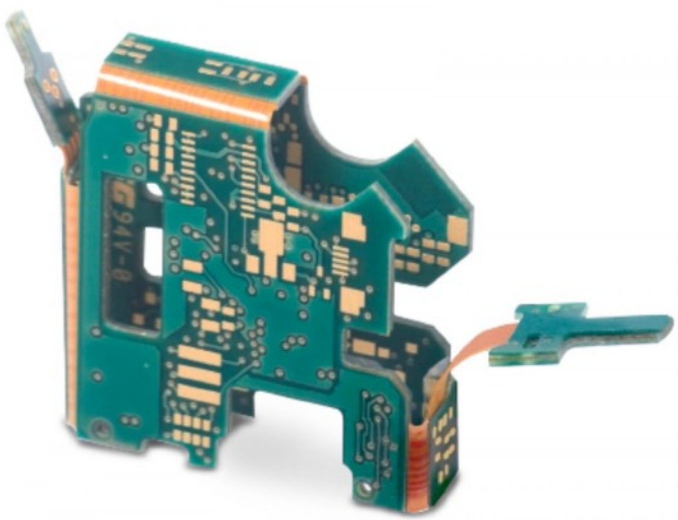
https://www.youtube.com/watch?v=BepAMlrJwXI



Flexible PCBs

Can also make flexible PCBs (called “flex”).

It is a copper on kapton (polyimide) sandwich instead of copper on FR4.



Rigid-flex combines FR4 and flex to merge cable connections into a mechanically complicated circuit.

Flexible PCBs

Can also make flexible PCBs (called “flex”).

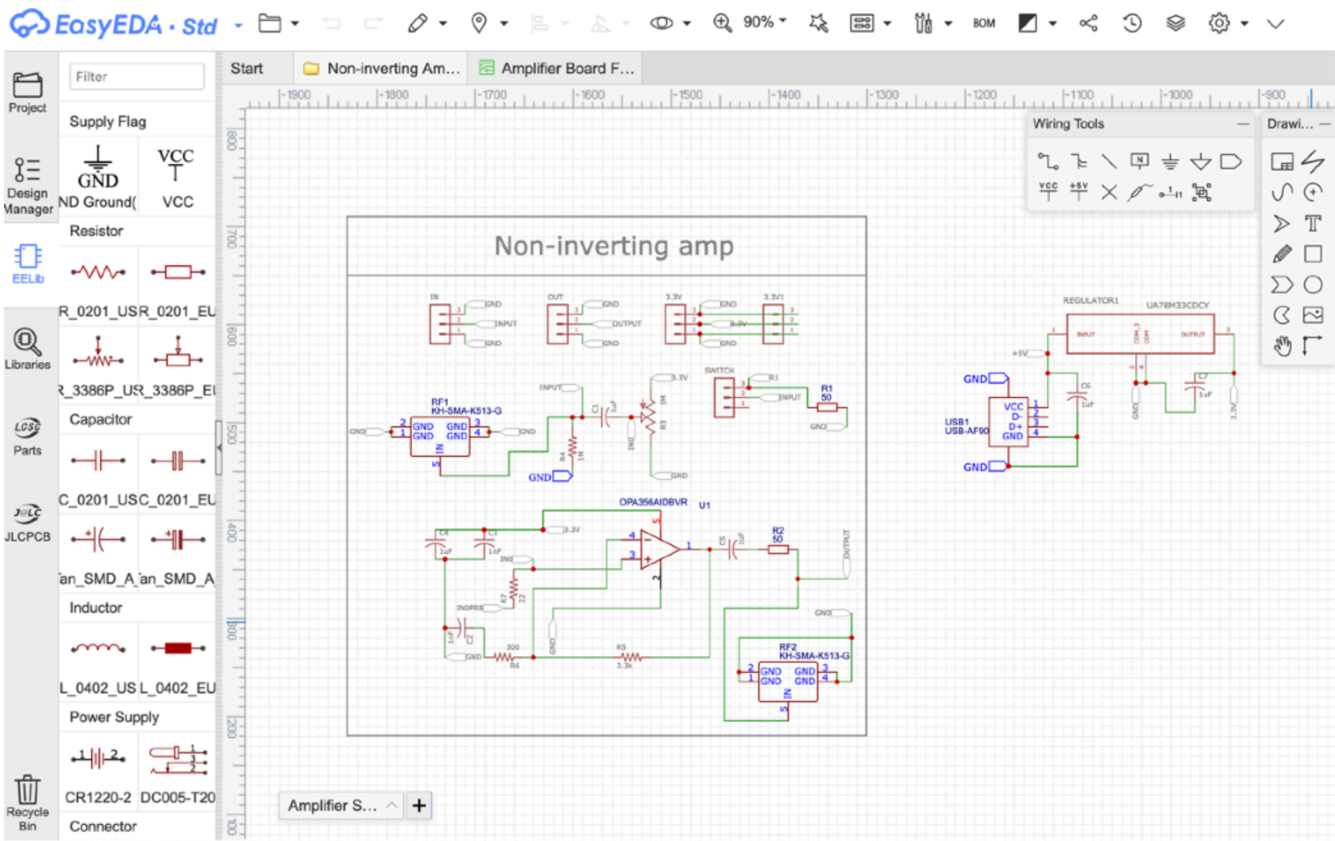
It is a copper on kapton (polyimide) sandwich instead of copper on FR4.

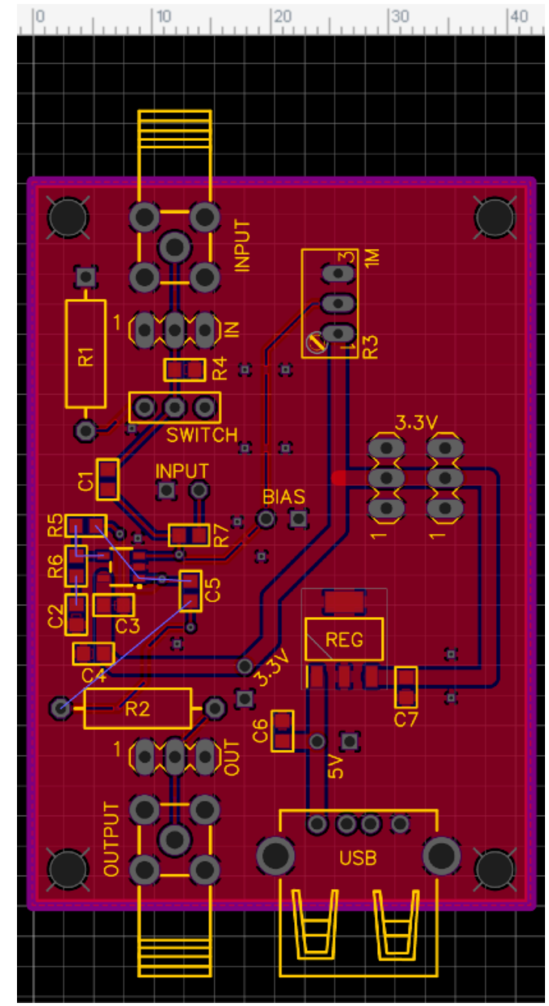
Can finely control impedance on flex cables. (Wide trace for power.)

