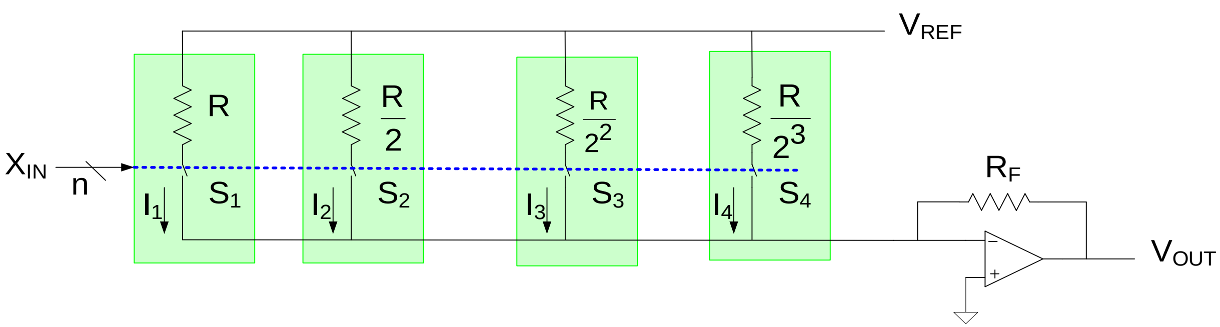
EE 505

Lecture 16

Current Steering DACs

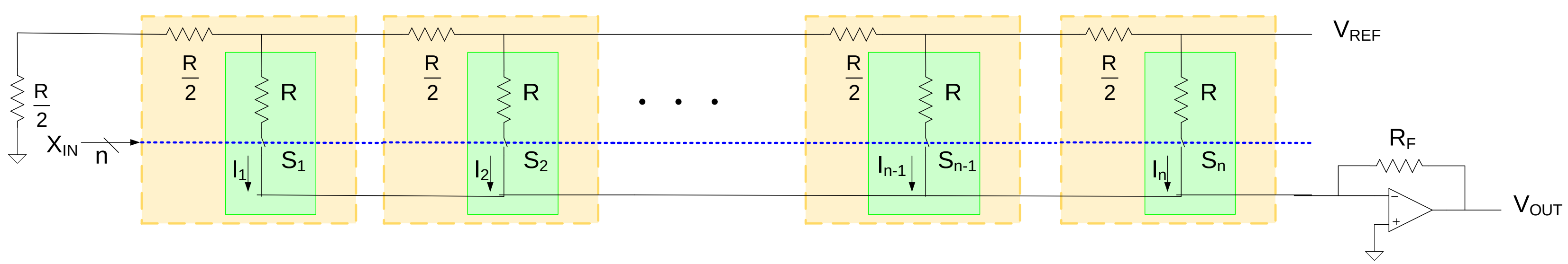
Current Steering DACs

Reduced Resistance Structure



2^n-1 cells

3n+1 cells



Is the R-2R structure smaller ?
Does the R-2R structure perform better?

What metric should be used for comparing performance?

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 (provided area appropriately allocated)

Review from Last Lecture

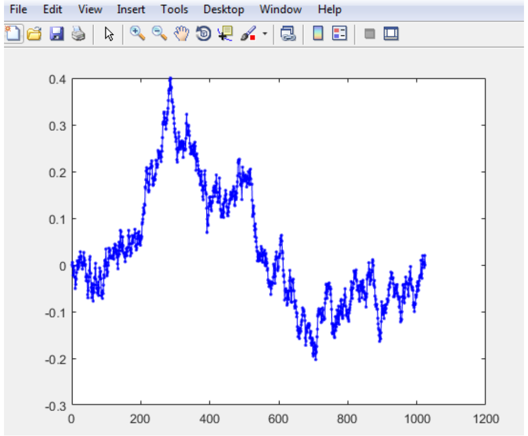
Comparison of Thermometer Coded and Binary Coded DACs

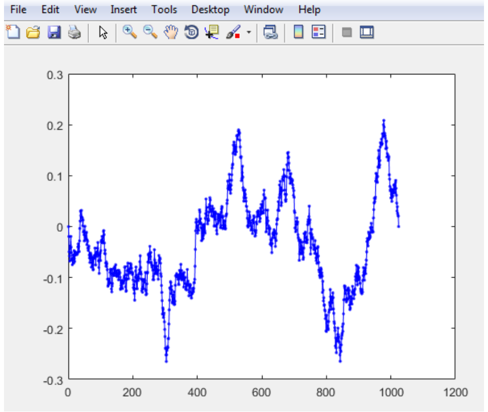
Example: n=10

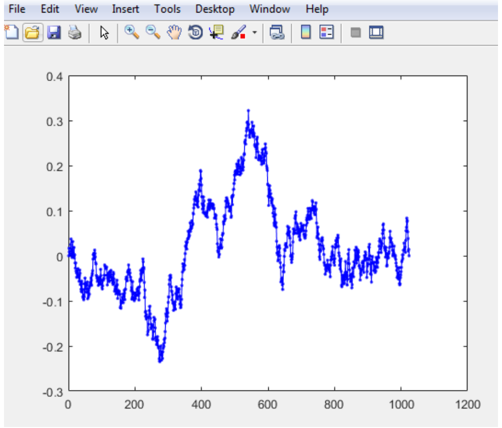
String DAC

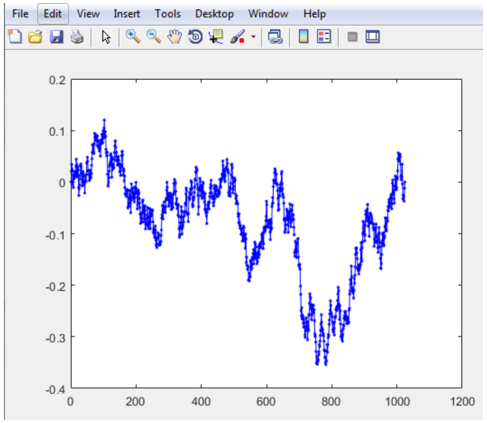
A_R=0.02µm
R_N=1K

Resistor Sigma= 14.14 Ω









Low DNL and random walk nature should be apparent

Review from Last Lecture

Comparison of Thermometer Coded and Binary Coded DACs

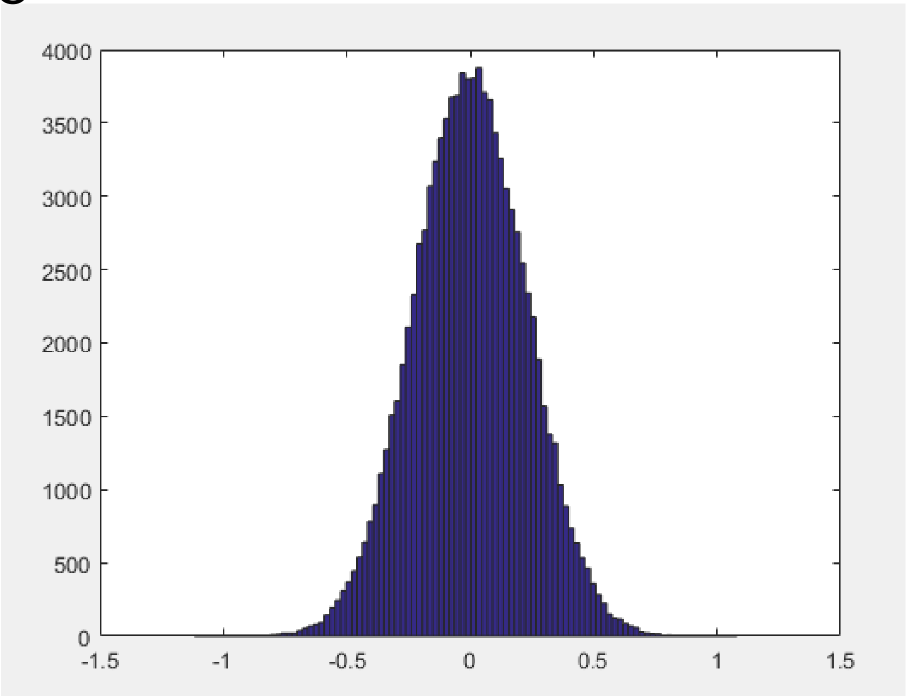
Example: n=10

String DAC

A_R=0.02µm

R_N=1K

Resistor Sigma= 14.14 Ω



INLkmax_mean = -2.11116e-05

INLkmax_sigma = 0.226783

Histogram of INL_{kmax} from 100,000 runs

Appears to be Gaussian

Review from Last Lecture

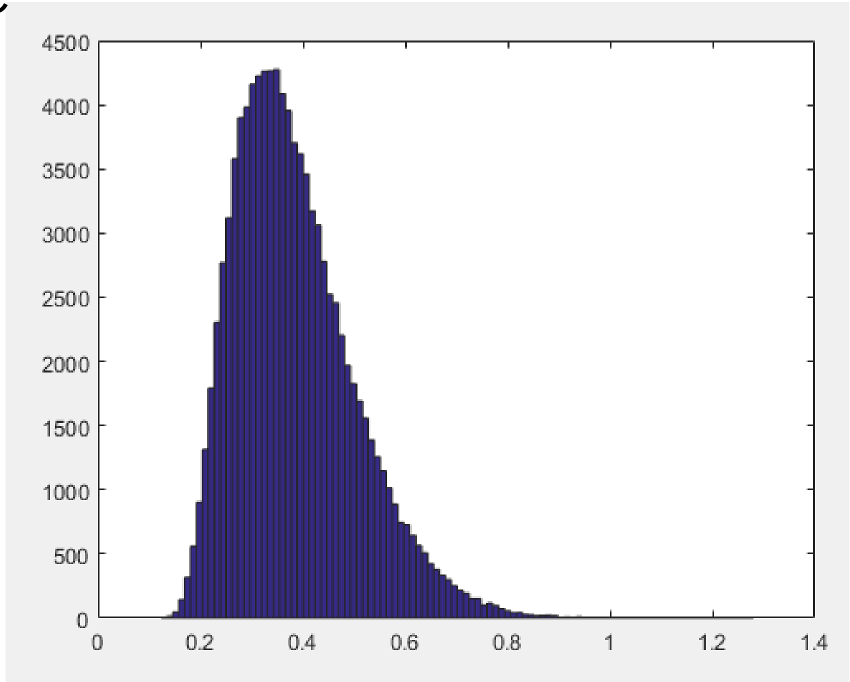
Comparison of Thermometer Coded and Binary Coded DACs

A_R=0.02µm
R_N=1K

Example: n=10

String DAC

Resistor Sigma= 14.14 Ω



INLmean = 0.384382
INLsigma = 0.117732

Histogram of INL from 100,000 runs

Not Gaussian

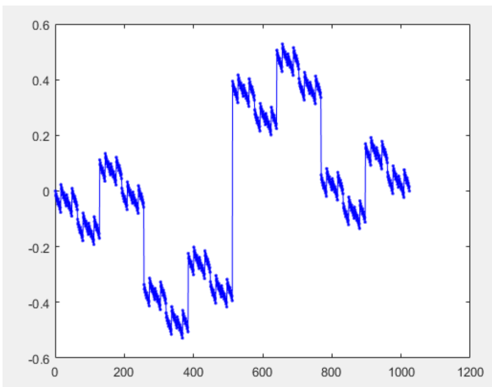
Comparison of Thermometer Coded and Binary Coded DACs

