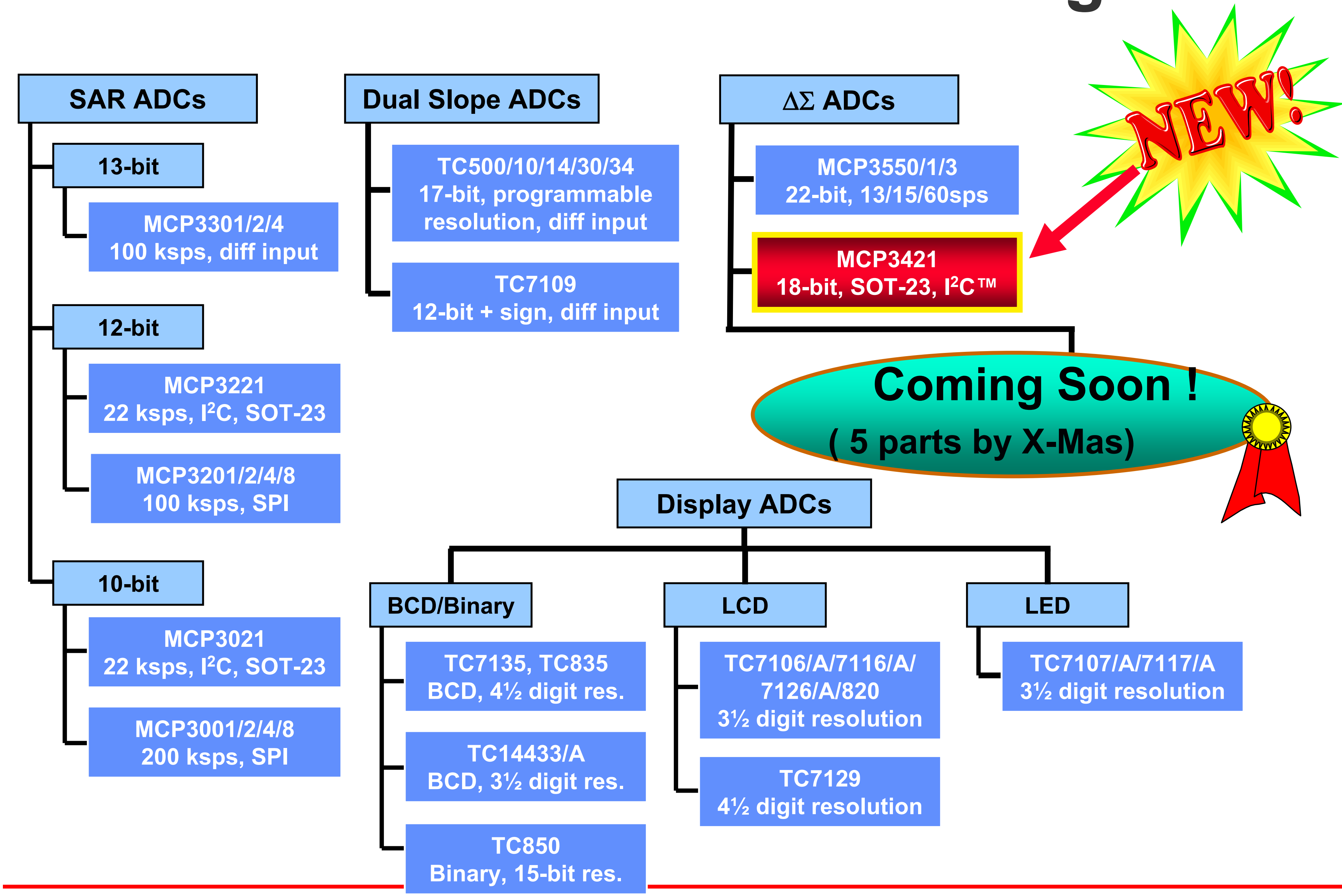
11075 ADC

Delta-Sigma Analog-to-Digital Converters for Sensor Applications

A/D Converter Offering



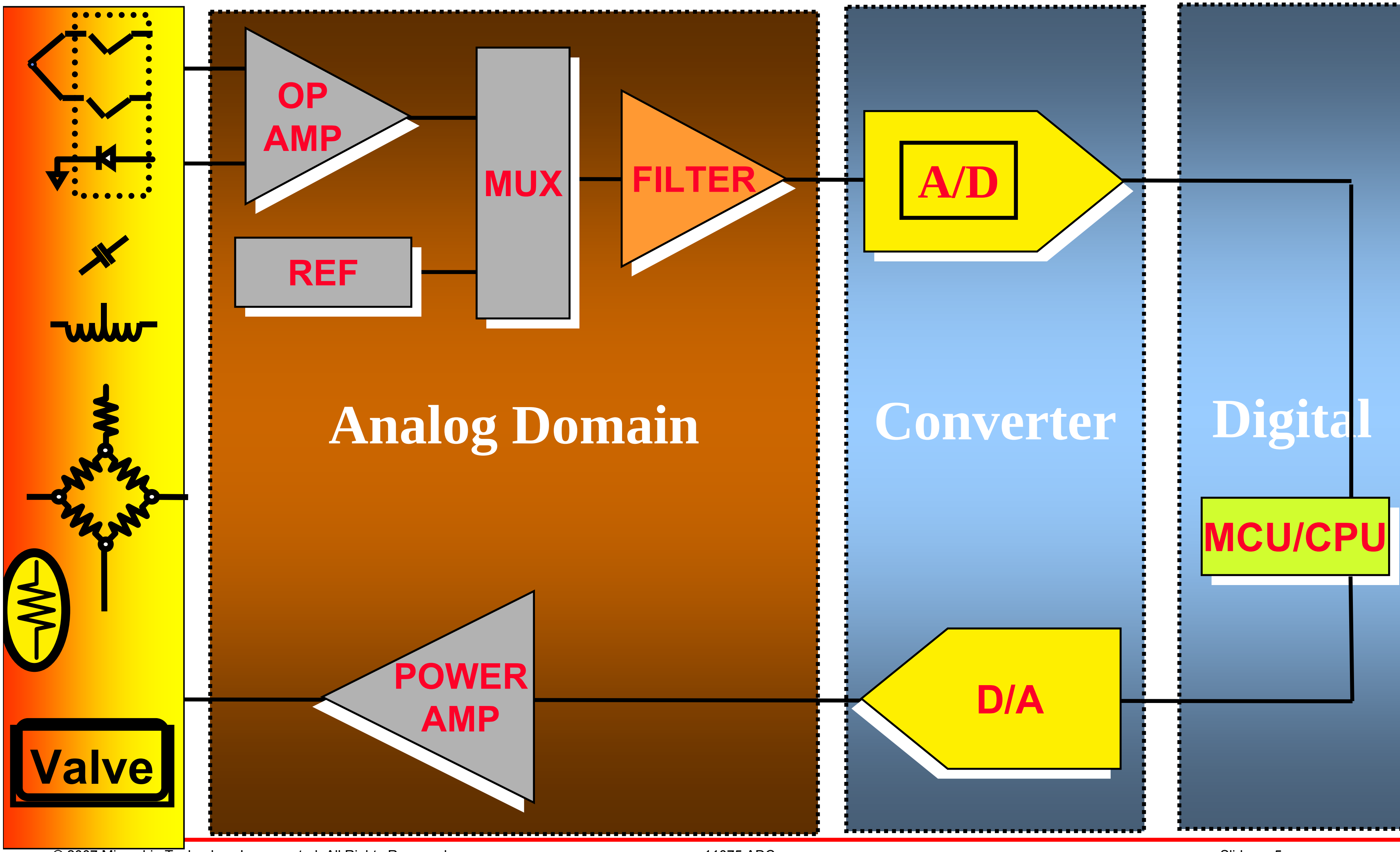
Class Agenda

1. ADC and Signal Theory Fundamentals
2. High-Resolution ADC Architectures
3. Microchip's ΔΣ ADC devices
4. How to use ΔΣ ADC Devices
5. Sensor Applications
6. Hands-On Class with MCP3421 Demo Board

Section 1

ADC and Signal Theory Fundamentals

Real World Signal Chain

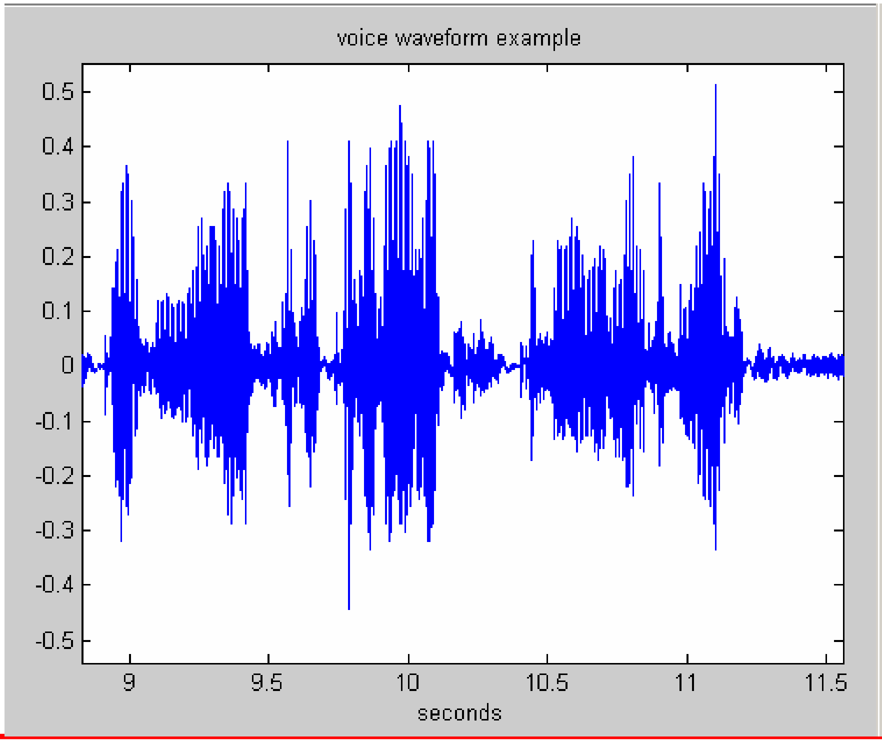


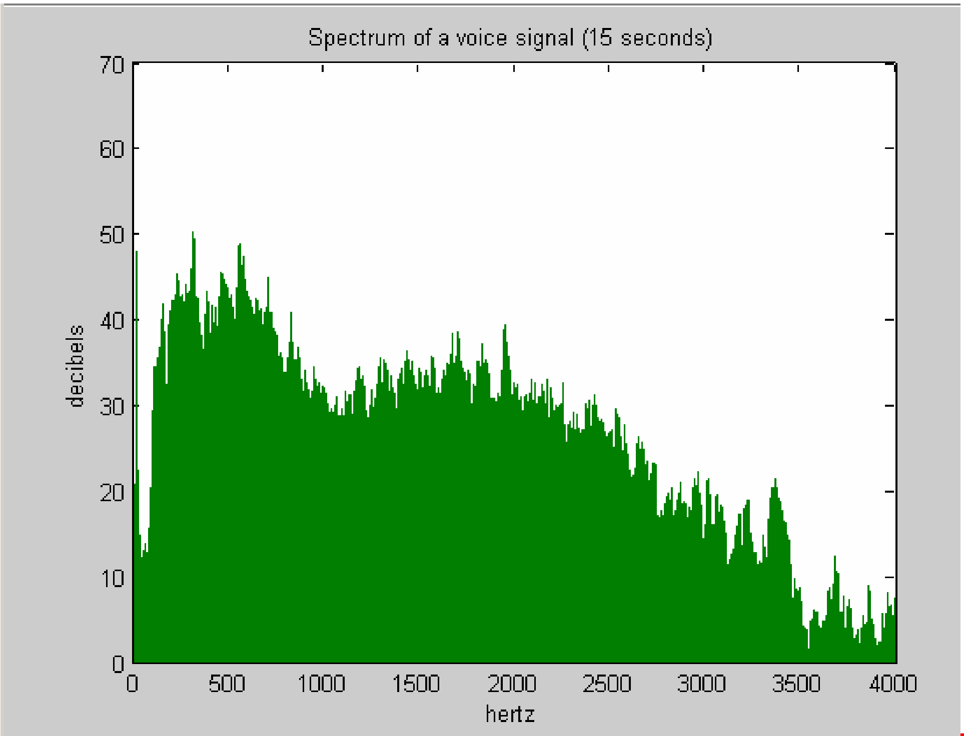
Representing Analog Signals

Any analog waveform can be described as a sum of multiple sinewave signal functions. (Fourier Analysis). We can represent the same signals with time or frequency domains

The power of the signal can be calculated with spectrum or time domain :

$$P_x = \frac{1}{T}\int_{-T/2}^{T/2} g^2(t)dt = \sum_{k=-\infty}^{\infty} {M_k}^2$$





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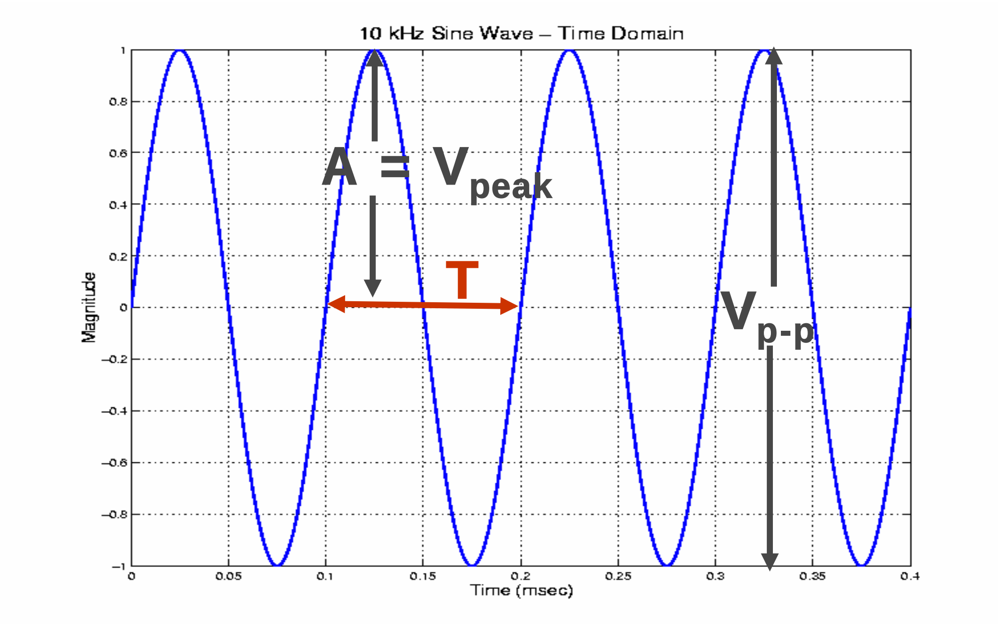
Components of an Analog Signal

$$V_a = A_\omega \sin(\omega t + \phi_\omega)$$



- A_ω : Amplitude (Peak)
- ω : Pulsation (rad.s^{-1})
- f : Frequency (Hz)
- t : Time (s)
- ϕ_ω : Phase (rad)
- T : Period (s)
- T = 1/f , $\omega = 2\pi f$

$$P_{AV} = \frac{1}{T}\int_{-T/2}^{T/2} V_a^{\,2}(t)\,dt = \frac{A^2}{2}$$

Average Instantaneous Power. Mean Square or Variance if mean=0

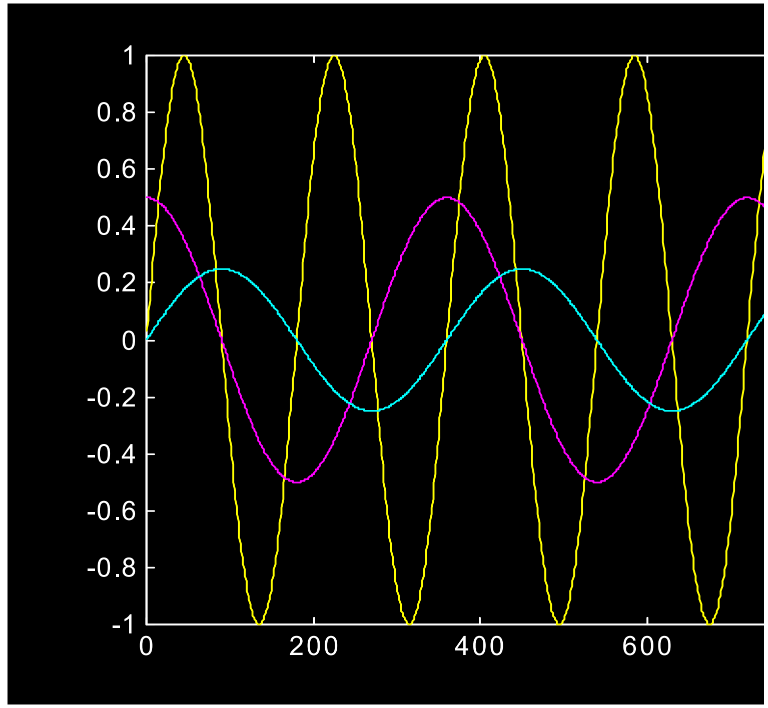
$$V_{rms} = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} V_a^{\,2}(t)\,dt} = \frac{A}{\sqrt{2}}$$

RMS Voltage (= DC voltage). “Std Deviation” if mean=0

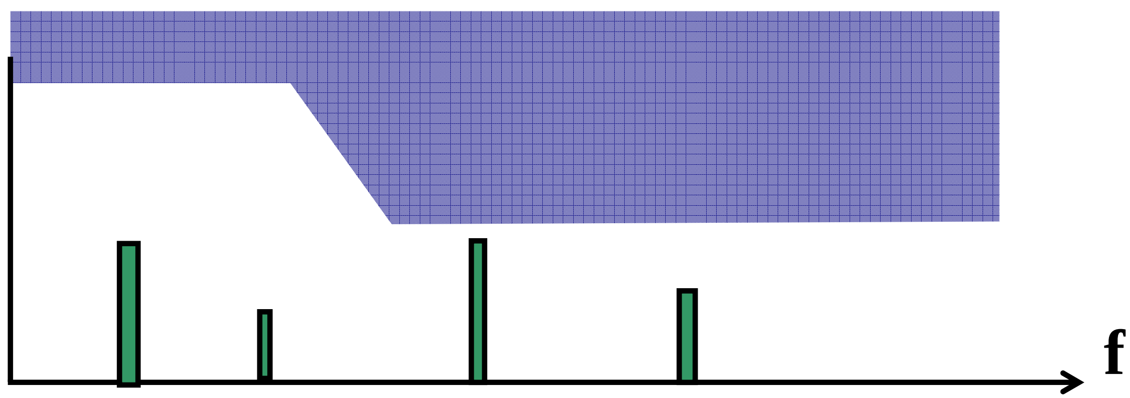
Time Harmonics of an Analog Signal

Any waveform can be described as a sum of multiple signal functions.

$$P_x = \frac{1}{T} \int_{-T/2}^{T/2} g^2(t)dt = \sum_{k=-\infty}^{\infty} M_k{}^2$$



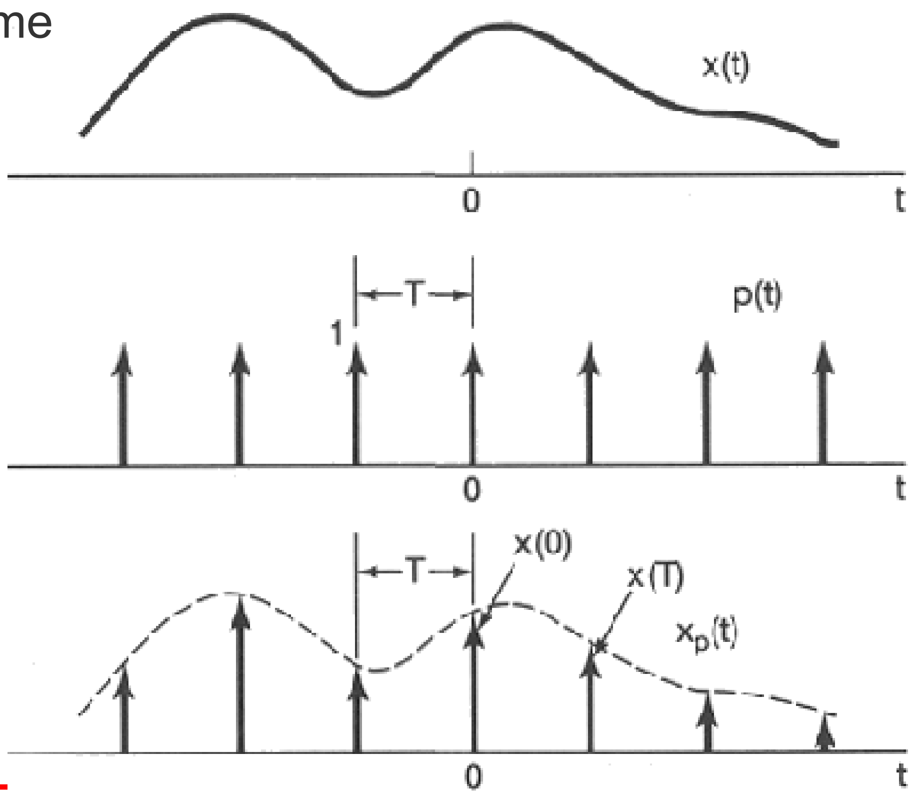
Any of these can be uniquely singled-out with appropriate filtering



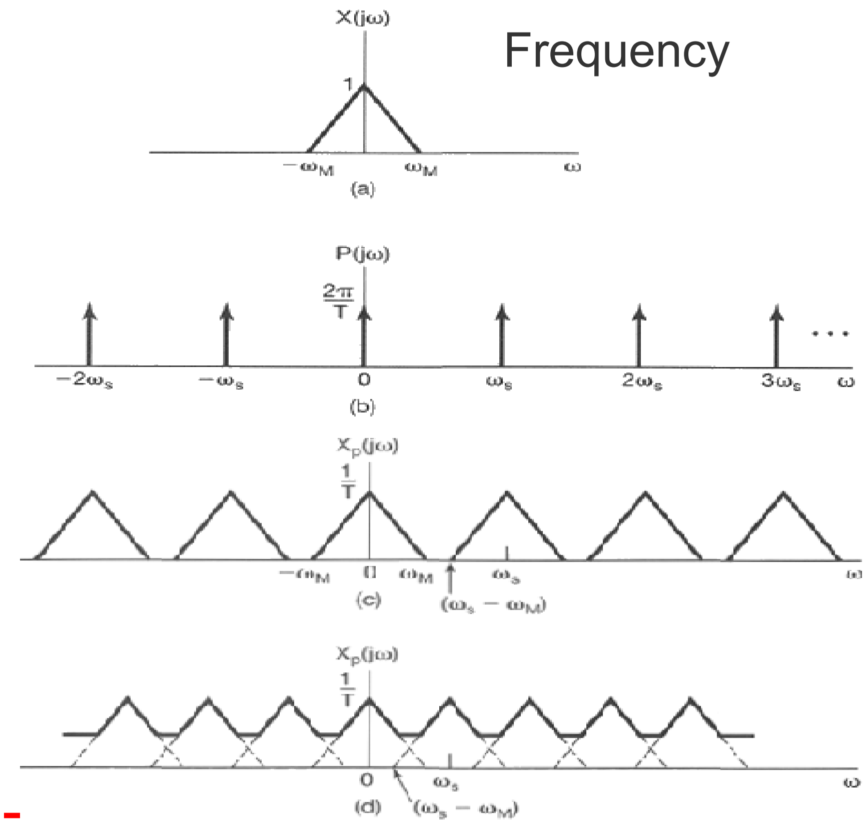
The Sampling Theorem

- « When sampling a signal, the sampling frequency must be greater than twice the bandwidth of the input signal (Nyquist frequency) in order to be able to reconstruct the original signal from the sampled version »

Time

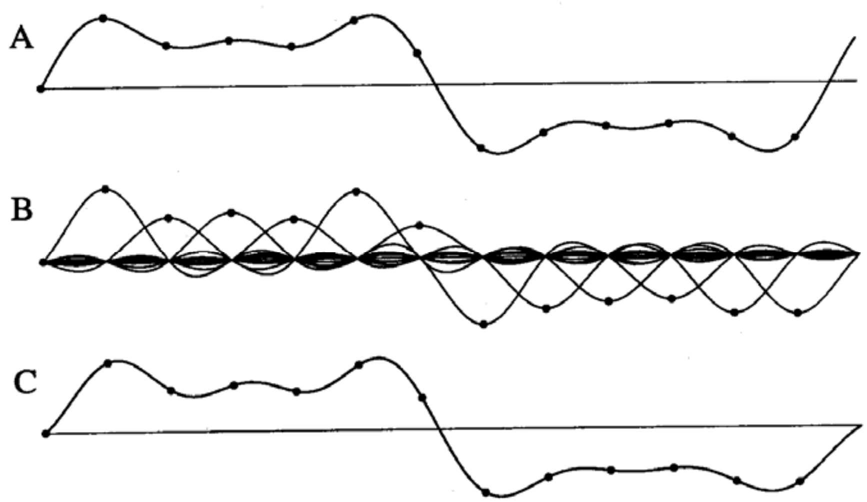


Frequency



The Sampling Theorem

- With certain conditions it is possible to reconstruct an analog signal perfectly from a sampled data stream
  - If input signal is band-limited, and
  - If you sample the signal at least greater than x2 the highest signal frequency component (The “Nyquist” Frequency)
  - Then, you can reconstruct the original signal by convolving the samples with an SINC kernel (Ideal digital-to-analog transfer function)

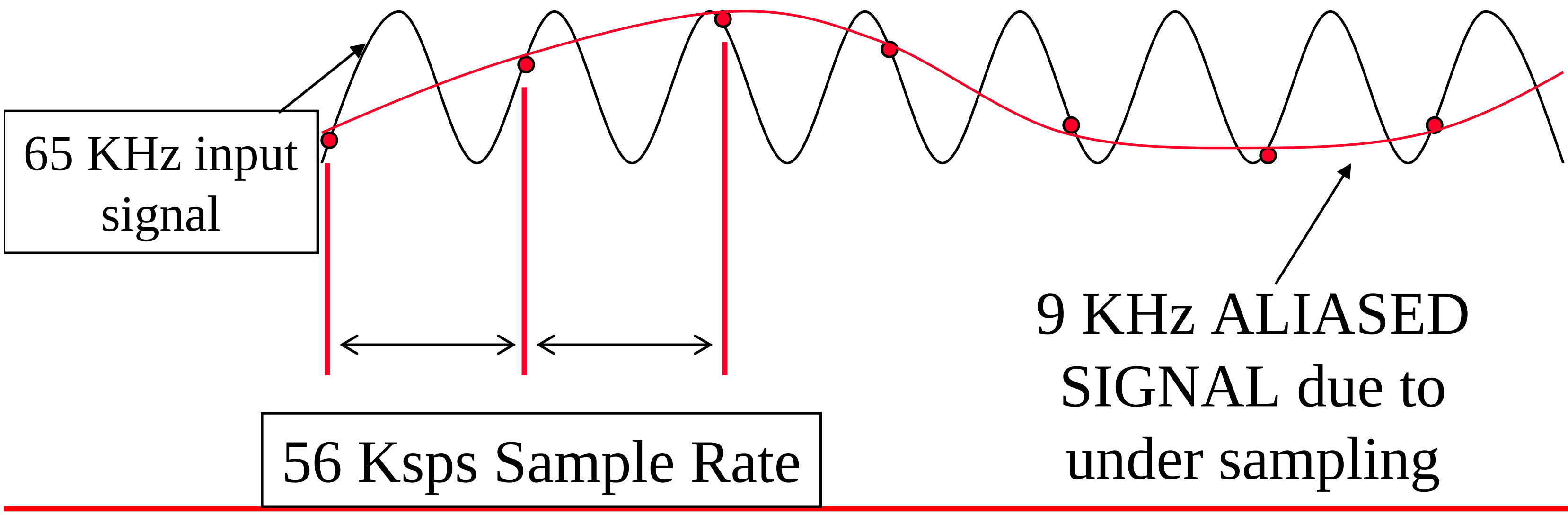


Under Sampling

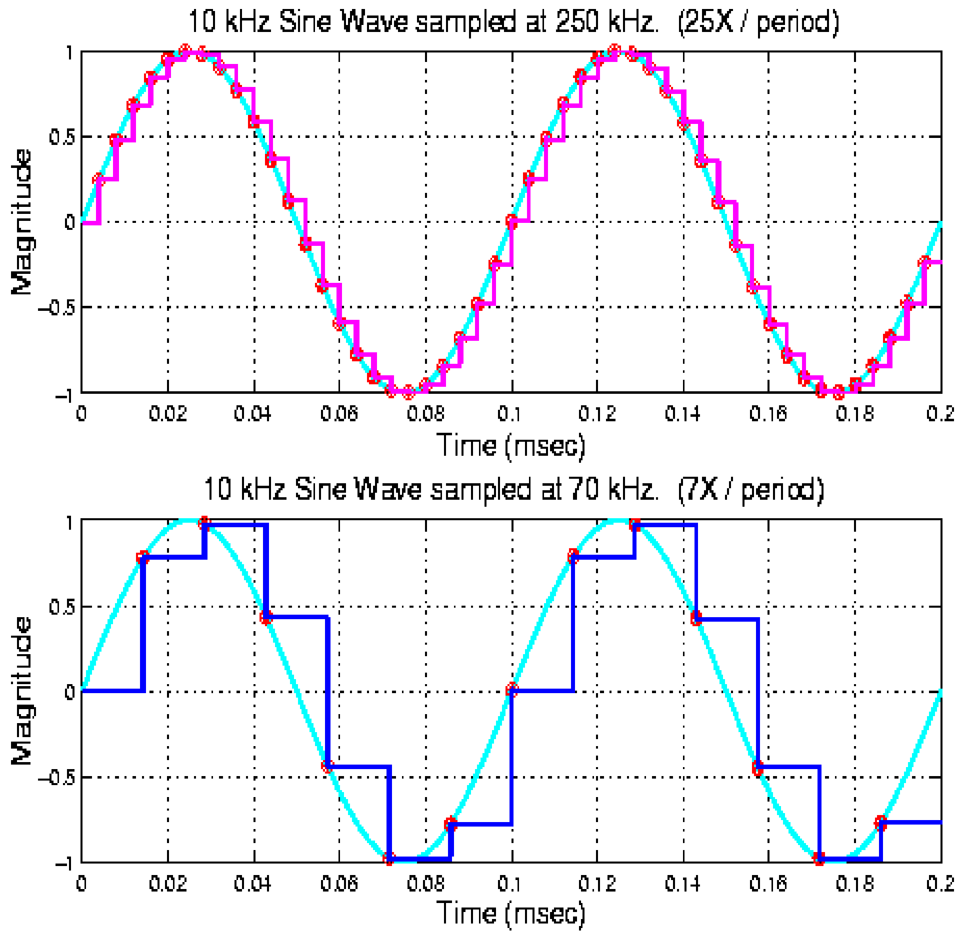
- When the A/D converter is not sampling input signal fast enough : The higher frequency signals create aliased frequency components will fall in your baseband
- In practice this means that the too-high frequencies will appear as lower frequencies, i.e. under an Alias!
- To see where they will fall into , you need to **fold your frequency spectrum into the baseband,** like folding a piece of paper :

$$f_{aliased} = \left| f_{in} - Nf_s \right|$$

N being the largest integer so that $f_{aliased}$ can fall in the baseband

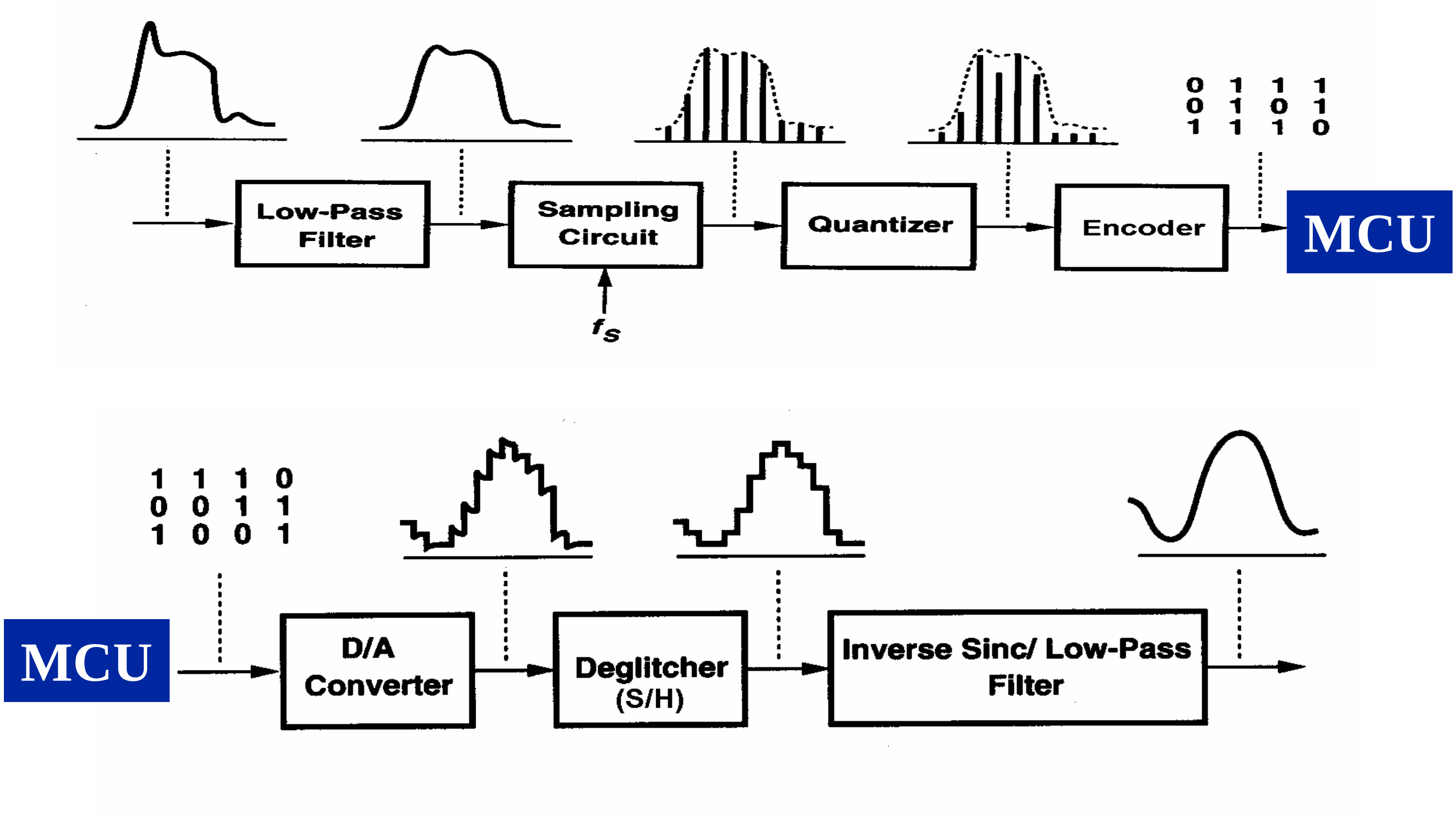


Choosing Sampling Frequency



- **Generally, faster is better to avoid aliasing, but ...**
- **Limited by physical constraints**
  - **Switch resistance, sampling capacitor**
  - **Amplifier settling time and power consumption**
  - **Jitter & aperture time**
- **Rule of thumb:**
  Sample at greater than 10X signal BW
  - **Minimises sampling effects (amplitude distortion)**
  - **Eases the anti-aliasing filter design (reduced filter order)**

The Analog/Digital Data Conversion Interface



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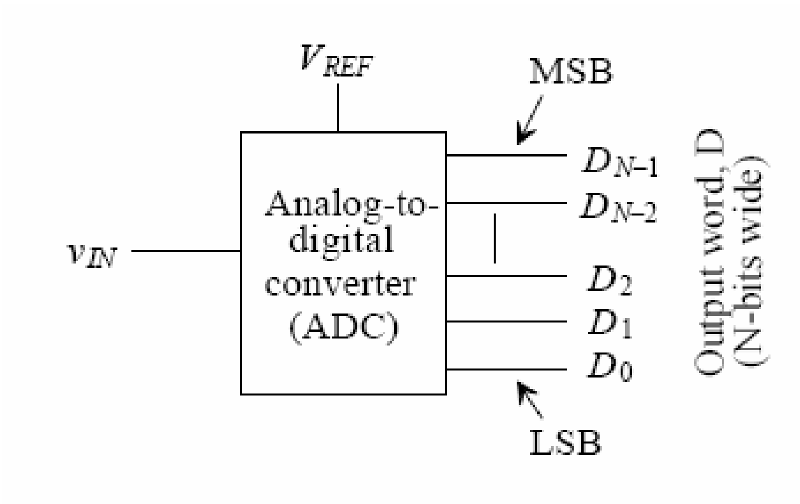
Ideal A/D Converter



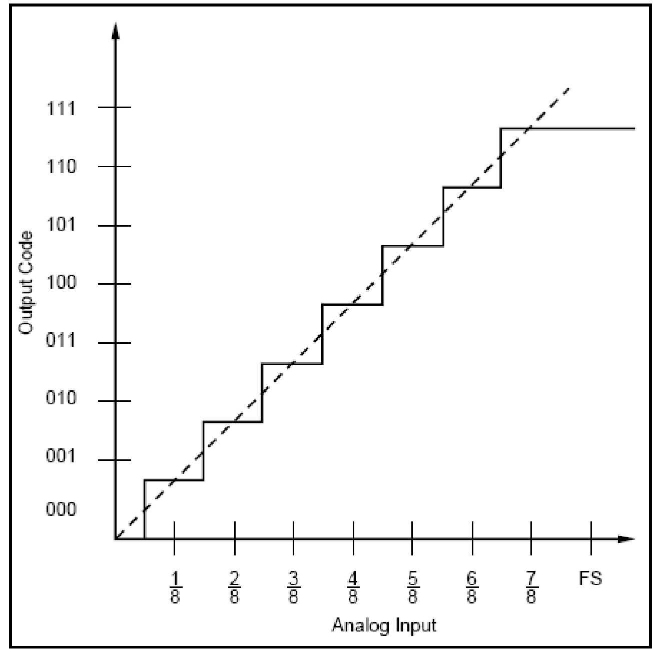
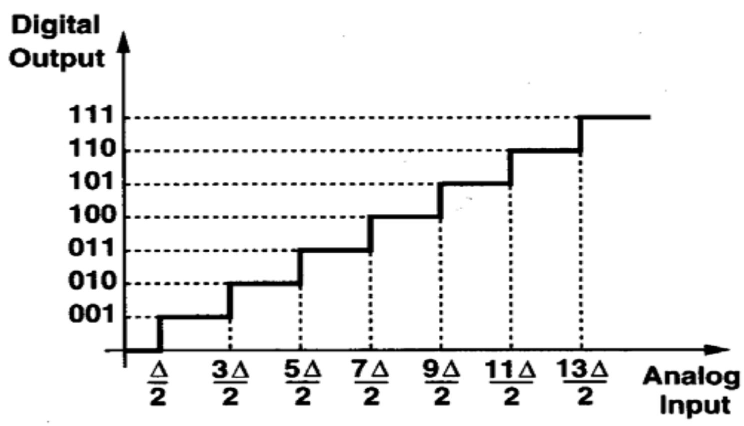


FIGURE 1. Ideal 3-Bit A/D Converter Transfer Function.

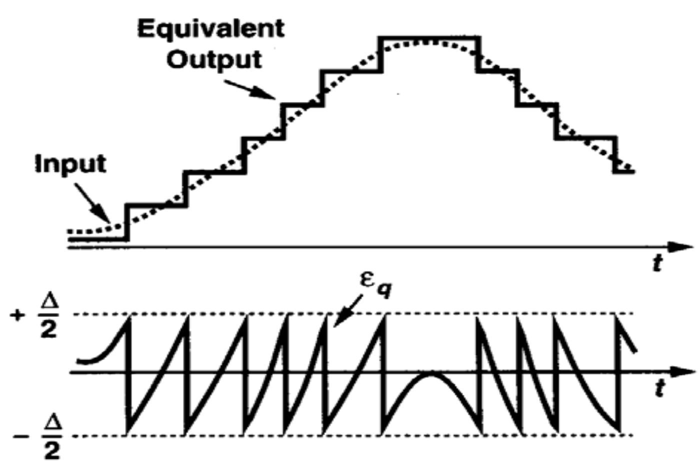
Unipolar N-Bit ADC	**1 LSB = $V_{REF}/2^N$**	**Code out = Round($V_{IN}/V_{REF} \times 2^N$)**
Bipolar N-Bit ADC	**1 LSB = $V_{REF}/2^{N-1}$**	**Code out = Round($V_{IN}/V_{REF} \times 2^{N-1}$)**

- An ideal ADC shows **quantization error** Δ due to the nature of the digital output
- Also called **quantization noise** although deterministic signal!

Uniform Quantizer (Binary EnCoder)



(a)



(b)

- "Linear" progression of quantization steps of "Uniform" width
- Max. input voltage = V_{ref}
- Quantizer step width, Δ, refers to the minimum change in input to change output code by 1, given by

$$\Delta = \frac{V_{ref}}{2^m}$$

- Quantization Error Signal Power:

$$\sigma_e^2 = \int_{-\Delta/2}^{\Delta/2} e^2 p(e)\,de = \int_{-\Delta/2}^{\Delta/2} e^2 \left(\frac{1}{\Delta}\right) de = \frac{\Delta^2}{12}$$

Output SNR of Quantizer (for Sine wave)

- N-bit Unipolar Quantizer with Input Signal:
  - Full Scale Sinewave function
  - Peak Value $=V_{ref}/2$
- Input signal power:

$$P_{AV}=\frac{\left(V_{ref}/2\right)^2}{2}=\frac{\Delta^2 2^{2N}}{8}$$

- Quantization noise power:

$$\sigma_e^{\ 2}=\frac{\Delta^2}{12}$$

- **Derivation of SNR**

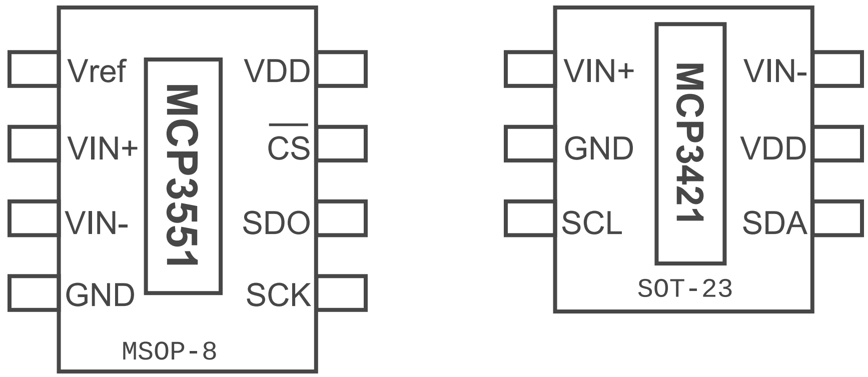
$$SNR_q=\frac{P_{av}}{\sigma_e^{\ 2}}=\left(\frac{3}{2}\right)2^{2N}$$

$$SNR_q(dB)=10\log_{10}\left(\frac{3}{2}\right)2^{2N}$$

$$=1.76+6.02N$$

- The quantization noise calculation assumes that the noise is uniformly distributed
- This formula can be improved with noise shaping in Sigma-Delta converters.