PCB layout

There are many PCB layout software packages:

KiCAD, AutoDesk Eagle, EasyEDA, Fritzing





Upload "Gerber" files, BOM, Pick-and-place file, and they mail you assembled boards. Cost is a few dollars (depending on parts). *Shipping extra*.

PCB layout

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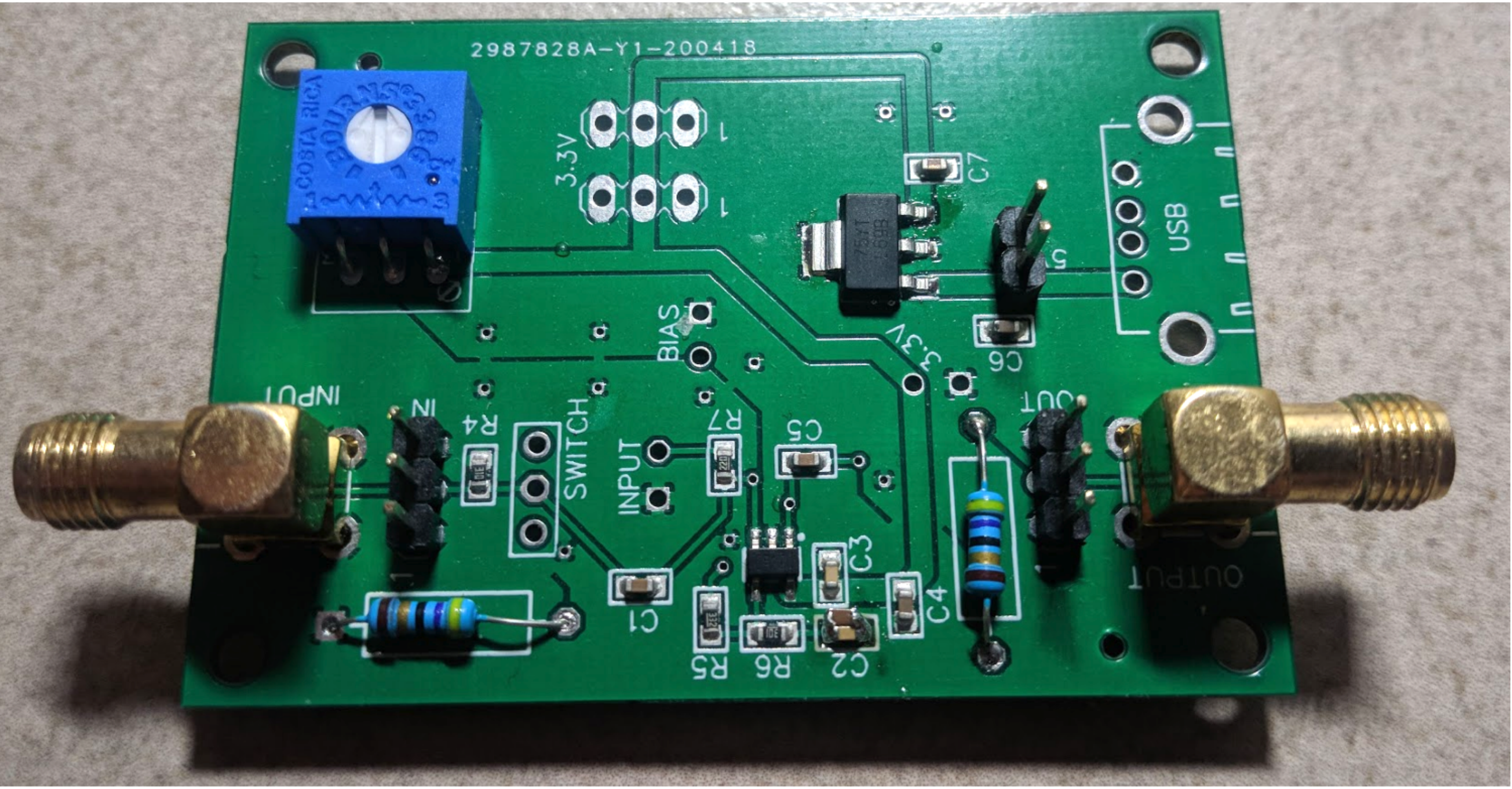
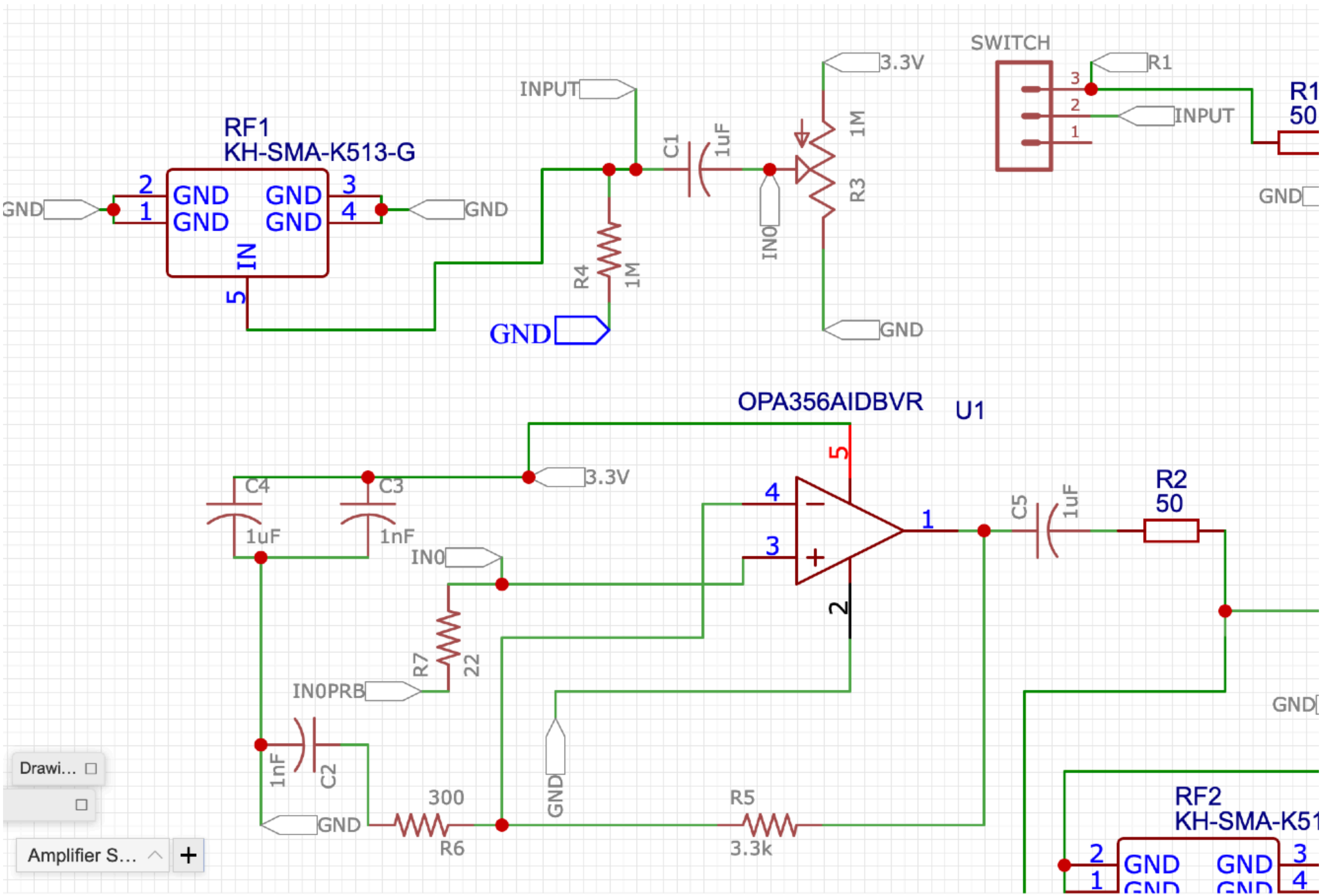