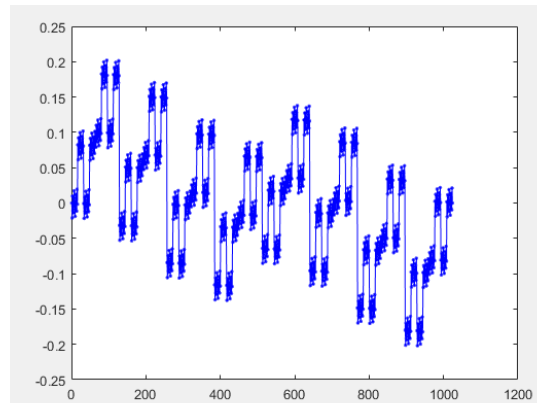
Example: n=10

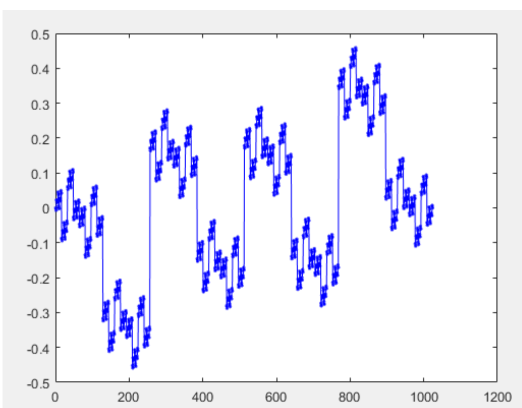
Binary DAC

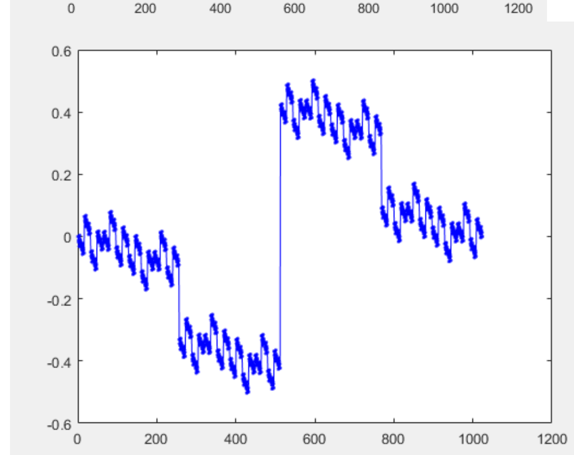
A_R=0.02µm
R_N=1K

Resistor Sigma= 14.14 Ω









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

Review from Last Lecture

Comparison of Thermometer Coded and Binary Coded DACs

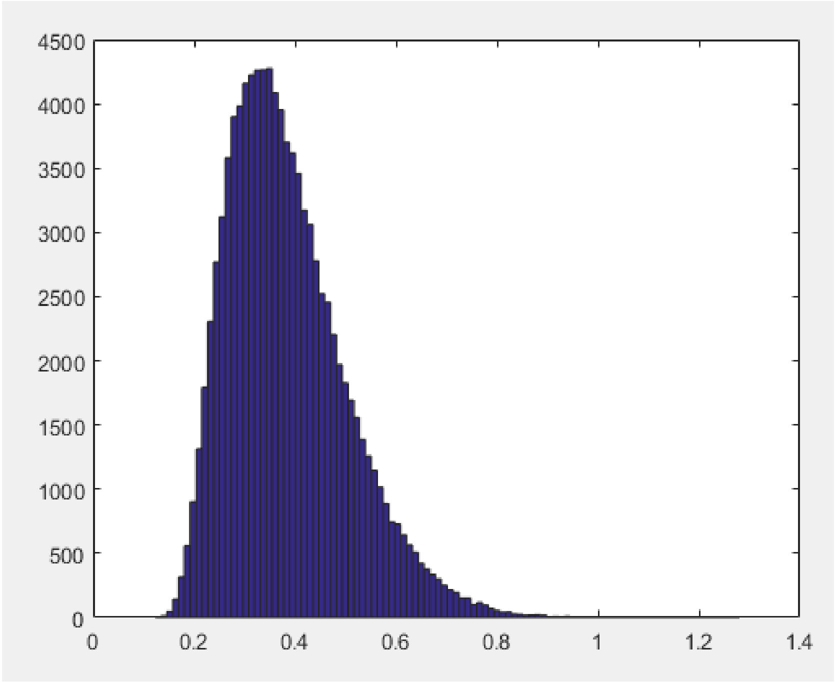
Example: n=10

A_R=0.02µm
R_N=1K

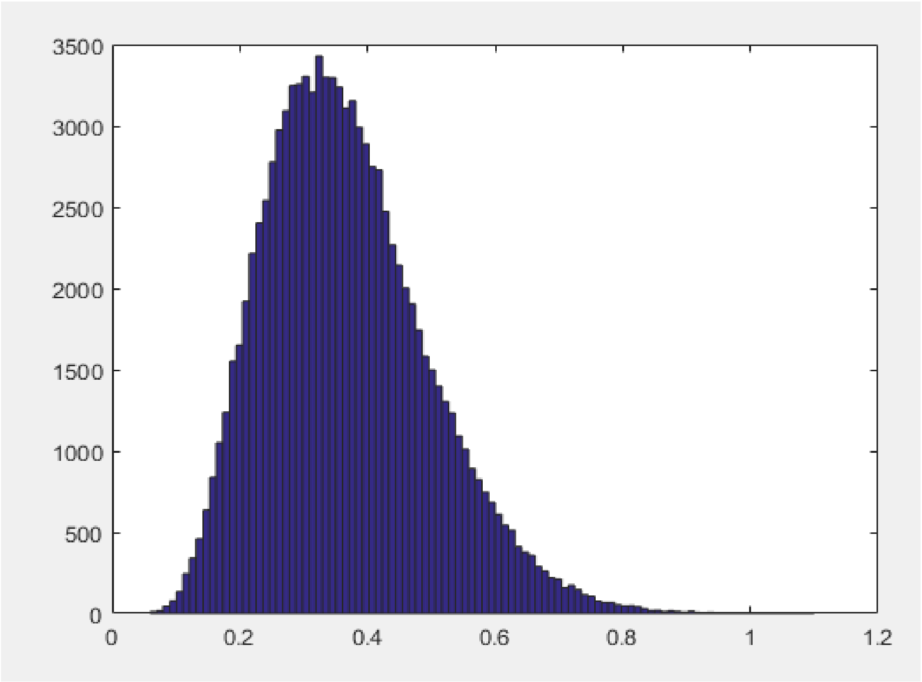
Resistor Sigma= 14.14 Ω

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=0.02µm
R_N=1K

Resistor Sigma= 14.14 Ω

Both structures have essentially the same area

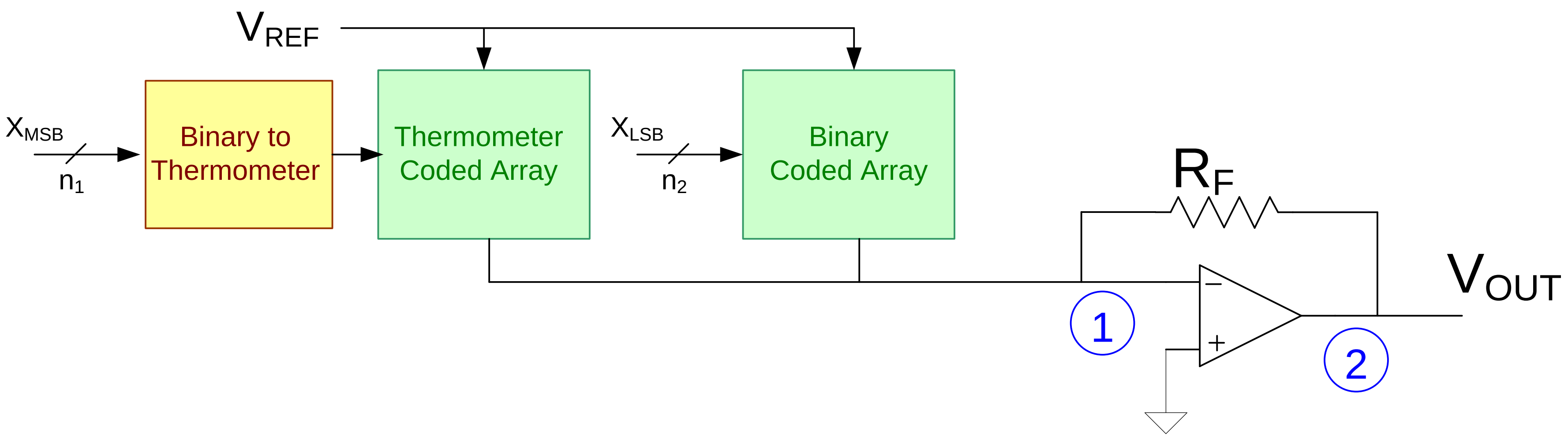
String DAC

Resolution = 10
AR = 0.02
Nruns = 100000
Rnom = 1000
Area Unit Resistor = 2µm^2
Resistor Sigma= 14.1421
INLkmax_mean = -2.11116e-05
INLkmax_sigma = 0.226783
INLmean = 0.384382
INLsigma = 0.117732
INLtarget = 0.5000
Yield(%) = 84.0120

Binary DAC

Resolution = 10
AR = 0.02
Nruns = 100,000
Rnom = 1000
Area unit resistor=2µm^2
Resistor Sigma= 14.1421
INLmean = 0.367036
INLsigma = 0.128294
INLkmax_mean = 0.000130823
INLkmax_sigma = 0.226276
DNLmean = 0.46978
DNLsigma = 0.227768
INLtarget = 0.5000
Yield (%) = 84.8580

Current Steering DACs



Segmented Resistor Arrays

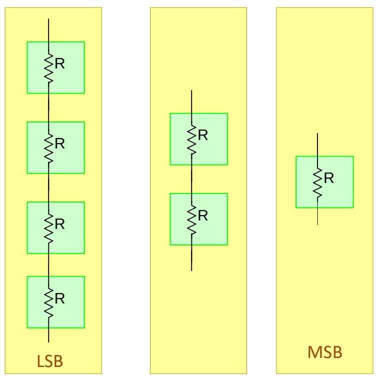
- Combines two types of architectures
- Can inherit advantages of both thermometer and binary approach
- Minimizes limitations of both thermometer and binary approach

Review from Last Lecture

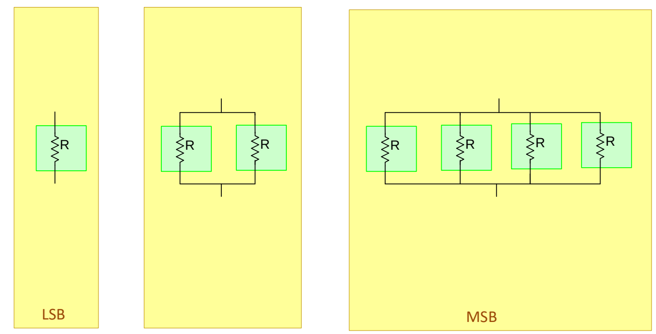
Current Steering DACs

Reduced Resistance Structure

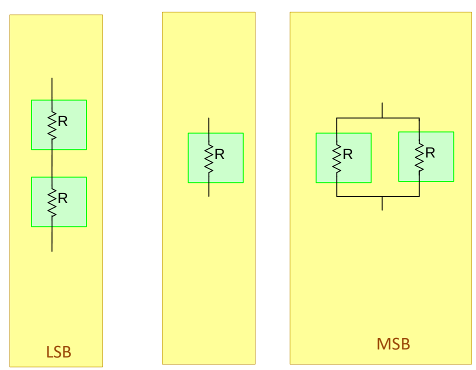
Is it better to use series unary cells to form R or parallel unary cells to form $\frac{R}{2^n}$?



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

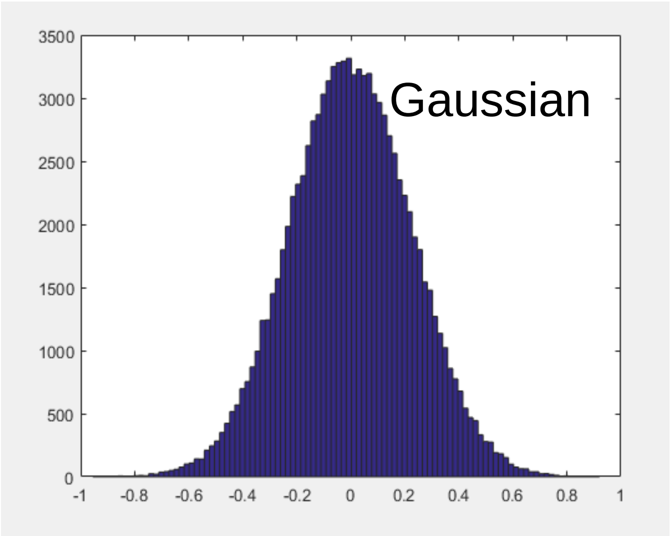
Comparison of INL_{kmax} and INL for String DACs

Example: n=10

A_R=0.02µm
R_N=1K

Resistor Sigma= 14.14 Ω

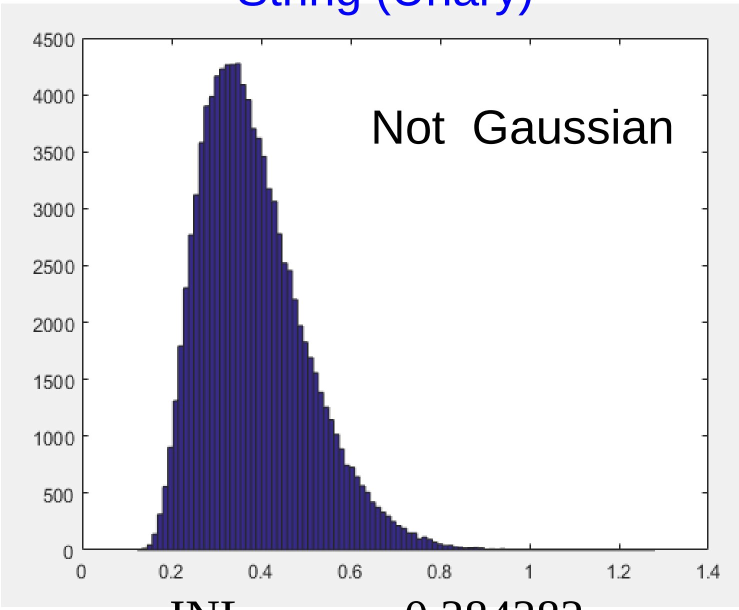
String (Unary)



INLkmax_mean = -.00526008
INLkmax_sigma = 0.23196

- Closed-Form Analytical Formulation Available

String (Unary)



INLmean = 0.384382
INLsigma = 0.117732

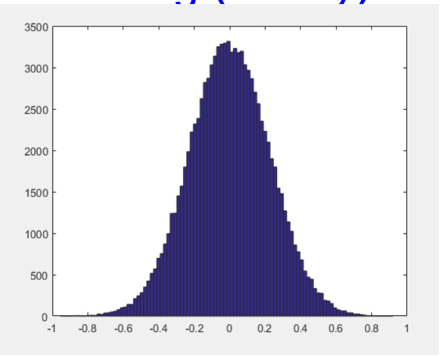
- No Closed-Form Analytical Formulation

Histogram of INL from 100,000 runs

File: BinaryWeightedDACInl.m

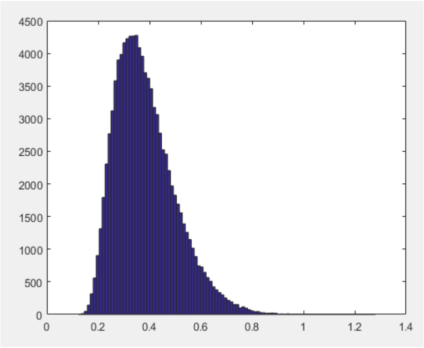
Comparison of INL and INL_{kmax}

String (Unary)

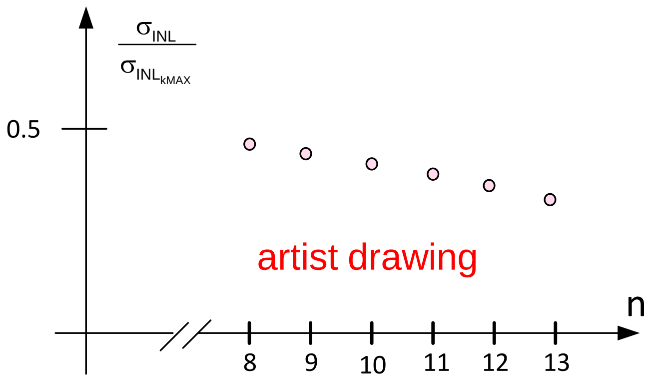


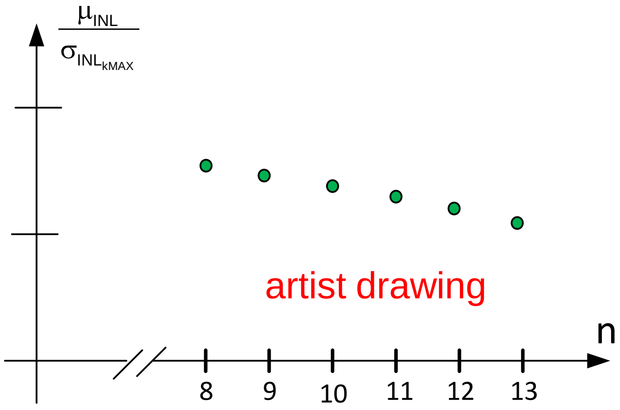
Histogram of INL_{kmax}

String (Unary)



Histogram of INL





These plots may be useful for providing insight into performance

Results similar for both String and Binary Structures

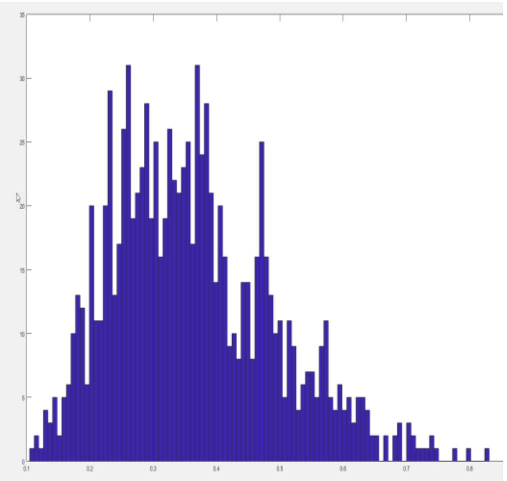
Monte Carlo Simulation Time can Become Large

