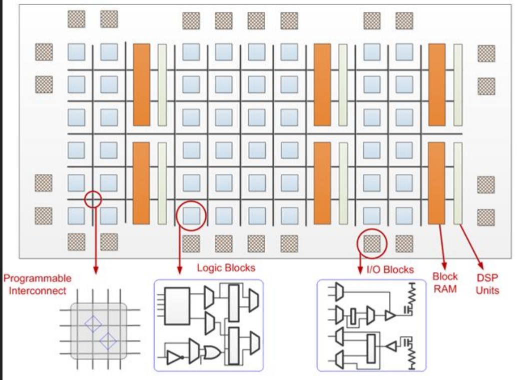
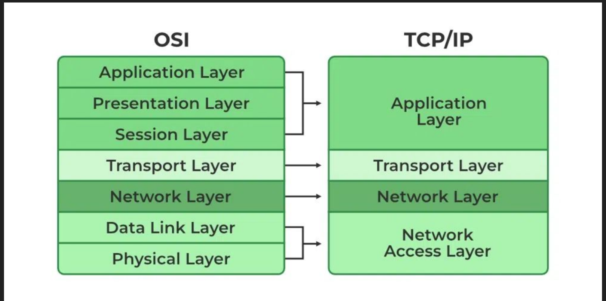
Front-end Electronics
&
Analog-Digital Converters

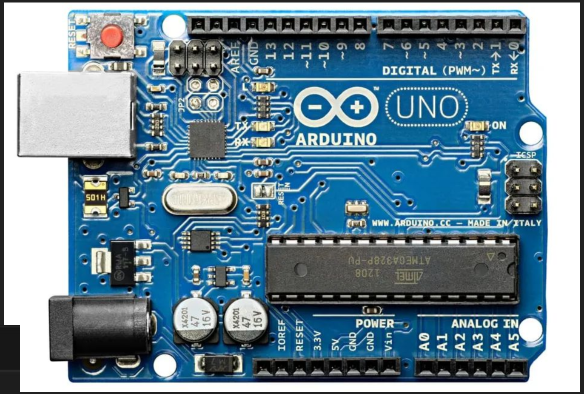
Suerfu Burkhant (KEK)

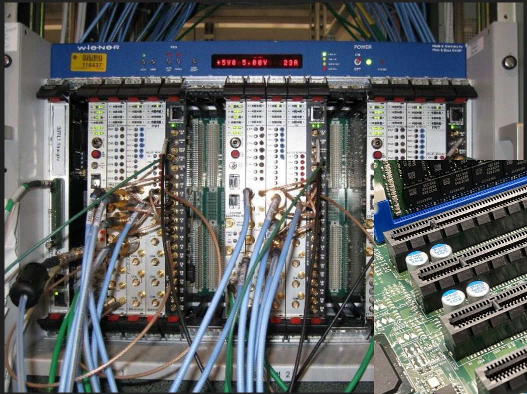
ISOTDAQ 2024 @ Hefei, China

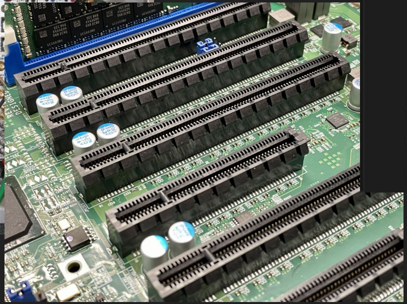
By now, you have already mastered these…











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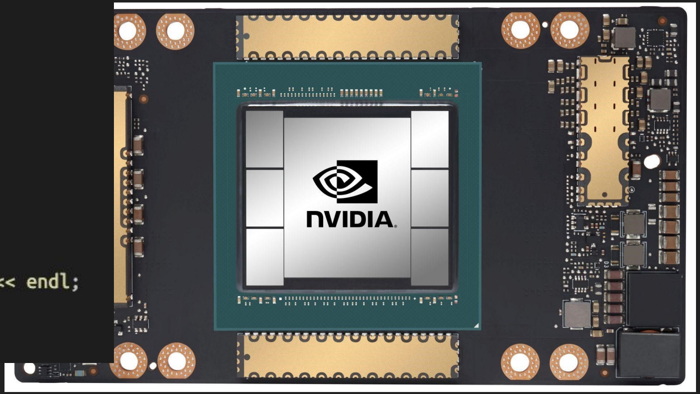
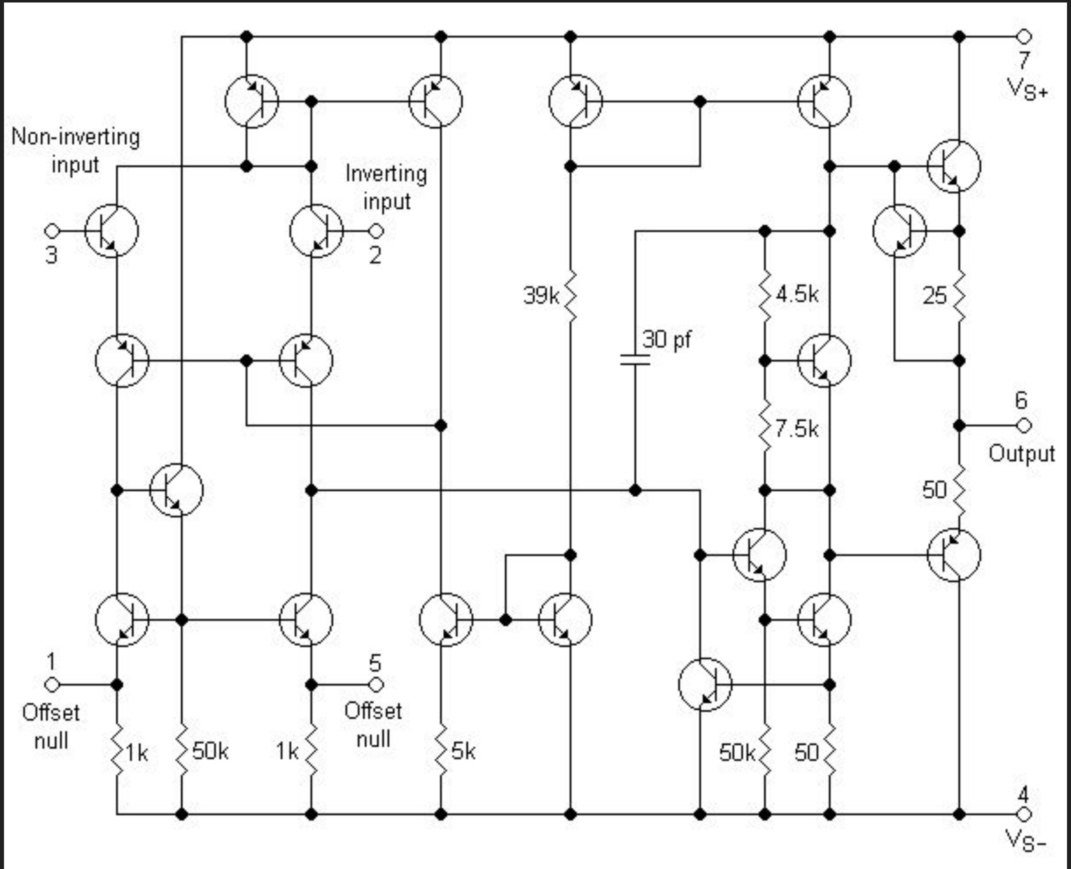
index.cpp > ...

You, 14 seconds ago | 1 author (You)

```cpp
#include <iostream>

using namespace std;

int main()
{
    string hello = "hello";
    string world = "world";

    cout << hello << world << endl;
    return 0;
}
```

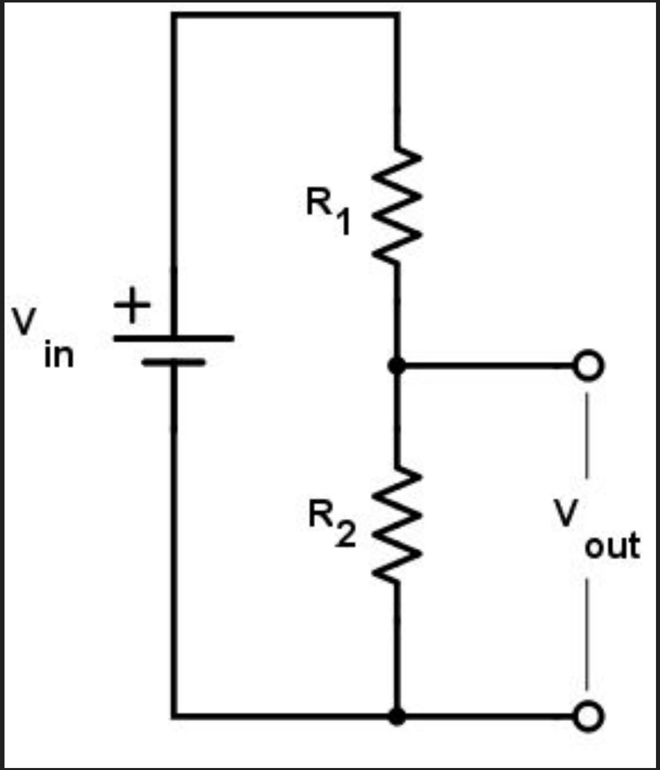


It's time to learn this!



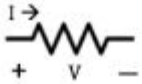
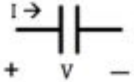
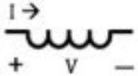
Are you familiar with …

- Voltage dividers



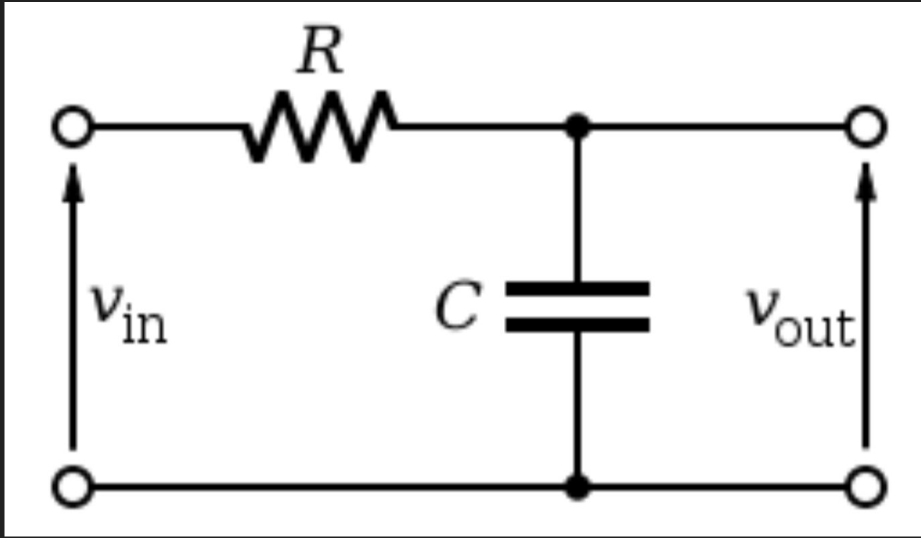
Are you familiar with …

- Voltage dividers
- Impedances

Circuit Element	Symbol	Current-Voltage Relationship in Time	Impedance
Resistor		$V = IR$	R
Capacitor		$I = C\frac{dV}{dt}$	$\frac{1}{j\omega C}$
Inductor		$V = L\frac{dI}{dt}$	$j\omega L$

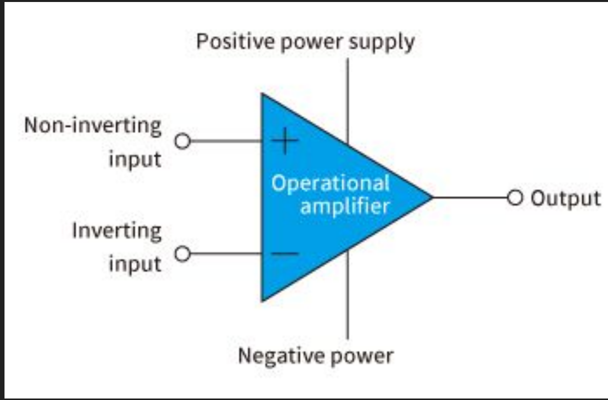
Are you familiar with …

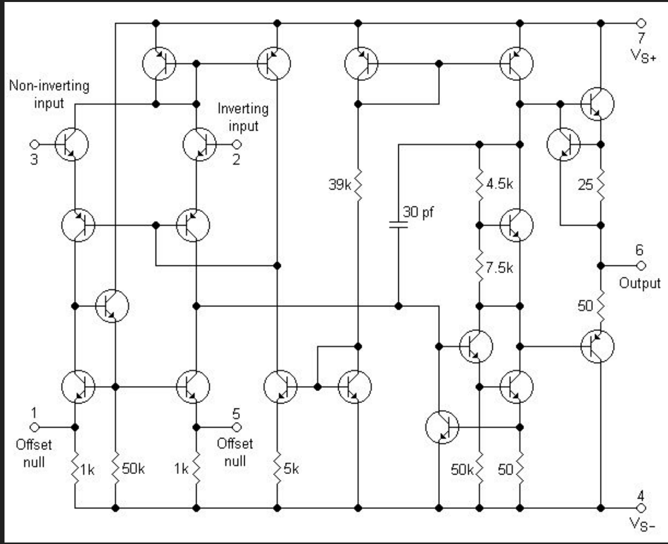
- Voltage dividers
- Impedances
- RC circuit



