

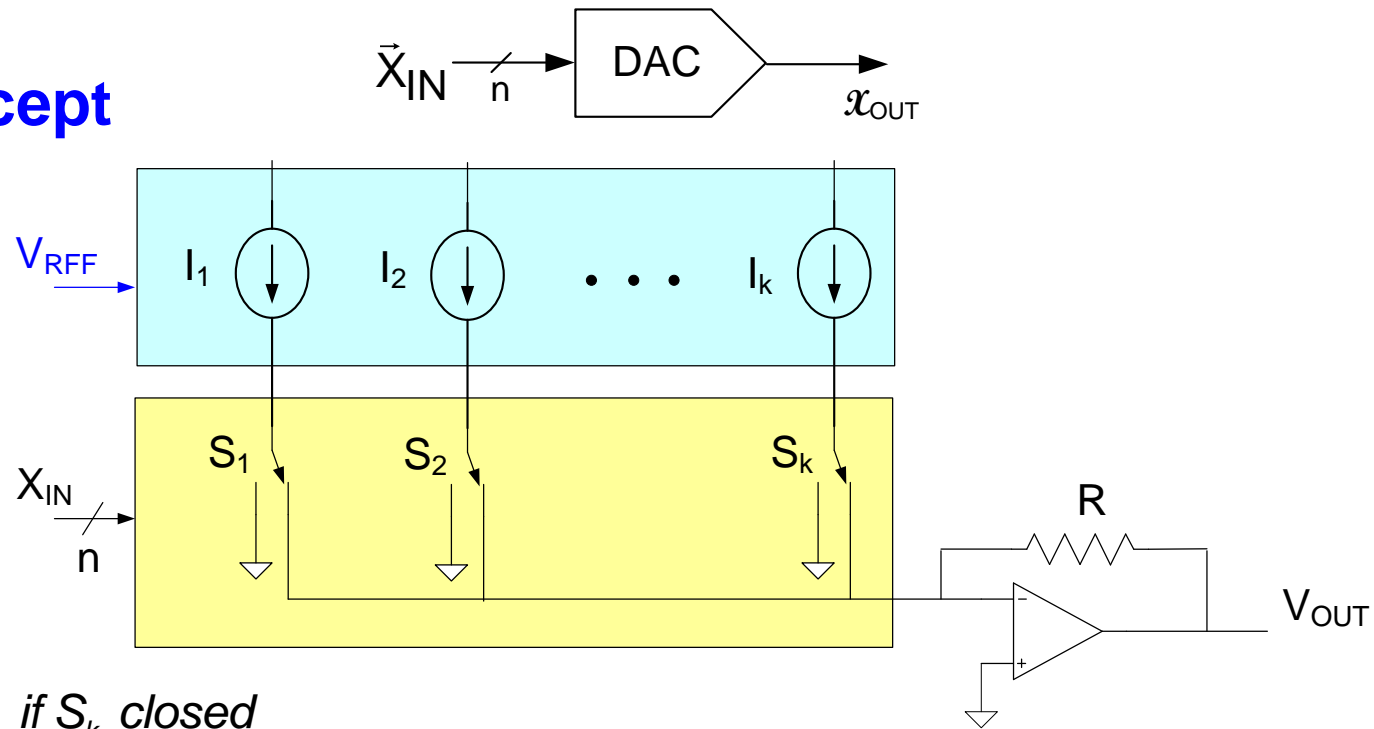
EE 505

Lecture 16

Current Steering DACs

Current Steering DACs

Concept

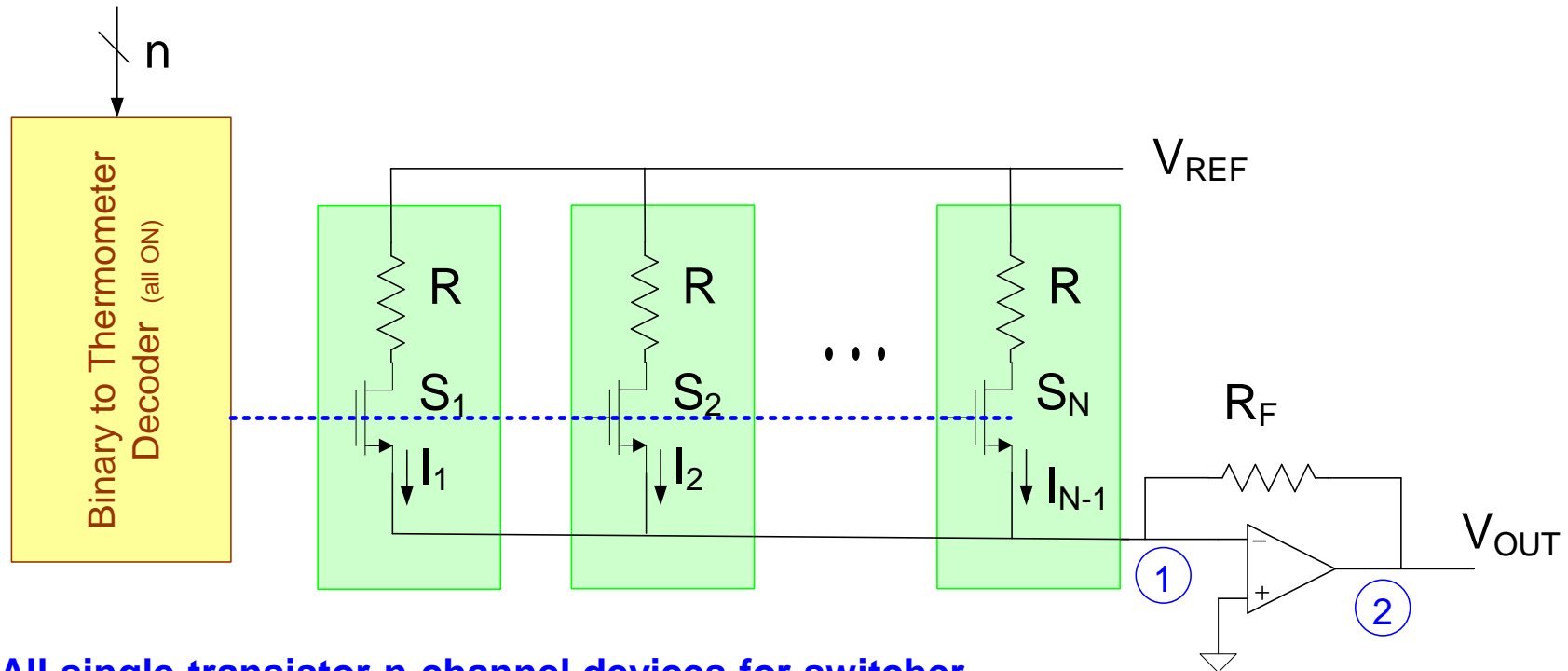


$$d_k = \begin{cases} 1 & \text{if } S_k \text{ closed} \\ 0 & \text{if } S_k \text{ open} \end{cases}$$

$$V_{OUT} = \left[\sum_{i=1}^k d_i I_i \right] (-R)$$

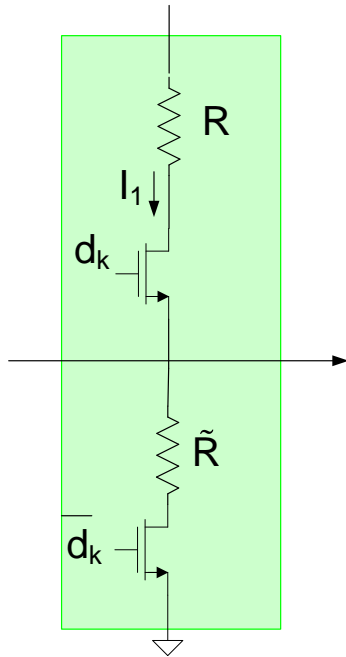
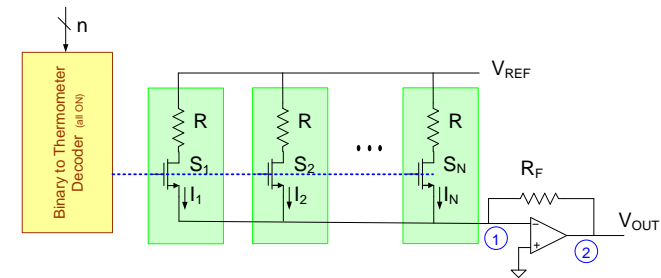
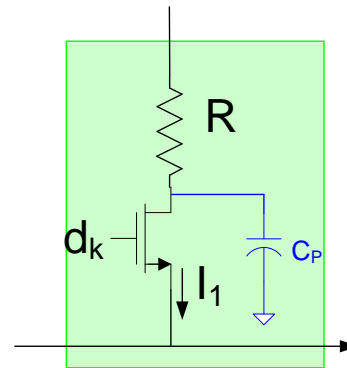
- Current sources usually unary or binary-bundled unary
- Termed bottom-plate switching
- Can eliminate resistors from DAC core
- Op Amp and resistor R can be external
- Can use all same type of switches
- Switch impedance not critical nor is switch matching
- Popular MDAC approach

Current Steering DACs



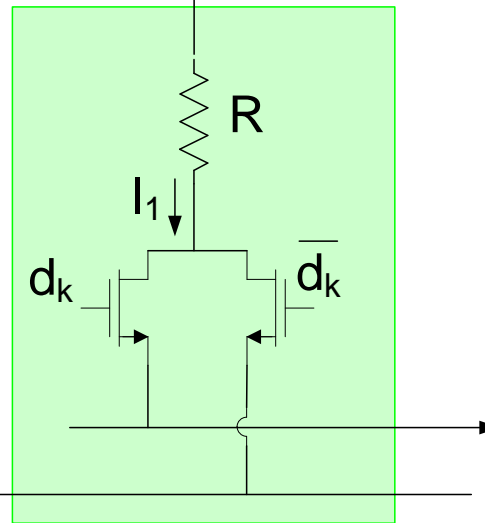
- All single-transistor n-channel devices for switcher
- Unary R :switch cells
- Parasitic capacitances on drain nodes of switches cause transient settling delays
- $R+R_{sw}$ is nonlinear (so nonlinear relationship between I_k and V_{REF}) but does not affect linearity of DAC
- Resistor and switch impedance matching important
- Previous code dependent transient (parasitic capacitances on drains of switches)

Current Steering DACs



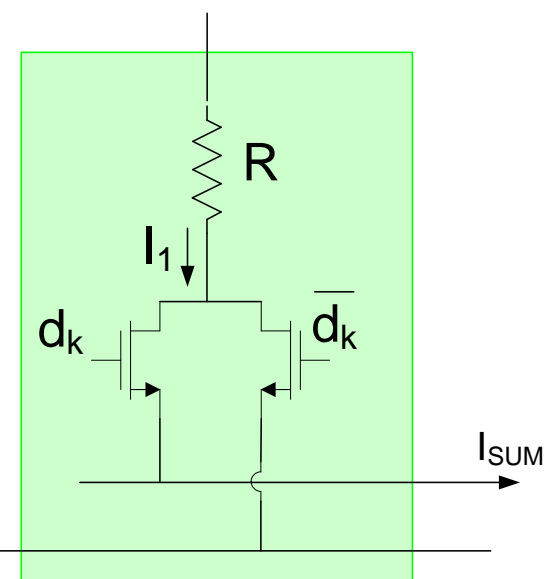
β Compensation

(Actually static β comp)
(keeps β at approximately $\frac{1}{2}$ for all codes,
reduces size of compensation capacitor))



C_p Compensation

(to keep C_p from charging to V_{REF} when off)

