



Using an Oscilloscope to Peek Below the Noise Floor

the DSP Magic of Lock-In Amplifiers

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Hackaday Supercon 2024



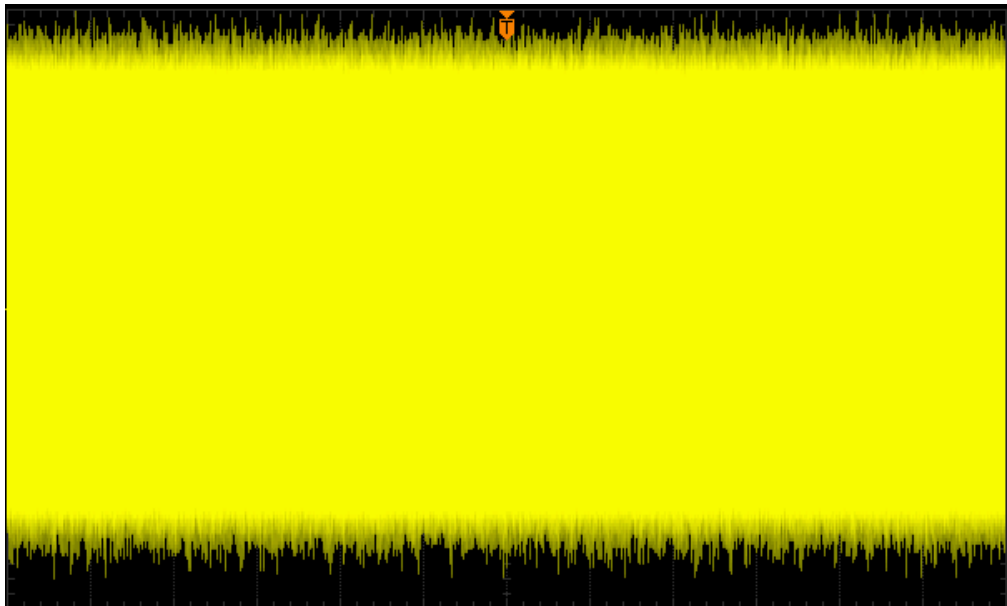
The Magic

Reject Noise, Return to Signal

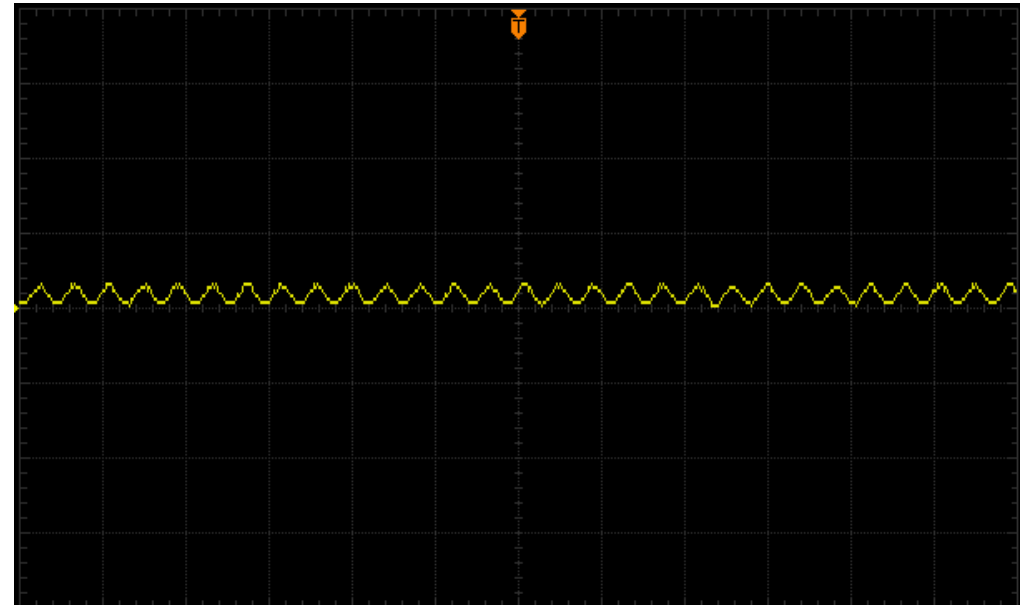
What If We Had Magic

Wouldn't it be magical if we could turn

this...

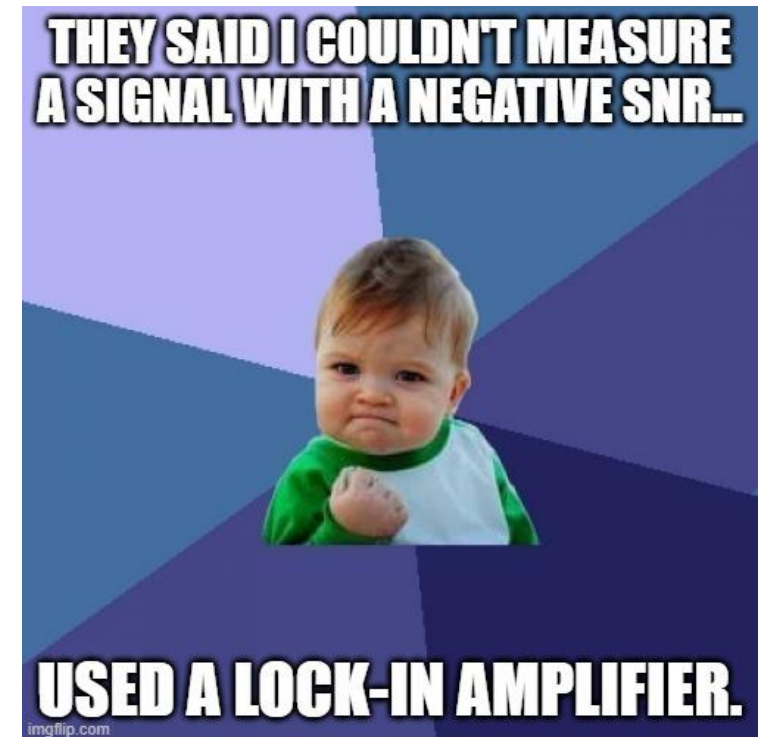


Into this?



