Electronic Instrumentation

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Introduction

- Goal of a measurement system:
  - Get the most out of a measurement or sensor
  - in terms of information quality
- How?
  - Filtering (averaging) and shielding
  - Compensation (e.g. feed-forward)
  - Correction (e.g. auto-zeroing)
  - Feedback
  - Modulation and correlation

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Accuracy, precision (resolution) and stability

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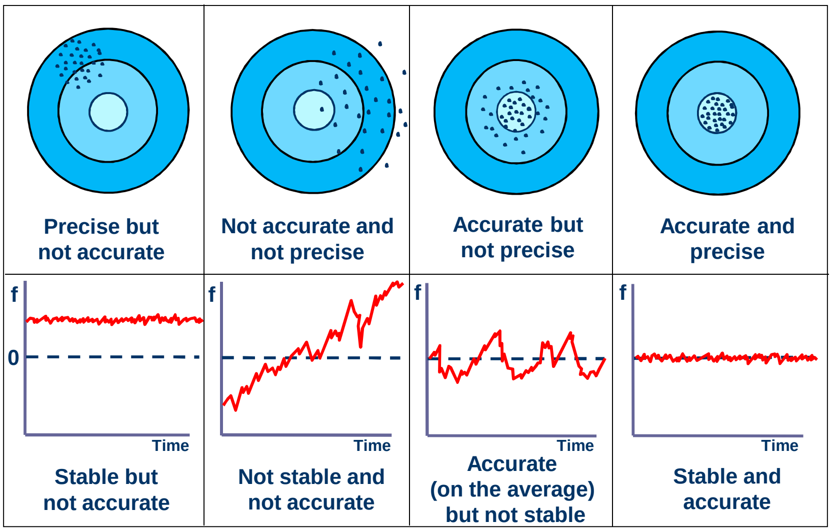

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Signal processing techniques

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Add-on techniques:

- filtering
  - prefiltering
  - postfiltering
  - correlation
- correction
  - post-processing (e.g. auto-zeroing, linearization)

Built in techniques:

- compensation
  - balancing
  - bridge
- feedback
  - requires an inverse transducer (actuator)
- modulation
  - chopping
  - spinning
  - swapping

Filtering: general principle

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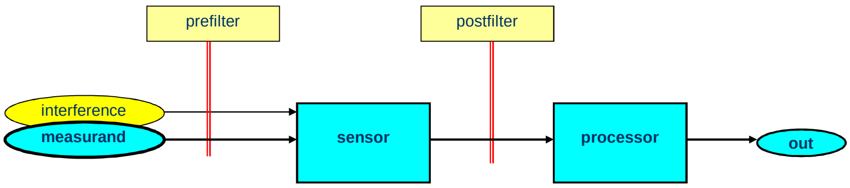

- reduces additive errors
- in a specified frequency band
- reduces the effects of thermal noise

Pre-filtering

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- Pre-filtering (prior to transduction)
- Mitigates the effects of:
  - *electrically induced* signals (capacitive) ⇒ **shielding**
  - *magnetically* induced signals (inductive)
    ⇒ reducing loop area; **shielding**
  - changes in environmental *temperature* ⇒ **isolation**
  - unwanted *optical* input ⇒ **optical filters**
  - *mechanical* disturbances (shocks, vibrations) ⇒ **dampers**
  - .....

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Electrically-induced interference

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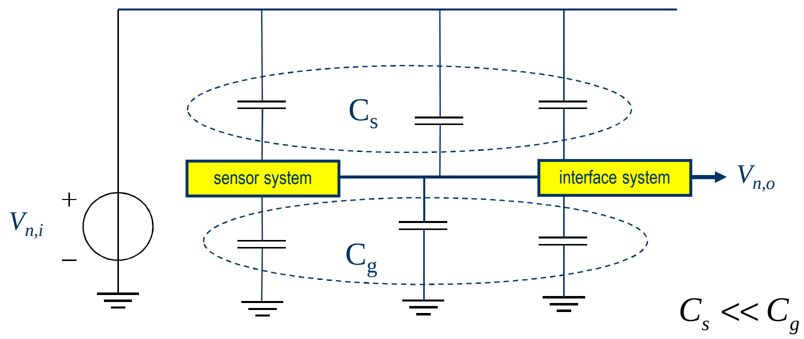

