Analog Integrated Systems Design

Lecture 04
Data Converters Specifications (1)

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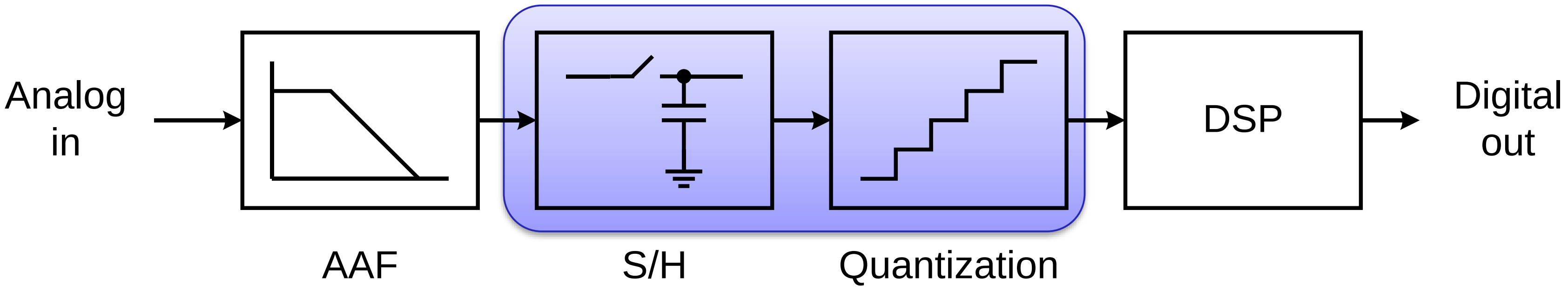
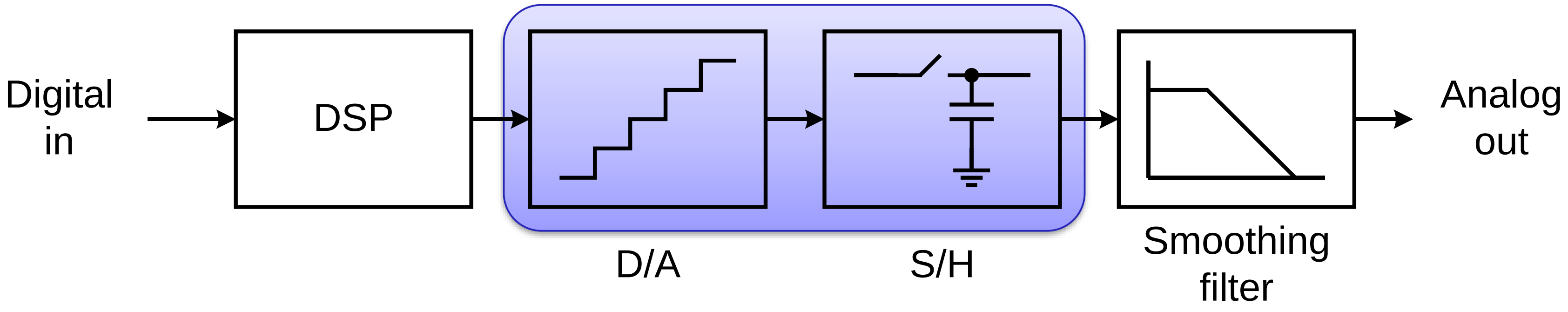
ADC and DAC

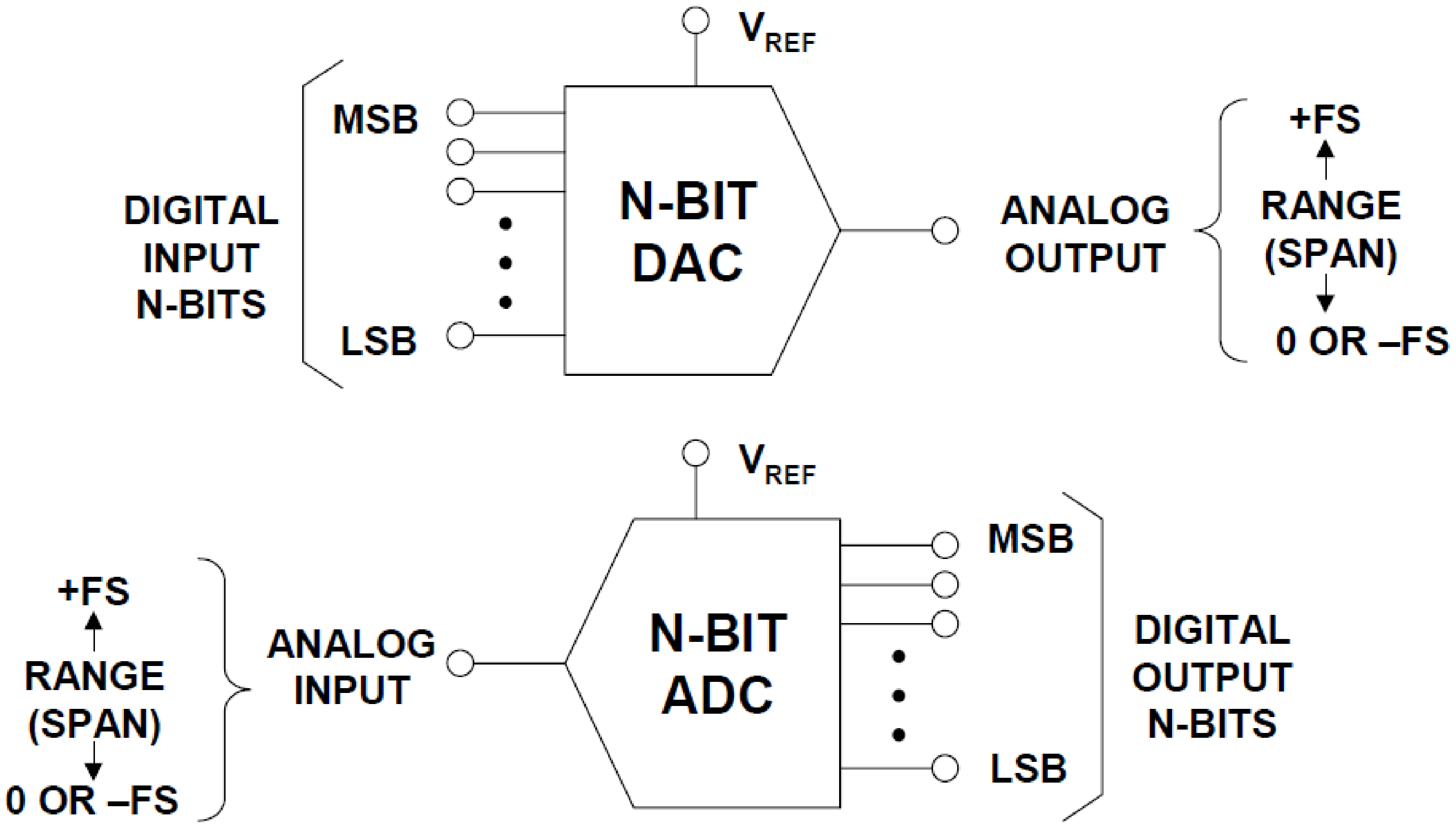
- ADC



- DAC



Unipolar vs Bipolar

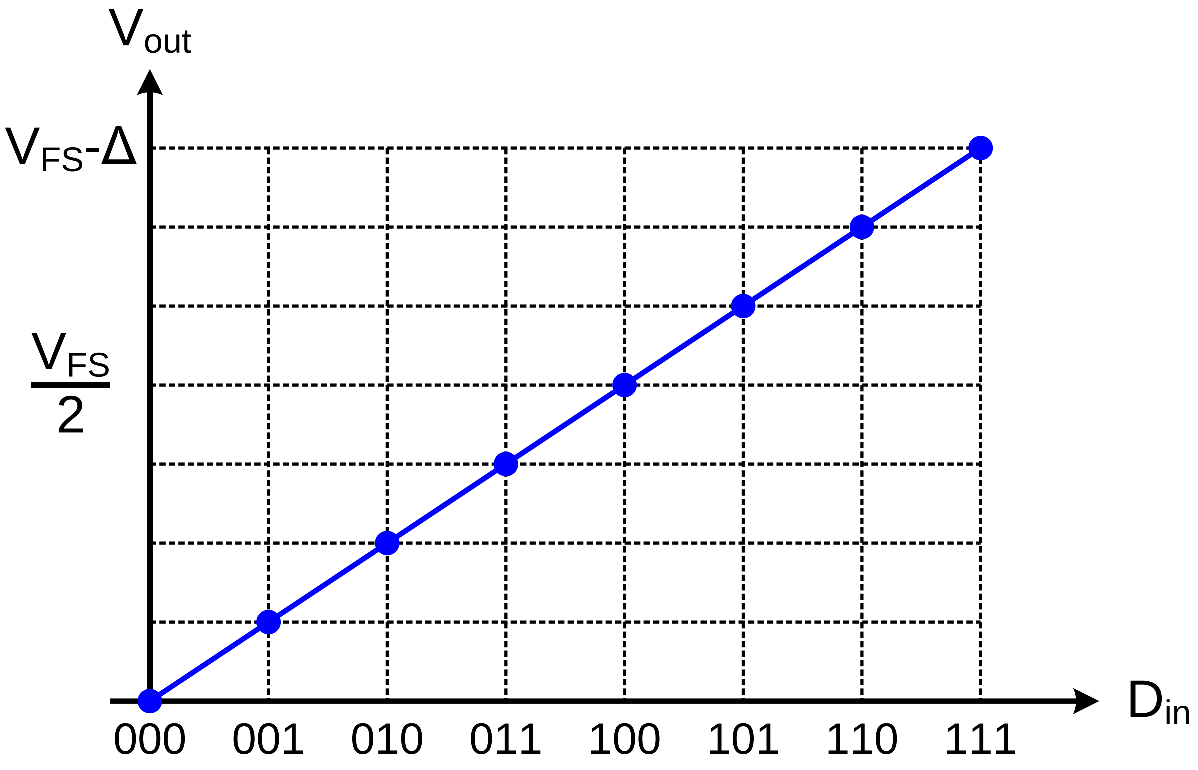


[W. Kester, 2005]

