DATA ACQUISITION
ELECTRONICS & TRIGGER

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DATA ACQUISITION

OVERVIEW

- **Sensor:**
  - detects a physical event or measures a physical quantity
  - transforms this into a *signal:* another quantity that is “easier” to perceive/measure/store
- **Detector:**
  (in nuclear and particle physics)
  - a collection of sensors, not necessarily of the same kind

YOU’VE BUILT A NICE DETECTOR. NOW WHAT?

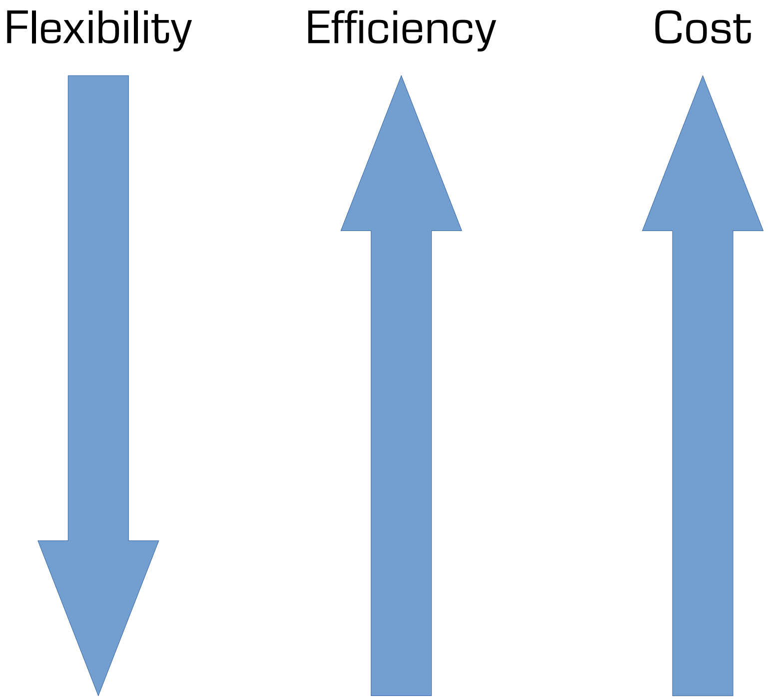
- **Data-acquisition (DAQ) system:**
  - receives signals from a detector and transforms them into data to analyse

THE MANY FUNCTIONS OF A DAQ SYSTEM

- **Trigger**:
  decide when to start "reading" the data from sensors
- **Signal processing**:
  amplification, analog-to-digital conversion, noise reduction, …
- **Collection**:
  gather signals from different sensors
- **Collation**:
  assemble signals corresponding to the same observed phenomenon
- **Filter**:
  discard faulty or uninteresting data
- **Storage**:
  for later analysis

HOW?

- **Specialised electronics:**
  - Custom or commercial integrated circuits (ICs)
  - Programmable logic devices (FPGAs)
- **General-purpose computers:**
  - Networks
  - Software



A REAL-WORLD EXAMPLE

- **Detector**:
  lenses + active-pixel sensors
- **Trigger**:
  human pressing trigger button
- **Signal processing, data collection, data collation**:
  onboard processor

- **Storage**: SD card
- **Filter**: human looking at screen

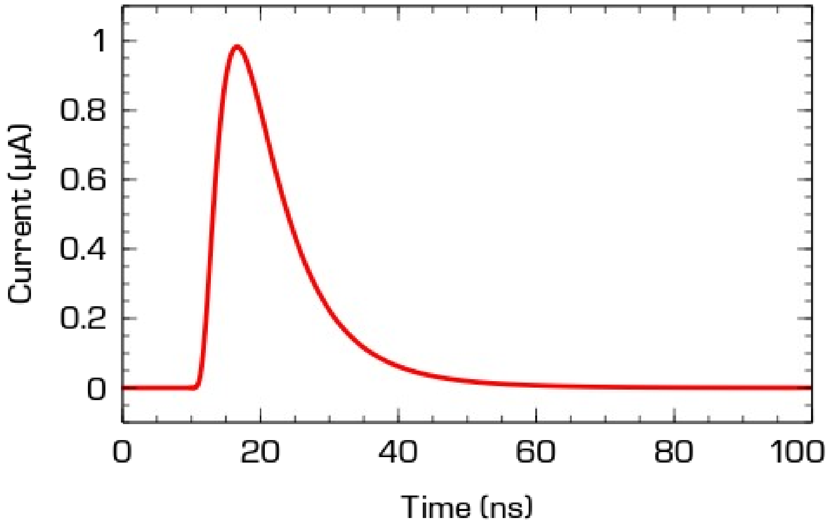
IMPORTANT QUANTITIES

- **Throughput**:
  the rate at which something (events, signals, bytes, packets, …) is processed
- **Latency**:
  the time between the beginning and the end of some process
- **DAQ efficiency**:
  the fraction of interesting phenomena that could be acquired
- **Scalability**:
  (not really a quantity)
  the ability of a system to accommodate higher or lower throughput

SIGNAL PROCESSING
OVERVIEW

THE SIGNAL

- Typically in NP/HEP* sensors measure some of these quantities:
  - presence of a particle
  - its time of arrival
  - magnitude of energy deposited
- In response, they usually produce **a small current pulse**
- Duration:
  from ~100 ps for a Si sensor
  to ~10 µs for inorganic scintillators



* nuclear physics / high-energy physics

READ-OUT ELECTRONICS

- Directly connected to the sensors
- Generic goal: sense analog signals and make a “usable” data out of them
- In practice:
  adapt signals to optimise different, sometimes conflicting properties
  - Minimum detectable signal (sensitivity)
  - Maximum detectable signal (dynamic range)
  - Speed (signal rate)
  - Timestamping precision
  - Pulse shape independence
- Without forgetting:
  - Compactness, reliability, power consumption, radiation hardness

WHY DIGITAL?

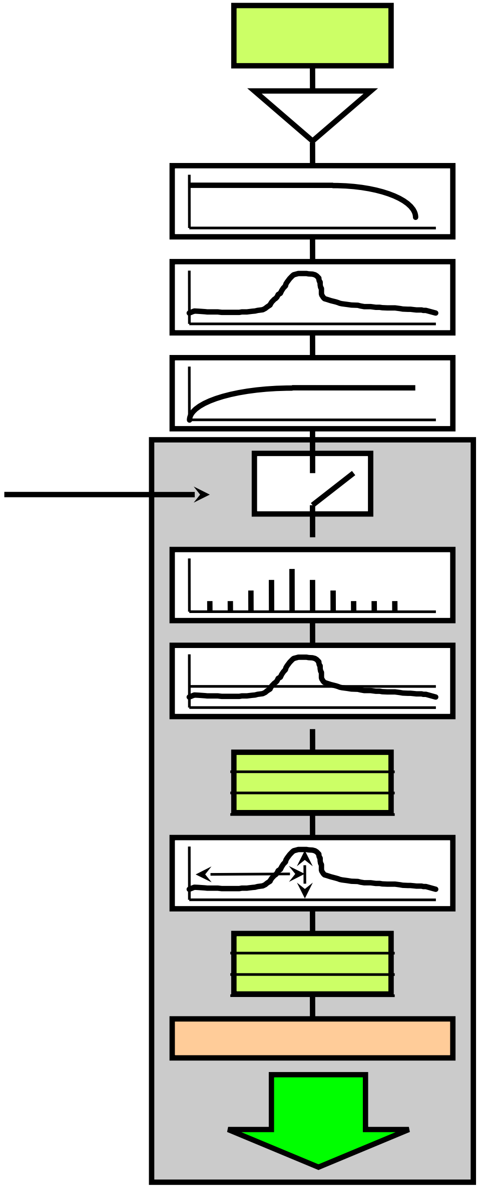
- All of this is easier with digital signals:
  - Protecting signals from noise
  - Buffering to derandomise or wait for trigger (more on this later)
  - Complex filtering
  - Compression
  - Long distance transport
- Digitisation "as soon as possible"