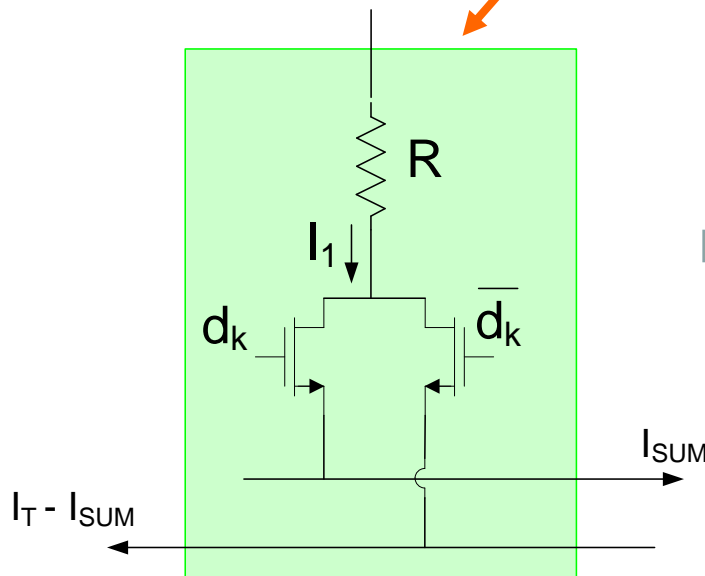
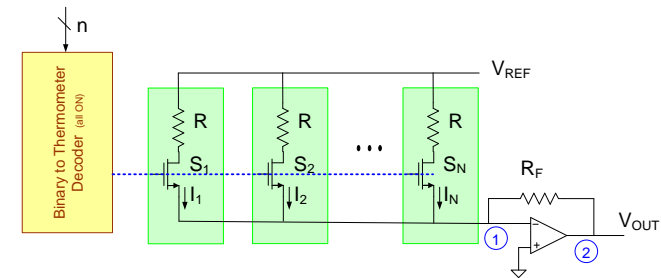
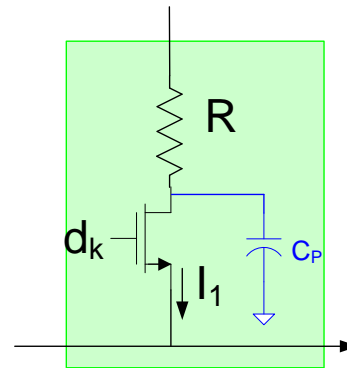


Differential Output
(inherent C_p compensation)

$I_T - I_{SUM}$

Review from Last Lecture

Current Steering DACs

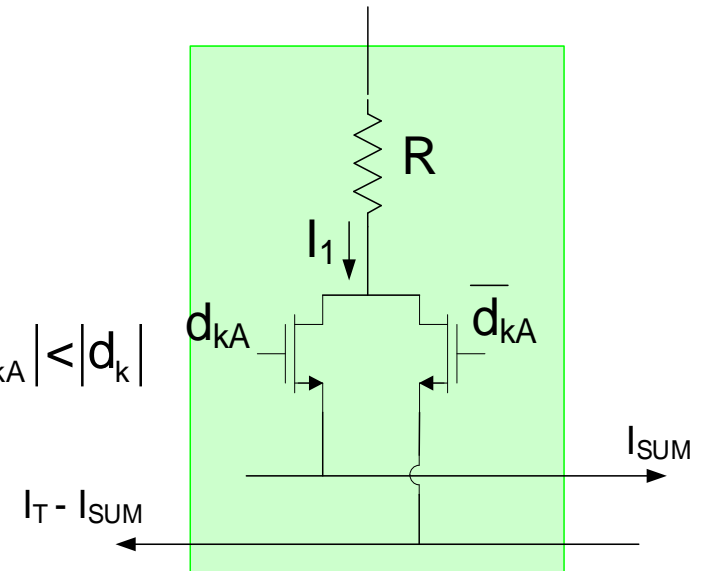


Differential Output

(inherent C_P compensation)



$$|d_{kA}| < |d_k|$$

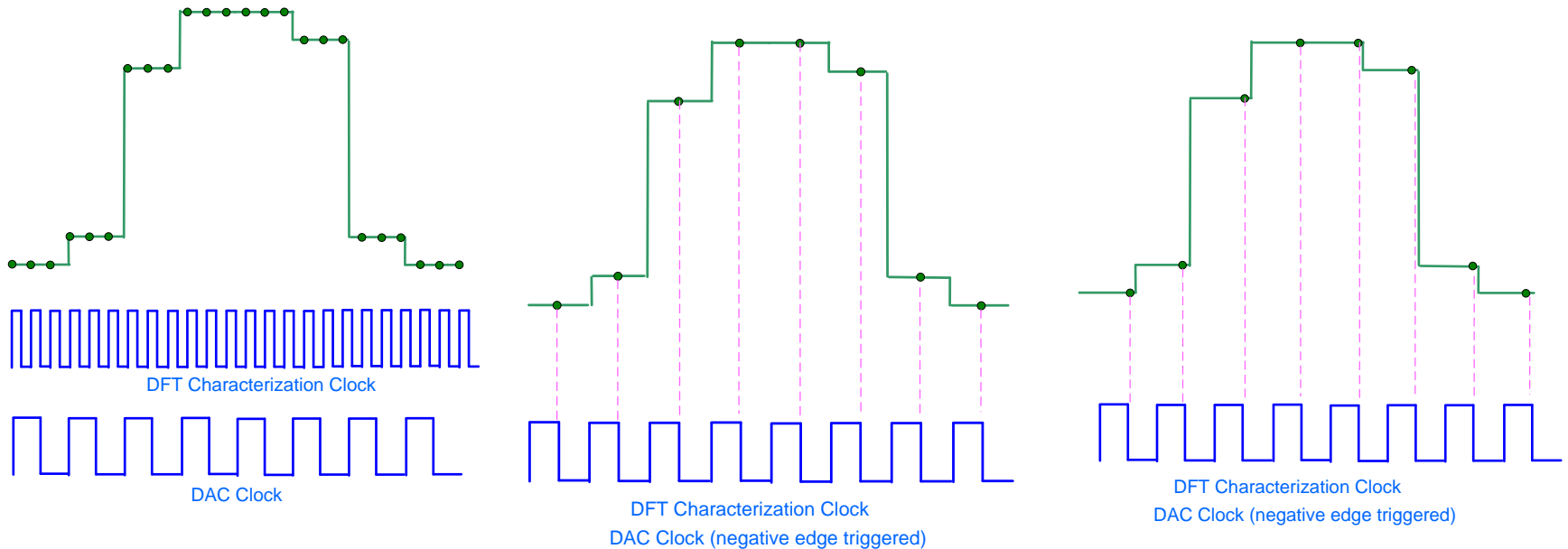


Differential Output

correction

- Steer current rather than switch current
- ~~Switch-pair becomes analog differential pair~~
- Signal swing needs to be just large enough to move current from left side to right side

Spectral Characterization of DACs (a measure of linearity)



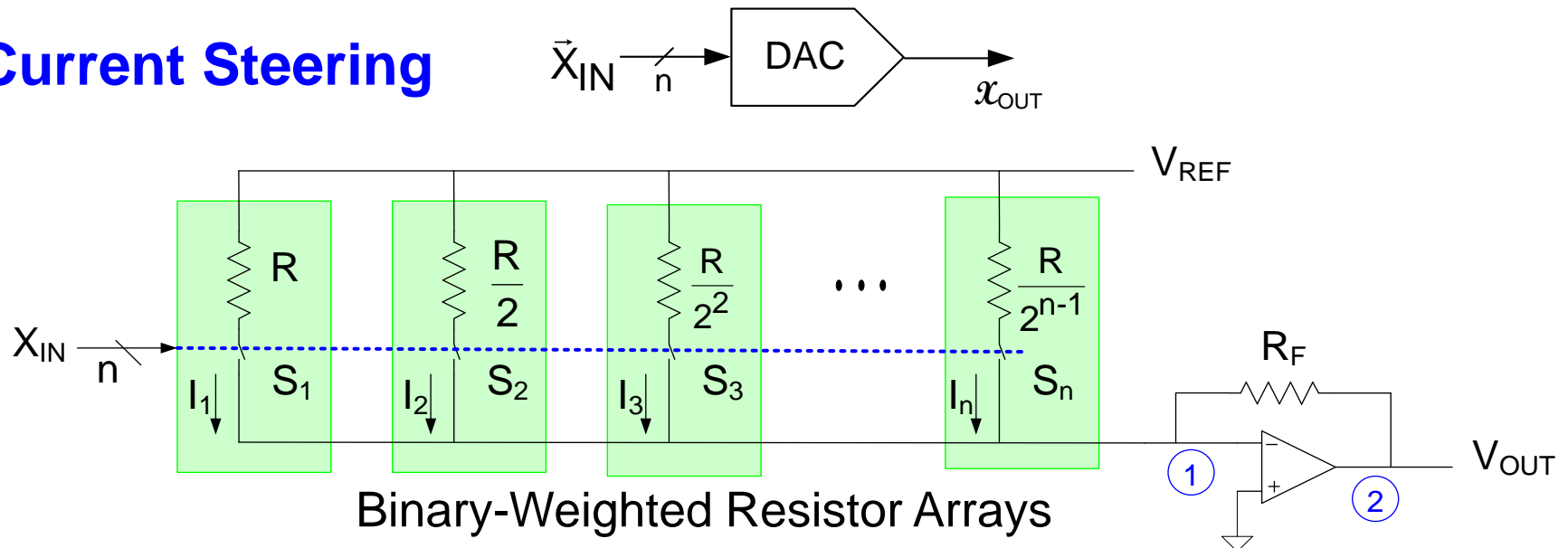
Assume Nyquist sampling rate is satisfied

Does it make a difference?

Yes ! But depends on application which is useful

Current Steering DACs

Current Steering



- Unary cells bundled to implement binary cells (so no net change in total number of cells)
- Need for decoder eliminated !
- DNL may be a major problem
- INL performance about same as thermometer coded if same unit resistors used
- Sizing and layout of switches is critical
- Large total resistance

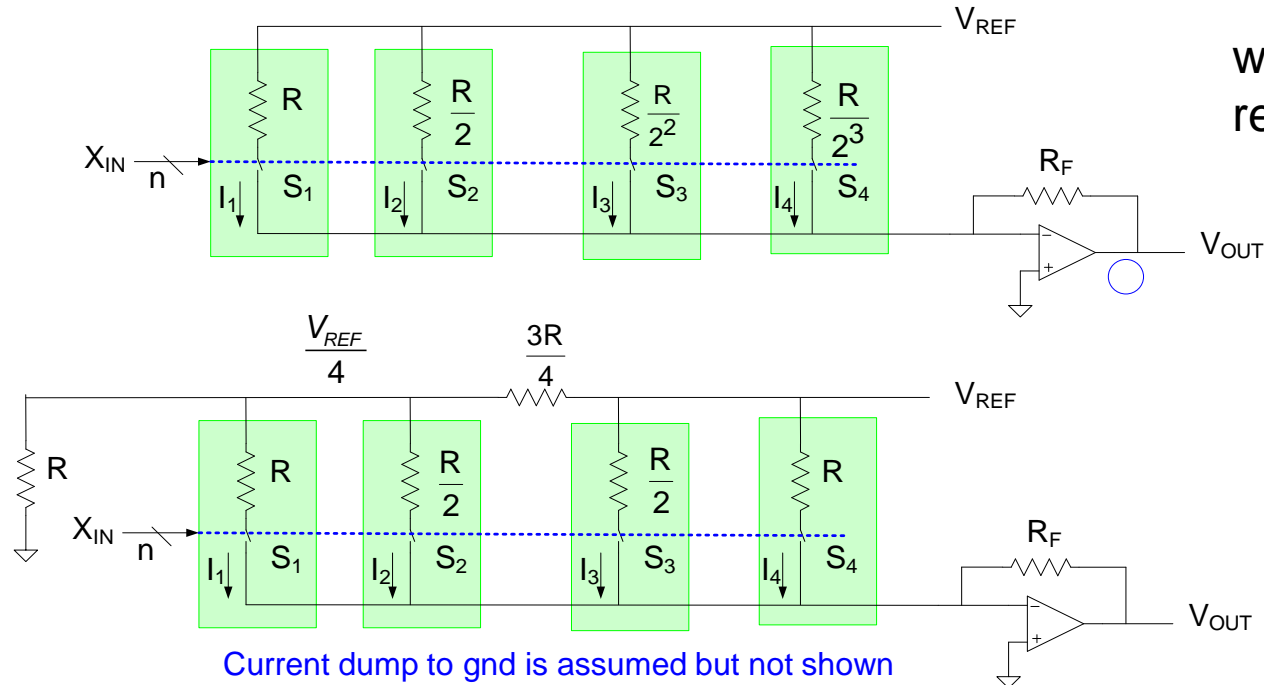
Observe thermometer coding and binary weighted both offer some major advantages and some major limitations