Are you familiar with …

- Voltage dividers
- Impedances
- RC circuit
- Op-amp





Are you familiar with …

- Voltage dividers
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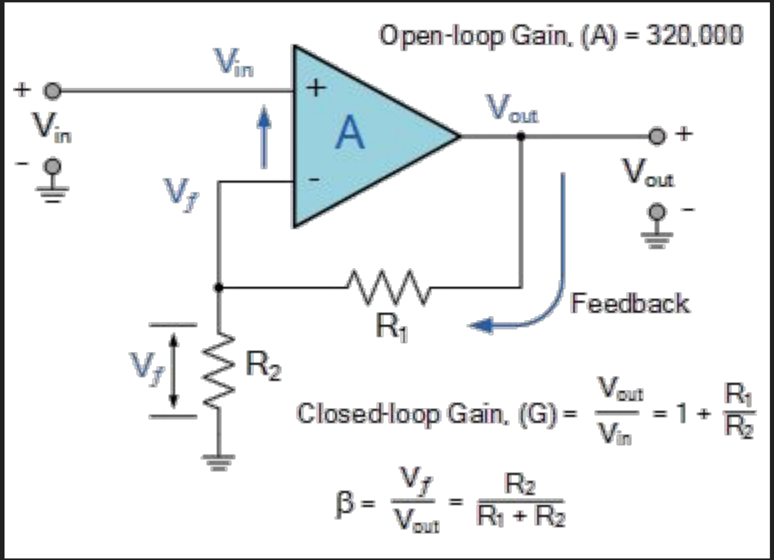
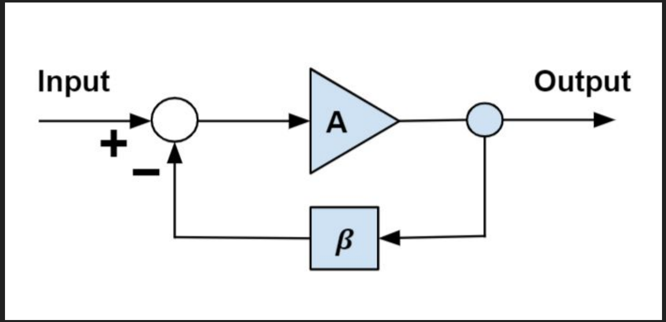
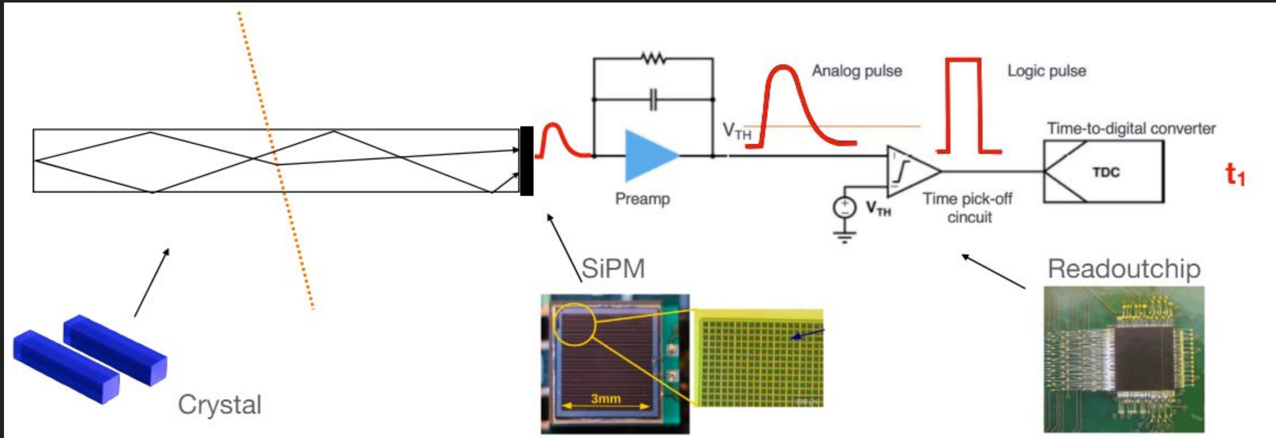
- RC circuit
- Op-amp
- Negative feedback





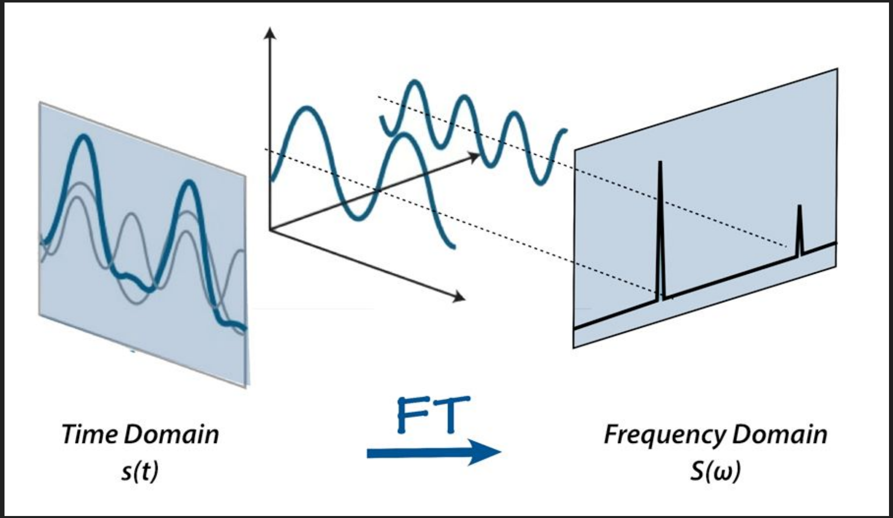
Are you familiar with …

- Voltage dividers
- Impedances
- RC circuit
- Op-amp
- Negative feedback
- Charge-sensitive pre-amplifiers
    - remember this slide from Timing for DAQ?



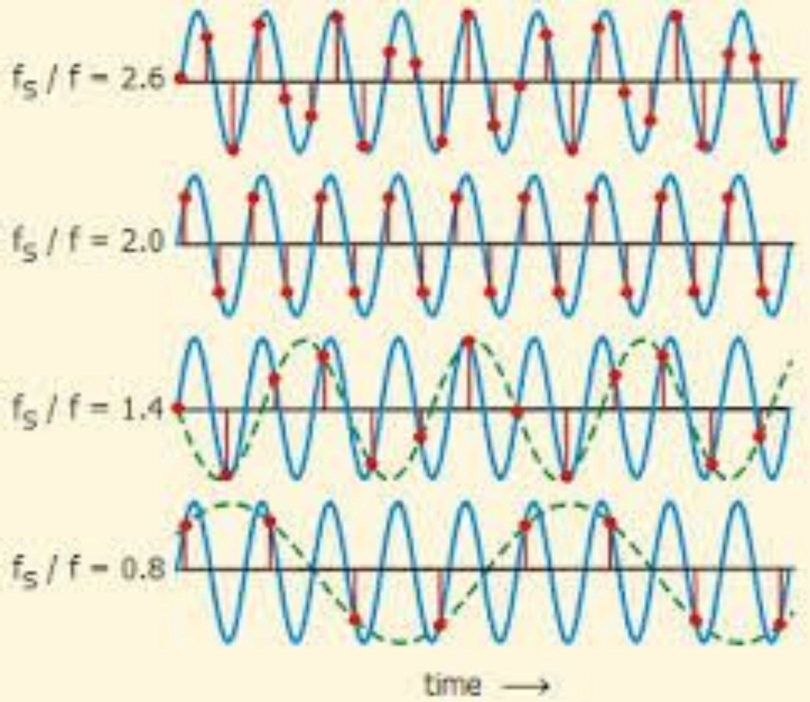
Are you familiar with …

- Voltage dividers
- Impedances
- RC circuit
- Op-amp
- Negative feedback
- Charge-sensitive pre-amplifiers
- Fourier transform



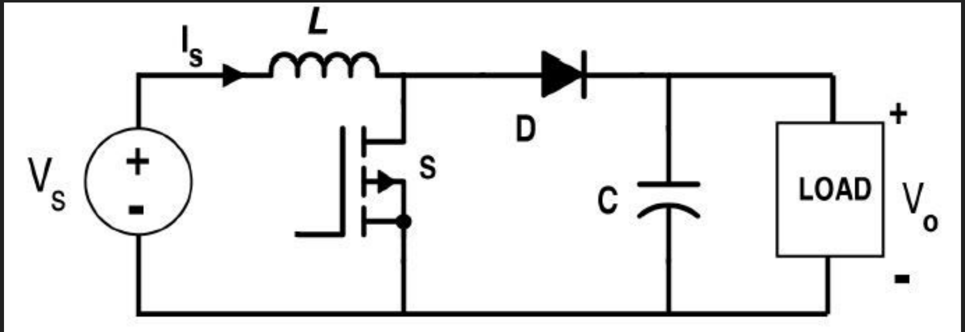
Are you familiar with …

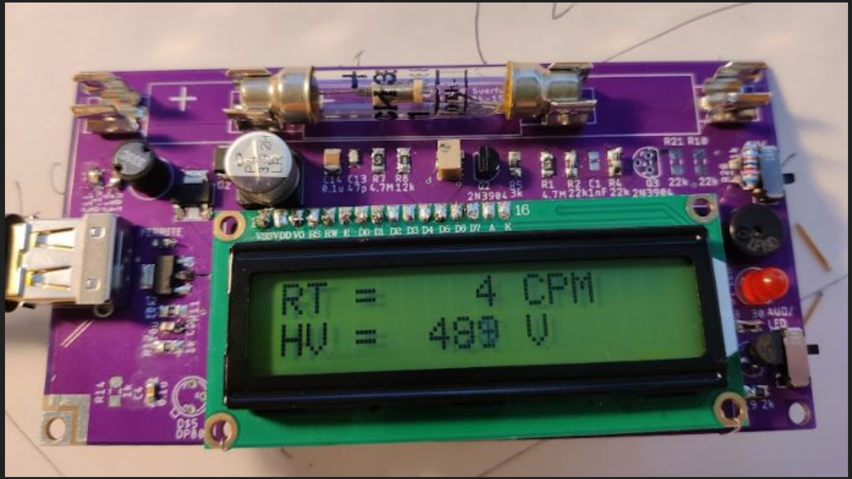
- Voltage dividers
- Impedances
- RC circuit
- Op-amp
- Negative feedback
- Charge-sensitive pre-amplifiers
- Fourier transform
- Nyquist-Shannon sampling theorem
  - You will or have already seen it in Lab 8.



Art of Electronics

An example by boost-converter





$V = L\, dI/dt$ — volt-second balance

$V_o/V_i = 1/(1-\delta)$

But where is f, L, R, C, …

Art of Electronics

Analog circuit is more than remembering the topologies of different circuits.

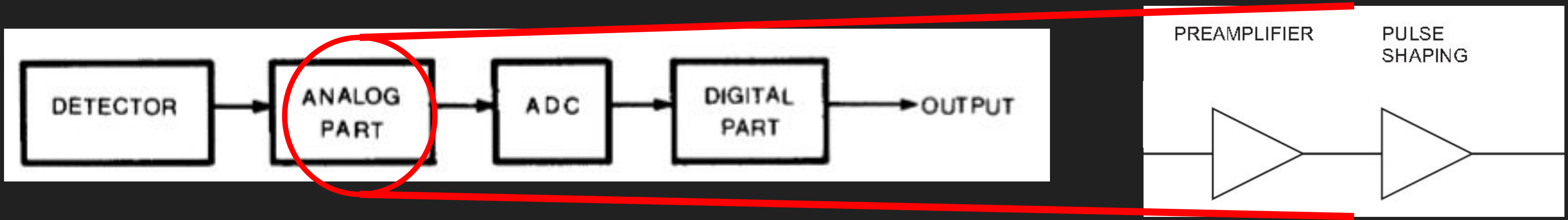
It is more about realizing the different trade-offs and balances between different elements.

"No one can gain without sacrificing something."

Front-end electronics, what is it?

Front-end electronics is a set of ***analog signal conditioning circuitry*** that interfaces to ADCs.

- Frequently consisting ***amplifiers*** and ***filters***



Many interesting properties are hidden as analog information. However, analog signal is VERY susceptible to noise and disturbances, so one needs to leave dangerous analog world as quickly as possible.

