MICRO-428: Metrology

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EPFL

MICRO-428: Metrology

Week Eleven: Electrical Metrology

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Reference Books

📖 *E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016*

📖 *S. Cova, "Sensors Signals and Noise – Course Slides", Politecnico di Milano 2016*
-> link: http://home.deib.polimi.it/cova/elet/lezioni/lezioni.htm

📖 B. Staszewski, *"Practical PLL Design for Frequency Synthesis and Clocking"*,
EPFL MEAD Course Slides, Lausanne 2016

📖 I.G. Hughes, T.P.A. Hase, *Measurements and Their Uncertainties*, 1st ed., 2010

📖 J.K. Blitzstein, J. Hwang, *Introduction to Probability*, 1st ed., 2015

Week 10 Summary

S

10.1 Charge, Current, Voltage: properties (microscopic), definitions, $I = {}^{dQ}/_{dt}$, $\mathrm{I} = {}^{V}/_{R}$ (Ohm's Law), $P = IV = I^2R = {}^{V^2}/_{R}$ (Ohmic (Joule's) heating)

10.2 Noise Background:

Recap: Noise as a Random Process (RP, §3.1).

Stationary and Wide-sense stationary (WSS) noise: constant mean + $K_{XX}(t, t+\tau) = K_{XX}(\tau)$

Noise Power (for WSS noise): $K_{nn}(0) = E\{n^2(t)\} = \overline{n^2(t)}$ $(= \sigma_n^2$ assuming 0 mean: $\mu_n = 0)$

Concept of Noise Spectrum and PSD (power spectral density), one-sided or two-sided:

$$S_n(t_1, \omega) = \mathfrak{I}\{K_{nn}(t_1, \tau)\}$$

White Noise (spectrally flat –> constant PSD, autocorrelation = Dirac delta)

Week 10 Summary

S

10.3 Noise sources:

- Thermal noise, e.g. in resistors. Is an example of white noise. Bilateral PSD: $2kTR$.
- kTC noise (thermal noise on capacitors), e.g. when opening a real switch: $\overline{V_0^2} = \frac{kT}{C}$
- Shot (or Poisson noise), e.g. current flow through a potential barrier, or in photon-counting devices.

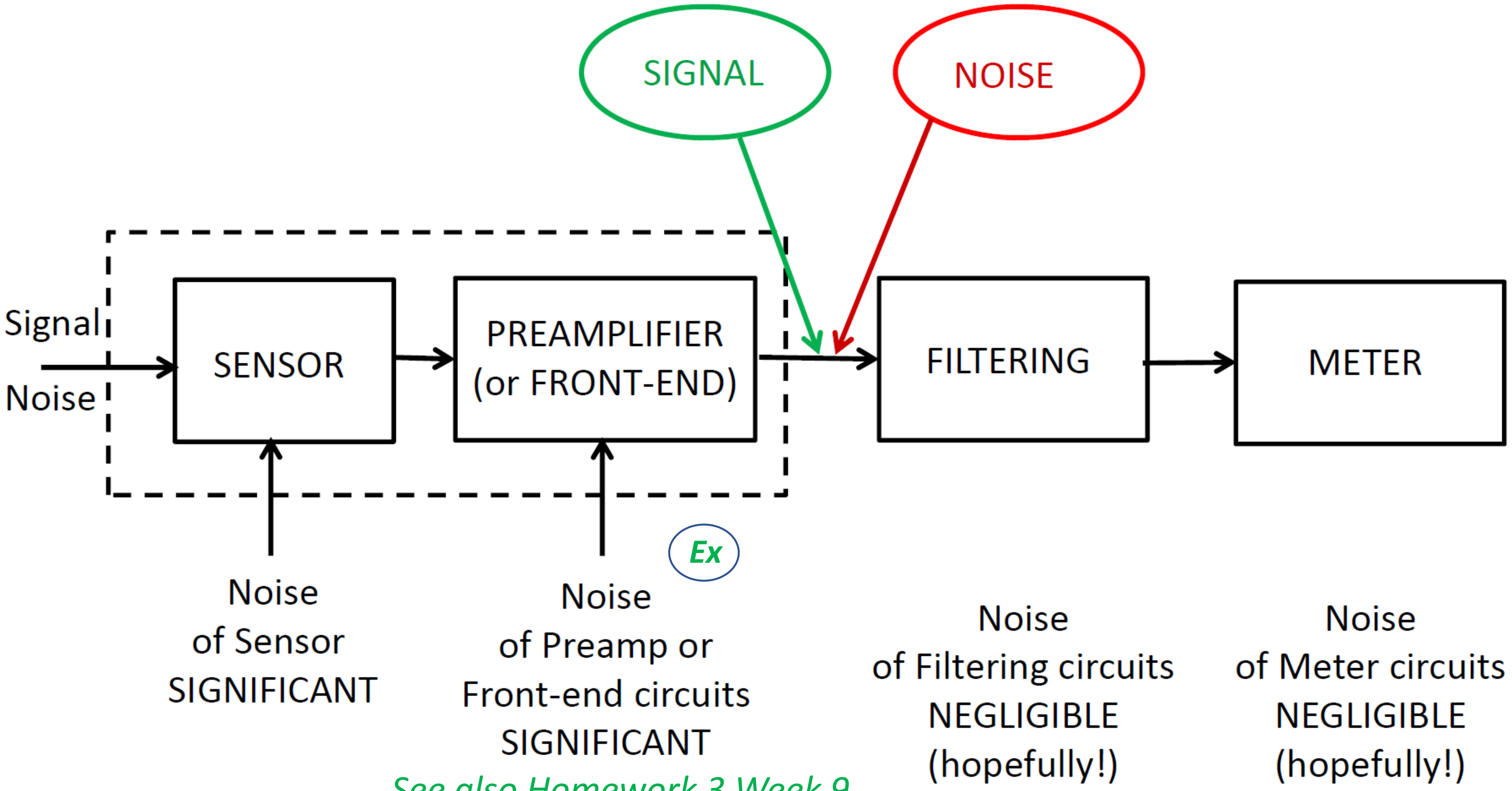
  Bilateral PSD: $S = qI$, WSS white noise.

NB: thermal and shot noise are irreducible. Excess noise examples:

- $1/f$ or flicker noise, approximatively $1/f$ power spectrum.
- RTS (Random Telegraph Signal) noise.
- Other…

Outline

11.0 Typical (Sensor) Measurement Set-up

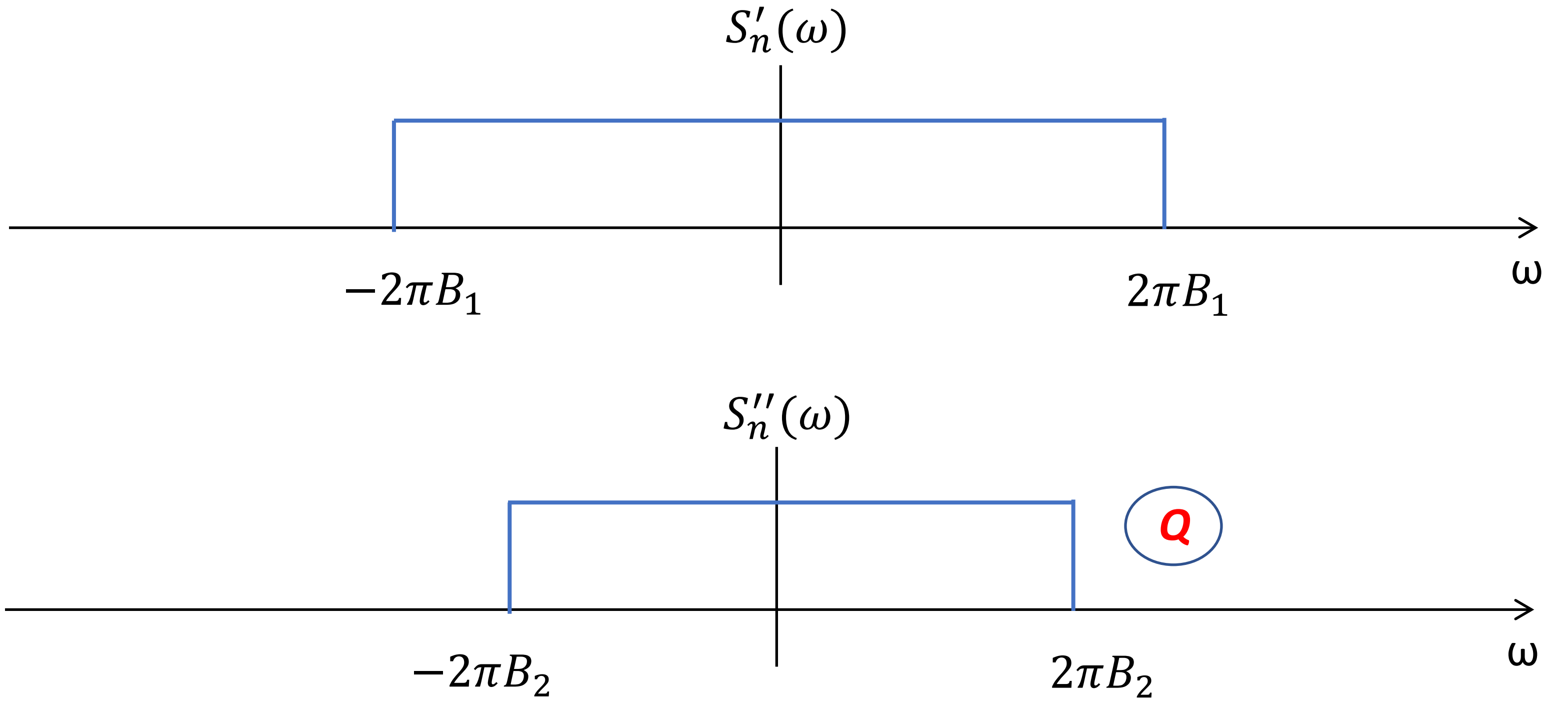


See also Homework 3 Week 9

S. Cova, “Sensors Signals and Noise, Course Slides”, Politecnico Milano 2016, “Noise 1”

11.1.1 Noise Reduction: Low-pass Filtering

- Low-pass filtering: limits the band of noise from above -> effective with white noise:



$\sigma_n^2 = 4kTR{\cdot}B_2 < 4kTR{\cdot}B_1$
where $B_1 > B_2$

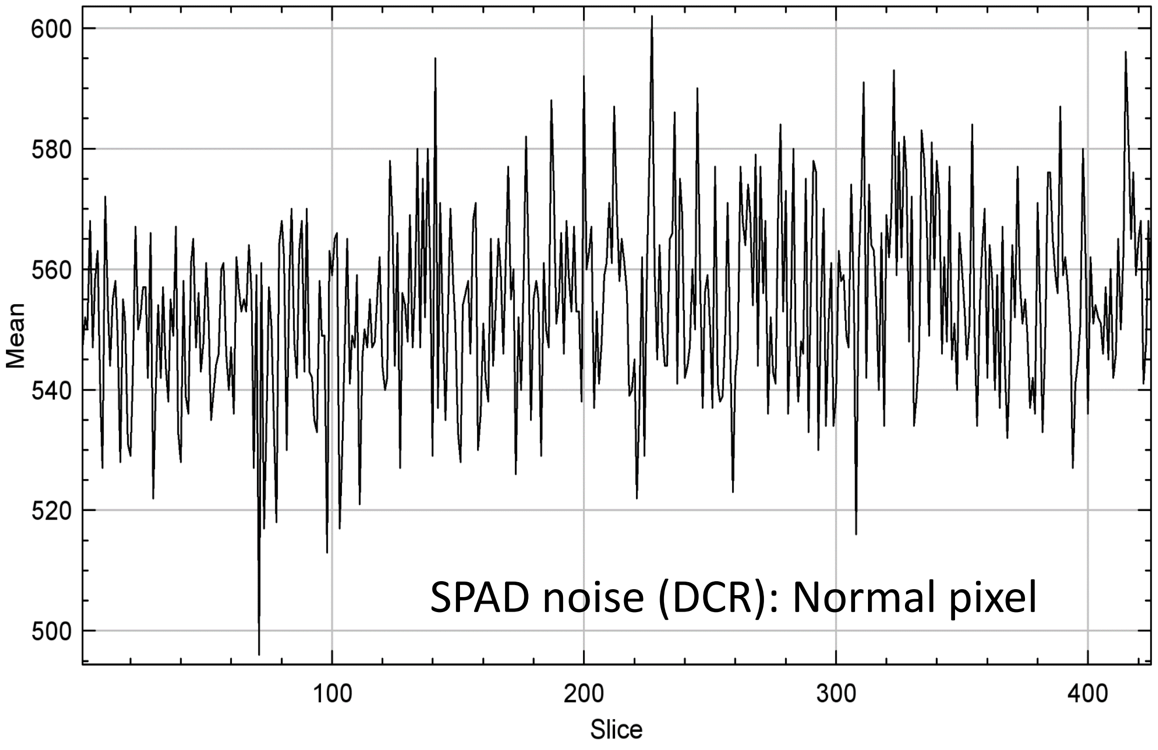
- Obvious, but limits the capability of detecting fast signals, e.g. achieving high frame rates in imaging, or fast transient signals

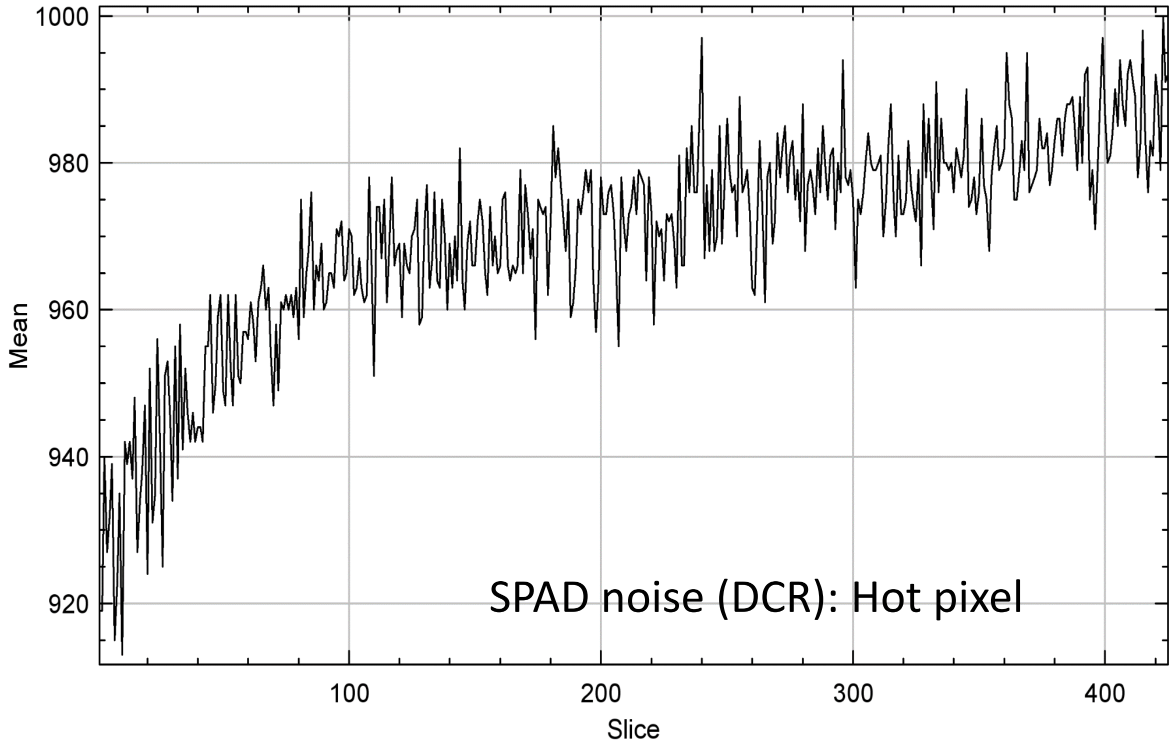
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.1.1 Noise Reduction: Correct for offset and drift

- Eliminate DC component (= offset)

- Same if the offset changes slowly over time (drift), e.g. due to temperature, aging, etc.



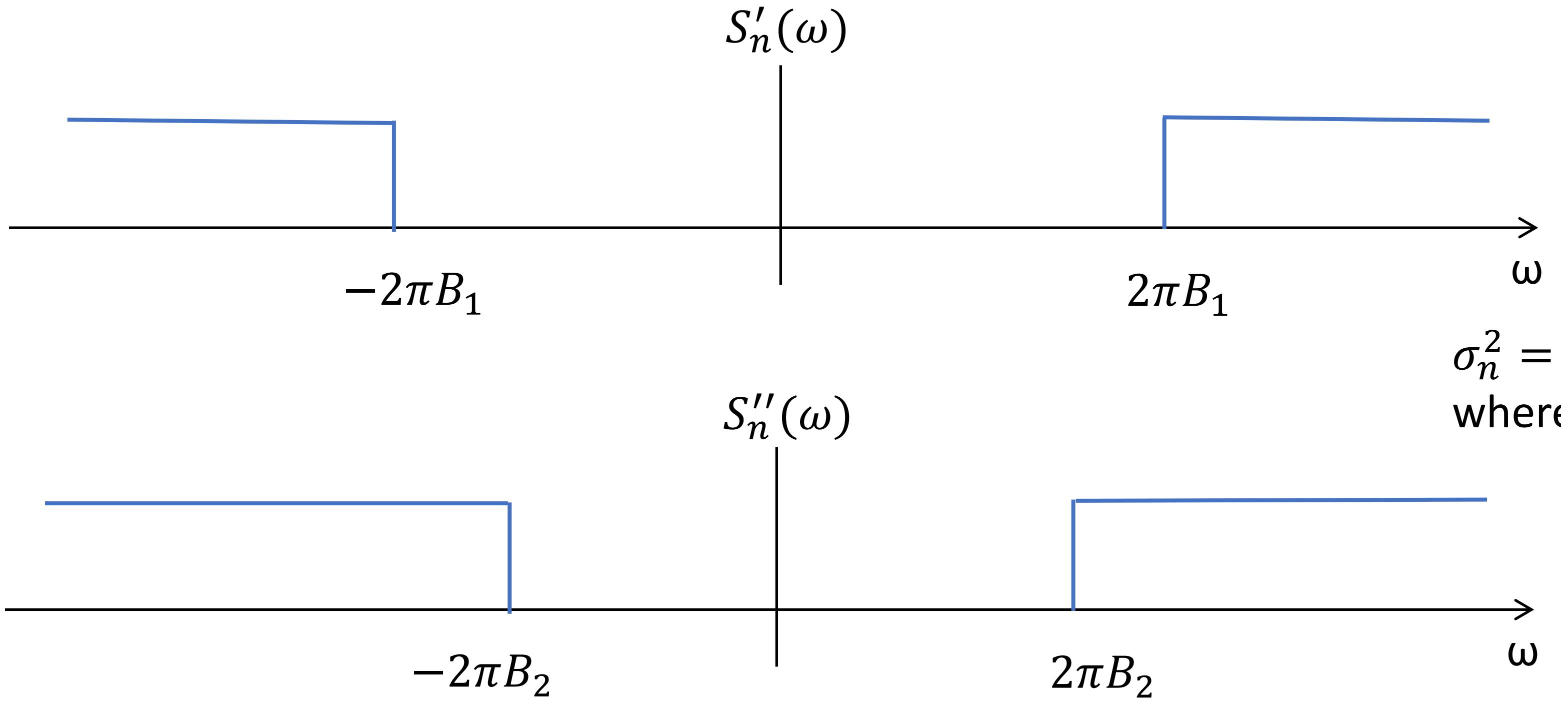


Probable cause: thermal drift
Estimated DAQ time: 9 s

📖 E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016; A. Ulku, 06022020 results

11.1.1 Noise Reduction: High-pass/band-pass Filtering

- High-pass filtering: limits the band of noise from below -> effective with white noise:



Band-pass:

$\sigma_n^2 = 4kTR\cdot(B_{max} - B_1) < 4kTR\cdot(B_{max} - B_2)$
where $B_1 > B_2$

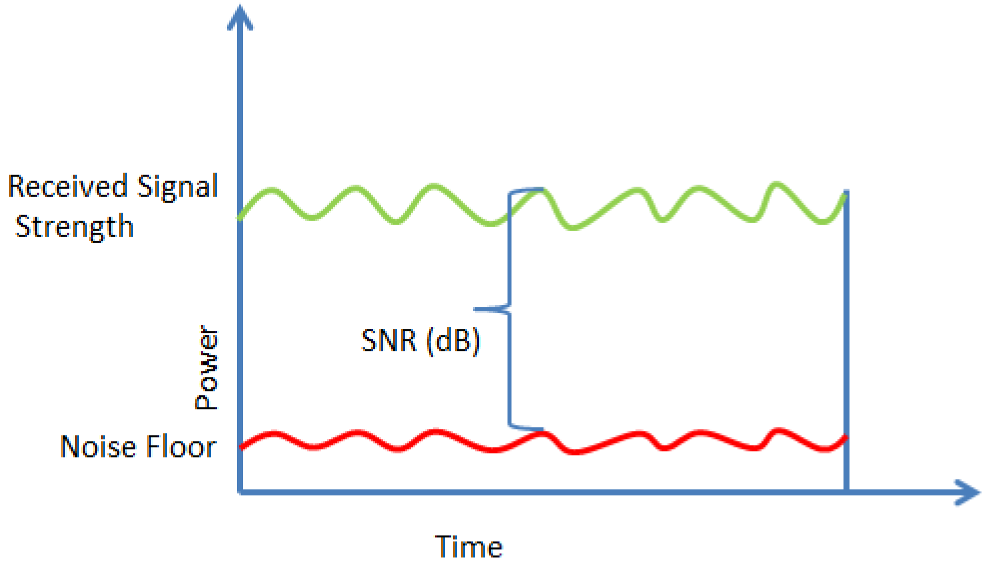
- HP filter are also effective in reducing noise, as they cut all low frequencies.
- However, they may also eliminate wanted slow signals -> cannot be used in imaging sensors.

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.1.2 Noise Reduction: Averaging Techniques

- "Signal averaging is a signal processing technique applied in the time domain, intended to increase the strength of a signal relative to noise that is obscuring it. "

- "By averaging a set of replicate measurements, the signal-to-noise ratio (SNR) will be increased, ideally in proportion to the number of measurements."



EN Wikipedia *Signal averaging*

11.1.2 Averaging Techniques

Given a signal $s(t)$ and noise $z(t)$, we assume that:

*weaker definition of white noise

- Signal $s(t)$ is uncorrelated to noise, and noise $z(t)$ is uncorrelated*.
- Signal power is $P_{signal} = E\{s^2\}$ and it is constant in the replicate measurements.
- Noise is random, with a mean of zero and constant variance in the replicate measurements:

$$E\{z(t)\} = \mu_{noise} = 0$$

$$Var\{z\} = E\{(z - \mu_{noise})^2\} = E\{z^2\} = P_{noise} = \sigma^2 \quad \text{: Noise Power}$$

EN Wikipedia *Signal averaging*

11.1.2 Averaging Techniques – Noise Power for Sampled Signal

- Assuming we sample the noise, we get a per-sample variance of

$$Var\{z\} = E\{z^2\} = \sigma^2$$

- However, the noise samples are uncorrelated, therefore (§8.4.5):

$$Var\{N_{avg}\} = Var\left\{\frac{1}{n}\sum_{i=1}^{n} z_i\right\} = \frac{1}{n^2} Var\left\{\sum_{i=1}^{n} z_i\right\} = \frac{1}{n^2}\sum_{i=1}^{n} Var\{z_i\}$$

- Since noise variance is constant (σ^2):

$$Var\{N_{avg}\} = \frac{1}{n^2} n\sigma^2 = \frac{1}{n}\sigma^2 = \frac{1}{n} P_{noise}$$

-> averaging *n* realizations of the same, uncorrelated noise reduces noise power by a factor of *n*

EN Wikipedia *Signal averaging*

11.1.2 Averaging Techniques – Noise Power for Sampled Signal

$$Var\{N_{avg}\} = Var\left\{\frac{1}{n}\sum_{i=1}^{n} z_i\right\} = \frac{1}{n^2} n\sigma^2 = \frac{1}{n}\sigma^2$$

N.B.: The averaging result is also valid when there are different (additive) independent noise sources, e.g. kTC noise and quantization noise, giving rise to independent random processes

Q Thermal noise? Flicker noise?

