Working with ADCs, OAs and the MSP430

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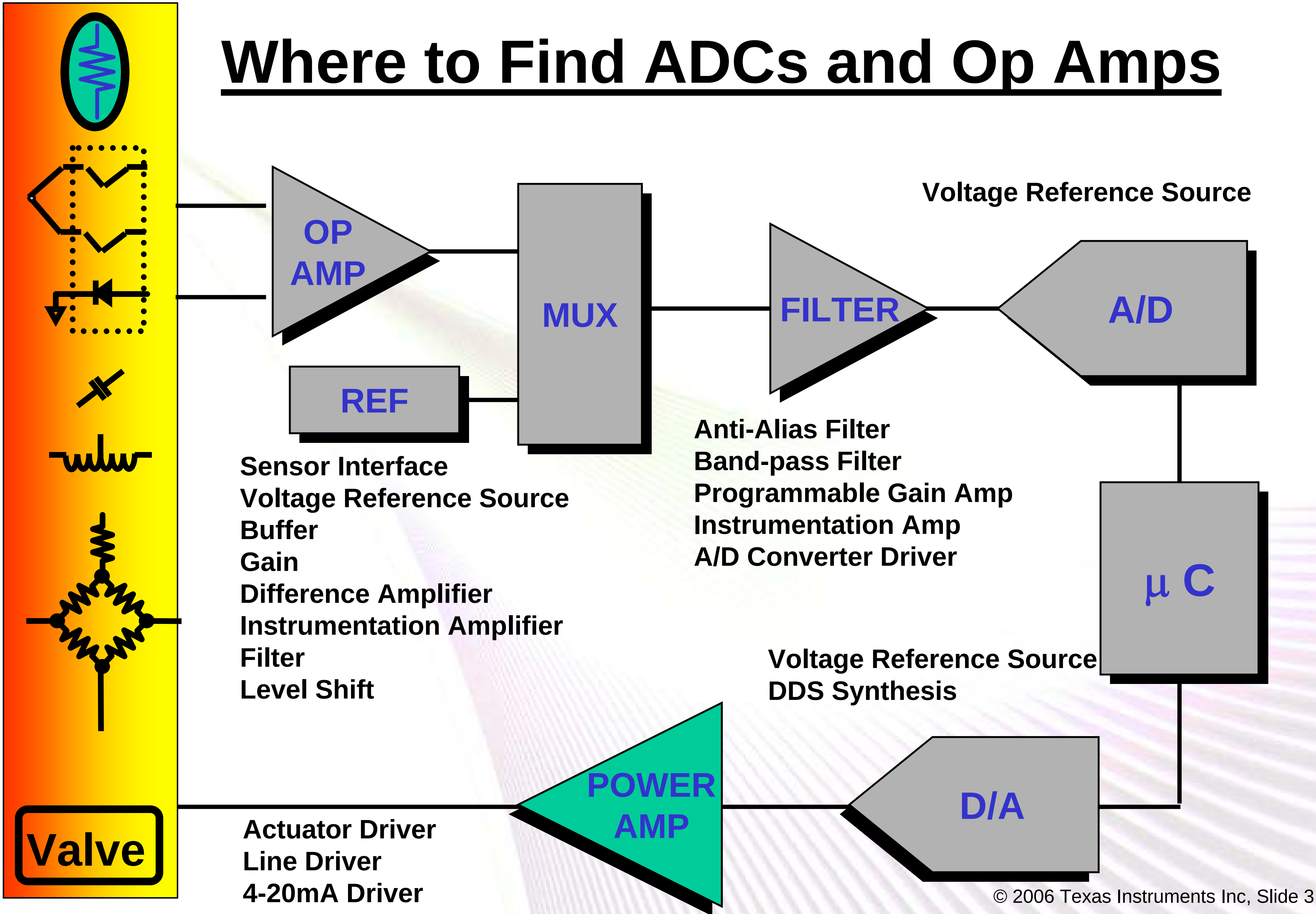
Agenda

- **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
Valve
OP AMP
REF
MUX
FILTER
A/D
Voltage Reference Source
μ C
D/A
POWER AMP
Sensor Interface
Voltage Reference Source
Buffer
Gain
Difference Amplifier
Instrumentation Amplifier
Filter
Level Shift
Anti-Alias Filter
Band-pass Filter
Programmable Gain Amp
Instrumentation Amp
A/D Converter Driver
Voltage Reference Source
DDS Synthesis
Actuator Driver
Line Driver
4-20mA Driver

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

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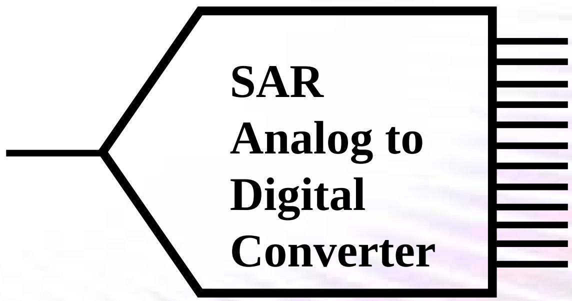
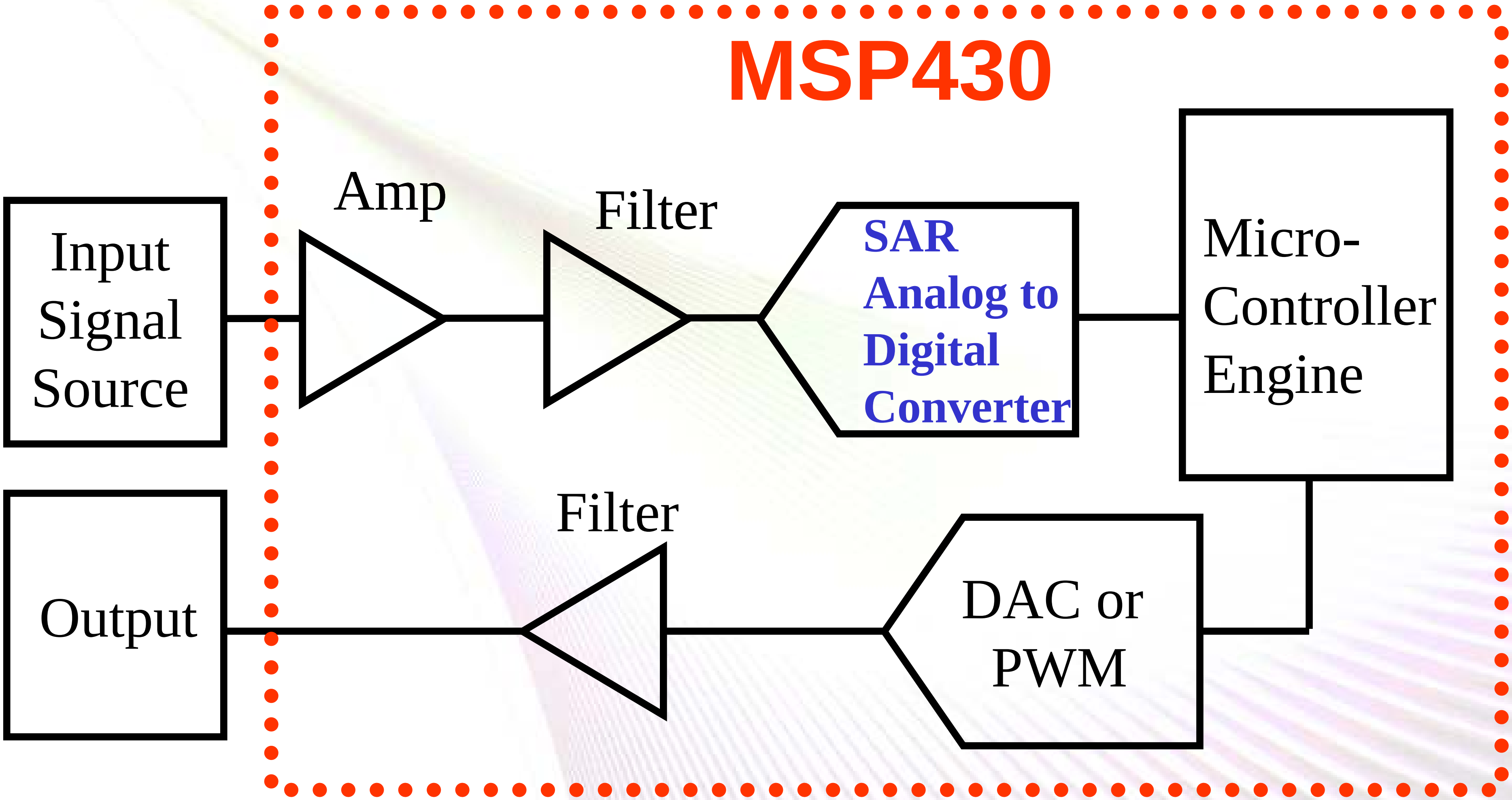
The SAR ADC

