

MSP430 Advanced Technical Conference 2006



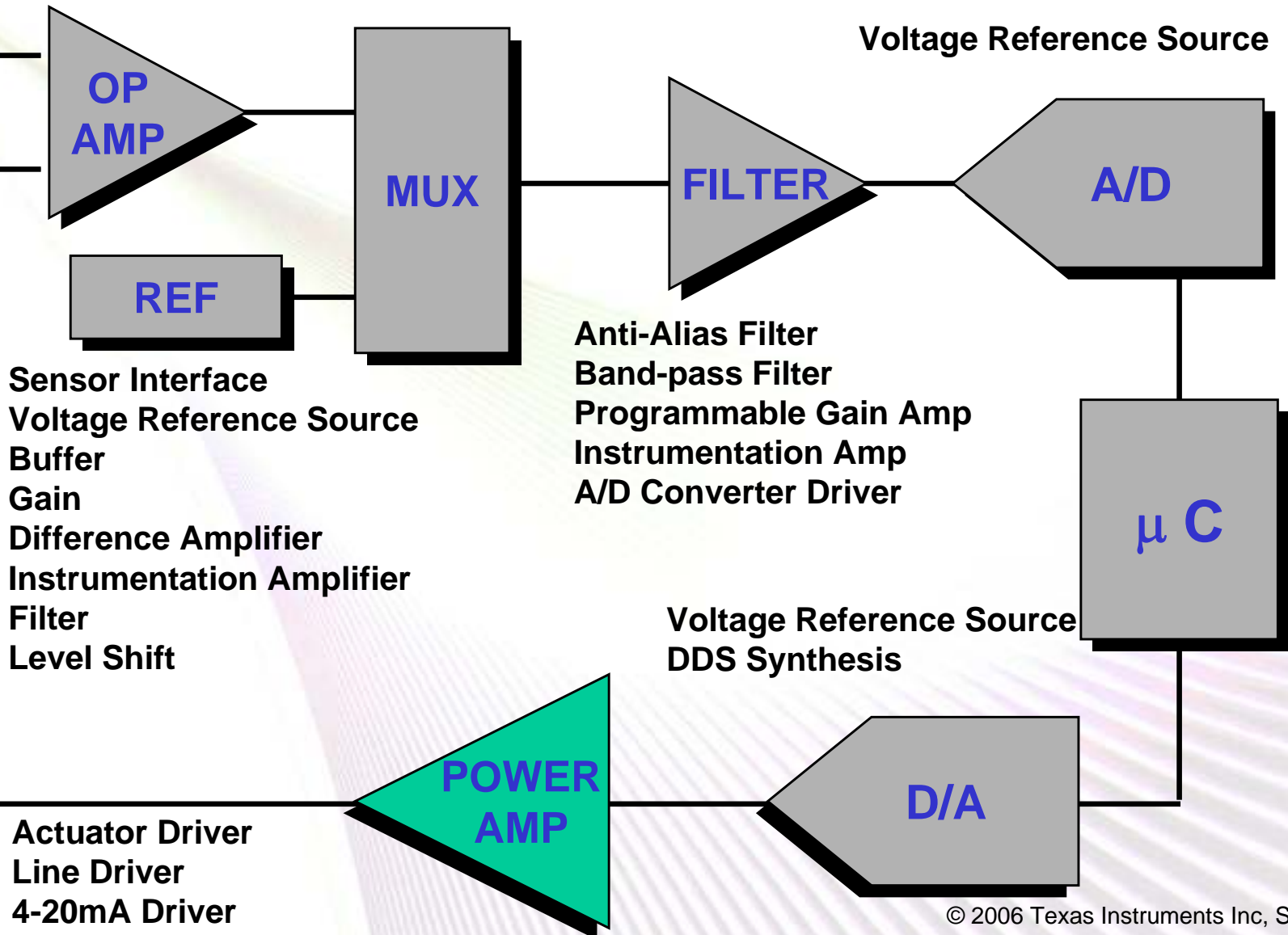
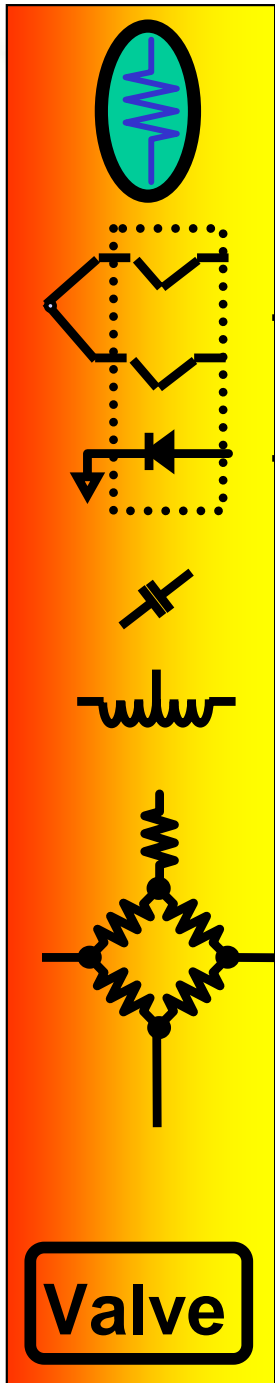
Working with ADCs, OAs and the MSP430

Bonnie Baker
HPA Senior Applications Engineer
Texas Instruments

Agenda

- **An Overview of the MSP430 Data Acquisition System**
- **SAR Converters**
 - The INS and OUTS of the SAR converter
 - Useful Applications
- **Using Op Amps**
 - Op Amp Configurations
 - Driving SAR Converters

Where to Find ADCs and Op Amps



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ADC Architectures

- **There are many different ADC Architectures**
 - Successive Approximation (SAR)
 - Sigma Delta (SD)
 - Slope or Dual Slope
 - Pipeline
 - Flash...as in quick, not memory
- **All converters in the MSP430 chips are SAR and Sigma Delta types**
- **SAR determines the digital word**
 - By approximating the input signal
 - Using an iterative process
- **How the Sigma Delta converter determines the digital word**
 - By oversampling
 - Applying Digital Filtering

Op Amp Architectures

- **The Different Types Op Amp Architectures**
 - Single Supply
 - Rail to Rail In
 - Rail to Rail Out
 - CMOS or Bipolar
 - Dual Supply
- **All Op Amps (OAs) in the MSP430 chips are Single Supply, CMOS**
- **Our CMOS Op amp**
 - Easily Configured with the MSP430 Controller
 - General Purpose, Buffer, Comparator, PGA, Differential Amp
 - Easily Programmed for
 - Optimized Gain
 - Bandwidth
 - etc

Agenda

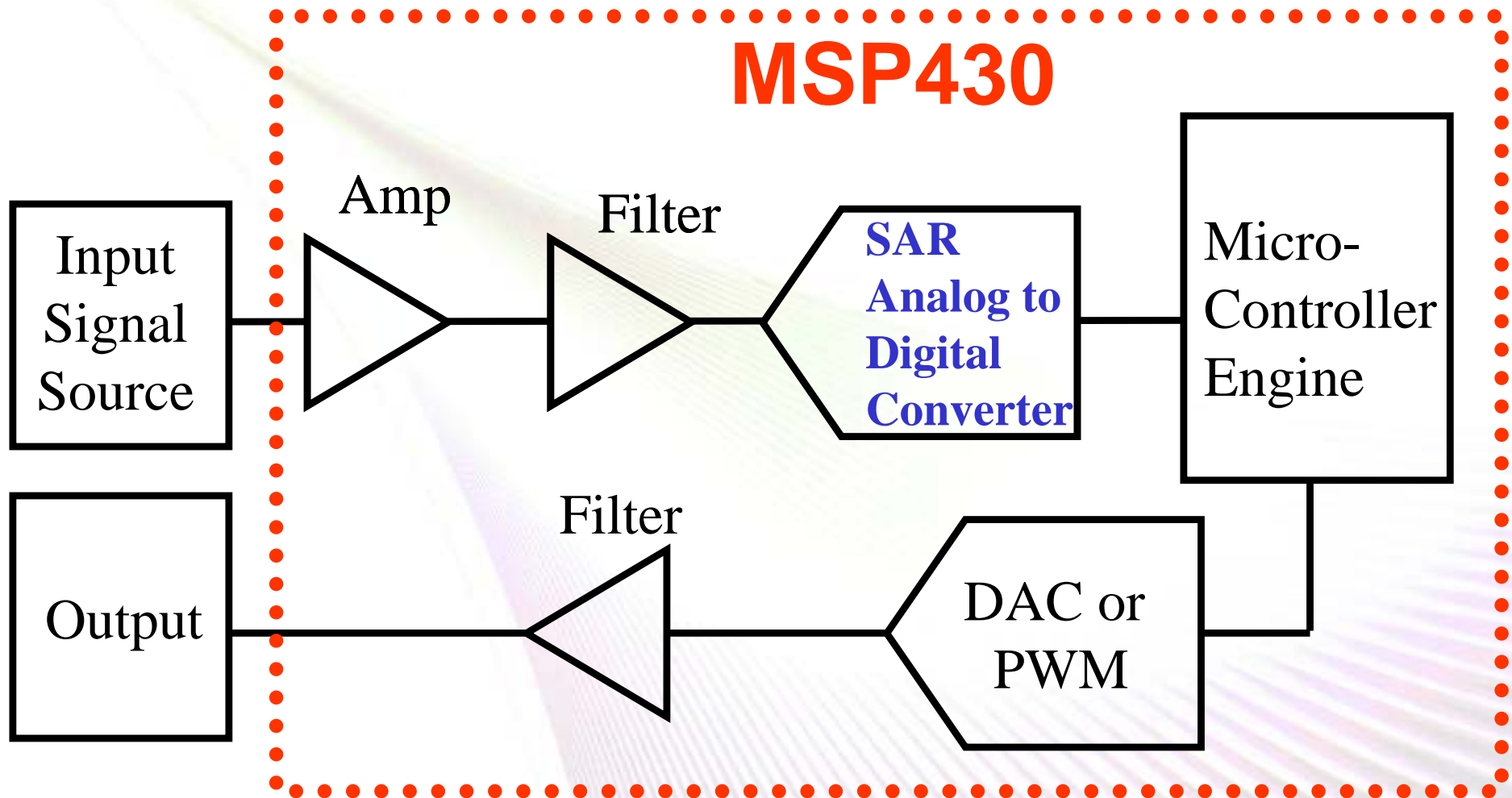
- **An Overview of the MSP430 Data Acquisition System**
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The SAR ADC

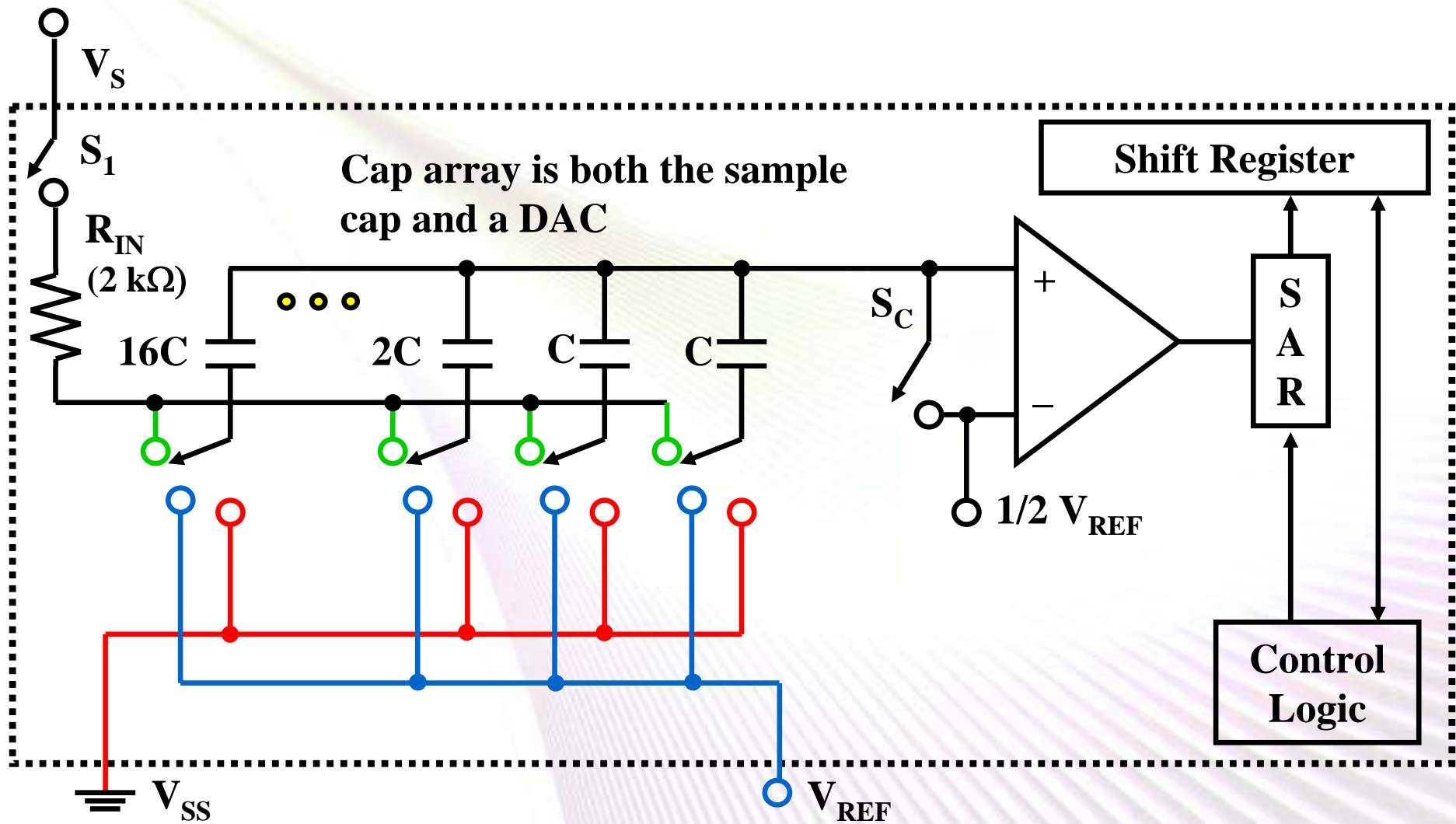
- **Most Serial ADCs are SARs or Sigma Deltas**
- **The MSP439 SAR Converter**
 - SAR ADC = Successive Approximation Register, Analog-to-Digital Converter
 - ADC12 – 12-bit Analog-to-Digital Converter
- **SARs are Best for General Purpose Apps**
 - Very Prevalent for Signal Level Applications: Data Loggers, Temp Sensors, Bridge Sensors, General Purpose
- **In the Market SARs**
 - Can be 8 to 18 bits of resolution
 - Speed range: >10 ksps to < 5 Msps
- **Usually require a Low-pass Filter before Analog Input**