Example: n=10

A_R=0.02µm
R_N=1K

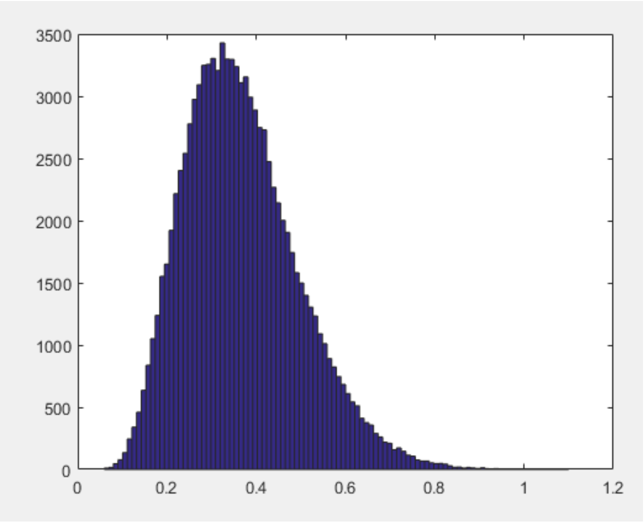
Resistor Sigma= 14.14 Ω

Binary DAC



Histogram of INL from 1000 runs

Binary DAC



Histogram of INL from 100,000 runs

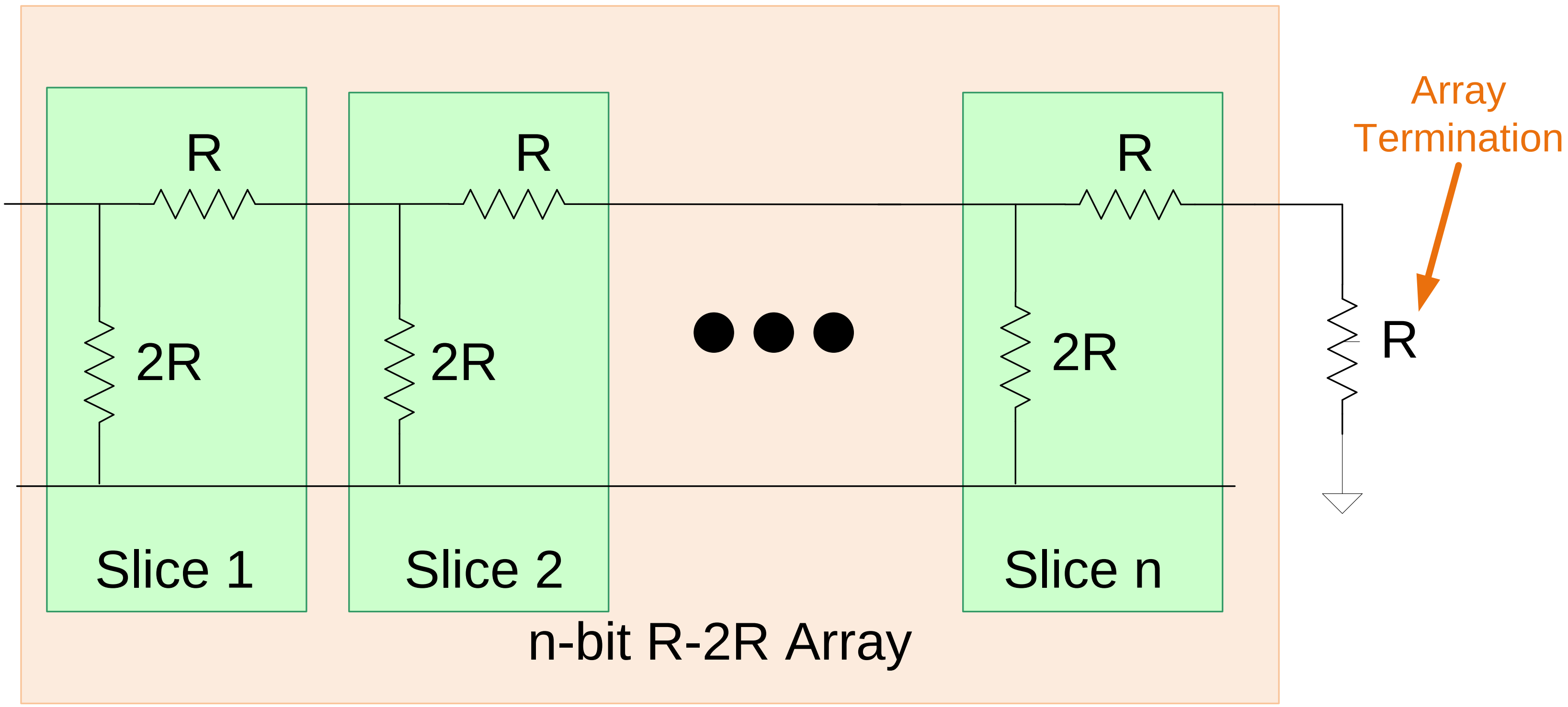
Can require a large number of runs for useful information

This should provide insight into length of Monte Carlo simulations needed to get useful results

File: BinaryWeightedDACInl.m

The R-2R Ladder

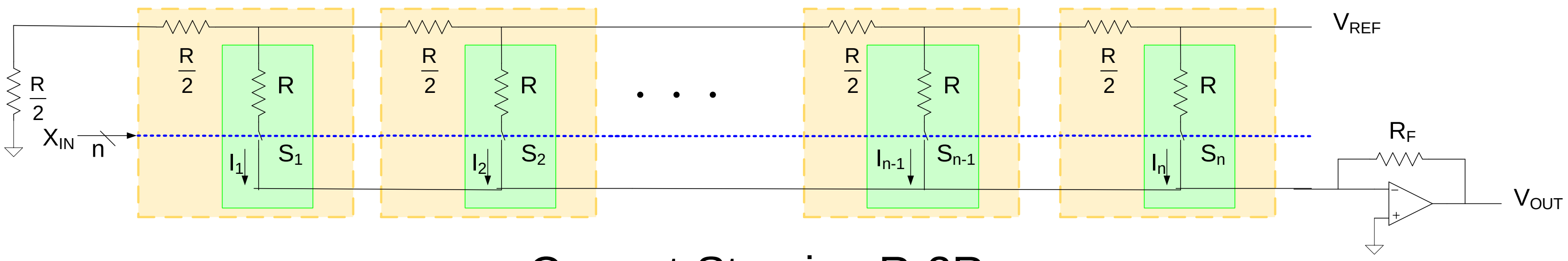
R-2R Resistor Arrays



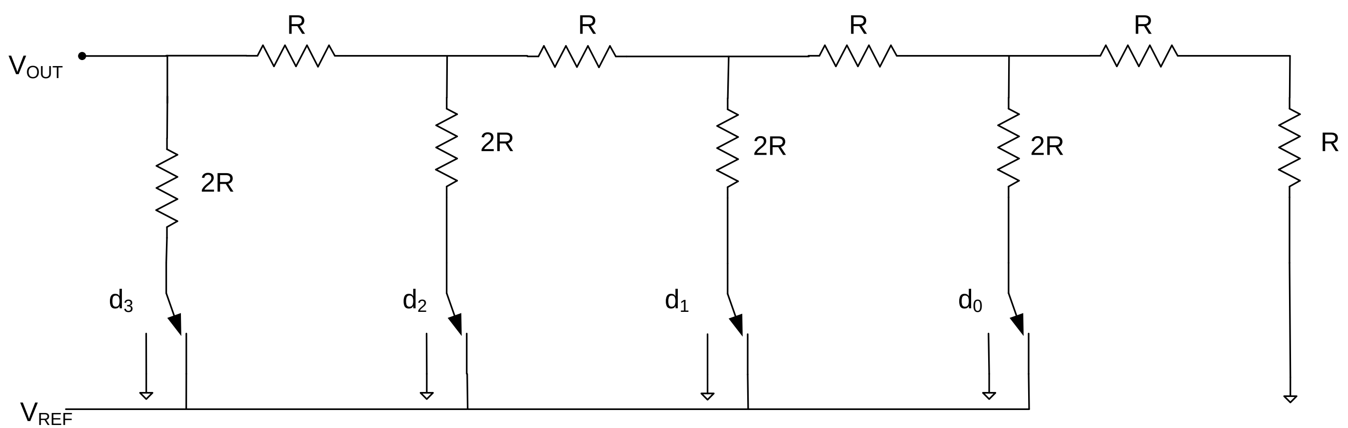
- Depicting relative resistor values (not how unary cells used)
- Conceptually, area goes up linearly with number of bit slices
- Can be used in many different ways

R-2R DAC

Various Implementations of the R-2R Structure



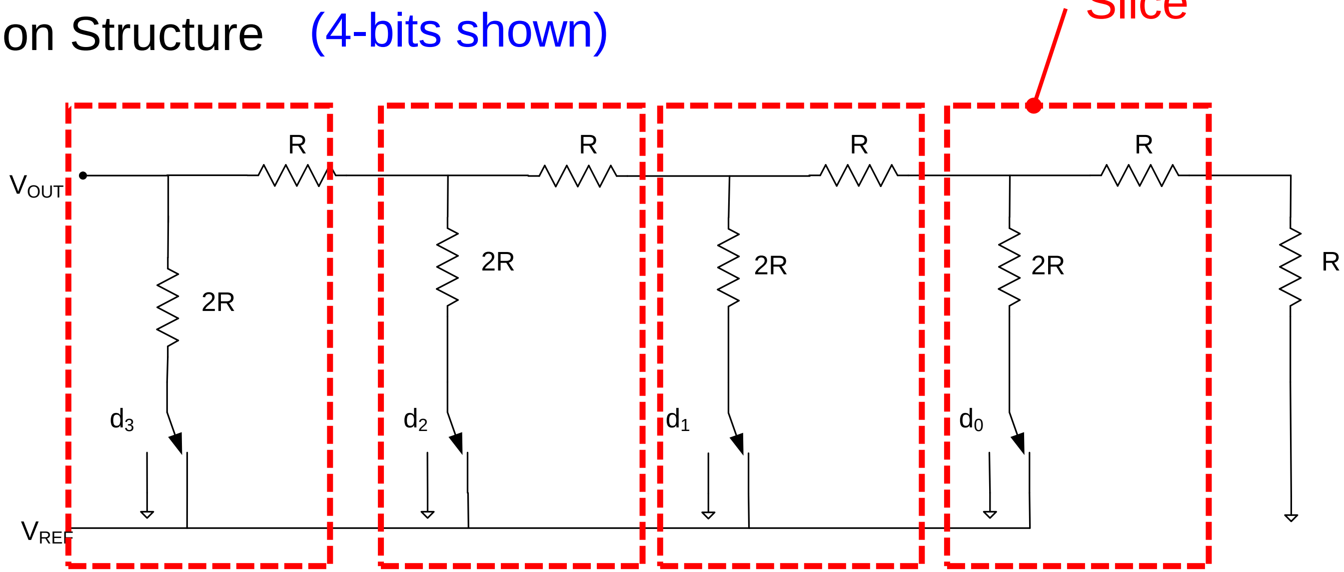
Current-Steering R-2R



Voltage Division R-2R

R-2R DAC

Voltage-Division Structure (4-bits shown)



By superposition:

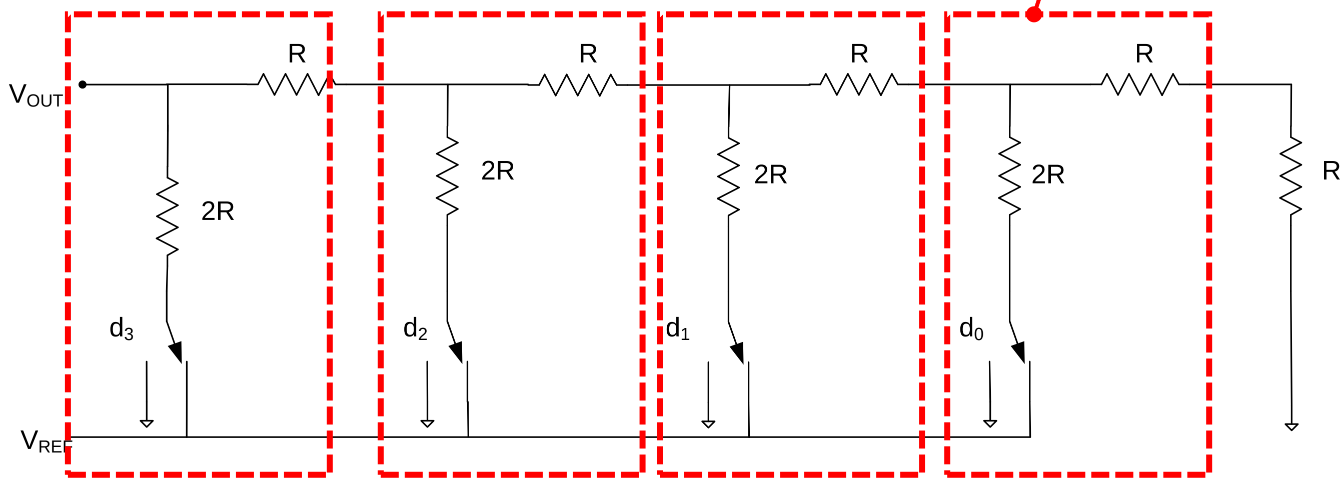
$$V_{OUT} = V_{REF} d_3 \bullet \frac{1}{2} + V_{REF} d_2 \bullet \frac{1}{4} + V_{REF} d_1 \bullet \frac{1}{8} + V_{REF} d_0 \bullet \frac{1}{16} = V_{REF} \sum_{k=0}^{3} \frac{d_k}{2^{4-k}} = V_{REF} \sum_{k=1}^{4} \frac{d_{4-k}}{2^k}$$

- No op amp required !!
- 2:1 Ratio matching of MSB slice most critical
- Total resistance goes up linearly with number of bit slices !!
- Conventional wisdom: area goes up linearly with number of bit slices
- Does conventional wisdom result in optimal designs?

R-2R DAC

Bit Slice

Voltage-Division Structure (4-bits shown)

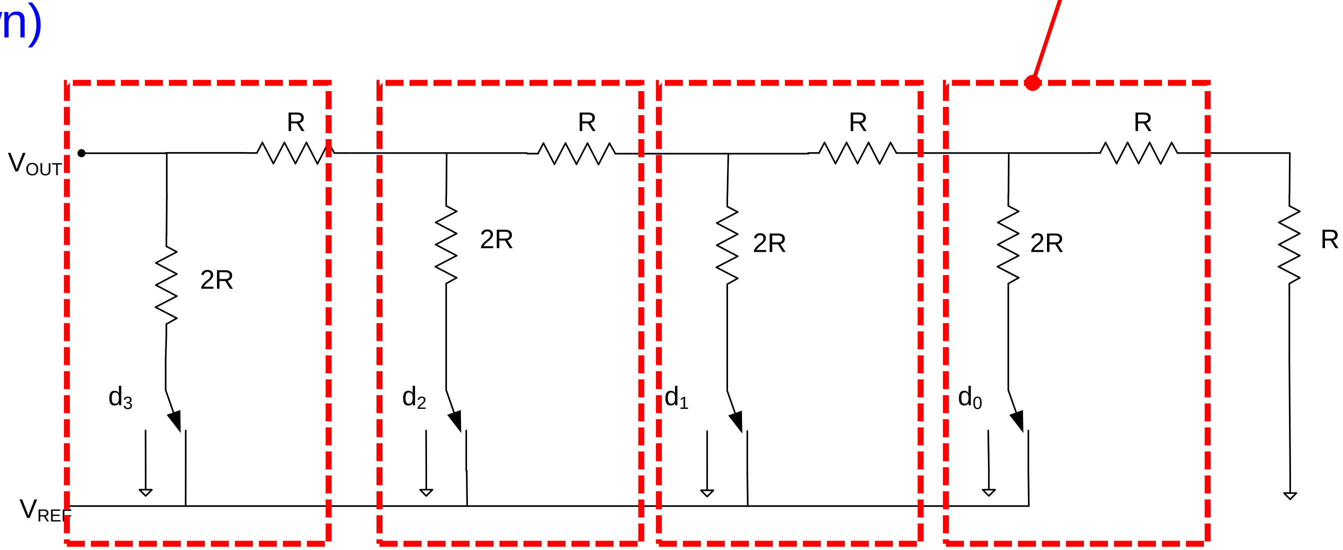


Limitations:

- Parasitic capacitances on all nodes must settle during all transitions
- Switch impedances imbalance 2R cells
- Analogous to top-plate switching
- Output impedance not 0

Is the output impedance code dependent?