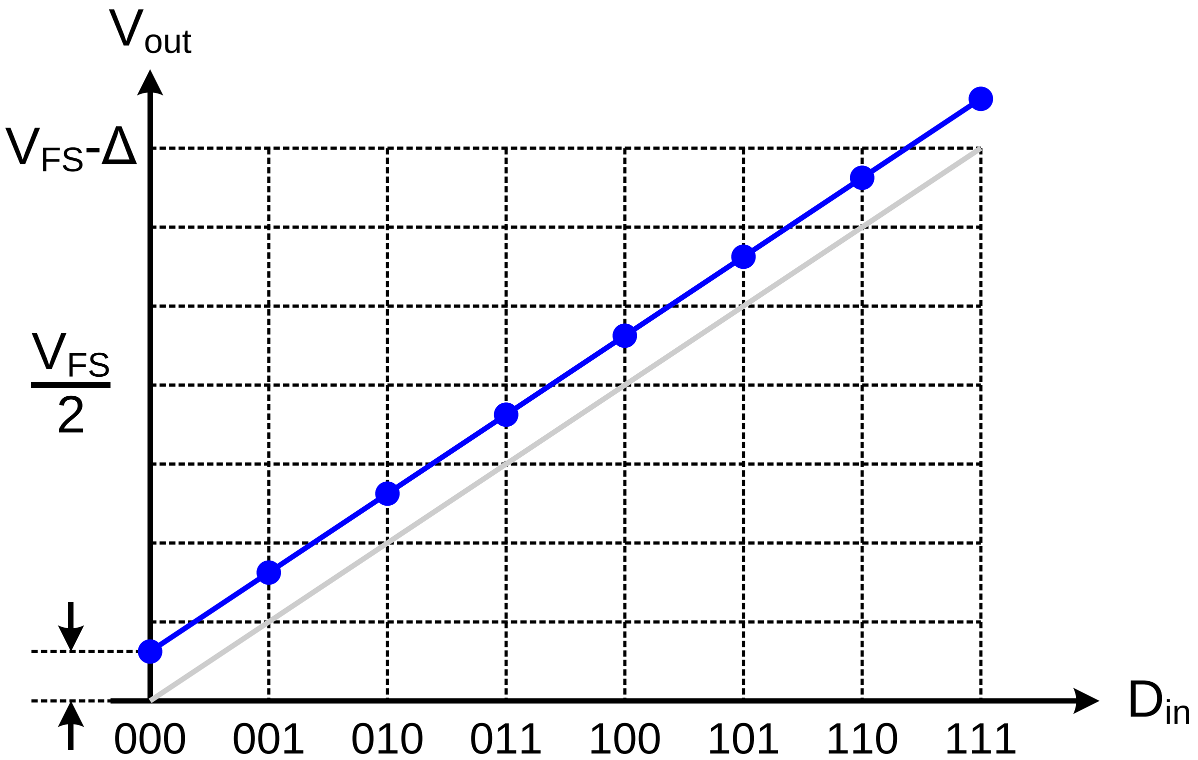
Static (DC) Specifications

- Offset Error
- Gain Error
- Monotonicity
- Linearity
  - Differential Non-Linearity (DNL)
  - Integral Non-Linearity (INL)