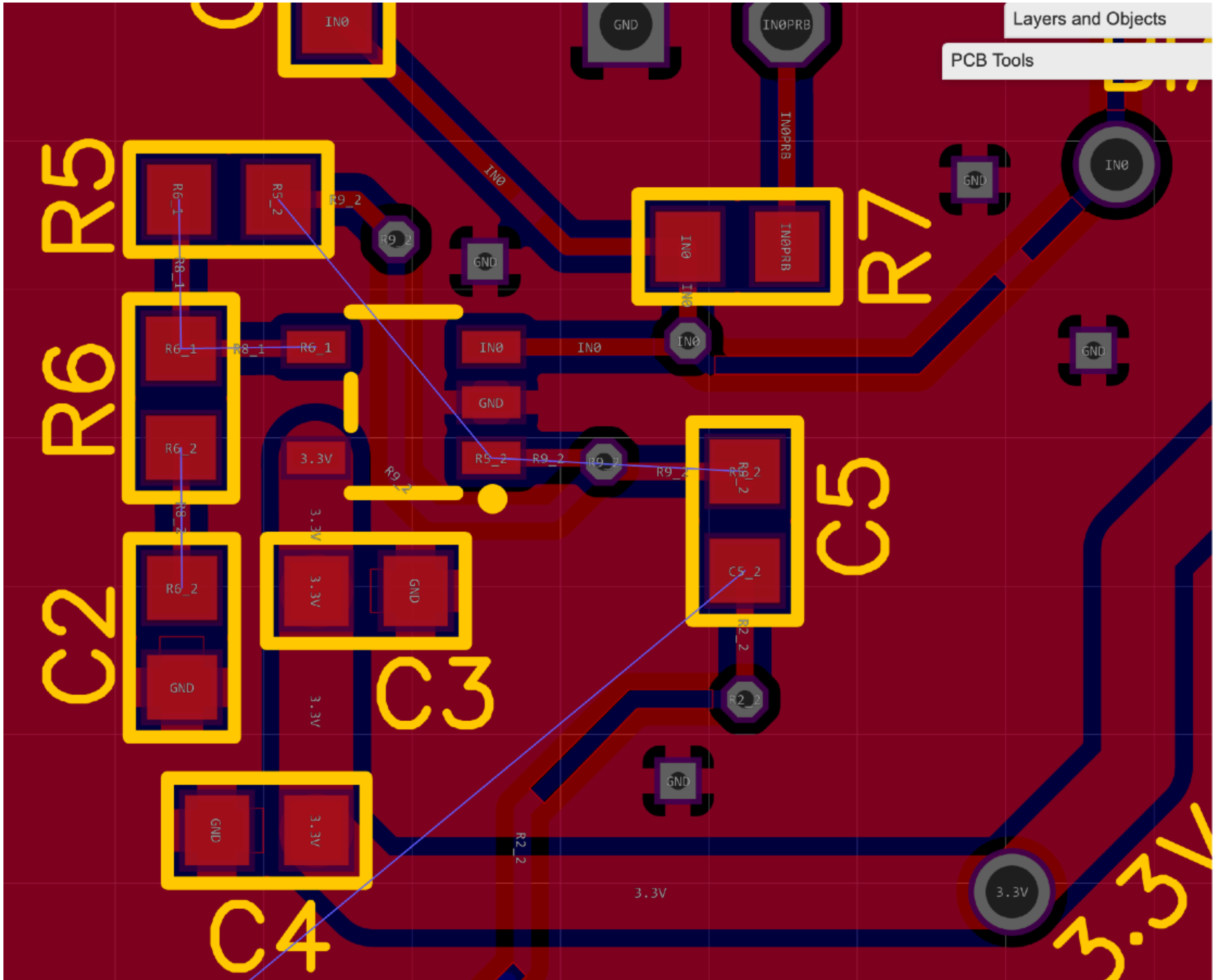
PCB layout

This should be a circuit you recognize.



PCB layout

The precise layout can optimize for low noise.



Short traces lower L.

Ground plane provides Faraday cage.

But, back side ground removed from input traces to reduce C.

C3 and C4 very close. C3 closest.

Power trace is fat.

Ground return path.

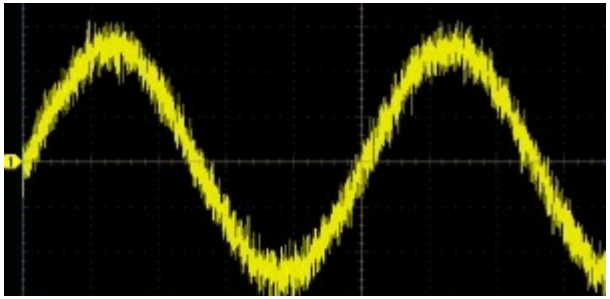
Low noise measurements

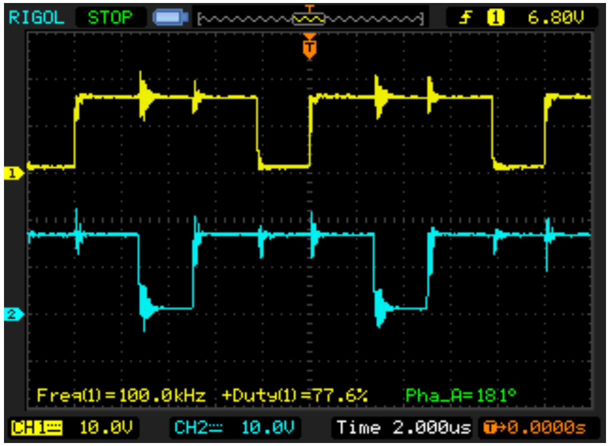
Those methods all help reduce noise, but there will always be some left.