Large DNL dominantly occurs at mid-code and due to ALL resistors switching together
Can unary cell bundling be regrouped to reduce DNL

Current Steering DACs

Reduced Resistance Structure

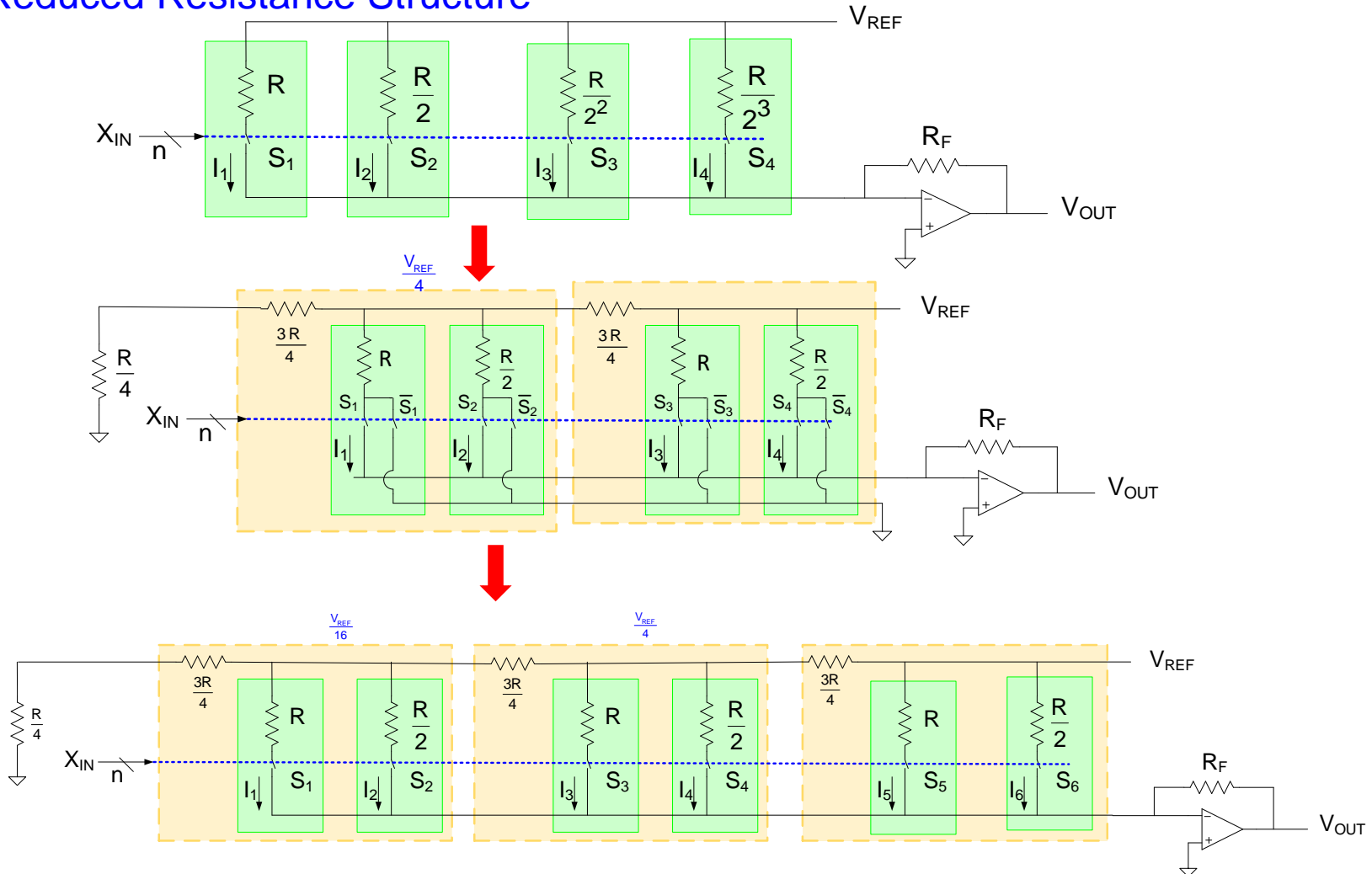
(actually concerned about number of unary cells, not total ohmic resistance)



- Significant reduction in resistance possible
- Can be inserted at more than one place to further reduce resistance values
- Introduces a “floating node” but voltage on floating node does not change (if current is steered)
- Current drawn from V_{REF} does not change with code
- Dummy switching can be used for β compensation
- If inserted at each intersection becomes R-2R structure

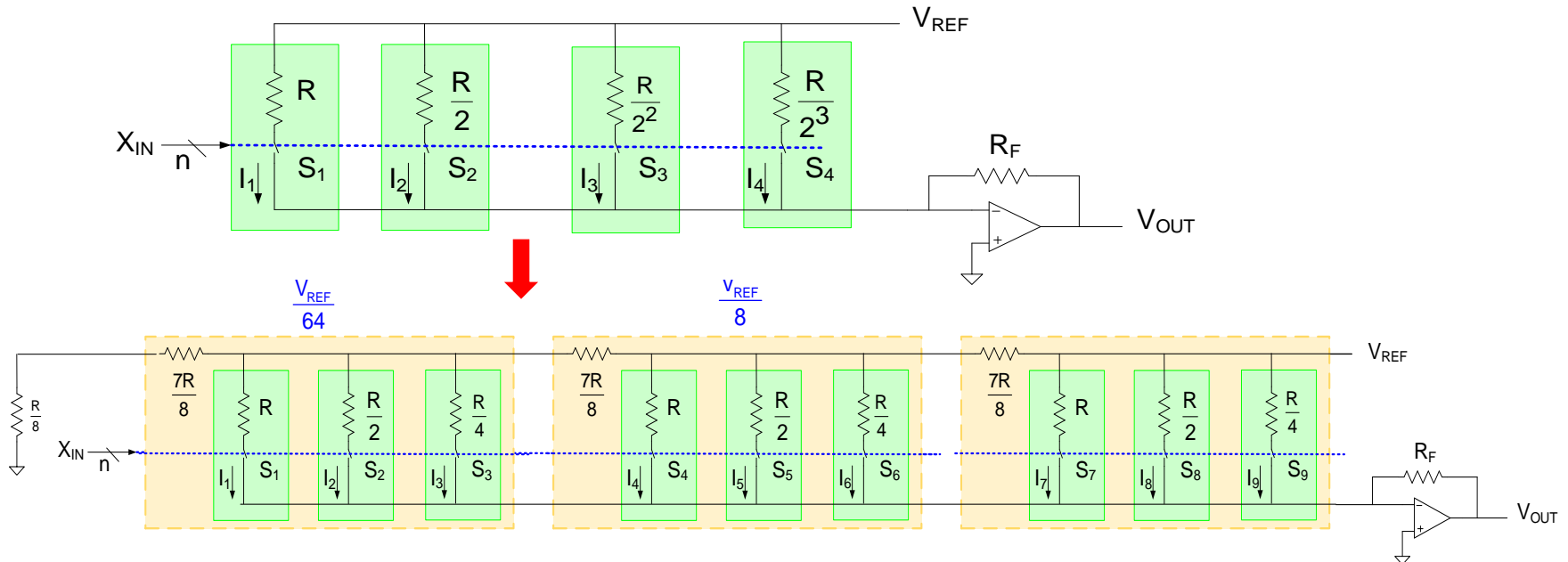
Current Steering DACs

Reduced Resistance Structure

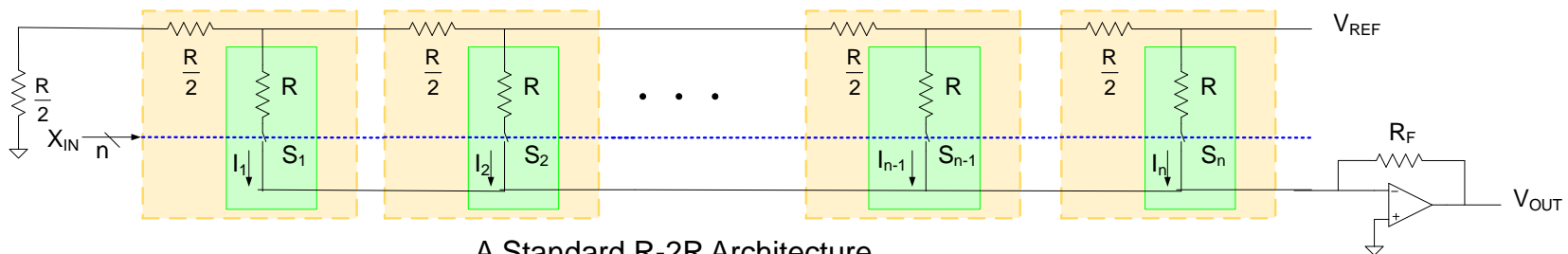


Current Steering DACs

Reduced Resistance Structure



OR

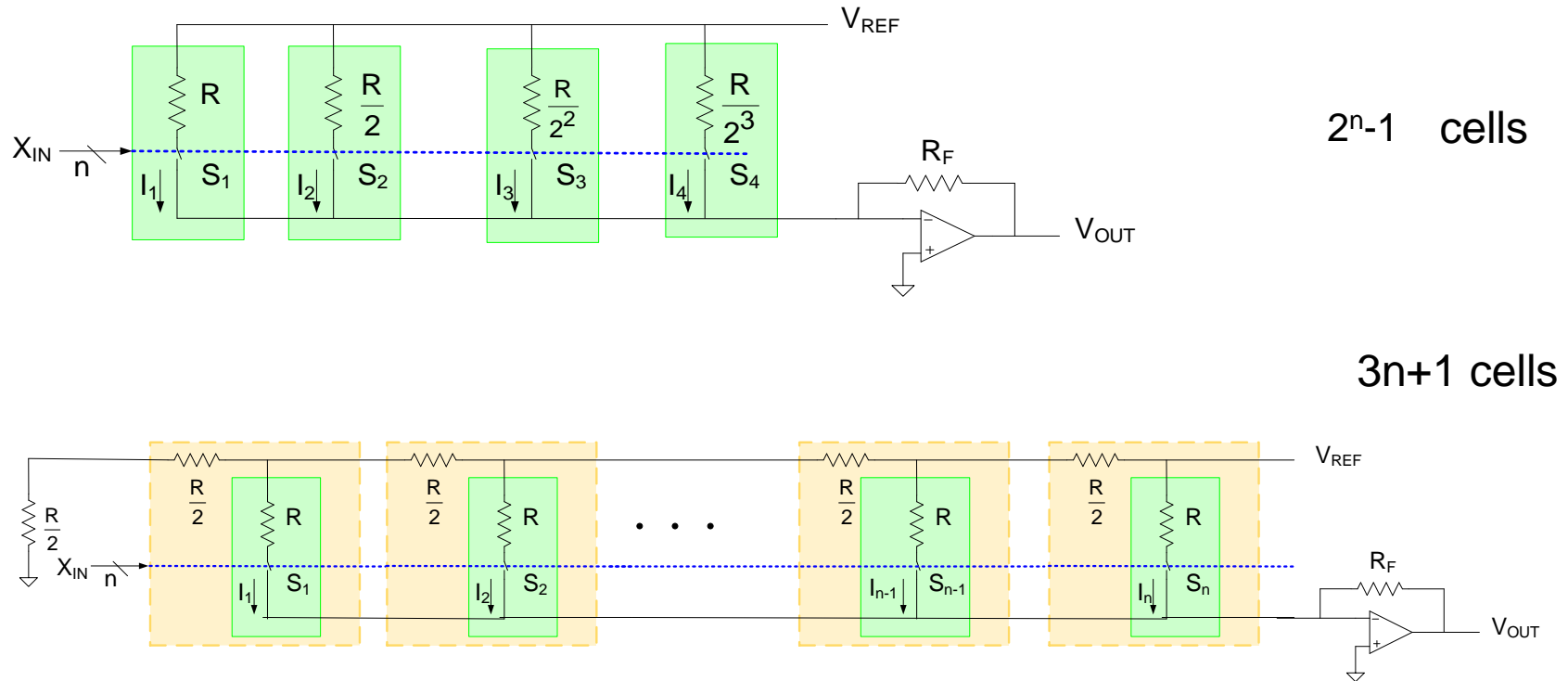


A Standard R-2R Architecture

with unary $R/2$ cells, required $3n+1$ cells compared to 2^n-1 cells for binary bundled array

