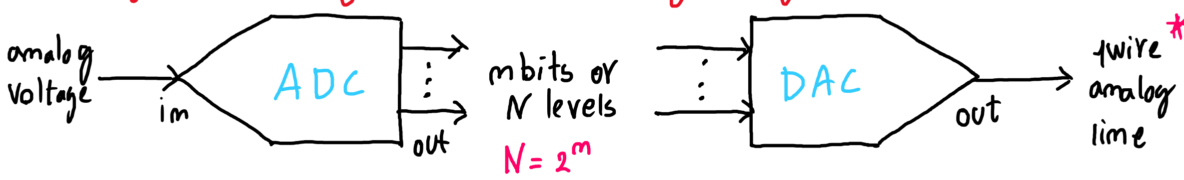
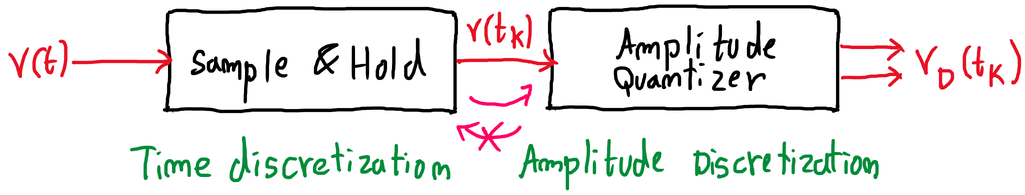
Data Aquisition Systems

* Digital to Analog (DA) and Analog to Digita (AD) Converters



*→ Note that V_{out} is quantized!

• ADC (or Voltemeter): Receives analog voltage and digitizes it.



Note: The order is not interchangeable!

Resolution: $\Delta V = \frac{D}{N} = \frac{D}{2^m}$

$\Delta V \Rightarrow$ Resolution / Minimum Voltage step

$D \Rightarrow$ Dynamic range of the input

$N \Rightarrow$ Number of levels/steps

$m \Rightarrow$ Number of bits

Max error: $\frac{\Delta V}{2}$

Quantization noise/uncertainty: $u_q = \sigma_q = \frac{\Delta V}{\sqrt{12}}$

Variance: $\sigma_q^2 = \frac{\Delta V^2}{12}$

Possible sources of errors in Converters:

Quantization → Max error: $\frac{\Delta V}{2}$

Offset: Affects where the ADC starts measuring. Easy to solve

Gain: Leads to different input steps size.

Differential Non-Linearity: Measures by how much a input step is deformed

$$DNL(s) = \frac{W(s) - W_i}{W_i}$$

W_i: ideal step size
$W(s)$: real step size
s: step number

Integral Non-Linerity: Total error due to deformed steps:

$$INL = \sum_{s=1}^{m-1} DNL(s)$$

m: number of bits

Sampling theorem: Information is not lost if a signal is sampled at a frequency that's twice the bandwith of the signal.

$f_s \geq 2 f_{Max}$ ⇐ in baseband! In pass band $f_s \geq 2\,Bw$

f_s: Sampling frequency

f_{Max}: Maximum frequency component of the signal

Bw: Bandwith of the signal

However in reality due to the finite duration of sampling (it's not instantaneous), which causes distortion, a much higher sampling rate is used

$f_s > 10 f_{Max}$!

If $f_s < 2f_{Max}$ theres aliasing, ie. the overlap of spetral replicas of the signal
↳ To avoid this one can use an anti-aliasing filter!

Clock jitter can cause errors in sampling!

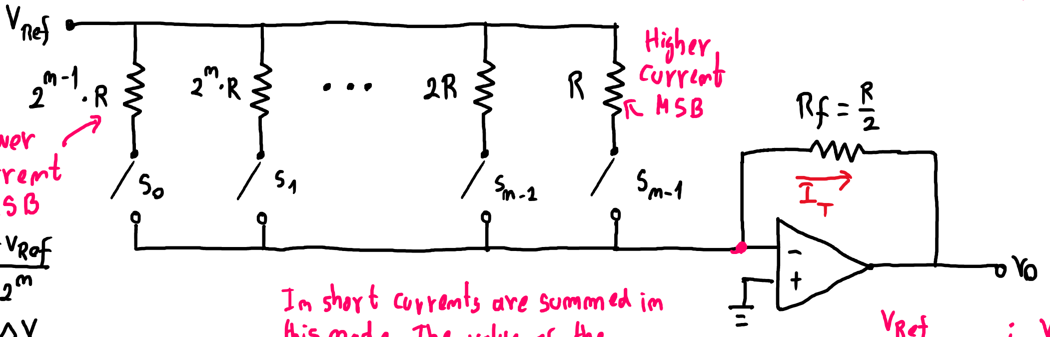
$$\Delta t < \frac{1}{2^m \pi f_{Max}}$$ Minimum jitter condition

Lesson #2

- DAC Topologies

Weighted R

Switch $S_i \Rightarrow$ Resistance $R_i = 2^{(m-1-i)} R$



Problems:
- Non-ideal switches
- Resistance mismatch
  ↳ Linearity errors
- Non-ideal Op Amp
  ↳ Gain errors
- Unstable V_{Ref}

$$\Delta V = \frac{-V_{Ref}}{2^m}$$

$$\sigma = \frac{\Delta V}{\sqrt{12}}$$

In short currents are summed in this mode. The value of the current I_i is proportional to R_i

$$I_i = \frac{V_{Ref}}{2^{(m-1-i)} R} = 2^i \frac{V_{Ref}}{2^{(m-1)} R}$$

↳ is 2^i if b_i is on, is 0 if b_i is off

So

$$I_T = \frac{V_{Ref}}{2^{(m-1)} R} \cdot (b_0 + 2b_1 + \dots + 2^{m-2} b_{m-2} + 2^{m-1} b_{m-1})$$

Op Amp is working as a transimpedance amplifier $\Rightarrow V_0 = -R_f \cdot I_T$