- **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

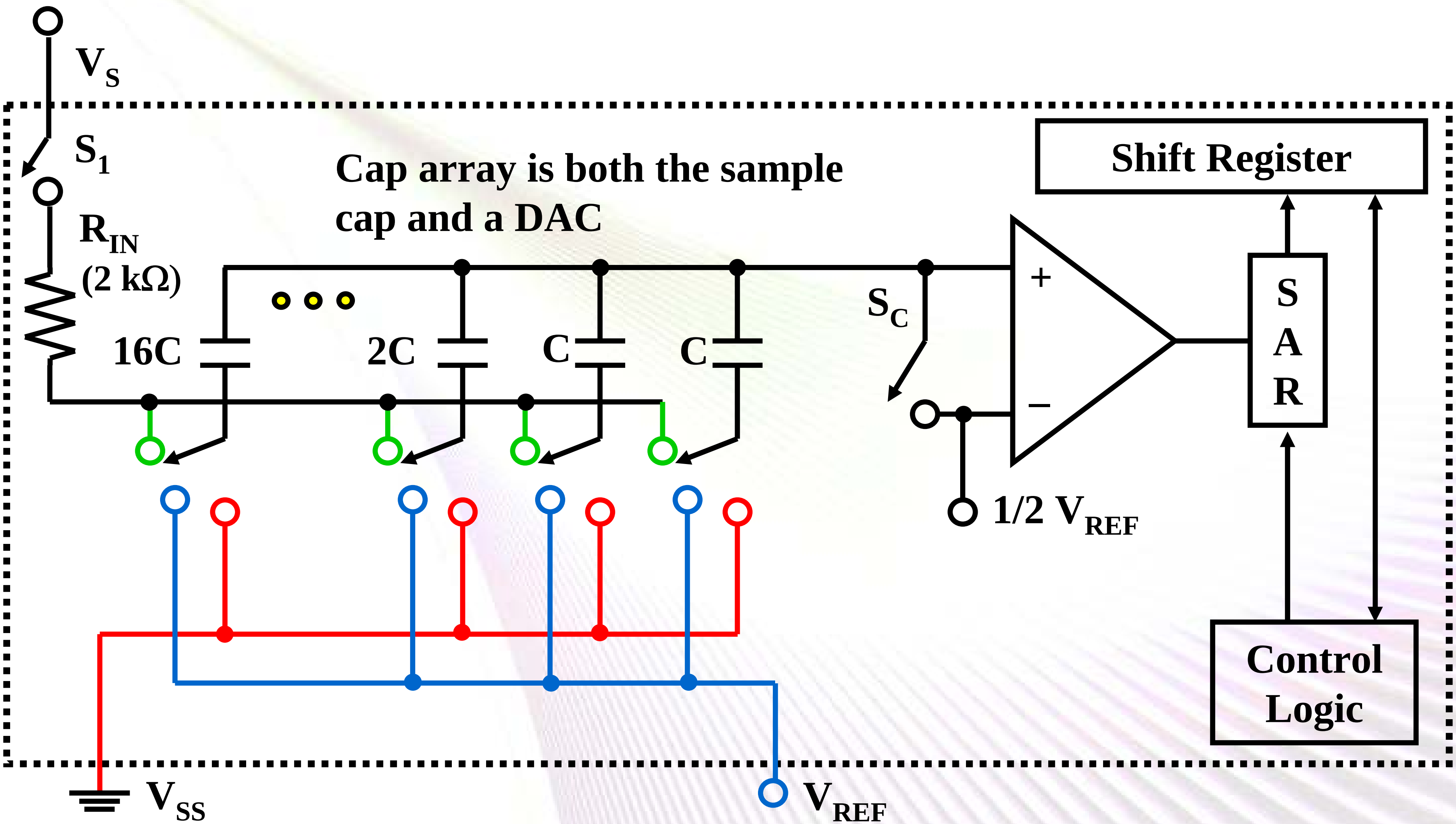


- **Usually require a Low-pass Filter before Analog Input**

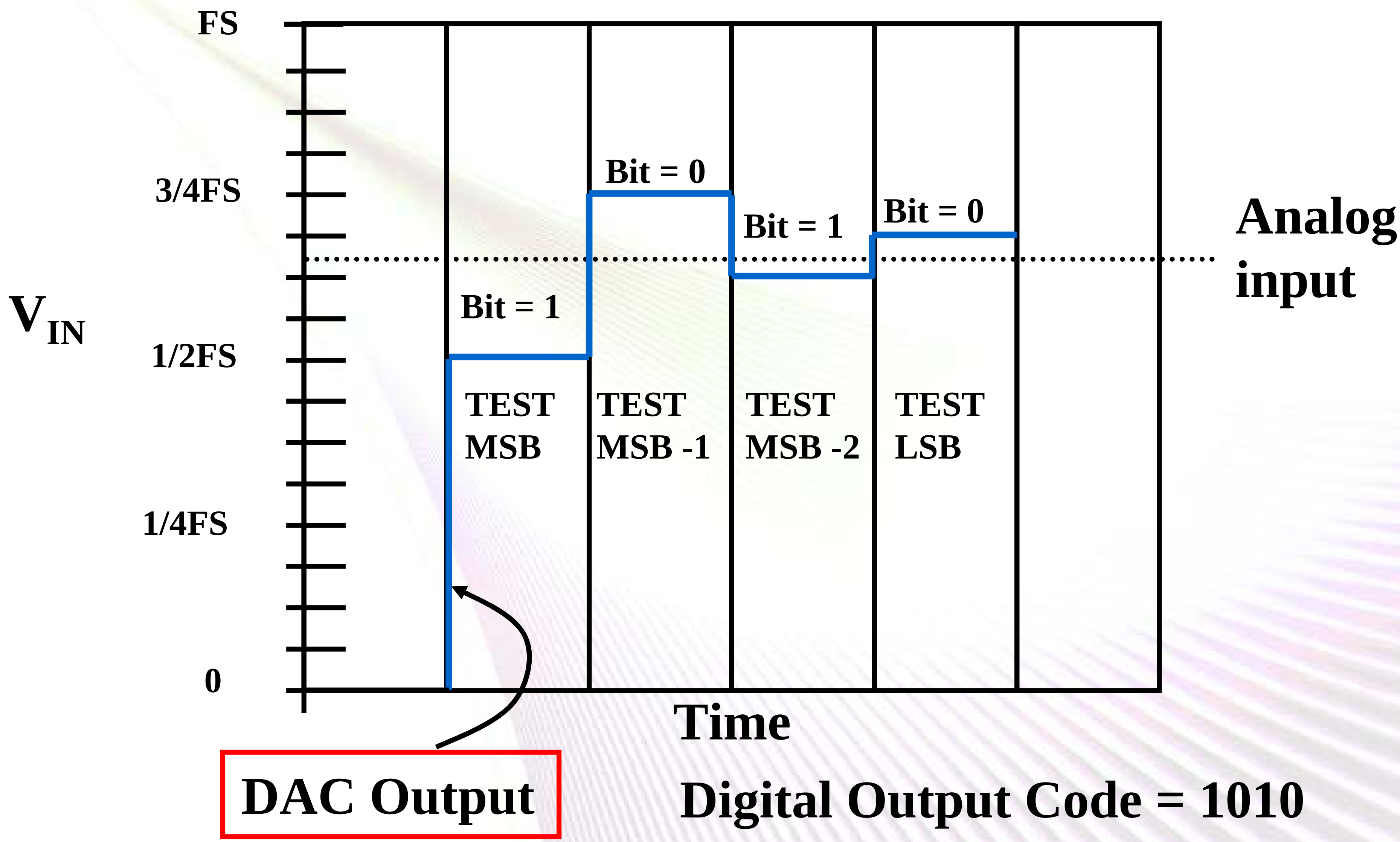
System Integration Using an A/D



SAR Converter – Block Diagram

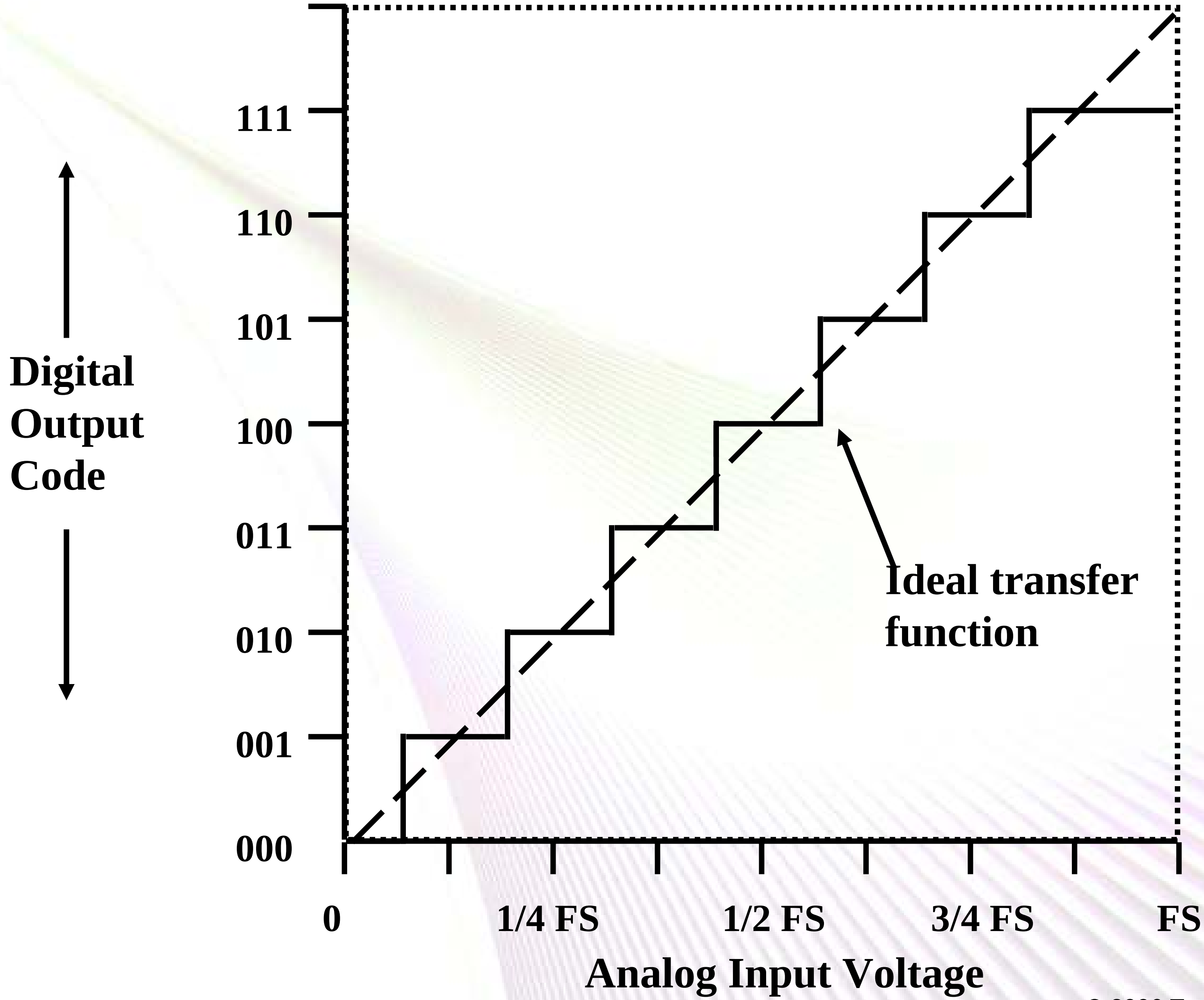


Successive Approximation Concept

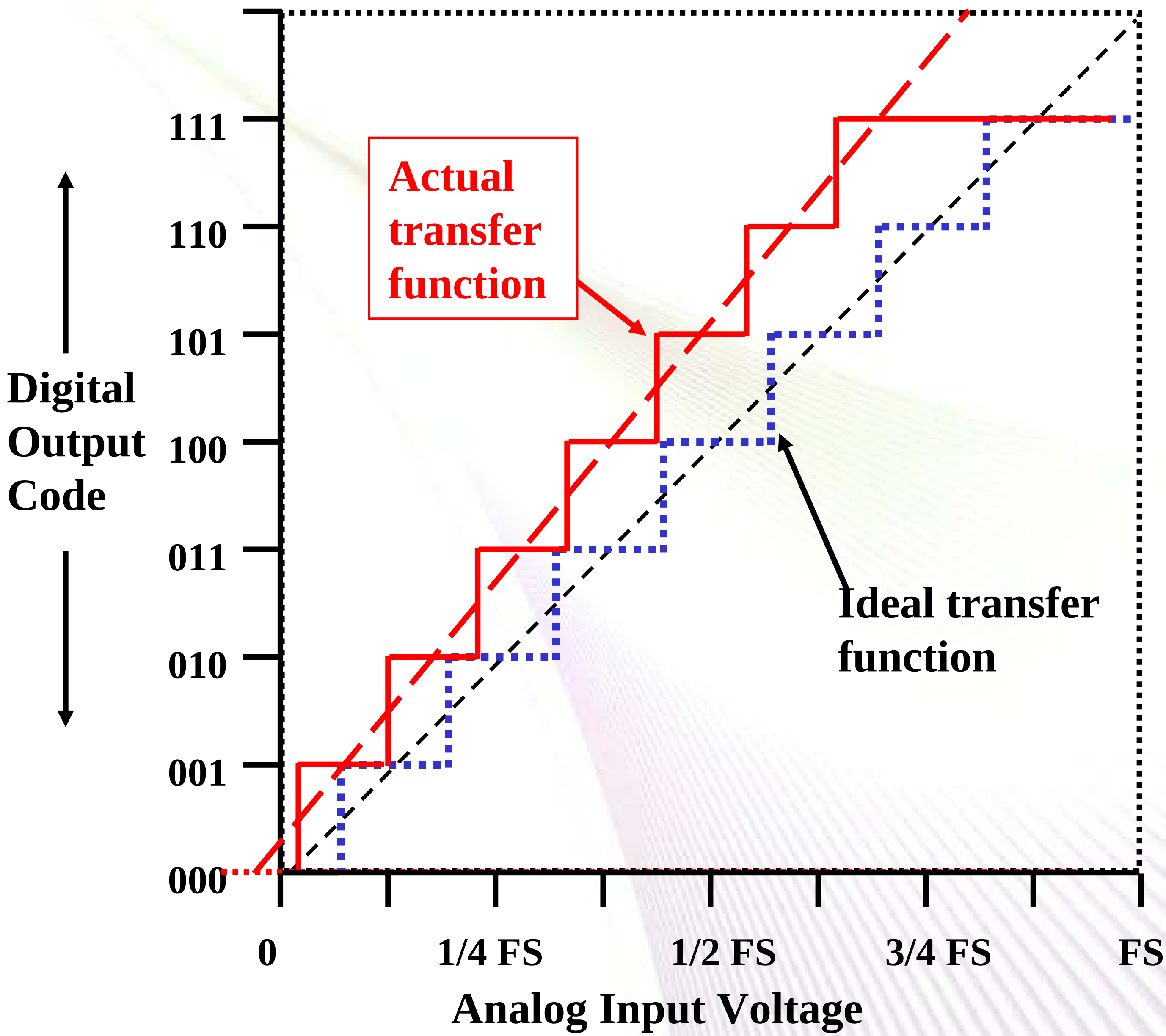


Digital Output Code = 1010