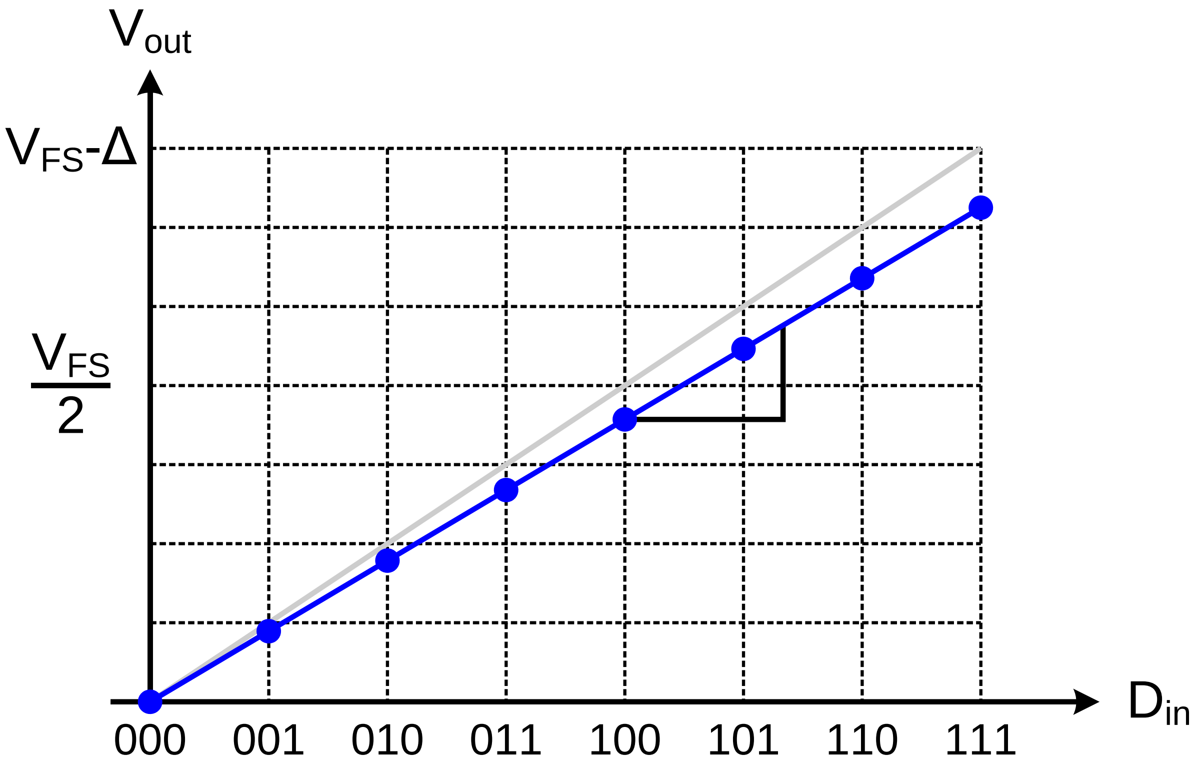
Ideal DAC Transfer Function



DAC Offset Error

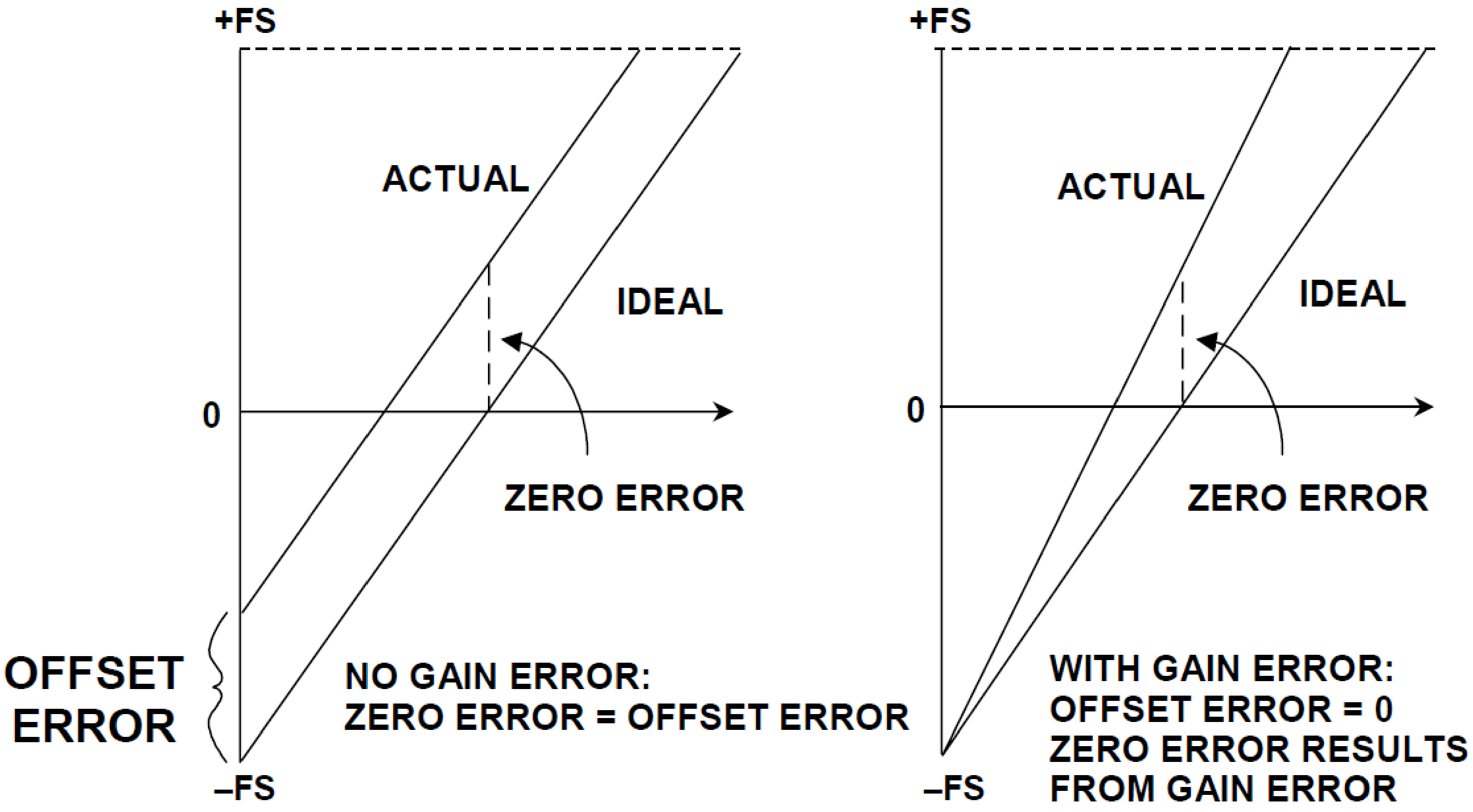


DAC Gain Error



Offset and Gain Errors

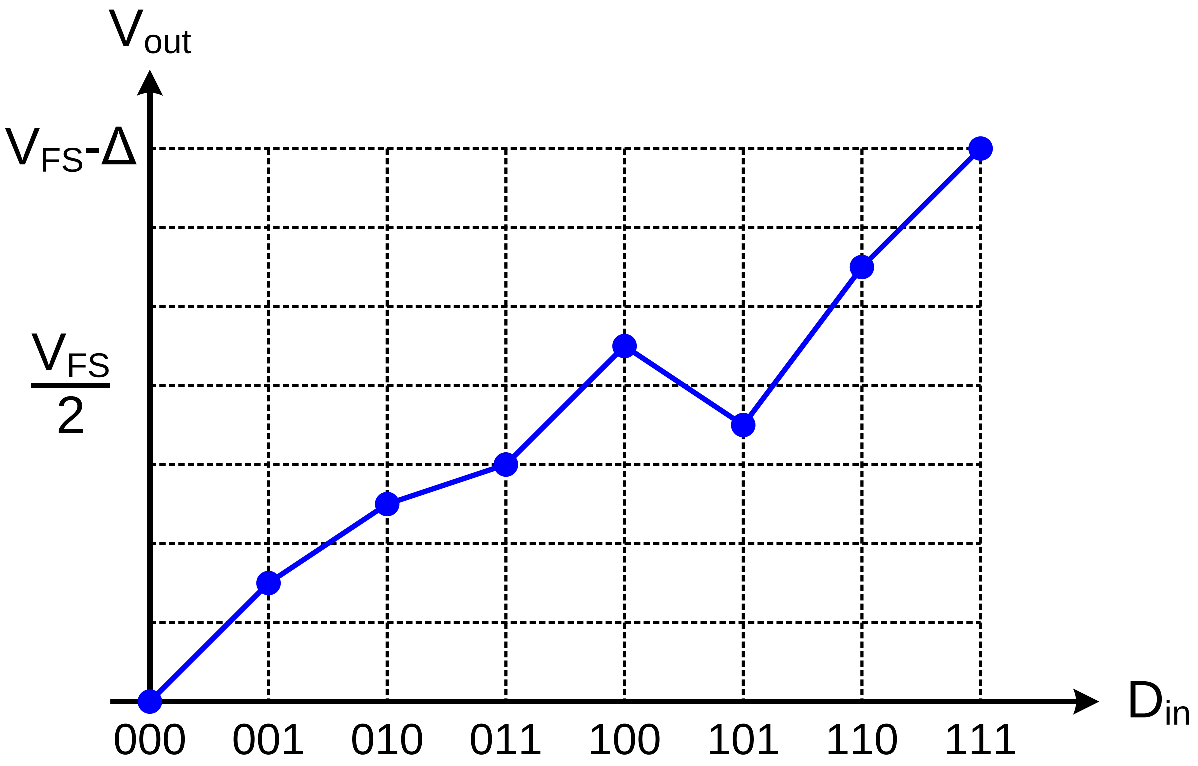
- Can be calibrated by two points.
- First, trim offset error. Next, trim gain error.



[W. Kester, 2005]

DAC Non-monotonicity

- Non-monotonicity can be catastrophic in control loops (why?).

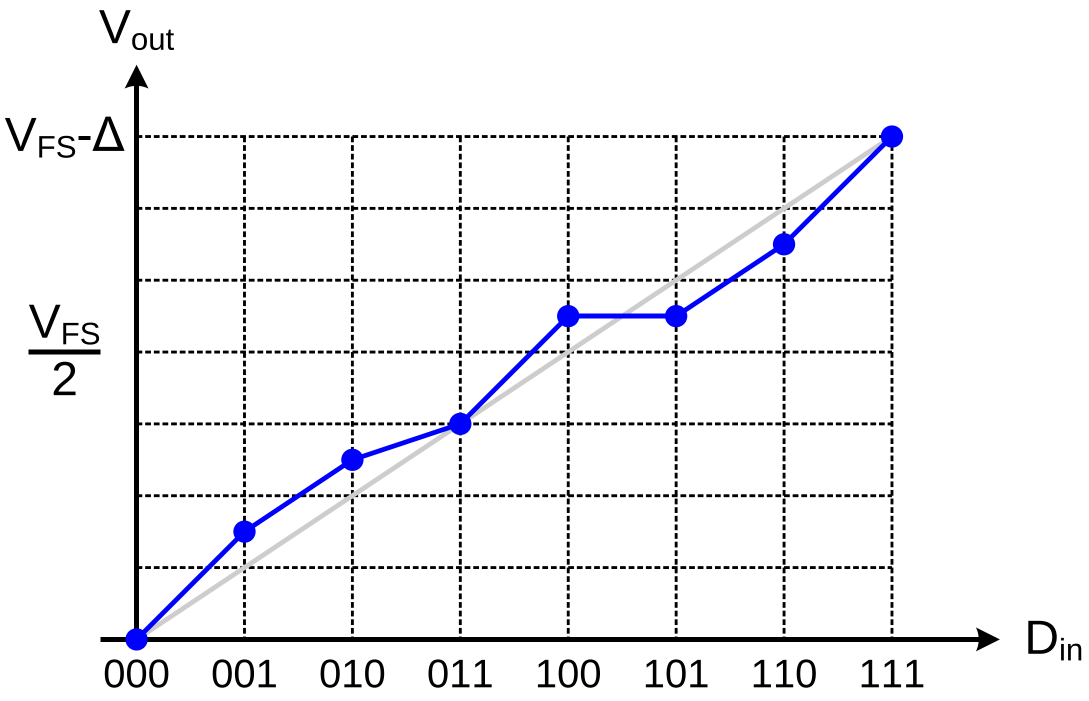


DAC Differential Nonlinearity (DNL)

- DNL = deviation of an output step from 1 LSB (= $\Delta = V_{FS}/2^N$)

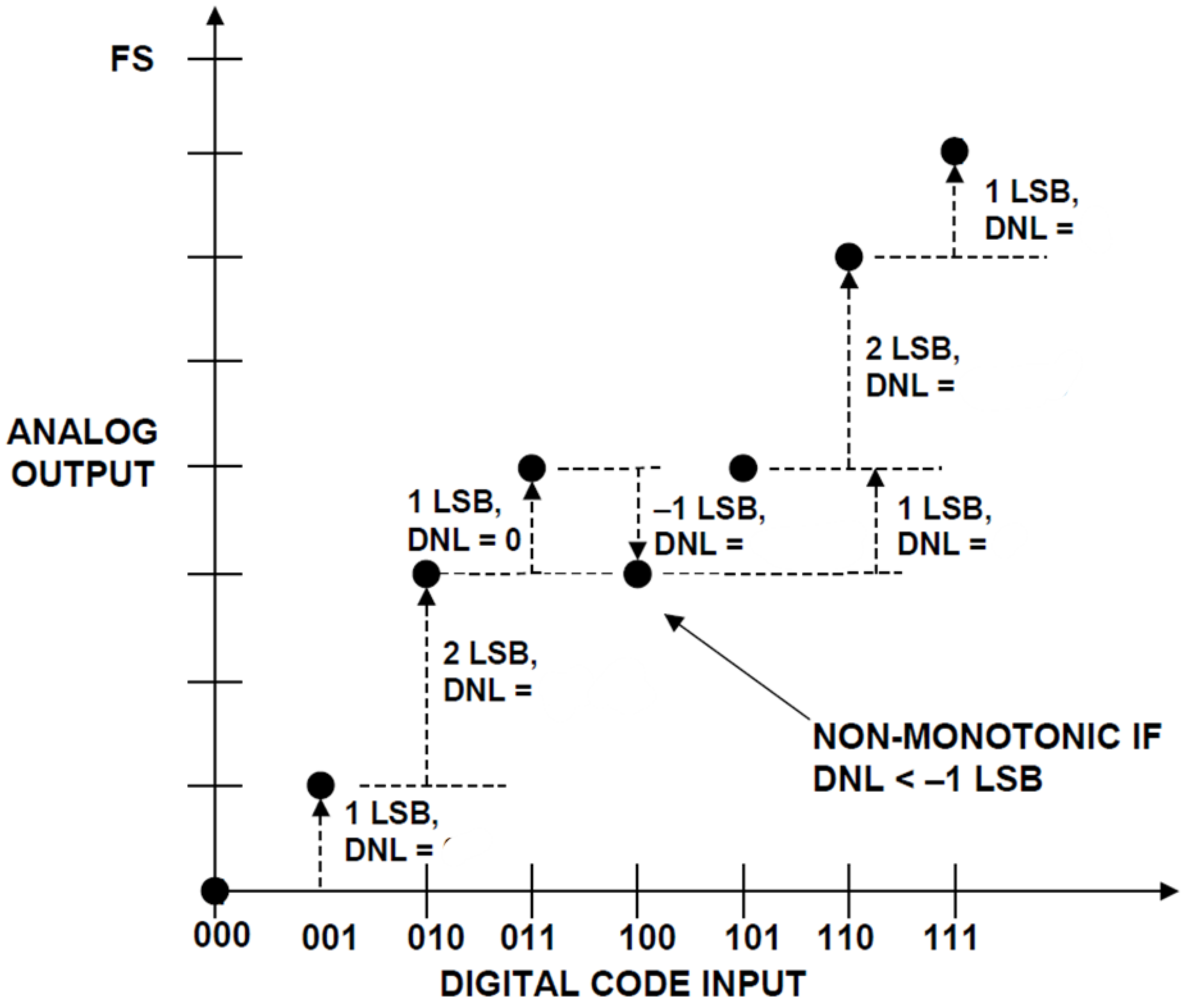
$$DNL_i = \frac{i^{th}\ \text{Step Size} - \Delta}{\Delta}$$

- What does DNL < -1 mean?