Is front-end electronics needed?

- Detector response is often seen as a current source.
- Voltage is produced when it charges up “some” capacitance.
- The size of voltage signal is simply Q/C:
  - it takes about 30 eV to ionize air => 1 MeV energy deposit will produce 30000 electrons.
  - detector capacitance is on order 10 pF => ***V ~ 0.5 mV***

Can you measure this signal easily?

Is front-end electronics needed?

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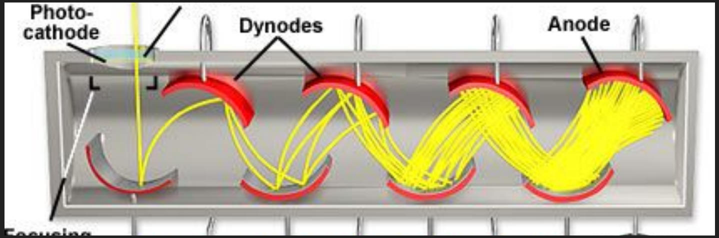
  - it takes about 30 eV to ionize air => 1 MeV energy deposit will produce 30000 electrons.
  - detector capacitance is on order 10 pF => ***V ~ 0.5 mV***
  - a 2-V, 12-bit digitizer has resolution ~ 0.5 mV

The maximum signal produced by an energy deposit as large as 1 MeV produces voltage signal as large as the smallest bit of a modern 12-bit flash ADC.

Is front-end electronics always needed?

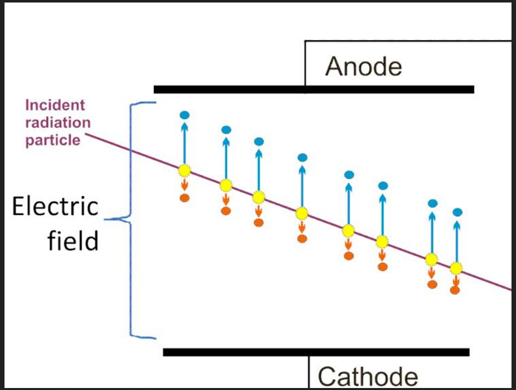
- In a scintillator, about 30 eV is needed to create a photon.
  - 1 MeV energy deposit will produce 30000 electrons.
  - secondary electron emission produces ~ 2^{12} = 1000 electrons per primary electron (12-stage dynode)
  - detector capacitance is on order 10 pF => ***V ~ 0.5 V***

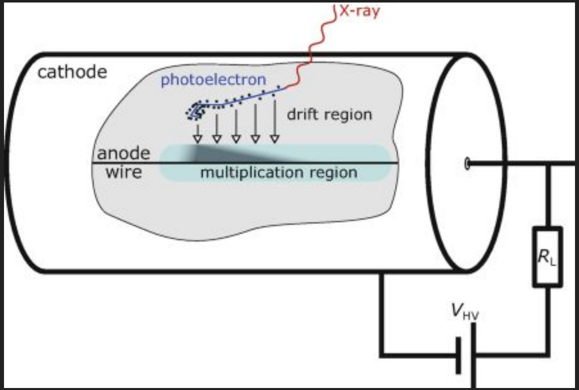
Q1: Can you measure this signal easily?

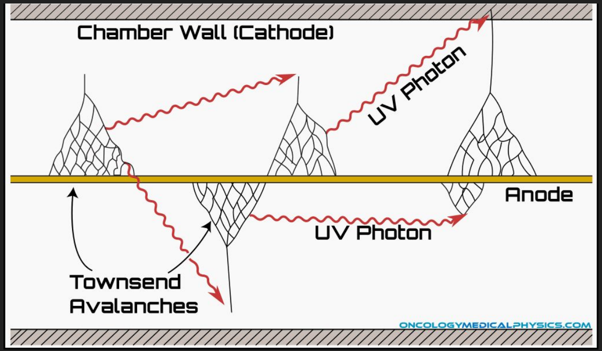


Q2: What’s the difference between the previous example?

Three flavors of detectors - electron

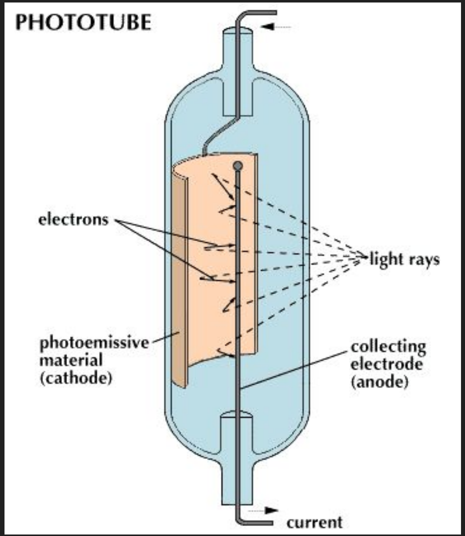


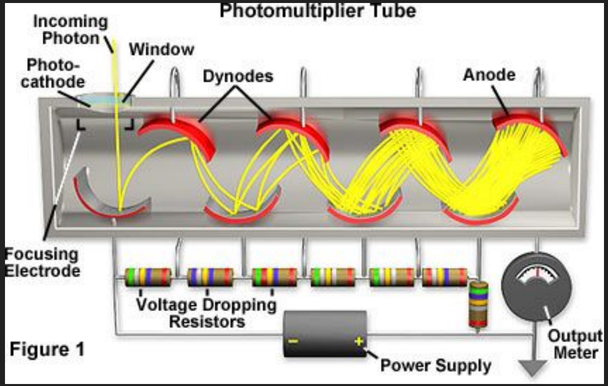


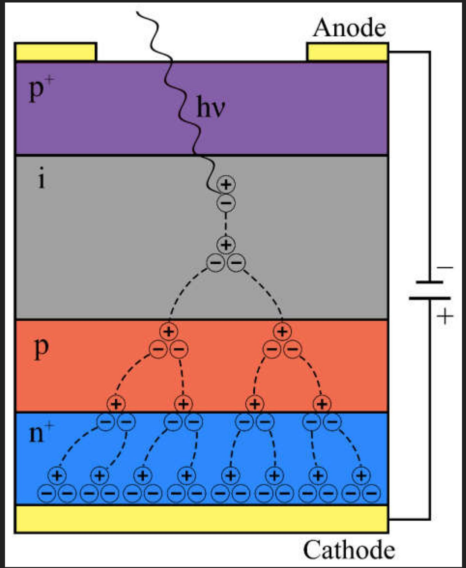


Ionization chamber	Proportional Counter	Geiger counter
No gain	Some gain	Huge gain
Very good linearity	Good linearity	No linearity at all

Three flavors of detectors - photon

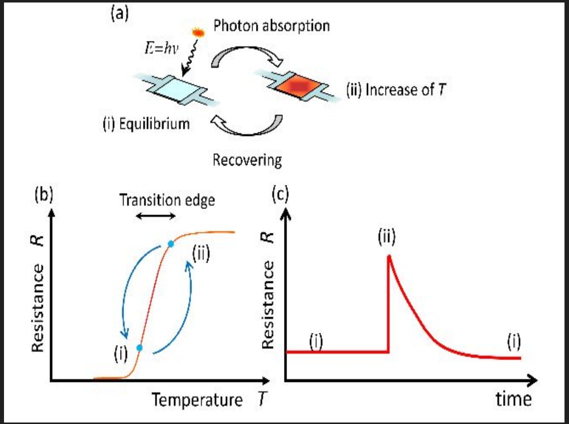


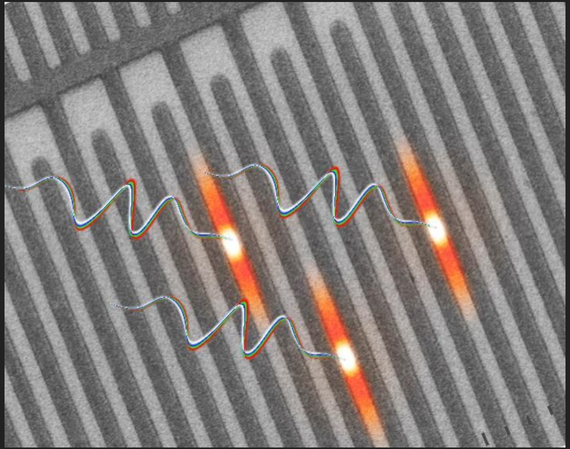




Phototube	Photomultiplier tube	SPAD
No gain	Some gain	Huge gain
Very good linearity	Good linearity	No linearity at all

Three flavors of detectors - phonon





Transition Edge Sensor

No gain

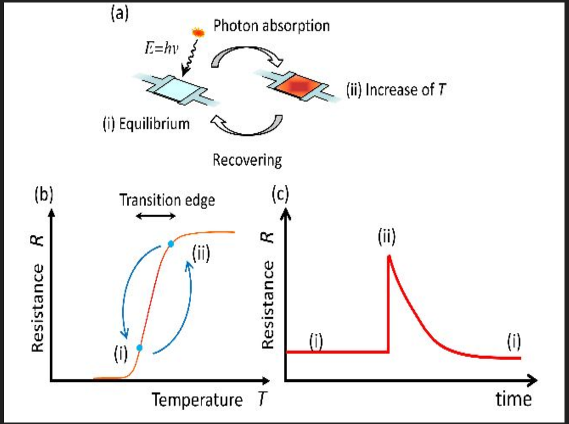
Very good linearity

SNSPD

Huge gain

No linearity at all

Three flavors of detectors - phonon



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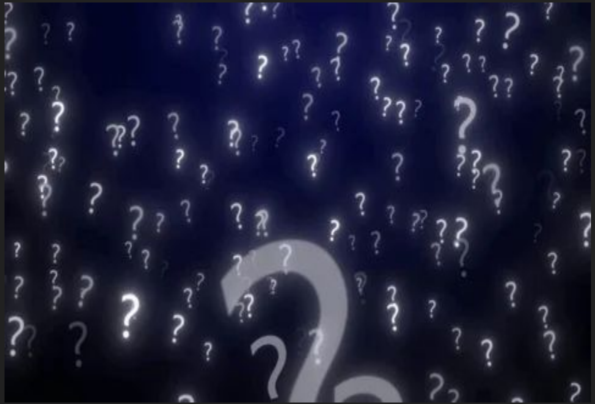
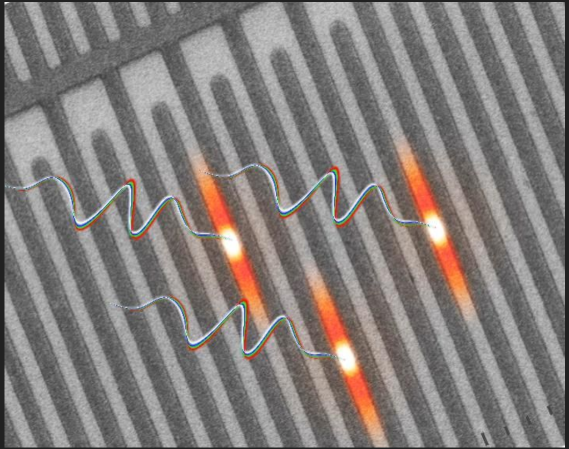


If you have any good idea, let's ***INVENT THE FUTURE TOGETHER!***



SNSPD

Huge gain

No linearity at all

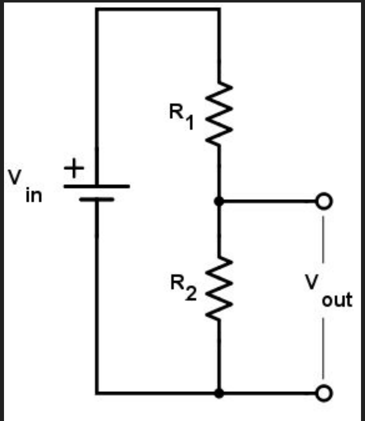
To amplify or not to amplify?

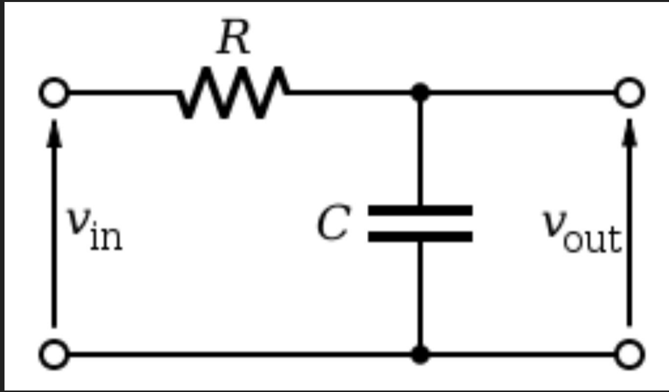
Some detectors come with “***intrinsic gain mechanism***”, and ***usually*** require none or little external gain, but this is not always true.