EN Wikipedia *Signal averaging*

11.1.3 Signal-to-Noise Ratio (SNR)

- Define Signal-to-Noise Ratio (SNR) as:

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{E\{s^2\}}{\sigma^2}$$

$$SNR_{dB} = 10log_{10}(SNR) = P_{signal,dB} - P_{noise,dB}$$

- Measure both signal and noise within the same system bandwidth. The SNR matters, rather than the absolute signal strength!
- SNR>1 (0 dB) means more signal than noise

NB: SNR can be measured w.r.to power or amplitude!

$$SNR_{dB} = 10log_{10}\left[\left(\frac{A_{signal}}{A_{noise}}\right)^2\right] = 20log_{10}\left(\frac{A_{signal}}{A_{noise}}\right) = A_{signal,dB} - A_{noise,dB}$$

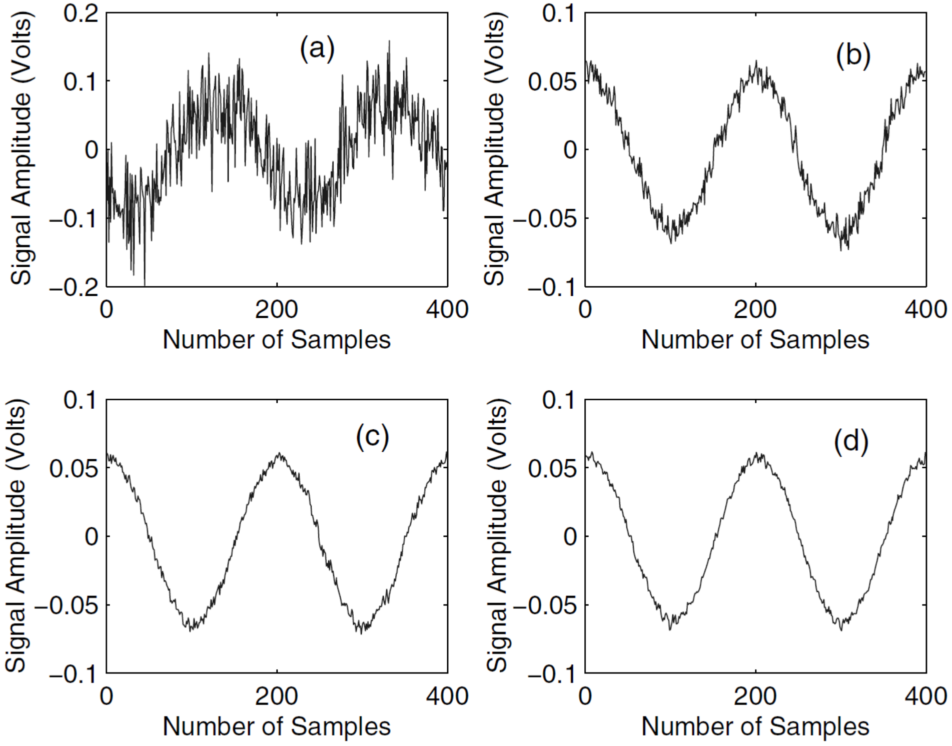
EN Wikipedia *Signal-to-noise ratio*

11.1.4 Averaging Techniques – Signal power for sampled signals

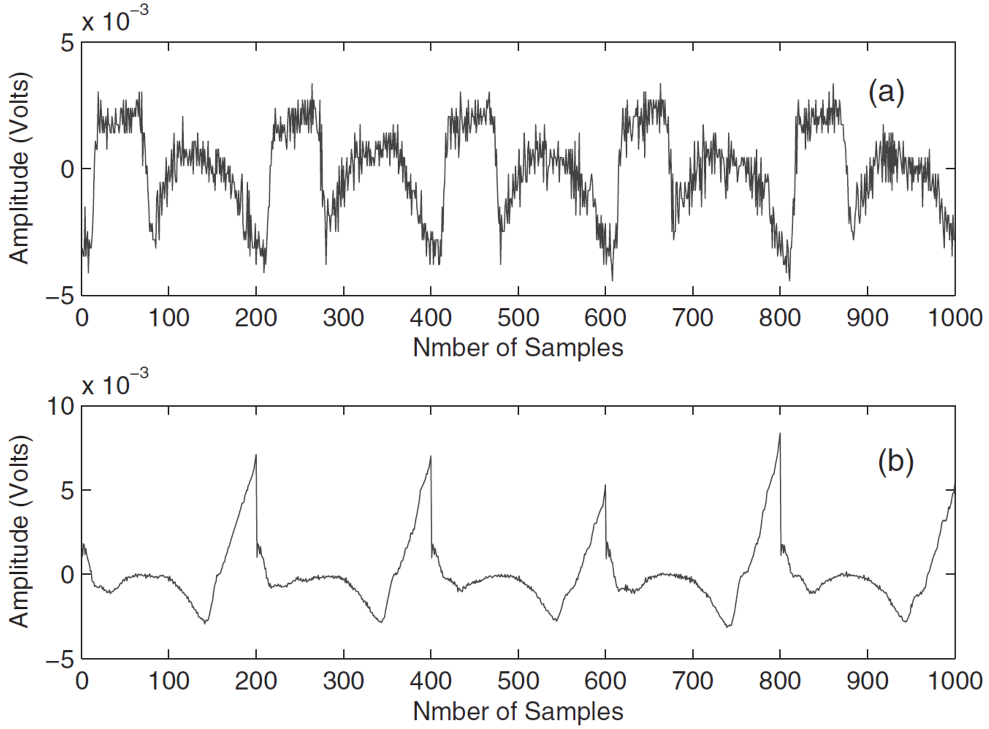
- In the case of a constant or repetitive signal, averaging allows us to increase the SNR as follows:

$$SNR_{avg,identical\ signals} = \frac{P_{avg,identical\ signals}}{P_{avg,noise}} = n\ SNR$$

-> signal adds coherently, noise incoherently



Repetitive signal

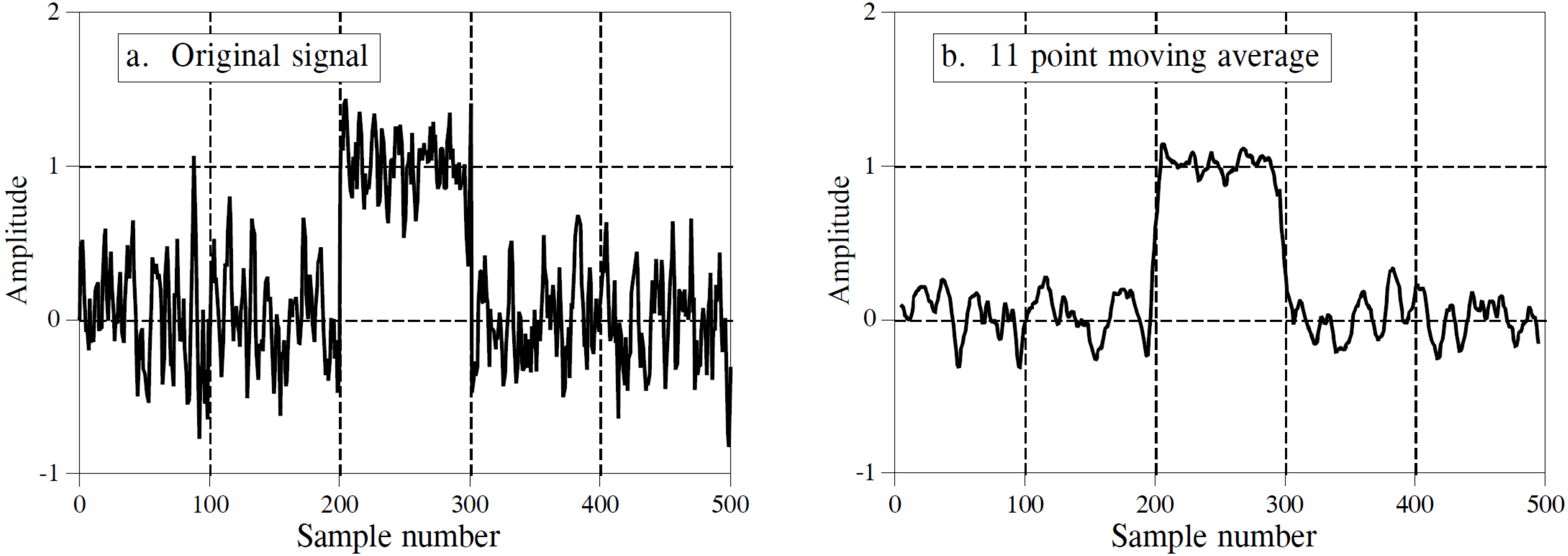


ECG signal, baseline-corrected before vs. after averaging (NB: home-made – still some work to do ☺)

EN Wikipedia *Signal averaging; U. Hassan and S. Anwar, EJP(31), 2010; https://physlab.lums.edu.pk/images/1/10/Physiological_signals.pdf*

11.1.4 Averaging Techniques – Signal power for sampled signals

- Constant signal -> Example: Moving average filter



NB: decreases the amplitude of the random noise (good), but also reduces the sharpness of the edges (bad) (very good smoothing filter – time domain action – but very bad low-pass filter – frequency domain action).

Analog Devices, *The Scientist and Engineer's Guide to Digital Signal Processing Moving Average Filters*, Ch. 15, 2003

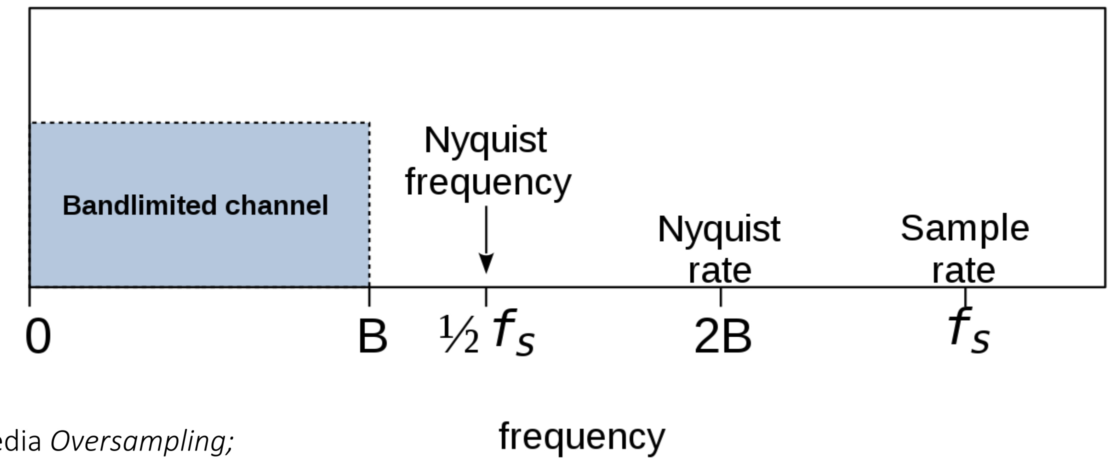
11.1.4 Averaging Techniques – Signal power for sampled signals

- Constant signal -> Employ Oversampling

Oversampling = sampling at higher than the Nyquist rate* =
2x highest frequency component of a bandwidth-limited signal

- Rationale: the observed signal is correlated since oversampling simply implies that the signal observations are strongly correlated
- NB: Oversampling can be helpful in avoiding aliasing by relaxing anti-aliasing filter performance requirements (without oversampling, it is very difficult to implement filters with the sharp cutoff necessary to maximize use of the available bandwidth)

Relationship of Nyquist frequency & rate (example)



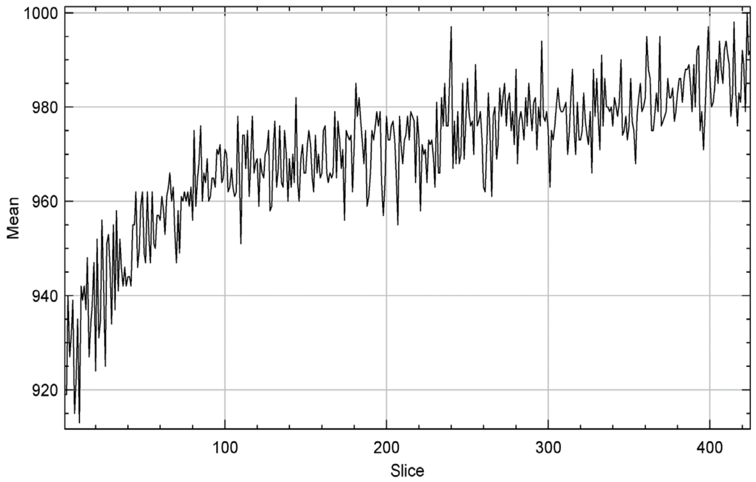
*which is not the Nyquist frequency (= half the sampling rate)!

By Bob K - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=94674142

Actel, *Improving ADC Results*, Jan. 2007; EN Wikipedia *Oversampling;*

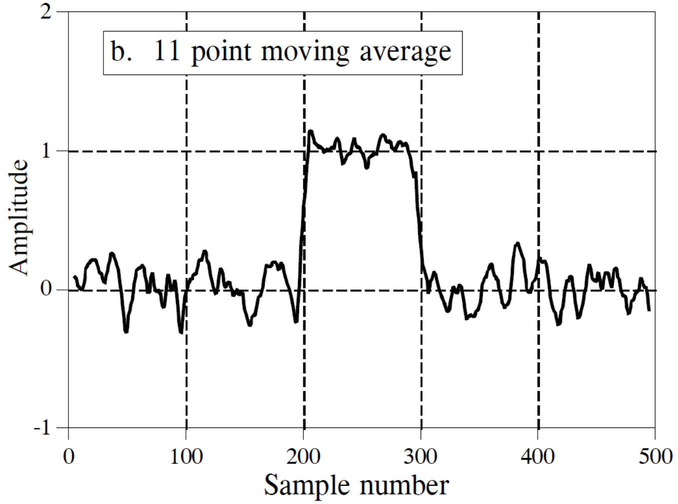
Take-home Messages/W11-1

- *Noise Reduction:*
  - Low-pass filtering, offset and drift correction
  - High-pass/Bandpass filtering
  - Averaging Techniques
    - Underlying conditions and noise power reduction
      - Independent noise sources
    - Signal-to-Noise ratio and its improvement
    - Filtering examples, oversampling



$$Var\{N_{avg}\} = \frac{1}{n} P_{noise}$$

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{E\{s^2\}}{\sigma^2}$$

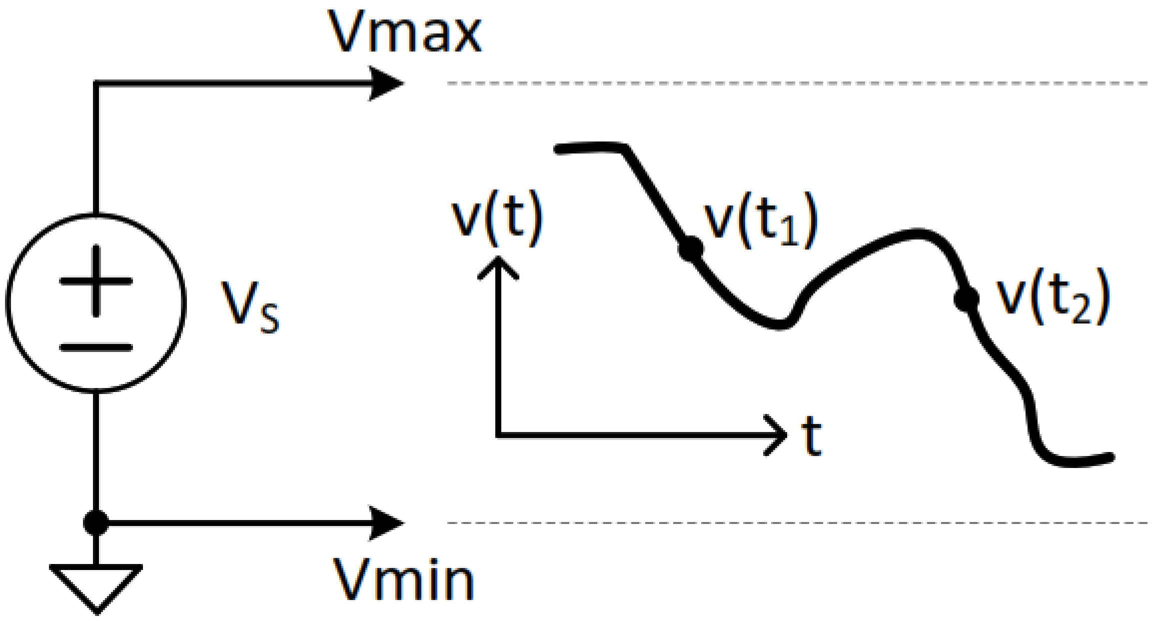


Outline

11.2.1 Electric Signals

- Electrical signal typically encodes the information as a voltage level v(t) versus time t.

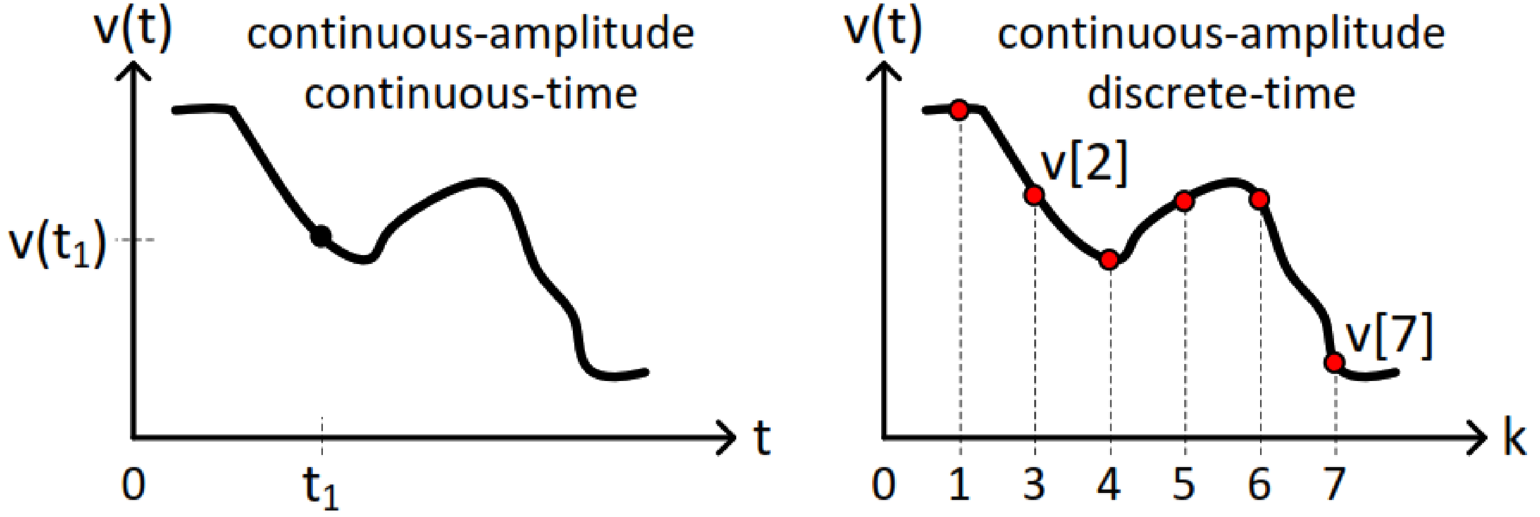
- Sometimes it could be a current level i(t) or charge level q(t).



B. Staszewski, *"Practical PLL Design for Frequency Synthesis and Clocking"*, *EPFL MEAD Course Slides, Lausanne 2016*

11.2.1 Electric Signals

- Analog signal amplitude is continuous
- Analog signal time can be continuous or discretized
- Discretization in time involves sampling methods (impulse, zero-order hold, sampled integration, etc.)

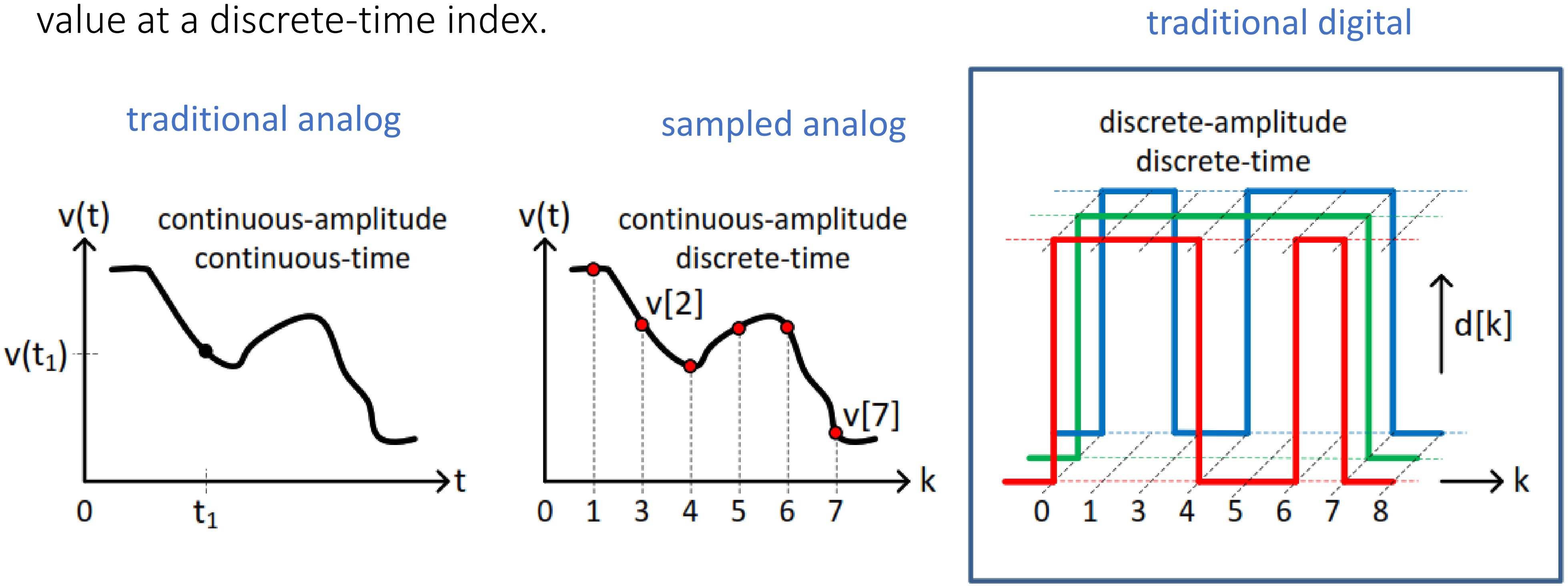


B. Staszewski, *"Practical PLL Design for Frequency Synthesis and Clocking"*, *EPFL MEAD Course Slides, Lausanne 2016*

11.2.1 Electric Signals

- Digital signals quantize v(t) into two levels (logic HIGH and logic LOW) and use an array of them

- Synchronous digital circuits use clocks, hence d[k] is a digital bit or word value at a discrete-time index.



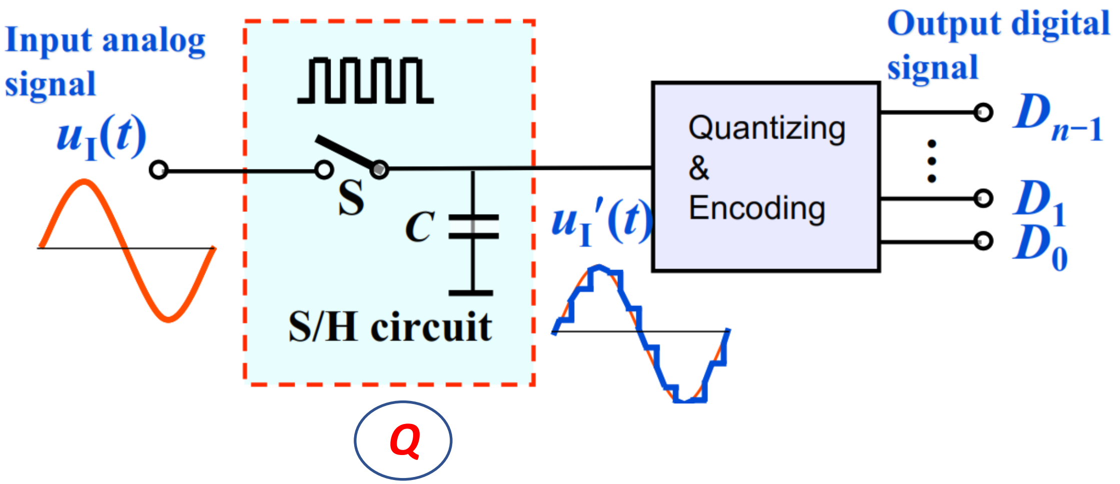
B. Staszewski, *"Practical PLL Design for Frequency Synthesis and Clocking"*, *EPFL MEAD Course Slides, Lausanne 2016*

11.2.2 Analog to Digital Converter (ADC)

- ADC provides a link between the analog world of transducers and the digital world of signal processing and data handling.

- ADCs are used virtually everywhere where an analog signal has to be processed, stored or transported in digital form.

- Some examples of ADC usage are digital voltmeters, cell phone, thermocouples, and digital oscilloscopes.



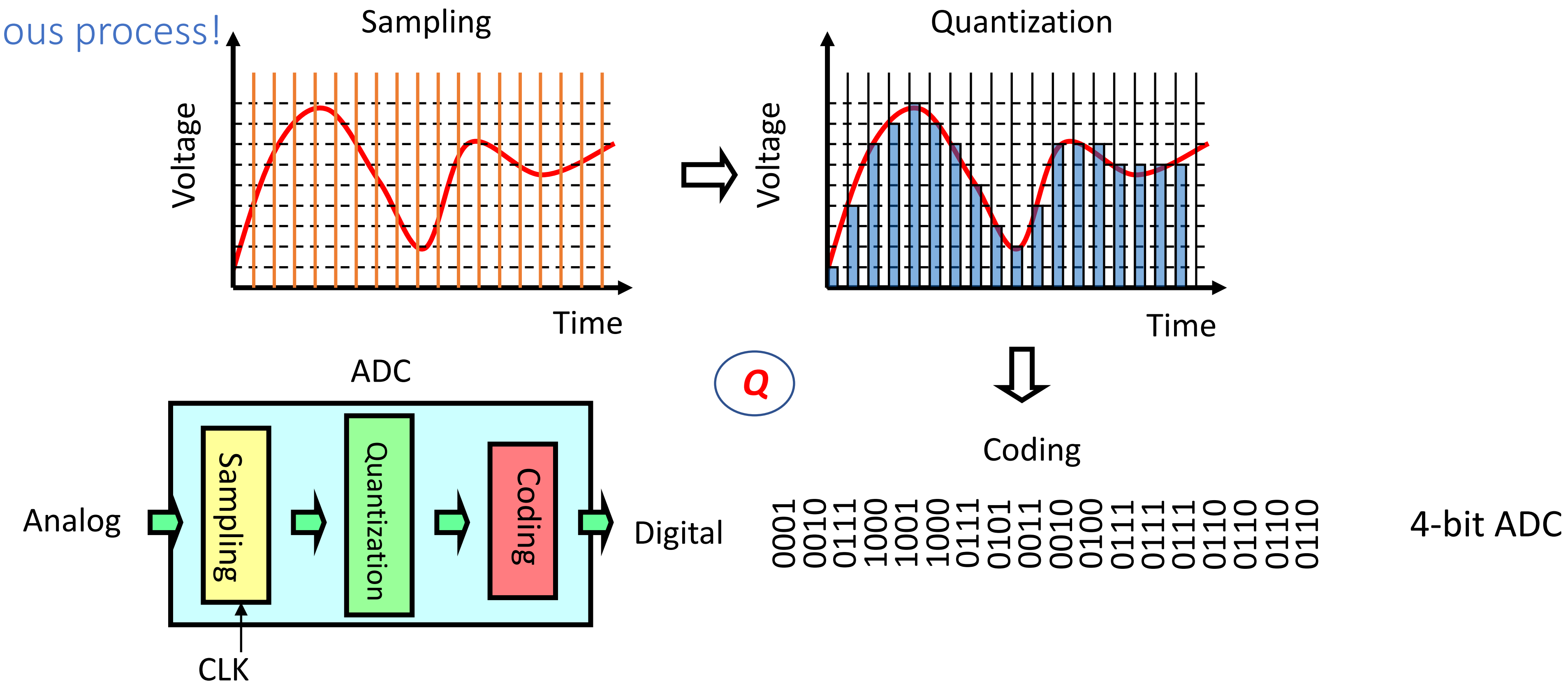
Two-step process:

1. Sampling and Holding (S/H)
2. Quantizing and Encoding (Q/E)

S/H: hold the input value constant during the time needed for a conversion (*conversion time*)

11.2.2 Analog to Digital Converter (ADC)

- An ADC (analog-to-digital converter) samples a voltage, a charge, or a current at discrete times and quantizes it (quantization in time and signal).
- Synchronous process!