[Y. Chiu, EECT 7327, UTD]

DAC DNL Example

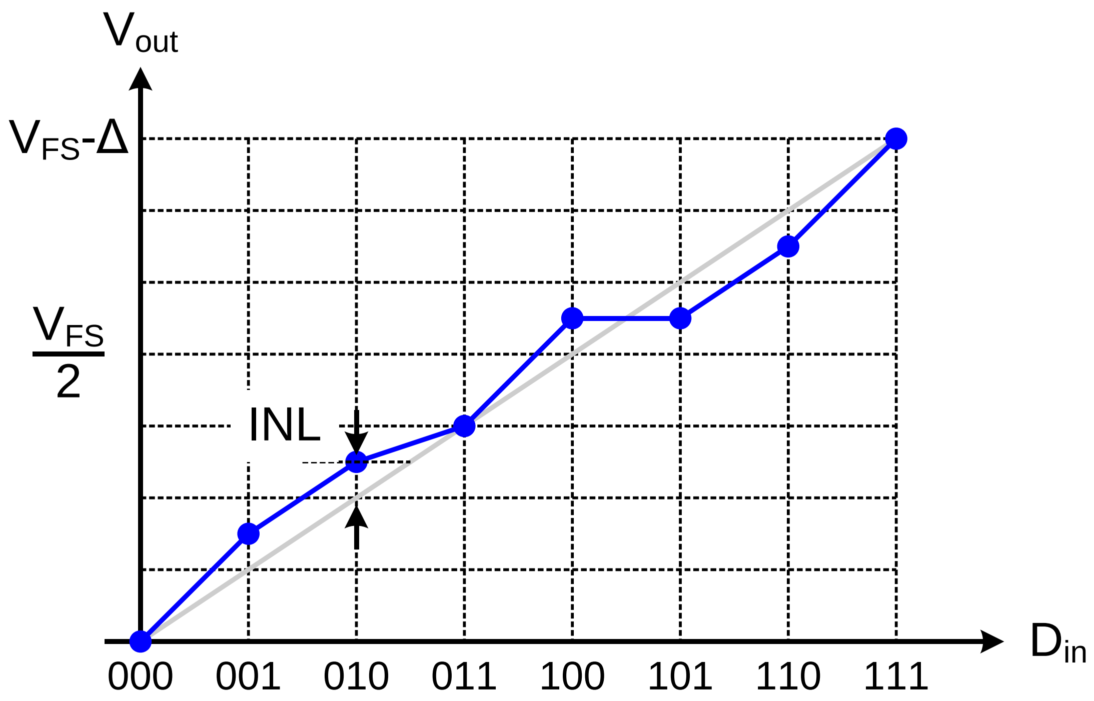


[W. Kester, 2005]

DAC Integral Nonlinearity (INL)

- INL = deviation of the output from the ideal transfer curve
- It can be shown that INL = cumulative sum of DNL

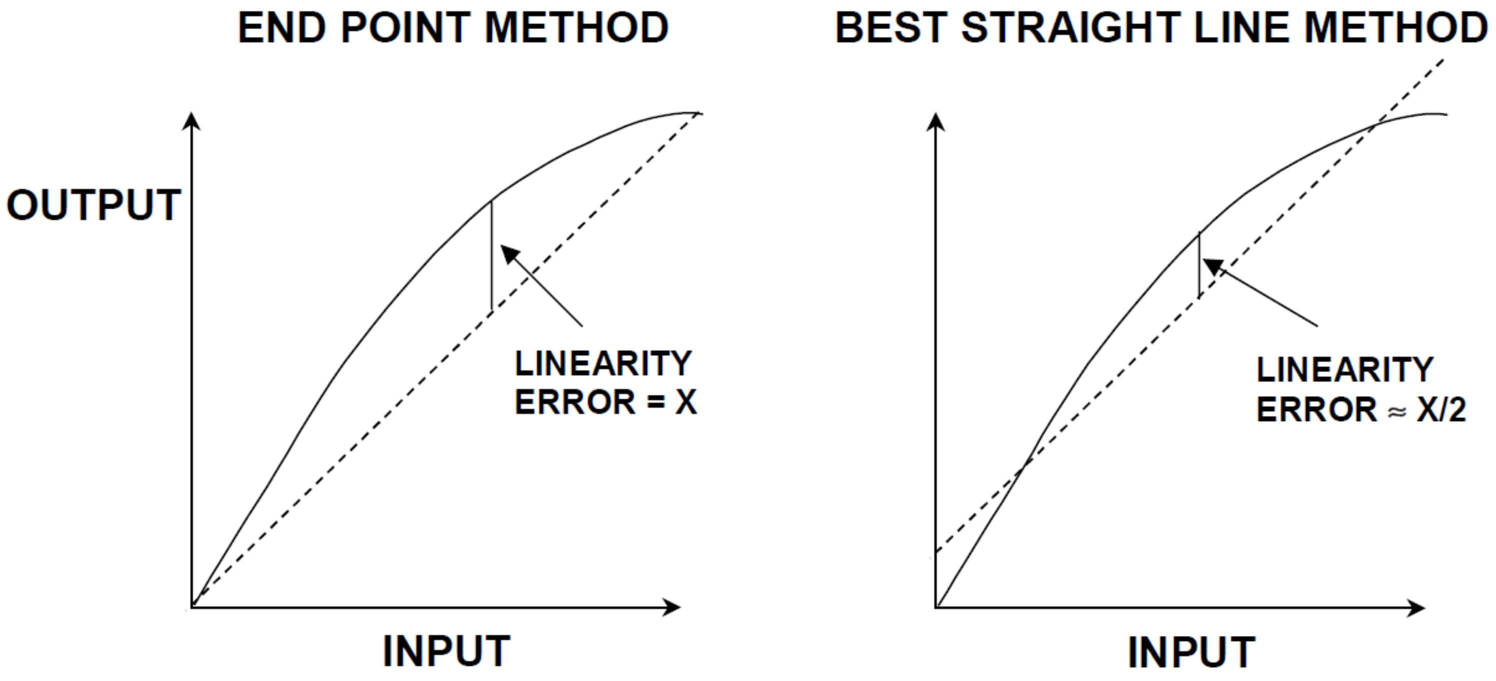
$$\boxed{INL_i = \sum_{j=0}^{i} DNL_j}$$



[Y. Chiu, EECT 7327, UTD]

INL Measurement Methods

- INL can be measured relative to:
  - A line joining the ideal end points ➔ More accurate
  - A best fit straight line ➔ May be misleading
- The peak-to-peak INL remains the same

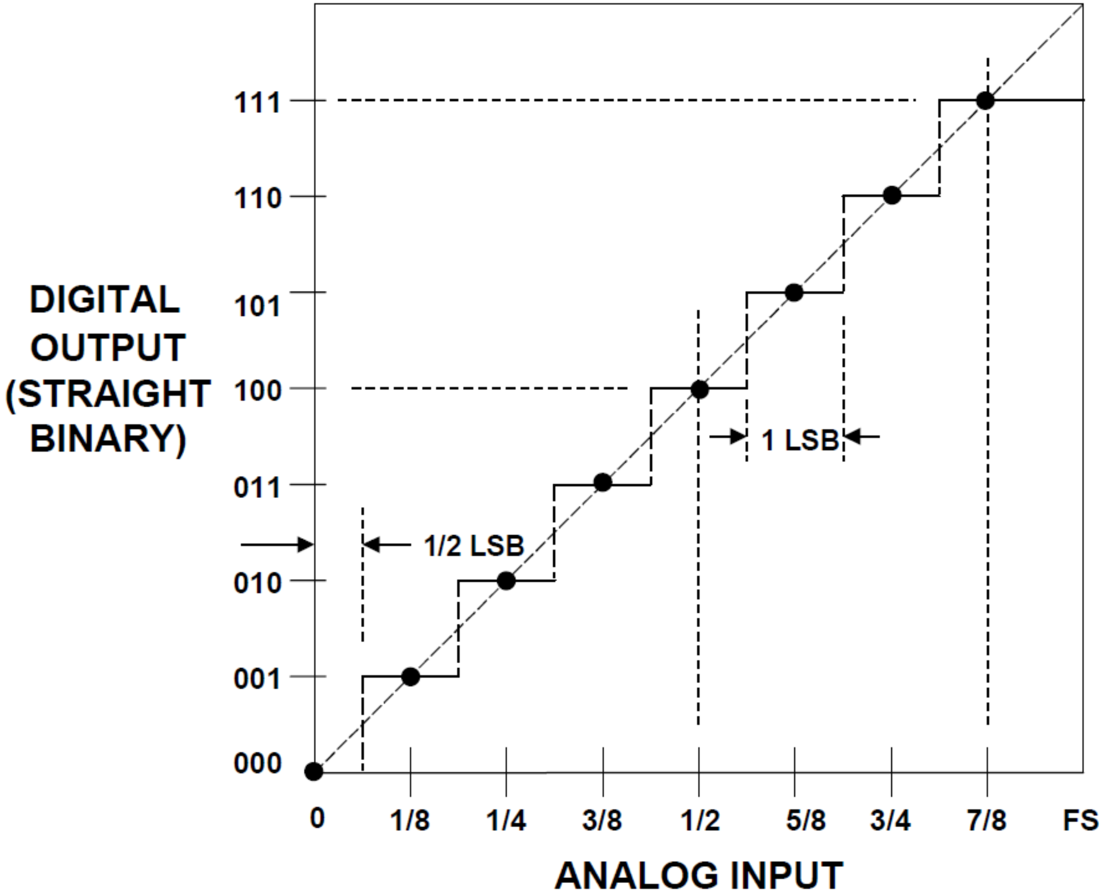


$\Sigma(INL) \neq 0$ $\qquad$ $\Sigma(INL) = 0$

[W. Kester, 2005]

Unipolar ADC Transfer Function

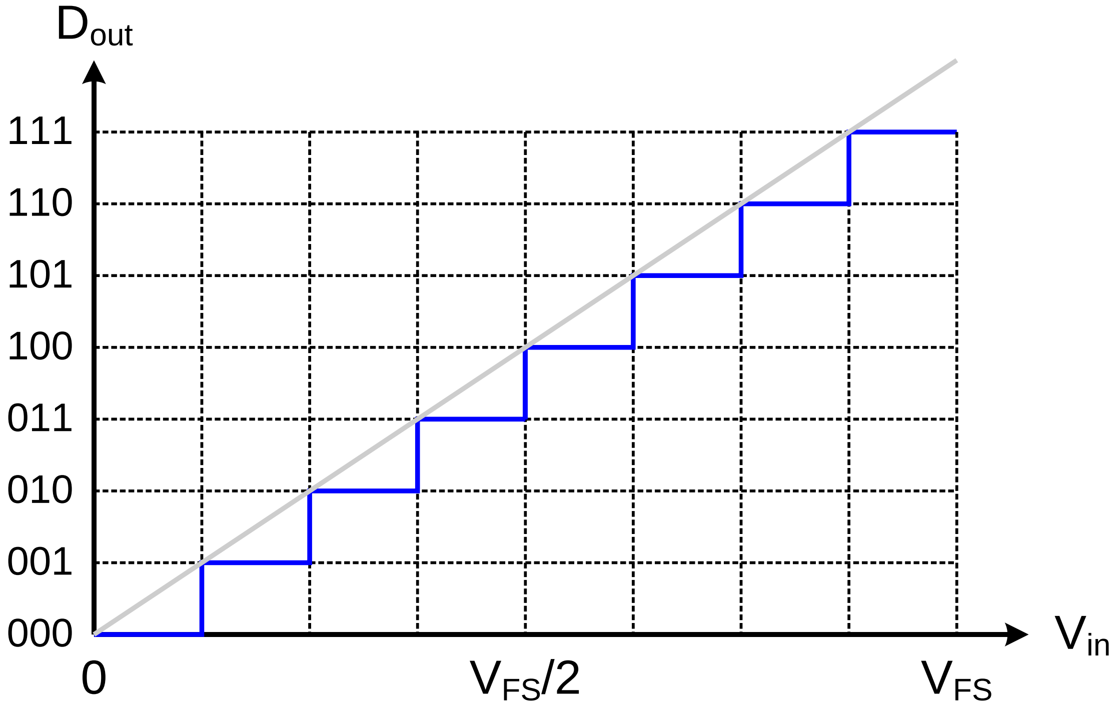
- The first transition is at LSB/2 (mid-tread quantizer)
- The transfer ccs is the line joining the code centers (black dots)
- Code centers are difficult to measure → use code transitions



