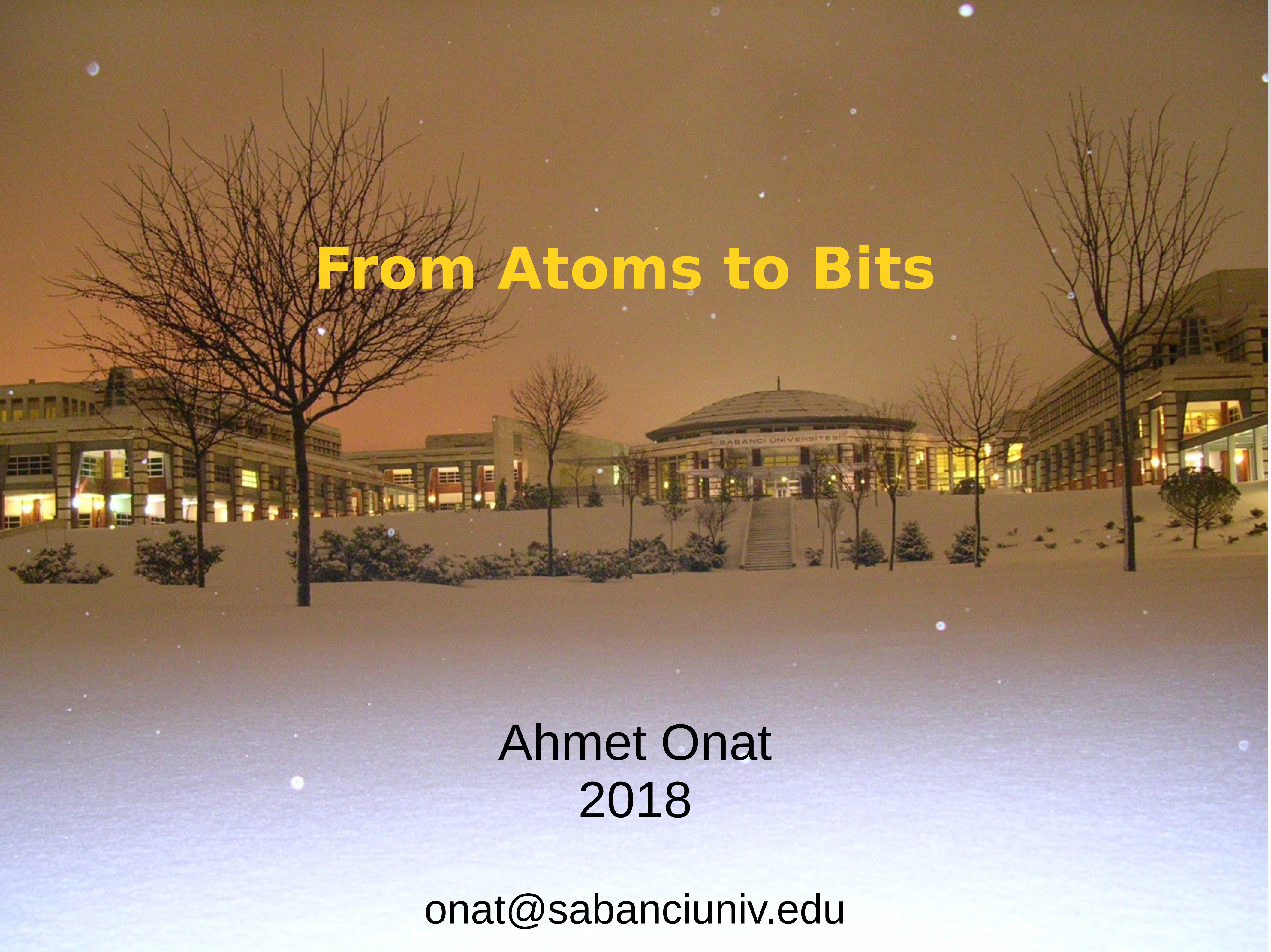


From Atoms to Bits

Ahmet Onat
2018

onat@sabanciuniv.edu

Layout of the Lecture

- Analog interfacing to sensors:
  - Signal conditioning
  - Sampling and quantization
  - Bridge circuits and instrumentation amplifiers
- Linearization
- Design for low power
- Digital interfacing to sensors

Desirable Sensor Characteristics

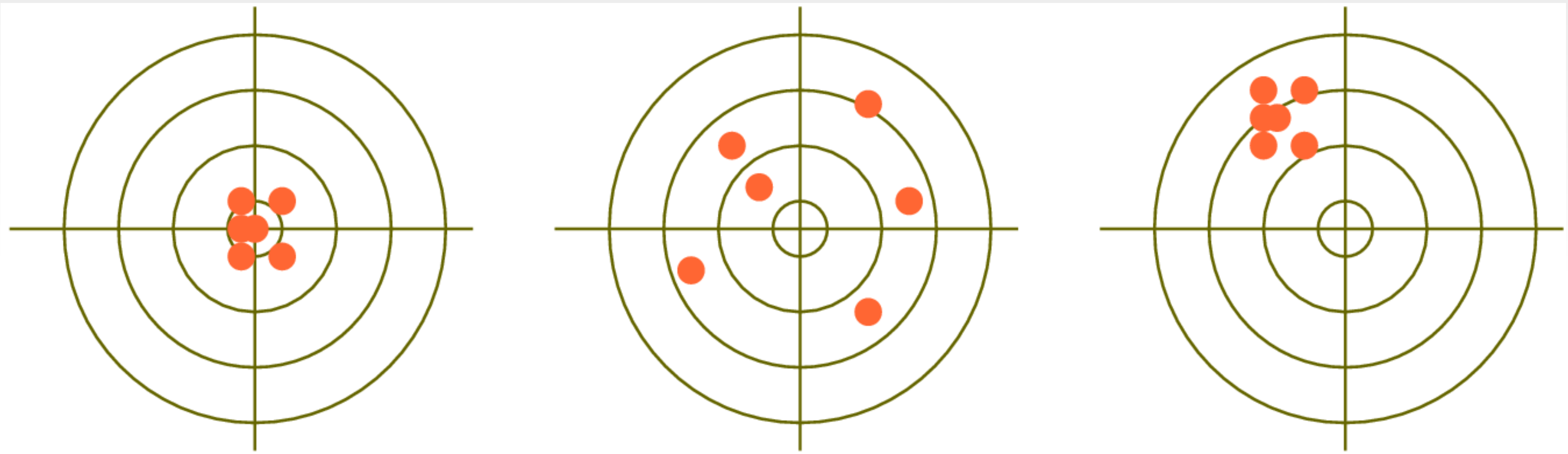
- Sensor reading equal to the measured quantity
- Suitable
    - accuracy, precision,
    - range, sensitivity → gain
    - resolution, etc.
- Low noise
- Linearity

Characteristics of Instrumentation

- Accuracy: How close is the measurement to measured.
- Precision: What is the uncertainty in the measurement.
- Range: Which value interval is measurable?
- Sensitivity: For a given change in input, the amount of the change in output.
- Resolution: Smallest amount of measurable change
- Repeatability: Under the same conditions, can we get the same measurement?

Accuracy - Precision

- How accuracy and precision are related?



Accurate,
Precise

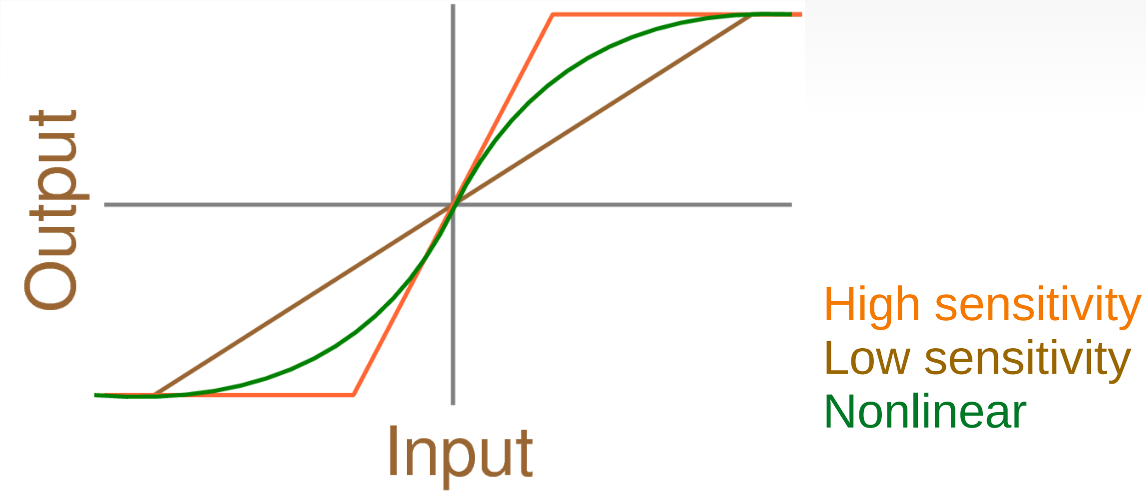
(In)accurate,
Imprecise

Inaccurate,
Precise

- Inaccurate but precise?
  - Metal ruler on a hot day: Same precision bad accuracy

Sensitivity - Range

- Generally high sensitivity sounds good.
- However, high sensitivity restricts range.
- Deliberately → nonlinear sensor can be used.

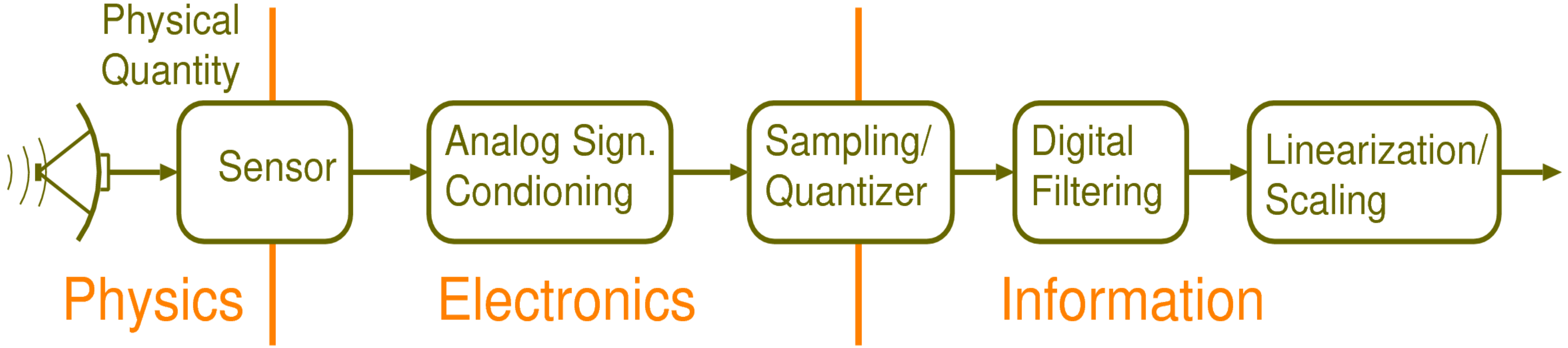


- 1mV precision;
  - 8bit: $0.256V$ range
  - 12bit: $4.096V$

Analog Interfacing to Sensors

There are 3 main stages in sensing:

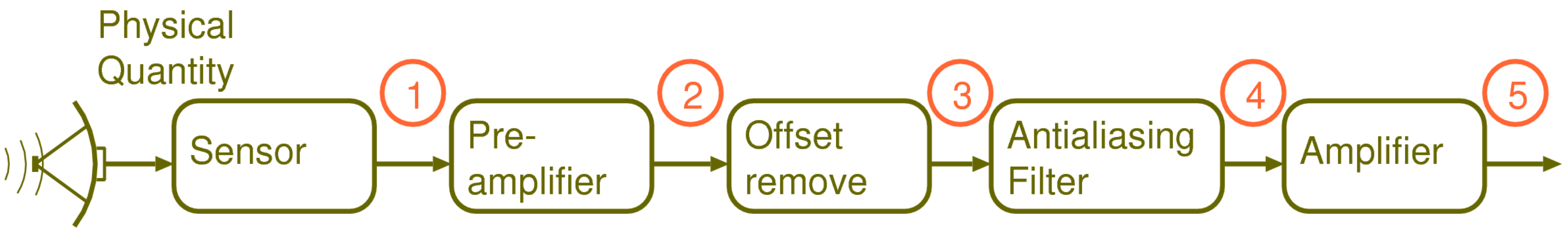
- Physics
- Electronics
- Information
- →Pysics will not be treated.



Signal Conditioning Electronics

Signal Conditioning System

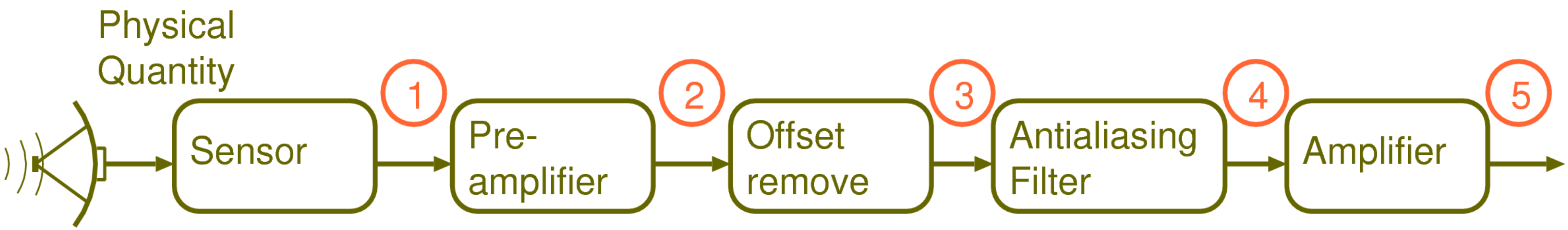
1. Sensor Output
2. Preamplifier stage
3. Removal of offset
4. Antialiasing filter
5. Amplifier



Signal Conditioning: Sensor

1. Sensor

- Low power electrical signal → { Low voltage / Low current }
- Wide frequency bandwidth
  - Aliasing during sampling
- Offset voltage
  - Prevents use of full quantizer range

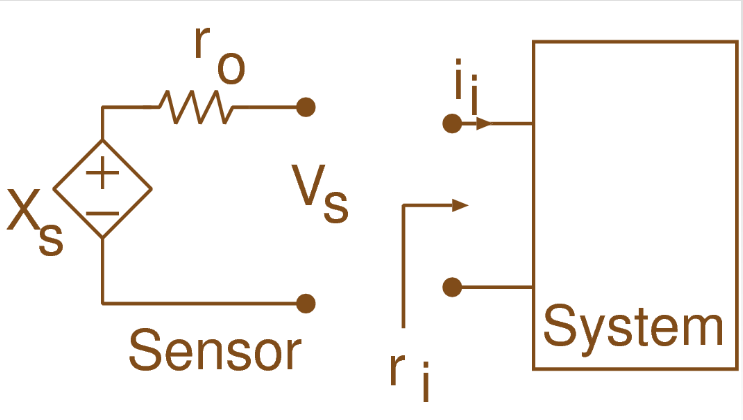


Signal Conditioning: Sensor

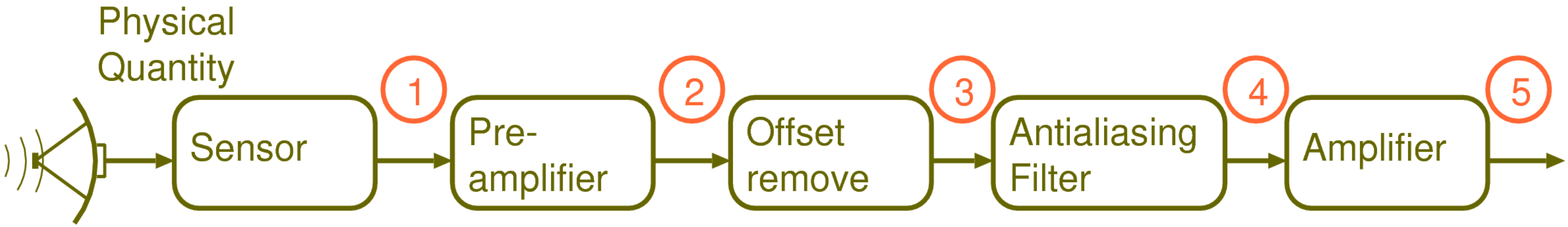
1. <u>Sensor</u>

- Voltage source with impedance
- $P_{o\,max} \rightarrow r_o = r_i$ OR
- $r_i \rightarrow \infty : V_s = X_s$

  (Calculate like a voltage divider)



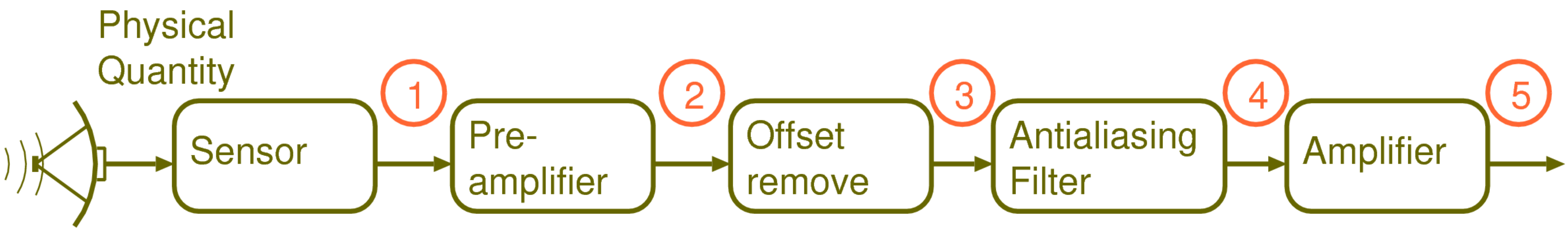
$r_i = V_s / i_i$



Signal Conditioning: Preamplifier

2. <u>Preamplifier stage</u>

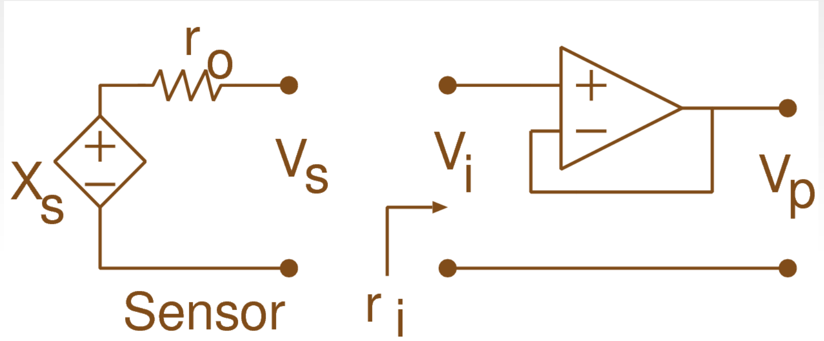
- Extract largest amount of power from signal or,
- Draw the least amount of current.
- Matched impedance circuit
- Low noise
- High gain



Signal Conditioning: Preamplifier

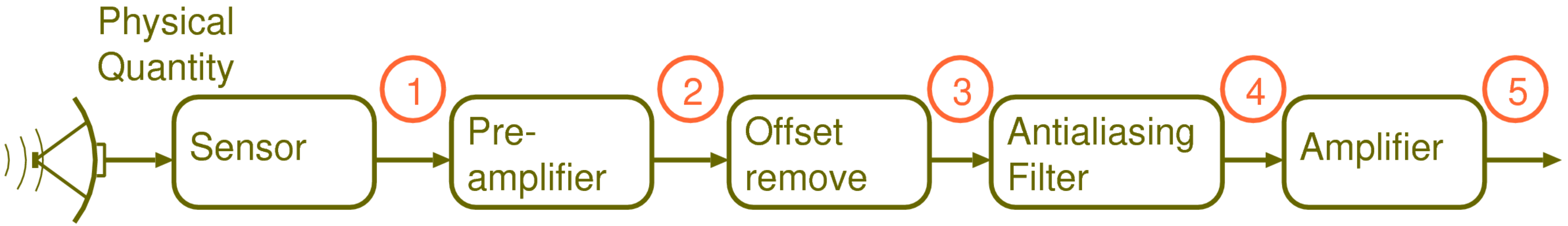
- Draw the least amount of current:

  Voltage follower configuration



$$r_i = 2\times 10^{17}\,\Omega$$

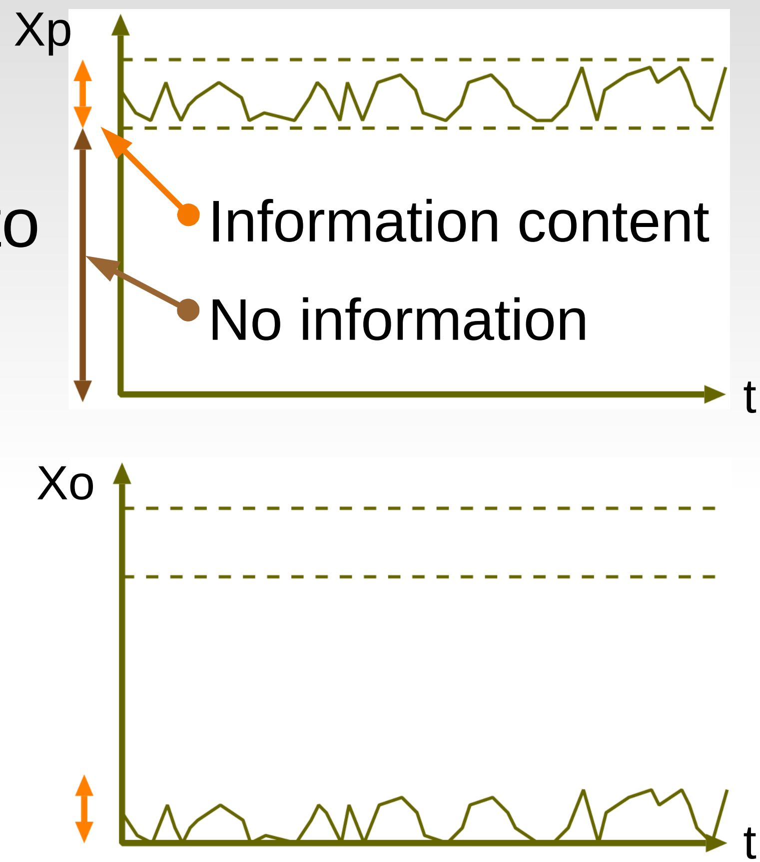
- Susceptibility to ESD increases.

