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Fundamentals of Data Converters

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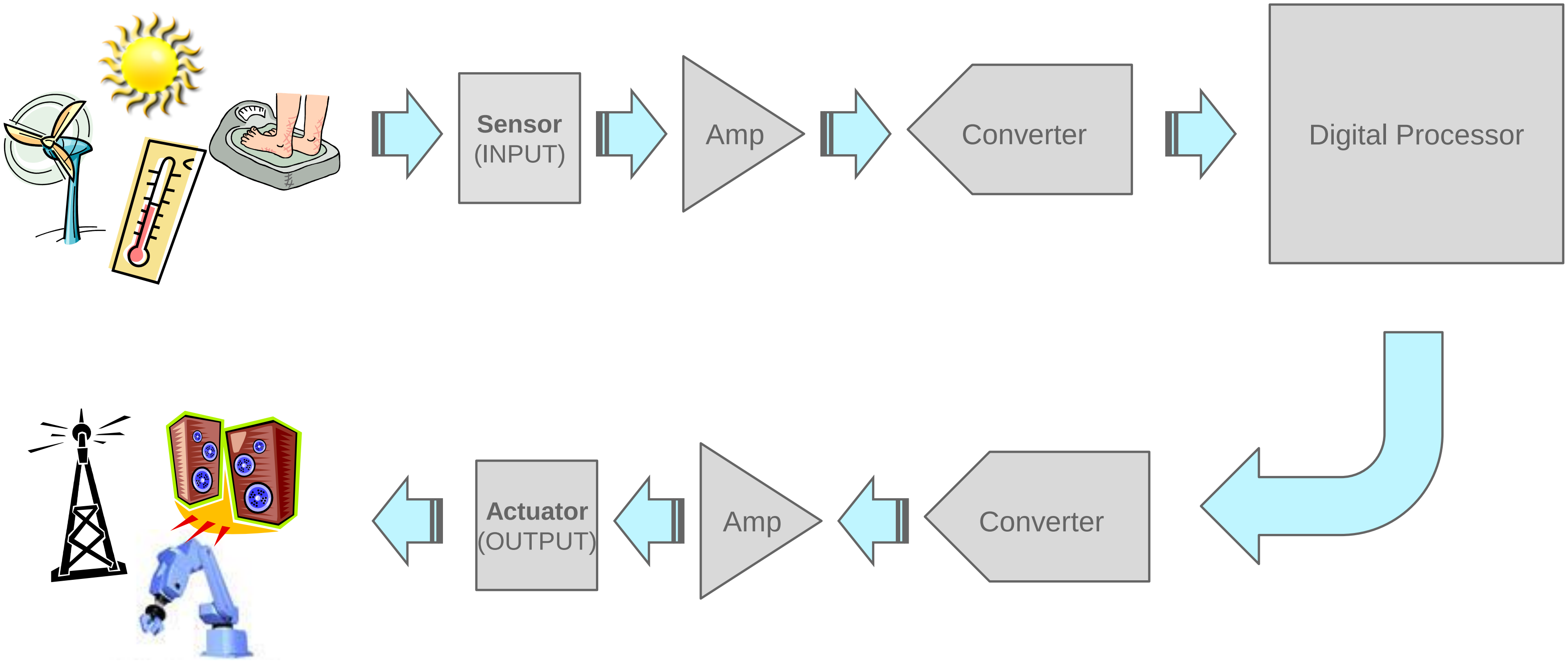
Director of Technical Marketing

9/14/2016

Analog to Electronic Signal Processing



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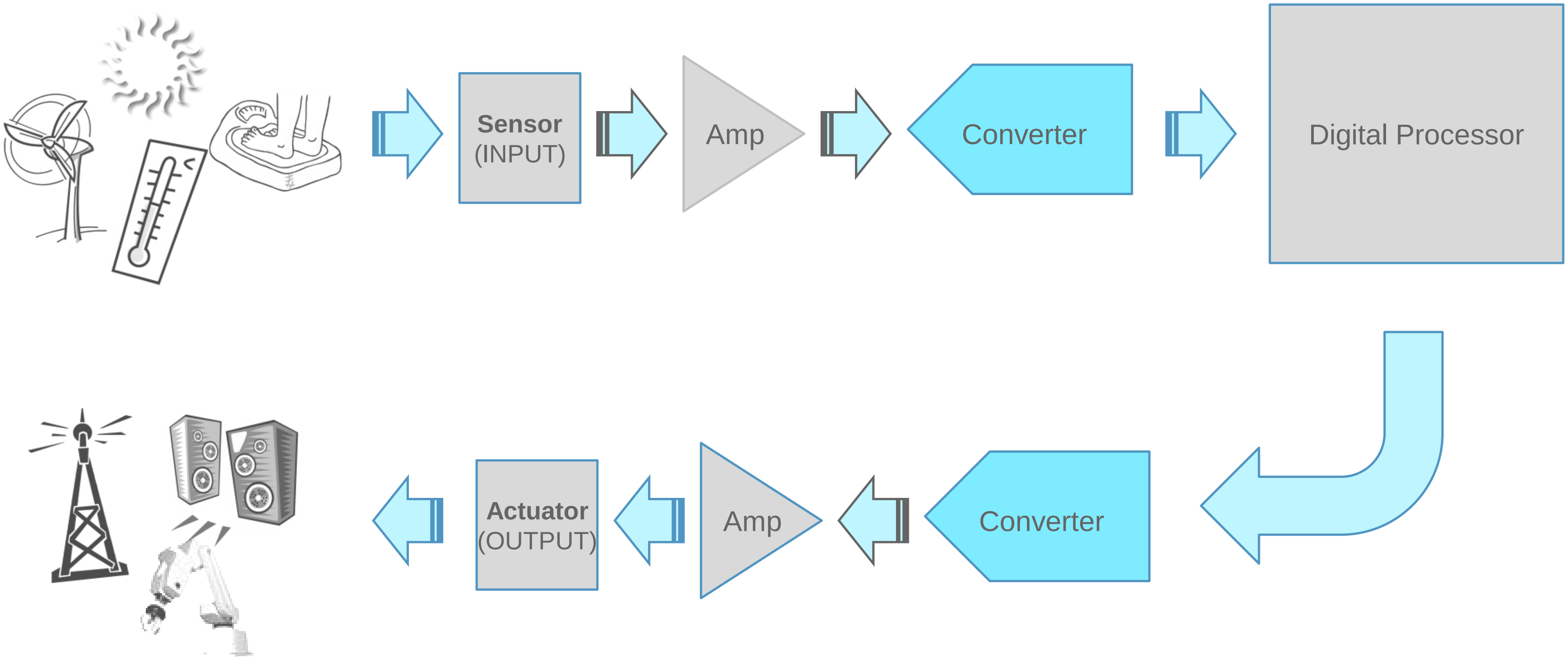
Analog to Electronic Signal Processing



Outline

- Sampled data system types
- Digitizing processes
- Data converters for measurement systems and errors
- Data converters for dynamic systems and errors
- Sampling system problems
- Structure and use of digital-analog converters
- Structure and use of analog-digital converters

Many Types of Sampled Data Systems

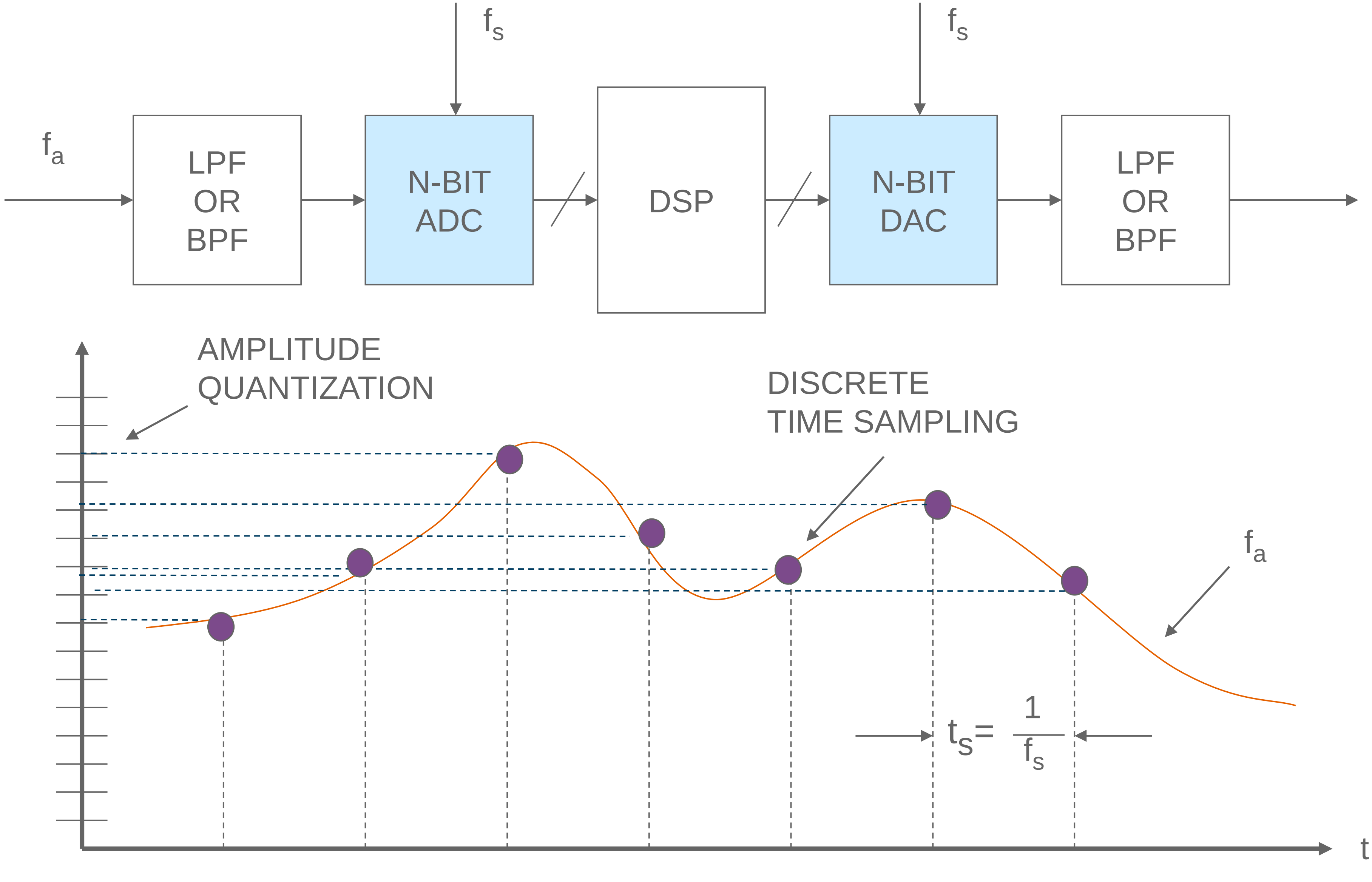
- Analog to digital converters
- Digital to analog converters
- Sample and hold amplifiers
- Peak detectors
- Comparators
- Switched cap filters

- Samples a continuous signal
- Domain conversion
  - Analog to digital
  - Digital to analog
  - Continuous time to discrete time
  - Continuous frequency to discrete frequency
- Sampling rate
  - Continuous, discontinuous

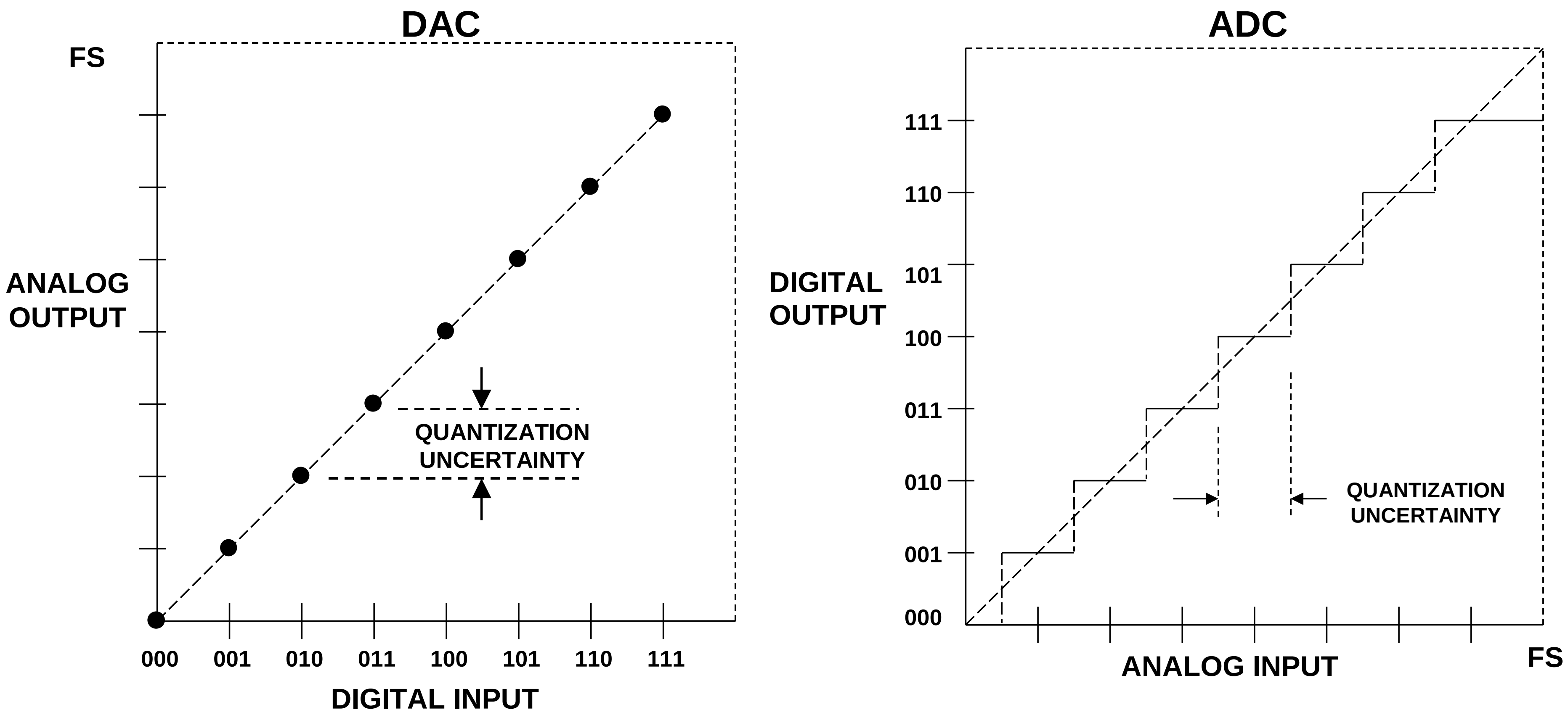
Analog and Digital Domains
Why Convert to Digital?

