Using an DSP to Peek Below the Noise Floor

the DSP Magic of Lock-In Amplifiers

Mark Omo / James Rowley

About Marcus Engineering

Marcus Engineering LLC

- Marcus Engineering is an **electronics-focused product development and prototyping organization**

- Founded in 2011
- 5,000sqft Office and Development Lab
- Around 10 Full-Time employees

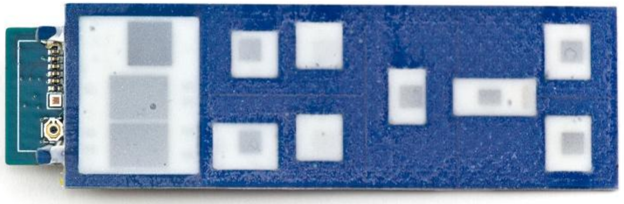
- High-end products
  - Medical, Industrial, Military, etc.

info@marcusengineering.com

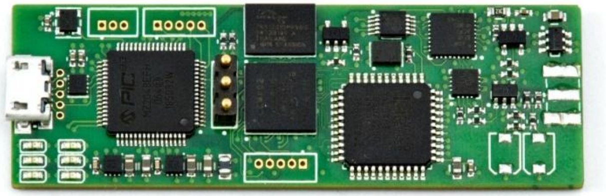
About Marcus Engineering

- Experts in a wide variety of sensing applications:
  - High dynamic range (160+dB)
  - NanoVolts to KiloVolts
  - FemtoAmps to KiloAmps
  - PPM Precision
  - GHz bandwidth

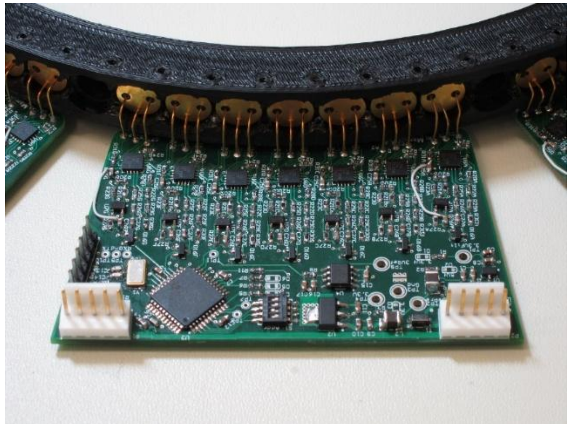
  - Accelerometers
  - Precision temperature
  - Energy measurement
  - Optical
  - Biomedical sensing (EEG/EKG)
  - Ultrasonic
  - Etc.



Ultra-compact, low-power sensing in 1 mm microscope slide form



20Msps high dynamic range sensor



Ultra high dynamic range (160dB+) sensor

Ultra High temperature (150C+) down oil well precision sensing system (communicates over 5 miles deep)

About Marcus Engineering

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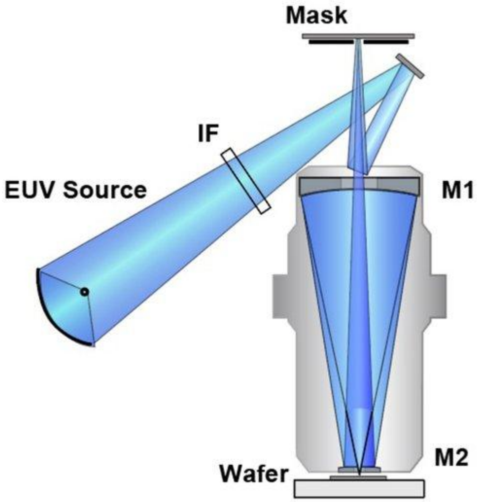
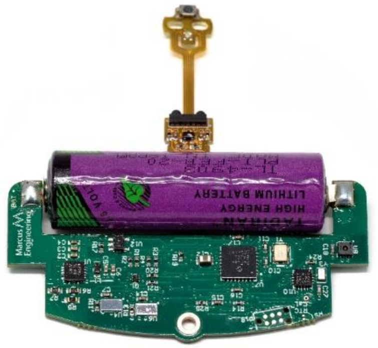
Also:

- Product Security (Medical/Industrial/etc.)
- Embedded Linux
- Power Electronics
    - nW to kW
    - USB-C/Laser Drive/Wireless Power/Etc.
- Optoelectronics
    - kW Laser Drive
    - Precision Detectors
- Precision Motor Control
    - Complex coordinated motion
    - Nanometer precision
    - BDLC/Steppers
- Ultra Low Power systems (mW/uW)
- Battery Systems
    - System Design
    - Charge and Battery Management
- Wireless
    - BLE/Wifi/RFID/GPS/etc.



Marcus Engineering Designed the motion control system for EUV Mirror inspection systems (**Sub nm** motion precision)

Medical Device incorporating embedded Linux and safety critical laser control



Military sensing system
20Yr life on a single battery

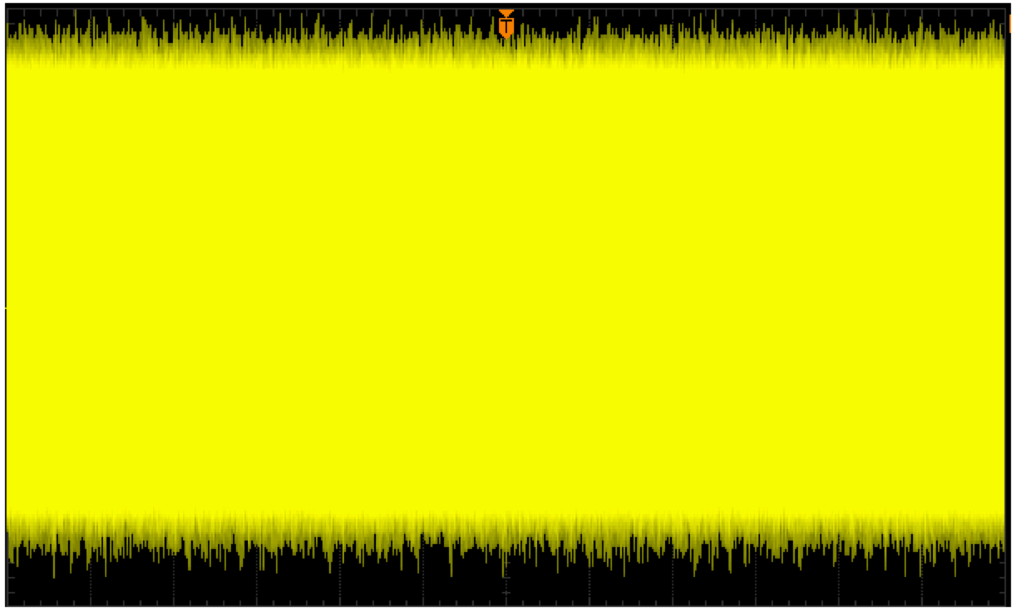
Lock in Magic

Reject Noise, Return to Signal

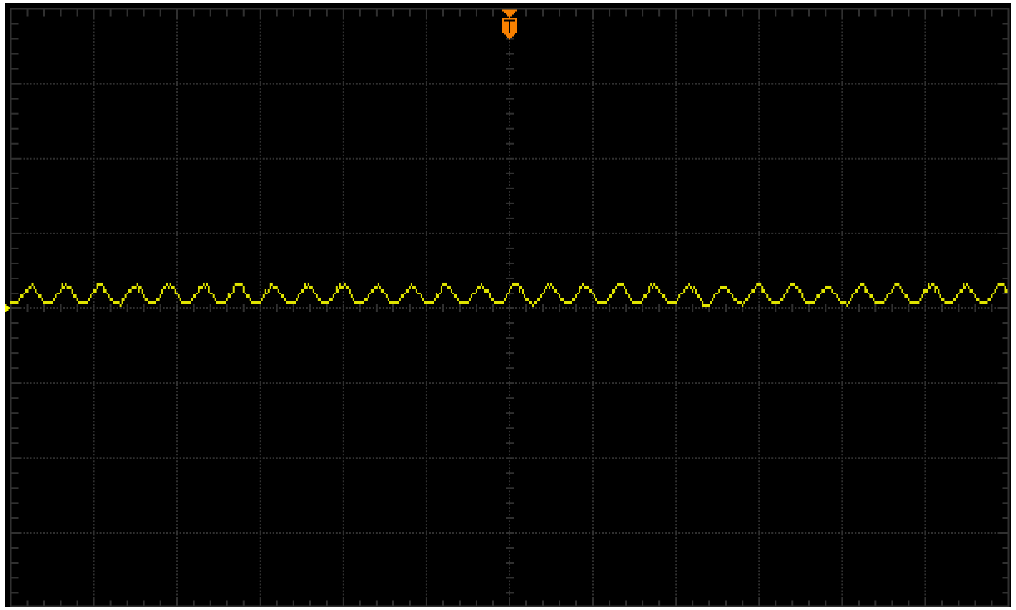
What If We Had Magic

Wouldn't it be magical if we could turn

this…



Into this?