The Magic is Lock-In Amplification

- A Lock-In Amplifier is the tool of choice in these applications.
- Lock in amplifiers can measure signals with *negative* SNR
- Basically, an ultra-narrow bandpass filter.
 - We'll explain *how* later...

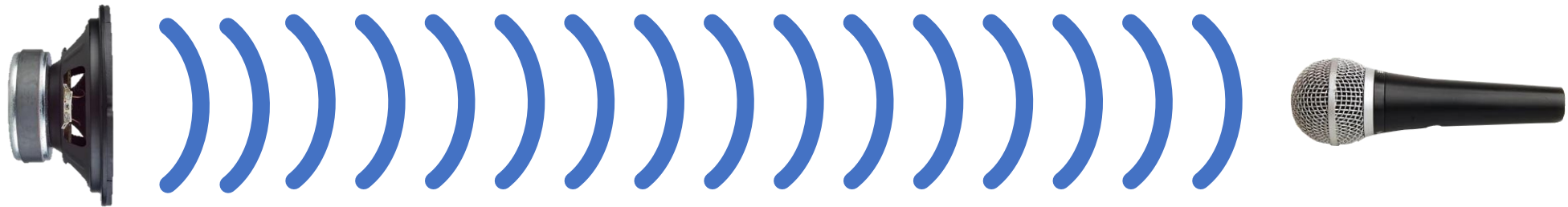


Measuring a Sound

Easy, Hard, or Easy?

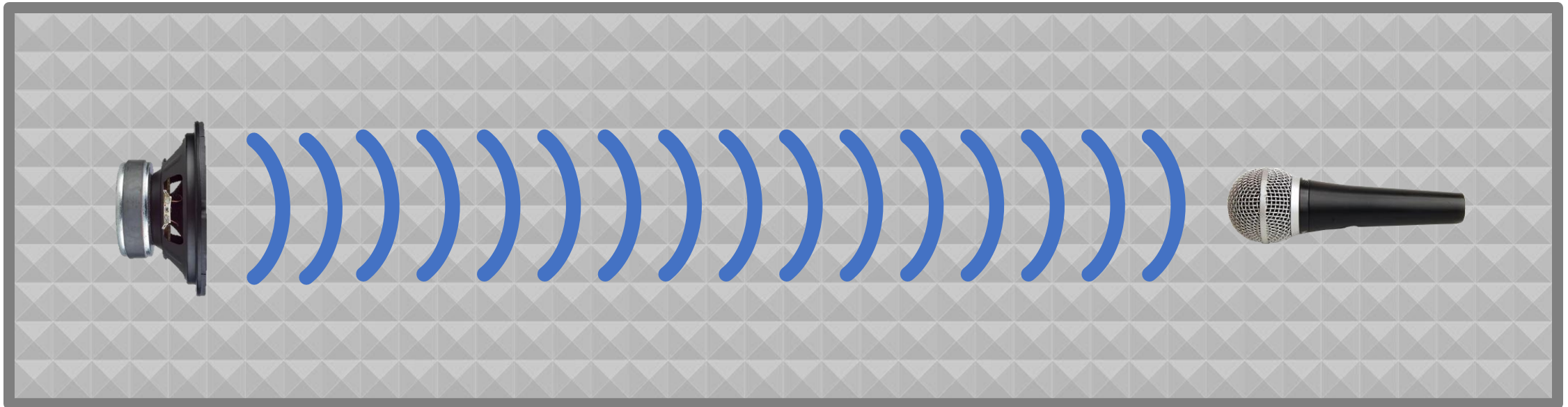
Measuring a Sound

- You've got a speaker, you've got a microphone.
- The microphone picks up whatever the speaker puts out.



Measuring a Sound

- You've got a speaker, you've got a microphone.
- The microphone picks up whatever the speaker puts out.
 - Well, maybe in a perfect world.



Measuring a Sounds

- You've got a speaker, you've got a microphone, and you've got a whole world full of other stuff making sound.
- The microphone picks up whatever the speaker puts out...
 - Plus a bunch of NOISE and INTERFERENCE!