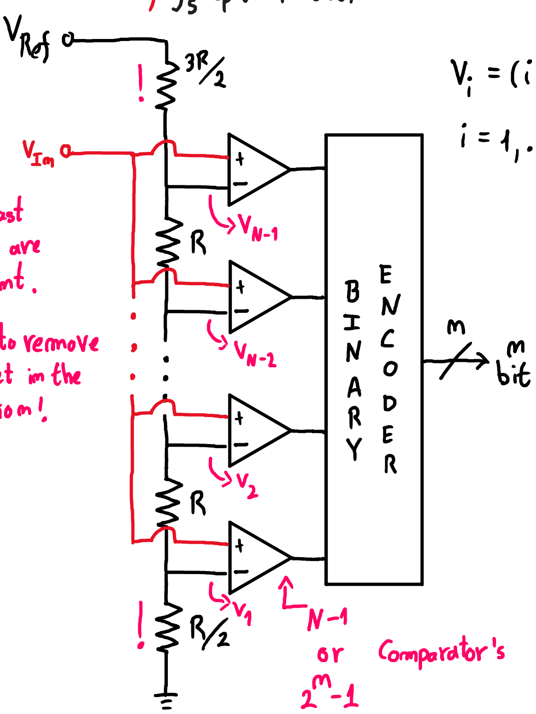
$$V_0 = -\frac{V_{Ref}}{2^{(m-1)} R} \cdot (b_0 + 2b_1 + \dots + 2^{m-2} b_{m-2} + 2^{m-1} b_{m-1}) \cdot \frac{R}{2} = -\frac{V_{Ref}}{2^m} (b_0 + 2b_1 + \dots + 2^{m-2} b_{m-2} + 2^{m-1} b_{m-1})$$

- ADC Topologies

Flash

Fastest $\begin{cases} T_{meas} \approx 1 \cdot T_s \\ f_s \text{ up to } 40\ GSa/s \end{cases}$

However ⇝ Circuit complexity $\propto 2^m$ $\Rightarrow$ Only used for low res. $m_{Max} \sim 8$bit



First and last resistance are different.
↳ Allows to remove the offset in the conversion!

$$V_i = \left(i - \frac{1}{2}\right) \frac{V_{Ref}}{N}$$

$$i = 1, \dots, N-1$$

Exercise:

$D = \pm 10V$

$m = 8$bit

$f_s = 1\ GSa/s$

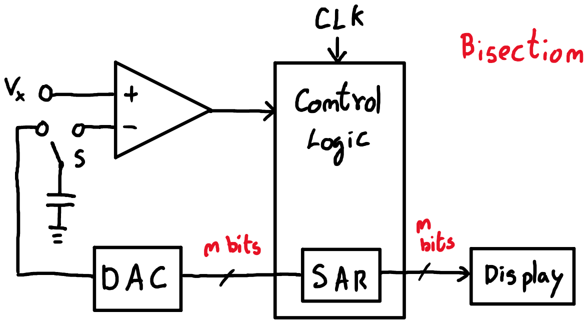
$$\Delta V = \frac{D}{2^m} = \frac{20}{2^8} \approx 80mV$$

$$\sigma = \frac{\Delta V}{\sqrt{12}} \approx 23mV$$

$$f_{Max} = \frac{f_s}{2} = 500MHz$$

Sucessive Approximation Register (SAR) ADC

$m=12$ $f_s=500\,kHz$ $m=16$ $f_s=200\,kHz$ $m=18$ $f_s=50\,kHz$



Bisection method → binary search algorithm m Comparisons ⇒ $\frac{1}{2^m}$ Resolution

$\Delta V = \frac{V_{FS}}{2^m}$ V_{FS} = Full Scale voltage

Comparison time: $T_{Comp} = m\,T_{clk}$ m usually between 2 and 5!

Acquisition time: $T_{acq} = m\,T_{Comp}$ ⇒ $f_s = \frac{1}{T_{acq}}$

Problem: Instantaneous noise can lead to a wrong decision ⇒ Wrong bit — Noise can be reduced by using a LP filter, but this reduces the speed.

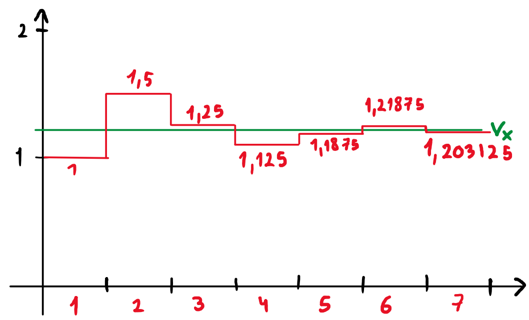
Accuracy depends on the internal reference, DAC quality and comparator noise.

Althought it has a lot bits and as such a high res, in reality its resolution is lower ⇒ 3 to 5 digits