ADC Ideal Transfer Function



ADC with Offset and Gain Error

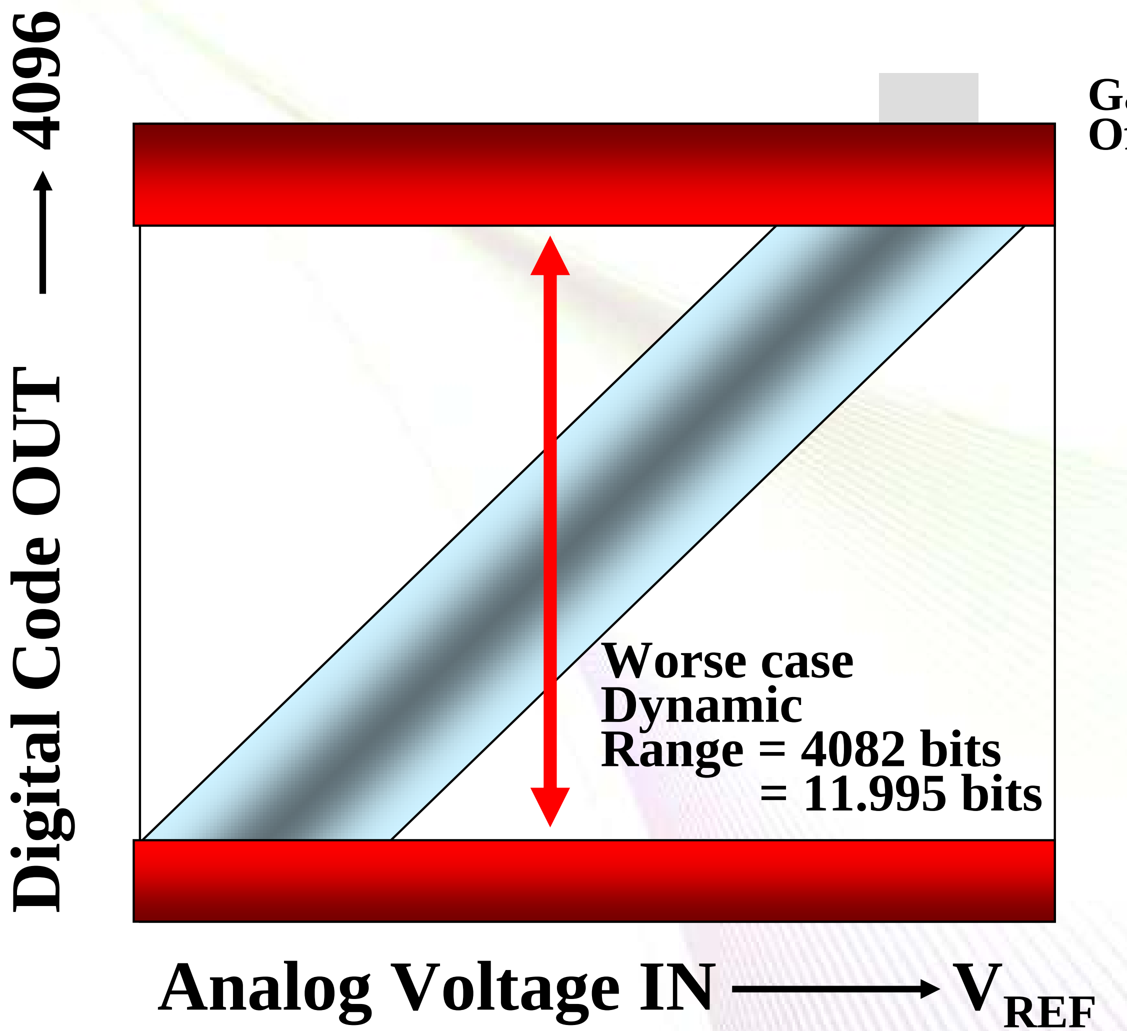


- y = a + (1+b)x

  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



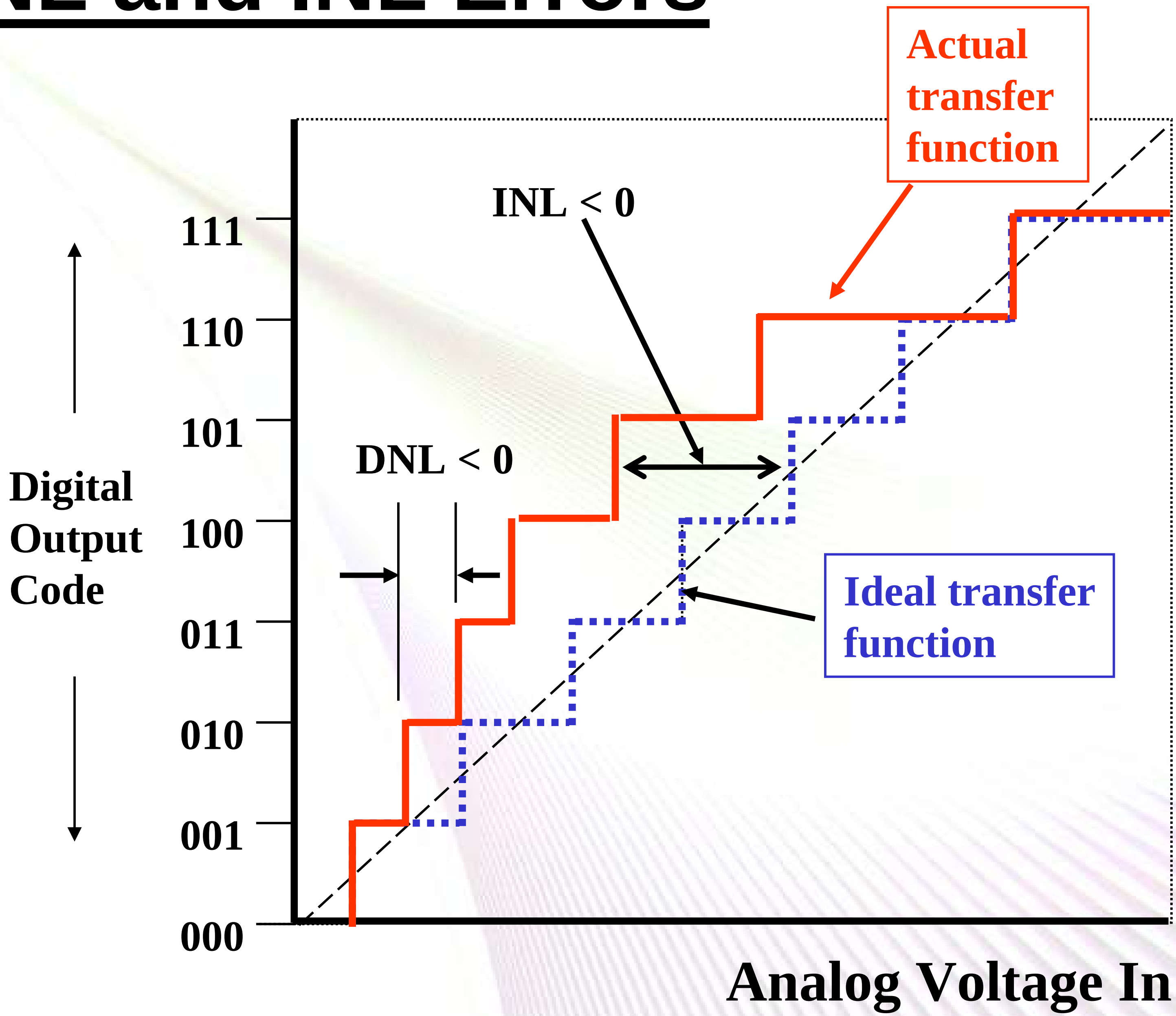
- **ADC12 specifications**

  Offset
  - E_O typ = ±2 LSB
  - E_O max = ±4 LSB

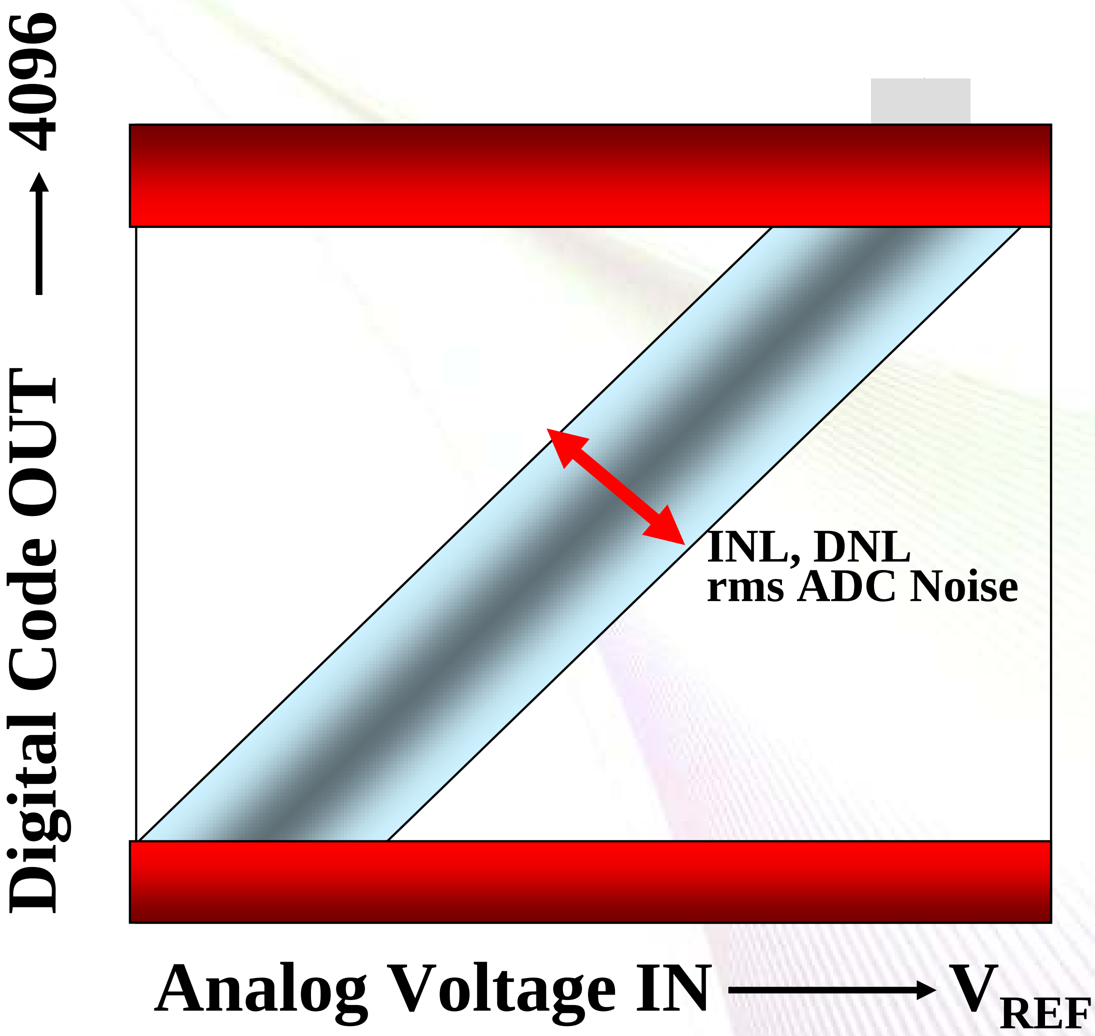
  Gain
  - E_G typ = ±1.1 LSB
  - E_G max = ±2 LSB (= ±0.0488%)