- SiPM works in the Geiger mode, but often a preamplifier is used to amplify/improve timing characteristics
- Sometimes PMTs require lower working voltages due to
    - heat load
    - breakdown
    - dark rate
    - suppress dynode afterglow

Basics of Analog Electronics

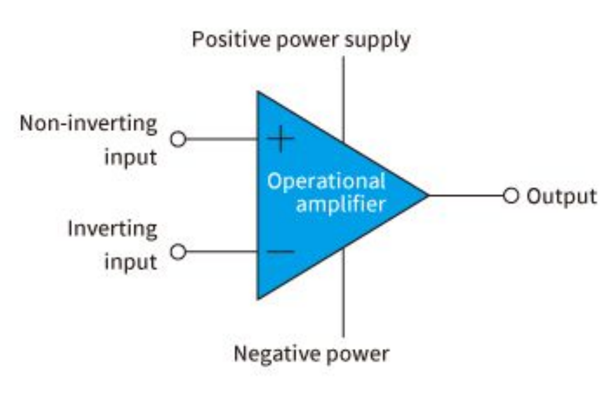
- Two resistors in series: voltage divider
- For a capacitor: $Z = 1/i\omega C$
  - a capacitor looks like infinite resistance at DC
  - a capacitor looks like short circuit at HF
- When you see a capacitor near a resistor, there is likely a time constant RC
- ***You cannot avoid tax and capacitance.***





Basics of Analog Electronics

- Operational amplifier (op-amp) is a device that
  - amplifies $V_+ - V_-$ by a large factor called open-loop gain
  - input terminal can be viewed as a very large resistor (little current flows into)



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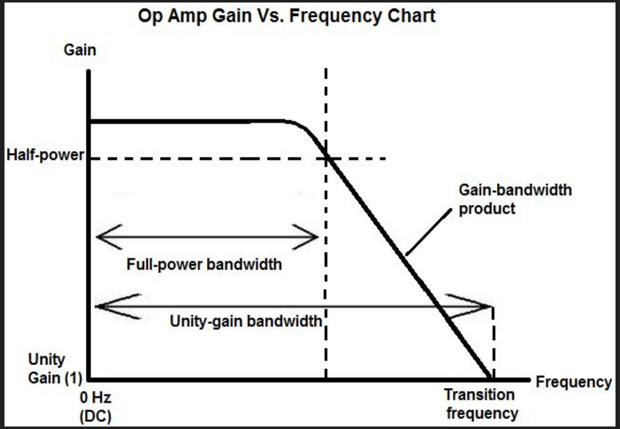
  - gain drops as frequency goes up
  - gain x bandwidth is often a constant (GBW)
    - trades gain for speed



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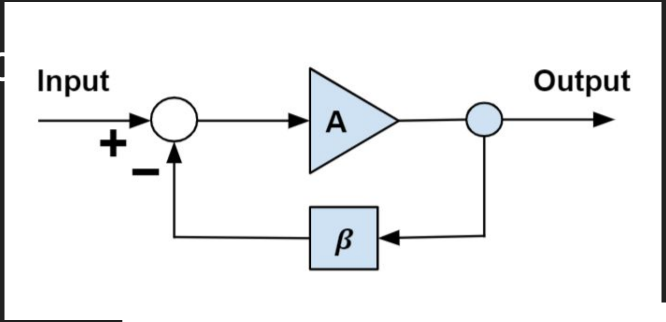
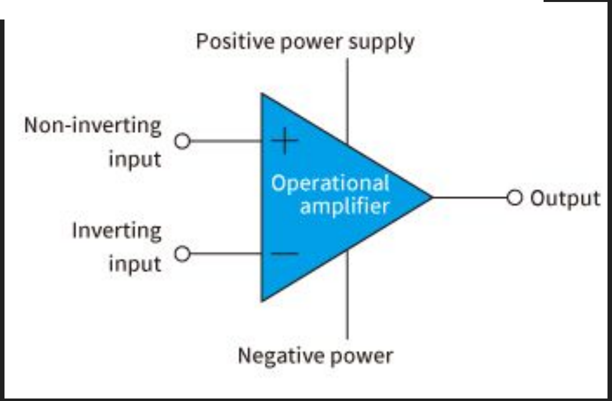
  - input terminal can be viewed as a very large resistor (little current flows into)
  - gain drops as frequency goes up
  - gain x bandwidth is often a constant (GBW)
    - trades gain for speed
- Almost always used with feedback loop

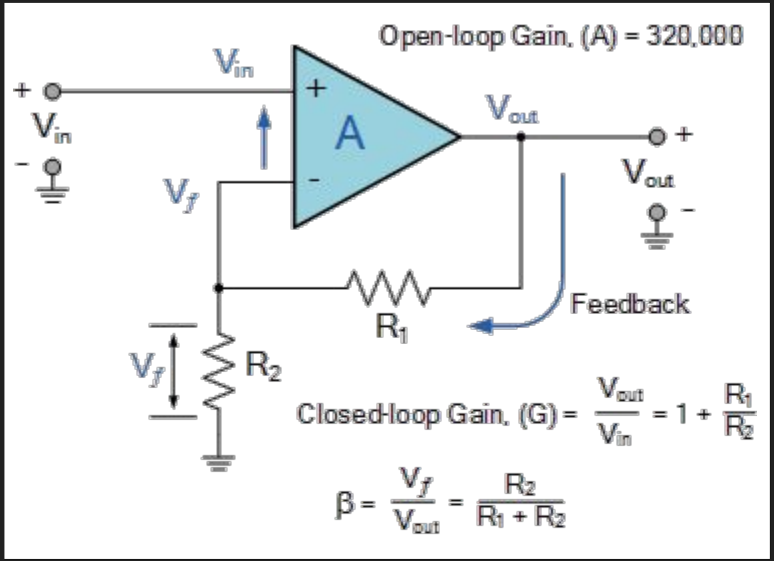


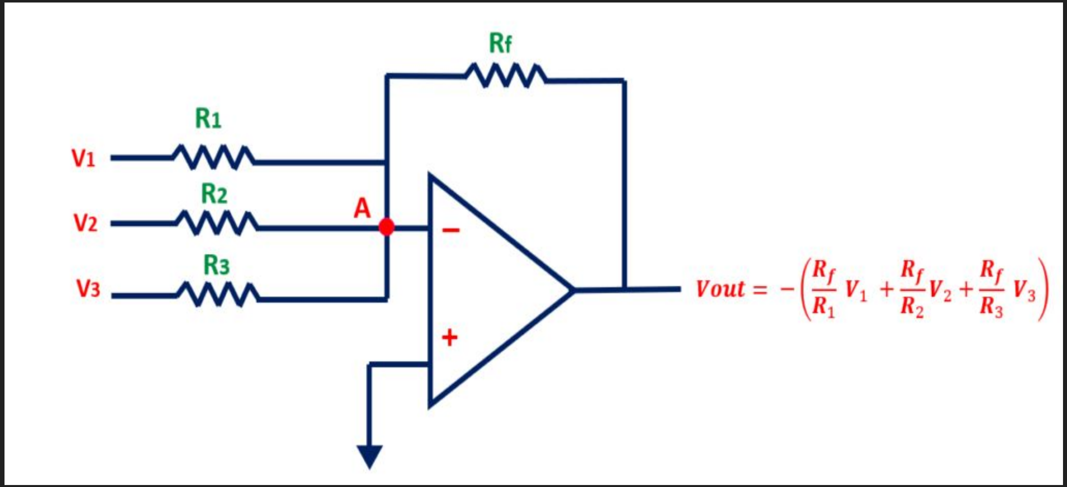


Oversimplified Rules of Op-amp

Op-amp will do whatever it can at the output terminal to

- make voltage at + and - terminals ***equal***
- ***no current*** flows into + and - terminals

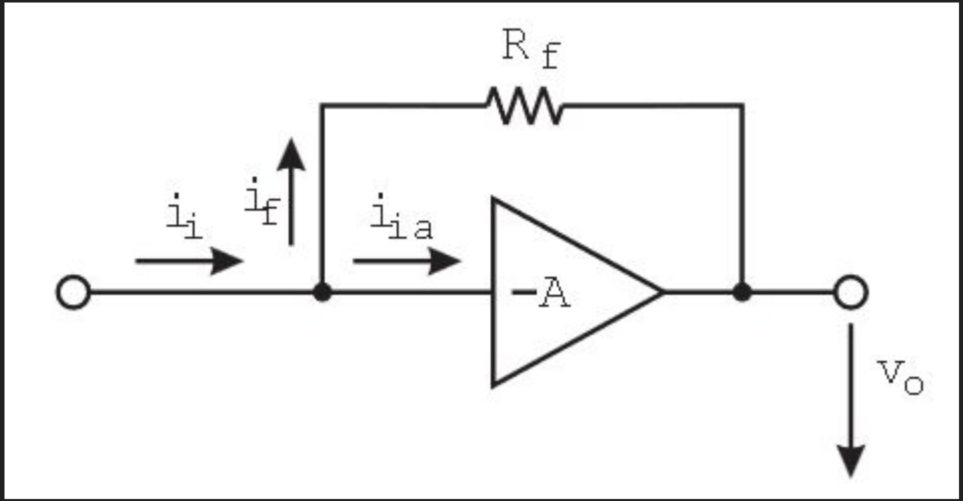




Current Shunt Feedback

What impedance will the input see？

Is it larger than or smaller than Rf?



Current Shunt Feedback

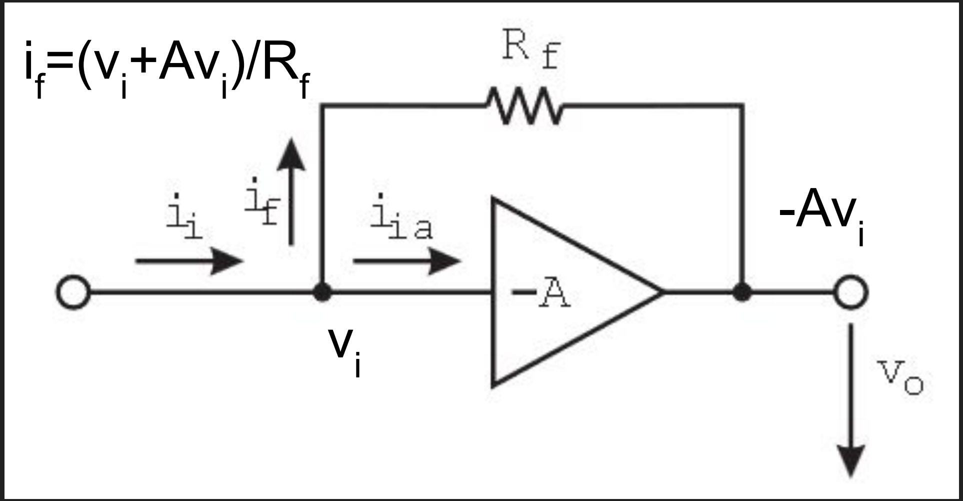
What impedance will the input see？

Is it larger than or smaller than Rf?

A: input will see ***Zin = Zf/(1+A)***

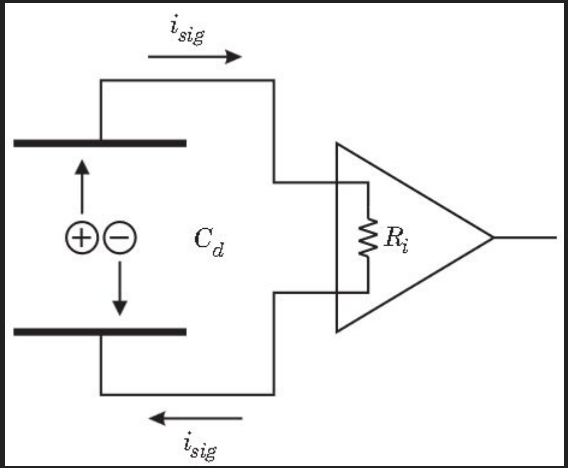
If Z = R, it looks like small R.

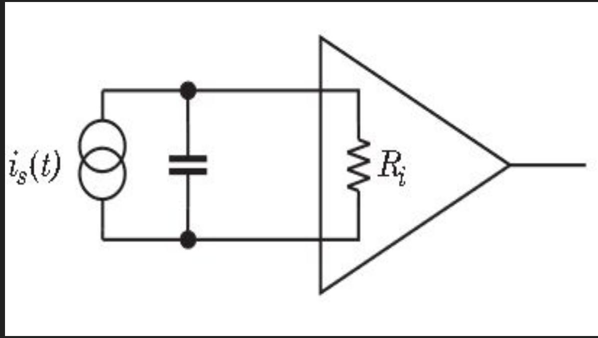
If Z = 1/iωC, it looks like a **large C**.