$V_{n,i}$: voltage noise source

C_s: capacitance between noise source and signal leads

C_g: capacitance between signal leads and ground

$$V_{n,o} = \frac{C_s}{C_g} V_{n,i}$$

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Shielding

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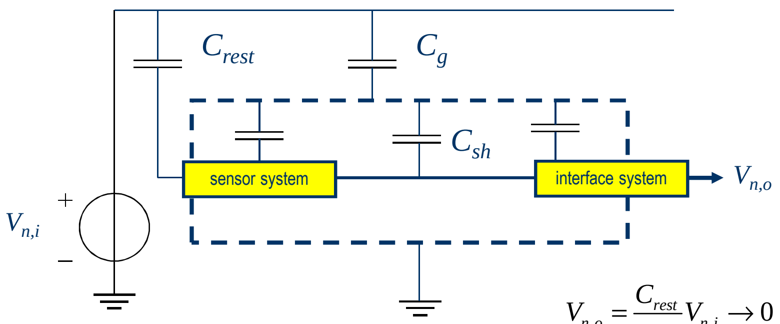

$$V_{n,o} = \frac{C_{rest}}{C_{sh}} V_{n,i} \rightarrow 0$$

C_{rest}: rest capacitance between noise source and signal leads

C_g: capacitance between noise source and ground

C_{sh}: capacitance between shield and signal leads

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Post-filtering

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- post-filtering (after transduction)
- in the electrical domain
  - *low pass, high pass, band pass*
  - *first order, ... higher order*
  - *characteristic (Butterworth, Bessel,...)*
  - *analog, digital*
  - *Matched filtering*
- If the time-domain characteristics of the measurand are known, correlation and windowing techniques can be used

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Post-filtering

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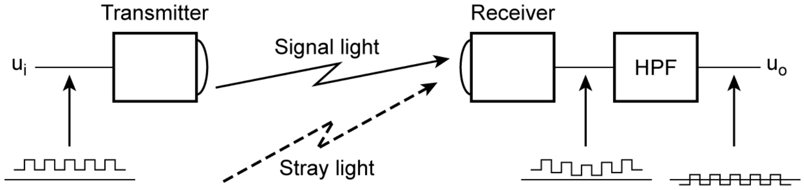

- High-pass filter removes 50Hz interference from ambient light sources

Correction

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- Add-on to an existing system
  - model-based correction (after calibration)
  - correction of cross sensitivities (extra sensors)
- Correcting for additive errors
  - auto-zeroing
  - CDS
- Correcting for multiplicative errors
  - linearization
  - 3-signal method (calibration of linear systems)

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Correction - Overview

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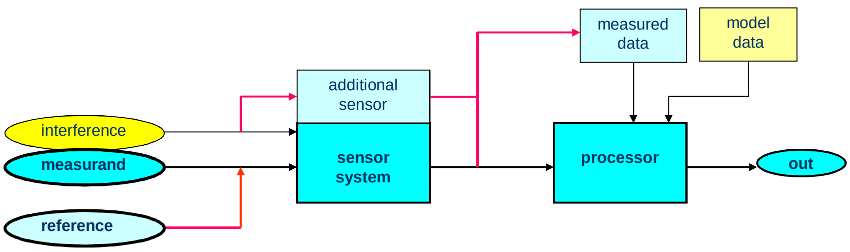

- Can cancel both additive and multiplicative errors
- But additional sensors and multiple errors limit the achievable accuracy

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Compensation

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- where?
  - pre-compensation (inherent design)
  - post-compensation (model-based signal correction)
- which strategy?
  - balancing
  - feedforward
  - feedback (with an actuator)

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Balancing: General principle

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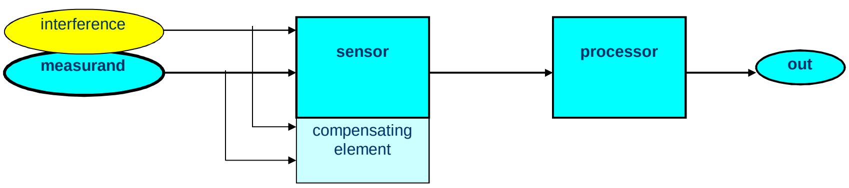

- reduces (common) additive errors
- improves dynamic range

Examples
- dummy sensor: used to compensate for environmental influences
- Extra temperature sensor: used to compensate for unwanted temperature dependencies

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Bridge compensator

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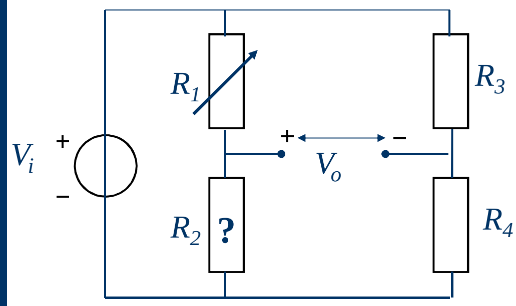
- for accurate *absolute* measurements of resistances



$$V_o = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_i$$

$$R_2 R_3 = R_1 R_4$$

$$R_2 = R_1 \left(R_4 / R_3 \right)$$

- Insensitive to CM disturbances e.g. temperature
- but requires an *accurate*, adjustable resistor