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

DNL and INL Errors

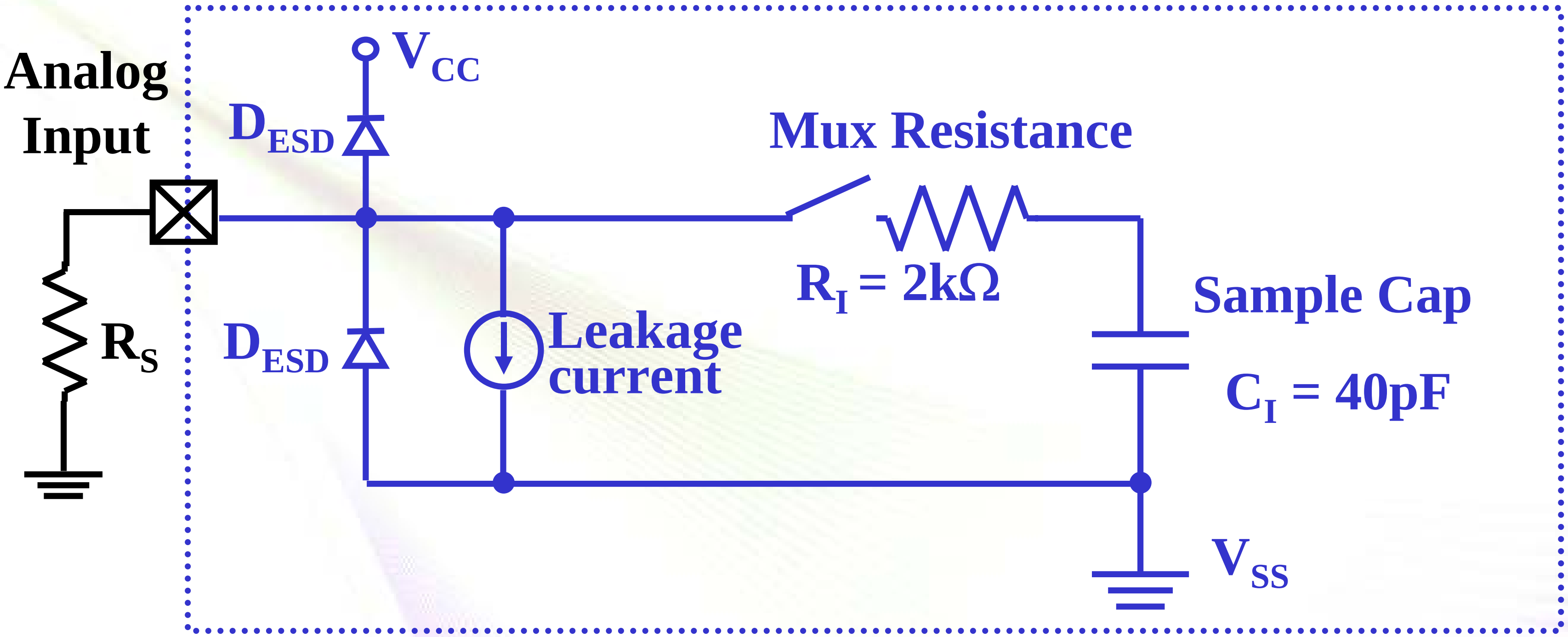


INL/DNL/Noise Impact on Dynamic Range



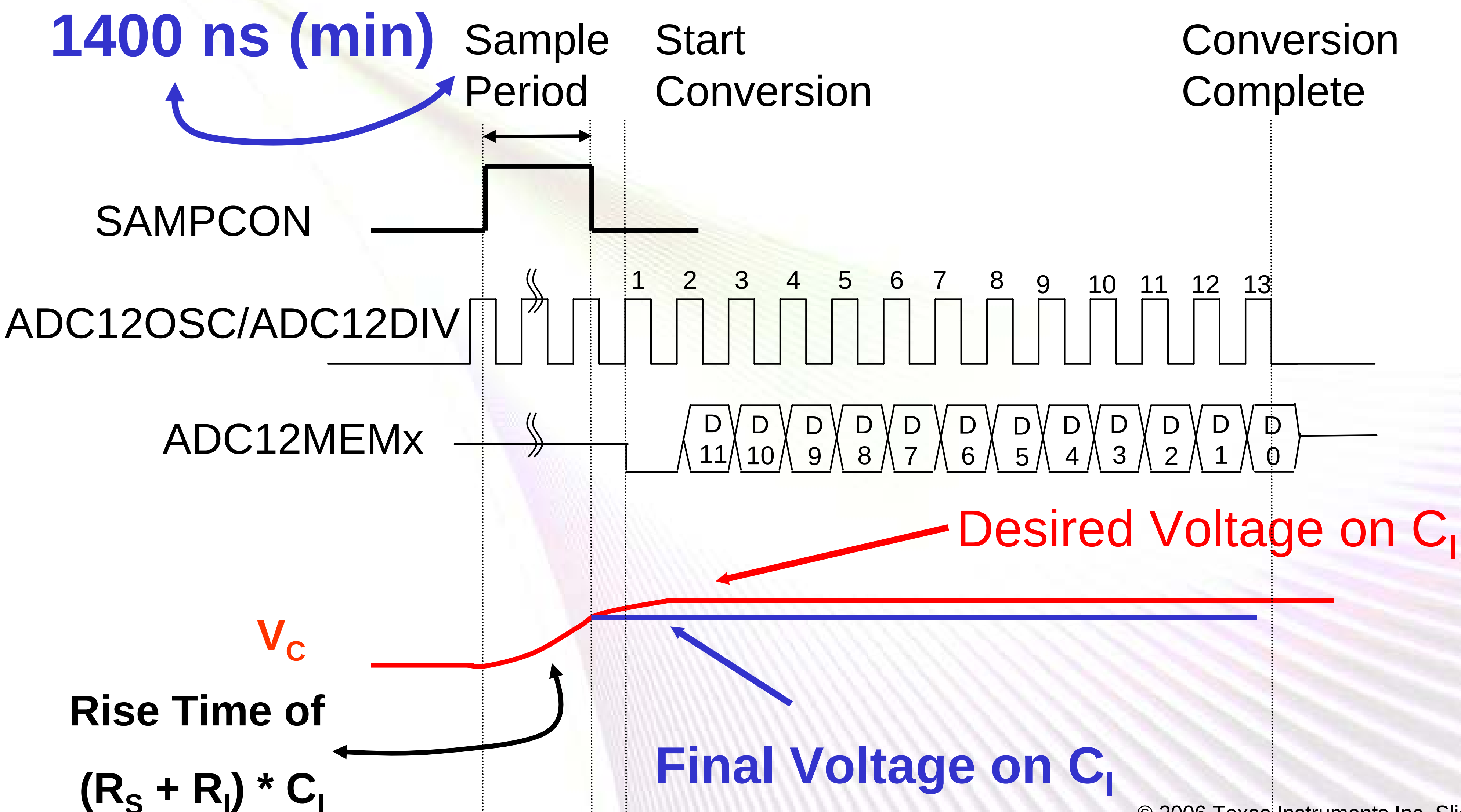
- **ADC12 specifications**
  - DNL error
  - E_D max = ±1.7 LSB
  - INL error
  - E_I max = ±1 LSB
  - 1 LSB = $(V_{R+} - V_{R-})/ 2^{12}$
- **INL, DNL and Noise errors move across the entire range**
- **Impacts the Effective Number of Bits (ENOB)**
- **Not Easily calibrated**
- **Effects Accuracy**

ADC Input Impedance



- **Input Internal Impedance is Relatively Low**
- **A High Impedance Source Increases Sample Cap Charging Time**
- **Rise Time of Voltage on CI ~ (RS + RI) * CI**

Sample Cap Charging Time



Alternative High Resolution Devices

- **ADC12**
  - Resolution = 12 bits
  - Minimum LSB size = VREF / 2n = 1.5 V / 212 = 366 mV
  - # channels = 12 to 16 (depends on part number)
- **ADS8341**
  - Resolution = 16 bits
  - Minimum LSB size = VREF / 2n = 2.7 V / 216 = 41.2 mV
  - # channels = 4
- **ADS1100**
  - Resolution = 16 bits
  - Minimum LSB size = VREF / 2n = 2*2.7 V / 216 = 82.4 mV
  - # channels = 1

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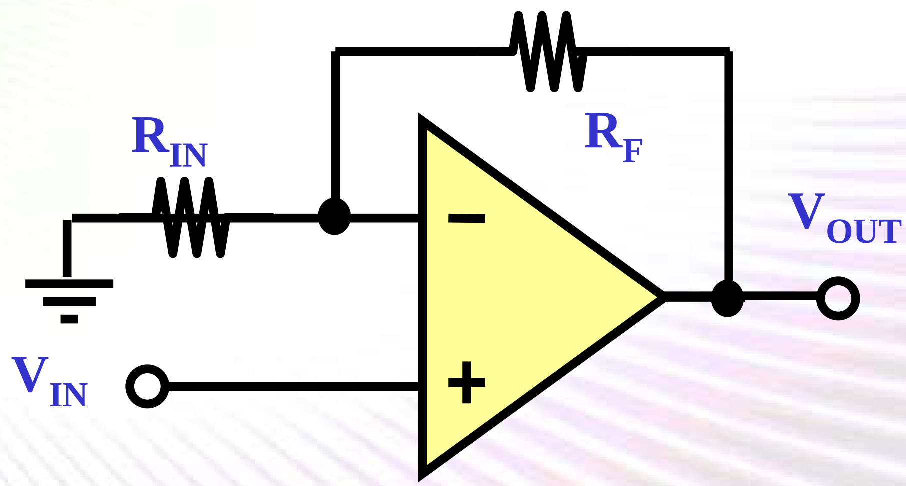
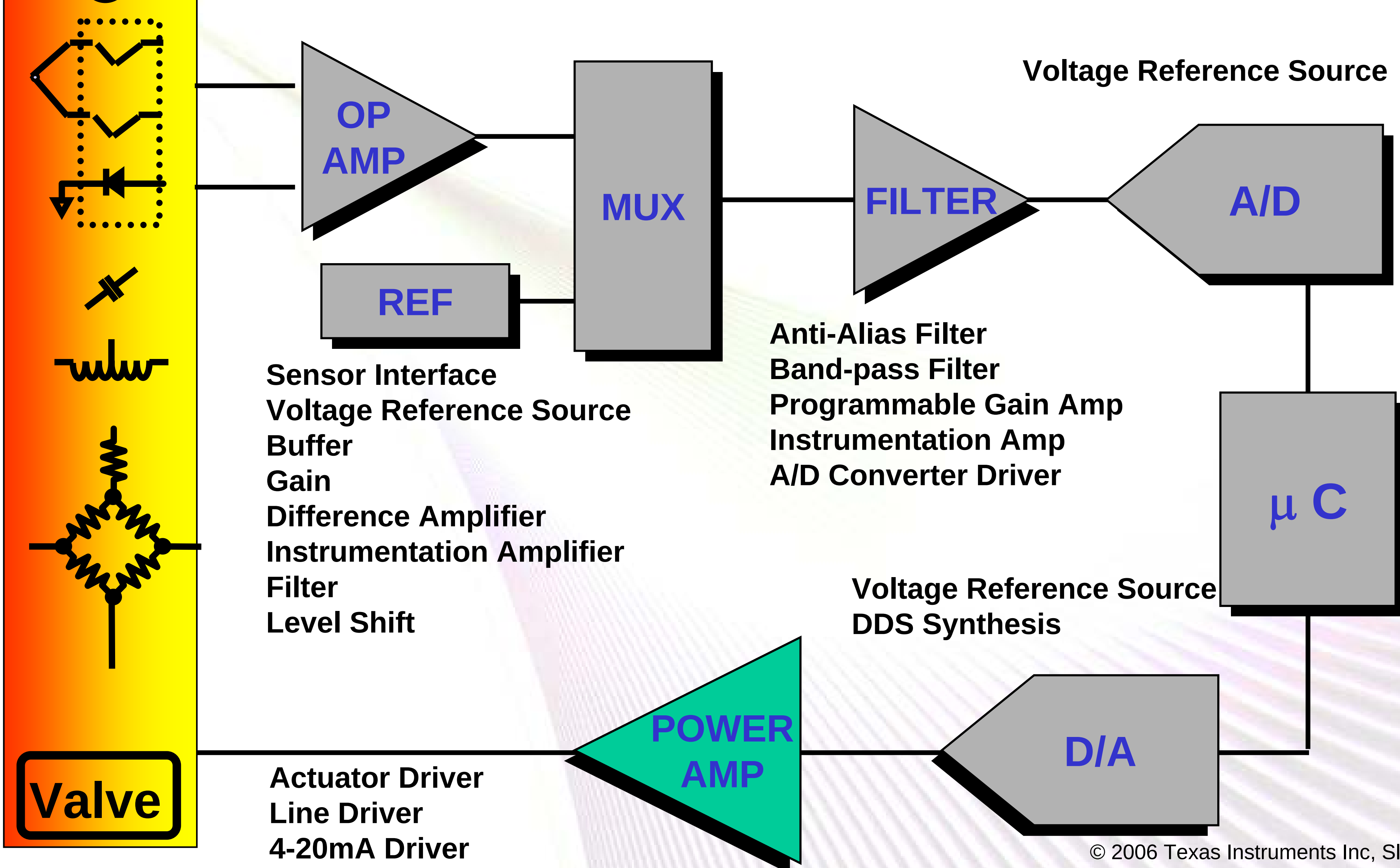
Operational Amplifiers

- **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



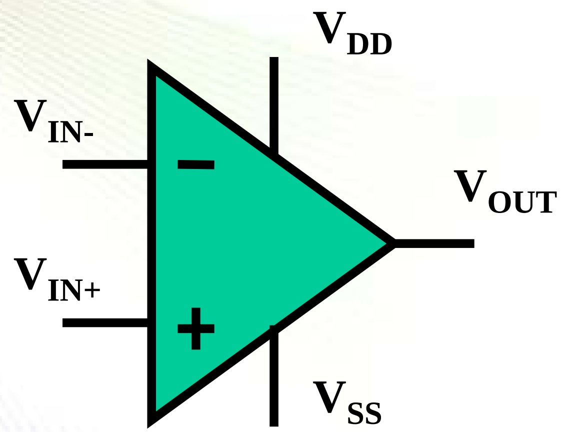
Where to Find Op Amps



Ideal Op Amp

POWER SUPPLY
- No min or max Voltage
- I_{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 = ∞



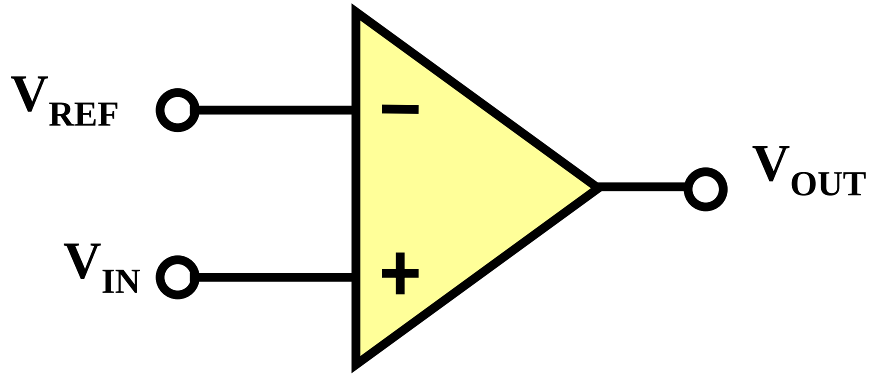
OUTPUT
- V_{OUT} = V_{SS} to V_{DD}
- I_{OUT} = ∞
- Slew Rate = ∞
- Z_{OUT} = 0 Ω