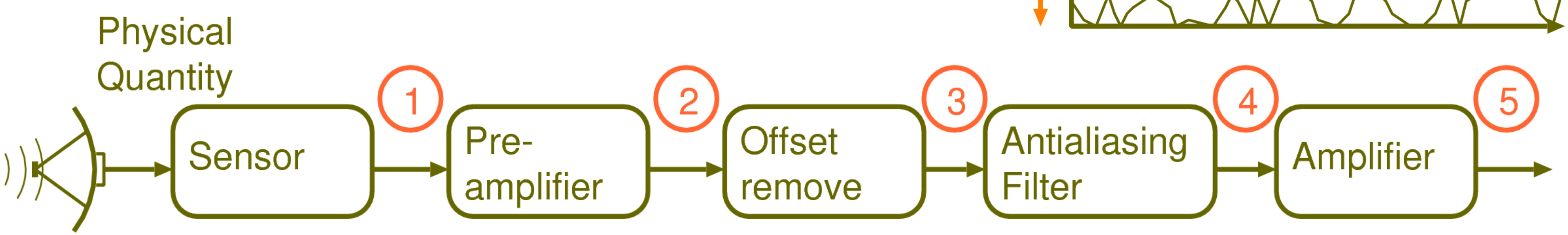


Signal Conditioning: Offset Removal

3. <u>Offset remove</u>

- The information content is confined to a small part of the signal range.
- Amplification will not allow max precision of the quantizer:
  2 MSB always set: 11xxxxxx
  12 bit ADC → 10bit ADC



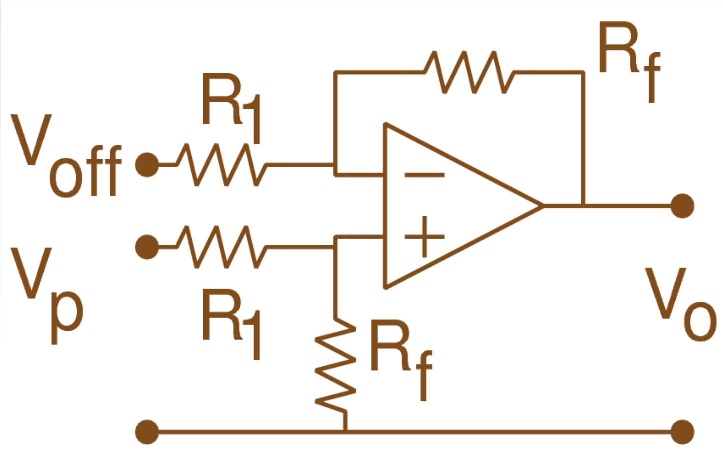


Signal Conditioning: Offset Removal

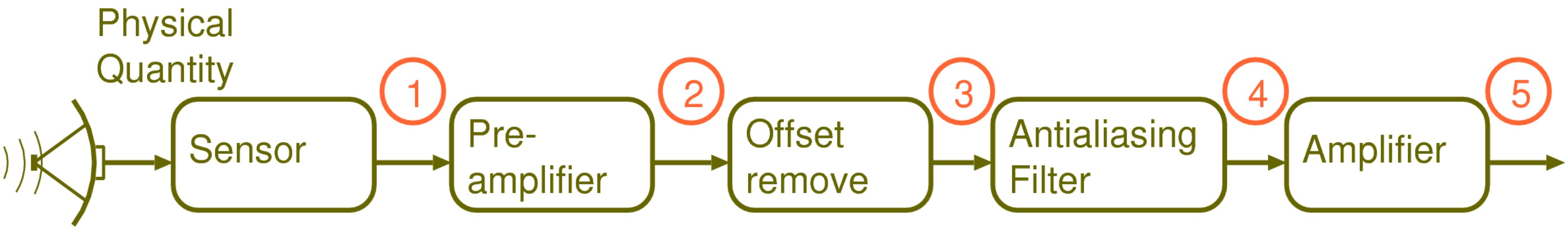
3. <u>Offset remove</u>

- Difference amplifier.

$$V_o = \frac{R_f}{R_1}\left(V_p - V_{off}\right)$$



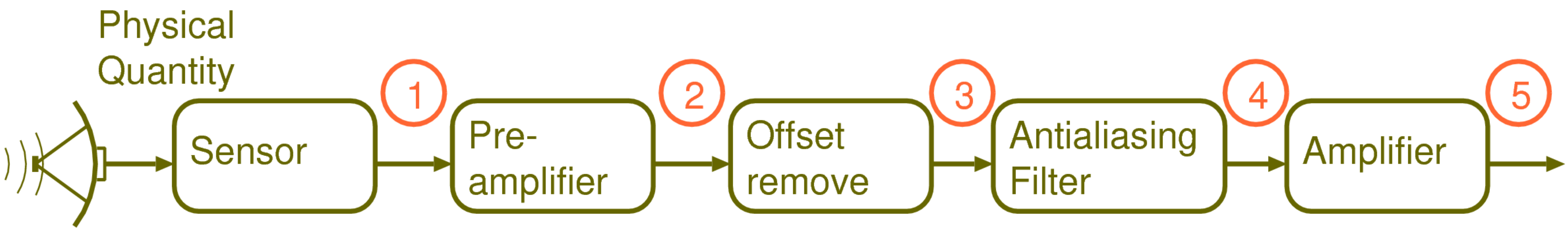
- V_{off} : Constant offset voltage for removal.



Signal Conditioning: Filter

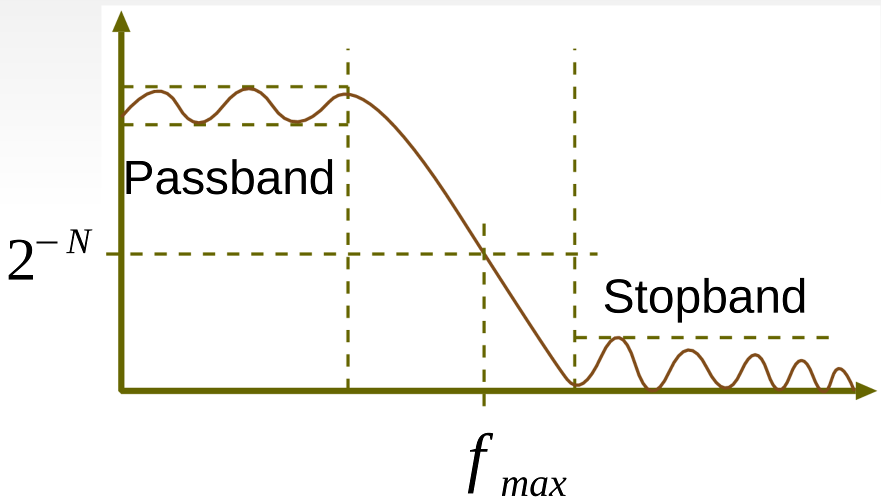
4. Antialiasing Filter

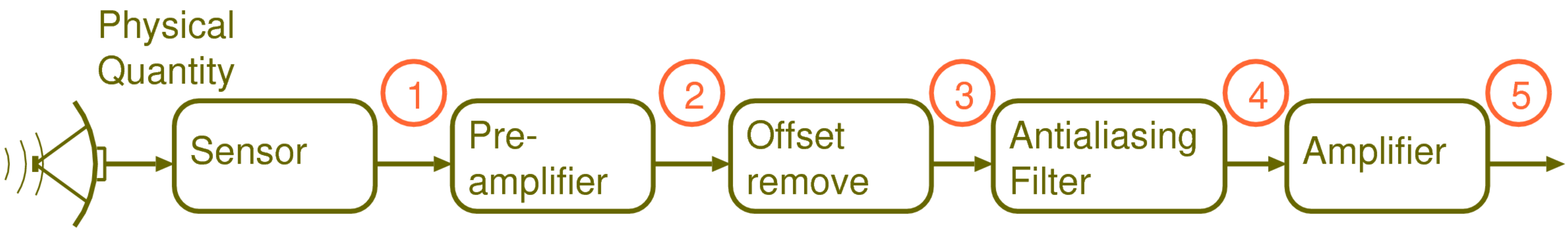
- "A bandlimited function is completely determined by its samples taken at more than twice the maximum frequency component"
- It is necessary to limit the bandwidth of the signal for:
  - Sampling
  - Noise suppression



Signal Conditioning: Filter

- Filter characteristic:
  - Passband ripple must be less than ADC resolution.
  - Bandwidth limit frequency at 2^{-N} gain.
- What order filter?



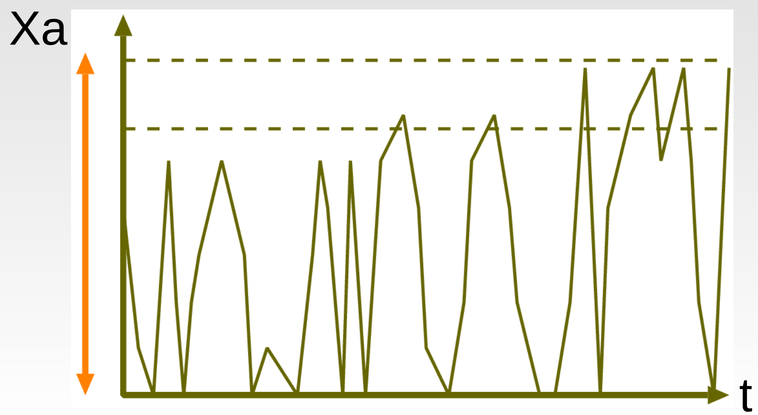


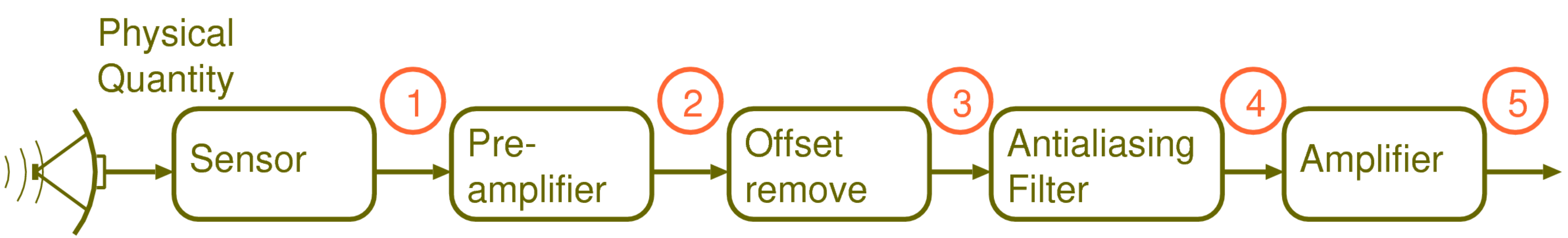
Signal Conditioning: Amplifier

5. <u>Amplification</u>

- Signal is amplified to the reference voltage of the ADC.

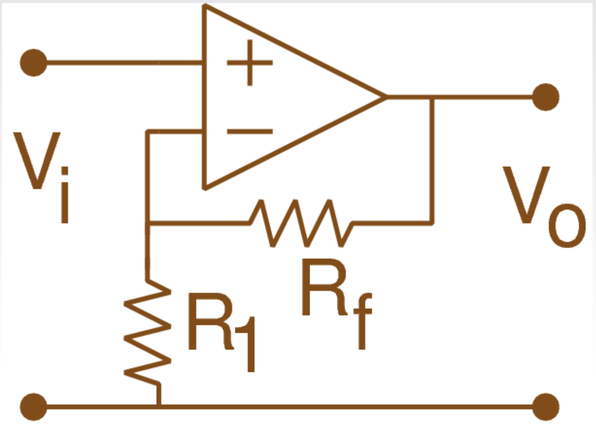
$$x_a(t) < x_{max} = V_{ref}$$





Signal Conditioning: Amplifier

- Simple non-inverting amplifier circuit.
- Ideal gain $(A \approx \infty)$: $\frac{V_o}{V_i} = \left(1 + \frac{R_f}{R_1}\right)$
- Actual gain: $\frac{V_o}{V_i} = \frac{A(R_1 + R_f)}{AR_1 + R_1 + R_f}$



- Error for $A=50{,}000$, $R_1=1k\Omega$, $R_2=9k\Omega$, $V_i=0.500V$:

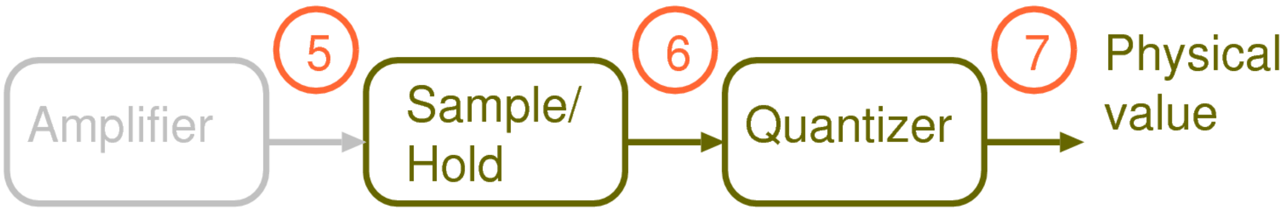
$$\left.\begin{array}{l} V_{o\infty} = 5.000\,V \\ V_{o50k} = 4.998\,V \end{array}\right\} e = 2000\,\mu V$$

2 counts on the quantizer

- For 5V, 12bit: $\Delta = 1221\,\mu V$

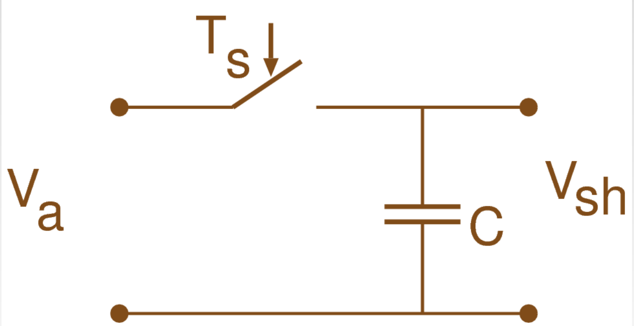
Data Converter

6. Sample and Hold
7. Quantizer



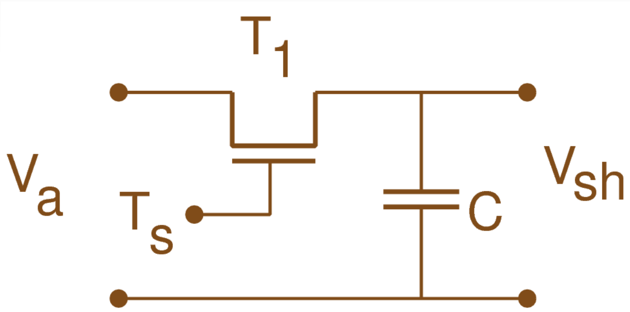
Sample and Hold

- Ideal sampling requires
  - zero duration and
  - infinite currents.



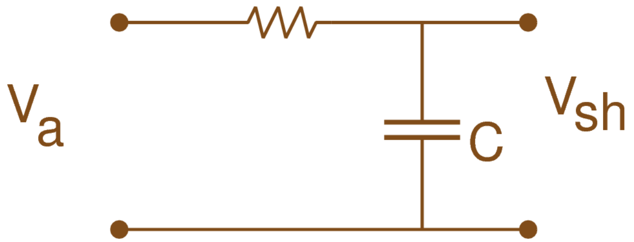
Ideal sample and hold

- Actual sampling uses a transistor…



Actual sample and hold

- The body resistance of the transistor turns the S&H into a low pass filter.



Sample and hold equivalent circuit

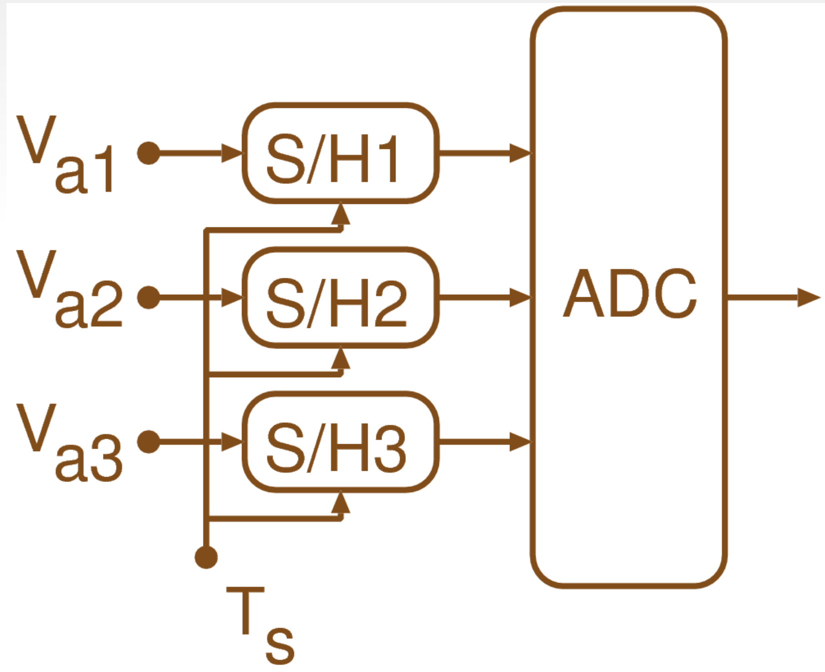
Sample and Hold

- Time constant of a 1st order RC filter:
- $\tau = RC\ s$
- It is necessary to keep sampling for at least 5τ to allow the capacitor to be charged to V_a
- Microcontrollers allow the adjustment of the charging period.
- Higher precision ADC requires longer charge times: “Acquisition Time”
- It is not possible to exceed $f = \frac{1}{5}\tau$ for sampling.