[W. Kester, 2005]

Ideal ADC Transfer Characteristic

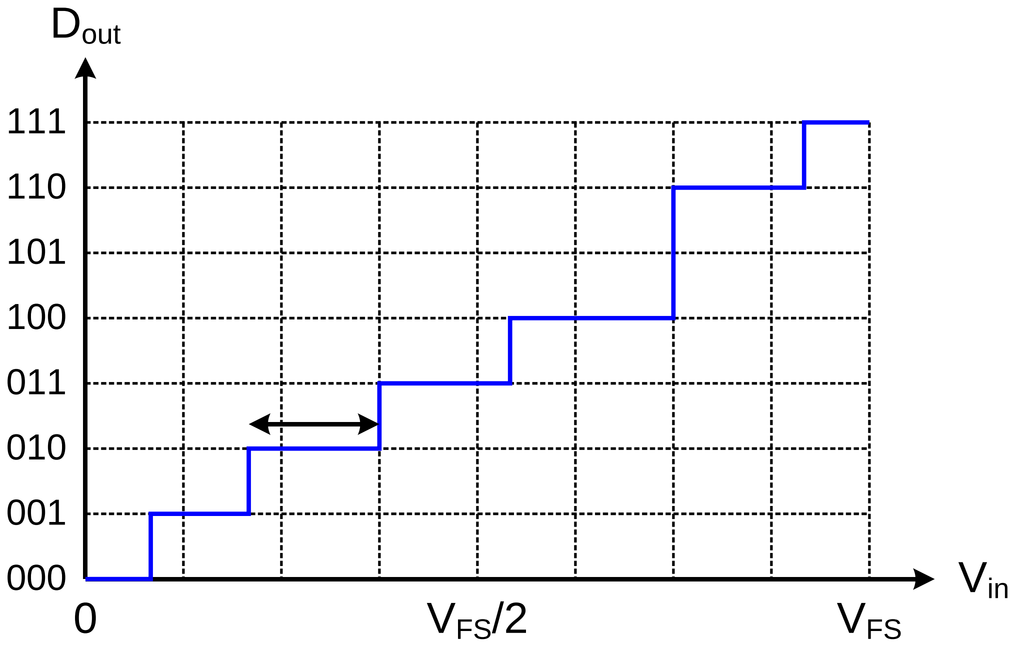
- Using floor/ceiling yields systematic offset error
- Offset and gain errors are usually not critical for ADCs
  - Can be trimmed (corrected) easily in the digital domain



ADC DNL and Missing Codes

- DNL and INL always measured on the analog axis
- DNL = deviation of code width from 1 LSB (= $V_{FS}/2^N = \Delta$)
  - Wide code → +ve DNL, narrow code → -ve DNL
- What does DNL = -1 mean? Can it be < -1?
- Can we have missing codes in DAC?

$$DNL_i = \frac{i^{th}\ \text{Step Size} - \Delta}{\Delta}$$

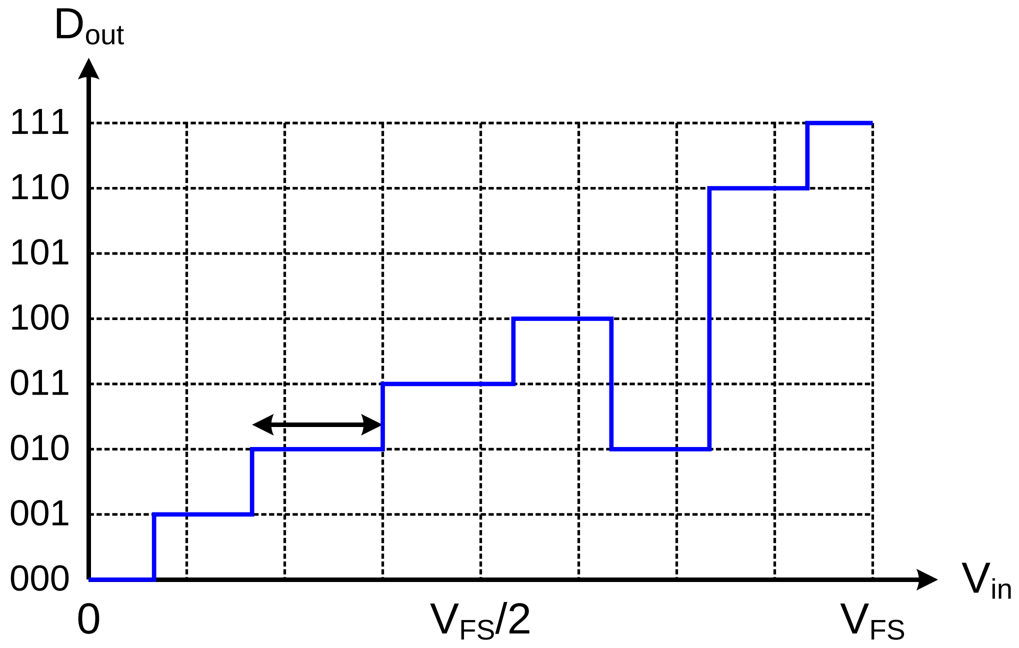


[Y. Chiu, EECT 7327, UTD]

ADC DNL and Non-monotonicity

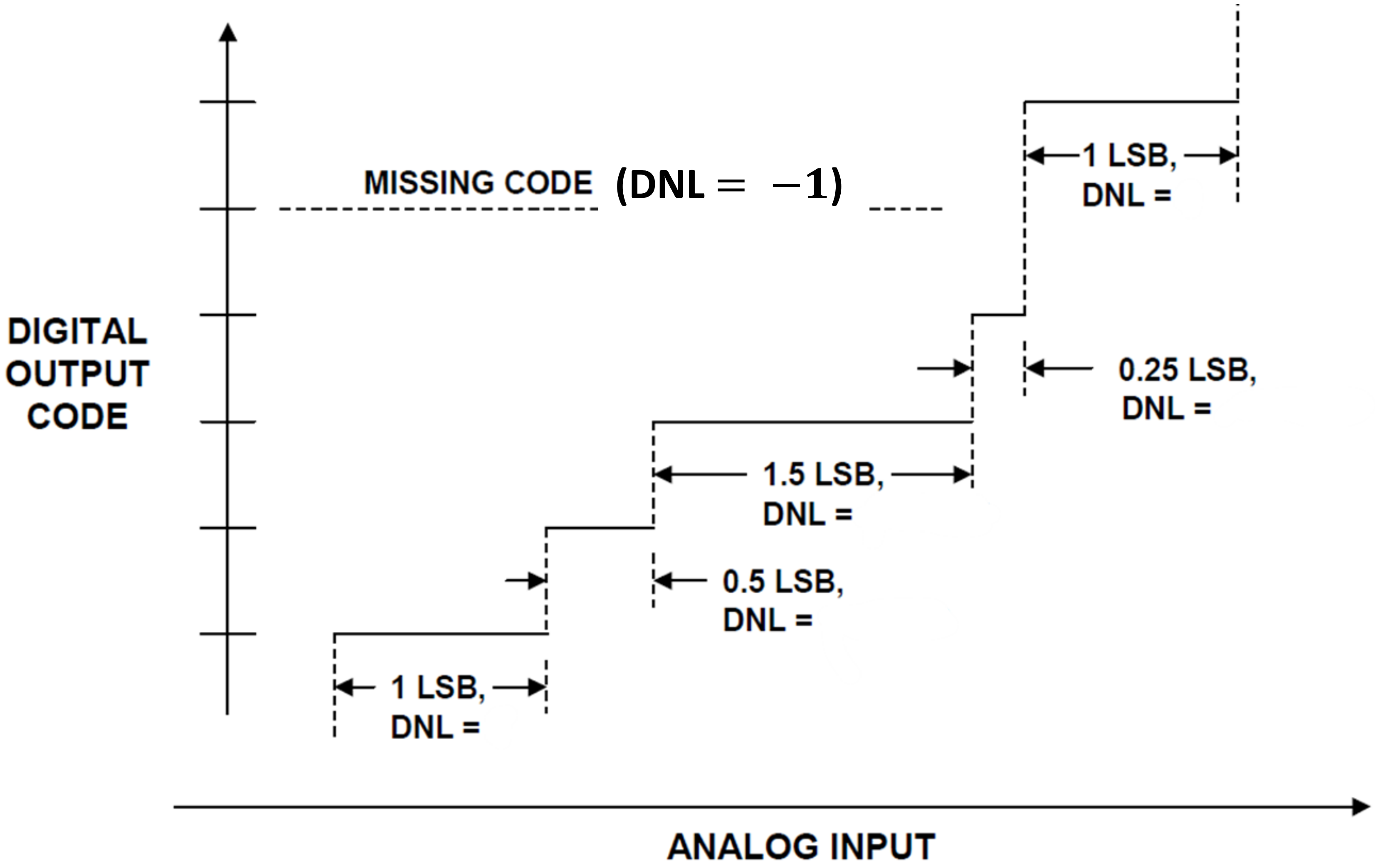
- DNL = deviation of code width from 1 LSB (= $V_{FS}/2^N = \Delta$)
  - Wide code → +ve DNL, narrow code → -ve DNL
- Can we characterize ADC non-monotonicity using DNL?