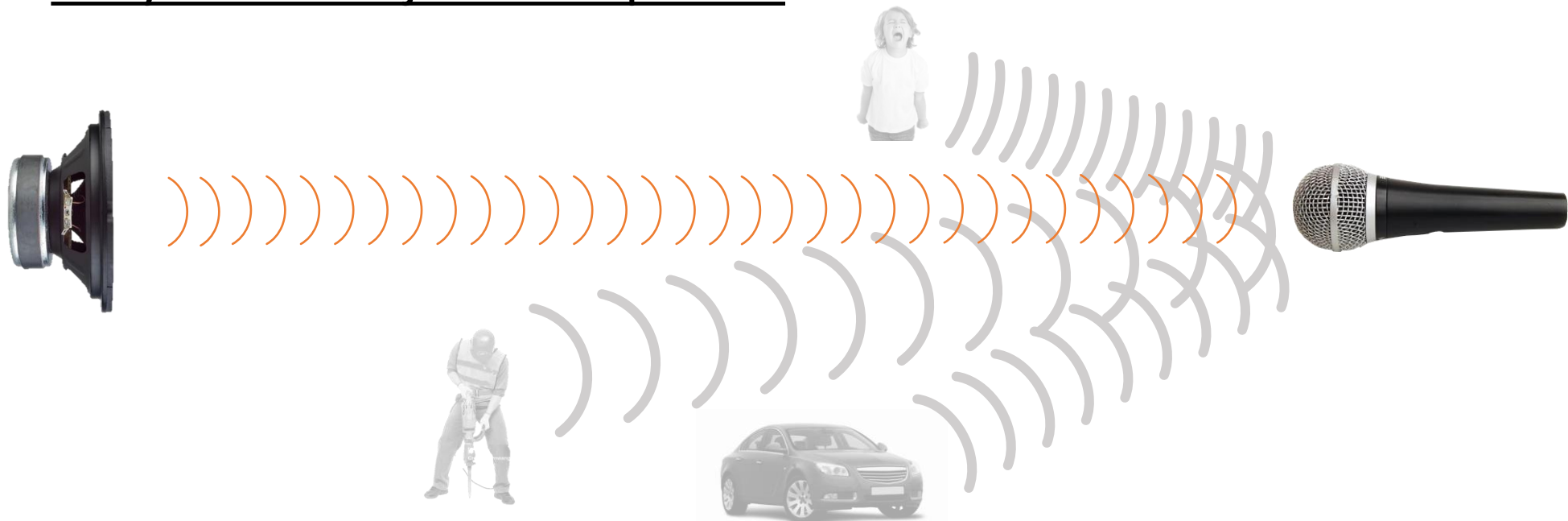
Measuring a Sounds

- The microphone picks up whatever the speaker puts out.
 - Plus a bunch of NOISE and INTERFERENCE!
- Such noise might be quite a bit louder than the speaker by tens to a **hundred dB**



Measuring a Sound

- The microphone picks up whatever the speaker puts out.
 - Plus a bunch of NOISE and INTERFERENCE!
- Such noise might be quite a bit louder than the speaker...
- Yet, with the magic of a Lock-In Amplifier, you can reject all that noise and truly measure just the speaker.





Measuring Anything

- But LIAs have much broader applications:
 - Ultra sensitive load cells
 - 3D Touch, long range/high sensitivity cap touch
 - Measuring ratio between signals
 - Ultra high (Giga/Terra Ohm) and low resistance (micro/nano Ohm) measurements
 - Catheter localization for surgery
- What problems might this help you solve?

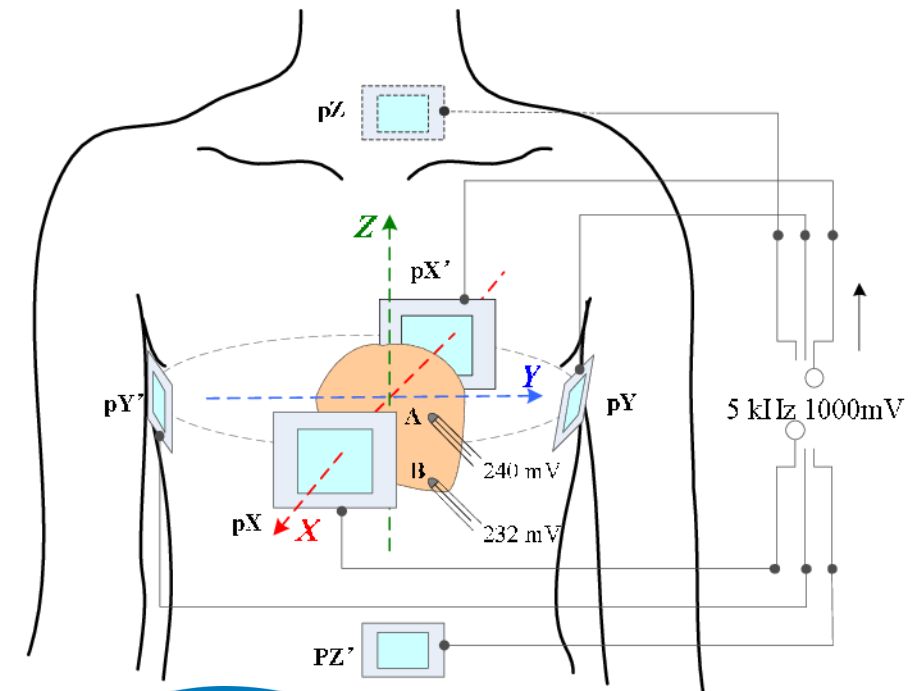


Figure 1. Representations of the catheter localization technique using the Orthogonal transthoracic electrical-field