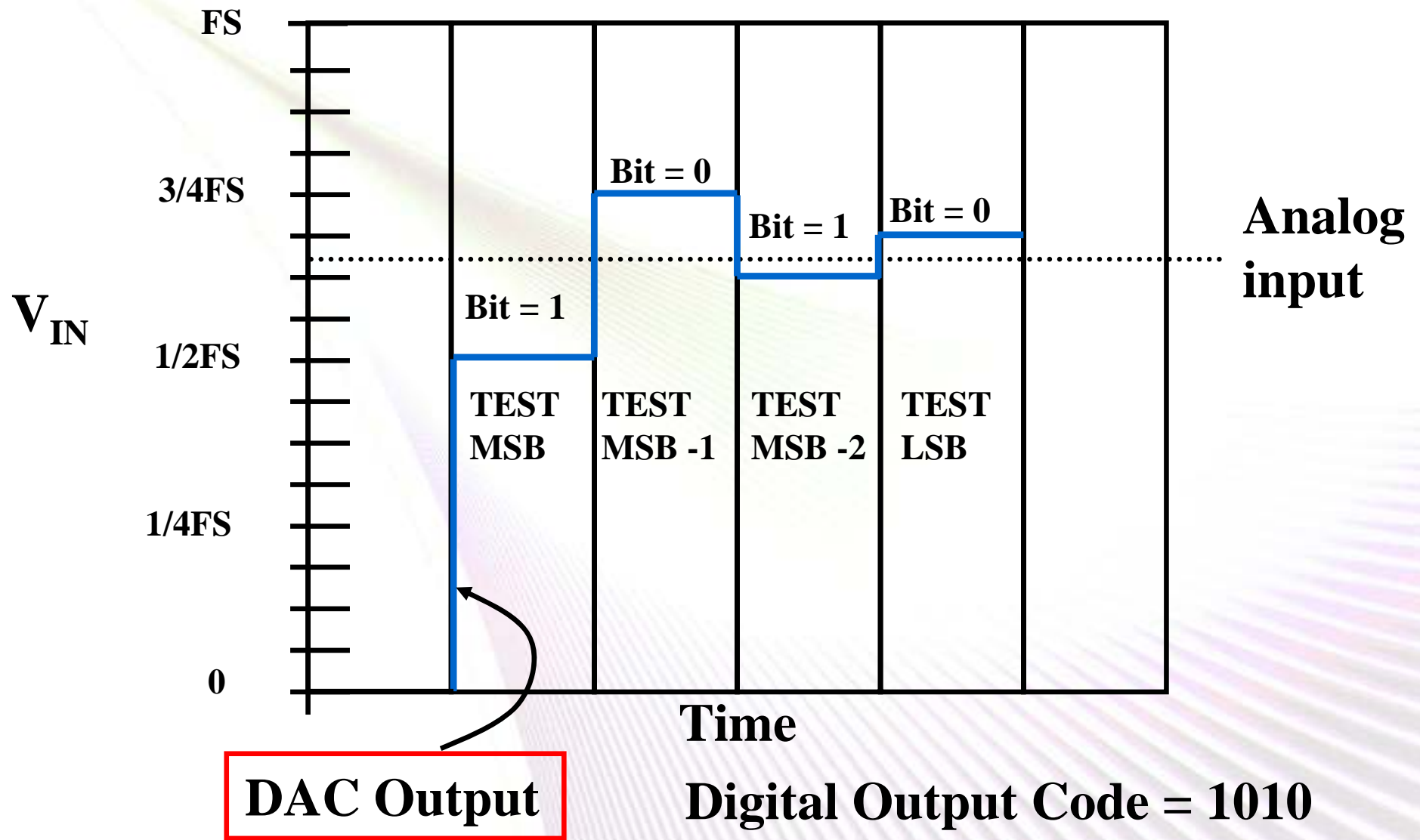
System Integration Using an A/D



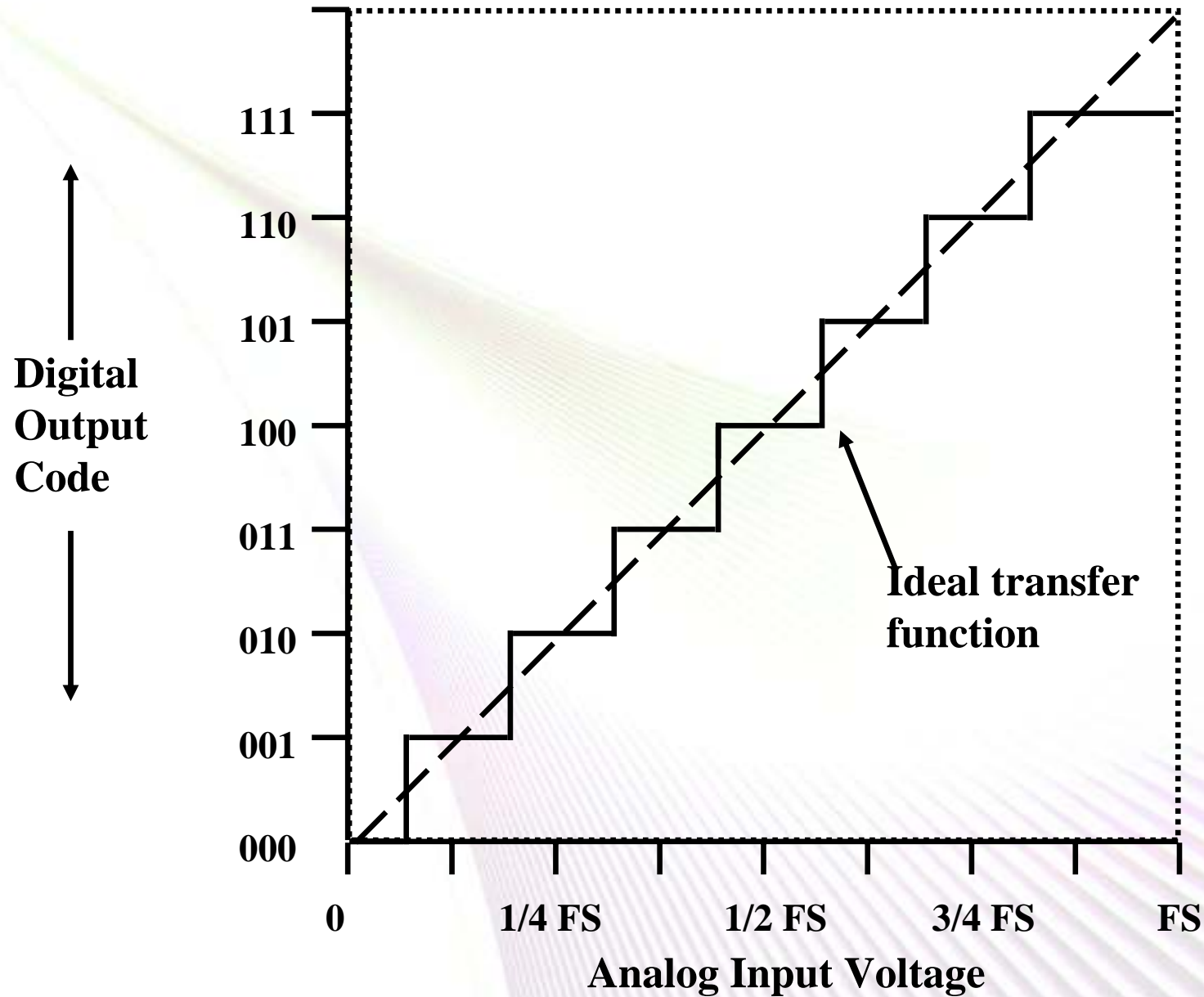
SAR Converter – Block Diagram



Successive Approximation Concept

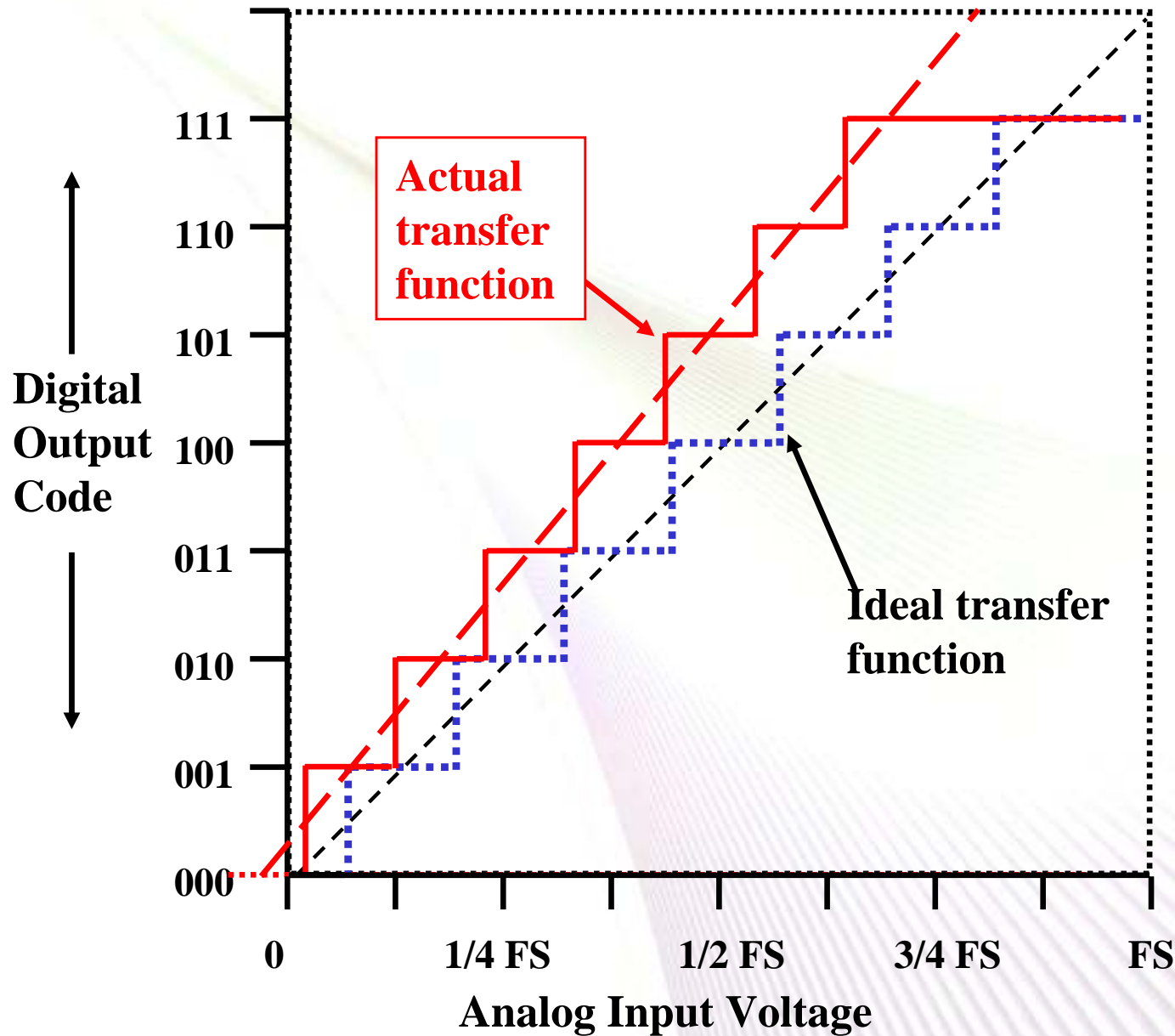


ADC Ideal Transfer Function



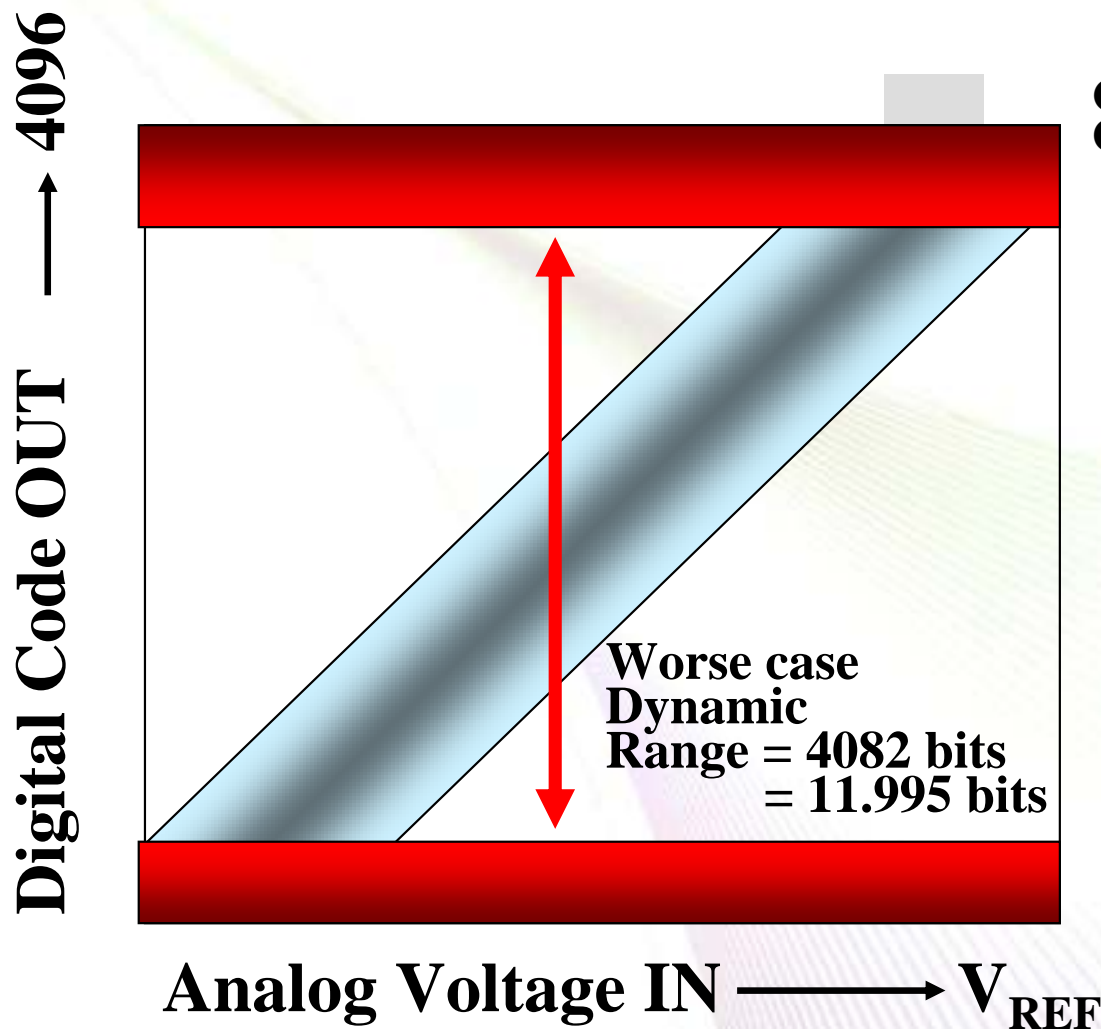
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ADC with Offset and Gain Error



- $y = a + (1+b)x$
where
y=digital out
x=analog in
a=offset err
b=gain err
- Every Ideal Code has Offset Error added
- Every ideal code is Multiplied by Gain Error

Offset/Gain Impact on Dynamic Range



Gain Error
Offset Error

- **ADC12 specifications**

Offset

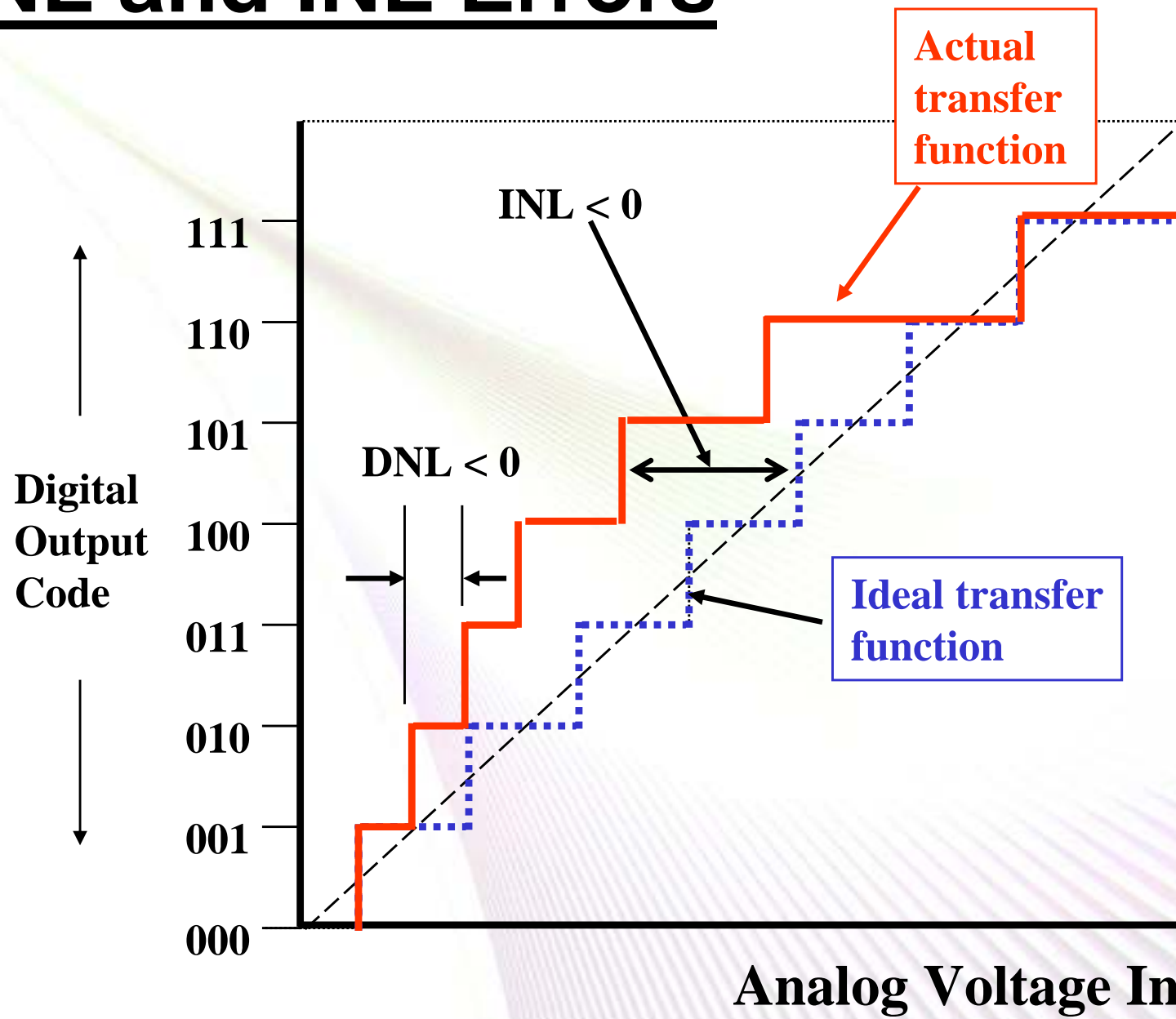