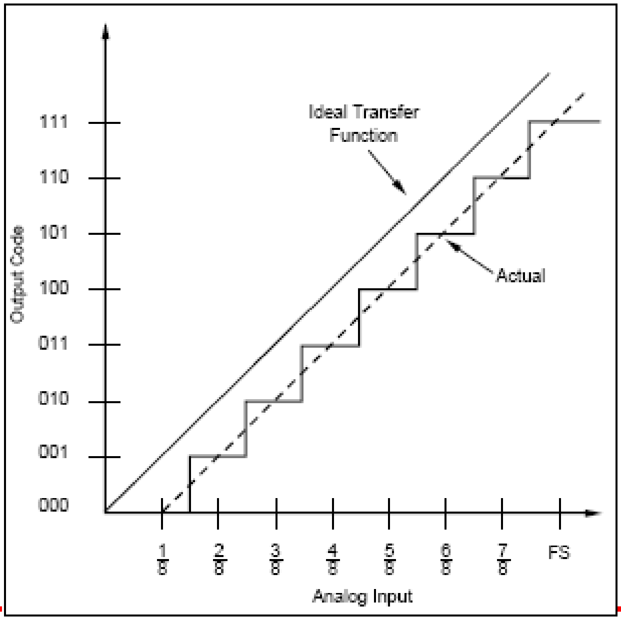
Real A/D Converter

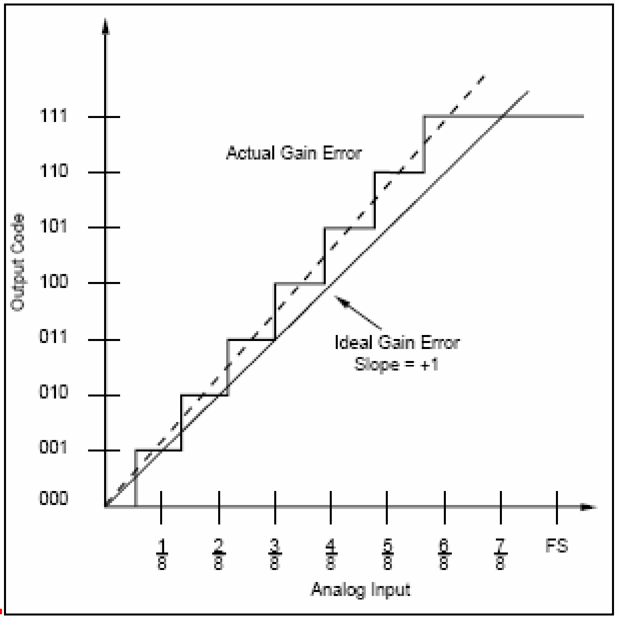


- Non-idealities and limitations due to CMOS implementation
- Static Errors affecting DC characteristics
  - Offset error , Gain error, INL, DNL…
- Dynamic Errors affecting AC characteristics
  - Noise, Distortion, Drift…
- Other Circuit limitations (PSRR, CMRR, stability, dynamic range, bandwidth, aliasing, latency, clock jitter, aperture time, power consumption,…)
- Digital Interface/Coding (SPI, I^{2}C™, binary 2's complement)

Linear Static Errors

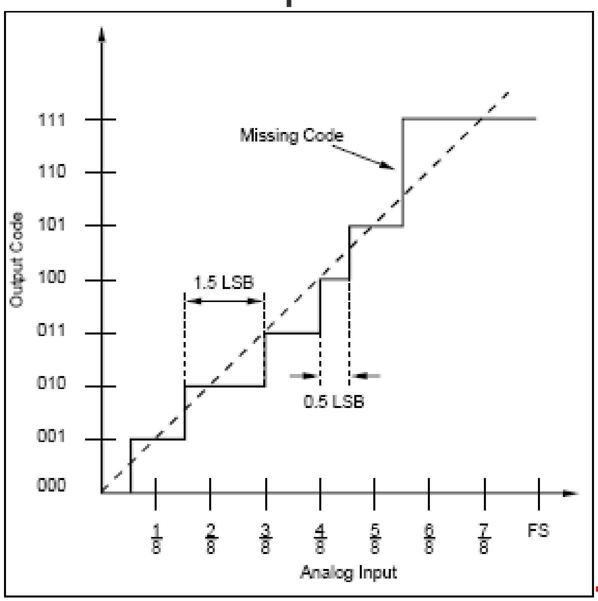
- Static errors that can be calibrated out (internally or externally with a MCU) by simple transformation
- Offset Error
  - Defined by the position of the zero
  - Correction with Translation
  - MCU operation : Addition
- Gain Error
  - Defined by the slope of the transfer function
  - Correction with Rotation
  - MCU operation : Multiplication



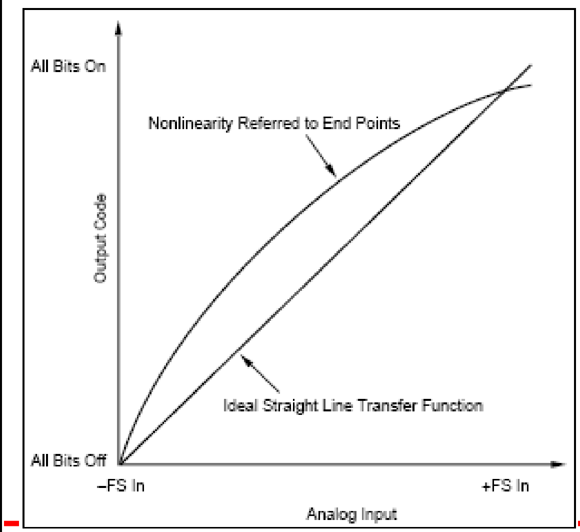


Non-Linear Static Errors

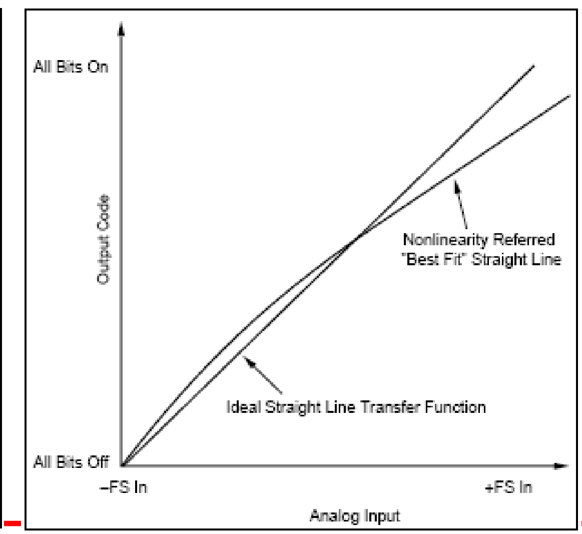
- Static Errors that cannot be calibrated out or at least not by simple transformations
- DNL Error
  - Transition Step Size
  - DNL<1 LSB → No missing codes
  - Correction with lookup table
- INL Error
  - Deviation from an ideal straight line after linear calibration
  - Correction with Distortion
  - MCU operation : 2^{nd} or 3^{rd} degree equation solving



End Points



Best Fit



Total Unadjusted Error

- **The** Total Unajusted Error (TUE) **is a common figure of merit for static errors**
- **Combination of:**
  - Offset Error
  - Gain Error
  - Linearity Error
  - Missing codes
- **Characteristic of the ADC**

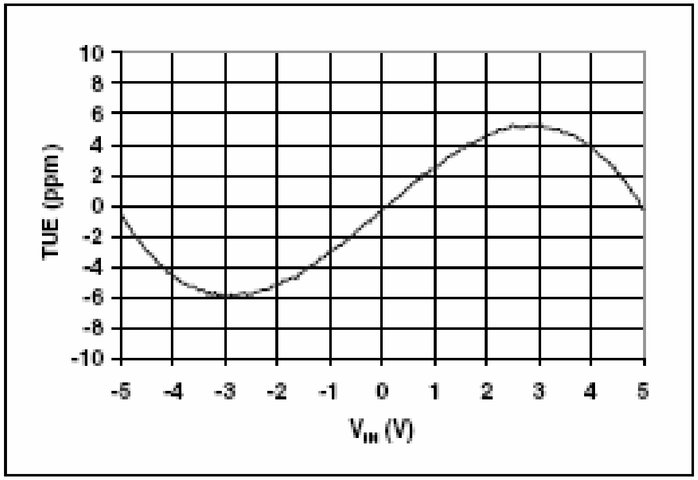


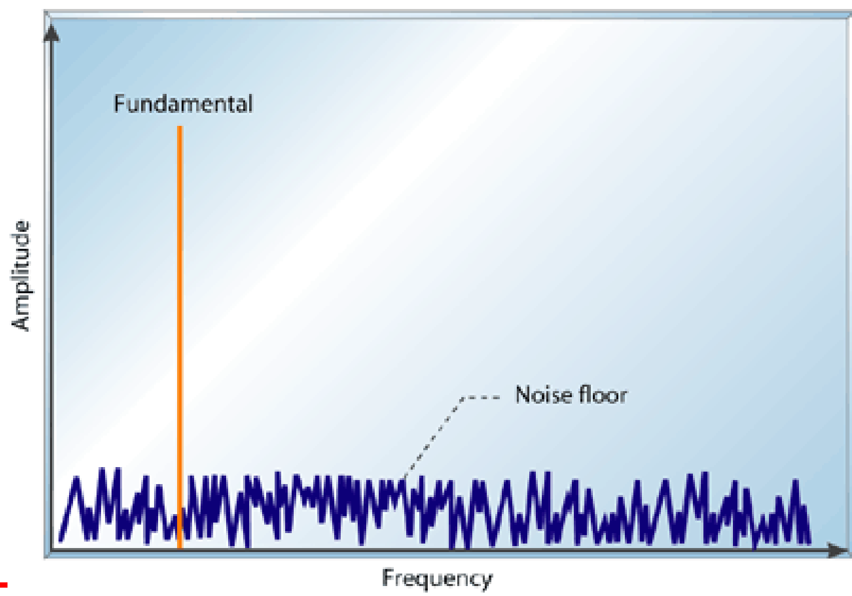
FIGURE 2-20: Total Unadjusted Error (TUE) vs. Input Voltage (V_{REF} = 5.0V).

- **Mostly impacted by analog process quality and calibration schemes efficiency**
- **Does not include VCM, power supply effects, beware of the conditions !**
- **TUE depends a lot on input voltage and Vref**

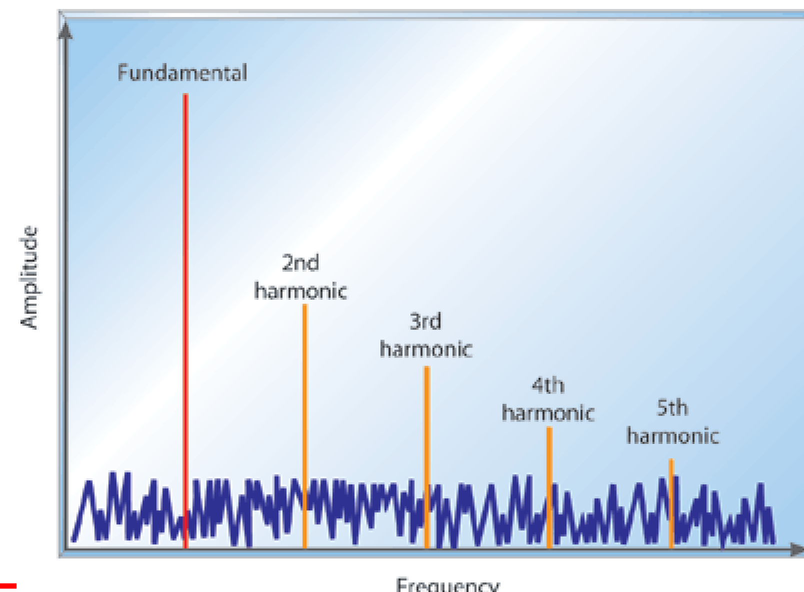
Dynamic Errors

- Deterministic errors : **depend only on the given input conditions (aliasing, distortion, tones,…)**
- **Non-deterministic errors : Imply randomness even with same conditions (noise, drift,…)**

- Noise : **Random variation of the output code with time (thus with frequency!)**

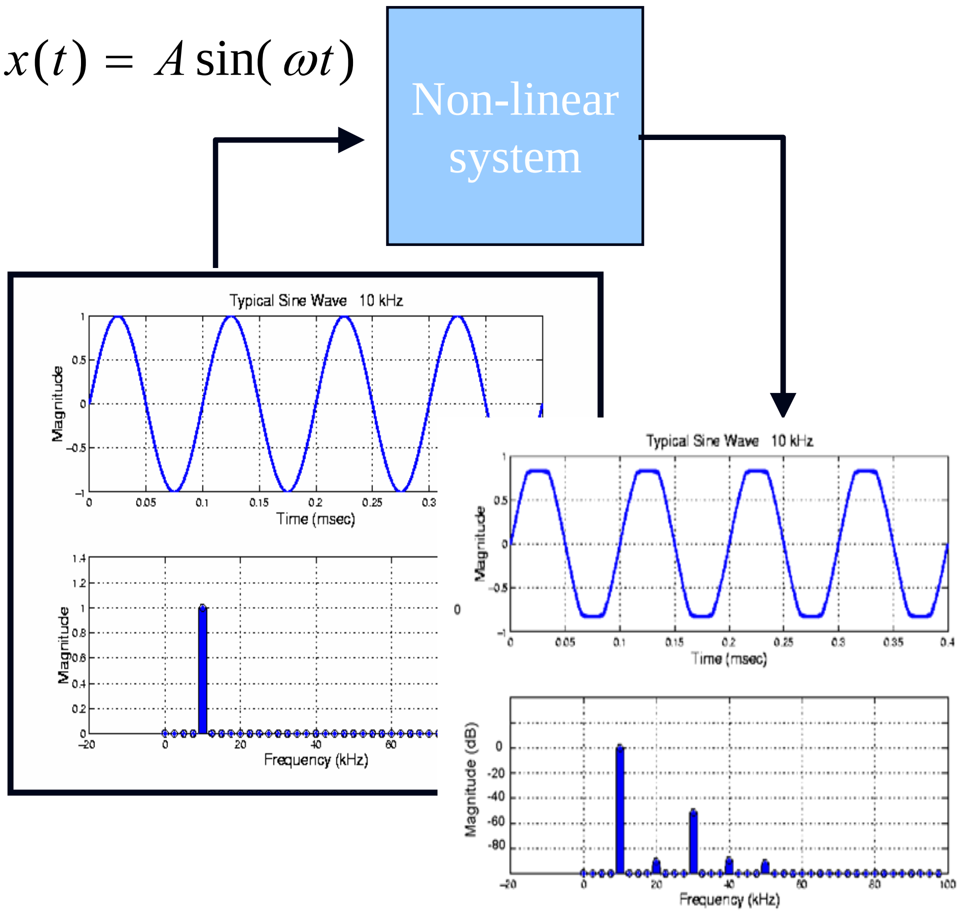


- Distortion : **Spurs in the output frequency spectrum (harmonics)**



Distortion and Linearity

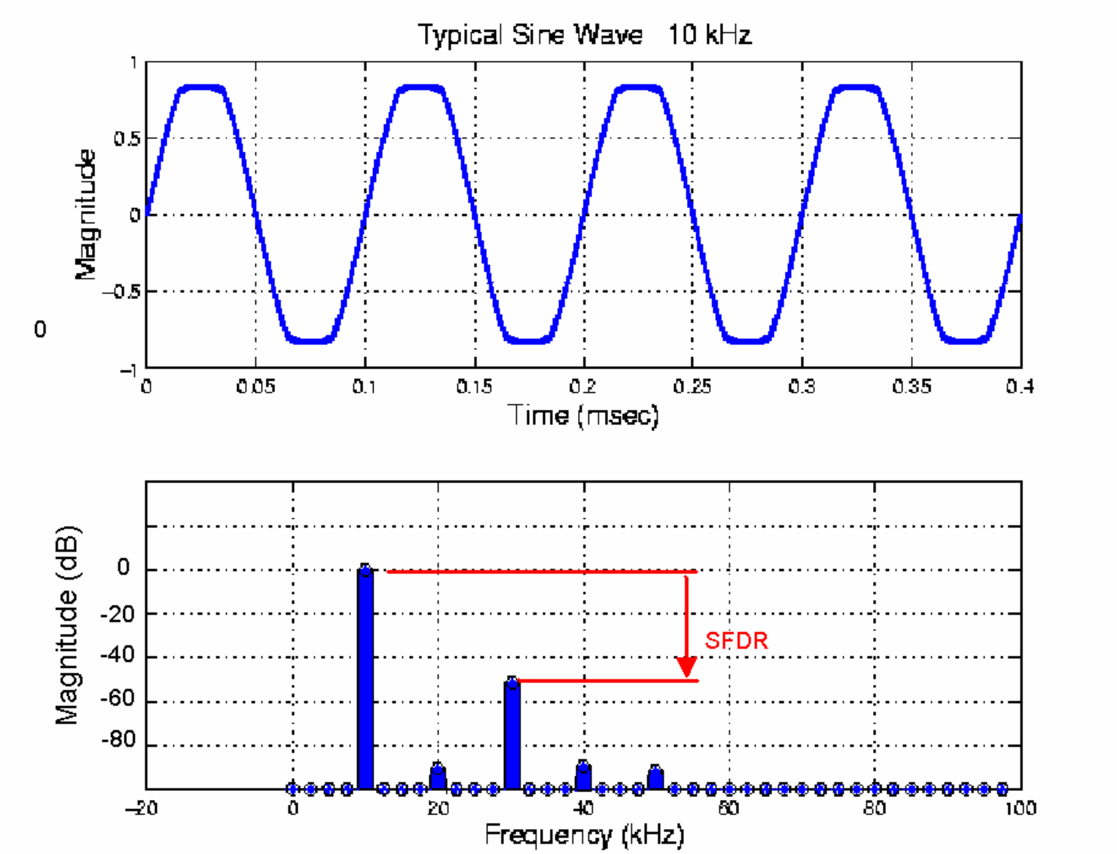
$$x(t) = A\sin(\omega t)$$



$$y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t)$$

- **Linear System: y = λ .x**
  - **Sine wave in → Sine wave out with same frequency and phase but different amplitude**
- Non-linear system:
  - **Sine wave in → Sine wave out + Harmonics @ integer multiples of the fundamental frequency**
  - **Cause spikes in the frequency spectrum : Distortion**
- THD (Total Harmonic Distortion) of the signal:
  - **Measure of the linearity of the system for AC signals**
  - **For DC signals, all harmonics are superimposed → INL**

Signal Distortion



- **SFDR = Spurious Free Dynamic Range**
  - **Magnitude of the largest harmonic relative to the fundamental**
  - **In this case, about 50dB = 0.32%**

THD = Total Harmonic Distortion

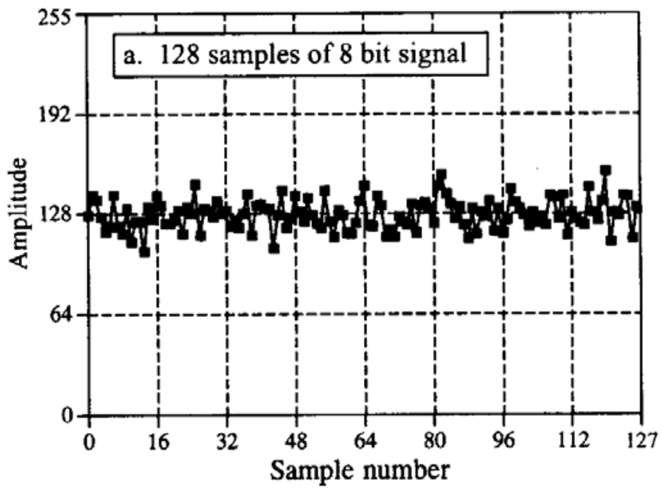
Measure of the power of all harmonics relative to the fundamental (usually close to a full scale input signal)

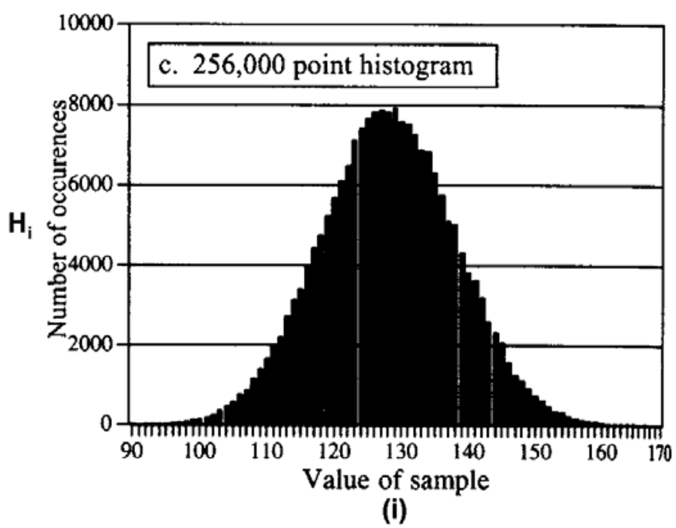
$$THD = \frac{P_{Harmonics\_Total}}{P_{Fundamental}}$$

$$THD_{dB} = 10\log\left(\frac{V_{h2}^{2} + V_{h3}^{2} + V_{h4}^{2} + \dots}{V_{f}^{2}}\right)$$

$$THD_{\%} = \frac{\sqrt{V_{h2}^{2} + V_{h3}^{2} + V_{h4}^{2} + \dots}}{V_{f}} \times 100$$

Output Noise Definition





- Noise is the variation over time of the output signal of a system driven by the same stimuli
- Variance, σ^2 is a measure of how spread out the distribution is, or a measure of variability (noise) for a static (DC) input signal.
- Computed as the average squared deviation of each signal sample from its mean.

$$\sigma_x^{\ 2} = \frac{1}{N} \sum_{i=0}^{N} (x_i - \mu)^2$$

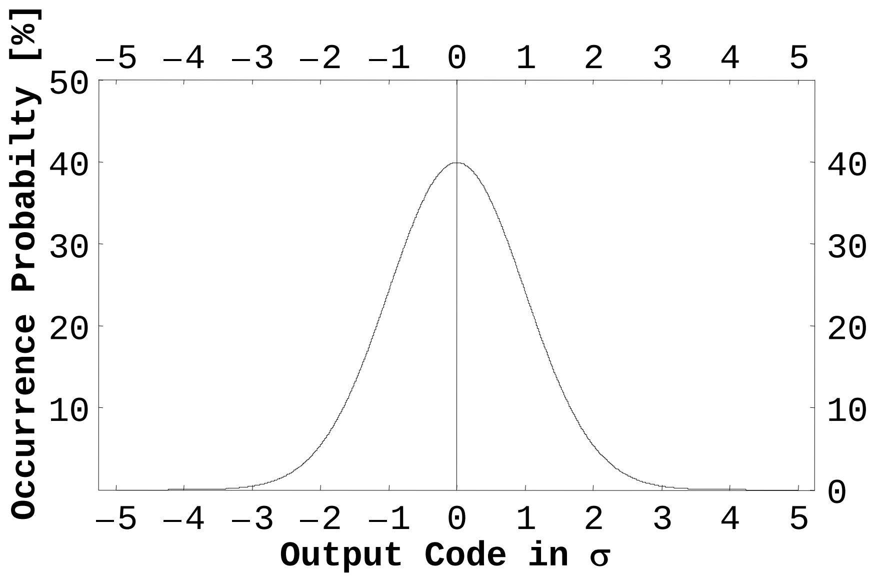
$$\sigma_x^{\ 2} = \frac{1}{N} \sum_{i=0}^{N} (i - \mu)^2 H_i$$

- Used to estimate the power of a quantization error signal

Noise Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-x^2}{2\sigma^2}\right)$$

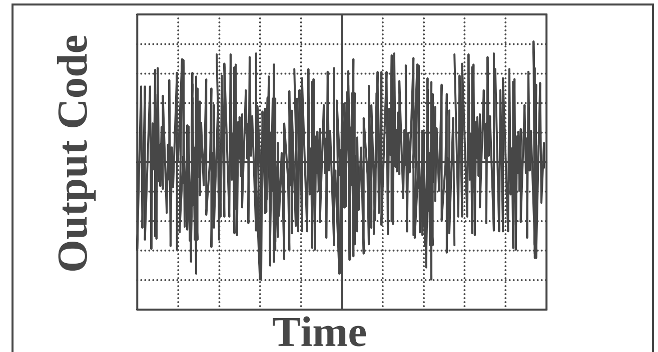
σ can be expressed in LSB, or mV

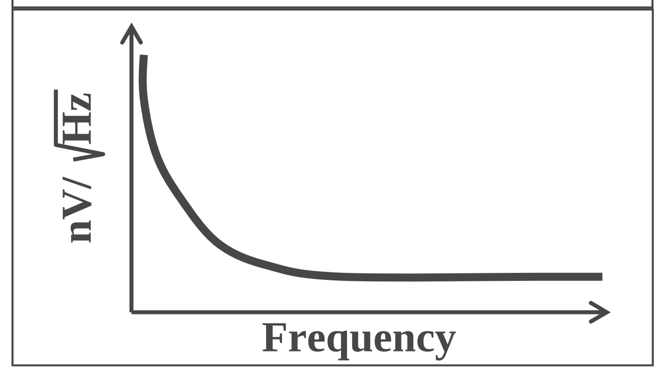


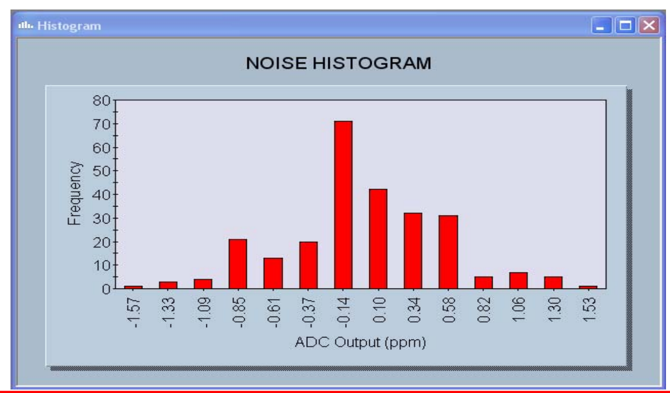
- Gaussian distribution is the most typical distribution for physical quantities like output noise
- Infinite spread but most of the probability is within the σ range which is the variance of the distribution : RMS noise
- **Noise adds in squares !** Averaging technique divides by √n the noise level if n samples are used
- Commonly-used modeling for analyzing system noise : Superposition of uncorrelated noise sources

Noise Representations

- As a non-certain signal, noise can be described with a statistical distribution giving a probability of output codes
- Noise units are in **nV/√Hz** : spot noise taken over a 1Hz bandwidth
- Output noise is one of the critical specifications of an ADC: it represents the total integrated noise during a conversion, measured in µV RMS
- Noise histogram gives output code distribution for a certain number of conversions
- A noise histogram on every code transition would give a complete "No missing code" check



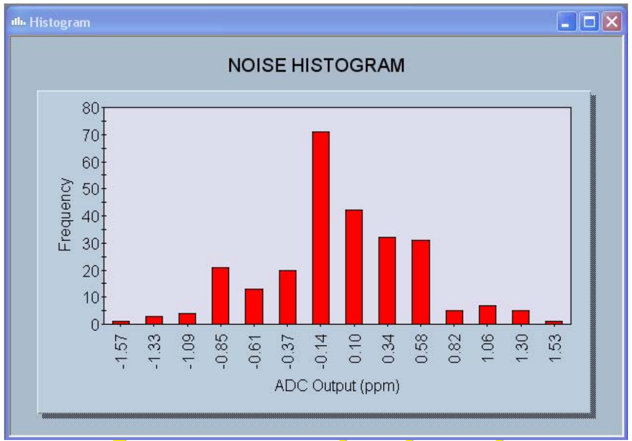




Reading Noise Histograms

- Reading noise **histograms** can give precise idea of noise distribution at one point. Noise distribution will vary with frequency and input conditions
- **Peak-to-peak** amplitudes are depending on low probability events (“outside of the bell”) thus hard to reproduce/evaluate
- The **Crest Factor** is the Ratio between Peak-to Peak signals and RMS signal. It is calculated here as a probability factor of occurring inside a certain range. Industry generally uses a crest factor of **6.6** to specify peak-to-peak noise **(99.9% event)**

Distribution range	Probability of output codes in the range	Probability of output codes not in the range
2.0 x RMS (1 sigma)	68 %	32 %
3.0 x RMS (1.5 sigma)	87 %	13 %
4.0 x RMS (2 sigma)	95.4 %	4.6 %
5.0 x RMS (2.5 sigma)	98.8 %	1.2 %
6.0 x RMS (3 sigma)	99.73 %	0.27 %
6.6 x RMS (3.3 sigma)	99.90 %	0.10 %
8.0 x RMS (4 sigma)	99.954 %	0.046%
10.0 x RMS (5 sigma)	99.994%	0.006%



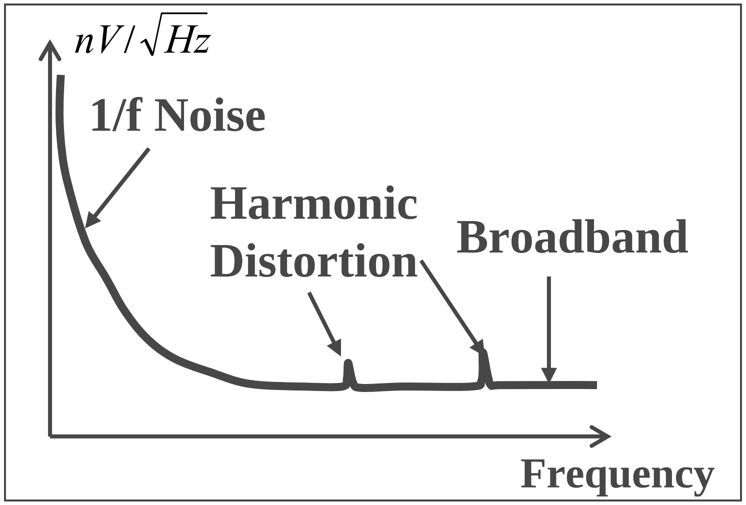
Average output code

Building a Low-noise System

- Evaluate your system requirements (resolution, noise floor, power consumption,…)
- Choose the best architecture (make a noise budget for the system)
- Know your transducer/sensor characteristics (output range, noise, accuracy,…)
- Evaluate/Calibrate static errors
- Evaluate and optimize the three types of Noise :
  - **Conducted Noise** : Noise created by the propagation of signals inside the system → Layout issues
  - **Radiated Noise** : Noise created by the environment of the system (RF, EMI…) → Packaging/chassis issues
  - **Device Noise** : Noise created by the electronic devices used in the system → Devices issues

Device Noise Overview

- For **Passive Devices**, ideally only resistors generate noise :
  - Resistors show thermal noise (equal to 4kT x R x BW)
  - Ideal Inductors and Capacitors are noise-free, but real ones have small series resistances



- **Active Devices** : All types of integrated transistors (CMOS,BJT…) have typically three different voltage noise sources
  - **1/f Noise** : due to random capture and release of charge carriers. Inversely proportional to frequency of operation
  - **Thermal noise** : Due to random thermal motion in resistive material. Typically broadband and independent of DC current
  - **Shot Noise** : Due to random diffusion and electron-hole pairs recombinations. Typically broadband, proportional to DC current

Effective Number of Bits

$$ENOB = \frac{\ln(FSR / RMS\ Noise)}{\ln(2)}$$

- Effective Number Of Bits (ENOB) **or Effective Resolution is a figure of merit for the noise performance of the ADC**
- **The effective resolution gives the** “noise-free” **resolution of the device, or the number of directly usable bits**
- **The effective resolution is usually much lower than the “No missing codes” resolution**
- MCP3551: 2.5 μV_{RMS} noise→ 21.9 bits **effective resolution with Vref=5V and 22 bits no missing codes !**
- **You can optimize the Effective Resolution by using larger Vref because noise floor is almost constant with Vref (look for admissible Vref range)**
- **Effective resolution is reduced by one bit for single-ended apps**

Resolution vs. Accuracy

- **Resolution** : Number of distinct output levels, number of bits available
- **Accuracy** : difference between the ideal converter transfer function and the actual transfer function :
  - **Total Unadjusted Error (TUE) for static measurements(DC).**
  - **Effective Resolution, SINAD for dynamic measurements (AC).**
- A 12-bit resolution ADC may be 10-bit accurate only !
- A 10-bit resolution ADC may have 12-bit level accuracy !
  - A 3-bit resolution ADC perfectly accurate

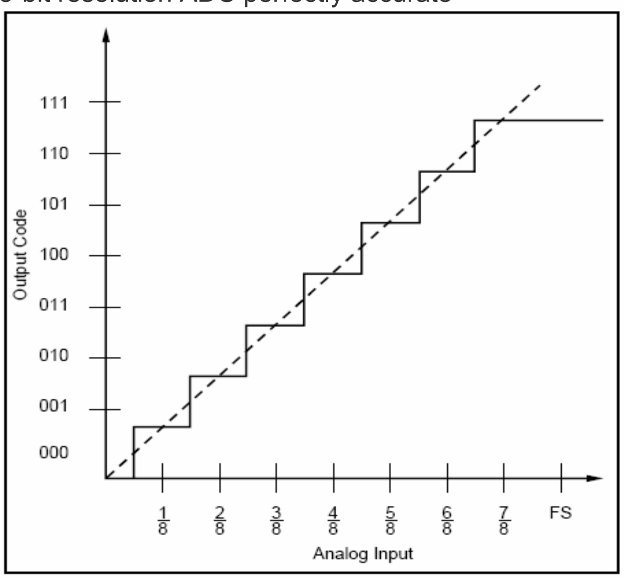
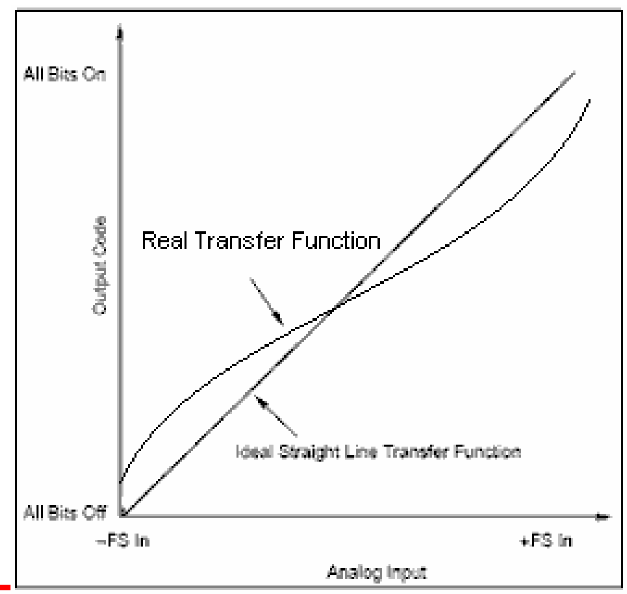
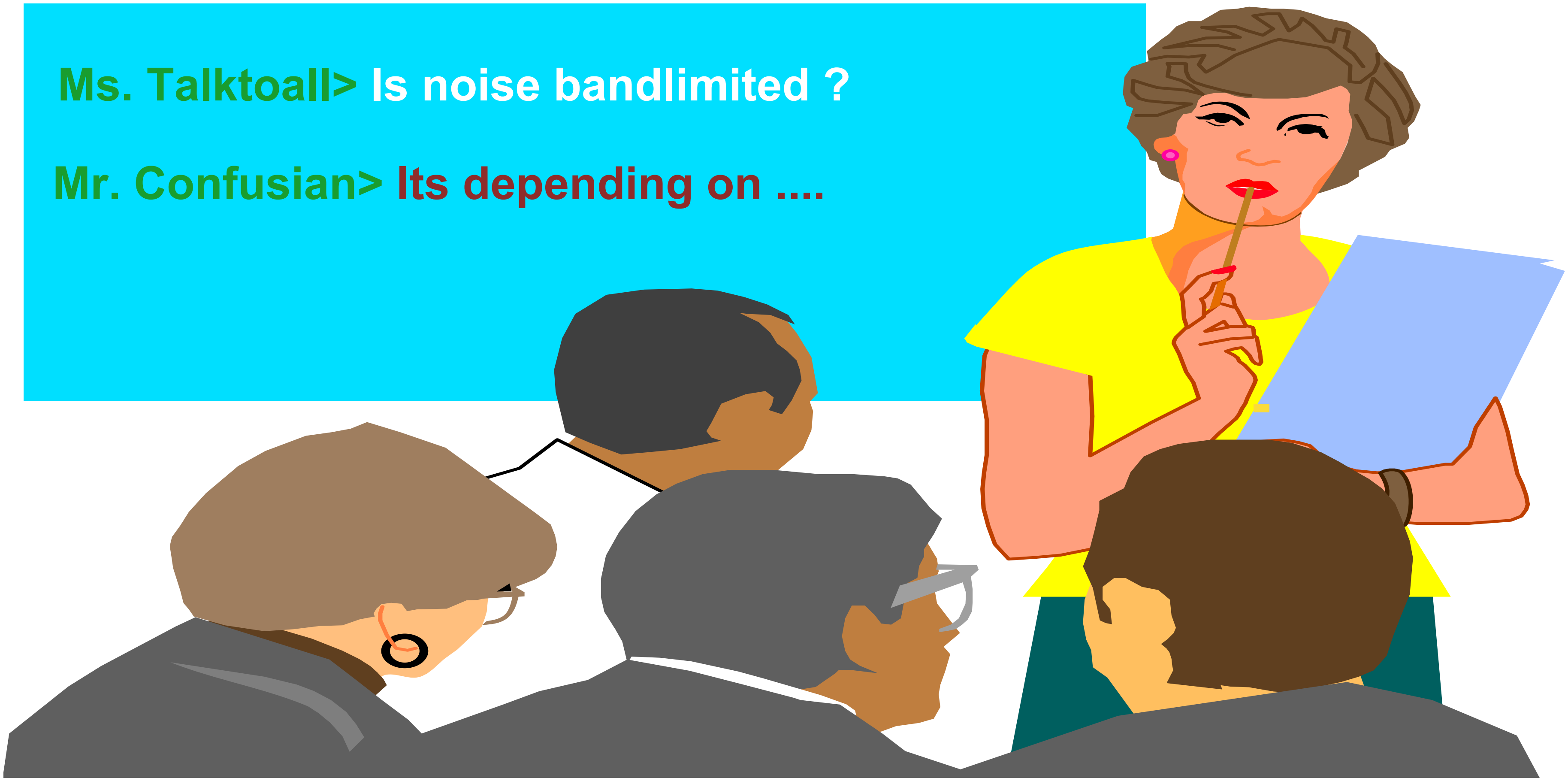


FIGURE 1. Ideal 3-Bit A/D Converter Transfer Function.

  - A 16-bit resolution ADC with 3-bit accuracy



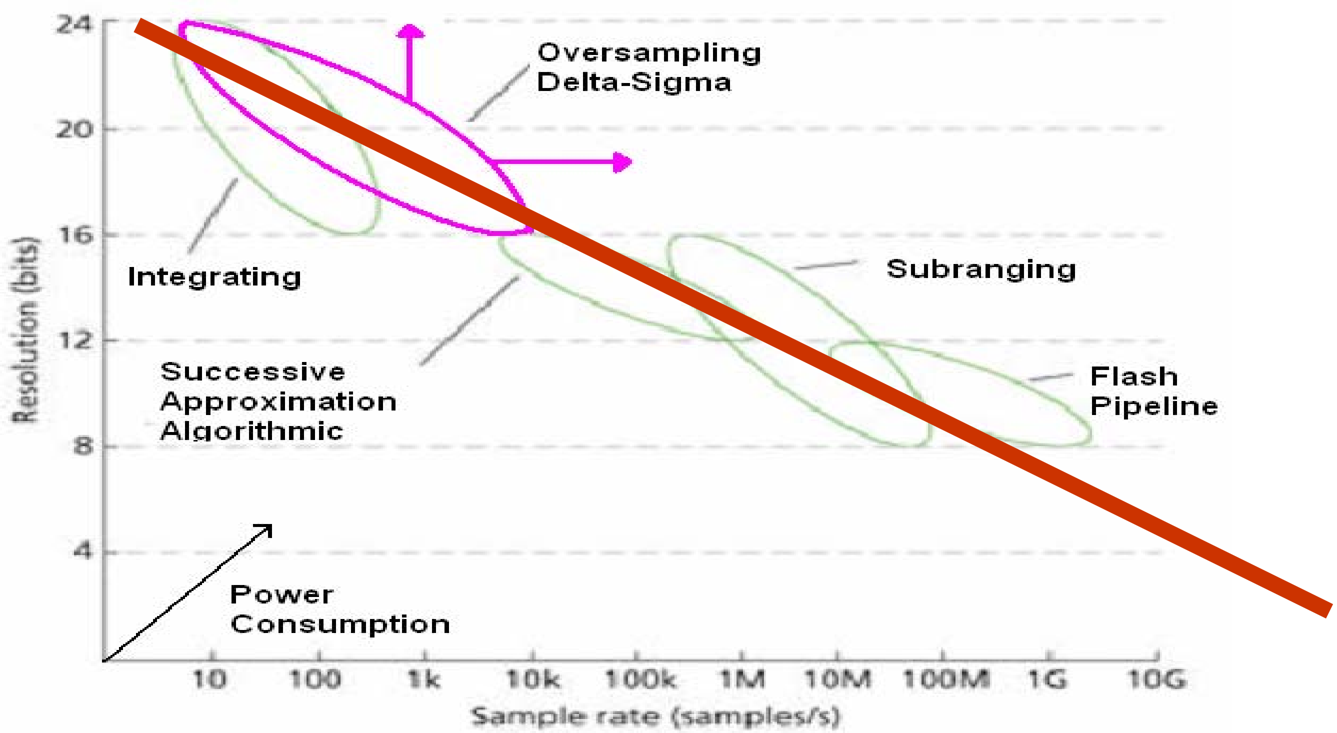
Questions?


Ms. Talktoall> Is noise bandlimited ?
Mr. Confusian> Its depending on ....

Section 2

High Resolution ADC Architectures

ADC Architectures Overview



- Delta-Sigma converters are mainly used for high-resolution, low bandwidth applications
- Microchip's approach to the market:
  - Lower power consumption, space-saving packages and higher resolutions

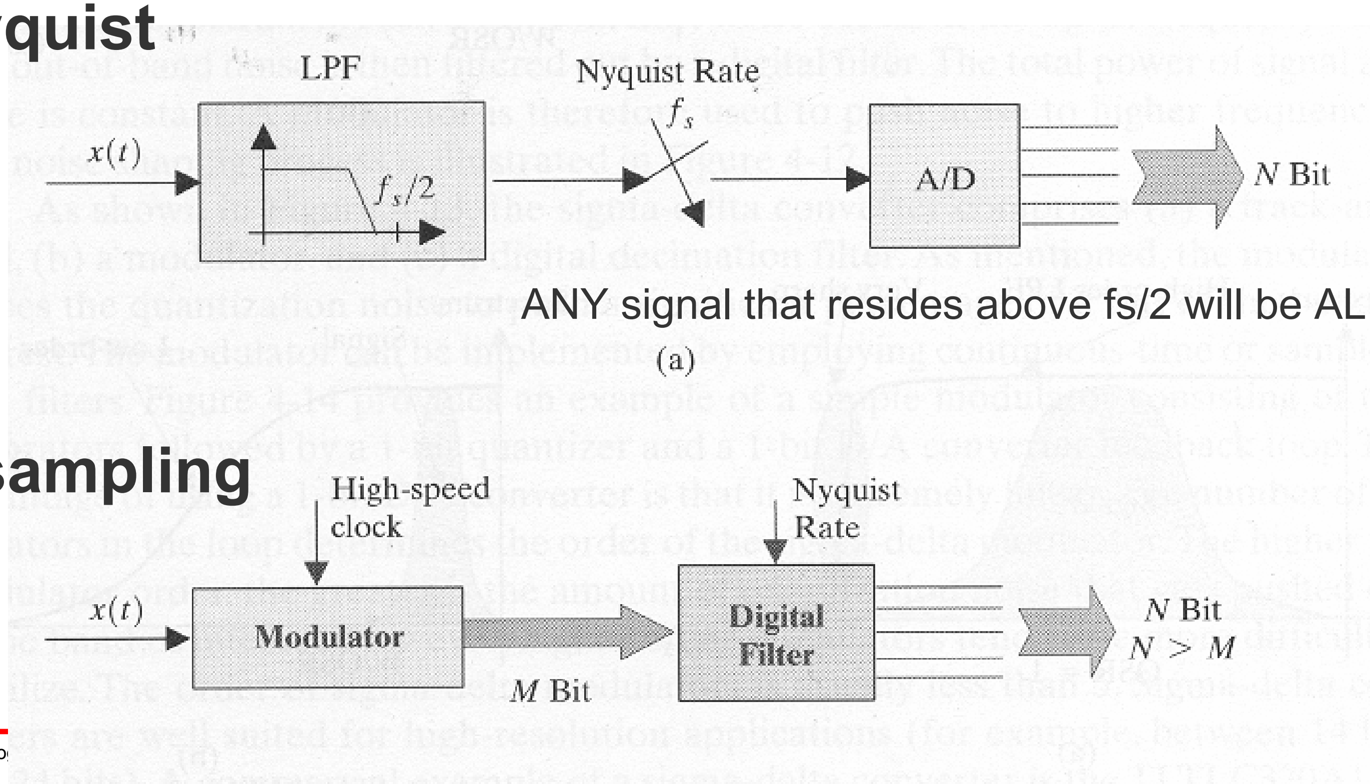
Nyquist vs. Oversampling

- Major advantage of oversampling ADCs is that they allow the specifications of the input anti-aliasing filter to be relaxed
  - → Lowers the implementation cost

Nyquist rate ADC = Sampler , Oversampling ADC = Averager

Nyquist

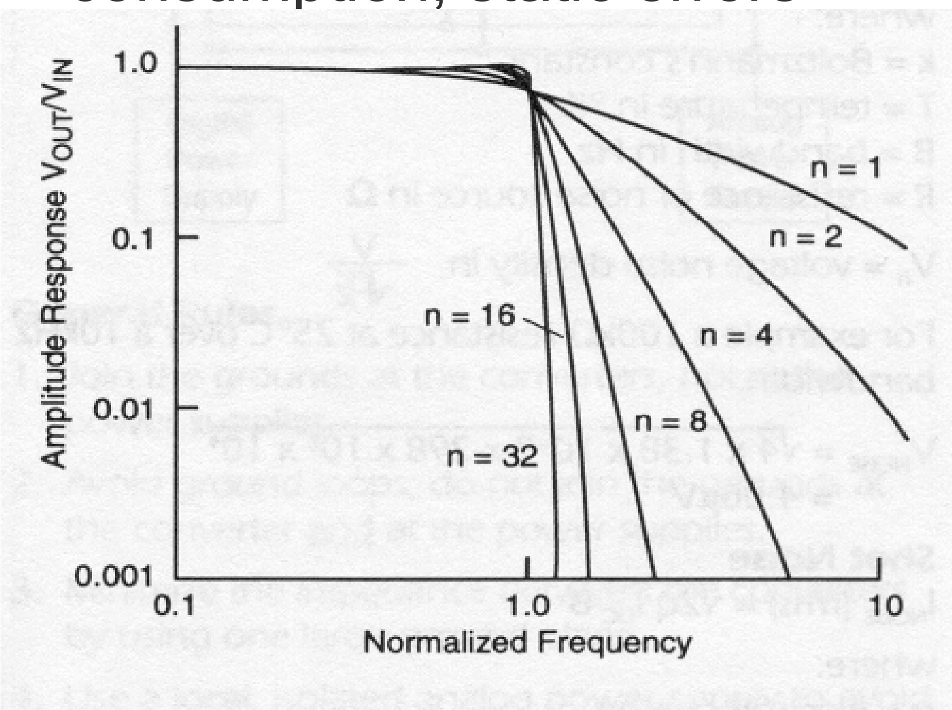
Oversampling

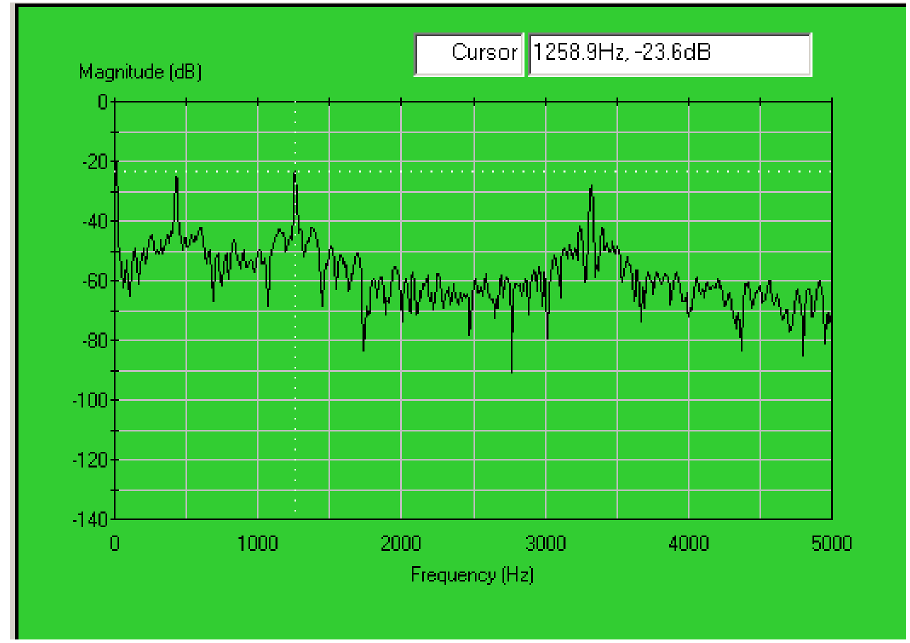


ANY signal that resides above fs/2 will be ALIASED

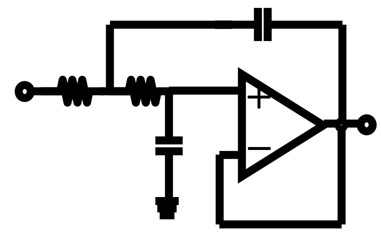
Active Analog Filters

- n = Filter order
- Higher Order gives Steeper Transition closer to brick wall
- Drawbacks : more expensive, more board space, power consumption, static errors