The Magic is Lock-In Amplification

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- 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…

Trying improve SNR with brute-force averaging

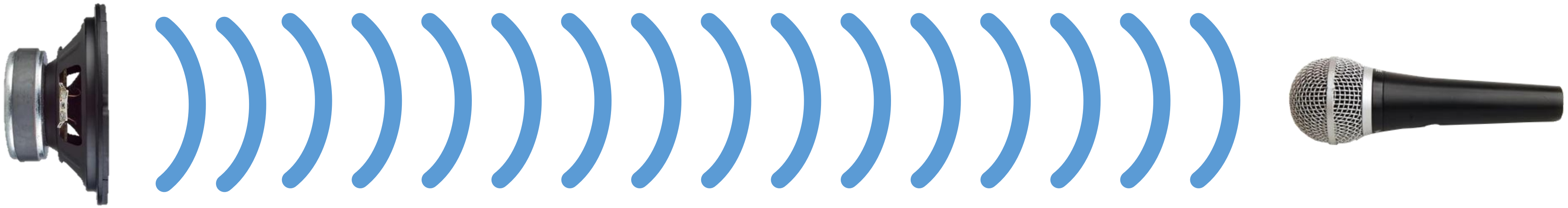
Using a Lock-In Amplifier to detect signals *below* the noise floor

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

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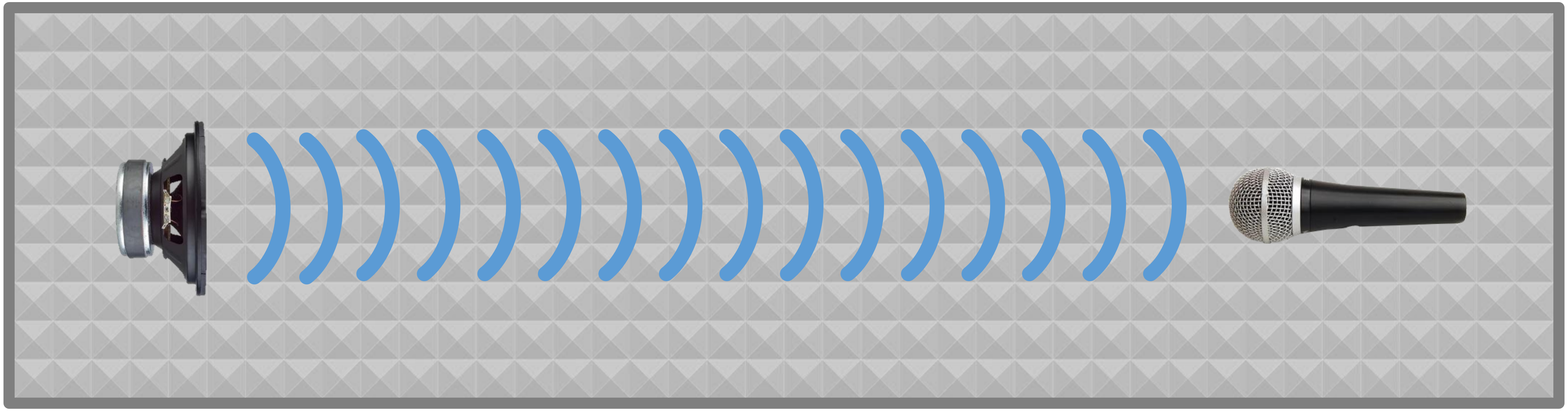
- You've got a speaker, you've got a microphone.
- The microphone picks up whatever the speaker puts out.
  - Well, maybe in a perfect world.



Measuring a Sounds

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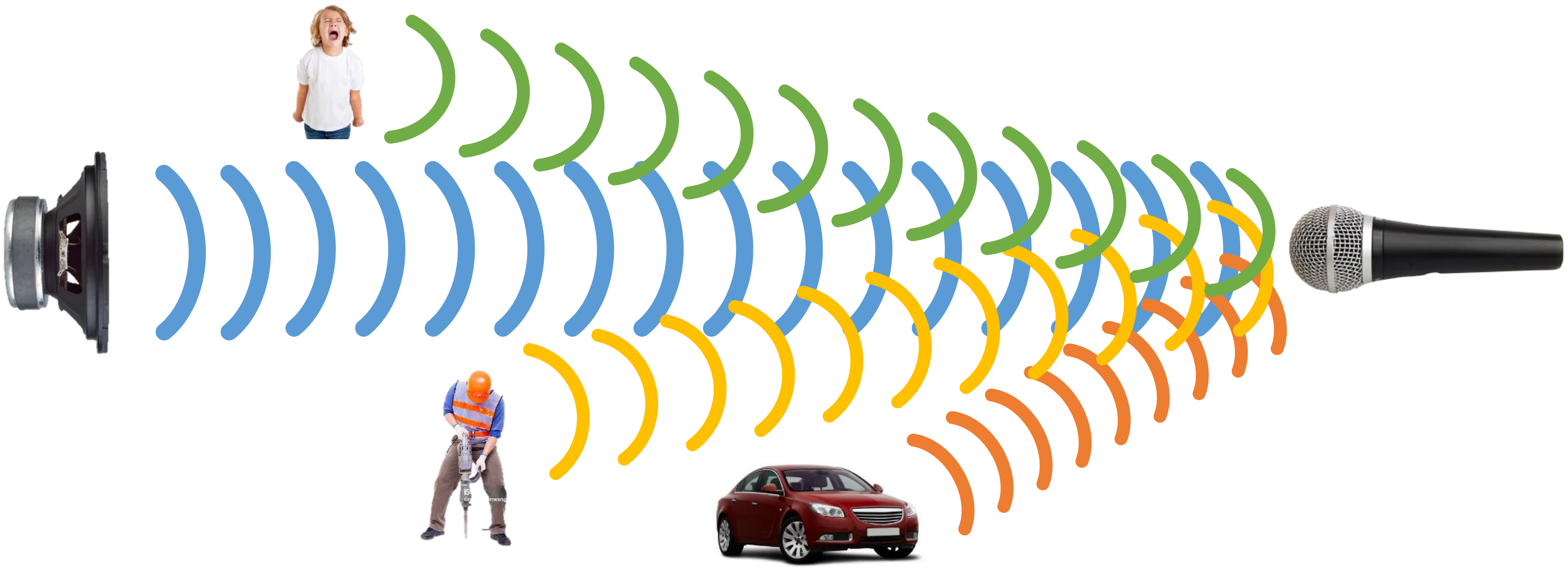
- You've got a speaker, you've got a microphone, and you've got a whole world full of other stuff making sound.
- The microphone picks up whatever the speaker puts out…
  - Plus a bunch of NOISE and INTERFERENCE!



Measuring a Sounds

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- 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

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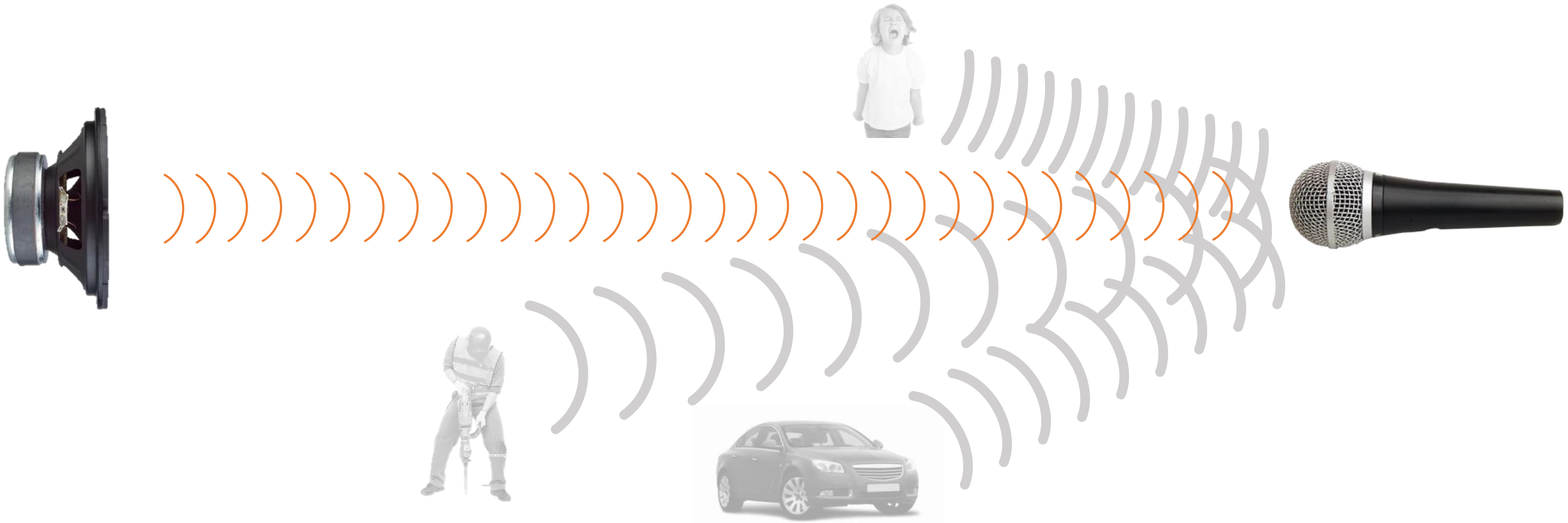
- The microphone picks up whatever the speaker puts out.
  - Plus a bunch of NOISE and INTERFERENCE!
- Such noise might be quite a bit louder than the speaker…
- Yet, with the magic of a Lock-In Amplifier, you can reject all that noise and truly measure just the speaker.