R-2R DAC



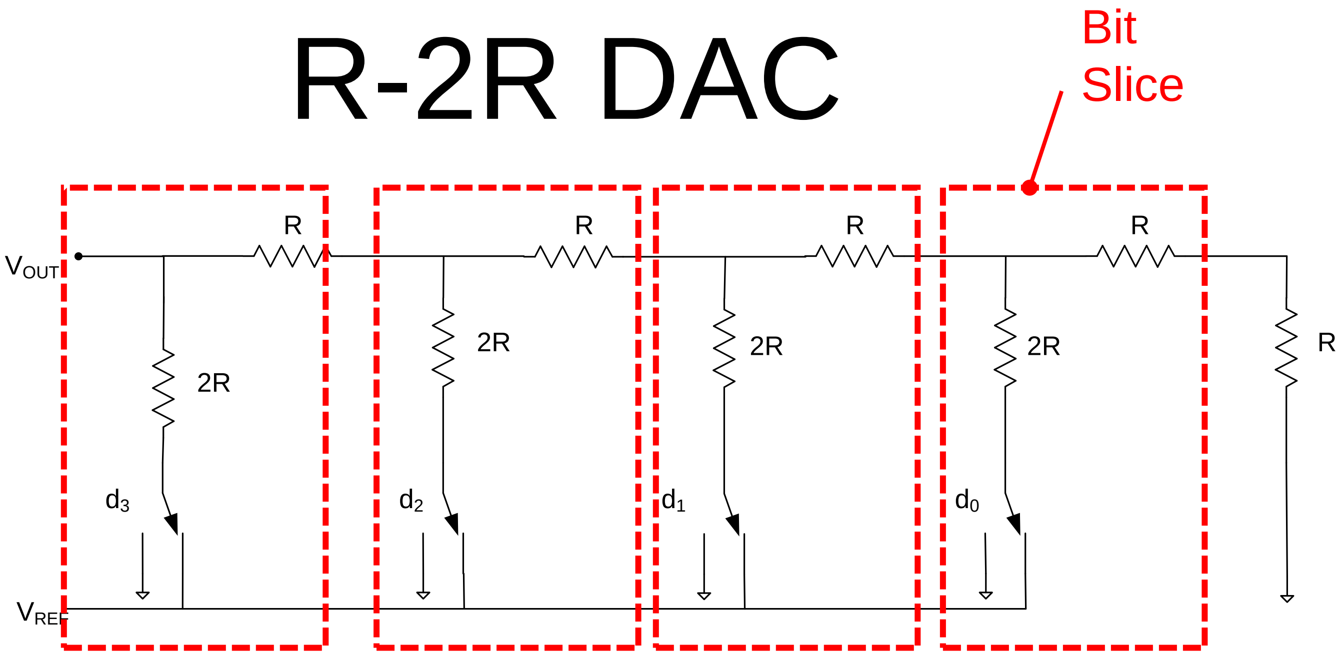
Limitations:

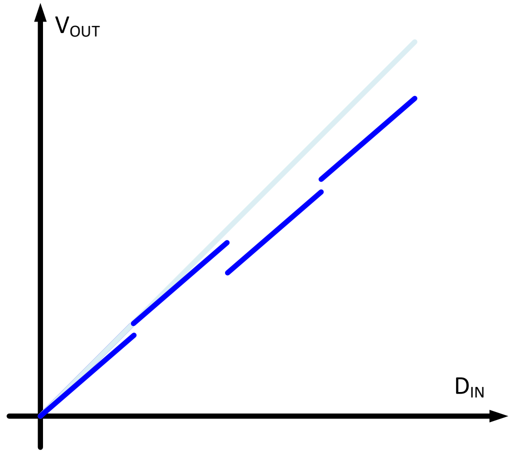
- Parasitic capacitances on all nodes must settle during all transitions
- Switch impedances imbalance 2R cells
- Analogous to top-plate switching
- Output impedance not 0

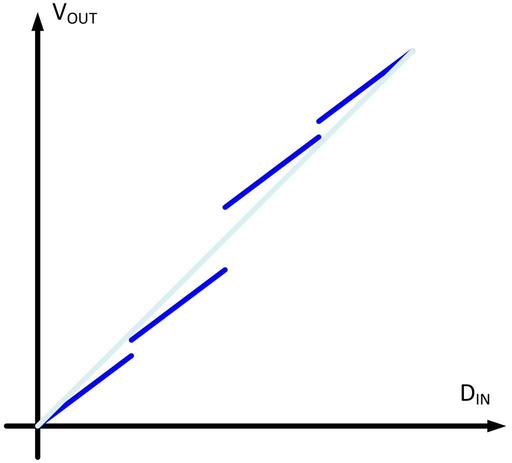
Is the output impedance code dependent?

No! Impedance facing Vout is always R

R-2R DAC

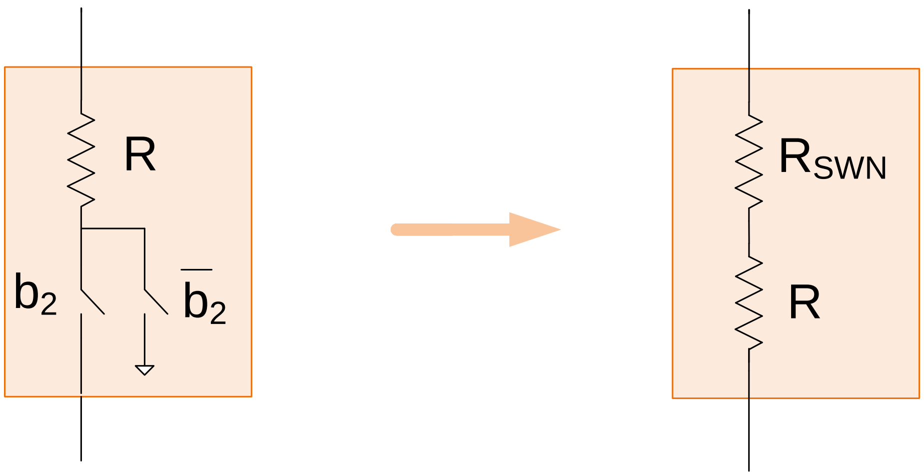






Large steps in output can occur
How should area be allocated?

R-2R Implementation



For Switched Cells

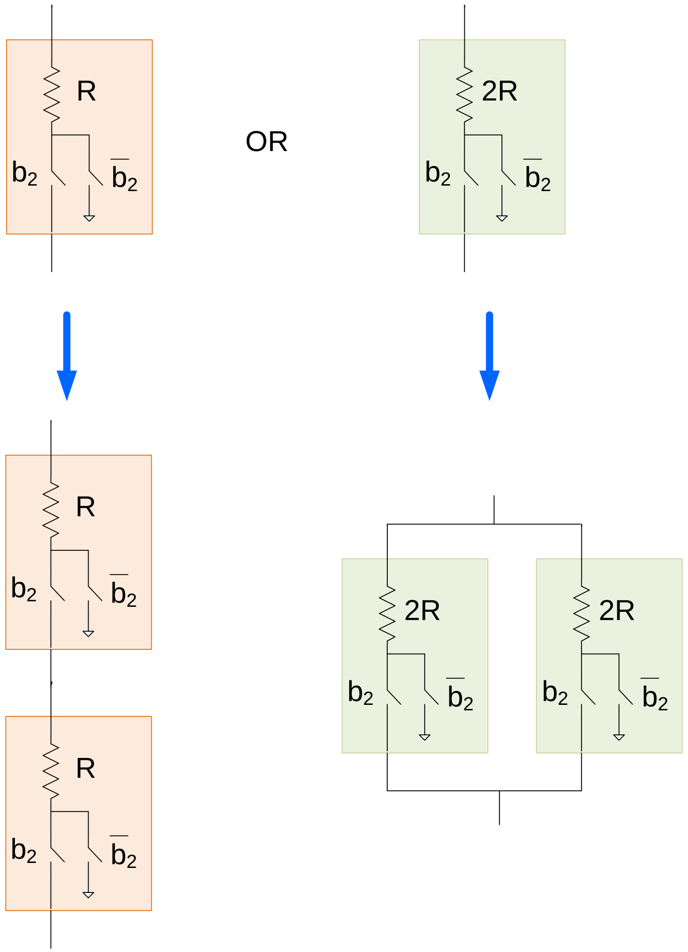
For Unswitched Cells

- Add resistor equal to nominal switch impedance in each unswitched cell
- Impedance equal to the nominal switch impedance
- Offers some improvement, particularly if all switches are bottom-plate switches

  (but for previous R-2R structure do not have all bottom-plate switches)

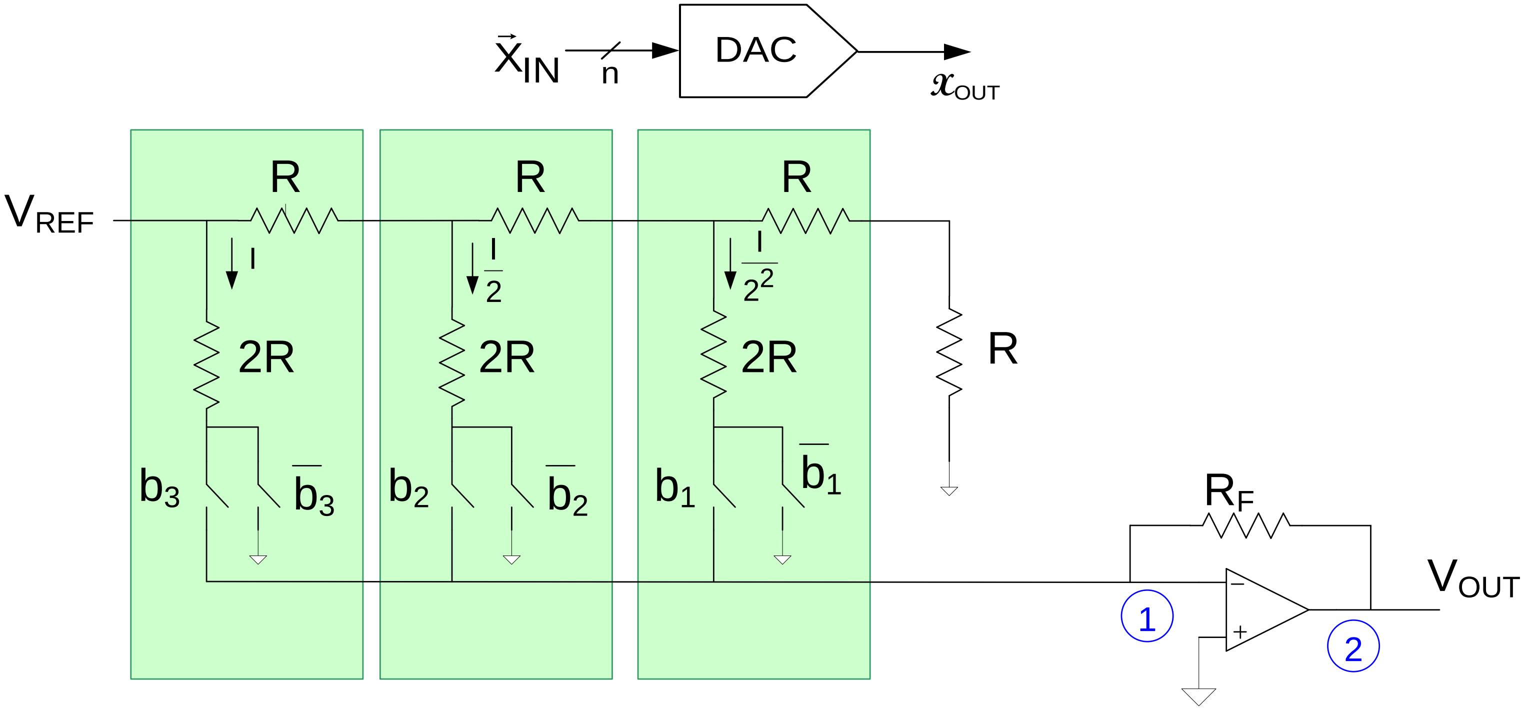
- Will not track with temperature and process variations

R-2R Implementation



- Unit cell widely used
- Switch included in cell even if not switched!
- Code dependence of switch impedance of concern (this can be addressed)
- Delays associated with turning on switches also of concern since some cells not referenced to same level as switches

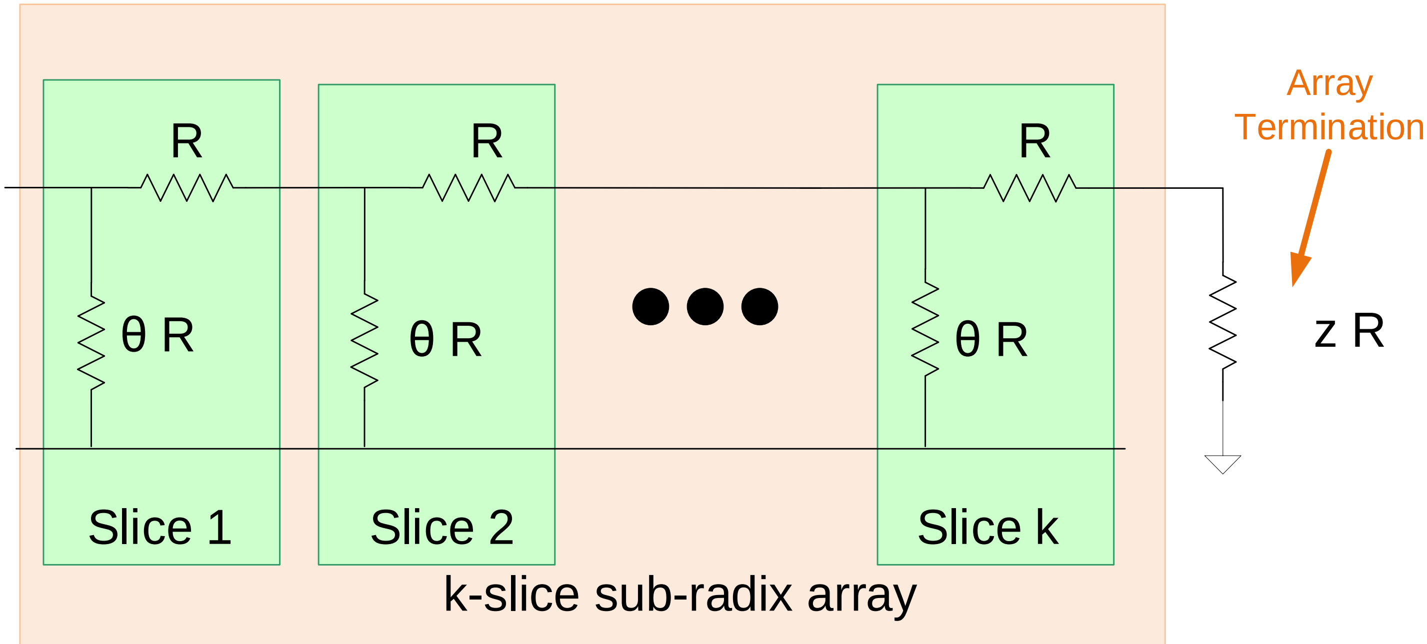
R-2R Current Steering DAC



- INL can get large in R-2R structures
- DNL can get large in R-2R structures

Sub-radix Array

Want Currents to Scale by $1/\theta$ (instead of ½) from each slice to the next



Typically $2.1 < \theta < 2.5$

Termination resistor must be selected so that same attenuation is maintained

Often only the first n_1 MSB "slices" will be sub-radix

Effective number of bits when using sub-radix array will be less than k

Can be calibrated to obtain very low DNL (and maybe INL) with small area

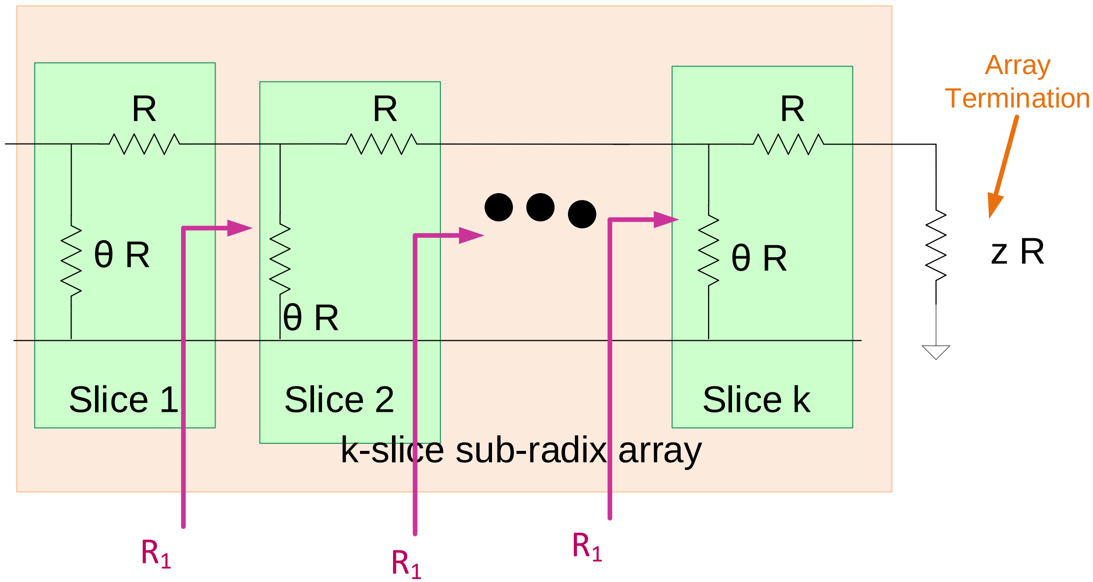
Sub-radix Array

It can be shown that the optimal value of z is given by the expression

$$z = \frac{3\theta + 1 - (1+\theta)\sqrt{1+4\theta}}{-1+\sqrt{1+4\theta} - 2\theta}$$