- $E_O \text{ typ} = \pm 2 \text{ LSB}$
- $E_O \text{ max} = \pm 4 \text{ LSB}$

Gain

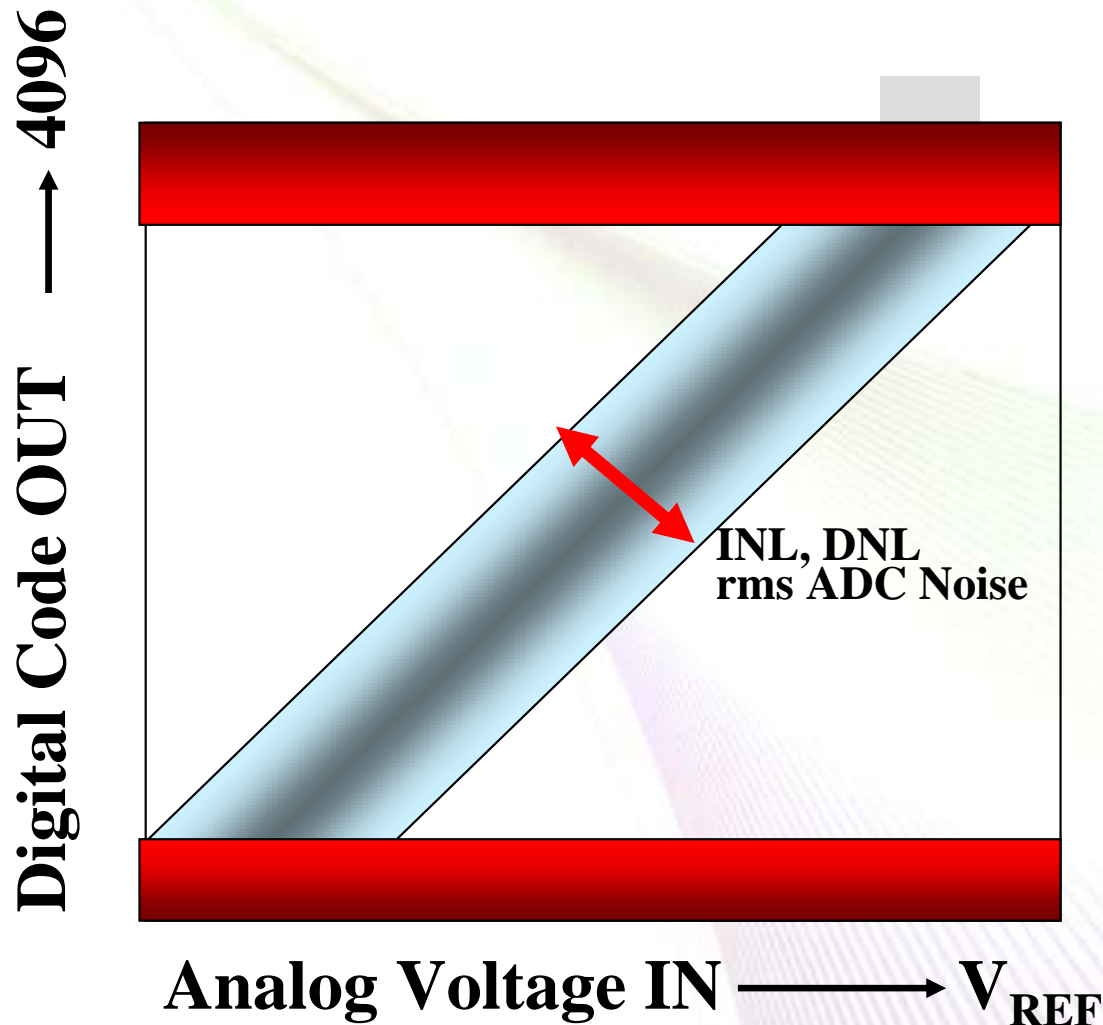
- $E_G \text{ typ} = \pm 1.1 \text{ LSB}$
- $E_G \text{ max} = \pm 2 \text{ LSB}$
(= $\pm 0.0488\%$)

- $1 \text{ LSB} = (V_{R+} - V_{R-}) / 2^{12}$
- Easy to calibrate

DNL and INL Errors

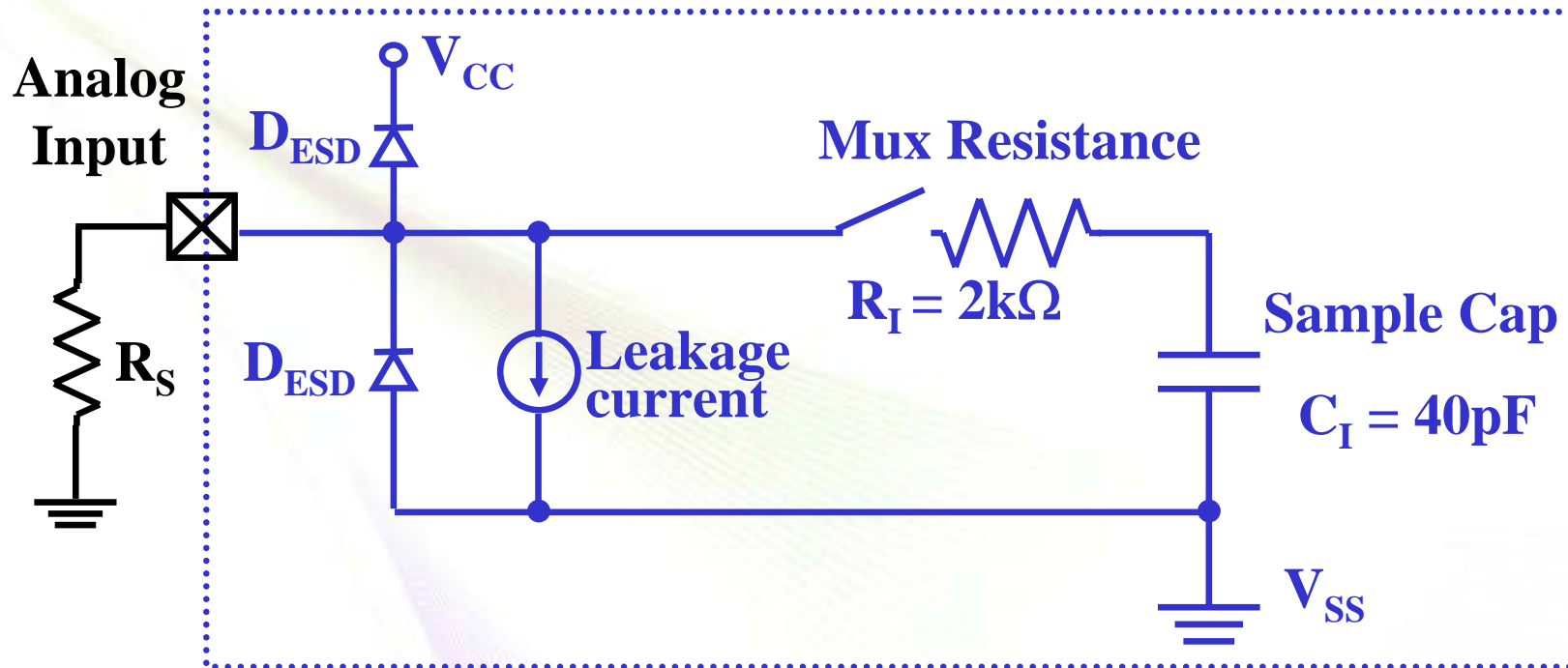


INL/DNL/Noise Impact on Dynamic Range



- ADC12 specifications
 - DNL error
 - $E_D \text{ max} = \pm 1.7 \text{ LSB}$
 - INL error
 - $E_I \text{ max} = \pm 1 \text{ LSB}$
 - $1 \text{ LSB} = (V_{R+} - V_{R-}) / 2^{12}$
- INL, DNL and Noise errors move across the entire range
- Impacts the Effective Number of Bits (ENOB)
- Not Easily calibrated
- Effects Accuracy