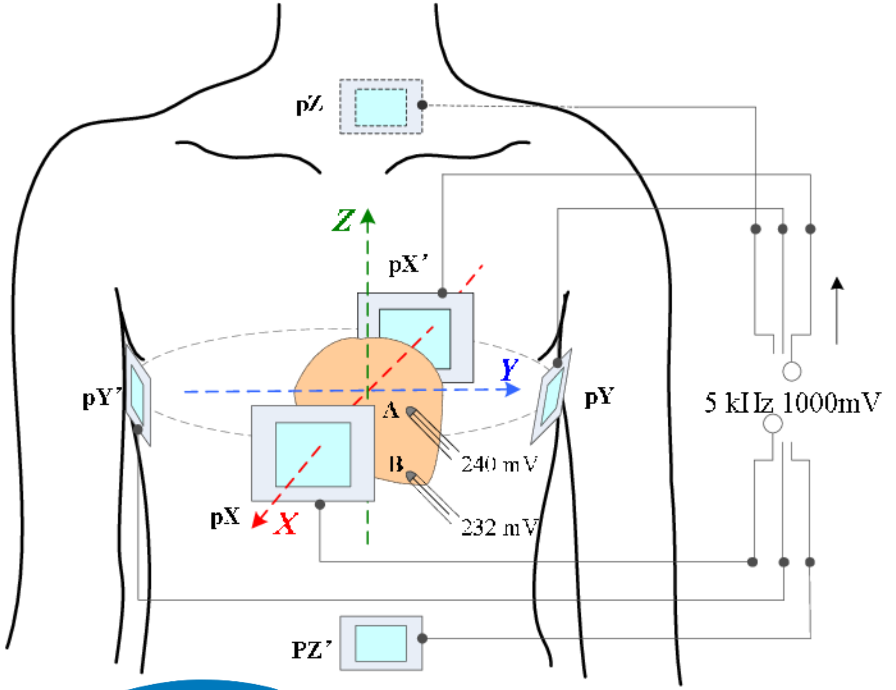


Measuring Anything

- But LIAs have much broader applications

- They are useful anywhere you:
  - Need to detect faint signals
  - Need to reject ambient interference
  - Need to detect phase or delay

    And
  - Control the stimulus
  - Have relatively low bandwidth



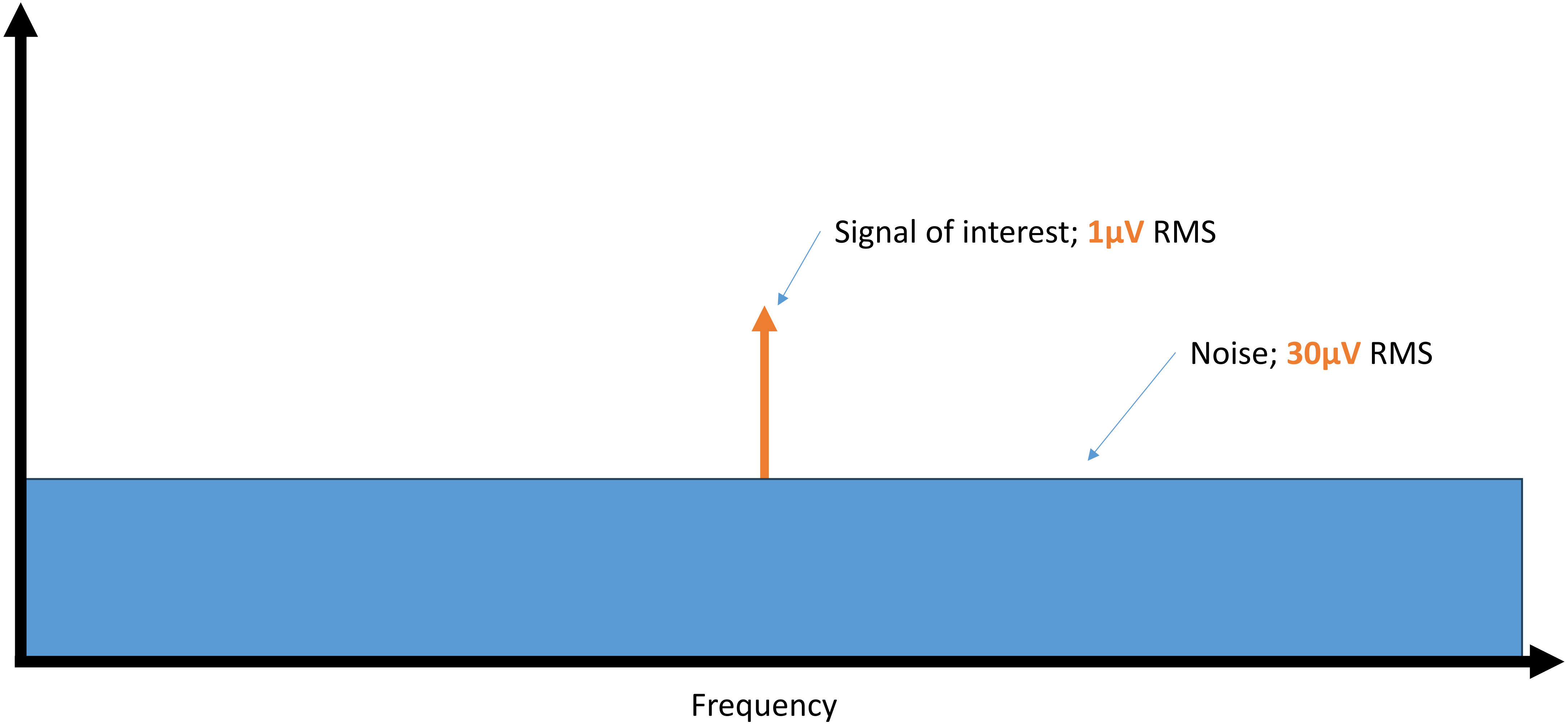
Fi... c representations of the catheter localization technique
...e Orthogonal transthoracic electrical-field

lock-in inside

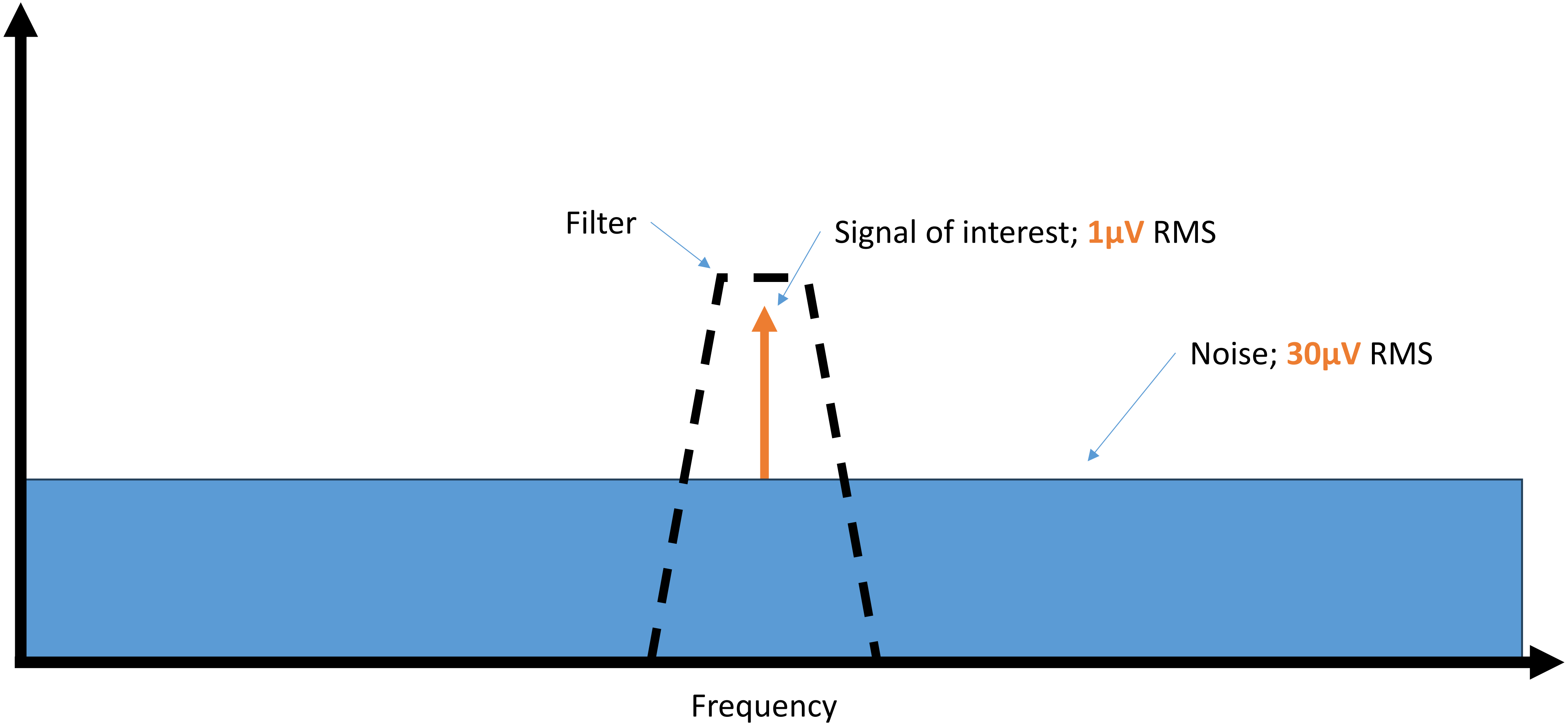
HOW

DSP Magic

How?



How? - Just* remove the noise!



How? - Just* remove the noise!