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

$0.00

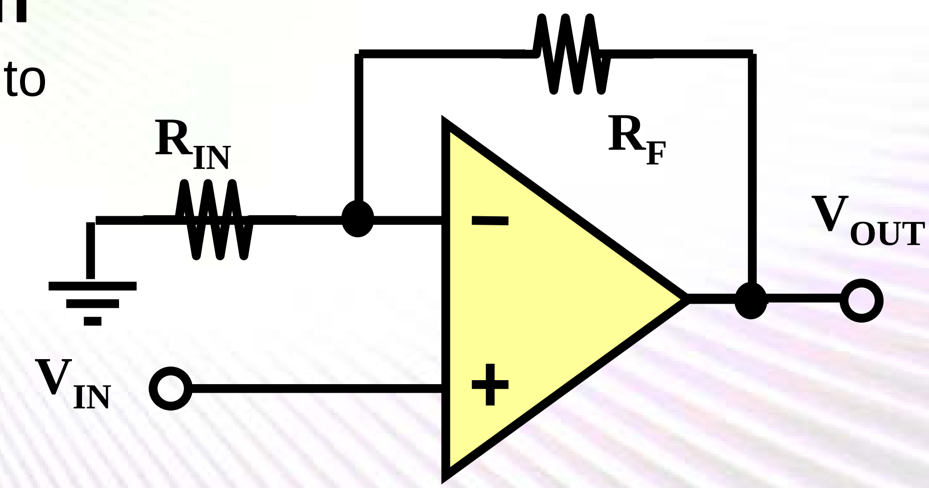
Open Loop vs Closed Loop Design

- **OAFCx = 011**
- **Open Loop Configuration**
  - In Comparator mode



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

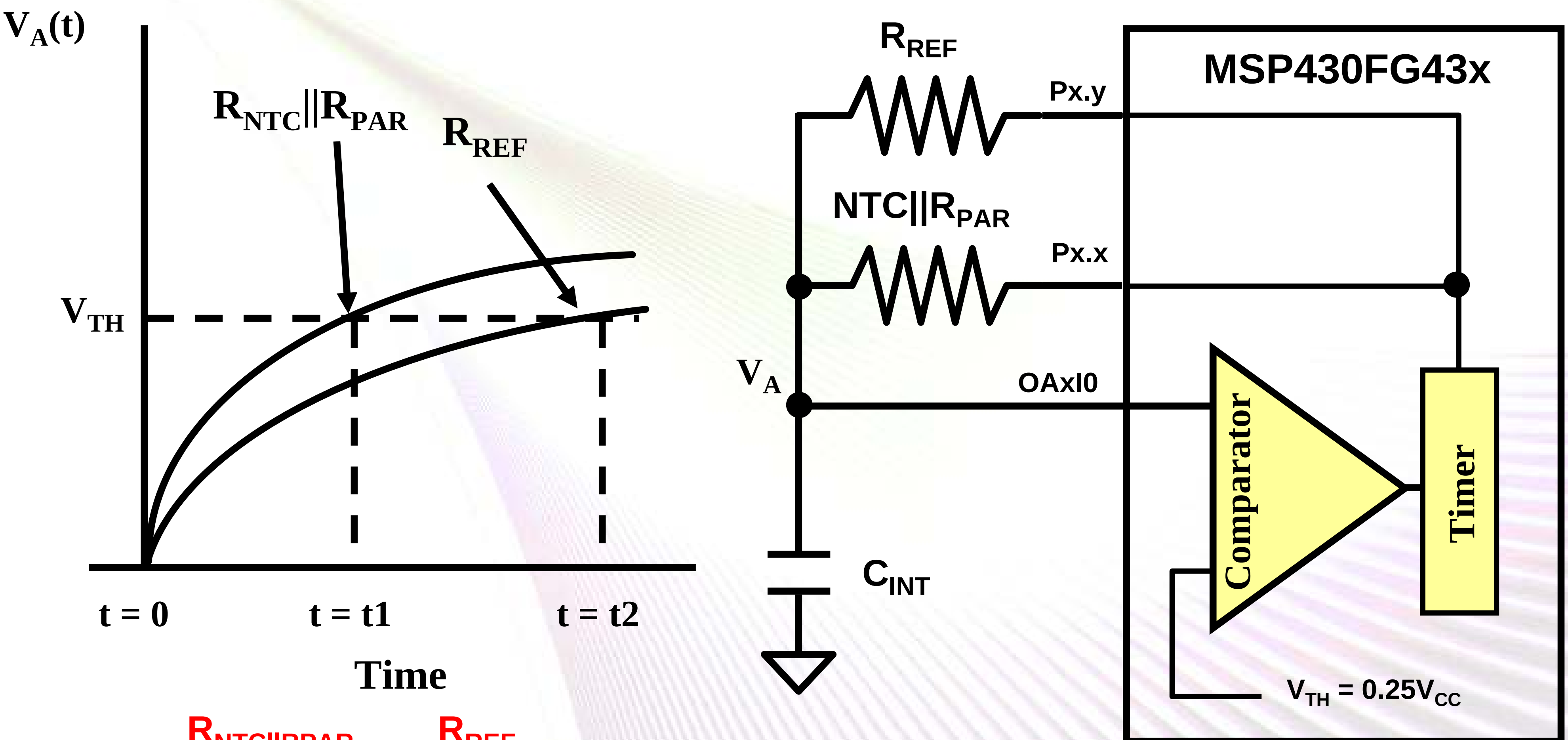
- **OAFCx = 000**
- **Closed Loop Configuration**
  - Always a Connection from Output to Inverting Input
  - Gain is Dependant on Resistors