Exercise: $D=+2V$ $m=7$ bit Total measurment time: $T_{acq} = 14\,ms$

$f_{clk} = 1\,MHz$ $T_{Comp} = 2\,T_{clk}$ Error rate for $V_x = 1205\,mV$

$T_{acq} = m\cdot 2\cdot T_{clk} = \frac{14}{1M} = 14\,ms$ ⇒ $f_s = 70\,kSa/s$



Comparison 1 0 0 1 1 0 1

$m=1 \Rightarrow V_{Comp} = \frac{D}{2^m} = 1V$

$m=2 \Rightarrow V_{Comp} = 0.5V$

$m=3 \Rightarrow V_{Comp} = 0.25V$

$m=4 \Rightarrow V_{Comp} = 0.125V$

$m=5 \Rightarrow V_{Comp} = 0.0625V$

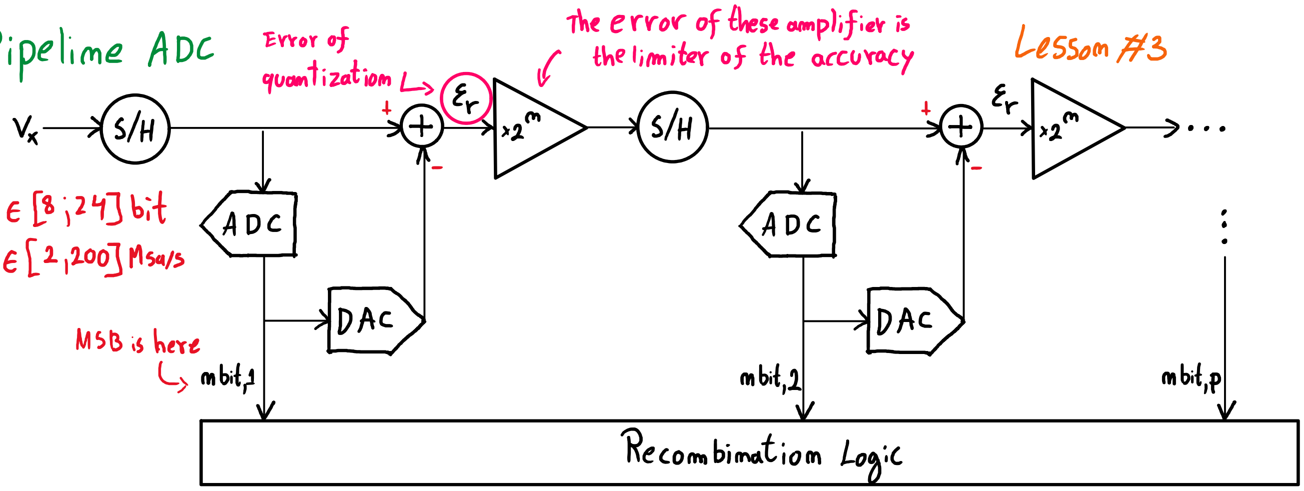
$m=6 \Rightarrow V_{Comp} = 0.03125V$

$m=7 \Rightarrow V_{Comp} = 0.015625V$

$Err = \frac{|V_x - V_{res}|}{V_x} = 0.1556\,\%$

Pipeline ADC

Lesson #3



$m \in [8;24]$ bit
$f_s \in [2;200]$ Msa/s

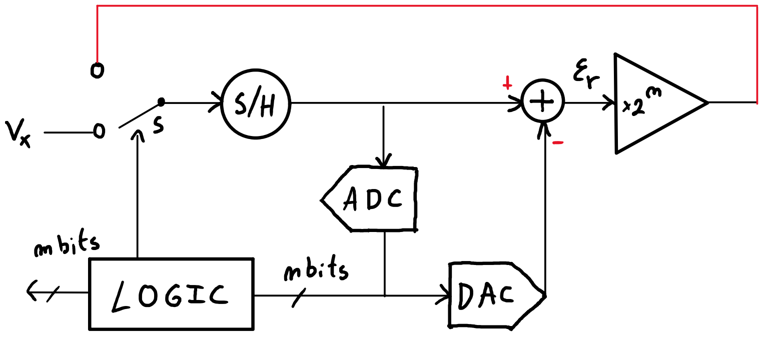
$mbit = m \times p$

Latency time $= p\cdot T_{clk}$

Conversion time $= T_{clk}$

m total bits of the pipeline ADC
m number of bits of a stage
p number of pipeline stages

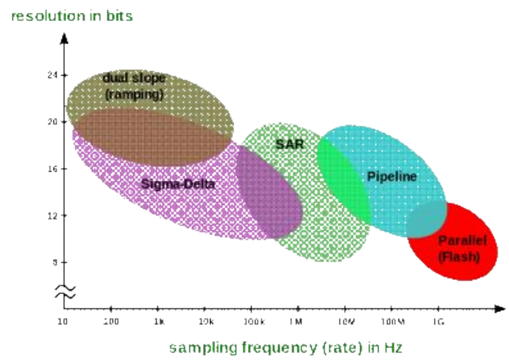
Recursive pipeline



Here the T_{acq} is $p \times T_{clk}$, the sampling freq is divided by the number of recursions p

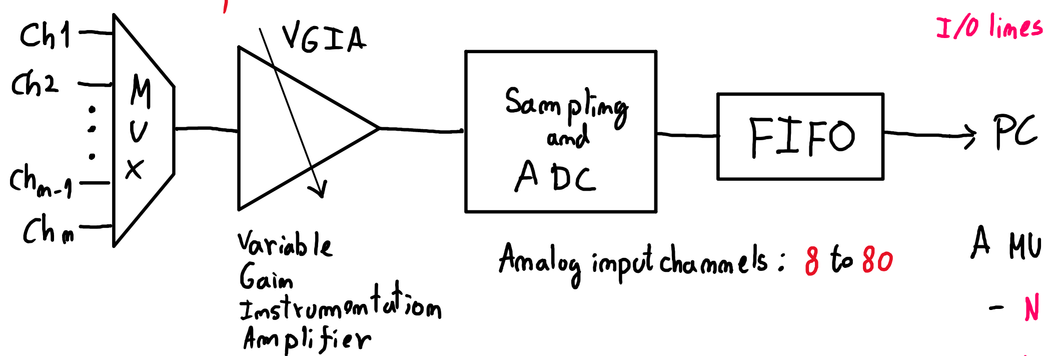
ADC Spec Table

	Frequency	Number of bits
Flash	Up to 40 GHz	8 ~ 12
SAR	50 K to 10 MHz	12 ~ 18
Pipeline	2 to 200 MHz	8 ~ 24



Fast but low res => Flash
Medium speed => Pipeline
Slower Speed => SAR

Data Acquisition Board



Analog input channels: 8 to 80

Some cards also have analog outputs, I/O lines, and synchronization channels (timer and trigger)

A MUX with N inputs allows for:
- N single ended signals
- N/2 differential signals

MUX (Multiplexer): Allows for the selection of different inputs, either single-ended or differential.

Variable Gain Instrumentation Amplifier: Allows for the use of the complete dynamic of the ADC by scalling the input

Sampling + ADC: Converts the voltage into a numeric value

FIFO: First-In First-Out Memory, allows for the sending of data to the PC data bus and/or directly to the RAM memory via DMA - Diret Memory Access.