Current Steering DACs

Reduced Resistance Structure



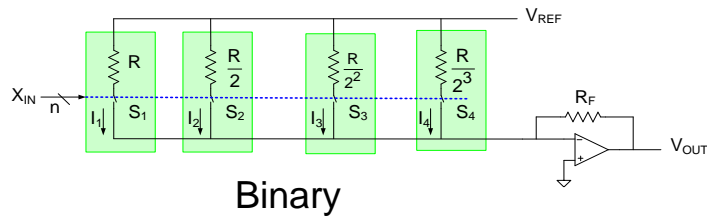
Is the R-2R structure smaller ?

Does the R-2R structure perform better?

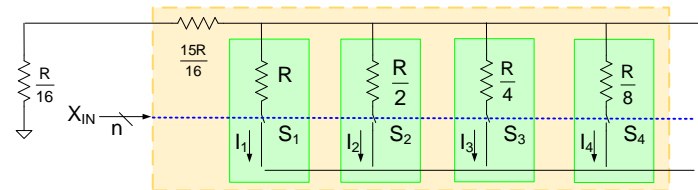
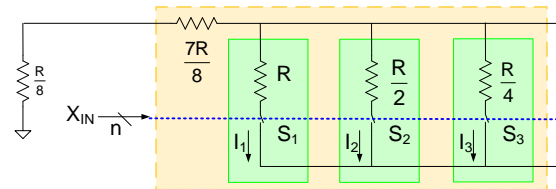
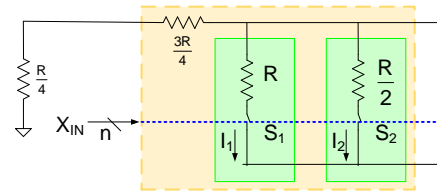
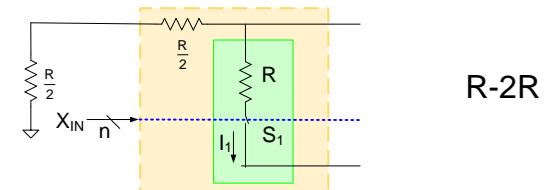
What metric should be used for comparing performance?

Current Steering DACs

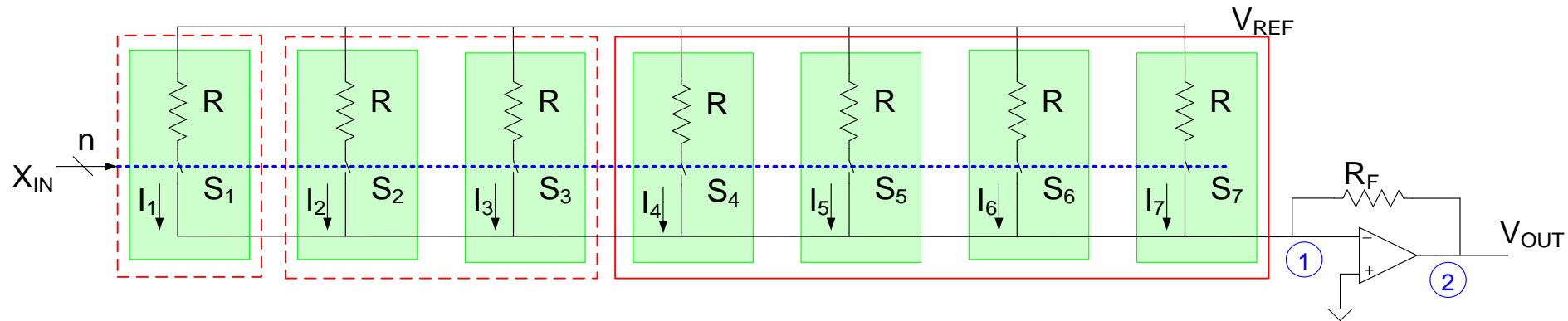
Reduced Resistance Structure



Slice Grouping Options with Series Resistors



Current Steering DACs



Binary-Weighted Resistor Arrays

Actual layout of resistors is very important

Performance of Thermometer Coded vs Binary Coded DACs

Conventional Wisdom:

- Thermometer-coded structures have inherently small DNL
- Binary coded structures can have large DNL
- INL of both structures is comparable for same total area

Comparison of Thermometer Coded and Binary Coded DACs

- Will consider String DAC but nearly same results for current-steering DACs
- Current Steering DAC will generate current from resistors
- For Binary Coded DAC, MSB: 2^{n-1} unary cells in parallel LSB: single unary cell

- Consider unit resistor of area $2\mu\text{m}^2$ (shape not critical)
- Matching parameter $A_R=0.02\mu\text{m}$
- $R_N=1\text{K}$ (not critical)

$$\sigma_R = \frac{R_N}{\sqrt{A}} A_{pR}$$

- Assume Gaussian Distribution of Resistors

Comparison of Thermometer Coded and Binary Coded DACs

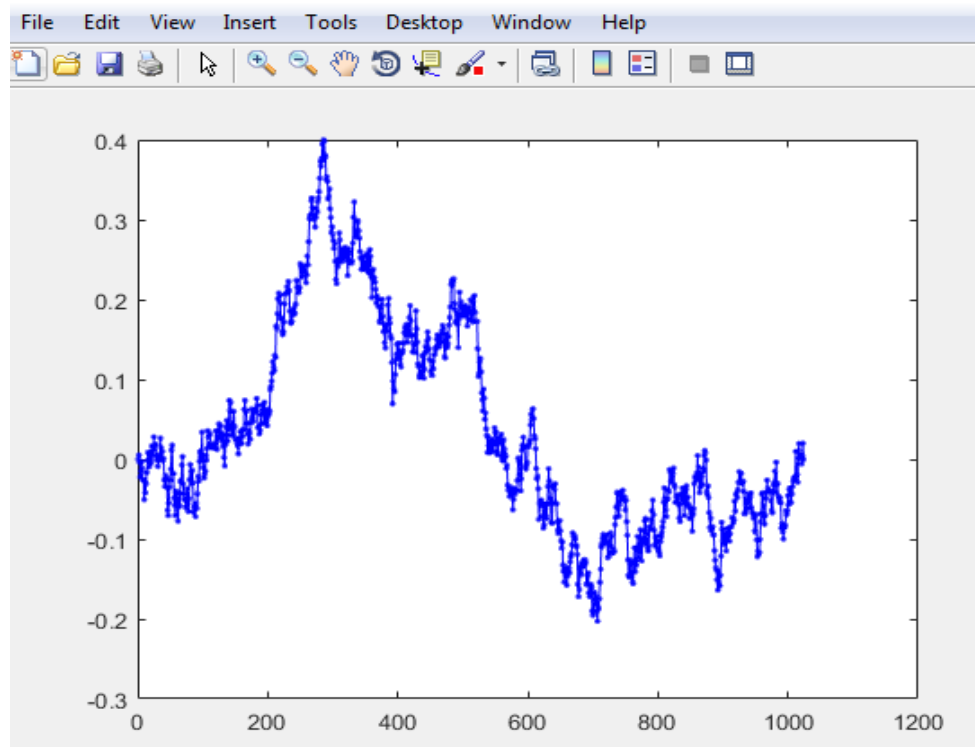
Example: $n=10$
String DAC



$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Resistor Sigma= $14.14\ \Omega$

Simulation 1: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

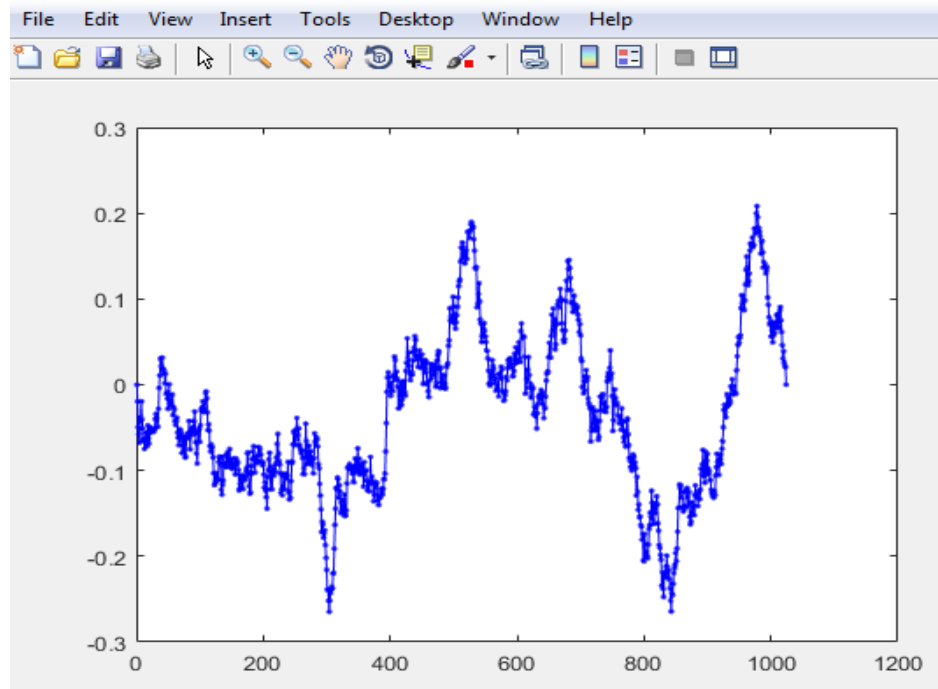
Example: $n=10$
String DAC



$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Resistor Sigma= $14.14\ \Omega$