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

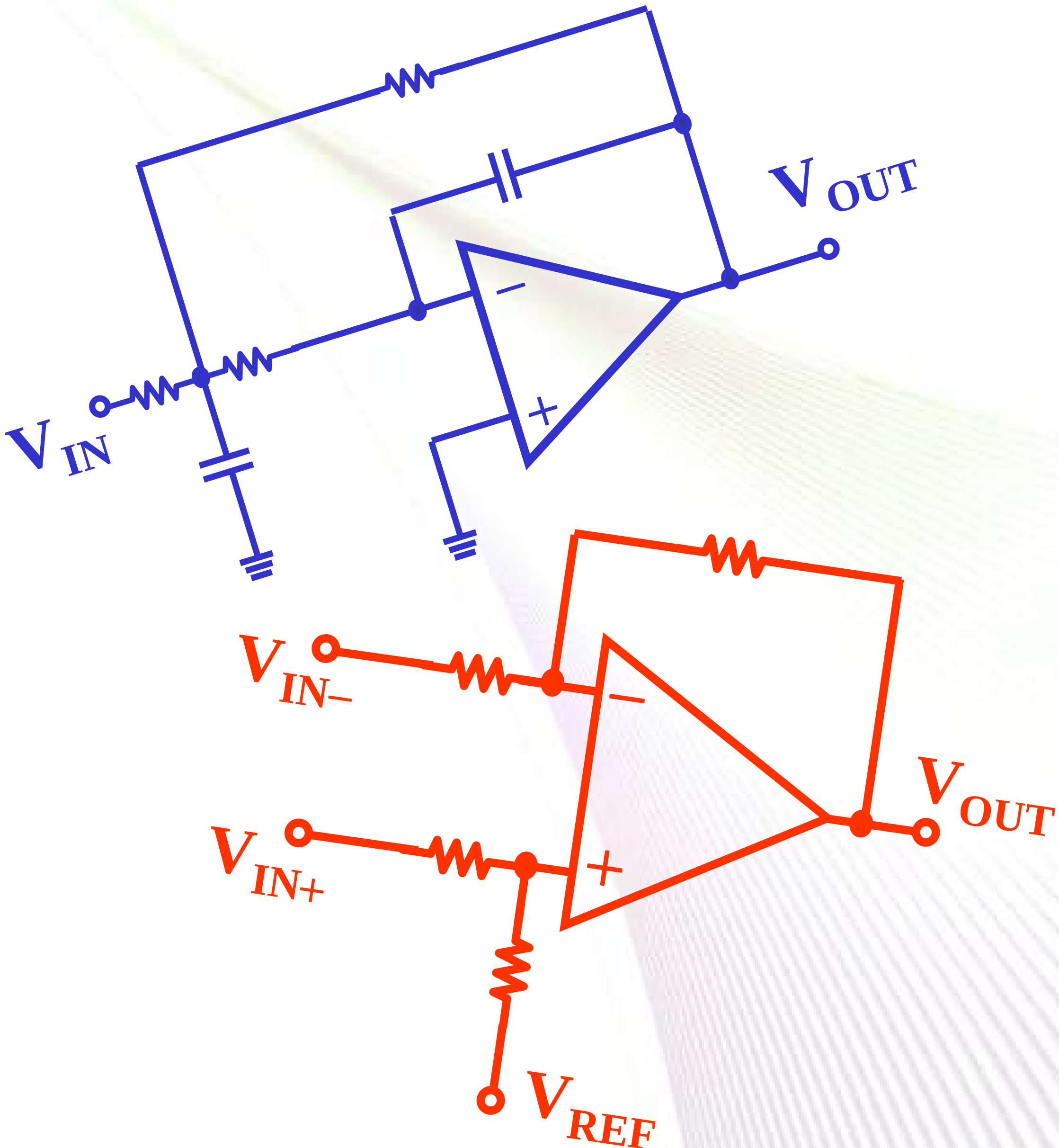
Comparator Mode – OAFCx = 011

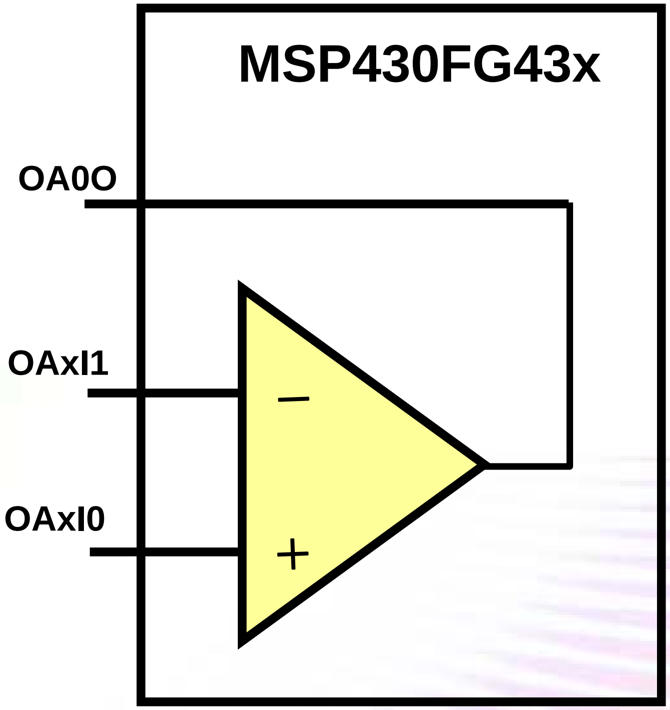
Temperature Sensor



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

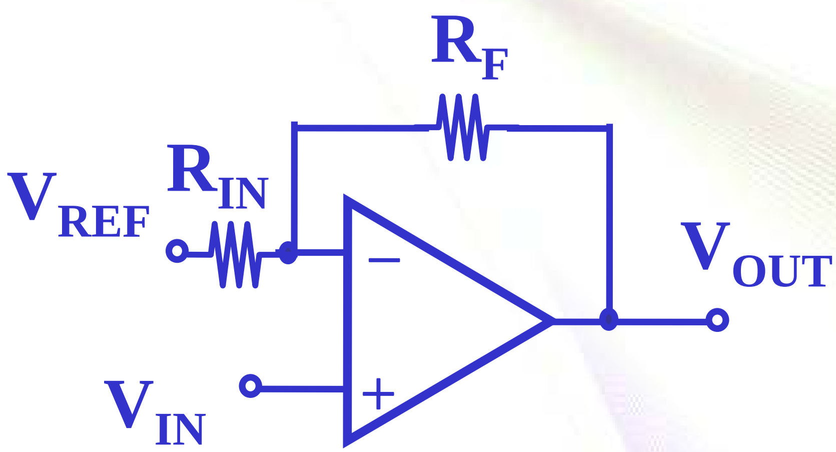
General Op amp Mode – OAFCx = 000

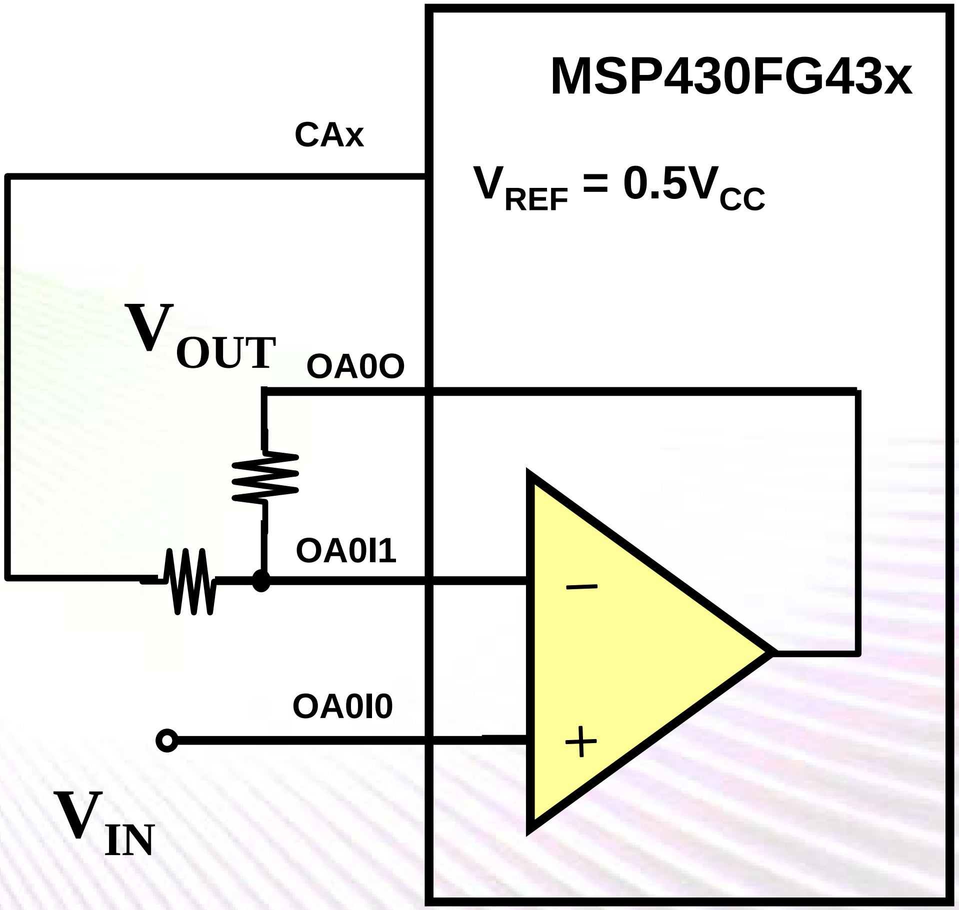




General Op amp Mode – OAFCx = 000

Non-inverting Gain

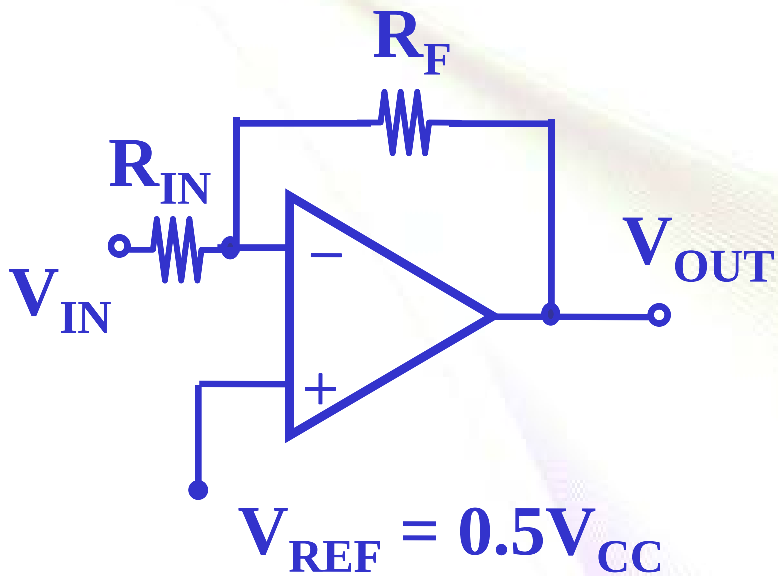


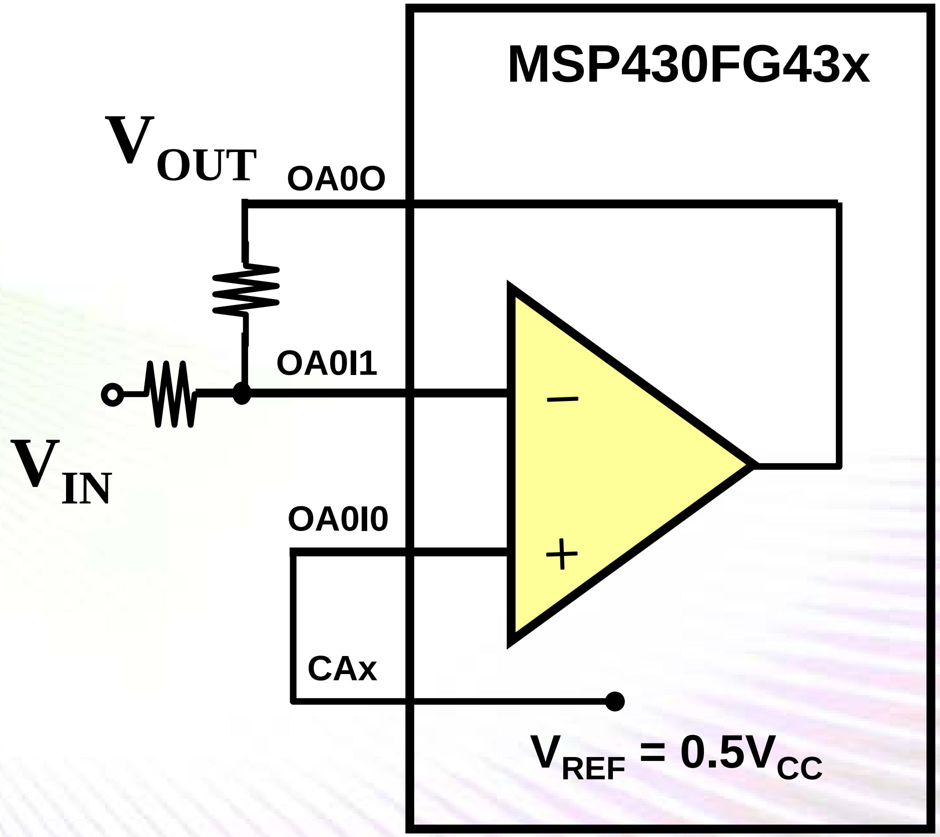


$$V_{OUT} = V_{IN}(1 + R_F/R_{IN}) - V_{REF} * R_F/R_{IN}$$

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

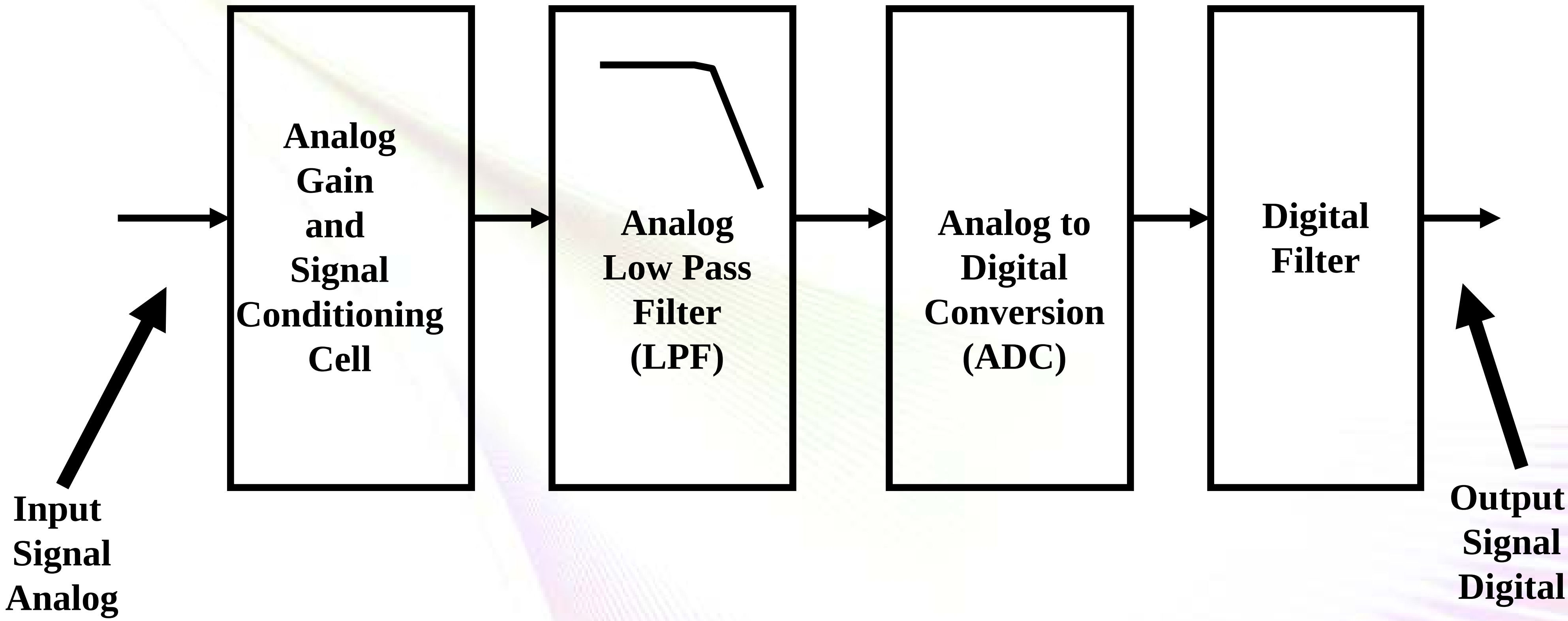
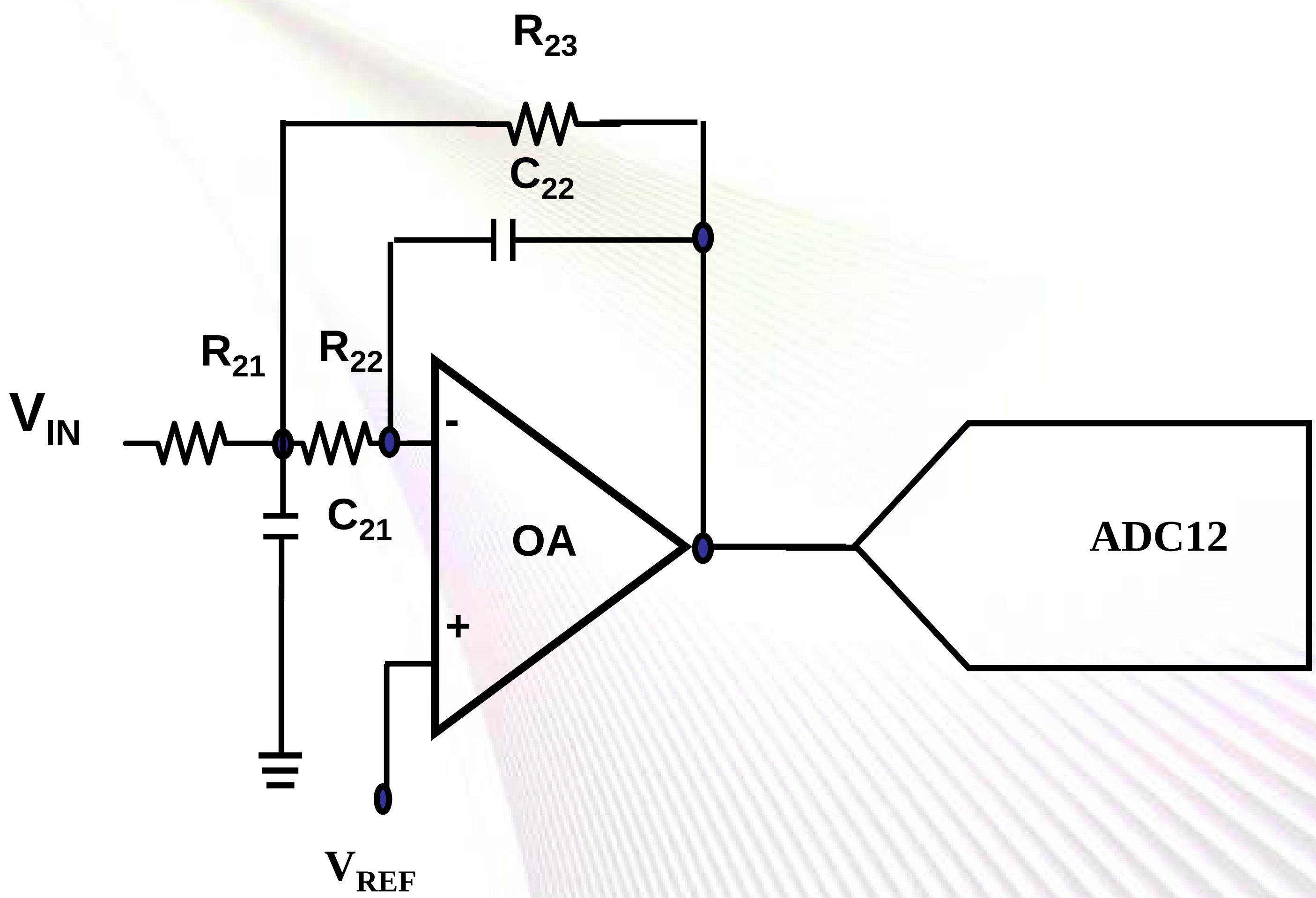