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Switched Cap "Resistor"

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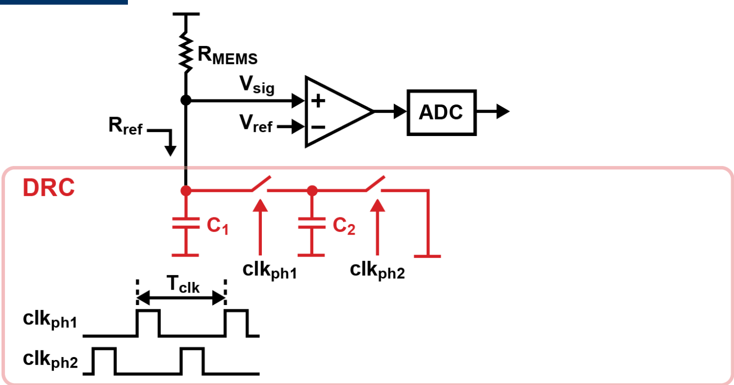

- Switched cap network emulates an adjustable resistance
  - Effective resistance value: $R_{ref} = T_{clk}/C_2$

M. Perrot et al., ISSCC 2012

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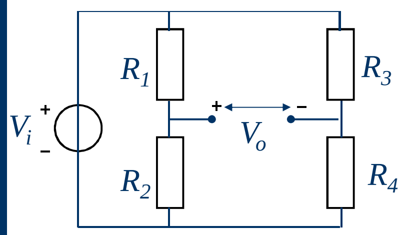
Bridge indicator

- measures small changes with respect to "an initial" value



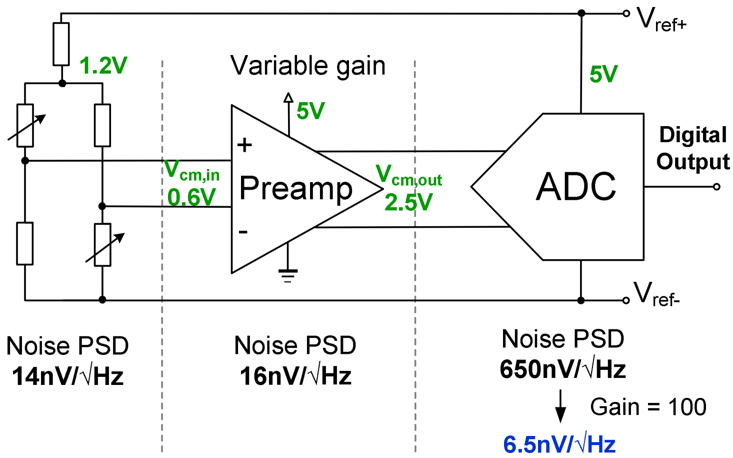
$$V_o = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_i$$

initially: resistances have values such that

$$R_{02} R_{03} = R_{01} R_{04}$$

- but output is sensitive to drift and error in V_i

Ratiometric readout



ADC and bridge use the same reference voltage V_{ref}

$\Rightarrow$ errors in V_{ref} do not affect digital output

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Assignment 8

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- Consider the ratiometric system shown on the previous slide. If the noise densities shown for the bridge, preamp and ADC, correspond to the situation when the bridge is balanced:

1. Calculate the resistance of each arm of the bridge
2. If the measurement BW is 10Hz, how many bits of resolution must the ADC have in order to ensure that the resolution of the system is determined by thermal noise rather than by quantization errors.
3. If the ADC has 20-bit resolution (**not** necessarily the answer to question 2 above) what percentage change in the resistance of a bridge element corresponds to a 1LSB change in its digital output.

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Differential measurements

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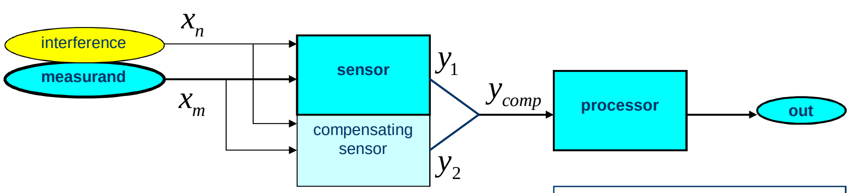

$$y_1 = S_{m1}x_m + S_{n1}x_n$$
$$y_2 = -S_{m2}x_m + S_{n2}x_n$$

} opposite sensitivity by design!