ANOTHER REAL-WORLD EXAMPLE

- Analog TV:
  - 48 channels
  - Standard definition (equivalent to 768x752 @ 25 fps)
  - 400 MHz of radio spectrum in the UHF band

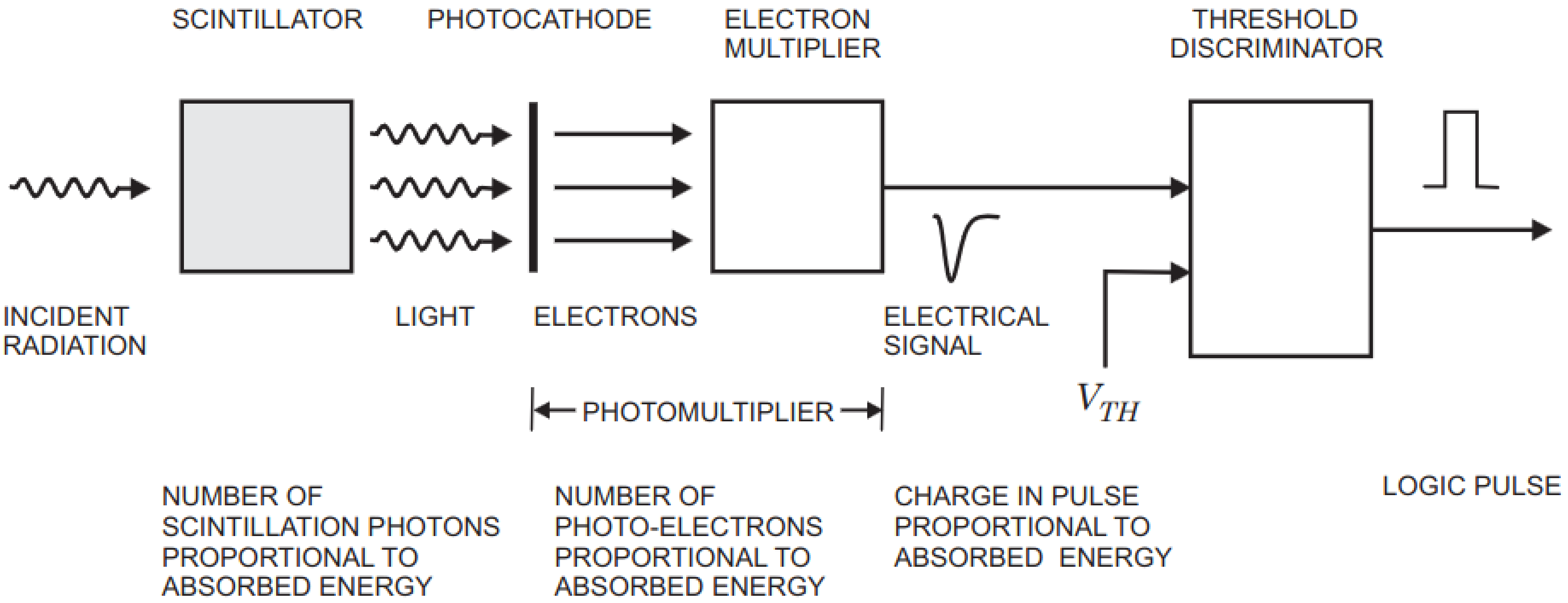
- Digital terrestrial TV
  - Hundreds of channels
  - High definition (1920x1080 @ 50 fps or more)
  - 200 MHz of radio spectrum
    - the rest was reused for 4G

A READOUT CHAIN



SIGNAL PROCESSING
ANALOG AMPLIFICATION

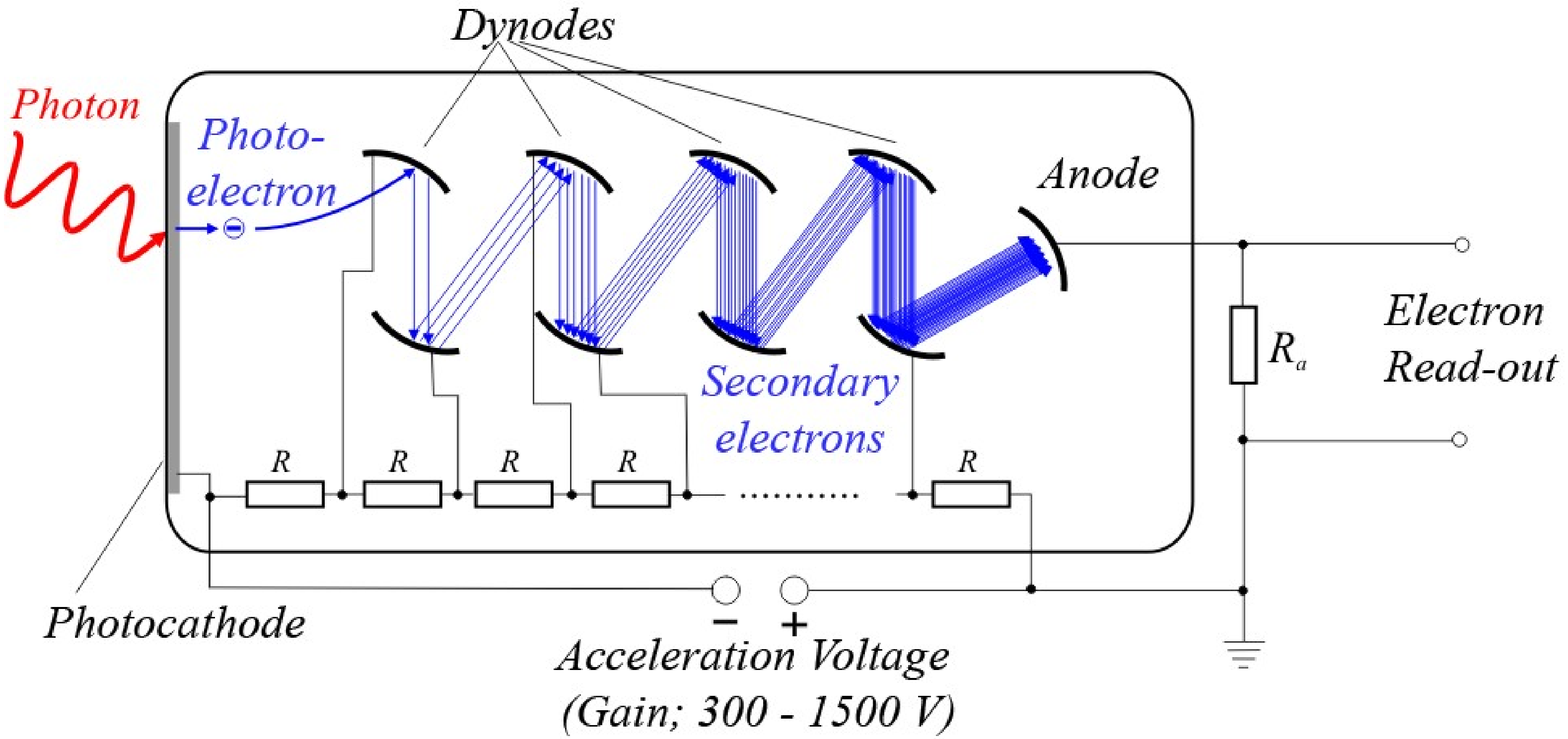
DETECTOR/AMPLIFIER: PHOTOMULTIPLIER



From H. Spieler "Analog and Digital Electronics for Detectors"