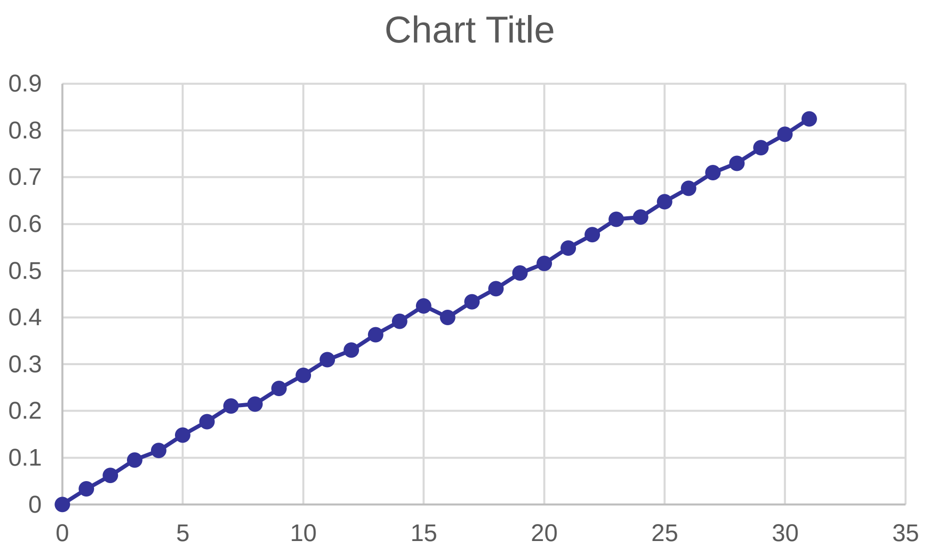
This derivation is in a file named Termination of Subradix.docx

Derivation based upon assuming the three impedances R_1 below must be the same



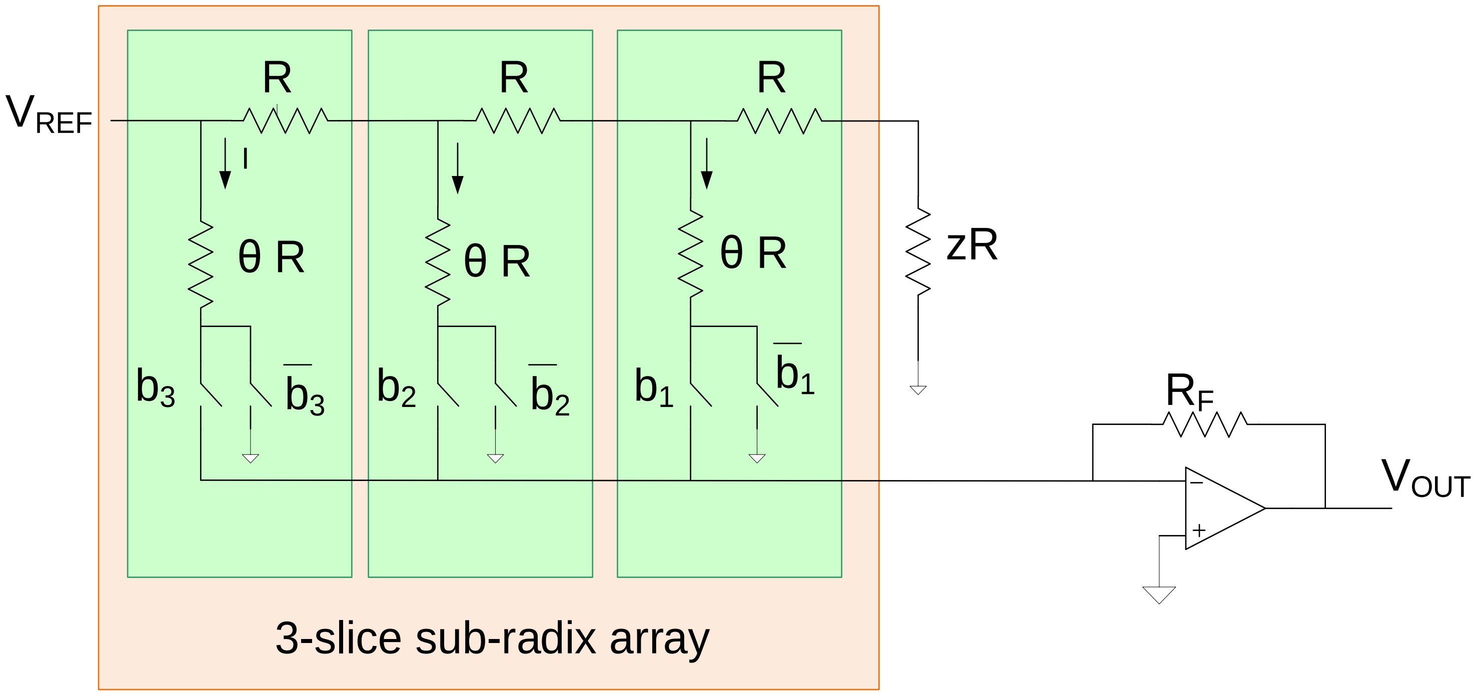
Output of an optimally terminated subradix DAC of 5 bits with θ=2.5 and z=1.15831

See file SubRadix DAC.xslx



θ selected so probability of large positive gap is very small

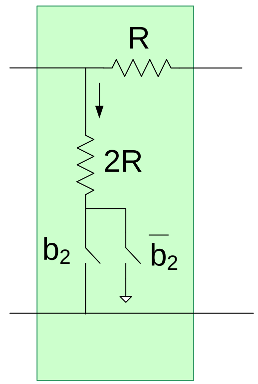
3-slice sub-radix DAC

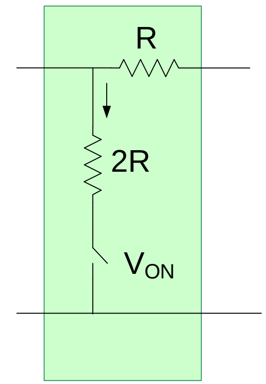


Typically θ is slightly greater than 2

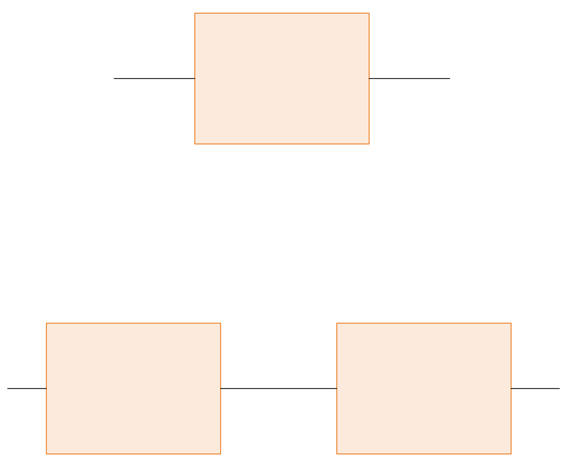
Does not eliminate large DNL errors but can eliminate gaps in output

R-2R Resistor Arrays

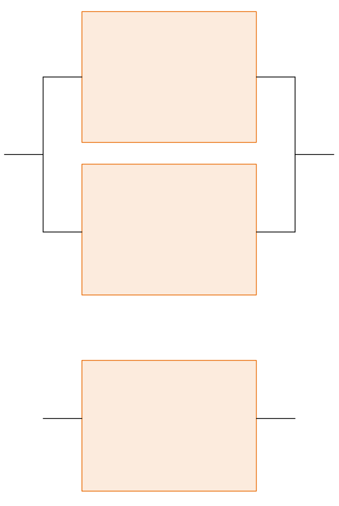




Does it make any difference how area is allocated?

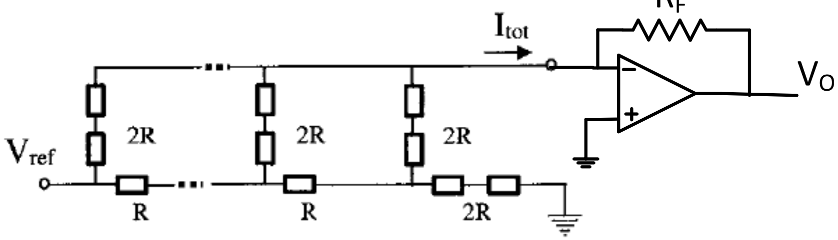


2R Area twice R Area

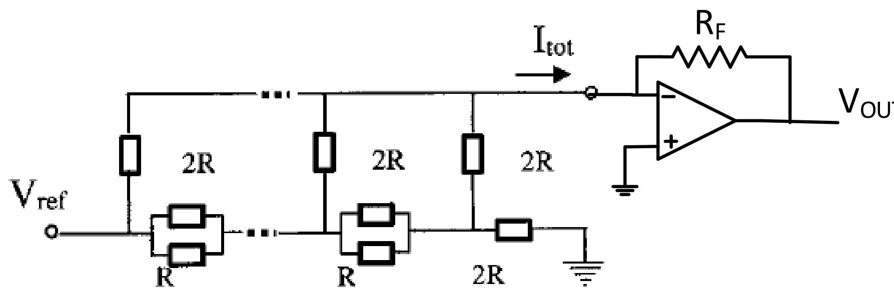


R Area twice 2R Area

Area Allocation for R and 2R Resistors

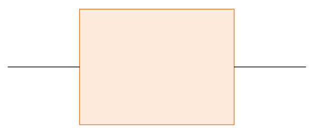


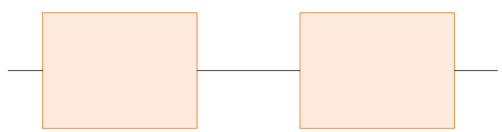
Switches not shown



Switches not shown

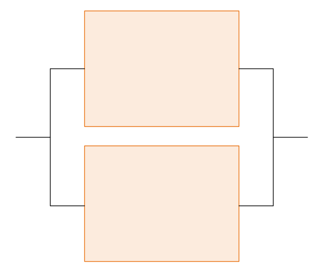
Series Layout

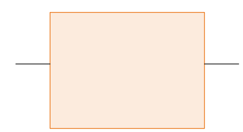




2R Area twice R Area

Parallel Layout

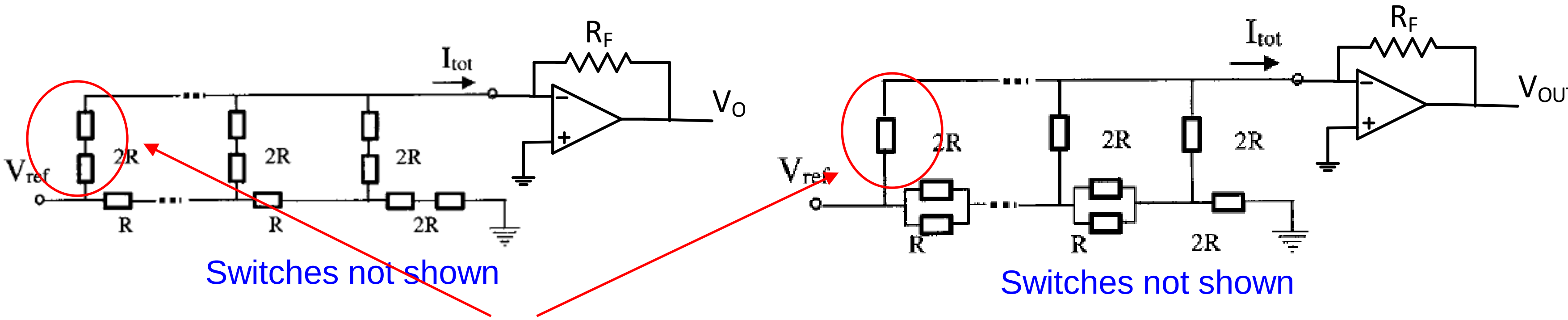




R Area twice 2R Area

Assume area in each slice if fixed

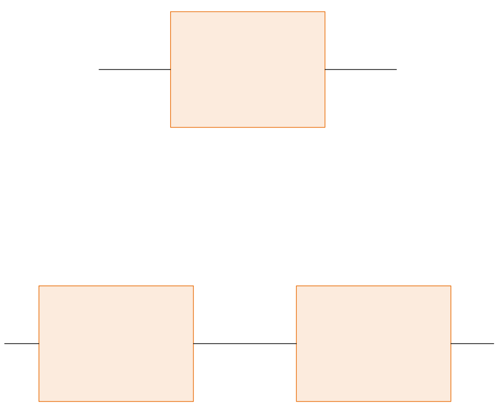
Area Allocation for R and 2R Resistors

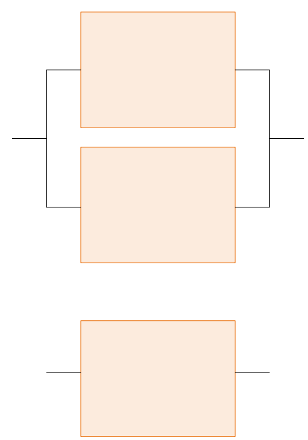


critical MSB current

Series Layout

Parallel Layout





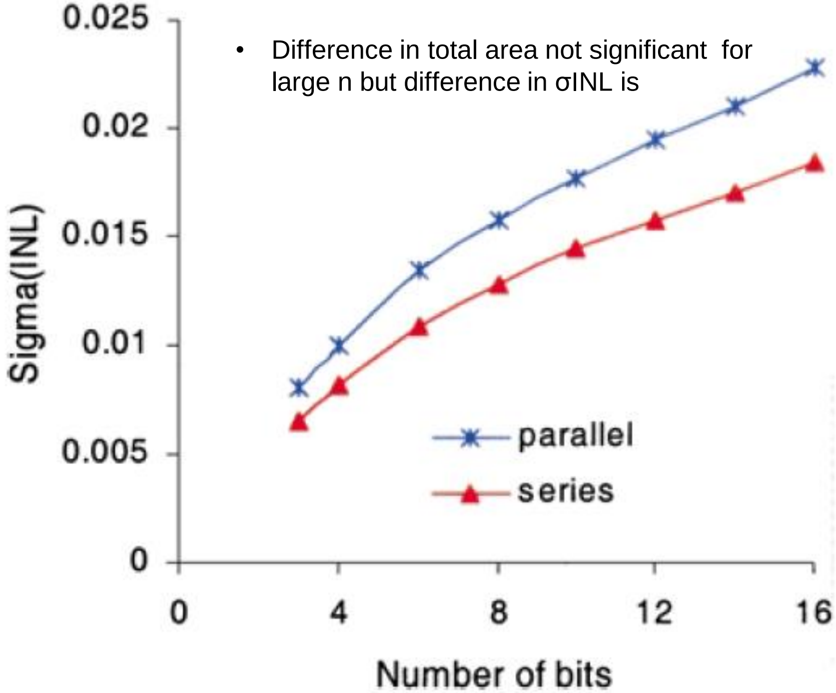
2R Area twice R Area

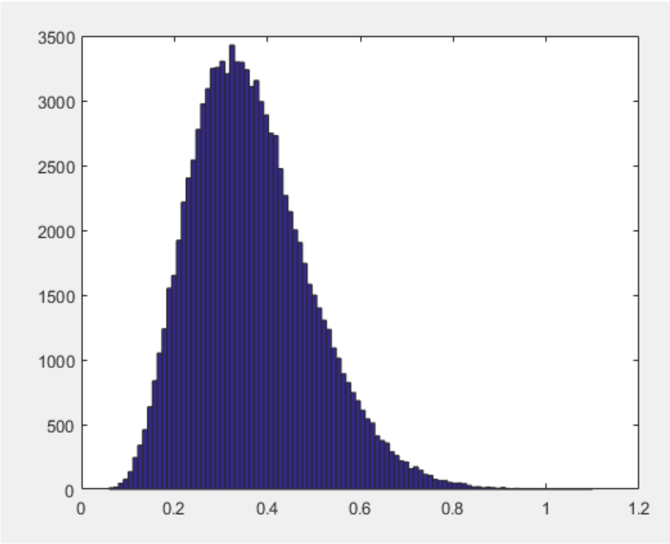
R Area twice 2R Area

Assume area in each slice if fixed

Area Allocation for R and 2R Resistors

- Number of cells (and hence total area) is not constant in these simulations
- Difference in total area not significant for large n but difference in σINL is