S_{m1}: sensitivity sensor 1 to measurand
S_{m2}: sensitivity sensor 2 to measurand
S_{n1}: sensitivity sensor 1 to interference
S_{n2}: sensitivity sensor 2 to interference

$$y_{comp} = (S_{m1} + S_{m2})x_m + (S_{n1} - S_{n2})x_n$$

$$y_{comp} = 2S_m x_m + \Delta S_n x_n = 2S_m\left(x_m + \frac{\Delta S_n}{2S_m}x_n\right)$$

$$CMRR = \frac{2S_m}{\Delta S_n}$$

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Differential capacitive displacement sensor

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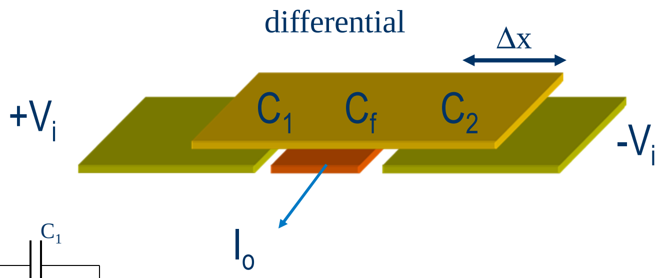

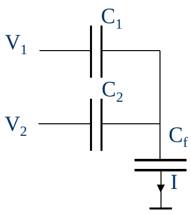

$$I_o = j\omega \cdot \frac{2\Delta C}{1 + 2C_o/C_f} \cdot V_i$$

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Differential sensor interface

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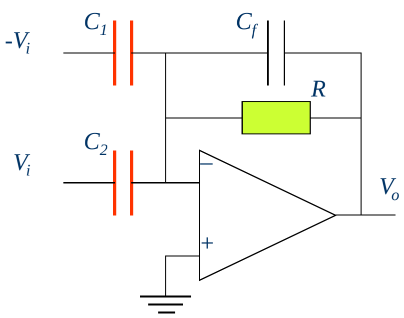

$$V_o = -\frac{V_i}{C_f}C_1 + \frac{V_i}{C_f}C_2$$

$$C_1 = C_o + \Delta C$$

$$C_2 = C_o - \Delta C$$

$$V_o = 2\frac{V_i}{C_f}\Delta C$$

- The resistance R reduces drift
- But it introduces extra noise and gives rise to a frequency-dependent transfer function

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The utility of feedback

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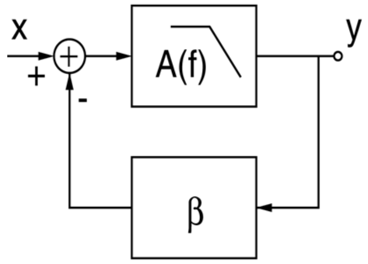
If A(f)•β >>1 ⇒ $A_{CL} \cong 1/\beta$.



For moderate 1/β, op-amp
DC gain is large enough!

β ⇒ Resistor/Capacitor ratios.
Resistors ⇒ 0.01%, 5 ppm/℃
Capacitors ⇒ 1%, 500 ppm/℃

$$A_{CL} = \frac{x}{y} = \frac{A}{(1+A\beta)}$$

⇒ A_{CL} can be very accurately defined.

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Feedback: General principle

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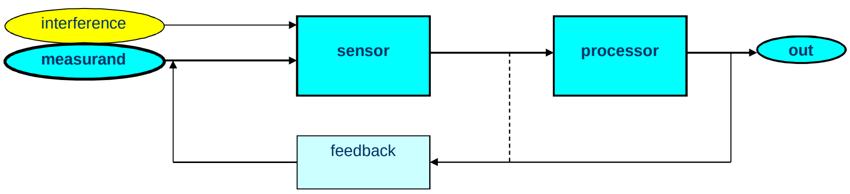

- reduces multiplicative errors
- improves dynamic behaviour

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General application of feedback

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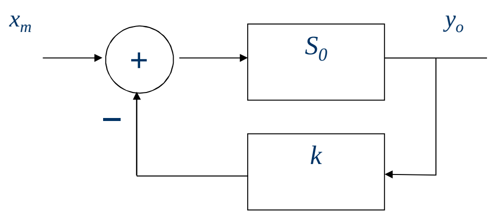

$$S_f = \frac{S_0}{1 + S_0 \cdot k}$$

$$\frac{dS_f}{S_f} = \frac{1}{1 + k \cdot S_0} \cdot \frac{dS_0}{S_0}$$

- Prerequisites for effective error reduction are:
  - high forward path transfer
  - stable feedback path transfer