- Analog signals are continuous and provide the entire signal
- Digital signals capture only a portion of the signal
- Why digitize?
  - Improved signal analysis potential
  - More robust storage
  - More accurate transmission
- Development objective of sampled data systems is to minimize effect of the sampling process

Sampled Data System: Sampling and Quantization



Transfer Functions for Ideal 3-Bit DAC and ADC



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Unipolar Binary Code, 4-bit Converter

BASE 10 NUMBER	SCALE	+10 V FS	BINARY
+15	+FS – 1 LSB = 15/16 FS	9.375	1111
+14	+7/8 FS	8.750	1110
+13	+13/16 FS	8.125	1101
+12	+3/4 FS	7.500	1100
+11	+11/16 FS	6.875	1011
+10	+5/16 FS	6.250	1010
+9	+9/16 FS	5.625	1001
+8	+1/2 FS	5.000	1000
+7	+7/16 FS	4.375	0111
+6	+3/8 FS	3.750	0110
+5	+5/16 FS	3.125	0101
+4	+1/4 FS	2.500	0100
+3	+3/16 FS	1.875	0011
+2	+1/8 FS	1.250	0010
+1	1 LSB = +1/16 FS	0.625	0001
0	0	0.000	0000

Bipolar Codes, 4-bit Converter

BASE 10 NUMBER	SCALE	±5V FS	OFFSET BINARY	TWOS COMP.	ONES COMP.	SIGN MAG.
+7	+FS – 1LSB = +7/8 FS	+4.375	1 1 1 1	0 1 1 1	0 1 1 1	0 1 1 1
+6	+3/4 FS	+3.750	1 1 1 0	0 1 1 0	0 1 1 0	0 1 1 0
+5	+5/8 FS	+3.125	1 1 0 1	0 1 0 1	0 1 0 1	0 1 0 1
+4	+1/2 FS	+2.500	1 1 0 0	0 1 0 0	0 1 0 0	0 1 0 0
+3	+3/8 FS	+1.875	1 0 1 1	0 0 1 1	0 0 1 1	0 0 1 1
+2	+1/4 FS	+1.250	1 0 1 0	0 0 1 0	0 0 1 0	0 0 1 0
+1	+1/8 FS	+0.625	1 0 0 1	0 0 0 1	0 0 0 1	0 0 0 1
0	0	0.000	1 0 0 0	0 0 0 0	*0 0 0 0	*1 0 0 0
–1	– 1/8 FS	–0.625	0 1 1 1	1 1 1 1	1 1 1 0	1 0 0 1
–2	– 1/4 FS	–1.250	0 1 1 0	1 1 1 0	1 1 0 1	1 0 1 0
–3	– 3/8 FS	–1.875	0 1 0 1	1 1 0 1	1 1 0 0	1 0 1 1
–4	–1/2 FS	–2.500	0 1 0 0	1 1 0 0	1 0 1 1	1 1 0 0
–5	–5/8 FS	–3.125	0 0 1 1	1 0 1 1	1 0 1 0	1 1 0 1
–6	–3/4 FS	–3.750	0 0 1 0	1 0 1 0	1 0 0 1	1 1 1 0
–7	– FS + 1LSB = –7/8 FS	–4.375	0 0 0 1	1 0 0 1	1 0 0 0	1 1 1 1
–8	– FS	–5.000	0 0 0 0	1 0 0 0		

CODES NOT NORMALLY USED IN COMPUTATIONS (SEE TEXT)

*		ONES COMP.	SIGN MAG.
	0+	0 0 0 0	0 0 0 0
	0–	1 1 1 1	1 0 0 0

Quantization: The Size of a Least Significant Bit (LSB)

RESOLUTION N	2^N	VOLTAGE (10V FS)	ppm FS	% FS	dB FS
2-bit	4	2.5 V	250,000	25	– 12
4-bit	16	625 mV	62,500	6.25	– 24
6-bit	64	156 mV	15,625	1.56	– 36
8-bit	256	39.1 mV	3,906	0.39	– 48
10-bit	1,024	9.77 mV (10 mV)	977	0.098	– 60
12-bit	4,096	2.44 mV	244	0.024	– 72
14-bit	16,384	610 µV	61	0.0061	– 84
16-bit	65,536	153 µV	15	0.0015	– 96
18-bit	262,144	38 µV	4	0.0004	– 108
20-bit	1,048,576	9.54 µV (10 µV)	1	0.0001	– 120
22-bit	4,194,304	2.38 µV	0.24	0.000024	– 132
24-bit	16,777,216	596 nV*	0.06	0.000006	– 144

***600nV is the Johnson Noise in a 10kHz BW of a 2.2kΩ Resistor @ 25°C**

Remember: 10-bits and 10V FS yields an LSB of 10mV, 1000ppm, or 0.1%.
All other values may be calculated by powers of 2.

Practical Resolution Needs for Data Converters

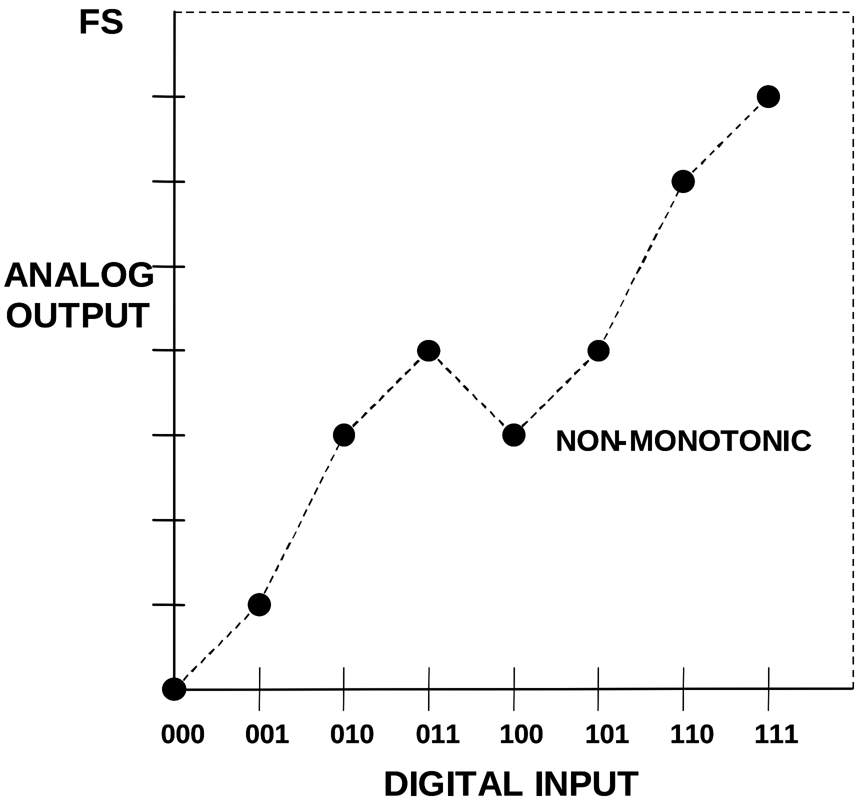
- Instrumentation measurements
  - Sensor resolution/accuracy of 0.5% = 1/200
  - 8 bits equivalent to 1/256 -- digitizing will lose information
  - 10x sensor resolution = 1/2000 -- 12 bits is 1/4096
  - Allows discrimination of small changes
  - Can also be driven by display requirements
- Dynamic signal measurements
  - Audio systems need better than 0.1% distortion at 5% of full scale
  - Equivalent to 1/20,000 -- 16 bits is 1/65,536

Primary Errors in Data Converters

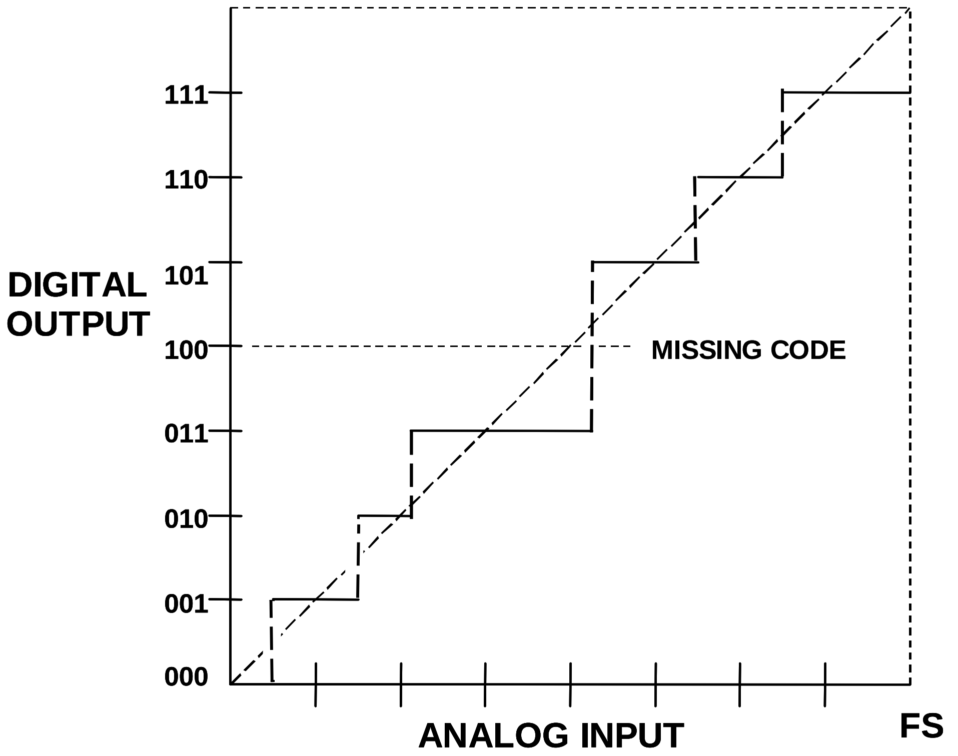
- Instrumentation and measurement
  - Described in LSBs(least-significant-bit), % of FS, ppm of FS
  - Offset error – the input level needed to change the first code
  - Gain/full-scale error – the input level need to change the last code
  - Nonlinearity – deviation of codes from the line from zero to FS
  - Differential nonlinearity – code-to-code deviation from 1 LSB
  - Transition noise – ADC uncertainty in code center point

Transfer Functions for Non-Ideal 3-Bit DAC and ADC

DAC



ADC



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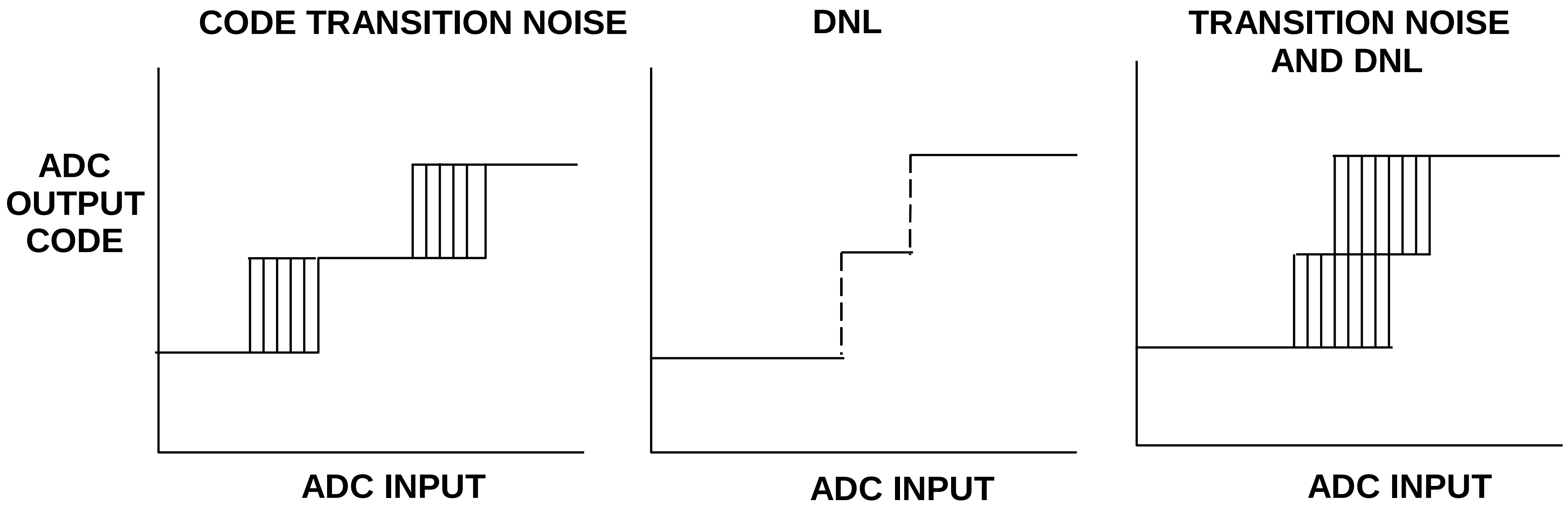
Combined Effects of Code Transition Noise and DNL



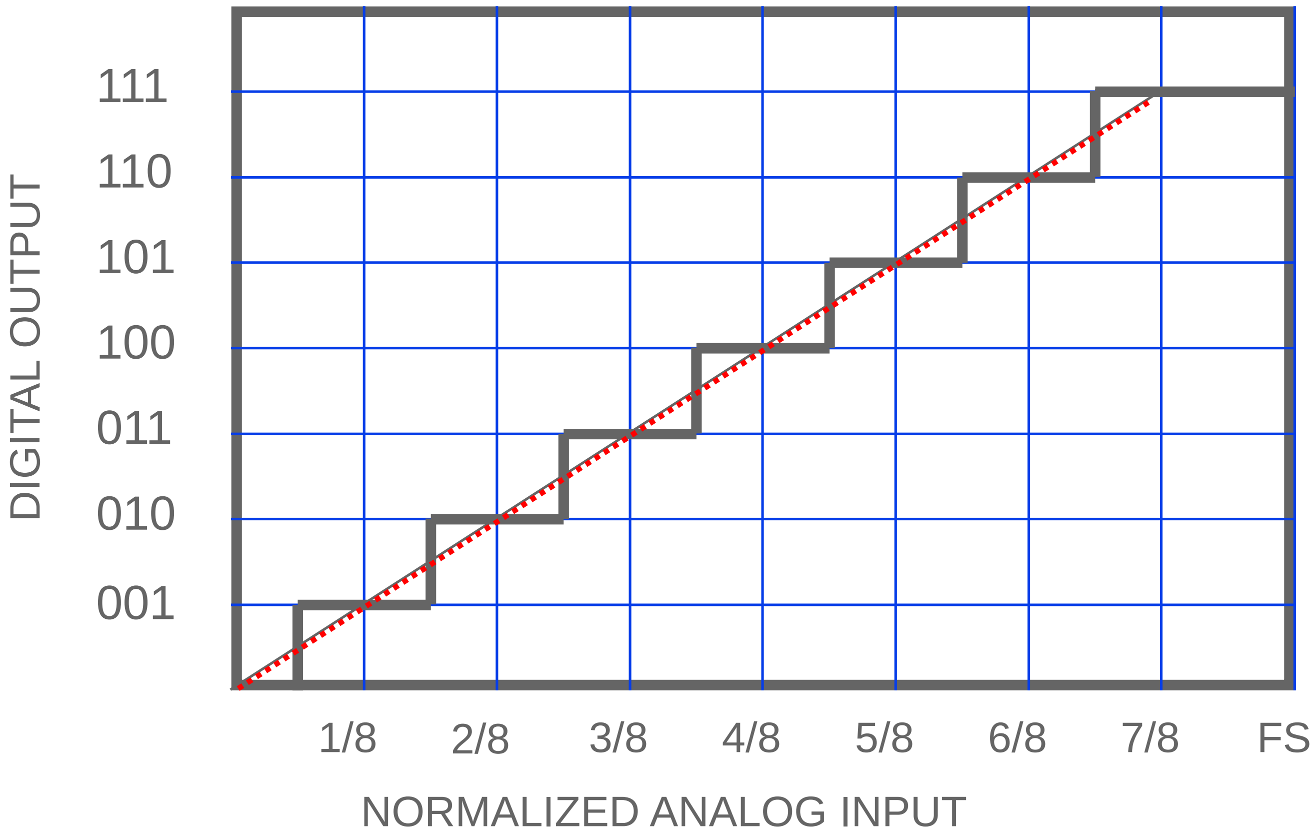
Primary Errors in Data Converters

- Dynamic systems
- SINAD (Signal-to-Noise-and-Distortion Ratio):
  - The ratio of the rms signal amplitude to the mean value of the root-sum-squares (RSS) of all other spectral components, including harmonics, but excluding DC.
- ENOB (Effective Number of Bits):

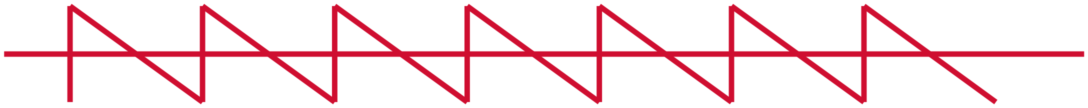
$$\text{ENOB} = \frac{\text{SINAD} - 1.76\text{dB}}{6.02\text{dB}}$$

- SNR (Signal-to-Noise Ratio, or Signal-to-Noise Ratio Without Harmonics:
  - The ratio of the rms signal amplitude to the mean value of the root-sum-squares (RSS) of all other spectral components, excluding the first 5 harmonics and DC
- SFDR (Spurious-Free-Dynamic-Range) Signal dynamic range in the bandwidth of interest containing no frequency noise spurs