DETECTOR/AMPLIFIER: PHOTOMULTIPLIER

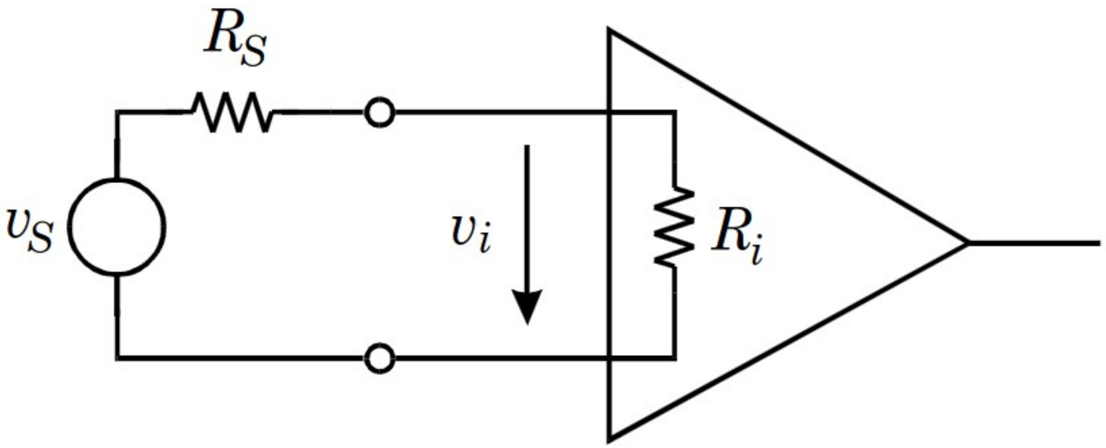
From Jan Krieger, https://commons.wikimedia.org/wiki/File:Photomultiplier_schema_en.png



- High intrinsic gain (i.e.: amplification) → no pre-amplifier required

IDEAL AMPLIFIERS: VOLTAGE

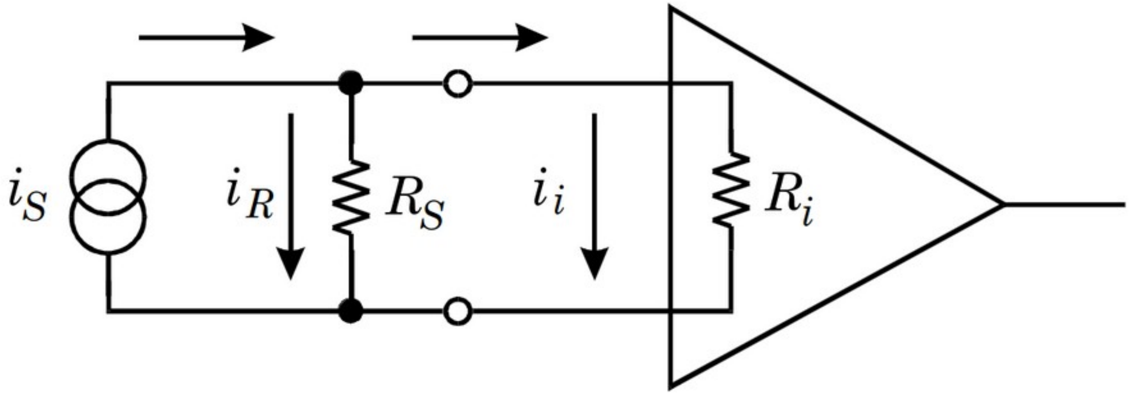
- Input voltage: $v_i = \frac{R_i}{R_S + R_i} v_S$
- If $R_i \gg R_S$, then $v_i \approx v_S$
- To amplify **voltages**,
  the input resistance
  (or reactance)
  should be **large** compared to
  the source resistance
  (or reactance)



From H. Spieler "Analog and Digital Electronics for Detectors"

IDEAL AMPLIFIERS: CURRENT

- Input current: $i_i = \frac{R_s}{R_s + R_i} i_S$
- If $R_i \ll R_S$, then $i_i \approx i_S$
- To amplify **currents**,
  the input resistance
  (or reactance)
  should be **small** compared to
  the source resistance
  (or reactance)



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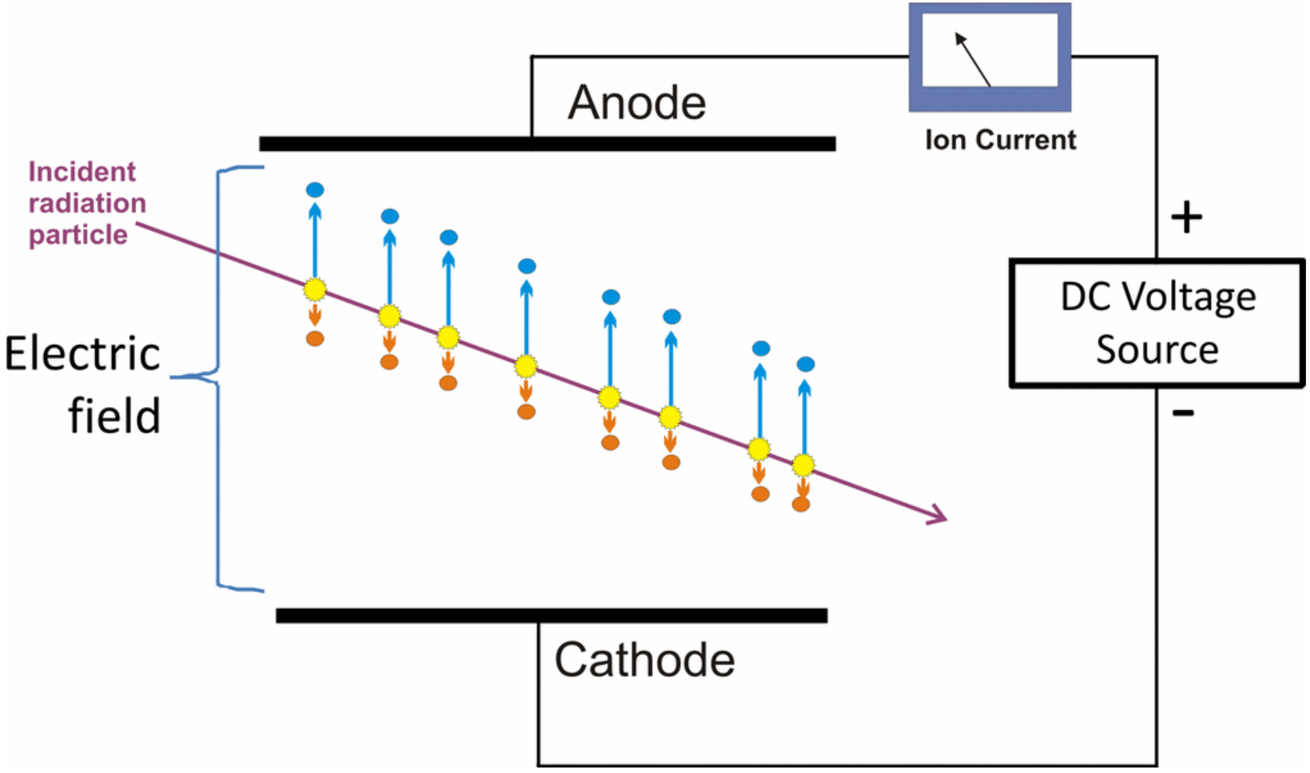
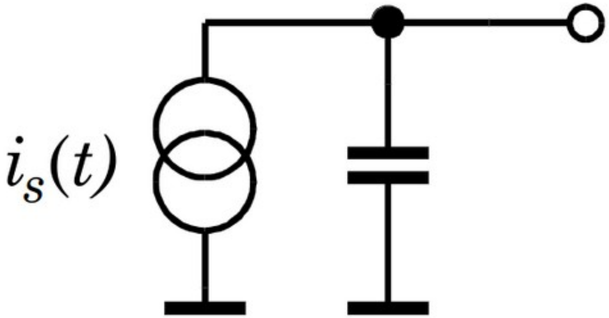
A SIMPLIFIED DETECTOR MODEL