There are various techniques to measure small signals in the presence of noise.

Too many to discuss in detail, but it is worth surveying them. They mostly rely on a single idea: use a unique feature of the signal. For example:

Frequency; use high, low, and band pass filtering to remove noise and keep signal.





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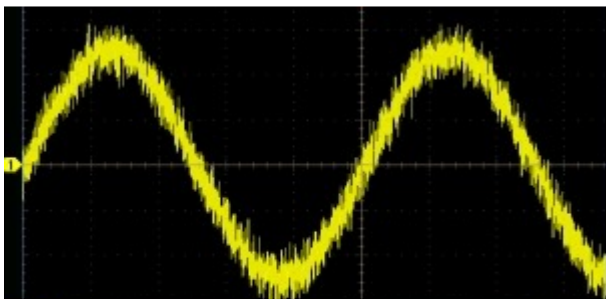

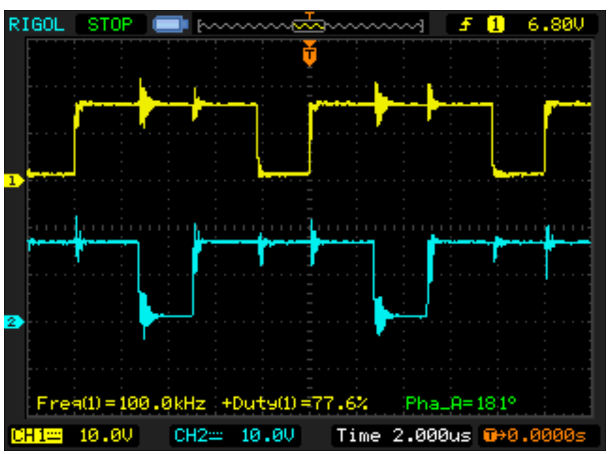

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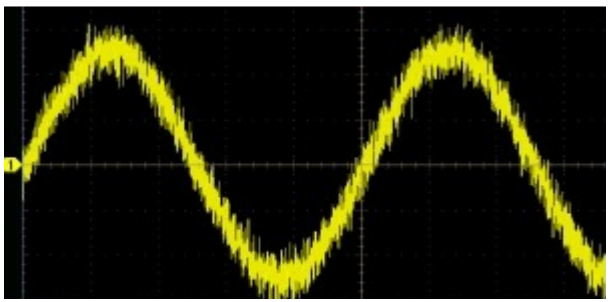

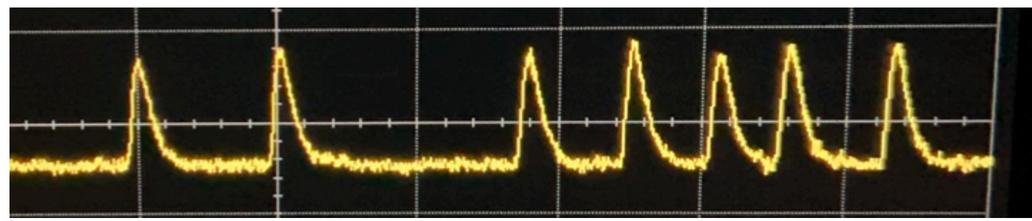

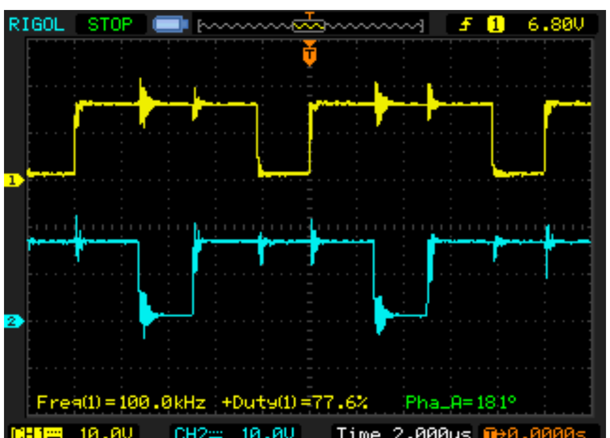

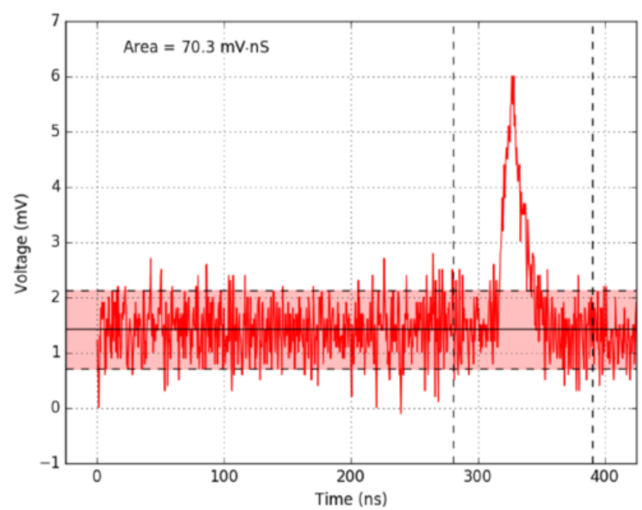

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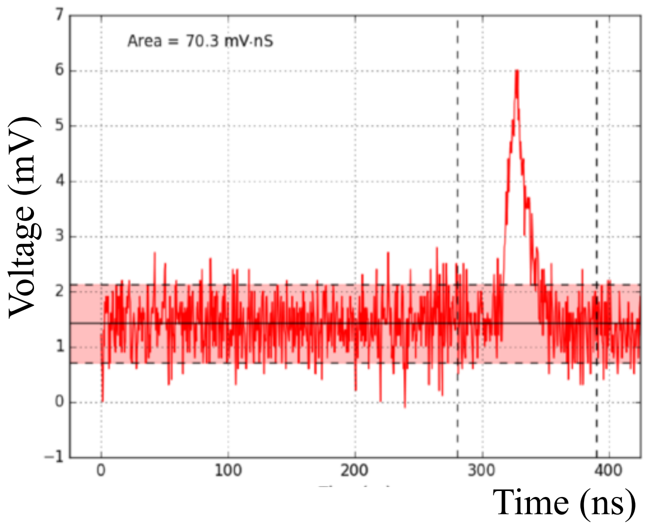