Quantization & Quantization Noise

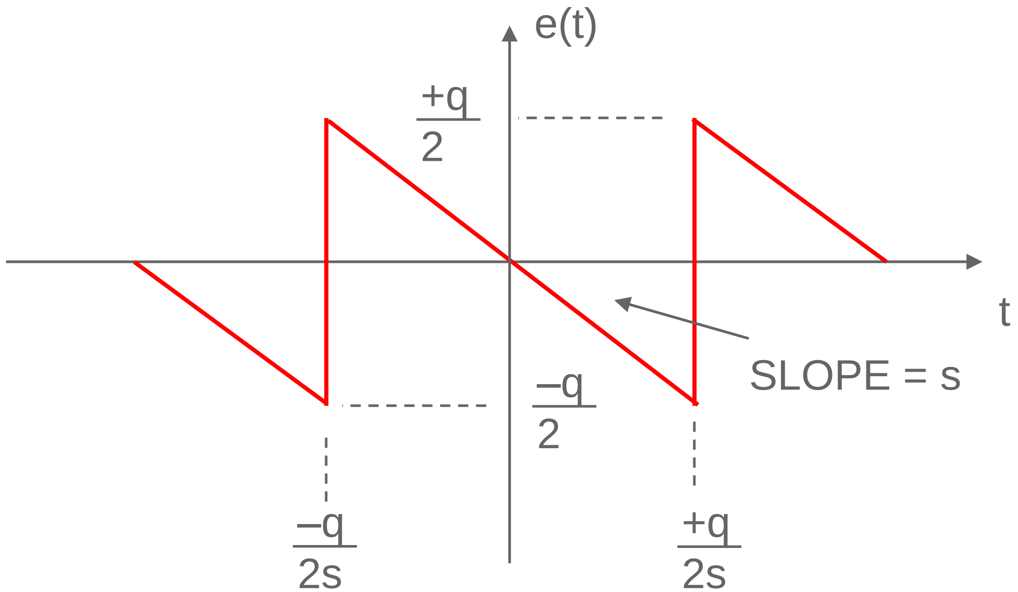


Quantization Error Function



quantization noise error: RMS value is LSB/3.464

Quantization Noise as a Function of Time



- ERROR = $e(t) = st, \quad \frac{-q}{2s} < t < \frac{+q}{2s}$
- MEAN-SQUARE ERROR = $\overline{e^2(t)} = \frac{s}{q}\int_{-q/2s}^{+q/2s} (st)^2\, dt = \frac{q^2}{12}$
- ROOT-MEAN-SQUARE ERROR = $\sqrt{\overline{e^2(t)}} = \frac{q}{\sqrt{12}}$

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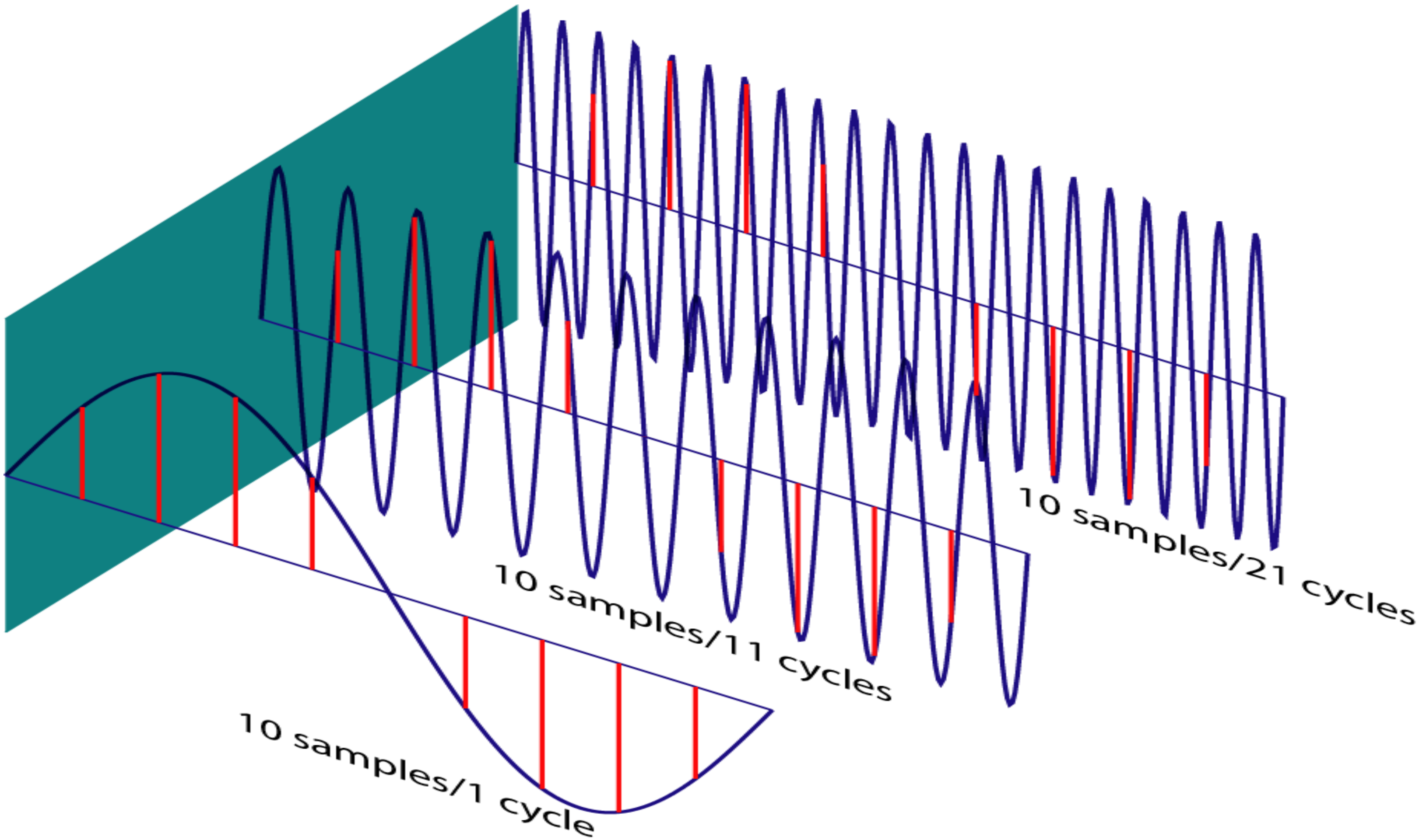
Ideal ADC Sampling
3 Different Frequencies, Sampled the Same



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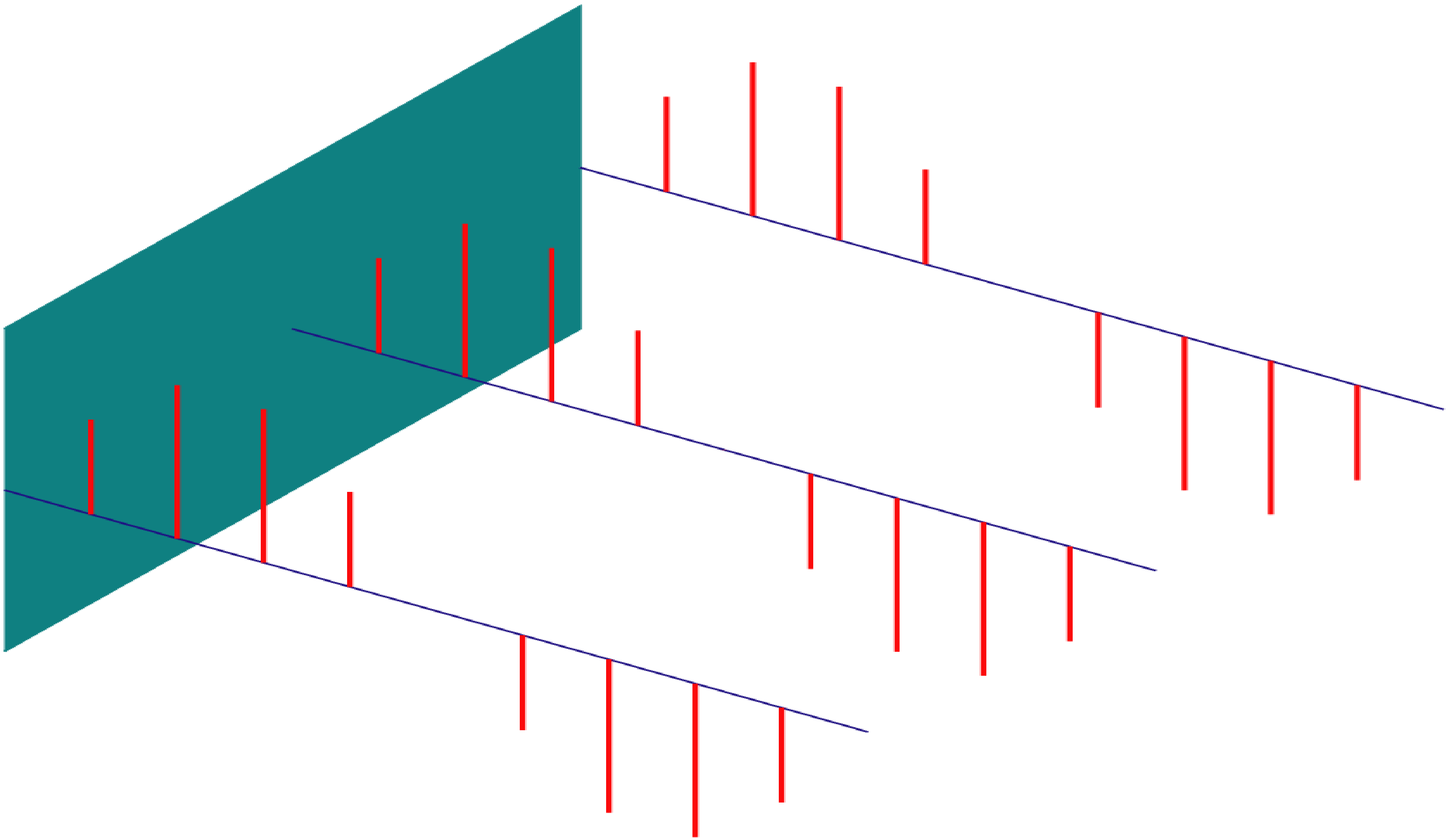
Ideal ADC Sampling
Once Sampled, Information is Lost



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Nyquist's Criteria

- A signal with a maximum frequency fa must be sampled at a rate fs > 2fa or information about the signal will be lost because of aliasing.

- Aliasing occurs whenever fs < 2fa

- A signal which has frequency components between fa and fb must be sampled at a rate fs > 2 (fb – fa) in order to prevent alias components from overlapping the signal frequencies

- The concept of aliasing is widely used in communications applications such as direct IF-to-digital conversion.

Aliasing occurs in Many Domains
Spatial, Temporal, etc.

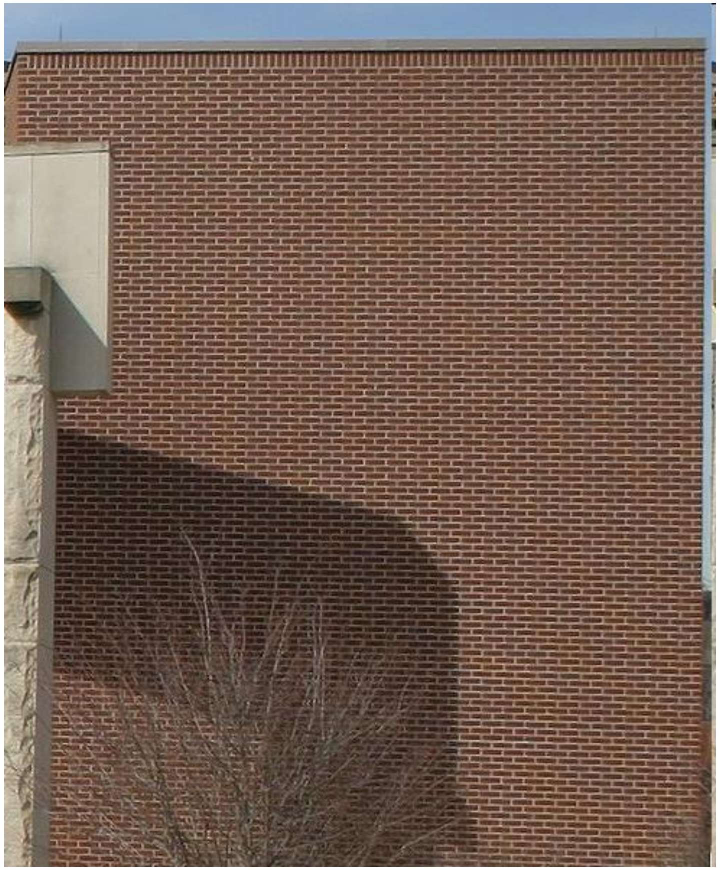
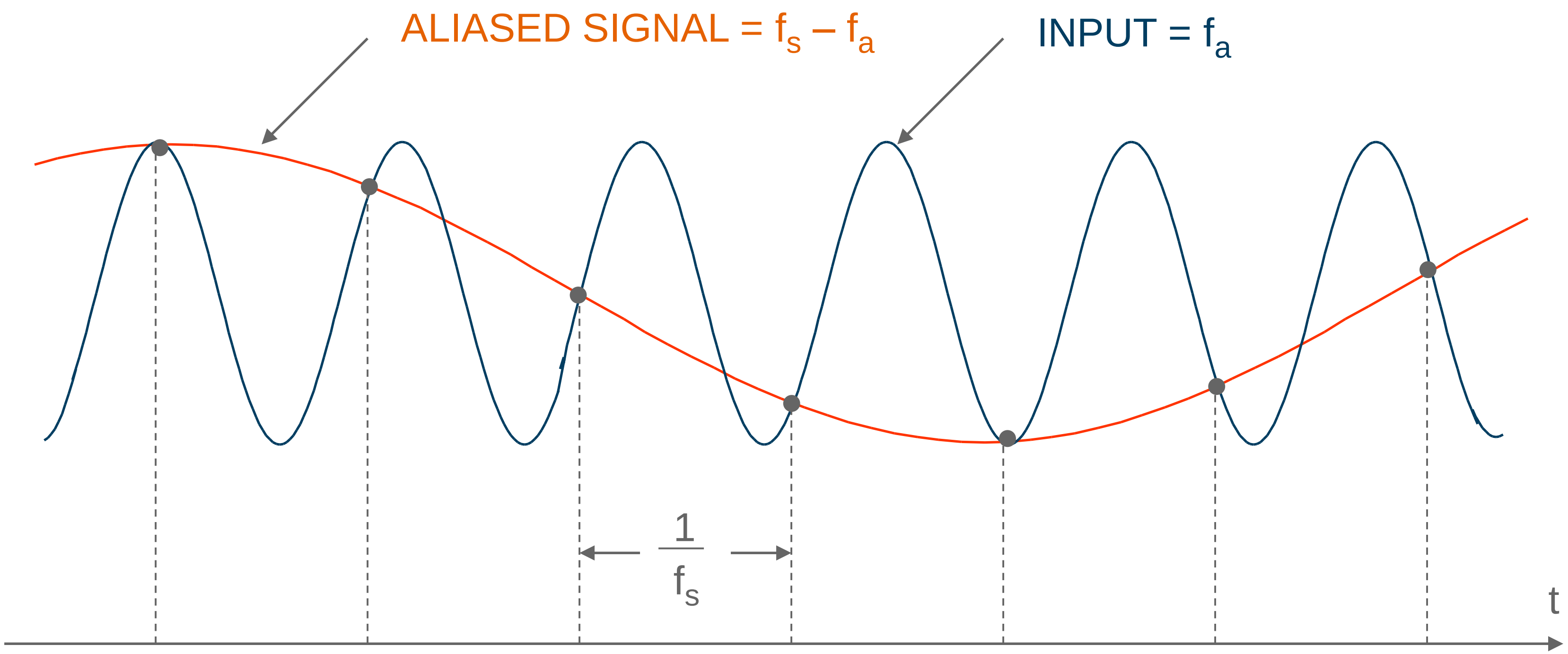