From Dougsim, https://commons.wikimedia.org/wiki/File:Ion_chamber_operation.gif



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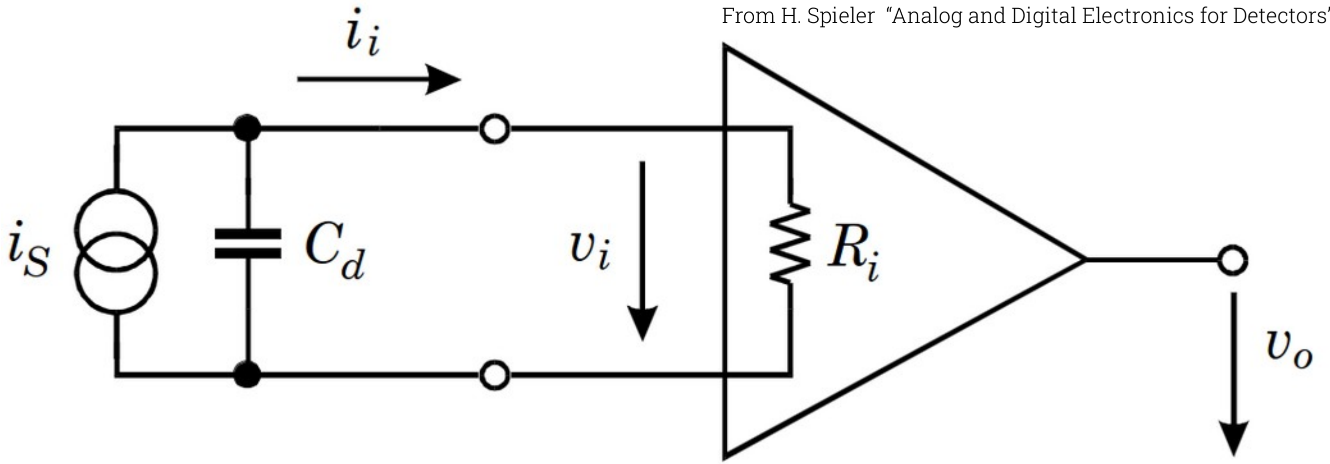
AMPLIFY!

From H. Spieler "Analog and Digital Electronics for Detectors"

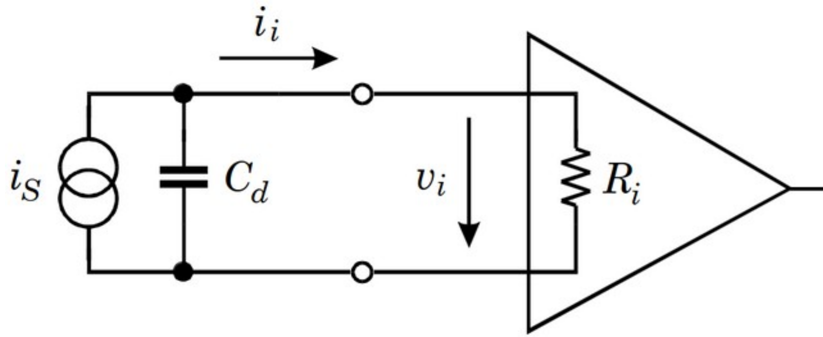
- The input is now an RC circuit

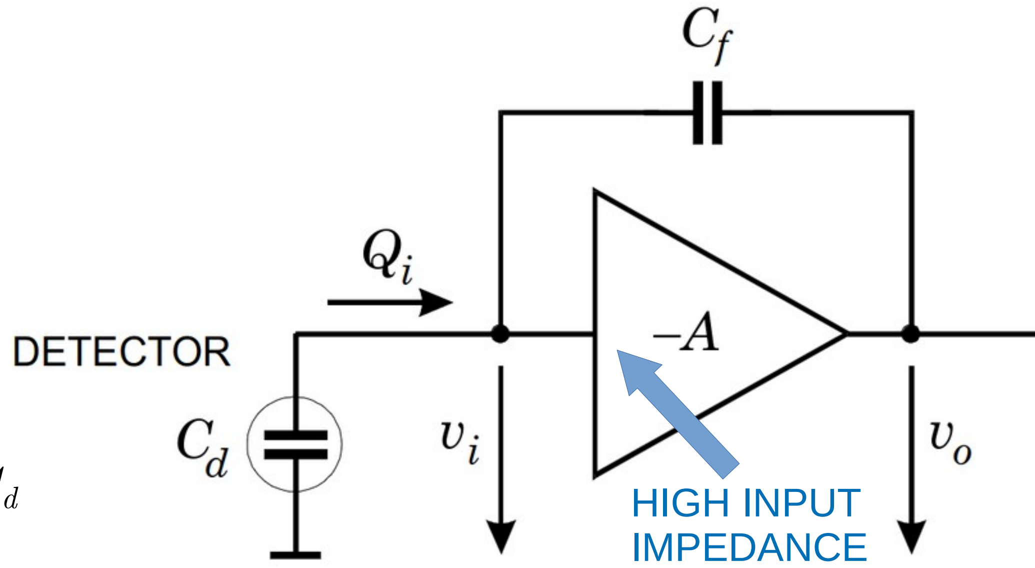


- If the signal pulse is short compared to the R_iC_d time constant, C_d discharges quickly and the amplifier senses the current pulse
- If the signal pulse is long compared to the R_iC_d time constant, C_d discharges slowly and the amplifier senses the voltage, which is proportional to the current integrated over time

CHARGE-SENSITIVE AMPLIFIER

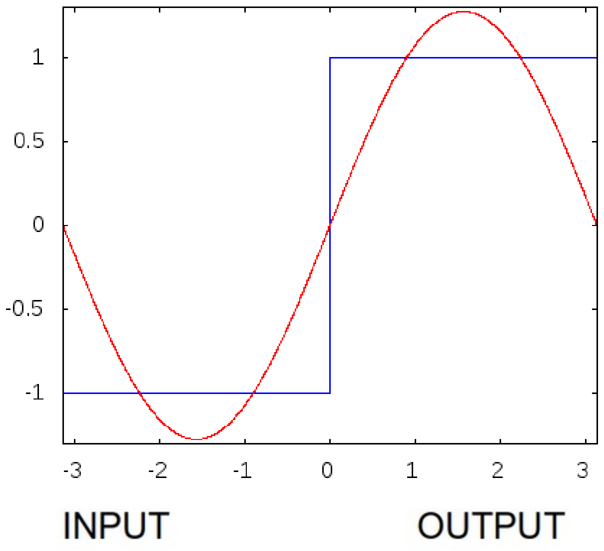
- Actually, we want to measure energy deposition:
  $E \propto Q_s = \int i_s(t)dt = V_i/C_d$
- Can we avoid depending on C_d, a sensor-specific value? YES!
- We need a specific amplifier
  - Input capacitance: $C_i = C_f\,(A+1)$
  - Output: $V_o \approx Q_i/C_f$
  - Sensed charge fraction:
    $Q_i/Q_S = C_i/(C_d + C_i) \approx 1$ if $C_i \gg C_d$



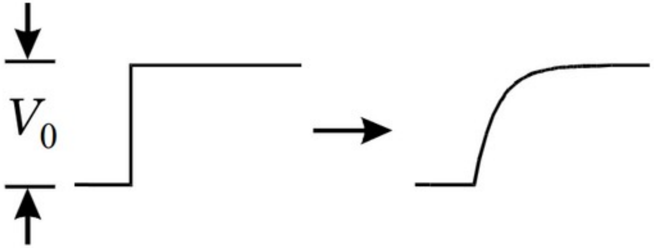


REAL-WORLD COMPLICATIONS

From Thenub314, https://commons.wikimedia.org/wiki/File:Fourier_series_for_square_wave.gif



- All we've talked about so far is true in an ideal world of spherical cows
- Back to planet Earth:
  - Real amplifiers do not respond immediately to input changes
  - For the output voltage to change, a capacitance at their output has to be charged
  - The high-frequency components of the input signal are suppressed by this, i.e.: the amplifier gain is not constant across all frequencies



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REAL-WORLD COMPLICATIONS

- Phase:
  - Amplifiers also shift the output signal in time with respect to the input (i.e.: they add a phase)
  - Unsurprisingly, this phase shift is also frequency-dependent!
- Input impedance:
  - Frequency dependent too!