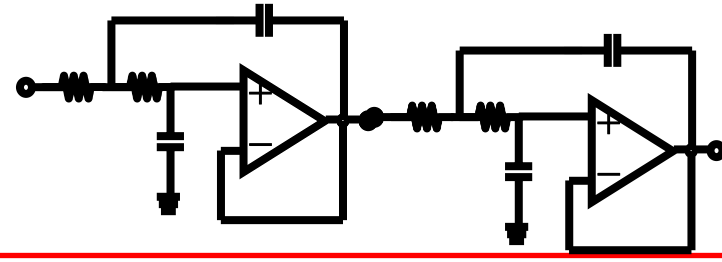




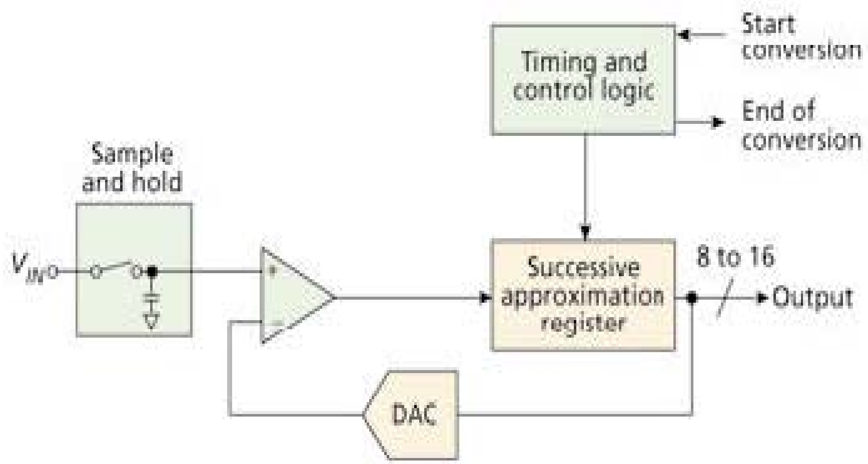
n = 2

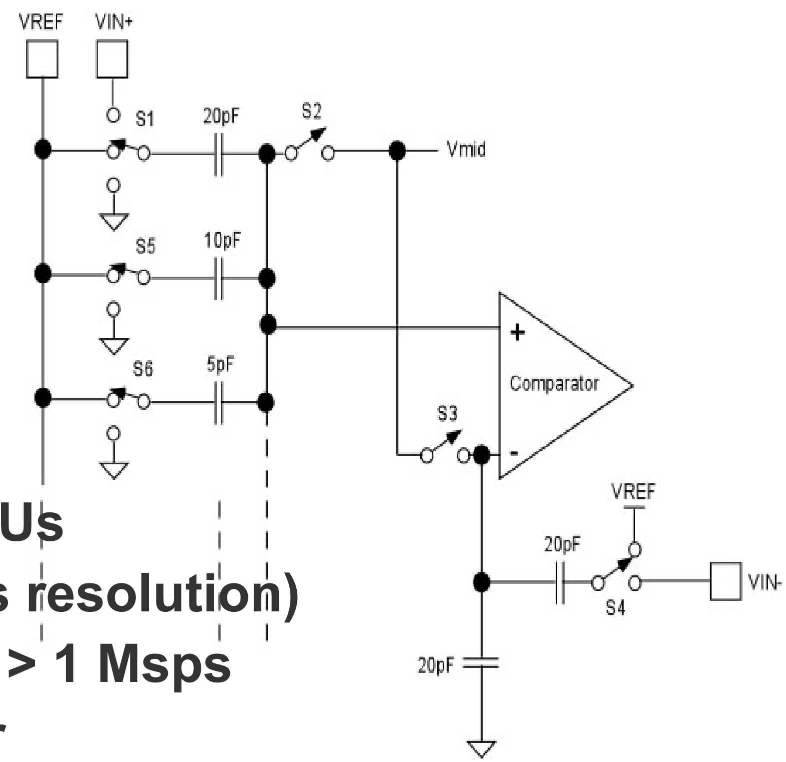


n = 4



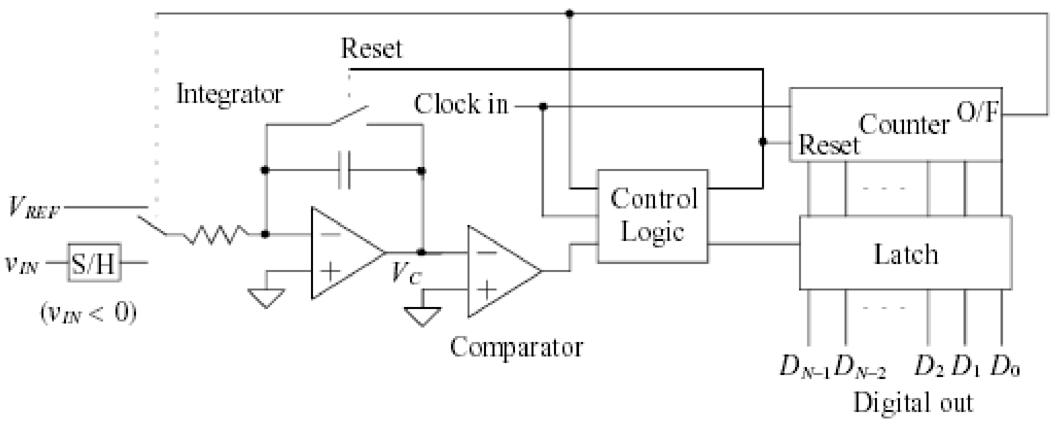
SAR ADC Architecture

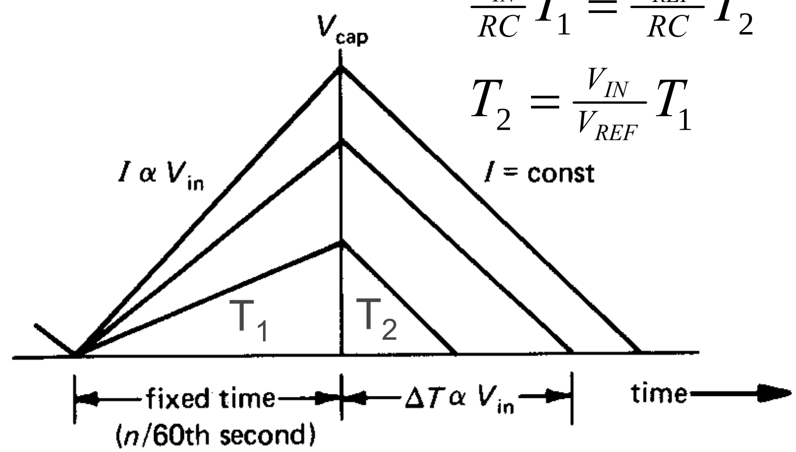




- Very prevalent, used inside many MCUs
- Prices are relatively low (Up to 16 bits resolution)
- Medium/high speed from <10 ksps to > 1 Msps
- Easy to multiplex, one-shot converter
- <u>Principal drawbacks</u>:
  - Stringent anti-aliasing filter is required at the input (Nyquist)
  - High resolution is expensive (mostly due to high-resolution DAC cost)
  - High linearity difficult to achieve (trimming)

Dual-Slope Architecture



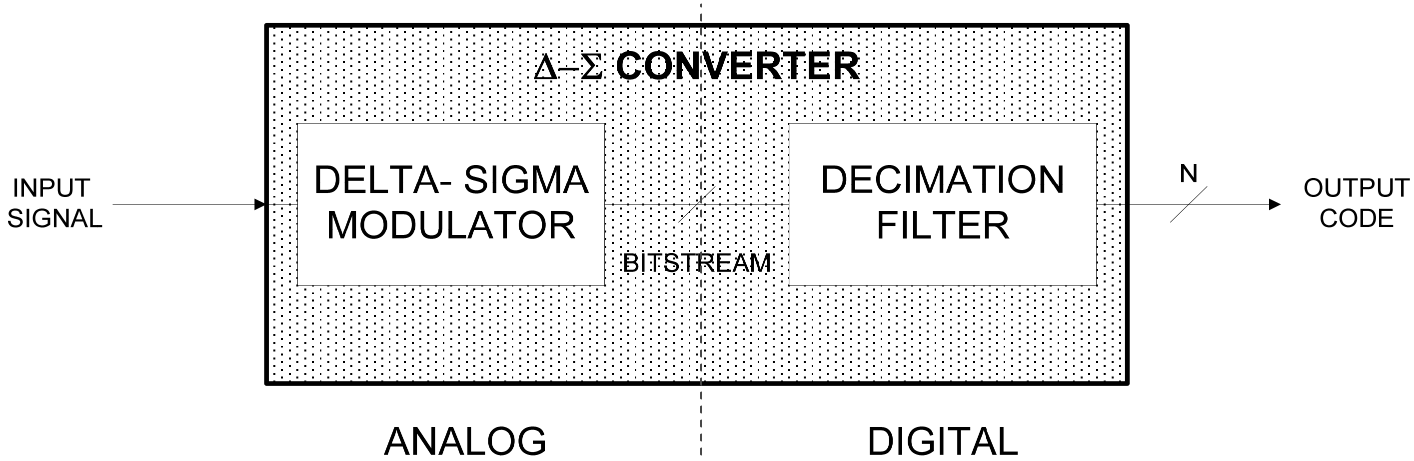


$$\frac{V_{IN}}{RC}T_1 = \frac{V_{REF}}{RC}T_2$$

$$T_2 = \frac{V_{IN}}{V_{REF}}T_1$$

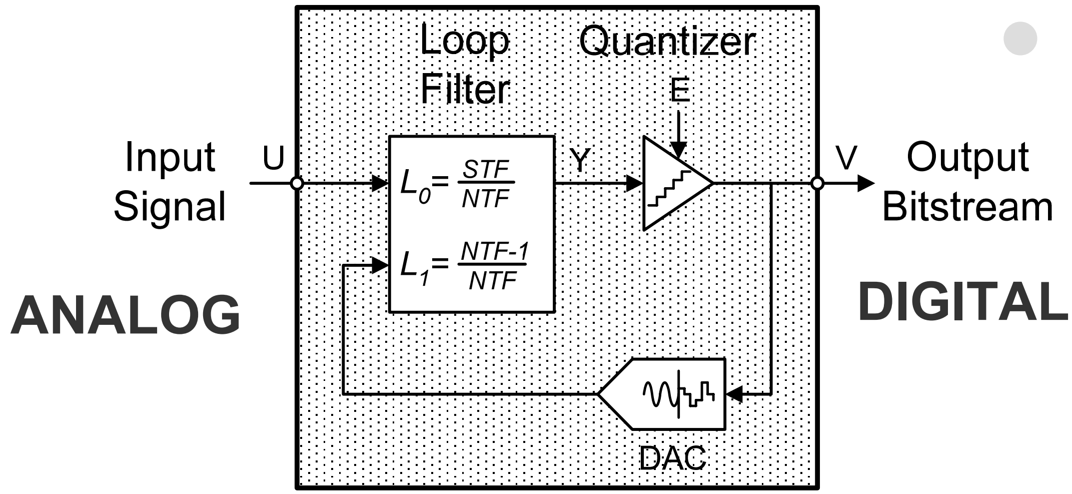
- **Standard high performance ADC … before Delta-Sigma**
- **High resolution up to 18-bit in CMOS(5½ digit DVMs)**
- **Small dependency on component tolerances**
- **Low output noise due to averaging**
- **High rejection of line frequencies**
- Principal drawbacks:
  - **Very low speed**
  - **External capacitors and resistors very often required**
  - **Comparator has to be as accurate as required precision**

The Delta-Sigma Architecture



- The modulator is an analog feedback loop which is sampling the input at a very fast rate **(oversampling rate >> Nyquist Rate)**
- It gives a very low resolution (usually 1-bit), very fast signal called **bitstream**, estimator of the input signal
- The bitstream contains **quantization noise** which is averaged out by the decimation filter to obtain a precise representation of the input
- The decimation filter processes the bitstream out of the modulator to obtain N-bit output codes at the Nyquist rate

The Delta-Sigma Modulator



- The modulator runs at the oversampling frequency f_s

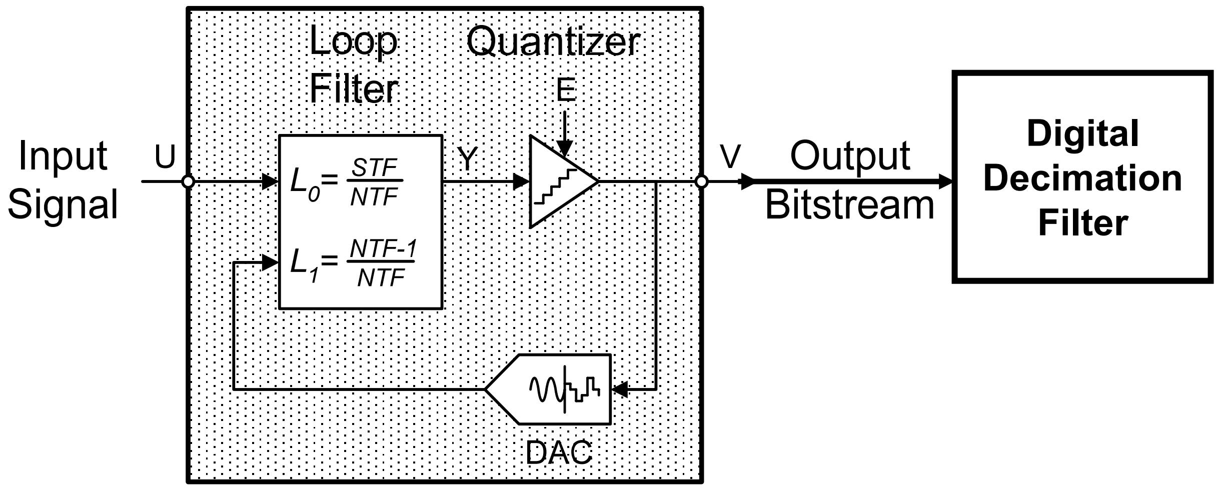
$$V(z) = STF(z)\,U(z) + NTF(z)\,E(z)$$

STF : Signal Transfer Function (V/U)

NTF : Noise Transfer Function (V/E)

- Modulation principle: **obtain a simple digital estimator of the incoming signal and reprocess it in the loop filter in order to minimize the error E introduced by the rough quantization**
- **STF ~ 1** in the signal bandwidth (Average in = Average out), **STF is a low pass filter**
- **NTF ~ 0** in the signal bandwidth to obtain good performance : Noise Shaping, **NTF is a high pass filter**
- The system is non-linear due to the presence of the quantizer
- The quantizer can be a simple comparator of a flash ADC
- The DAC can be either 1-bit (inherently linear) or multi-bit

Delta-Sigma ADC: A Washing Machine

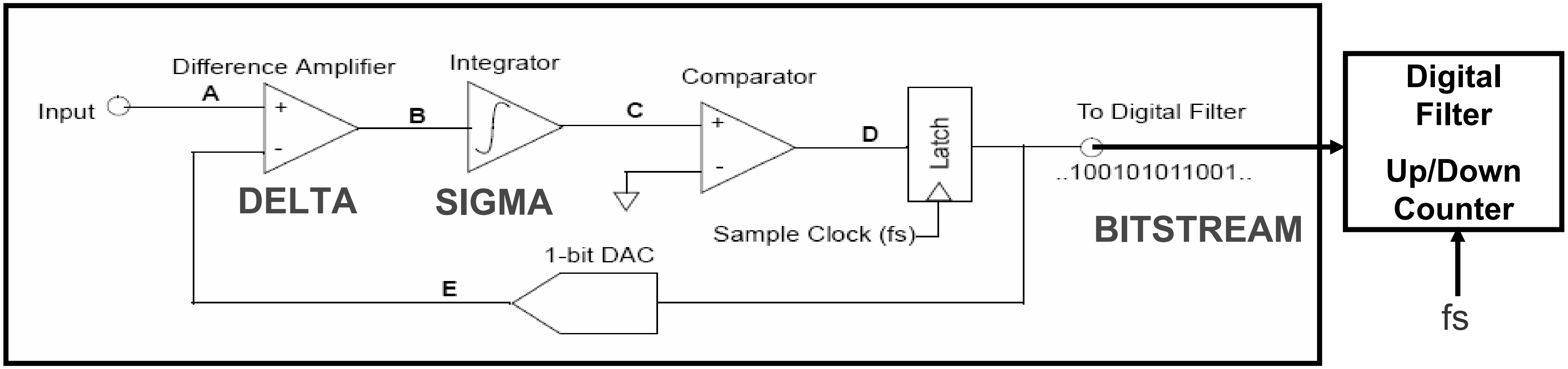


=

- E= Quantization Noise = detergent
- U= Input Signal = Clothes
- V= Output Bitstream = Clothes not dried
- Output Code= Dried Washed Clothes
- Over sampling Ratio = Number of rounds for drying
- Modulator = Washer
- Digital Filter = Dryer & Softener
- Conversion = Clothes Wash
- Modulator order = Temperature

- Faster OSR gives Faster conversion = Faster wash
- Higher order gives better results, higher OSR too
- Digital filter "softens" bit stream to give less rough data

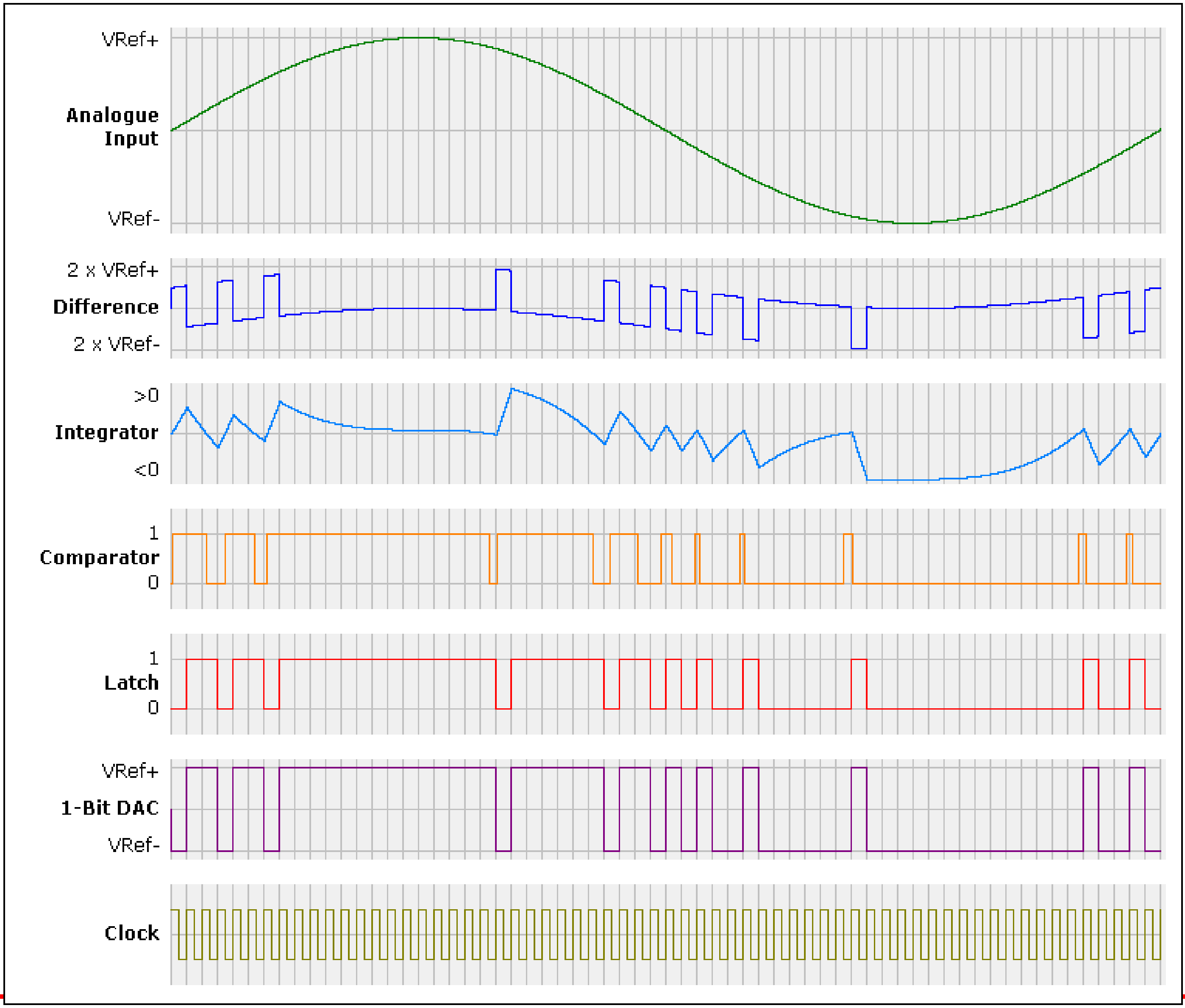
First Order Modulator Example (MCP3421)



- Made from simple building blocks (op amp, comparator, up-down counter for digital filter)
- After N steps, the integrator and the counter are reset (Incremental ADC)
- If |Vin|<Vref the loop is stable, no need for input scaling
- High resolution needs many samples per conversion

  (2^N samples for N bits)
- Fully differential structures and bipolar outputs improve resolution by 1 bit and noise figures by 6 dB

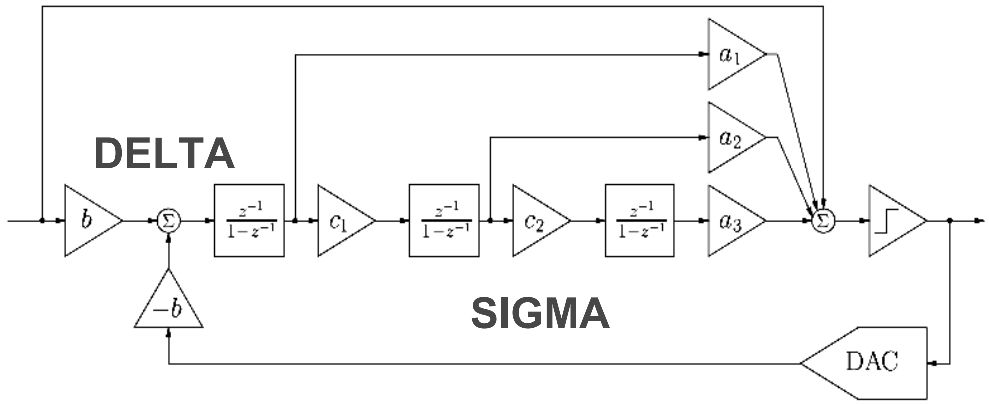
First Order Modulator Signals (MCP3421)



High Order Modulator Example (MCP355X)

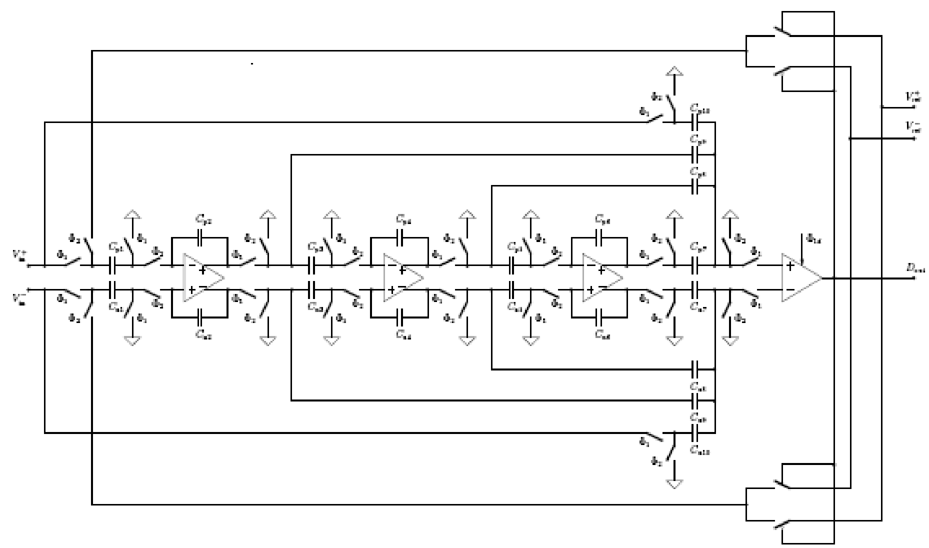
- 3rd order single-bit single-loop switched capacitors modulator using cascade of feed-forward integrators
- Transfer functions :

STF(z) = 1 → Low distortion

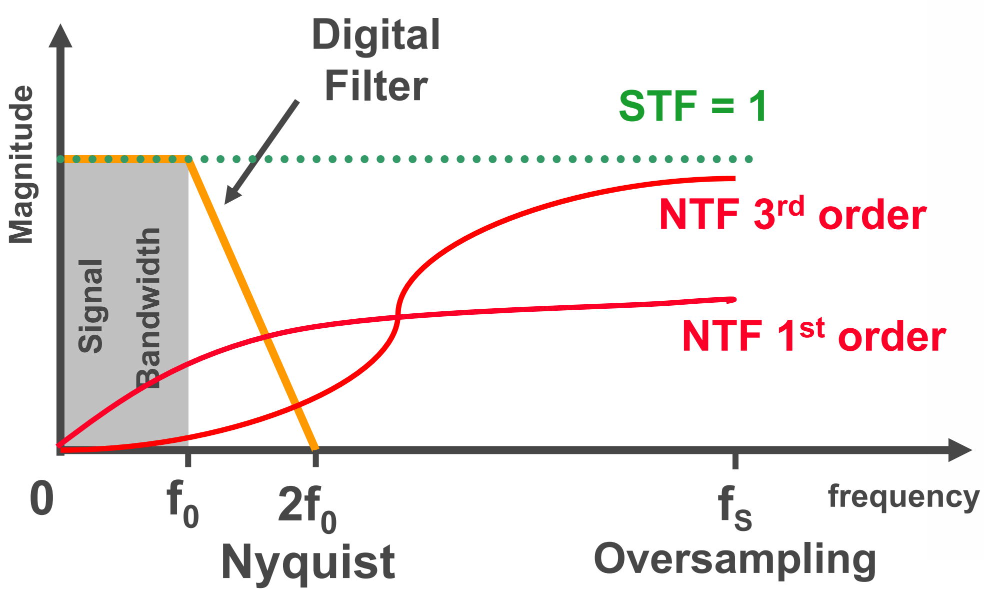


$$NTF(z) = \frac{(z-1)^3}{z^3 + (ba_1 - 3)z^2 + (bc_1a_2 - 2ba_1 + 3)z + bc_1c_2a_3 - bc_1a_2 + ba_1 - 1}$$

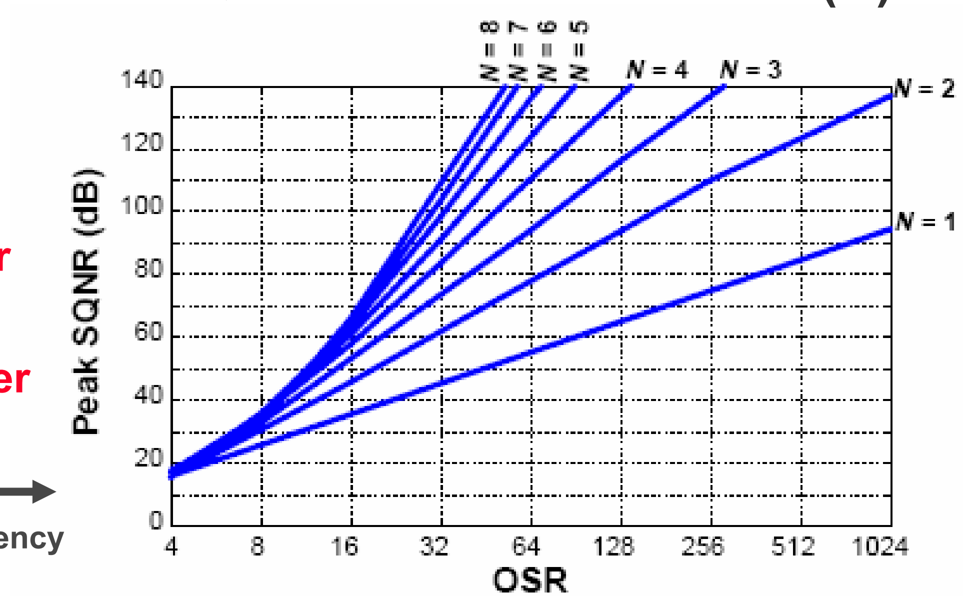
- **3 zeros located at z=1 (DC!) to cancel quantization noise in desired bandwidth**
- 1-bit DAC has inherent linearity → Low INL
- Coefs realized by capacitors ratio can be very precise
- Only first stage is crucial (high gain, low offset). Front-end needs great care (circuit, layout)



Over sampling & Noise Shaping

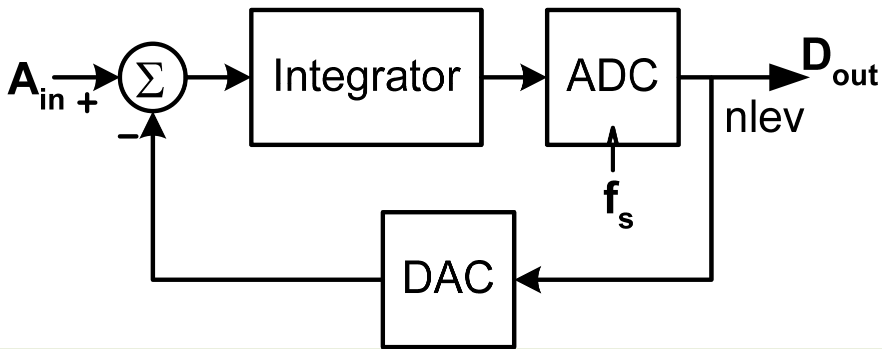


SNQRmax vs OSR vs order (N)



- **Noise shaping :** Quantization noise high pass filtering
- The **modulator order** is the number of integrators in the loop filter. It defines also the number of NTF zeros in the signal bandwidth thus the order of noise shaping
- **Over sampling ratio (OSR) :** Ratio between over sampling frequency and Nyquist frequency. It is the decimation rate of the digital filter
- The **SNQR** depends on modulator order and OSR

Multi-Bit Architecture : A New Trend



- Replacing the 1-Bit DAC by a multi-bit DAC improves :
  - Resolution by the number of bits in DAC
  - Stability of the loop thus dynamic range
  - Quantization noise figures are scaled down by the number of levels (nlev-1) in DAC
- But INL is impacted because DAC non-linearity error comes directly at front-end
- Problem: How to make the DAC linear enough? (>16 bits)
- Solution: Dynamic Element Matching, Multiple pulsing

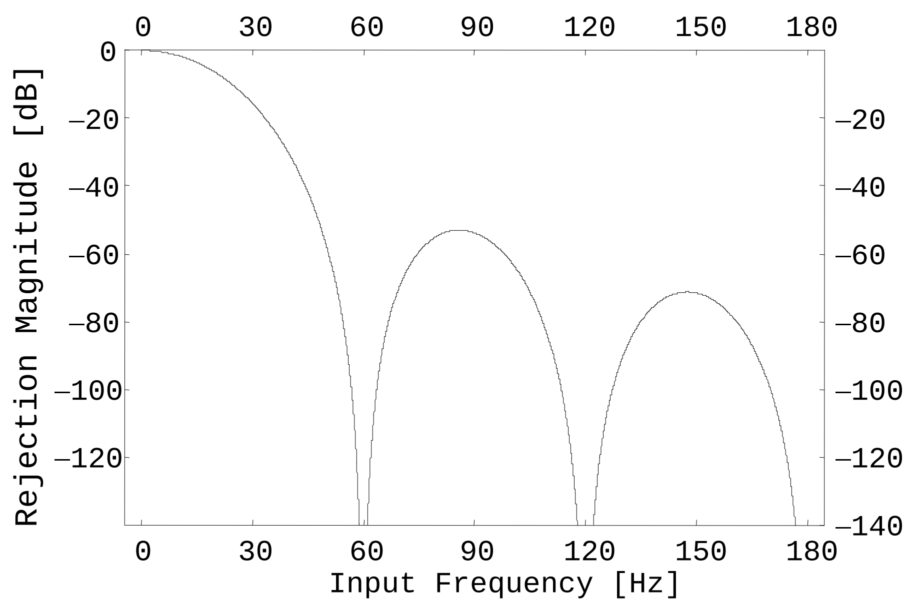
Digital Decimation Filter

- The SINC or comb filter is the most common … and the simplest to implement !
- It calculates a moving average of the bit stream and acts as a windowing function
- For a L-th order modulator, a L+1-th order filter is recommended because of quantization noise filtering issues
- Main notch frequency at $f=f_s/(OSR.(L+1))$ depends on internal oscillator accuracy

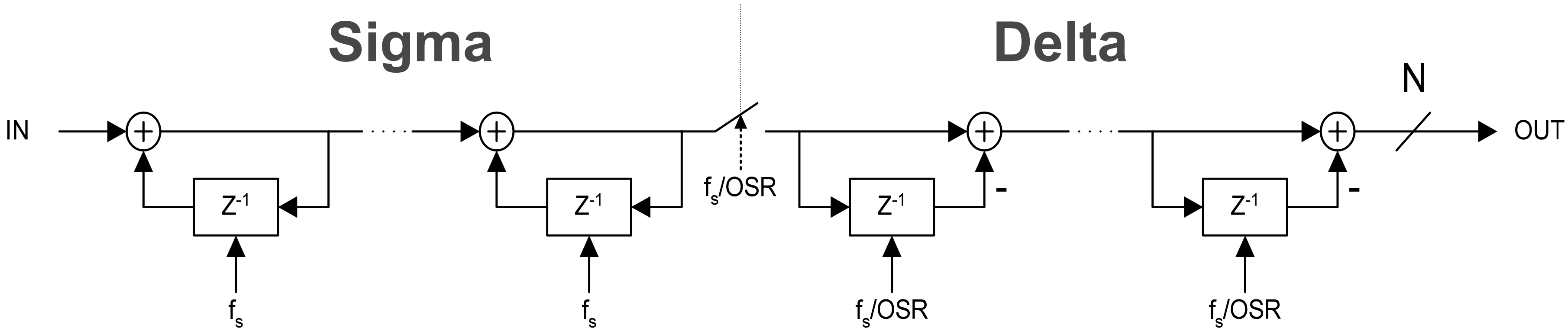
$$D(z)=\left(\frac{1+z^{-1}+z^{-2}+\ldots+z^{1-OSR}}{OSR}\right)^{L+1}$$

SINC filter transfer function

$$D(z)=\frac{1}{\mathrm{OSR}^{L+1}}\left(\frac{1-z^{-OSR}}{1-z^{-1}}\right)^{L+1}$$



Digital Filter Implementation



- Hogenauer structure, scalable and easy to implement
- Series of integrators (sigma) followed by a down-sample and by a series of differentiators (delta)
- Sigma operations are OSR times faster than delta ones
- Inputs can be 1-bit or multi-bit bit streams
- Use of 2's complement arithmetic to avoid saturation
- Desired resolution sets filter registers length
- Other transfer functions and structures exist based on the same philosophy

Benefits of ΔΣ modulation

- High resolution achievable (20+ bits <1μV LSB)
- High linearity if 1-bit DAC is used
- Excellent line frequency and noise rejection
- Analog process requirements are minimized
- Anti-aliasing filter and overall signal conditioning requirements are minimized
- Filtering is done in the digital section → low power consumption
- Easy to multiplex, limited memory
- Applications: Wide dynamic range, low frequency

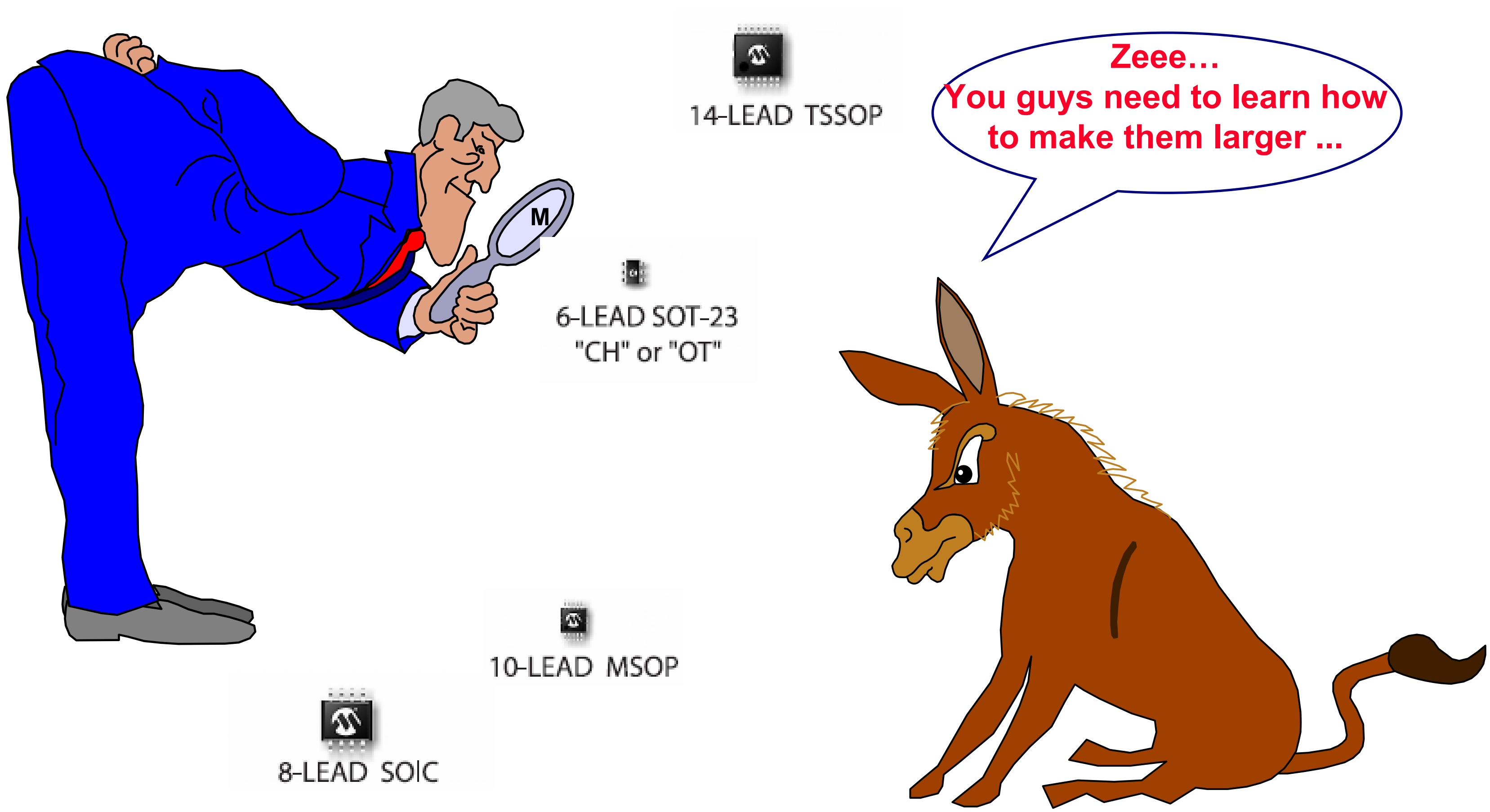
Questions?

Mr. Curiousway> **What's so good about delta-sigma ADC ?**

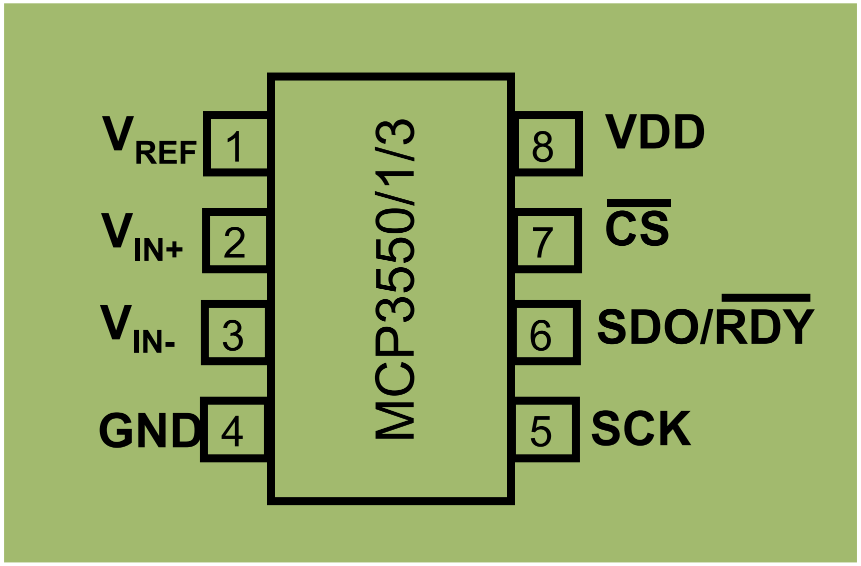
Mr. Franchborn> **Oh, there are many highlights ....**

Section 3
Microchip's ΔΣ ADC Devices

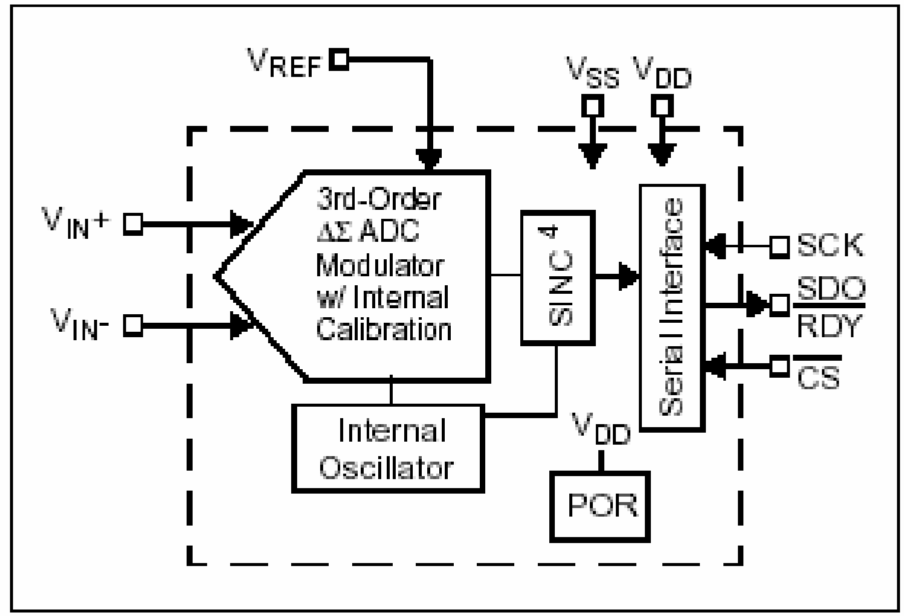
Let's see … What are the MCP3421 …. MCP355x ?