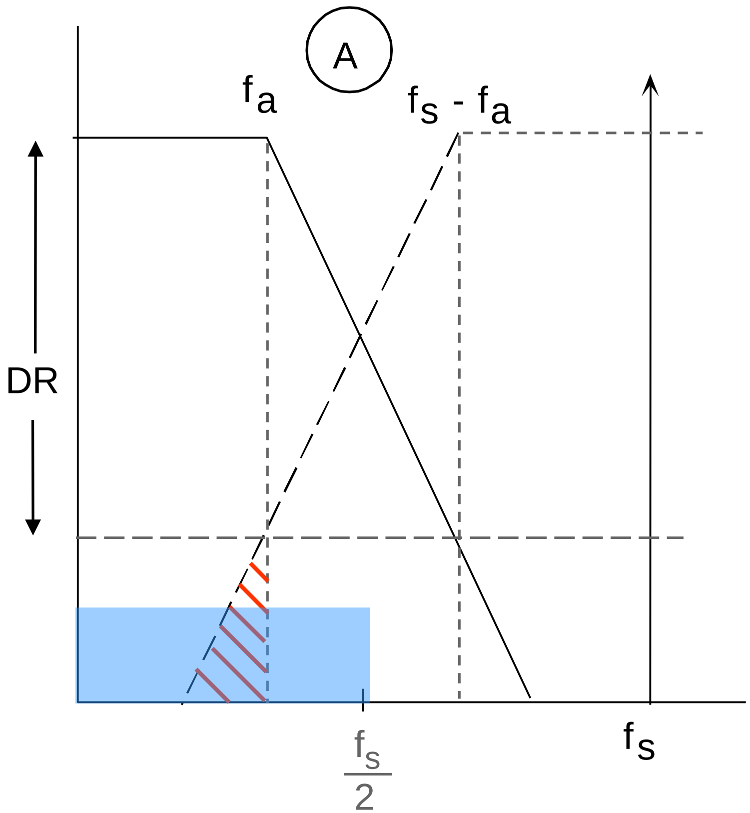
Image Source : Wikipedia

Sampling & Aliasing in the Time Domain



NOTE: f_a IS SLIGHTLY LESS THAN f_s

Baseband Antialiasing Filter Requirements



STOPBAND ATTENUATION = DR

TRANSITION BAND: f_a to $f_s - f_a$

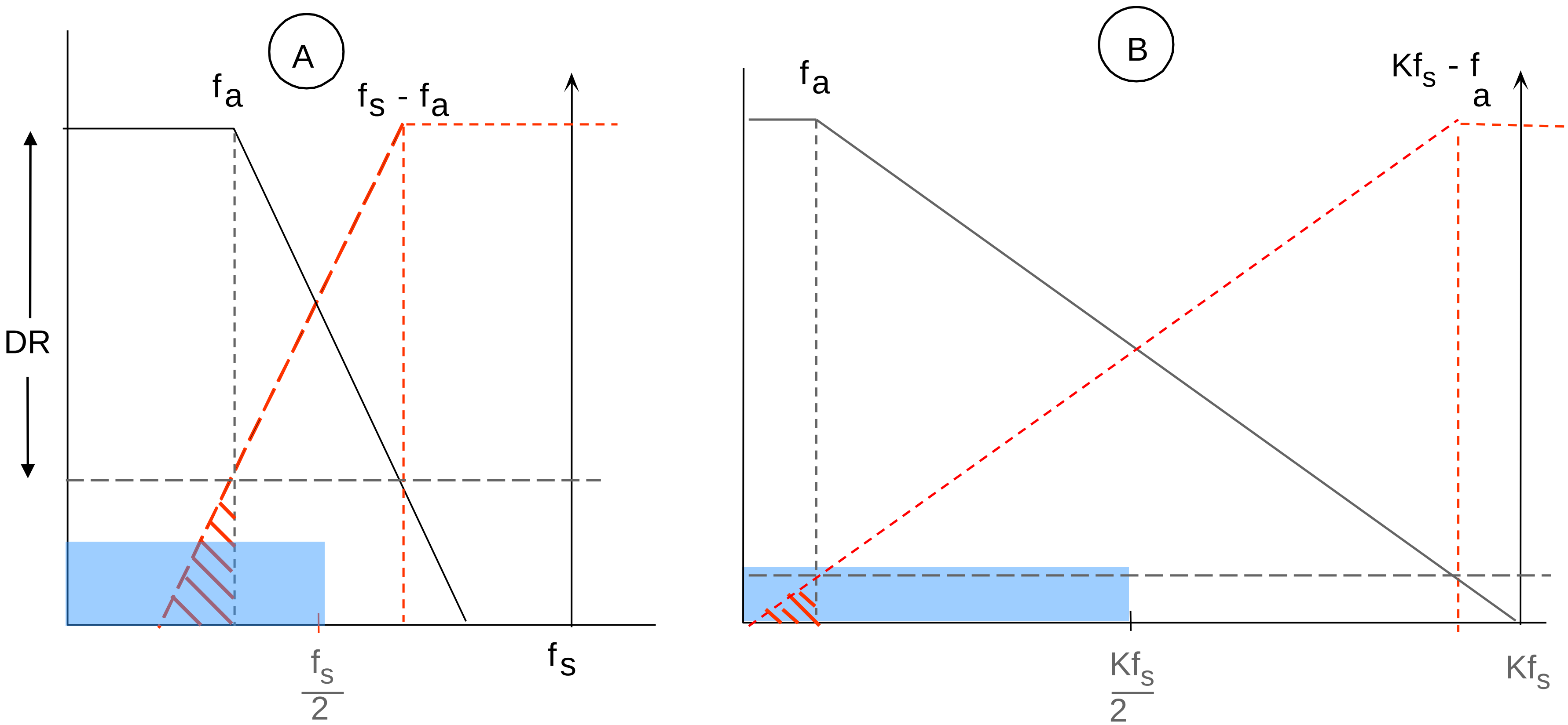
CORNER FREQUENCY: f_a

Anti-Alias Filter Prevents Aliasing
Contributes to Dynamic Range

Anti-Alias Filter Objectives

- Brick Wall (Steep/Deep Rolloff)
- Linear Passband
- Linear Phase

Oversampling Relaxes Requirements on Baseband Antialiasing Filter



STOPBAND ATTENUATION = DR

TRANSITION BAND: f_a to $f_s - f_a$

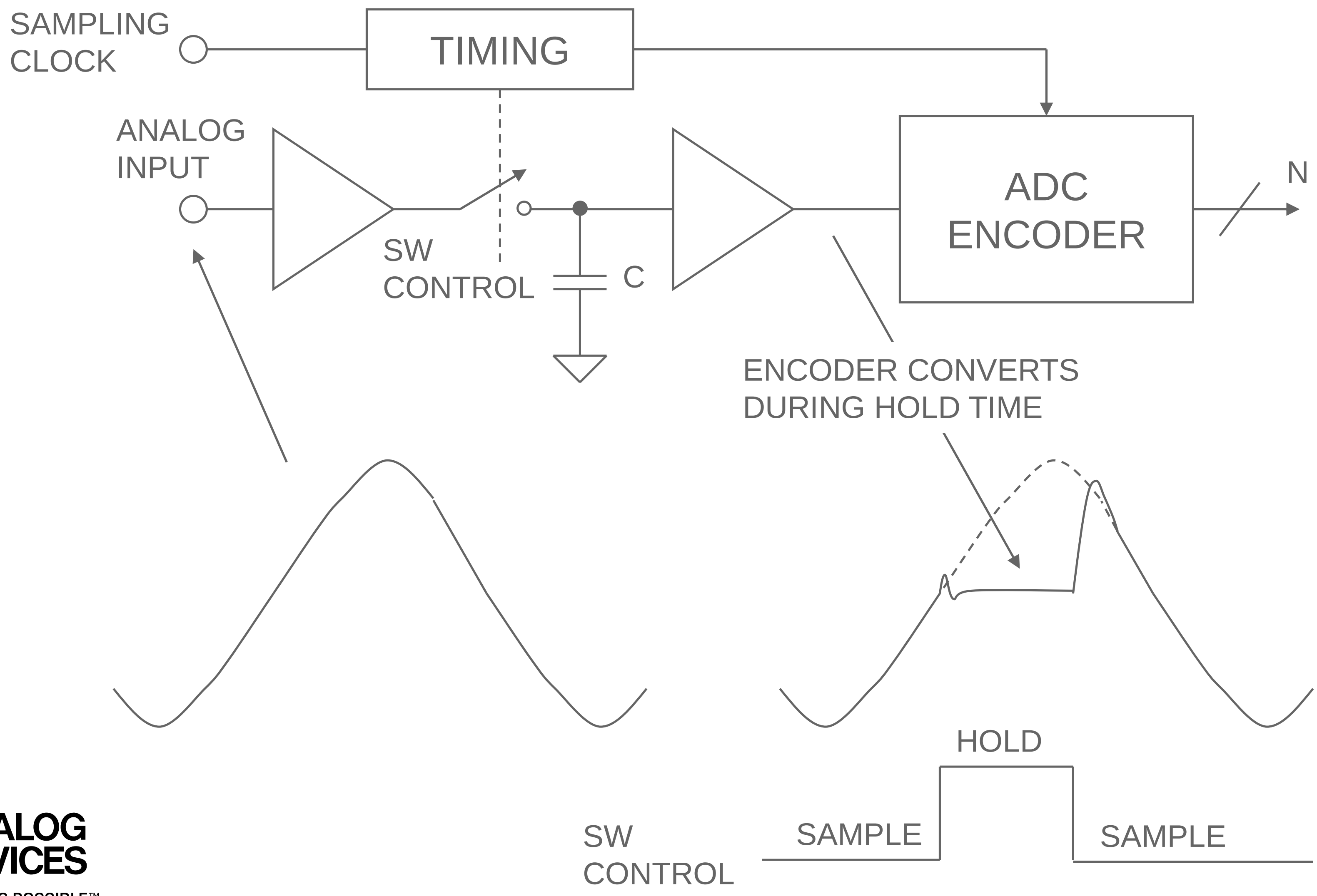
CORNER FREQUENCY: f_a

STOPBAND ATTENUATION = DR

TRANSITION BAND: f_a to $Kf_s - f_a$

CORNER FREQUENCY: f_a

Sample-and-Hold Function
Required for Digitizing AC Signals



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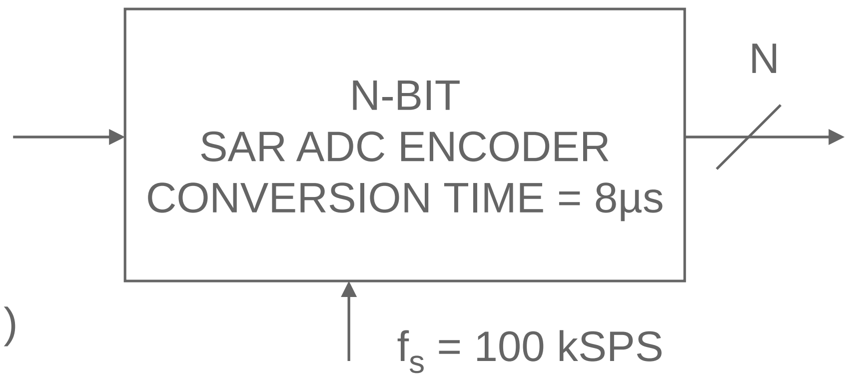
Input Frequency Limitations of Non-Sampling ADC (Encoder)

ANALOG INPUT

$$v(t) = q\left[\frac{2^N}{2}\right]\sin(2\pi f t)$$



$$\frac{dv}{dt} = q\,\frac{2^N}{2}\,2\pi f\cos(2\pi f t)$$

$$\left.\frac{dv}{dt}\right|_{max} = q\,2^{(N-1)}\,2\pi f$$

$$f_{max} = \frac{\left.\frac{dv}{dt}\right|_{max}}{2^{(N-1)}\,2\pi q}$$

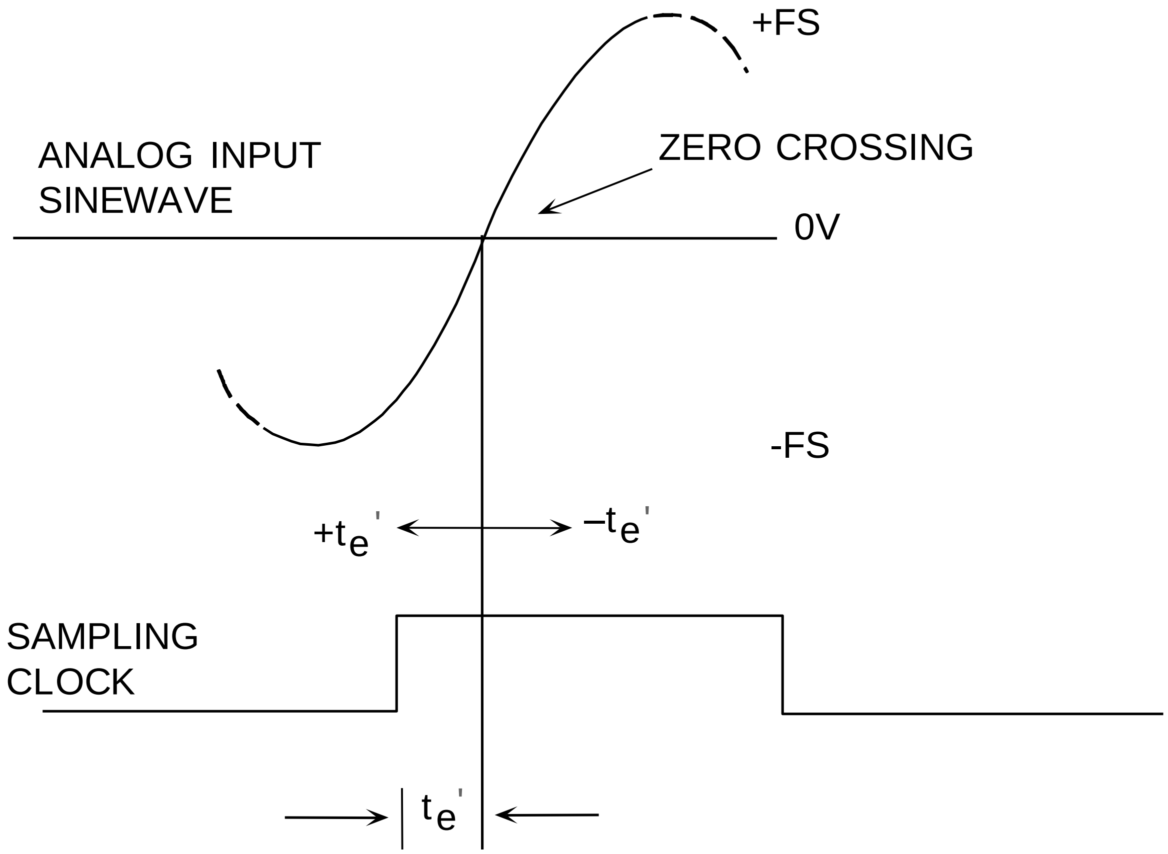
$$f_{max} = \frac{\left.\frac{dv}{dt}\right|_{max}}{q\pi\,2^N}$$

EXAMPLE:

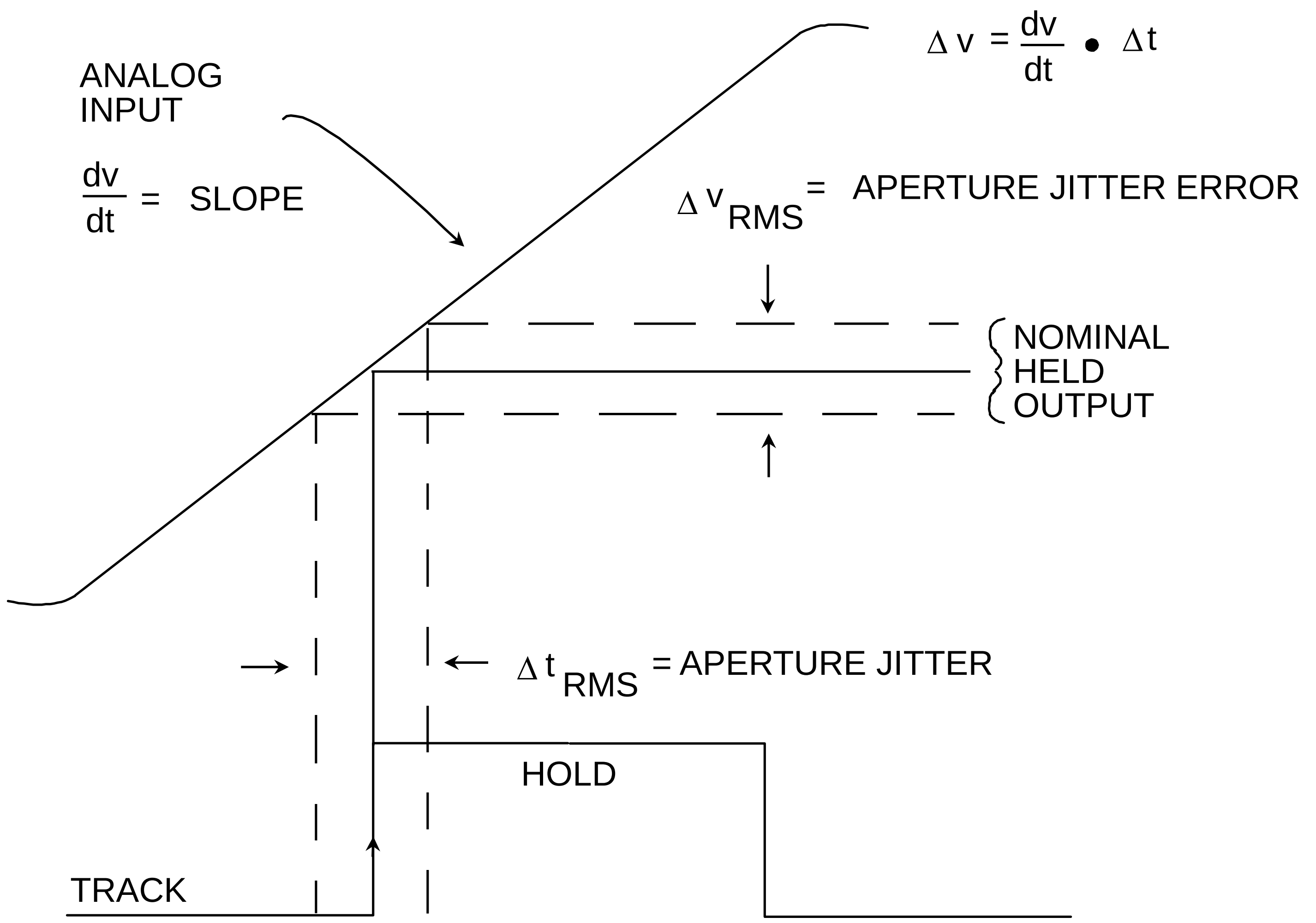
dv = 1 LSB = q
dt = 8µs
N = 12, 2^N = 4096

f_{max} = 9.7 Hz

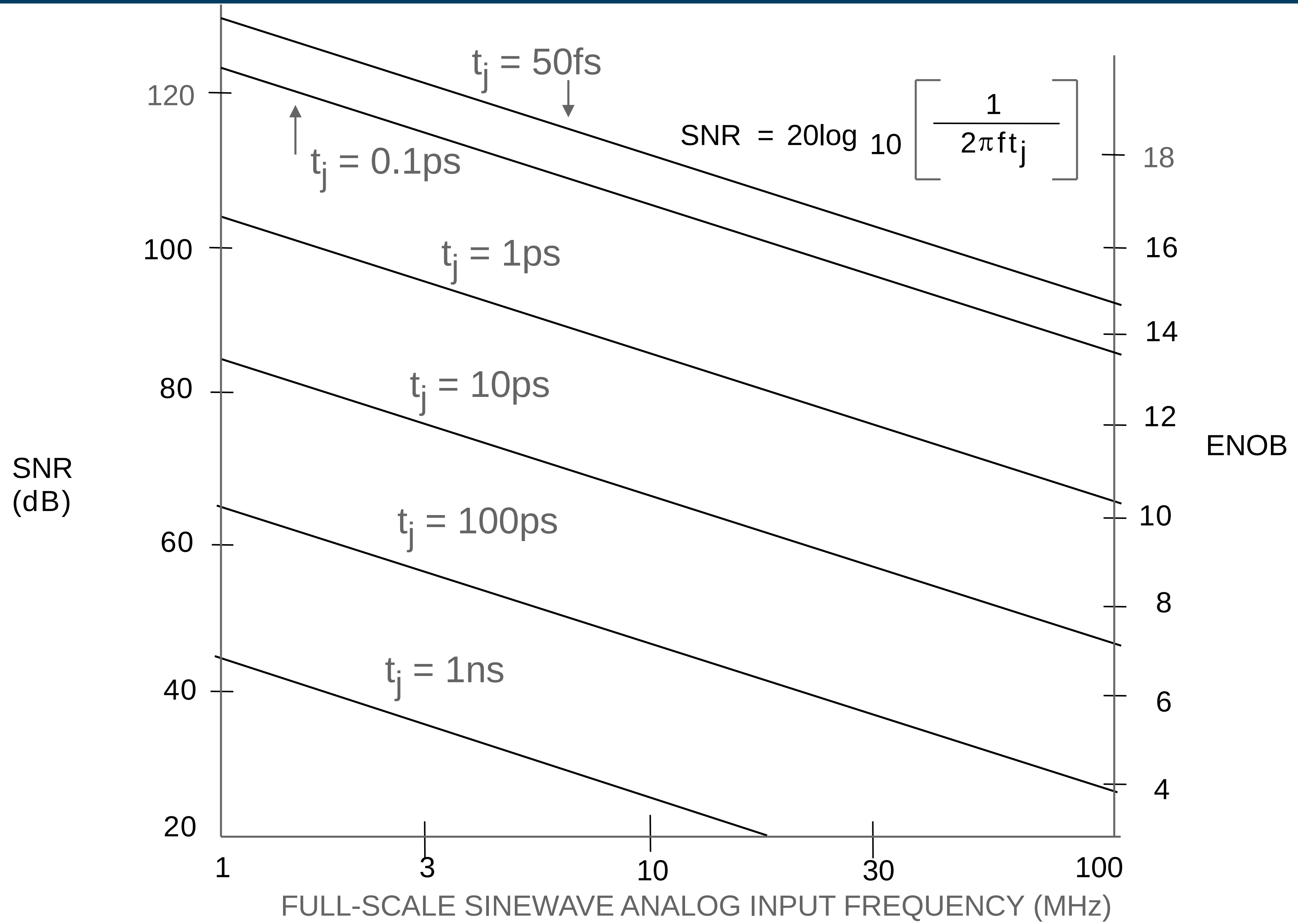
Effective Aperture Delay Time Measured with Respect to ADC Input



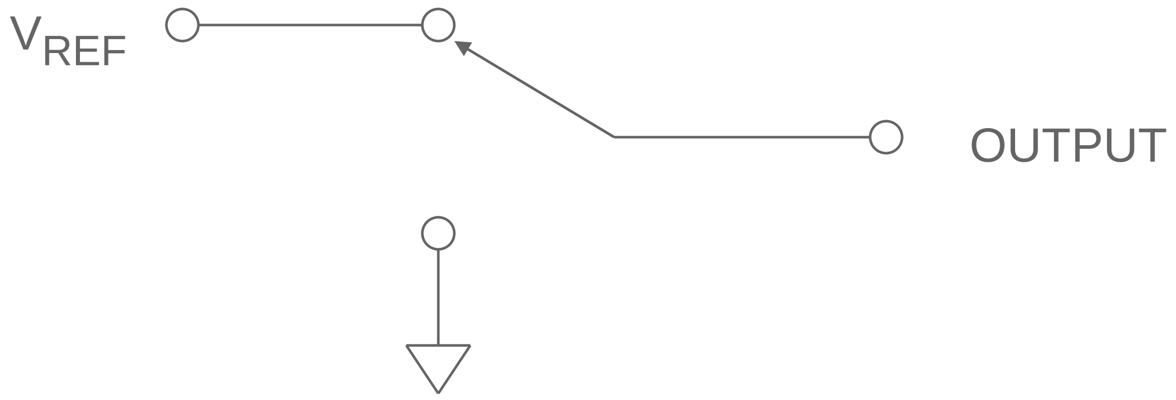
Effects of Aperture Jitter and Sampling Clock Jitter



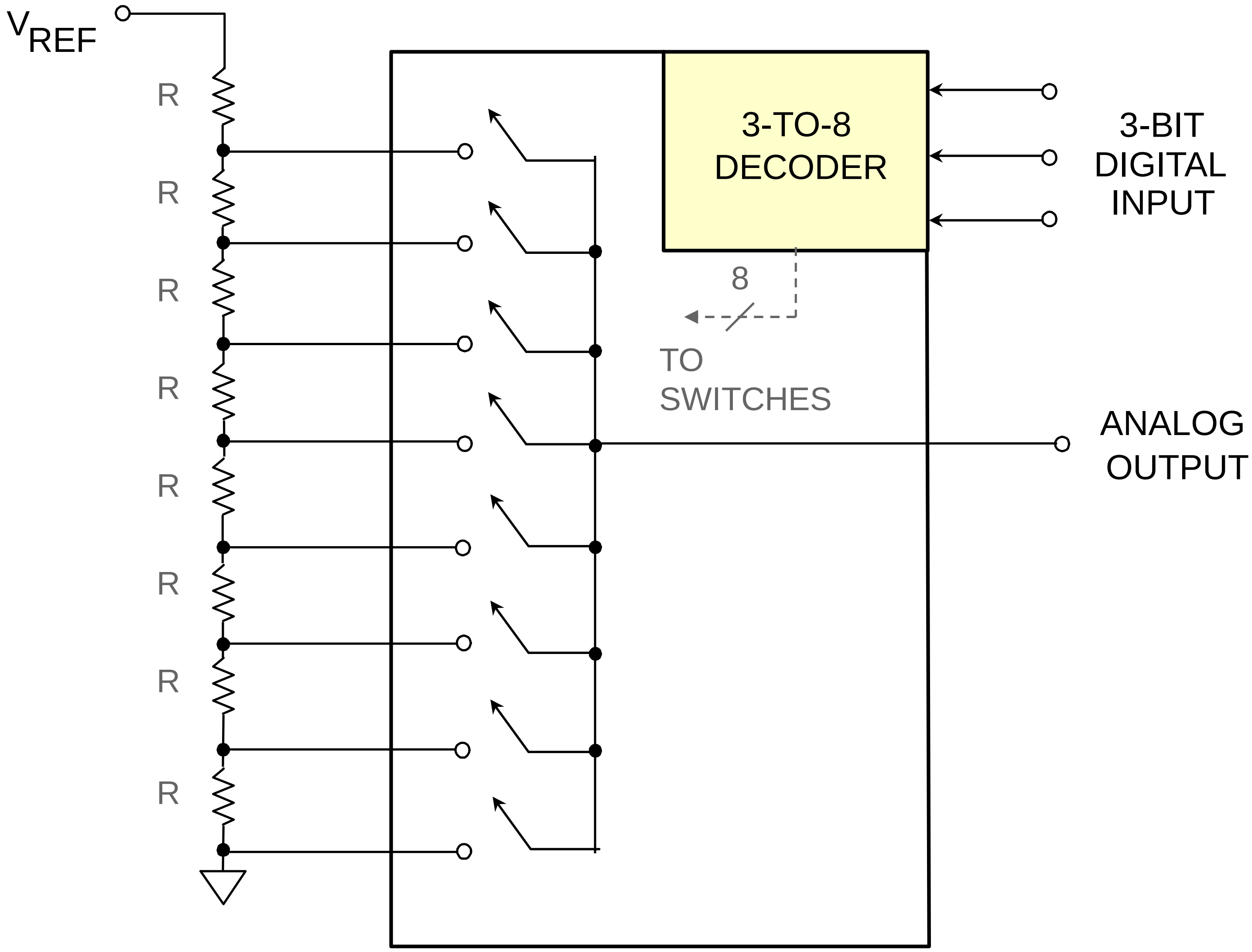
Theoretical SNR and ENOB Due to Jitter vs. Fullscale Sinewave Analog Input Frequency



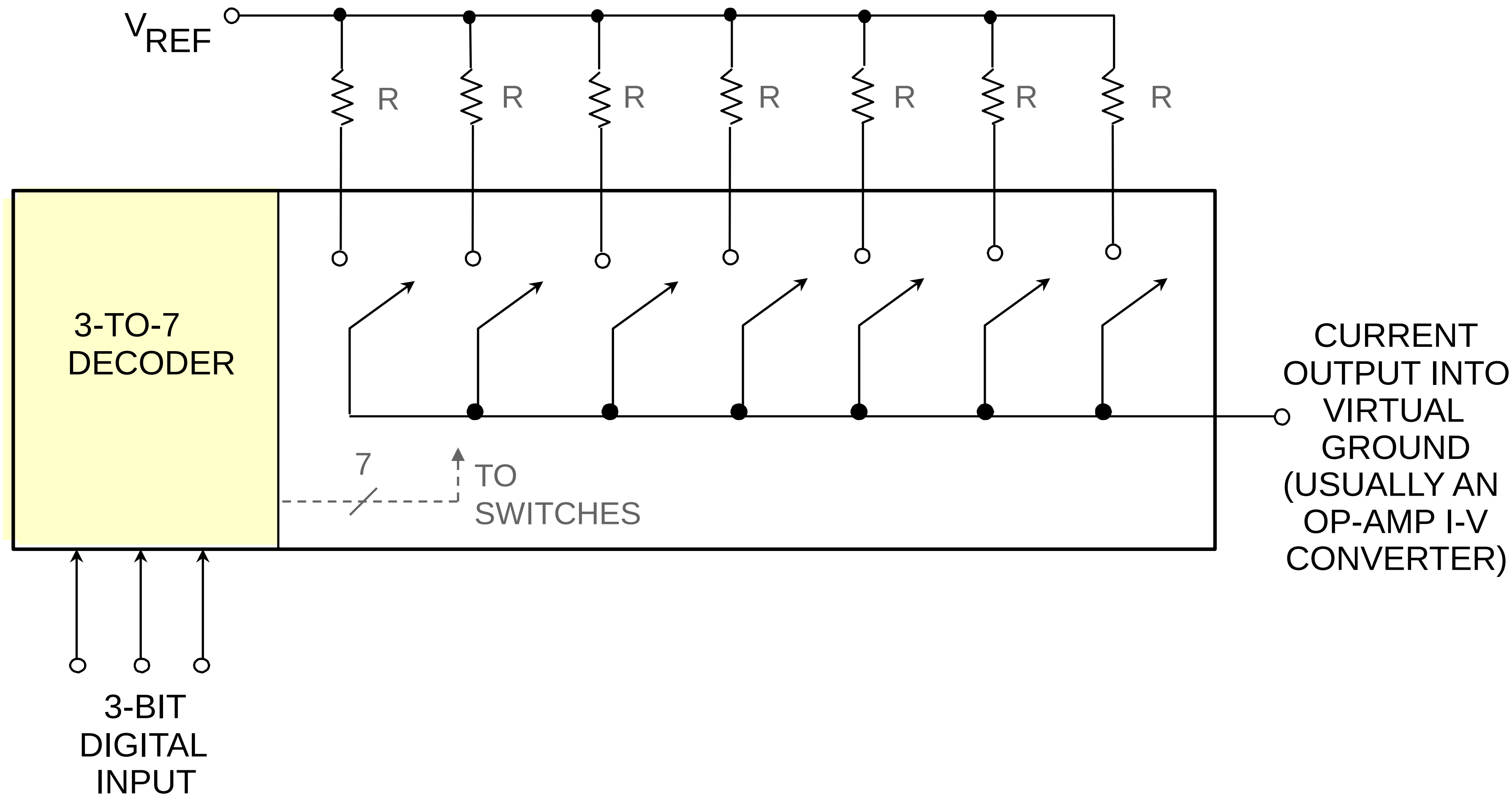
1-Bit DAC:
Changeover Switch (SPDT)



Simplest Voltage Output Thermometer DAC: The Kelvin Divider (AKA - "String DAC")