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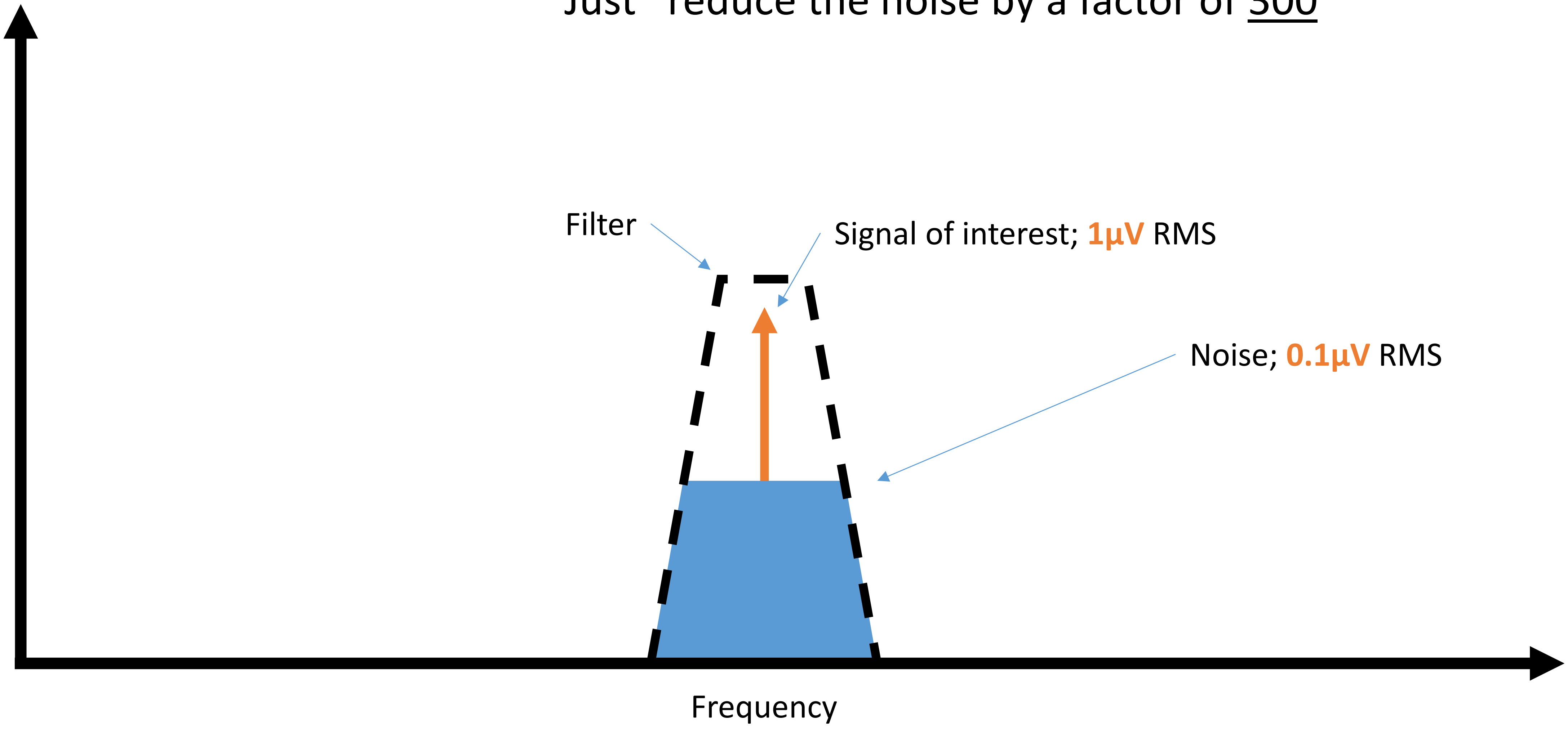
*"Just" reduce the noise by a factor of 300



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**

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

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

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?

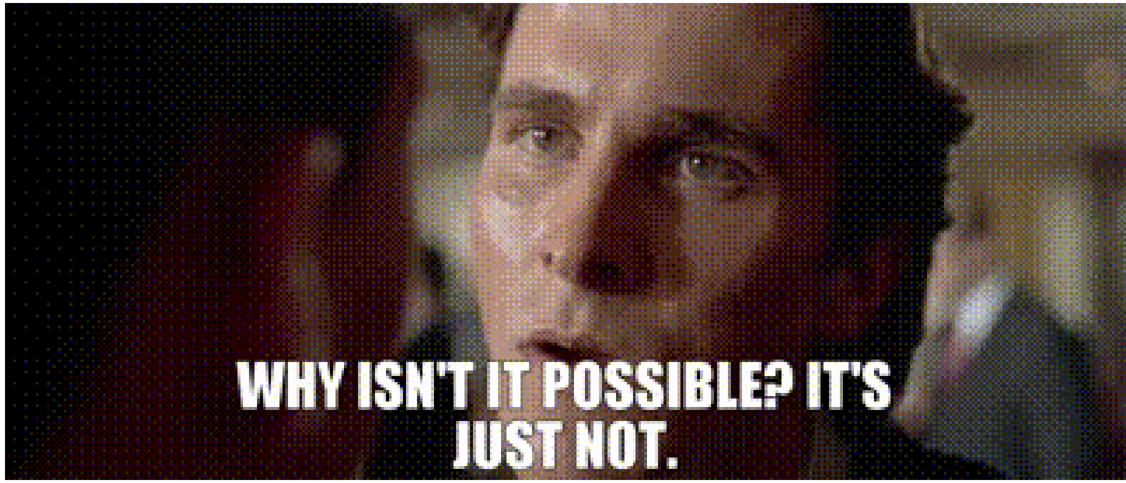
- Filters are measured by there Q-Factor

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

We need a filter width 1/90,000th 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!

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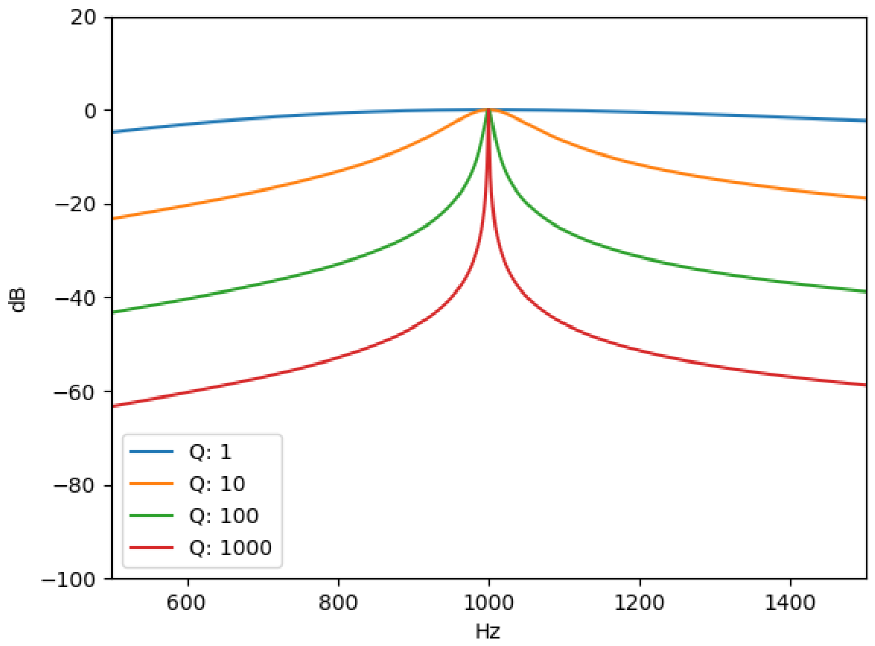
2 simple steps!

- 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

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How?

- High School Trig!

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

$$\downarrow$$

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

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!

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

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**

No not this

Phasor

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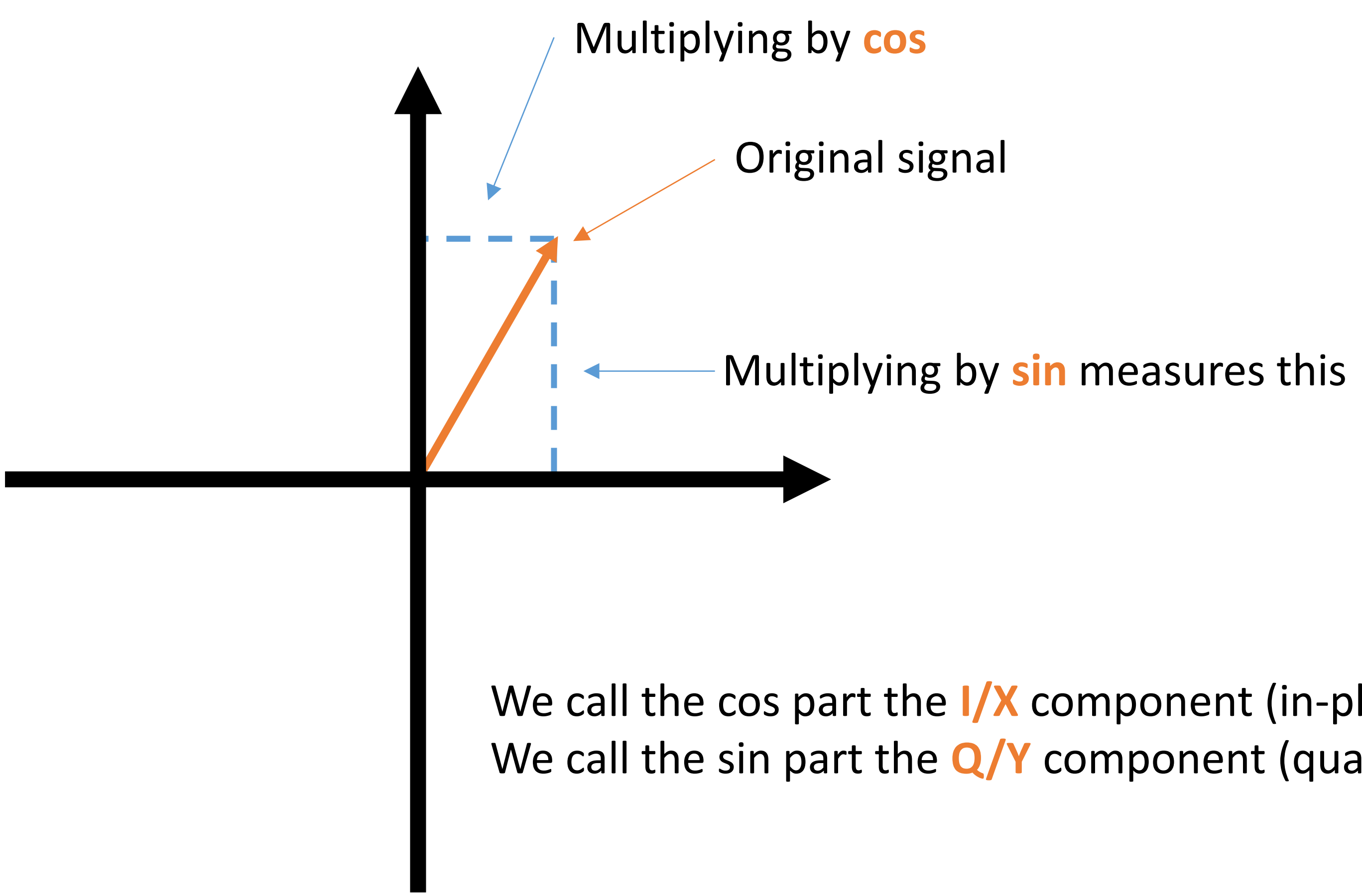
$$\text{Amp} = \sqrt{I^2 + Q^2}$$

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



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

Now Average!