ADC Input Impedance



- **Input Internal Impedance is Relatively Low**
- **A High Impedance Source Increases Sample Cap Charging Time**
- **Rise Time of Voltage on $C_I \sim (R_S + R_I) * C_I$**

Sample Cap Charging Time

1400 ns (min)

Sample Period

Start Conversion

Conversion Complete

SAMPCON

ADC12OSC/ADC12DIV

ADC12MEMx

1 2 3 4 5 6 7 8 9 10 11 12 13

D D D D D D D D D D D D
11 10 9 8 7 6 5 4 3 2 1 0

Desired Voltage on C_1

V_c

Rise Time of

$(R_s + R_l) * C_1$

Final Voltage on C_1

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Alternative High Resolution Devices

- **ADC12**

- Resolution = 12 bits
- Minimum LSB size = $V_{REF} / 2^n = 1.5 \text{ V} / 2^{12} = 366 \text{ mV}$
- # channels = 12 to 16 (depends on part number)

- **ADS8341**

- Resolution = 16 bits
- Minimum LSB size = $V_{REF} / 2^n = 2.7 \text{ V} / 2^{16} = 41.2 \text{ mV}$
- # channels = 4

- **ADS1100**

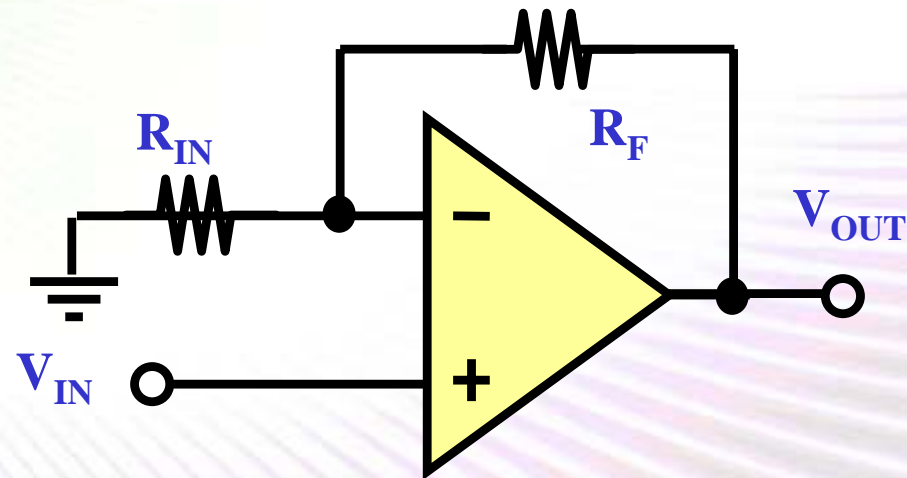
- Resolution = 16 bits
- Minimum LSB size = $V_{REF} / 2^n = 2 * 2.7 \text{ V} / 2^{16} = 82.4 \text{ mV}$
- # channels = 1

Agenda

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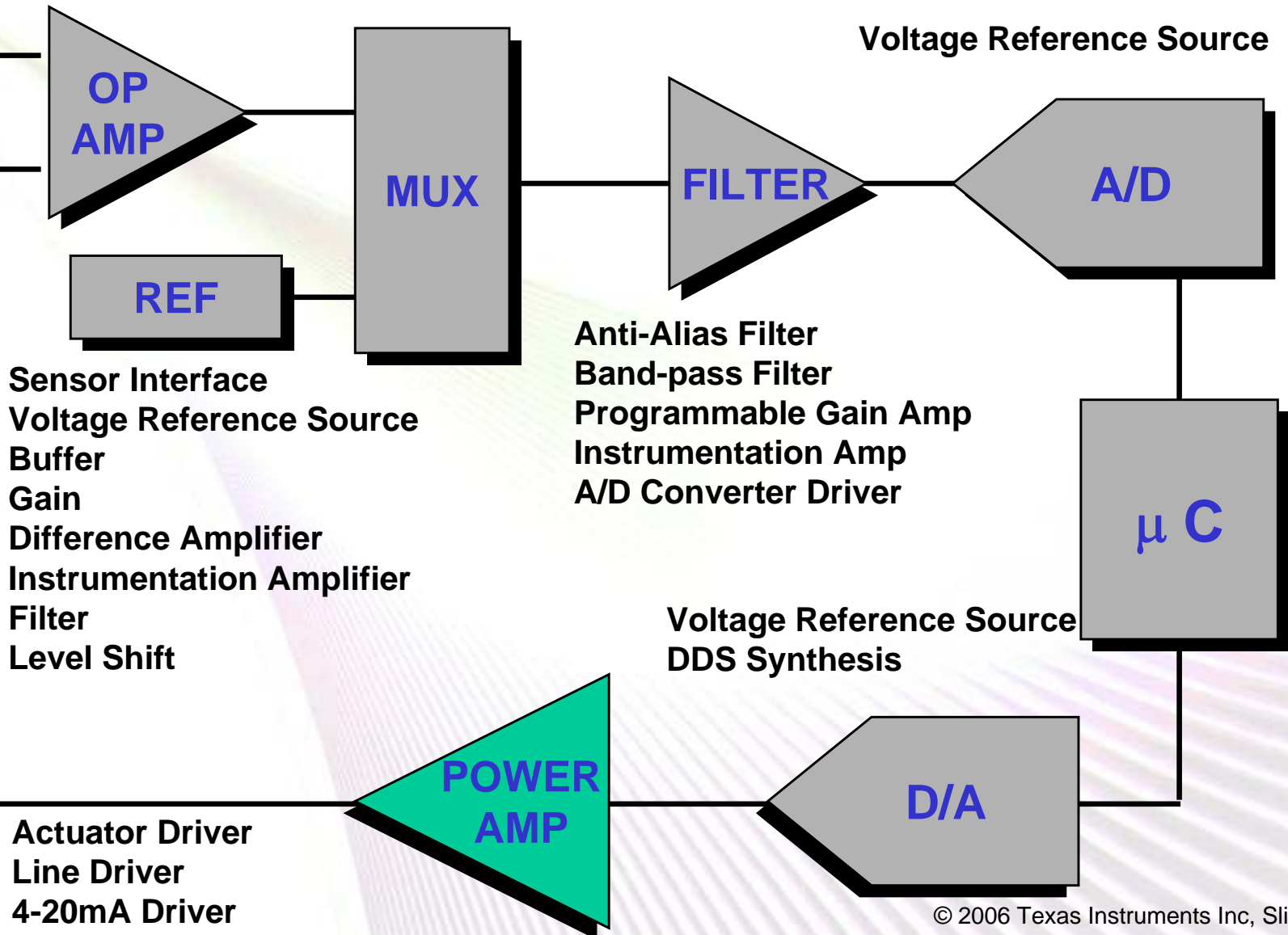
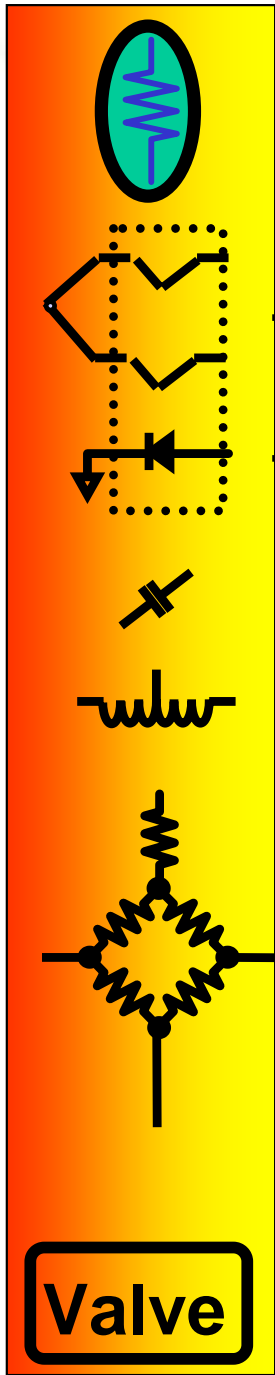
Operational Amplifiers

- Most Prevalent Building Block in Analog Circuits
- Very Flexible - Large Variety of Functions
- Circuits We Will Talk About
 - General Purpose Op amp
 - Unity Gain Buffer
 - Comparator
 - PGA (Programmable Gain Amplifier)
 - Differential Amplifier



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Where to Find Op Amps



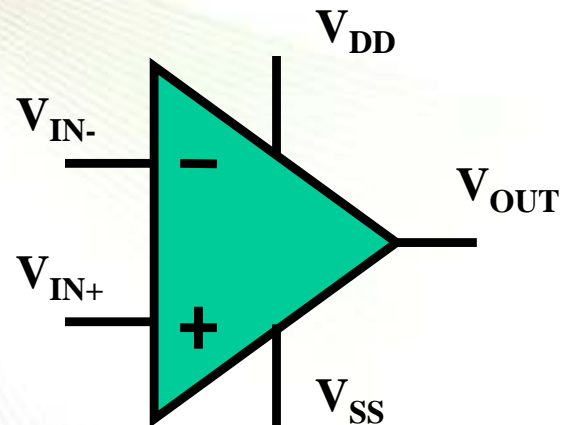
Ideal Op Amp

POWER SUPPLY

- No min or max Voltage
- $I_{\text{SUPPLY}} = 0$ Amps
- Power Supply Rejection = ∞

INPUT

- Input Current (I_B) = 0
- Input Impedance (Z_{IN}) = ∞
- Input Voltage (V_{IN}) → no limits
- Zero Noise
- Zero DC error
- Common-Mode Rejection = ∞



OUTPUT

- $V_{\text{OUT}} = V_{\text{SS}}$ to V_{DD}
- $I_{\text{OUT}} = \infty$
- Slew Rate = ∞
- $Z_{\text{OUT}} = 0 \Omega$

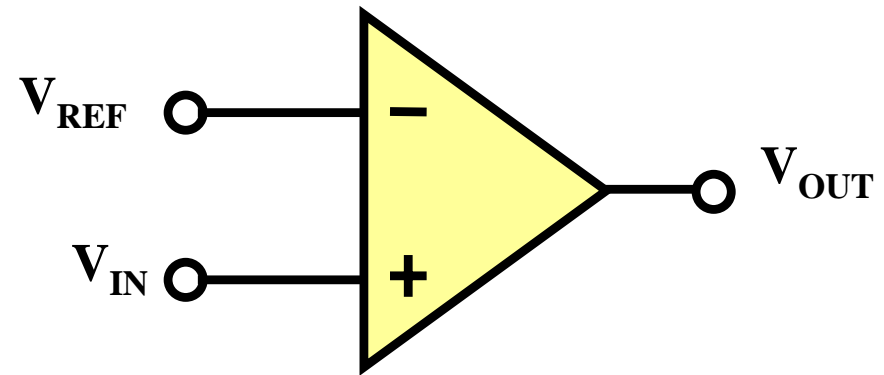
SIGNAL TRANSFER

- Open Loop Gain = ∞
- Bandwidth = 0 → ∞
- Zero Harmonic Distortion

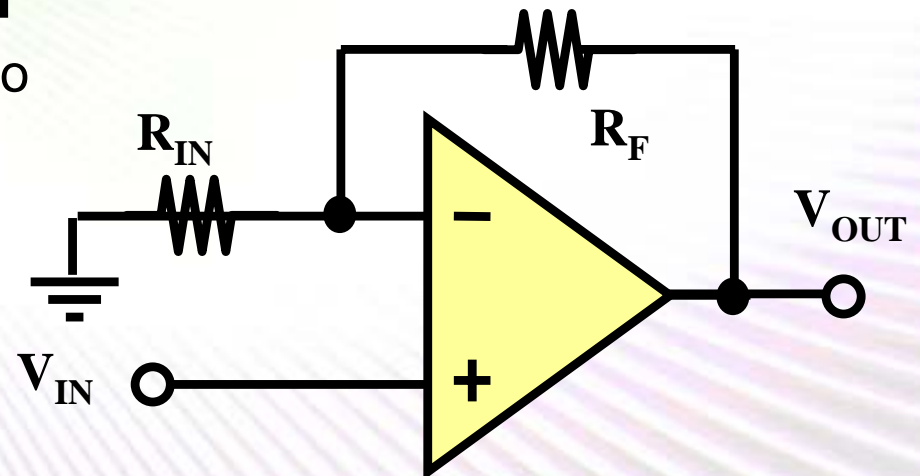
\$0.00

Open Loop vs Closed Loop Design

- **OAFcx = 011**
- **Open Loop Configuration**
 - In Comparator mode
- **OAFcx = 000**
- **Closed Loop Configuration**
 - Always a Connection from Output to Inverting Input
 - Gain is Dependant on Resistors