The Simplest Current Output Thermometer (Fully-Decoded) DAC



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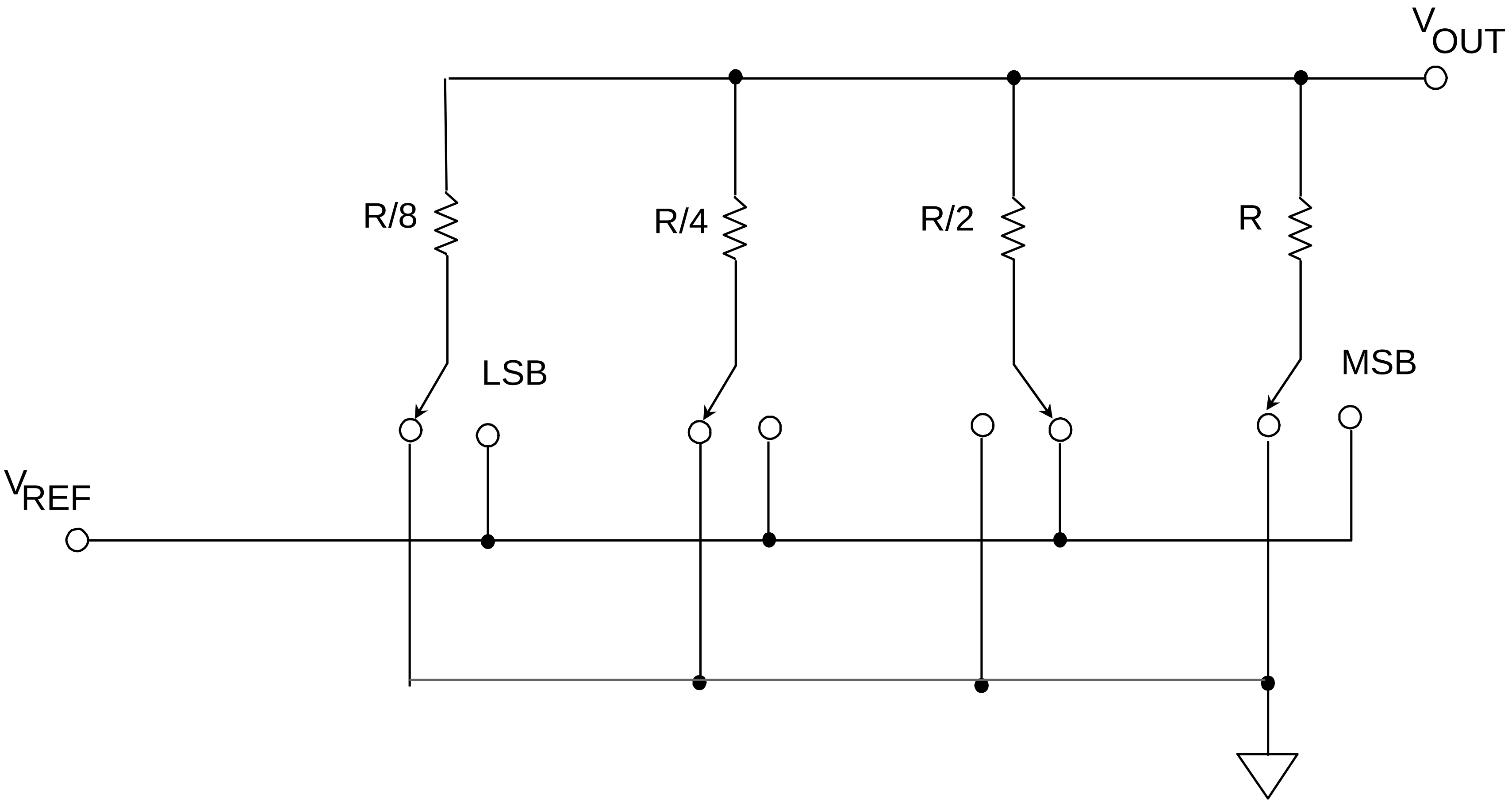
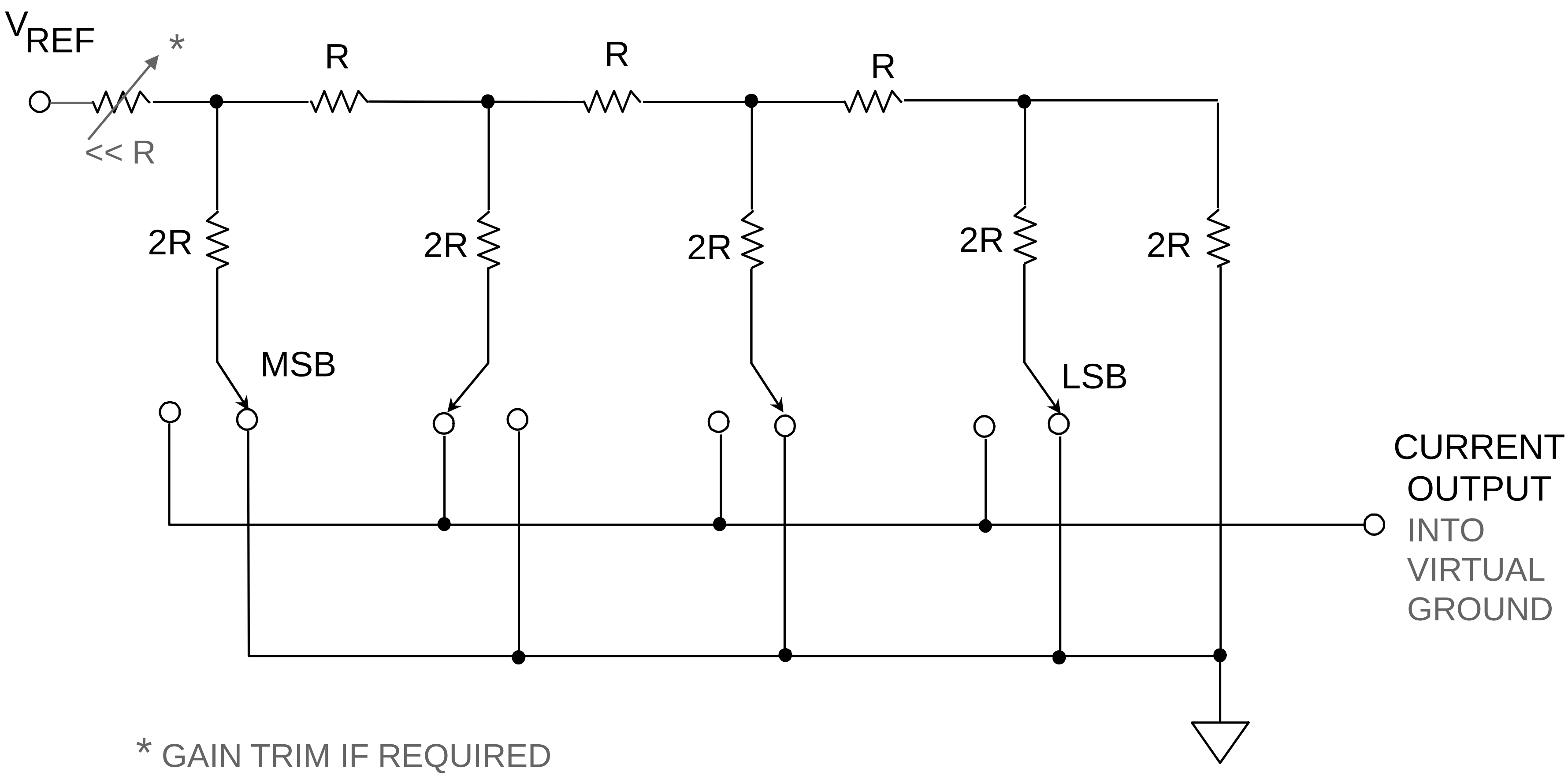
Voltage-Mode Binary Weighted Resistor DAC