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Example 1: Accelerometer

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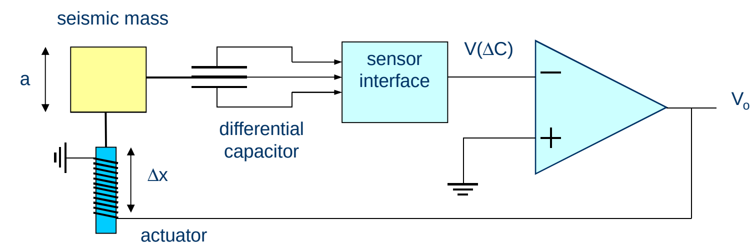

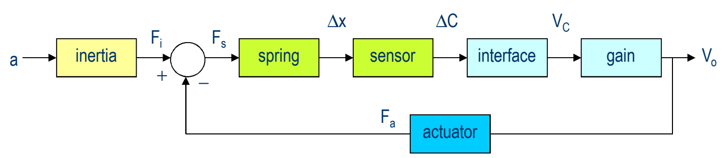

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Analysis of a feedback accelerometer (1)

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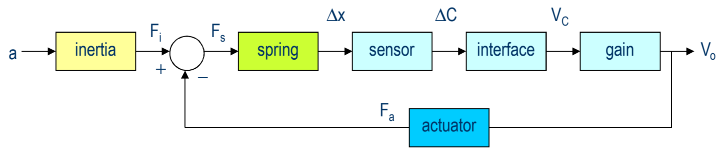

H_i: transfer from acceleration a to inertial force F_i
H_s: transfer from force F_s on sensor to displacement Δx
H_e: transfer from displacement to output voltage V_o
H_a: transfer of actuator: from output voltage V_o to F_a

$$V_o = \frac{H_s H_e}{1 + H_a H_s H_e} H_i a$$

$$if: H_a H_s >> 1:$$

$$V_o = \frac{H_i}{H_a} a$$

Independent of system parameters of the spring, sensor, interface, gain factor

Transfer function depends only on mass and actuator

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Example 2: Wind sensor

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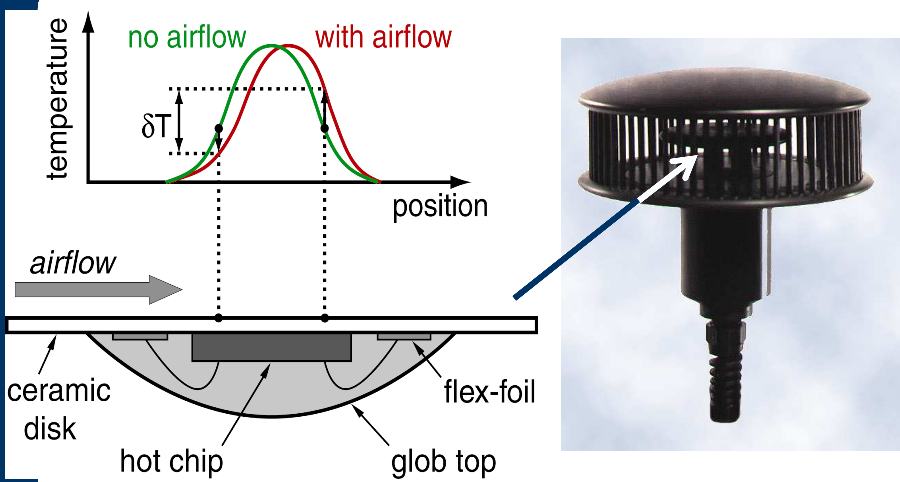

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Thermal balancing

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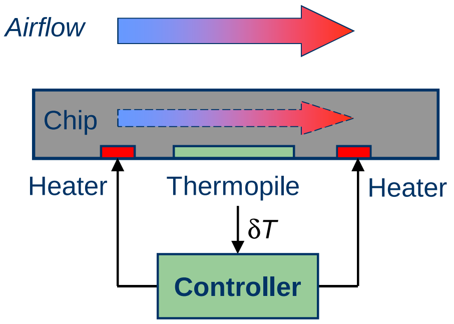
Sensor Cross-Section



- Airflow induces an on-chip temperature gradient δT
- This is sensed by an on-chip thermopile and cancelled by a pair of heaters
- Transfer function only depends on the heaters (resistors) and their supply voltage