A Realistic Model of Detector

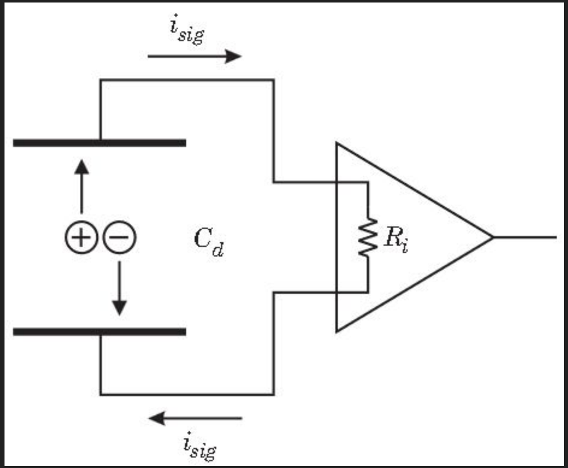
- Detector response is a current source
  - integral => total energy
- Detector always have some capacitance
  - pn junction, cables, between pins
- The current/charge needs to go somewhere
  - capacitor
  - resistor

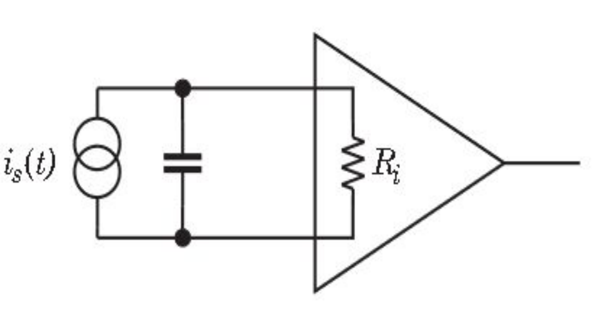




A Realistic Model of Detector

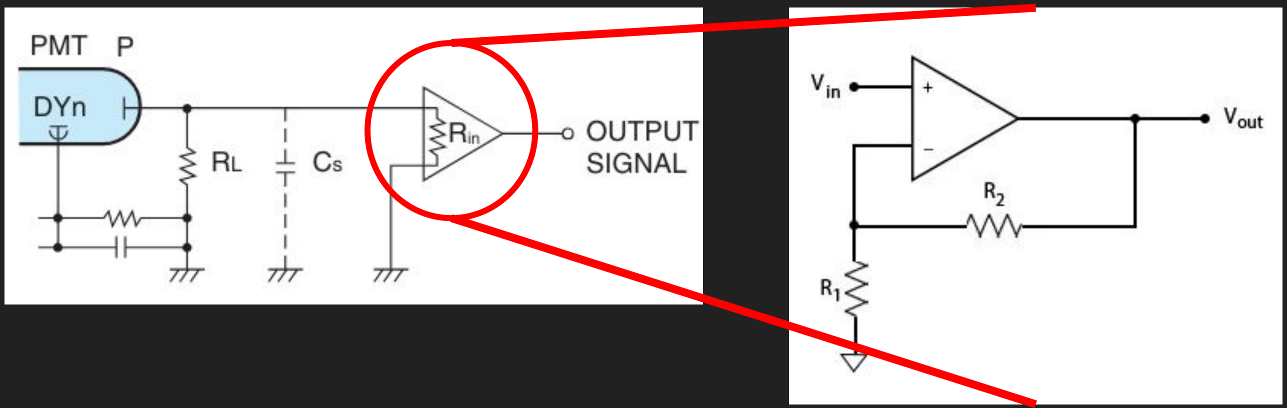
- Time constant τ = Ri x Cd
  - if τ is large, charge will accumulate on the capacitor and then discharges slowly through the resistor
    - Vo = Q/Cd
  - if τ is small, instantaneously discharges through the resistor
    - Vo = i(t) x Ri





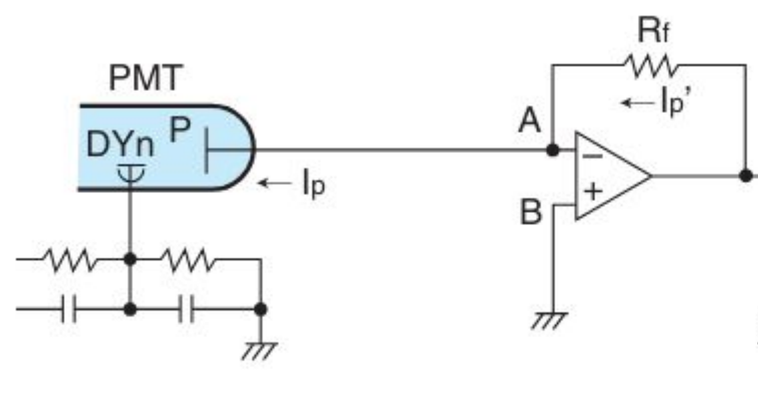
Types of op-amps often used in preamplifiers

- ***Voltage Amplifier:***
  - current flows through a load resistor, which gets amplified
- Pro: simple, robust, easy to implement
- Con: signal limited by R_{Load}



Types of op-amps often used in preamplifiers

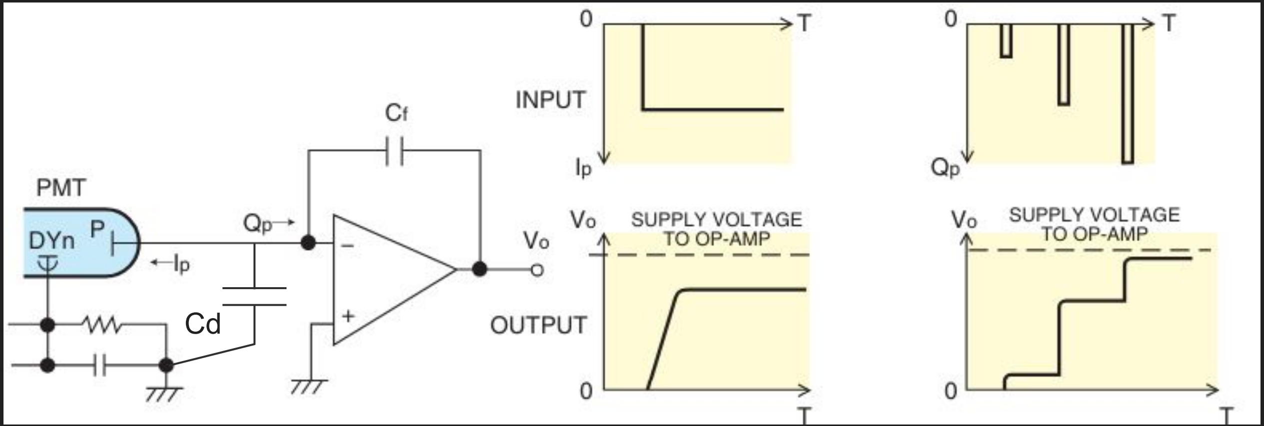
- ***Trans-Impedance Amplifier:***
    - current flows into virtual ground, which flows through Rf
- Pro: fast (do you see why?), can be implemented w/ COTS, controllable signal w/ Rf
- Con: oscillation, bandwidth and time constant limited by Rf



$$BW_{TIA} = \sqrt{\frac{GBW}{2\pi R_F C_D}}$$

Types of op-amps often used in preamplifiers

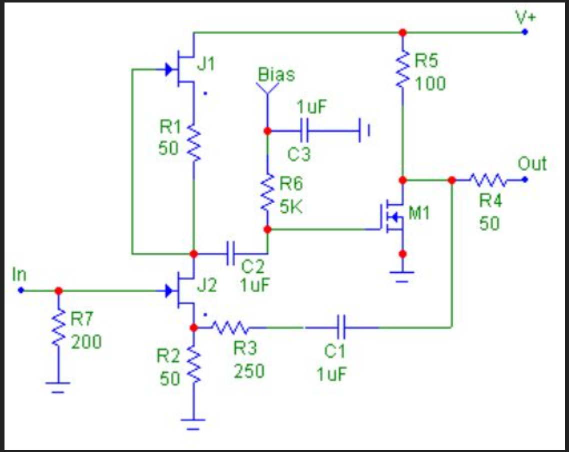
- ***Charge-Sensitive Amplifier:***
  - current gets integrated onto feedback capacitor (remember 1/(1+A)?)
  - do you want a small Cf or a large Cf?
- Pro: output is independent of detector capacitance
- Con: needs a reset circuit to discharge the capacitor

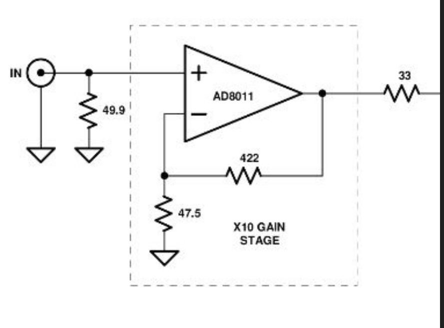


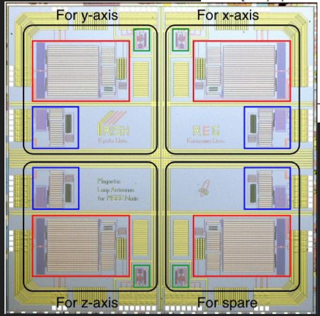
GBW = Cd/Cf x ω

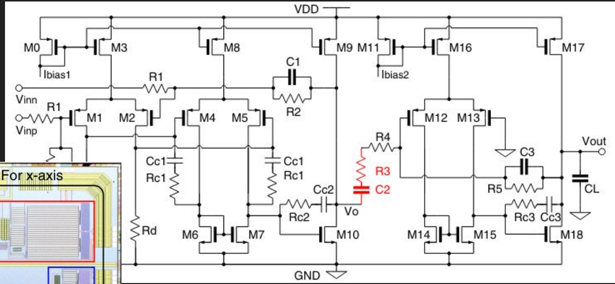
Types of op-amps often used in preamplifiers

- Preamplifiers are not necessarily implemented with op-amps.
  - It may come in discrete components
  - Cascode / common-base amplifiers still very often
- Or it may come in ASICs in demanding/large scale applications.

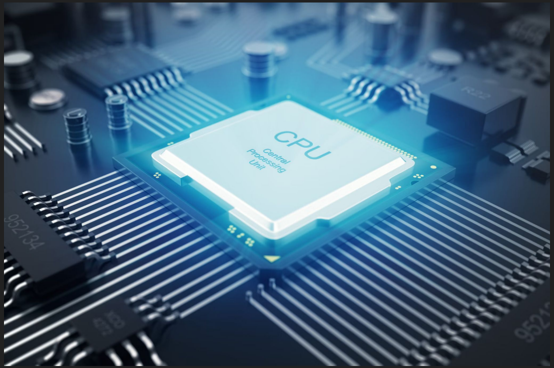


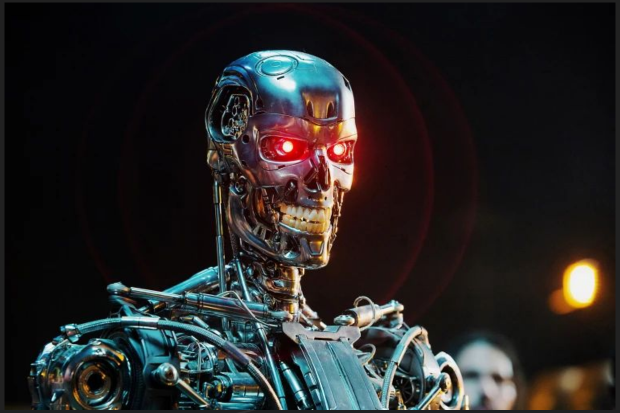






CPU v.s. FPGA v.s. ASIC





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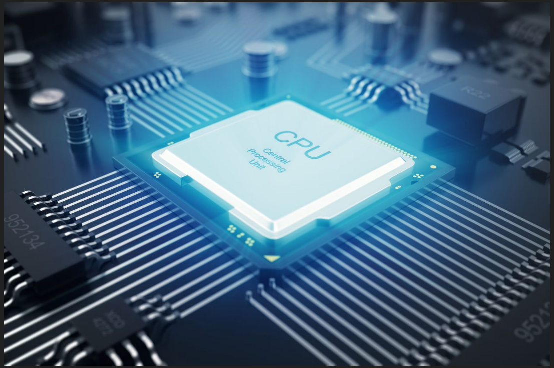