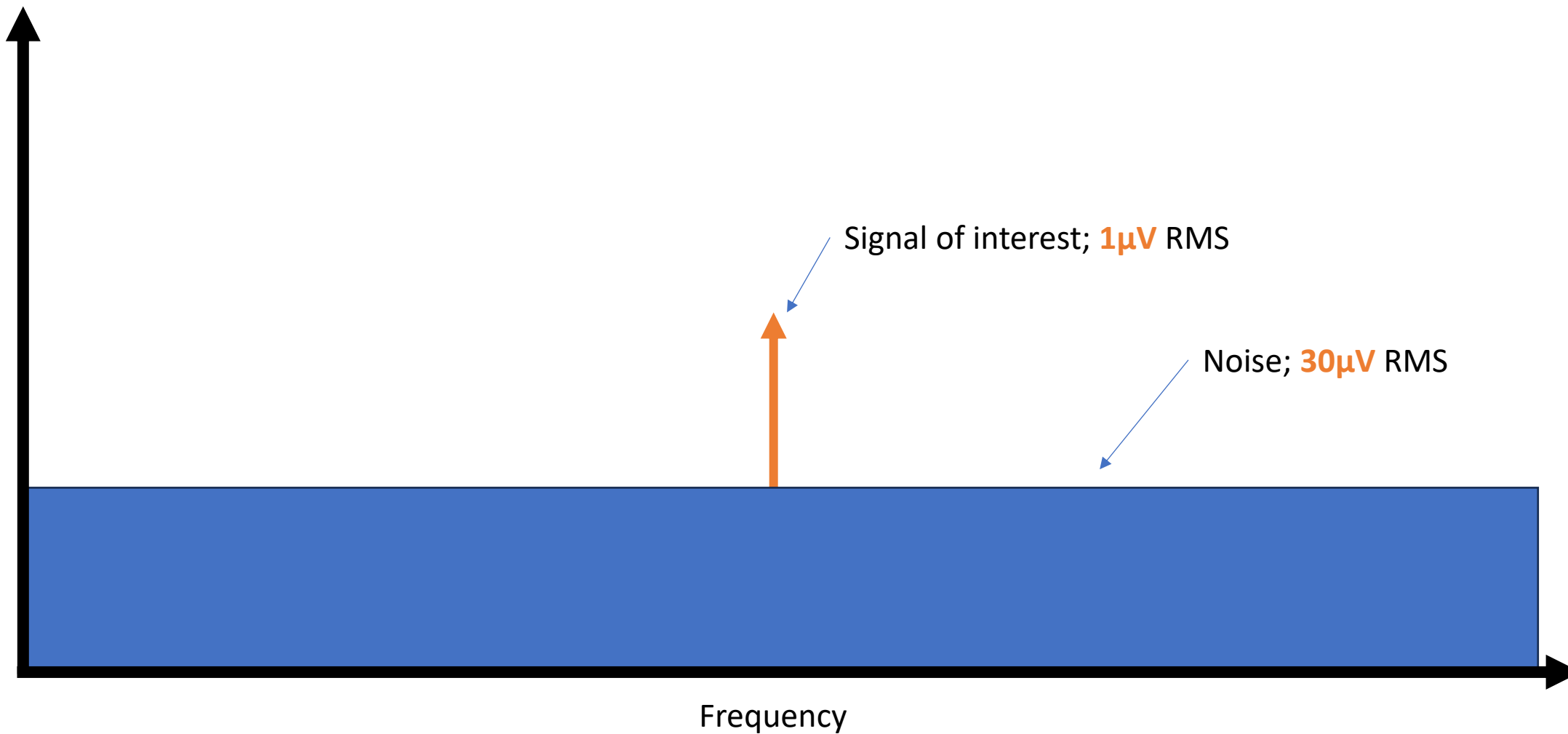
lock-in
inside

HOW

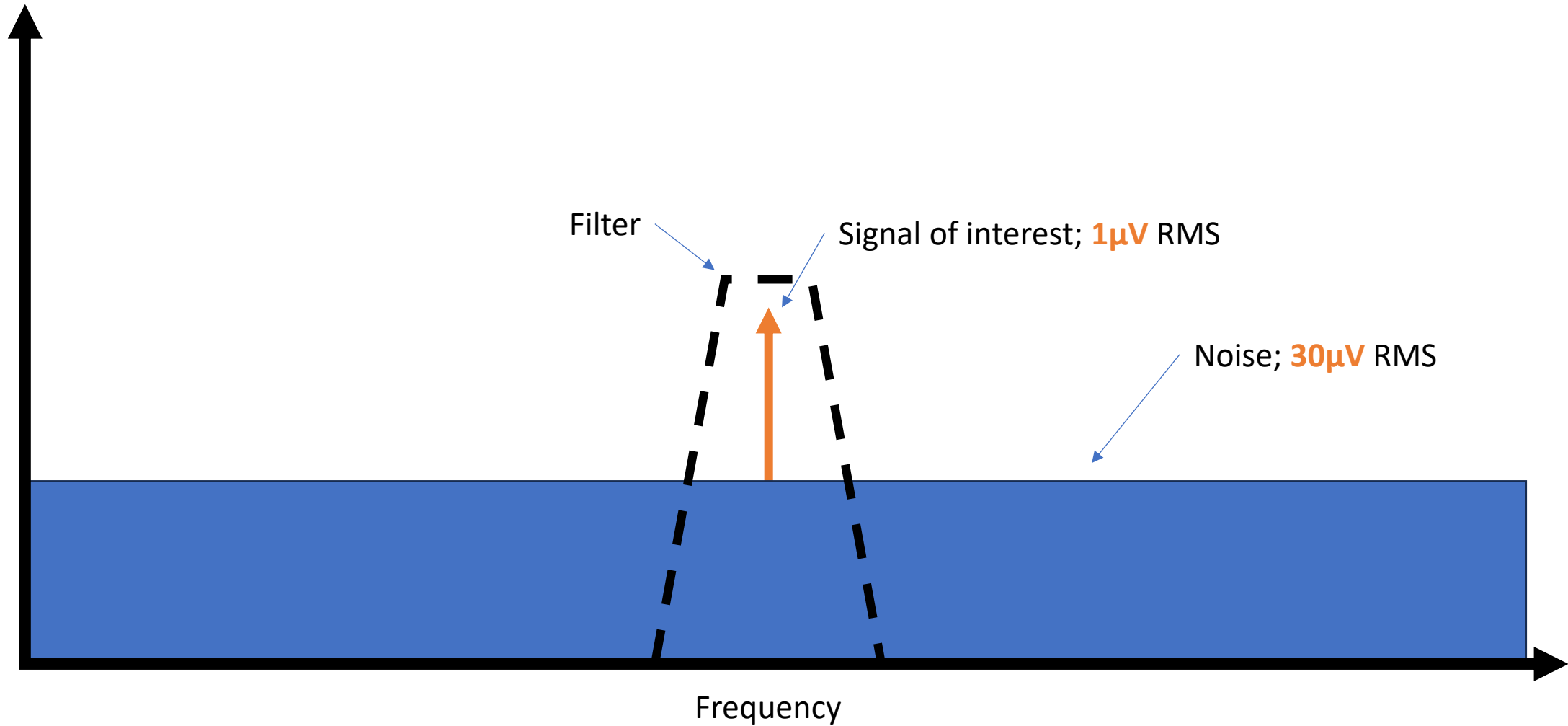
DSP Magic



How?

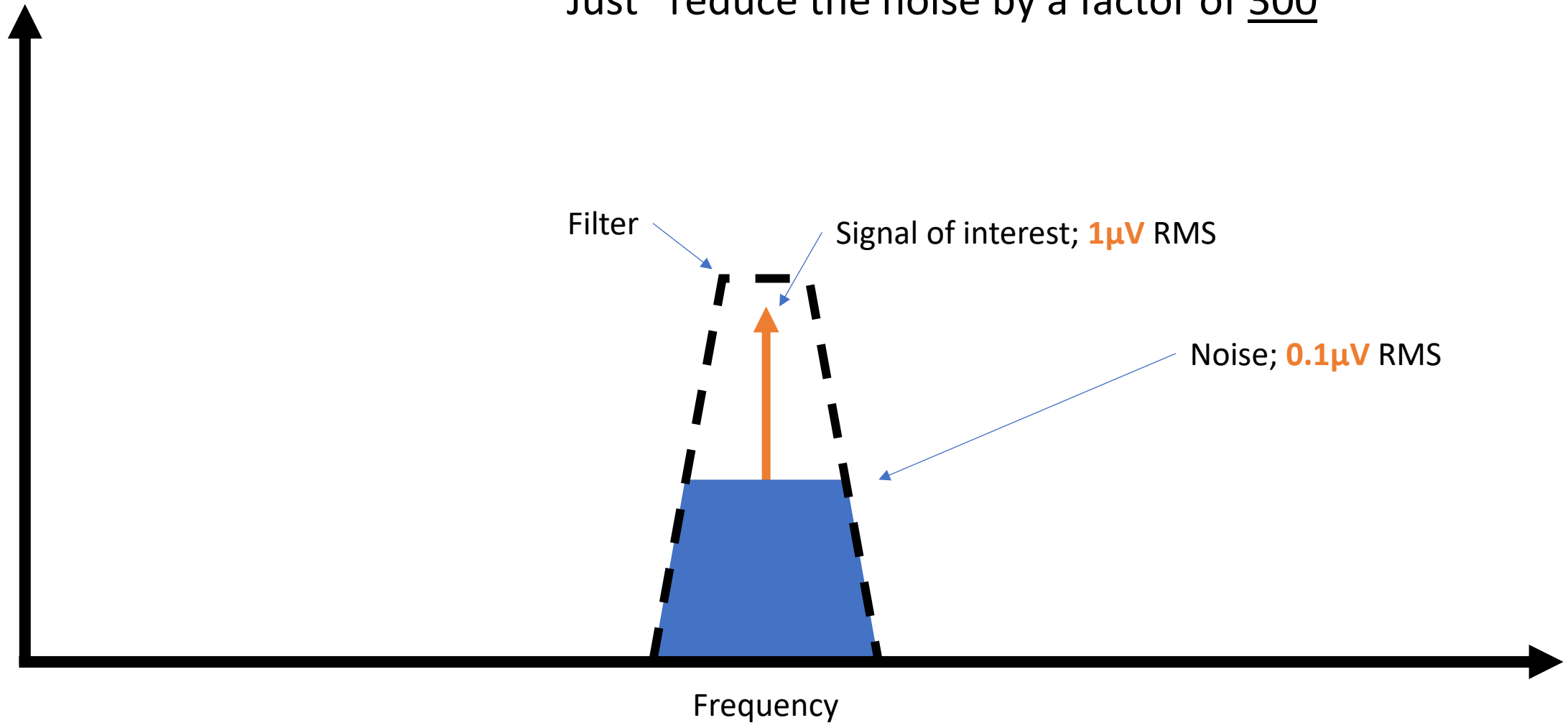


How? - Just* remove the noise!



How? - Just* remove the noise!

*"Just" reduce the noise by a factor of 300





How? - Filter the noise

How good a filter do we need?

To get a reduction of x in noise you need a reduction of x^2 in bandwidth

- Noise is measured as **power per Hz**
- But we want the **voltage** to be reduced by x
- Power is proportional to **voltage squared**

$$P = \frac{V^2}{R}$$

$$V = \sqrt{P \cdot R}$$

To reduce the voltage by **300x** we need to reduce the power by $300^2 = \mathbf{90,000}$ times

How? - Filter the noise

$$Q = \frac{\text{Center Freq}}{\text{Filter Width}}$$

How good a filter do we need?

- Filters are measured by there Q-Factor

$$Q = \frac{0.5}{1/90,000} = 45,000$$

We need a filter width $1/90,000^{\text{th}}$ of the original

- 50,000 pole Butterworth filter
- 8,000 pole Chebyshev filter
- 80 pole (crappy) Elliptic filter

Practical filters top out around $Q=100$



How? – Lock In!