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Wind sensor chip

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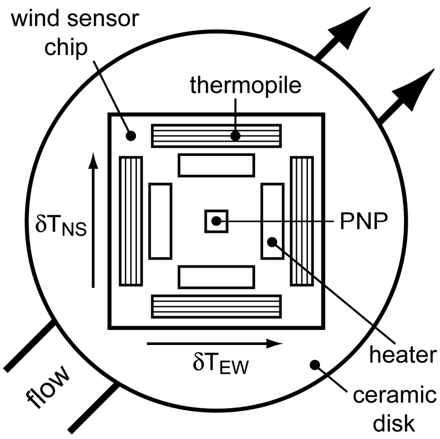
- On-chip heaters
- Thermopiles ⇒ wind induced temperature differences δT_{NS} & δT_{EW}
- On-chip controllers nulls δT_{NS} & δT_{EW}
- $|\delta P|$ ⇒ wind speed
- arg(δP) ⇒ wind direction



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Smart wind sensor chip

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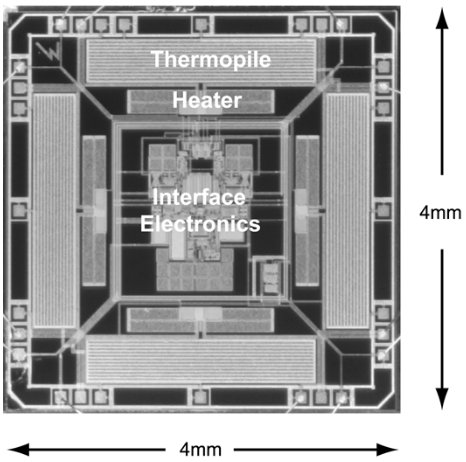
- Digital outputs
  δP_{NS} & δP_{EW}
- After calibration:
  Speed error: ± 4%
  Angle error: ± 2°
- Comparable
  to conventional
  wind sensors
- But no moving parts!



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Modulation: General principle

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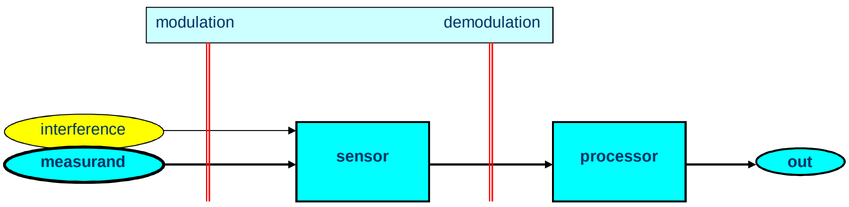

- Basic ideas: shift information to a quiet frequency bands OR make information more robust
- Reduces additive errors
- In particular, offset, drift, LF noise and gain error

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Modulation types

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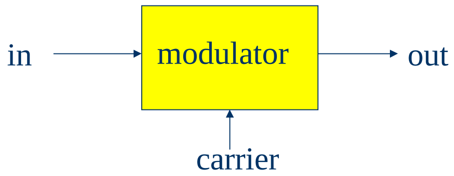

- AM modulation: Chopping, synchronous detection, dynamic element matching
- FM modulation: Used to make information more robust to amplitude variations
- Pulse-width (or duty-cycle) modulation: also used to make information more robust to amplitude variations, also used for simple digital-to-analog conversion

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The Thermal Management Challenge!

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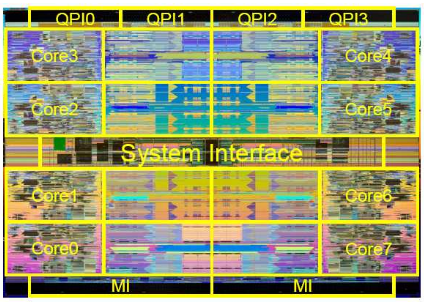

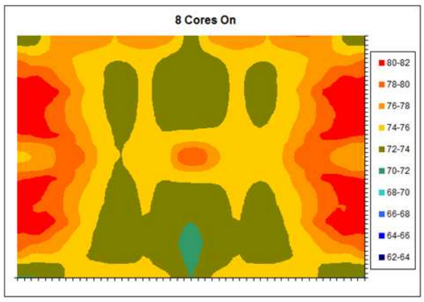

Intel 45nm Xeon

Courtesy of S. Rusu Intel

- SoCs and multi-core processors $\Rightarrow$ multiple hot spots
- Hot spot location depends on (dynamic) workload $\Rightarrow$ multiple (20+) temperature sensors

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Thermal Diffusivity Sensing

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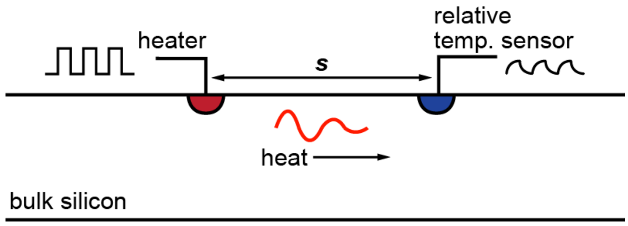