MCP3550/1/3 Delta Sigma ADCs



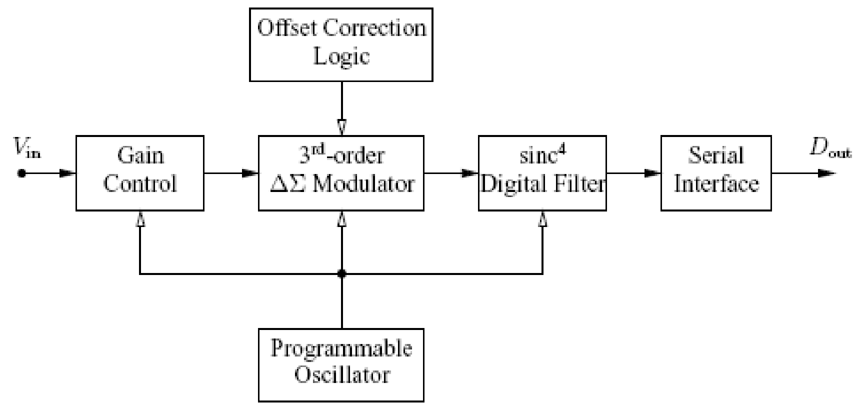
Block Diagram

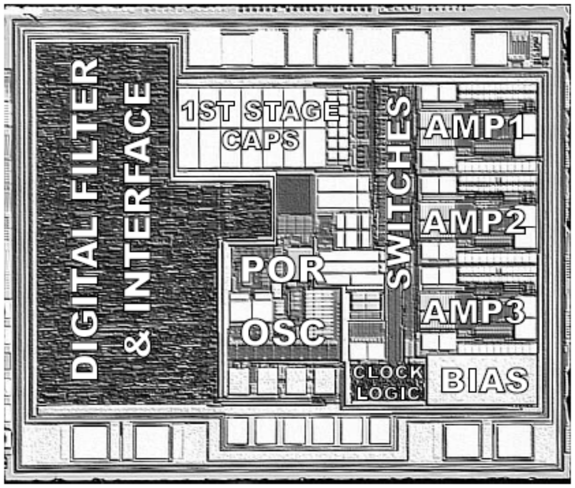


DEVICE	OUTPUT DATA RATE	ENOB RMS with Vref=5V	50/60 Hz Rejection
MCP3550-50	12.5 SPS	21.9 bits	-120dB @ 50Hz
MCP3550-60	15 SPS	21.9 bits	-120 dB @ 60Hz
MCP3551	13.75 SPS	21.9 bits	-85dB from 47 to 63 Hz
MCP3553	60 SPS	20.6 bits	N/A

MCP355X Architecture

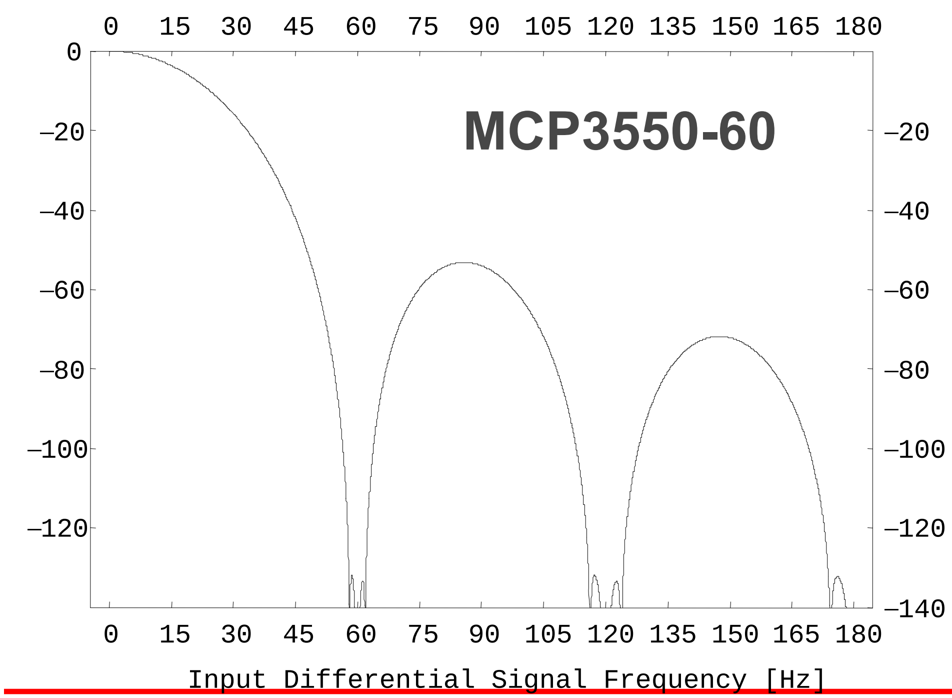
- 3rd order modulator with 1-bit DAC (OSR=512 for MCP3550/1, OSR=128 for MCP3553)
- Auto-calibration for offset and gain errors
- Modified 4th order SINC filter for extended 50/60Hz rejection
- Low-tempco, low drift internal oscillator
- VDD Monitoring (POR @ 2V)
- 3-wire SPI interface
- 8-pin MSOP package

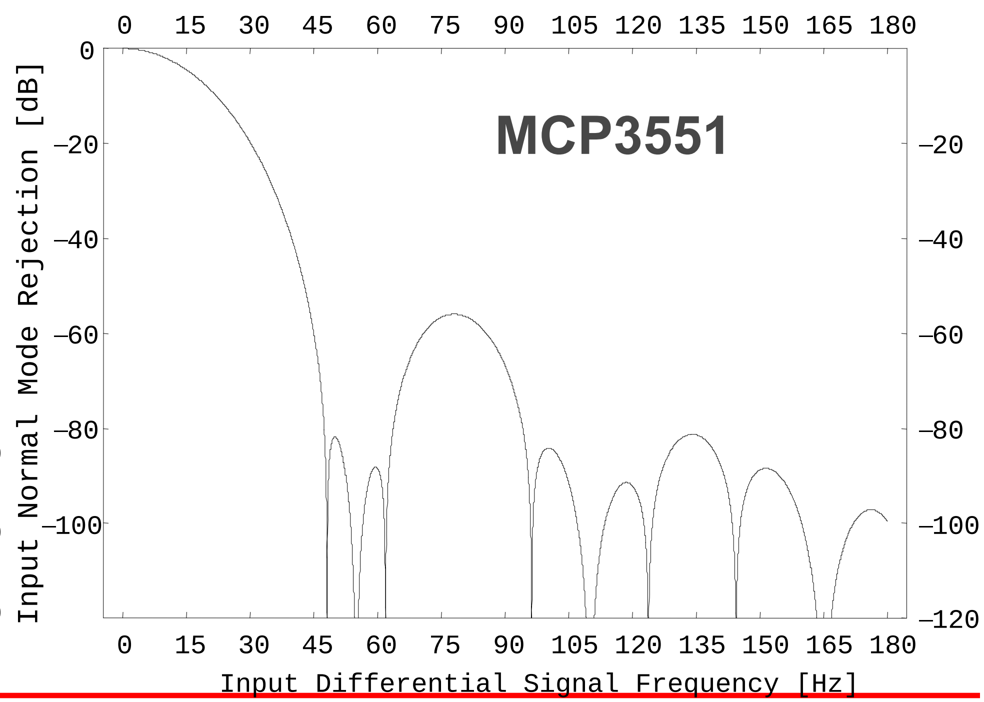




MCP355X Decimation Filter

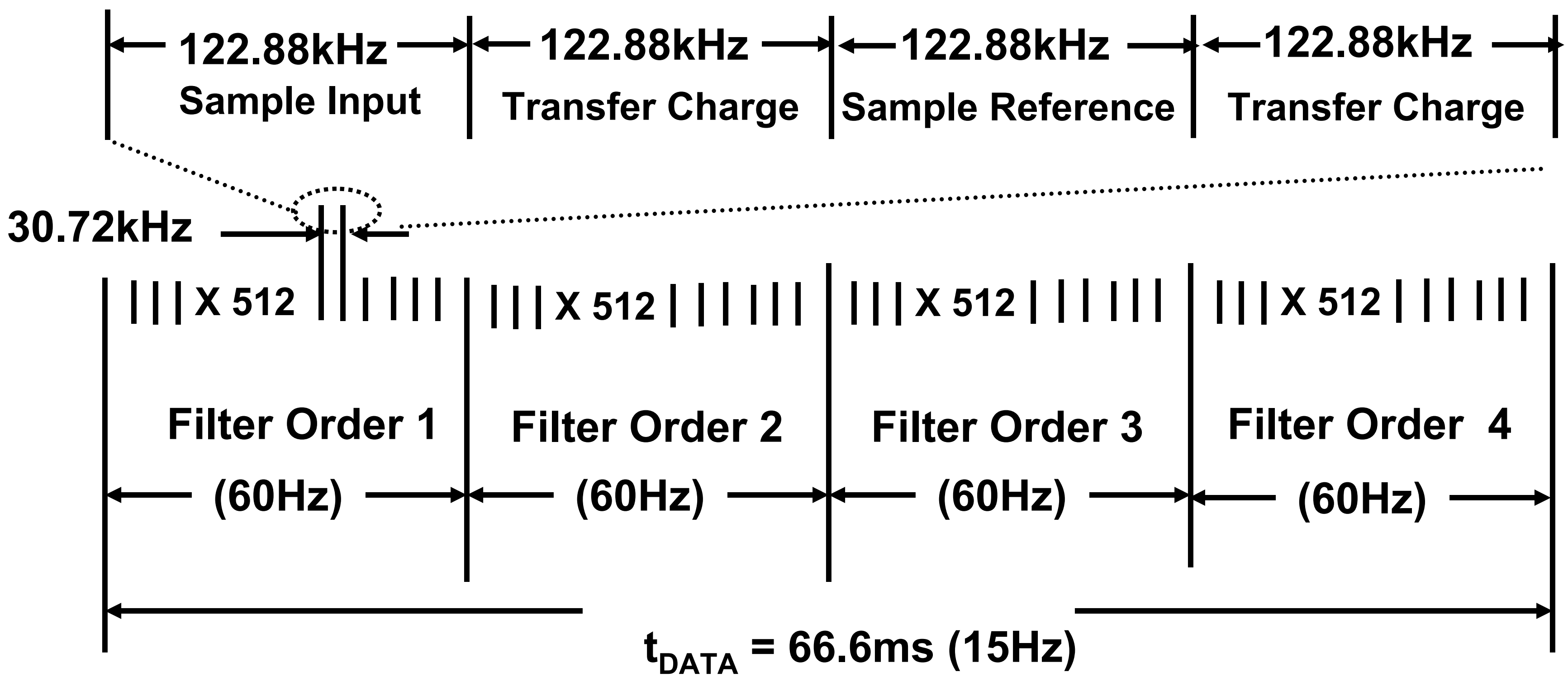
- 4-th order modified SINC filter with staggered zeros for wider notches → Less constraints on notch centering
- MCP3551 : >80dB rejection from 49 to 61 Hz. Reduce inventory cost for different markets (USA, Europe, Asia)
- MCP3550-50/60 : >120dB rejection around chosen frequency (50 or 60 Hz ±2%)





MCP355X Internal Timings

- 3^{RD} Order Modulator, 4^{th} Order SINC Filter
- SINC filter zero is at 60Hz (50Hz)
- Sampling Frequency at Input is 30.72 kHz (25.6kHz) ← ***
- Switching Frequency at Input is 122.88 kHz (102.4kHz) ← ***
- Overall Data Rate at output is 15Hz (12.5Hz)



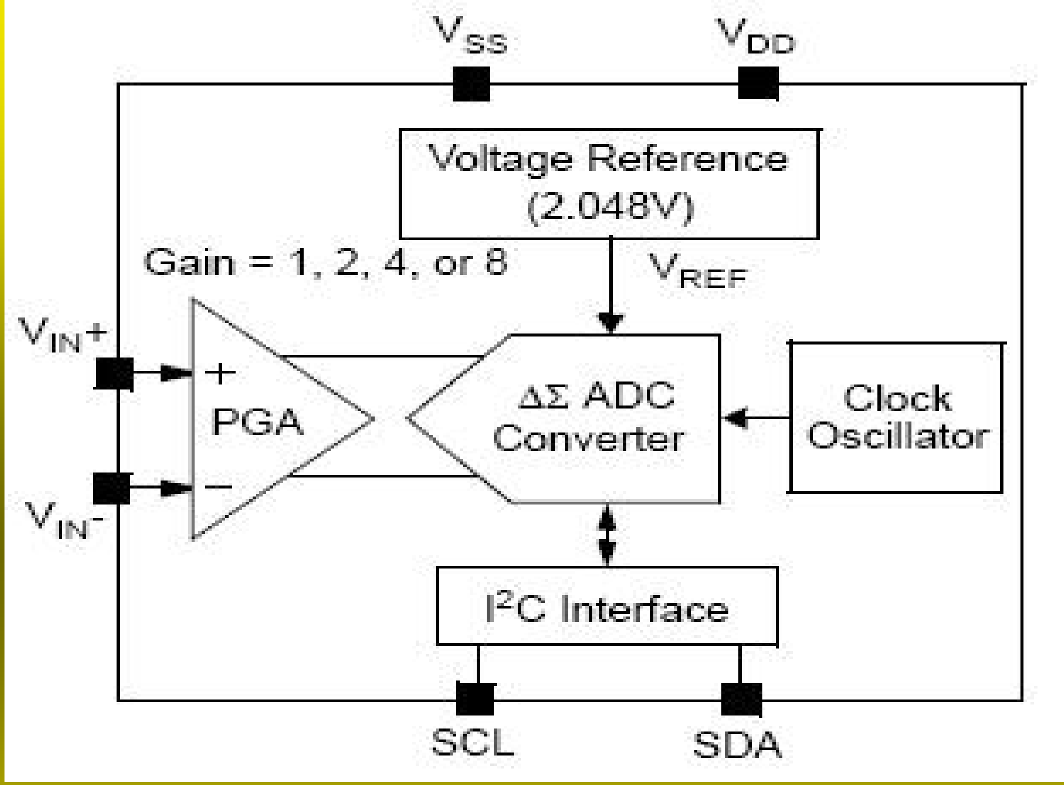
MCP355X Calibrations

- MCP355X auto-calibration for offset and gain errors is processed real-time (no delay, no internal disconnection of inputs)
- "On-the-fly" calibrations permit faster data rate and open the way to continuous operation without calibration phase

- **Offset Calibration: "Fractal algorithm"**
- Generalization of chopper algorithm
- Principle: switch back and forth in a special way with adapted switch-cap circuit to cancel integrators offset

- **Gain Calibration: "Rotating Caps"**
- Dynamic Element Matching and scaling of the input caps
- Principle: DEM principle averages caps matching error and cancels gain error

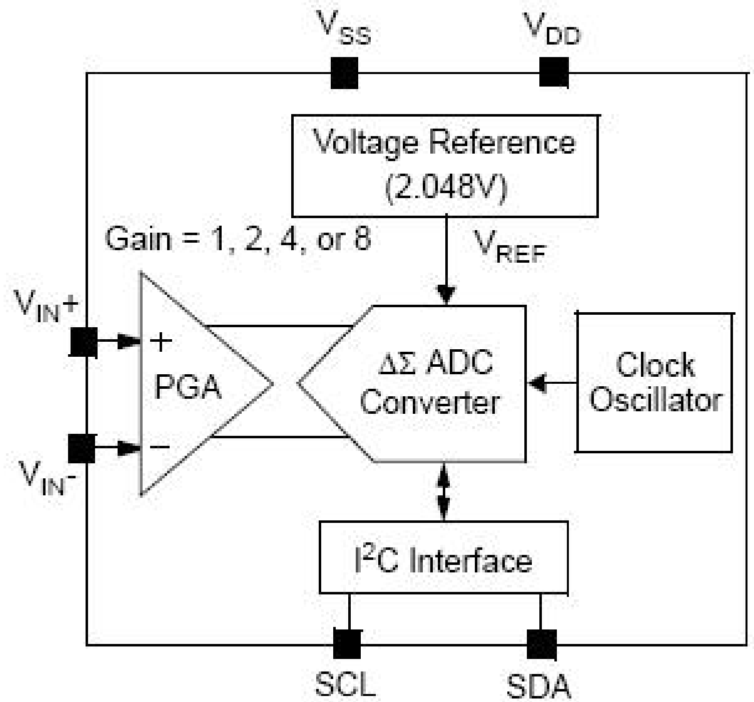
New Delta-Sigma ADC: MCP3421

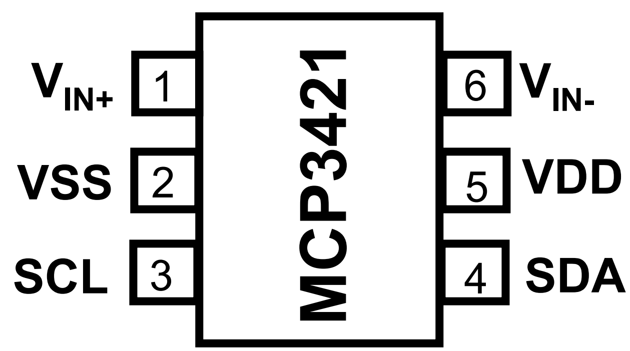


18-bit, Low-Power
Analog-to-Digital (A/D) Converter
in 6-pin SOT-23 Package

MCP3421 Architecture

- 1st order modulator with Multi-Bit 5-Level DAC, 1st order SINC filter
- Programmable OSR/Resolution
- Internal Bandgap Voltage Precision Reference (2.048V) with very low tempco
- Multi-Bit linear DAC and Chopper Vref
- 2-wire I²C™ hi-speed 3.4 MHz interface
- VDD Monitoring (POR @ 2V)
- 6-pin SOT23 package





MCP3421: 18-bit, SOT-23 ΔΣ A/D Converter

- 12/14/16/18-bit resolution
- 3.75 to 240 sps sampling speed
- On-board Precision Chopper Vref (2.048V)
- On-board PGA (1:8)
- On-board oscillator
- Extended temperature range: -40°C to +125°C
- Wide VDD Range : 2.7V to 5.5V
- I^2C™ serial interface:
  (normal, fast and high-speed 3.4 MHz modes)

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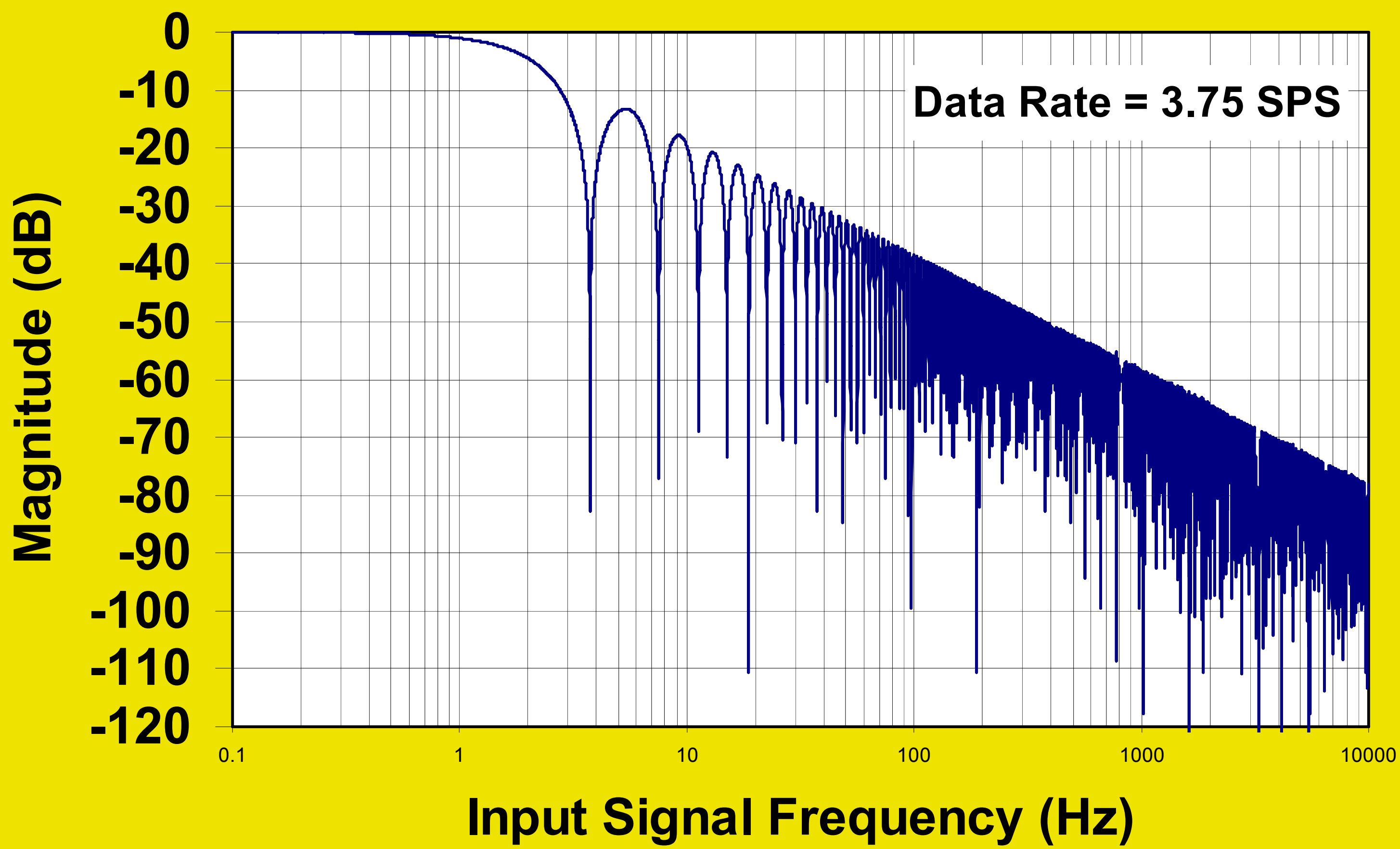
MCP3421 Key Specifications

- 6-lead SOT-23 (world's highest resolution ADC in SOT-23)
- 155 µA continuous conversion current
  - <0.5 µA one-shot conversion current
- Output noise 1.5 μV_{RMS} <<1LSB@18 bits (V_{in}=0V)
- INL 10 ppm typ. of FSR
- Gain Error 0.05% typ. including Vref and ADC error
- 15 µV typ. Offset (~1 LSB@18 bits)
- Excellent CMRR (105 dB) and PSRR (100 dB)
- Low Tempcos (offset:50 nV/°C, gain:5 ppm/°C)
- No latency (pipeline delay, conversion latency)

MCP3421 SINC Filter



- 1st notch at 3.75/15/60/240 Hz depending on 18/16/14/12 bit resolution
- Beware of Oscillator frequency large range (not trimmed, not enough room!)

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What's in MCP3421 ?

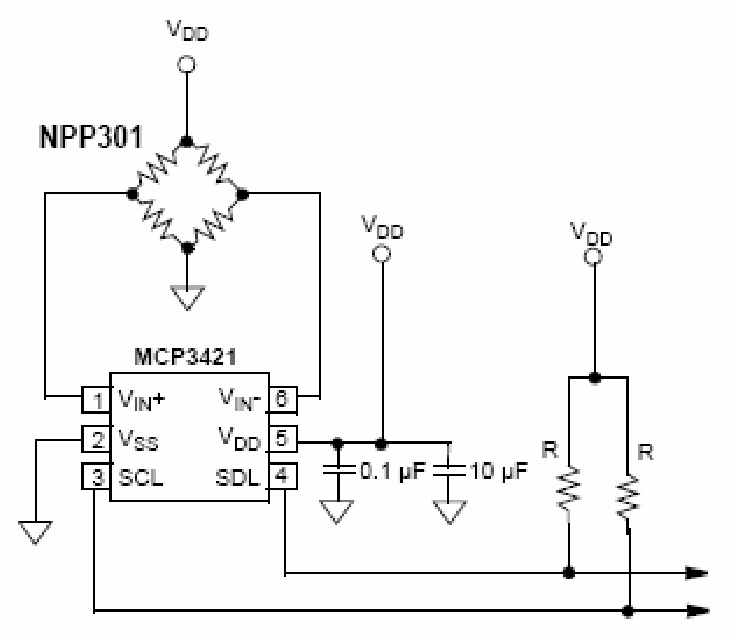
- MCP3421 incorporates two new algorithms in order to improve resolution and output noise

- **5-Level Linear Multi-Bit DAC**
- Replaces 1-bit DAC and improves by 2 bits the resolution
- Principle: Multiple charge transfer using same Vref capacitance
- Inherently linear because using same capacitance

- **Bit stream Dependent Chopper algorithm for Vref**
- Chopper synchronous with sampling frequency
- Principle: Adapts chopper frequency to bit stream for improved offset and 1/f noise reduction (10x less 1/f noise compared to std)

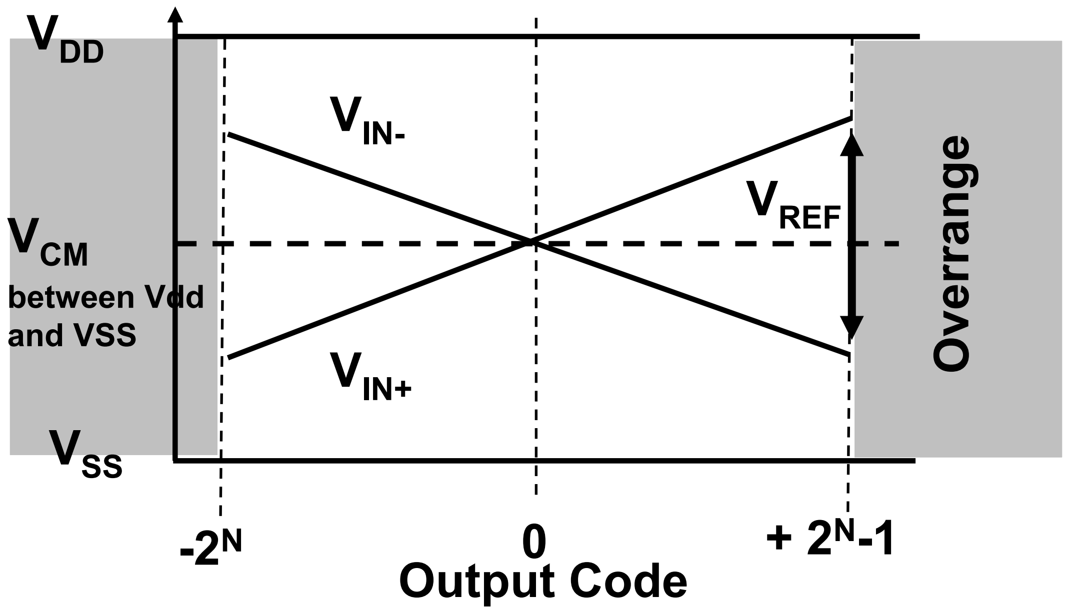
MCP3421 Target Application List

- Bridge sensing for pressure, strain, and force
- Temperature sensing with RTD, thermistor or thermocouple
- Weigh scales
- Instrumentation
- Data acquisition
- 6-digit DVMs
- Sensor interface
- Strain-gauge transducers
- Industrial process control



Pressure Measurement

Overranging, Code Locking



- V_{IN+}, V_{IN-}, V_{REF} , V_{CM} between V_{SS} - 0.3V and V_{DD} + 0.3V to avoid ESD diode turn-on
- $VCM=(V_{IN+} + V_{IN-})/2$
- $VIN= V_{IN+} - V_{IN-}$

- **MCP355X: Overranging**
- If $|V_{IN}|$ >Vref, OVH or OVL bits = 1 (data becomes 23 bits long)
- Codes roll over, continue to get accurate data, MCP355X is operational up to 12% past V_{REF}
- **MCP3421: Code Locking**
- If $|V_{IN}|$ >Vref, Code is locked to maximum : $+2^N-1$ or -2^N depending on sign and resolution (N bits mode)

Power Consumption Efficiency

$$ADC\ Efficiency = \frac{Power}{2^{ENOB} \times f_{OUT}}$$

- The ADC efficiency **is a figure of merit in order to compare different ADCs Power consumption**
- It corresponds to **the energy needed to achieve the effective resolution at a certain data rate. The units are in pJ/Effective bit of data.** An efficient ADC has thermal noise and quantization noise on the same order of magnitude
- Microchip is one of the leaders in ADC efficiency **compared to similar ADC manufacturers (MCP355X, MCP3421)**
- **MCP3551 ADC Efficiency = 13 pJ/EB** @VDD=5V
- **MCP3421 ADC Efficiency = 7.5 pJ/EB** @VDD=5V, this counts also the Vref consumption !!!

MCP3421 Competition

*Note: Prices are not official numbers.

Part Number	Max Res (bits)	Speed (sps)	Current max (uA)	Noise (uV RMS)	INLmax (ppm)	Vref	Price	PKG
MCP3421	18/16	3.75/15	190	1.5	35	Int 2.048V	$1.75	SOT23-6
ADS1110	16	15	350	3.1	100	Int 2.048V	$1.75	SOT23-6
ADS1100	16	8	150	0.7	125	VDD	$1.95	SOT23-6
AD7788	16	16.6 (2x latency)	80	1.5	50	Diff. Ext	$1.99	MSOP-10
AD7790	16	9.5	80/140 (buffer)	1.1	15	Diff. Ext	$2.96	MSOP-10
LTC2481	16	6.2	250	0.84	10 (Vref)	Diff. Ext	$1.85	DFN-10
LTC2483	16	6.8	250	0.6	10 (Vref)	Diff. Ext	$1.65	DFN-10
LTC2433	16	6.8	300	1.45	20	Diff. Ext	$1.95	MSOP-10
MAX1409	16	60	1090 (periph.)	8	53	Int or Diff. Ext	$5.85	SSOP-20
MAX1368	20	5	960 (LCD)	1.5	Not spec.	Int or Diff. Ext	$7.98	TQFP-48
LTC2430	20	6.2	300	2.8	20 (Vref)	Diff. Ext	$4.45	MSOP-10
LTC2431	20	6.2	300	2.8	20 (Vref)	Diff. Ext	$4.55	SSOP-16
LTC2435	20	12.5	300	4	20 (Vref)	Diff. Ext	$3.55	SSOP-16

MCP3421 Available Resource

- MCP3421 Datasheet (DS22003b) in English, Chinese, and Japanese
- Battery Fuel Gauge Demo Board
- MCP3421 Mini-Demo Board (I^2C™ Interface)
- Many Application Notes, publications, and Eval boards are coming soon
- Samples available online
- www.microchipdirect.com
  - Devices available

Bibliography on MPC355X

- **Datasheet : MCP3550/1/3 (DS21950) in English and Chinese**
- **Dev Tools**
  - MCP3551 Delta-Sigma ADC Demo Board
  - MCP355X Sensor Application Developer's Board
  - MCP355X Tiny Application Sensor Demo Board
- **User Guides**
  - MCP3551 22-Bit Delta-Sigma ADC PICtail Demo Board User's Guide (English and Japanese)
  - MCP355X Sensor Application Developer's Board User's Guide
  - MCP355X Tiny Application Sensor Demo Board User's Guide
  - Mixed Signal PICtail Demo Board User's Guide
- **Application Notes**
  - AN1007 - Designing with the MCP3551 Delta-Sigma ADC (English and Japanese)
  - AN1030 - Weigh Scale Applications for the MCP3551 - Weigh Scale Applications for the MCP3551
  - MCP3551 App Note Source Code
- **Scientific articles and conferences**

  - V. Quiquempoix, P. Deval, A. Barreto, G. Bellini, J. Markus, J. Silva,and G. C. Temes, “A Low-Power 22-bit Incremental ADC with 4 ppm INL, 2 ppm Gain Error and 2 µV DC Offset”, IEEE ESSCIRC’05 Conference (Sept 2005)
  - V. Quiquempoix, P. Deval, A. Barreto, G. Bellini, J. Markus, J. Silva,and G. C. Temes, “A low-power 22-bit incremental ADC,” IEEE Journal of Solid-State Circuits (Invited Paper), vol. 41, no. 7, p. N/A, July 2006, in press.
  - Janos Markus, Philippe Deval, Vincent Quiquempoix, Jose Silva and Gabor C. Temes,” Incremental Delta-Sigma Structures for DC Measurement: an Overview”, IEEE CICC Conference 2006 (Invited Paper)

MCP3421 Part Numbering

I^2C™ Address

Package:
OT = 6-lead SOT-23

Part Type (MCP3421):

MCP3421A0T-E/OT

T&R

MCP: Microchip Peripheral

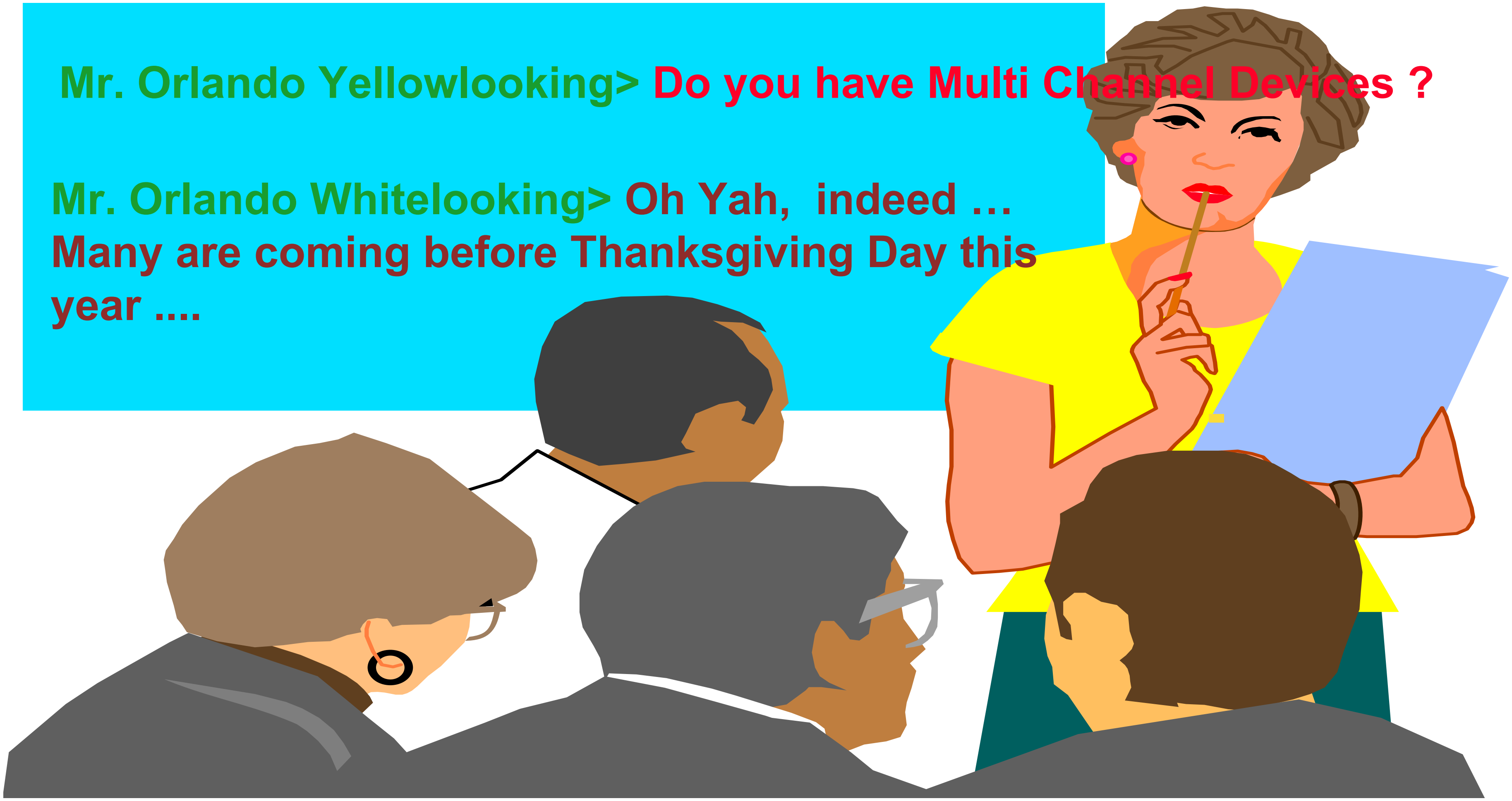
Temp:
E = - 40°C to + 125°C

These packages are Lead-free!

Questions?

Mr. Orlando Yellowlooking> Do you have Multi Channel Devices ?

Mr. Orlando Whitelooking> Oh Yah, indeed … Many are coming before Thanksgiving Day this year ....



MCP342X Teaser

- Multi-Channel Versions of the MCP3421 to come soon !!

DEVICE	CHANNELS	I2C ADDRESS	PACKAGE
MCP3421	1 Diff.	Program at factory	SOT23 6 pin
MCP3422	2 Diff.	Program at factory	SOIC, MSOP, DFN 8 pin
MCP3423	2 Diff.	2 select pins 8 addresses	MSOP, DFN 10 pin
MCP3424	4 Diff.	2 select pins 8 addresses	SOIC,TSSOP 14 pin

- MCP3424 Samples Available Now !!

MICROCHIP **MCP3424 PRODUCT BRIEF**

Four Channel 18-bit ΔΣ A/D Converter with I^{2}C Interface

FEATURES

- Four ADC Input Channels
- Differential Inputs (Vin+, Vin-)
- On-board Voltage Reference:
  - Accuracy: 2.048 V +/- 0.05%
  - Drift: 5 ppm/C
- Programmable Gain Amplifier (PGA):
  - Gain Selection: 1, 2, 4 or 8
- Selectable Resolution with no Missing Code:
  - 18 bits: Sample Rate = 3.75 SPS
  - 16 bits: Sample Rate = 15 SPS
  - 14 bits: Sample Rate = 60 SPS
  - 12 bits: Sample Rate = 240 SPS
- INL: 10 ppm of FSR (FSR = 4.096/PGA)
- One-Shot or Continuous Conversion Option
- Auto-Calibration of Internal Offset and Gain per Each Conversion
- On-board Oscillator
- I^{2}C™ Interface:
  - Eight Available Addresses
  - Two Address Selection Pins (A0, A1)
  - Standard, Fast and High Speed Modes
- Single Supply Operation: 2.7V to 5.5V
- Low Current Consumption
- Extended Temperature Ranges: -40C to 125C

APPLICATIONS

- Temperature Sensing with RTD, Thermistor, and Thermocouple
- Bridge Sensing for Pressure, Strain, and Force
- Portable Instrumentation
- Factory Automation Equipment
- Consumer Goods

DESCRIPTION

The MCP3424 is a family of high performing MCP342x delta-sigma devices from the Microchip Technology Inc. The MCP3424 is a four channel low noise, high accuracy ΔΣ A/D converter with differential inputs and up to 18 bits of resolution. The on-board 2.048V reference voltage enables an input range of ± 2.048 V differentially (Δ voltage = 4.096V).

The device can perform analog-to-digital conversion at rates of 3.75, 15, 60, or 240 samples per second depending on the user controllable configuration bit settings using the two-wire I^{2}C serial interface. During each conversion, the device calibrates offset and gain errors automatically. This provides accurate conversion results from conversion to conversion over variations in temperature and power supply fluctuation.

The user can select the PGA gain of x1, x2, x4, or x8 before the analog-to-digital conversion takes place. This allows the MCP3424 device to convert a smaller input signal with high resolution.

The MCP3424 device has two conversion modes: (a) One-Shot Conversion mode and (b) Continuous Conversion mode. In One-Shot conversion mode, the device enters a low current standby mode automatically after one conversion. This reduces current consumption greatly during idle periods. In continuous conversion mode, the conversion takes place continuously at the set conversion speed. The device updates its output buffer with the most recent conversion data.

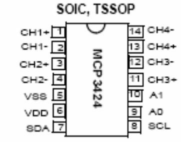
The device has two address selection pins (A0 and A1). The user can select the two address bits (A0, A1) by connecting these pins to a logic level (i.e., tie to V_{DD}, V_{SS}, etc.).

The MCP3424 operates from a single 2.7V to 5.5V power supply and has a two-wire I^{2}C compatible serial interface for a standard (100 kHz), fast (400 kHz), or high speed (3.4 MHz) mode.

The MCP3424 is available in 14-pin SOIC and TSSOP packages.

PACKAGES

SOIC, TSSOP



SOIC: Narrow-150 mil body, TSSOP: 4.4 mm body

THIS DOCUMENT IS UNCONTROLLED UNLESS OTHERWISE STAMPED. It is the users responsibility to ensure this is the latest revision prior to using or referencing this document.	Page	SPEC. NO.	REV.
2002/02/26 Microchip Technology, Inc.	1 of 2	Preliminary	A

Questions?

Mr. C. VeryCheap> What is MCP3425?

Mr. T. Butchertop> Yeah, It's the most cheap delta-sigma device on earth. We are shipping it now ...

Section 4

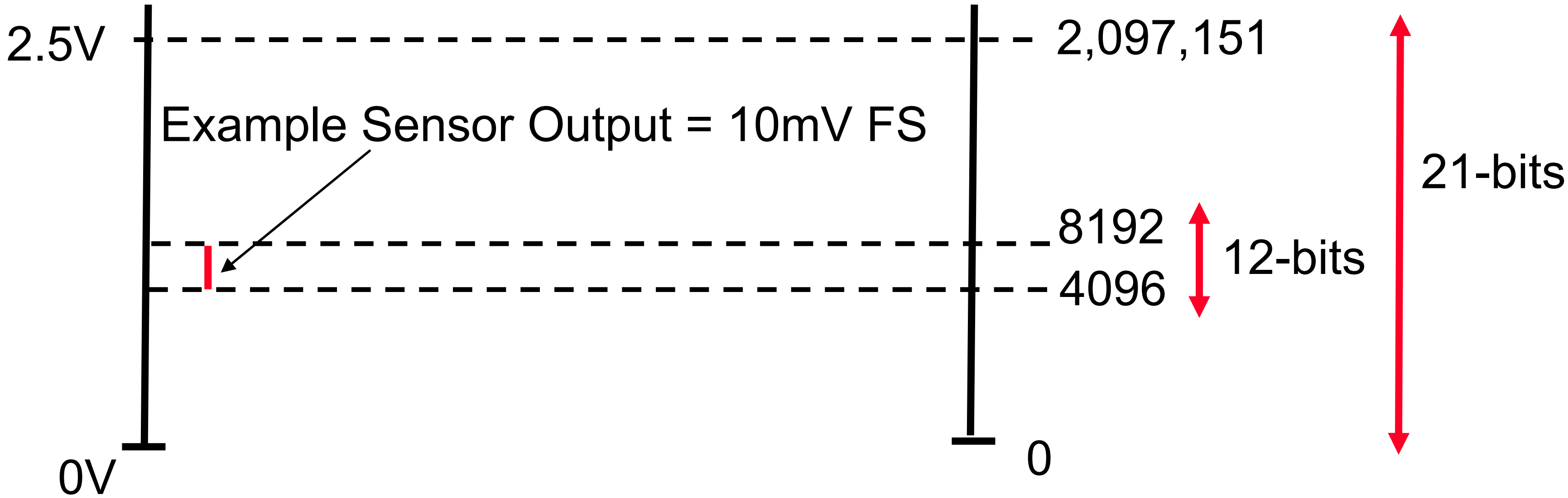
How to use ΔΣ ADC Devices

Think in Volts not in bits !!

- **Designer/Vendor:**
  - "My converter is a 22-bit one !"
- **Customer:**
  - "I only need 12 bits resolution ! I don't think I need your product ! It must be an expensive one !
- **Designer/Vendor:**
  - "But if you look at your sensor, there is only 10 mVp-p full scale signal, this leads to a 2.5 υV Resolution, which is my ADC resolution with a Vref=5V"
- **Customer:**
  - "Thus You meet my requirements! You are in ! It's always a pleasure to work with Microchip !"

Effective Resolution at Sensor output

- **ENOB@sensor = ADC ENOB – Unused dynamic Range**
- **Unused Dynamic Range = ln(2*Vref/FSR@sensor)/ln(2)**



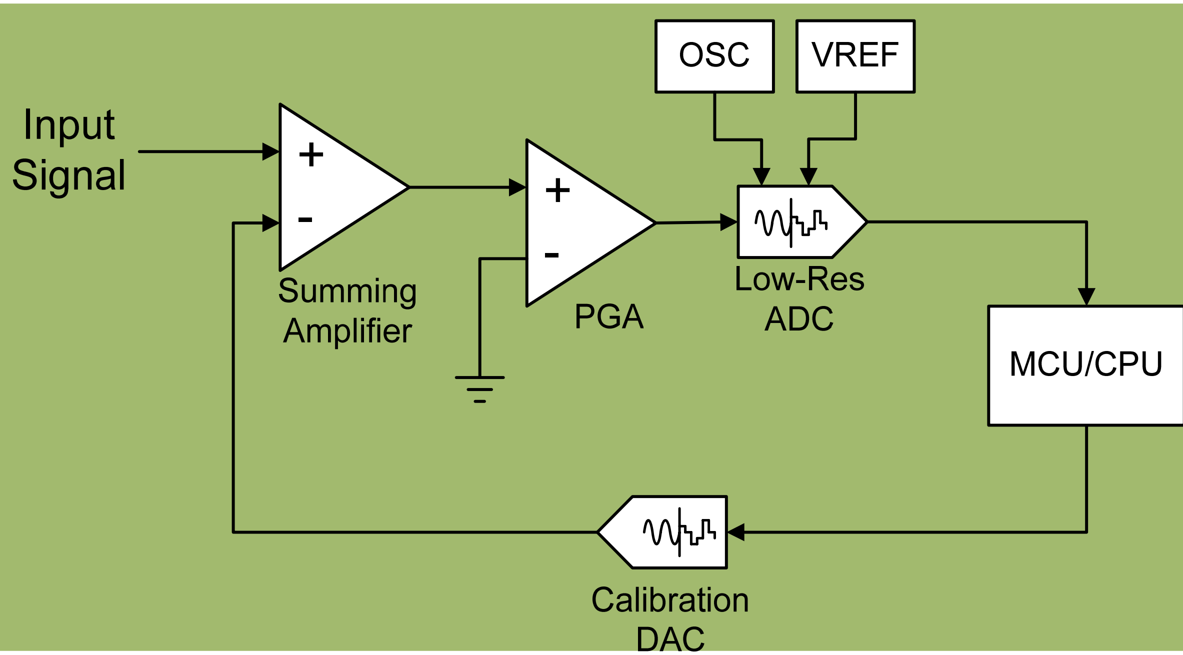
- Vref=2.5V, Single-ended app, FSR@sensor=10mV
  - Unused Dynamic Range= 8 bits
  - ENOB ADC=20 bits (MCP3551), Noise=2.5 uV RMS
  - ENOB@sensor = 12 bits

System Design Consideration

- ***Know your transducer/sensor:***
  - **Full-scale Voltage signal range**
  - **Desired Voltage resolution**
  - **Output Noise, Distortion**
  - **Non-linearity, static errors**
  - **Common mode Voltage Range**
  - **Power supply, Output Impedance**
  - **Bandwidth, needs sampling or averaging, synchro**
- **Minimize external components**
- ***Think about static errors induced by ADC: Can you calibrate? Look at TUE specs !***
- **Calculate Effective Resolution achievable on sensor's output**

Reduce Signal Conditioning Circuitry

- **Before**

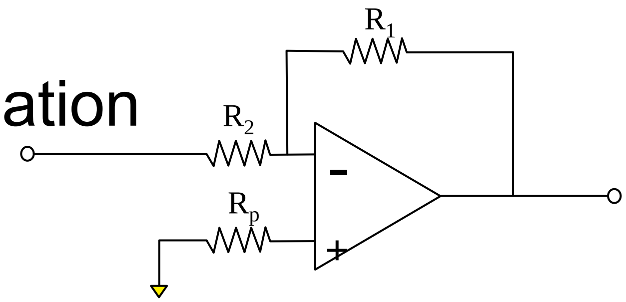


- **NOW**

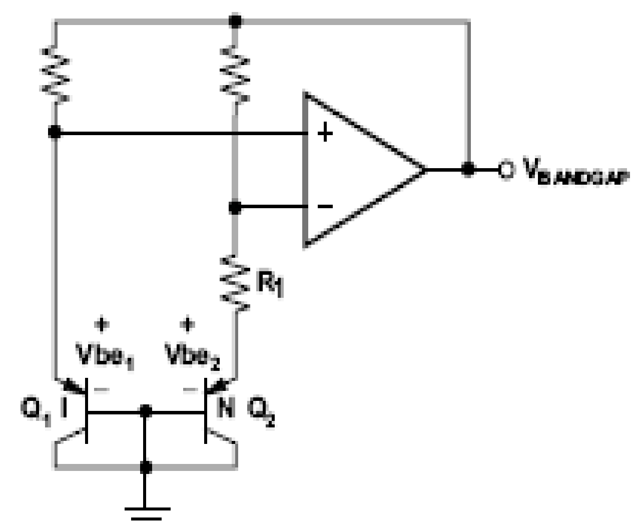
Remove unnecessary signal conditioning circuits !