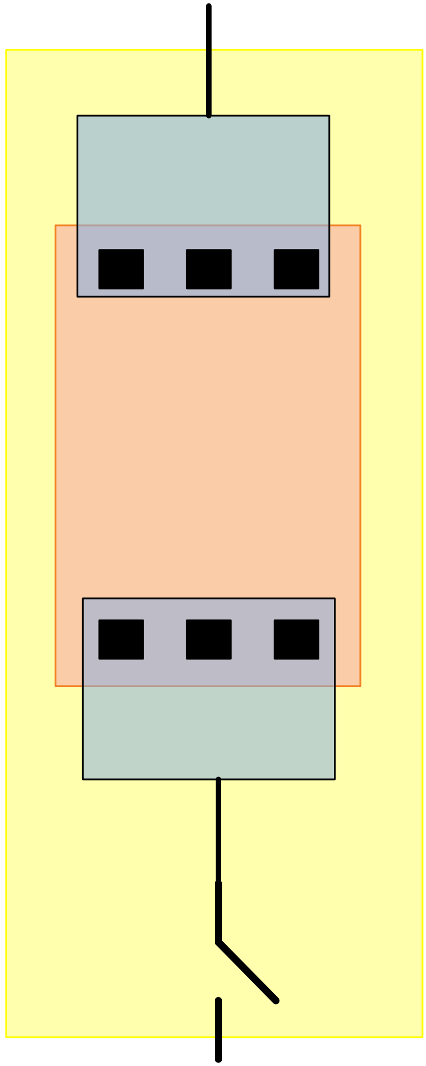


Yield is affected by both mean and standard deviation of the non-Gaussian pdf

Standard deviation of parallel layout is somewhat more (but uses less cells for n small)

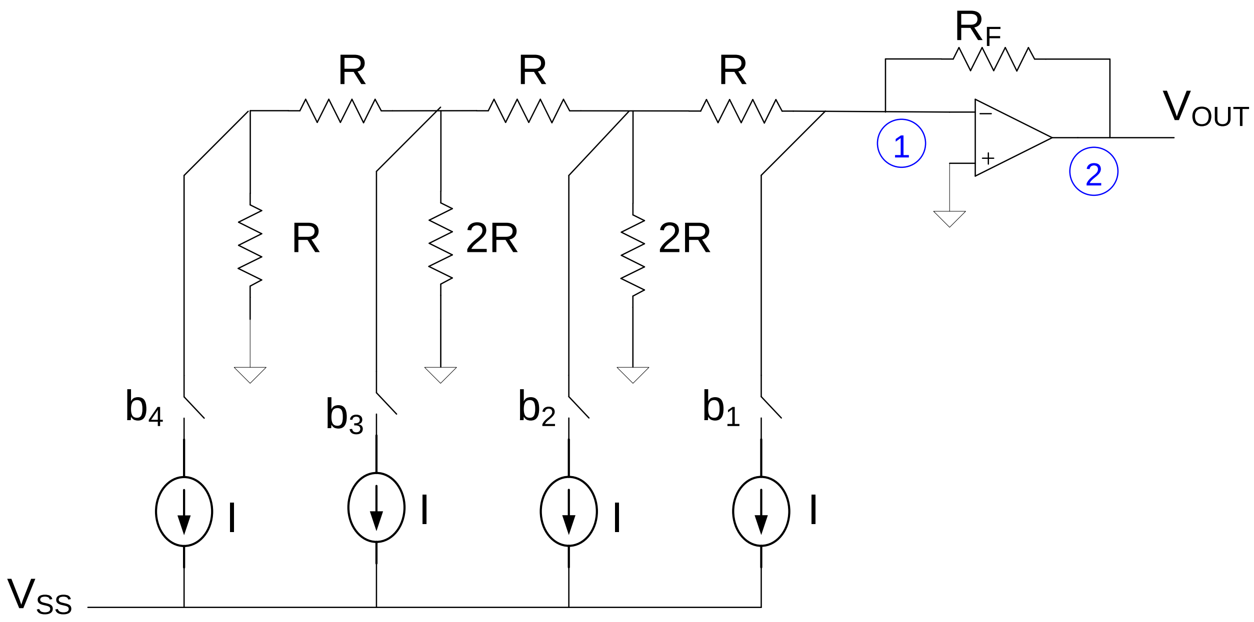
Area allocation between slices also affects yield

Challenges with all R-based DACs



- Switch Impedance
- Contact Resistance
- Variability
  - Resistor
  - Contact Resistance
  - Switch Impedance
- Parasitic Capacitances

Another R-2R DAC



Eliminates series switch resistance when switching resistors

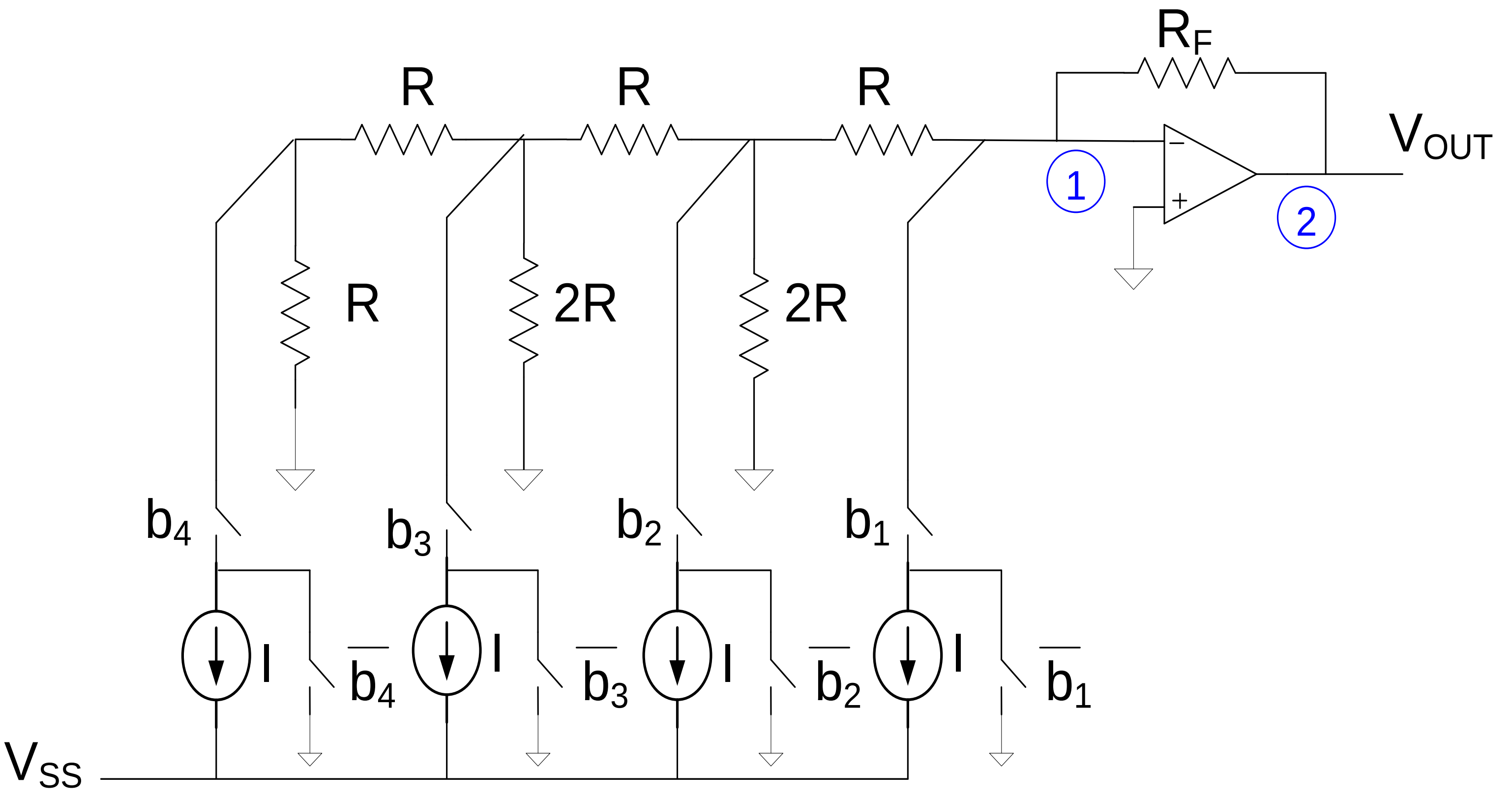
Series resistance in current source does not affect current

Must match both resistors and current sources

Current flow will pull capacitance on switch nodes to low before current sources leave saturation

Current flow will change power dissipation based upon digital code

Another R-2R DAC



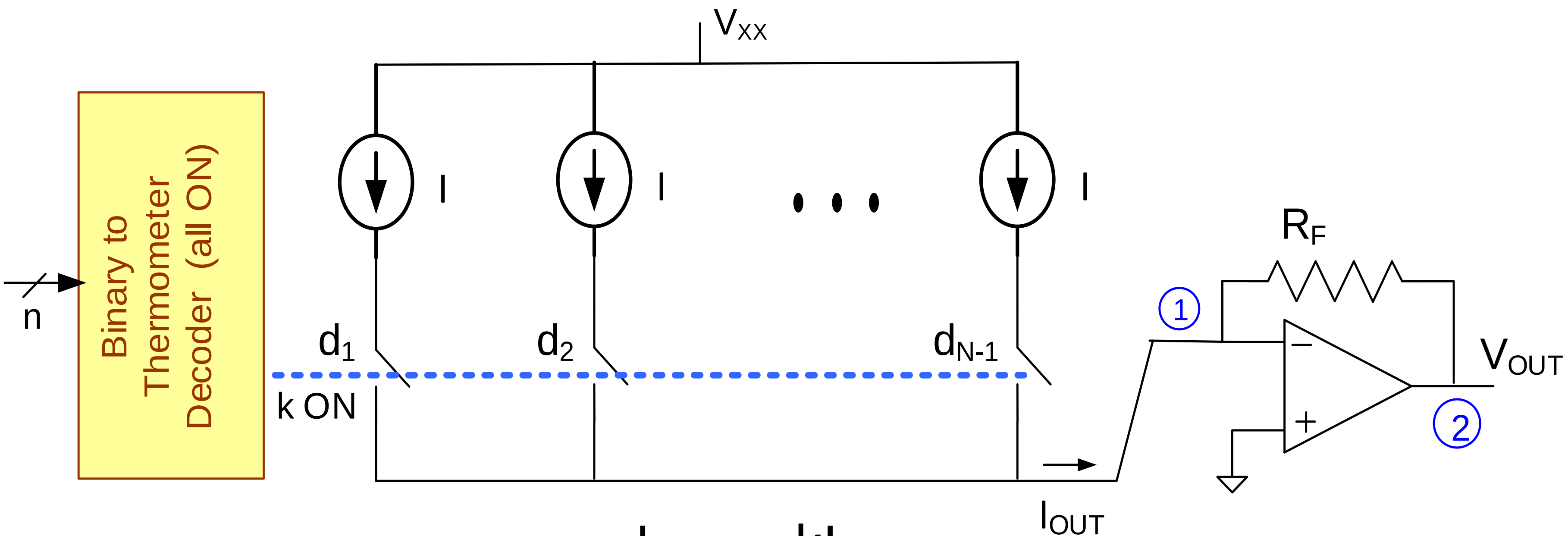
Switch will pull capacitance on switch nodes to GND instead of V_{SS}

Power dissipation will not be code dependent

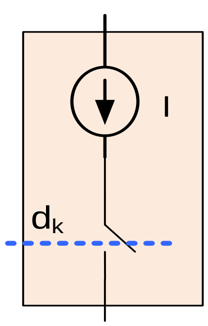
Stay Safe and Stay Healthy !

End of Lecture 16

Current Steering DAC



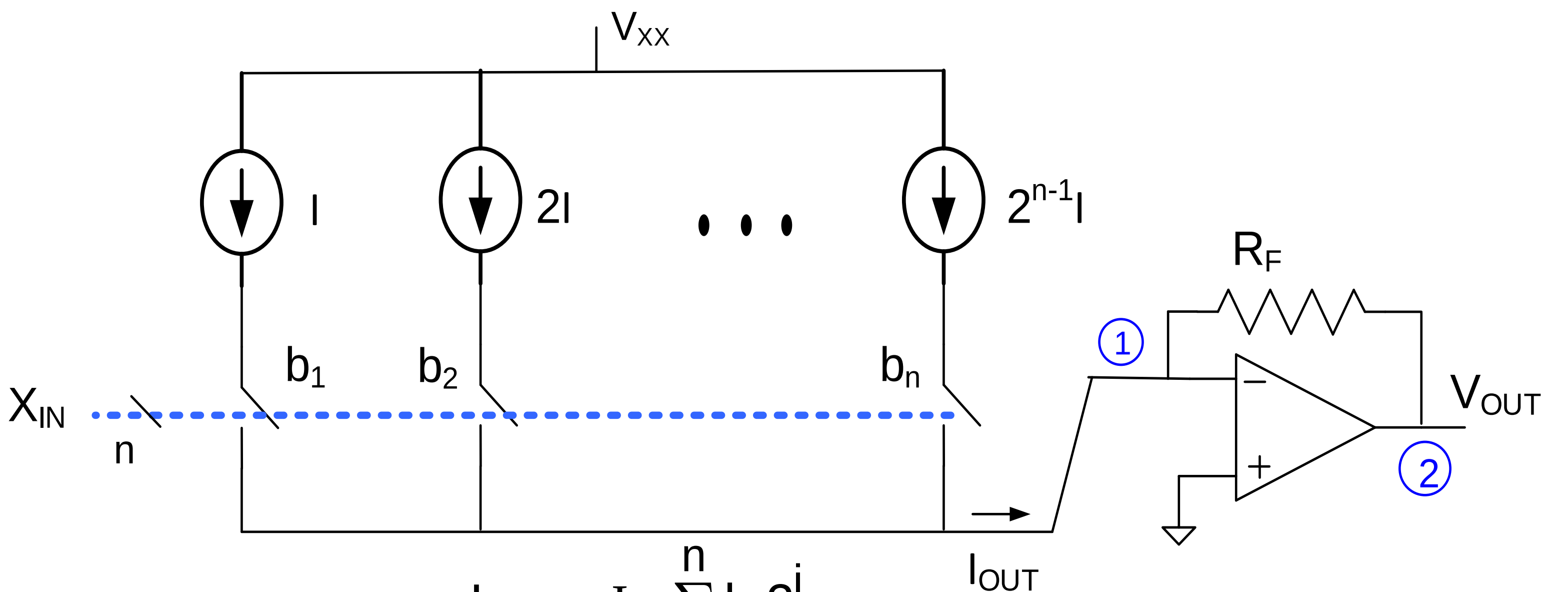
$$I_{OUT} = kI$$



Unary Slice Cell

- Switch impedance of little concern
- Bottom-plate switching
- Low DNL
- Decoder impractical for large n