$$DNL_i = \frac{i^{th}\ \text{Step Size} - \Delta}{\Delta}$$



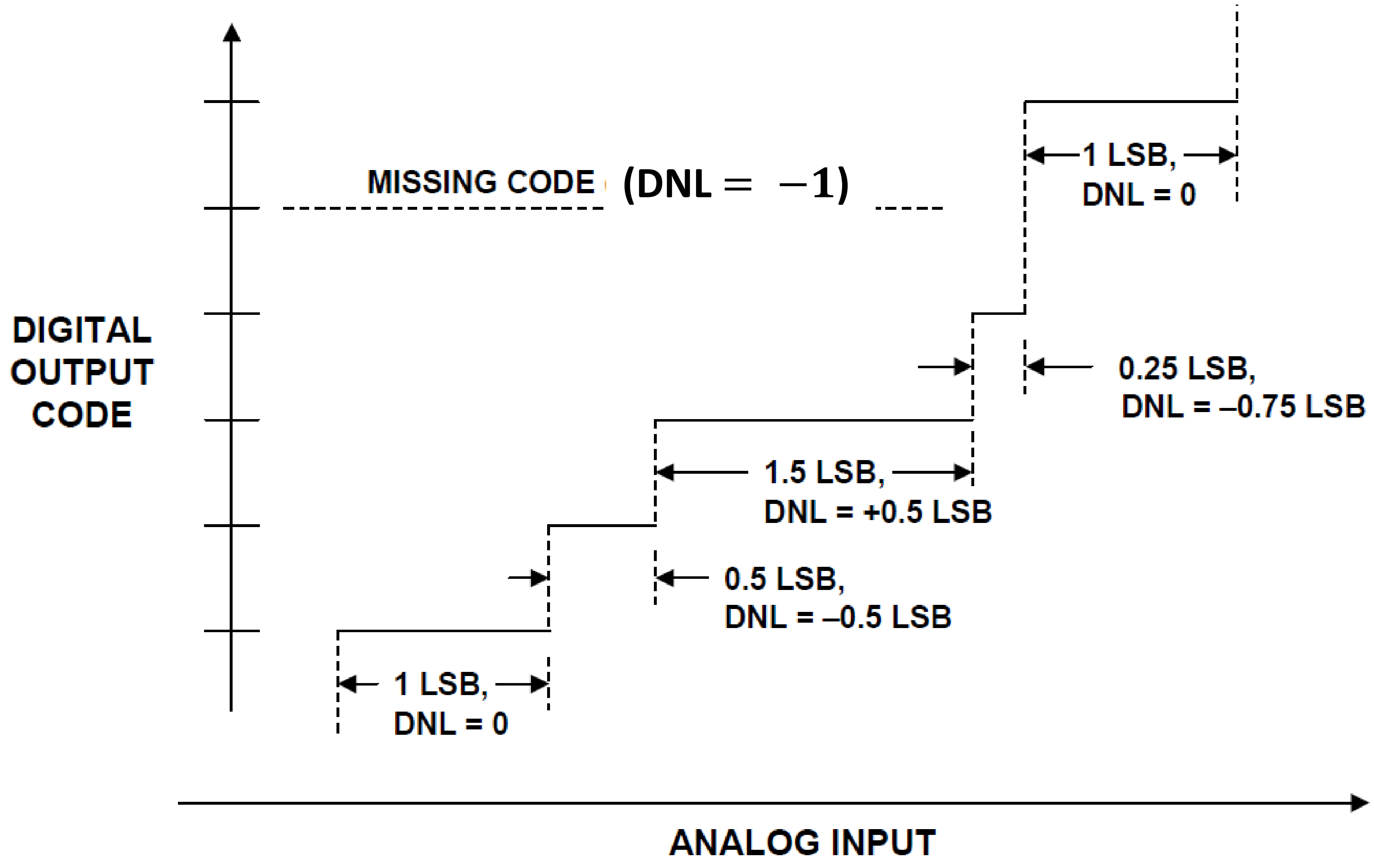
[Y. Chiu, EECT 7327, UTD]

ADC DNL Example



[W. Kester, 2005]

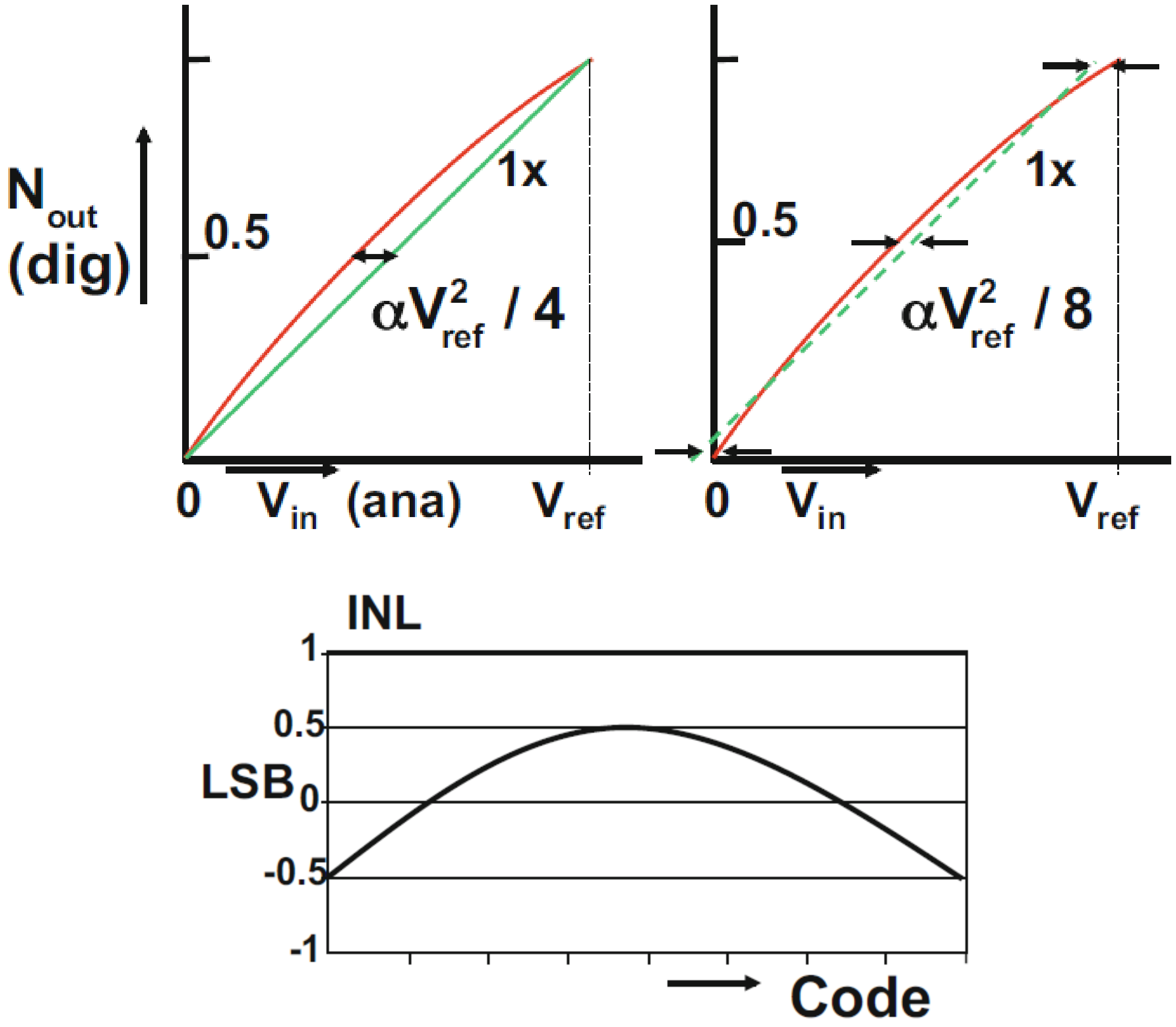
ADC DNL Example



[W. Kester, 2005]

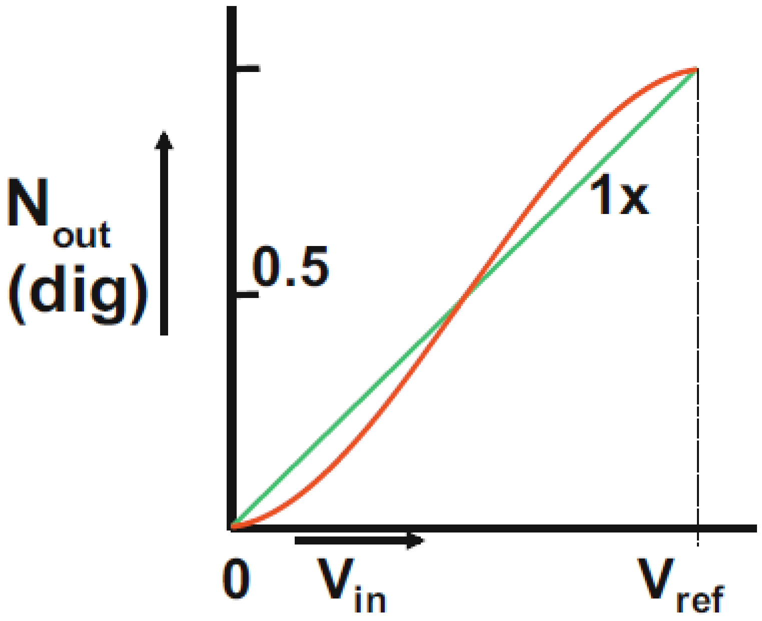
INL Types: 2^{nd} Order Distortion

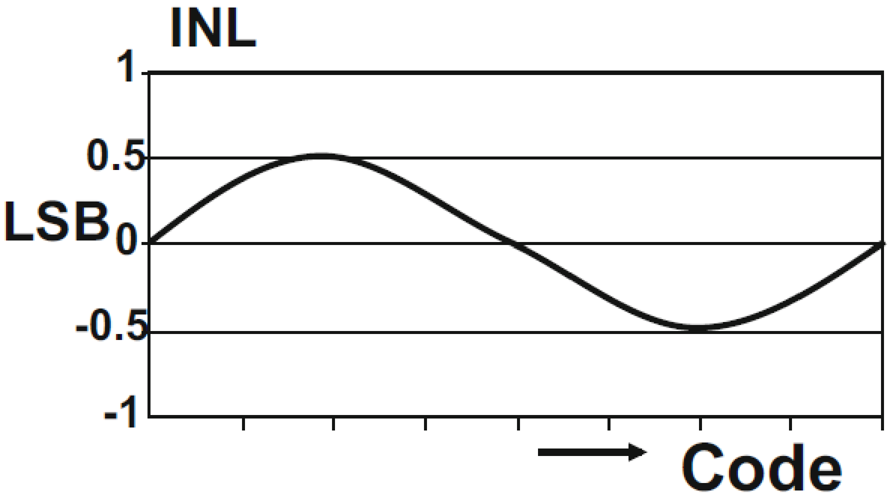
- Using "best-fit" straight line will center the INL curve around zero.