Sample and Hold

- Sampling several signals at the same instant.
- Several ADC can be used.

- More commonly, synchronous sampling, sequential conversion:



- In specialized applications several ADC are used: Motor current sampling, lab measurement etc.

Sampling of Continuous Time Signals

- The Fourier transform of a continuous time signal is given by:

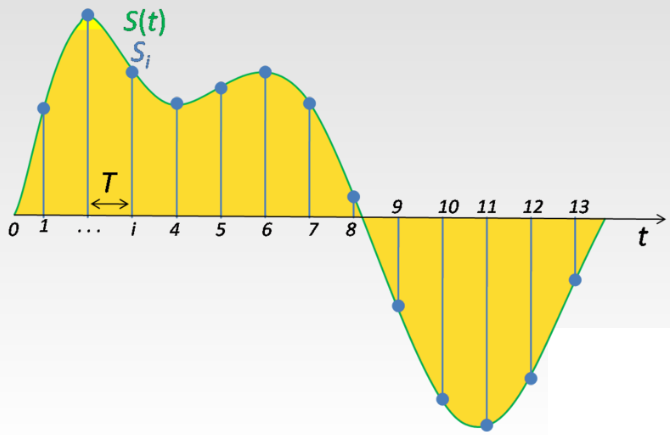
$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-2\pi f t} dt$$

$$x_s(t) : x(nT_s); \quad T_s = 1/f_s$$

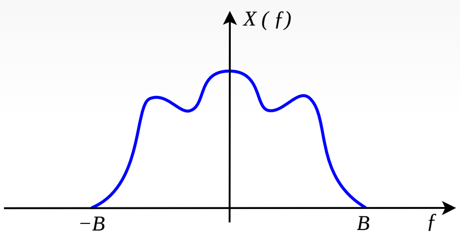
$$X_s(f) = \sum_{k=-\infty}^{\infty} X(f + kf_s)$$

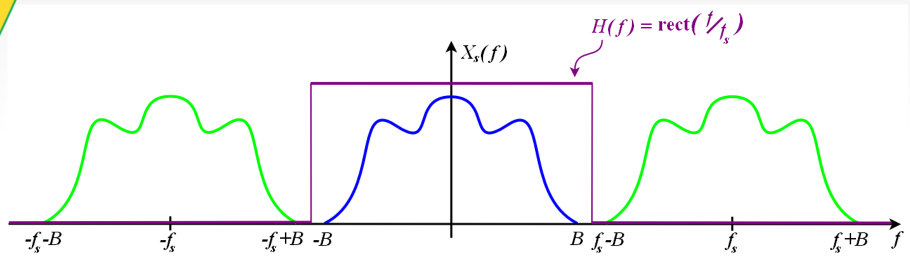
- When a signal is sampled by f_s, its frequency spectrum becomes periodic by f_s.

Sampling of Continuous Time Signals

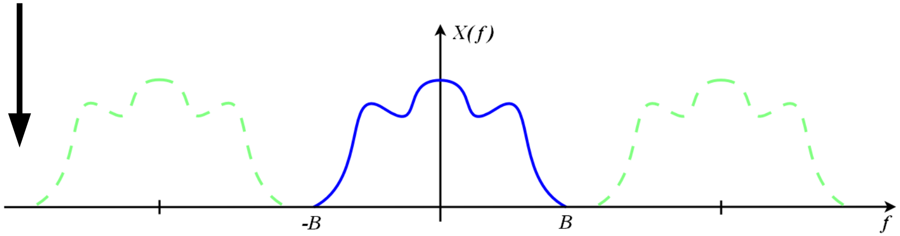


Sampled. Note spacing





Continuous time signal
frequency spectrum

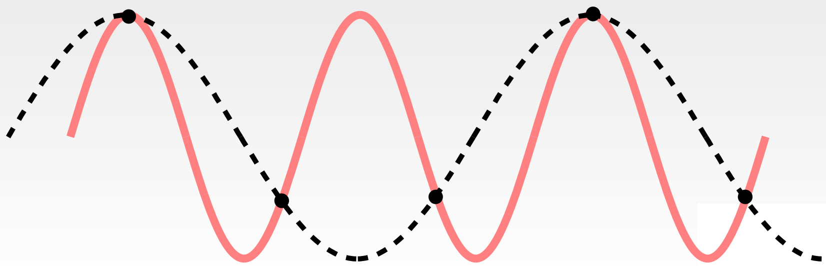


With correct filtering, original signal
can be exactly recovered.

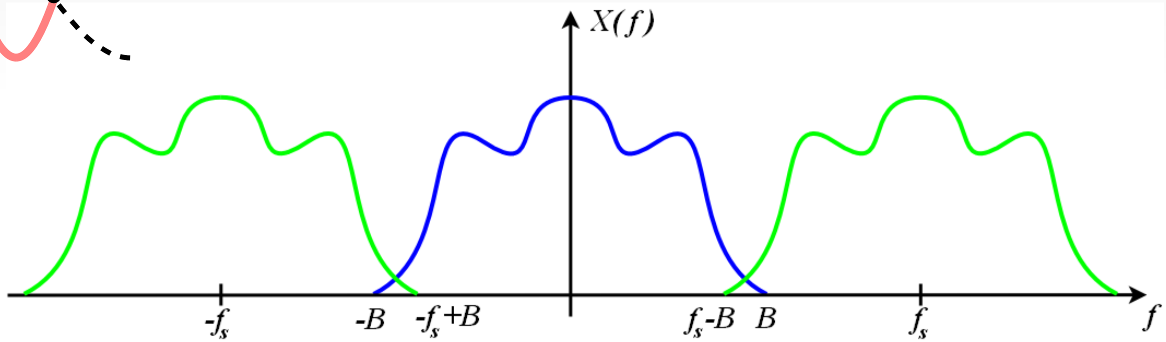
Source of figures: Wikipedia.org

Sampling of Continuous Time Signals

- However, if low sampling frequency is used:

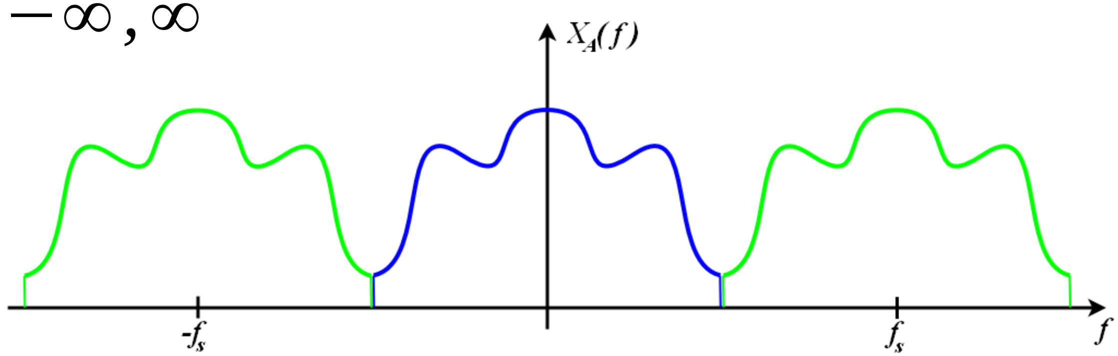


$$X_s(f)=\sum_{k=-\infty}^{\infty} X(f+kf_s)$$



- There are overlaps:

$$[(k+1)f_s-B, kf_s+B], k\in-\infty,\infty$$



Which are added up.

- Original signal is lost.

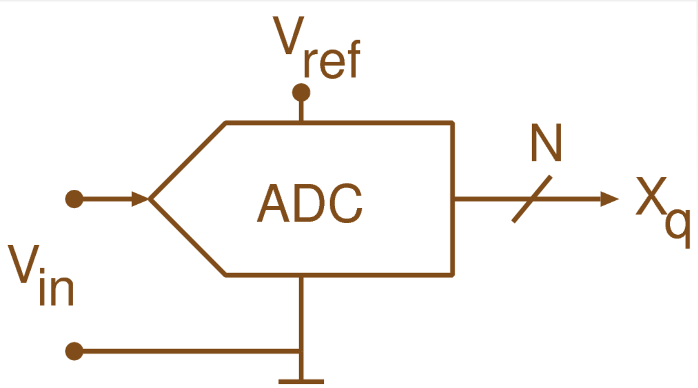
Source of figures: Wikipedia.org

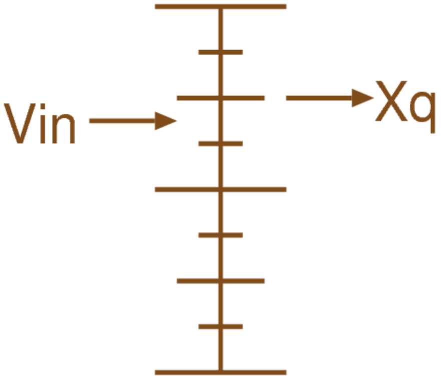
The Data Converter AKA Quantizer

- Analog to digital conversion (ADC) is a search operation.

$$x_q = \left\lfloor 2^N \frac{V_{\text{in}}}{V_{ref}} + \frac{\Delta}{2} \right\rfloor$$

$$\Delta = V_{ref} / 2^N$$

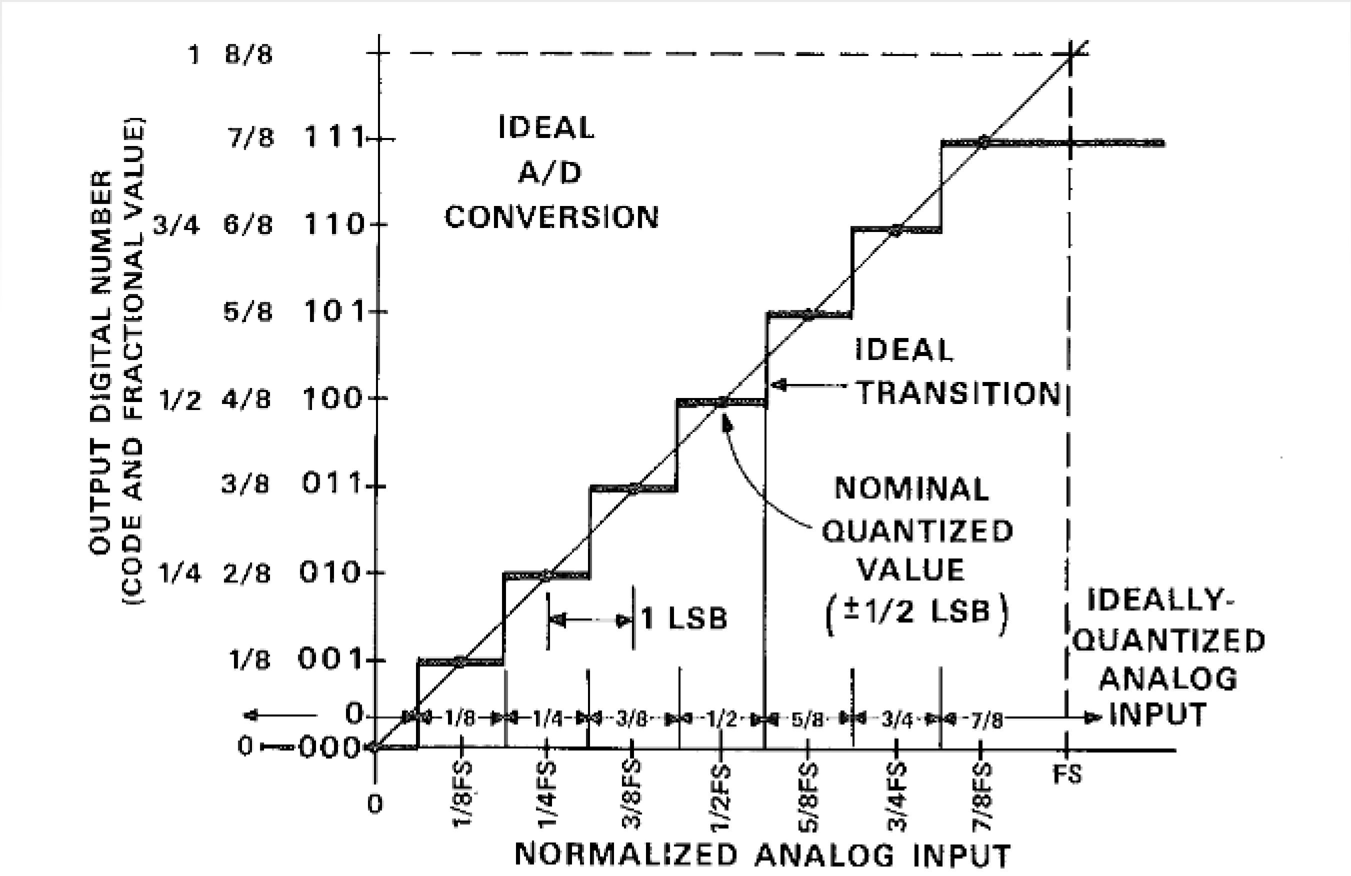




- Precision is limited to finite value,
- Information about input is lost.
- Time consuming OR complex operation.

The Data Converter AKA Quantizer

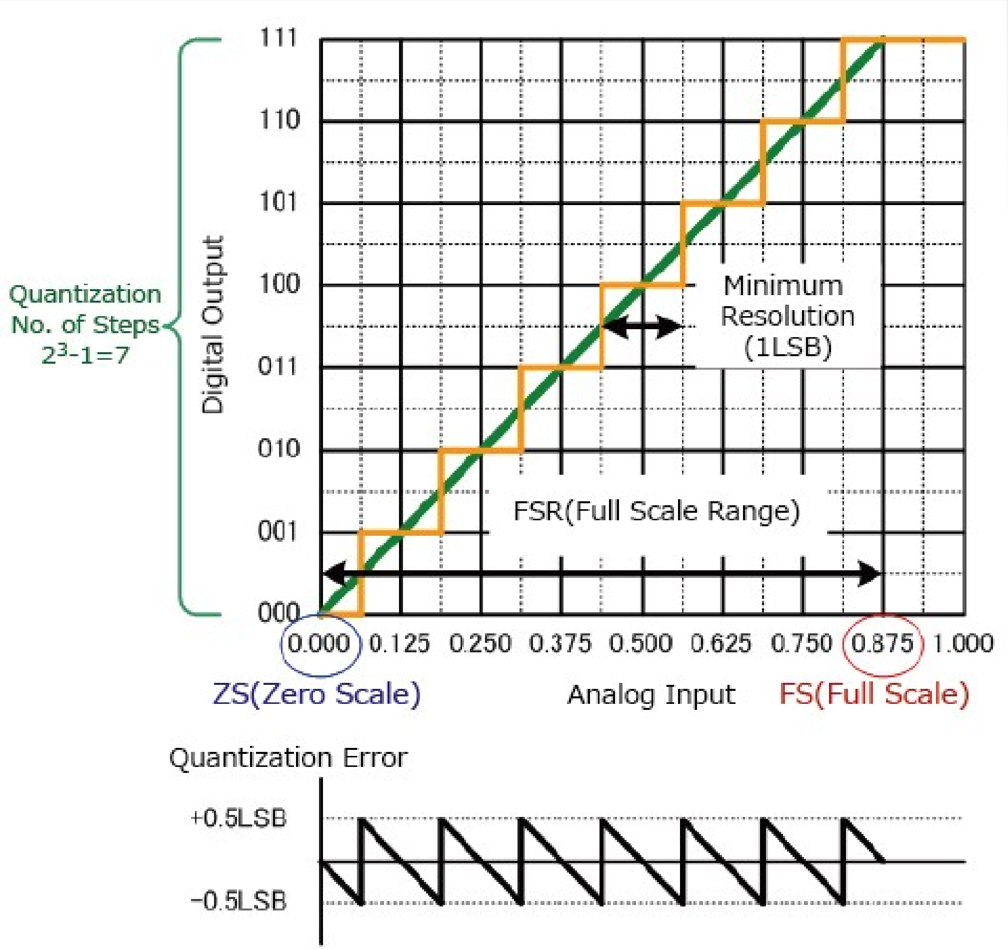
- Ideal, normalized, 3 bit quantizer.



Source of figures: D.H. Sheingold, Analog Digital Conversion Handbook, 1986

Quantization Error as Linear Noise

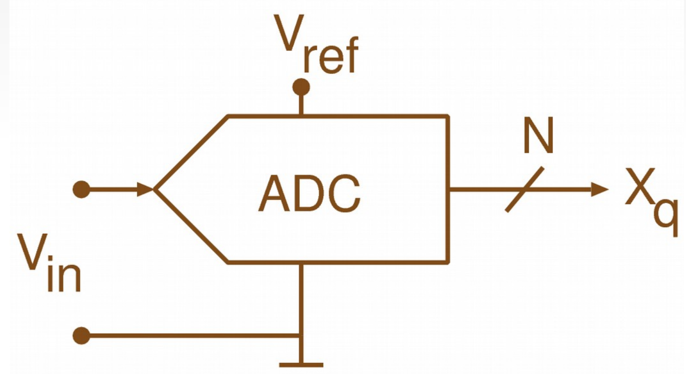
- V_{in} is ambiguous →
- Quantization can be modeled as additive noise.