- Heater generates small heat pulses (mWs)
- Temperature sensor picks up delayed pulses (mVs)
- Resulting thermal delay is temperature-dependent
- Exploits the strengths of CMOS technology:
  - Lithography → accurate spacing ***s***
  - Pure silicon substrate → D_{Si} is well-defined
  - Fast circuits → accurate delay measurements

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A CMOS ETF

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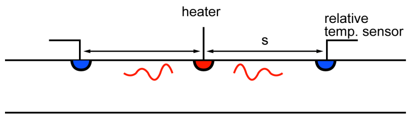
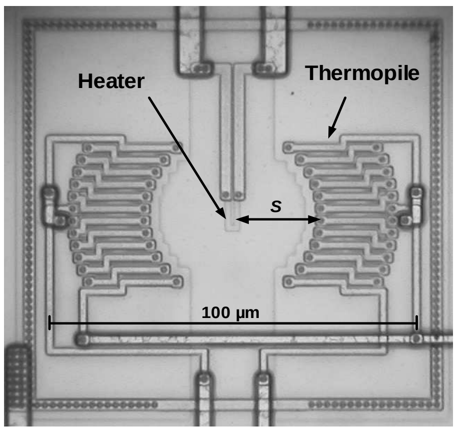
- Heater = n⁺-diffusion resistor
- Temp. sensor = p⁺/Al thermopile
- Can be made in any IC process!
- Circular, differential layout for maximum output





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Smart TD Sensor

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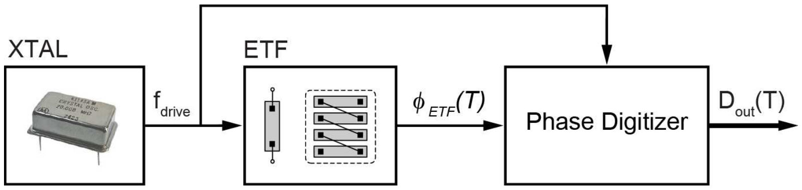

$$\phi_{ETF} \propto s\sqrt{f_{drive} / D_{Si}}$$

- At room temp, s =20µm, f = 100kHz ⇒ ϕ_{ETF} ~ 90°
- Quartz-crystal clock generates f_{drive} (typ. 100s of kHz)
- ϕ_{ETF} is digitized by a *phase-domain* ΣΔ modulator
- Resolution is mainly limited by ETF's thermal noise

[van Vroonhoven, Makinwa, ISSCC 2008]

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Phase Digitizer

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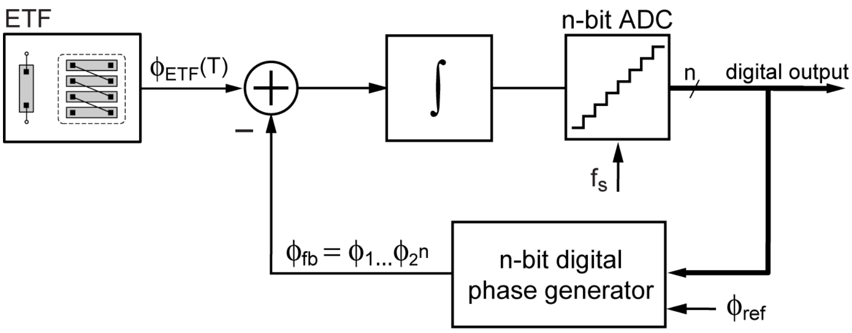

- How to accurately measure the phase of a small (1mVpp) and noisy signal?
- Use feedback, an ADC and a *digital* phase generator
- Then digitally filter the result (few Hz BW)

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Phase-Domain ΔΣM

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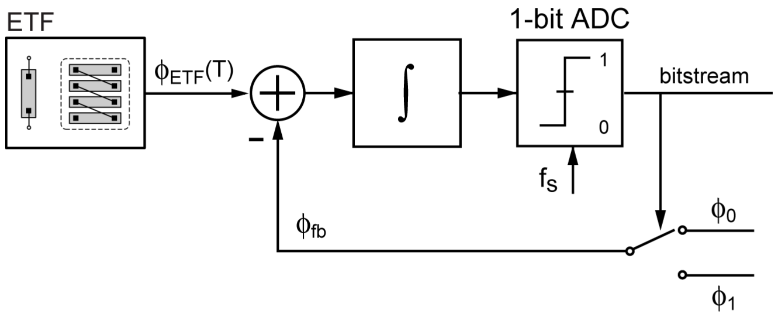

- Since the sensor's BW is so low, we can over-sample its output and then average ⇒ a 1-bit ADC is enough!
- This technique is known as sigma-delta modulation
- 12-bit resolution in 0.5Hz BW → f_s > 2kHz → easy!