Since a DAQ, usually, only has one ADC, it's sampling frequency must be divided by the number of active channels

$$f_s = \frac{f_{Max,ADC}}{N_{signals}}$$

Dynamic and Resolution in a DAQ Board

The gain of the amplifier should be chosen to make the signal best fit the ADC dynamic.

Ideally, we would like to have : $D_{Signal} \cdot G = D_{ADC}$

In this case, we would use the full dynamic of the ADC, however gain is usually discretized.

So we have to settle for: $D_{Signal} \cdot G \leqslant D_{ADC}$

Chosing G to maximize the input dynamic without surpassing the ADC dynamic

Resolution
- Dimensional - Minimum detectable voltage - $\Delta V = \dfrac{D_{ADC}}{G \cdot 2^m}$
- Adimensional - $\delta = \dfrac{1}{N} = \dfrac{1}{2^m}$

Communication Protocols

Lesson # 4

Serial interface RS-232

Serial communication takes place through three lines

2 - R_x Receiver

3 - T_x Transmitter

5 - GND Both Rx and Tx are reffered to it

Single ended and Async!

There are more pins/lines, but are not required!

Key parameters:

Data	Control	Voltage
0 (Space)	Asserted	+3 to +15 V
1 (Mark)	Deasserted	-3 to -15 V

A word is composed by:

Data packet of the ASCII character A

0	1 0 0 0 0 0 1	0	1 1
Start bit	7 Data bits	Parity bit	Stop bits

Baud rate - 9.6 to 115.2 kbit/s

Problem? For n peripherals n cables are needed!

Solution
- RS-422 → Allows for multiple receivers
  - With 4 wires both can be Full Duplex!
- RS-485 → Half Duplex. Allows for multiple receivers and transmitters
  - Allows for 35Mbit/s up to 10m and 100kbit/s up to 1.2Km

IEEE-488 Protocol (GPIB)

Paralel interface GPIB - General purpose interface bus

Key parameters

- 8 data lines (DIO1 - DIO8) in TTL 0-5V
- 5 interface lines
- 3 handshake lines

Data is sent in ASCII → 7bits + 1 parity bit → 1 byte

Maximum: 15 devices connected
- 20 meters of connection lenght
- 1 Mbyte/s of speed Typical ≈ 400 kbytes/s

Each instrument in a bus takes one (or more) of the following roles:

- Listener - Receives data
- Talker - Transmits data
- Controller - Manages the bus
- Idler - In standby

USB Interface

USB - Universal Serial Bus
↳ serial standard, allows up to 127 devices

4 Pins: VBUS - Power Supply (+5V) up to 500 mA!
D^- - "received" data
D^+ - "transmited" data
GND - reference (0V)

Data transfer speeds:

USB 1.0 ⟶ 1.5 Mbit/s
USB 1.1 or 2.0 full speed ⟶ 12 Mbit/s
USB 2.0 high speed ⟶ 480 Mbit/s — Half Duplex
USB 3.0 super speed ⟶ 4.8 Gbit/s — Full Duplex
↳ Peak current in VBUS 900 mA

When a new device is connected to the bus, it's assigned an adress. Afterwards its sync-ed with the receiver clock and sends a stream to indicate what type of data transfer will be done:

A single cable can be up to 5m.
Using hubs the maximum distance is 30m.

Control: Command and status operations ie. instrument control

Interrupt: Latencies guaranteed, few data transfered ie. optical mouse

Bulk: Latencies not guaranteed, transfer large data packets ie. Passing files from mobile to PC

Isosinchronous: Continuous data transfer ie. Video streaming / web cam

USB 3.0 has traffic routing.
So non-relevant devices can be inactive, only turning on if they need to be used!