2 simple steps!

- Shift the signal to 0Hz
- Average

$$Q = \frac{\text{Center Freq}}{\text{Filter Width}}$$

Q factor of a filter at DC is **0!**



Shift the signal to 0Hz

How?

- High School Trig!

$$\sin(x) \cdot \sin(y)$$



$$\frac{1}{2} \sin(x + y) + \frac{1}{2} \sin(x - y)$$

Shift the signal to 0Hz

$$\frac{1}{2} \sin(x + y) + \frac{1}{2} \sin(x - y)$$

What if: $x = y$

Just filter this out!

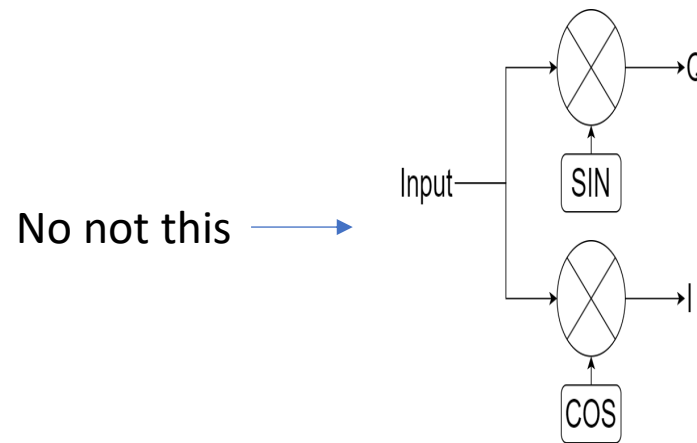
Leaving just the DC!

$$\cancel{\frac{1}{2} \sin(2x)} + \frac{1}{2} \sin(0)$$

But wait what about the phase?

For those of you in the back muttering about **phase**

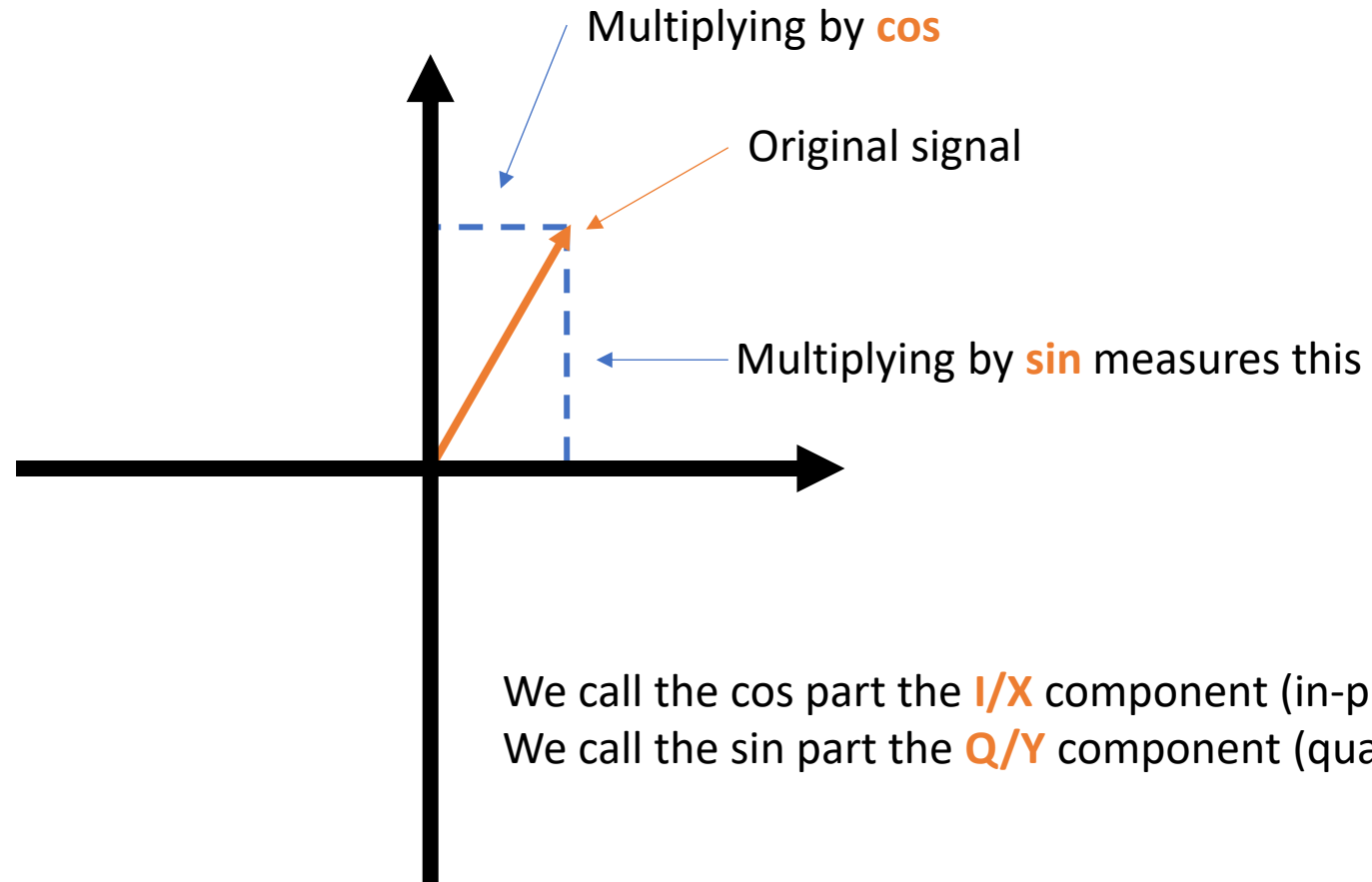
Turns out we can represent our original signal as a **phasor**



Phasor

$$\text{Amp} = \sqrt{I^2 + Q^2}$$

$$\text{Phase} = \arctan\left(\frac{Q}{I}\right)$$



We call the cos part the **I/X** component (in-phase)
 We call the sin part the **Q/Y** component (quadrature)



Now Average!