E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 ADC – Ideal Case

- Resolution or LSB:

The smallest change in analog signal that will result in a change in the digital output.

$$\Delta V = \frac{V_r}{2^N}$$

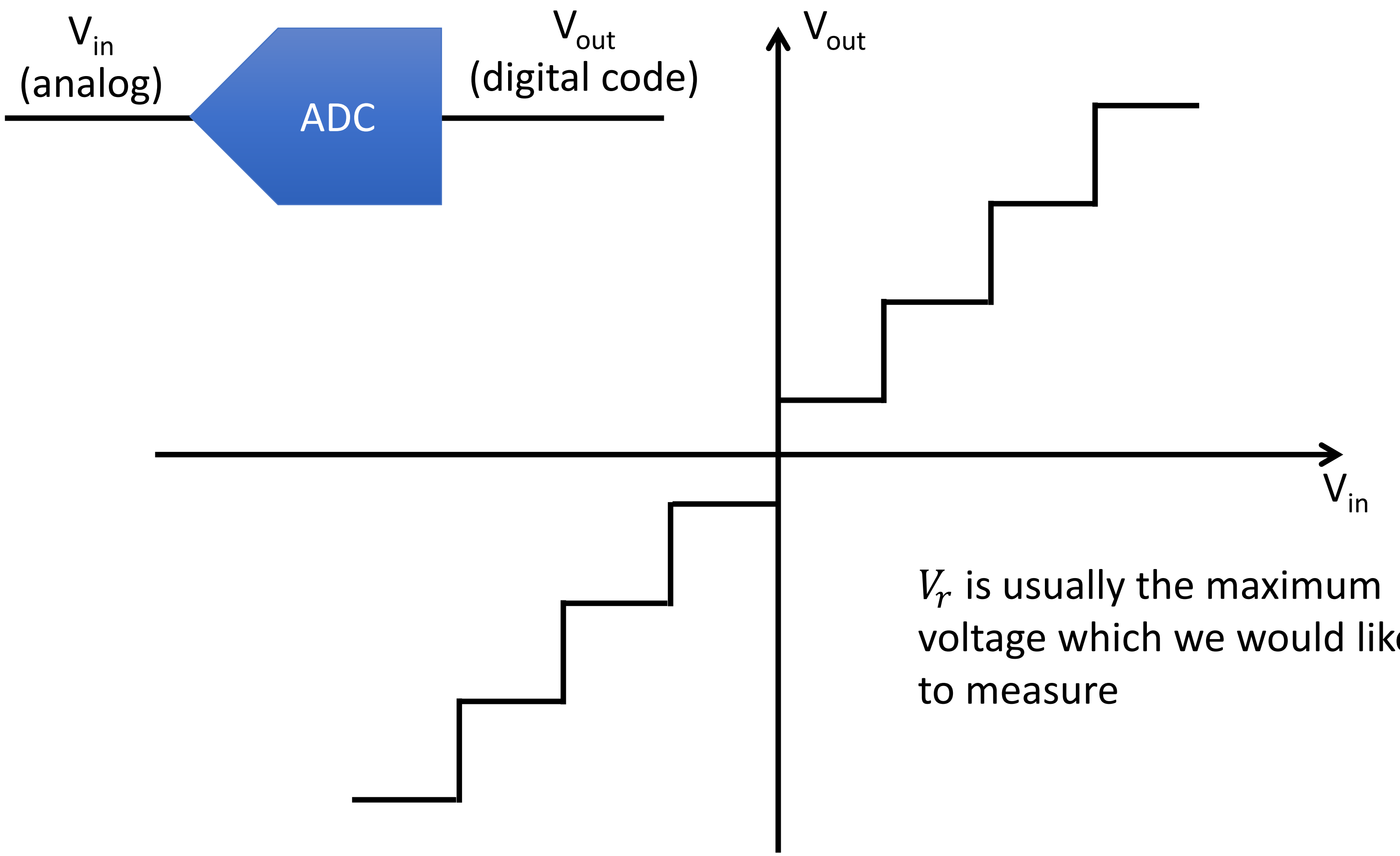
Q

V_r = Reference Voltage Level

N = # of bits

2^N = # of states

ΔV = Resolution



V_r is usually the maximum voltage which we would like to measure

E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

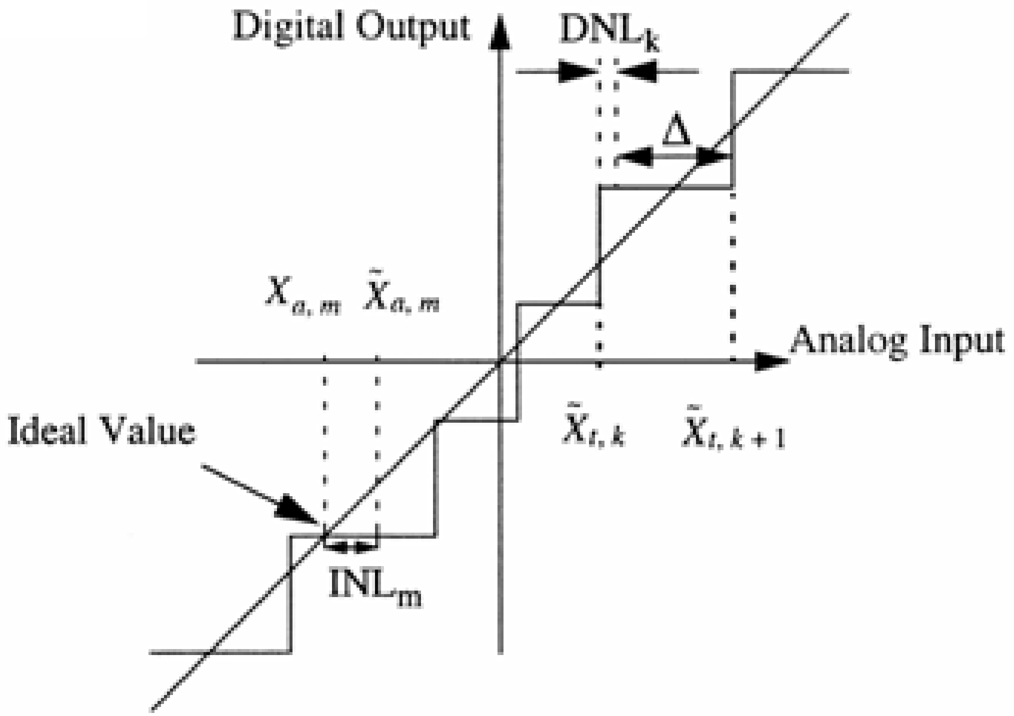
11.2.2 ADC – Real Case

- Non-idealities:
  - Differential non-linearity (DNL)
  - Integral non-linearity (INL)

$$DNL_j \equiv \frac{Width_{ACTUAL,j} - Width_{IDEAL}}{Width_{IDEAL}}$$

$$INL_j = \sum_{k=0}^{k=j} DNL_k$$

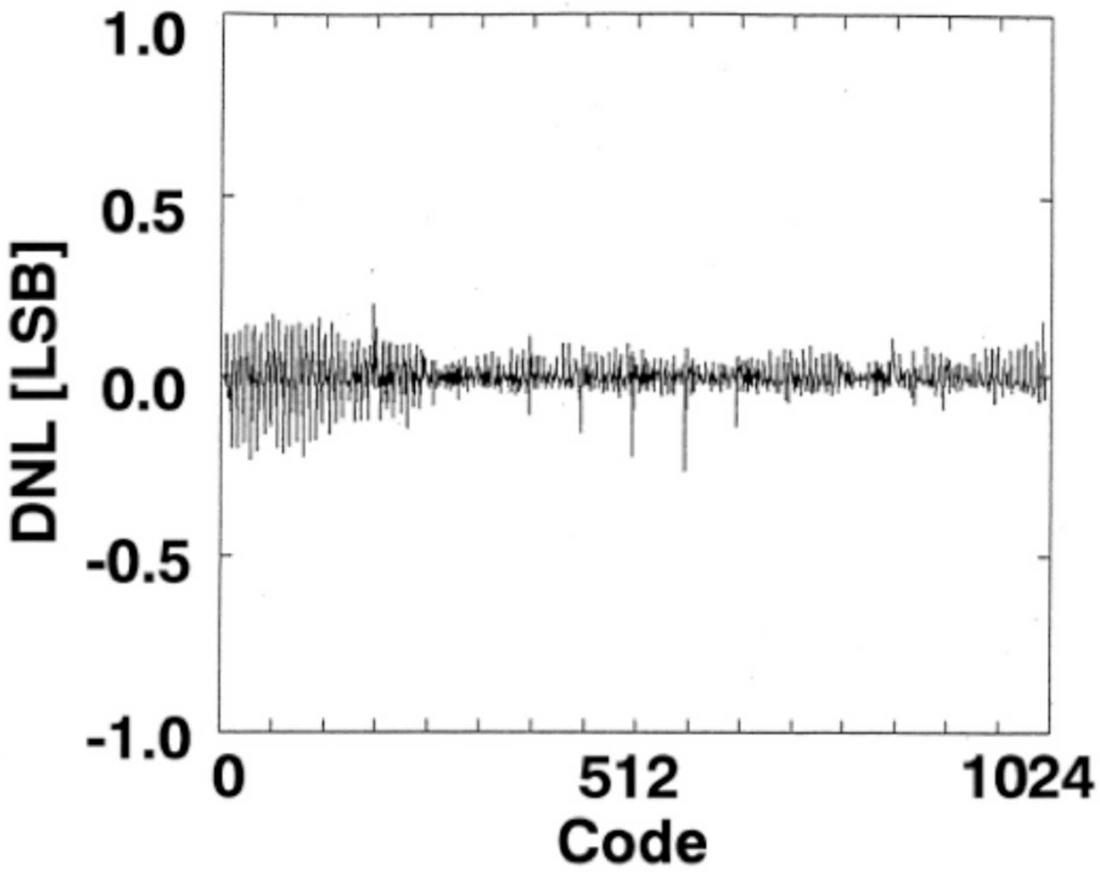
$$DNL_j = INL_{j+1} - INL_j$$

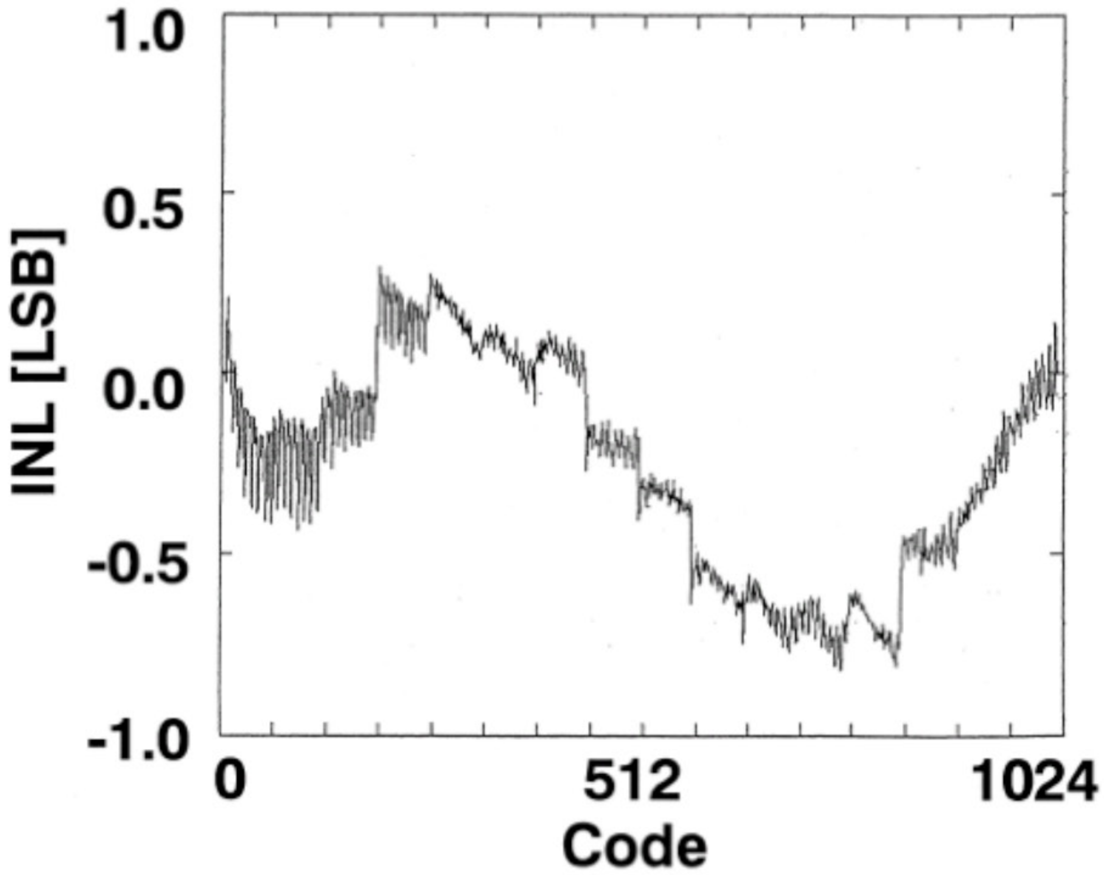


INL = deviation of transfer curve from ideal (linear)

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 ADC – Real Case, Example





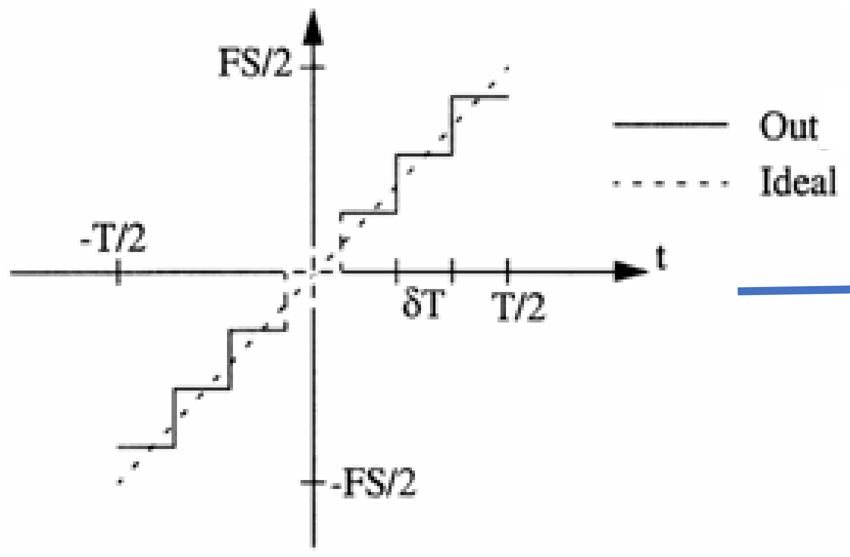
Q

Source: A. Matzusawa

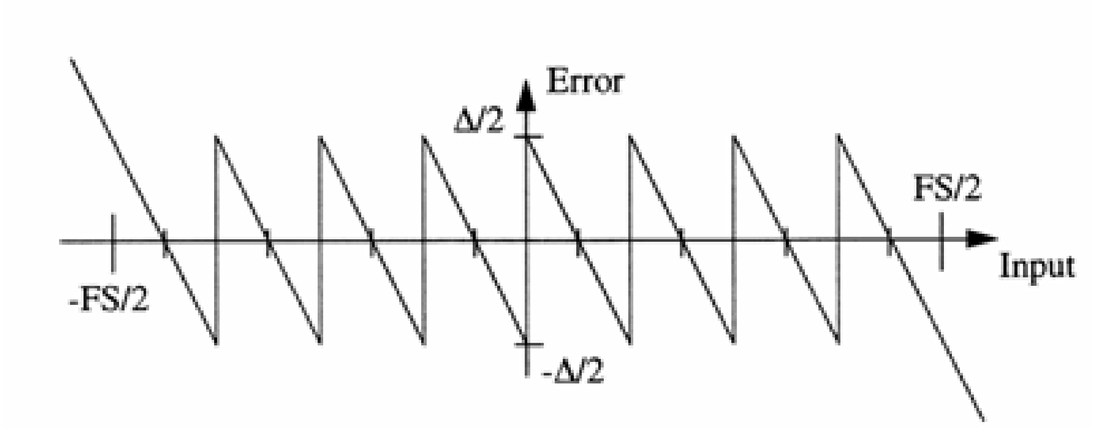
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 ADC – Quantization Noise

Transfer characteristics



Quantization noise (error = Out-In)



$$\sigma_{noise}^2 = P_{noise} = \int_{-\Delta/2}^{\Delta/2} e^2 P_U(e)de = \int_{-\Delta/2}^{\Delta/2} e^2 \frac{1}{\Delta} de = \frac{\Delta^2}{12}$$

Uniform distribution (ideal ADC)!

$$PDF\colon\ P_U(e) = \begin{cases} \frac{1}{\Delta}, & |e| < \frac{\Delta}{2} \\ 0, & \text{otherwise} \end{cases}$$

See also W9 3.0.1

E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.2.2 ADC – Quantization Noise vs. Oversampling

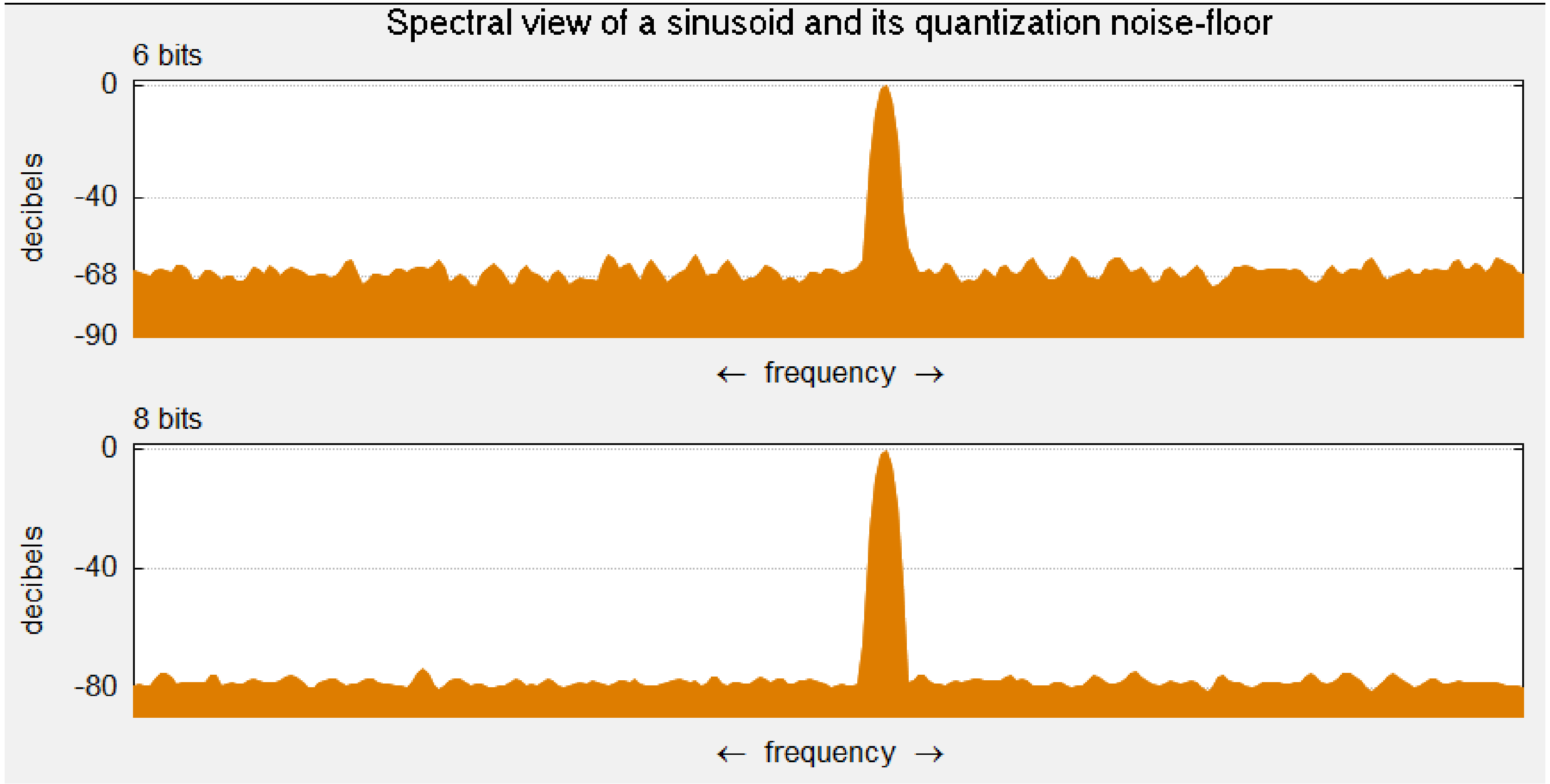
- Signal-to-quantization-noise ratio (SQNR):

64 levels (6 bits) vs. 256 levels (8 bits) -> measurable difference in the noise floors

$$SQNR = 20log_{10}(2^Q) = 6.02 \cdot Q + 1.76 \quad \text{dB, Q=\# of quantization bits}$$

- Is distributed from 0 to the Nyquist frequency (= half the sampling rate)

- *In addition*: if part of the ADC's bandwidth is not used, as is the case with oversampling, some of the quantization error will occur out-of-band, effectively improving the SQNR for the bandwidth in use.



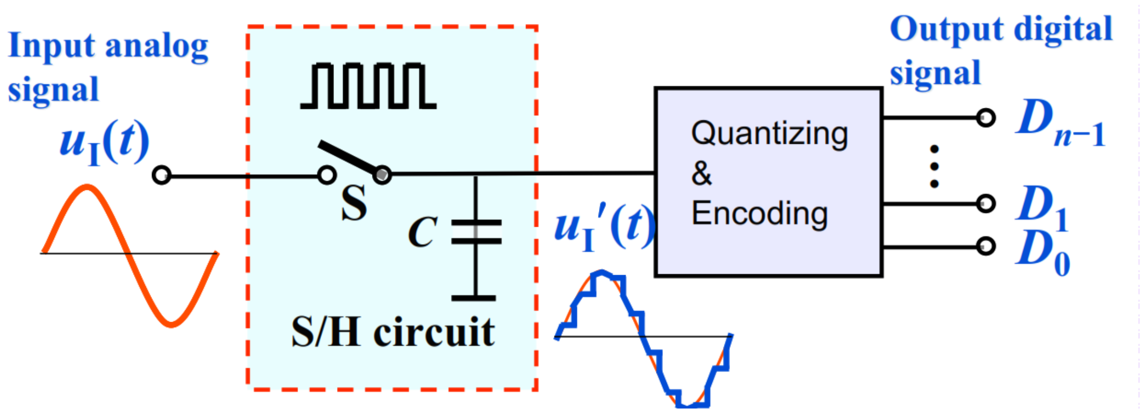
EN Wikipedia *Analog-to-digital converter*

11.2.2 ADC – Quantization Noise

- Example of oversampling application: audio frequency ADCs

- Q: sampling of a constant signal -> do I only have quantization noise?

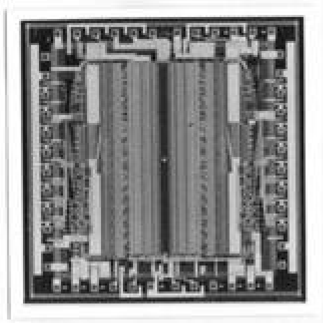
Q



-> in practice no, because of kTC (thermal) noise intrinsic in the S/H process!

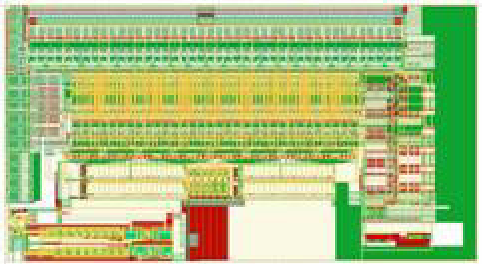
11.2.2 ADC in CMOS

Matsuzawa, ISSCC 1991



6b, 1GHz ADC
2W
1.5um Bipolar

Sushihara, et al, ISSCC 2000

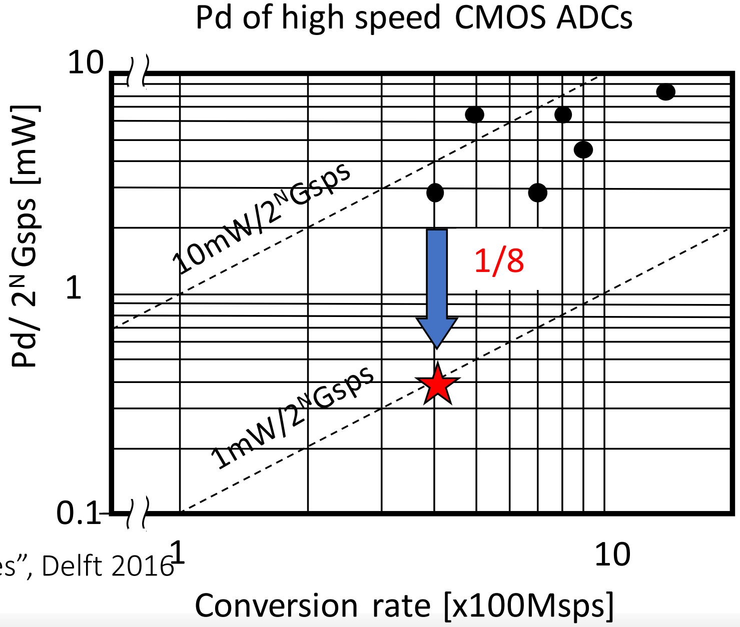


6b, 800MHz ADC
400mW, 2mm^2
0.25um CMOS

Sushihara and Matsuzawa, ISSCC 2002

World lowest Pd HS ADC

7b, 400MHz ADC
50mW, 0.3mm^2
0.18um CMOS



Pd = power dissipation. Horizontal = conversion rate.
Power per bit normalized in units of Gsps.