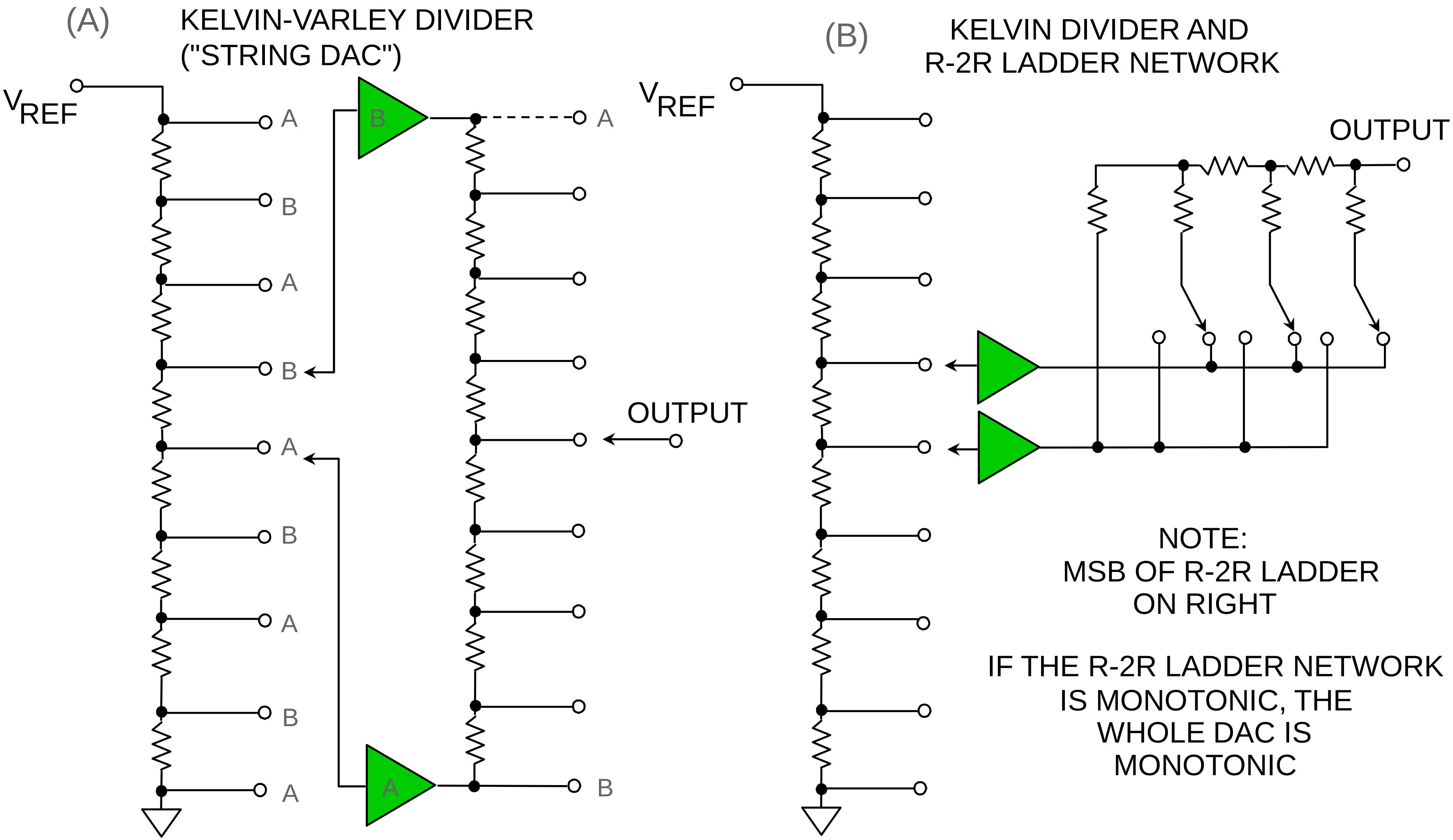


Current-Mode R-2R Ladder Network Resistor-Based DAC

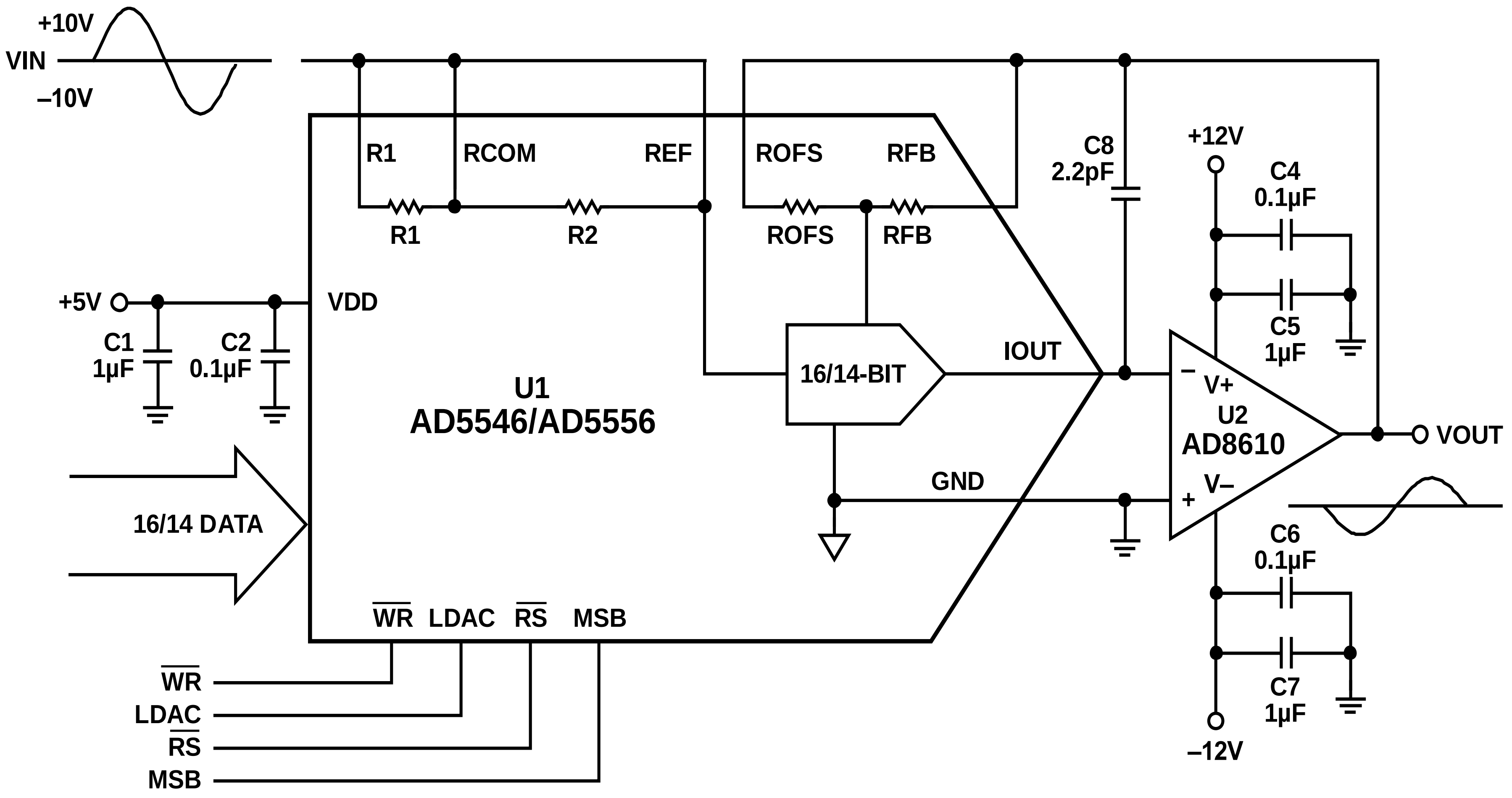


* GAIN TRIM IF REQUIRED

Segmented Voltage Output DACs



Circuits from the Lab
Multiplying DAC attenuates AC signal



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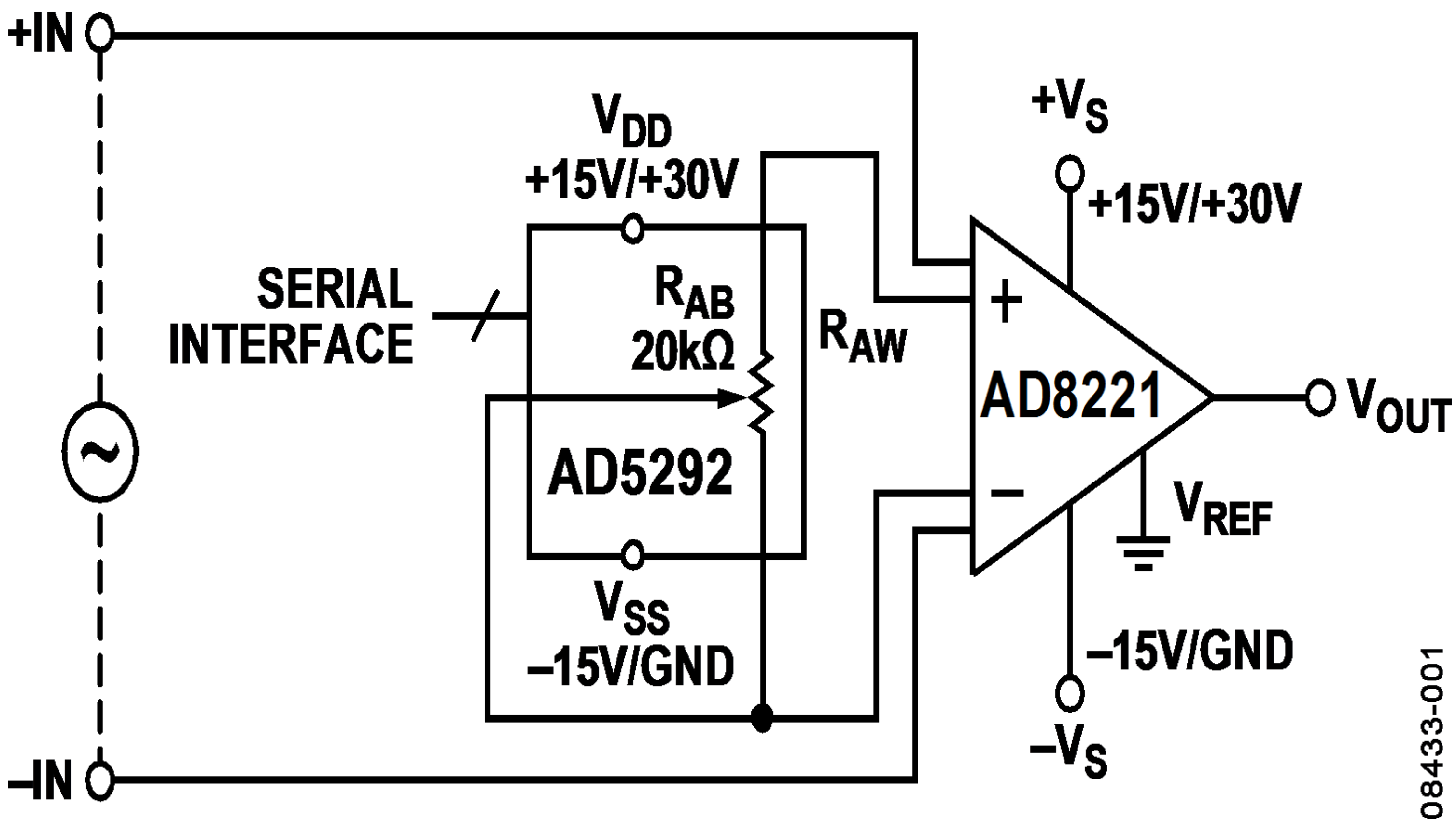
Digital Potentiometer Applications

- Amplifier and other component adjustment
  - Connect across offset-adjust pins
  - Gain adjustment or fine tuning
- System calibration
  - Digital pots inserted in strategic system locations
  - System tune-up automatically or manually
  - Non-volatile RAM setting returns on system power-up
  - RAM can be one-time program or re-programmable
  - Settings can be stored centrally and transmitted for system re-adjustment

Circuits from the Lab
Digital Potentiometer Gain Adjustment



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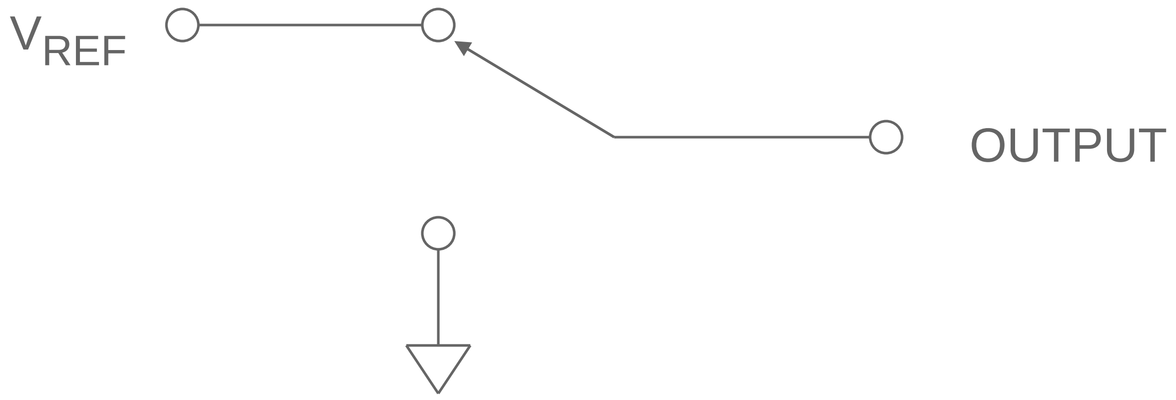
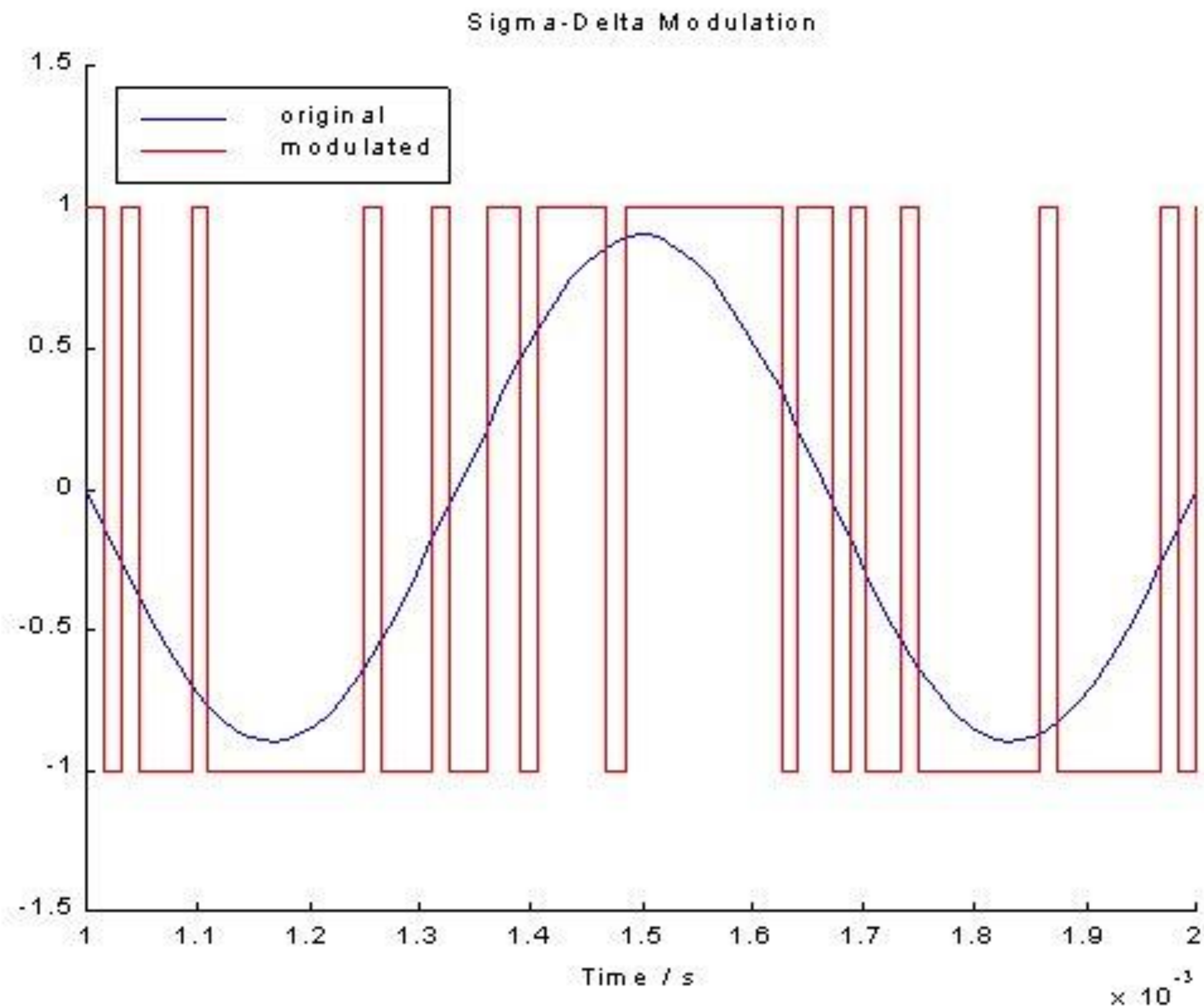
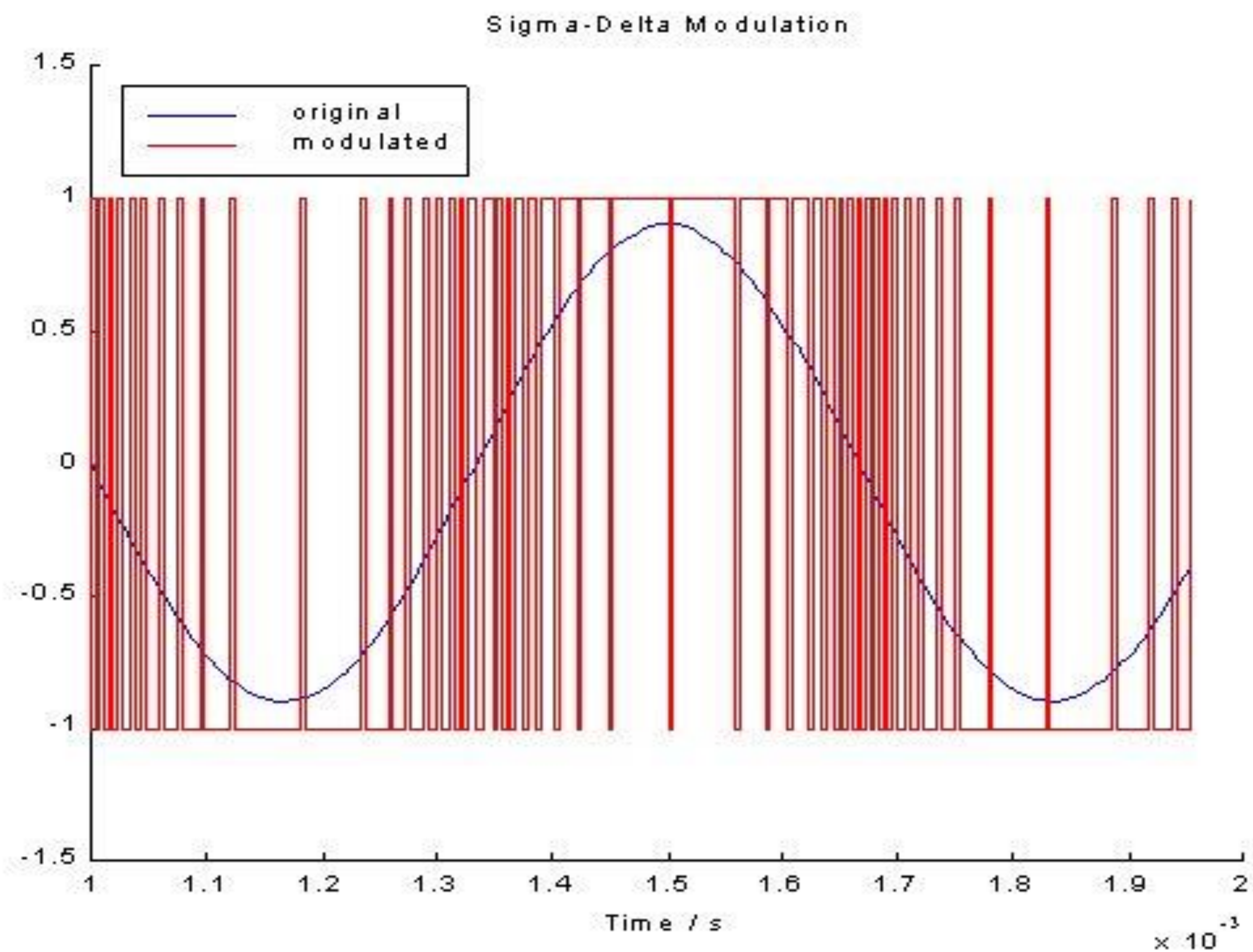
1-Bit DAC:
Highly-sophisticated Digital-Audio DAC



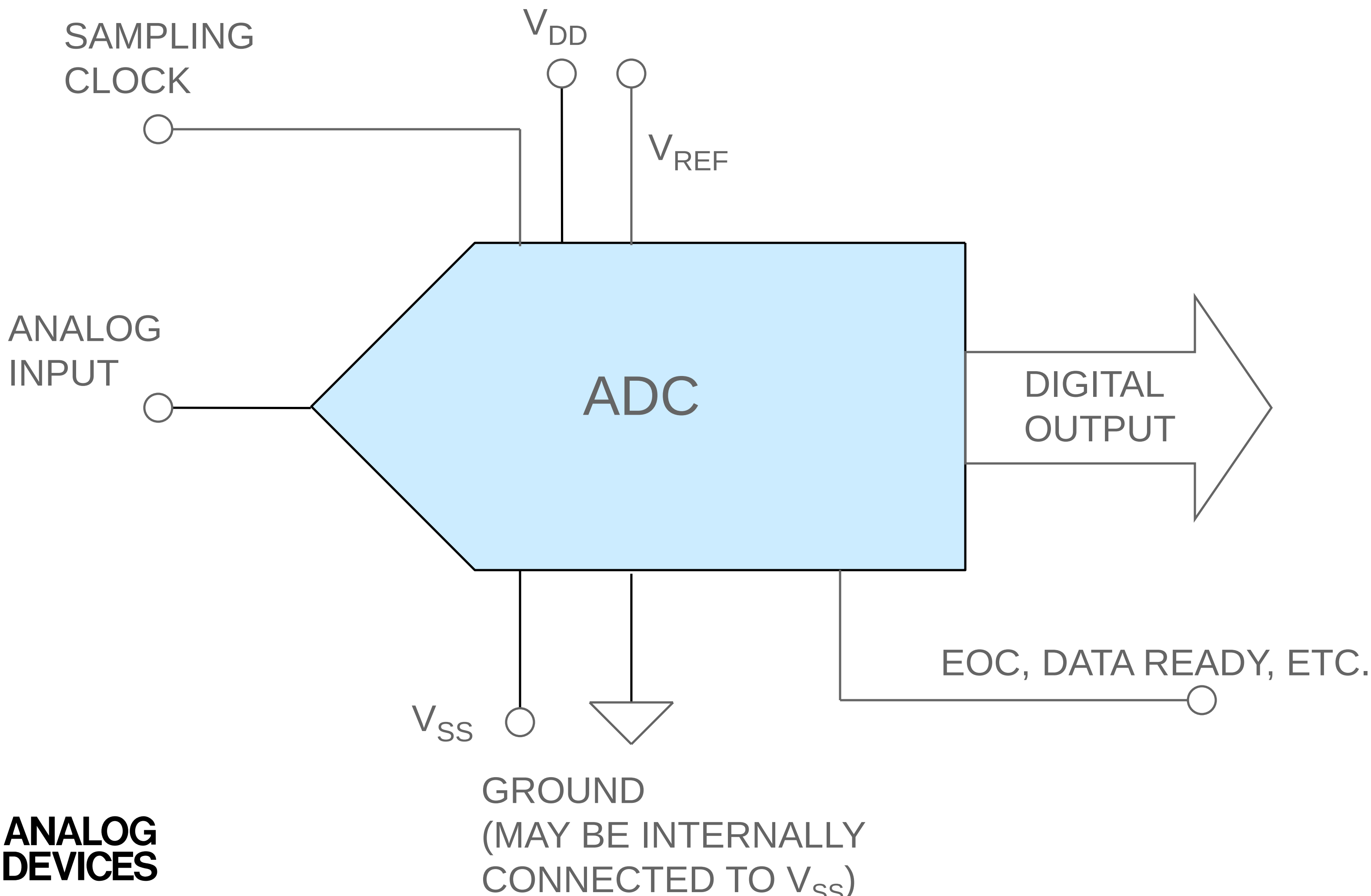
Sampled Data System: Sampling and Quantization