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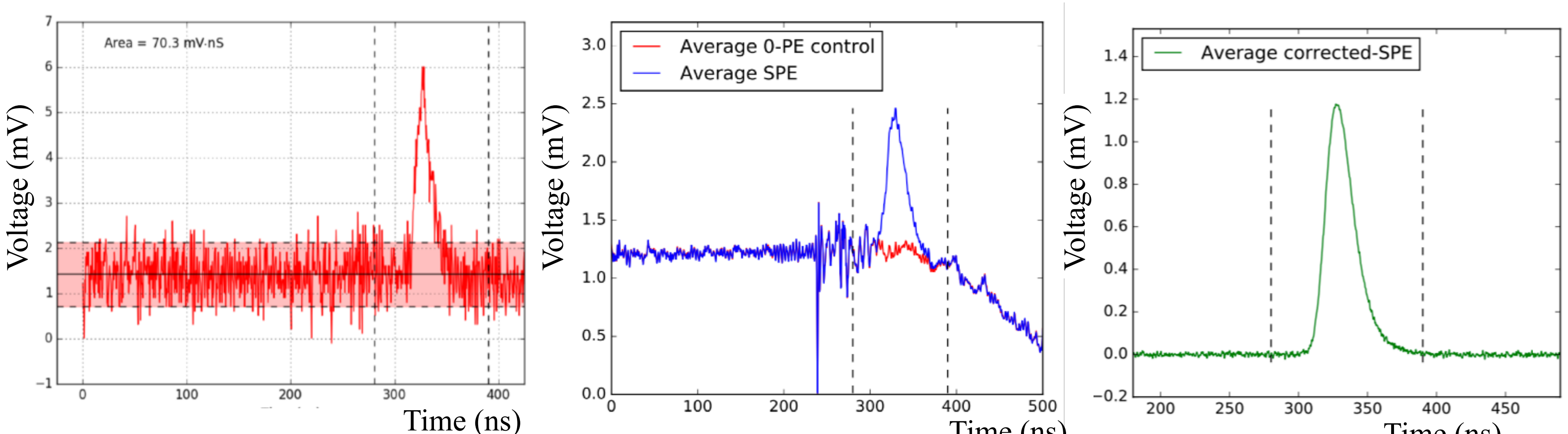

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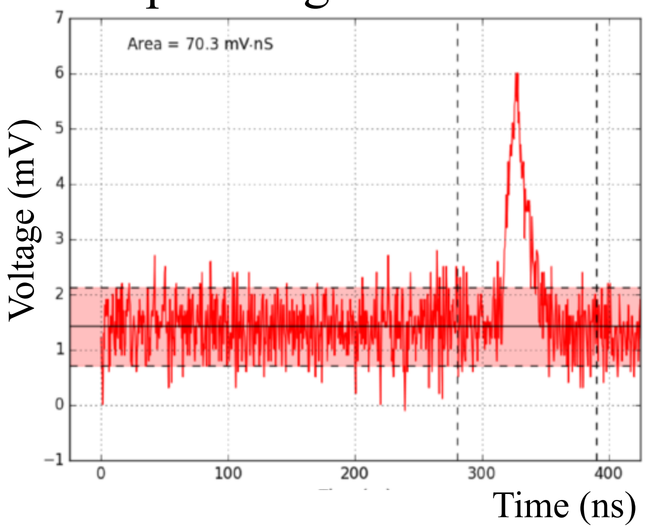
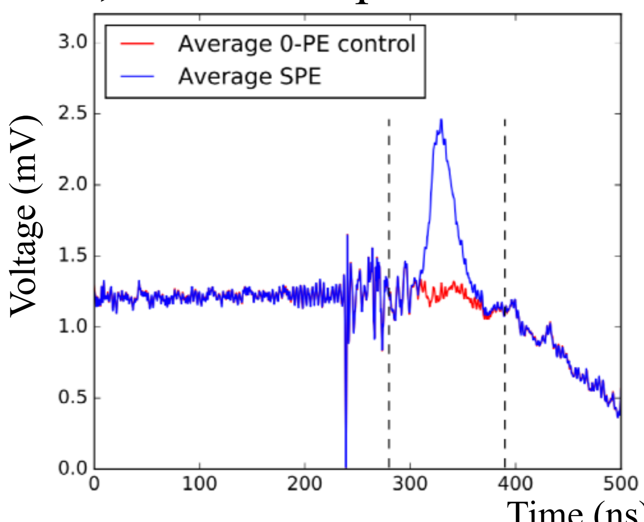
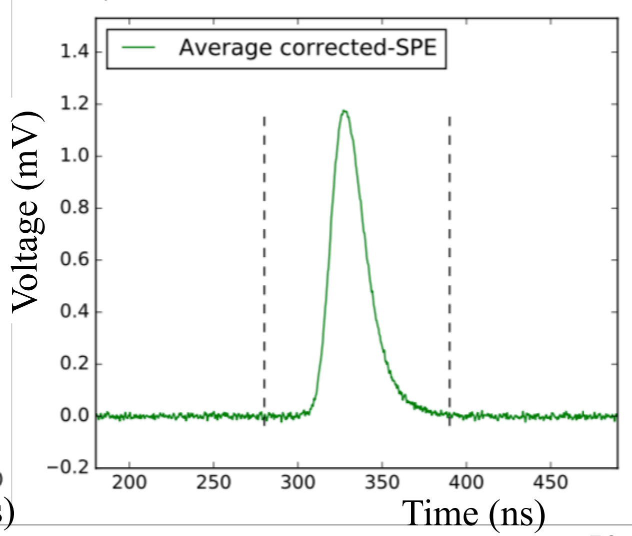
- Helps to digitize the waveforms, ie save scope traces and analyze "offline".







Low noise measurements: Lock-in amplifier

Putting together the frequency, timing, and repeating is *very powerful*.

That is the idea of a Lock-In Amplifier.

E.g., suppose you wanted to measure the brightness of a dim LED on a bright day.

The sun is a noise source that you can't reduce. But it is random.

Repeatedly pulse the LED at a known frequency & phase (time) to average away noise.

But, need to filter out only that specific frequency.

This is modulate-demodulate, a la AM radio.

$$A\sin(\omega_1 t)\sin(\omega_2 t + \phi) = \frac{A}{2}\left[\cos[(\omega_1 - \omega_2)t - \phi] - \cos[(\omega_1 + \omega_2)t + \phi]\right]$$

Tune the pulsing and measurement frequency to be equal: $\omega_1 = \omega_2$

so the cosine in the first term vanishes, and the second term can be removed with a low-pass filter. Then

$$A\sin(\omega_1 t)\sin(\omega_2 t + \phi) = \frac{A}{2}\cos\phi$$

Adjust the phase to zero, and you get a measurement of the constant amplitude.