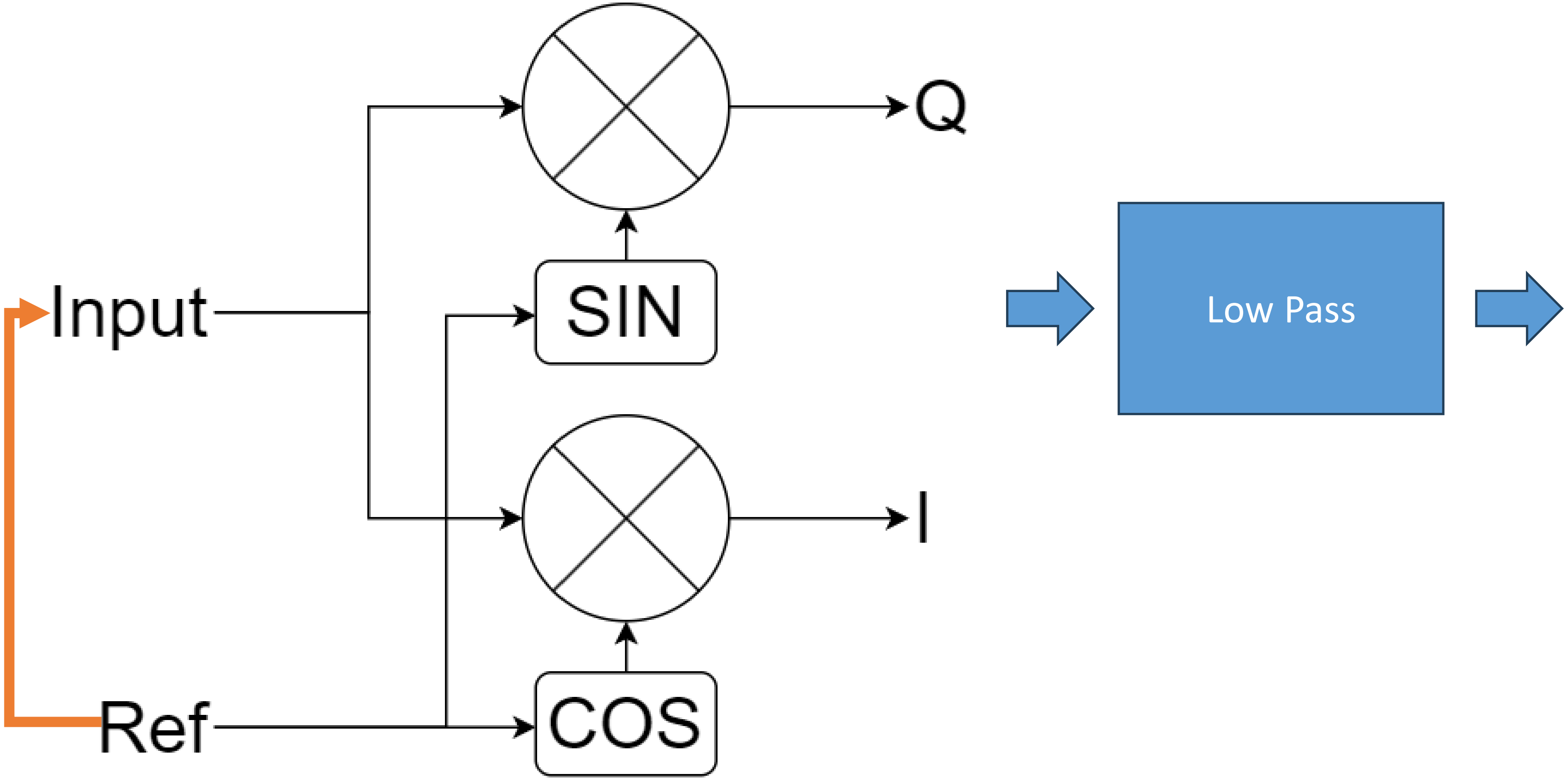
The longer we average for, the narrower the filter!

- 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



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

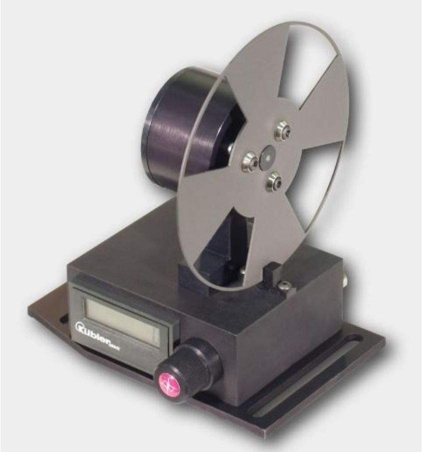
$$\text{Phase} = \arctan\left(\frac{Q}{I}\right)$$

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



How much noise reduction do I get?

- Rules of thumb
  - Noise reduction $= \sqrt{\text{Number of Cycles}}$
  - For sensing shot for at least 8 samples per period
  - Output sample rate:
    ADC rate / 8 samples per period / averaging cycles

Practical Considerations

How do I implement this?

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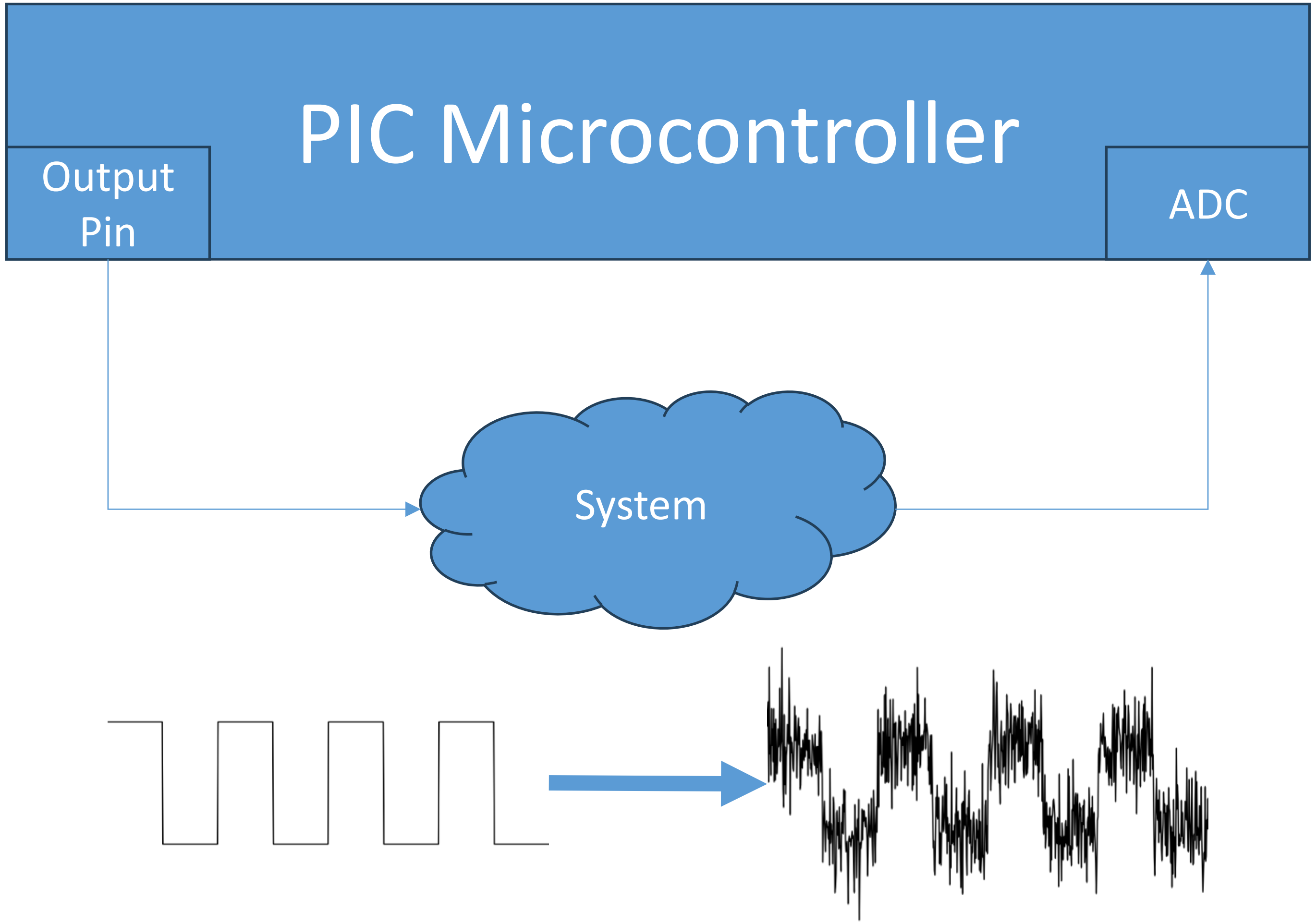
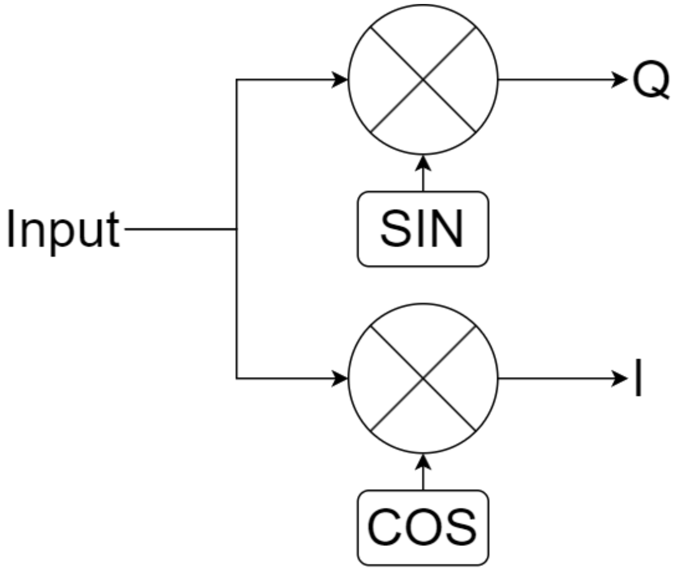
Lock-In technique works **just as well** with a **square wave** input!