SIGNAL PROCESSING
FILTERING AND SHAPING

FLUCTUATIONS vs. NOISE

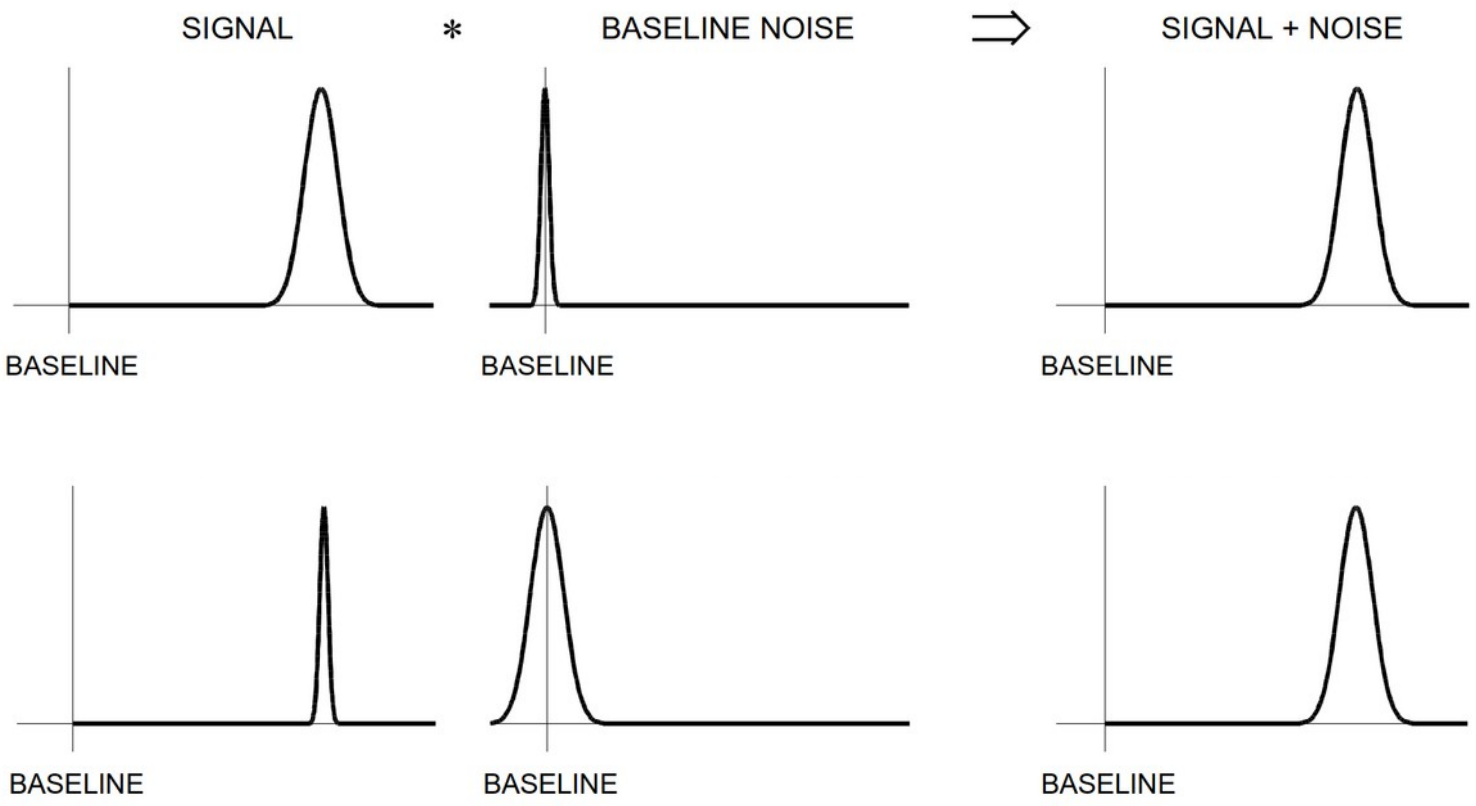
- Signals are affected by:
  - Fluctuations intrinsic to the detection process: identical particles with the same momentum and energy will not always generate identical signals
  - Baseline fluctuations in the electronics ("noise")
- Often both of them affect the signal
- They are independent, so their contributions add in quadrature:

$$\Delta E = \sqrt{\Delta E^2_{fluc} + \Delta E^2_{noise}}$$

- Often, the detection fluctuations obey this formula:

$$\Delta E_{fluc} \propto \sqrt{E}$$

PICK YOUR BATTLES



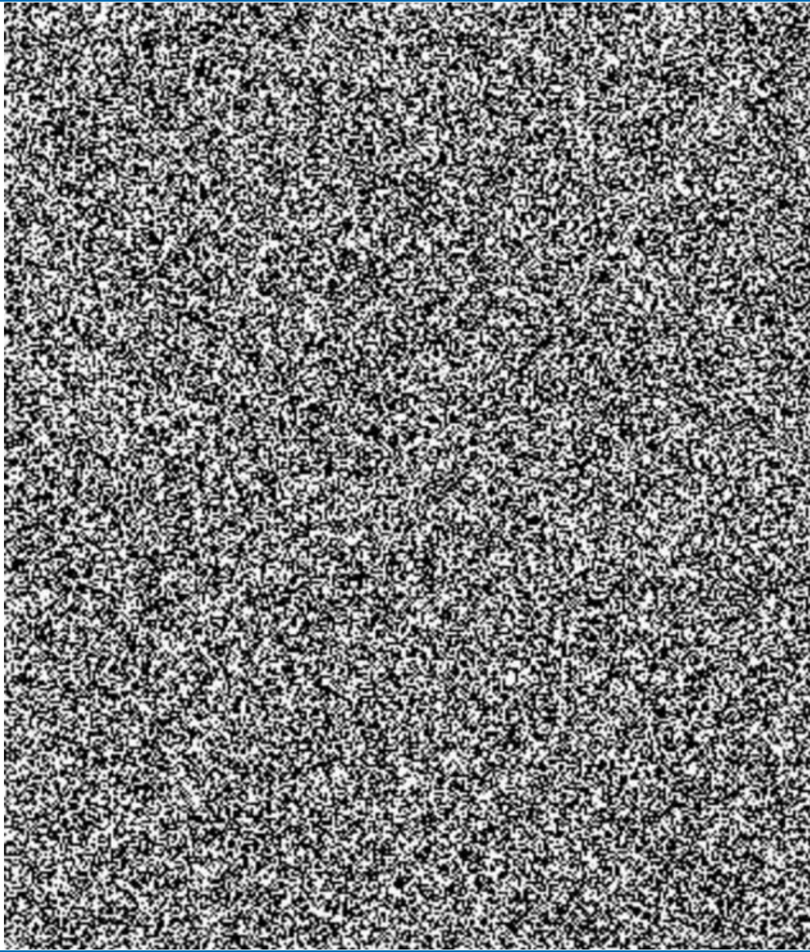
ALL GOOD!

SIGNAL-TO-NOISE RATIO MUST BE IMPROVED

BANDWIDTH AND NOISE

- Electronics noise is essentially:
  - Thermal noise:
    created by velocity fluctuations of charge carriers in a conductor
  - Shot noise:
    created by fluctuations in the number of charge carriers (e.g. tunneling events in a semi-conductor junction)
- It is **white noise**:
  same intensity at different frequencies

  → Larger frequency range == more noise!