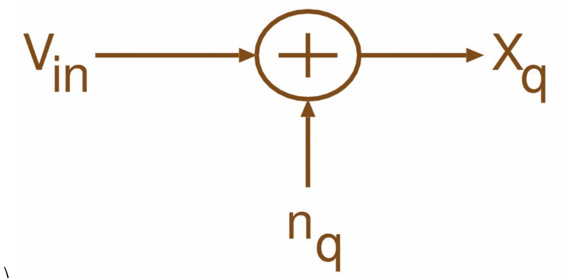
$$x_q = V_{\text{in}} + n_q$$

Quantization Error as Linear Noise

- Vin is not known →
- Quantization can be modeled as additive noise.



$$x_q = V_{in} + n_q$$

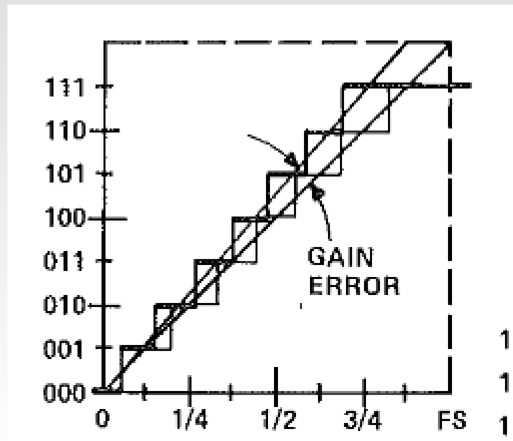


$$SNR_{dB} = 6.02N + 1.76$$

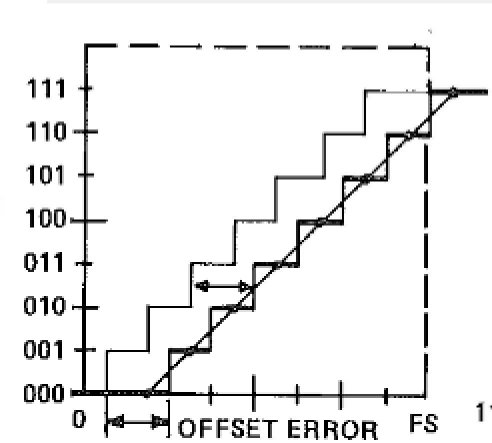
$$\left(V_{in} = A\sin(\omega t),\ \text{N bit quantizer}\right)$$

Quantizer Performance

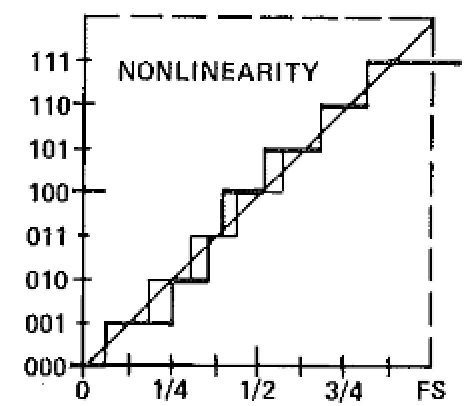
- Gain not unity:



- Does not start from zero:



- Step change voltages are not uniform:

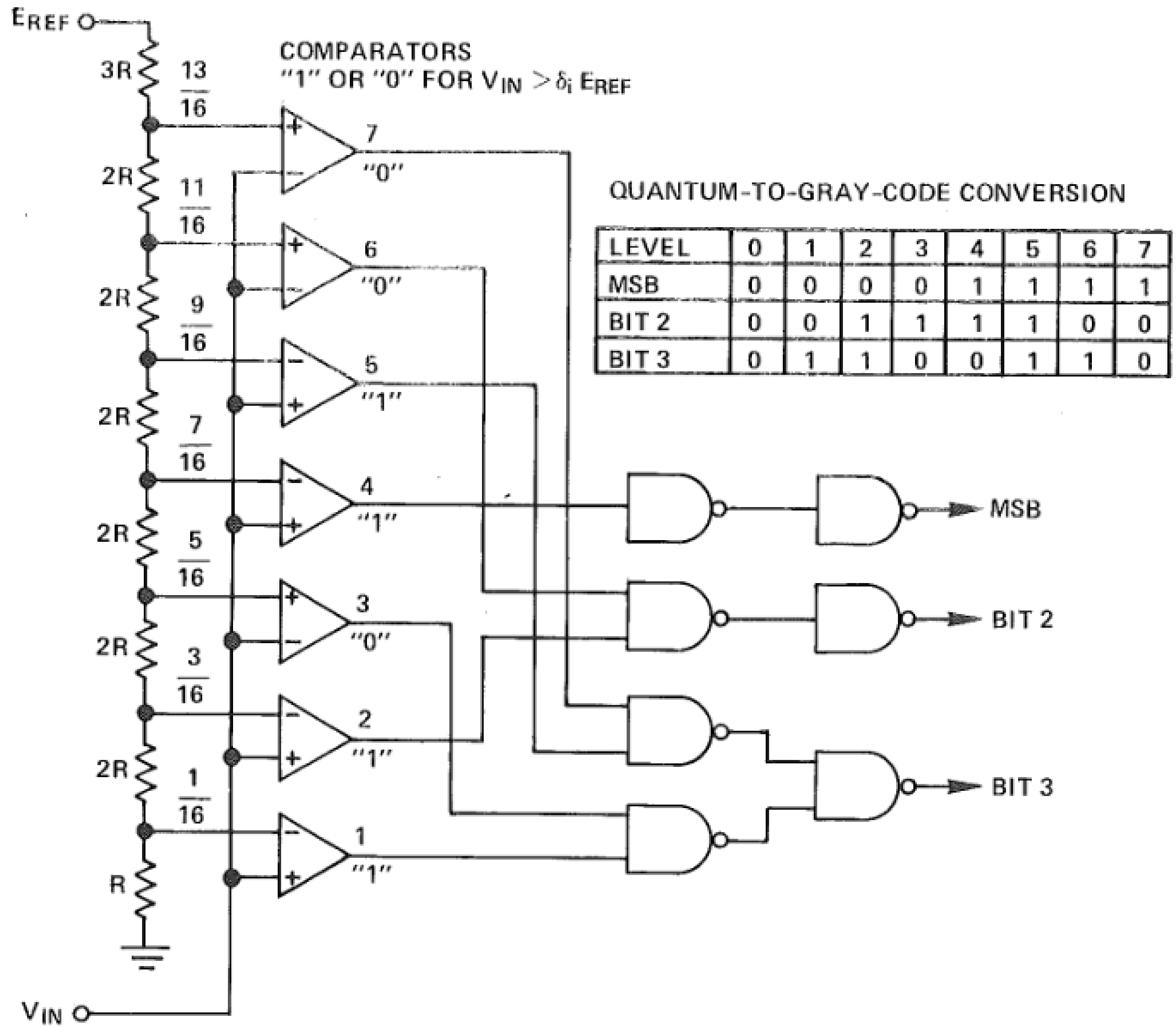


- Each can be corrected in software (not easily)

Source of figures: D.H. Sheingold, Analog Digital Conversion Handbook, 1986

Quantizer Realizations: Flash

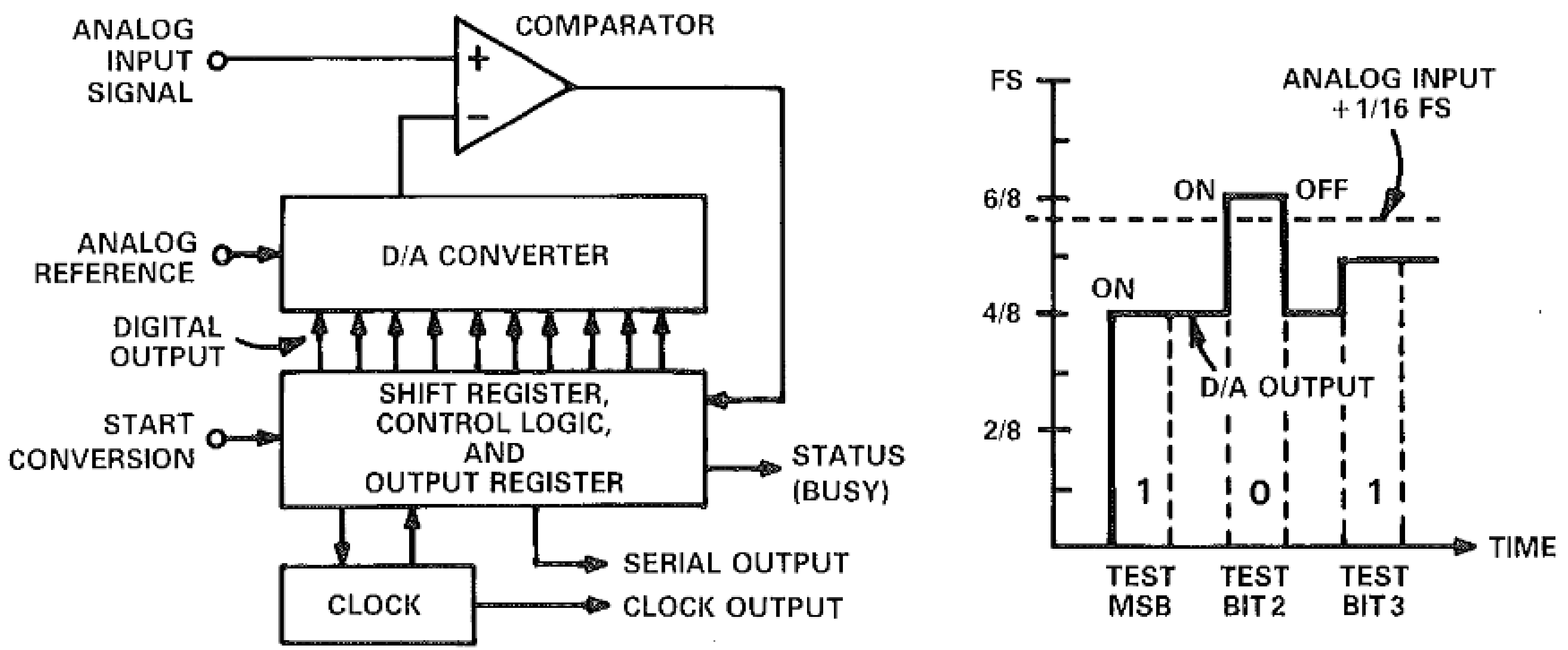
- Low latency
- High complexity O(2^N)
- Bad linearity



LEVEL	0	1	2	3	4	5	6	7
MSB	0	0	0	0	1	1	1	1
BIT 2	0	0	1	1	1	1	0	0
BIT 3	0	1	1	0	0	1	1	0

Quantizer Realizations: Successive Approx.

- Higher latency.
- Low complexity.
- Good linearity.

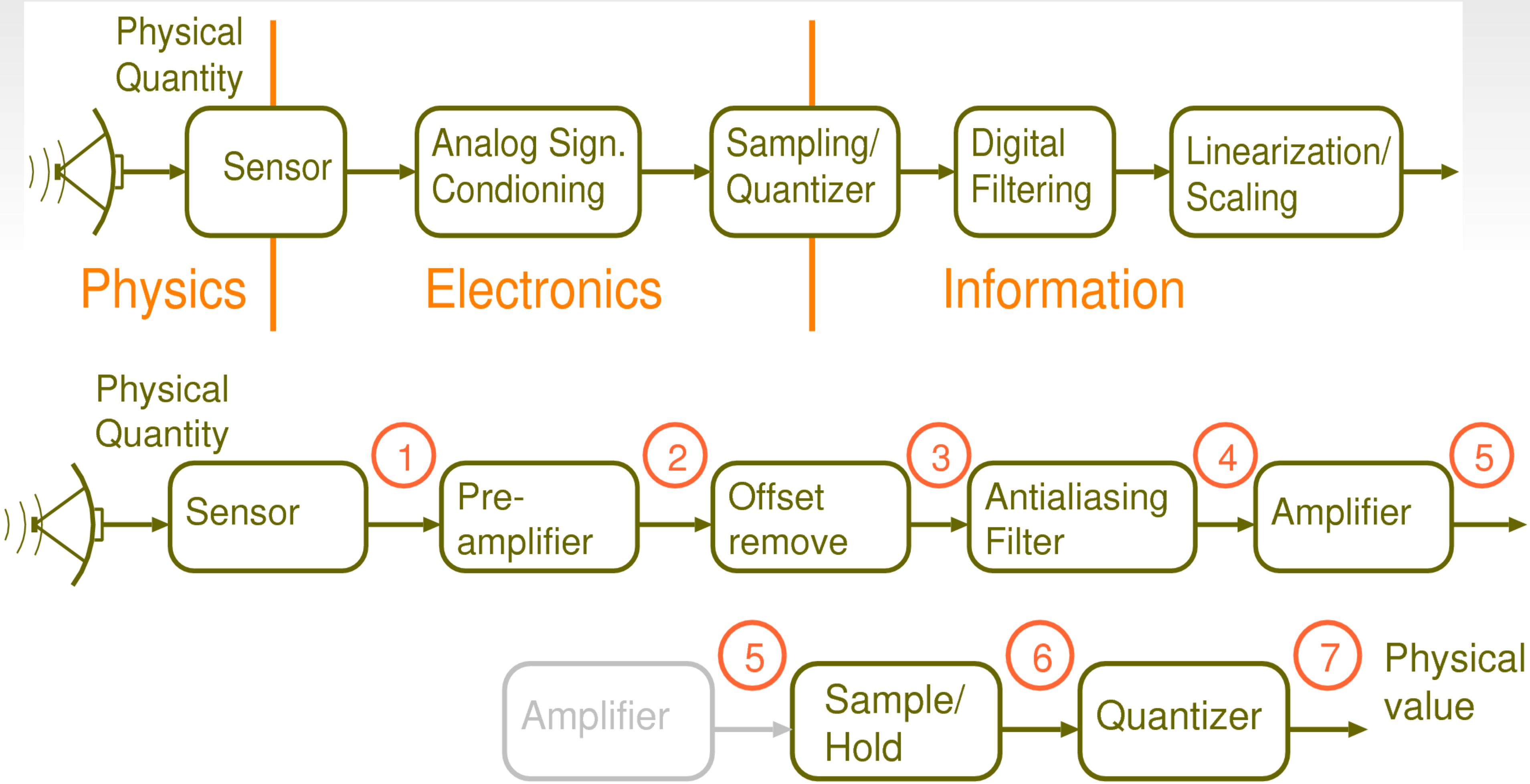


Source of figures: D.H. Sheingold, Analog Digital Conversion Handbook, 1986

Digital Signal Processing

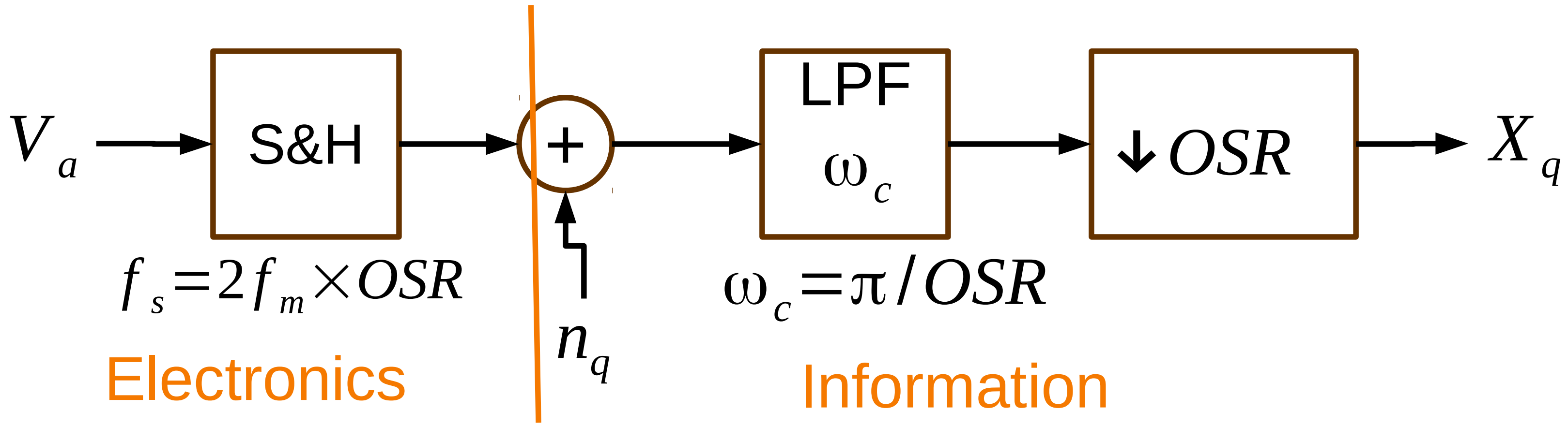
From Physical Quantity to Physical Value

- The final stage is digital signal processing.



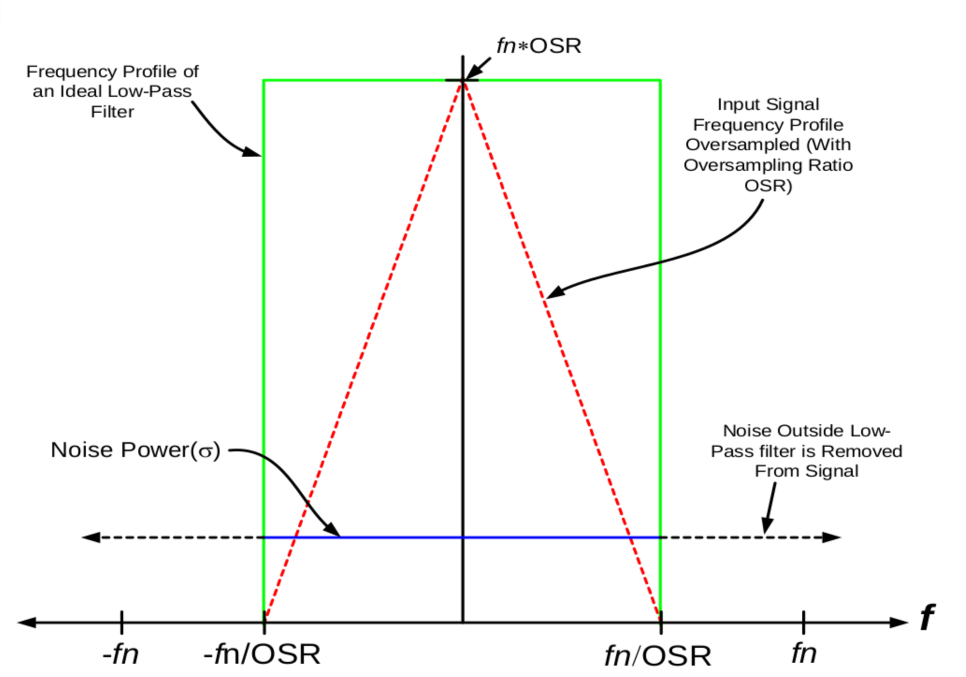
Oversampling / Noise Shaping

- Signal is sampled at much higher rate than Shannon.
- After ADC, DSP low pass filter is applied.
- Low order anti-aliasing filter is sufficient.
- Increase in precision is obtained due to averaging.