Source: A. Matzusawa

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 30 Years of ADC Progress

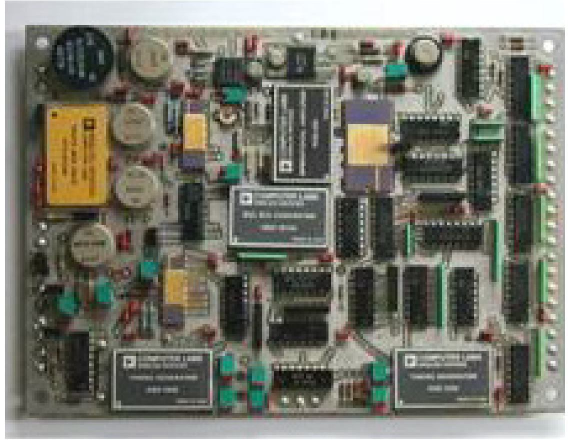
- Improvements in the last 20 years:

  1/2000 x power   1/200,000 x cost

1980

Conventional product

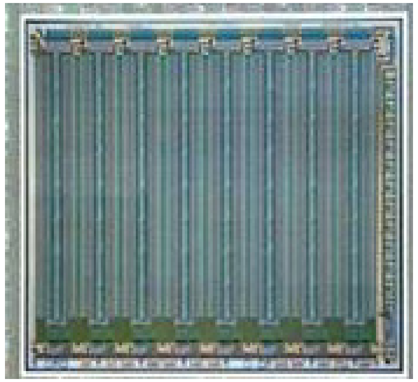
Board Level (Disc.+Bip)
20W
$ 8,000



1982

World 1st Monolithic

Bipolar (3um)
2W
$ 800

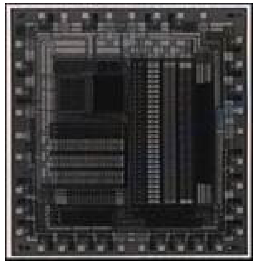


T. Takemoto and A. Matsuzawa, JSC, pp.1133-1138, 1982.

1993

World lowest power

CMOS (1.2um)
30mW
$ 2.00

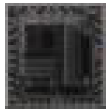


K. Kusumoto and A. Matsuzawa, ISSCC 1993.

2006

SoC Core

CMOS (0.15um)
10mW
$0.04



Source: A. Matzusawa

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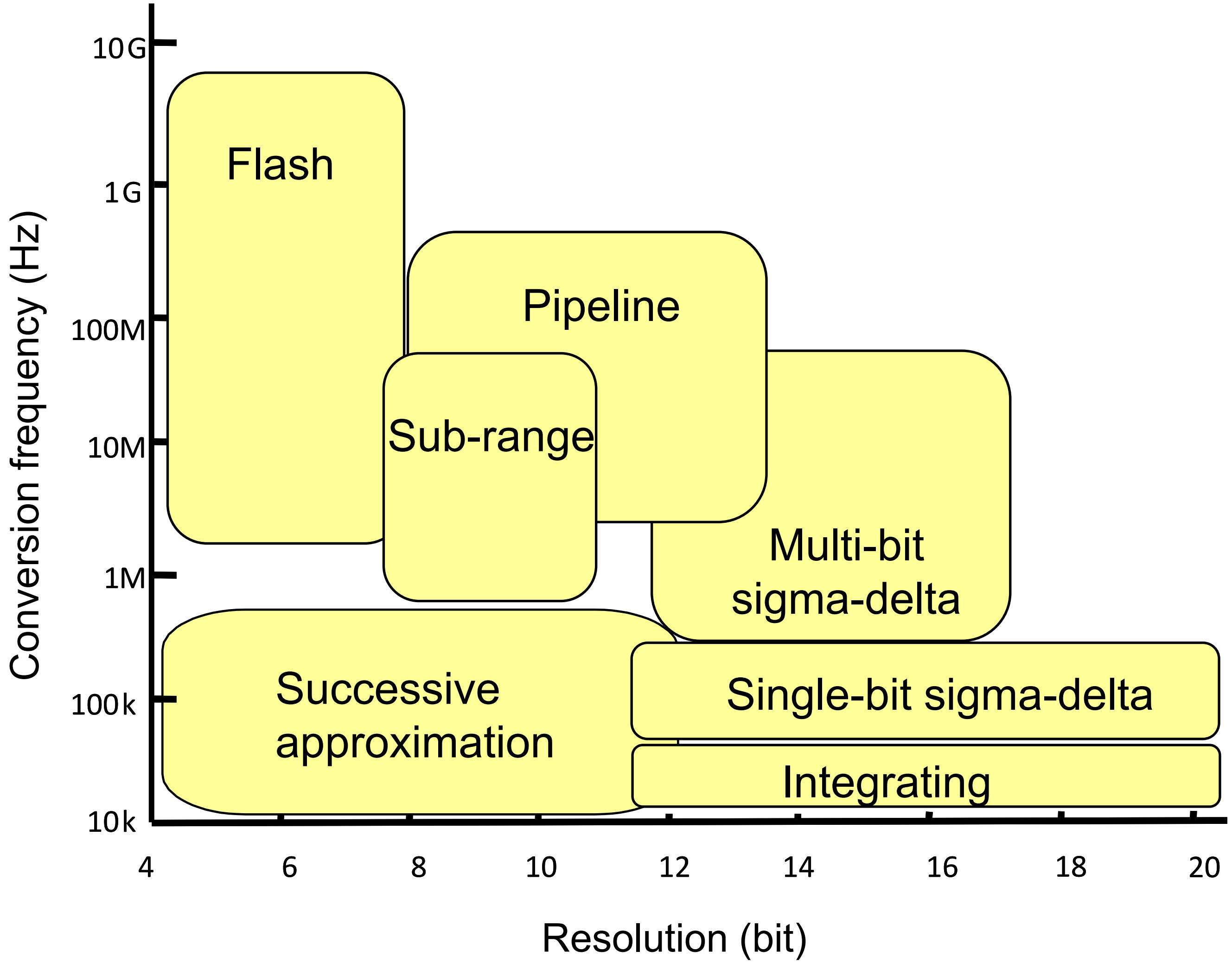
E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

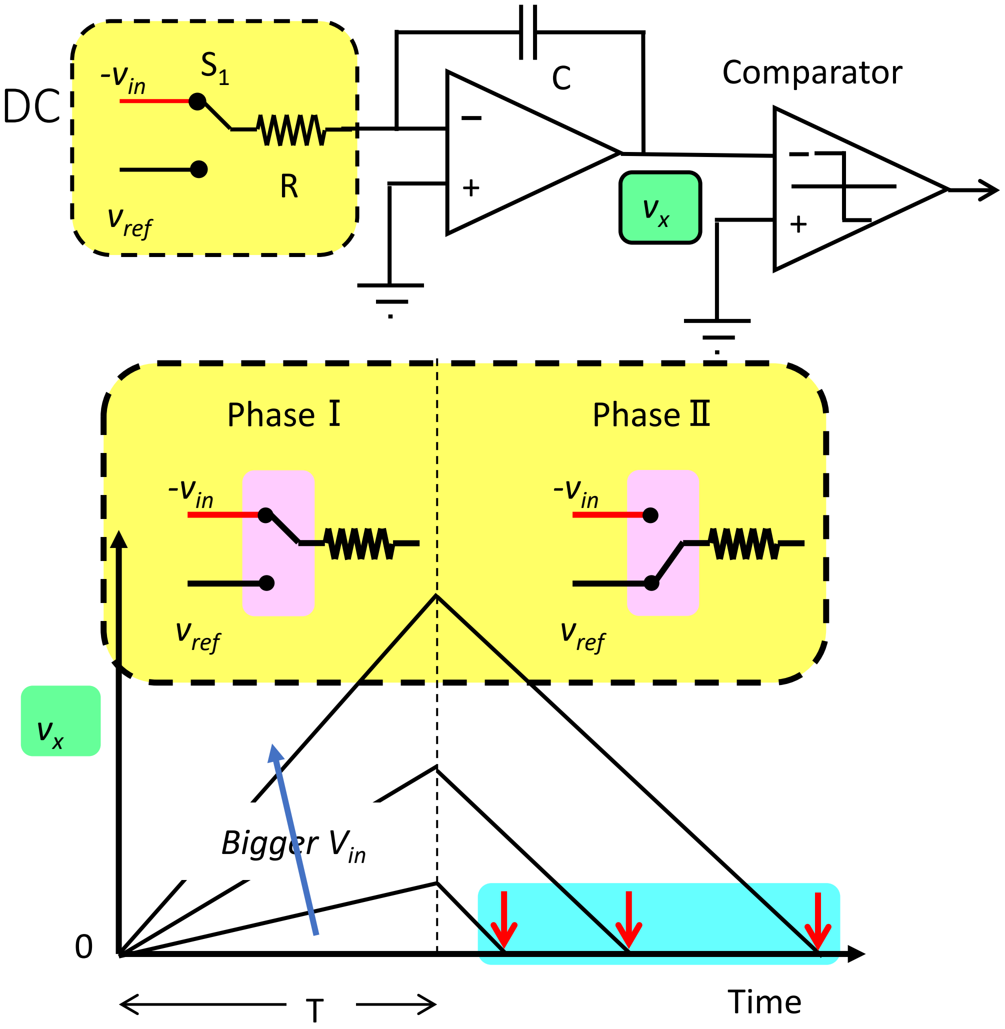
11.2.2 ADC - Architectures



E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.2.2 Integrating ADC

- Perhaps the most frequently used ADC
- Slow but high resolution
- Used for example in voltmeters



Features:
High resolution (<20b)
Low speed
Small DNL
Can implement zero offset voltage
Small area

Integrating OpAmp with capacitive feedback – charge capacitor in phase 1, discharge in phase 2 (opposite polarity), and measure the time until complete discharge (Vref = 0).

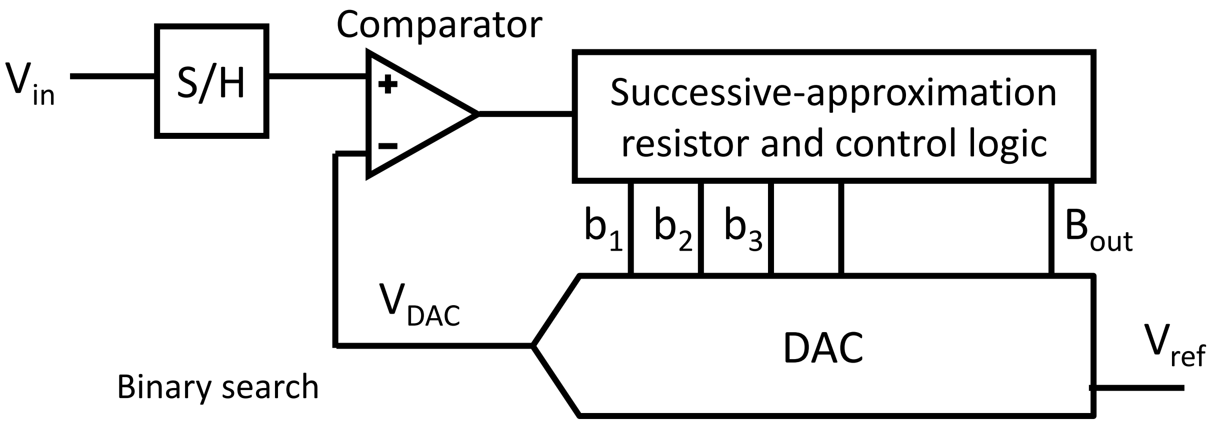
$$V_x(T) = \int_0^T \frac{-V_{in}}{RC} d\tau = \frac{V_{in}}{RC} T$$

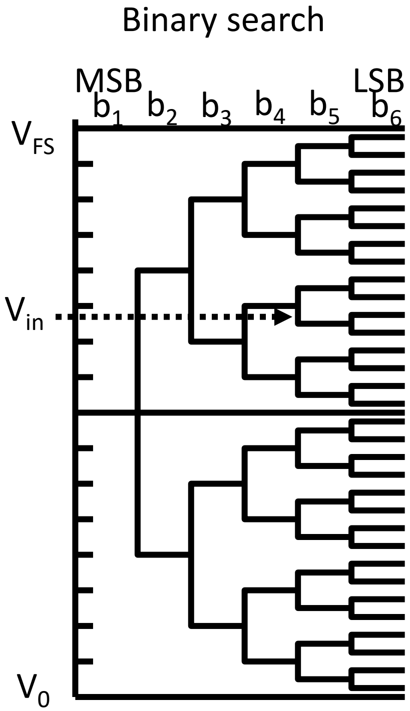
Concept: A. Matzusawa

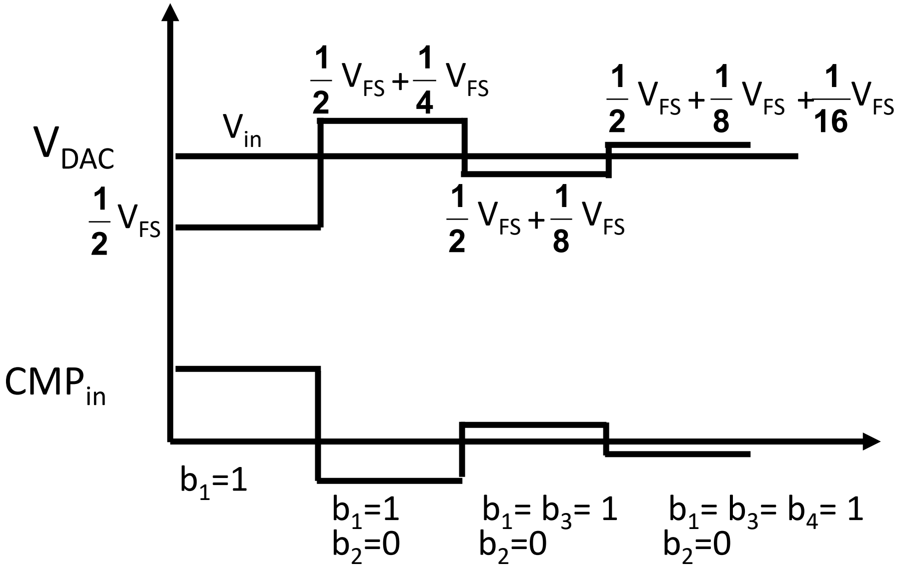
E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.2.2 Successive-Approximation ADC

- Uses a n-bit DAC to compare DAC and original analog results.
- Successive Approximation Register (SAR) supplies an approximate digital code of V_{in} to DAC.
- Comparison changes digital output to bring it closer to the input value.
- Uses Close-loop Feedback Conversion.
- n cycles are needed for n bits







E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

Concept: A. Matzusawa

11.2.2 Successive-Approximation ADC

Advantages

- Capable of high speed and reliable
- Medium accuracy compared to other ADC types
- Good trade-off between speed and cost
- Capable of outputting the binary number in serial format
- Conversion time independent of amplitude of V_{in}

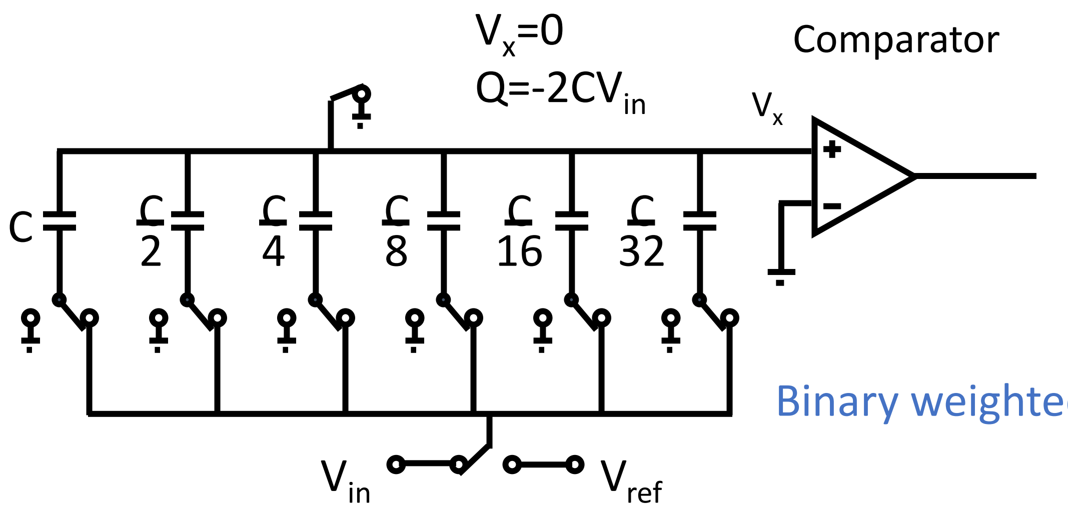
Disadvantages

- Higher resolution successive approximation ADCs will be slower
- Speed limited to ~ 5 Msps

11.2.2 Charge-redistribution ADC

S

1) Sampling

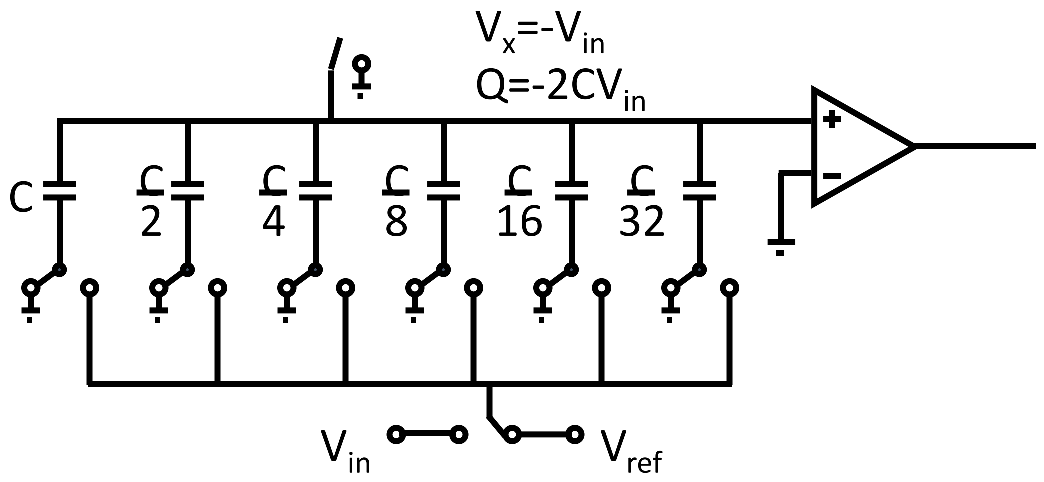


1) Input signal is stored on a capacitor bank with a total capacitance value of 2C.

"C" is the unit capacitor and is laid-out in a standardized manner.

Binary weighted Capacitor array

2) Hold



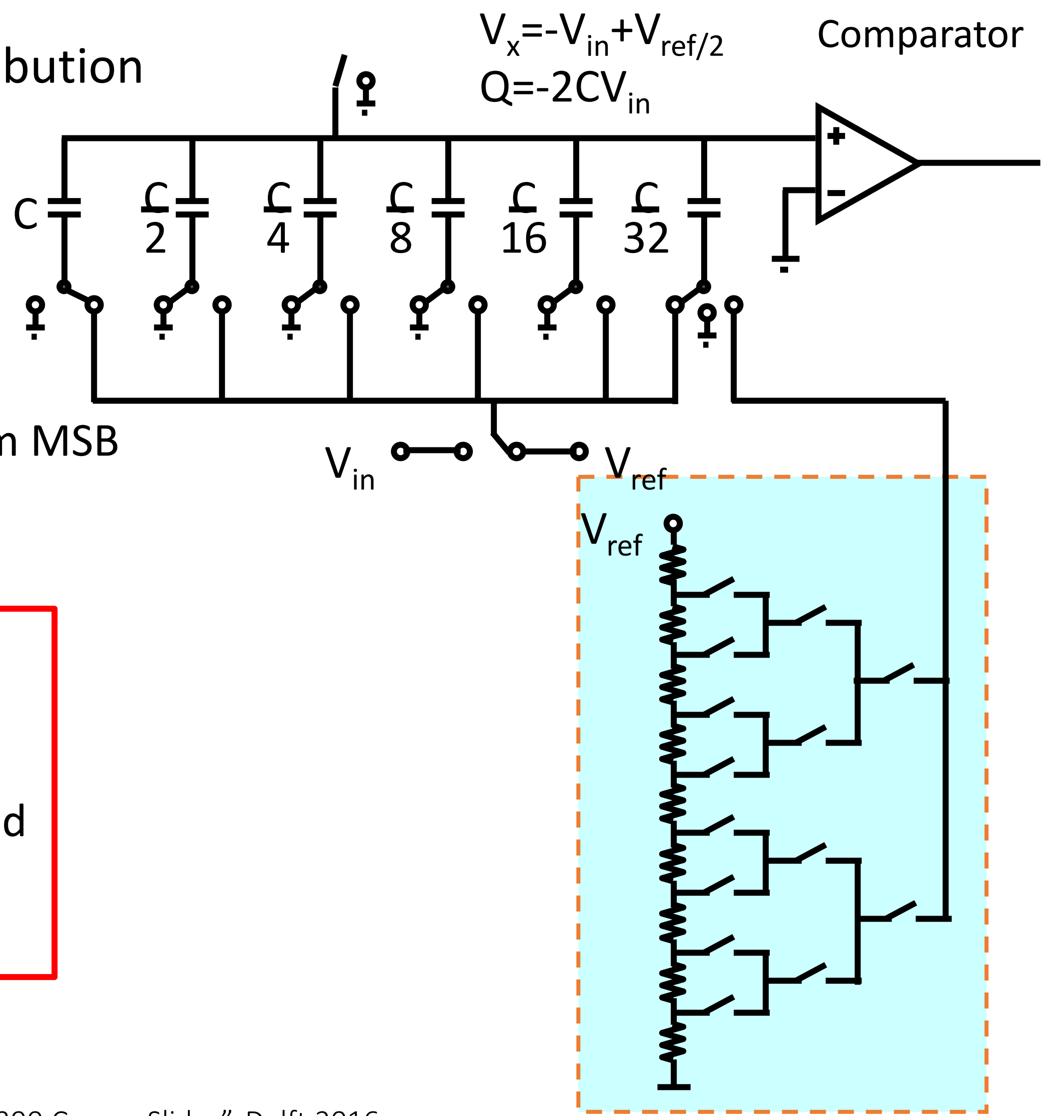
2) NB: can not hold the charge indefinitely!

Source: A. Matzusawa

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 Charge-redistribution ADC

3) Charge redistribution



Determine from MSB

3) The ground plates of the capacitors are switched one after the other from ground to the reference voltage. Depending on the original value of the input voltage, the comparator will decide to keep the MSB switch in this position or return to ground. Every bit is subsequently tested.