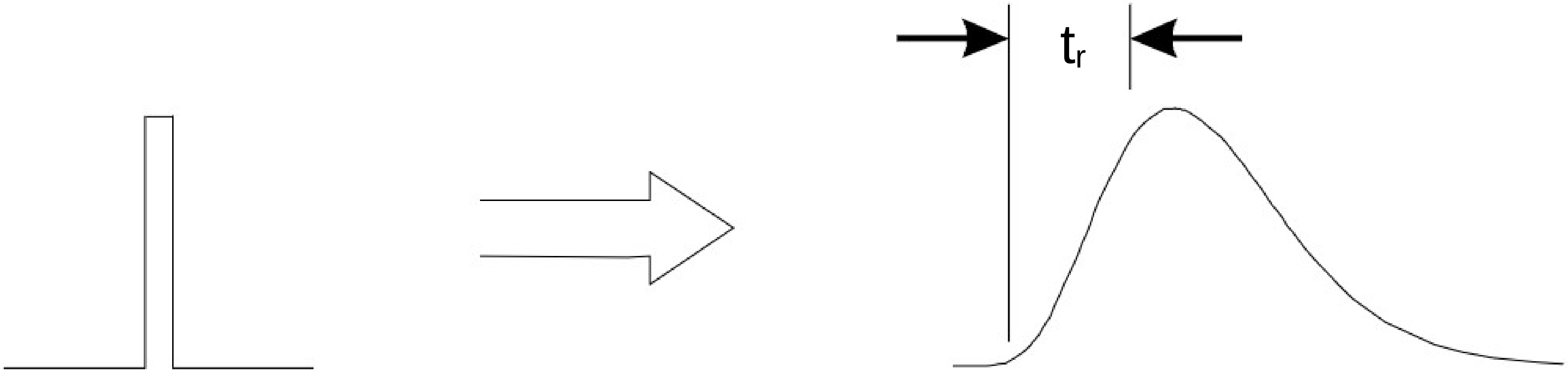
BANDWIDTH AND RISE TIME

- The bandwidth B of an amplifier is the frequency range for which the output power is at least half of the nominal amplification
- The rise-time t_r of a signal is the time in which a signal goes from 10% to 90% of its peak-value
- For an amplifier whose frequency response can be modeled as a RC low-pass filter: $B \cdot t_r = \text{const}$
- To have fast rising outputs (small t_r), a high-bandwidth amplifier is needed, but higher bandwidth == higher noise power

  → **shape the pulse to make it "smoother"**

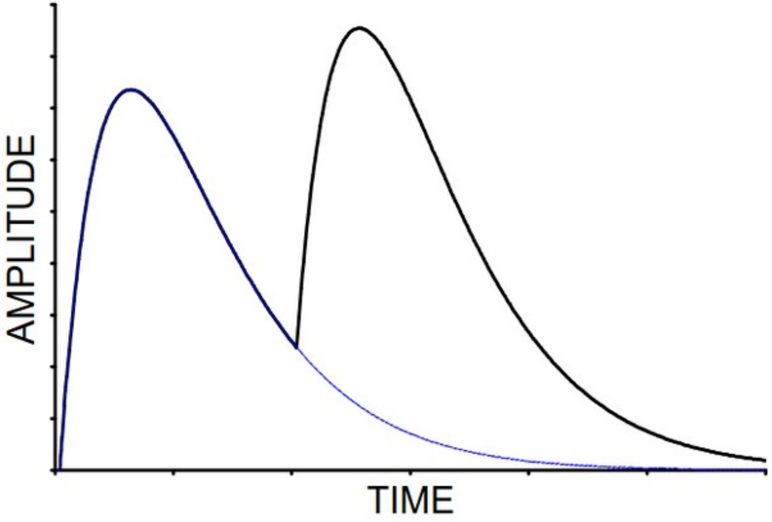
BROADENING PULSES

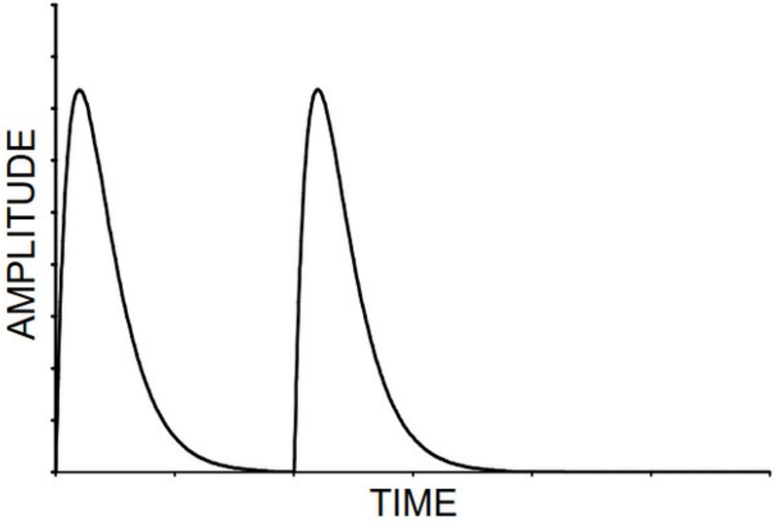
- Fast rising pulse is made more gentle
- Rise time t_r is increased
- Amplifier bandwidth can be reduced and so noise is reduced as well



... IN MODERATION

- Low-bandwidth pulses last longer
- Successive pulses might “pile-up”
- Noise might be low now, but the detector cannot separate two different signals anymore!

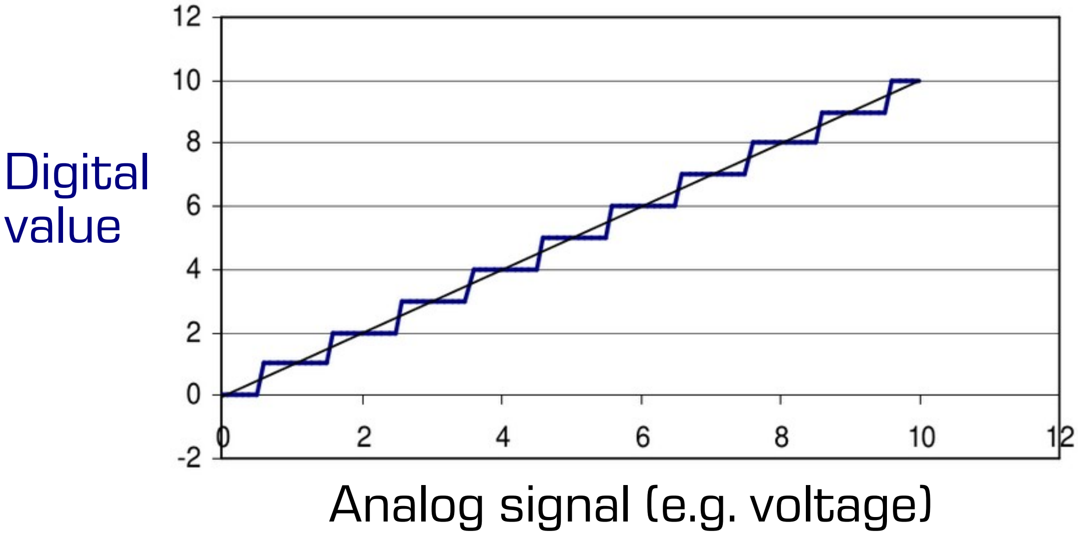




SIGNAL PROCESSING
DIGITIZATION

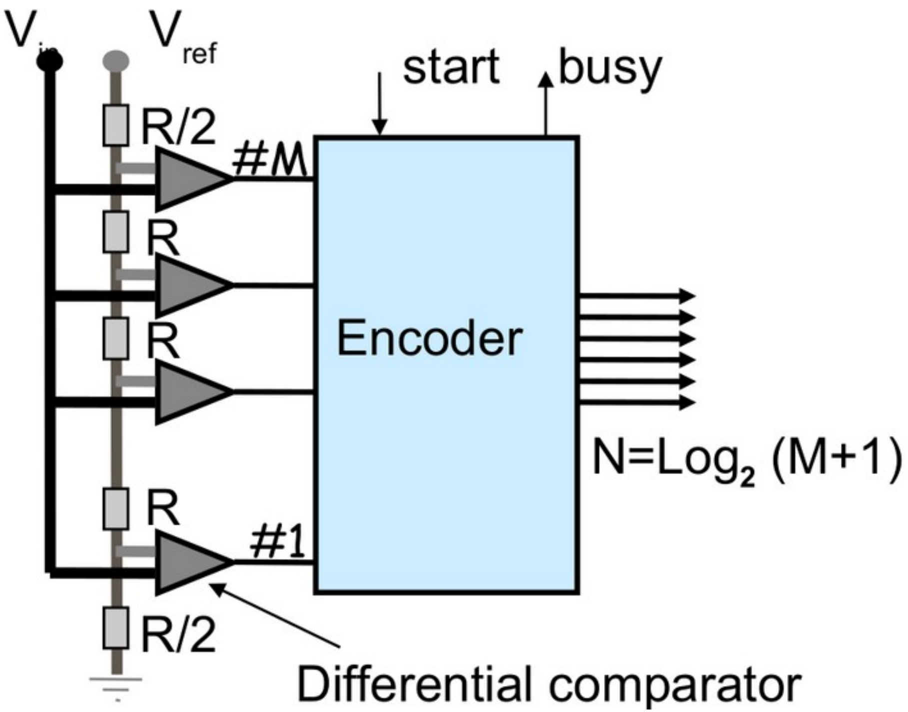
DIGI-WHAT?