[M. Pelgrom, 2017]

INL Types: 3rd Order Distortion

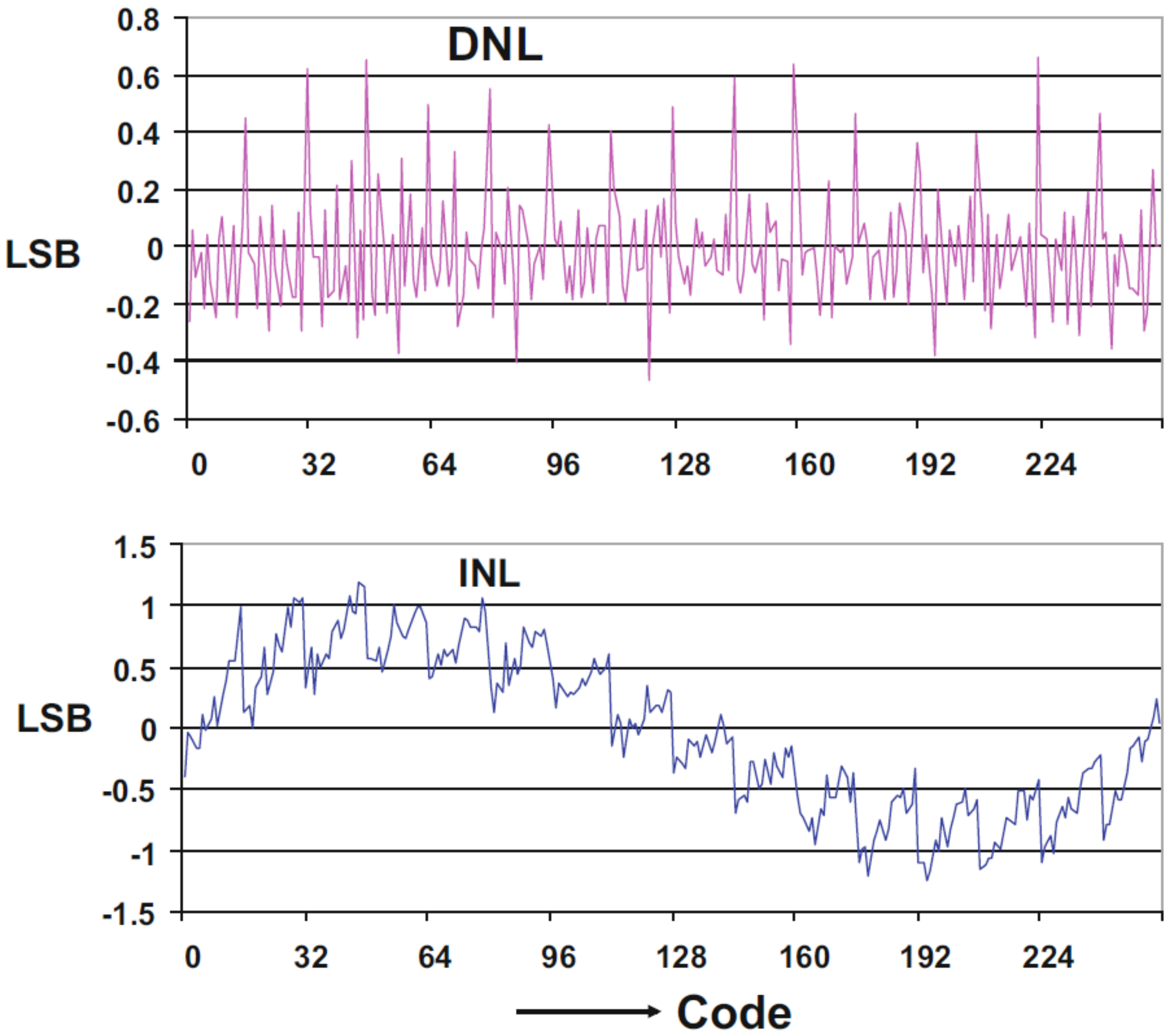




[M. Pelgrom, 2017]

ADC DNL/INL Example

- DNL/INL plotted against digital code not analog input
  - More about this next lecture



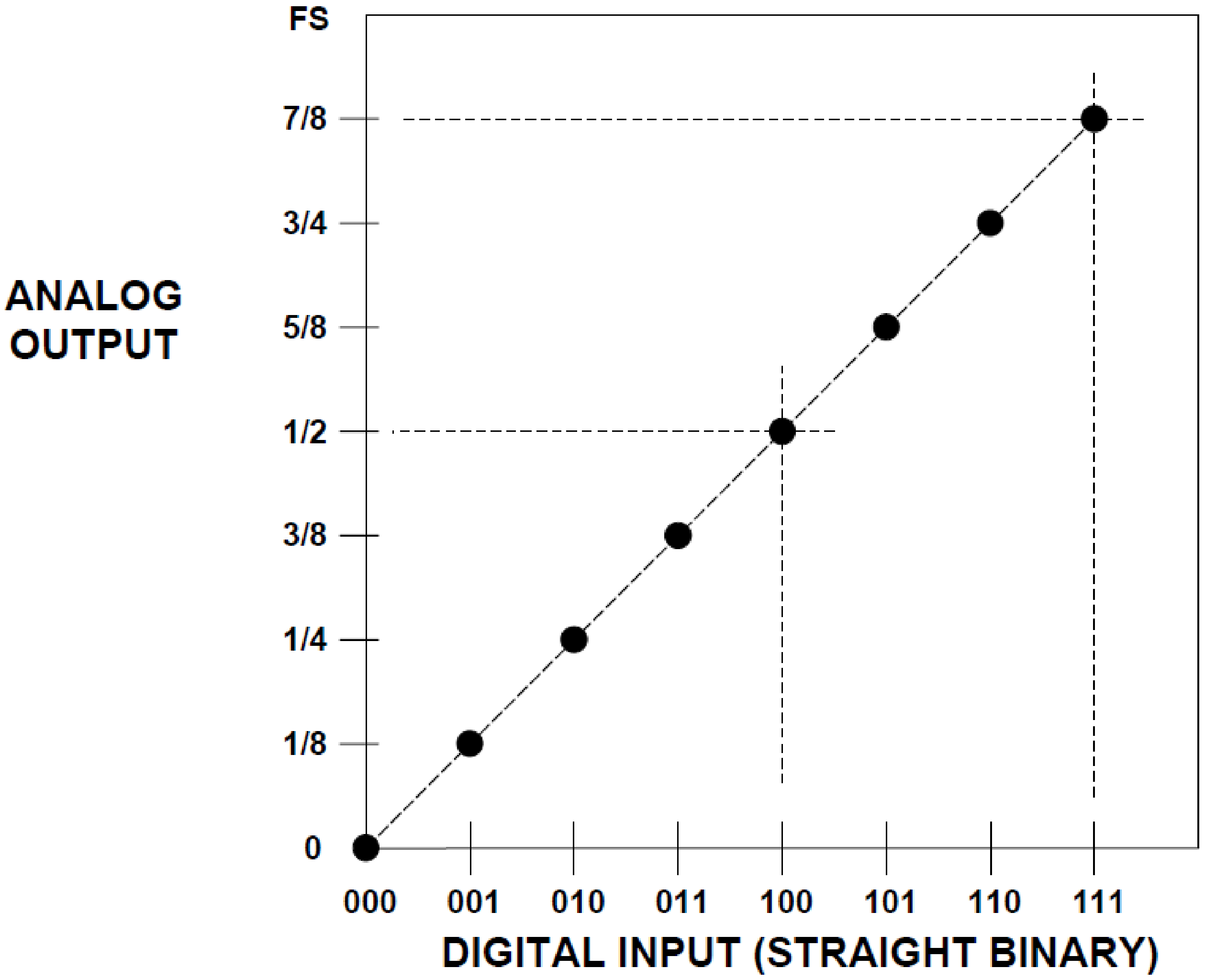
[M. Pelgrom, 2017]

References

- M. Pelgrom, Analog-to-Digital Conversion, Springer, 3rd ed., 2017.
- W. Kester, The Data Conversion Handbook, ADI, Newnes, 2005.
- B. Boser and H. Khorramabadi, EECS 247 (previously EECS 240), Berkeley.
- B. Murmann, EE 315, Stanford.
- Y. Chiu, EECT 7327, UTD.

Thank you!