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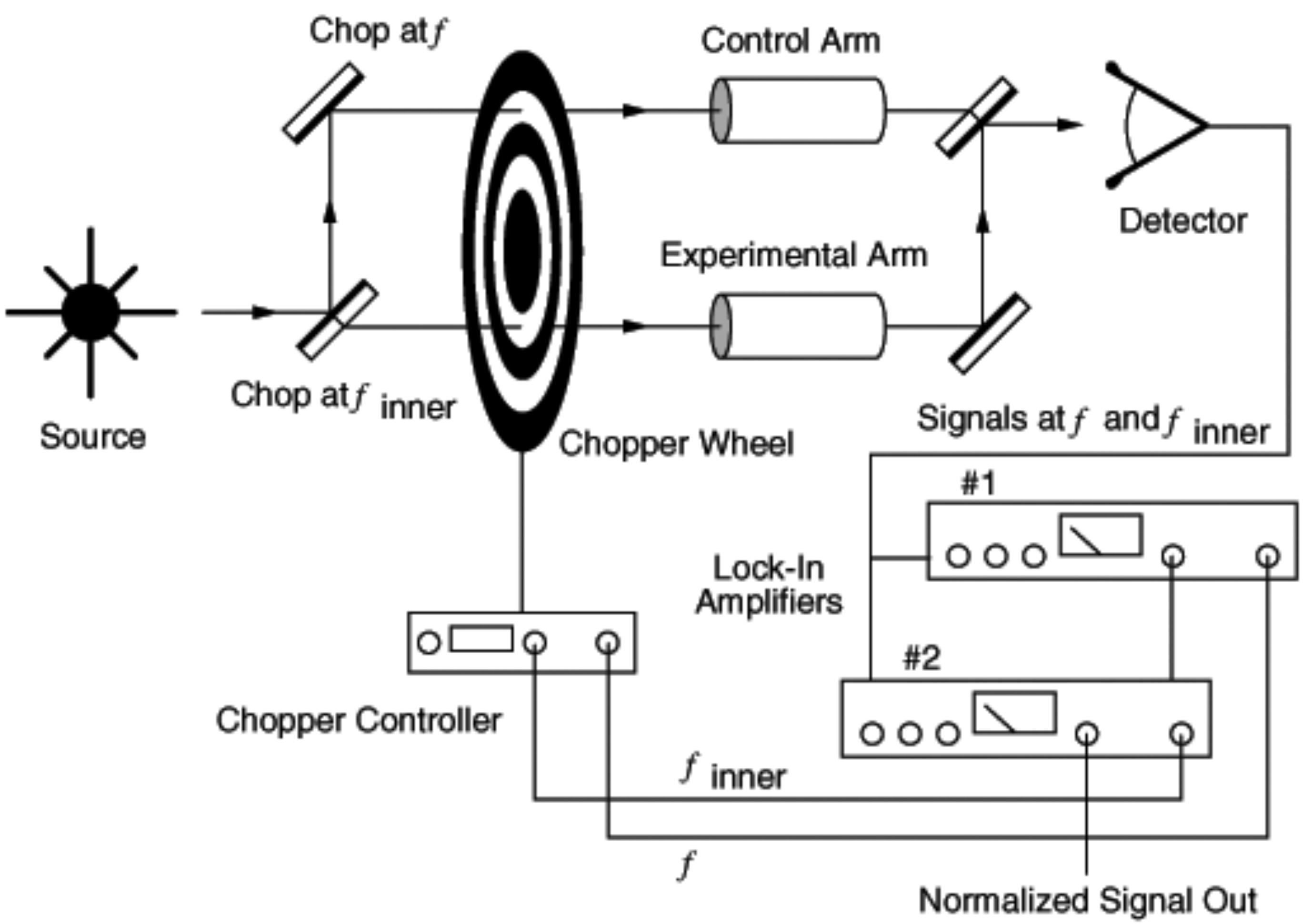
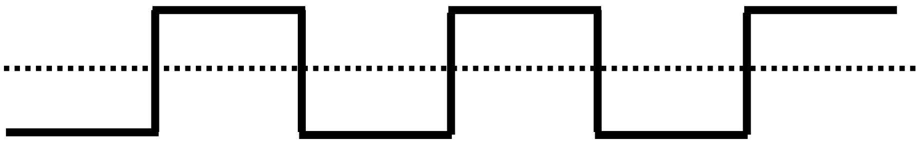
You can do this with a DC source by "chopping it".



Low noise measurements: Lock-in amplifier

We can easily make a modulator if the signals are square waves.



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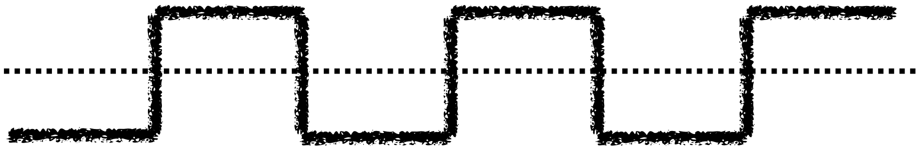

Noise is random, signal is alternating.
So invert the low parts and average.
That keeps signal (amplitude) but cancels noise.

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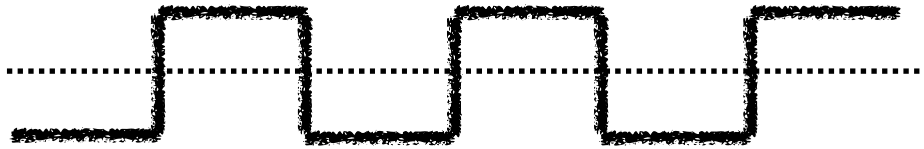