If needed

Resistor ladder for higher resolution

Features:
High resolution
Low power
Relatively low speed
Easy calibration
Needs multi-clock

Source: A. Matzusawa

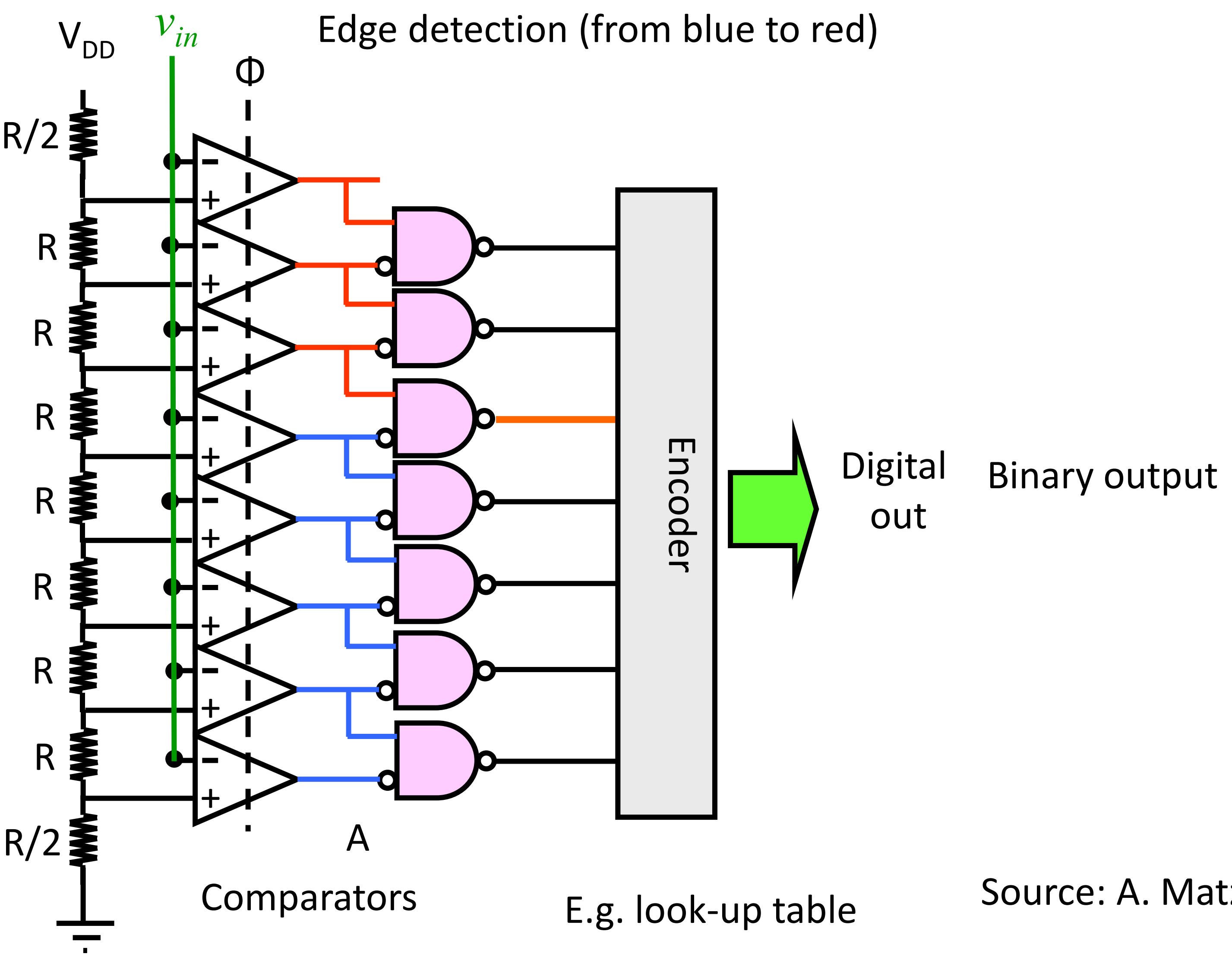
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 Flash (Direct Conversion) ADC

- Fundemental Components for N bit Flash (direct conversion) ADC:
  - 2^N comparators
  - 2^{N-1}Resistors
  - Control Logic

Features:

- Low resolution (<8 bits)
- High power
- Ultra-high speed
- Large input capacitance



Source: A. Matzusawa

📖 E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.2.2 Flash (Direct Conversion) ADC

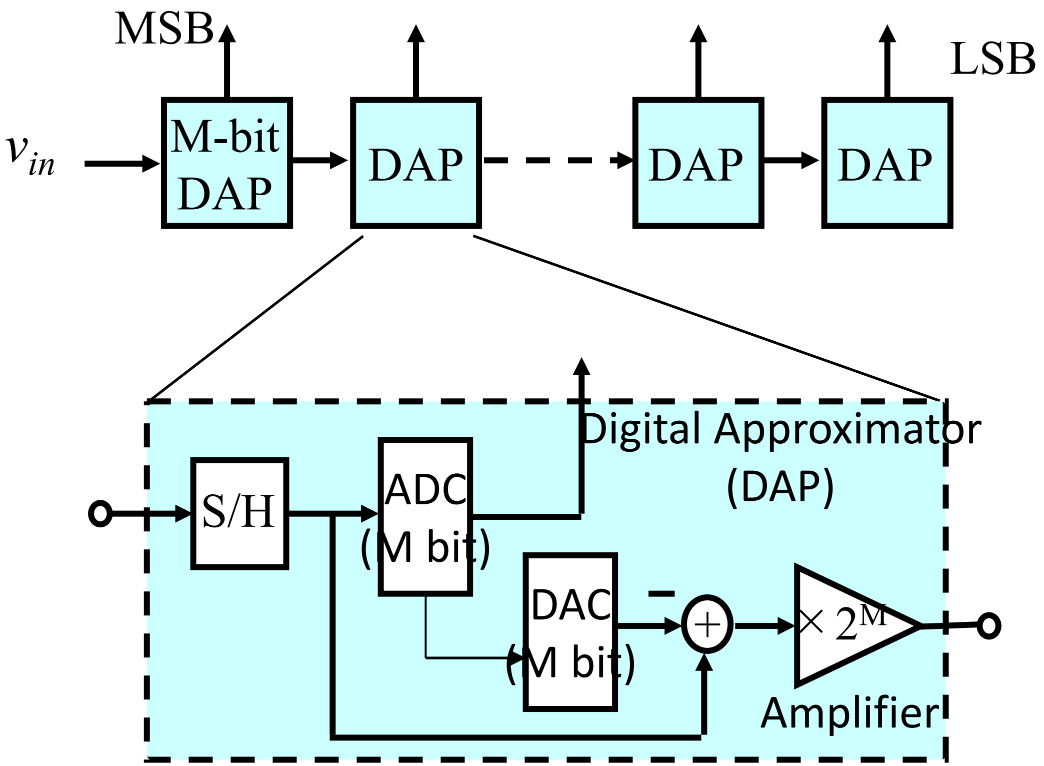
<u>Advantages</u>

- Very fast (fastest)
- Very simple operational theory
- Speed is only limited by gate and comparator propagation delay

<u>Disadvantages</u>

- Expensive
- Prone to produce glitches in the output
- Each additional bit of resolution requires twice the comparators

11.2.2 Pipelined ADC



Conventional M is 1 or 1.5

- Each amplification stage reduces the input referred noise
- Stages can be sized accordingly

Features:
High resolution (<20 bits)
Low power
Moderate speed
Appropriate for column-parallel mode

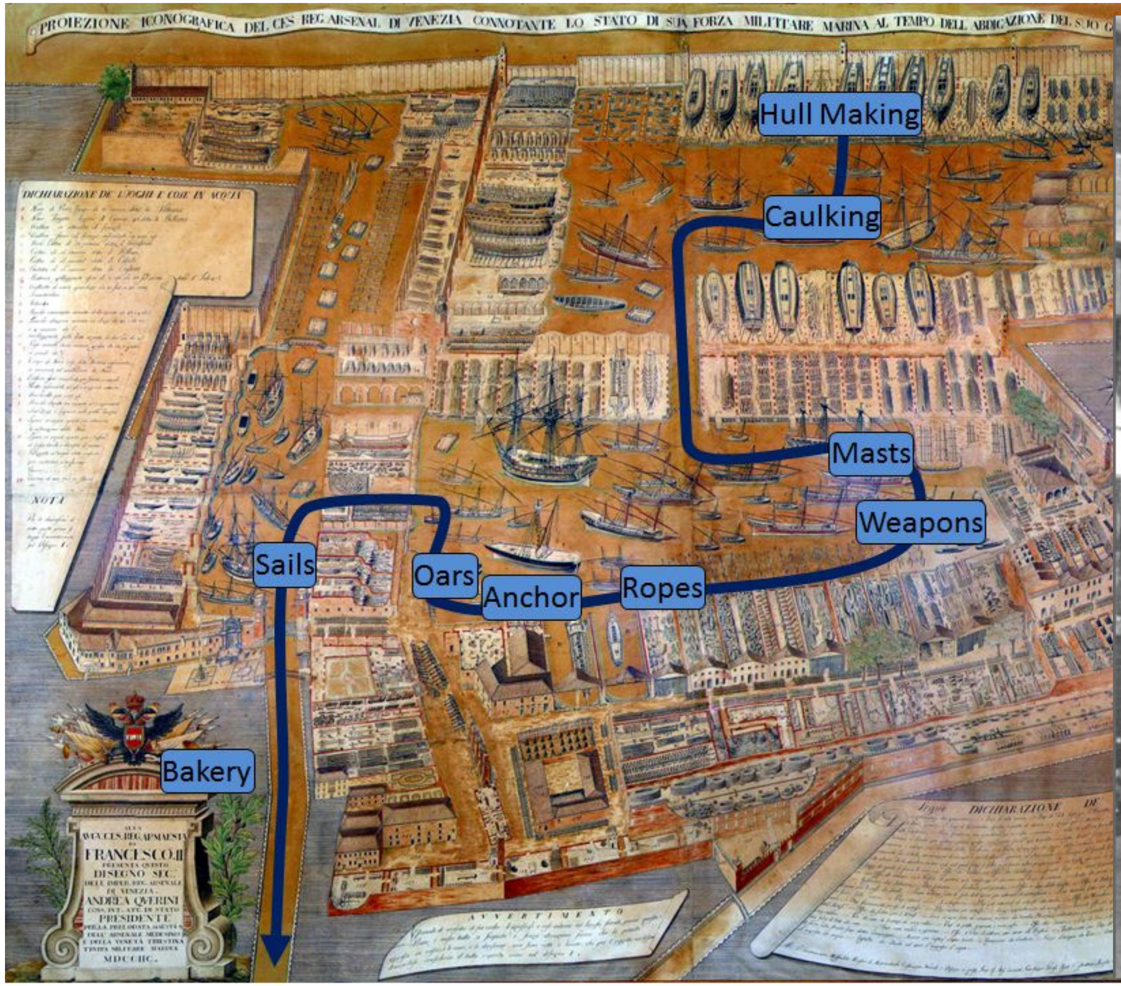
Refined version of successive approx. ADC, which has "only" a single comparator and DAC
Advantage: works in a pipeline fashion – don't need to wait until a conversion finishes to start another one!

Source: A. Matzusawa

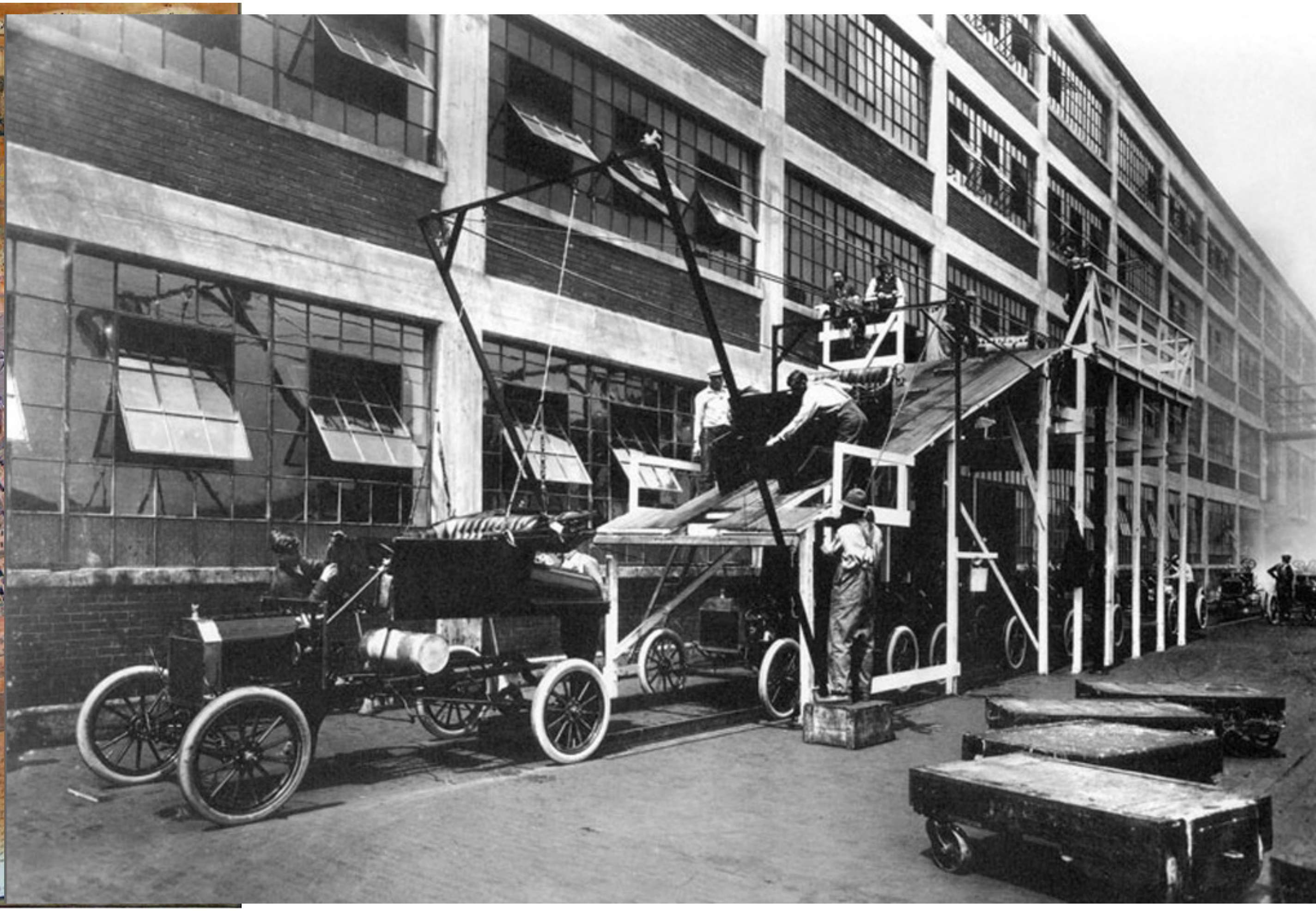
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.2.2 Assembly Line/Pipeline

Arsenal of Venice Material Flow Overview (1797)

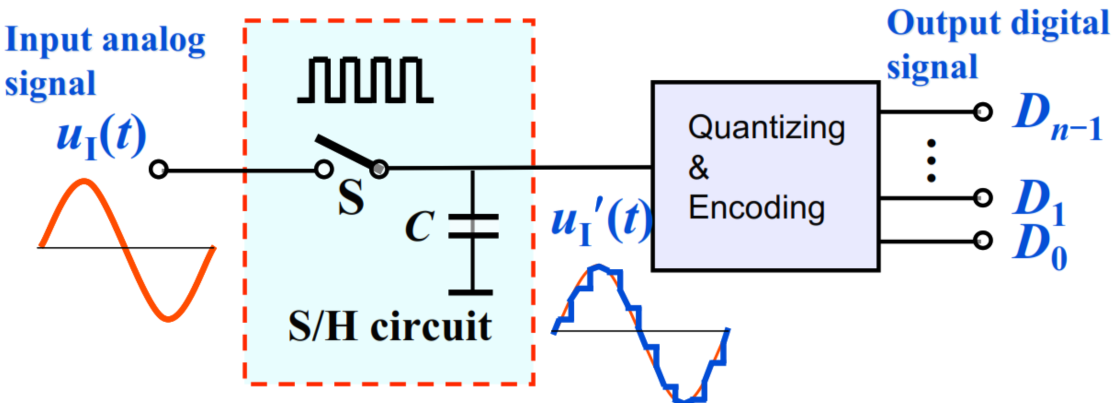


Henry Ford's Model T assembly line (1913)

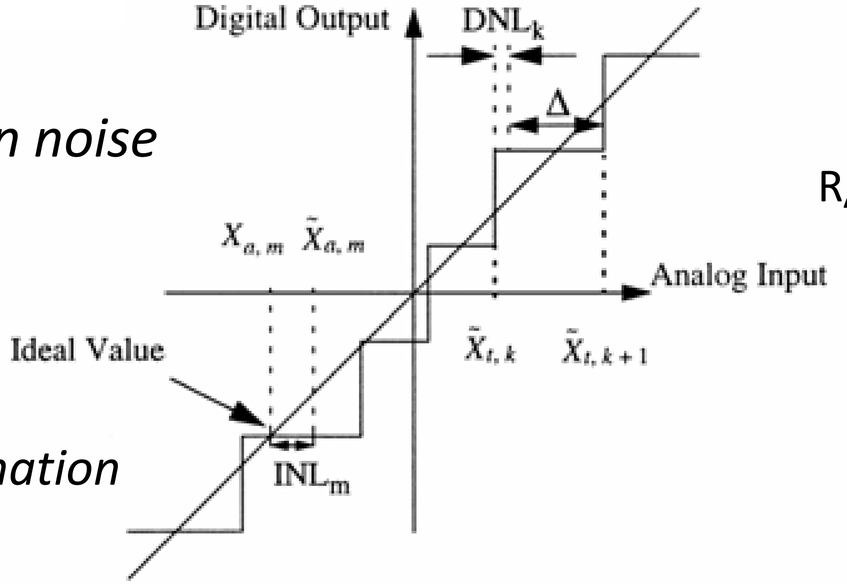


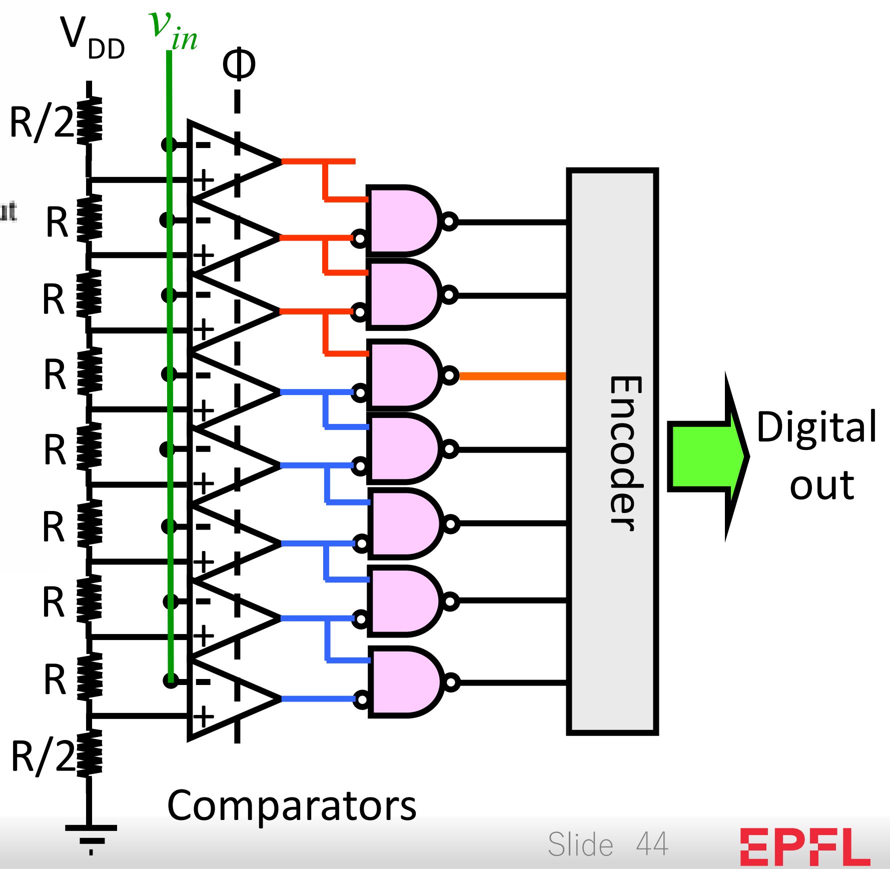
https://www.allaboutlean.com/material-flow-arsenal-of-venice/arsenal-of-venice-material-flow-overview/ https://www.wwno.org/post/henry-fords-assembly-line-turns-100

Take-home Messages/W11-2



- *Sampling of electrical signals*
- *Analog-to-Digital converters:*
  - *Basics*
  - *INL, DNL, Quantization noise*
  - *ADC architectures*
    - *Integrating*
    - *Successive-approximation*
    - *Flash*
    - *Pipelined*





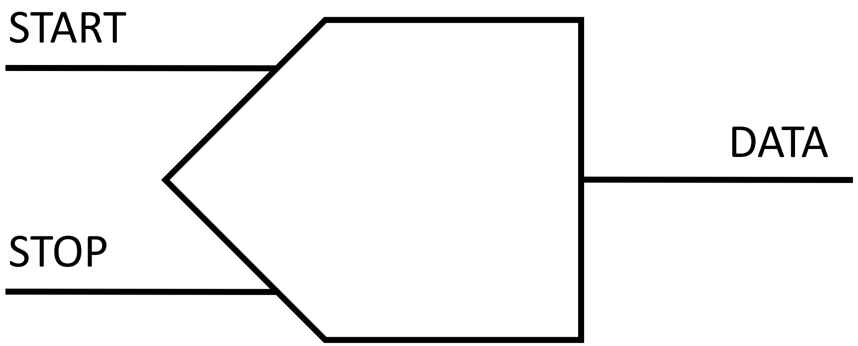
Outline

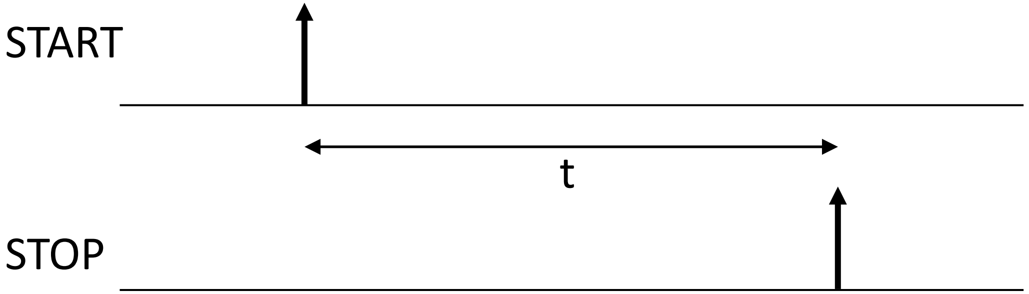
11.3 Time to Digital Converter (TDC)

- TDCs have been used for more than 20 years in the field of particle and high-energy physics, where precise time-interval measurement is required.
- Time-to-Digital Converters (TDCs) are suitable for use in most time measurement applications.
- These TDCs measure time intervals from zero to the millisecond range at a resolution of better than 10ps.

Q

- These products are suitable for use in industrial, medical, automotive and scientific systems and equipment.

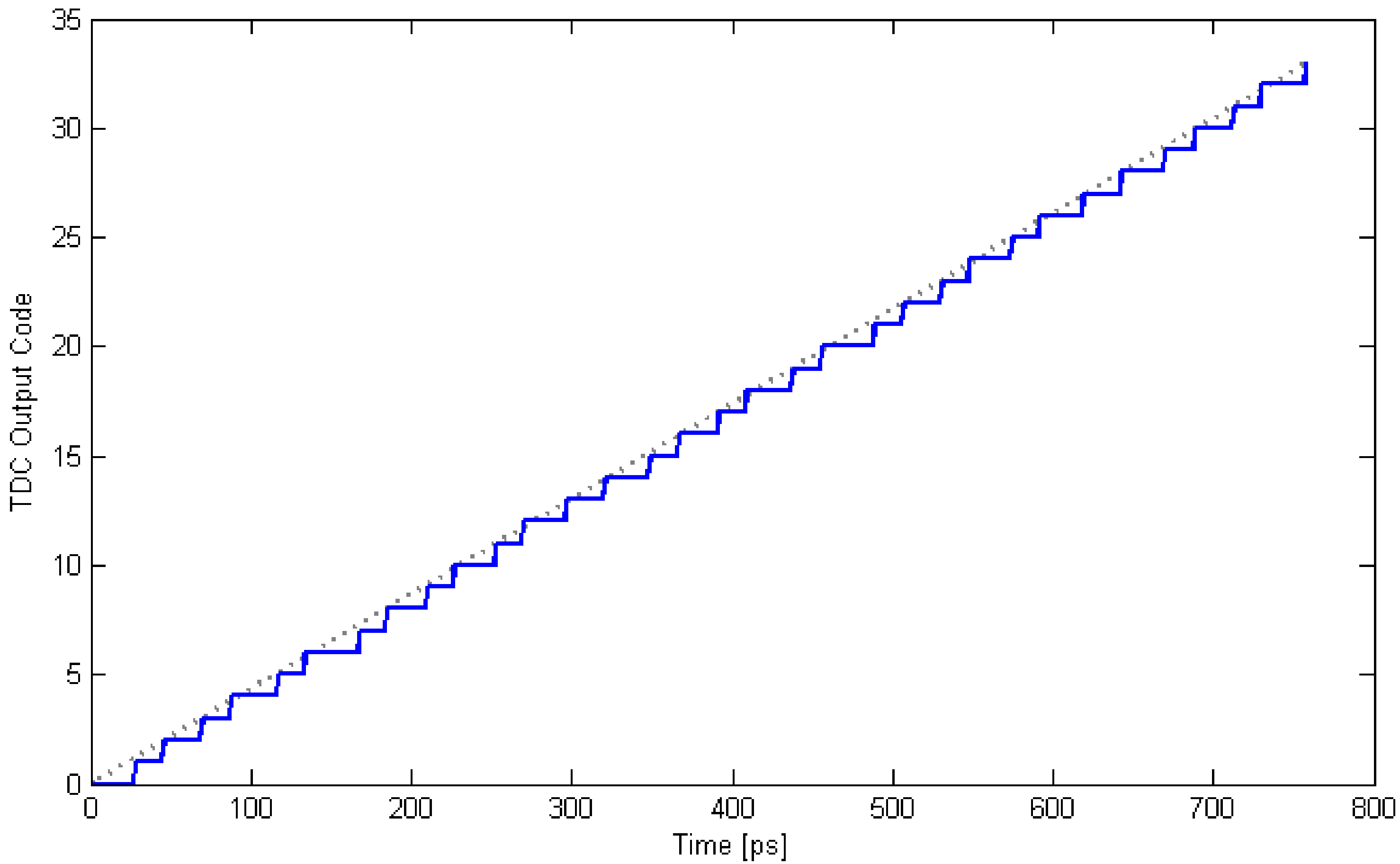




E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.3 TDC – Nonidealities

- Signals are non-Dirac
  - Non-zero rise time
  - Non-zero width
- START-STOP sequence is not regular
- Signals (e.g. clocks) have jitter in
  - Time
  - Amplitude



- Temperature, Supply voltage, process variations -> PVT variations (process, voltage, temperature) -> process corners

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

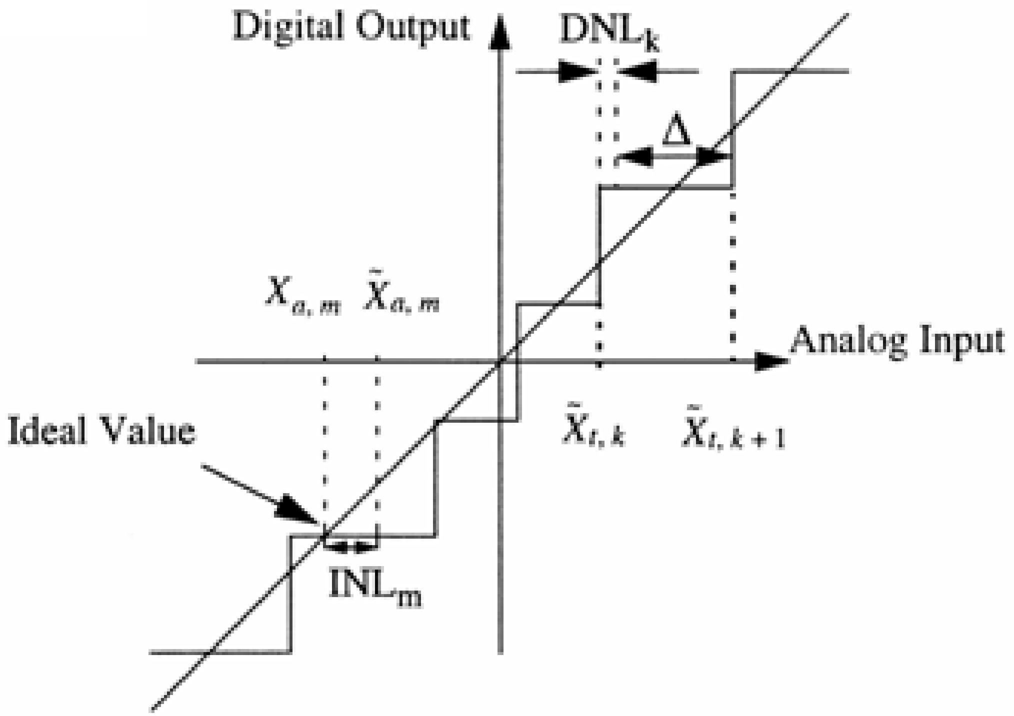
11.3 TDC – Real Case

- Non-idealities
  - Differential non-linearity (DNL)
  - Integral non-linearity (INL)

$$DNL_j \equiv \frac{Width_{ACTUAL,j} - Width_{IDEAL}}{Width_{IDEAL}}$$

$$INL_j = \sum_{k=0}^{k=j} DNL_k$$

$$DNL_j = INL_{j+1} - INL_j$$



Width on x-axis: time bin width.