- Digitization, or analog-to-digital conversion (ADC) simply means creating a binary representation of an analog value



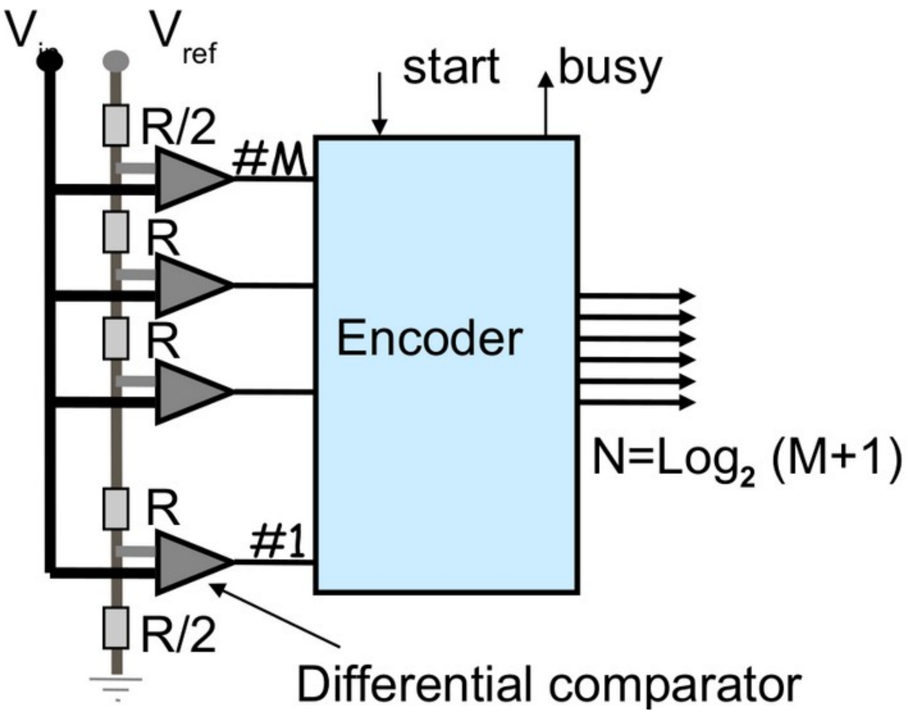
- Finite resolution, finite range,
  but: can be processed with digital electronics and software!

FLASH ADC



- Input voltage is compared with M fractions of a reference voltage: $V_{ref}\,(m\text{-}1/2)/M$
- Result is encoded into a compact binary form of N bits
- Simplest and fastest ADC implementation
- But not cheap:
  - Range $\propto$ n. of comparators
  - Resolution $\propto$ n. of comparators

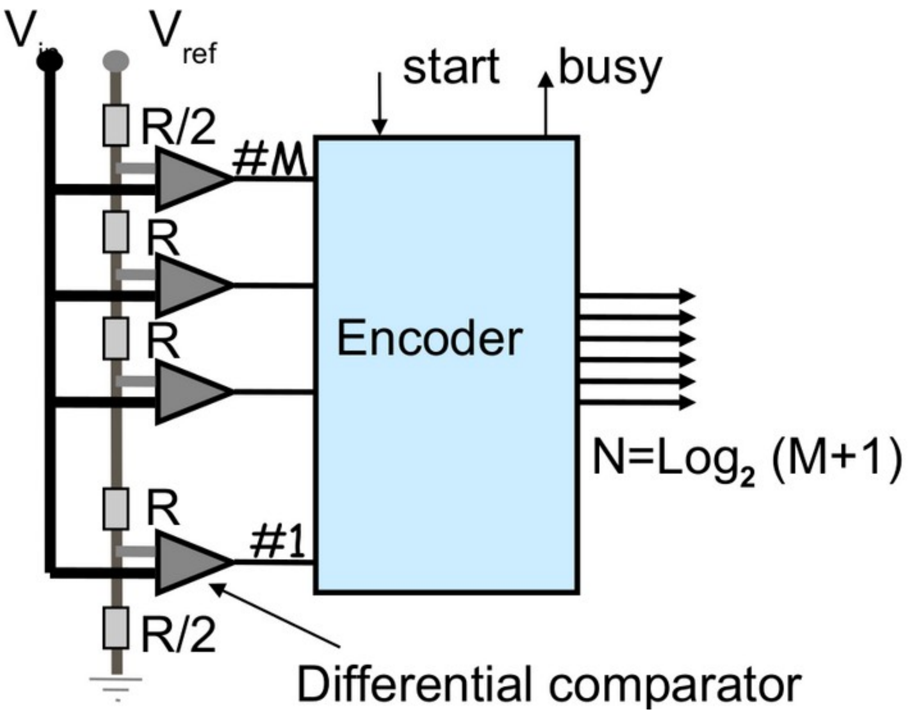
FLASH ADC EXAMPLE



Example with $M=3$, so $N=2$

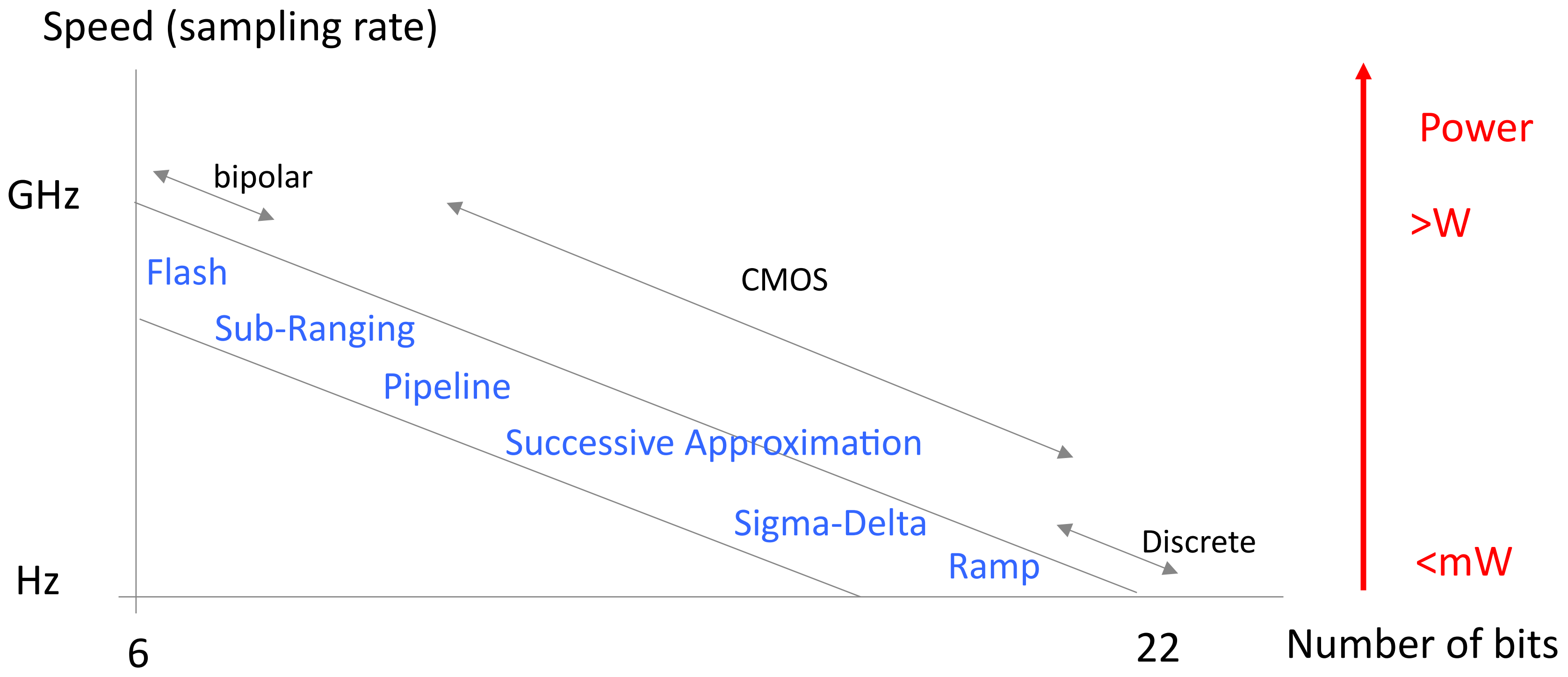
V_{in}/V_{ref}	Comparison results	Output bits
$x<1/6$	0 0 0	0 0
$1/6\leq x<3/6$	0 0 1	0 1
$3/6\leq x<5/6$	0 1 1	1 0
$x\geq 5/6$	1 1 1	1 1