Other Protocols

Firewire: up to 800 Mb/s Similar to GPIB

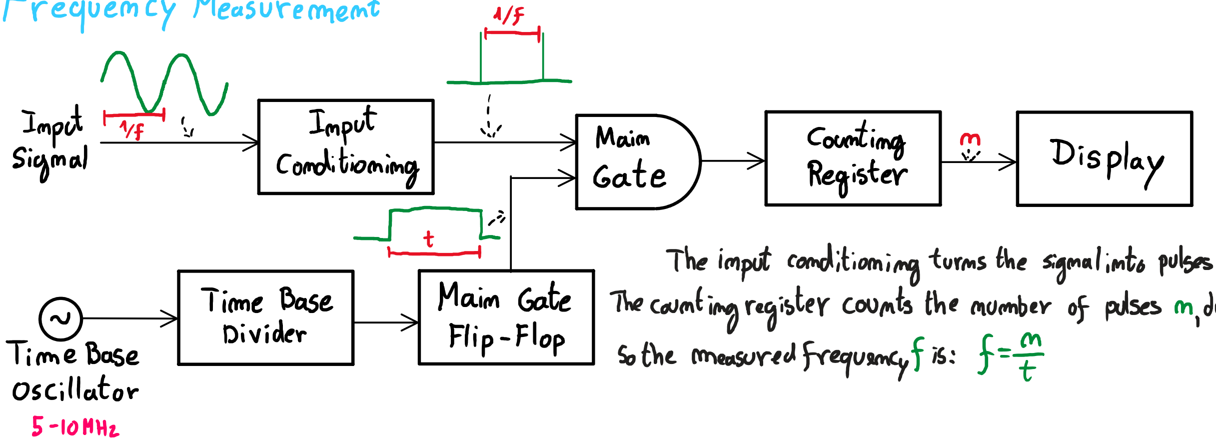
E-Sata: Up to 3.2 Gb/s Used in HD

Thunder bolt: Up to 10 Gb/s Very simple protocol

Electronic Counters

Lesson #6

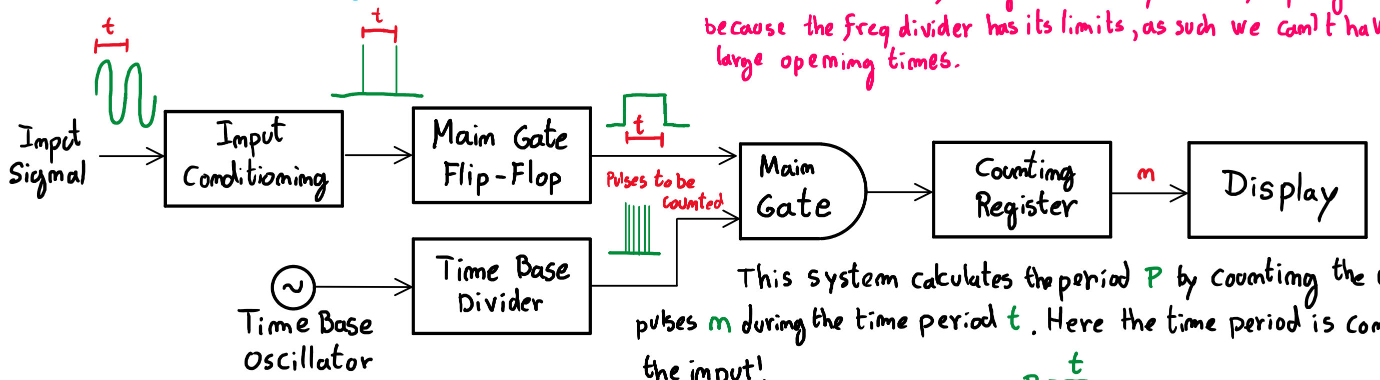
Frequency Measurement



The input conditioning turns the signal into pulses.
The counting register counts the number of pulses n, during the time period t.
So the measured frequency f is: $f = \frac{n}{t}$

Period Measurement

Note that this allows for higher accuracy in low freq signals because the freq divider has its limits, as such we can't have large opening times.

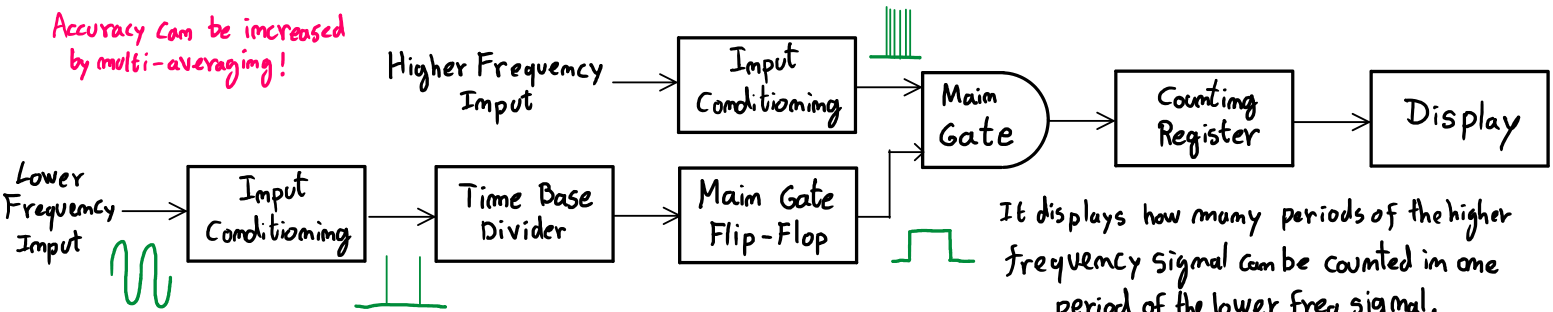


This system calculates the period P by counting the number of pulses m during the time period t. Here the time period is controlled by the input!

$$P = \frac{t}{m}$$

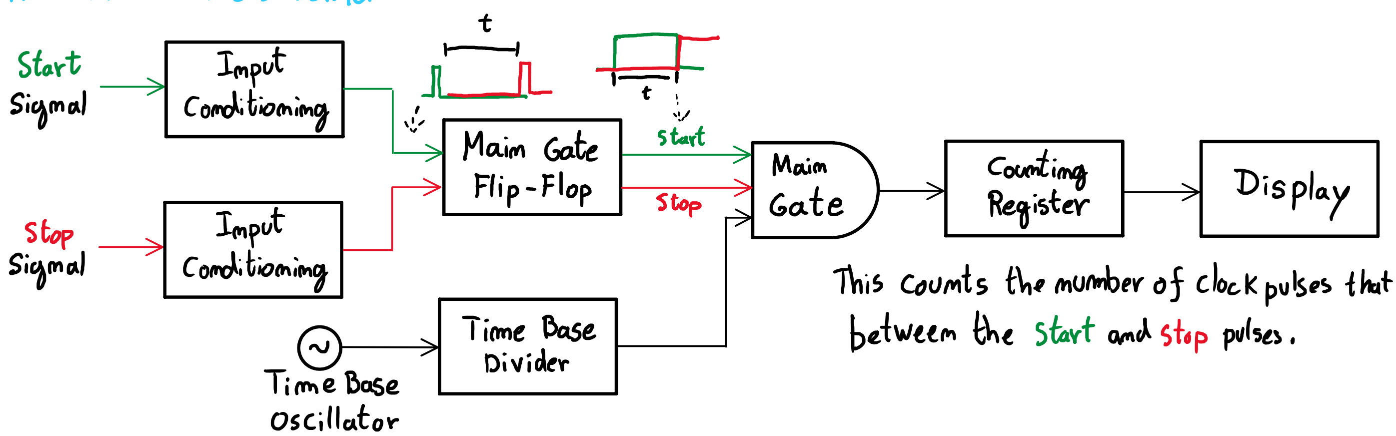
Frequency Ratio Measurement

Accuracy can be increased by multi-averaging!