Simulation 2: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

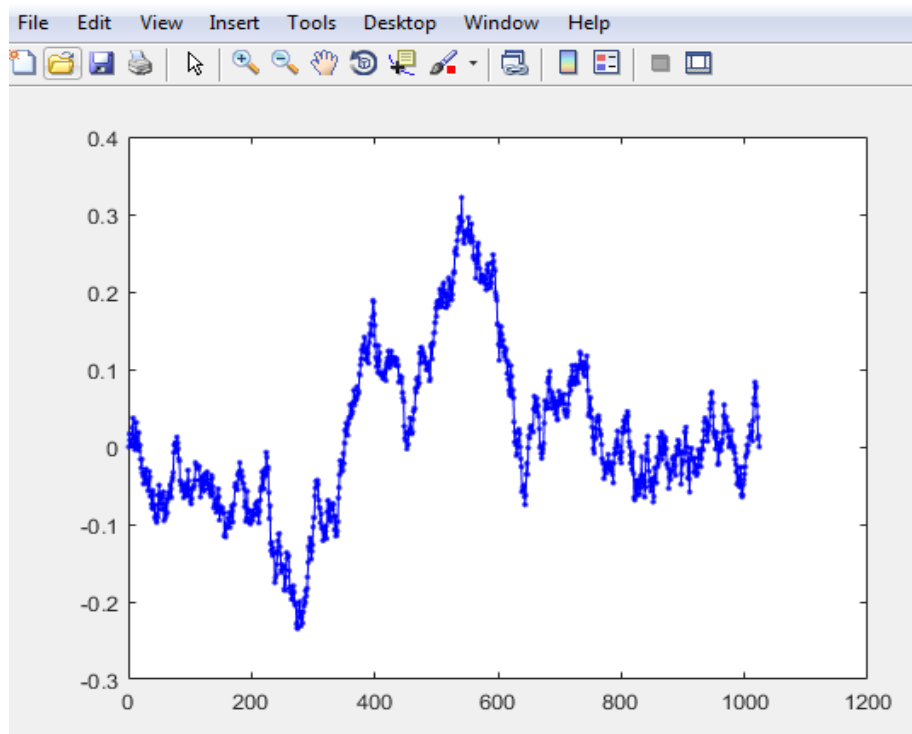
String DAC



$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Resistor Sigma= $14.14\ \Omega$

Simulation 3: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

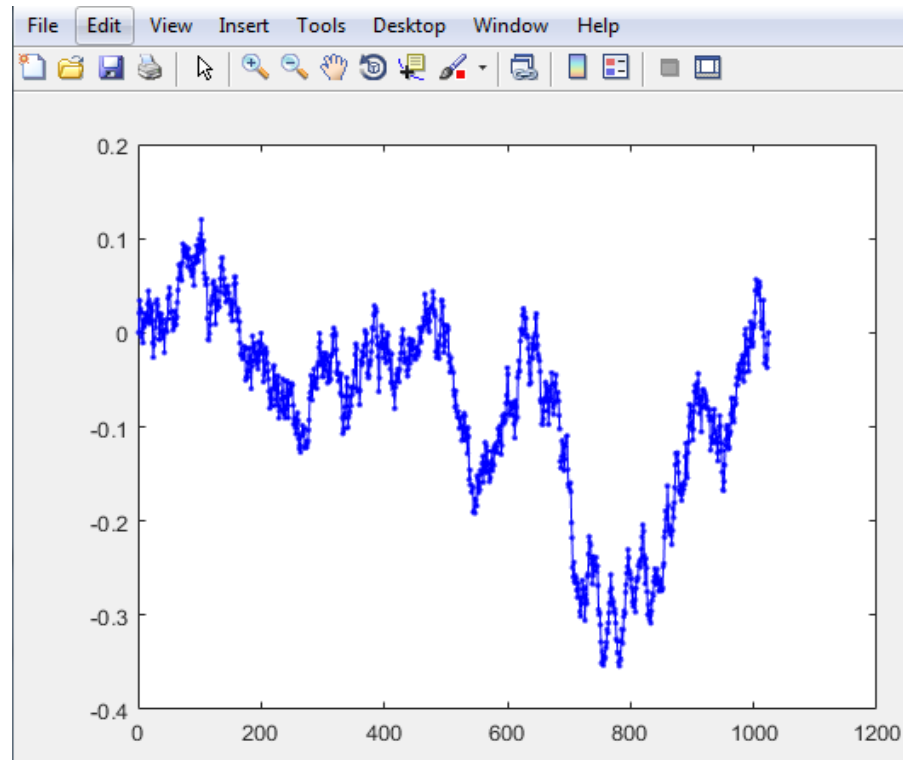
Example: $n=10$
String DAC



$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Resistor Sigma= $14.14\ \Omega$

Simulation 4: INL_k



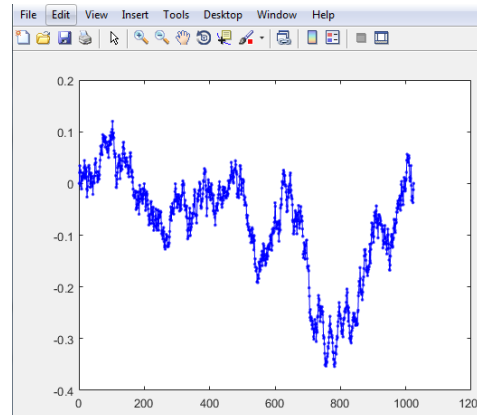
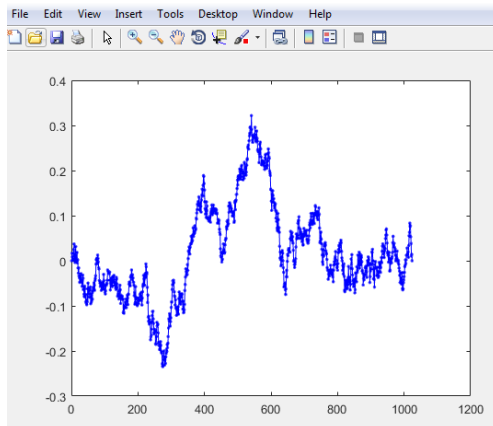
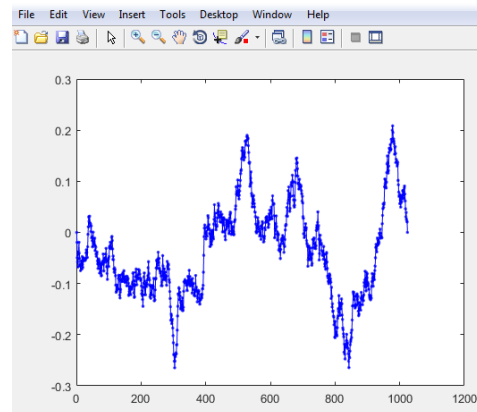
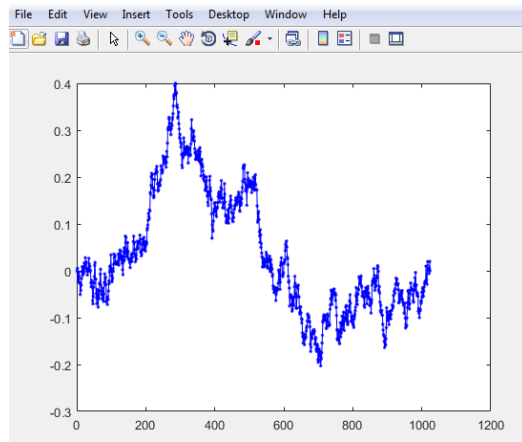
Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$
String DAC

$$A_R = 0.02 \mu\text{m}$$
$$R_N = 1\text{K}$$



Resistor Sigma = 14.14Ω



Low DNL and random walk nature should be apparent

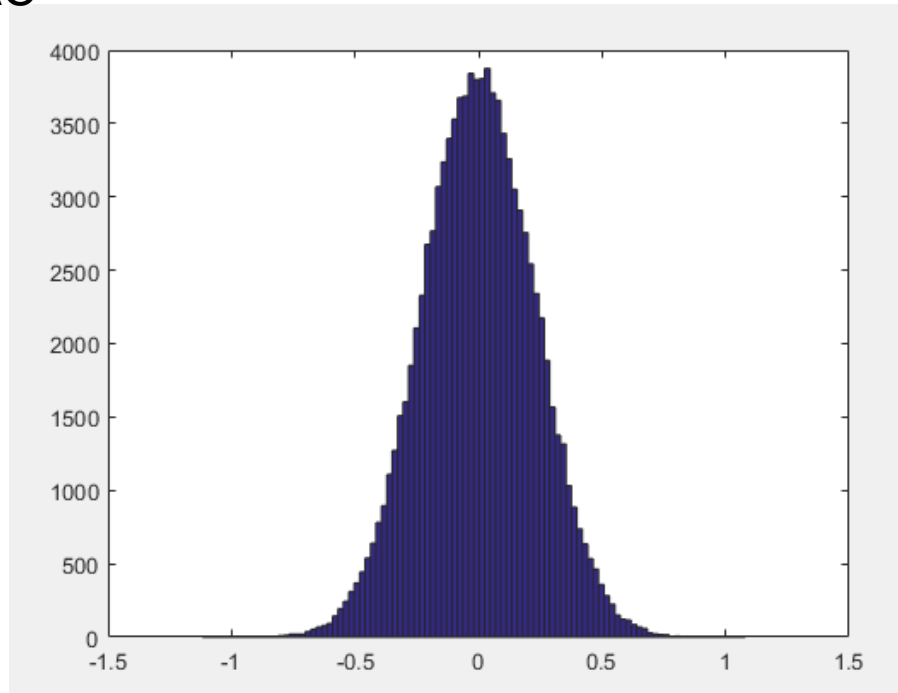
Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$
String DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma= $14.14\ \Omega$



INLkmax_mean = $-2.11116\text{e-}05$

INLkmax_sigma = 0.226783

Histogram of INL_{kmax} from 100,000 runs

Appears to be Gaussian

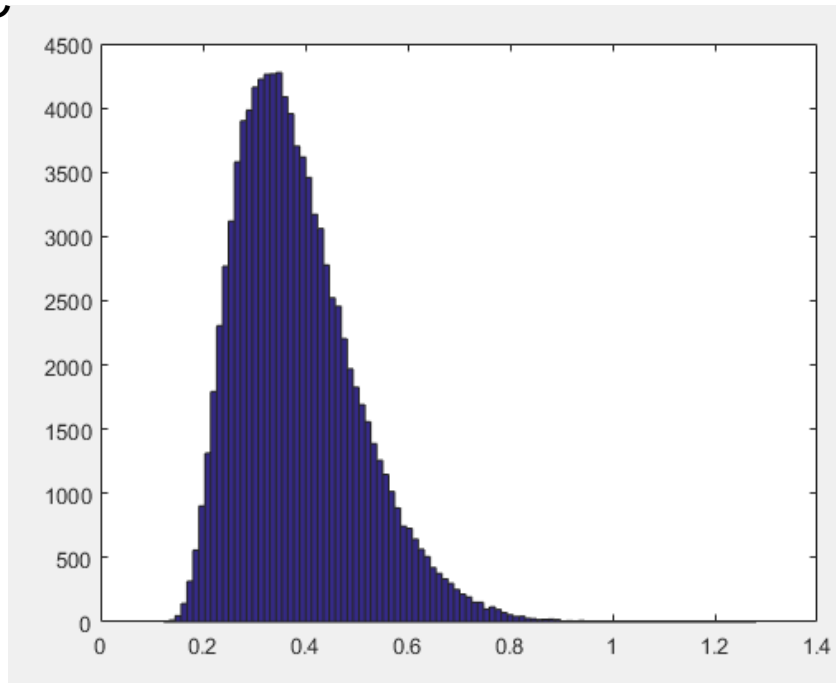
Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$
String DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma= $14.14\ \Omega$