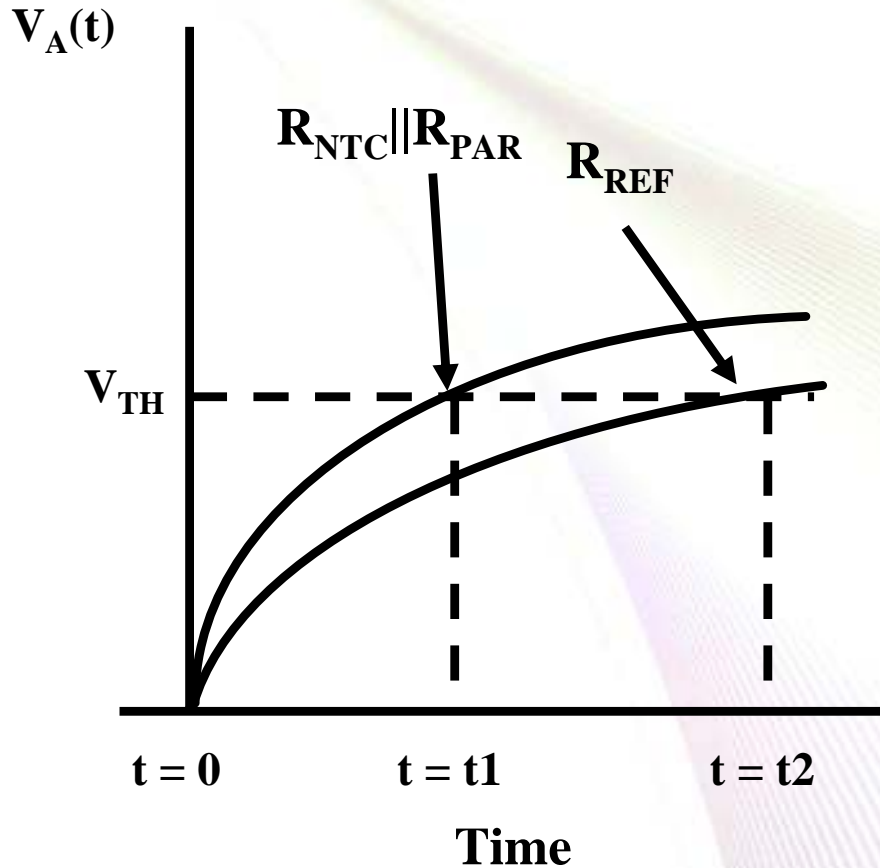
$V_{OUT} = \text{High for } V_{IN} > V_{REF}$
 $V_{OUT} = \text{Low for } V_{IN} < V_{REF}$



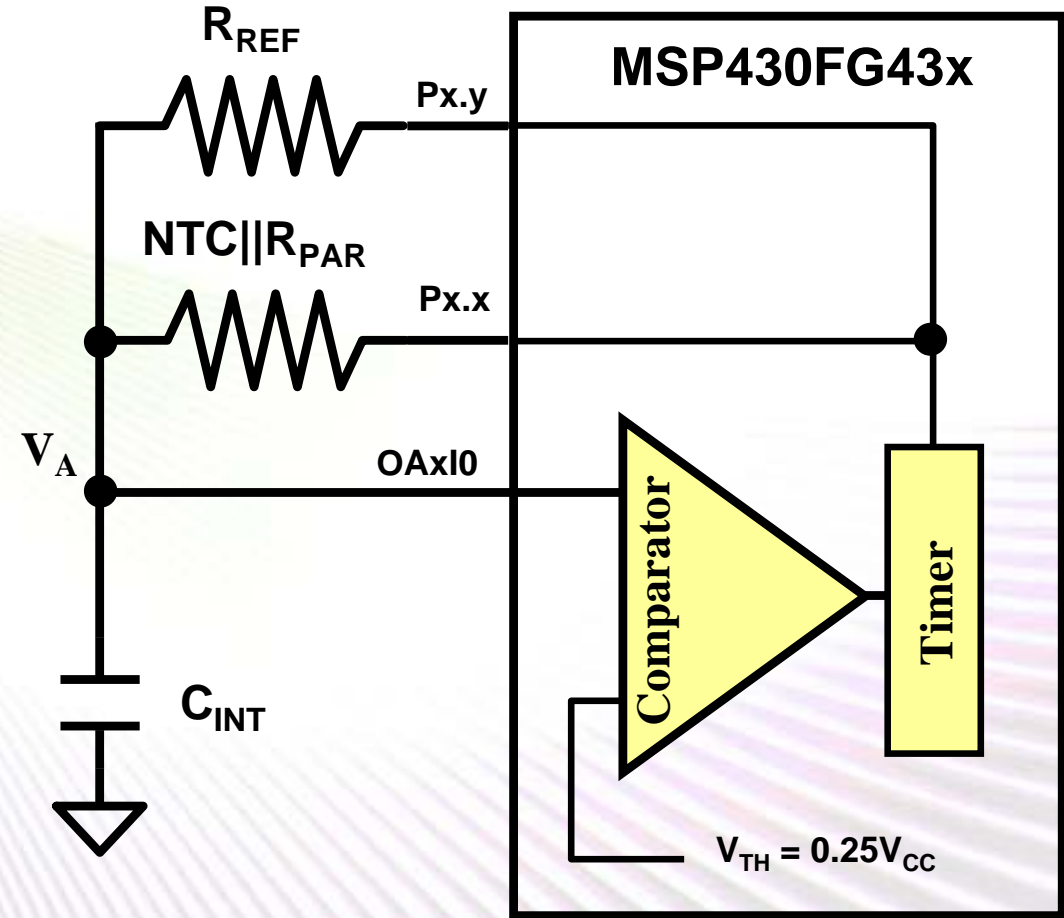
$$V_{OUT} = (1 + R_F / R_{IN}) (V_{IN})$$

Comparator Mode – OAFcX = 011

Temperature Sensor

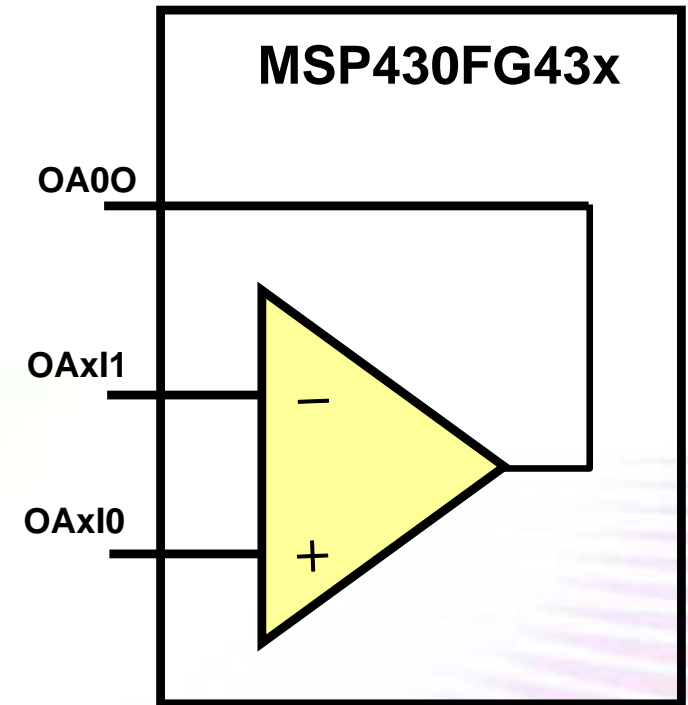
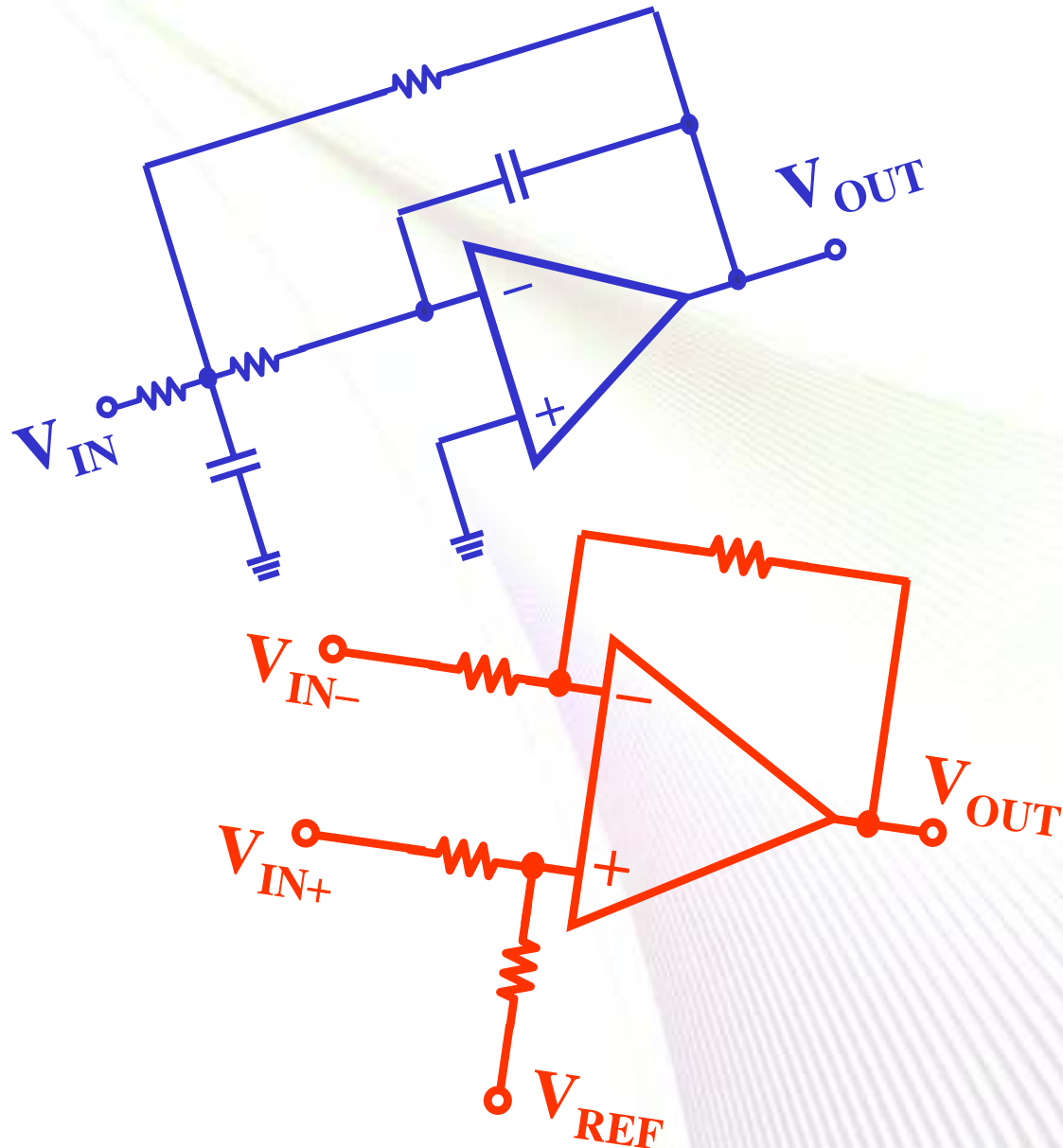


$$\frac{R_{NTC} || R_{PAR}}{t_{NTC} || R_{PAR}} = \frac{R_{REF}}{t_{REF}}$$



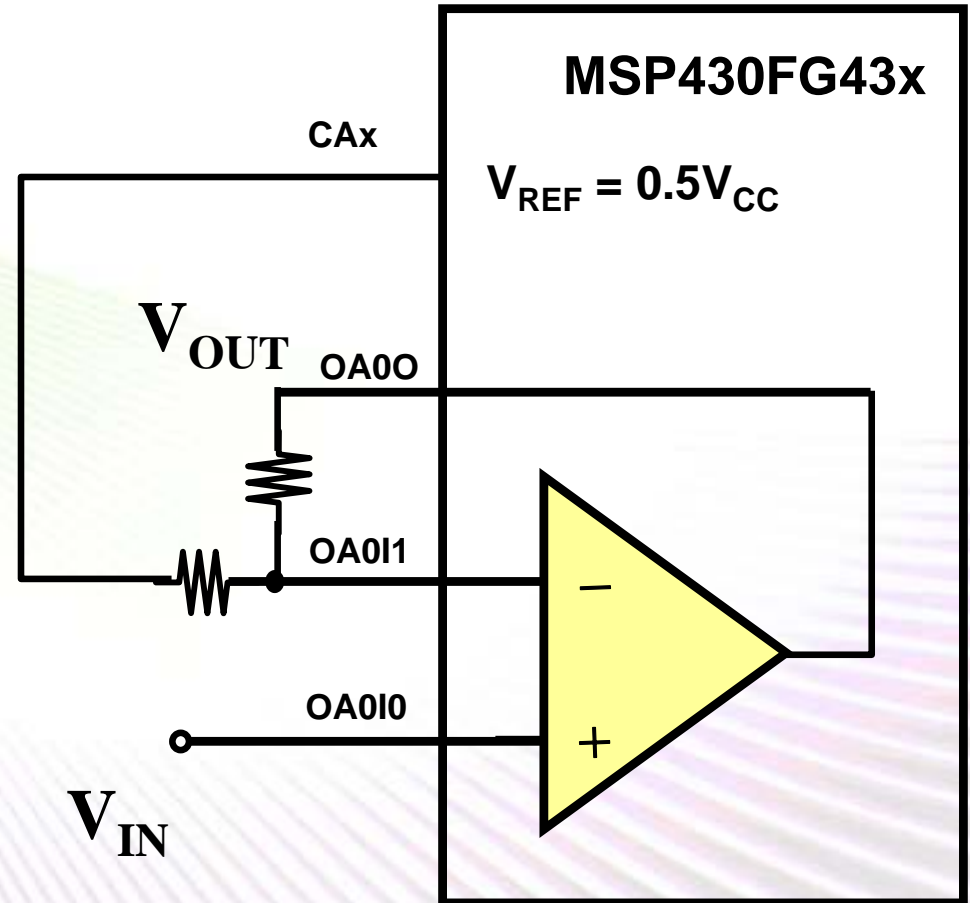
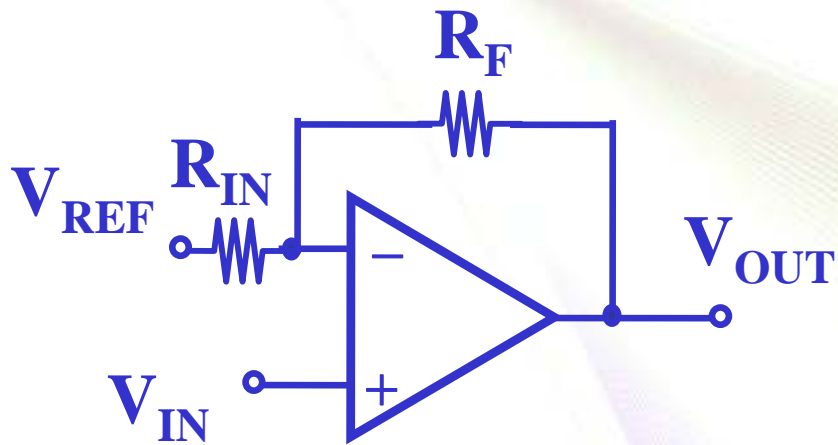
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General Op amp Mode – OAFcx = 000