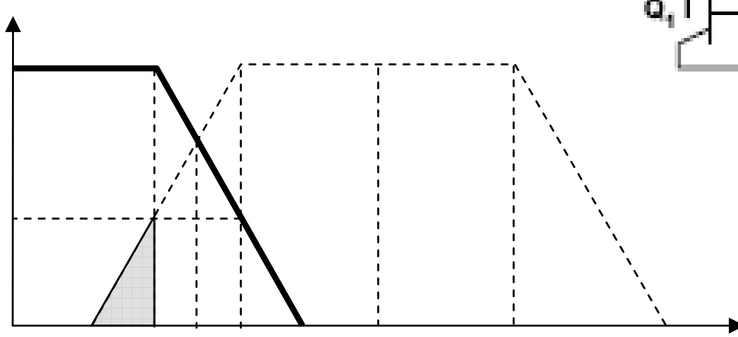
ADC Support Circuits

Signal Conditioning: -
Buffer
- Gain / Attenuation
- Active Filter
- Level Shift
- Differential to Single-ended conversions



Voltage Reference
(Bandgap Voltage Ref)





Filtering : Anti-Aliasing, Bypass Caps

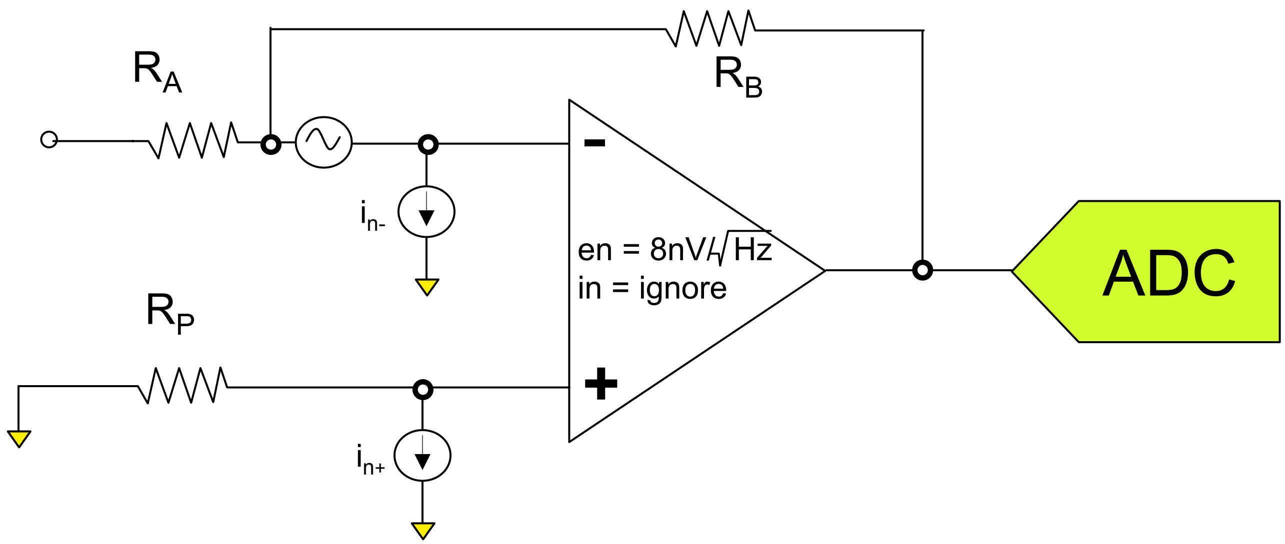
Selecting Signal Conditioning Amplifier

- Operational Amplifiers
  - Ideal for small single ended signals.
  - Used where common mode voltage is NOT an issue

- Differential Amplifiers
  - Best for low (<100) gain differential signal - fixed
  - Most commonly used to translate a differential signals to single ended in present of high common mode voltage. Current shunt
  - Relatively low input impedance (10K – 1M)

- Instrumentation Amplifiers
  - High gain variable (up to 10,000), high common mode rejection and high input impedance
  - Connect directly to sensor

Example of Amplifier Noise Calculation



$R_A = R_B = 1K$
Gain=1
$R_P = 0$

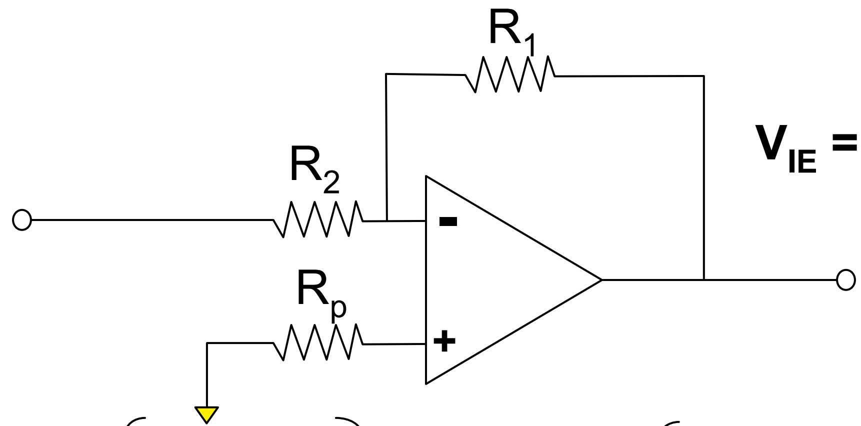
BW 20 -20KHz
1 LSB = 44µV
Vnoise at ouput = 12.4 µV
SNR=20log(1/12.4 µV) = 98dB
T=25

$$V_{Nrms} = \sqrt{153.6uV^2 + 7.68uV^2 + 7.68uV^2} = 12.4uV$$

I_n is the noise current source

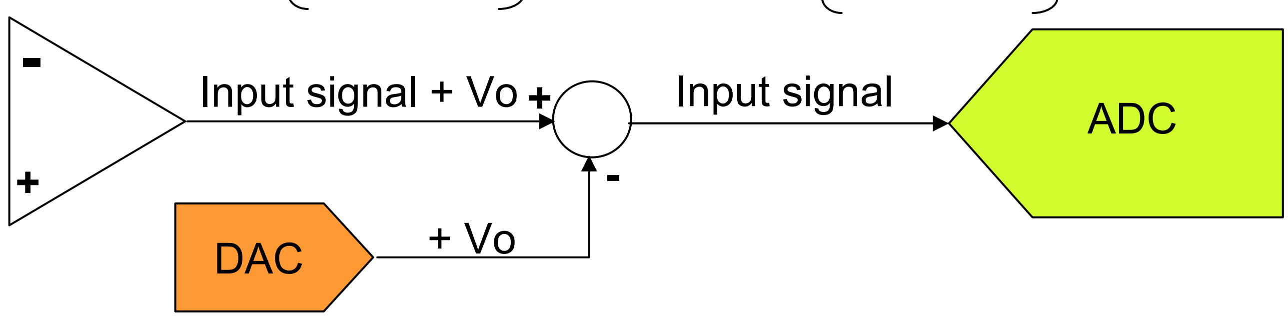
DC Input Offset Errors

$$V_{IE} = V_{OS+Ib} + V_{CMRR} + V_{PSRR}$$



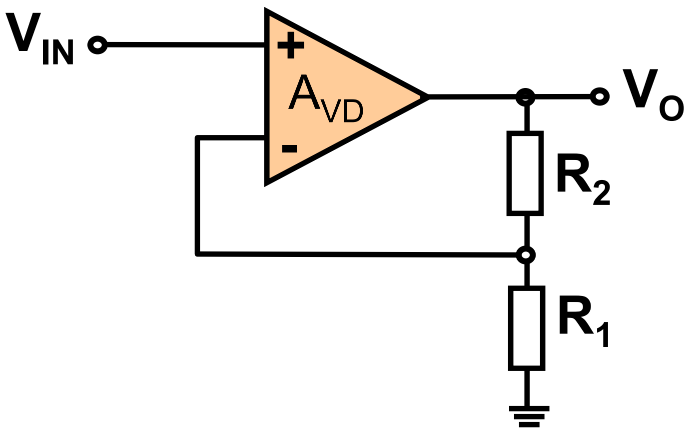
$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

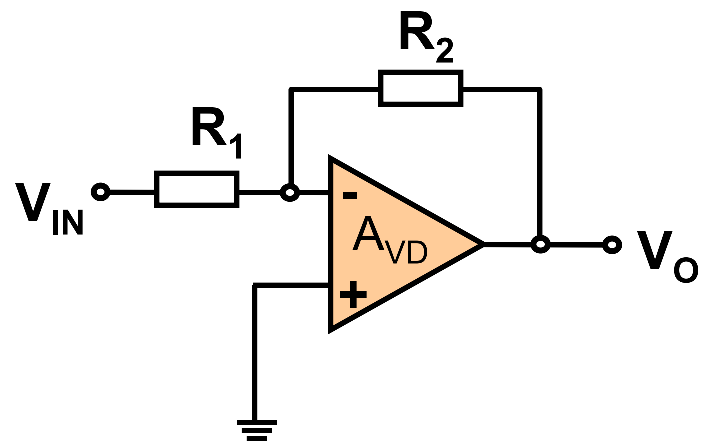
$$V_o = \pm V_{os}\left\{1 + \frac{R_1}{R_2}\right\} \pm I_{B+} R_p \left\{1 + \frac{R_1}{R_2}\right\} \pm I_{B-} R_1$$



If not calibrated , offset of the opamp will be seen as a signal thus it will contribute to ADC output offset error

DC and AC Parameters – Signal Gain Error





Non-inverting Amplifier Gain

$$A = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{1 + \frac{1}{A_{VD}\beta}}\right)$$

Inverting Amplifier Gain

$$A = -\left(\frac{R_2}{R_1}\right)\left(\frac{1}{1 + \frac{1}{A_{VD}\beta}}\right)$$

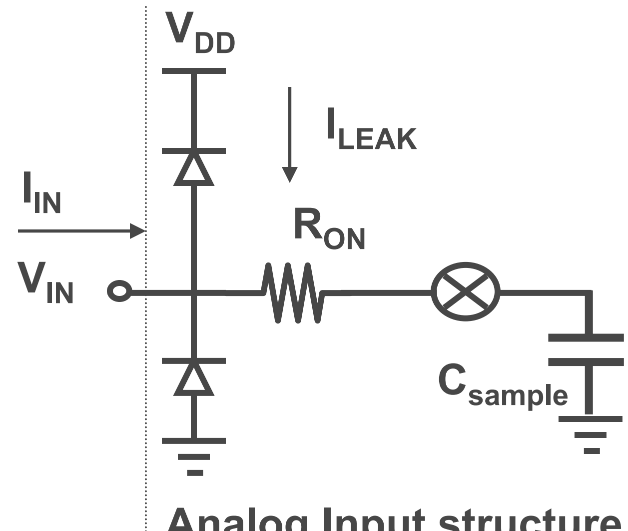
β = **Feedback factor** $\left(\frac{R_1}{R_1+R_2}\right)$

A = Closed-loop gain

Switched-Cap Input Structure

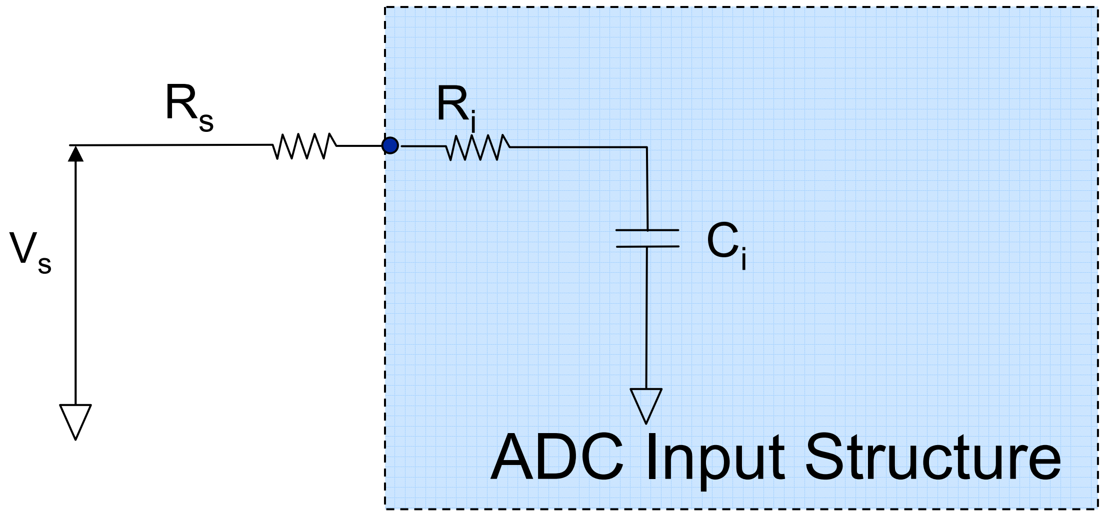
- Analog inputs are a switched capacitor stage where the sampling cap is charged and discharged
- A switched cap is acting like a resistor thus input current is proportional to voltage input
- Input impedance is proportional to $1/(f_s.C_s)$ and can be several MΩ (MCP355X, MCP3421 input impedance about 2 MΩ typ.)
- Leakage current comes from ESD input diodes
- For absolute accuracy, you need to consider input R-C settling time here . Input should settle to within 1/14 time constants of sample time for 1 ppm accuracy.
- Example: MCP3551 switching frequency = 112640Hz . Source impedance has to be chosen so that

  $\tau < 14/112640 = 634$ ns



Analog Input structure

Input Equivalent Circuit



$R_t = R_s + R_i$

Input Step: 0 -Vs

$$V_c = V_s \left\{ 1 - e^{\left(\frac{-t_c}{R_t C_i} \right)} \right\}$$

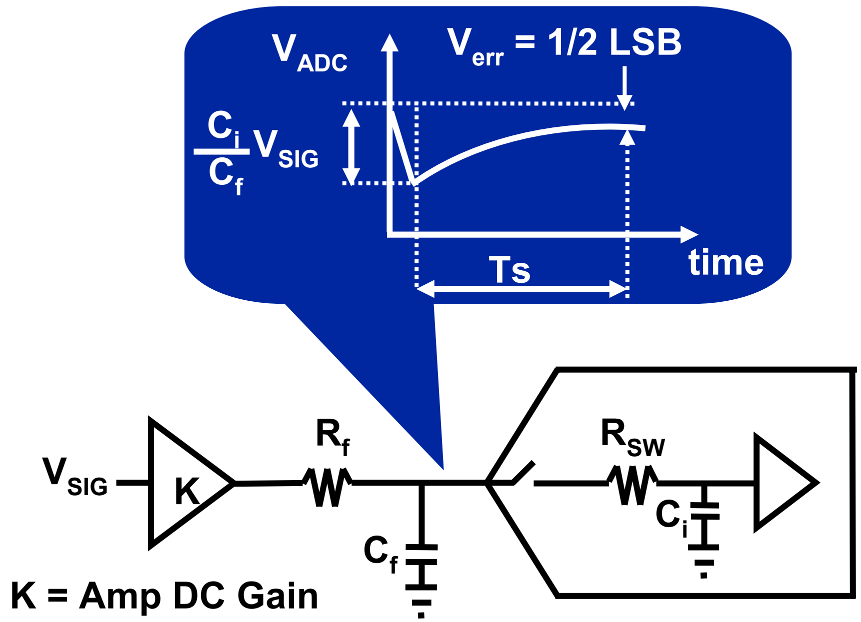
$$V_{c\ 1/2\ LSB} = V_s - \frac{V_s}{2^{N+1}}$$

Settling time for a 16-bit system :

$$t_{c\ 1/2\ LSB} = R_s + R_i \times C_i \times \ln(131072)$$

RC Buffer Selection

- **Typical Op Amp output and SAR ADC input**



$$V_{ADC} = V_{SIG} - V_{err}$$

where $V_{err} = C_i / C_f \cdot V_{SIG} \cdot e^{-t/\tau}$

Solve for V_{err} with

$t = T_S, \quad \tau = R_f C_f,$

$V_{SIG} = FSR, \; V_{err}\big|_{t=T_s} \le 1/2 \, LSB,$

Rule of thumb!

$$C_f \ge 10 \cdot C_i$$

$$R_f \le -\frac{T_S}{10 \times C_i \times \ln\left[10 \times 2^{-(n+1)}\right]}$$

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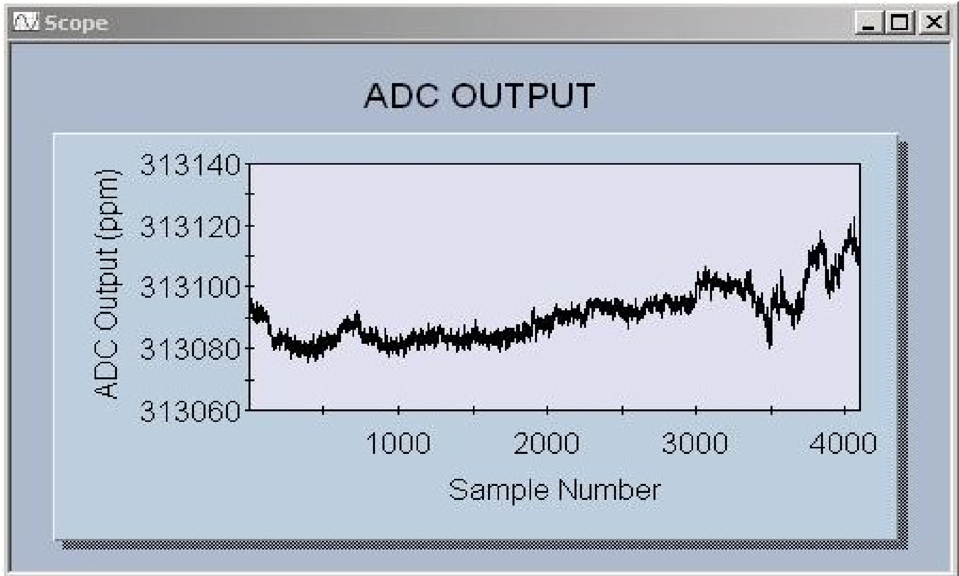
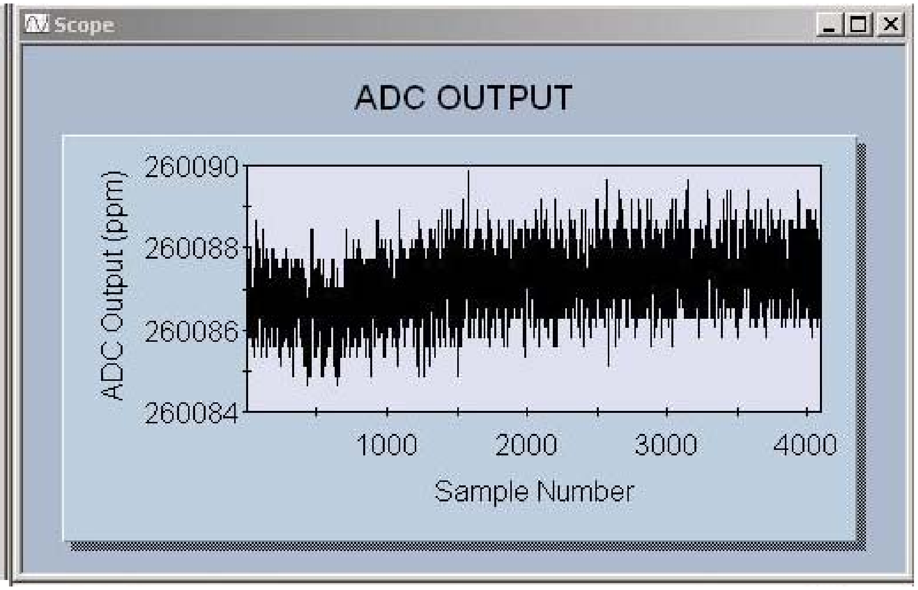
Voltage Reference Selection

- Most important choice after ADC
- Low noise, low drift reference, calculate your error budget
- Look at 1/f noise corner frequency, the lower the better, this noise cannot be averaged!
- Beware of heating, look for low tempcos
- Low power is always appreciated in battery applications (think about total power budget)
- Choose a Vref value that matches your application (ex: low value for better linearity)
- Low output impedance is preferable

Voltage Reference Drift

- Output codes with a poor reference:
  - ~40ppm of V_{ref} or 100µV of drift (V_{ref} = 2.5V)
- Output codes with a stable reference:
  - ~2ppm of V_{ref} or 5µV of drift (V_{ref} = 2.5V)





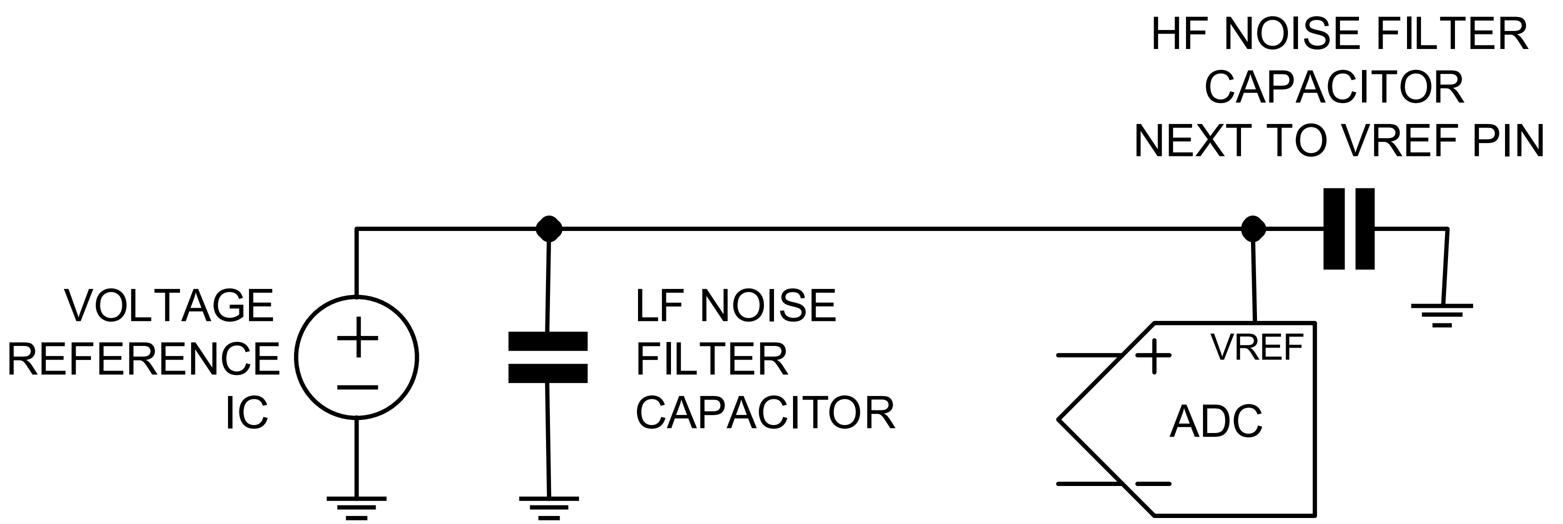
- If you write $V_{ref} = V_{refDC} + V_{refnoise}$ you can write output code as :
  - Output Code = $V_{in}/(V_{refDC}+V_{refnoise}) \times 2^N = V_{in}/V_{refDC} \times 2^N \times 1/(1+V_{refnoise}/V_{refDC})$
- Code Out ~ $V_{in}/V_{refDC} \times 2^N$ - $V_{in}/V_{refDC} \times 2^N (V_{refnoise}/V_{refDC})$

Static Term

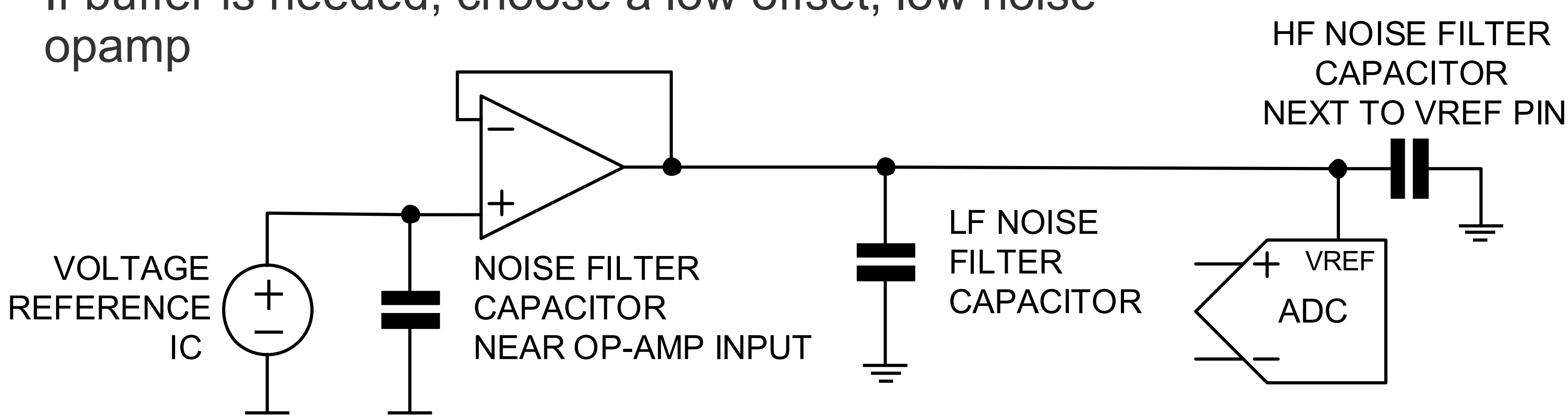
Term with V_{ref} noise error

Becomes very important when Vin close to V_{refDC}

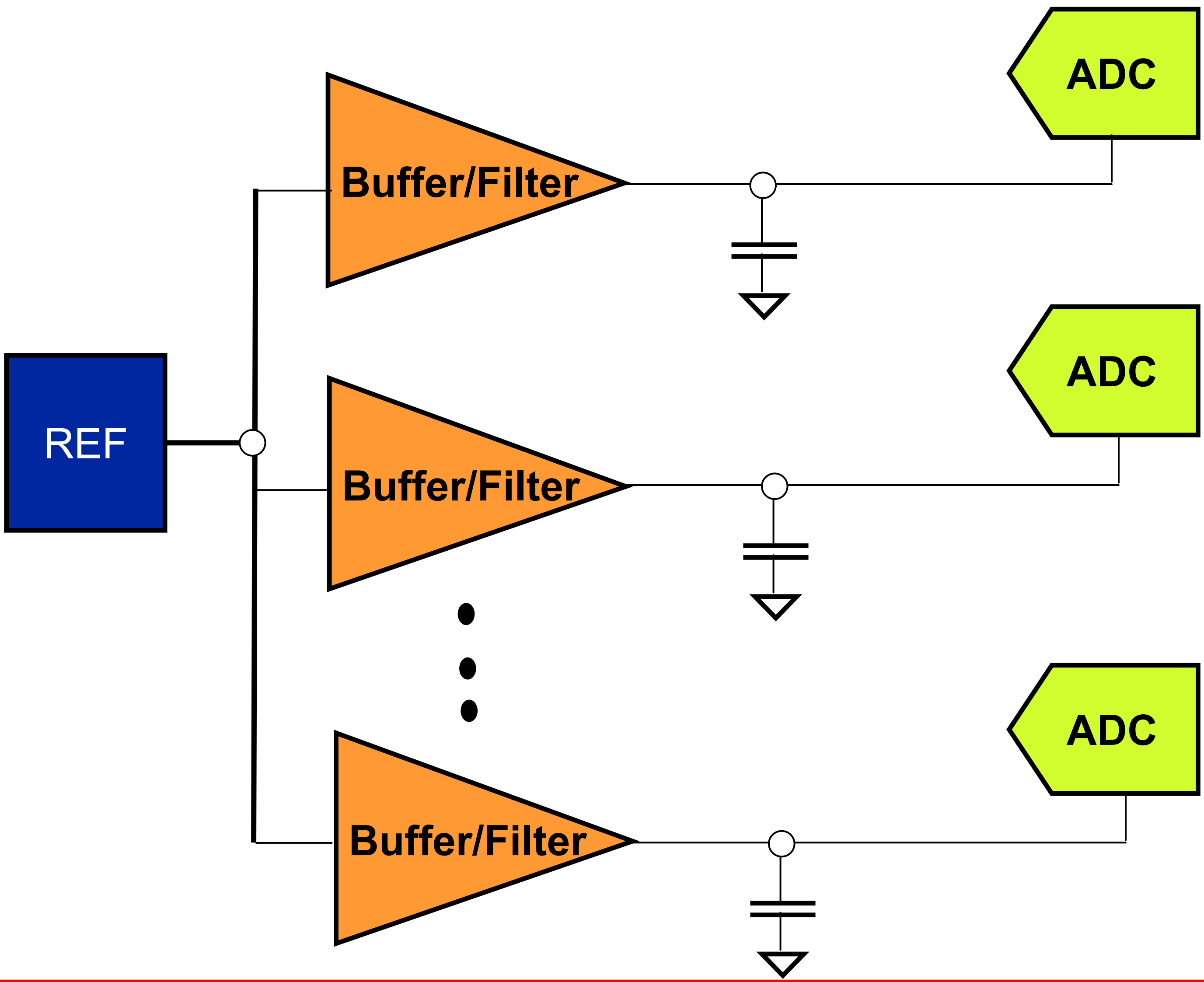
Buffered/Unbuffered Reference Circuit



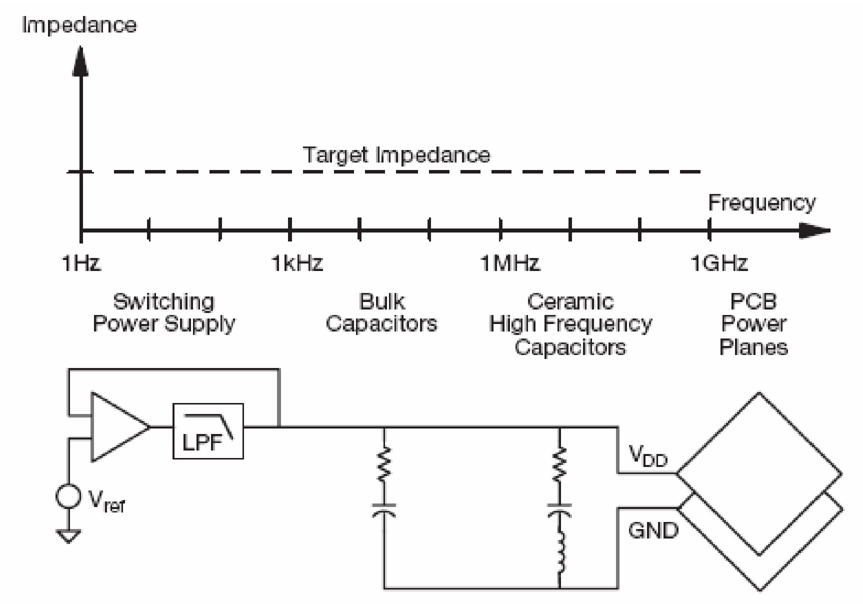
- Most of the time no buffer is needed (if not many circuits to drive)
- If buffer is needed, choose a low offset, low noise opamp

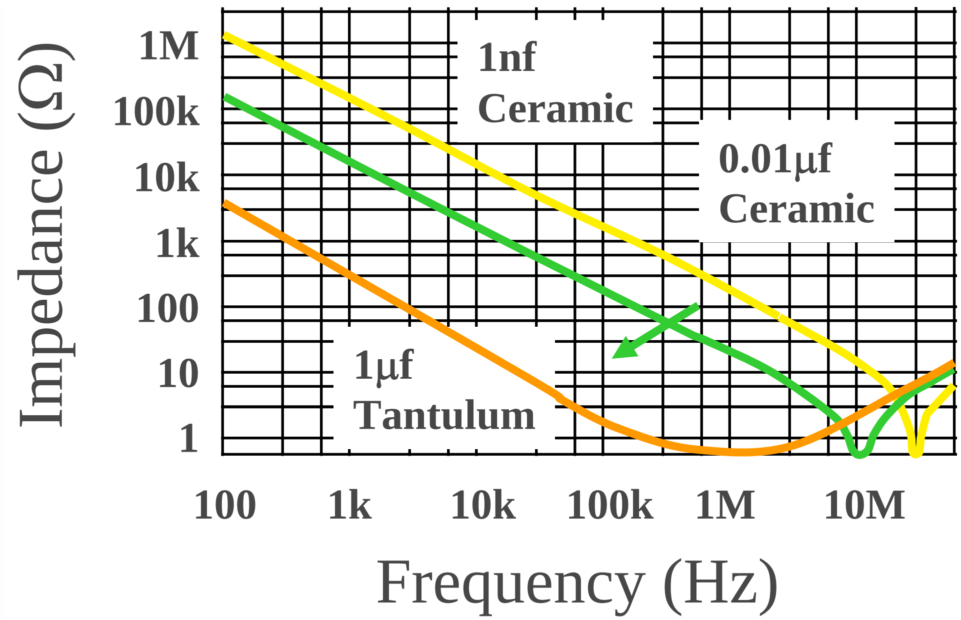


Reference Distribution



Choosing Bypass Capacitors





- **Bypass capacitors act as a charge reservoir for current spikes caused by fast edges. The bypass caps have to meet a low target impedance over the full frequency range to have a good system PSRR**
- **Try to put different caps in parallel covering different frequency ranges:**
  - **Low MHz** range : **high capacitance**, low ESR
- **Tantalum Electrolytic** - Small size, large values, medium inductance
  - **High MHz/GHz** range : medium capacitance, **low ESL**
- **Ceramic** - Small size, low cost, good stability, low ESL, NPO, X7R

Anti-Aliasing Filter Passband Attenuation Considerations

- An analog filter is required to limit the BW of the input signal (as per the sampling theorem)
- The maximum variation in the passband must be less than the resolution of the ADC

$$\Delta \le \frac{1}{2^N}$$

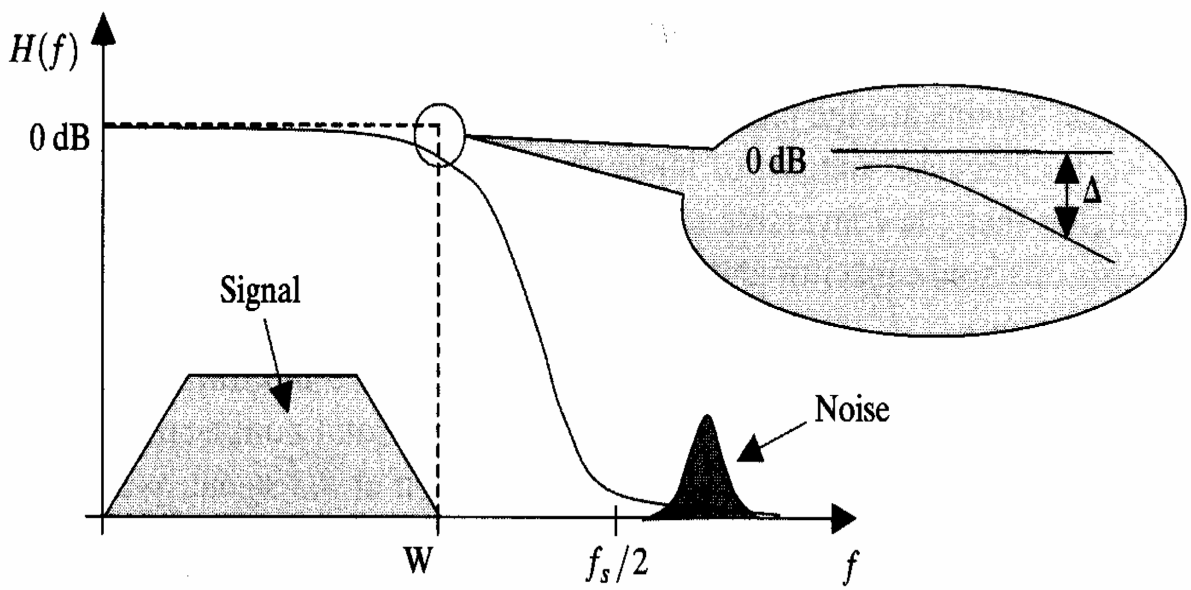
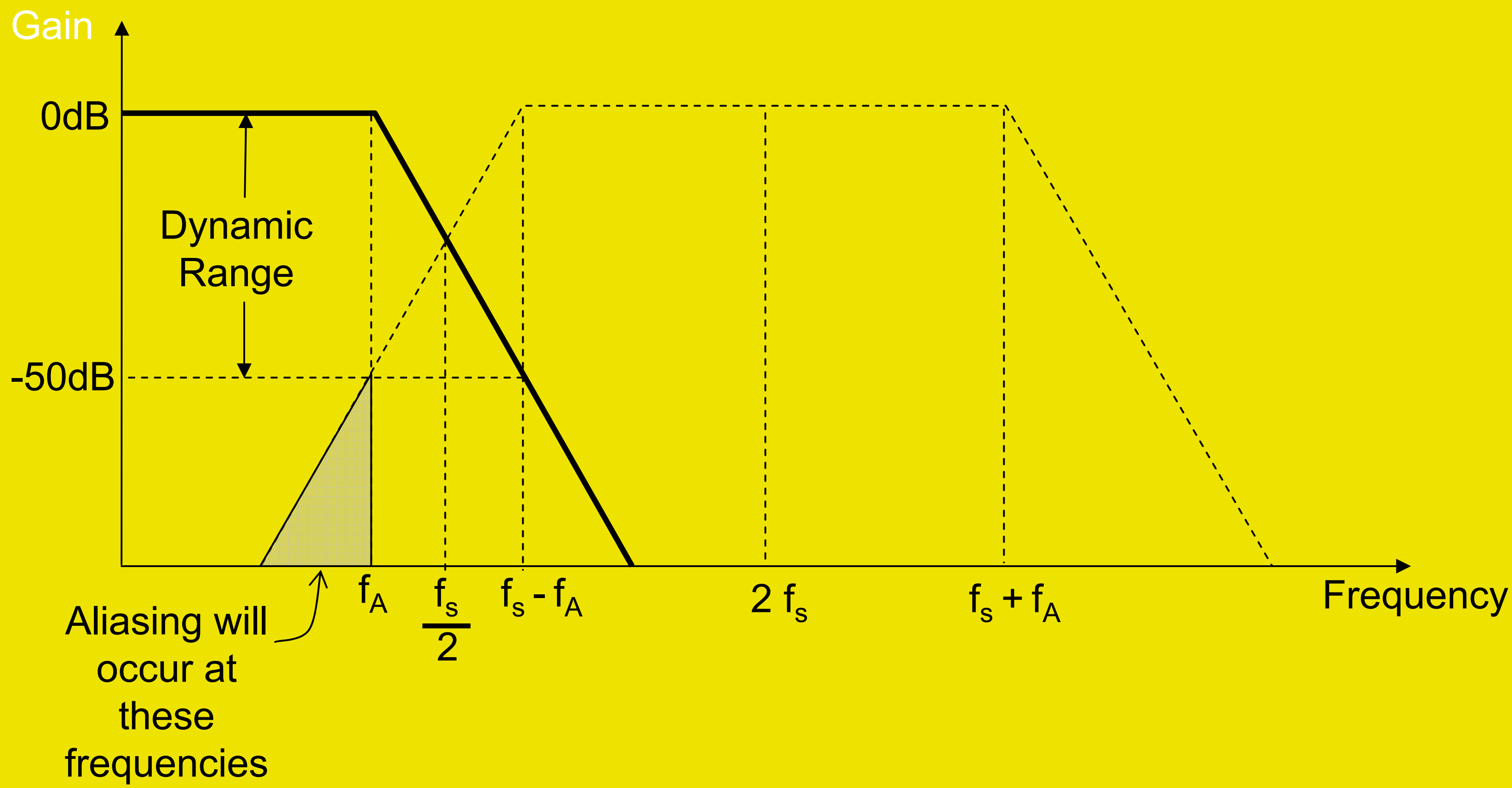


FIGURE 3-4 Analog lowpass filter design.

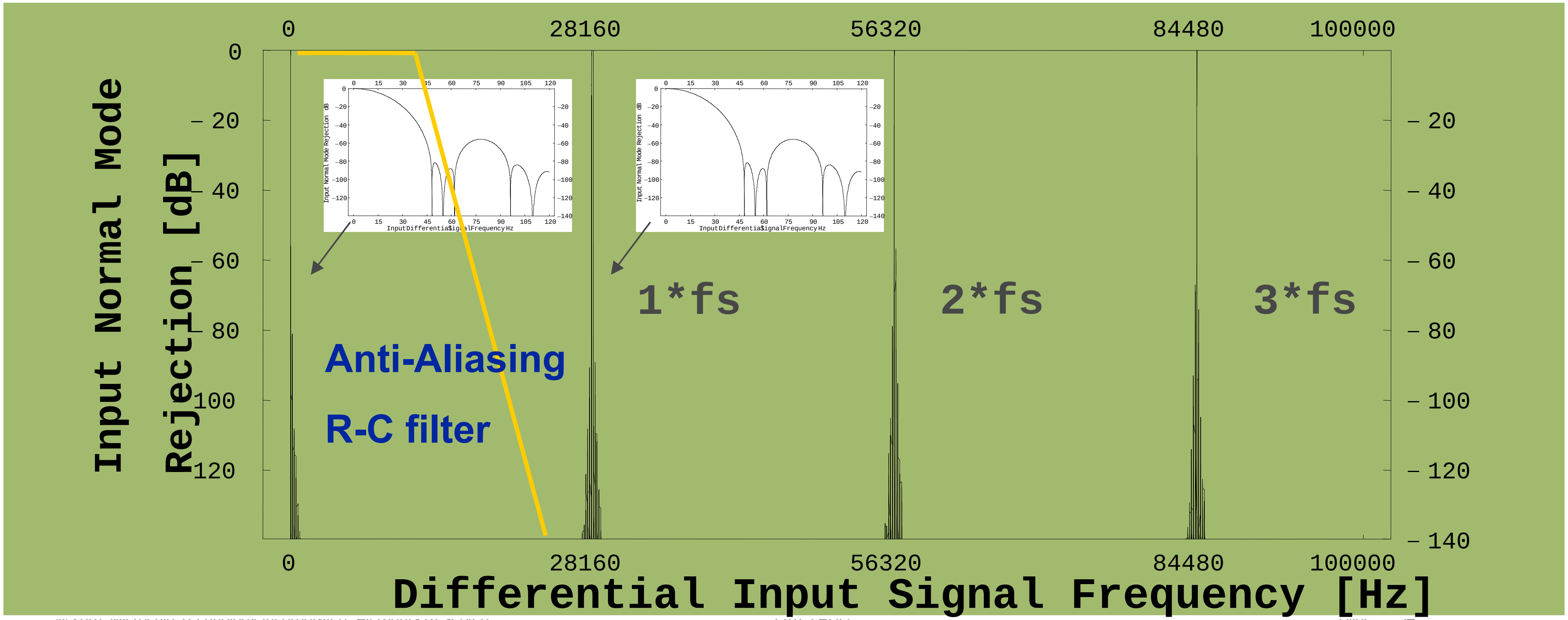
Anti-Aliasing Filter



50-dB, alias-free range is insufficient for 16 bits.