Figure 4.1

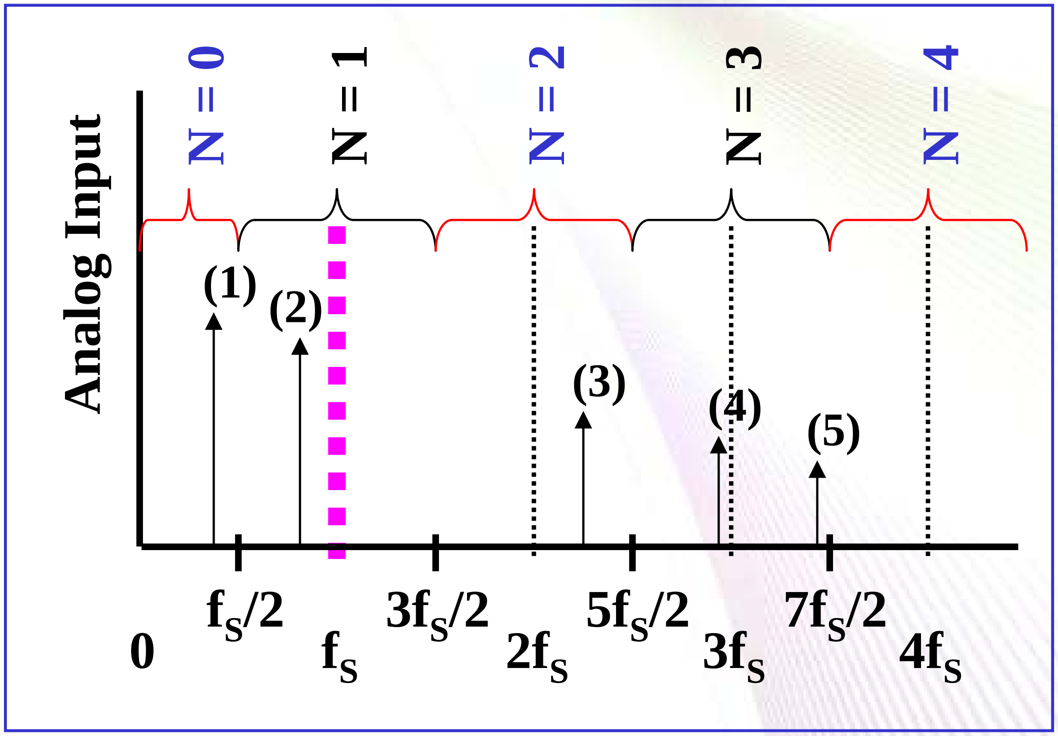
Noise Reduction with a Low Pass Filter

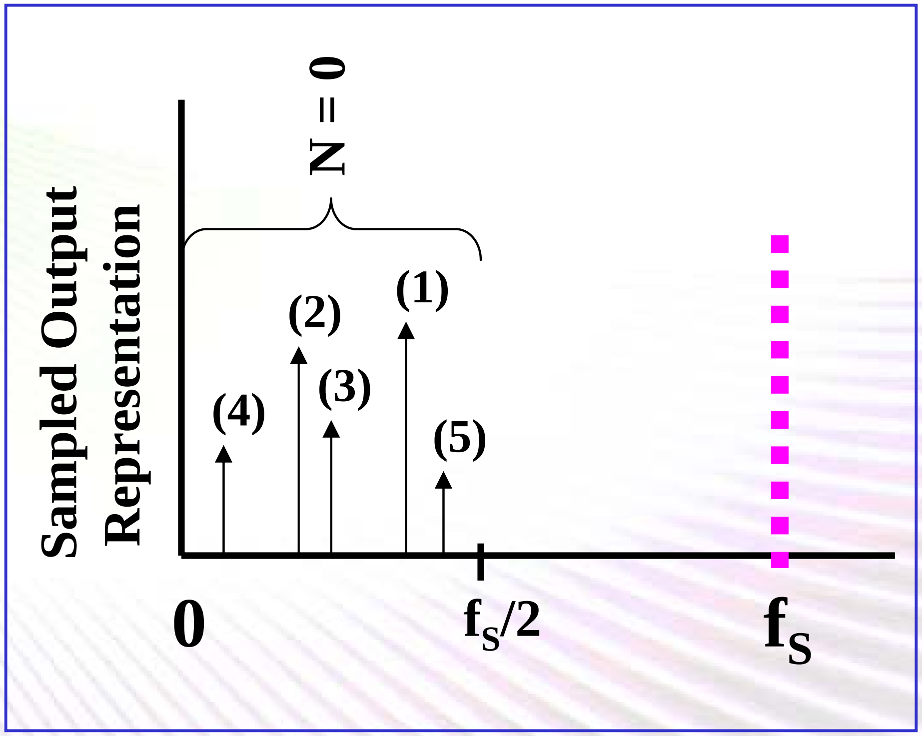
Noise Reduction or Anti-aliasing Filter



Anti-alias Filter :: Nyquist Theorem

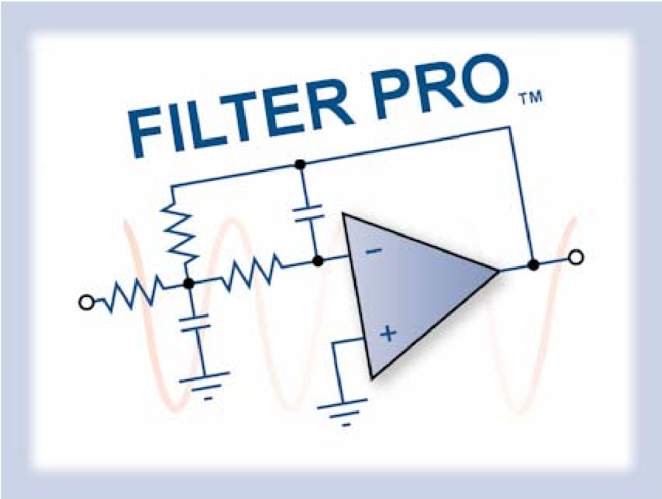
Signal at the Input of the A/D Converter → $f_{ALIASED} = |f_{IN} - Nf_S|$ **Find N by making** $f_{ALIASED} < f_s / 2$ → **Digital Representation at the Output of the Converter**





Filter Pro Software

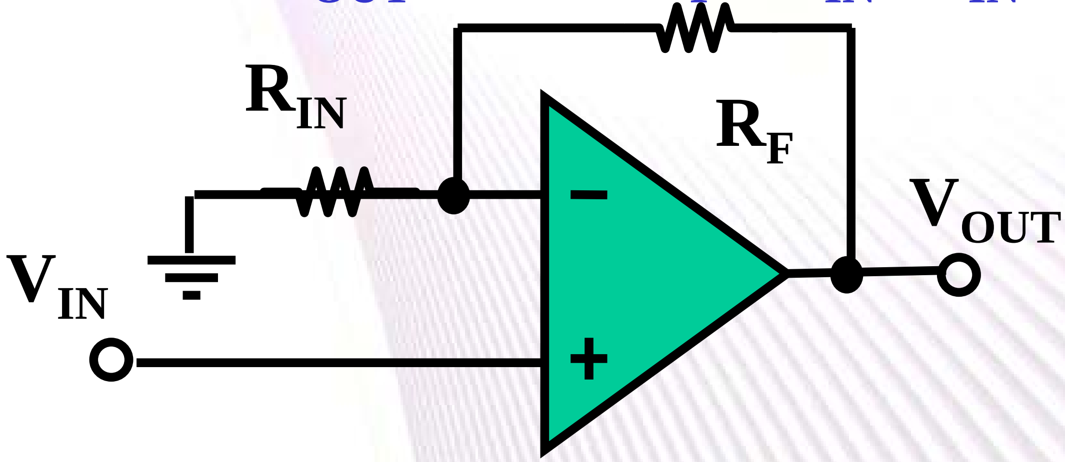
- **Filter synthesis tool for designing**
  - Multi-section filter
  - Low-pass Filter
  - High-pass active filter
- **Supports**
  - 2nd to 10th order
  - Multiple-feedback (MFB) Filter Topology
  - Sallen-Key Filter Topology
- **www.ti.com**