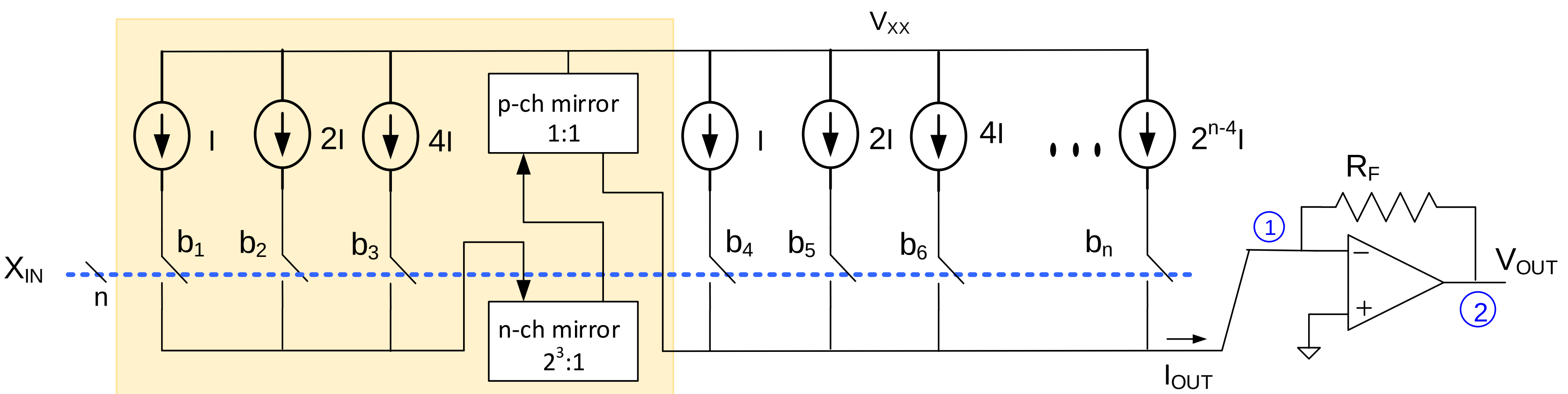
Current Steering Binary DAC



$$I_{OUT} = I \bullet \sum_{i=1}^{n} b_i 2^i$$

- eliminates decoder
- DNL not good for large n
- area ratio from MSB source to LSB source too large for large n (can make I only so small)

Current Steering Binary DAC

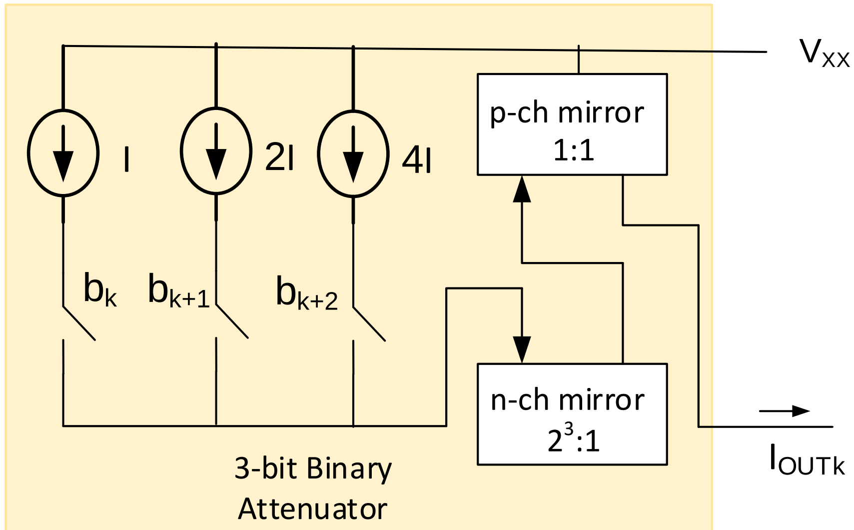


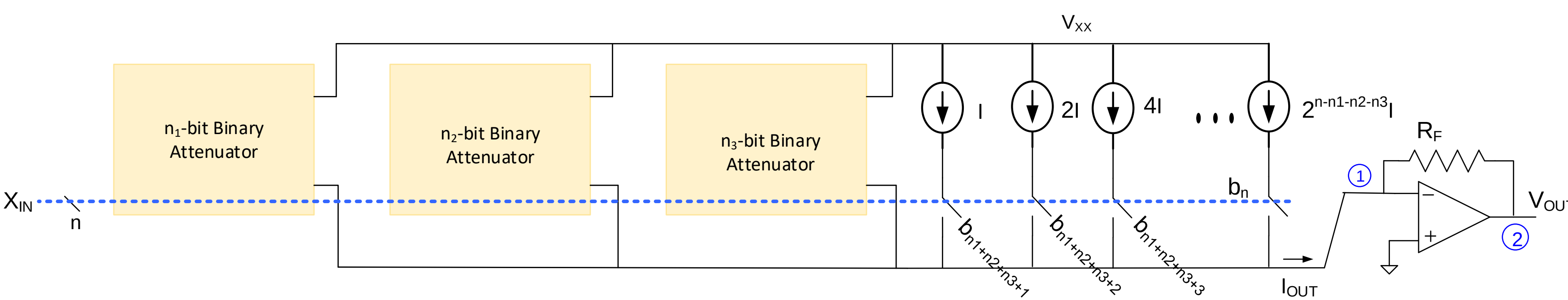
$$I_{OUT} = I \bullet \sum_{i=1}^{n} b_i 2^i$$

- reduces total current spread of bit cells
- reduces total number of bit cells (since cells are bundled)
- can repeat mirror current attenuator
- can change number of bits in each current attenuator stage
- Scale currents down in LSB portion rather than scale current up in MSB portion

How is performance affected by reducing the number of unary cells?
Is too much area allocated to the LSB cells?

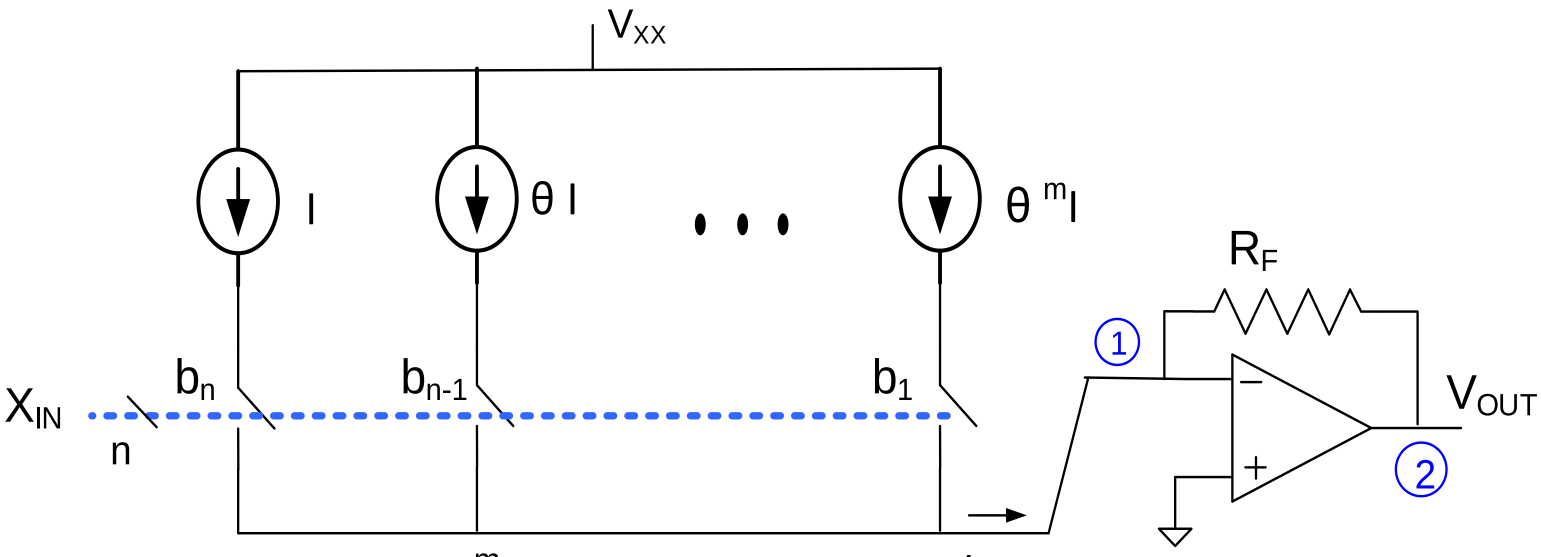
Current Steering Binary DAC





- LSB performance not critical
- Limit number of binary attenuators to avoid accumulating too much error

Sub-Radix Current Steering DAC



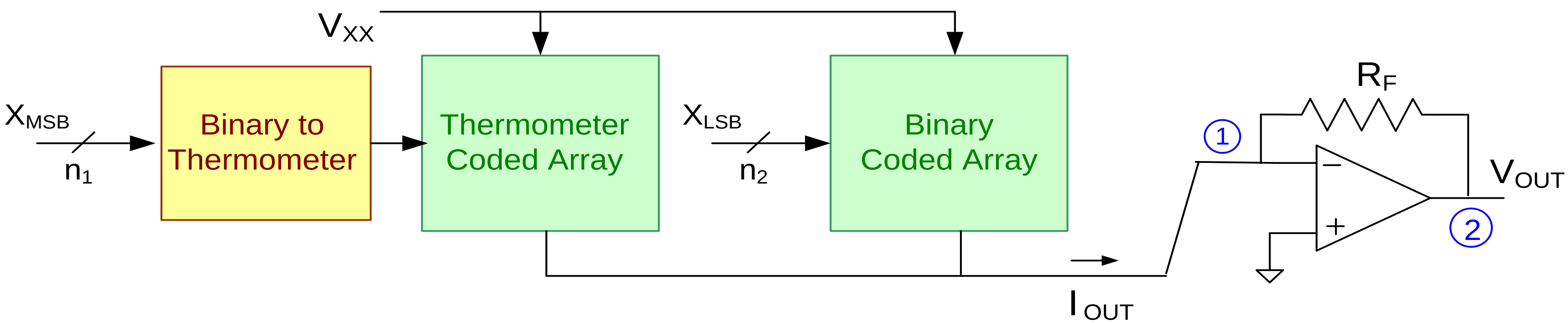
$I_{OUT} = I\sum_{i=1}^{m} \tilde{d}_i \theta^i$ m>n-1

Typically 1.9<θ<1.99 (Depending on ratio-matching accuracy of current sources)

Takes smaller steps so takes more steps to cover range

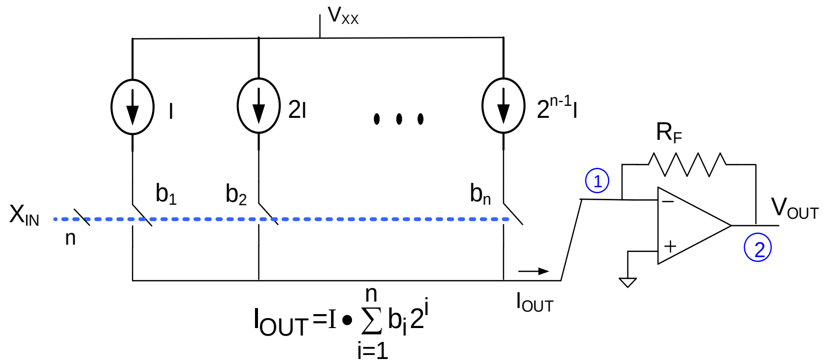
Current Steering DAC

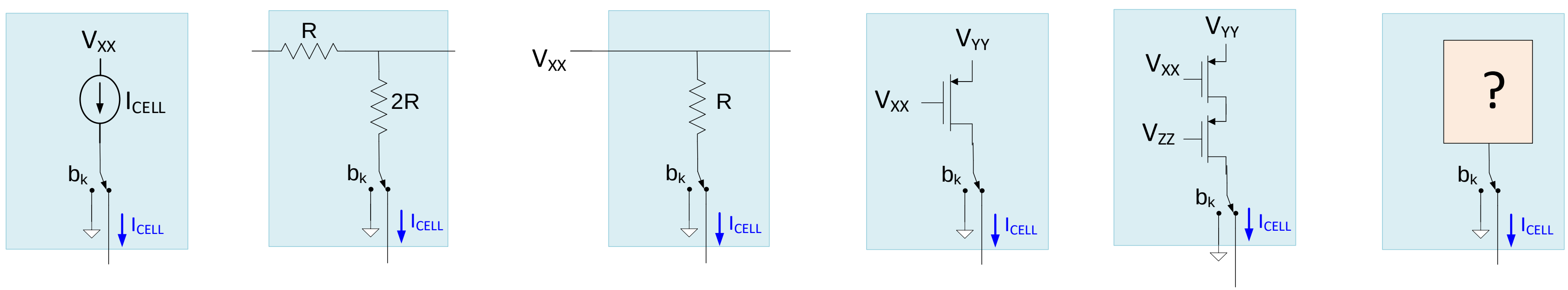
Segmented Structure Widely Used



- Binary code LSBs to reduce Decoder Complexity
- Thermometer Code MSB to manage DNL
- Partitioning between Thermometer and Binary Coding is critical

What Cells Are Used for Current Steering DAC





- What characteristics are important in a given process ?

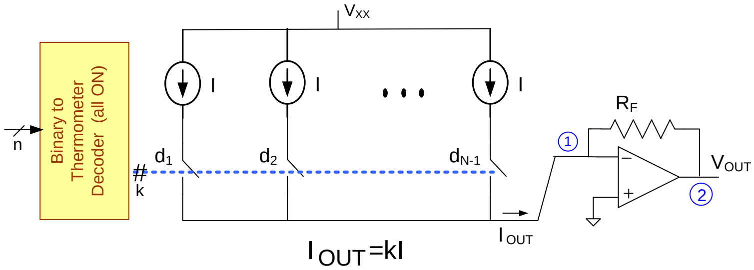
  R_{OUT}? Speed?

  Matching? Power ?

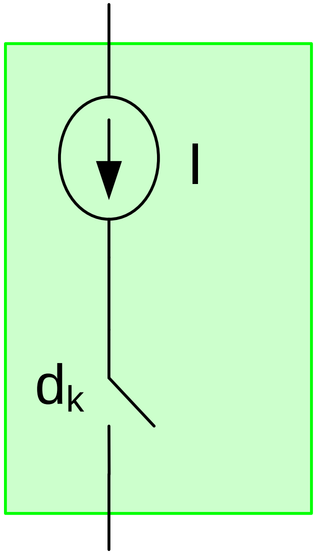
  Area (cost) ? Linearity ?

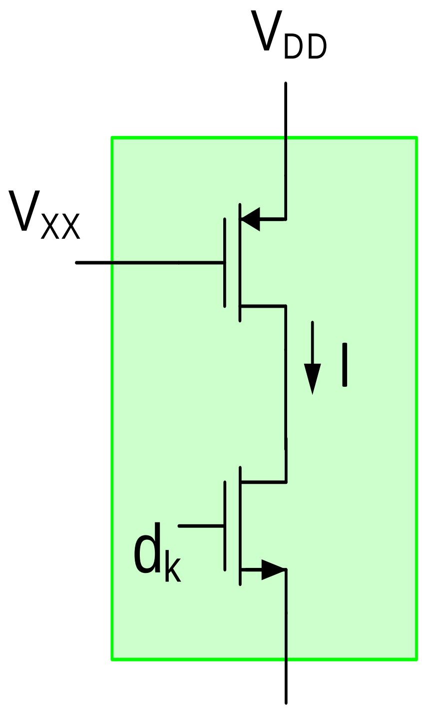
- What cells are used ?