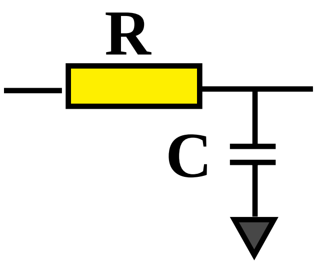
Anti-Aliasing Filter

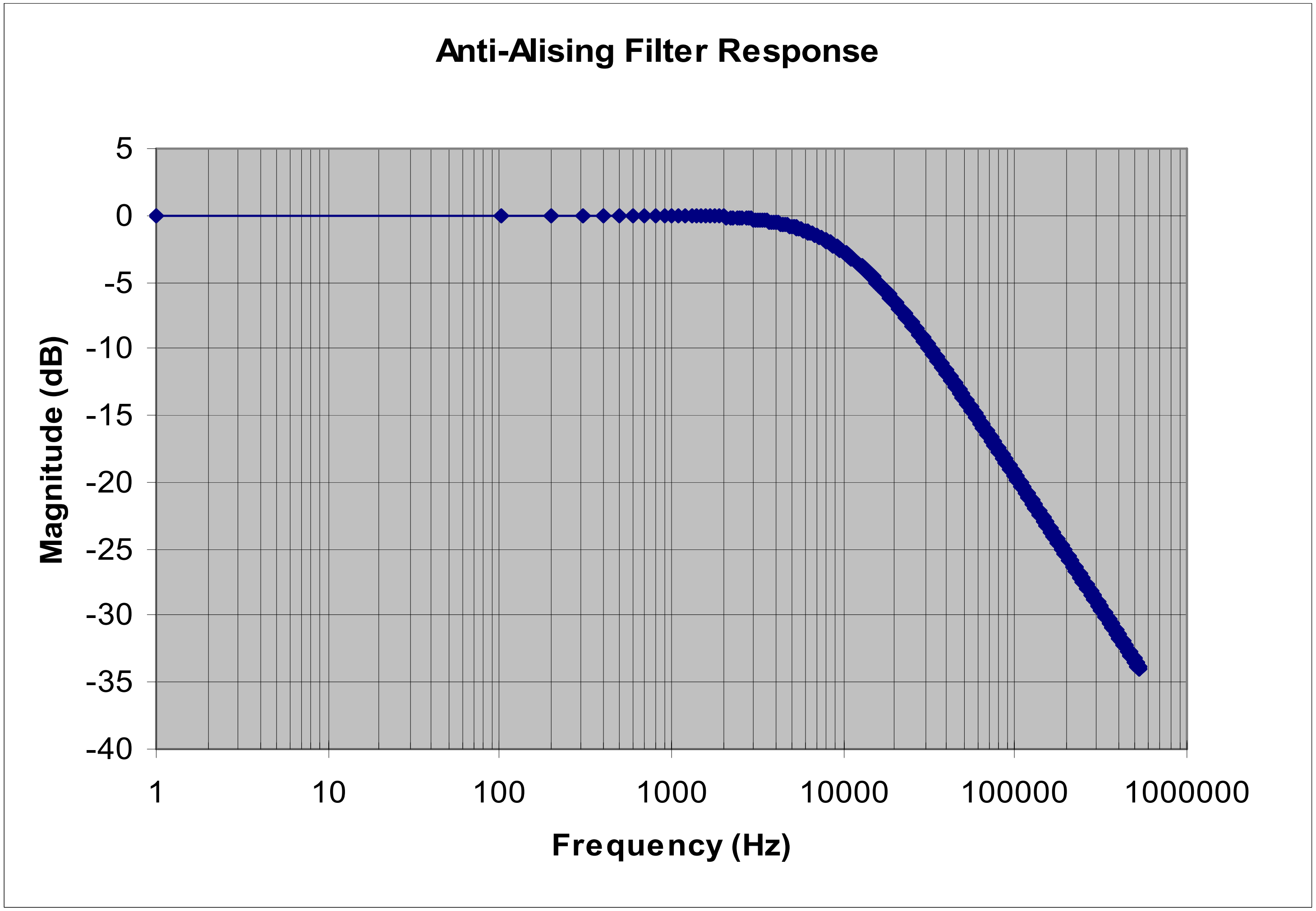
- **For higher frequencies, greater than 120dB rejection at all frequencies except, around multiples of the over sampling rate**
- Consider 1st order anti-aliasing filter design (**Simple RC!**)
- Locate R-C filter close to MCP355X/3421 analog input pins



EX: Simple RC Anti-Alising Filter

R = 150 Ω
C = 0.1uF





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PCB Layout strategies

- Experiment different implementations for layout: Use the converter to validate your PCB layout experiments!
- System noise can be as low as 5µV RMS even with a 2-layer board
- More layers are preferred for very quiet systems (testers, instrumentation…)
- The key of layout is routing discipline
- Grounding is the first thing to consider
- The more symmetrical the better
- The simpler the better

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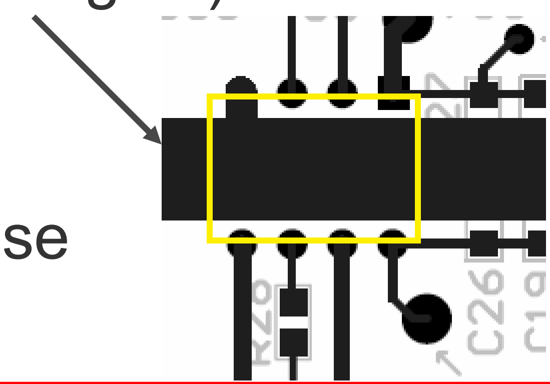
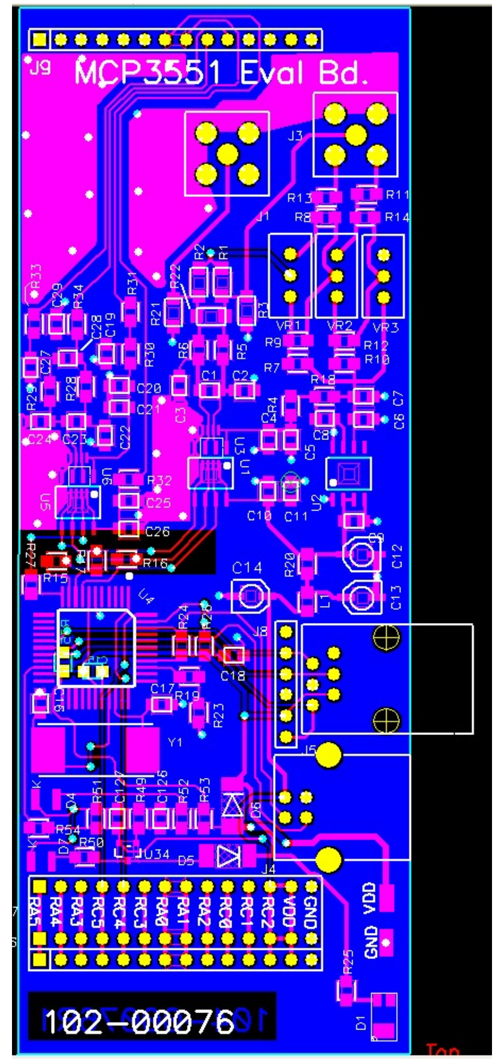
PCB Layout : Ground

- A low-noise, accurate system must have a stable, quiet reference point: GROUND !
- Provide current return path, wide power supply traces
- Separate ground planes AGND and DGND but do not split them : star connection between AGND and DGND
- Good decoupling , for ex. 1uF tantalum w/ 0.1uF ceramic
- Grounding, grounding, grounding: ground plane under and around the MCP355X (2" x 2" region)
- Minimize electric fields, magnetic fields, temperature gradients
- No CUTS or SLITS or SLOTS (these act as antennas)



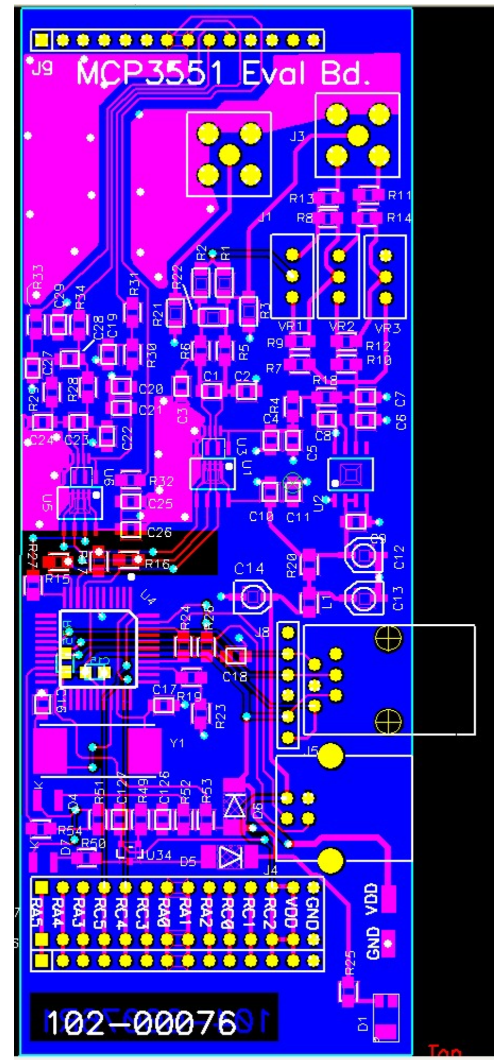
PCB Layout: Analog signals

- Keep minimal length lines
- Thermo-coupling effects are huge in PCB vias
  - If possible no Vias on VIN+, VIN-, VREF
  - If vias, try to match them between VIN+, VIN-, VREF
- Minimize electric fields, magnetic fields, temperature gradients
- Isolate VIN+, VIN-, VREF lines from fast switching or full swing digital signals, split PCB
- Match VIN+, VIN- lines for minimal offset
- Interface directly with transducer



PCB Layout: Digital signals

- **Digital signals do not only induce noise but also repetitive transient spikes that cause deterministic errors**
- Isolate fast transients, full swing digital signals from the rest
- Fast edges on the edge !
- Digital circuits should have their own supply
- **Since reading and converting can be done simultaneously,** use series resistors (10kΩ) on digital interface signals



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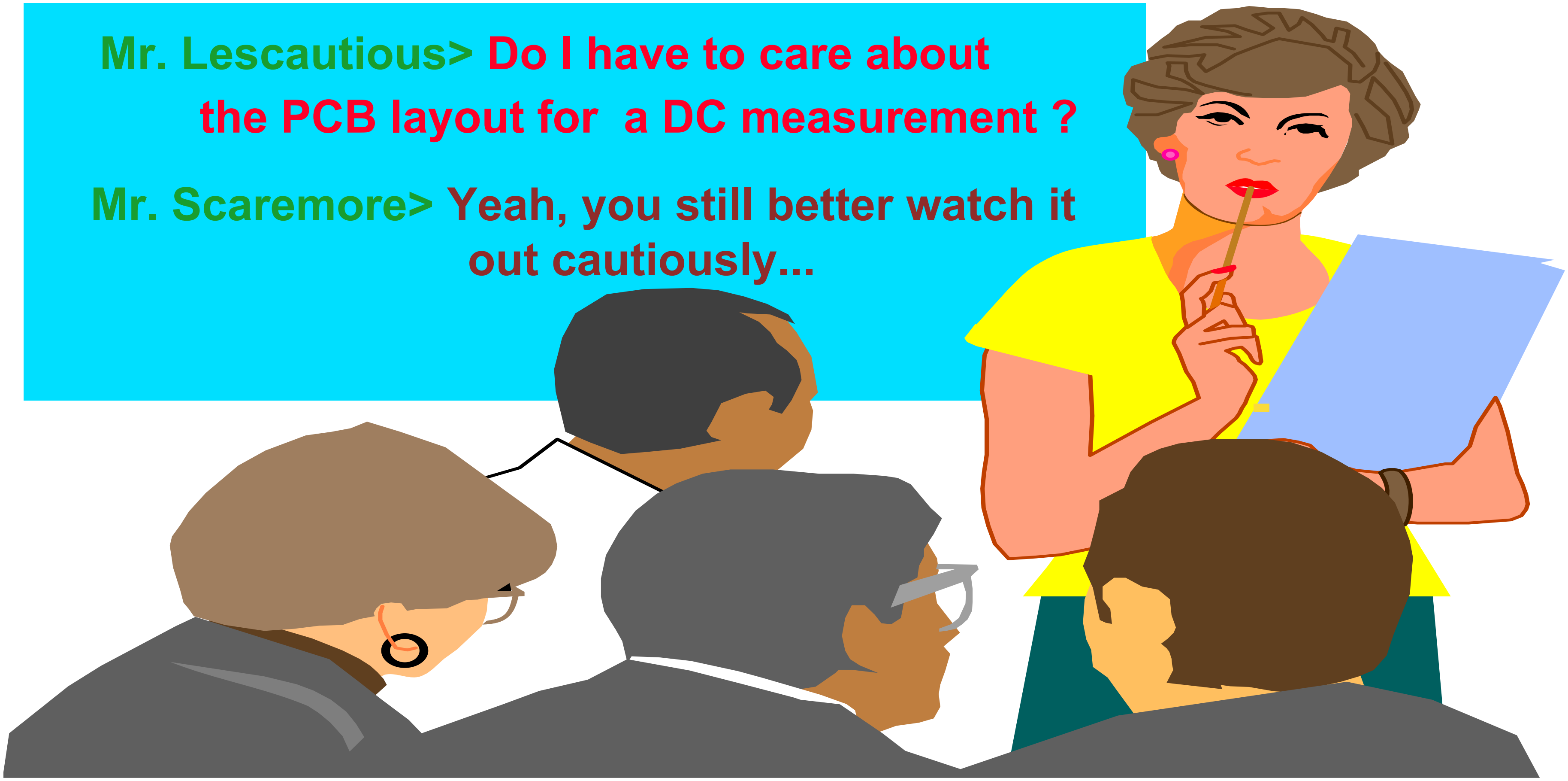
Questions?

Mr. Lescautious> Do I have to care about the PCB layout for a DC measurement ?

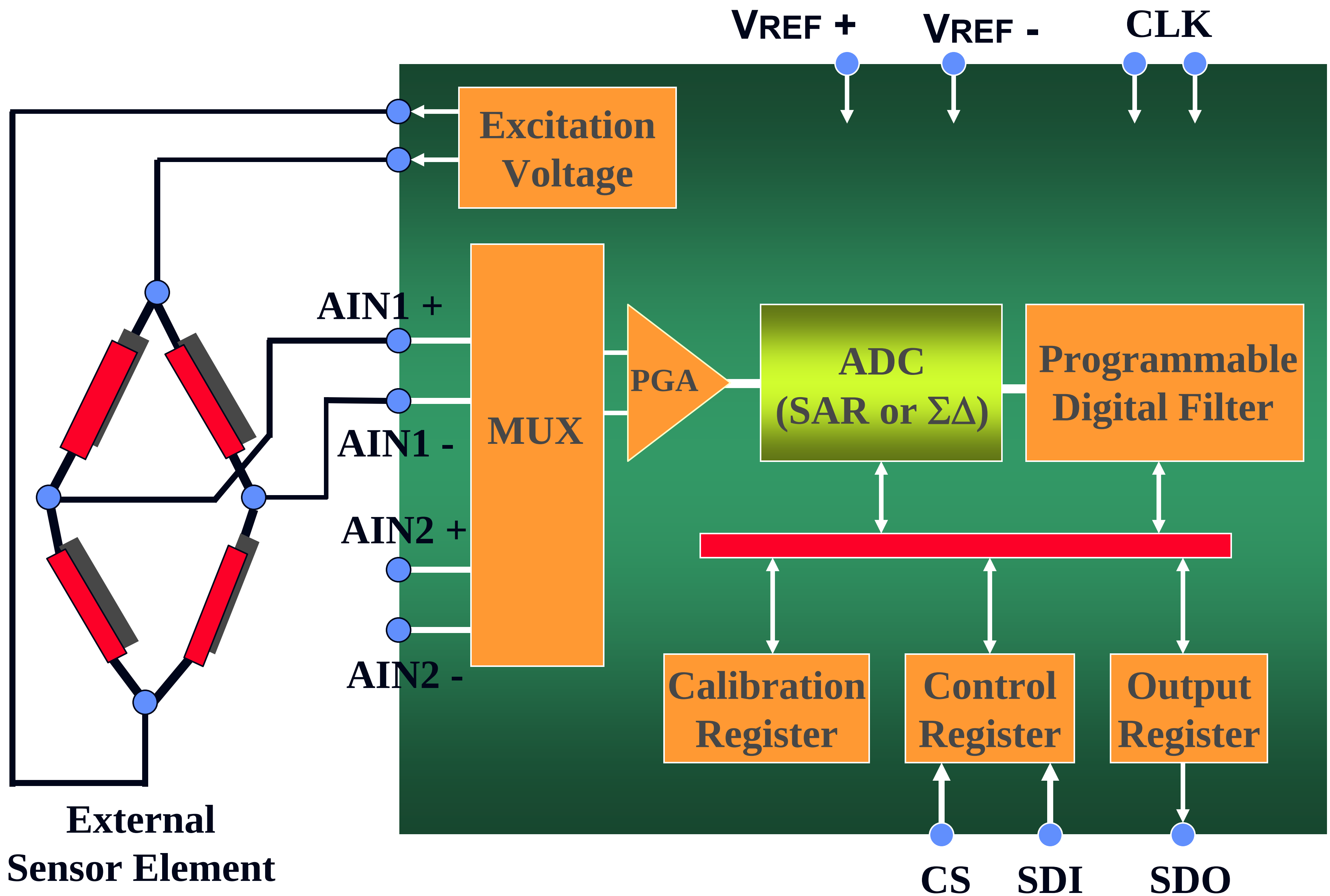
Mr. Scaremore> Yeah, you still better watch it out cautiously...



Section 5

Sensor Applications

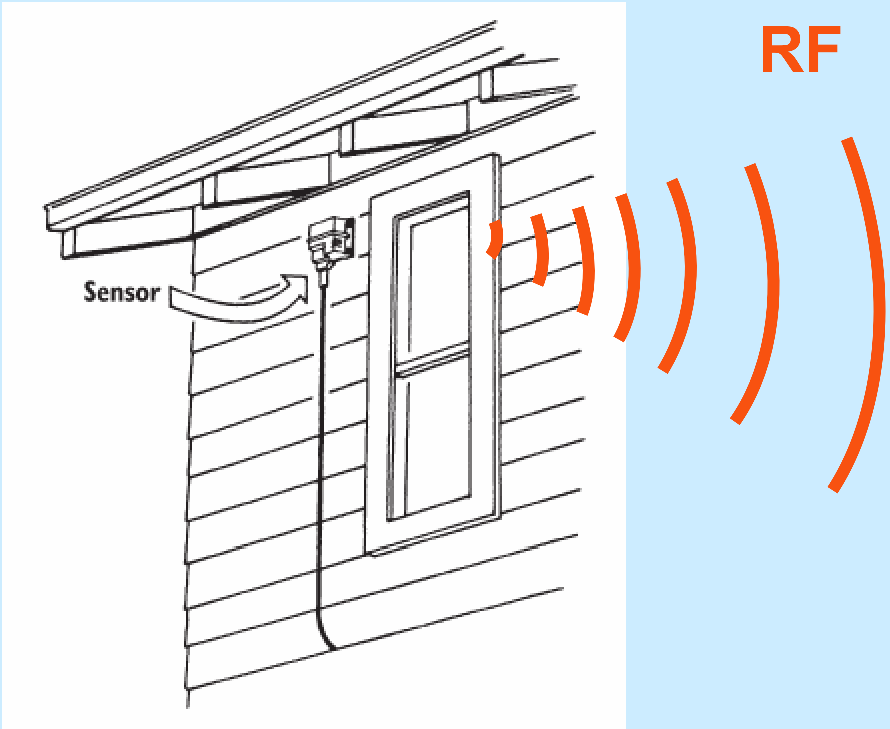
Universal Sensor Interface



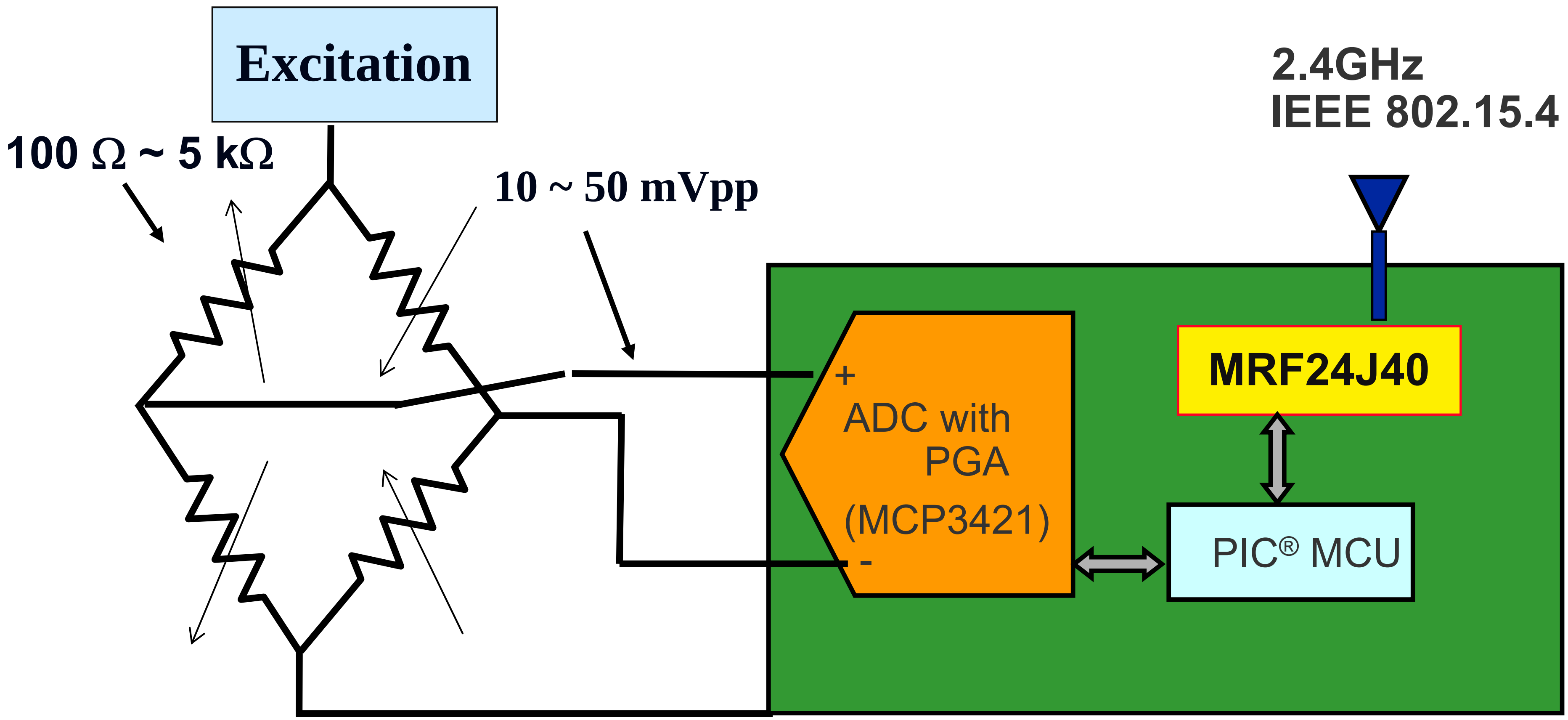
Sensor Classifications?

- Pressure Sensors
- Temperature Sensors
- Thermocouple
  - RTD (Resistive Temperature Detec
  - Thermistor
  - Bandgap
  - Silicon
- Humidity & Due Point Sensors
- PIR (Passive Infra Red) Sensors
- Hall Effect/Magnetoresistive Sensors
- Gas Sensors

What about Wireless Interface ?



RF Pressure Sensor and Its Interface



Measurement Range:
0 to ~ 250 PSI

Pressure/Strain Sensors

- **Sensor Configuration:**
  Piezoresistive Wheatstone Bridge
- **Sensor Excitation:** Regulated Voltage/Current
  - Excitation Voltage: 5 V (typical), 12 V (max)
  - Excitation Current: 2 mA to 20 mA (max)
- **Sensor Output Configuration:** Differential
- **Output Swing (full scale):**
  - Typical: 10 mVpp to 50 mVpp
  - Mostly: > 4 mVpp
- **Sensor Element Resistance:** 100 Ω ~ 5 kΩ range
- **Sensitivity:** ~ 1 mV/PSI, **Response Time:** <100 usec

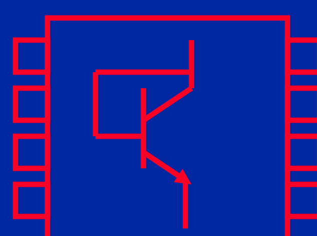
Temperature Sensing Technologies

Thermocouple

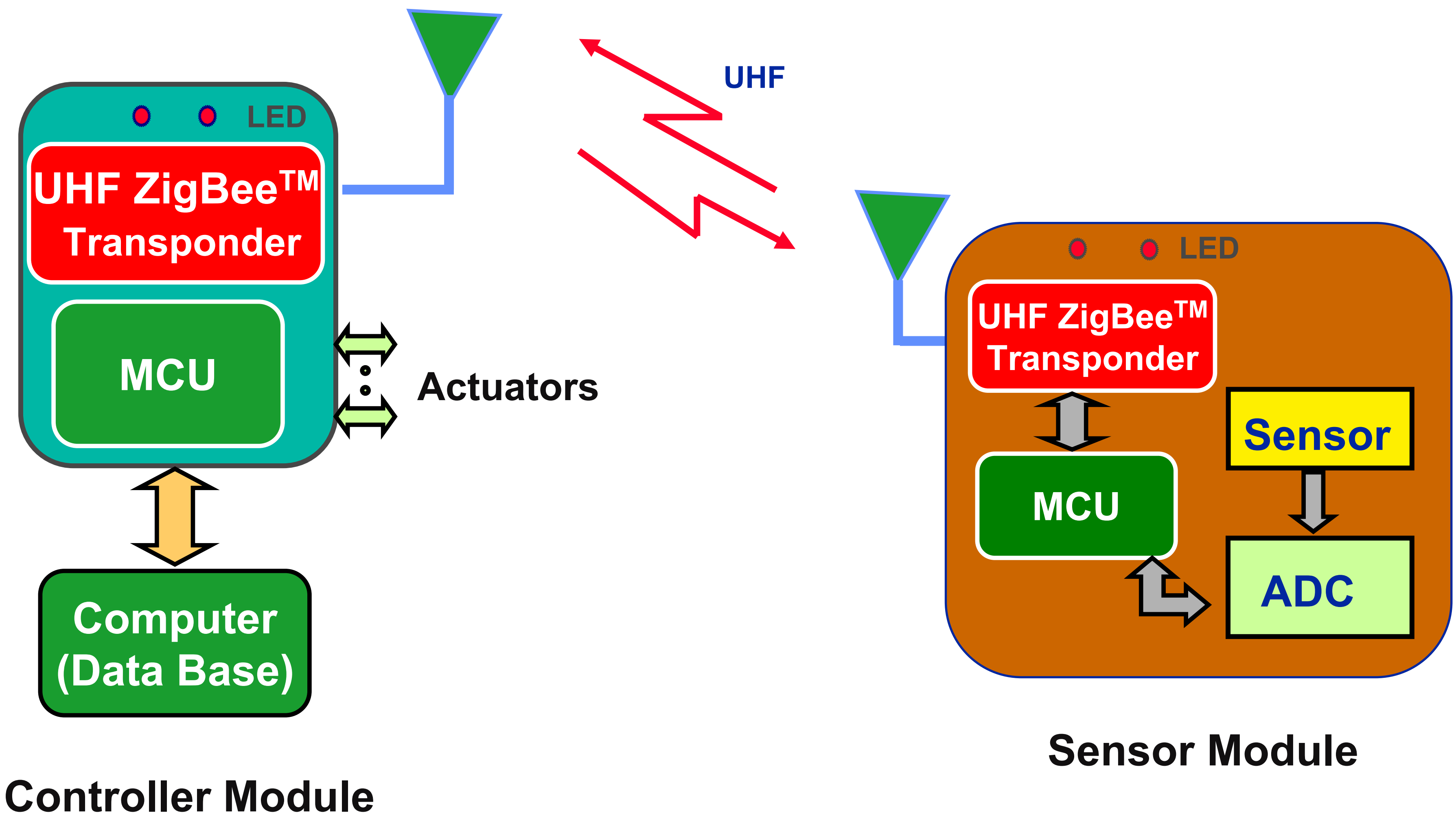
RTD

Thermistor

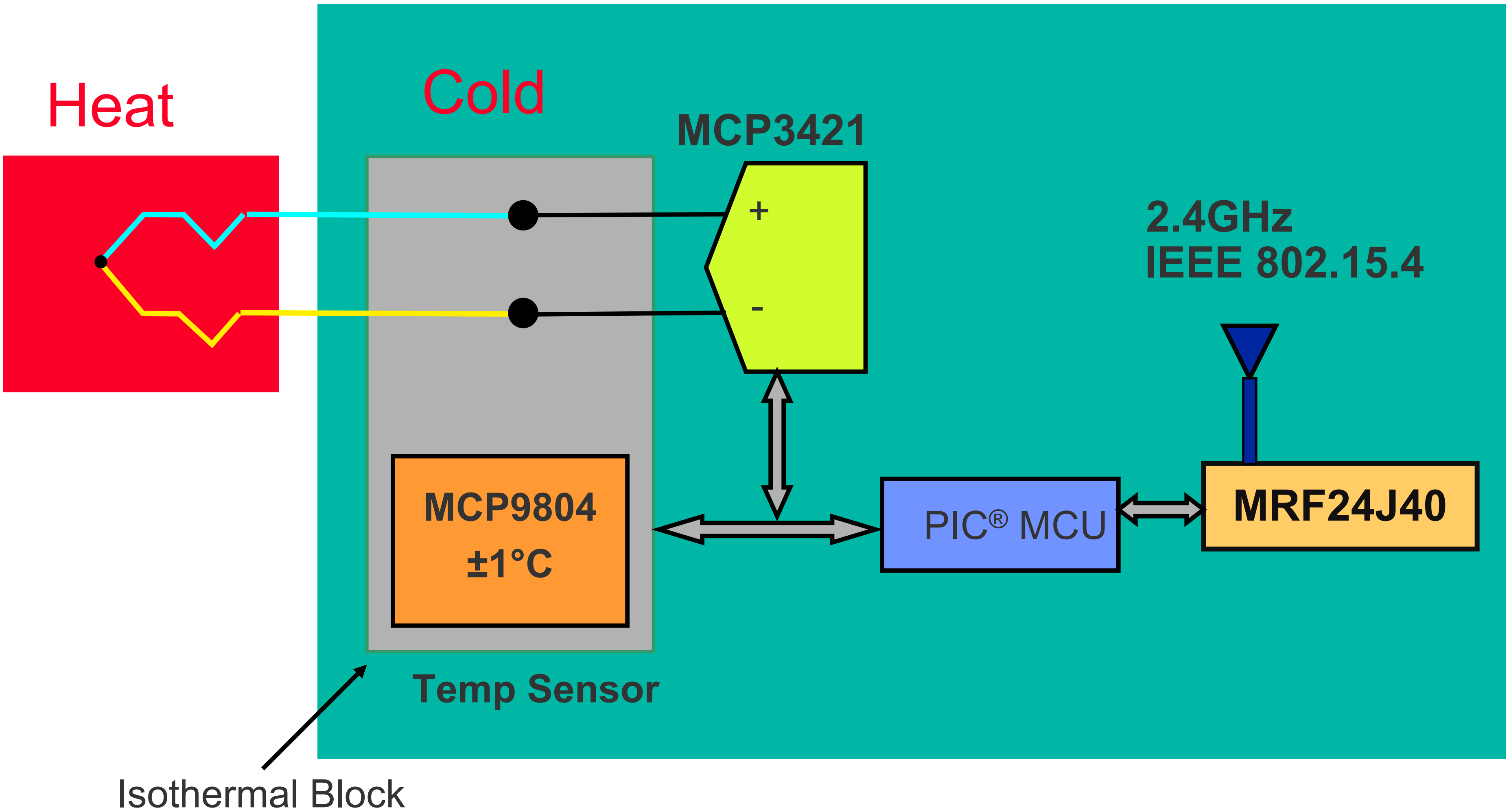
Silicon IC Sensor



RF Remote Sensing of Temperature



RF Thermocouple Solution



Thermocouple Types

Type	Materials	Typical Range °C	EMF (mV)
T	Copper vs Constantan	-270 to 400	-6 to 20
J	Iron vs Constantan	-210 to 1200	-8 to 69
K	Chromel vs Alumel	-270 to 1370	-6 to 54
E	Chromel vs Constantan	-270 to 1000	-9 to 76
S	(Pt-10%Rh) vs Pt	-50 to 1768	-0.2 to 18
B	(Pt-13% Rh) vs (Pt-6% Rh)	0 to 1820	0 to 13
R	(Pt-13%Rh) vs Pt	-50 to 1768	-0.2 to 21
N	(Ni-Cr-Si) vs (Ni-Si-Mg)	-270 to 1300	-4 to 47

Thermocouple Sensors

- **Sensor Type:** Type J and K are most common
- **Sensor Excitation:** Not needed
- **Requirement:** Cold Junction Compensation (Temp compensation circuit in the signal conditioner)
- **Output Configuration:** Differential
- **Output Swing (full scale):** 0 mV to 50 mV (typical)
  - **Type J:** 0 V to 41 mV for temp change from 0C to 750C
  - **Type K:** 0 V to 50 mV for temp change from 0C to 1250C
- **Sensitivity:** 55 uV/C for Type J, 39 uV/C for Type K
- **Applications:** Stoves, Engines, Thermopiles

Microchip's Thermocouple Solution (MCP3421)

- Temperature measurement resolution
  - K-type Thermocouple : -270°C to 1370°C
  - Voltage resolution: ~40µV/°C
  - ADC Resolution of: 2µV/LSb ~ 0.05°C/LSb

Microchip's Thermocouple Solution (MCP3551)

- ADC characteristics
  - Fully-Differential analog input
  - Input Range: $-V_{REF}$ to V_{REF}

    (V_{REF} = 0.1V to 5.5V)
  - Resolution:

    128µV/LSb → 256LSb/°C

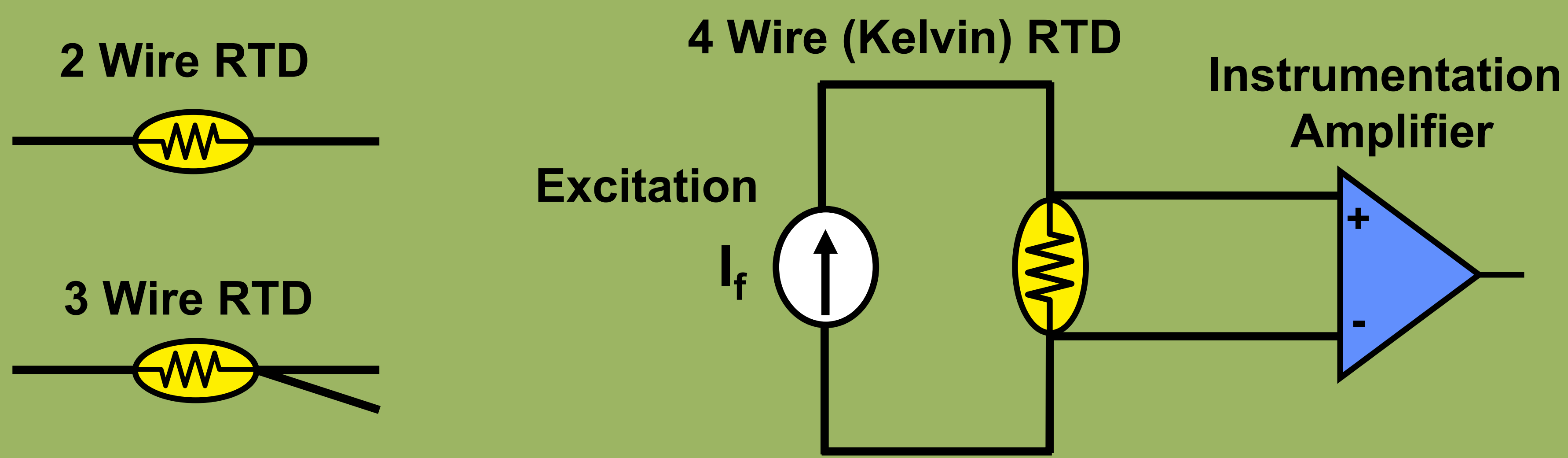
$$LSb = \frac{\mathbf{2.0}}{\mathbf{2^{22}}} = 0.47\mu V / LSb$$

Microchip's Thermocouple Solution

- ADC characteristics
  - Offset Error:
    - 3µV / 12µV (typ. / max.) or
    - 6 LSb / 24 LSb (typ. / max.) or
    - 0.02°C / 0.09°C (typ. / max.)
  - Offset Drift:
    - 0.04ppm/°C (typ.)

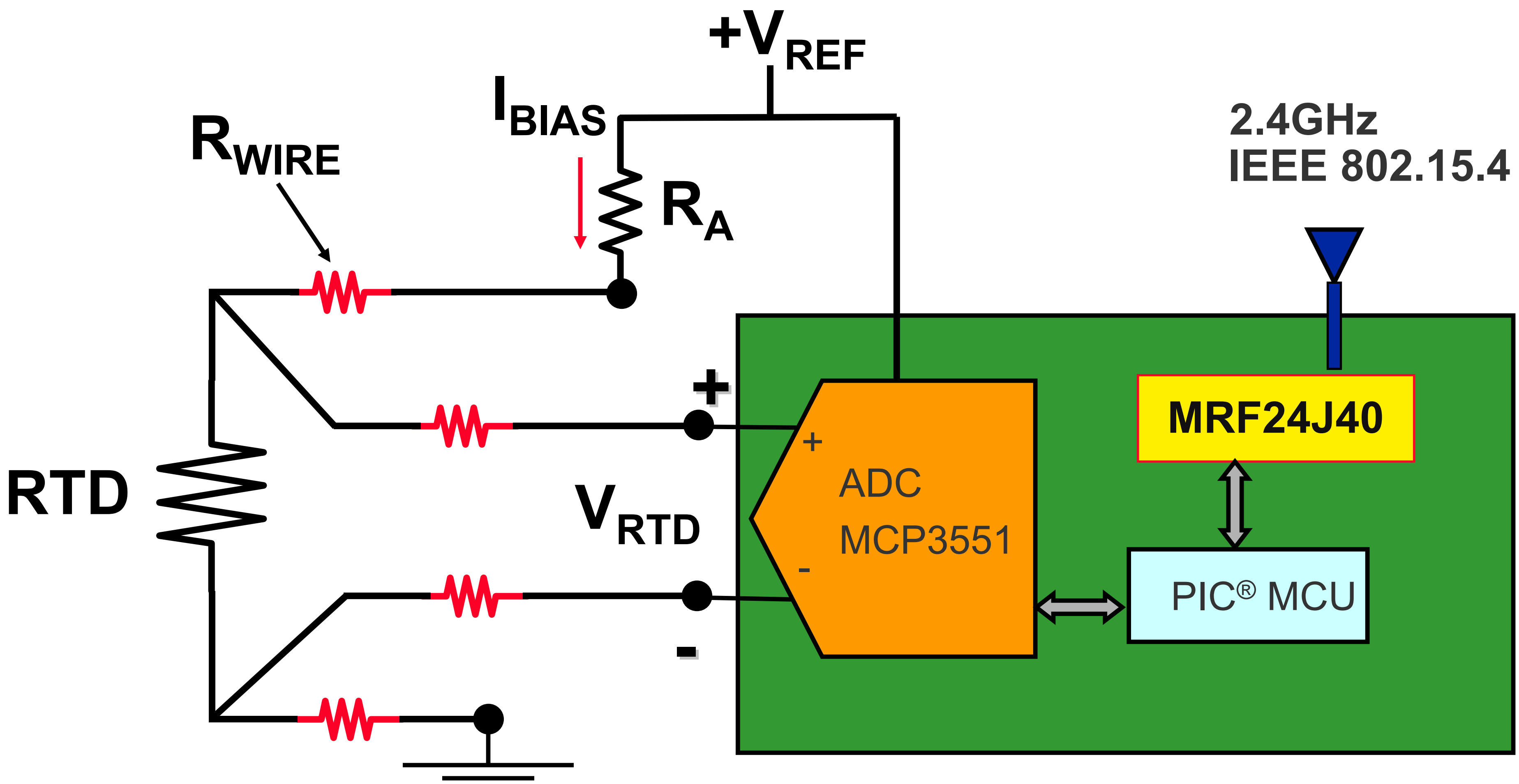
RTD Applications

- Platinum, nickel or copper metals
- Typical resistance is *100*, 200, 500, 1000 or 2000Ω
- Platinum temperature coefficient = 0.00385 Ω / Ω / °C
- Two, three and four wire (Kelvin) configurations
- ~ Δ 100 ohm range



RF RTD Solution

- 4- wire RTD Microchip Solution



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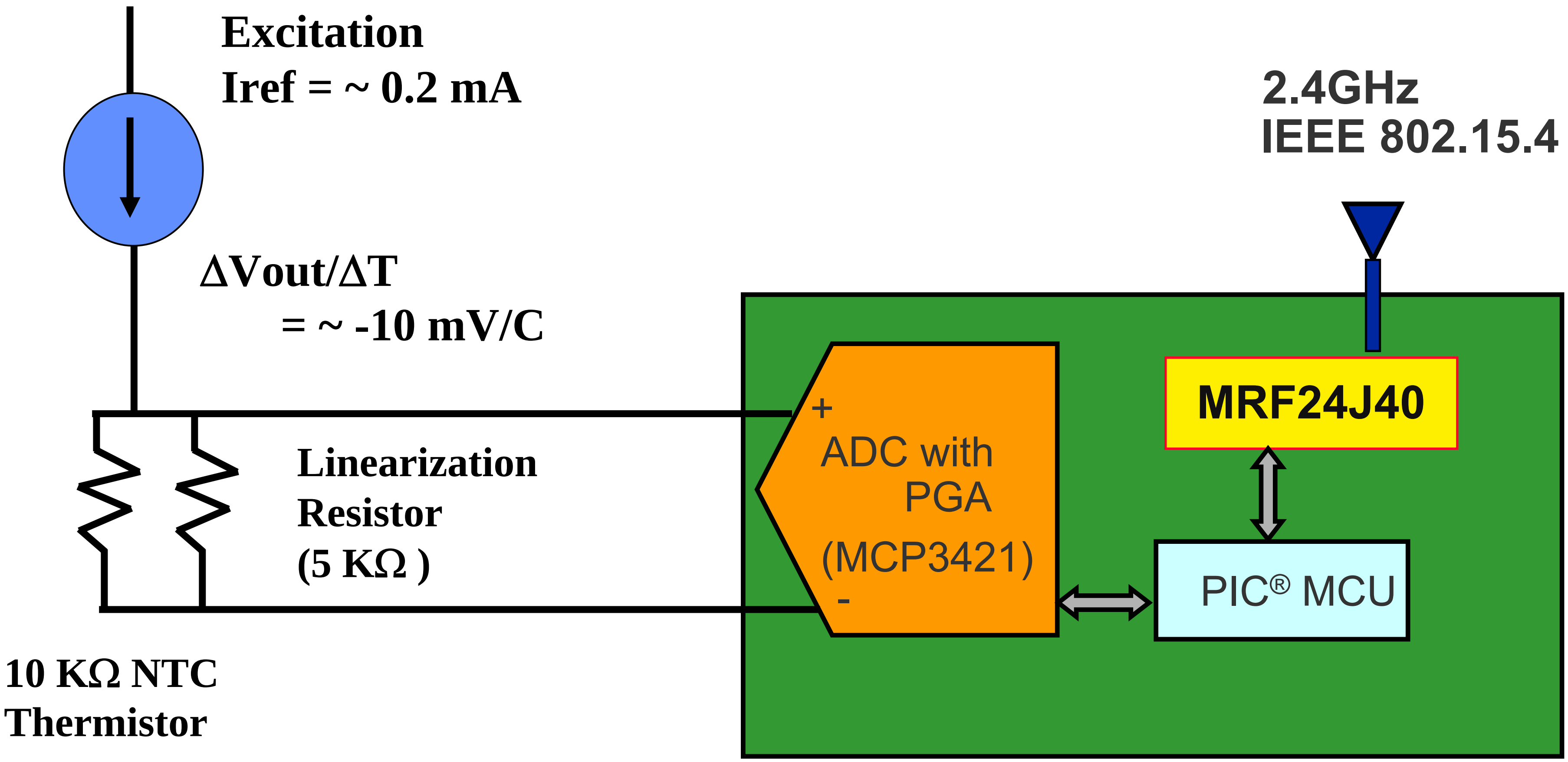
Thermistor Sensors

- Sensor Type: Two wire connections
- Sensor Excitation: Vref or Iref
- Output Configuration: Differential or Single-Ended
- Output Swing (full scale): 0 mV to 50 mV (typical)
  - Resistance changes from 32 Kohms to 2 kohms when temp changes from 0C to 100C
- Sensitivity: ~ -10 mV/C
- Applications: Medical equipment, engine coolant, oil and air temp measurement in transportation industry

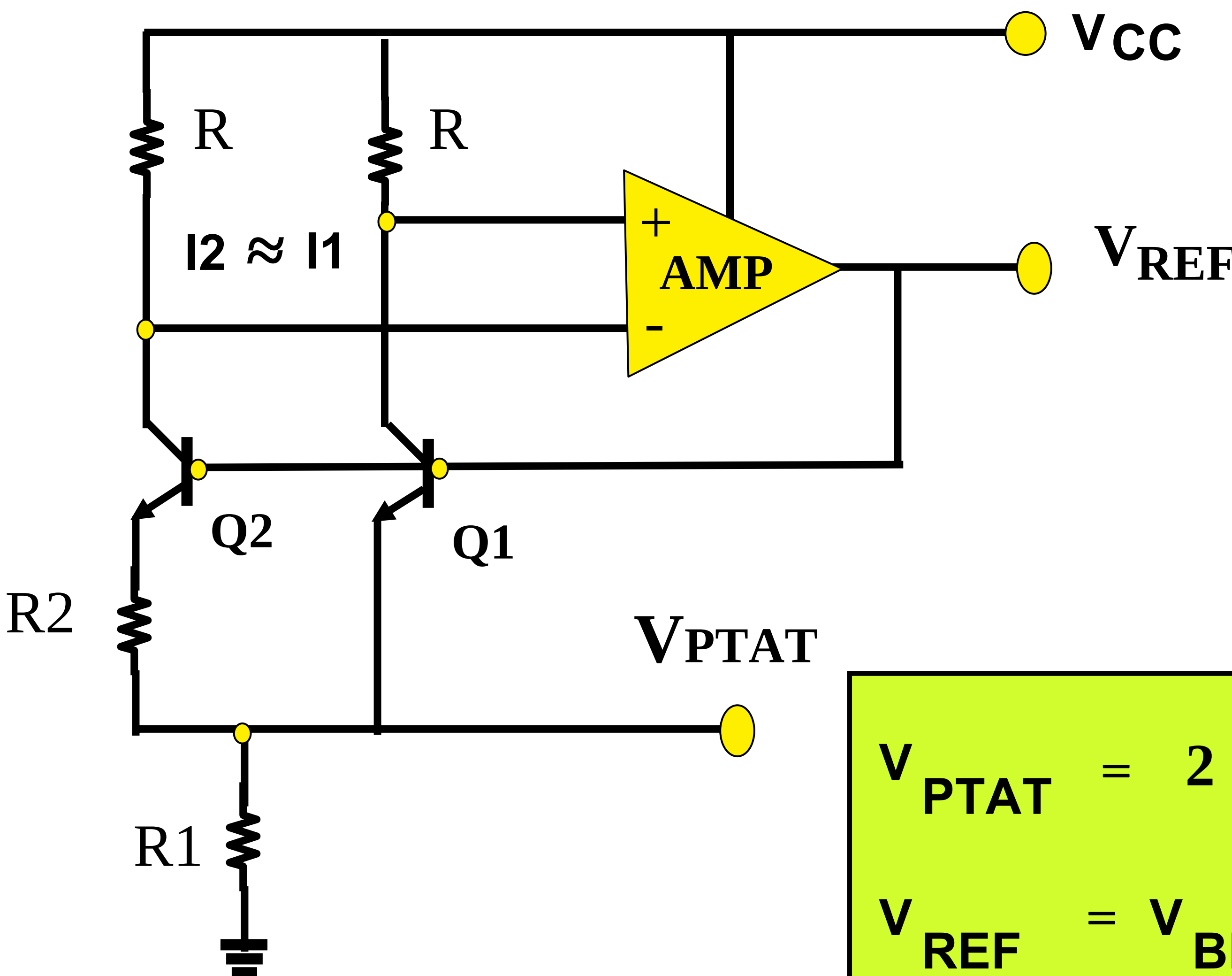
RF Thermistor Applications



Bandgap Temperature Sensors

- Sensor Configuration:
  - Brokaw Cell: OP Amp + two current sources + One diode, or OP Amp + one current source + Two diodes
- Output Configuration: Single End
- Sensitivity: ~ 10 mV/C
- Applications: Battery Management, Power supply (Over temp shutdown), Cellular/PCS (Power Amp's temp compensation, Thermal sensing), etc.