Unipolar DAC Transfer Function



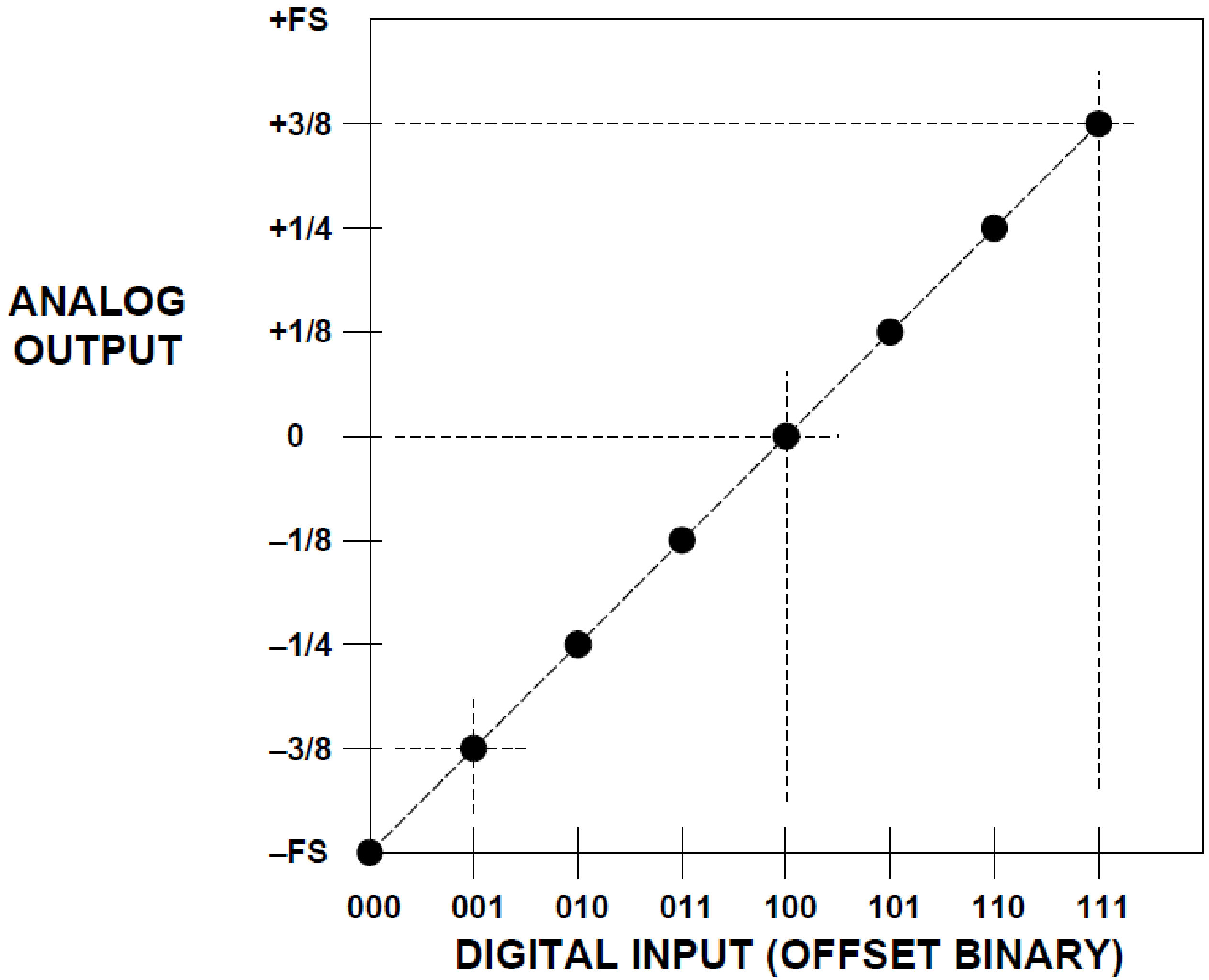
[W. Kester, 2005]

Unipolar Code Example

BASE 10 NUMBER	SCALE	+10V FS	BINARY	GRAY
+15	+FS – 1LSB = +15/16 FS	9.375	1 1 1 1	1 0 0 0
+14	+7/8 FS	8.750	1 1 1 0	1 0 0 1
+13	+13/16 FS	8.125	1 1 0 1	1 0 1 1
+12	+3/4 FS	7.500	1 1 0 0	1 0 1 0
+11	+11/16 FS	6.875	1 0 1 1	1 1 1 0
+10	+5/8 FS	6.250	1 0 1 0	1 1 1 1
+9	+9/16 FS	5.625	1 0 0 1	1 1 0 1
+8	+1/2 FS	5.000	1 0 0 0	1 1 0 0
+7	+7/16 FS	4.375	0 1 1 1	0 1 0 0
+6	+3/8 FS	3.750	0 1 1 0	0 1 0 1
+5	+5/16 FS	3.125	0 1 0 1	0 1 1 1
+4	+1/4 FS	2.500	0 1 0 0	0 1 1 0
+3	+3/16 FS	1.875	0 0 1 1	0 0 1 0
+2	+1/8 FS	1.250	0 0 1 0	0 0 1 1
+1	1LSB = +1/16 FS	0.625	0 0 0 1	0 0 0 1
0	0	0.000	0 0 0 0	0 0 0 0

[W. Kester, 2005]

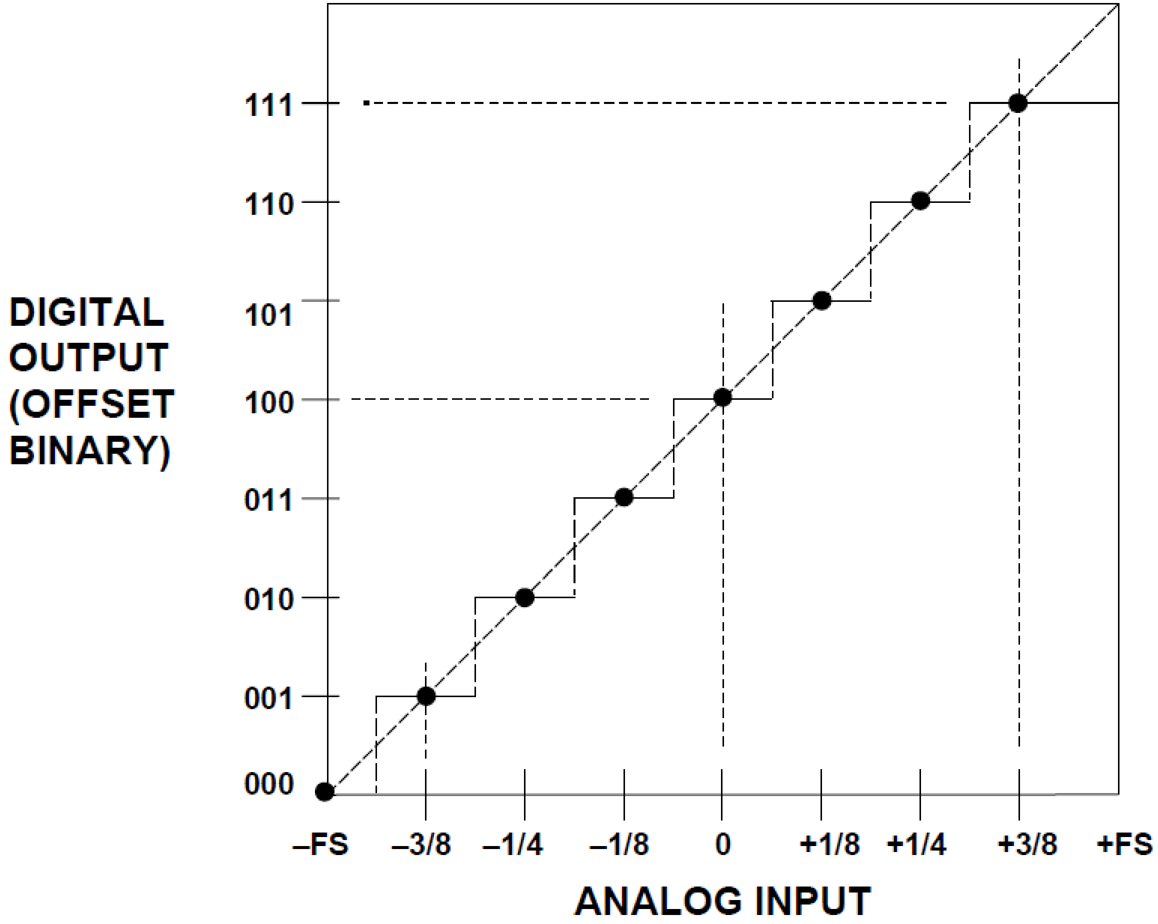
Bipolar DAC Transfer Function



[W. Kester, 2005]

Bipolar ADC Transfer Function

- Mid-tread quantizer: The stair-case is flat around zero input
- Mid-rise quantizer: The stair-case rises at zero.



[W. Kester, 2005]

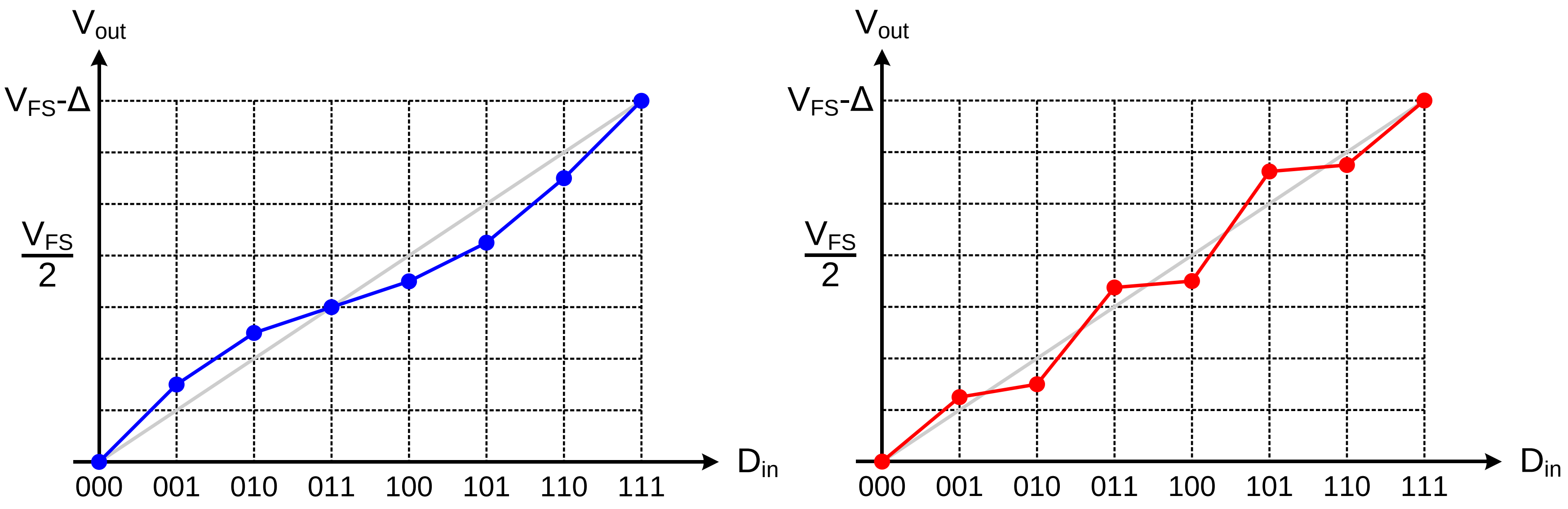
Bipolar Code Example

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

[W. Kester, 2005]

DNL vs INL Errors

- DNL measures the uniformity of quantization steps, or incremental (local) nonlinearity
  - Small input signals are sensitive to DNL.
- INL measures the overall, or cumulative (global) nonlinearity
  - Large input signals are often sensitive to both INL and DNL.



Smooth ccs Noisy ccs