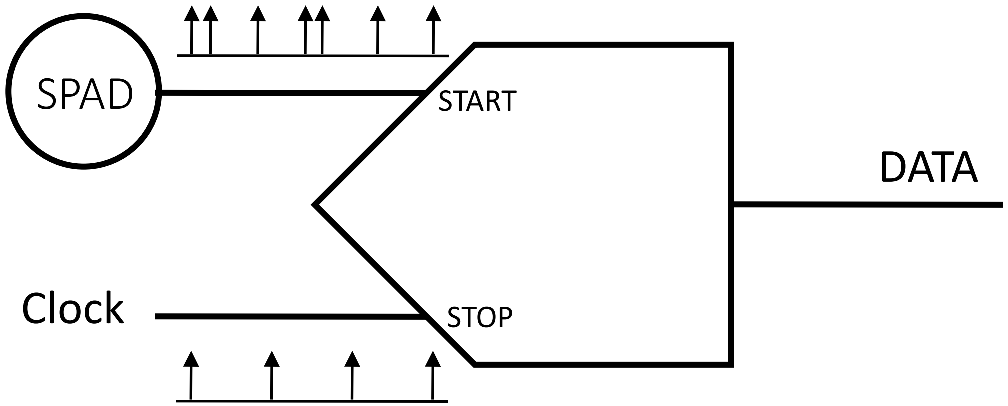
E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.3 TDC – Metrology: Optical Tests

A) (Code) Density test: free running SPAD (e.g. natural light source)*

B) Single-shot experiment (e.g. repetitive pulsed laser illumination):

- Histogram Δt_i, i=[1…N] (Time-correlated single-photon counting – TCSPC)

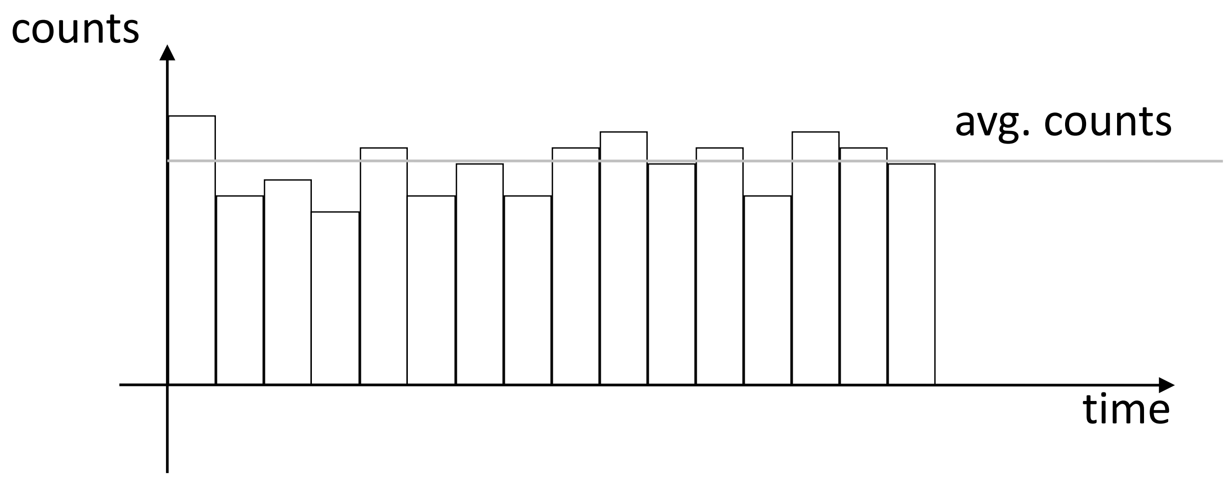


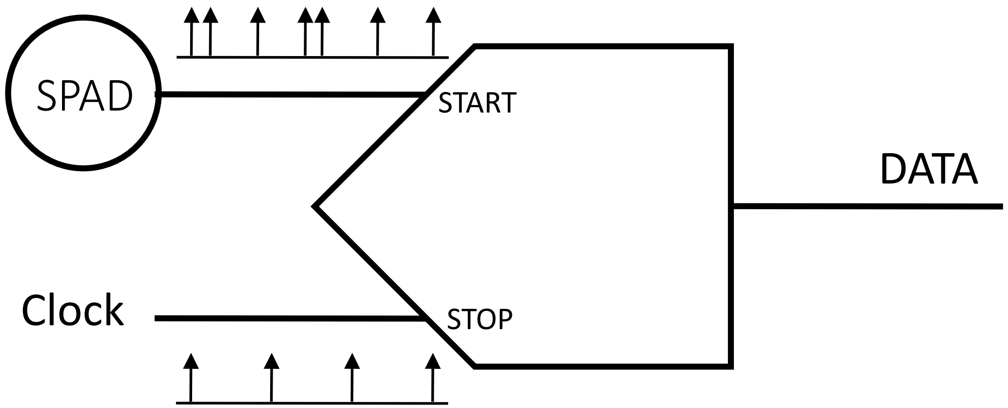
*could also be done electrically

📖 E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3 TDC – Metrology: (Code) Density Test

- Poisson-distributed uniform START generator (e.g. by using a free running SPAD and a natural light source – no laser)
- Measure statistics of TDC measurements per bin
- Normalize to average counts -> differences are DNL points





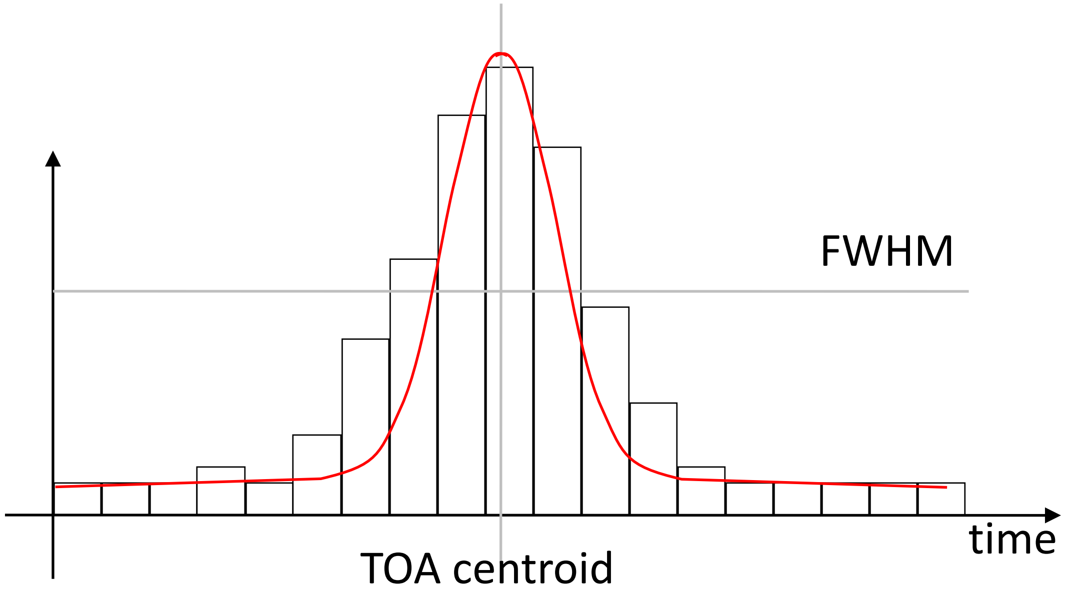
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

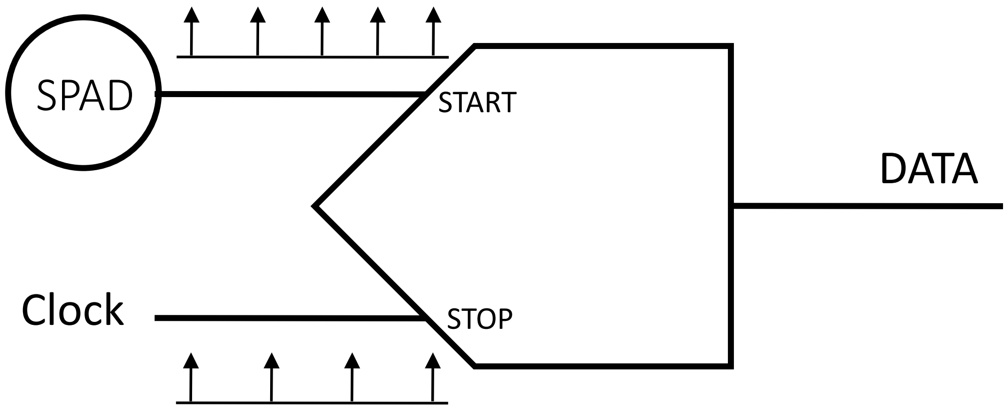
11.3 TDC – Metrology: Single Shot Precision

Q

- Repeat measurement of single time-of-arrival (e.g. with pulsed laser at fixed repetition frequency) and construct histogram

- Derive statistics by Gaussian fitting and calculation of FWHM or σ or 3σ.

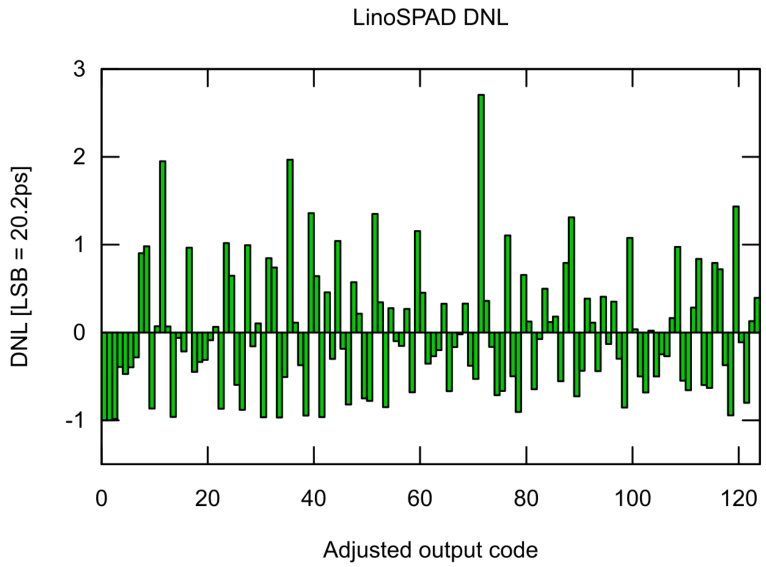


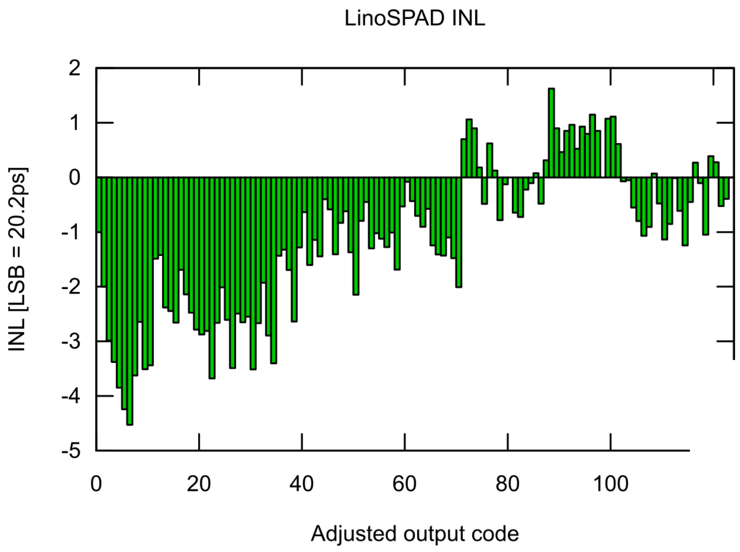


The resulting (Gaussian) timing distribution contains all measurement uncertainties, combined quadratically if independent

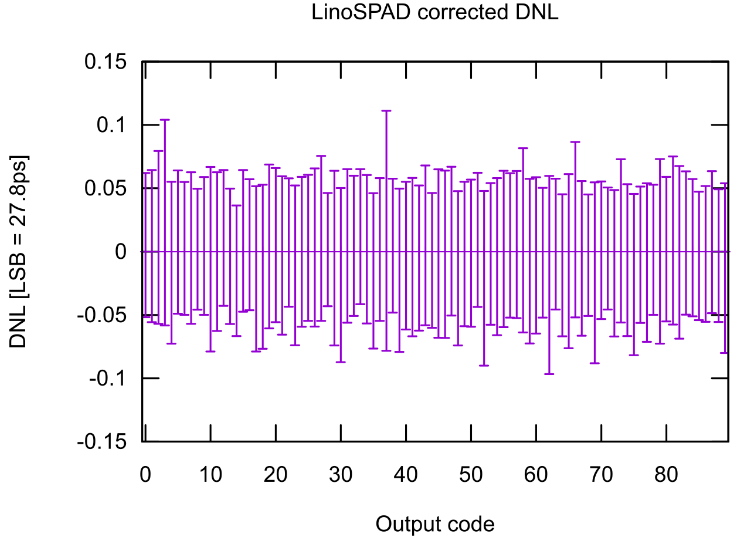
E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

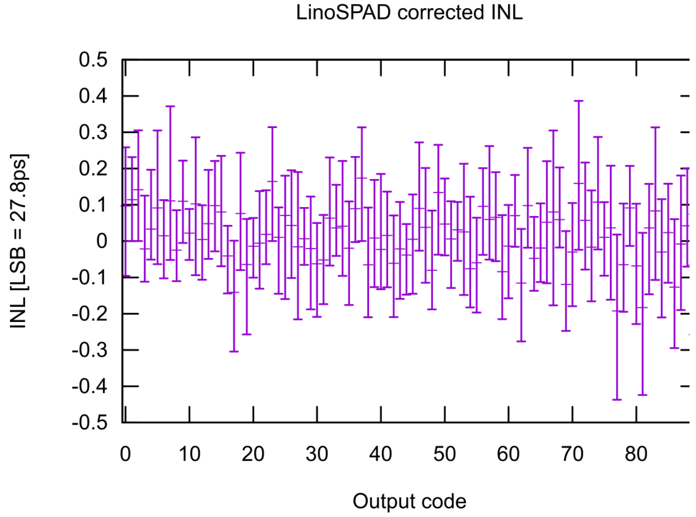
11.3 TDC – DNL vs INL and Accuracy

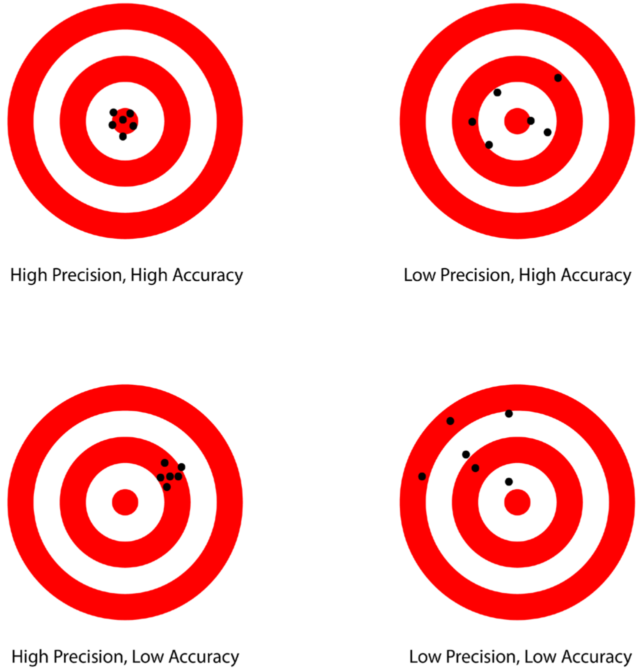




Calibration of a Time-to-Digital converter
S. Burri, EPFL, MDPI Instruments, 2018







E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

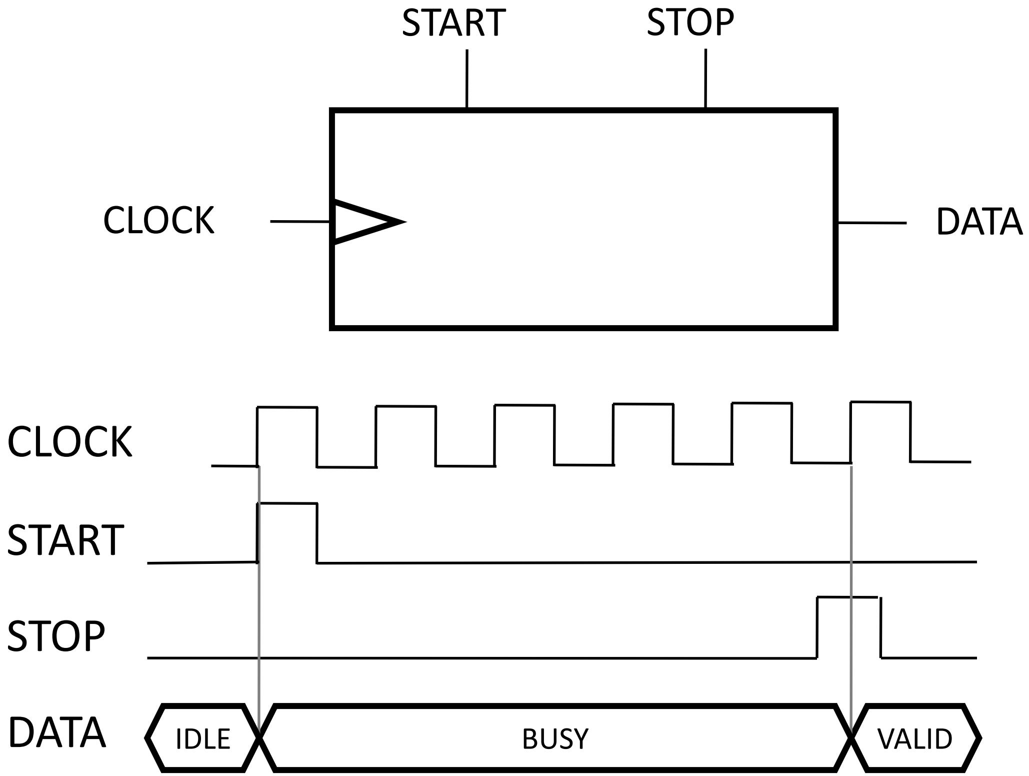
11.3 TDC – Architectures

- Counter – Register
- Delay Chain
- Phase Interpolator
- Vernier Lines
- Pulse Shrinking
- Ring Oscillators

11.3.1 TDC: Counter - Register

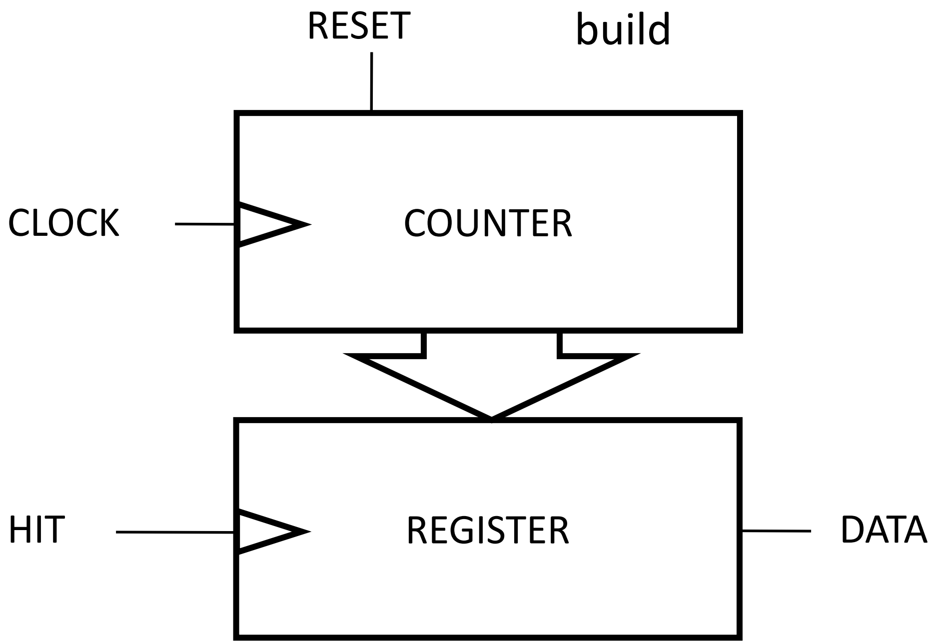
- Resolution: $\tau = 1/f_{clock}$ Q
- Conversion rate = 1/latency

Latency = time necessary to do one full conversion.
Simply count the # of clock cycles.



Advantages

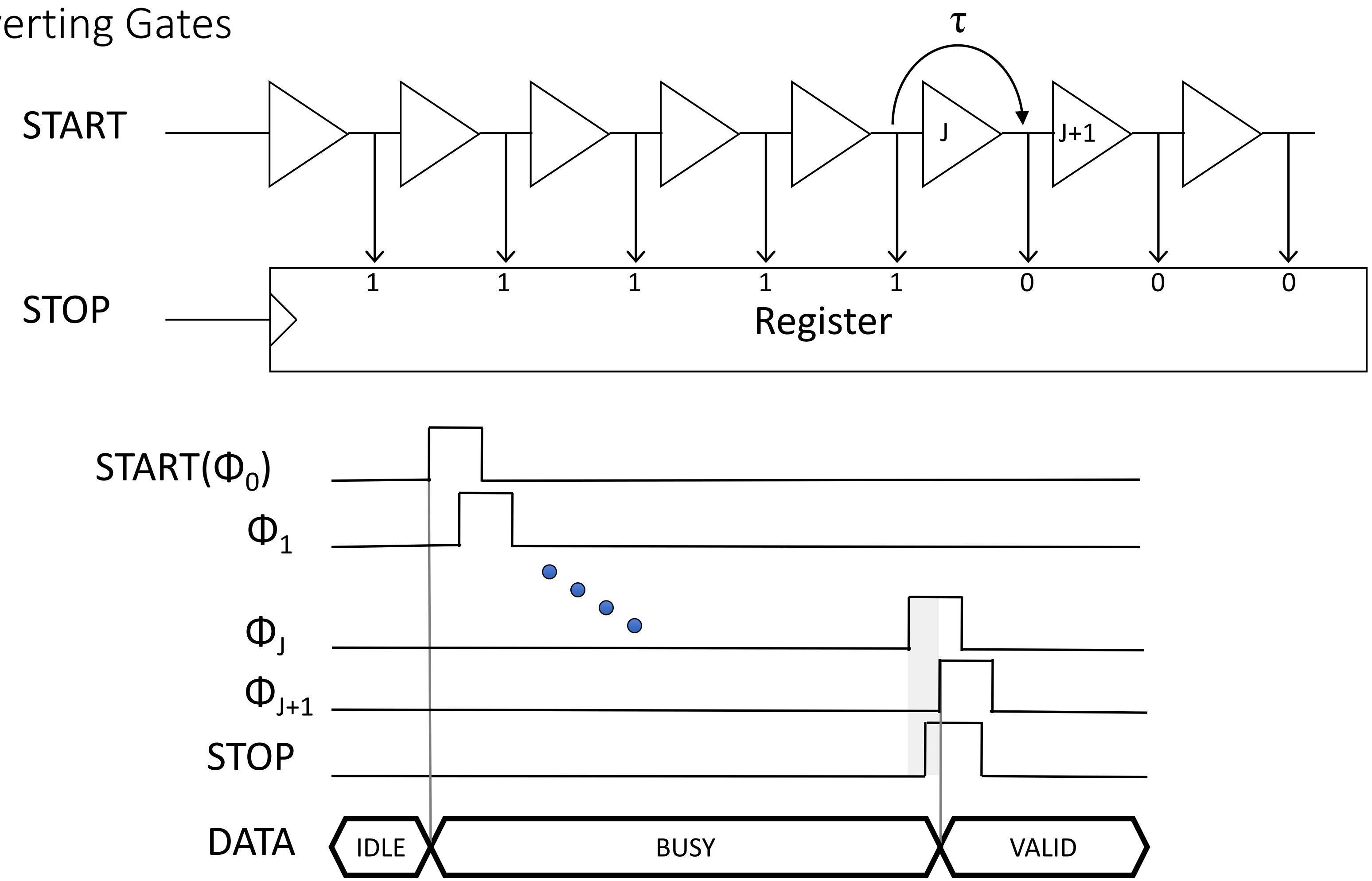
- Fast counter can be shared among many HIT lines
- Fast registers easier to build



E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.2 TDC: Delay Chain

- Non-Inverting Gates



START = signal, STOP = clock.