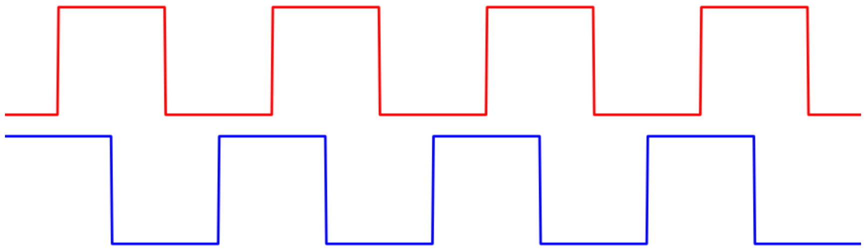
Toggle the stimulus
Read with ADC



Data Processing



- Sin/Cos reference digital signals



- Just alternate from -1 to 1

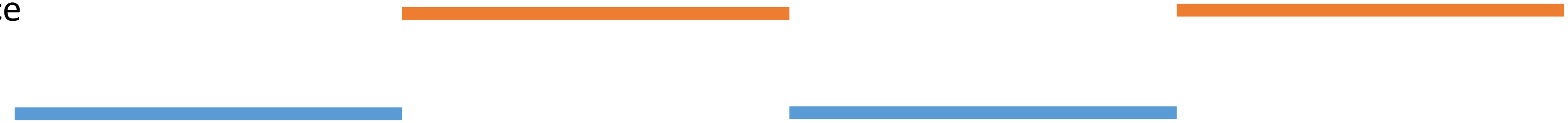
Software Implementation

- I/Q Running signals (repeat for both phases)

Input:

```
[ 1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 15]
```

Reference Signal:



Multiplied (invert value):

```
[-1, -2, -3, -4,  5,  6,  7,  8, -9,-10,-11,-12, 13, 14, 15, 15]
```

Software Implementation

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Filter

- Leaky IIR
  - For ~8 sample moving average
  - Subtract 1/8th from the accumulator
  - Add 1/8th of input to accumulator

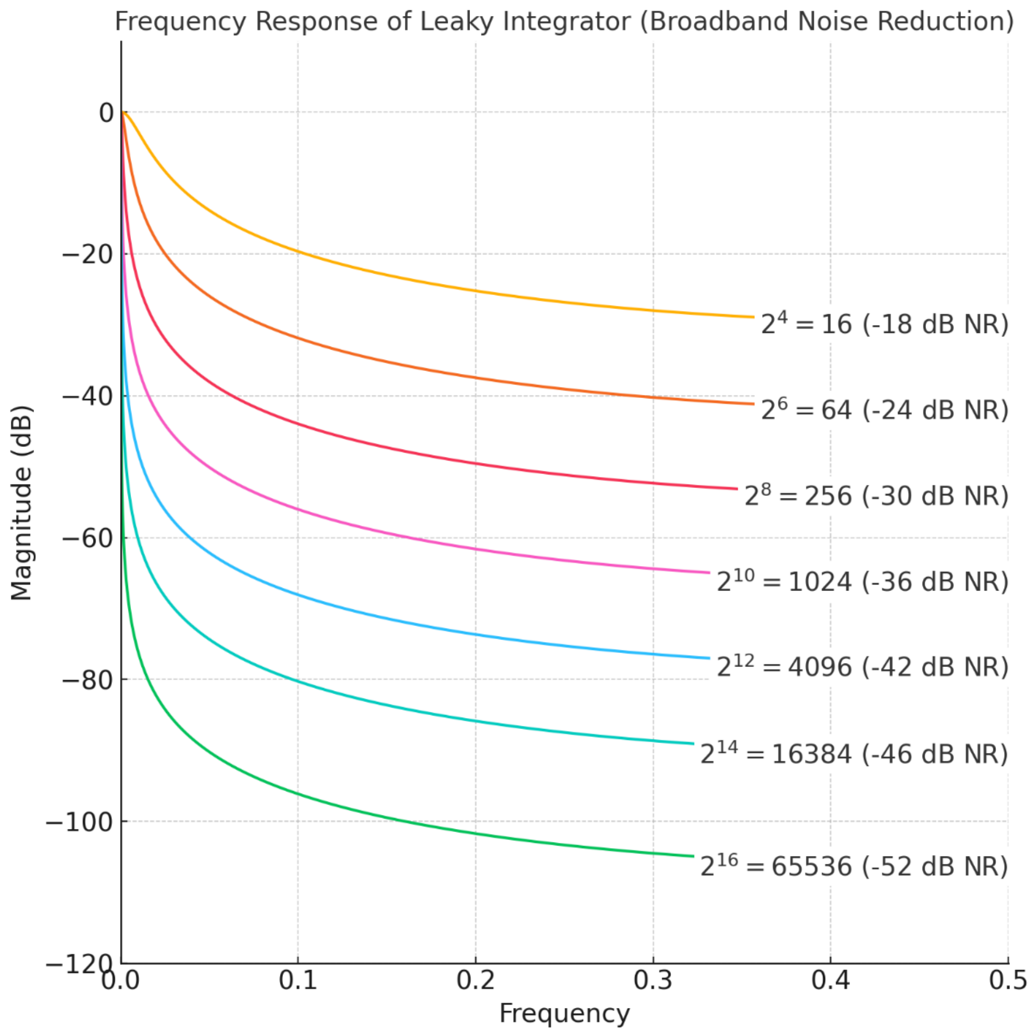
```
// 2^x i.e. 3 → 8 sample
#define LEAK_PER     3
#define PERIOD       8

int16_t i_acc = 0;
int16_t q_acc = 0;
uint8_t sample_index = 0;

void lockin_process_sample(int8_t x)
{
    i_acc -= (i_acc >> LEAK_SHIFT);
    if (sample_index < (PERIOD >> 1)) {
        i_acc += x;
    } else {
        i_acc -= x;
    }

    q_acc -= (q_acc >> LEAK_SHIFT);
    // for Q, we toggle sign when (sample_index + 2) < 4
    if ((sample_index + 2) < (PERIOD >> 1)) {
        q_acc += x;
    } else {
        q_acc -= x;
    }

    sample_index = (sample_index + 1) & (PERIOD - 1);
}
```

Combined (I/Q)

- 8 cycle period
  - **9dB** improvement
  - `int16` accumulator

- 512 cycle period
  - **27dB** improvement
  - `int16` accumulator limit

- 65,536 cycle period
  - **52dB** improvement
  - `int24` accumulator



On a Real Chip

Sample Period	Noise Reduction	PIC16F13145 (100ksps ADC)	PIC32A (40MSPS ADC)
8	9	1.5kHz	625kHz
512	27	25Hz	9.8kHz
65,536	50	11 per/minute (0.2Hz)	76Hz

PIC16F13145 CIP Demo!