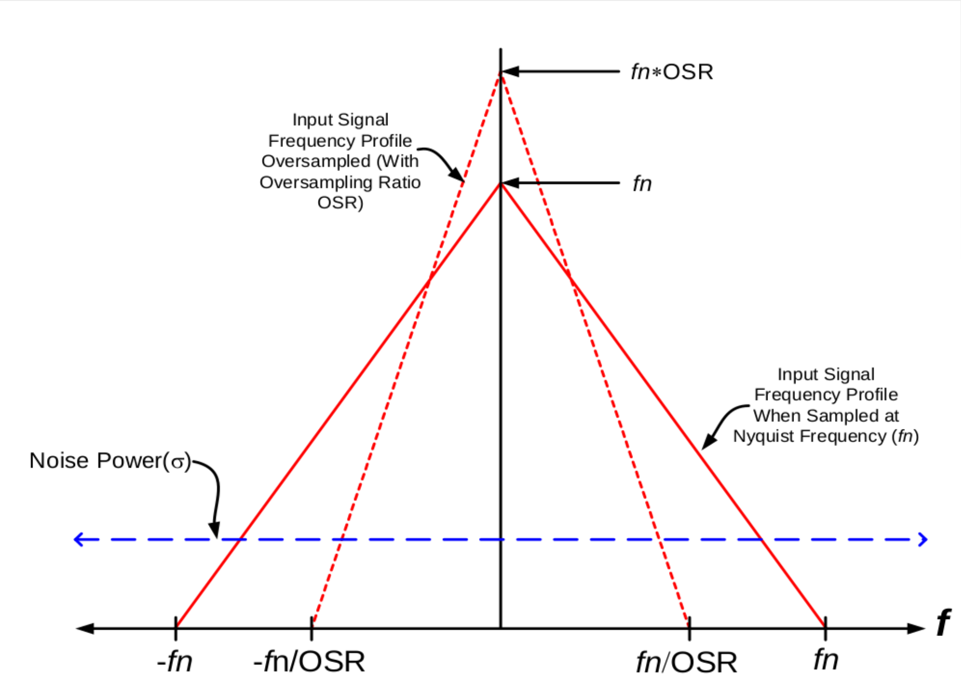
Oversampling / Noise Shaping

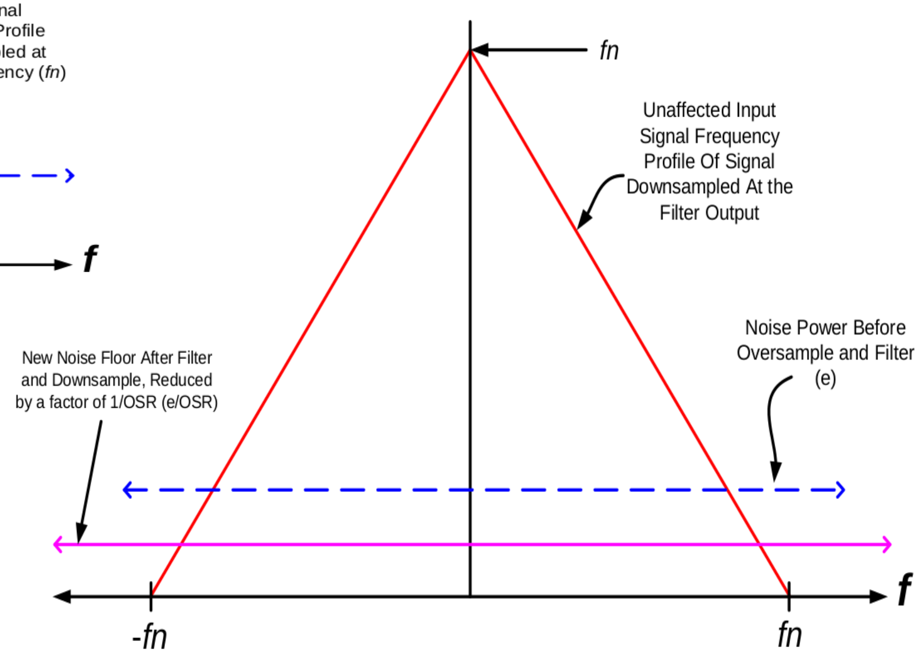
- Sampling rate is much higher than required by Shannon theorem.
- Quantization noise power is constant, regardless of sampling rate.
- Signal spectrum amplitude is inreased proportionally.
  $$V_a(f)' = V_a(f) \times OSR$$
- Signal occupies less of the digital bandwith.
  $$f'_{max} = f_{max} / OSR$$



Oversampling / Noise Shaping

- Downsampling by OSR brings the signal back to desired band.





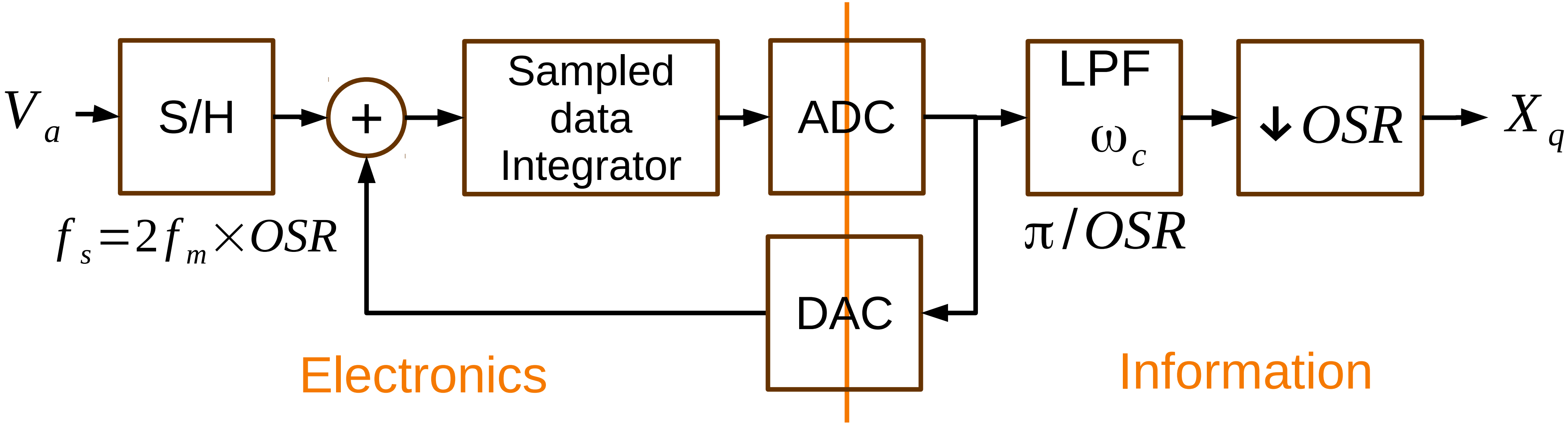
Oversampling / Noise Shaping

- Oversampling increases the ADC precision.
- OSR= $4^w \rightarrow \mathrm{w}$ bit increase in quantizer precision.
- For 4 bit increase: OSR=4^4=256 times oversampling.
- 44.1KSPS → 11.3MSPS is too much!

- Oversampling can be augmented with noise shaping to improve ratio.

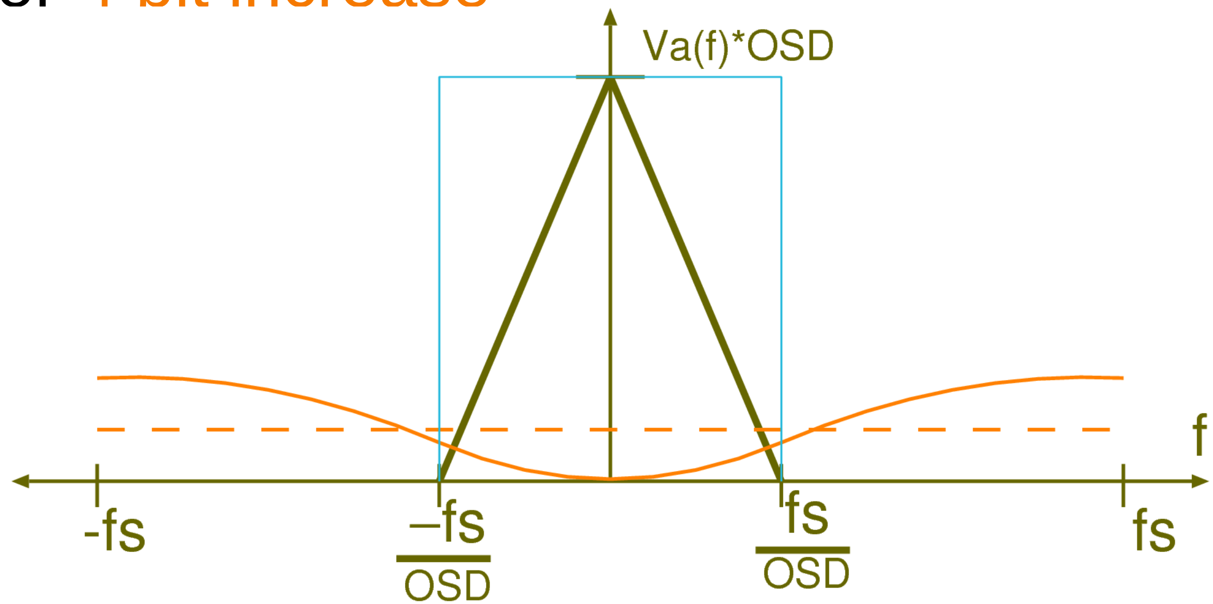
Oversampling with Noise Shaping

- Quantization noise is injected during ADC.
- The fedback system causes the quantization noise spectrum to be
  - low at low frequencies.
  - Higher at high frequencies.



Oversampling with Noise Shaping

- The feedback loop has different gains for
  - quantization noise and
  - Signal.
- Quantization noise is concentrated towards higer frequencies.
- OSD=8 is sufficient for 4 bit increase vs. OSD=256

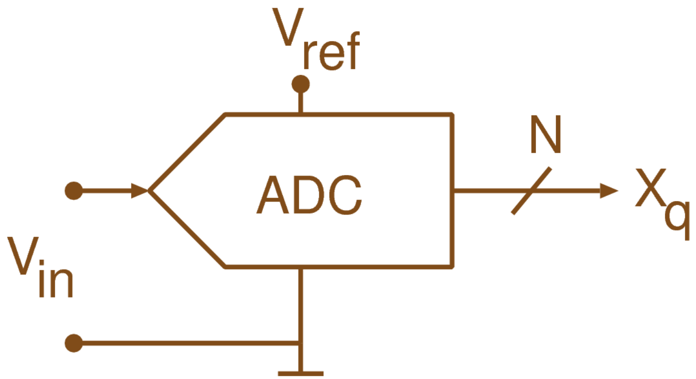


High Precision Applications

Reference Voltage

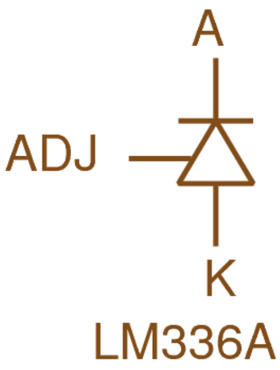
- Changes in V_{ref} have the same effect as changing the input voltage.
- Compensation for:
  - Temperature
  - Manufacturing tolerances

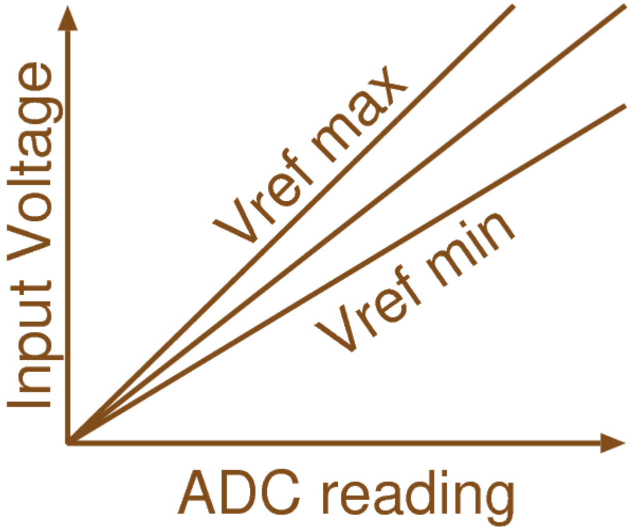
$$x_q = \left\lfloor 2^N \frac{V_{\text{in}}}{V_{ref}} + \frac{\Delta}{2} \right\rfloor, \quad \Delta = V_{ref} / 2^N$$



Reference Voltage Tolerance

- LM336A-2.5: $2.5V$ reference diode.
- $2.44 \sim 2.54V$ at 25^o.
- 8 bit ADC, $V_{in}=1V$: $\begin{cases} V_{ref}=2.44\,V \rightarrow x_q=100 \\ V_{ref}=2.54\,V \rightarrow x_q=104 \end{cases}$
- How to calibrate?





Reference Voltage Tolerance

Calibration of reference voltage tolerance

1. Multiply by correction coefficient in software

   - Firmware in each device must be different.

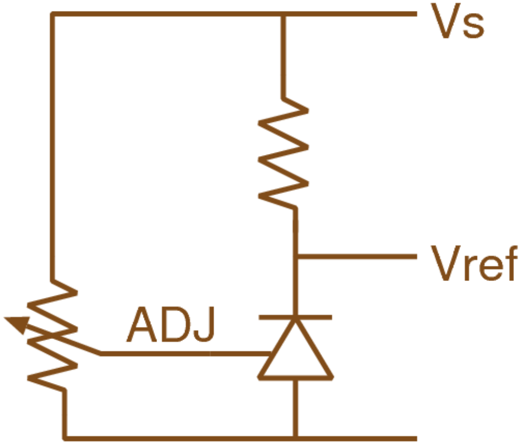
   - In 8 bit processors, correction multiplication is difficult.

2. Electrical adjustment:

   - Manual labor

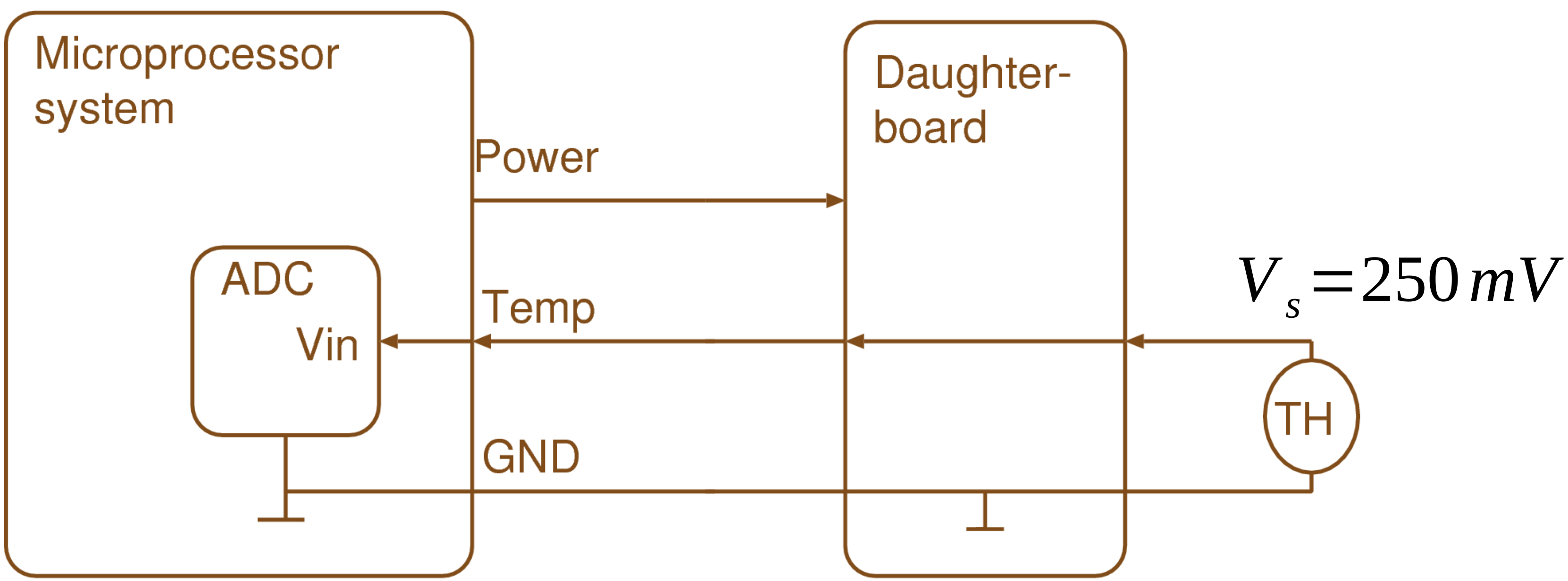
   - Long term drift

   - Temperature dependence of VR



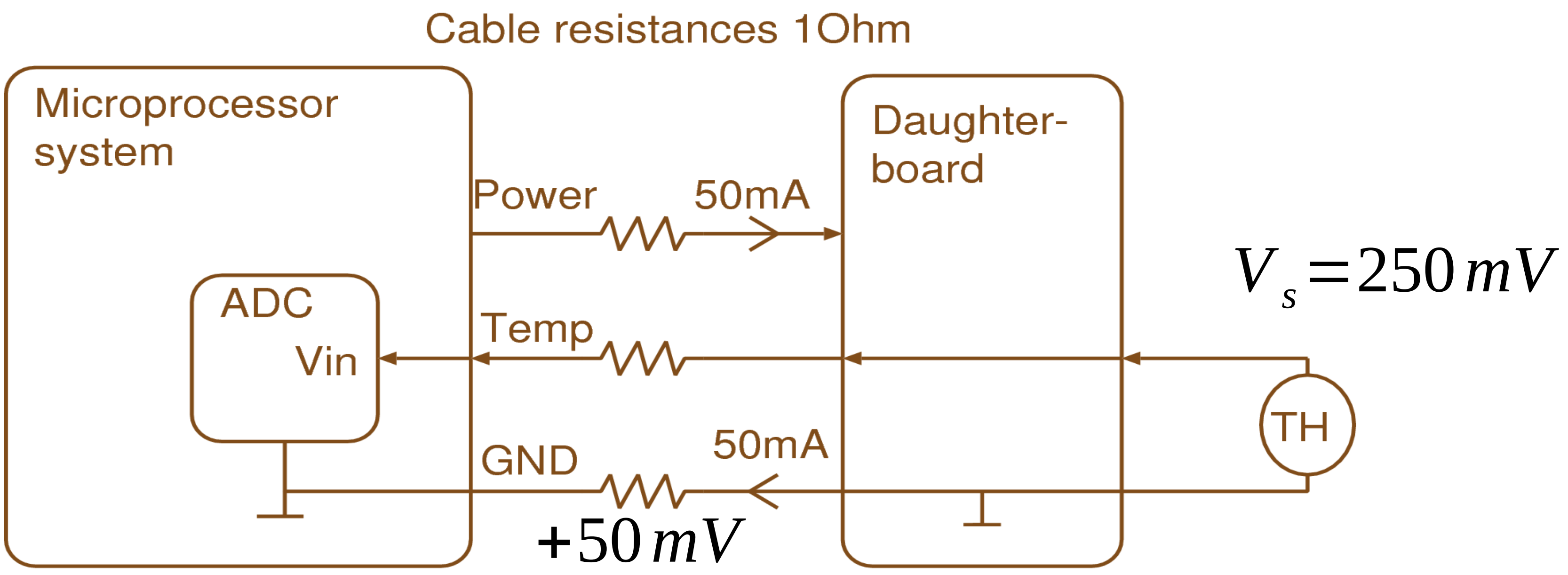
Common Ground Problems

- Microprocessor with daughterboard for temperature sensor.
- GND shared between
  - Daughterboard electronics
  - Sensor voltage



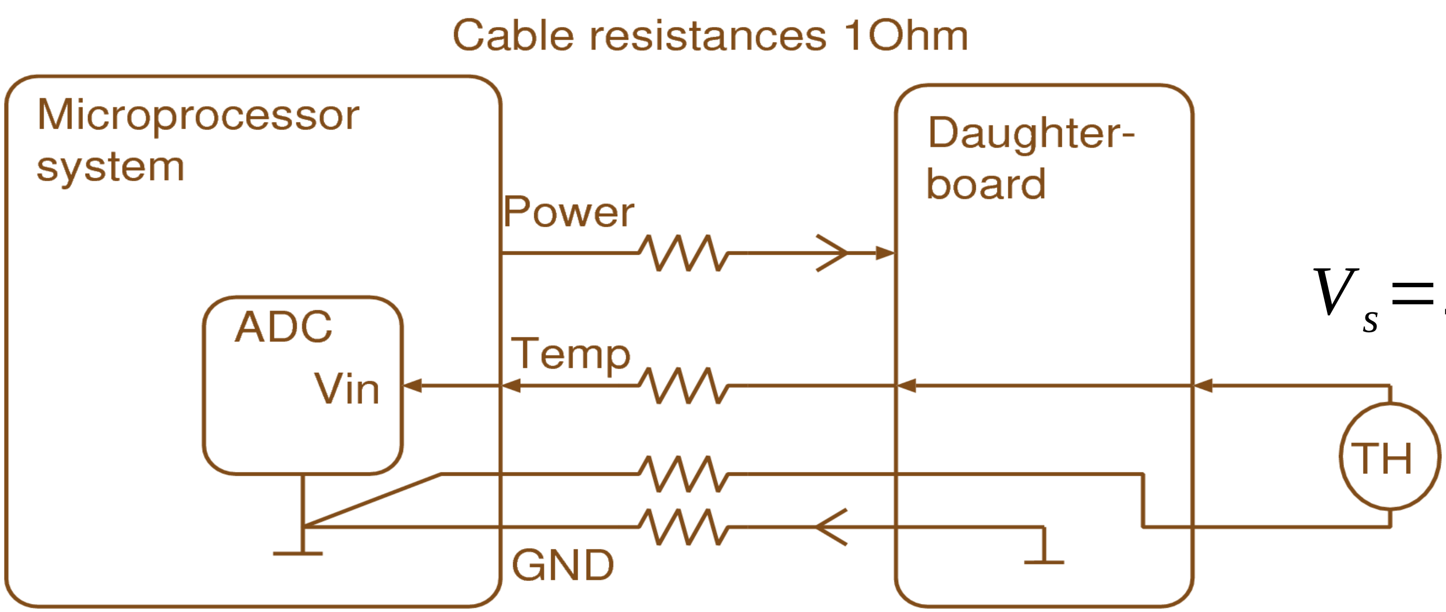
Common Ground

- Connection cables have 1Ω resistance.
- Daughterboard draws $50mA$ current.
- ADC reads 20% more: $300mV$



Common Ground

- Connection cables have 1Ω resistance.
- Daughterboard draws $50mA$ current.
- Ground of the sensor is separated.
- Single ground distribution point.