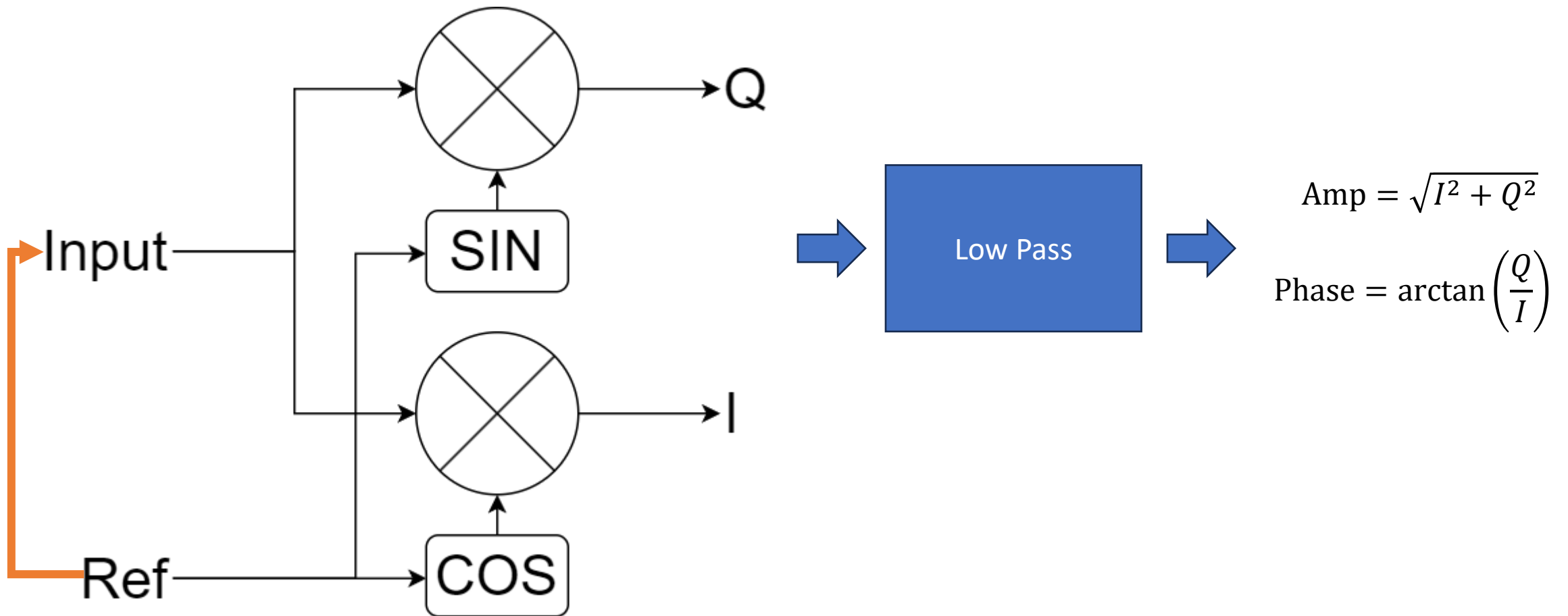
The longer we average for, the narrower the filter!

- Average for 0.1 seconds -> 10Hz filter*
- Average for 1 second -> 1Hz filter*
- Average for 10 seconds -> 0.1Hz filter*

For our example if we had 1MHz of bandwidth, we need a **10Hz filter**, so we only need to **average for a tenth of a second!**

*Very approximately, also averaging has a terrible filter shape use explicitly designed filters.

Final system

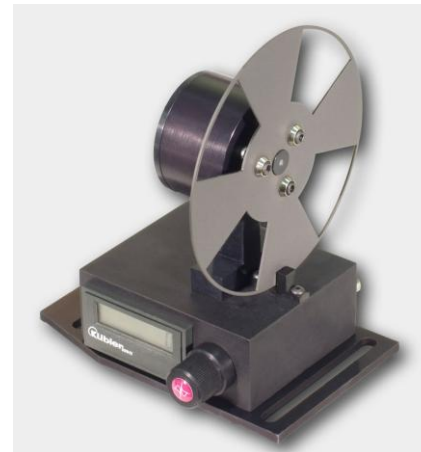


What if I want to measure a DC signal?

Make the signal AC!

Turn it on and off as some frequency to shift it up

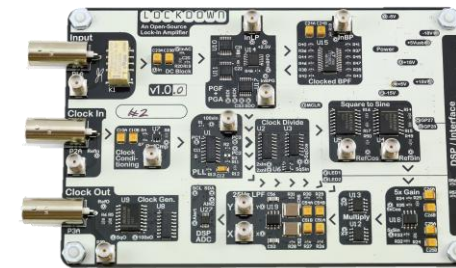
Optical chopper, for
“chopping up” a DC light
signal



Practical Options

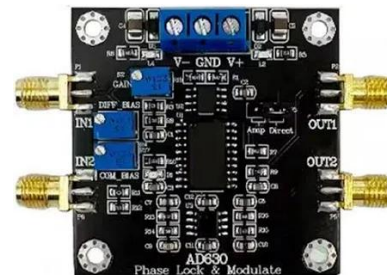
How is this really done – Tradeoffs

- Commercial LIAs
 - Expensive
- DIY – Discrete
 - Fairly complex to build
- DIY – Digital Signal Processing
 - Just need an ADC!
 - Like the one in your oscilloscope!
 - (That's what we're doing today!)