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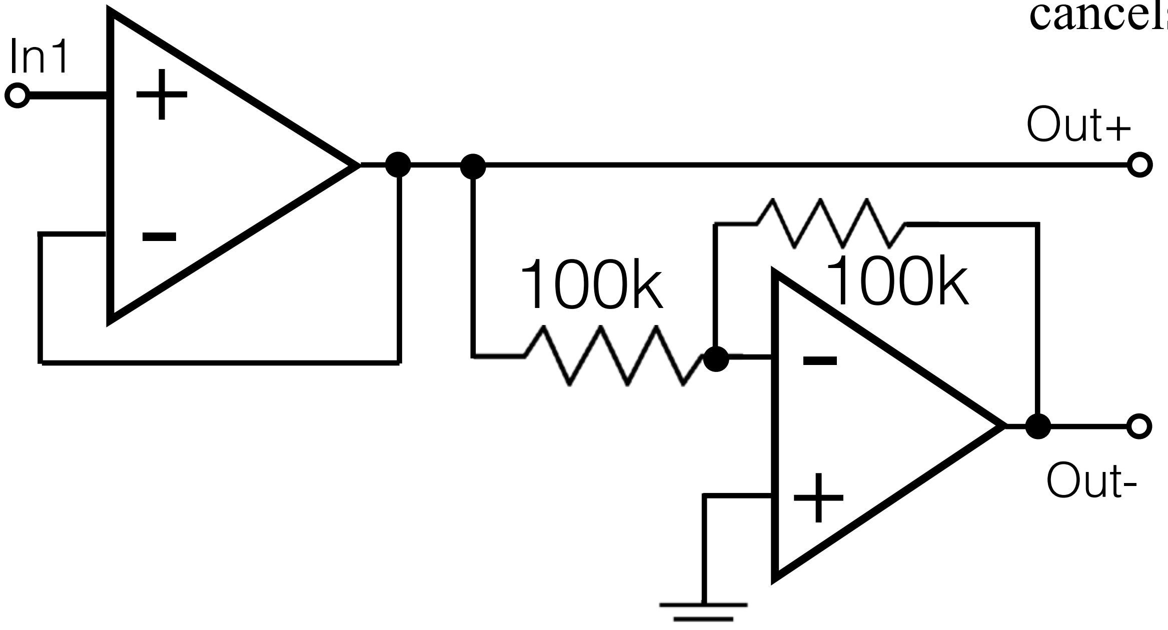

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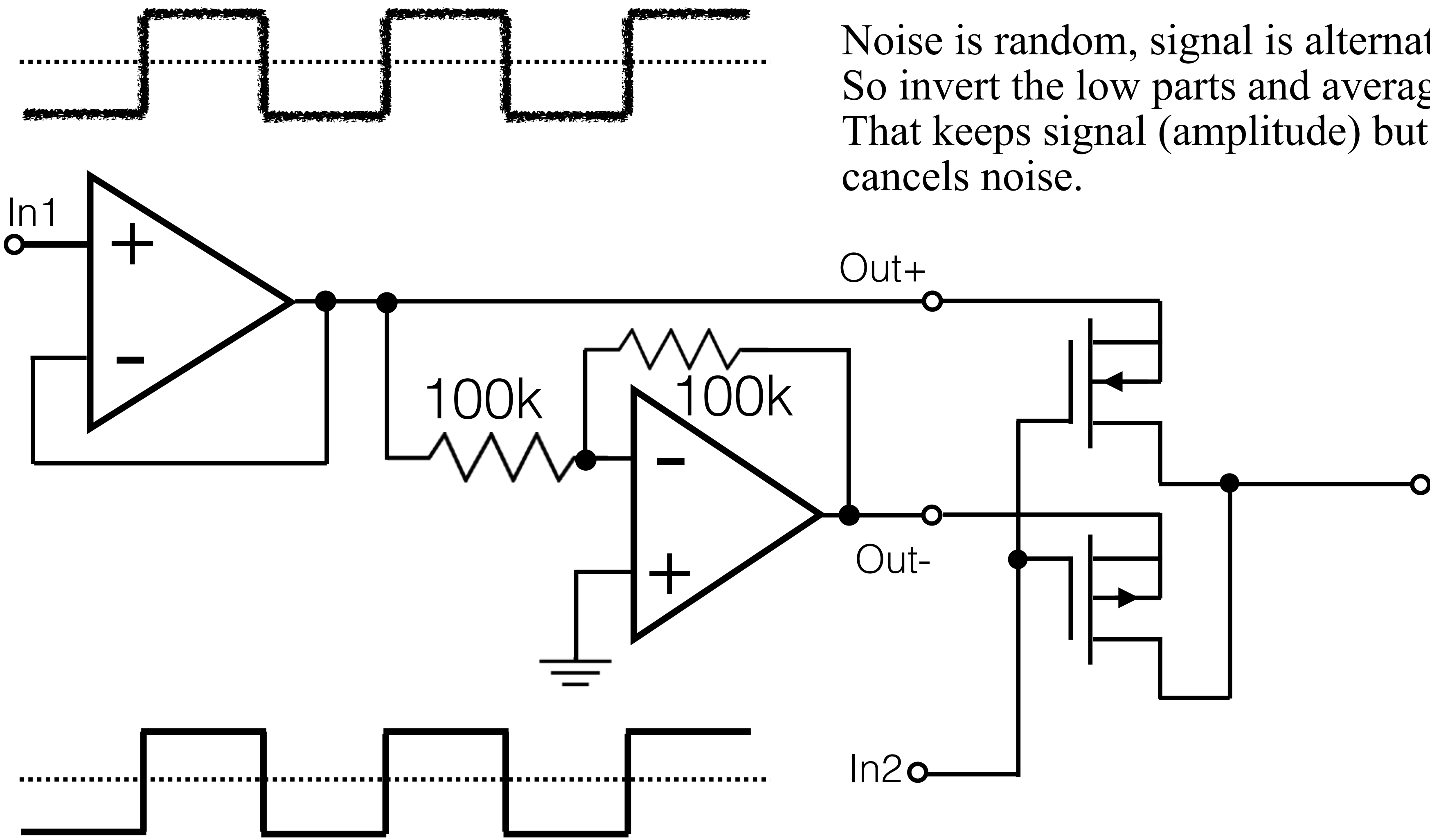

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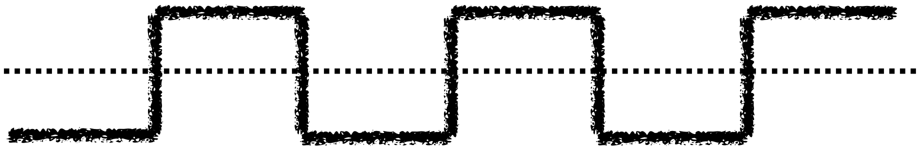