Silicon Temp Sensor Applications



$$V_{PTAT} = 2\frac{R1}{R2}\left(\frac{kT}{q}\right)\ln(N)$$

$$V_{REF} = V_{BE\ (Q1)} + V_{PTAT}$$

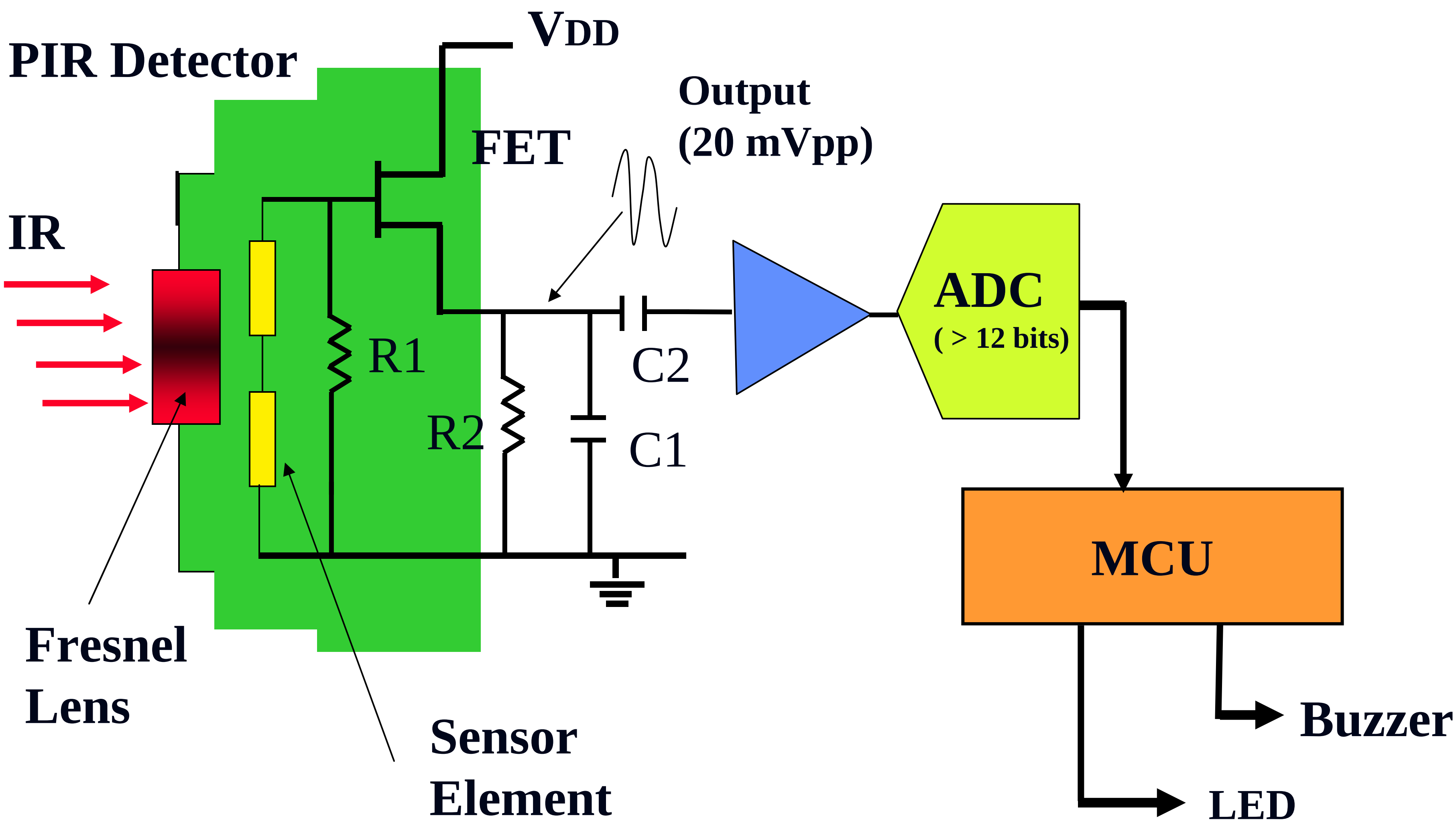
Temperature Sensor Summary

Sensor Type	Temp	Requirement	Sensitivity	Output
Thermocouple	-180C to 2000 C	Cold Junction Compensation	55 uV/C @J 39 uV/C @K	0 to 50 mV
RTD	-200C to 650 C	Current or Voltage Excitation	0.00385/Ω/ Ω /C	0 to 50 mV
Thermistor	-100C to 300C	Current or Voltage Excitation	-4.4 %/C @25C	~ 100 mV to ~ V
Bandgap	-50C to 150 C	Current Excitation	-2.2 mV/C	~ Volts

Humidity & Due Point

- **Sensor Type:** Capacitive (most common) , Resistive, or Thermal Conductive Measurement
- **Sensor Configuration:** Mostly two connection points (excitation input and output)
- **Sensor Excitation:**
  - AC excitation for Capacitive and Resistive Sensor: 5Vpp @ 30 Hz - 100 KHz range
  - DC Excitation for Thermal Conductive sensor
- **Sensitivity:** 0.2 ~ 0.5 pF for 1% RH change
- **Output Range:** 0 ~ 30 mV for Cap and Thermal,
  - a few volts for Resistive measurement
  - Capacitive: Between 100 and 500 pF
  - Resistive: 1 Kohm to 100 Mohms
- **Sensor Response Time:** 10 ~ 60 Sec

PIR Sensor Applications



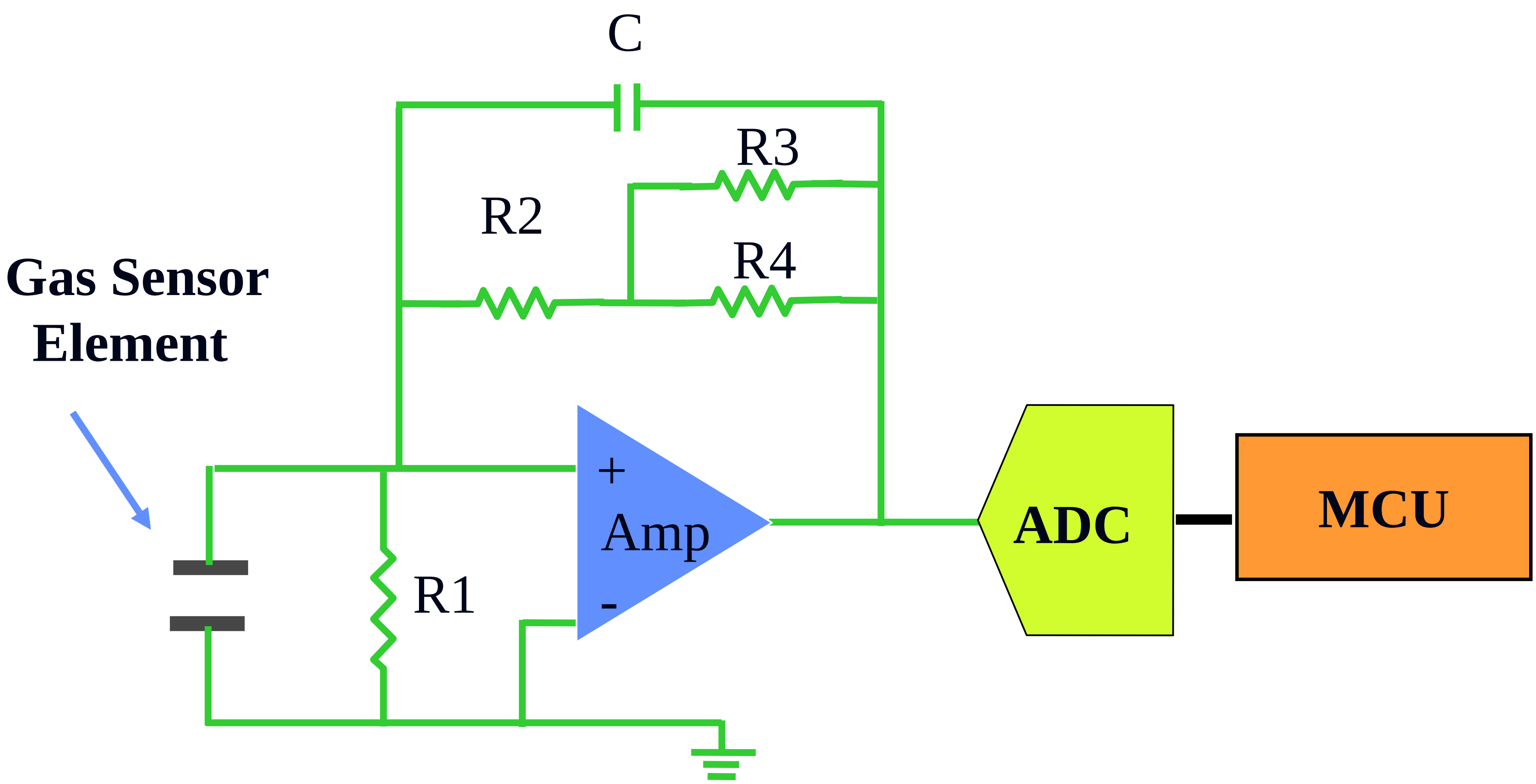
PIR Sensors

- Sensor Configuration: Three connections for FET (Drain, Source, Ground)
- Sensor Excitation (Supply Voltage): 2.5 - 15 V
- Sensor Output Configuration: Single Ended
- Sensor Output Swing: 0 to 20 mVpp @5Vsup
- Sensitivity: >1.3 mVpp
- Applications: Security (motion detection), Remote Temp Sensing, Flame Detection, Automatic Light Switches, Household Appliances, etc.

Hall Effect, Magnetic Field Magnetoresistive Sensors

- Sensor Configuration: Wheatstone Bridge (Typical)
- Sensor Excitation: Regulated Voltage
  - Excitation voltage: 5 V (typical), 12 V (max)
- Sensor Output Configuration: Differential
  - Excitation voltage: 5 V (typical), 12 V (max)
- Sensor Output Swing: ~ - 30 mV to 30 mV @5Vsup
- Sensitivity: ~ 1 mV/V/Gauss
- Applications: Electronic Compass, Automotive Pedal Position sensing, Position and Angular Sensing, Medical, etc.

Gas Sensor Applications



Gas Sensors

- Example: CO Detector
- Sensor Configuration: Two or three electrodes. Mostly four pin connections
- Sensor Supply Voltage: 2 V to 12 V
- Sensitivity: ~ 50 nA/PPM
- Detection Range: 0 to 1000 PPM
- Sensor Response Time: < 50 sec

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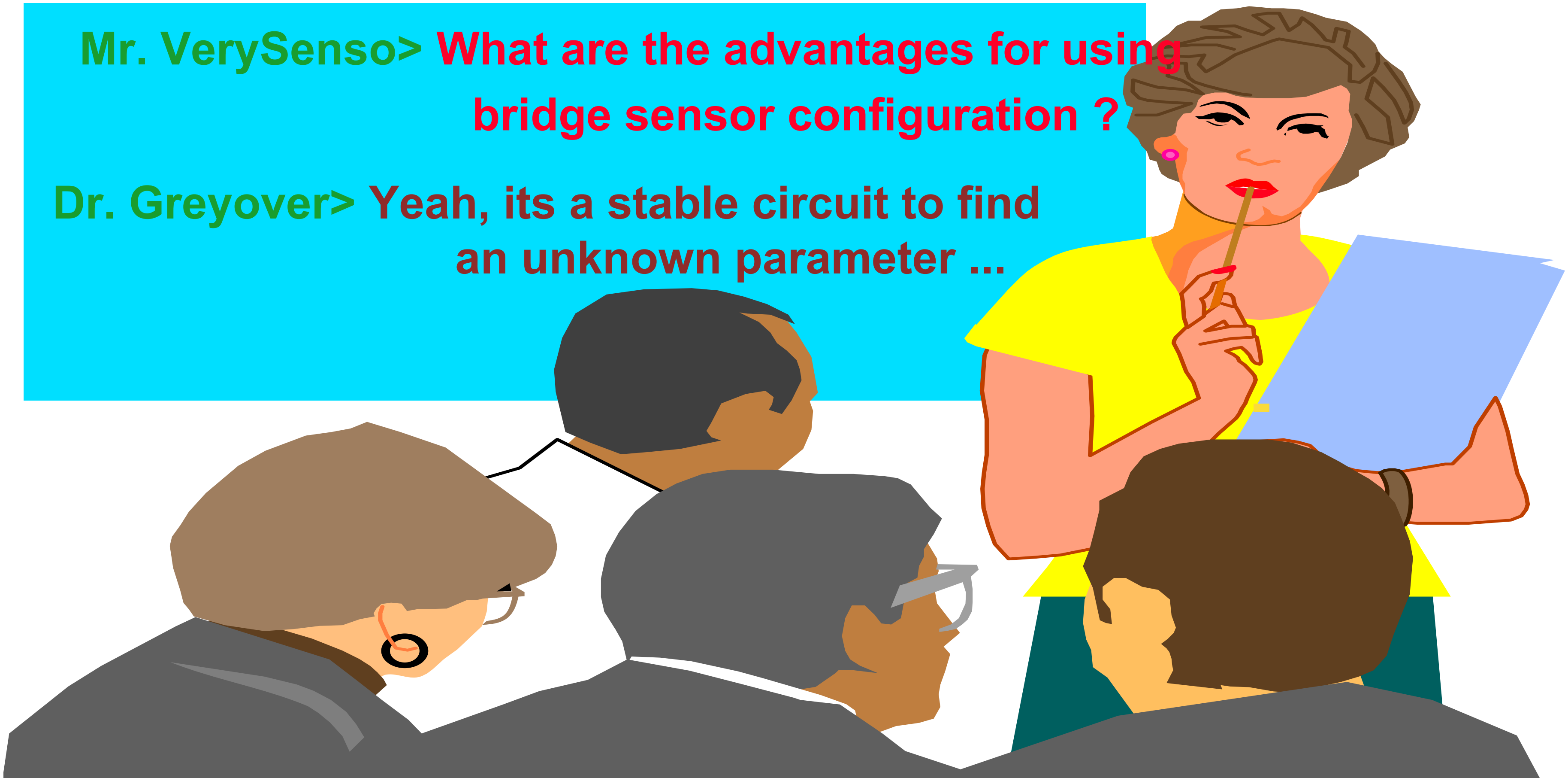
Sensor Interface Summary

Type	Configuration	Excitation	Outputs	Output Range	Sensitivity
Pressure	Wheatstone Bridge	5V(typ), 12V(max) 2mA ~ 20mA	Differential	Typ: 10mVpp~50mVpp, Mostly > 4mVpp	~1mV/PSI Response <100us
Thermocouple	Type J & K	Not Needed	Differential	Type J : 0 ~ 41mV Type K : 0 ~ 50mV	Type J : 55uV/C Type K : 39uV/C
Thermistor	Two wire connections	Vref or Iref	Differential Single-ended	Typ: 0mV ~ 50 mV Resistance 32K ~ 2K	Typ: ~10mV/C
RTD	Two/Three/Four wire (Kelvin)	Vref or Iref > 0.2mA	Differential	Typ: 0mV ~ 50mV	0.00385 ohm/ohm/C
Bandgap	Brokaw Cell	Need Vref or Iref	Single-ended	~ Volts	~10mV/C
Humidity	Capacitive, Resistive or Thermo Conductive	AC/DC 5Vpp@30Hz-100kHz	Single-ended	Cap : 0~30mV 100~500pF) Resistive: Few Volts (1K ~ 1Mohm)	0.2~0.5pF
PIR	FET Connections Drain, Source, GND	2.5V ~ 15V	Single-ended	0 ~ 20mVpp @ 5Vsupl	~1.3mVpp
Hall Effect	Wheatstone Bridge	Regulated 5V(typ), 12V(max)	Differential	-30mV ~ +30mV @5Vsupl	~1mV/V/Gauss
Gas	2/3 electrodes Typ: 4 pins	2V ~ 12V	Differential	0 ~ 2V	~50nA/PPM

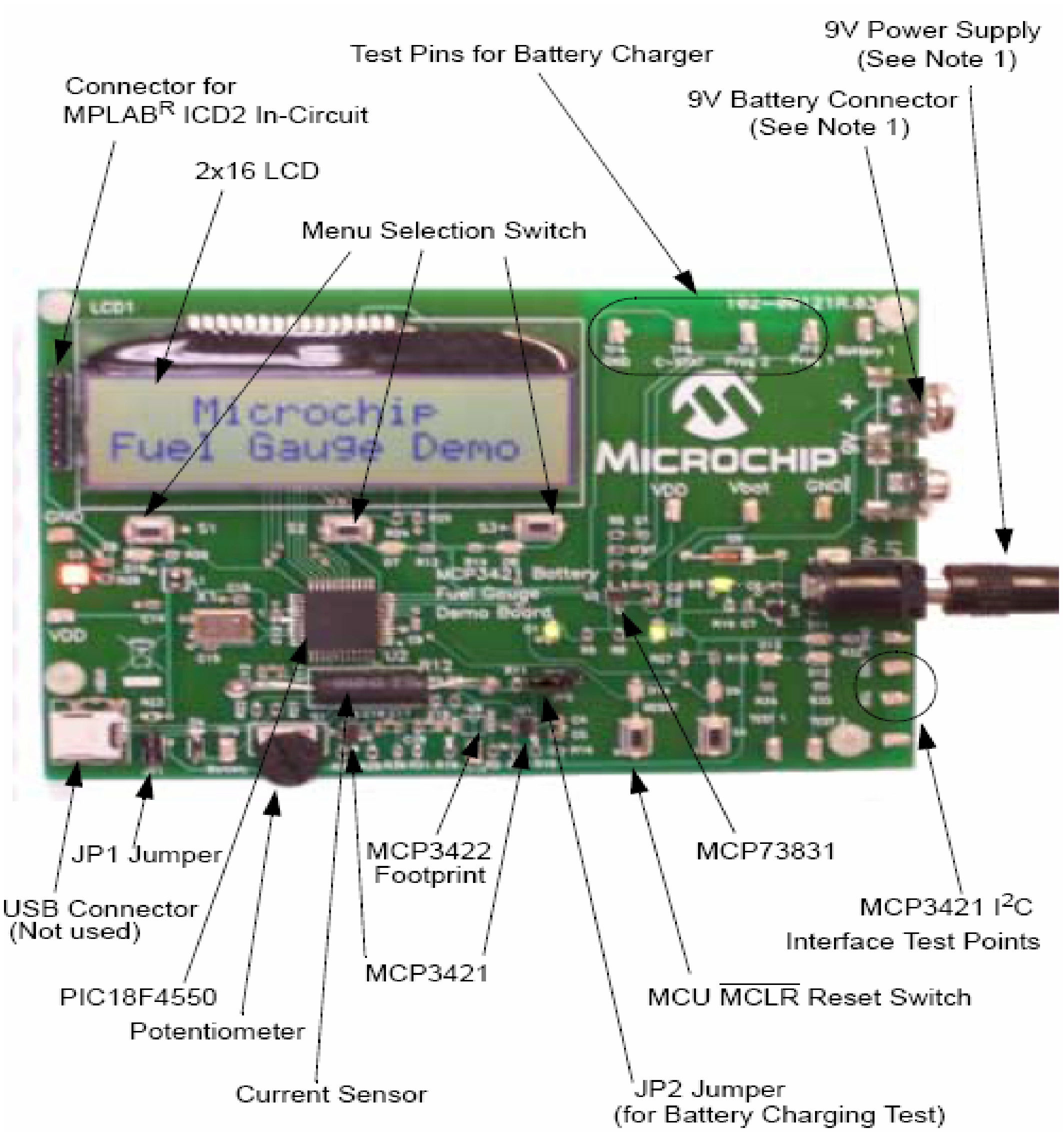
Questions?


Mr. VerySenso> What are the advantages for using bridge sensor configuration ?
Dr. Greyover> Yeah, its a stable circuit to find an unknown parameter ...

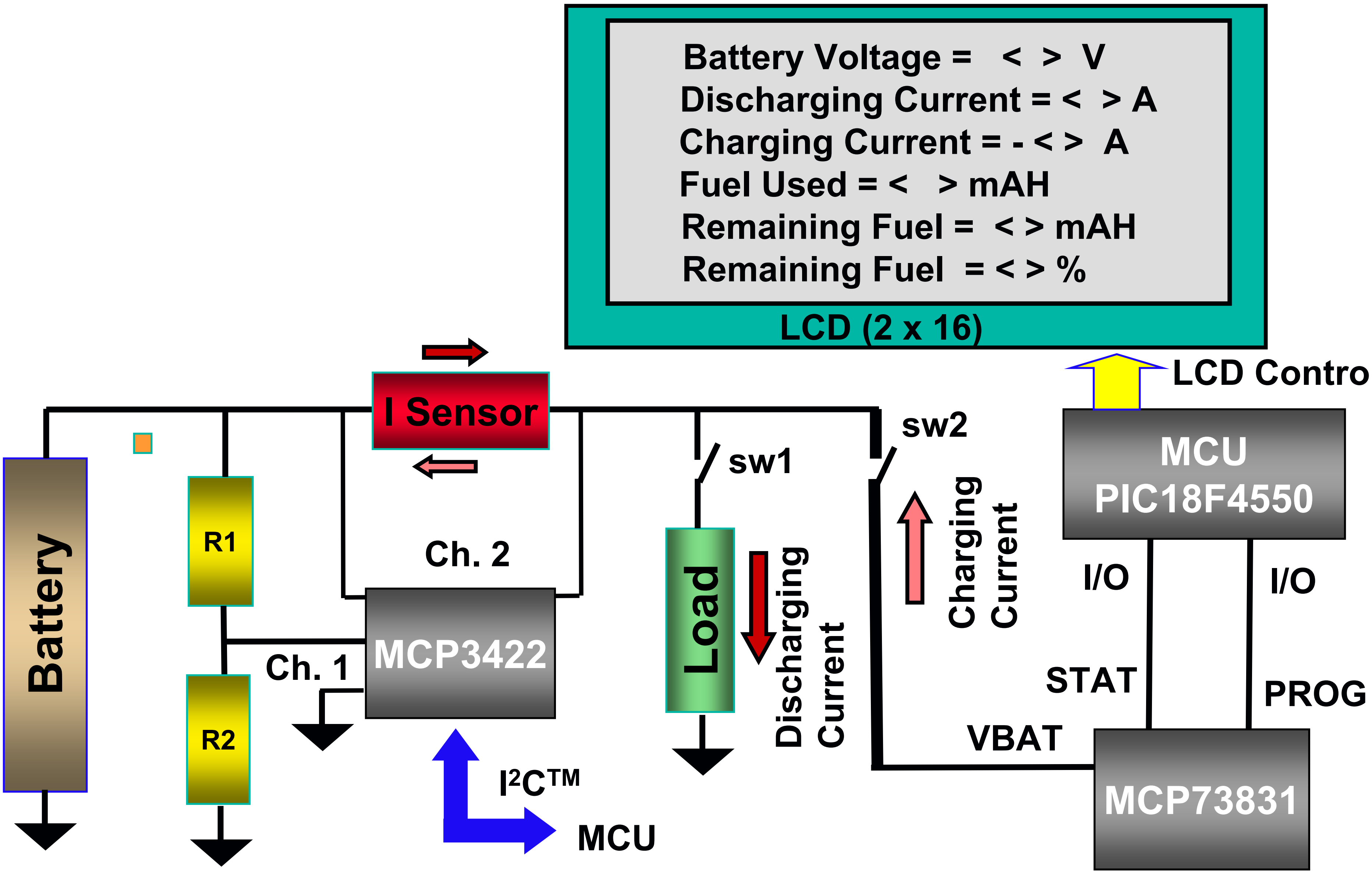
Section 6

Hands-On Class: MCP3421 Battery Fuel Gauge

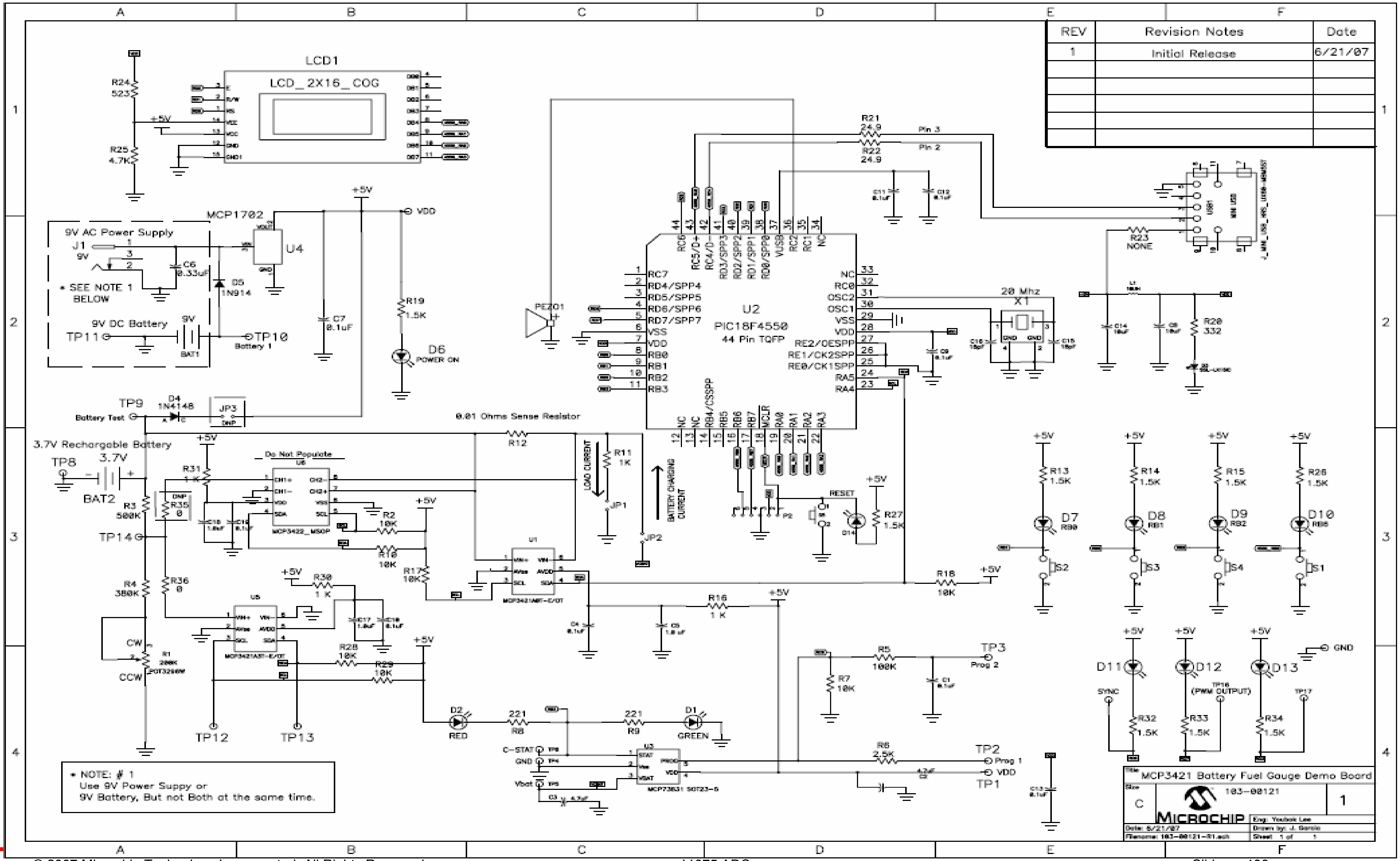
Battery Fuel Gauge Demo Board



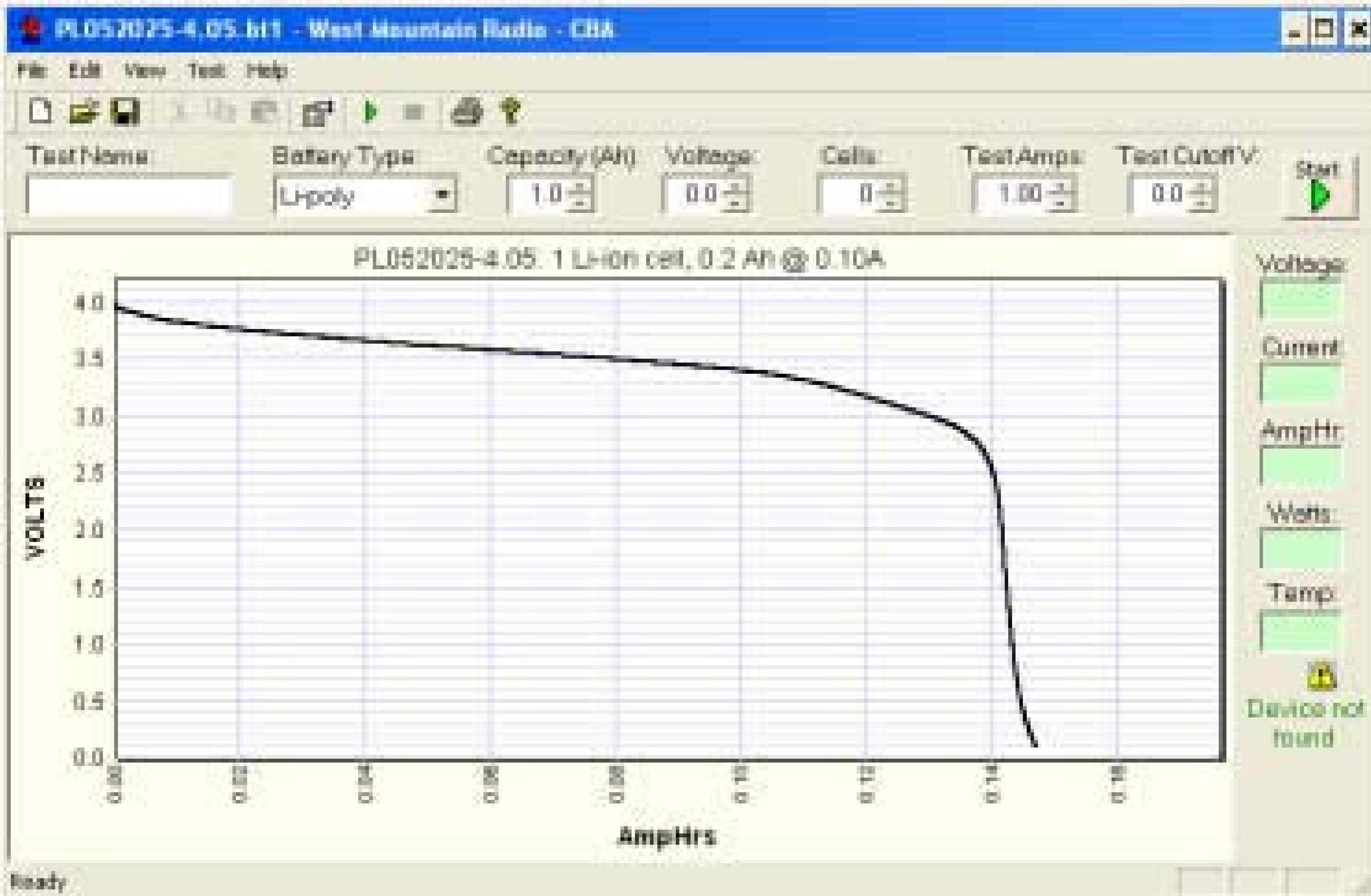
Battery Fuel Gauge Diagram



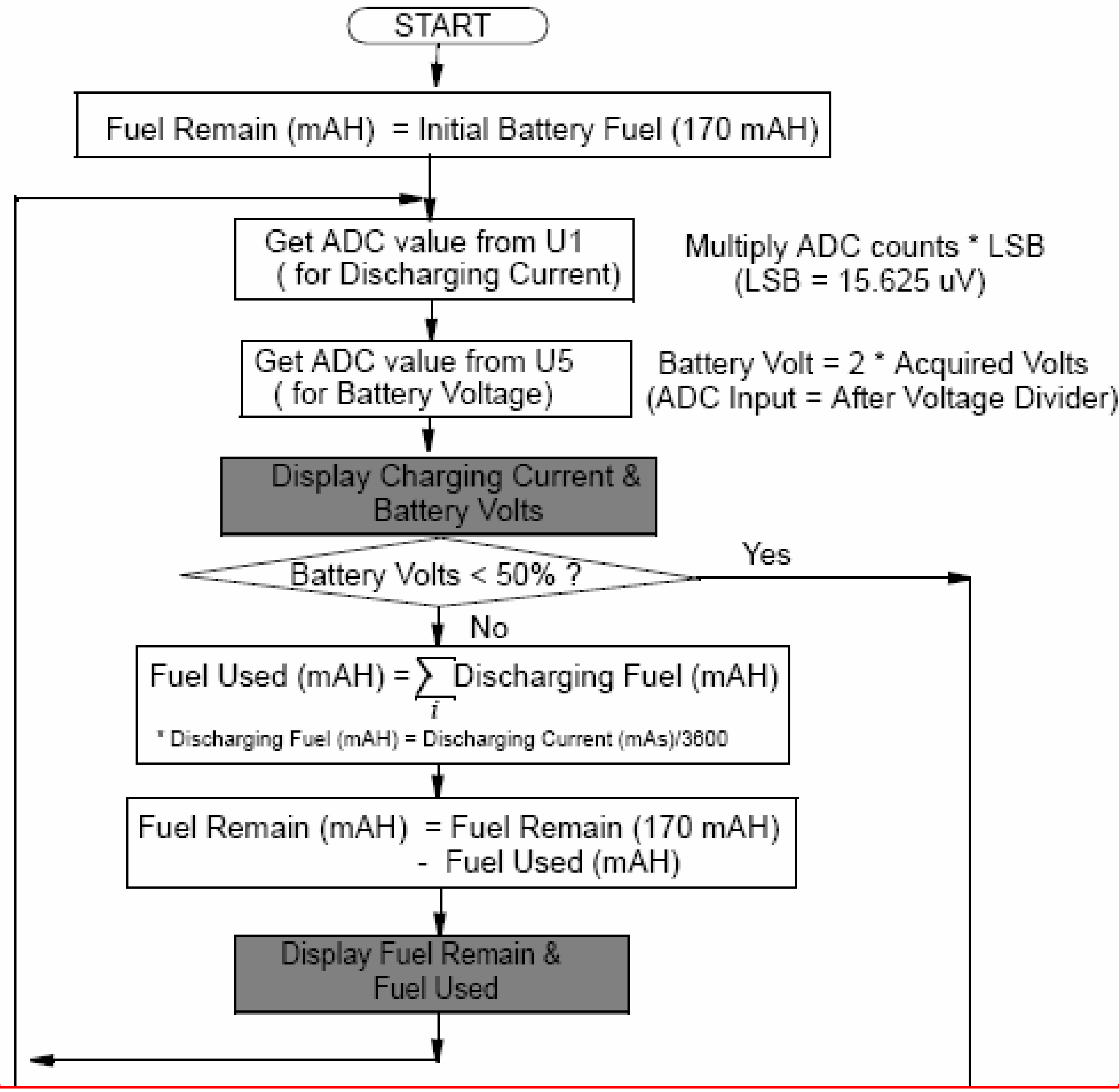
Battery Fuel Gauge Schematics



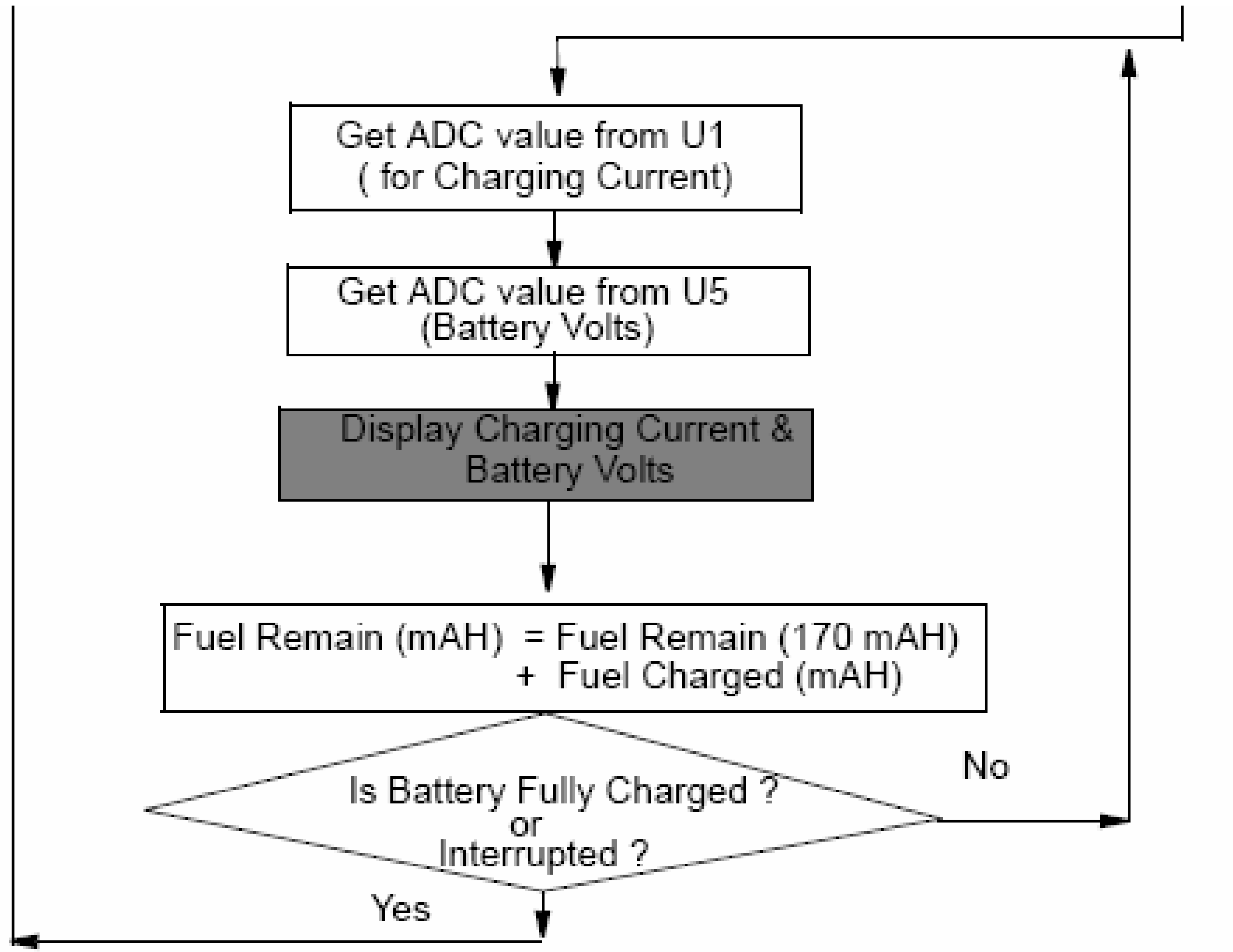
Li-Polymer Battery Characteristics



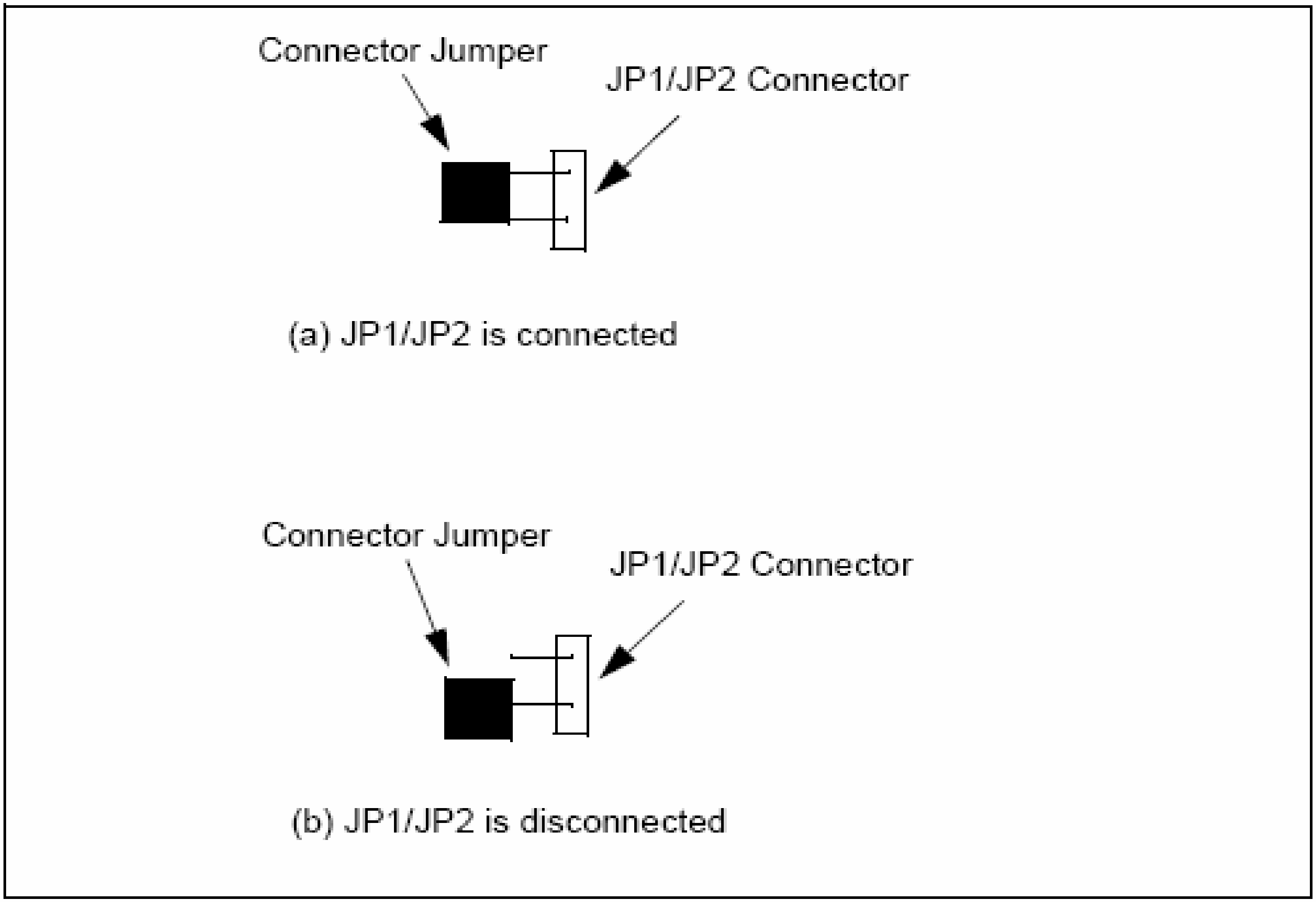
Computation Algorithm



Computation Algorithm



JP1 and JP2 Connectors



Experiment with 1.5 V AAA Battery

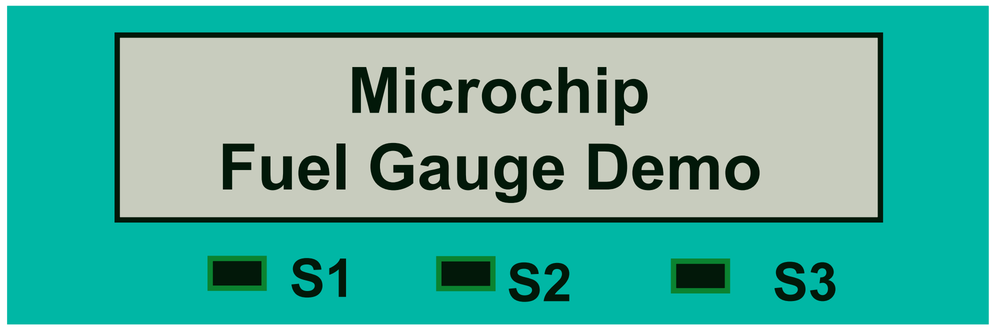
- **Step 1: Connect JP2 and disconnect JP1.**
- **Step 2: Connect 9V Power Supply or 9V Battery to the Demo Board.**

Note: Do not connect both.

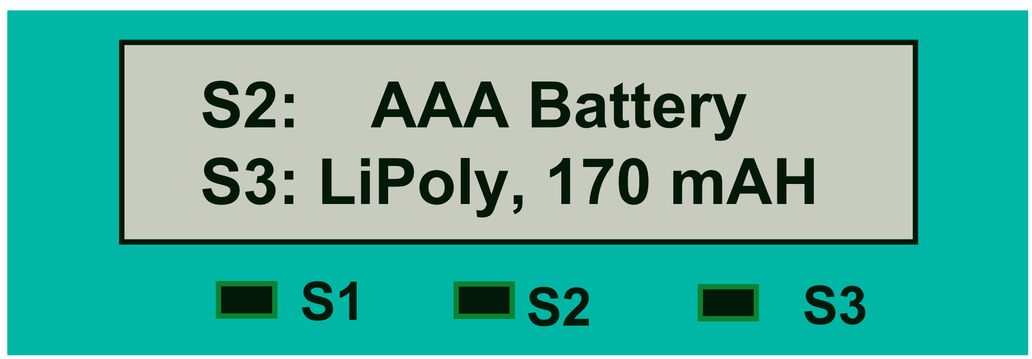
- **Step 3: Connect AAA-1.5V Battery clips to the BAT2 (+ RED) and Gnd (- Black).**

Experiment with 1.5 V AAA Battery

- **Step 4:** The LCD will display the following message:

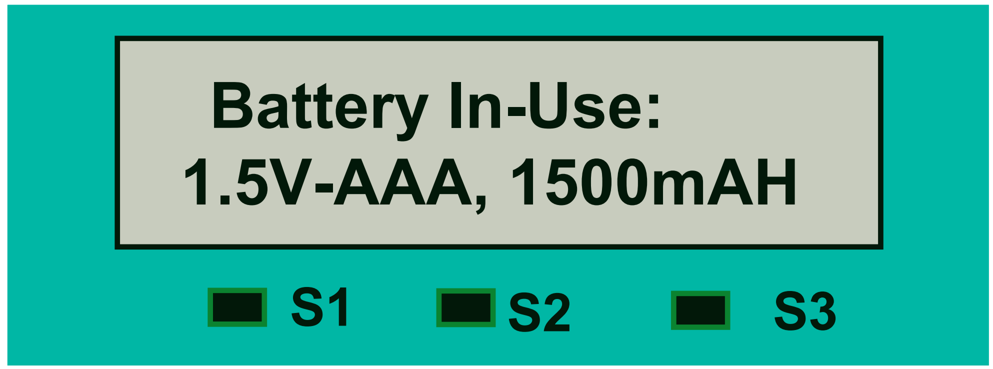


- **Step 5:** Press S3, the LCD will display the following message:



Experiment with 1.5 V AAA Battery

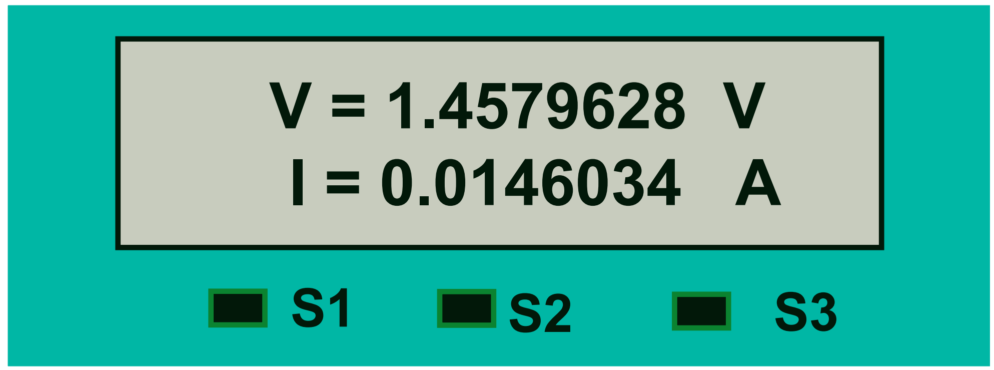
- **Step 6: Press S2, the LCD will display the following message:**



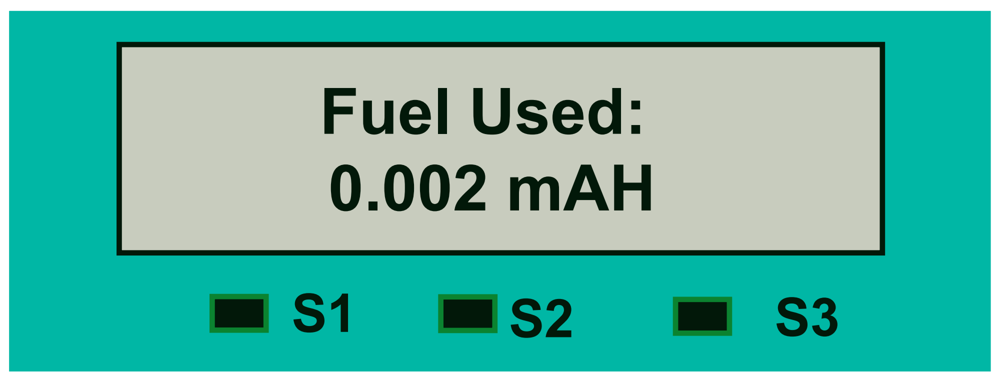
- **Step 7. Press S3, the LCD will display the following message:**

Experiment with 1.5 V AAA Battery

- **The LCD will display the Battery Voltage and Current:**



- **A second later, the LCD will display the fuel used:**



Experiment with Rechargeable 4.2 V Li-Polymer Battery

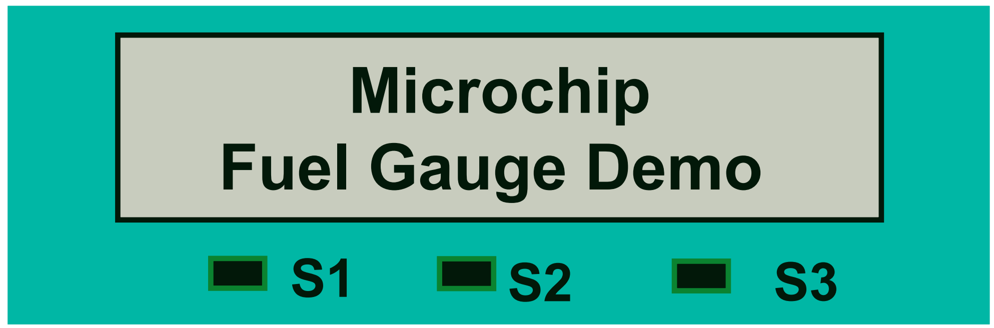
- **Step 1: Connect JP2 and disconnect JP1.**
- **Step 2: Connect 9V Power Supply or 9V Battery to the Demo Board.**

  Note: Do not connect both.