Sampled Data System: Sampling and Quantization



Basic ADC with External Reference



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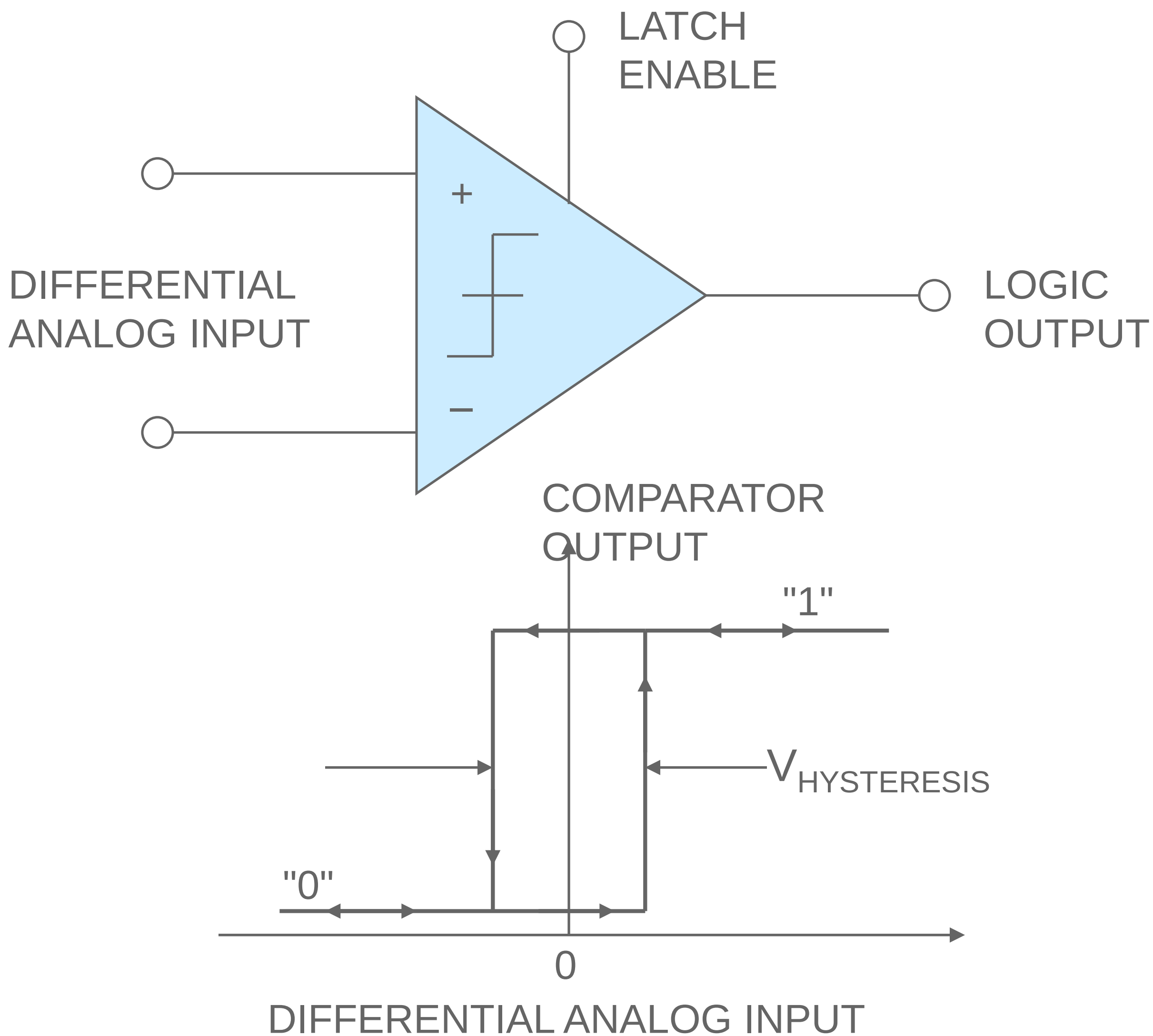
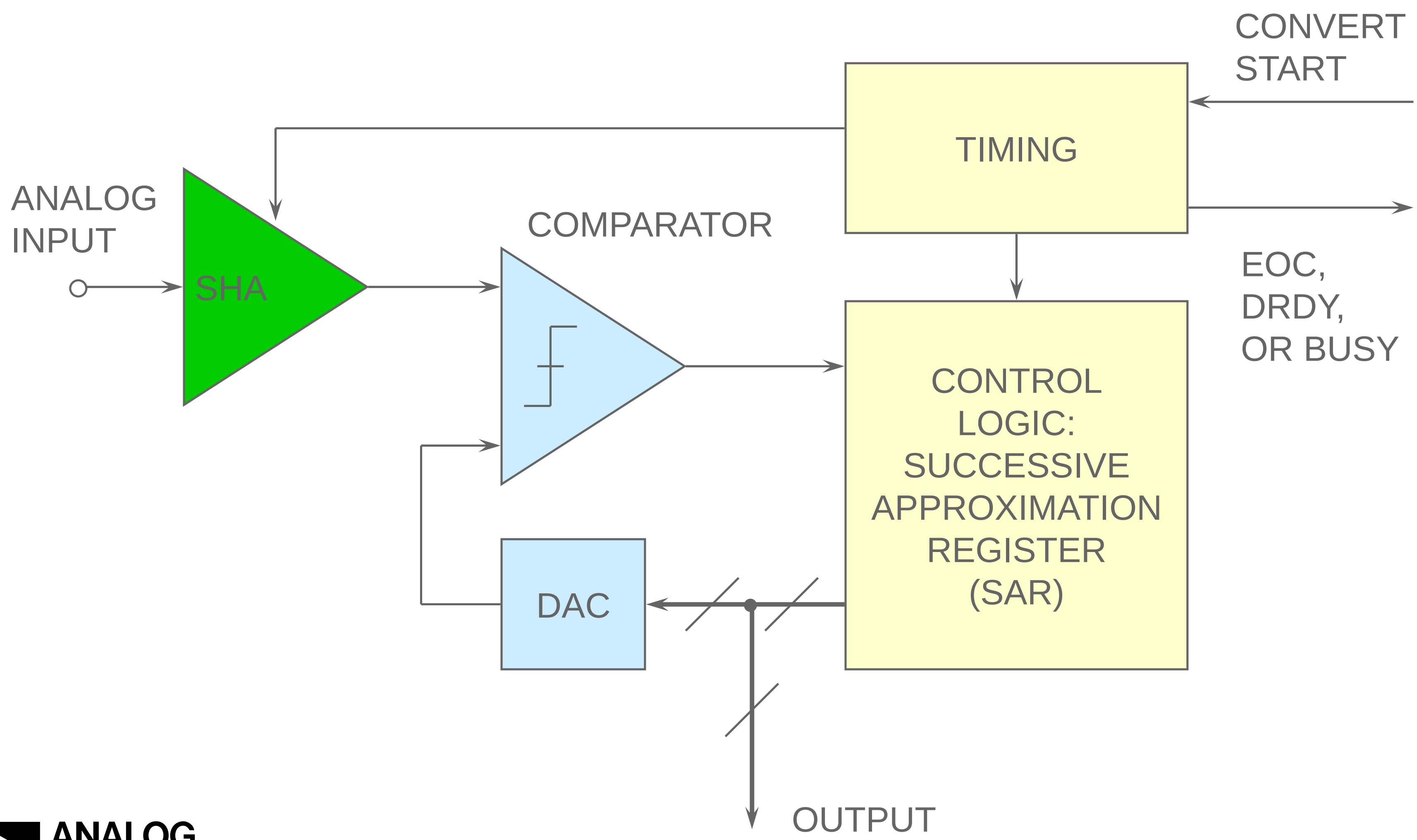
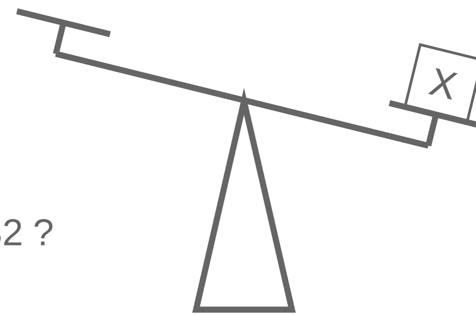
The Comparator: A 1-Bit ADC



Basic Successive Approximation ADC (Feedback Subtraction ADC)



Successive Approximation ADC Algorithm Analogy Using Binary Weights

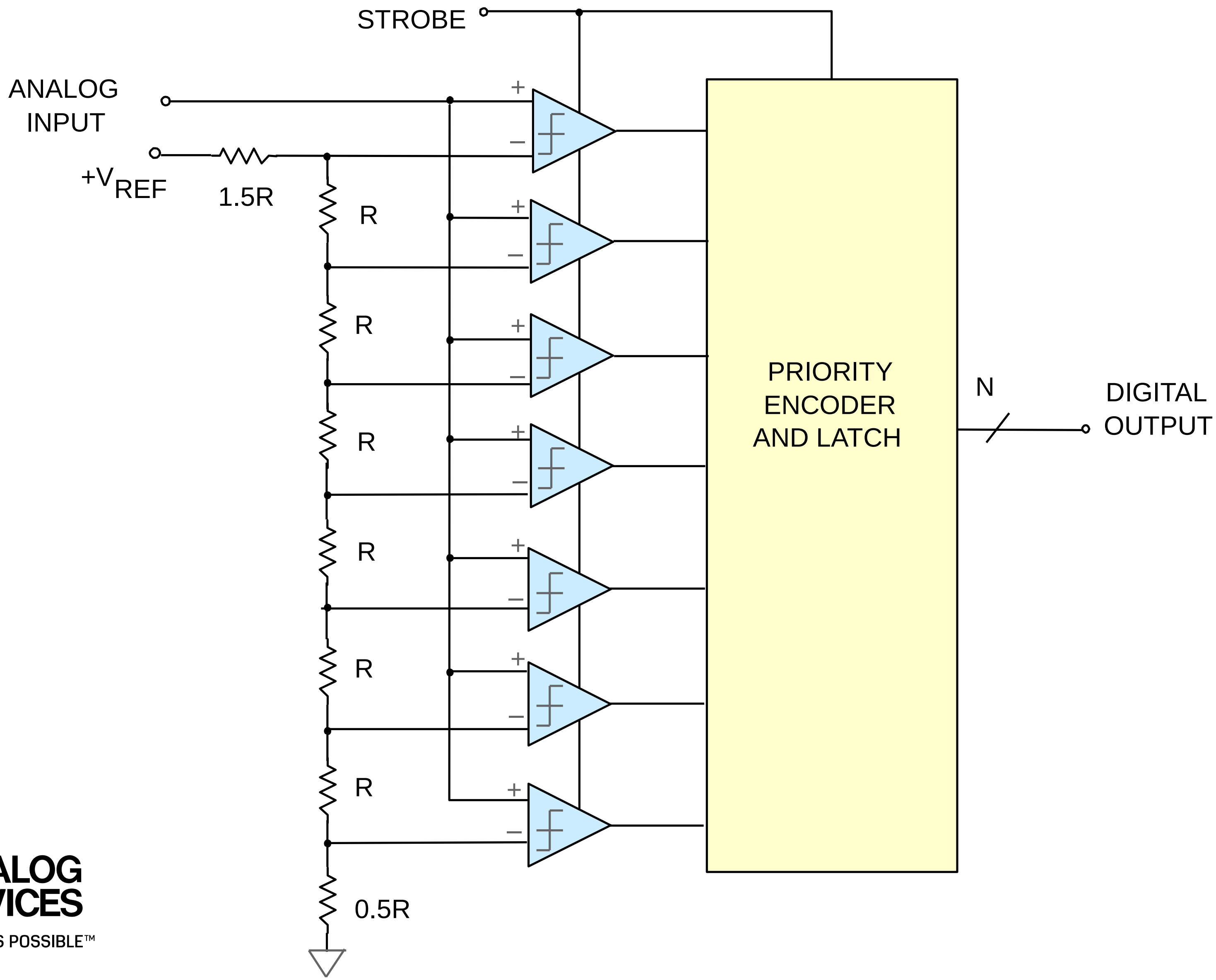


ASSUME X = 45

TEST			
IS X ≥ 32 ?	YES	RETAIN 32	1
IS X ≥ (32 +16) ?	NO	REJECT 16	0
IS X ≥ (32 +8) ?	YES	RETAIN 8	1
IS X ≥ (32 +8 + 4) ?	YES	RETAIN 4	1
IS X ≥ (32 +8 + 4 + 2) ?	NO	REJECT 2	0
IS X ≥ (32 +8 + 4 + 2 + 1) ?	YES	RETAIN 1	1

TOTALS: $X = 32 + 8 + 4 + 1 = 45_{10} = 101101_2$

3-bit All-Parallel (Flash) Converter



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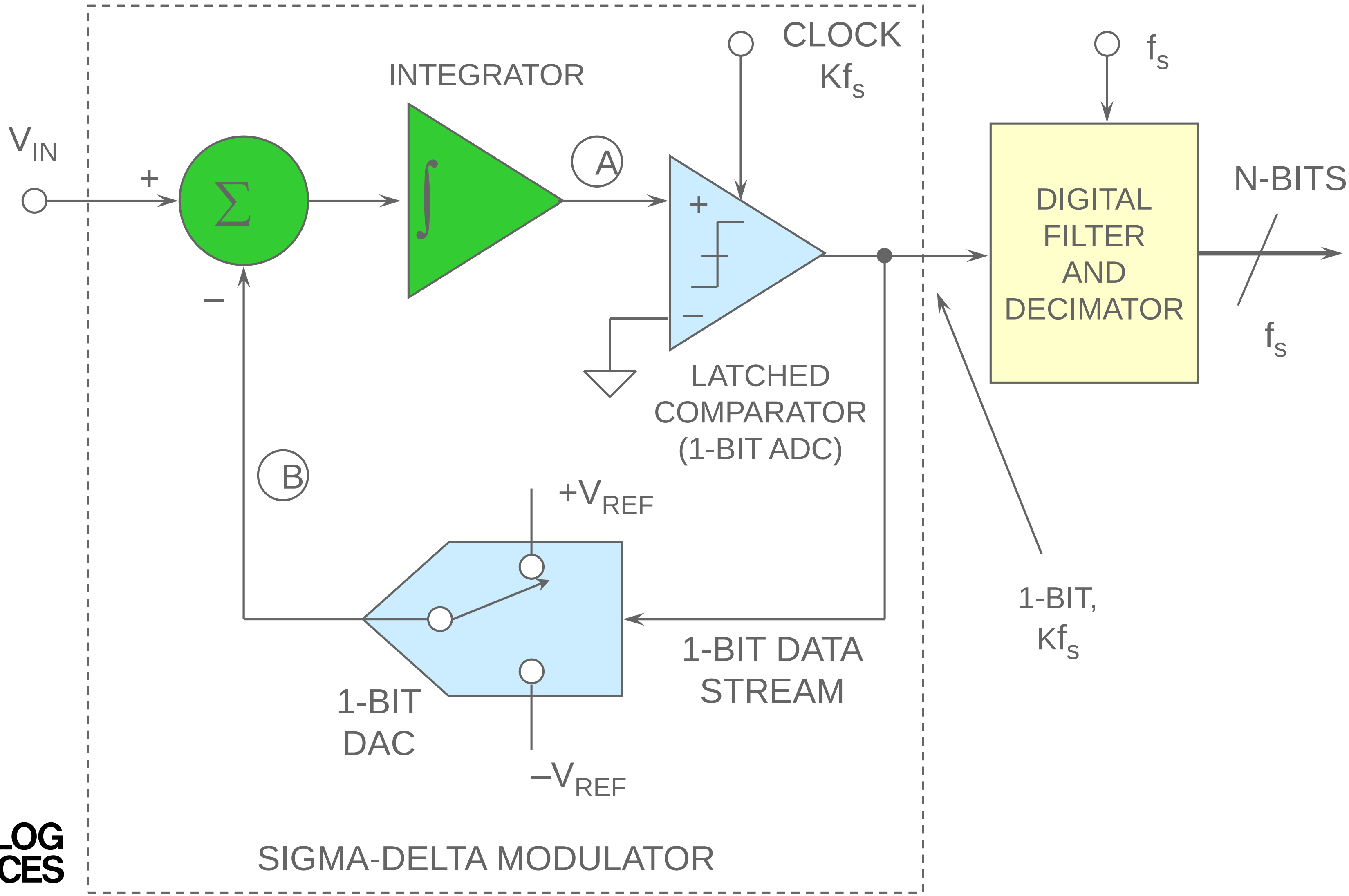
Sigma-Delta ADC - First-Order Modulator



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