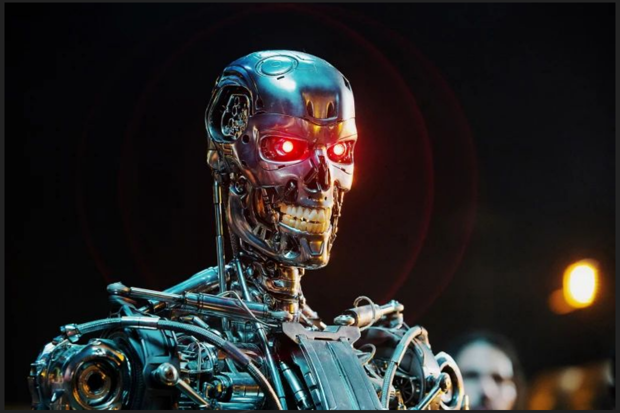

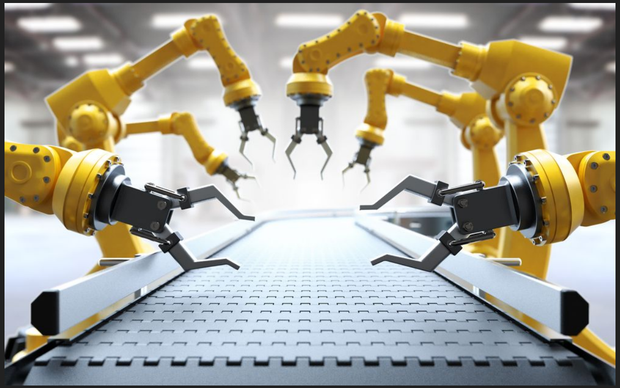

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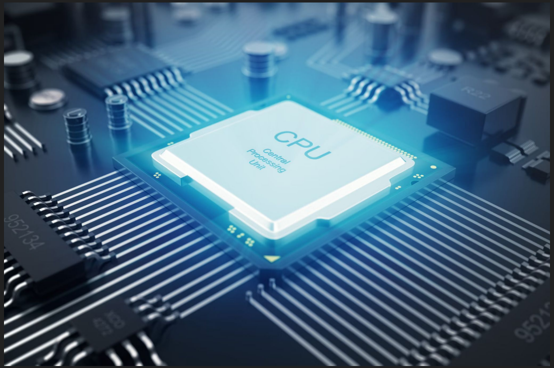

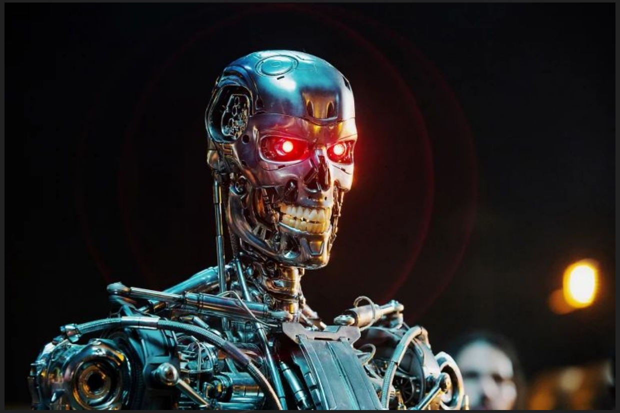

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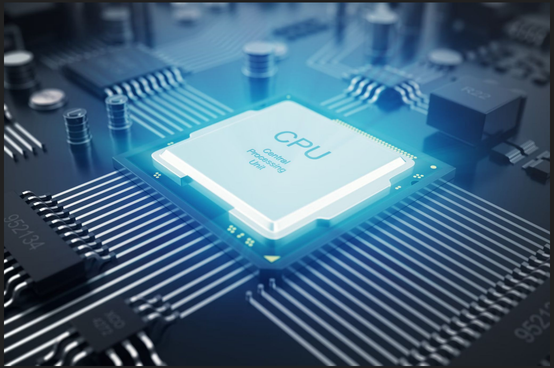
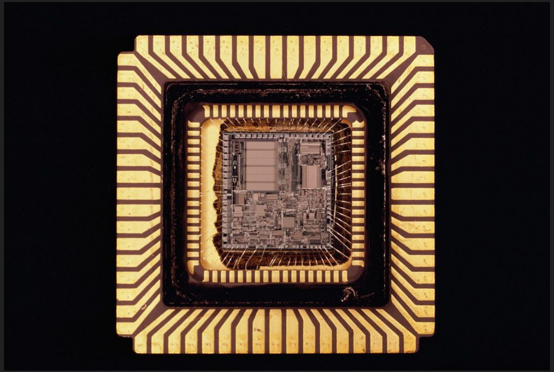
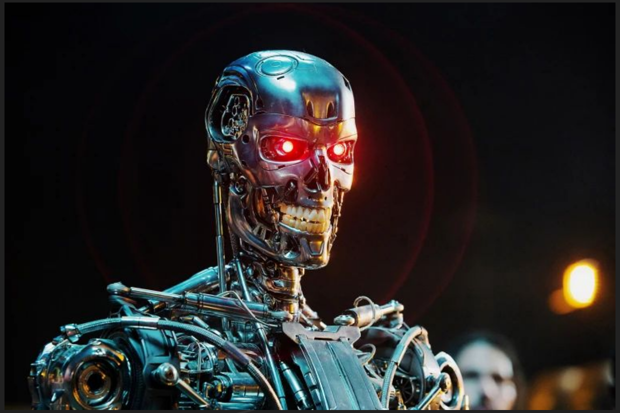
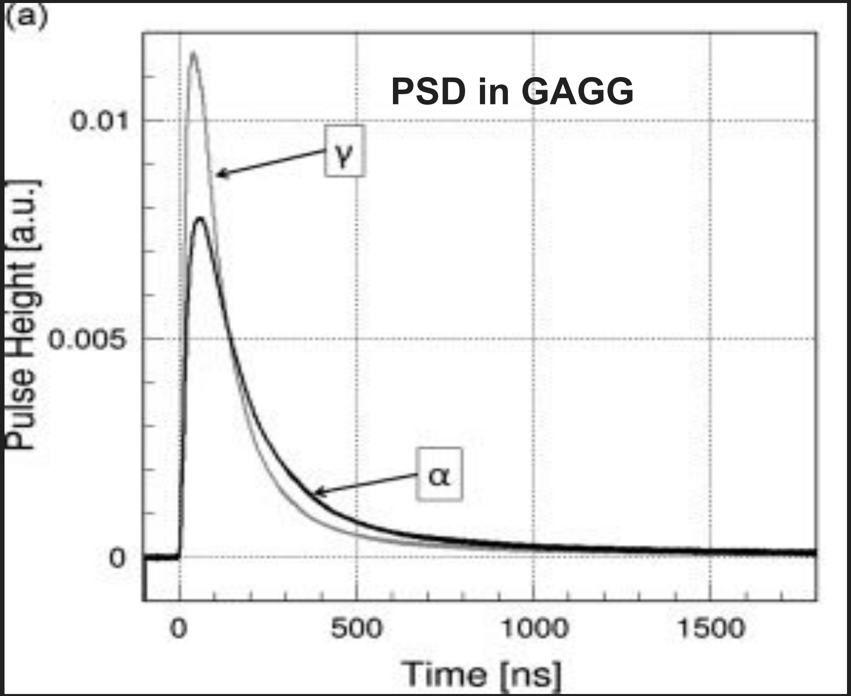


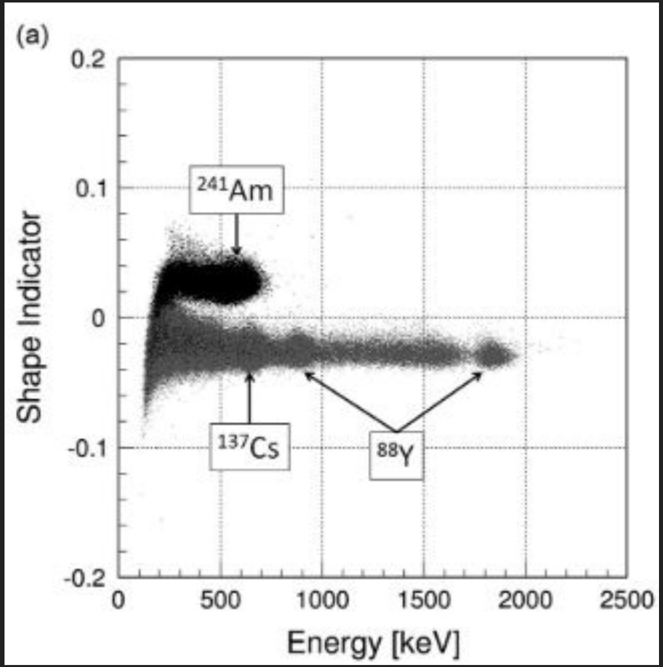




Shape or not to Shape - What is your data?

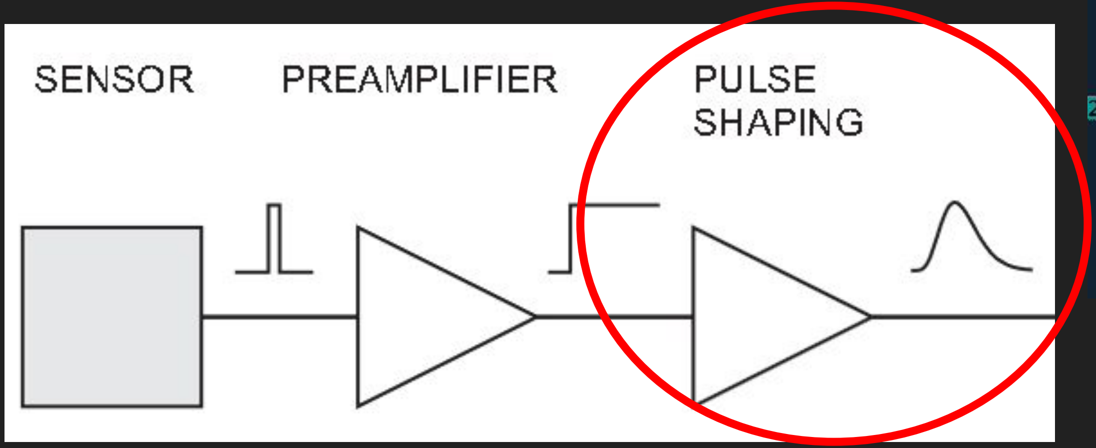
- Sometimes ***waveform digitization is preferred*** because it keeps the maximum possible information => VSA/TIA





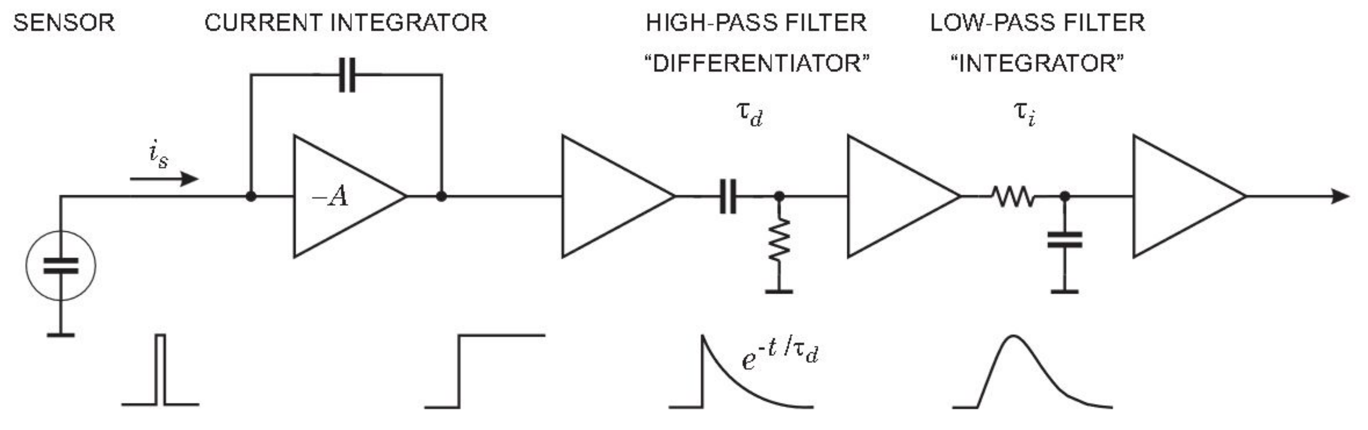
Shape or not to Shape - What is your data?

- In other cases, you simply want a single number representing energy/time/position etc.
  - signal needs to be integrated (CSP/CSA)
  - the output waveform is not the most friendly to work with



What is Pulse Shaping?