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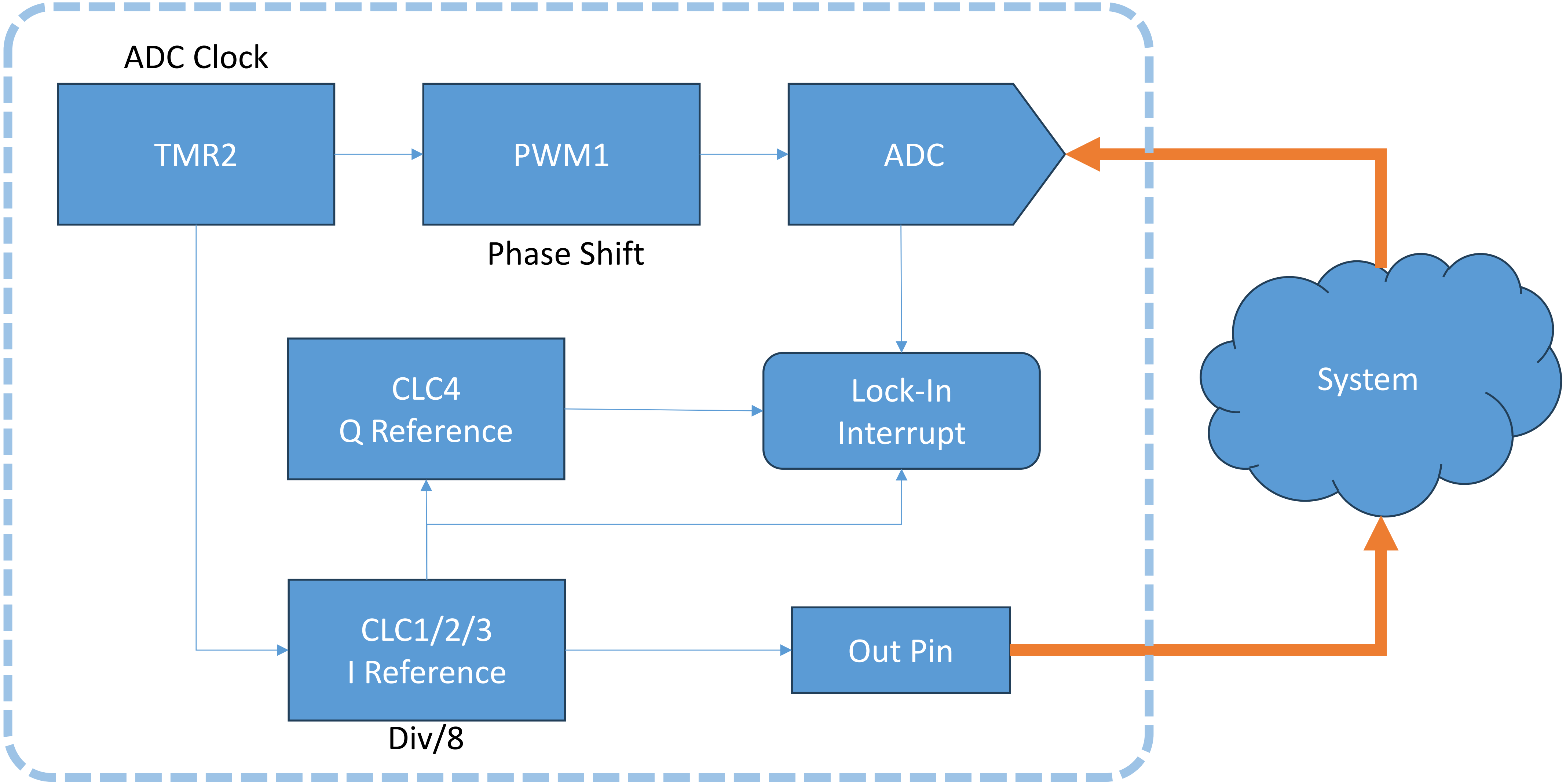
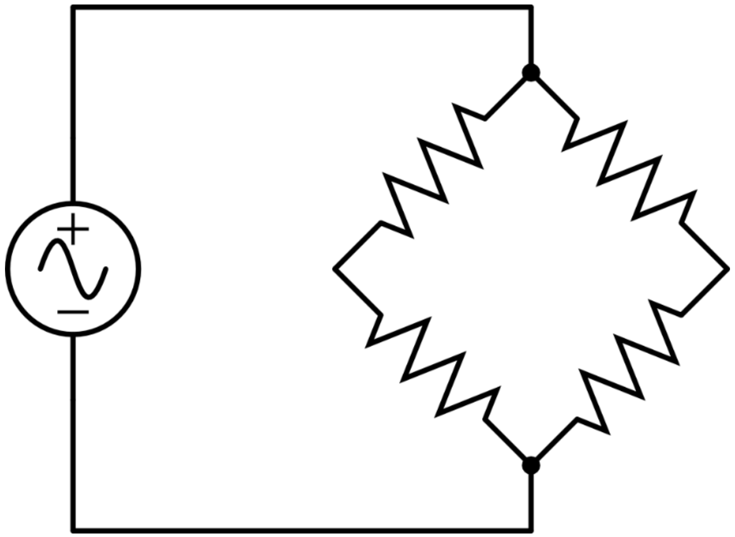


Applications

High Bit-Depth / Interference Rejection

- Lock-In excels when making very sensitive measurements, averaging over a long time
- Lock-In also excels at **rejecting time-varying interference**
  - It measures **only the modulation signal**

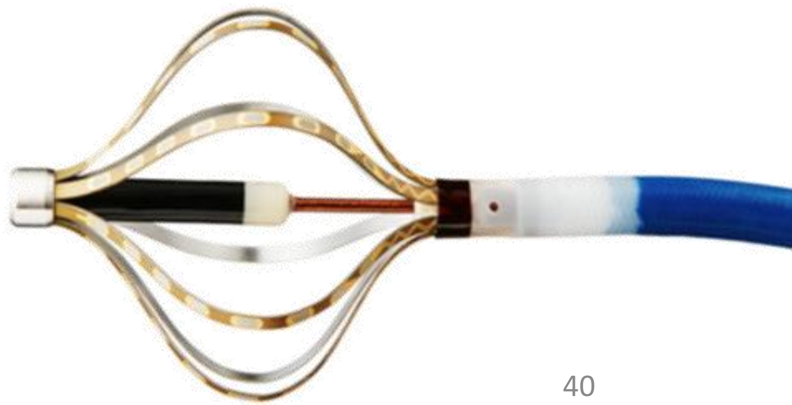


For example, in precision/noise bridge measurement

Low signal allows for lower power
Or omitting an amplifier

Catheter Localization

- **Cardiovascular Catheters** are used in many **minimally-invasive** medical procedures
  - Used to Map or Modify vessels and organs
- But clinicians **need to know where the catheter is** inside the body!



Catheter Localization

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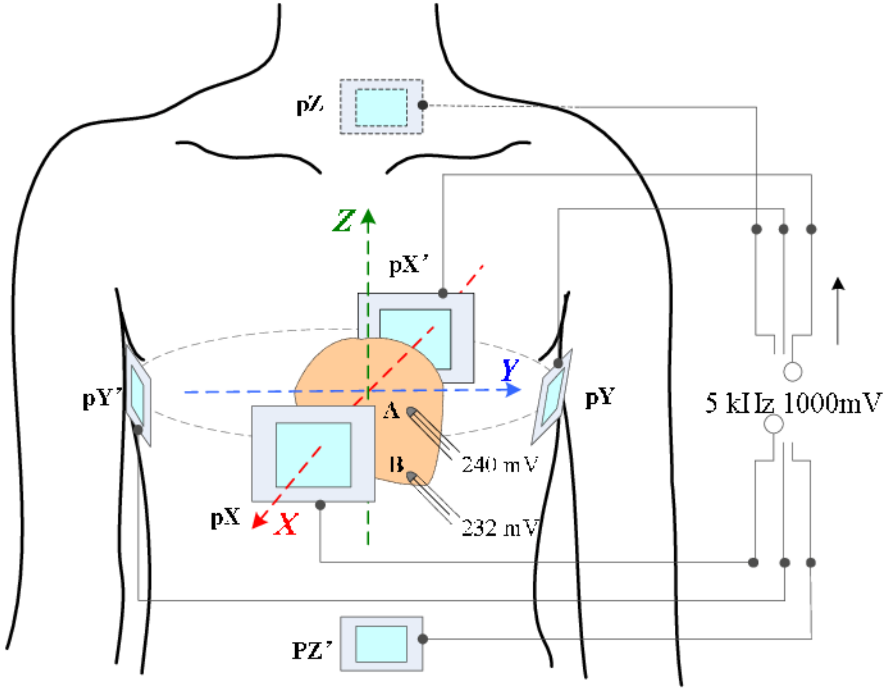
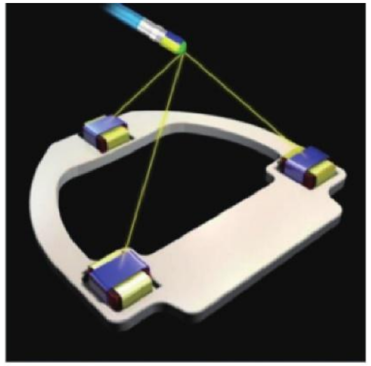
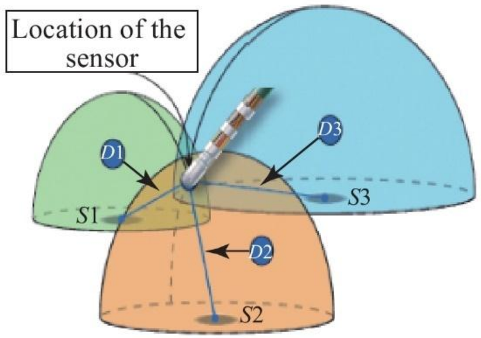
- An external coil generates multiple magnetic fields through the patient's body
- Tiny sensors in the catheter tip detect these fields
- Relative strength of each field reveals each sensor's location, and overall orientation of tip.







Catheter Localization – Lock In!

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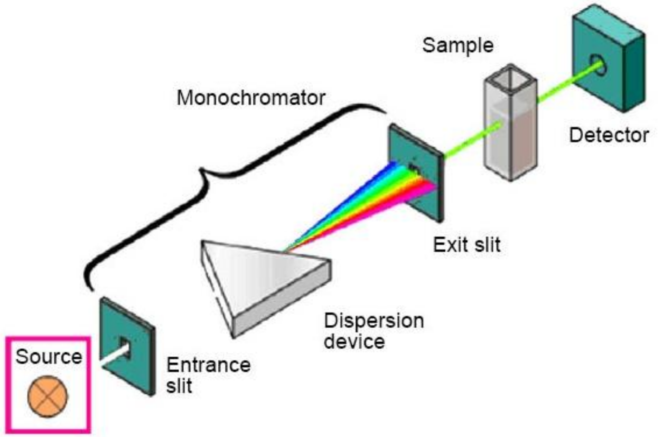
- Cath tip sensors are generally tiny coils which produce current in the presence of magnetic fields – **including undesired fields**.
- Locking the sensor measurement to the transmitting coil **eliminates interference** from environmental magnetic fields.

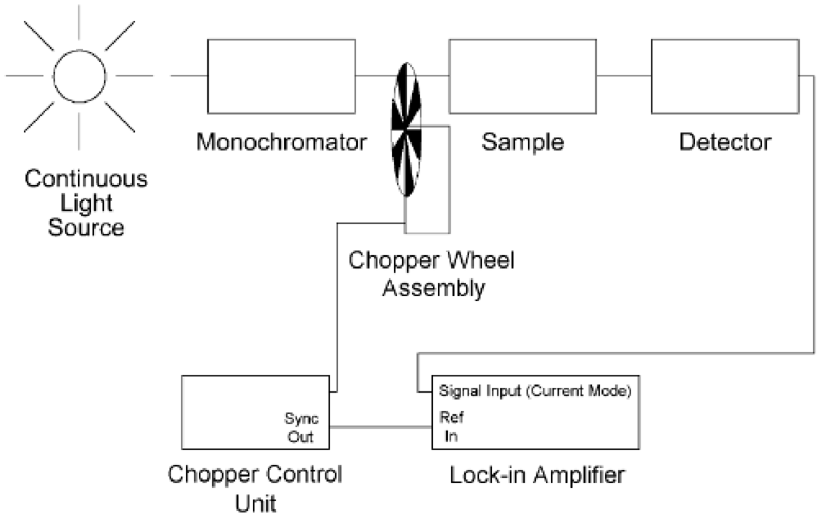
Spectroscopy

- **Emitting** one or more wavelengths of light to go through or reflect off of a sample, onto a **detector**.
  - Adjusts which wavelengths are sent to **measure transmissivity or reflectivity spectrum** of sample.
- But, **ambient light** is present too!