Tradeoffs: Commercial

- Standalone instruments from companies like Stanford Research Systems
- Cheapest units start at 3 grand...
- There are also some cheaper dev boards for chips like AD630 for ~\$100!



SR865A Lock-In Amplifier



- 4 MHz frequency range
- Low noise I & V inputs
- Data logging & analysis
- Differential source

SR860 Lock-In Amplifier



- 500 kHz frequency range
- Low noise I & V inputs
- Data logging & analysis
- Differential source

SR2124 Analog Lock-In



- Low noise, all analog design
- 200 kHz measurement range
- Low noise I & V inputs

SR844 RF Lock-In Amplifier



- 200 MHz measurement range
- 80 dB dynamic reserve
- Internal reference source

Tradeoffs: DSP with an Oscilloscope

- Or any ADC, really.
- The better the ADC, the better the results!
 - Bit depth
 - Buffer depth
 - Sampling rate
- One channel is used as the reference input, while the other(s) are used for the signals of interest.
- **Cost: you probably already have one!**



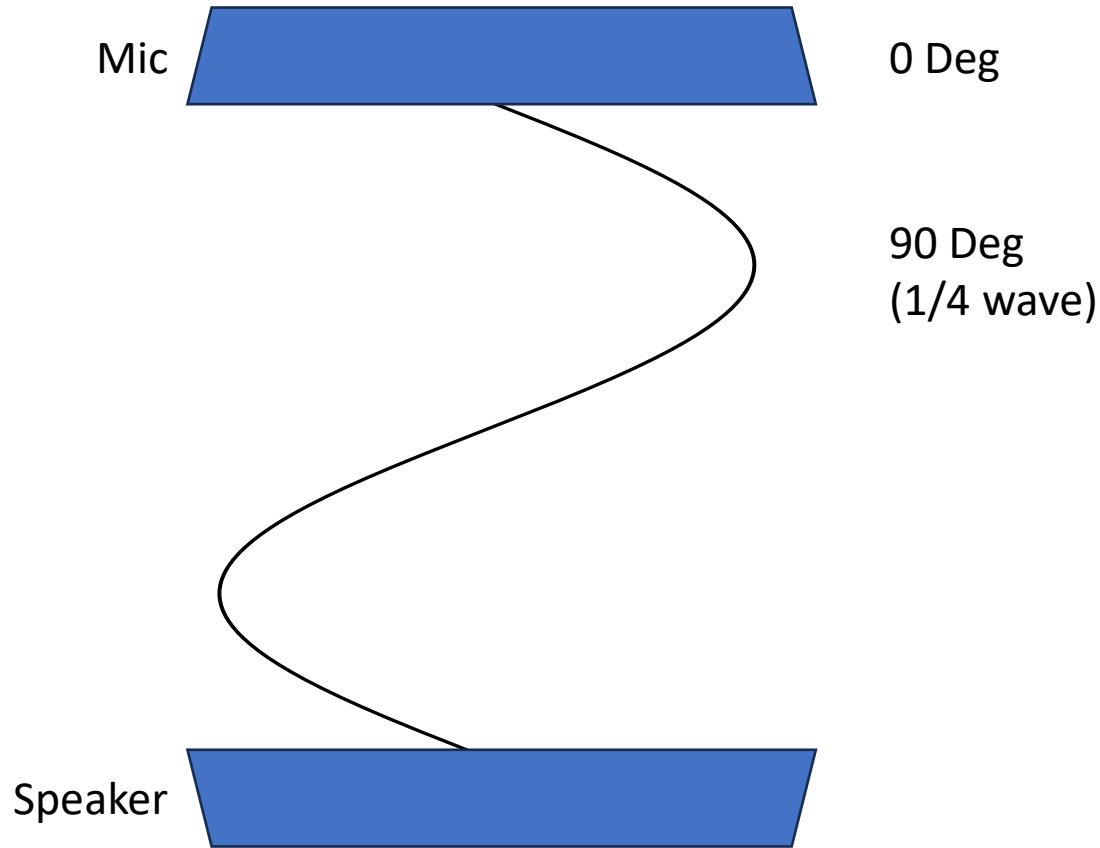


Specs and Tradeoffs

- Averaging is limited to memory depth of oscilloscope, which limits the rejection of other frequencies.
- Noise floor of the system is higher due to at least quantization noise, and also the whole frontend is not designed to be as low-noise usually.
- Some numbers:
 - Noise reduction = $\sqrt{\text{Number of Cycles}}$
 - Generally, you want to keep the input at or below 4 points per cycle (0.5x Nyquist)
 - We can reduce the noise by $\frac{\sqrt{N}}{2}$ if we have N points of memory in our scope
 - Rigol DS1054Z has 12M points so we can get a 1700x reduction

Demo!

What else can we do?



If we adjust the distance between the mic and speaker and look at the phase

We can measure the **speed of sound!**

8.5cm should be 90deg



TRY IT

- Code's on GitHub:
 - <https://github.com/O-scope-Lock-In-Amplifer/O-scope-Lock-In-Amplifier>
- Tested/working with:
 - Rigol DS1054Z
- Designed to be easy to add support for other instruments.
 - Contribute yours!
- And let us know what you think!