Signal propagates and clock freezes the registers.

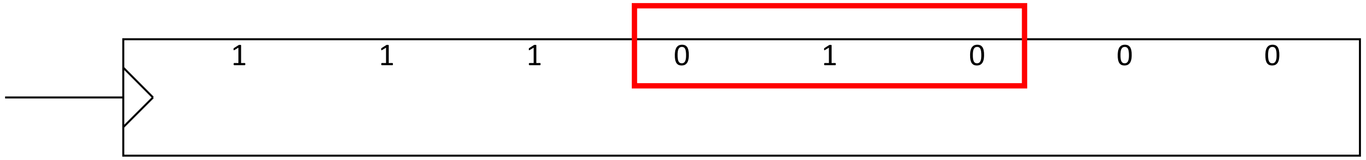
Tau = time for one gate transition, can be in the 10's of ps range.

Gate = simple buffers.

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.2 TDC: Delay Chain

- Resolution: τ = delay element
- Conversion rate = 1/latency
- Latency = N $\times$ τ
- Need a thermometer decoder: N➔$\log_2(N)$
- Issues: metastability, bubbles

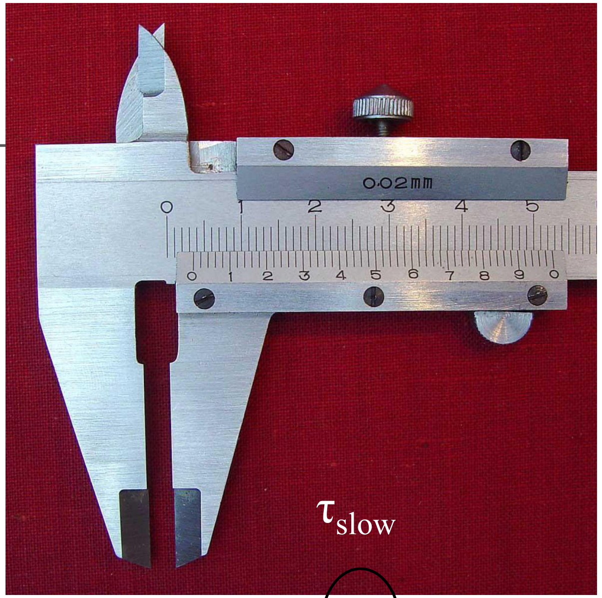


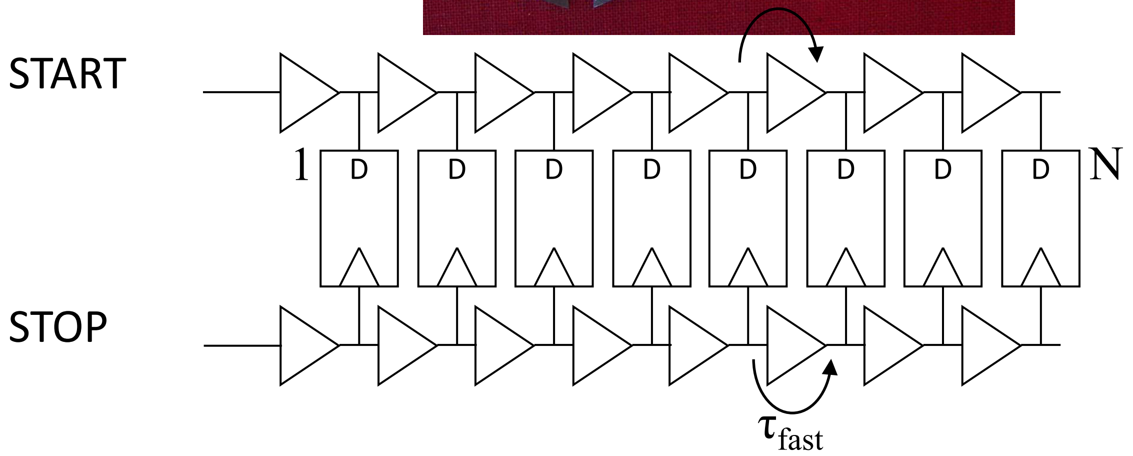
E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.3 TDC: Vernier Lines

- Resolution: $\tau = \tau_{slow} - \tau_{fast}$ (does not depend on a gate delay!), $T = n(\tau_{slow} - \tau_{fast})$
- Conversion rate = 1/latency
- Latency = $N \times \tau_{slow}$
- Need a thermometer decoder: N ➔ $\log_2(N)$
- Each stage consists of two buffers and one flip-flop
- Issues: metastability, matching

Pierre Vernier, 1631





Two delay lines, a fast and a slow one. The START signal is injected in the slow one. The STOP signal occurs later but propagates faster and catches up at a certain point with the slow one -> detection of the point where both are in phase.

📖 E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.3 TDC: Vernier Lines

- Resol
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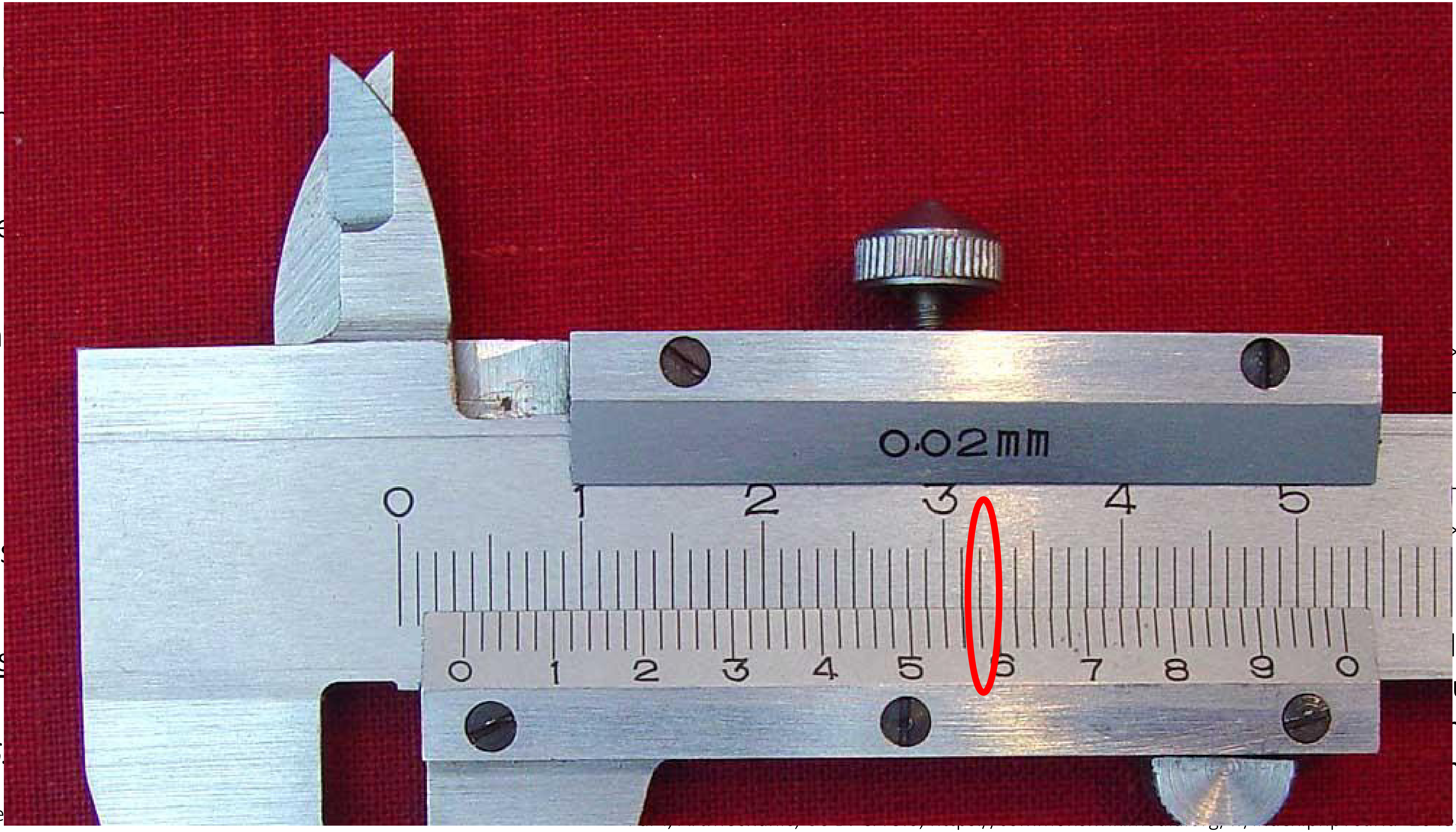
- Need
- Each
- Issues



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Pierre Vernier, 16

E. Charbon, "Image Se

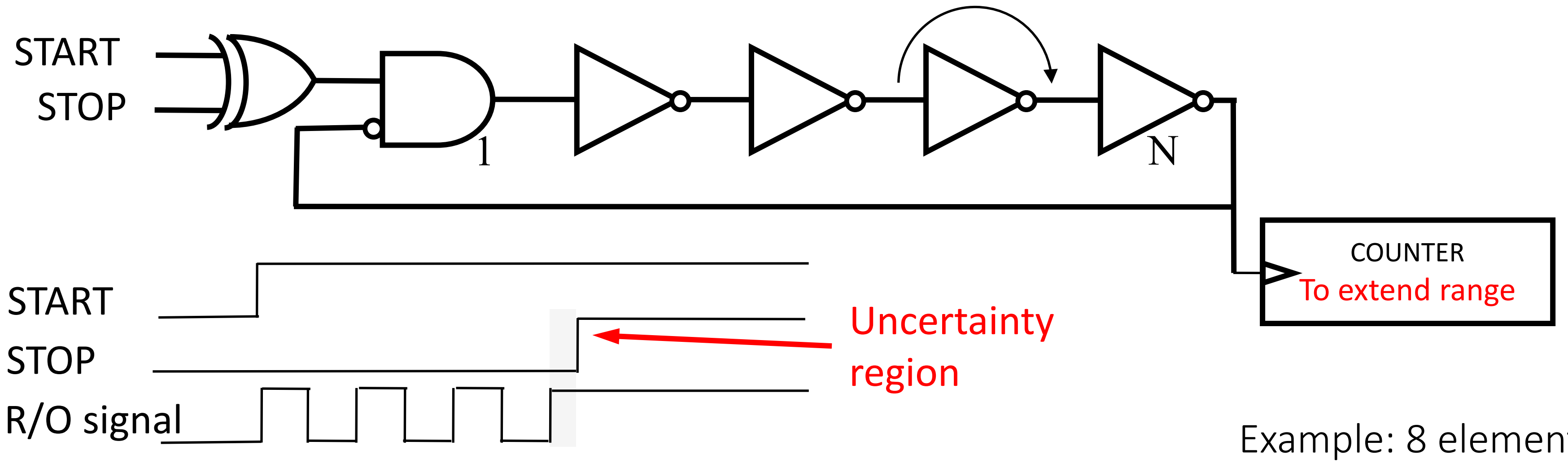
58

11.3.4 TDC: Ring Oscillator

- Resolution: τ = delay element
- Conversion rate = 1/latency
- Latency = N $\times$ τ
- Need a thermometer decoder: N➔$\log_2(N)$
- Issues: metastability, matching, asymmetric load

Main idea: have the signal recirculating instead of using a long linear chain. Circulates until the stop signal comes.

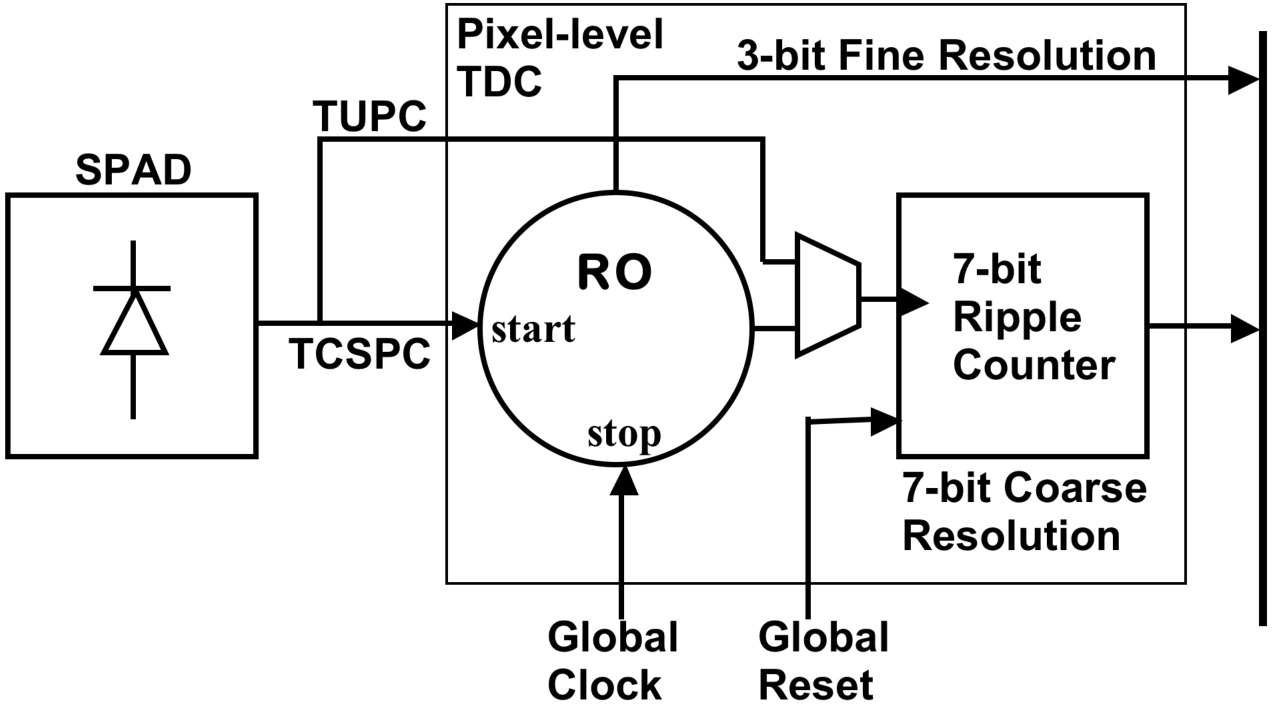
Each time it circulates, a counter is incremented -> can use much less delay elements.

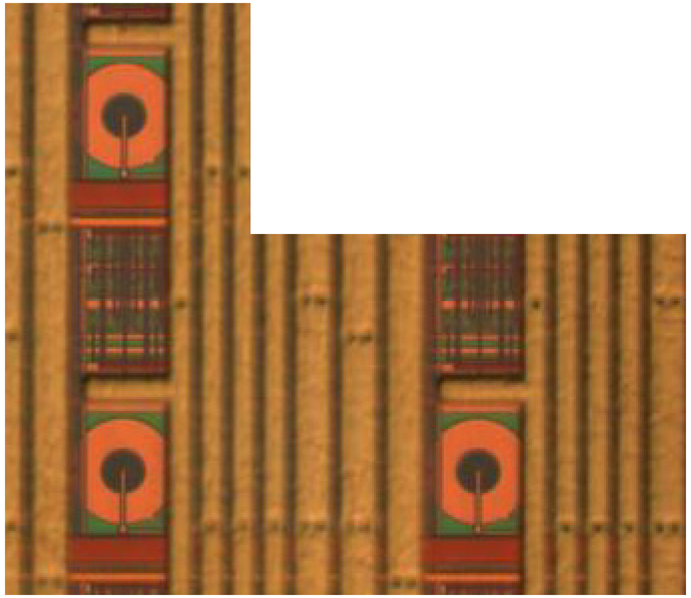


Example: 8 elements -> 3 bits

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.6 TDC: Example: MEGAFRAME Pixel



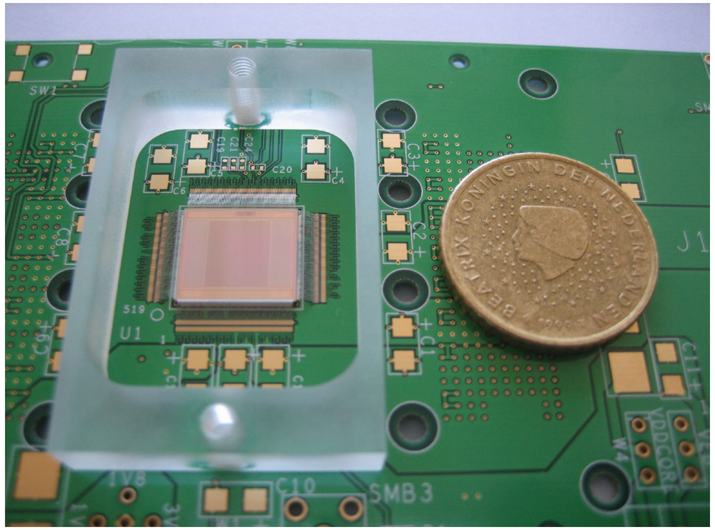


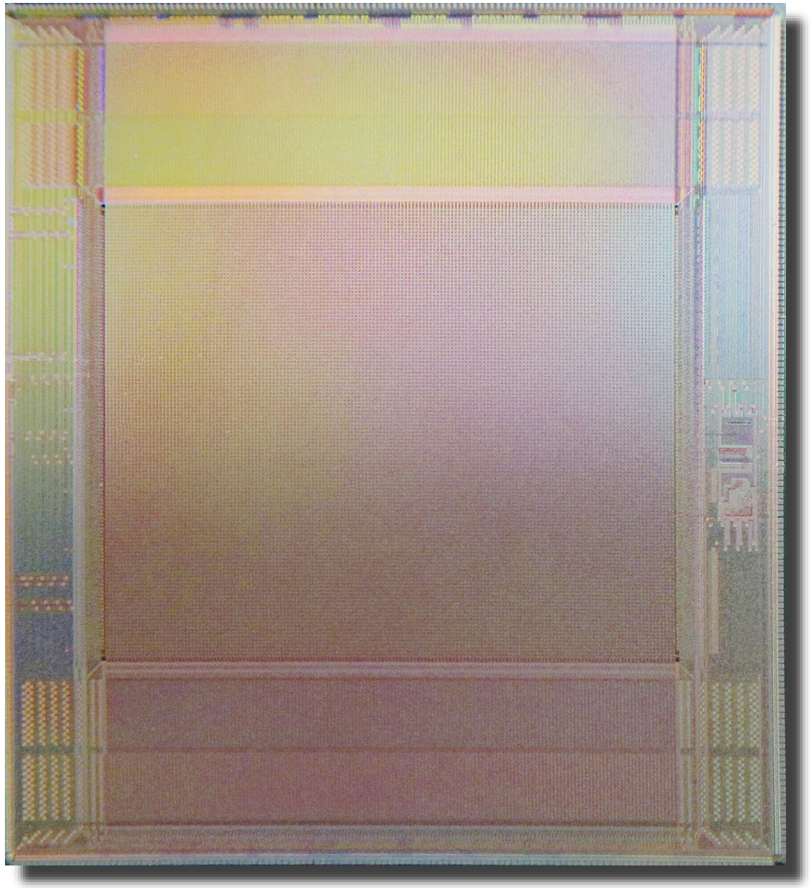
E. Charbon, “Image Sensors – ET 4390 Course Slides”, Delft 2016

11.3.6 TDC: Example: MEGAFRAME Pixel

- Format: 160x128 pixels
- Timing resolution: 55ps
- Impulse resp. fun.: 140ps
- DCR (median): 50Hz
- R/O speed: 250kfps
- Size: 11.0 x 12.3 mm^2

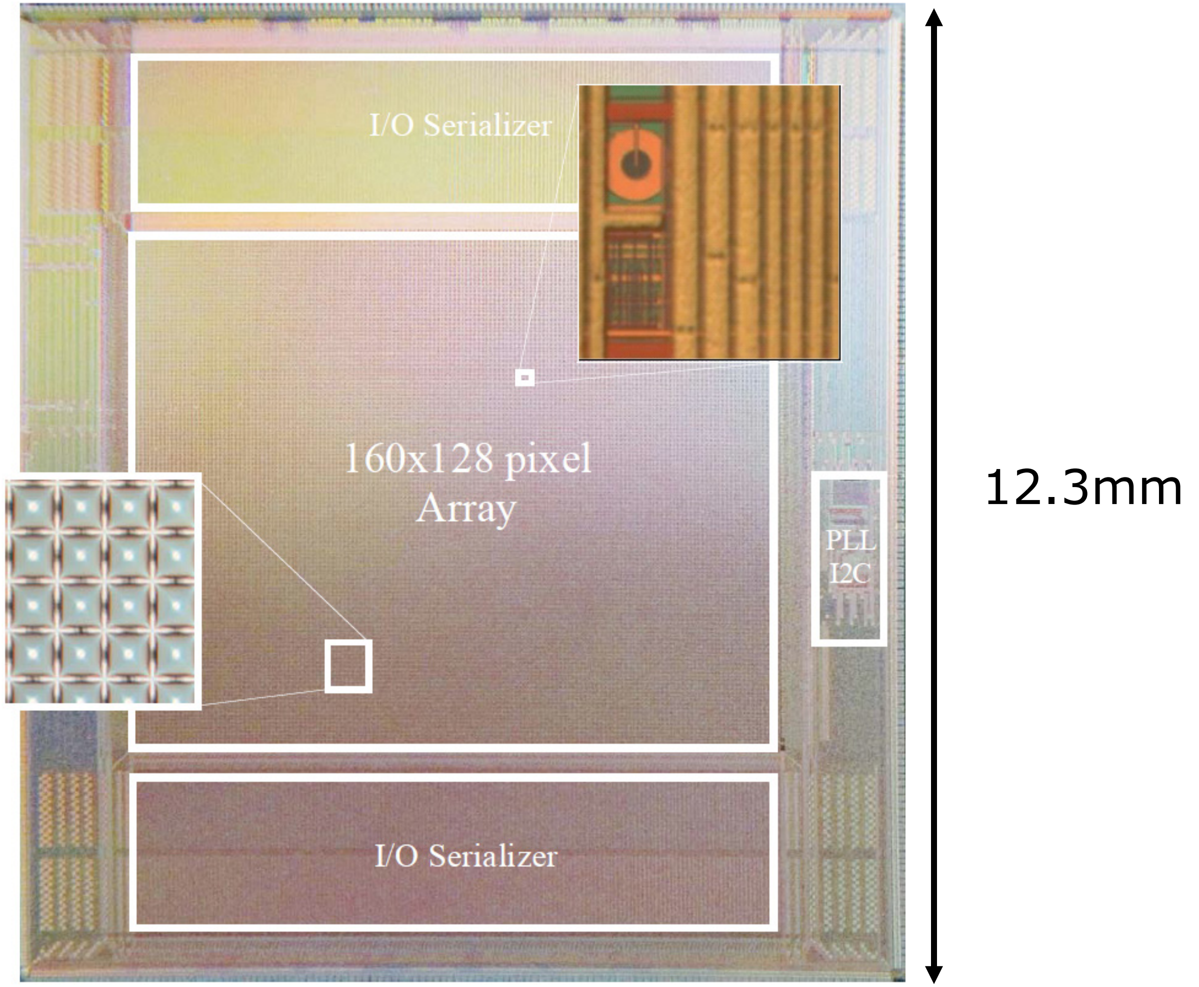
TDC
Ring oscillator (3 bits) + counter (7 bits) = 10 bits





E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.6 TDC: Example: MEGAFRAME Pixel



C. Veerappan, J. Richardson, R. Walker, D.-U. Li, M. W. Fishburn, Y. Maruyama,
D. Stoppa, F. Borghetti, M. Gersbach, R.K. Henderson, E. Charbon, *ISSCC2011*

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016

11.3.8 TDC Summary: Basic Definitions

Bin size or resolution – τ (sec)

- Minimum distance between time events that can be resolved [LSB]

Range (sec)

- Maximum time difference that can be measured

Conversion rate (MS/sec)

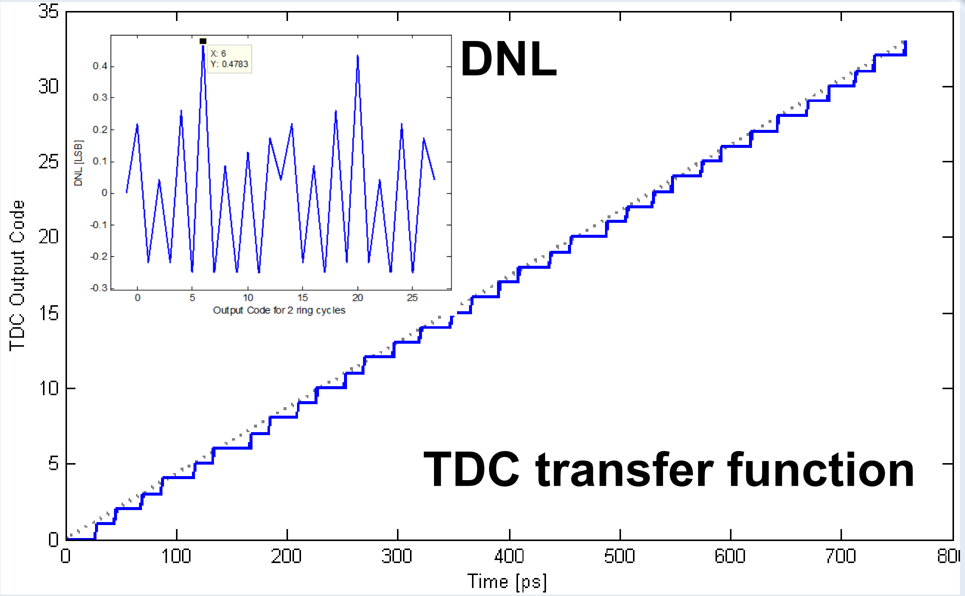
Latency (sec)

Non-linearities (LSB)

- Differential non-linearity (DNL)
- Integral non-linearity (INL)

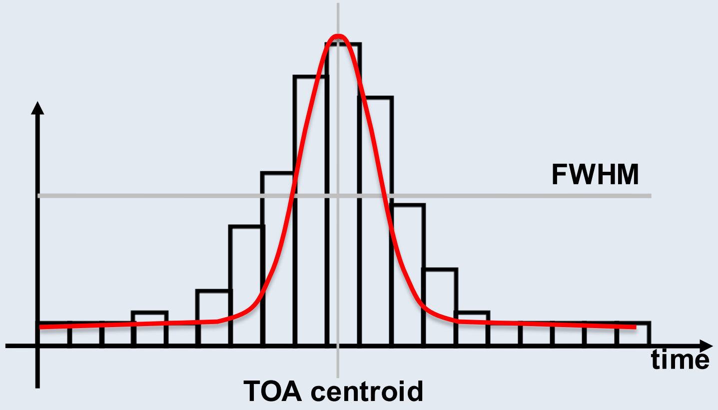
Single-shot precision (sec)

TDC non-ideality



SSA

Derive statistics by Gaussian fitting and calculation of FWHM or σ or 3σ.