INLmean = 0.384382
INLsigma = 0.117732

Histogram of INL from 100,000 runs

Not Gaussian

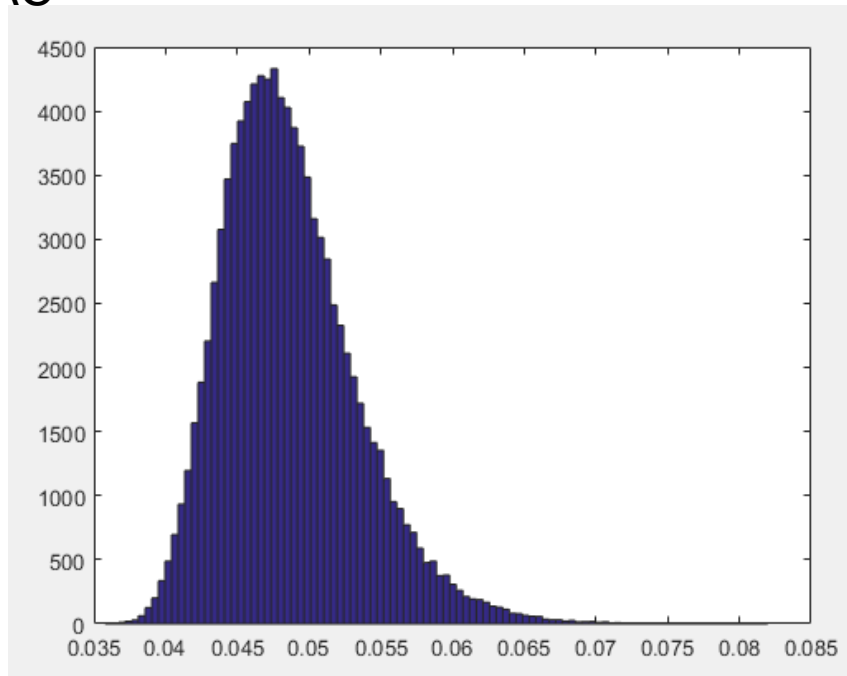
Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$
String DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma = $14.14\ \Omega$



DNLmean = 0.0486494
DNLsigma = 0.00471025

Histogram of DNL from 100,000 runs

Not Gaussian but both mean and sigma are very small

Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

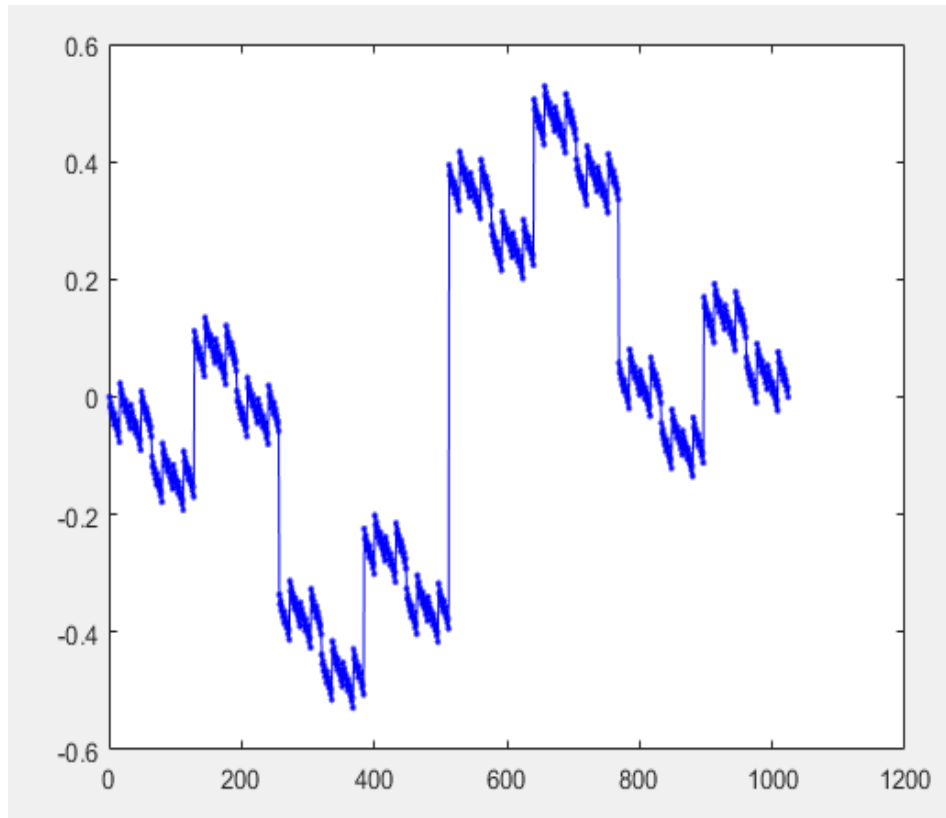


Resistor Sigma= 14.14 Ω

Binary DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Simulation 1: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

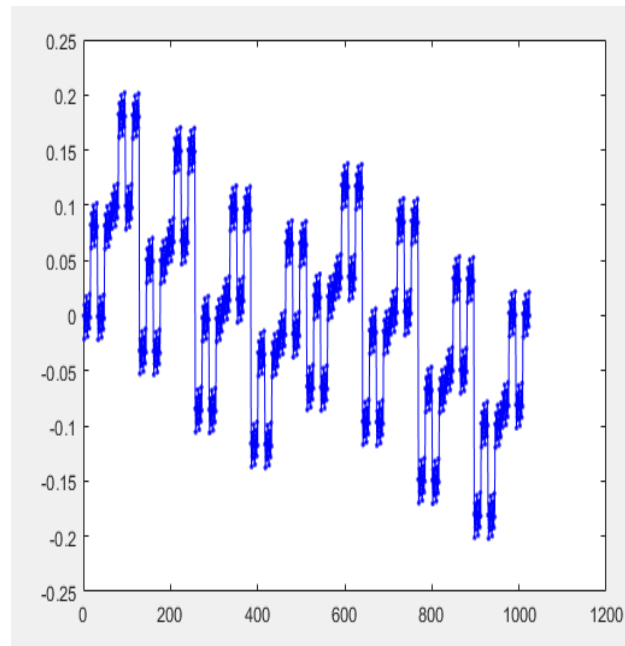
Binary DAC

Simulation 2: INL_k



$A_R=0.02\mu m$
 $R_N=1K$

Resistor Sigma= 14.14Ω



Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

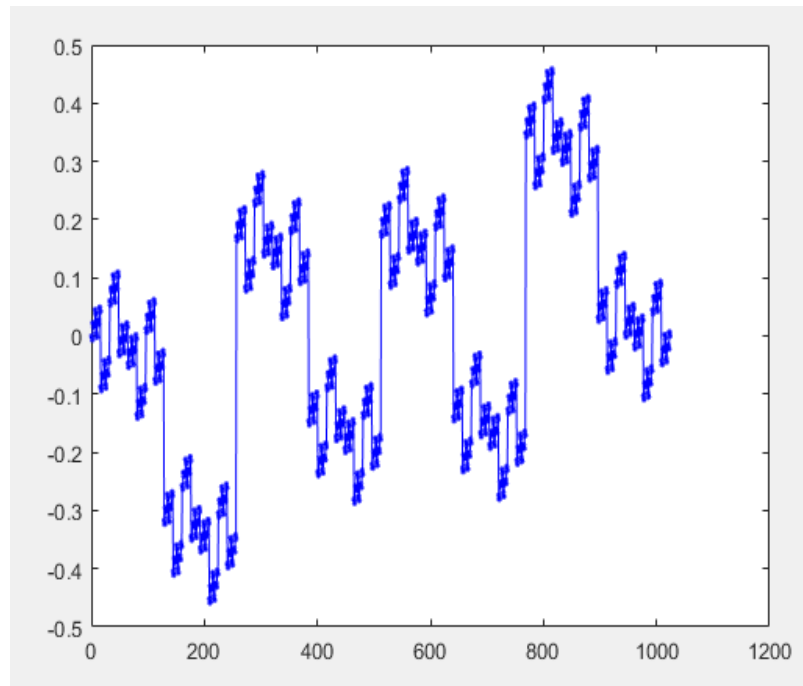


Resistor Sigma= 14.14Ω

Binary DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Simulation 3: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

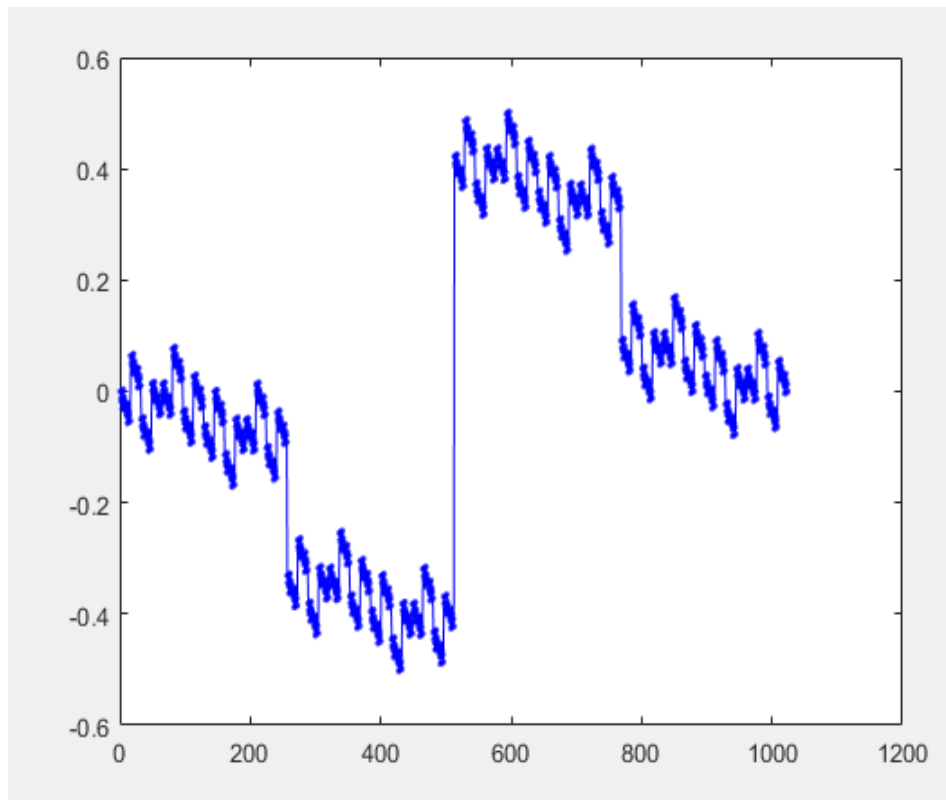


Resistor Sigma= 14.14 Ω

Binary DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Simulation 4: INL_k



Comparison of Thermometer Coded and Binary Coded DACs

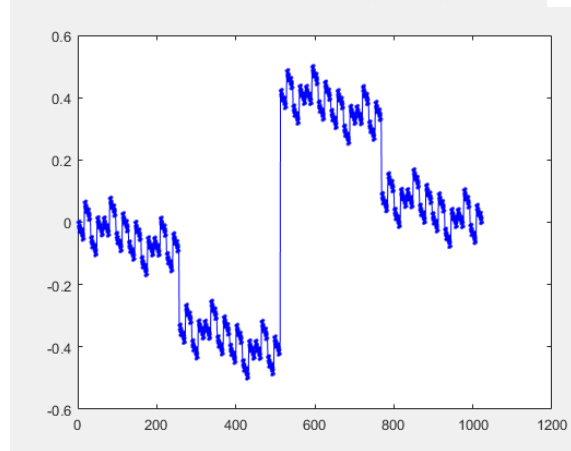
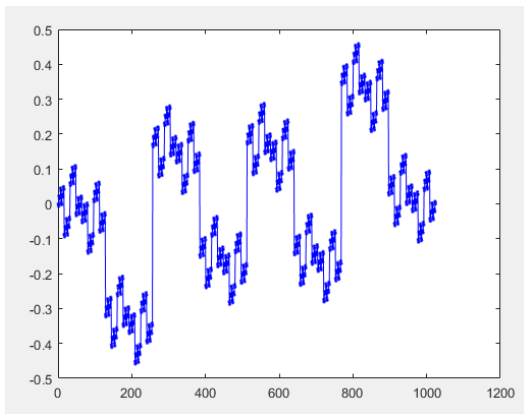
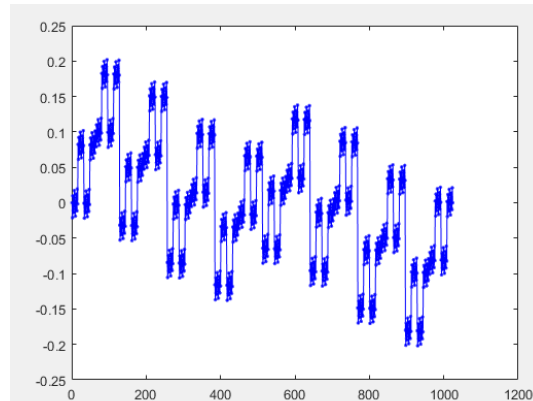
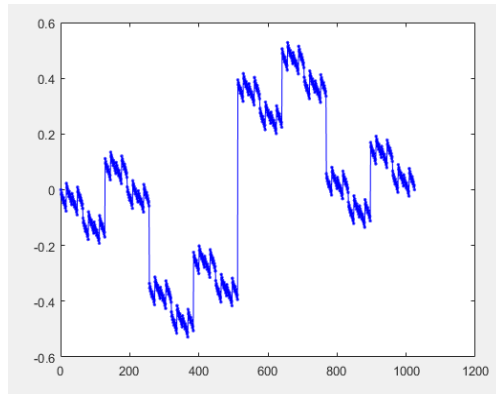
Example: $n=10$