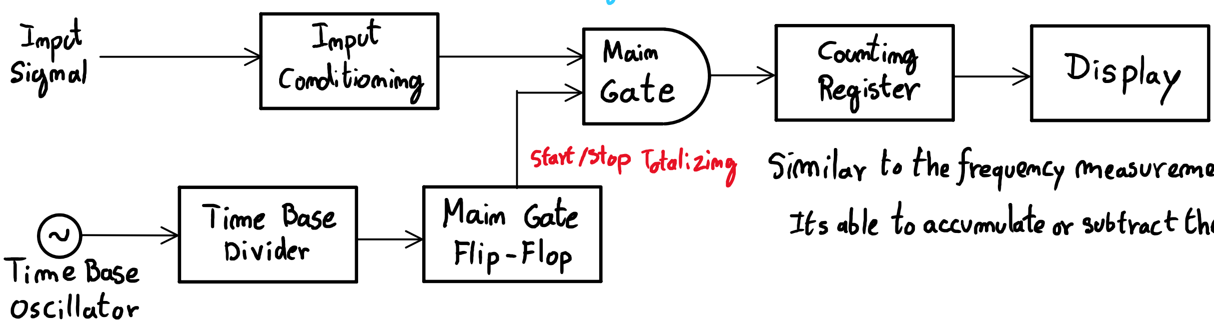
It displays how many periods of the higher frequency signal can be counted in one period of the lower freq signal.

Time Interval Measurement



This counts the number of clock pulses that happen between the Start and Stop pulses.

Total Measurement between Two Signals



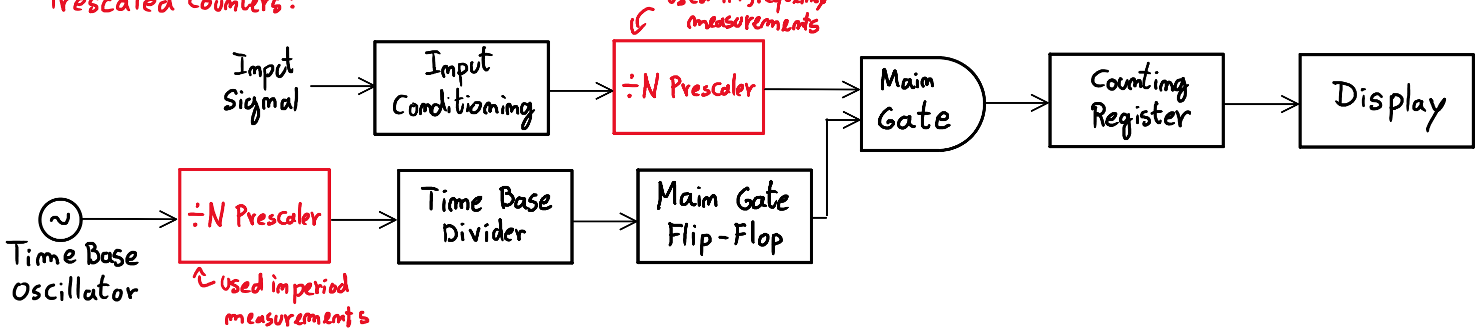
Similar to the frequency measurement mode.
It's able to accumulate or subtract the counts!

Other Functions

Normalized counters: The instrument shows the measured frequency multiplied by a numeric constant: $f_{display} = \alpha \cdot f_{meas}$
Used to present measurements in rpm or when measuring flow.

Programmed counters: Are able to send an electrical signal when the count exceeds the user defined limit.
Can be used to control other devices.

Prescaled counters:

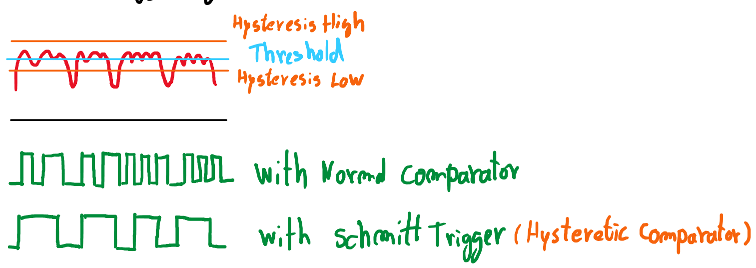


One way to increase the maximum conversion rate, without exceeding the limitations of the gate and register, is to insert a N divider. This reduces the input frequency by a factor of N, which in turn means that to obtain the same number of counts, the time that the gate stays open has to increase by the same factor!

Downsides: Compared to a counter without prescaling, this leads to a lower accuracy in the same measurement time. Also rates of measurement bellow 1ms are not usable

Input Signal Conditioning

1 - Sensibility : The smallest signal countable by a counter. Can be improved by using an amplifier. Too much sensitivity may cause false triggering events due to noise. To avoid this a Schmitt Trigger is used.



2 - AC-DC Coupling : If the DC Component of the signal is filtered out (AC) or not (DC)

3 - Trigger Level : the voltage levels where the trigger happens. Both the high and low levels.

4 - Slope Control : Its used to decide whether the Schmitt Trigger should generate a pulse on the rising or falling edge of the signal.

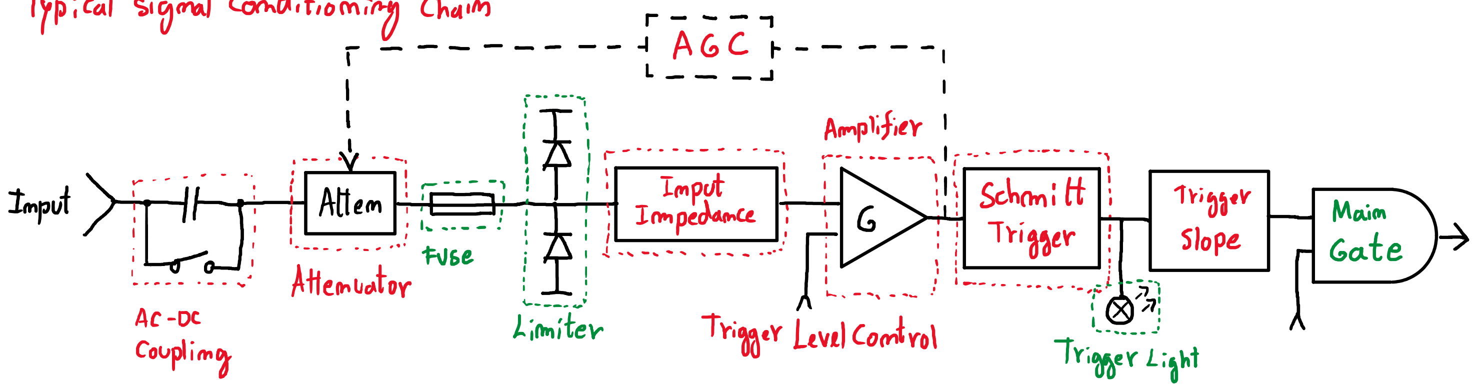
5 - Dynamic range : Linear range for the input usage

6 - Attenuator : Adapt the range of the signal to the one of the counter

7 - Input impedance : High impedance (1MΩ) for up to 1MHz and 50Ω for higher freqs.