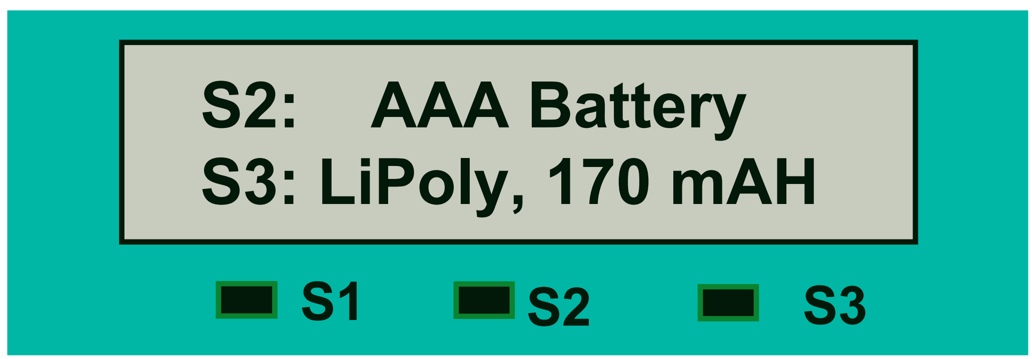
- **Step 3: Connect 4.2V Li-Poly Battery clips to the BAT2 (+ RED) and Gnd (- Black).**

Experiment with Rechargeable 4.2 V Li-Polymer Battery

- **Step 4: The LCD will display the following message:**

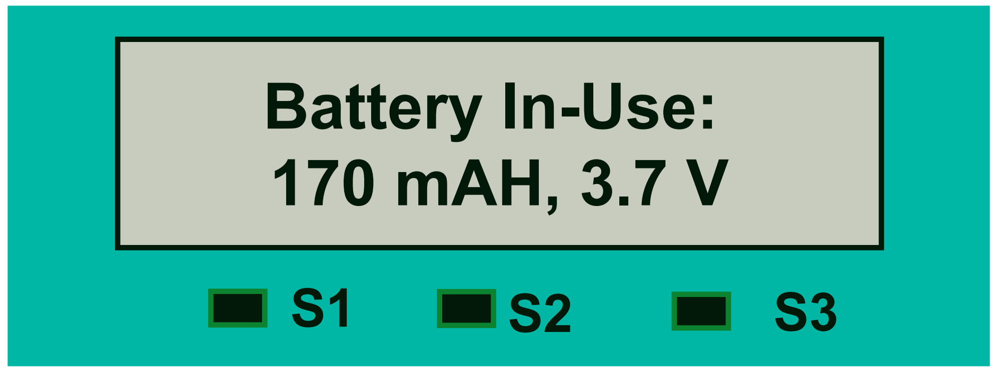


- **Step 5: Press S3, the LCD will display the following message:**



Experiment with Rechargeable 4.2 V Li-Polymer Battery

- **Step 6: Press S3, the LCD will display the following message:**

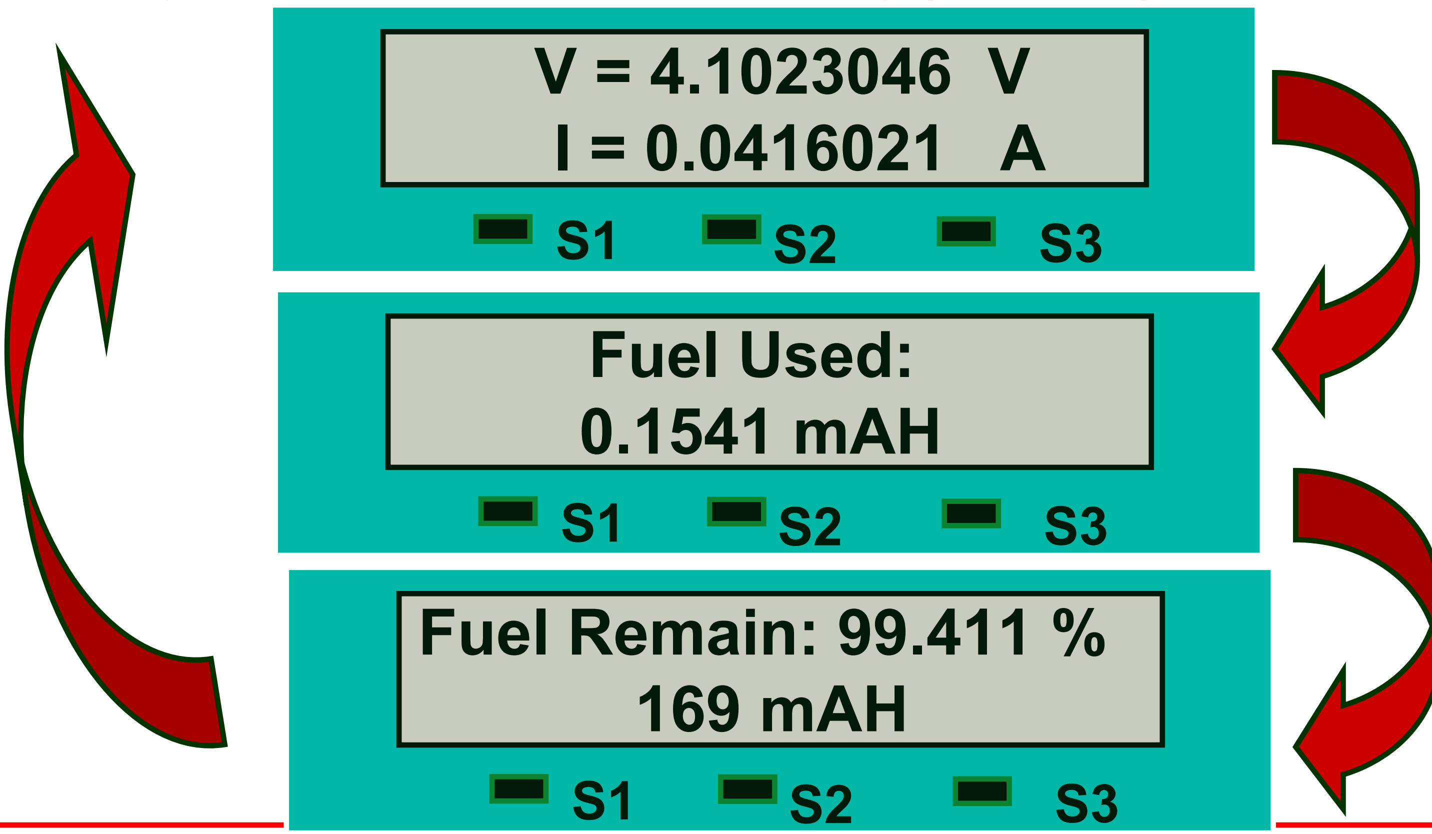


- **Step 7. Press S3, the LCD will display the following message:**

Experiment with Rechargeable 4.2 V Li-Polymer Battery

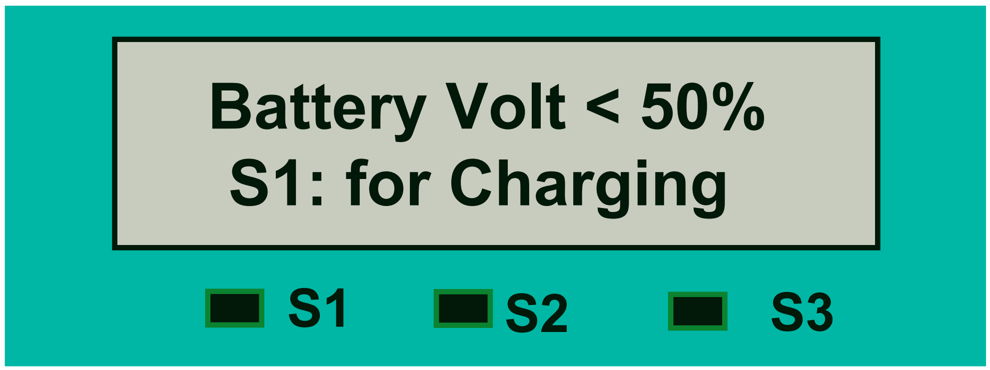
- **Step 8:** **The LCD will display (A) Battery Voltage and Current, (b) Fuel Used and (c) Fuel Remain by itself.**

Note: The device calculates the Fuel Remain under assumption that the battery is started with a 100% capacity (170 mAH).



Experiment with Rechargeable 4.2 V Li-Polymer Battery

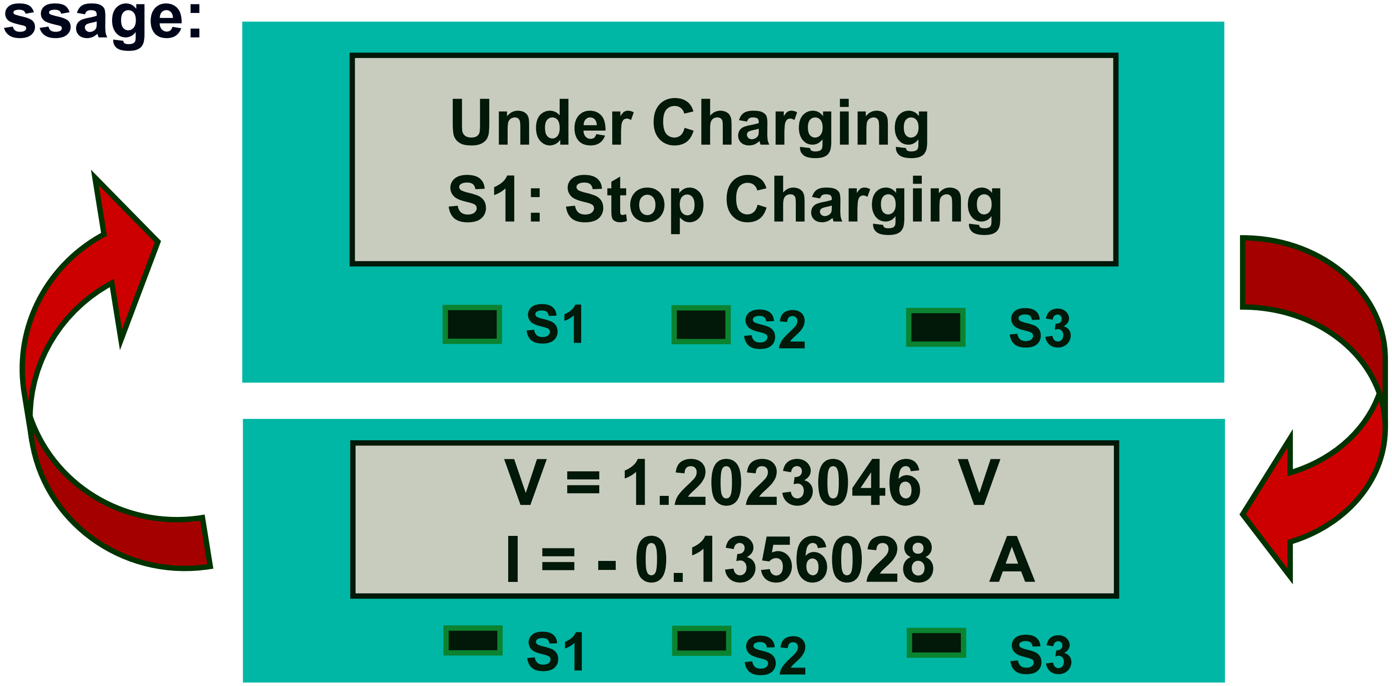
- **Step 9: If the battery voltage drops below 50% (2 V), then the LCD will display:**



- **Step 10. Disconnect JP2 and Connect JP1. This allows the current flows into the battery from the Battery charger output (U3).**

Experiment with Rechargeable 4.2 V Li-Polymer Battery

- **Step 11: Press S1, the LCD will display the following message:**



- **Step 12: During charging, the LCD will display Battery Volts and Current.**

Note that the negative sign of the current.

Experiment with Rechargeable 4.2 V Li-Polymer Battery

- **Step 13. The device will exit charging mode if the Battery voltage is greater than 4.2 V (fully charged) or if you press S1.**

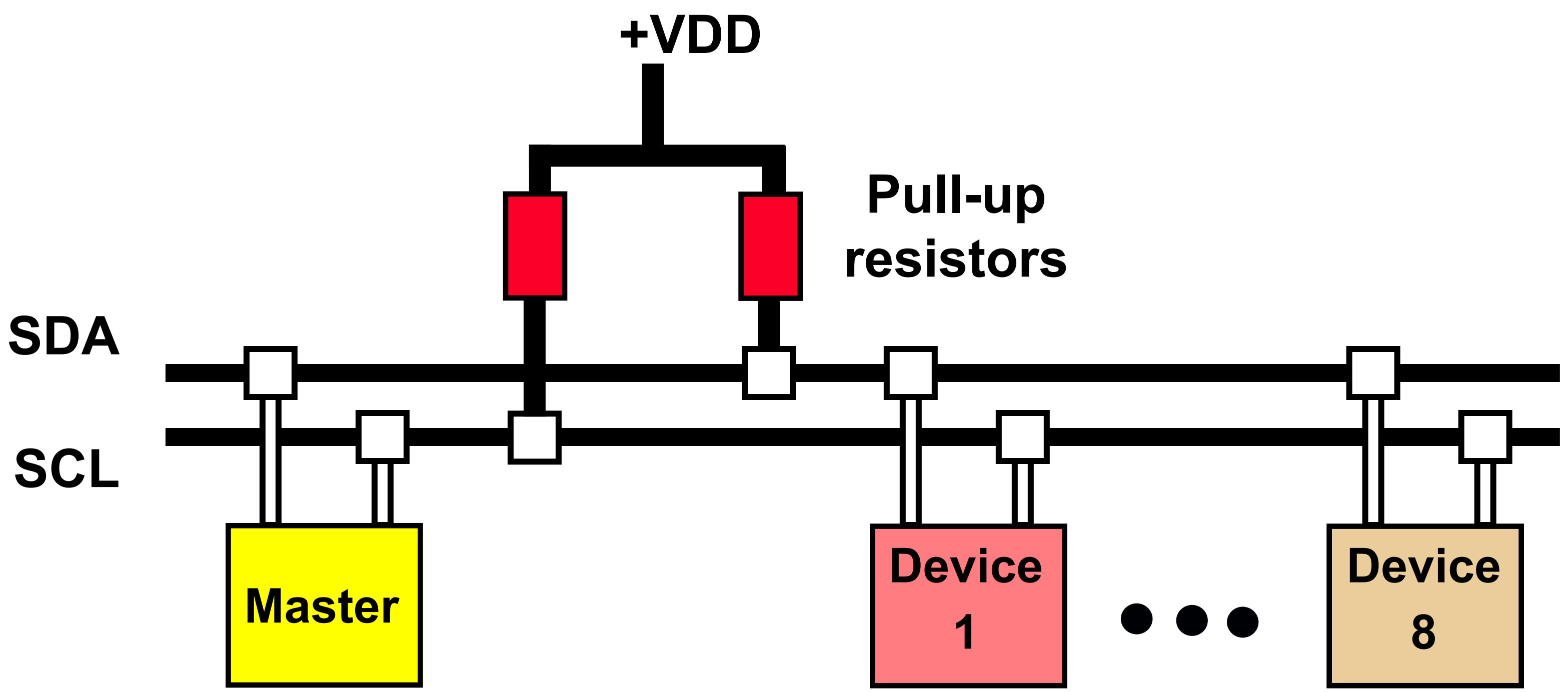
- **Step 14: Once the it exits the charging mode, disconnect JP1 and connect JP2.**

- **The device will repeat Step 8 ...**

MCP3421 I^2C^{TM} Communication Test

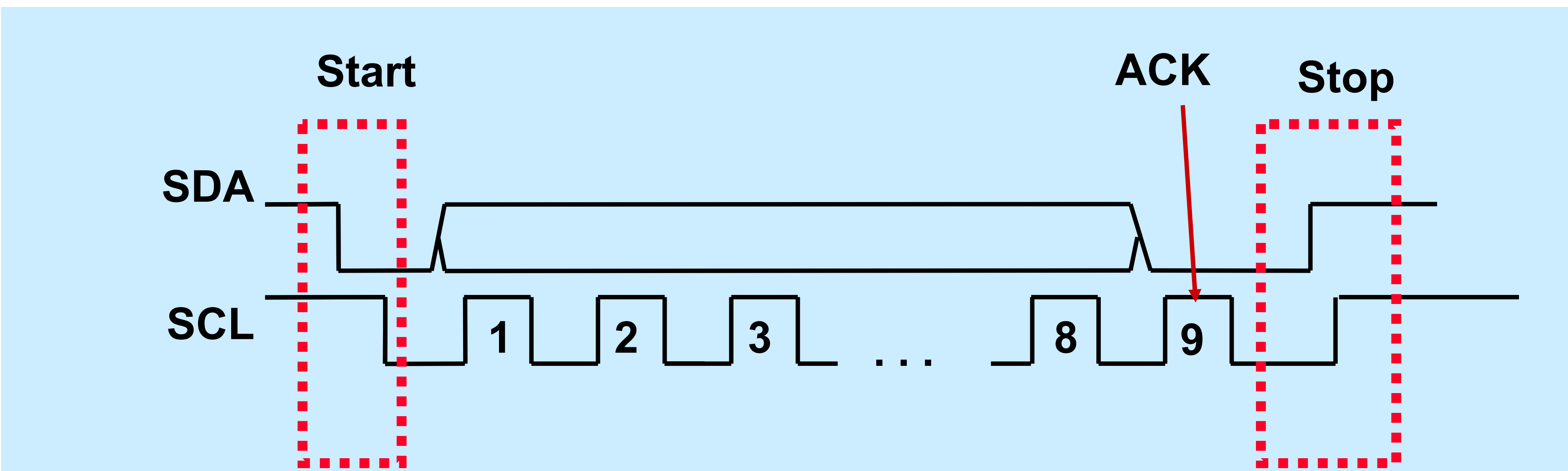
1. Connect Oscilloscope Probe 1 to SCL test point.
2. Connect Oscilloscope Probe 2 to SDA test point.
3. Connect Oscilloscope Probe 3 to Sync test point.
4. Set Oscilloscope Trigger to Ch.3.
5. See Figs 5-4 and 5-2 of the MCP3421 Data Sheet.

I^2C™ Hardware Overview

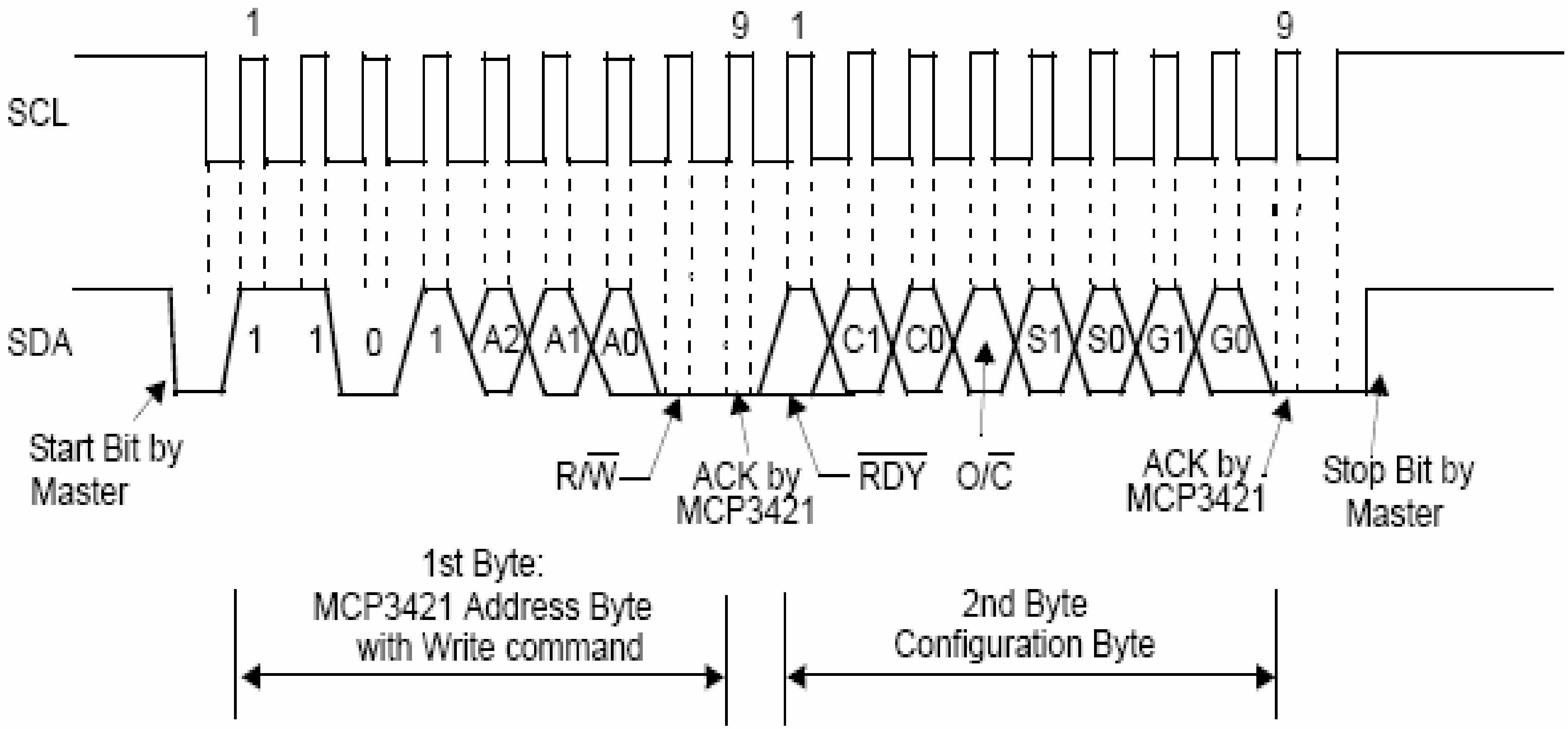


I^2C^{TM} Communication

- **Start** and **Stop** Condition:
  - Generated by Master
  - After Start Condition: Bus is Busy
  - After Stop Condition: Bus is Free

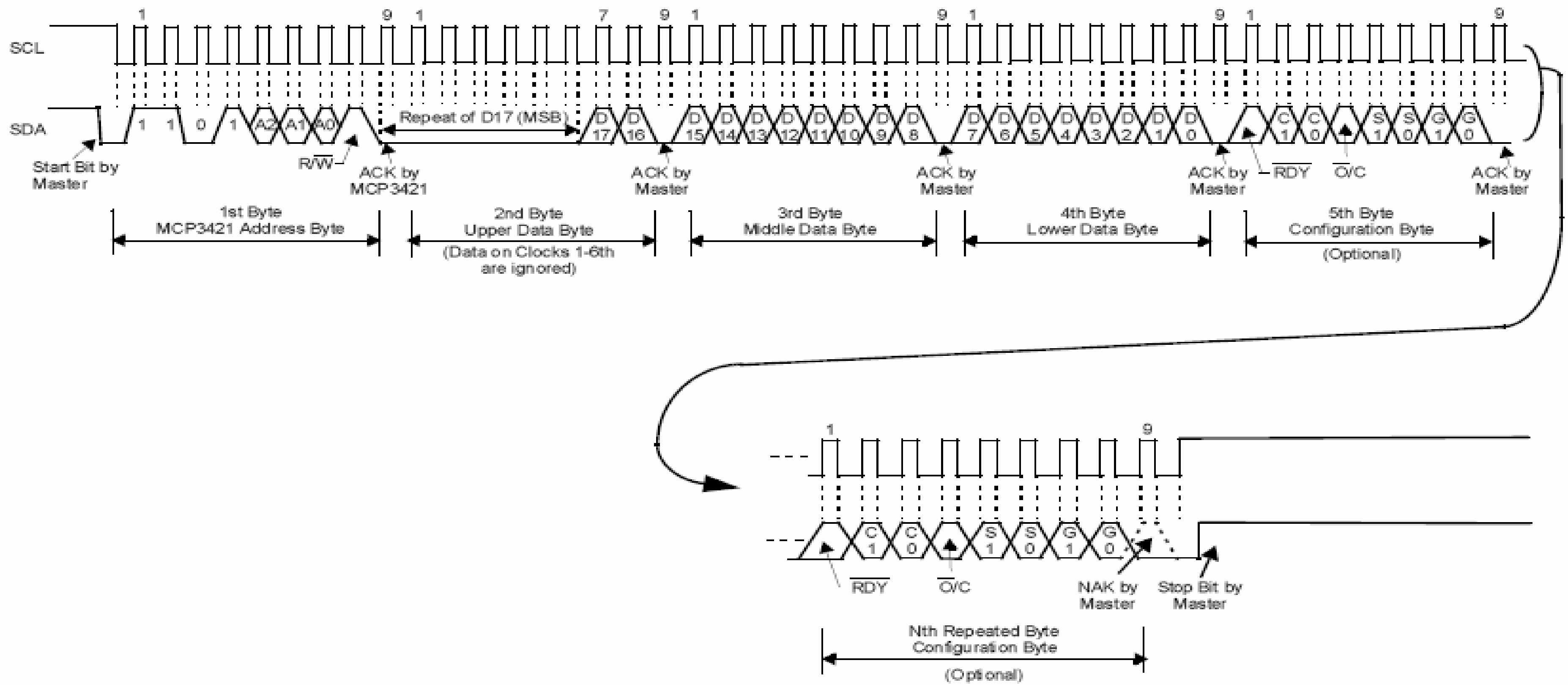


MCP3421 I^2C^{TM} Communication



Note:
- Stop bit can be issued any time during writing.
- **MCP3421** device code is 1101.
- Address Bits A2- A0 = 000 are programmed at factory unless customer requests different codes.

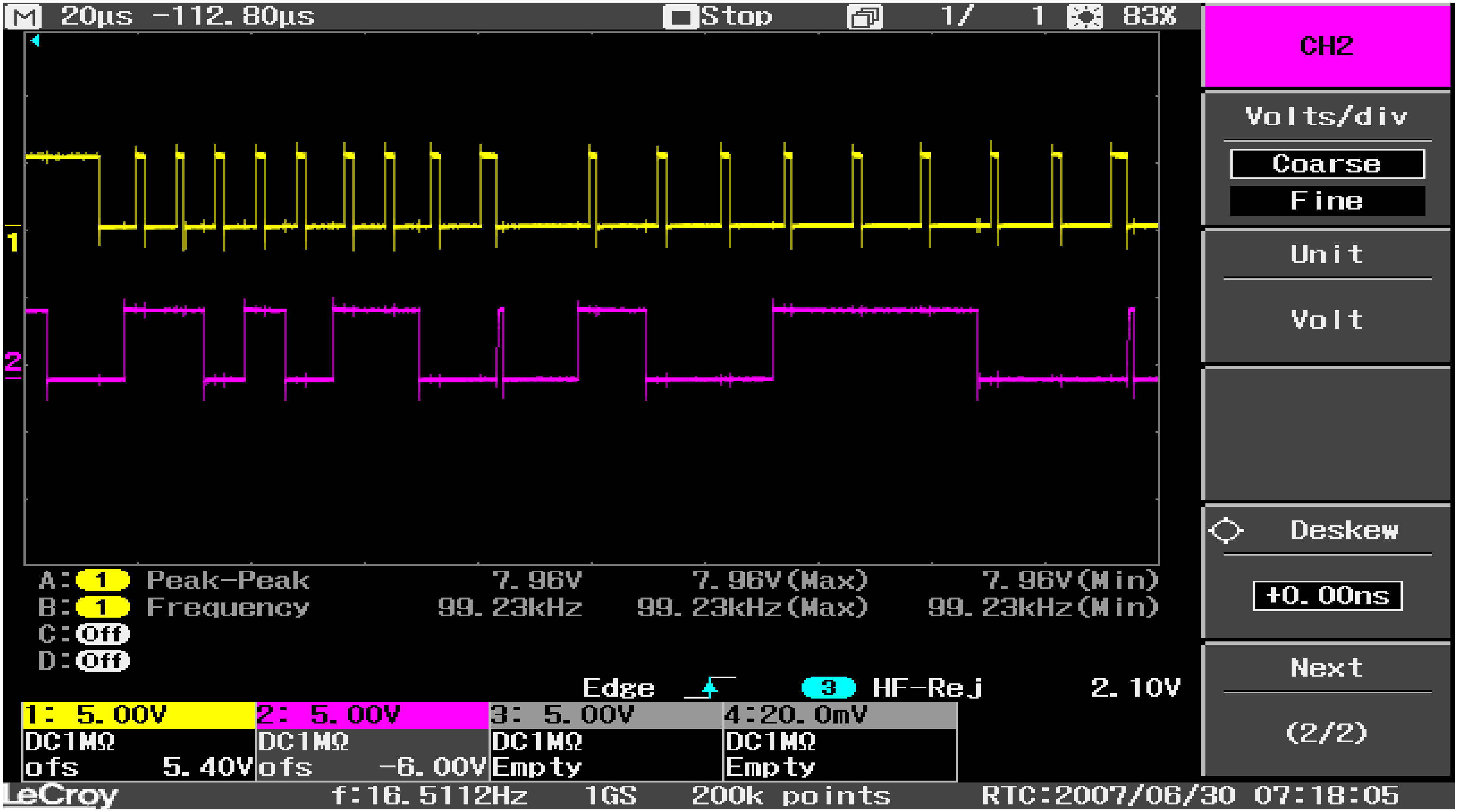
MCP3421 I²C™ Communication



Note:
- – MCP3421 device code is `1101`.
- – Address Bits A2- A0 = `000` are programmed at the factory unless customer requests specific codes.
- – Stop bit or NAK bit can be issued any time during reading.
- – Data bits on clocks 1 - 6th in 2nd byte are repeated MSB and can be ignored.

MCP3421 I²C™ Communication Test

A. Writing Configuration Register



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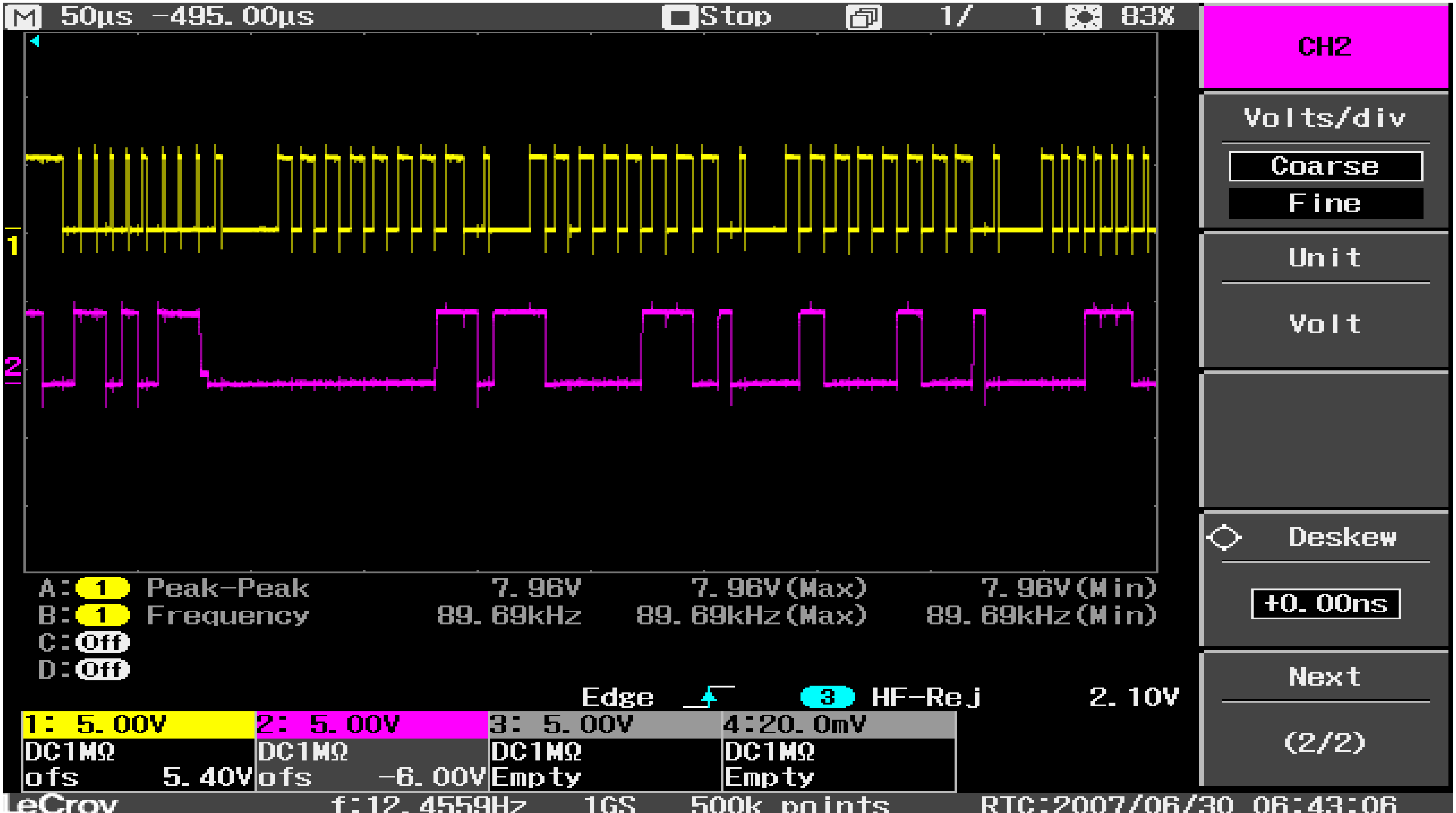
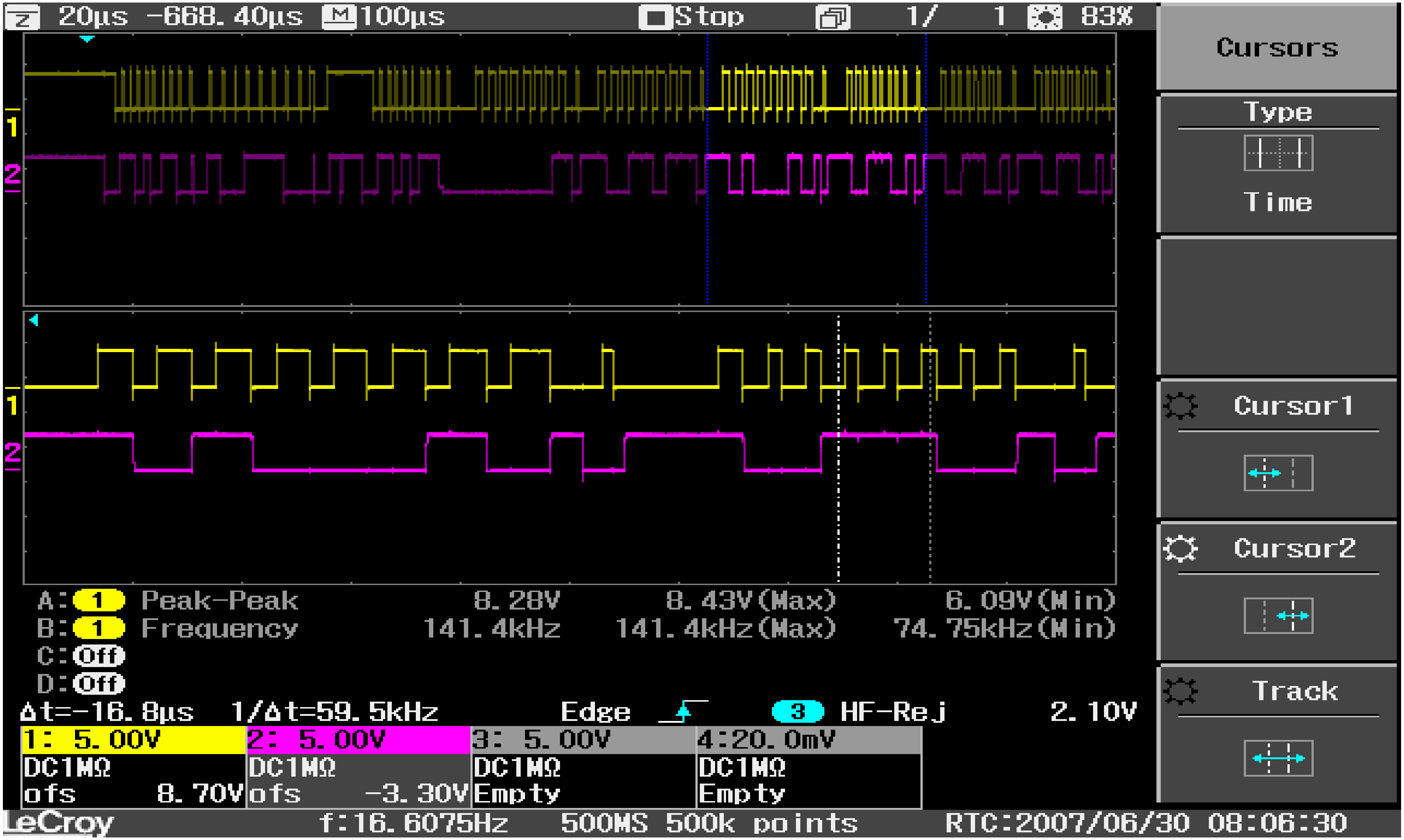
MCP3421 I^2C^{TM} Communication Test

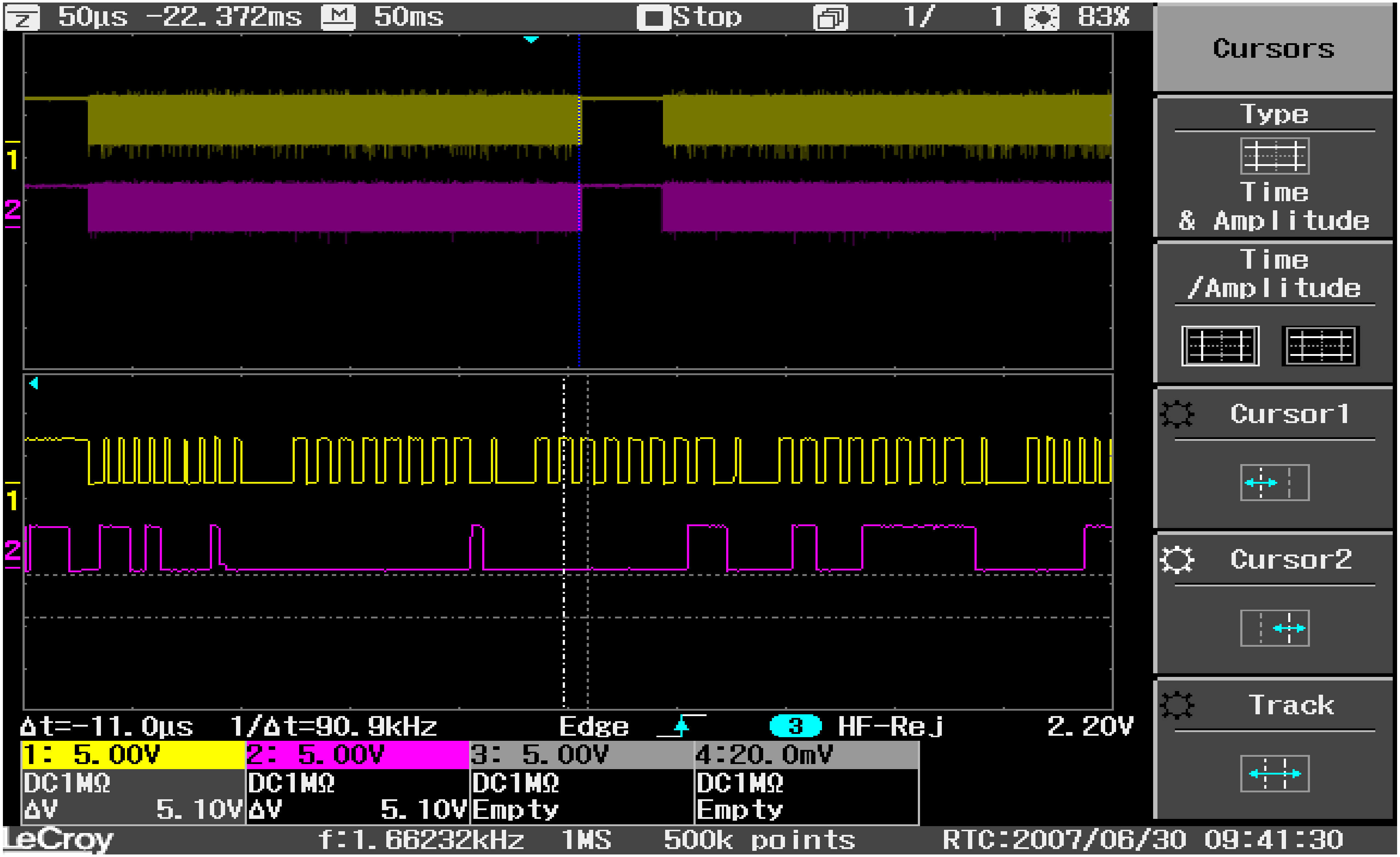
B. Reading Conversion Data



MCP3421 I^2C^{TM} Communication Writing and Reading



MCP3421 I^{2}C^{TM} Communication Test: Continuous Conversion Mode



MCP3421 I^2C^{TM} Communication Test

Questions:

1. What is the Device Address ?
2. What is the PGA setting ?
3. What is the operating bit mode ?
   (12, 14, 16, or 18 bits)
4. How long it takes to finish one conversion ?
5. What is the ADC Value ?

Questions?

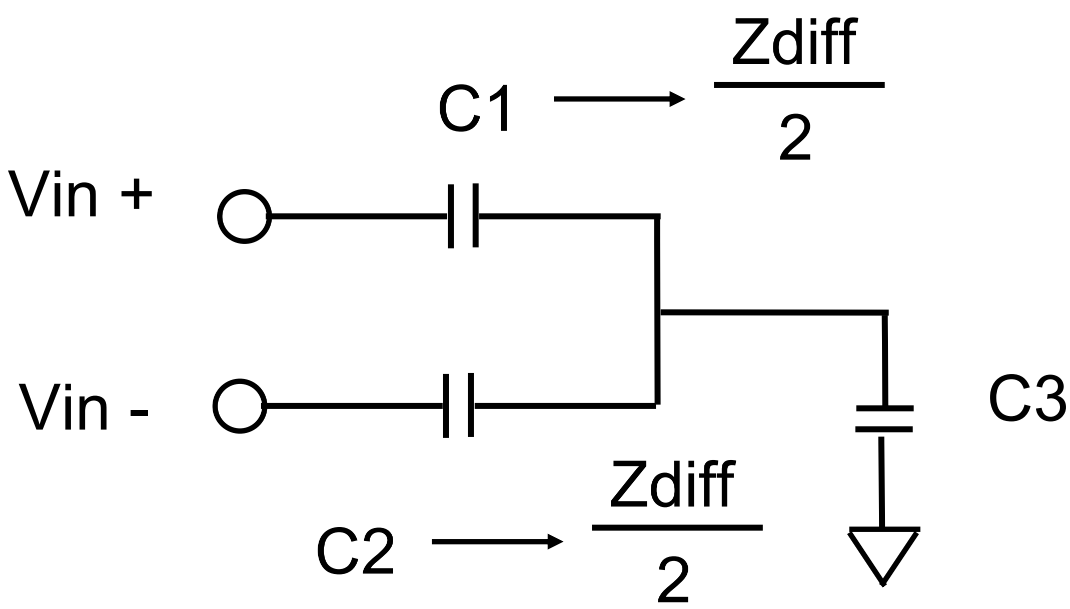
Ms. Changestop> Can I modify this demo kit for other purposes ?

Dr. Easisayer> Of course. Its made for easy modifications .....

Thank You!

Appendix

MCP3421 Input Structure



Values of C1 and C2 change with PGA Settings

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