Resistor Sigma= 14.14 Ω

Binary DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Large DNL bit INL does not appear to be much different than for string DAC

Comparison of Thermometer Coded and Binary Coded DACs

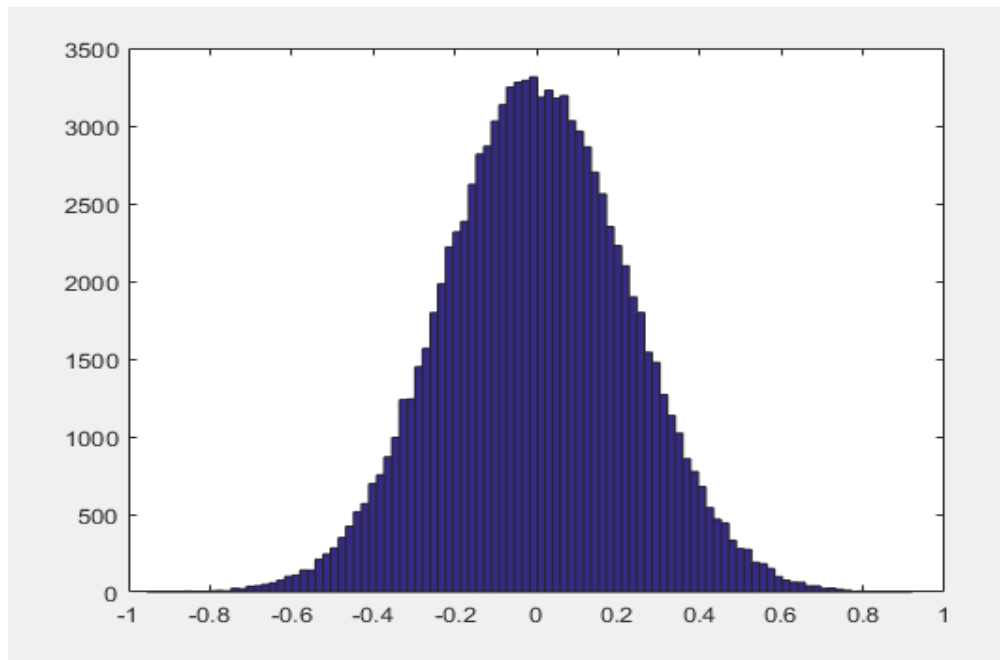
Example: $n=10$

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma = $14.14\ \Omega$

Binary DAC



INLkmax_mean = $-.00526008$

INLkmax_sigma = 0.23196

Histogram of INL_{kmax} from 100,000 runs

Appears to be Gaussian

Comparison of Thermometer Coded and Binary Coded DACs

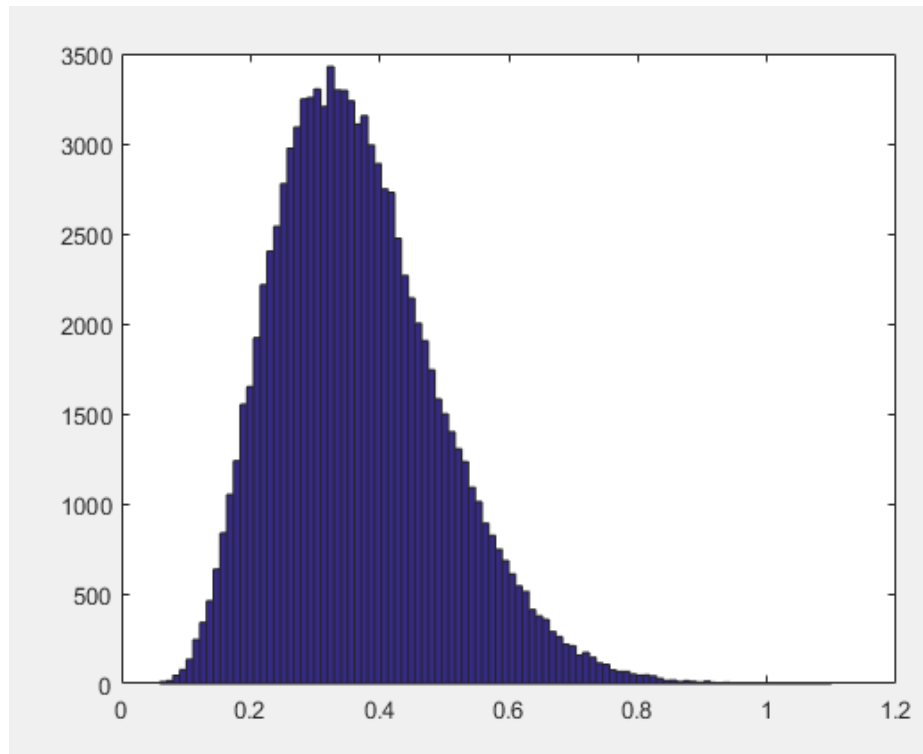
Example: $n=10$

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma= $14.14\ \Omega$

Binary DAC



Histogram of INL from 100,000 runs

Not Gaussian

INLmean = 0.368441
INLsigma = 0.126133

Comparison of Thermometer Coded and Binary Coded DACs

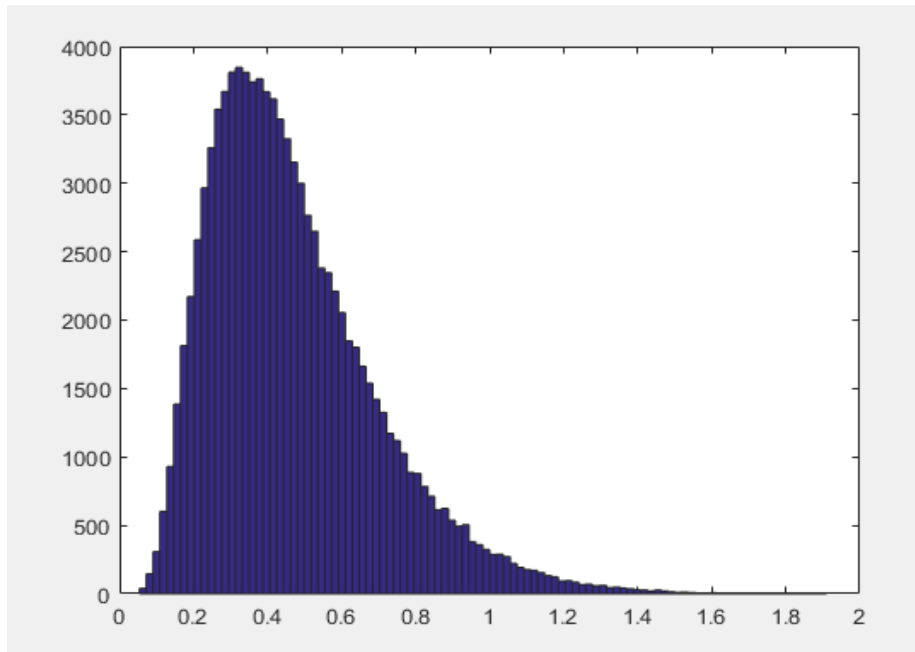
Example: $n=10$

Binary DAC

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma= $14.14\ \Omega$



DNLmean = 0.46978

DNLsigma = 0.227768

Histogram of DNL from 100,000 runs

Not Gaussian and both mean and sigma are not small

Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

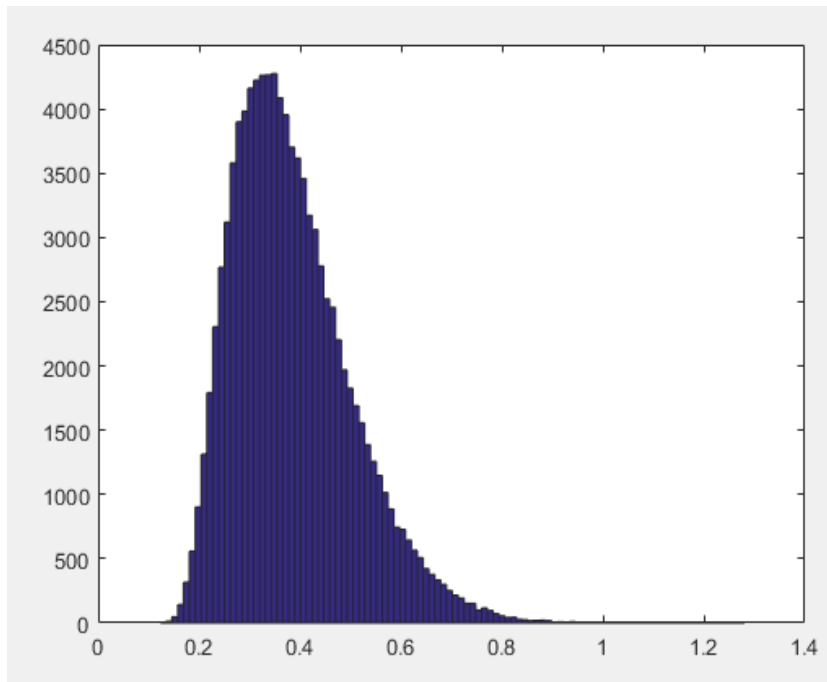
$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



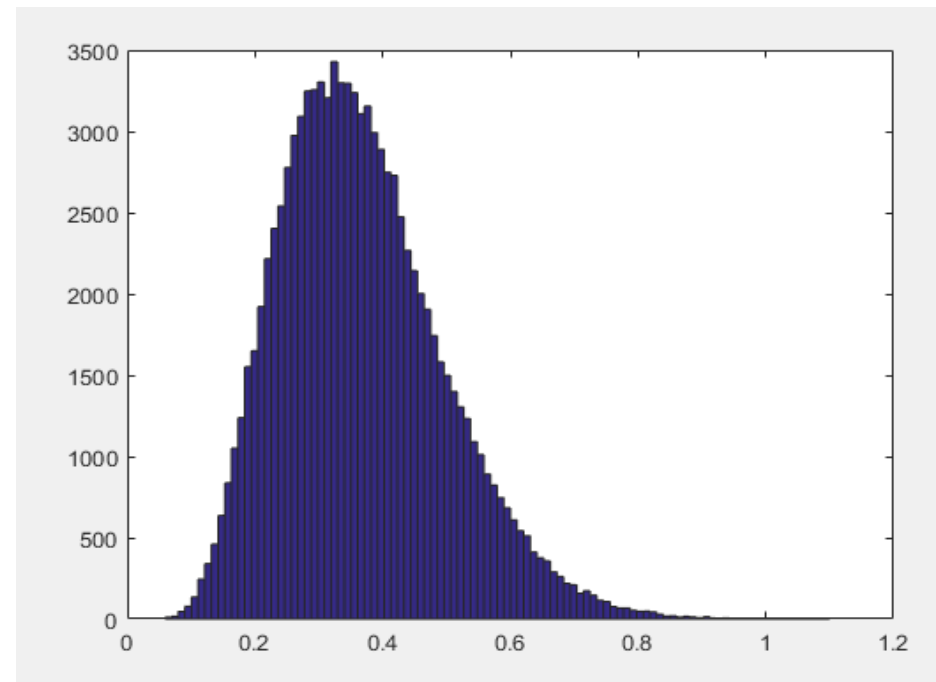
Resistor Sigma= $14.14\ \Omega$

Both structures have essentially the same area

String DAC



Binary DAC



Histogram of INL from 100,000 runs

Since mathematical form for PDF is not available, not easy to analytically calculate yield