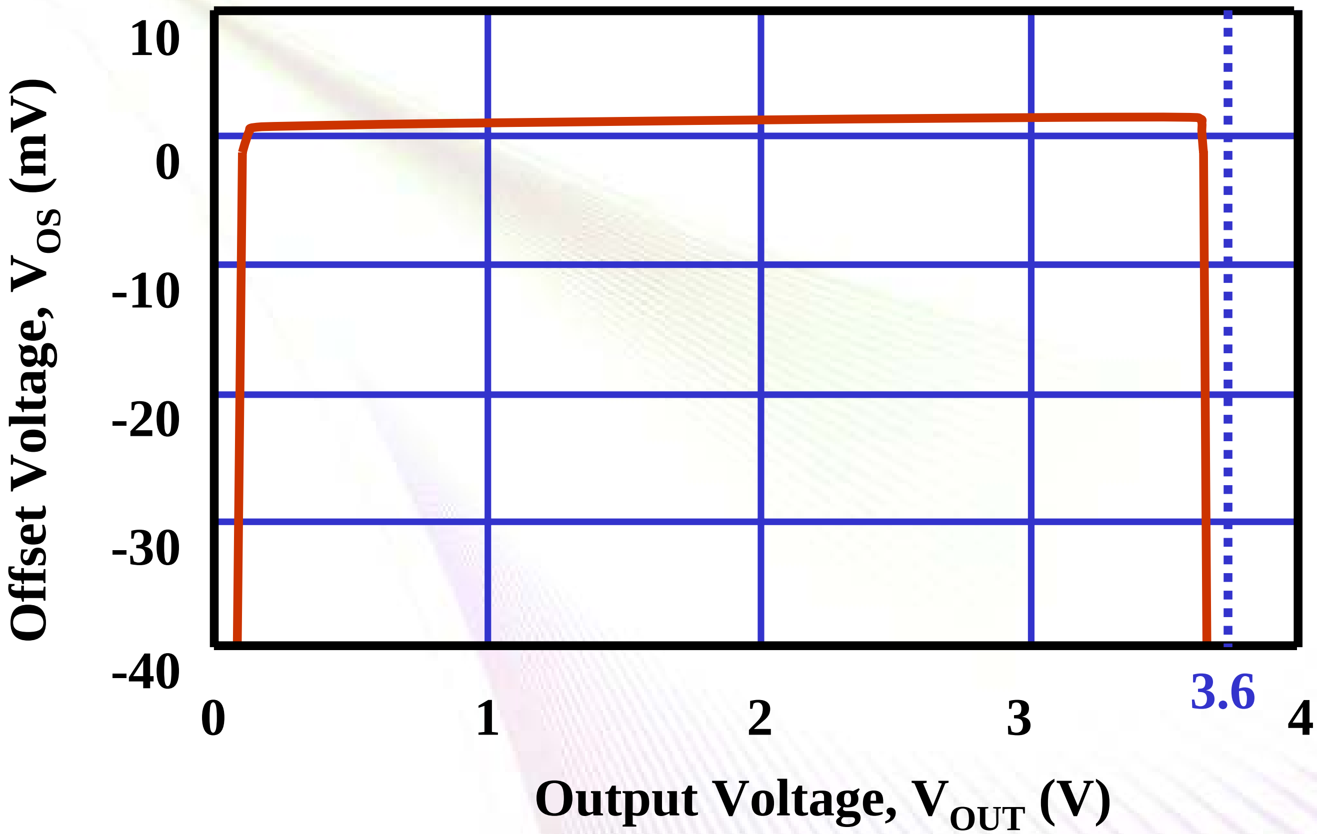
Operational Amp Output Swing

- 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}

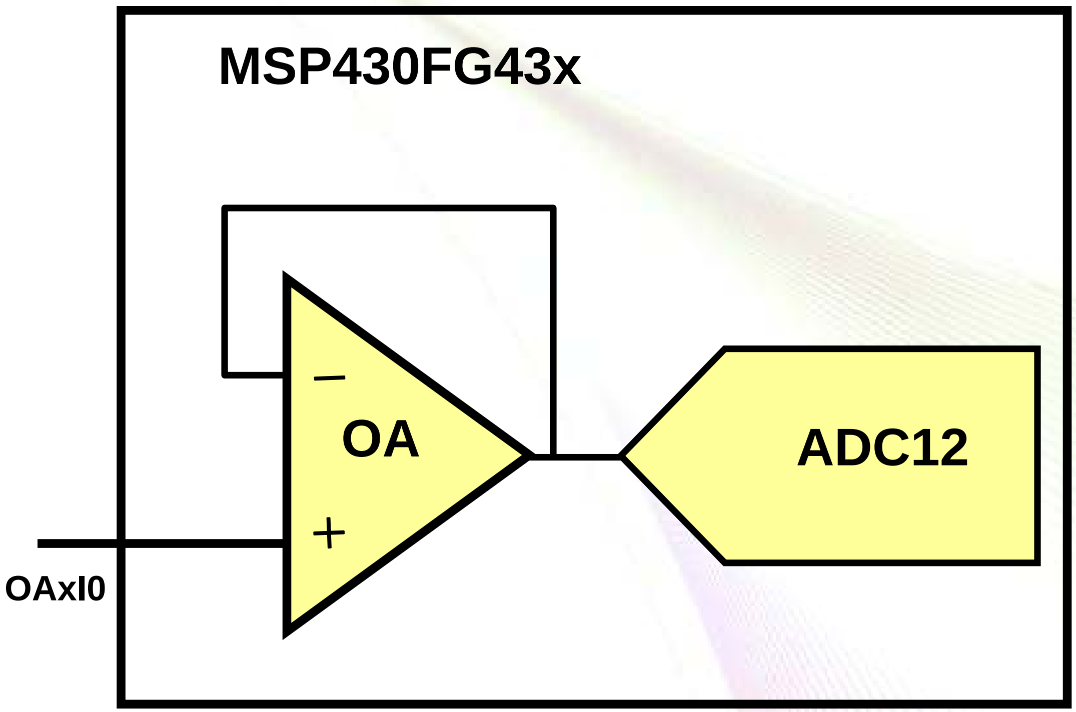
$V_{OUT} = (1 + R_F / R_{IN}) V_{IN}$



Operational Amp Output Swing



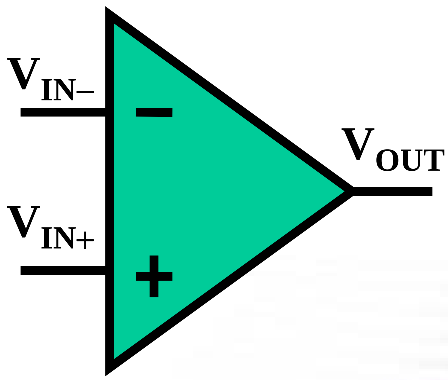
Unity Gain Buffer Mode – OAFCx = 001



- 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

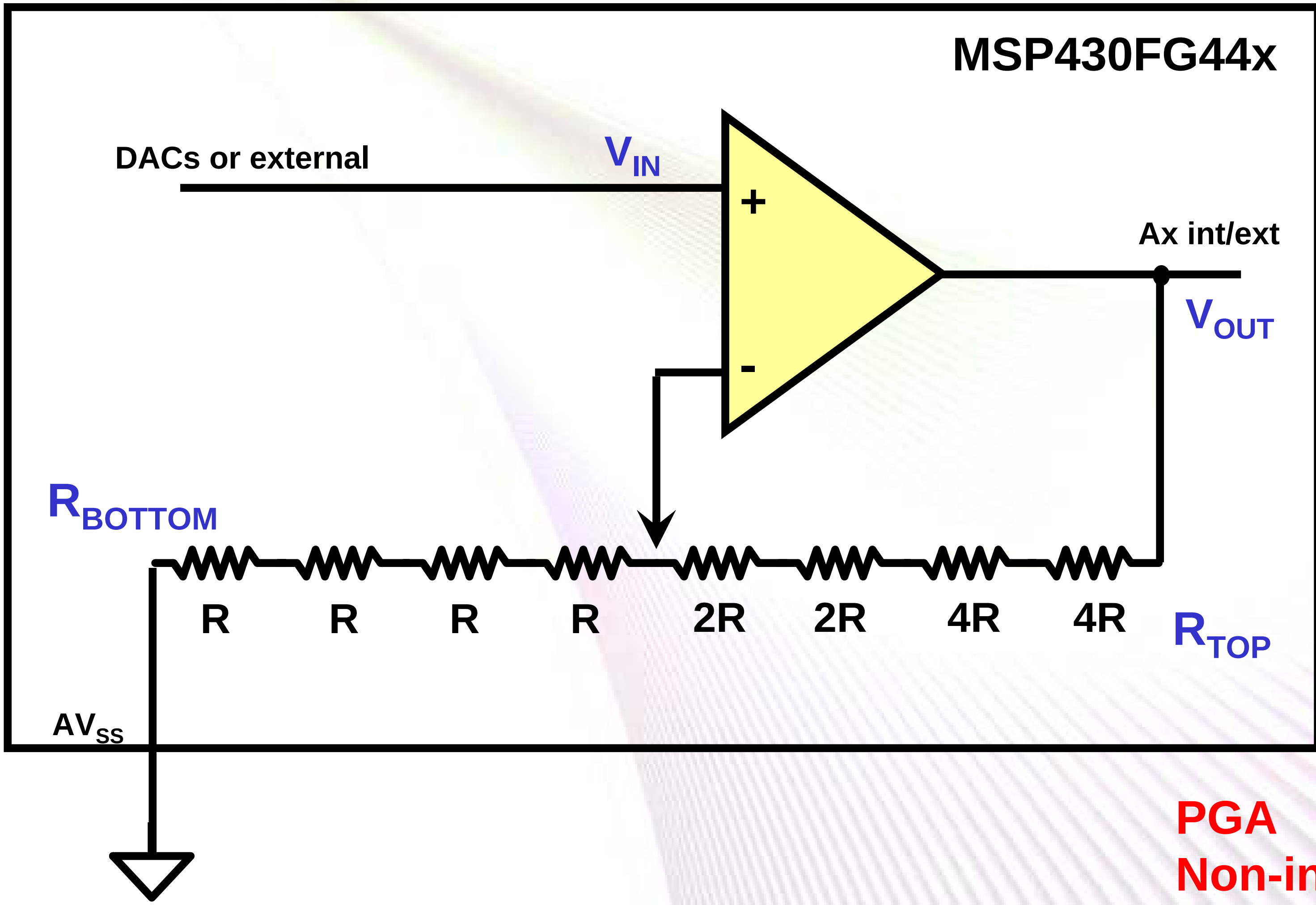
- **RRIP ON =**
  (VSS - 0.1V) {min} to (VCC + 0.1) {max}
- **Charge pump on input stage is turned on**
- **Great Feature, not all amps have this!**



- **RRIP OFF =**
  (VSS - 0.1V) {min} to (VCC - 1.2) {max}
- **(Appropriate for Gains > 2)**

PGA Mode –
Non-inverting Mode OAFCx = 100

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



RRIP off

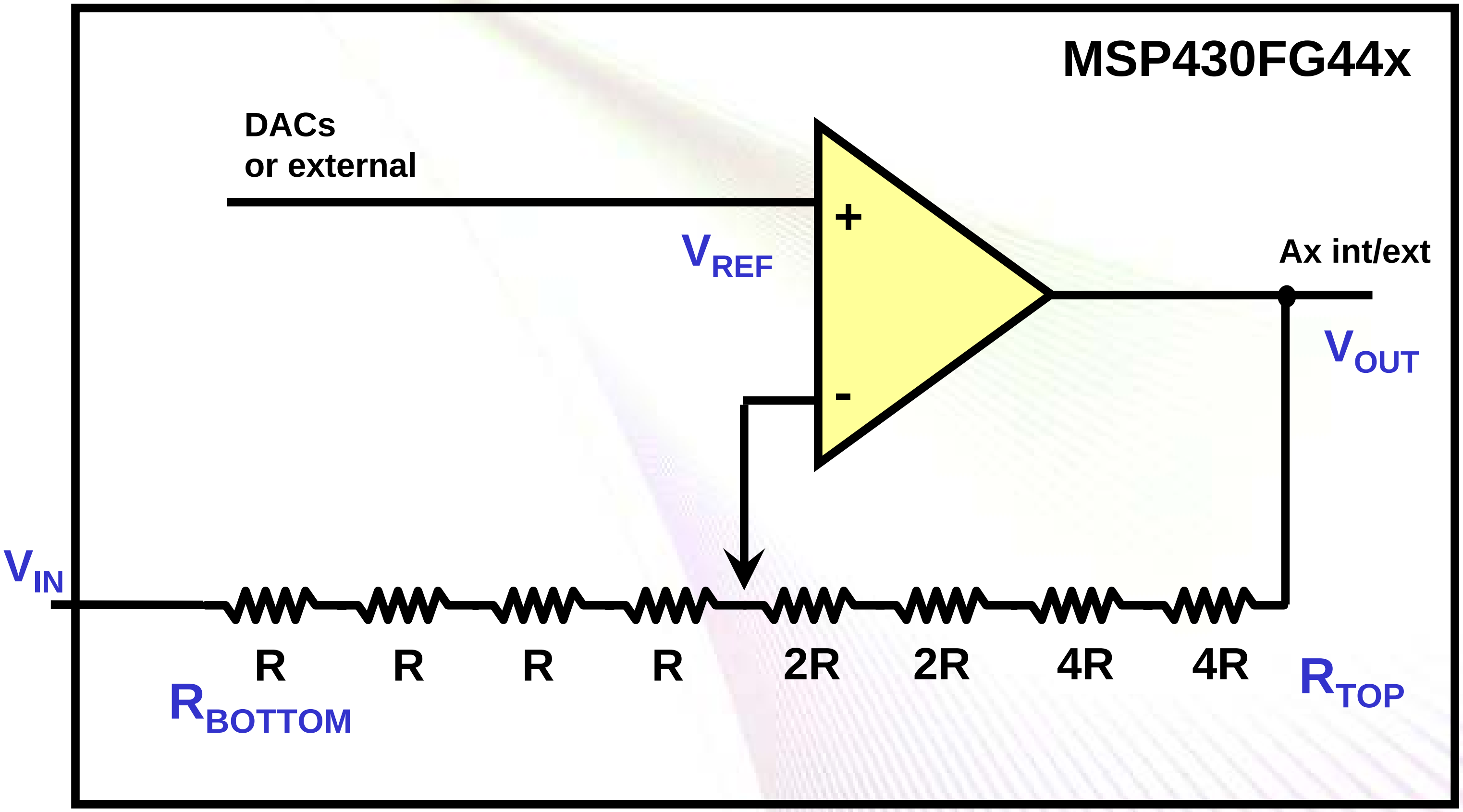
OAxCTL1	
111100x1	G=16
110100x1	G=8
101100x1	G=3.33
100100x1	G=4
011100x1	G=2.67
010100x1	G=2
001100x0	G=1.33
000100x0	G=1

RRIP on

PGA Non-inverting

PGA Mode –
Inverting Mode OAFCx = 110

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



RRIP off

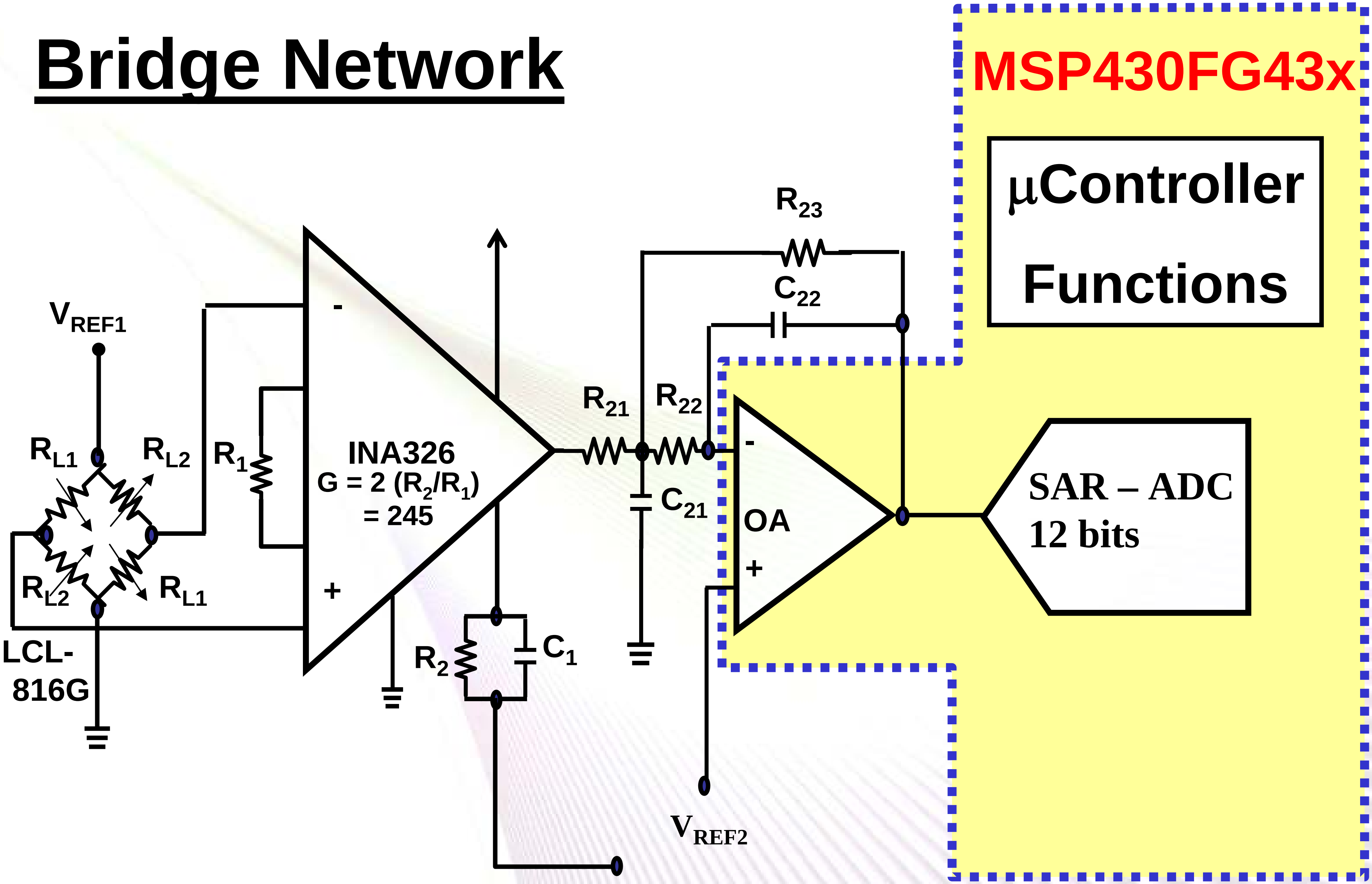
OAxCTL1

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

RRIP on

PGA Inverting

Bridge Network



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!**

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Interface	interface.ti.com	Digital Control	www.ti.com/digitalcontrol
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
RFID	www.ti-rfid.com	Telephony	www.ti.com/telephony
Low Power Wireless	www.ti.com/lpw	Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

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