General Op amp Mode – OAFcX = 000

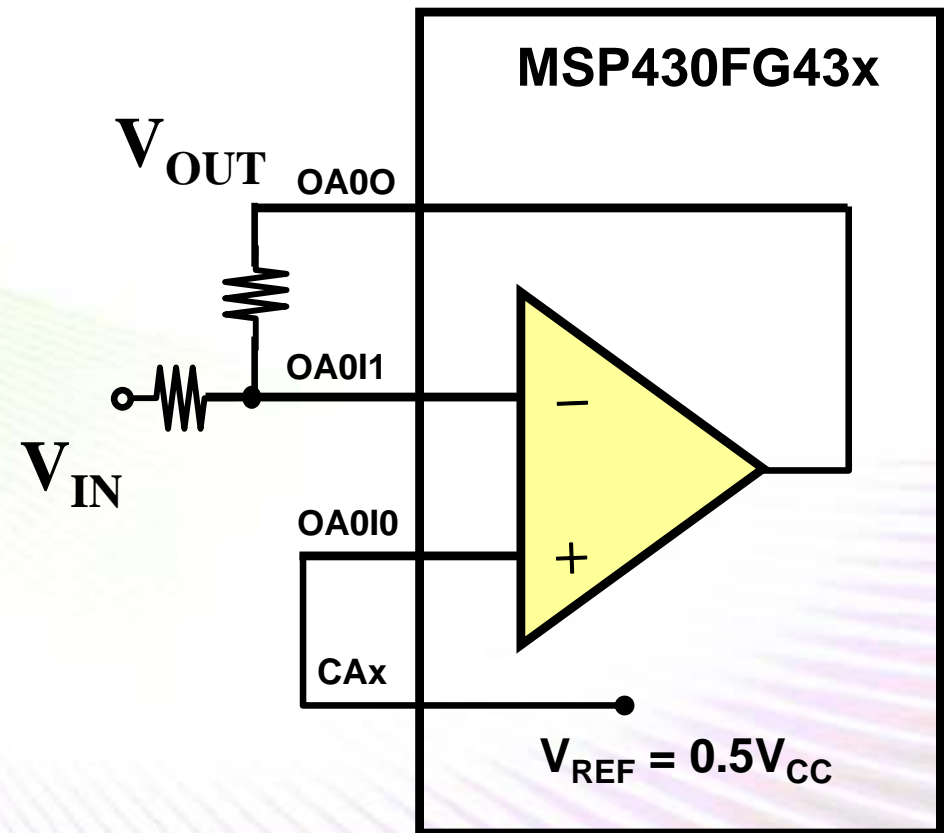
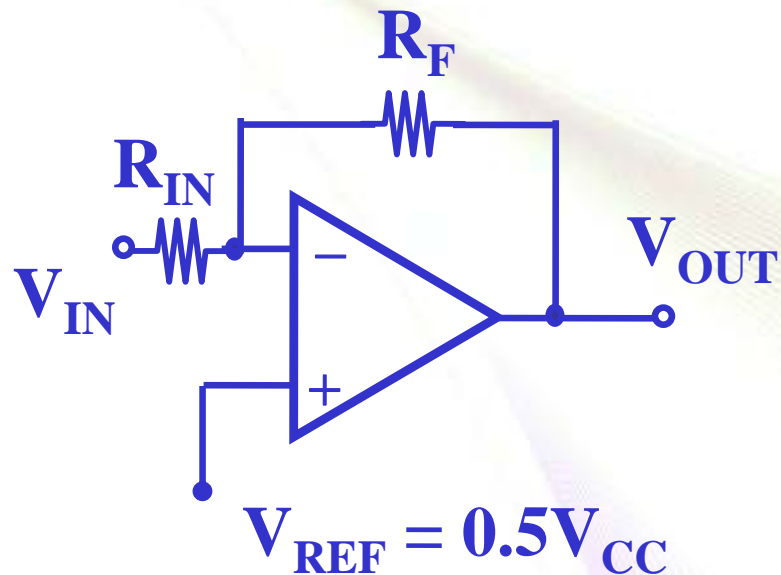
Non-inverting Gain



$$V_{OUT} = V_{IN} (1 + R_F/R_{IN}) - V_{REF} * R_F/R_{IN}$$

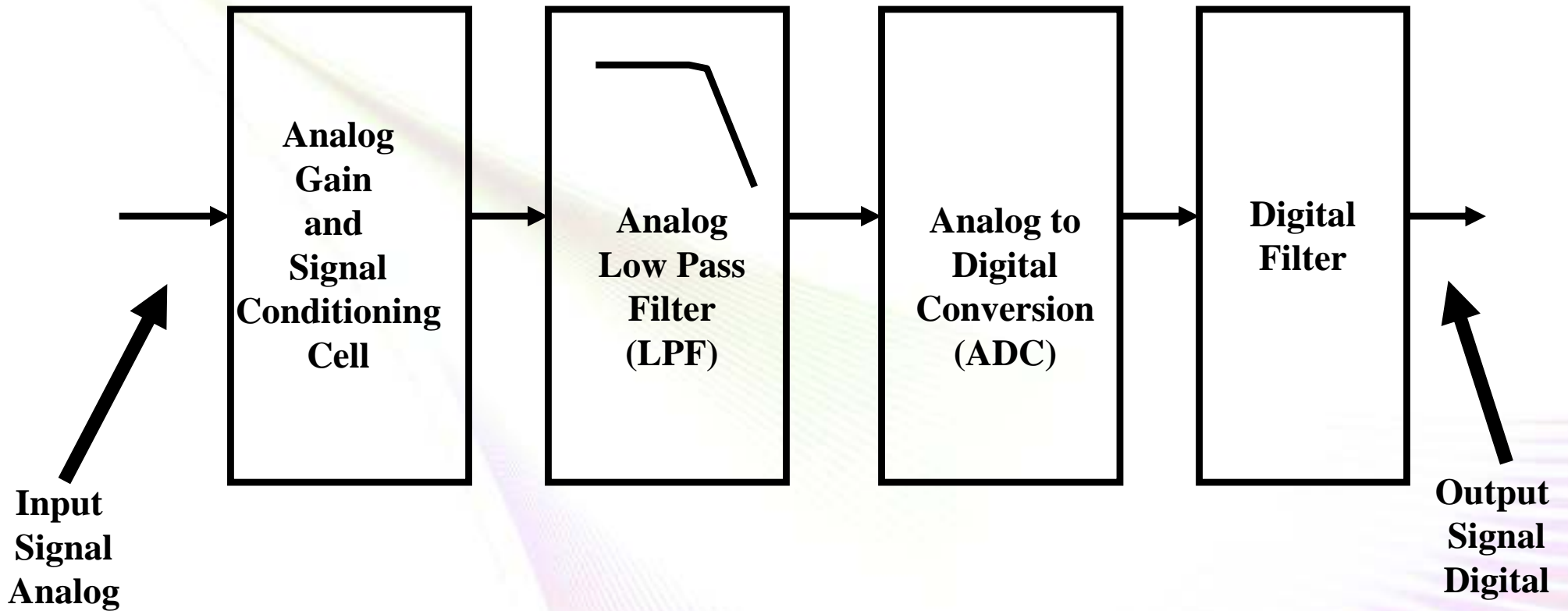
General Op amp Mode – OAFCx = 000

Inverting Gain



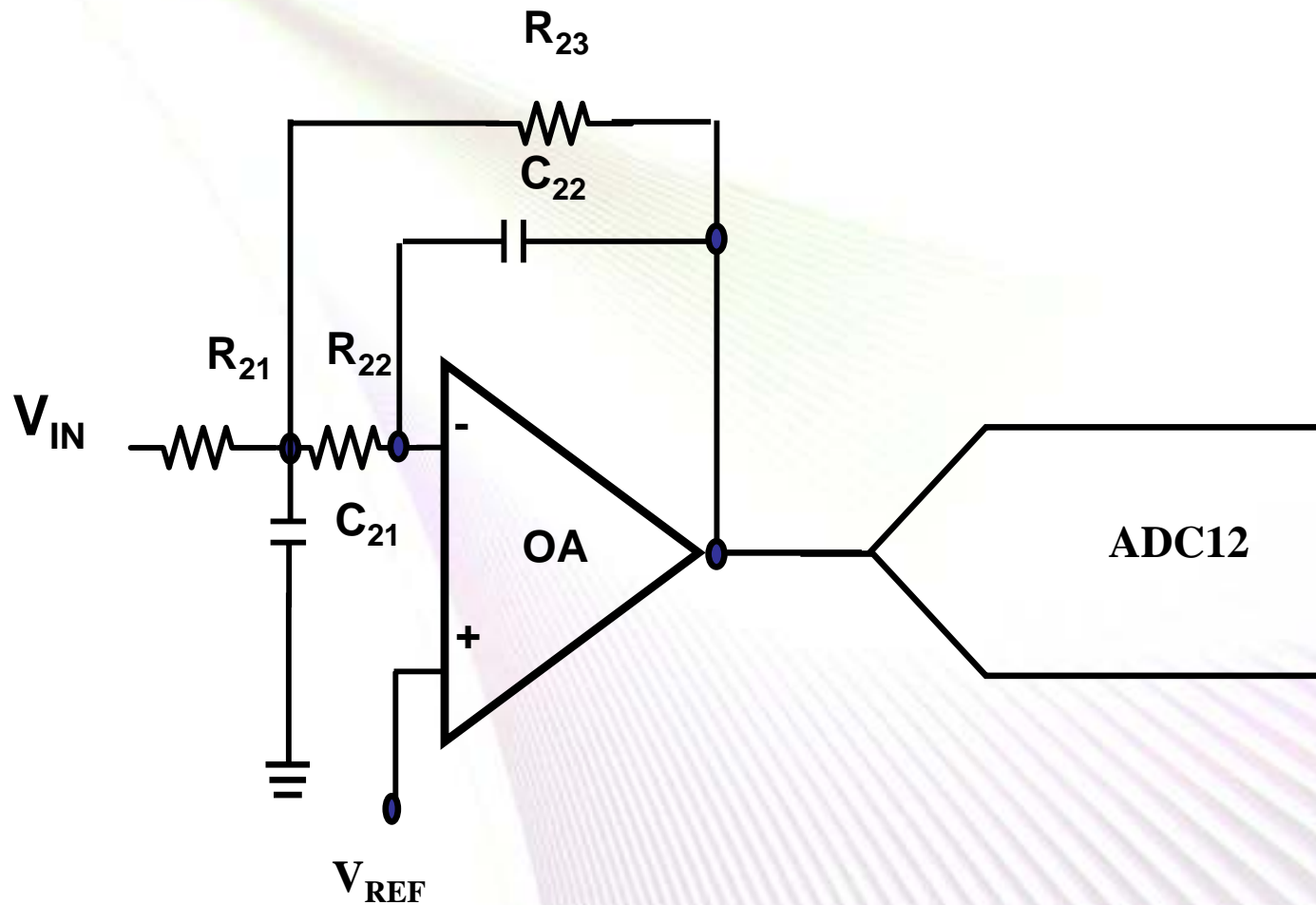
$$V_{OUT} = V_{REF} (1 + R_F/R_{IN}) - V_{IN} * R_F/R_{IN}$$

