Reducing noise; precision measurements
Noise

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“I can’t hear you over the background noise.”
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The primary star light in our original example of an exoplanet sunset.
Other radio stations leaking into our sidebands.
Uncontrolled transmitters, eg microwave ovens overlap WiFi spectrum.
CMB
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Power supply bounce

Power supply sag
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Capacitive pickup
Power supply bounce
Power supply sag
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

\[ \overline{v_n^2} = 4k_B TR \]

So RMS noise in a frequency range is

\[ v_n = \sqrt{\overline{v_n^2} \Delta f} = \sqrt{4k_B TR \Delta f} \]

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 $\Delta t$ 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.
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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.

![Circuit diagram showing parasitic elements connected to an amplifier circuit.](image-url)
Parasitics

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

A simple non-inverting amp isn’t so simple.
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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: $V_{out} = -RC \frac{dV_{in}}{dt}$
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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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If you put a resistor at the end of the line (termination resistor) it will cause reflections unless $R = X$. 
Transmission lines

If you put a resistor at the end of the line (termination resistor) it will cause reflections unless \( R = \frac{1}{2} \).

\[
\begin{align*}
V_{\text{in}} & \quad (\text{resistor}) & \quad \frac{1}{2} & \quad V_{\text{out}} \\
\text{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.)} \\
\text{Need } \textit{impedance match} \text{ to avoid reflections.} \\
\textit{Impedance mis-match} \text{ reflects signal. (Common physics jargon.)}
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Transmission lines

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.)
Cable impedance

Need *impedance match* to avoid reflections.

Most Coaxial cables are 50Ω. Some 75Ω.

Fast oscilloscopes have 50Ω input impedance option.
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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$\sim 30$ pF/foot

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 $X_{\text{in}} = 50\Omega$. 

Cable impedance

Twisted pair ribbon cable typically has \( \sim 100\Omega \) 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

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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 $\geq 0.2$ 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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For example, see https://jlcpcb.com/ and YouTube videos linked there.
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.
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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.*
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PCB layout

This should be a circuit you recognize.
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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- Pulse shape; fit for the pulse shape so noise gets fitted away.
- Timing; if you know when your signal comes you reduce noise effect, and can fit for slow variations in a pre-sample.

![Graph showing time (ns) vs. voltage (mV)](image)
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- **Repeating & averaging**: multiple measurements average away noise; measure pickup...
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Repeating & averaging: multiple measurements average away noise; measure pickup Helps to digitize the waveforms, ie save scope traces and analyze “offline”.

![Waveform graphs](image-url)
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.
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. You can do this with a DC source by “chopping it”.

![Diagram of Lock-In Amplifier](image)
Low noise measurements: Lock-in amplifier

We can easily make a modulator if the signals are square waves.
Low noise measurements: Lock-in amplifier

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

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