Spectroscopy – Lock In!

- Ambient light is present too.
  - Some models have the sample out in the open.
  - Even if not, perfectly blocking all light is hard.
- **Modulate the light source** and lock the receiver to that frequency!
  - Possible with monochromatic, array, and FTIR techniques.



Spectroscopy – Pulse Oximetry

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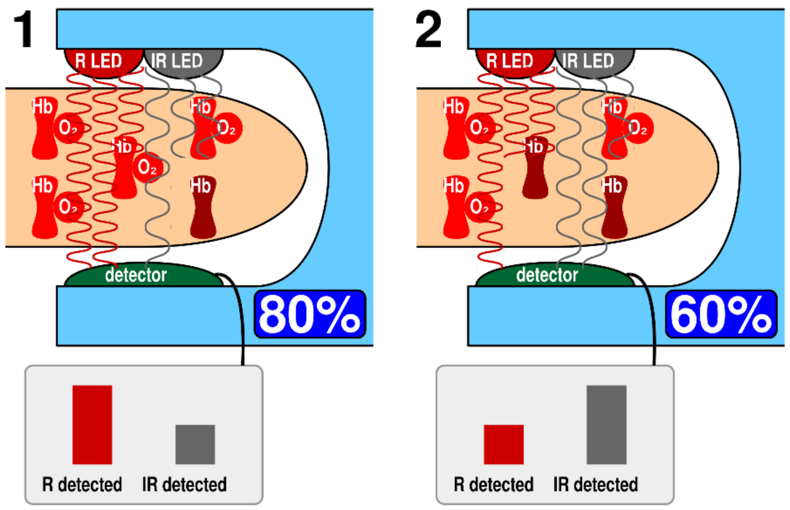
- A special case of spectroscopy is **pulse oximetry**.
  - Pulse Ox sensors measure the transmissivity or **reflectivity of hemoglobin** in the blood at **two** particular wavelengths – the **ratio reveals its oxygenation**.
- Lock In Amplification, as before, rejects ambient light interference, improving accuracy.
- **Lower cost** LEDs drivers etc.



Ultrasonic Flow Measurements

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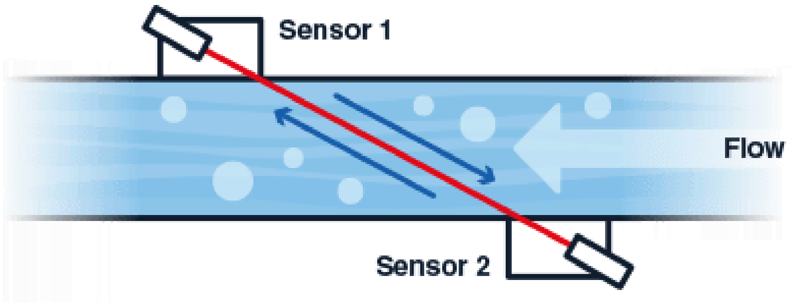
- Fluid flow measurement is important to process control in many industries
  - Mechanical flow meters require maintenance
- A pair of ultrasonic transducers on the outside of the pipe can measure flow.

- By measuring the phase shift you can measure the time of flight without precision timing and in **significantly nosier environments** (than TOF would allow)



Impedance Measurement

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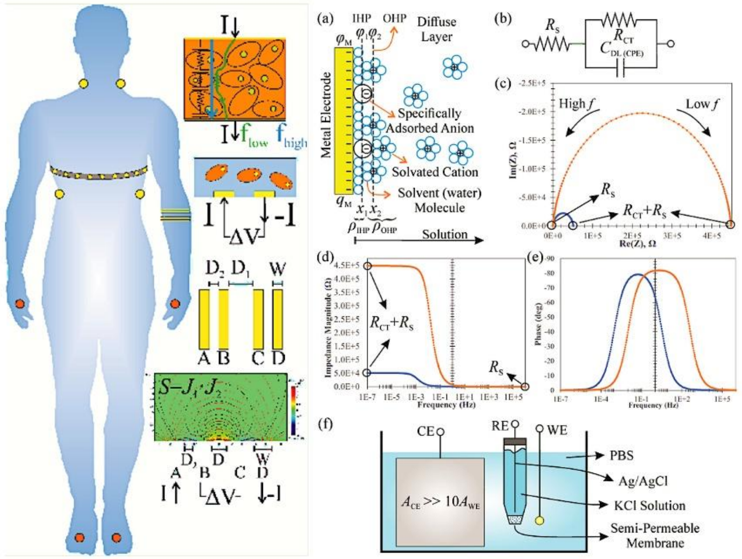
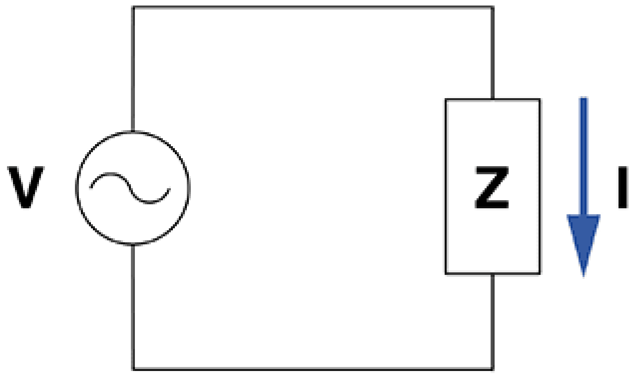
- Leverage Phase Sensitive Detection to measure the phase and gain of an element
  - Bioimpedance
    - Complex Lab measurements
    - Fat estimation in scales
    - Etc.
  - Component impedance measurement
    - Inductive Proximity Sensor
  - Electrical impedance tomography
  - Dielectric spectroscopy





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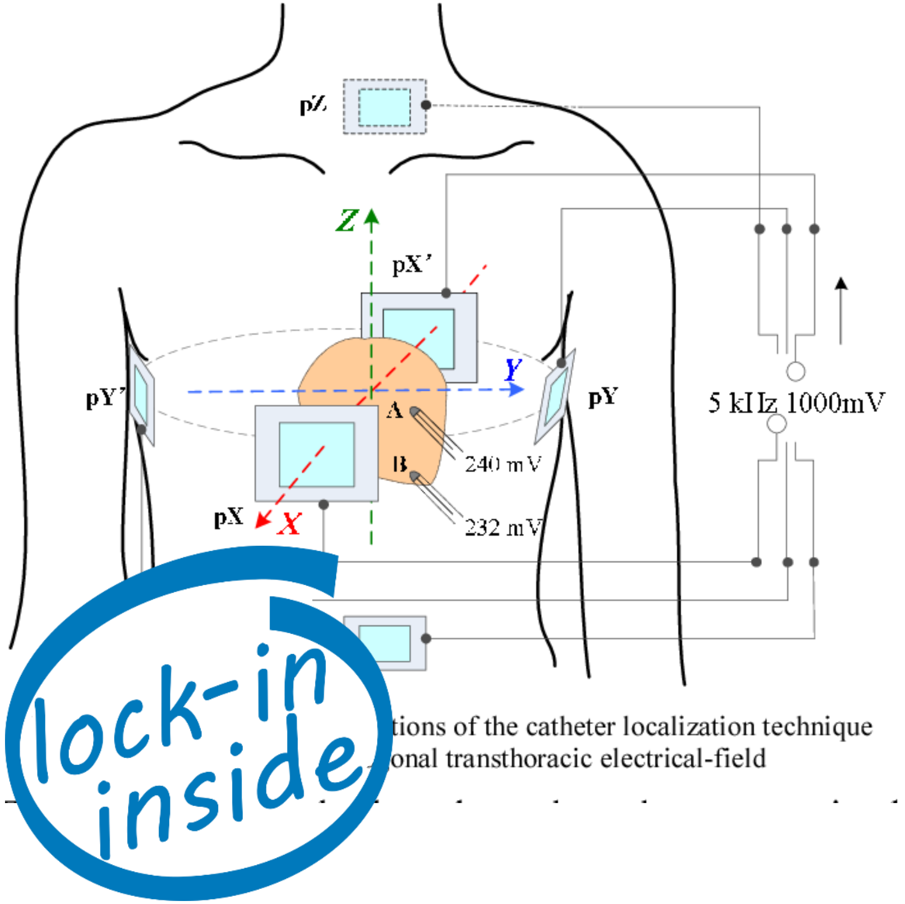
Measuring Anything

- Need to detect faint signals
- Need to reject ambient interference
- Need to detect phase or delay

    And

- Control (or sense) the stimulus
- Have relatively low bandwidth (Hz to <1MHz)



Resources

- Principles of Lock-in Detection

  https://www.youtube.com/watch?v=ZIjBRA2S0NQ

- Basic Mathematical Treatment

  https://www.zhinst.com/americas/en/resources/principles-of-lock-in-detection

- DSP Description

  https://www.thinksrs.com/downloads/pdfs/applicationnotes/AboutLIAs.pdf

- (Book) Lock-in amplifiers: principles and applications by Mike Meade

  https://archive.org/details/Lock-inAmplifiersPrinciplesAndApplications/Lock-inAmplifiersMlMeade/page/n45/mode/2up