Data Acquisition System



Noise Reduction with a Low Pass Filter

Noise Reduction or Anti-aliasing Filter



Anti-alias Filter :: Nyquist Theorem

Signal at the
Input of the A/D
Converter



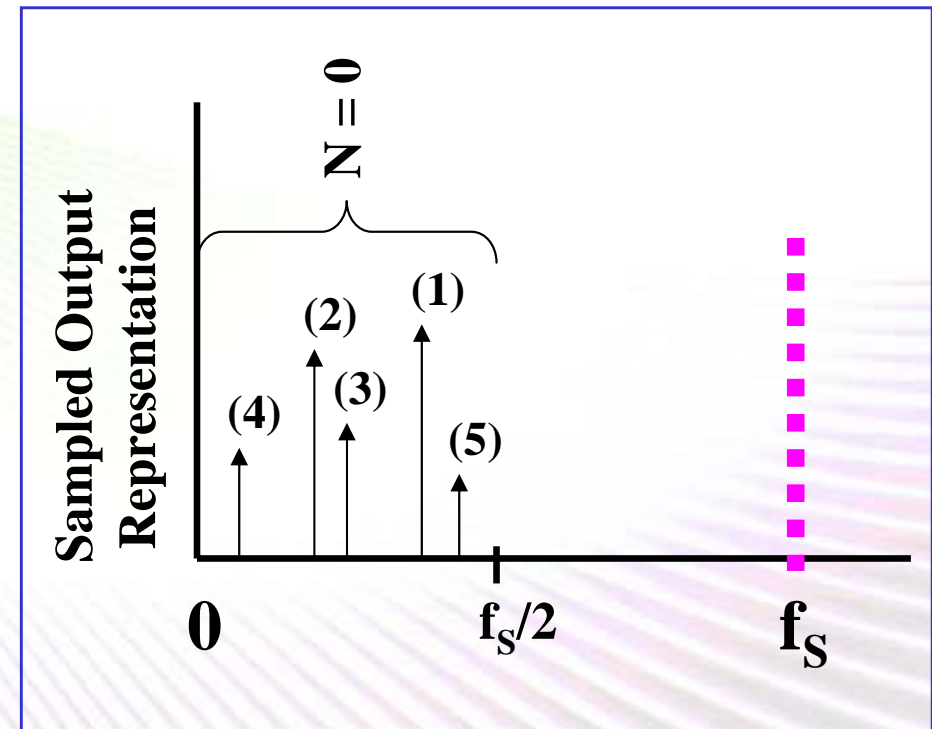
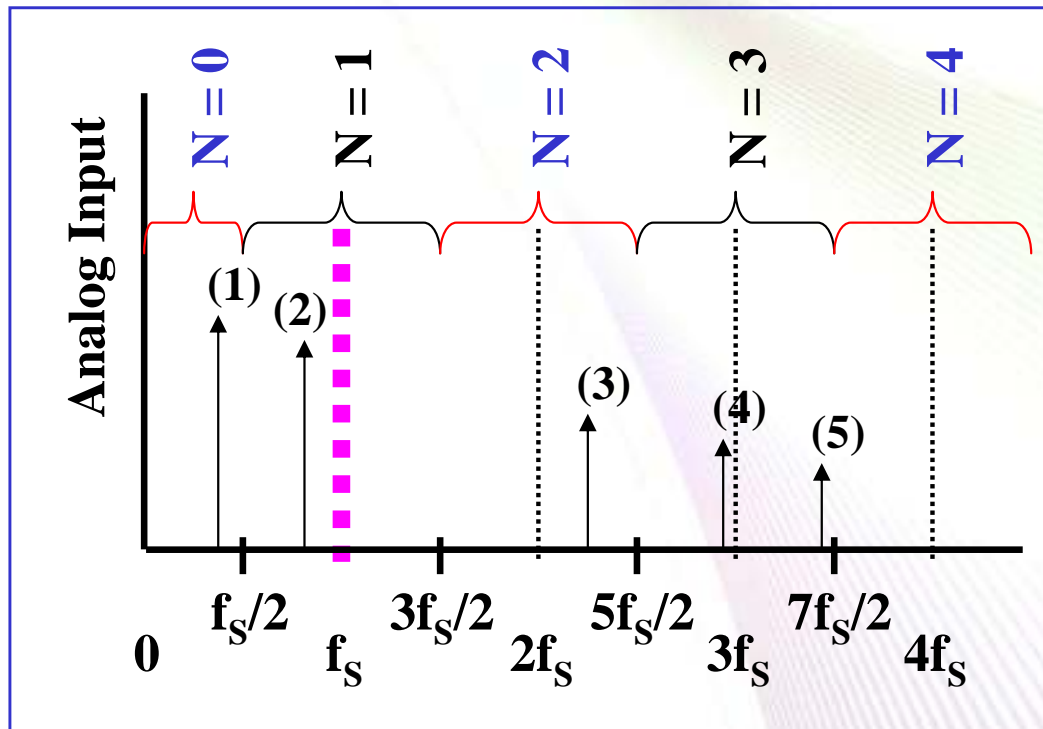
$$f_{\text{ALIASED}} = |f_{\text{IN}} - Nf_s|$$

Find N by making

$$f_{\text{ALIASED}} < f_s / 2$$

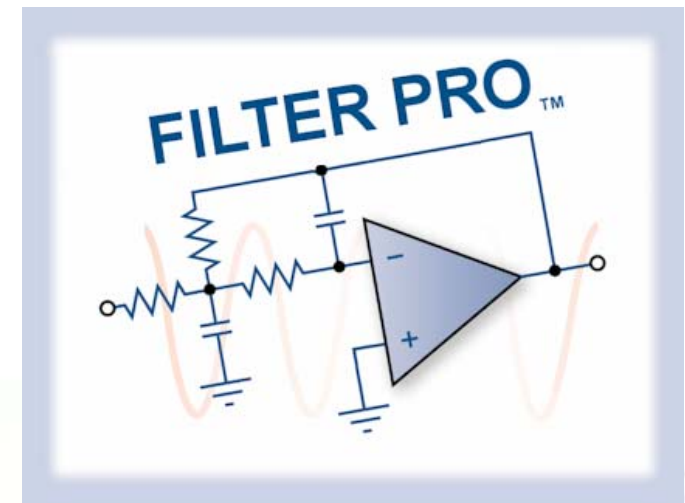


Digital Representation
at the
Output of the Converter



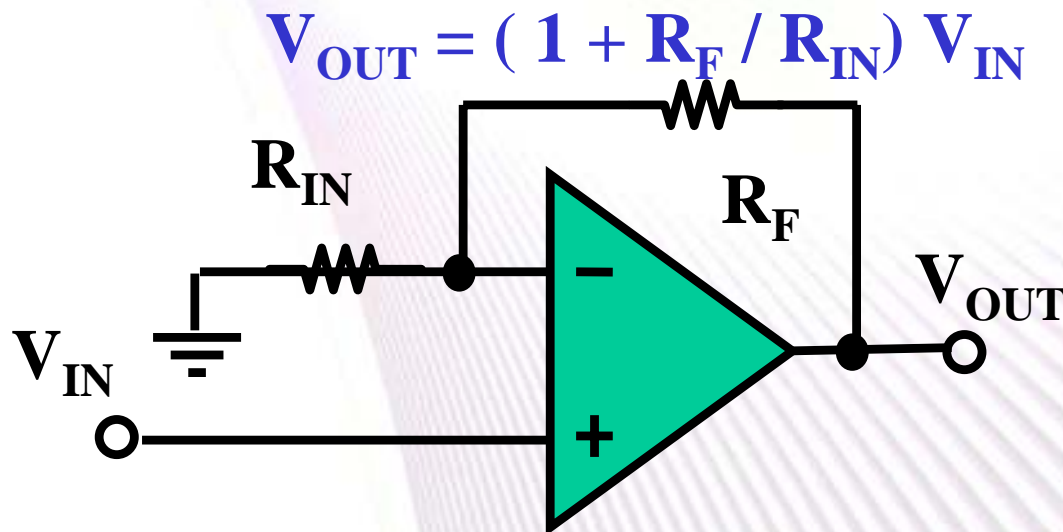
Filter Pro Software

- **Filter synthesis tool for designing**
 - Multi-section filter
 - Low-pass Filter
 - High-pass active filter
- **Supports**
 - 2nd to 10th order
 - Multiple-feedback (MFB) Filter Topology
 - Sallen-Key Filter Topology
- **www.ti.com**



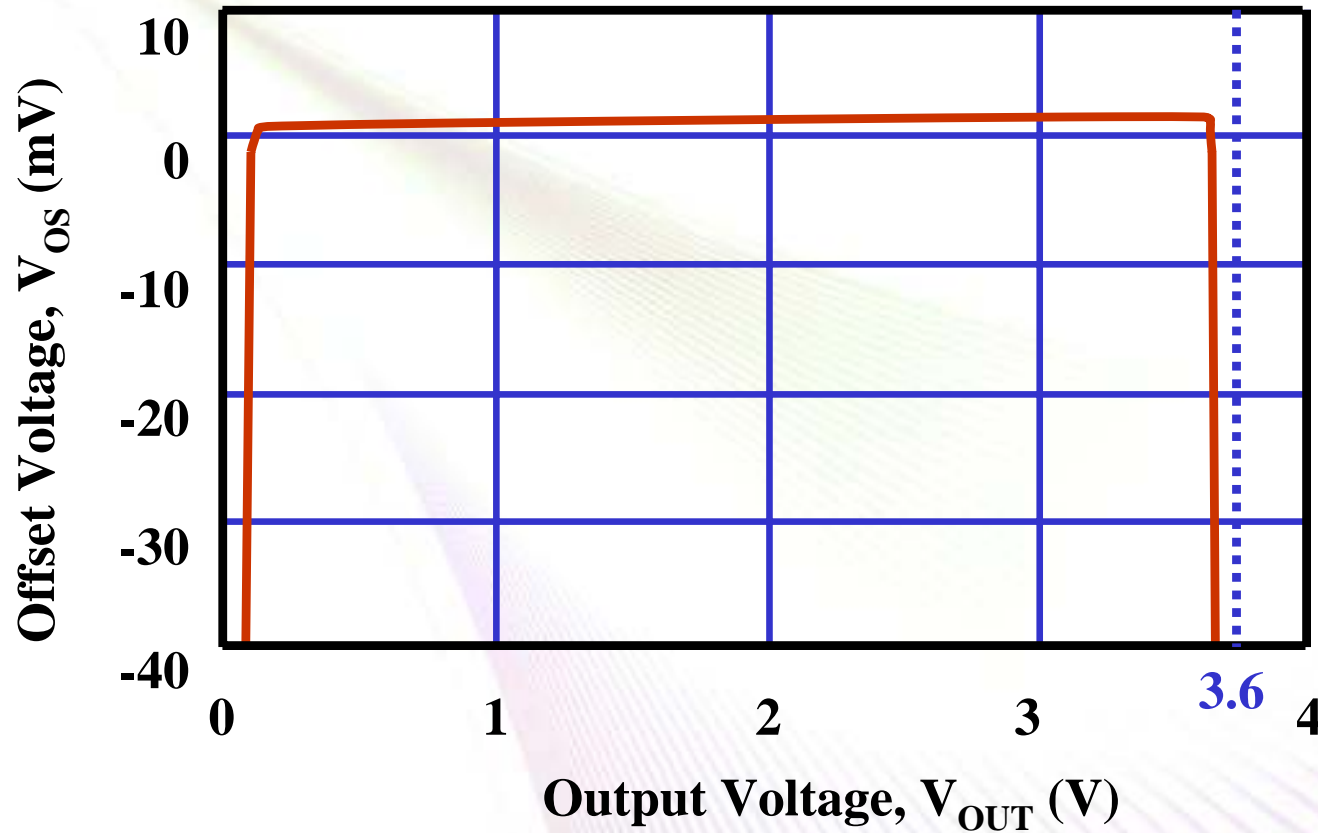
Operational Amp Output Swing

- Rail-to-Rail Output Operation does not Exist
- How Close the Amplifier's Output can Come to the Power Supplies (or "rails") and still be Linear
- MSP430FG43x =
(VSS + 200mV) {min} to (VCC- 200mV) {max}



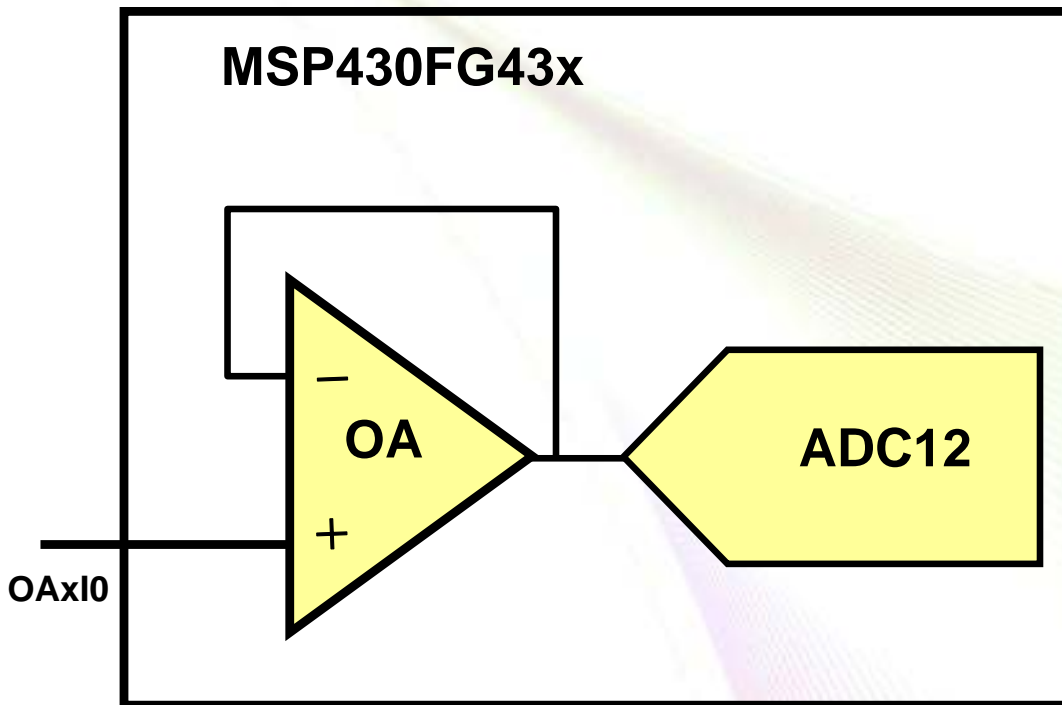
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Operational Amp Output Swing