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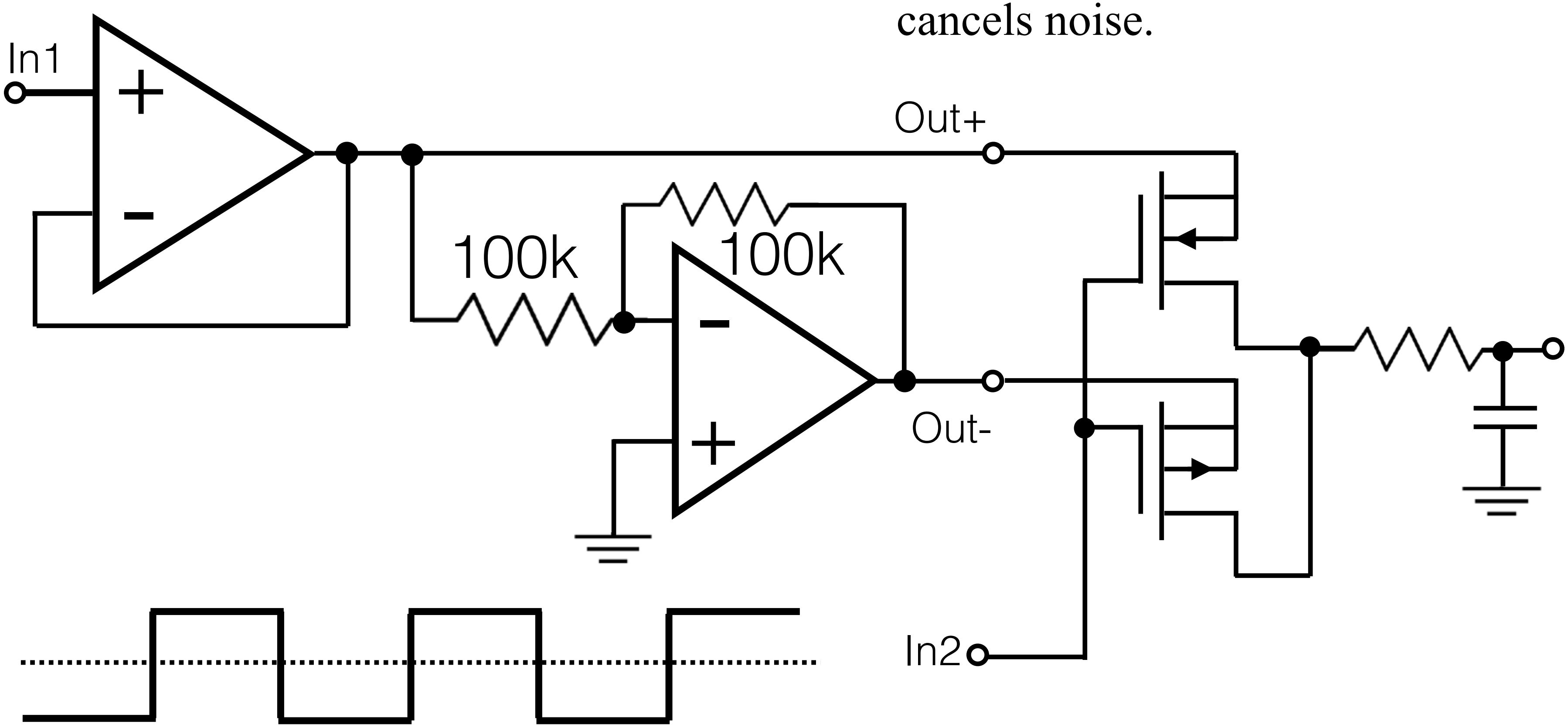

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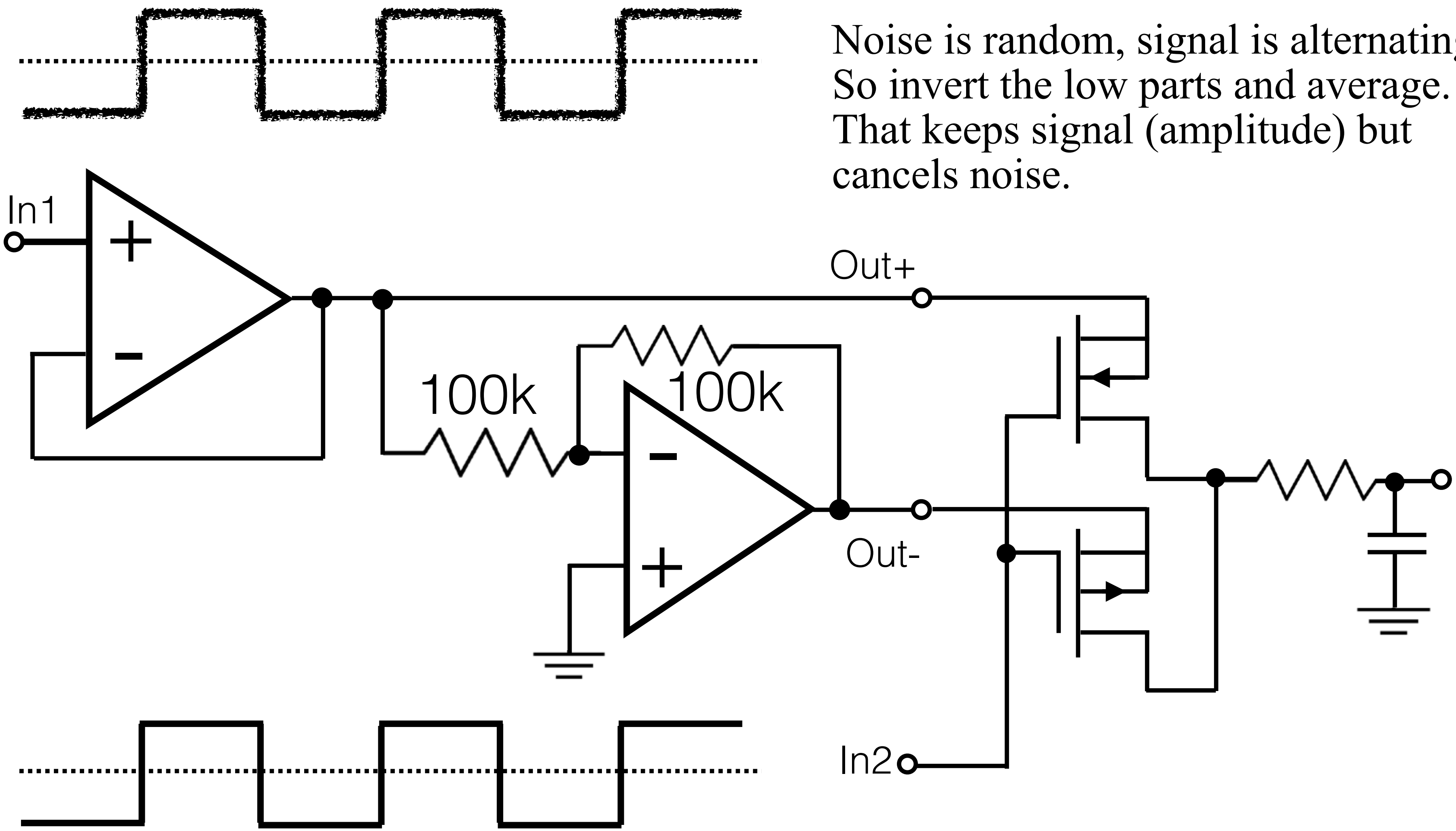

This can precisely measure any DC value, or any AC signal's V(t) if the modulator is much higher frequency than the signal's frequency.