Comparison of Thermometer Coded and Binary Coded DACs

Example: $n=10$

$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$



Resistor Sigma= $14.14\ \Omega$

Both structures have essentially the same area

String DAC

Resolution = 10 $AR = 0.02$
Rnom = 1000 Area Unit Resistor = $2\mu\text{m}^2$
INLkmax_mean = $-2.11116\text{e-}05$
INLmean = 0.384382
INLtarget = 0.5000

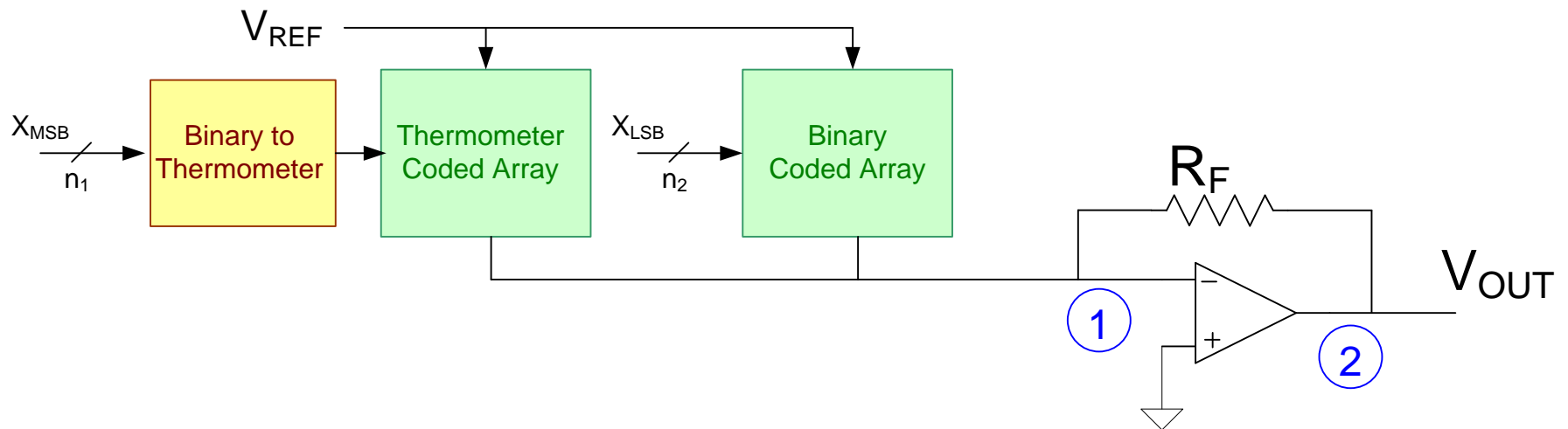
Nruns = 100000
Resistor Sigma= 14.1421
INLkmax_sigma = 0.226783
INLsigma = 0.117732
Yield(%) = 84.0120

Binary DAC

Resolution = 10 $AR = 0.02$
Rnom = 1000 Area unit resistor= $2\mu\text{m}^2$
INLmean = 0.367036
INLkmax_mean = 0.000130823
DNLmean = 0.46978
INLtarget = 0.5000

Nruns = 100,000
Resistor Sigma= 14.1421
INLsigma = 0.128294
INLkmax_sigma = 0.226276
DNLsigma = 0.227768
Yield (%) = 84.8580

Current Steering DACs

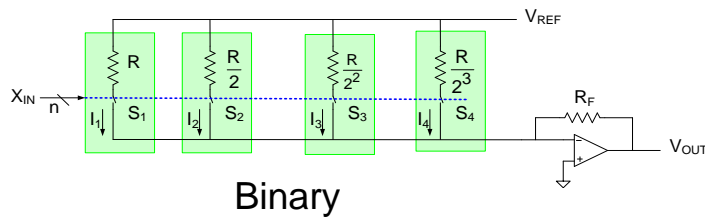


Segmented Resistor Arrays

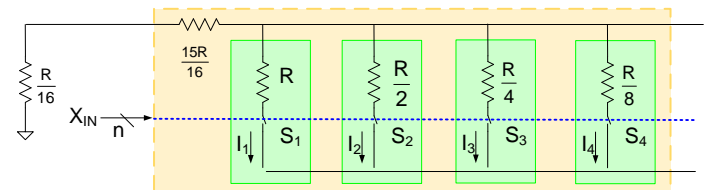
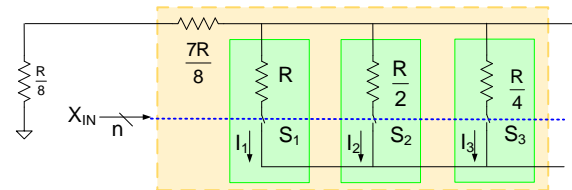
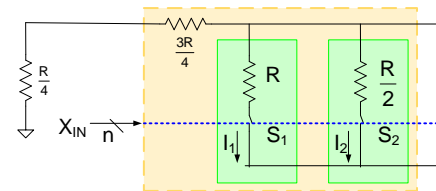
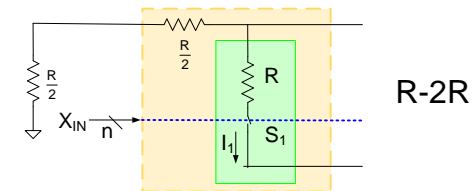
- Combines two types of architectures
- Can inherit advantages of both thermometer and binary approach
- Minimizes limitations of both thermometer and binary approach

Current Steering DACs

Reduced Resistance Structure



Slice Grouping Options with Series Resistors



Is it better to use series unary cells to form R or parallel unary cells to form $\frac{R}{2^n}$?

In the two scenarios, is the dominant area allocated to the MSB or the LSB part of the ladder?

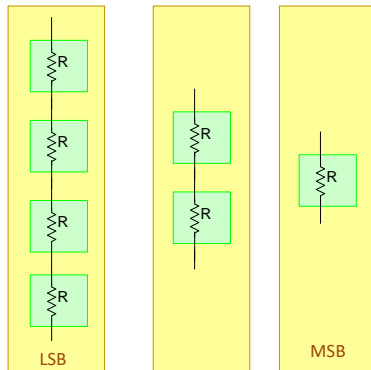
Will this choice make much difference in yield?

What yield-related performance metric will be most affected?

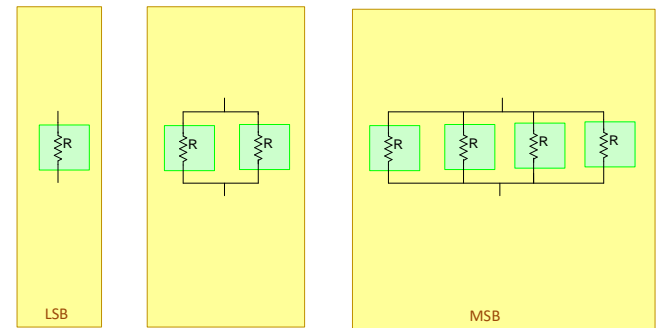
Current Steering DACs

Reduced Resistance Structure

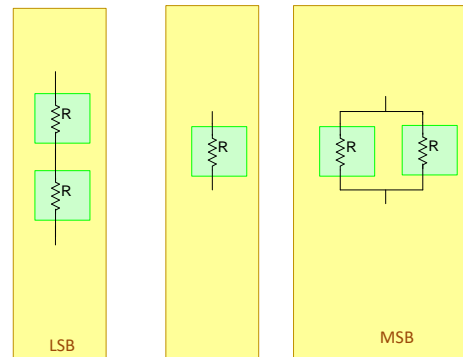
Is it better to use series unary cells to form R or parallel unary cells to form $\frac{R}{2^n}$?



$2^n - 1$ cells



$2^n - 1$ cells



for n odd $2^{\frac{n+3}{2}} - 3$ cells

n	Series	Parallel	Split
3	7	7	5
5	31	31	13
7	127	127	29
9	511	511	61
11	2047	2047	125
13	8191	8191	253
15	32767	32767	509

Comparison of Thermometer Coded and Binary Coded DACs

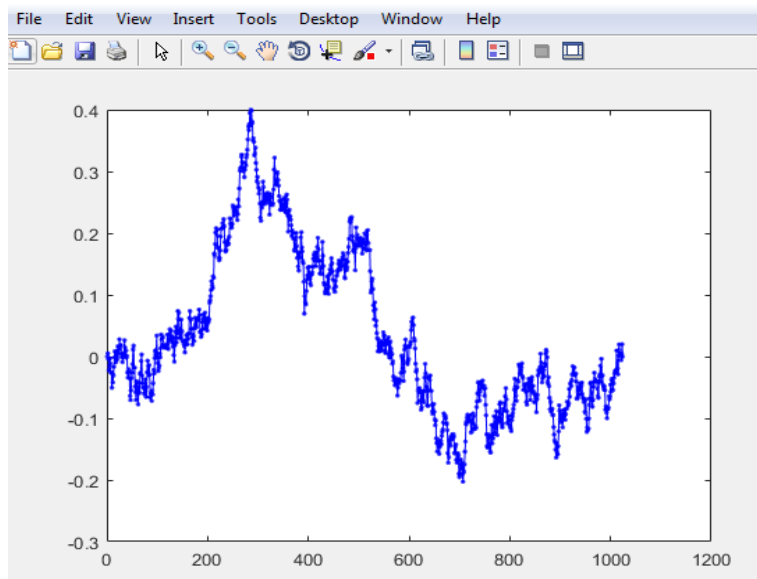
Example: $n=10$
String DAC



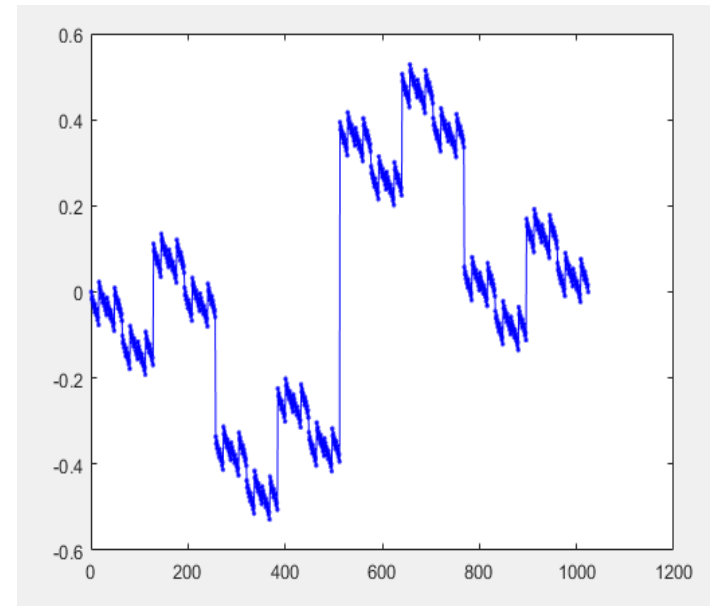
$A_R=0.02\mu\text{m}$
 $R_N=1\text{K}$

Resistor Sigma= $14.14\ \Omega$

Simulation 1: INL_k



String



Binary Weighted

Actual outputs will differ significantly



Stay Safe and Stay Healthy !

End of Lecture 16