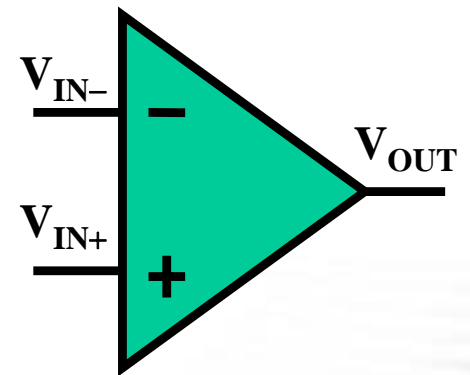
Unity Gain Buffer Mode – OAFCx = 001

- Op Amp Internally connected as a buffer
- Non-inverting input available on a Controller pin
- Op Amp Output connected directly to ADC12



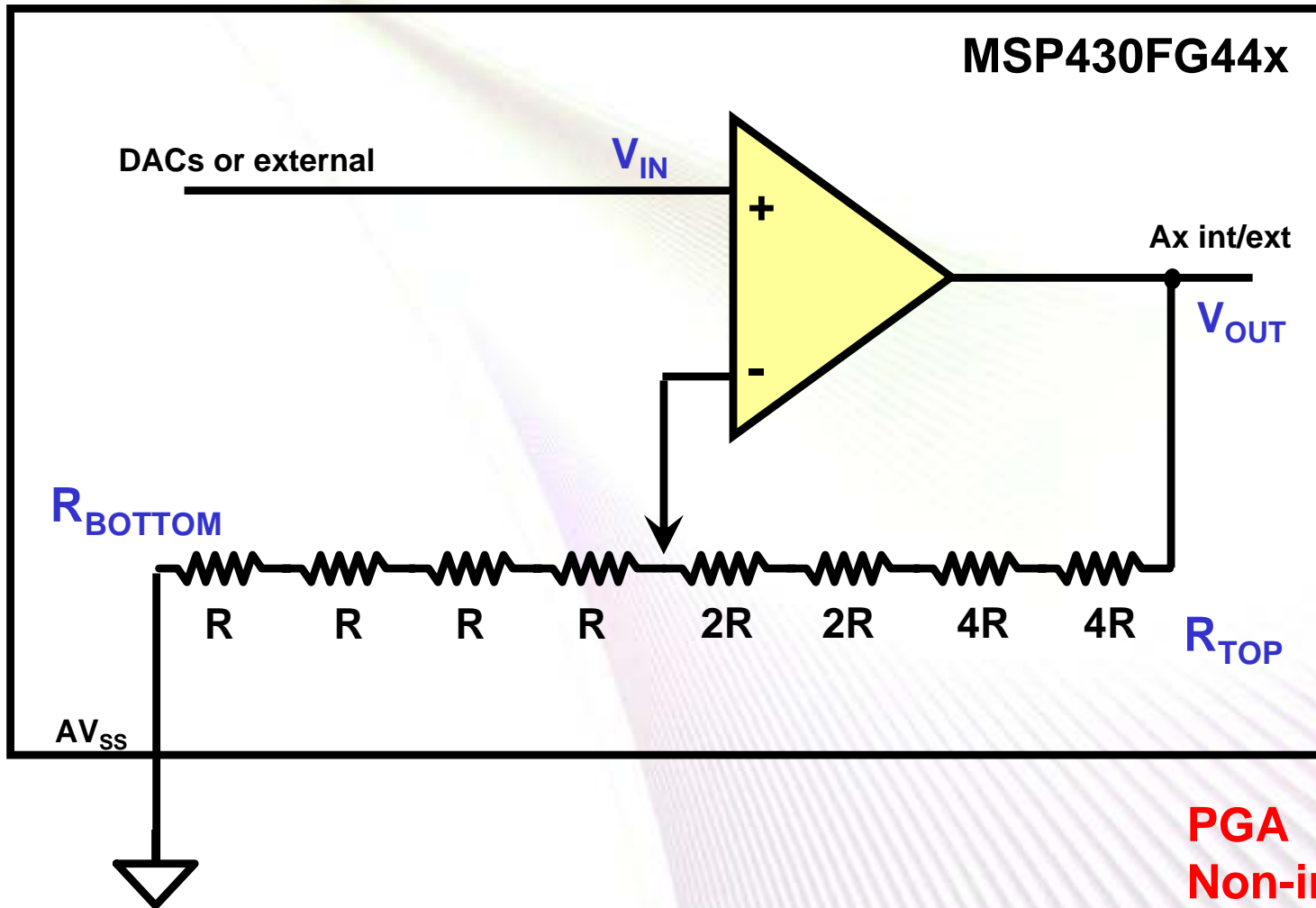
Op Amp Input Voltage Range

- **RRIP ON =**
 $(V_{SS} - 0.1V)$ {min} to $(V_{CC} + 0.1)$ {max}
- **Charge pump on input stage is turned on**
- **Great Feature, not all amps have this!**
- **RRIP OFF =**
 $(V_{SS} - 0.1V)$ {min} to $(V_{CC} - 1.2)$ {max}
- **(Appropriate for Gains > 2)**



PGA Mode – Non-inverting Mode OAF_{Cx} = 100

$$V_{OUT} = G V_{IN}$$



RRIP off

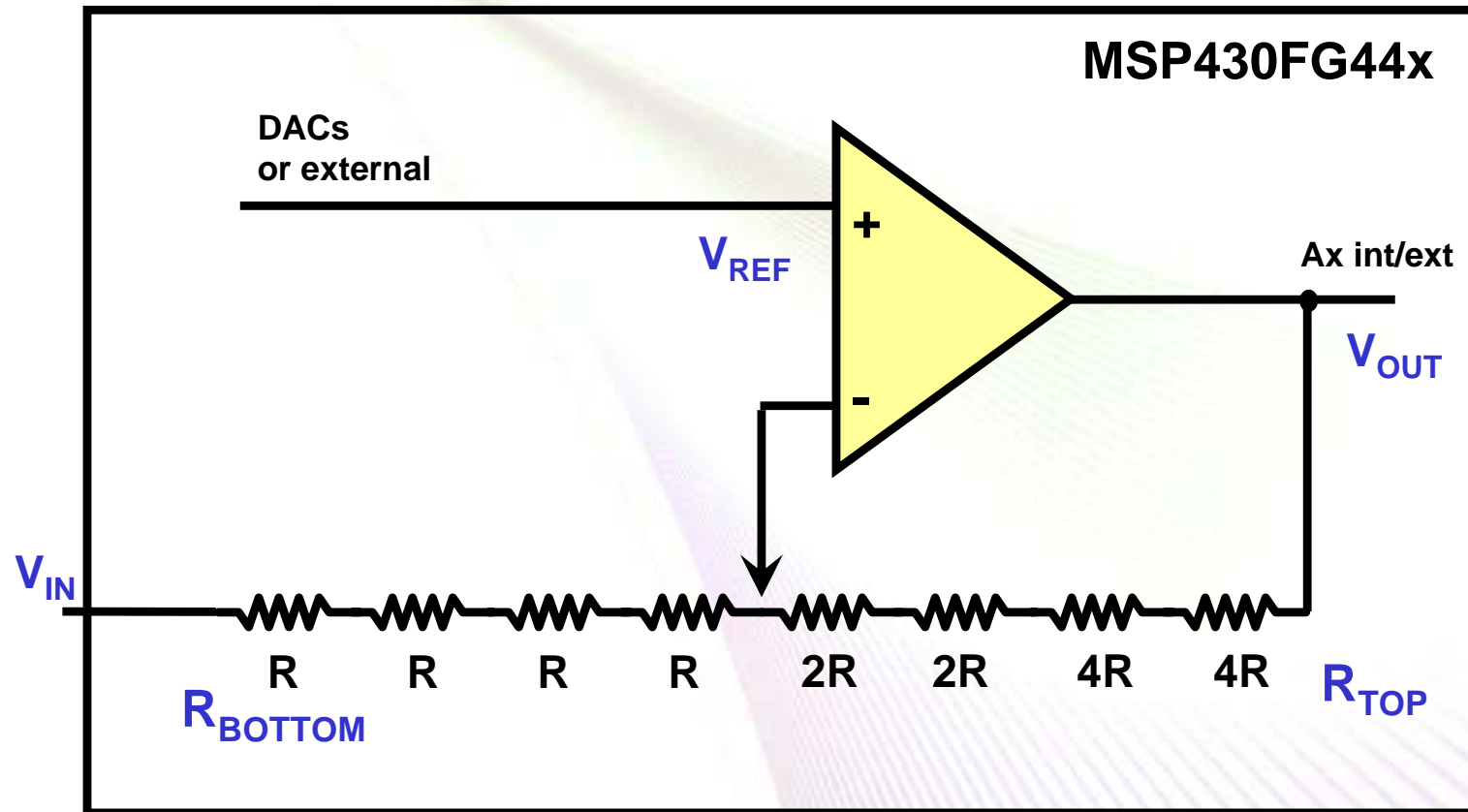
<u>OAxCTL1</u>	
111100x1	G=16
110100x1	G=8
101100x1	G=3.33
100100x1	G=4
011100x1	G=2.67
010100x1	G=2
001100x0	G=1.33
000100x0	G=1

**PGA
Non-inverting**

RRIP on

PGA Mode – Inverting Mode OAF_{Cx} = 110

$$V_{OUT} = G V_{IN} + V_{REF}(1 - G)$$



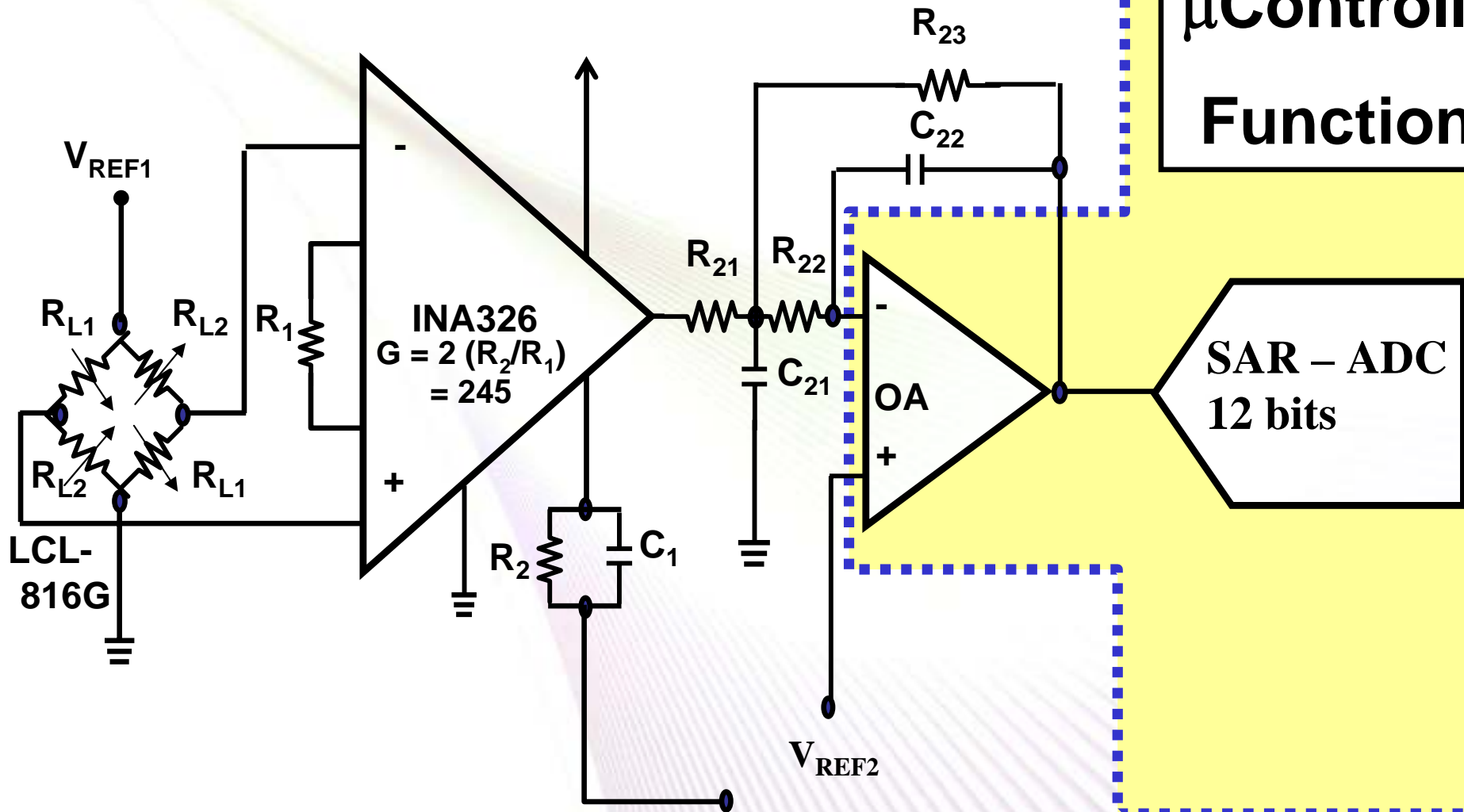
RRIP off

<u>OAxCTL1</u>	
111110x1	G=-15
110110x1	G=-7
101110x1	G=-4.33
100110x1	G=-3
011110x1	G=2.67
010110x1	G=-1.67
001110x1	G=-1
000110x0	G=-0.33

**PGA
Inverting**

RRIP on

Bridge Network



MSP430FG43x

**μController
Functions**

**SAR – ADC
12 bits**

Summary

- **12-bit SAR Converter – ADC12**
 - 12-bit Resolution and Accuracy
 - Excellent Dynamic Range
 - For more Resolution – Discrete Options
- **Operational Amplifier – OA**
 - Standard Single Supply CMOS Op Amp
 - Rail-to-rail Input
 - Rail-to-rail Output
 - Six Configurations or Modes
 - For more Accuracy – Discrete Options
 - For more Complexity – Discrete Options
- **MSP430 Analog Options – Very Useful!**

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