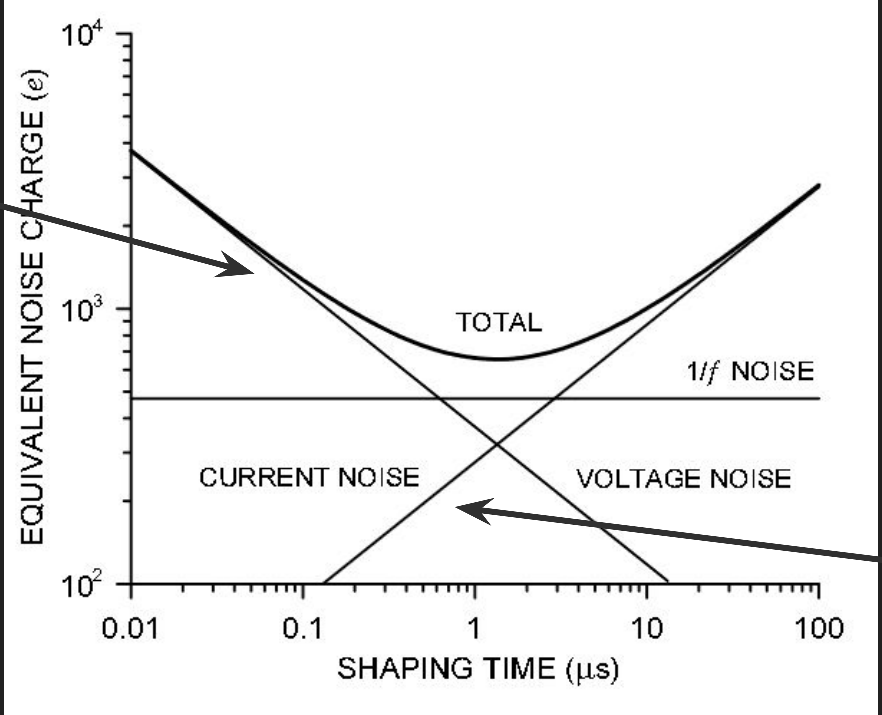
- Intuitively, you want the pulse to return to baseline asap.
- Fundamentally, signal and noise are both represented by some "spectrum" in the Fourier space
- To improve SNR, frequencies outside ROI should be filtered.

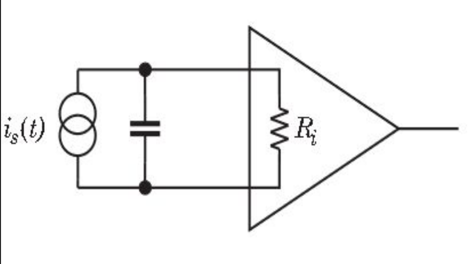


CR-RC shaper

What is Pulse Shaping?

series resistance thermal noise

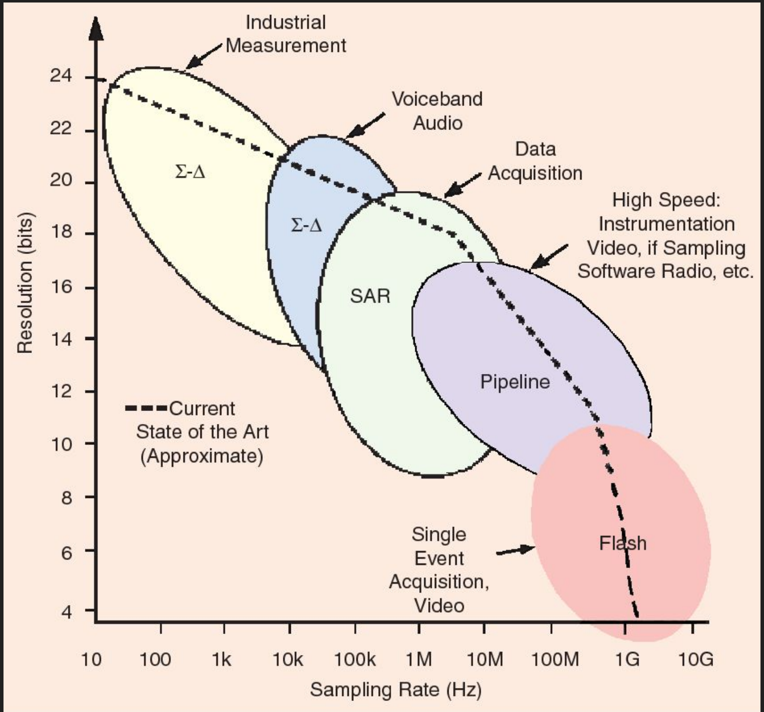




bias current charging input capacitor

ADC: last stop before safe zone

- Hybrid circuitry that encodes the analog value into a digital value
- Important parameters:
  - sampling frequency
  - resolution/bit-depth



- ***There also exists a trade-off***

Can I substitute MCU for ADC?

- ATMEGA328P: ~ $2.8
  - 6-channel, 12-bit, 15 ksps

Can I substitute MCU for ADC?

- ATMEGA328P: ~ $2.8
  - 6-channel, 12-bit, 15 ksps
- Searching for ADCs with similar specs on Digikey…

LTC2309CUF#TRPBF IC ADC 12BIT SAR 24QFN *Analog Devices Inc.*	3,604 In Stock	1 : **$9.28000** Cut Tape (CT) 2,500 : **$5.06818** Tape & Reel (TR)
LTC2309IUF#PBF IC ADC 12BIT SAR 24QFN *Analog Devices Inc.*	8,645 In Stock	1 : **$11.11000** Tube
LTC2309HF#PBF IC ADC 12BIT SAR 20TSSOP *Analog Devices Inc.*	899 In Stock	1 : **$11.73000** Tube

LTC2309CF#PBF IC ADC 12BIT SAR 20TSSOP *Analog Devices Inc.*	1,687 In Stock	1 : **$6.52000** Tube
LTC2309IF#PBF IC ADC 12BIT SAR 20TSSOP *Analog Devices Inc.*	3,682 In Stock	1 : **$11.11000** Tube
LTC2309IUF#TRPBF IC ADC 12BIT SAR 24QFN *Analog Devices Inc.*	1,728 In Stock	1 : **$11.11000** Cut Tape (CT) 2,500 : **$6.06606** Tape & Reel (TR)

ADC: last stop before safe zone

- Hybrid circuitry that encodes the analog value into a digital value
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  - ENOB
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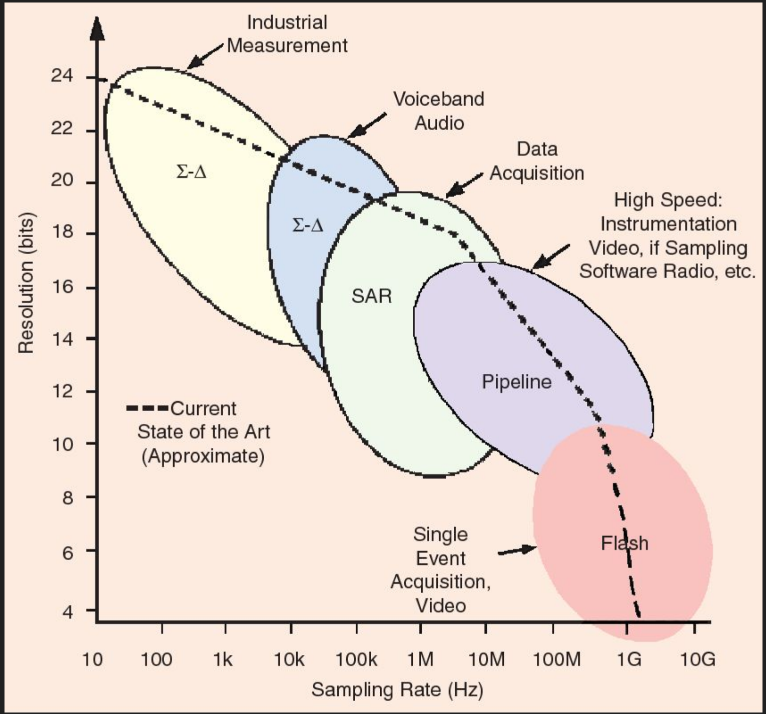

ADC: last stop before safe zone

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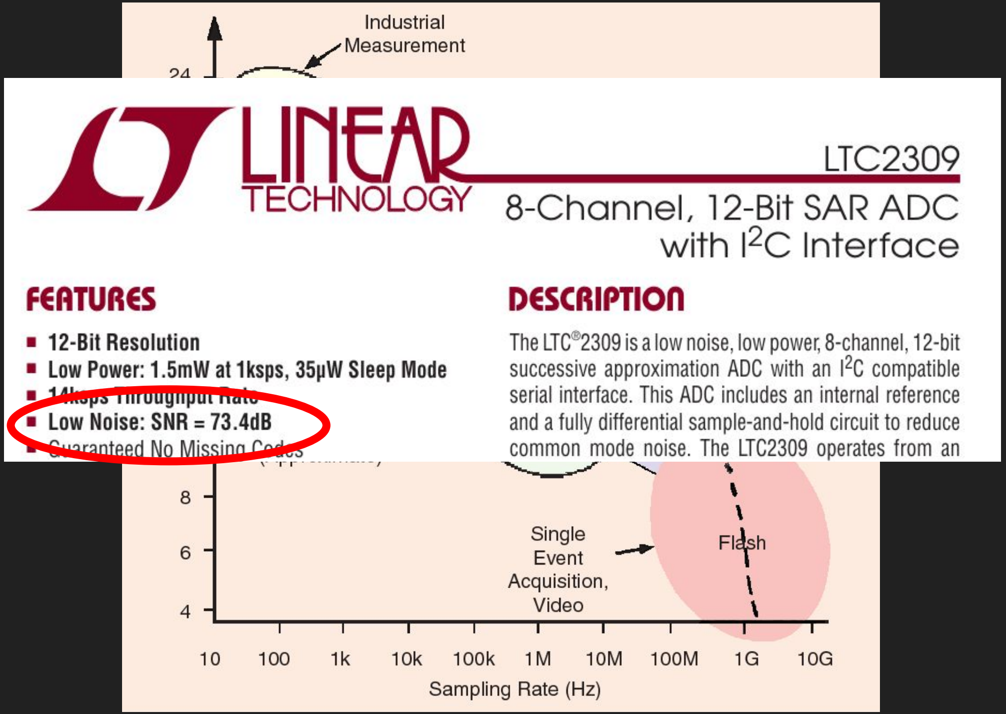
6.02 x 12 + 1.76 = 74 !



ADC: last stop before safe zone

Microcontroller will give you a result whenever asked.

It is great for turning lights on and off.

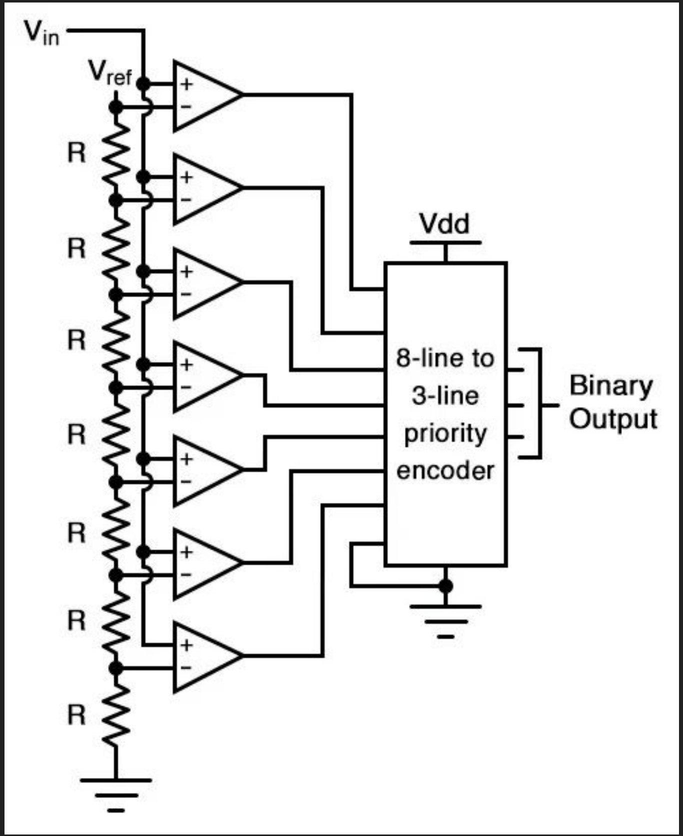
But don’t use it to claim new physics.

Some Common Types of ADC

- Flash ADC:
  - fastest
  - difficult to scale/increase resolution
  - power-hungry

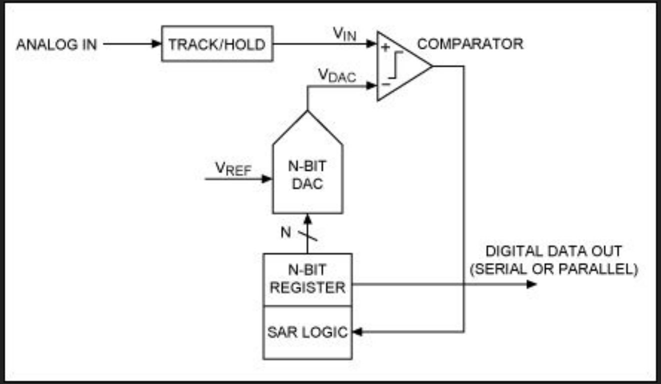
- Mostly ~100s MHz to a few GHz

- Warning: new ADC architectures are emerging!
  - Radio industry has rolled out 12-bit, 10-GHz folding ADC (ADC12DJ5200RF).