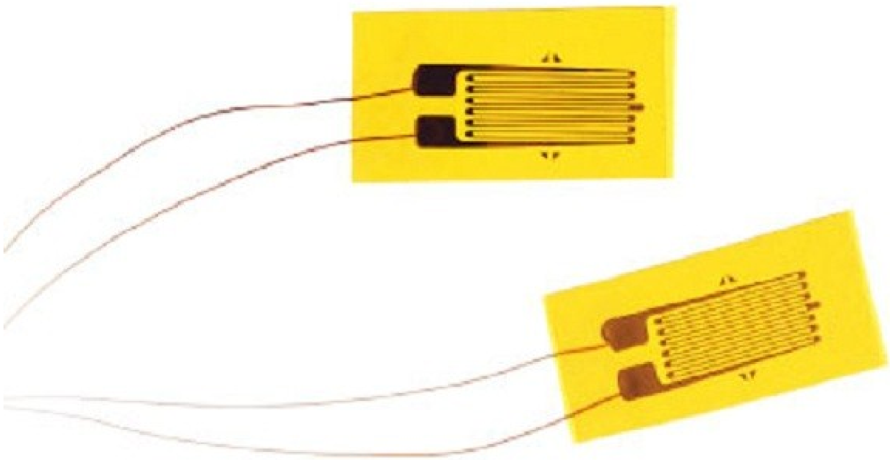


$$V_s = 250\,mV$$

Secondary Sensors

Secondary Sensors

- Electrical component values may change in response to a change in a physical variable.
- Change is small; 0.1% or less.
- Straightforward measurement of value:
  - May have large offset error.
  - May depend on other variables (temperature etc.)
  - Require high precision.

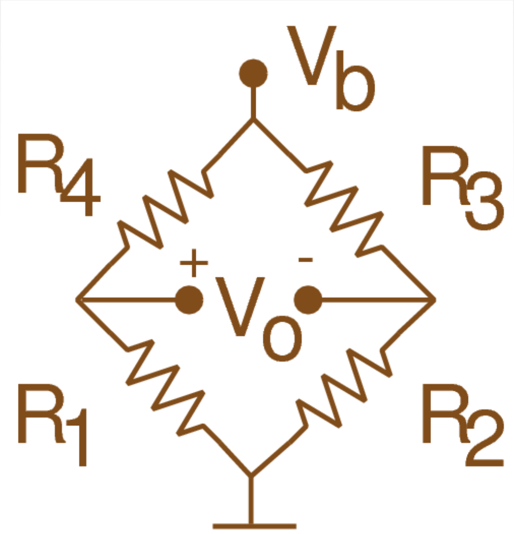


Sensor Bridges

- Balanced bridge circuits.
- Output voltage derived from resistor divider.

$$V_o = V_b \frac{R_1}{R_1 + R_4} - V_b \frac{R_2}{R_2 + R_3}$$

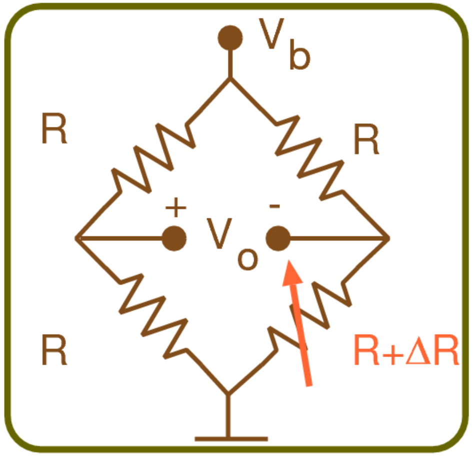
For $\frac{R_1}{R_4} = \frac{R_2}{R_3}$ → $V_o = 0\,V$



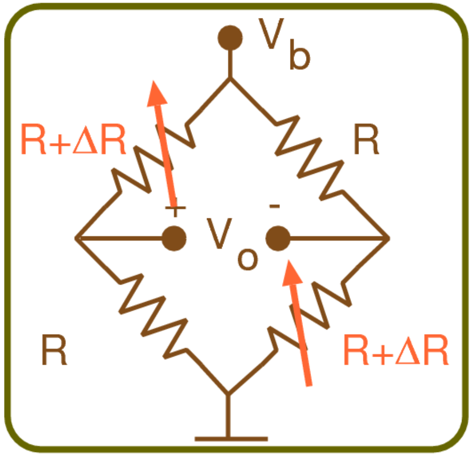
- No bias. → Large gain can be used.

Types of Bridge Circuits

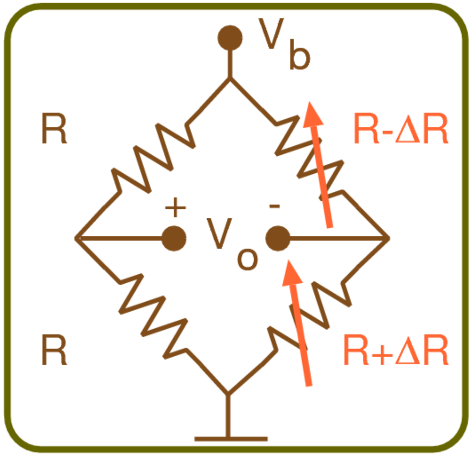
- Bridge may consist of 1, 2, 4 elements.
- Larger elements have better sensitivity.
- V_o depends on V_b → Stable supply.
- Measurement load must be zero.



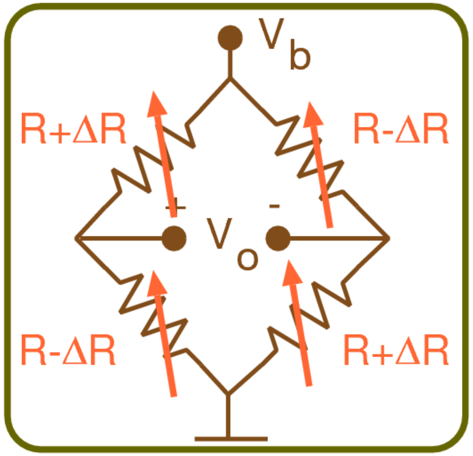
$$V_o = \frac{V_b}{4} \frac{\Delta R}{R + \Delta R/2}$$



$$V_o = \frac{V_b}{2} \frac{\Delta R}{R + \Delta R/2}$$



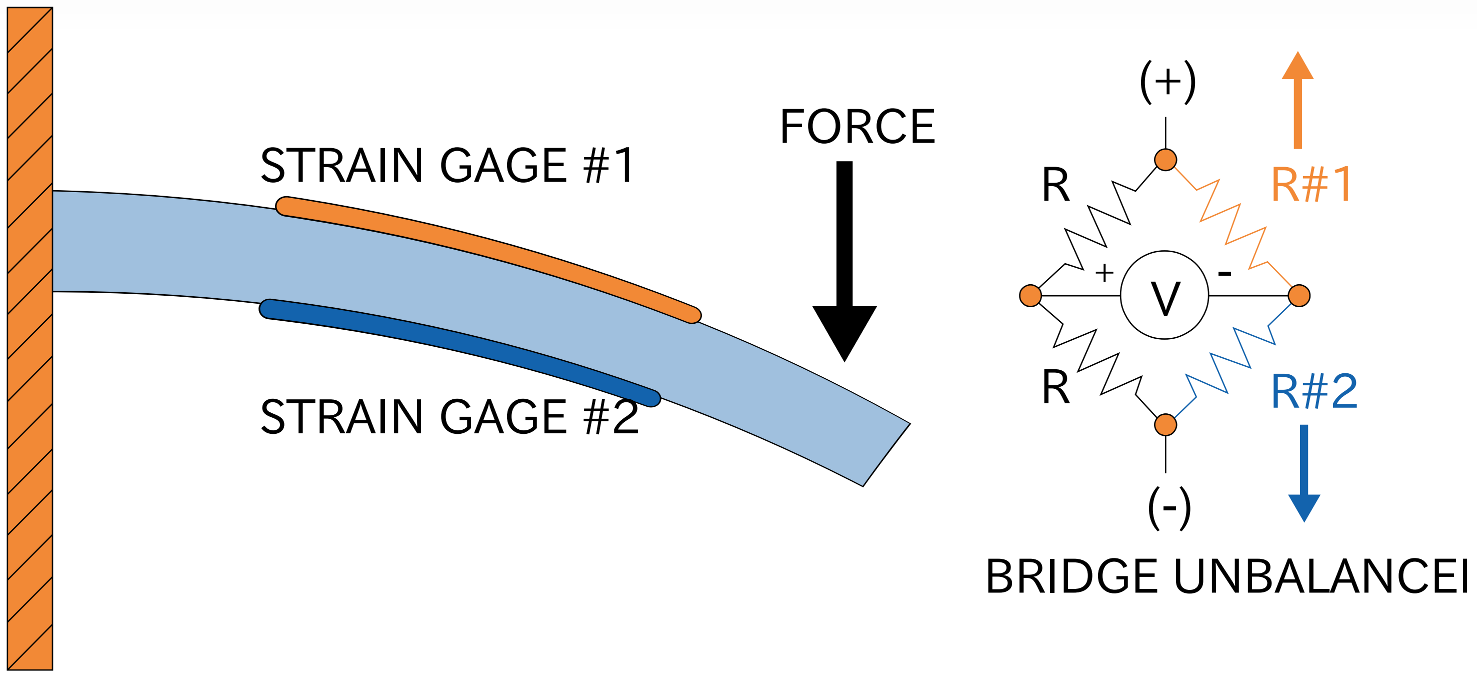
$$V_o = \frac{V_b}{2} \frac{\Delta R}{R}$$



$$V_o = V_b \frac{\Delta R}{R}$$

Example Use of Bridge

- Strain gage measures bending strain.
- R_1 and R_2 change in opposite directions.
- Stretch measurement eliminated.

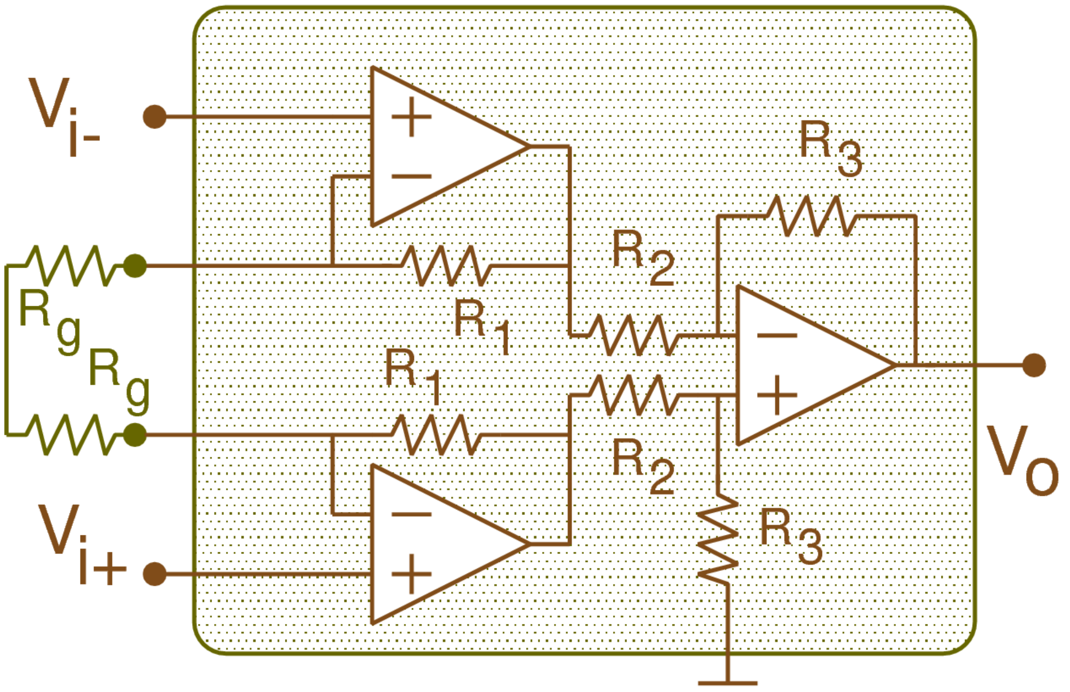


Source of figure: DEWESoft

Amplifiers for Sensor Bridges

- Instrumentation amplifier is used.
- High input impedance
- High CMRR
- Gain is set by external resistor Rg.
- Many good chips exist
  AD620 etc.

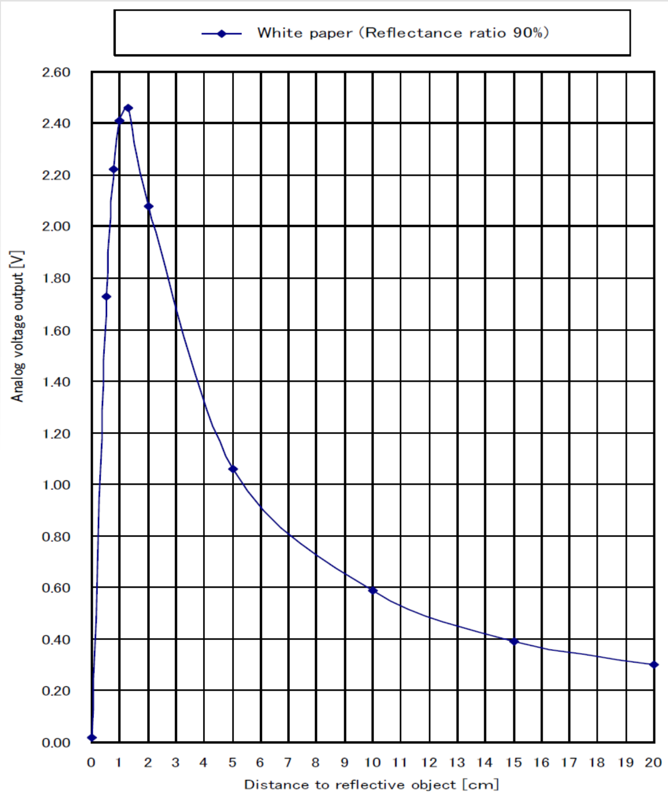
$$V_o = (V_{i+} - V_{i-}) R_1 \left(\frac{1 + R_1}{R_g} \right) \left(\frac{R_3}{R_2} \right)$$



Linearization, Calibration

Sensor Commissioning

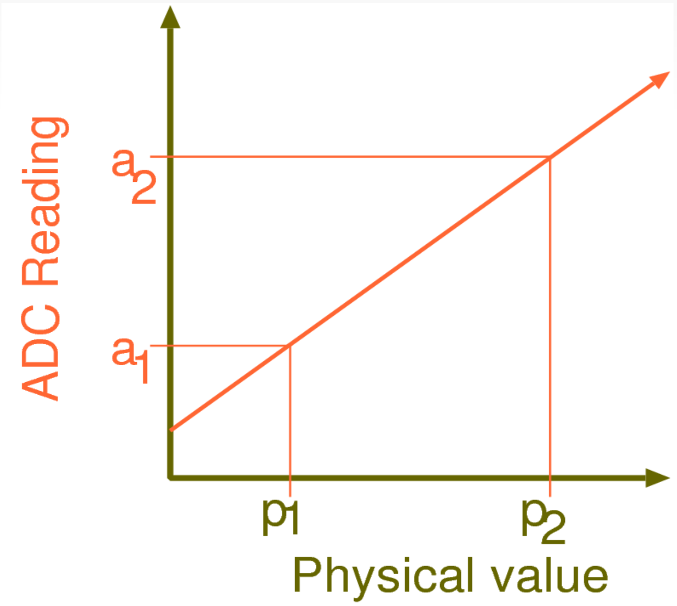
- The sensor output is generally not:
  - Linear
  - Calibrated
- Determine inverse function to obtain physical value from the readings.
- Calibrate the sensor to increase the accuracy of the readings.



Sharp GP2Y0A41SK0F
Reflective distance sensor.
Distance vs output voltage

Linearization

- Sensor linear offset and gain correction
- Calibration measurements: $\begin{cases} a_1 = mp_1 + b \\ a_2 = mp_2 + b \end{cases}$
- Calculate constants: $m = \dfrac{a_2 - a_1}{p_2 - p_1}$,
  $b = a_1 - mp_1$
- During runtime: $p_m = \dfrac{x_m - b}{m}$
- Periodic calibrations may be needed: Use electronic switch to connect reference.



Lookup Table – Worst Case

- Extreme nonlinearities.
- Wasteful of memory.
  16bit → 32bit: 262kB ROM.

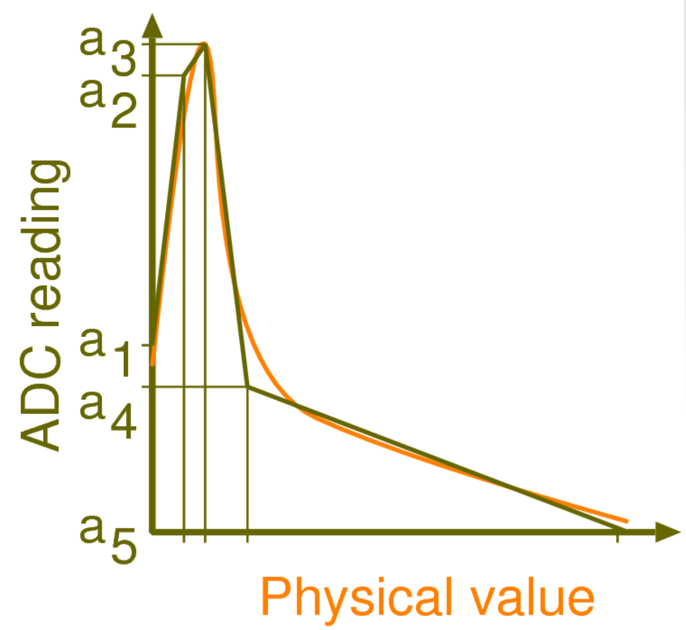
  STM32F405RGT6: 1MB ROM
  STM8s103F: 8kB ROM

- If multiple sensors must be fused, even larger footprint.

ADC	Physical
0	234
1	200
2	192
3	216
...	...
1022	48
1023	132

Piecewise Linearization

- In a certain range of readings, use a specific linearization.
- Smaller memory footprint
- More run-time computation
- Worse error



In Range	Slope	Offset
a1~a2	m1	b1
a2~a3	m2	b2
a3~a4	m3	b3
a4~a5	m4	b4

Curve Fitting

- With several sensors, curve fitting can be performed.