Histogram representation

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016; P. Padmanabhan, EPFL, 2019

11.3.8 TDC Summary: Architectures

Simple/Basic
- Counter
- Delay-chain
- Phase interpolator
- Vernier line
- Ring oscillator

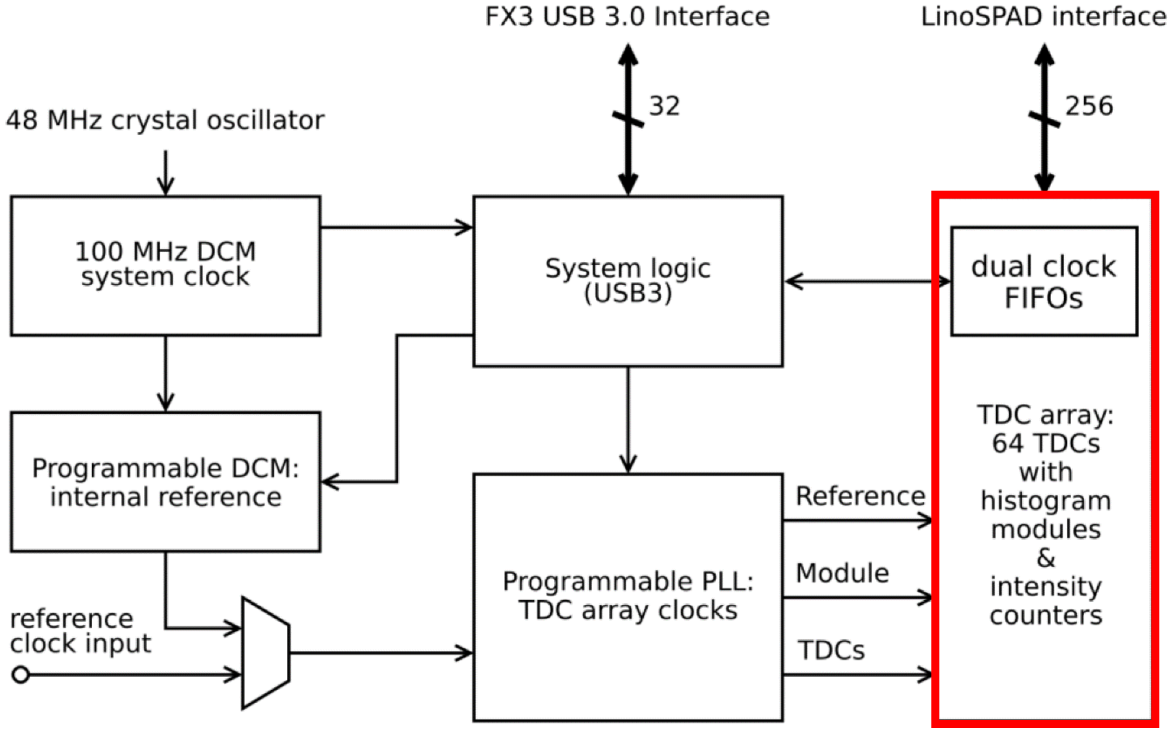
Composite
- Counter + Phase interpolators
- Ring oscillators + Counters
- Ring oscillators + time difference amplifier (TDA)
- …and many more

E. Charbon, "Image Sensors – ET 4390 Course Slides", Delft 2016; P. Padmanabhan, EPFL, 2019

11.3.8 TDC implementations (on FPGAs)

TDC implementation

- ✓ **On ASICs**
- ✓ **On FPGAs**



FPGA TDC example- LinoSPAD camera

[S. Burri et al., Sensors 2017]

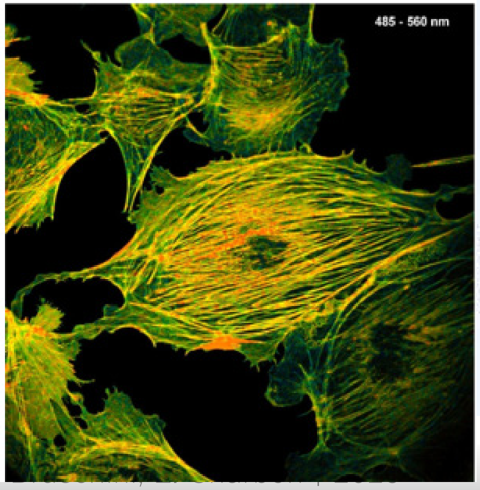
11.3.9 TDC Application Example: Time-resolved Imaging

- Suppose you could timestamp or gate every photon you detect -> time-resolved detector
- Suppose an imager comprises a number of pixels with a time-resolved detector -> time-resolved imager or time-resolved image sensor

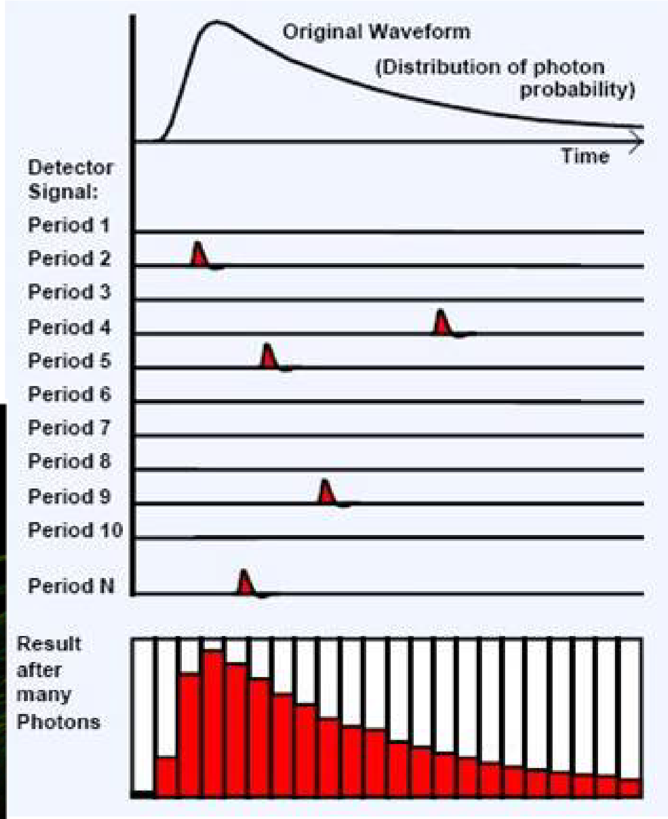
High Speed Binary Imaging

(a)

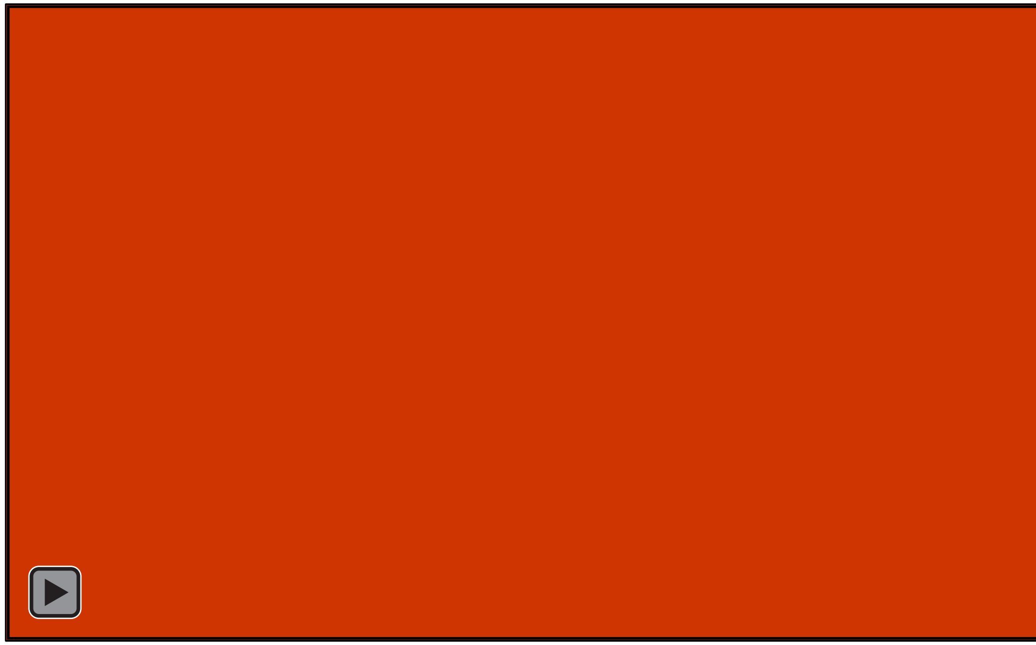
Nanosecond Lifetimes!



Time-Correlated Single Photon Counting

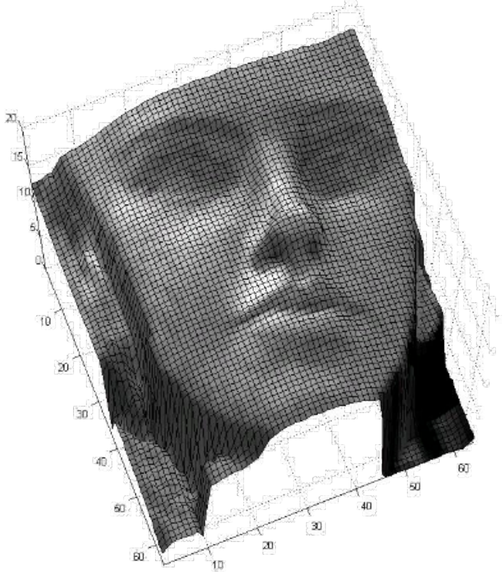


Light Detection and Ranging



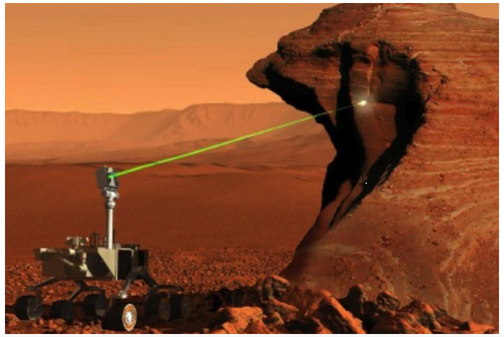
cm/mm level precision!

11.3.9 TDC Application Example: Time-resolved Imaging



- **3D imaging**
  - Mechanism: time-of-flight (TOF) detection
- **Molecular imaging**
  - Mechanism: fluorescence lifetime imaging microscopy (FLIM)

- **Positron emission tomography**
  - Mechanism: time-coincidence of gamma rays originated from a positron-electron annihilation
- **Time-resolved Raman spectroscopy**
  - Mechanism: time-gating for fluorescence filtering
- Or simply, fast or strobe imaging for scientific applications

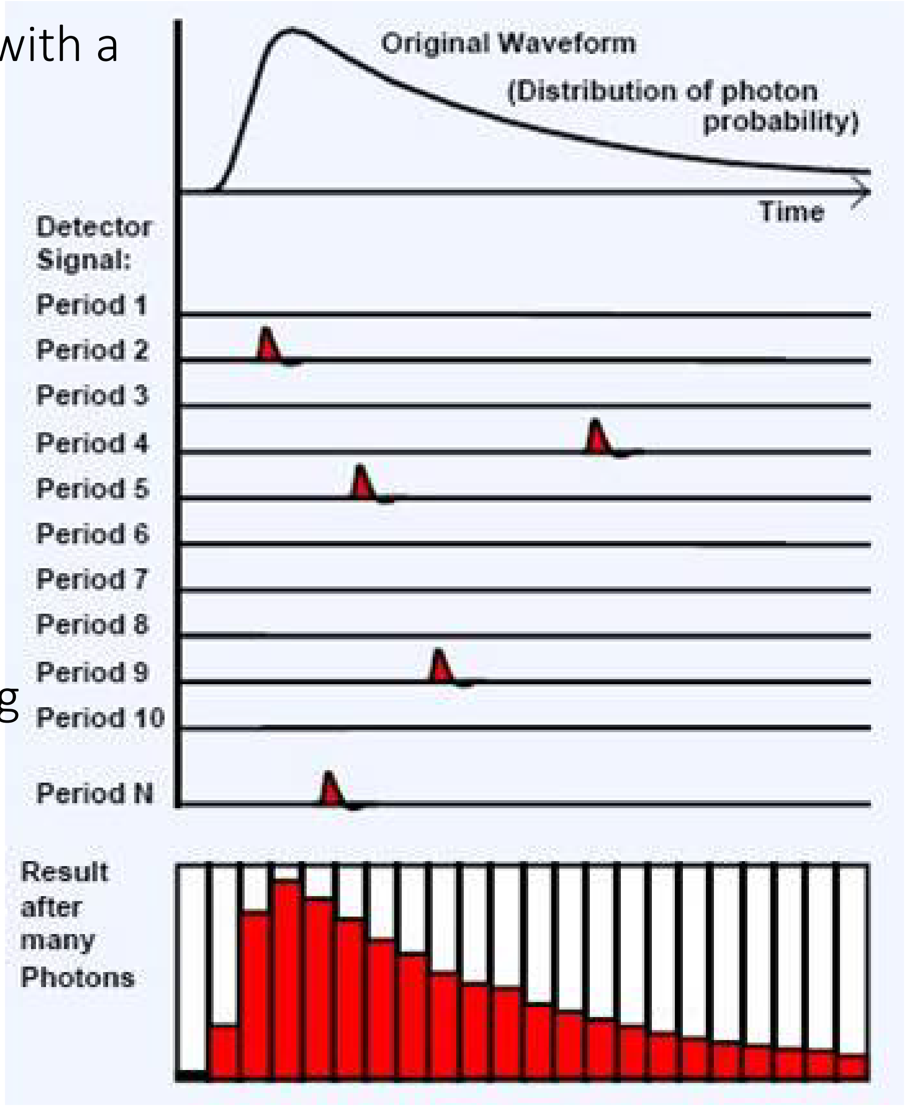


11.3.9 TDC Application Example: TCSPC

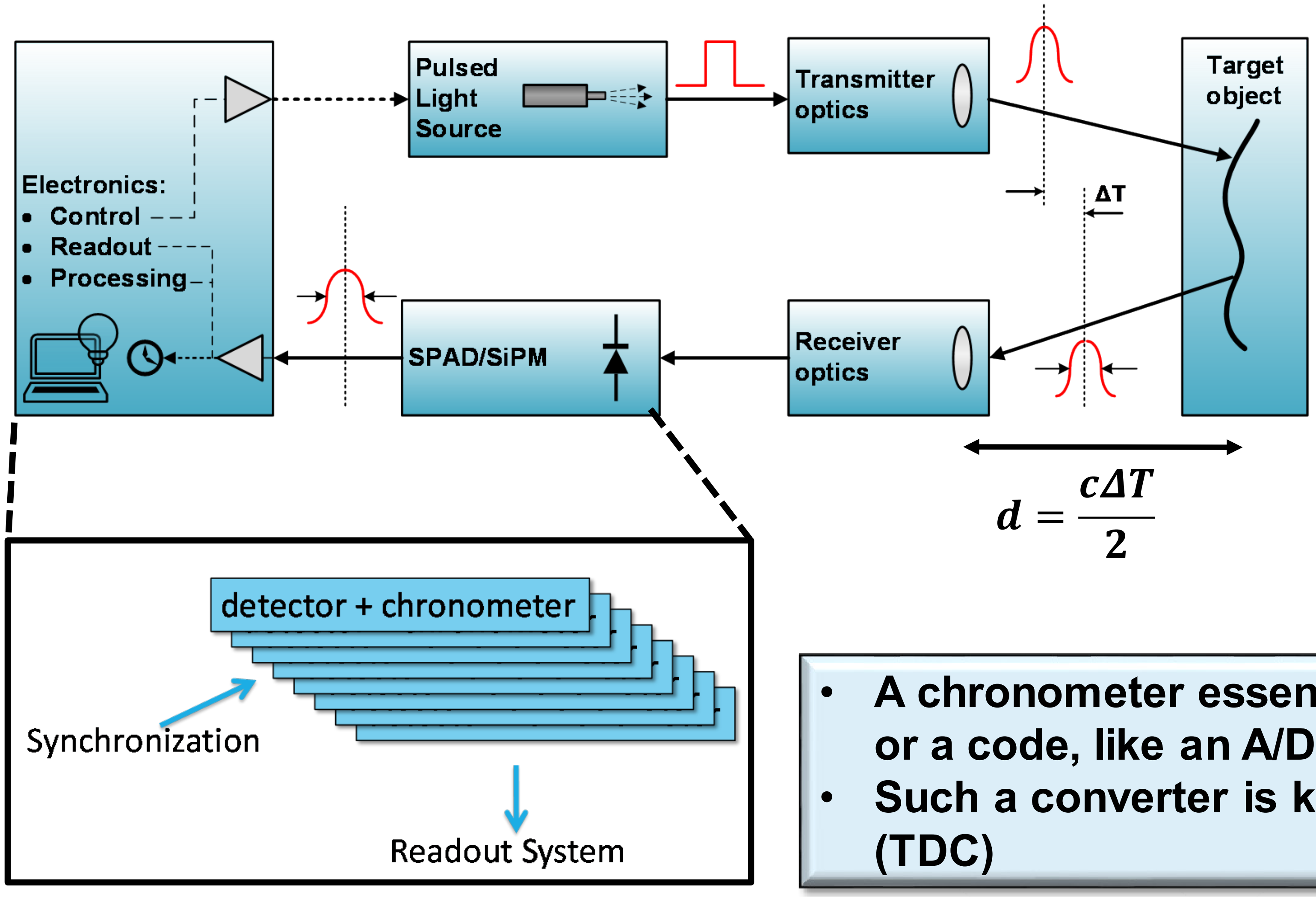
- Assume that a given process triggered by light produces photons with a certain probability distribution function $PDF(t)$
- Then one can measure it by repeating a measurement of a single photon time-of-arrival N times and building a frequency statistics known as histogram $h(t)$
- It can be shown that:

$$h(t) \rightarrow PDF(t) \text{ for } N \rightarrow \infty$$

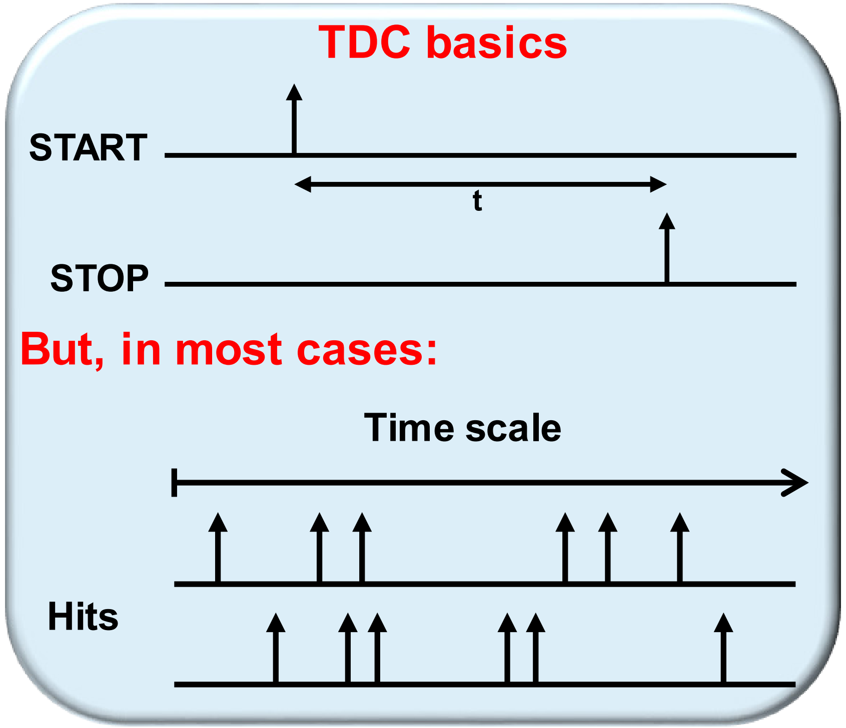
- This technique is known as time-correlated single-photon counting (TCSPC)



11.3.9 TDC Application Example: Time-of-Flight System



$$d = \frac{c\Delta T}{2}$$



- **A chronometer essentially converts time onto a number or a code, like an A/D converter**
- **Such a converter is known as time-to-digital converter (TDC)**

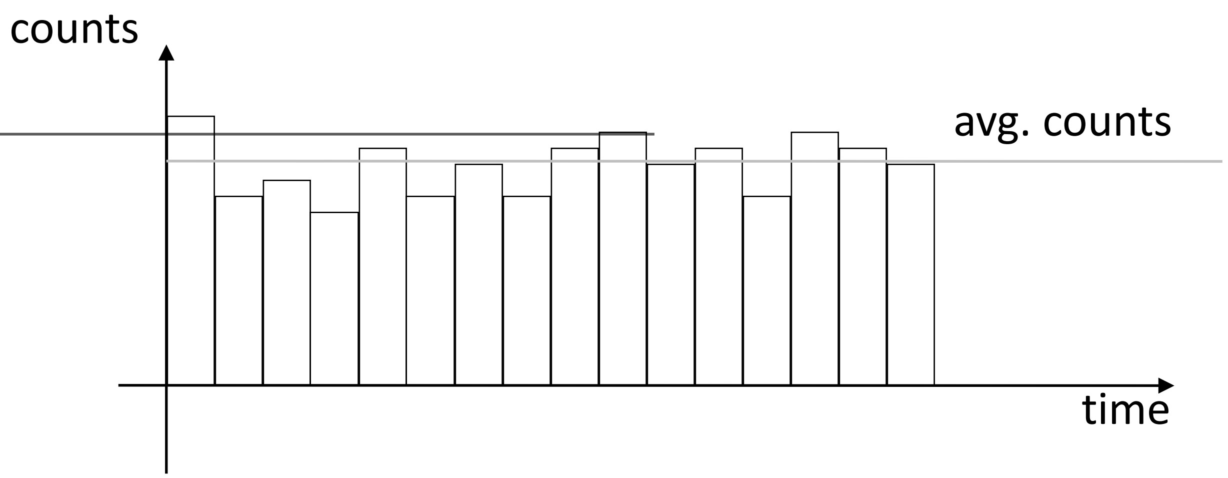
11.4 Homework slides (see Exercises)

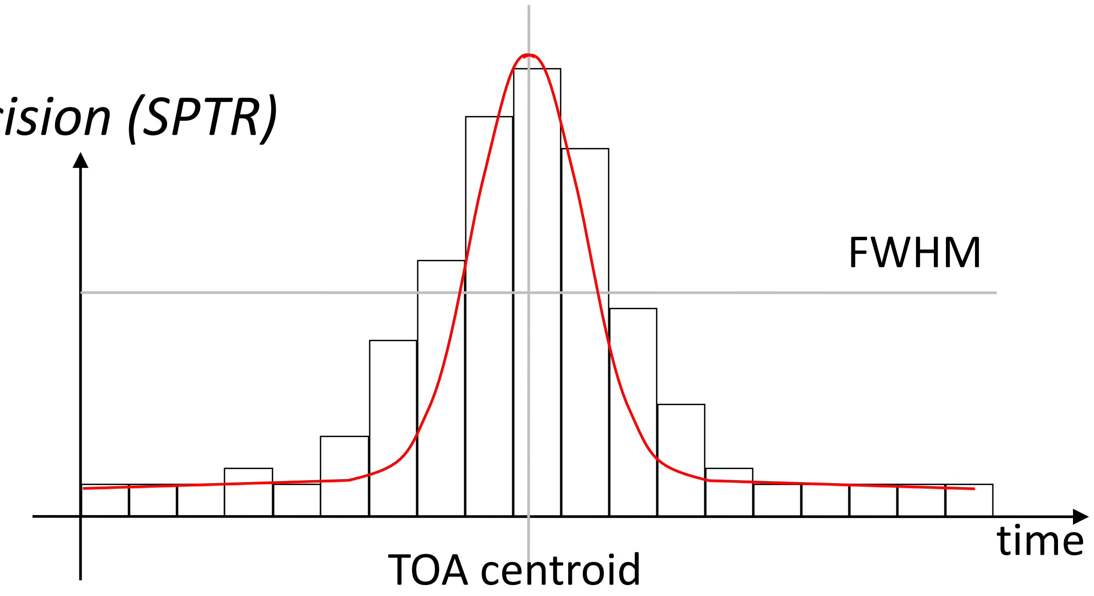
- Homework 1: Design and analysis of a FLIM System
- Homework 2: Design and analysis of a LIDAR system
- Homework 3: Design and analysis of a PET System

→ These *Case Studies*, based on material from W8-W11, represent possible exam topics.

Take-home Messages/W11-3

- *Time-to-Digital converters:*
  - *Basics*
  - *INL, DNL*
  - *Metrology: code-density test, single-shot precision (SPTR)*
  - *TDC architectures*
    - *Counter-register*
    - *Delay chain*
    - *Vernier lines*
    - *Ring oscillator*
  - ***Application examples!***





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