FLASH ADC CHARACTERISTICS



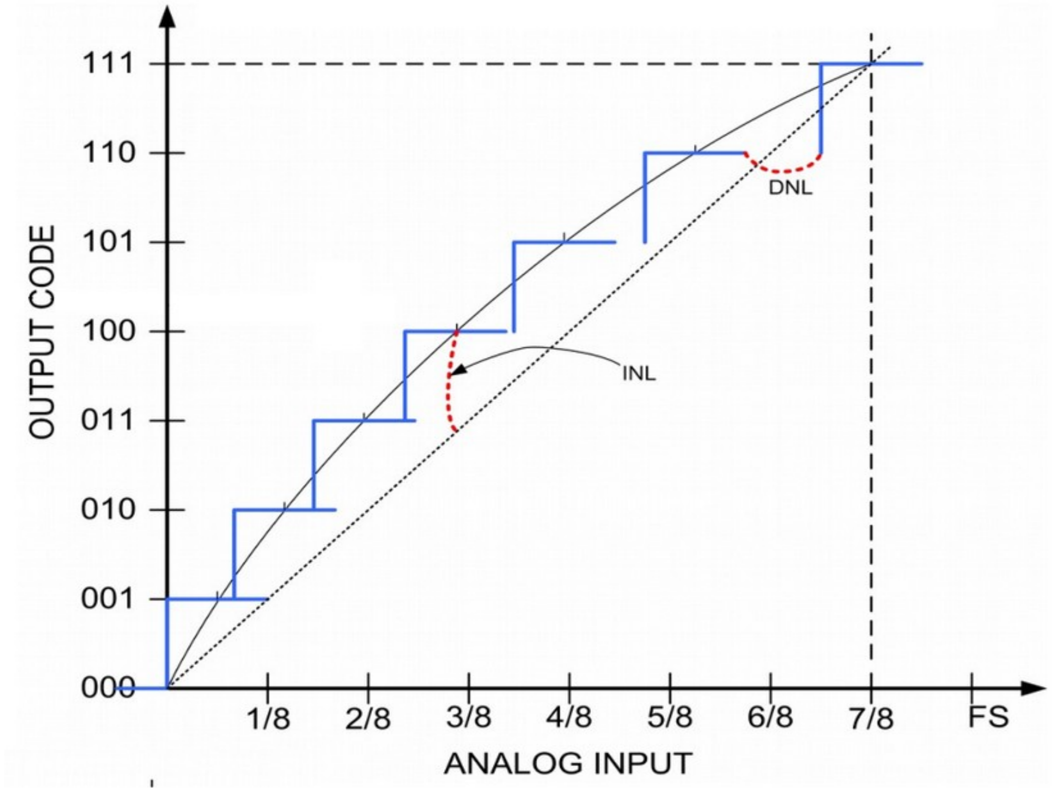
- Resolution
  (a.k.a.: LSB, least significant bit):
  $\mathrm{LSB} = V_{ref} / M = V_{ref} / 2^N$
- Quantization error: $\pm \mathrm{LSB}/2$
- Dynamic range: $V_{ref} / \mathrm{LSB} = \mathrm{M}$
- With different R_1, …, R_M,
  a non-linear-scale ADC can be made
  - Range: >M
  - With **log** scale: the *relative* resolution and quantization errors are constant

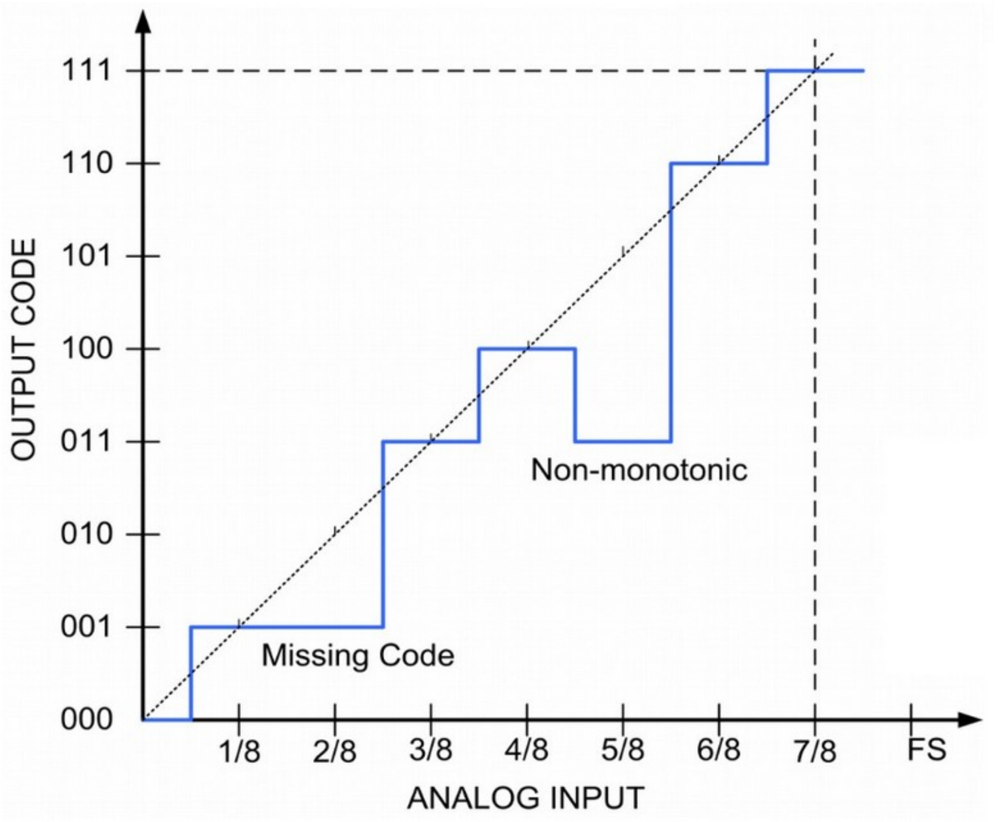
ADC ZOO



- Trade-off between speed and resolution (number of bits)

ADC ERRORS


111
110
101
100
011
010
001
000
OUTPUT CODE
DNL
INL
1/8
2/8
3/8
4/8
5/8
6/8
7/8
FS
ANALOG INPUT


111
110
101
100
011
010
001
000
OUTPUT CODE
Non-monotonic
Missing Code
1/8
2/8
3/8
4/8
5/8
6/8
7/8
FS
ANALOG INPUT

TDC: ADC FOR TIMINGS