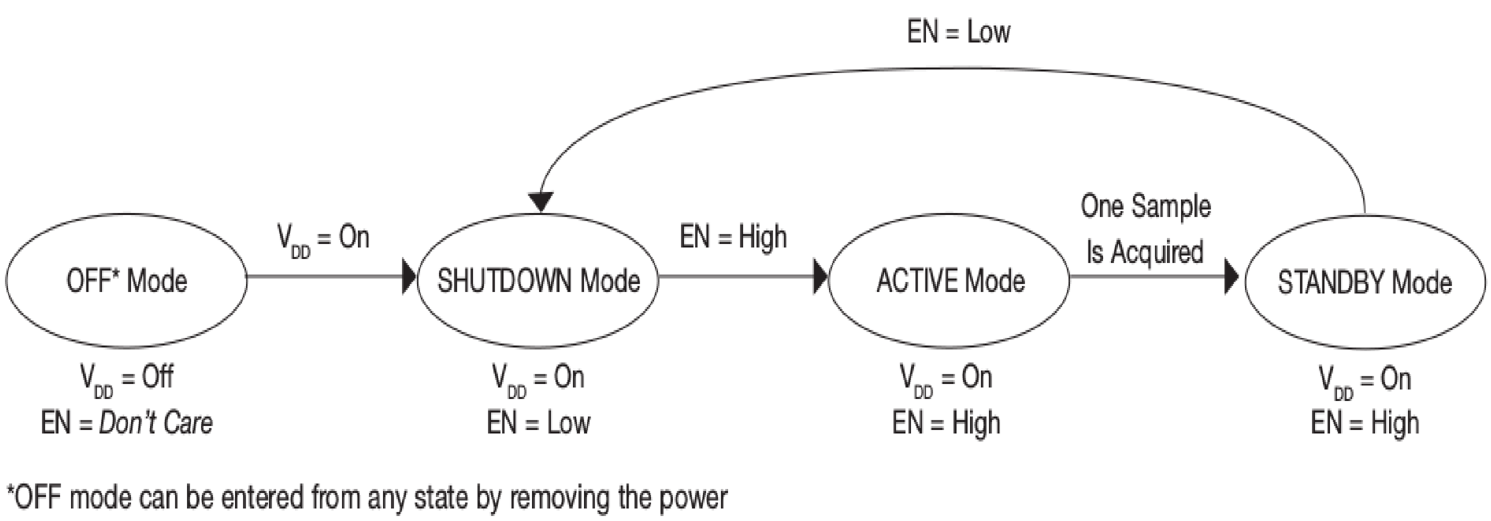
$$p = c_{10} + c_{11} a_1 + c_{12} a_2 + \ldots + c_{21} a_1^2 + c_{22} a_2^2 + c_{23} a_1 a_2 + \ldots$$

- Coefficients:
    - Calculated before shipment
    - By operator, using calibrated measurement samples
    - Automatic, periodic calibrations

Low power Sensing

Low Power Sensing

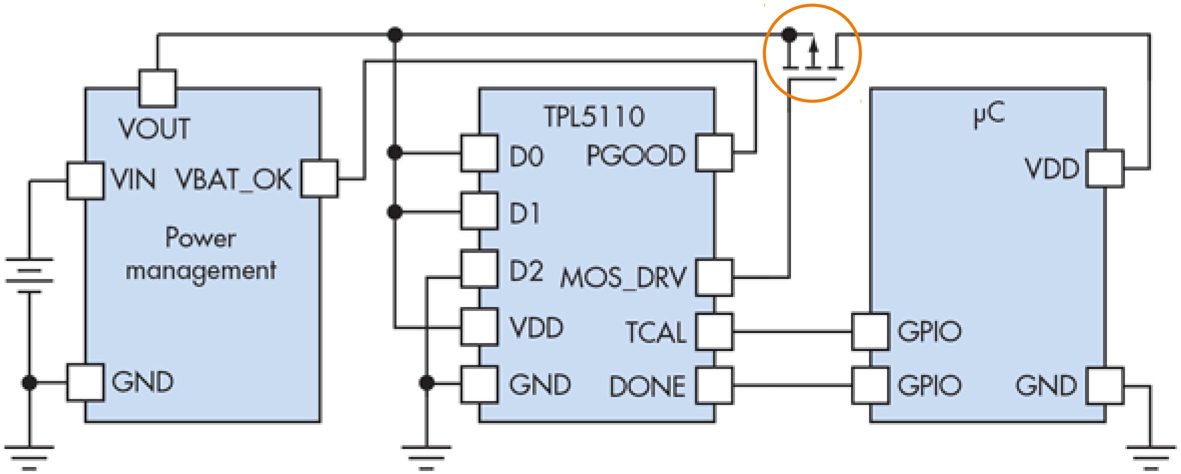
- Power reduction through low duty cycle.
- “Intelligent” sensor with power modes.
- Sensor powered down when not needed.
- Whole system powered down most of the time.



Source of figure: NXP, “Low-Power Sensing” White Paper.

Low Duty Cycle Operation

- Most processors have sleep timers.
  - Processor consumes power during sleep
  - I/O pins used to power down sensors may keep consuming power.
- Many power management chips are on the market.

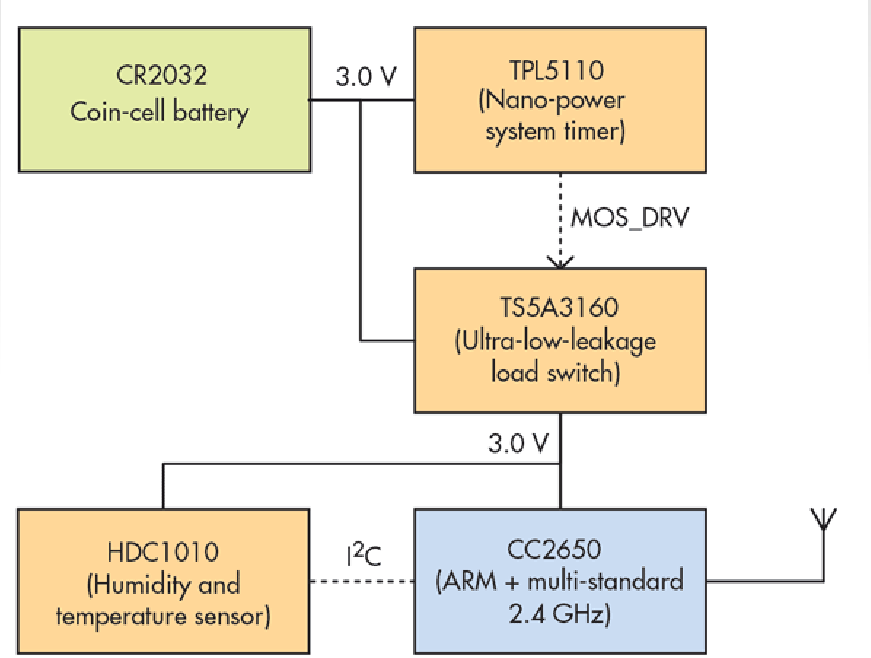


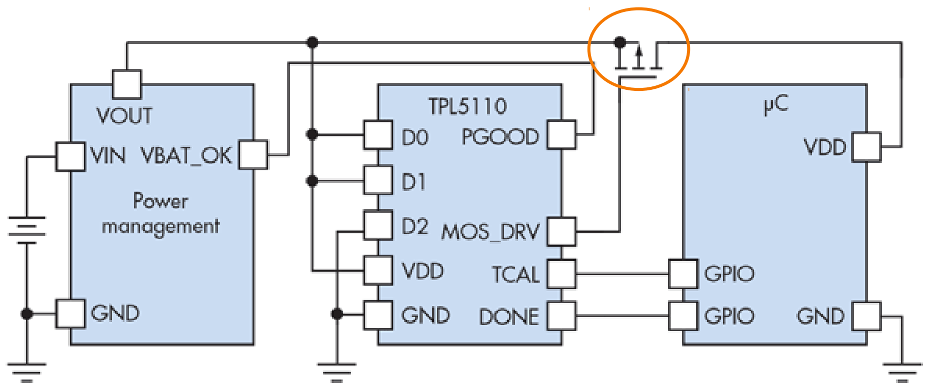
TI TPL5110 System timer

Low Duty Cycle Operation

- Processor sets sleep time
- Timer turns off power:
  Whole system is switched off.

- Processor sleep mode: 1µA
- Timer sleep mode: 35nA



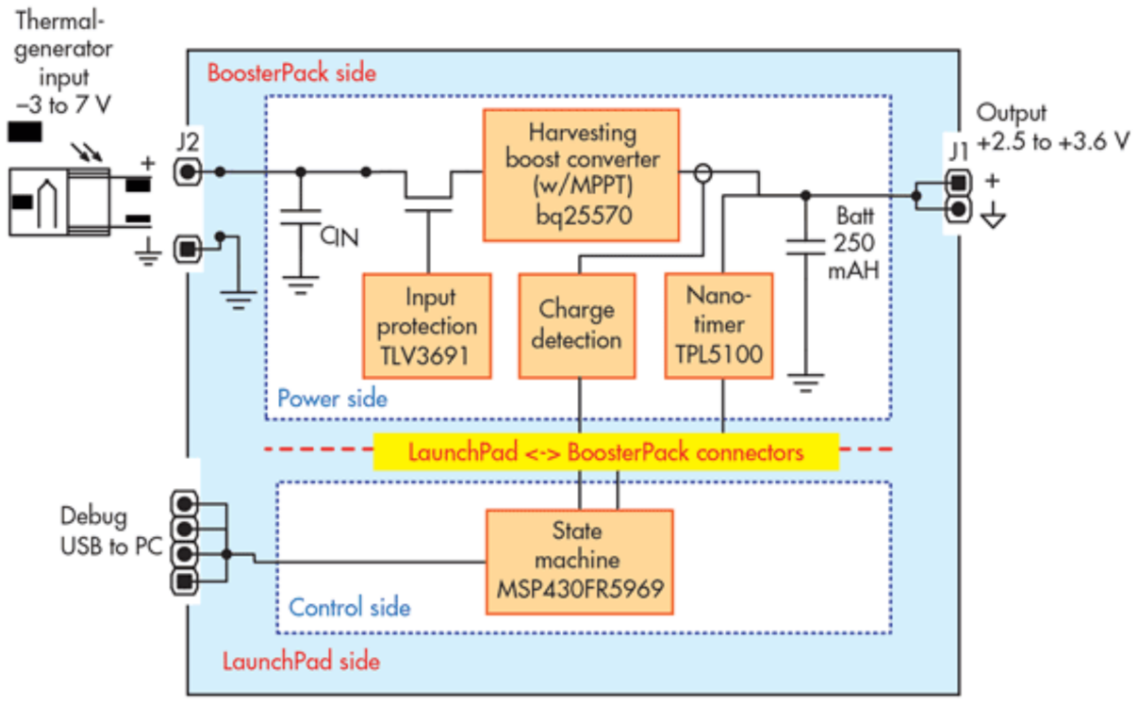


Energy Harvesting

- Solar cells, piezo devices, thermoelectric generators etc.
- Maximum power must be derived from the generator.

  $$P = V \times I$$

- Stored in a battery.

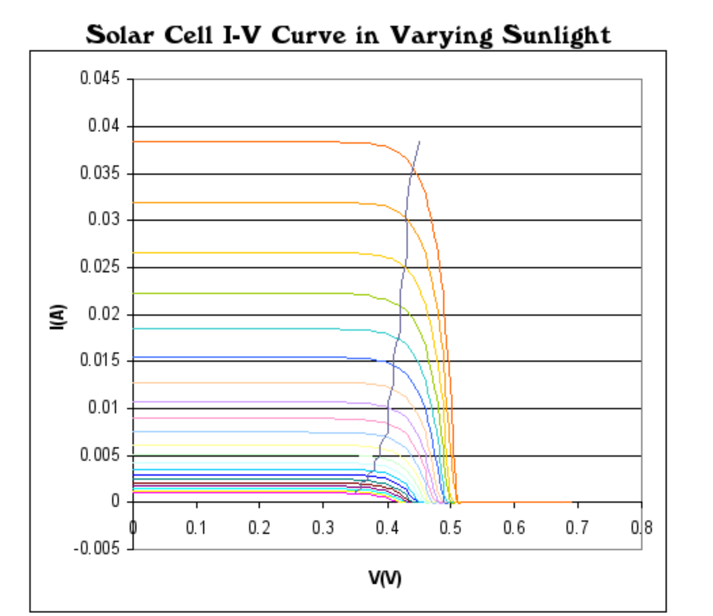


Solar Cell Basics

- Efficiency.
  - 8%~45%. General commercial: ~15%
  - Solar Flux: 1kW/m^2 noontime.
  - ~150W/m^2.
- Power output.
  - More current draw, less voltage.

$$P = V \times I$$

  - Track the best V~I ratio. (!)
- Power conversion.
  - Change voltage as required.
  - → buck/boost converter- regulator.



Solar Cell Sizing

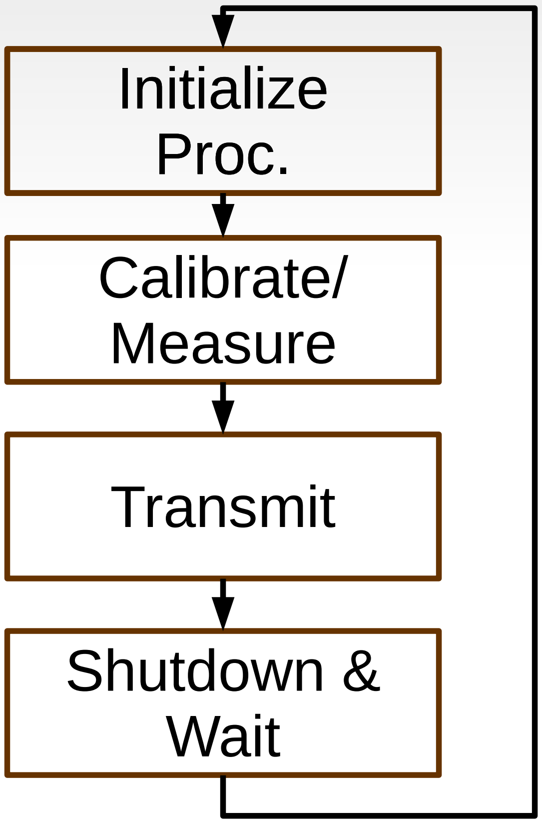
- Determine
  - power consumption (V_{cc}, I_c)
  - duty ratio (seconds/hr): V_{cc} x I_c x s

    → Energy requirement
- Size the battery: 3.7V, 0.5Ah etc.
- Size the solar cell:
  - Use the peak sun hour of deployment location.
  - Budget
  - Safety margin

    →Area of the solar cell required.

FLOPs per Watt

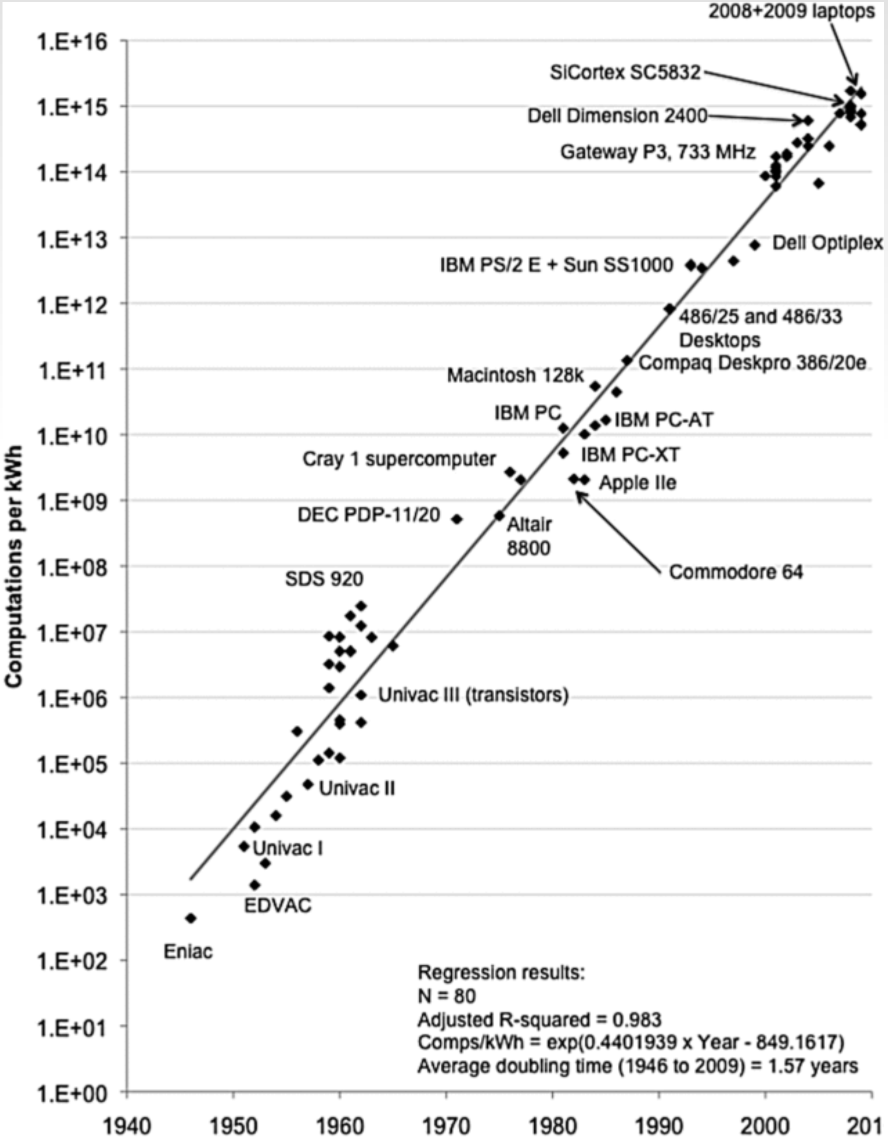
- Processor clock can be actively throttled.
- Low clock speed:
  - Low power consumption
  - Long active time
- High clock speed:
  - High power consumption
  - Short active time
- Most suitable FLOPS/W depends on mode, active peripherals etc.