8 - Automatic Gain Control : The system can automatically control its sensitivity.

Typical signal conditioning Chain



Measurement Errors

4 main types of errors:

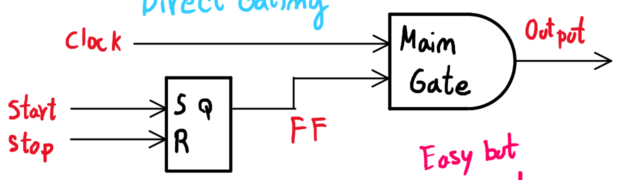
- Counting Errors ±1;
- Errors of the time base;
- Trigger errors;
- Systematic errors. ⇜ Averaging can't solve this!

Averaging can help solve this!

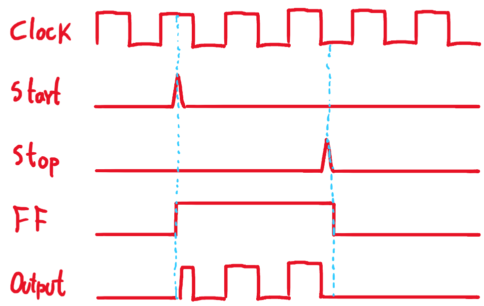
Random errors: Can significantly degrade the resolution of time interval measurements.

Types of Gating for time interval

Direct Gating



Easy but not used

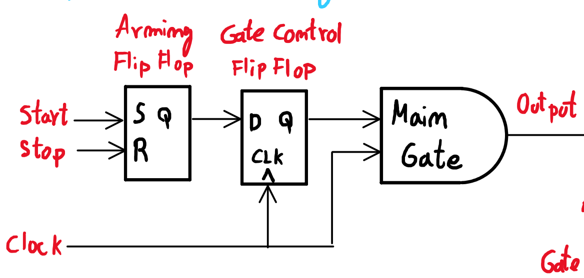


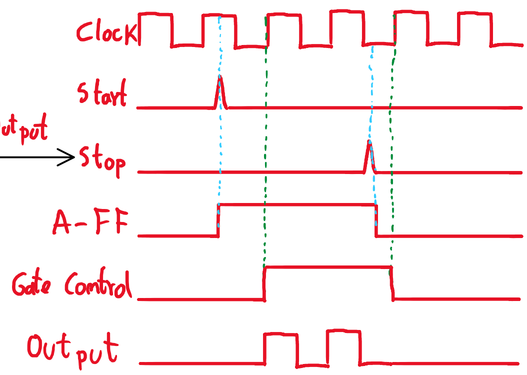
Truncating the clock can lead to count errors.

Some of the errors are not estimable.

Not possible to measure time intervals smaller than the minimum measurable pulse width.

Synchronized Gating





No clocks are truncated

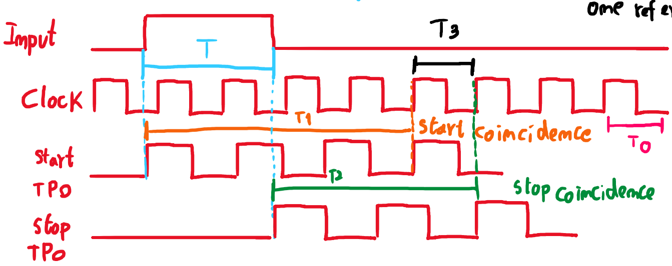
The measurements will show distortion, which cannot be measured ⤼ Can be fixed by averaging

Possible to measure time intervals smaller than the minimum measurable pulse width.

Other options | Analog interpolation ⤳ This method truncates the clock, and then tries to estimate by how much it was truncated by measuring the time lost and compensating for it.

| Dual vernier interpolation ⤷ This method works by finding two coincidences one referenced to the start of the counting other to the stop. To further reduce the error the diference of those two coincidences is accounted for!

⇓



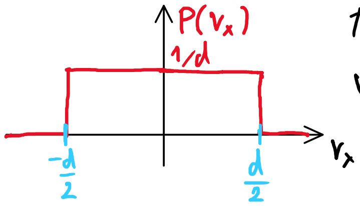
Note that the start and stop clocks have periods equal to : $T_0 + \frac{T_0}{N}$

$$T_1 + T_3 = T + T_2 \Rightarrow T = T_0\,[N_3 + (1 + 1/N)(N_1 - N_2)]$$

Effective Number of Bits (ENOB)

Lesson #7

Let us assume a signal, $V_x(t)$, whose value is random, given by the following distribution:



The signal dynamic is $D = \pm \frac{d}{2} = |d|$

We can also calculate its Variance $\sigma_S^2 = \frac{D^2}{12}$

If this signal is quantized using m bits, we will have a maximum resolution of $Q = \Delta V = \frac{D}{2^m}$

This quantization will also have a variance: $\sigma_q^2 = \frac{Q^2}{12} = \frac{1}{12}\left(\frac{D}{2^m}\right)^2 = \frac{1}{2^{2m}} \cdot \frac{D^2}{12} = \frac{\sigma_S^2}{2^{2m}}$

Quantization noise

So we can write the signal to noise ratio (SNR)

$$SNR = \frac{S}{N} = \frac{\sigma_S^2}{\sigma_q^2} = 2^{2m}$$ → This result holds only for an ideal quantizer