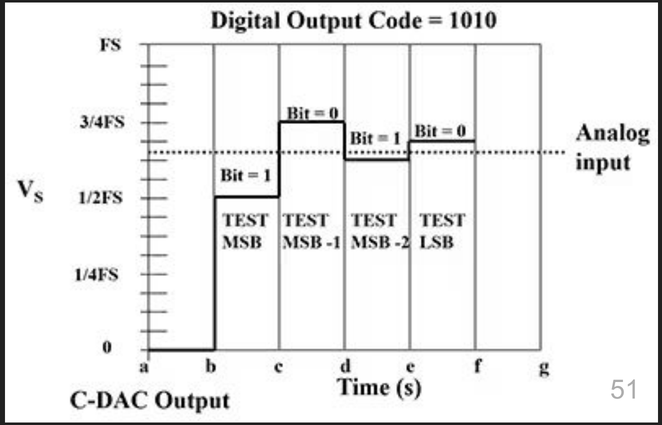
Some Common Types of ADC

- SAR ADC (Suc. Approx. Register):
  - medium speed
  - medium resolution
  - power-efficient, small-form factor



- ADCs in microcontrollers are mostly this type.

- Warning: an ADC not comparable to that of a MCU will cost 10+ times more.



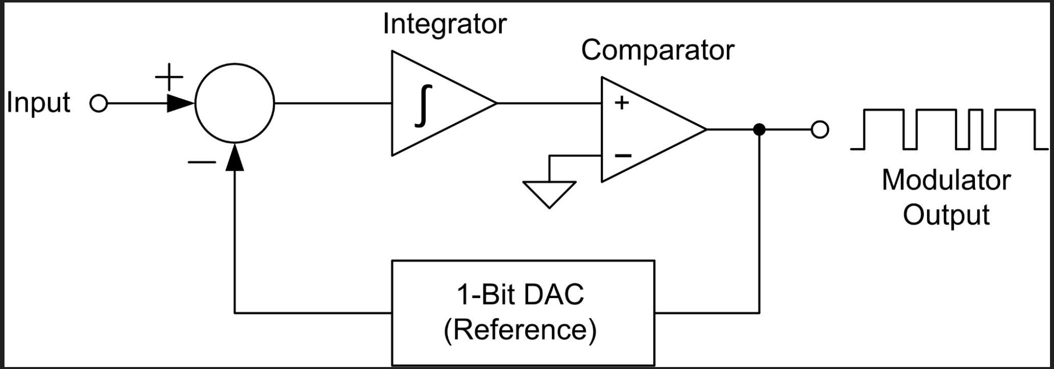
Some Common Types of ADC

- Sigma-Delta:
  - slowest
  - best resolution
  - complex

    not power-efficient

- It is mostly used where precise information about a slowly-varying signal is needed

How does Sigma-Delta achieve this?



Some Common Types of ADC

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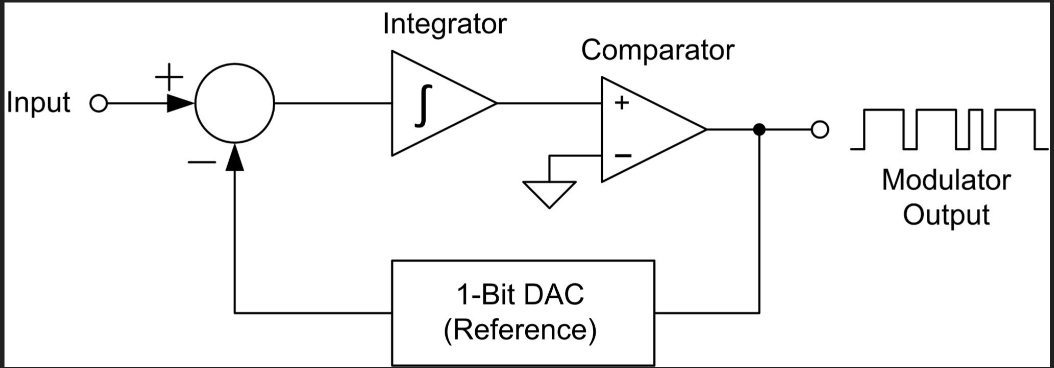
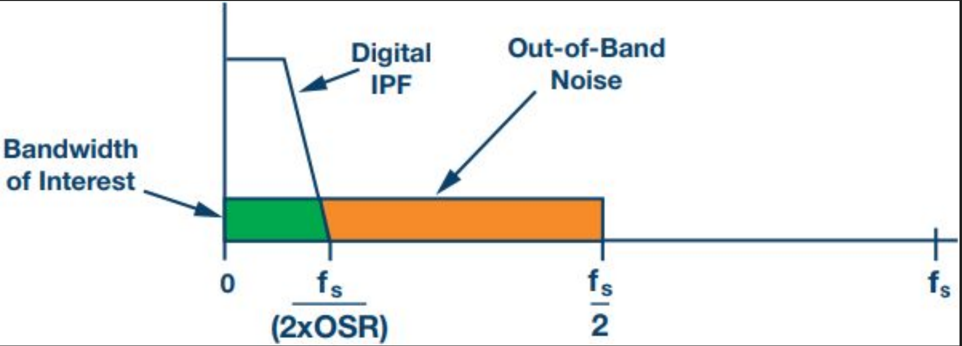
By oversampling!





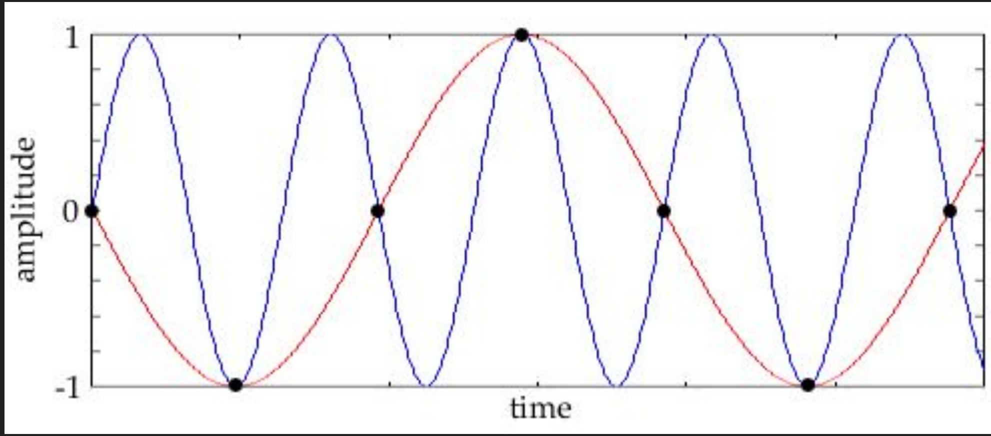
Sampling and Aliasing

"A sine wave can be perfectly reconstructed if it is sampled at at least twice its frequency."

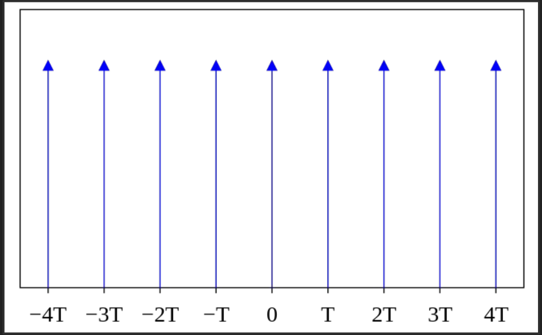
Aliasing refers to a high-frequency signal appearing to be a lower frequency when undersampled.

Q1: does this always happen?

Q2: why does this happen?



What is Digitization?

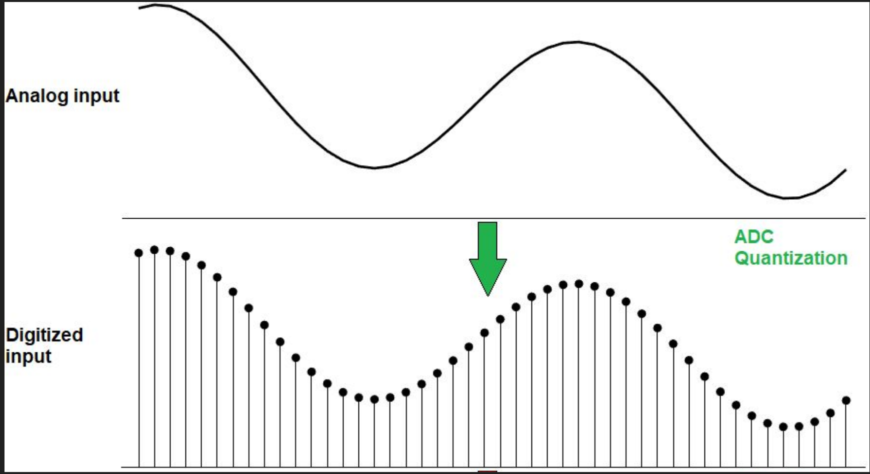


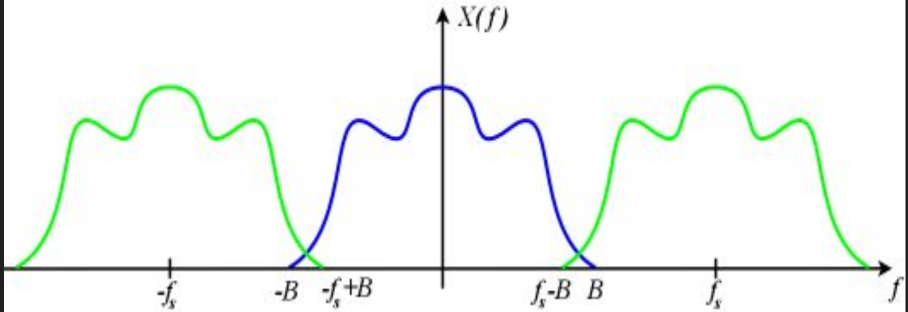
Digitization = f(t) x delta comb

FT of delta-comb is another delta-comb.

In freq. domain, convoluting with another delta-comb

Filter before digitize!





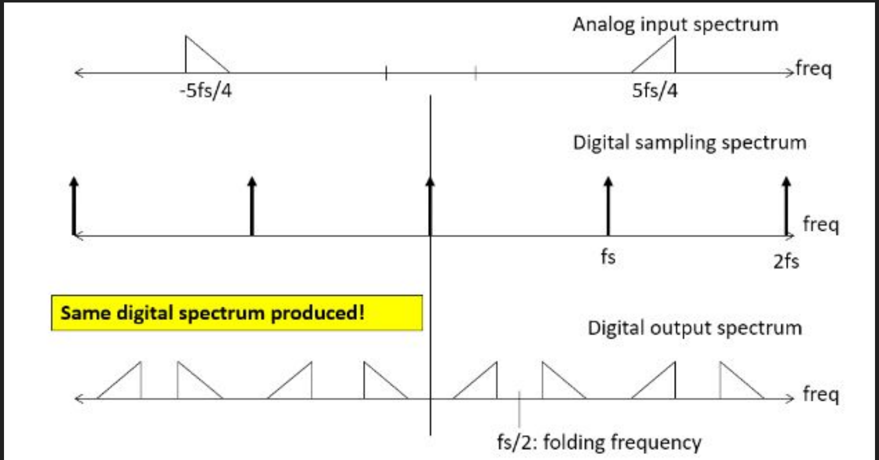
Is Aliasing Bad?

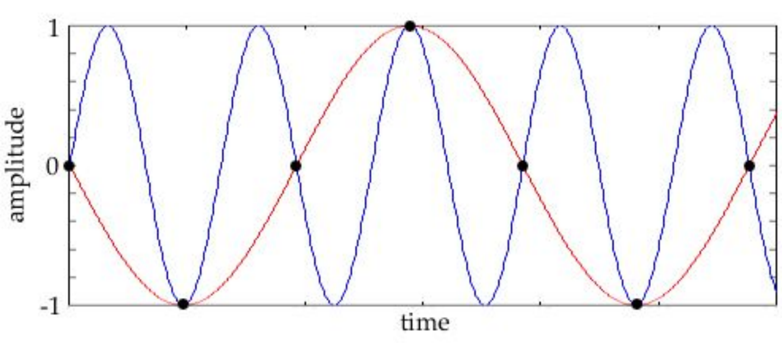
Aliasing can help sample a higher frequency signal using an ADC with less sampling rate.

How is this achieved? => a technique called “undersampling”.

The only requirement is Nyquist frequency larger than the ***bandwidth*** of the signal.

The signal needs ***bandpass-filter***.





Summary

- Analog/front-end electronics is often a balance between gain and bandwidth.
- Three commonly used topologies for preamplifiers, each with different characteristics.
- Sometimes waveform digitization is performed, sometimes the signal is integrated and then filtered for best SNR.
- Use a dedicated ADC!
- In sampling, it is bandwidth that really matters, not the absolute sampling rate and signal frequency.