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Subtracting phase?

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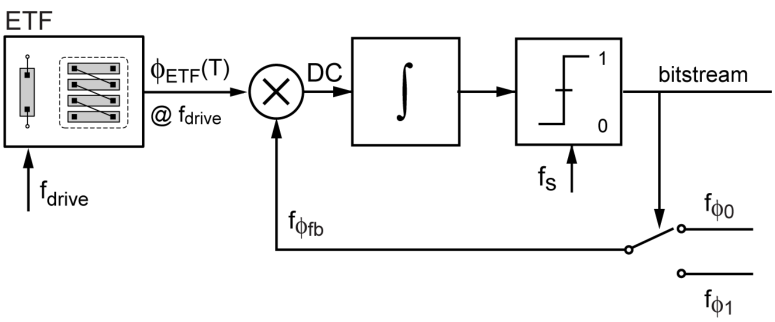

- Use a synchronous detector!
- DAC references are just phase-shifted copies of f_{drive} → multiplier inputs are at same frequency
- DC $\propto$ $\cos(\phi_{ETF} - \phi_{fb}) = 0$ when $\phi_{fb} = \phi_{ETF} - 90°$
- Approx. linear close to $(\phi_{ETF} - \phi_{fb}) = 90°$

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Performance

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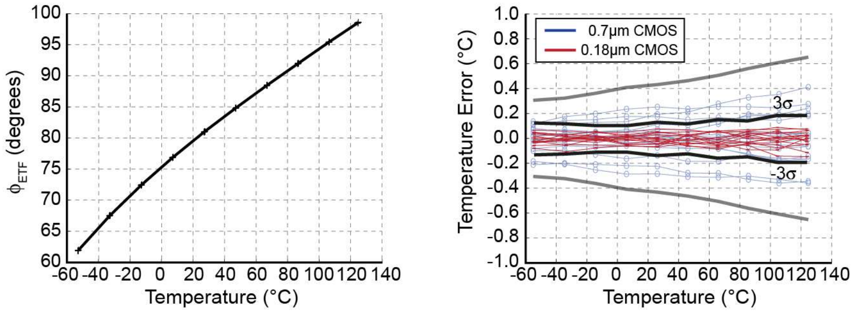

- ***Untrimmed*** spread is mainly limited by lithography
  - ±0.6ºC (3σ) in 0.7µm CMOS
  - ±0.2ºC (3s) in 0.18µm CMOS (same ETF layout)
- Accurate, and scales!

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Overview: Signal processing techniques

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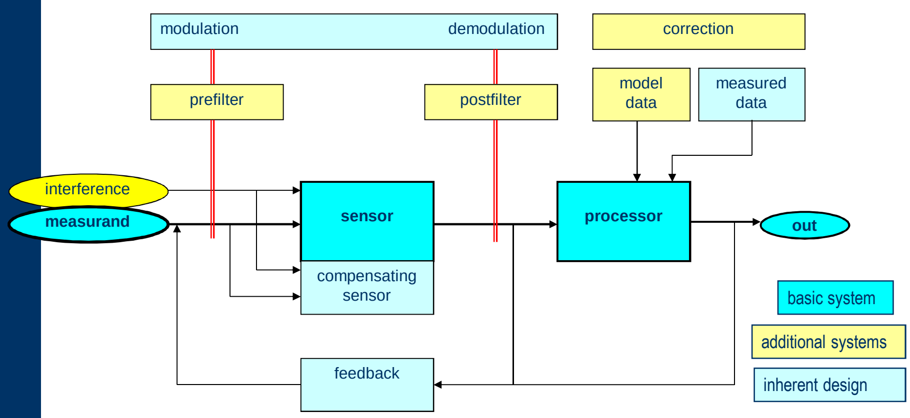

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THE END!

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Assignment 9

ET8.017
El. Instr.

- The thermal diffusivity of silicon is proportional to $1/T^{1.8}$ where T is absolute temperature
- If an electrothermal filter has a phase shift of 90° at 300K, calculate its phase-shift at the extremes of the military temperature range, i.e.-55°C and 125°C
- A smart TD sensor employs a phase digitizer. How many bits of resolution should it have in order to achieve a temperature-sensing resolution of 0.1°C?
- If the phase digitizer employs the feedback architecture shown on slide 38 and uses a chopper as a phase detector, what range of phases must its phase DAC provide in order for the sensor to cover the military range?

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