→ We can re-write this and for m: $m = \frac{1}{2}\log_2(SNR)$ → Number of bits

→ In an ideal converter, we only have quantization noise. In a real one the noise is:

$$N_T = N_q + N_{A/D} + N_{ext} > N_q$$

N_q: Quantization noise

$N_{A/D}$: Converter internal noise

N_{ext}: External noise

N_T: Total noise

And this can be written as variances!

$$\sigma_T^2 = \sigma_q^2 + \sigma_{A/D}^2 + \sigma_{ext}^2$$

So extending the definition of $SNR = \frac{\sigma_S^2}{\sigma_T^2}$ we define ENOB or m_e

$$ENOB = m_e \equiv \frac{1}{2}\log_2\left(\frac{\sigma_S^2}{\sigma_T^2}\right) = m - \frac{1}{2}\log_2\left(1 + \frac{\overbrace{\sigma_{A/D}^2 + \sigma_{ext}^2}^{\text{Added noise!}}}{\sigma_q^2}\right)$$

Note: -6dB in $\frac{S}{N}$ ⇒ a loss of 1 bit.

The ENOB give us the number of bits that carry information about the signal. All the other bits are noise!

Data Representation

Types of graphs:
- Quantitative: Axes with numerical values. Must always have the corresponding unit.
- Qualitative: Serves to indicate trends or tendencies.

Cartesian Plane:
- x - Abcissa: independent / command / input variable
- y - ordinate dependent / output variable

It's good pratice to have $u(x) \ll u(y)$, so the command variable presents the higher accuracy

To present $u(y)$ one can use Error Bars to indicate a confidence interval which must be specified.

Another way to present data in the Cartesian Plane is to use Polar Coordinates:
- Radial: $\rho = \sqrt{x^2 + y^2}$
- Angular: $\theta = \arctan\left(\frac{y}{x}\right)$

Note: $x = \rho\cos(\theta)$

$y = \rho\sin(\theta)$

Logaritmic Scale

Useful when we want to display values which vary by several orders of magnitude!

$z|_{log} = \log_B(z/z_0)$ B is the base and z_0 is the reference

Example

$P|_{dB} = 10\log_{10}(P/P_0)$ $B=10$, $z_0 = P_0 = 1W$

$P|_{dBm} = 10\log_{10}(P/P_0)$ $B=10$, $P_0 = 1mW$

$V|_{dB} = 20\log_{10}(V/V_0)$ $B=10$, $V_0 = 1V$

A diagram can be:

Semilogaritmic | log-lin: Diode curve
| lin-log: Phase in Bode Plot

Bilogaritmic | log-log: Amplitude in Bode Plot or Signal Power Spectrum

Interpolation

While measuring a set of finite and discrete values is obtained. To make the data more readble we can interpolate to fill the gap between the discrete values, by using a interpolating function.

Interpolating function: A continuous function, which passes through the two points and provides a presumed trend of the input to output relationship.

- Linear: Simplest. Consists in joining the points with straight lines. → Does not use the information of the previous and following points. Thus not the best reconstruction
- Cubic polinomial: Curve that posses throught the samples with this equation: $S_i(x) = ax^3 + bx^2 + cx + d$ → The first and second derivatives are continuous
- Sinc: The convulotion of the samples with $\text{sinc}(x) = \frac{\sin(x)}{x}$ → Derived from the ideal lowpass filtering of the signal. The interpolation which guarantes the Nyquist theorem.

Fitting

Often the sampled data presents a depence $y=f(x)$ which can be reasonably approximated by a known function. Fitting is the process through which we can obtain the parameters of the function that better fits the data.

One way to do it is the Least Square Fitting in which the parameters of $f(x)$ are those who minimize the distance between the measured y and $f(x)$. This distance usually is defined as the sum of the standard deviations between $f(x)$ and y.

$$\phi = \sum_{i=1}^{m} \delta_i^2 = \sum_{i=1}^{m} (y_i - f(x_i))^2$$

m: number of samples
ϕ: function to minimize

An important specific case is the Linear LS where $y = mx + q$ and the parameters to be calculated are m and q

Using ϕ it's possible to write

$$\phi(m,q) = \sum_{i=1}^{m} \delta_i^2 = \sum_{i=1}^{m} [y_i - (mx_i + q)]^2 \implies$$

$$\frac{\partial\phi}{\partial m} = 0 \Rightarrow m\sum x_i^2 + q\sum x_i = \sum x_i y_i$$

$$\frac{\partial\phi}{\partial q} = 0 \Rightarrow m\sum x_i + mq = \sum y_i$$

Now to find the minimum!

Note that the derivative equals zero means inflection points both maximums and minimums, however, in this case since the second derivative is always positive it can only be a minimum

With 2 equations and 2 variables we have:

$$m = \frac{m\sum x_i y_i - \sum x_i \sum y_i}{m\sum x_i^2 - (\sum x_i)^2}$$

$$q = \frac{\sum y_i - m\sum x_i}{m} = \bar{y} - m\bar{x}$$

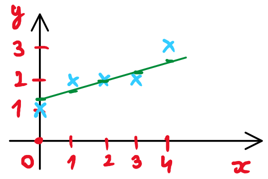
!

Exercise

Use Linear LS in this data:

$x_i = \{0, 1, 2, 3, 4\}$

$y_i = \{1, 2, 2, 2, 3\}$



$$m = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}$$

$$q = \frac{\sum y_i - m\sum x_i}{n} = \bar{y} - m\bar{x}$$

$$m = \frac{5(0+2+4+6+12) - 10\times 10}{5(0+1+4+9+16) - (10)^2} = \frac{20}{50} = 0.4$$

$$q = \frac{10 - 0.4\times 10}{5} = \frac{6}{5} = 1.2$$

$f(x) = 0.4x + 1.2$

$f(0) = 1.2$

$f(1) = 1.6$

$f(2) = 2$

$f(3) = 2.4$

$f(4) = 2.8$