Koomey's Law

- "...the power needed to perform a task requiring a fixed number of computations will fall by half every 1.5 years,"

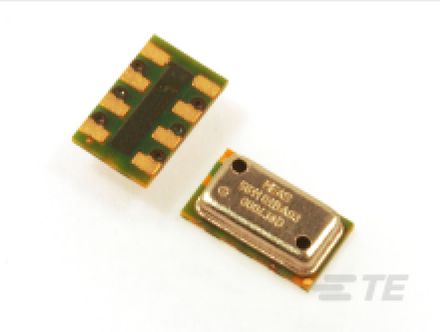
J.Koomey, S.Berard et al, "Implications of Historical Trends in the Electrical Efficiency of Computing", IEEE Annals Hist. Comp, V33-3, pp. 46~54, 2011



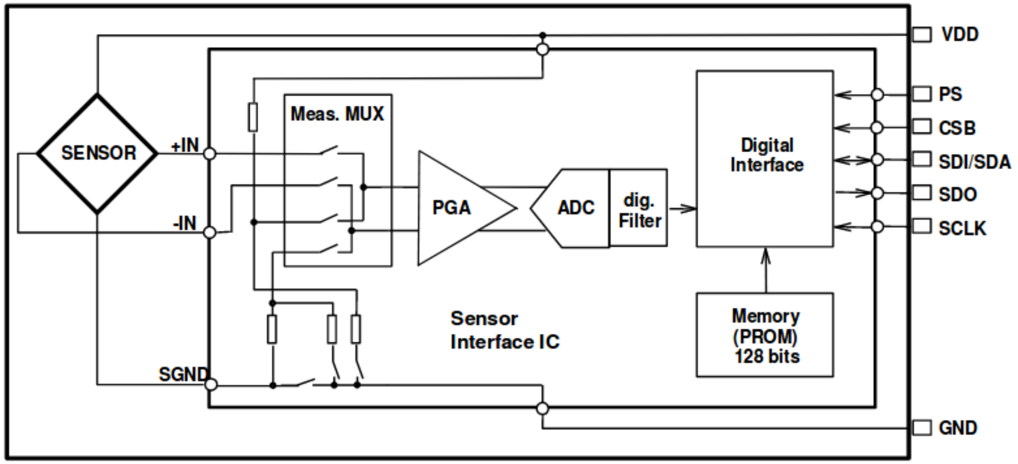
Integrated Sensors

High Precision Applications

- MP5611 barometric pressure sensor.
  (MEAS Switzerland)
- Accurate to 1ft of absolute altitude.
- 24bit ADC ($\Delta \approx 200nV$)
- Discrete implementation requires expensive signal conditioning circuits.



FUNCTIONAL BLOCK DIAGRAM



Integrated Sensors

- High precision applications require great engineering and calibration effort.
- Many sensors are offered in:
  - Sensor +
  - Signal conditioning +
  - Power management +
  - Subsystem control packages
- End user connects the sensor over “I^2C, “SPI” “CAN” etc.

(Some) References

- A.V. Oppenheim, R.W. Schafer, “Discrete-Time Signal Processing”, Prentice-Hall, 2009
- Stuart Ball, “Analog Interfacing to Embedded Microprocessor Systems”, Elsevier, 2003
- Tattamangalam R. Padmanabhan “Industrial Instrumentation”, Springer, 2000
- Paul Pickering, “Designing Ultra-Low-Power Sensor Nodes for IoT Applications”, Texas Instruments, 2006
- J.Koomey, S.Berard et al, “Implications of Historical Trends in the Electrical Efficiency of Computing”, IEEE Annals Hist. Comp, V33-3, pp.46~54, 2011
- Jack G. Ganssle “The Art of Programming Embedded Systems, Academic Press, 1992
- D.H. Sheingold, “Analog Digital Conversion Handbook”, Analog Devices, 1986

Contact Information

Ahmet Onat

- Sabanci University, Istanbul, Turkey
- Mail: onat@sabanciuniv.edu
- Web: http://people.sabanciuniv.edu/onat

Research projects

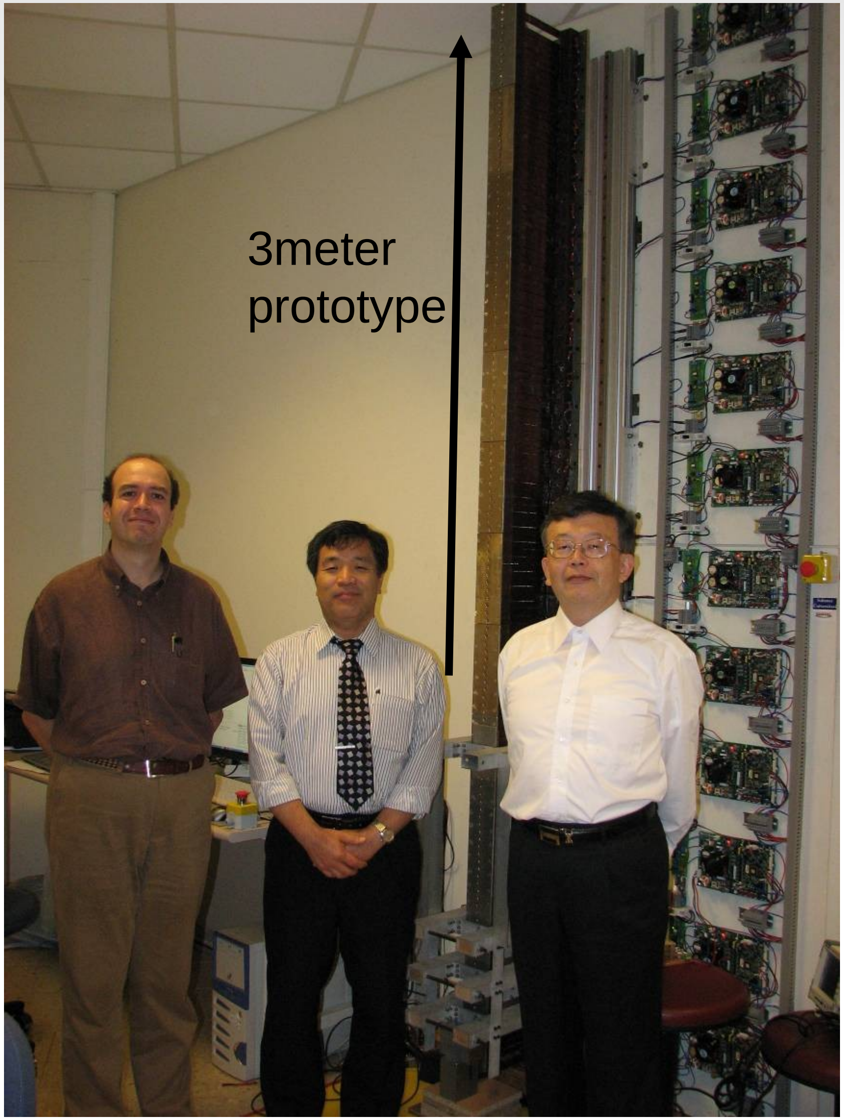
- I am carrying out projects in
  - Reinforcemet learning for dynamic systems
  - Networked real-time systems. Internet of Things IoT
  - Haptic interfaces for 3D displays
  - Linear motor design
  - Underwater autonomous robots
- See:

  http://people.sabanciuniv.edu/onat

- Enthusiastic students are welcome to help!

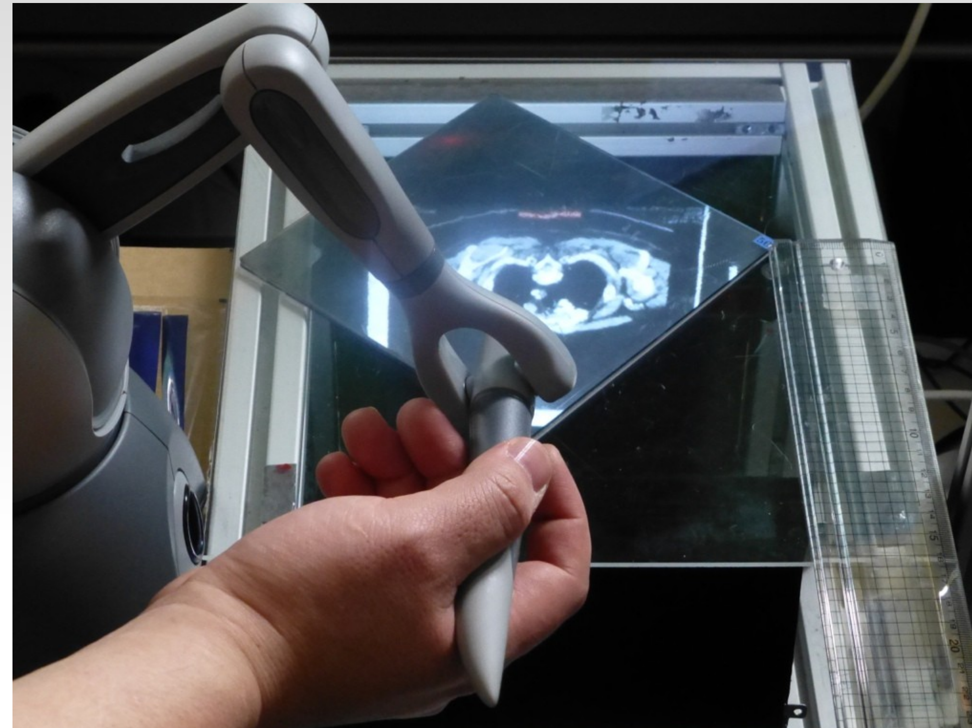
Linear motor elevators

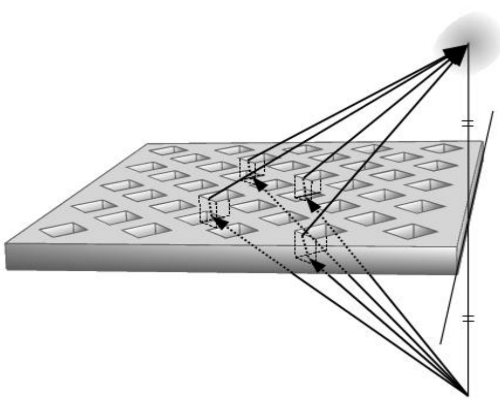
- Vertical linear motor design
- Project funded by Fujitec, Japan
- 2007-2013
- 450kg payload, 1000m length
- Prototype, patents, publications
- Magnetic, electronic, control, safety design

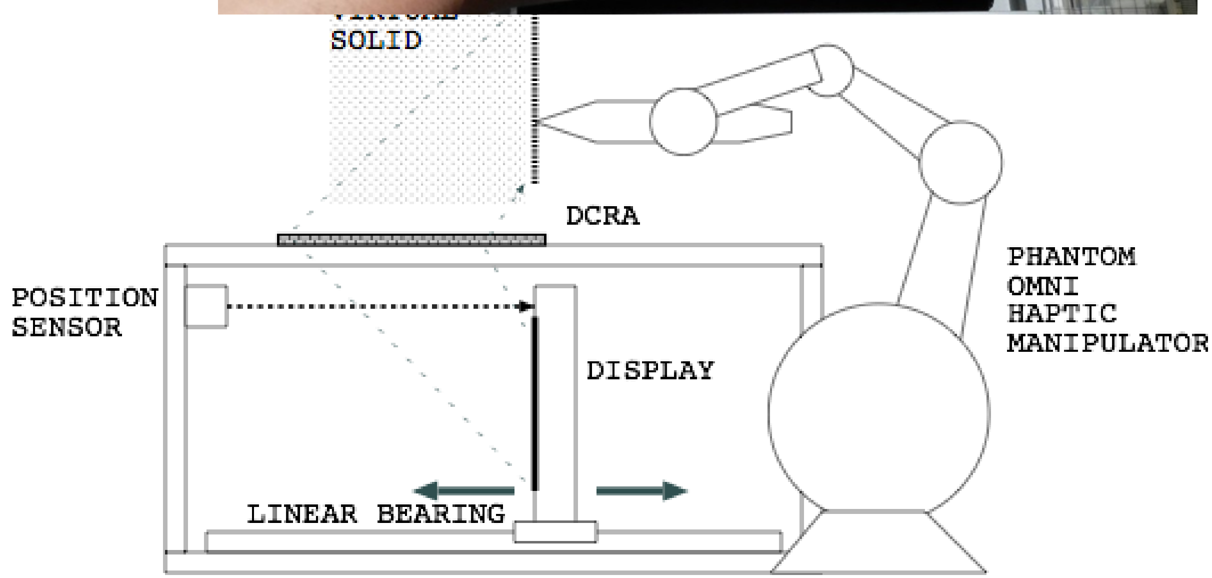


Dihedral Corner Reflector Array (DCRA)

- A passive optical device
- That can create **real reflections** to form **floating images in the air**
- Haptic feedback for projected solid objects

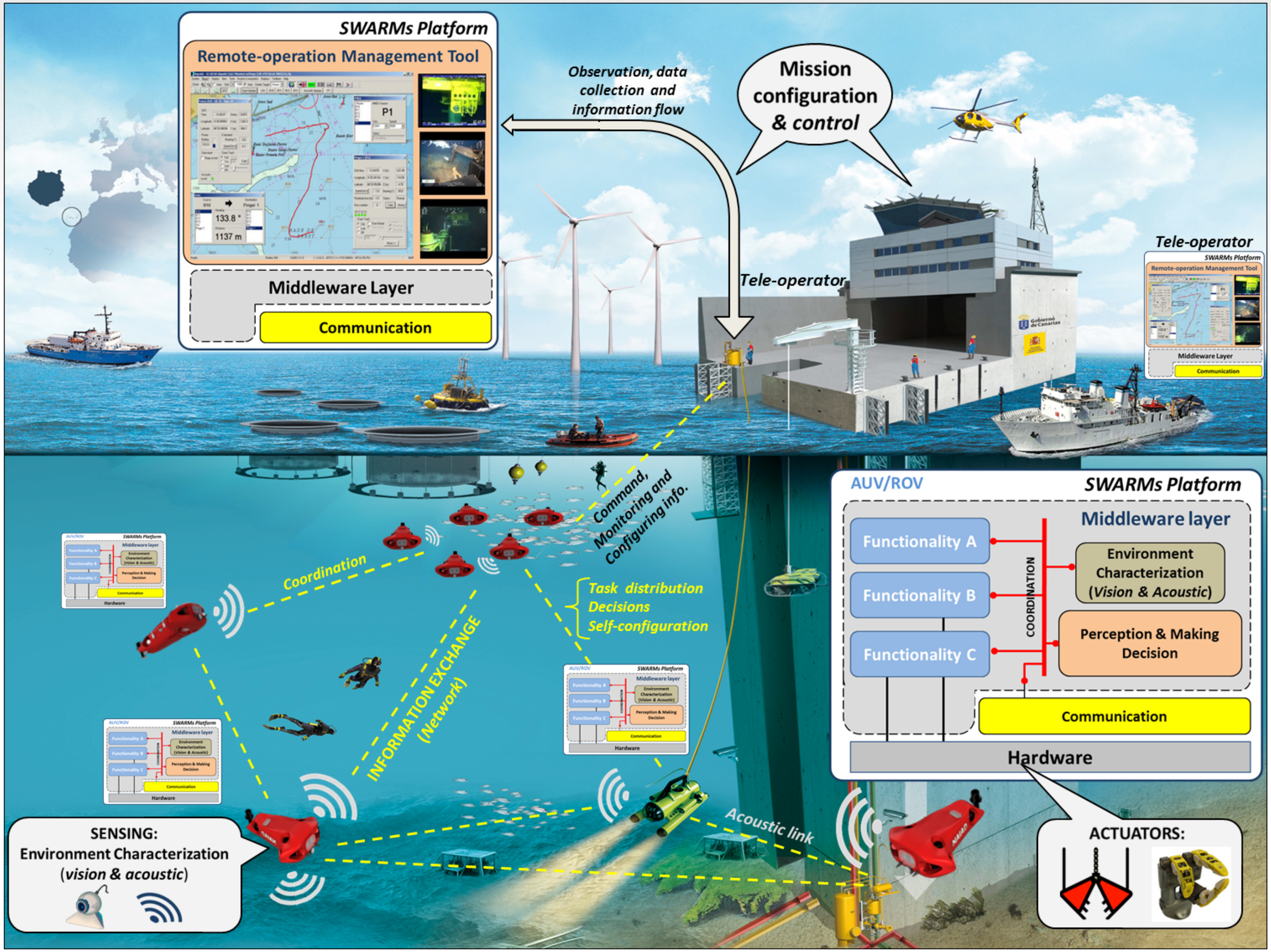






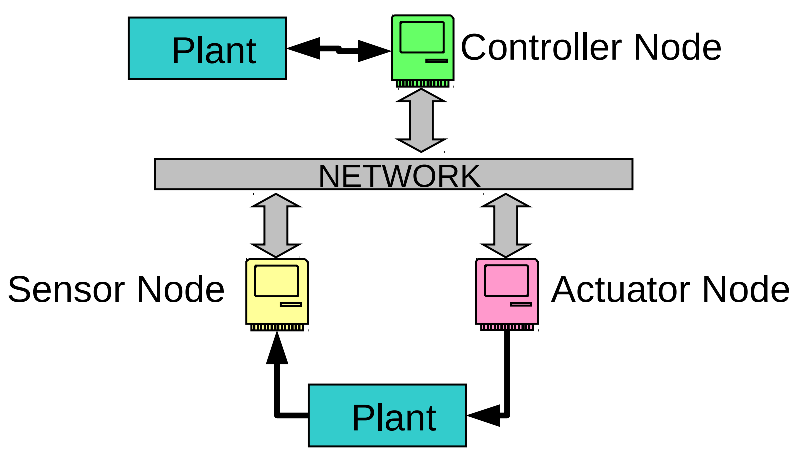
SWARMS

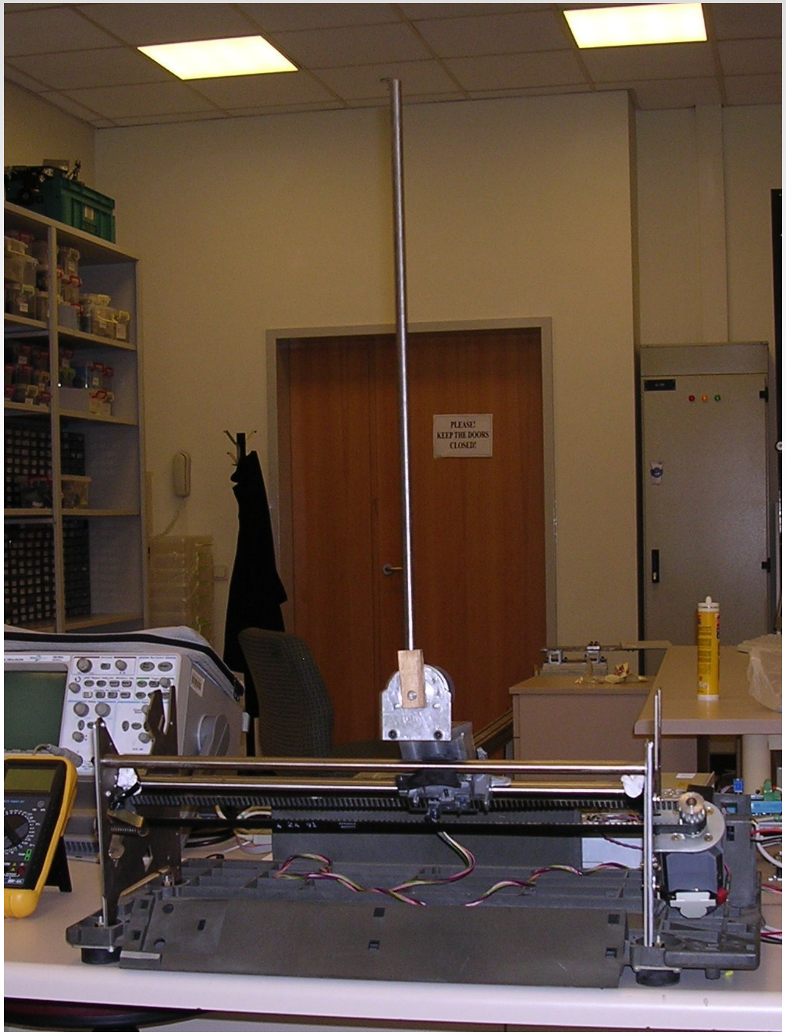
- Modeling of underwarter autonomous vehicles (IoT)



Networked control systems

- A novel method for control over networks with
  unpredictable delay & data loss
- Stability analysis, simulation & prototype
- Tolerant of large amounts of delay
- Also wireless Ethernet application
- Publications & prototype control systems





Laboratory work

Will be programming:

- ARM prcessor using 'C' language
- Blink lights,
- Move servos,
- Communication,
- Real-Time OS...