Current Steering DAC



Current Source Bit Cells:





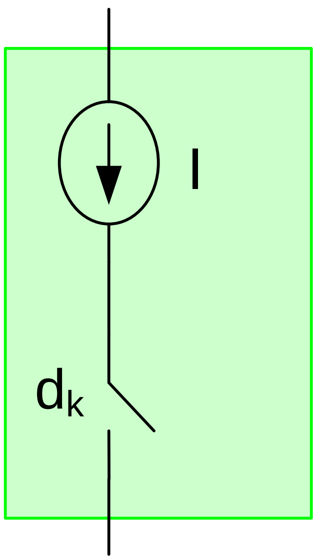
Bottom plate switching

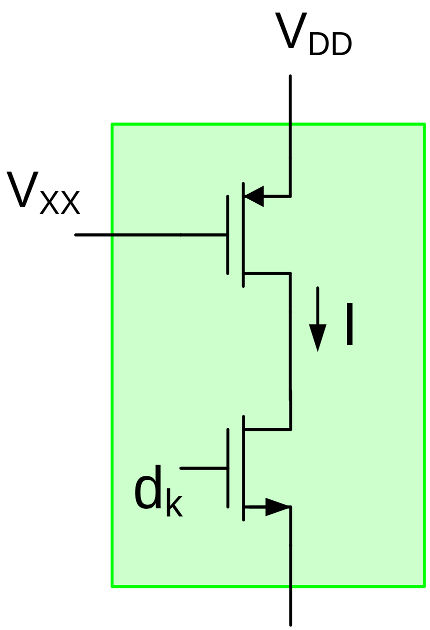
Is output impedance of current sources of concern?

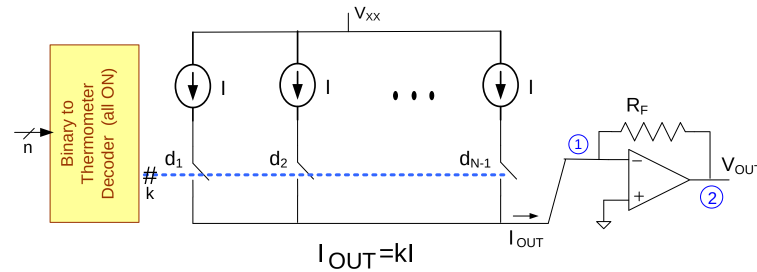
No ! Matching is important but linearity is not

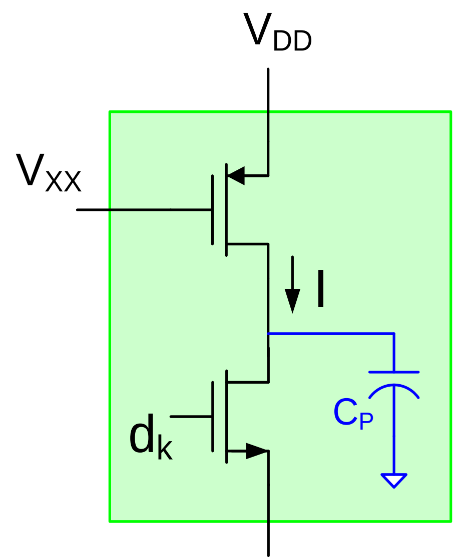
Current Steering DAC

Current Source Bit Cells:





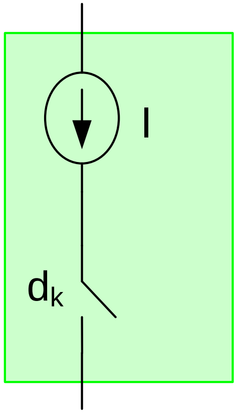


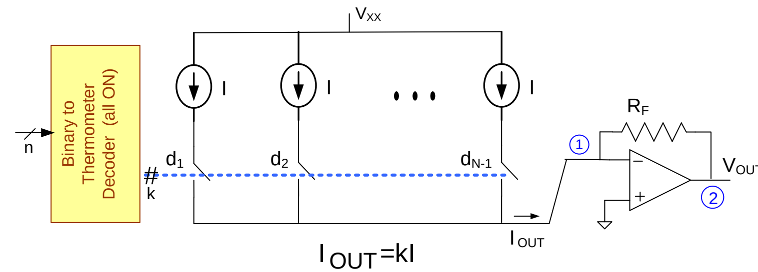


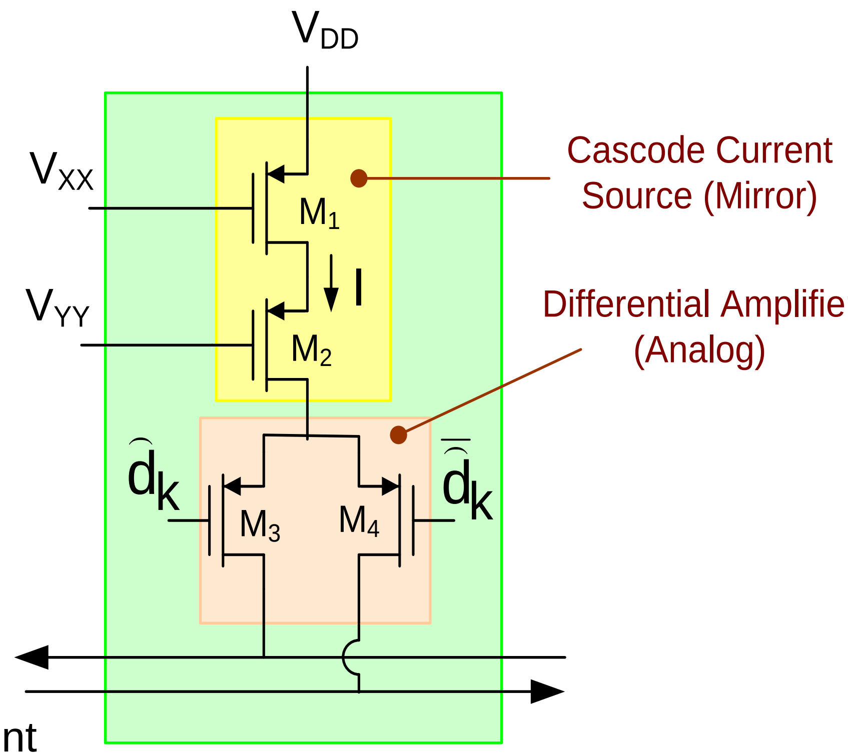
Parasitic capacitance will charge to V_{XX} before current source saturates

Power dissipation is code dependent

Current Steering DAC

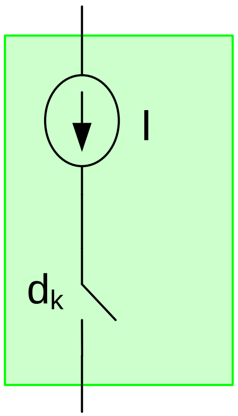


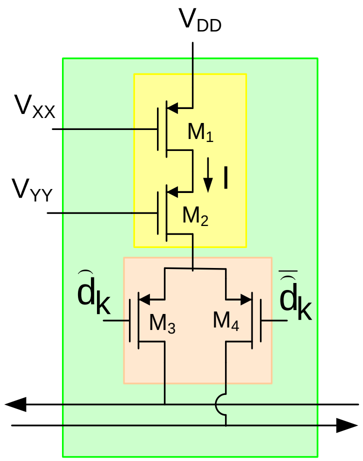


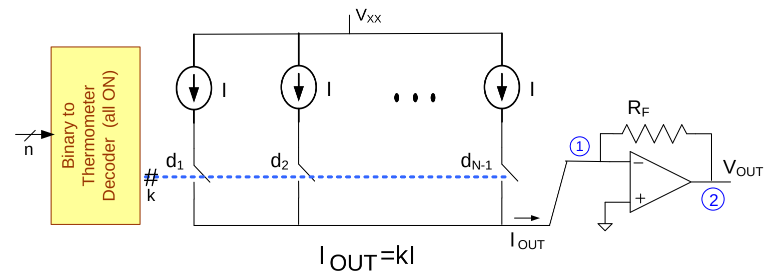


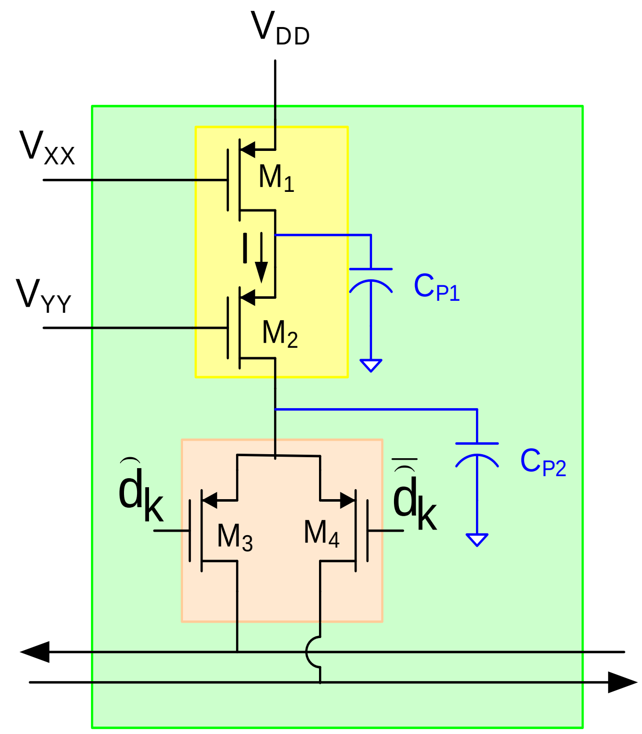
- Current steering instead of current switching
- Power dissipation in current sources remains constant
- Smaller gate voltages can be used to steer current
- Dump current can provide differential DAC output

Current Steering DAC



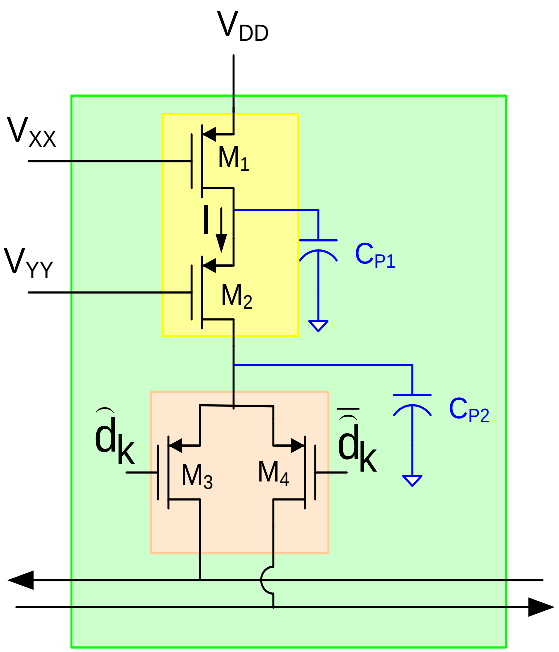


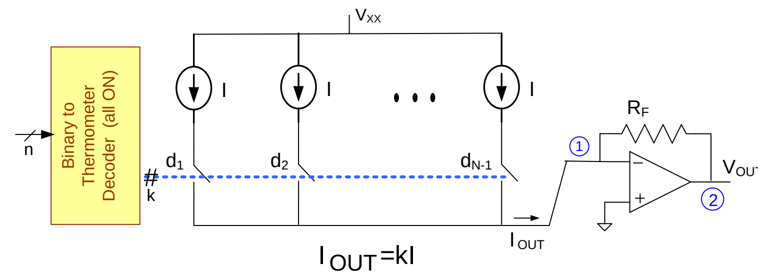


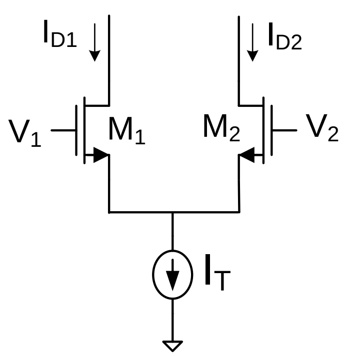


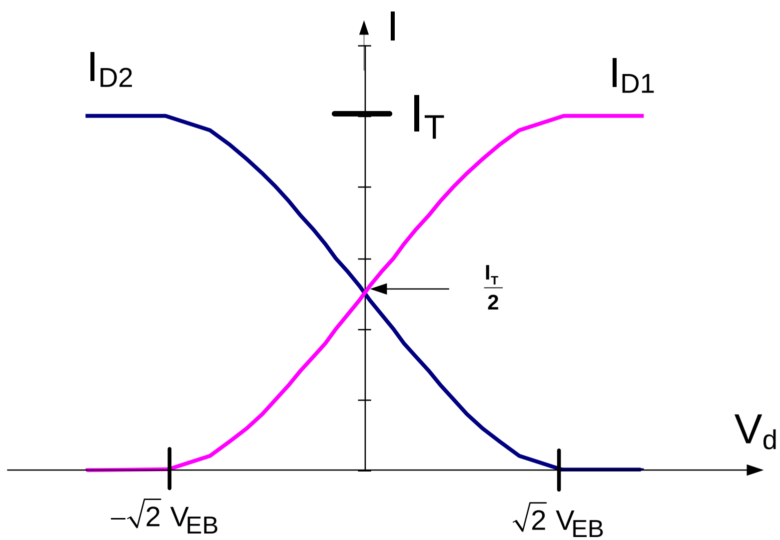
- Parasitic capacitances do not charge and discharge
- Current steering provides inherent cascading
- This structure is a double-cascode

Current Steering DAC





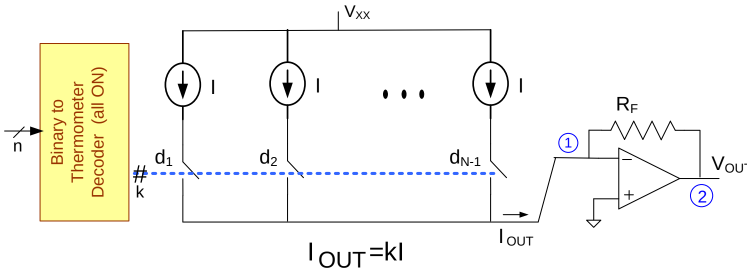


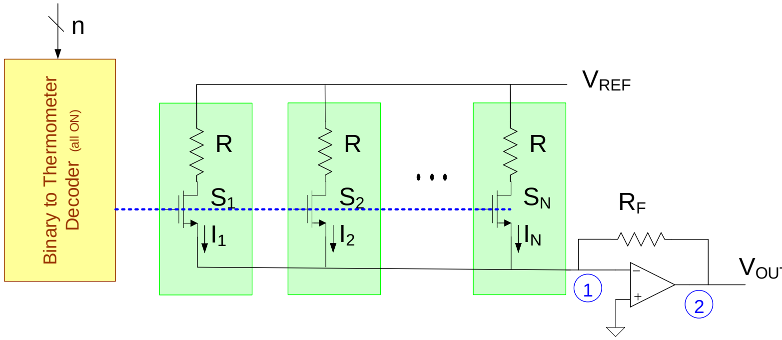


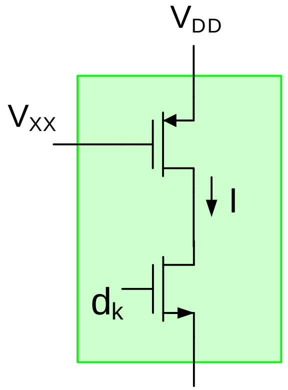
Signal swings only need to be large enough to steer current

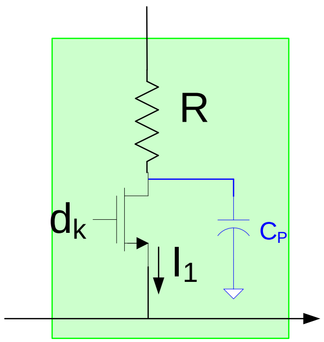
Current Steering DAC Comparison

Current-source bit vs Resistor-Based Bit Cell





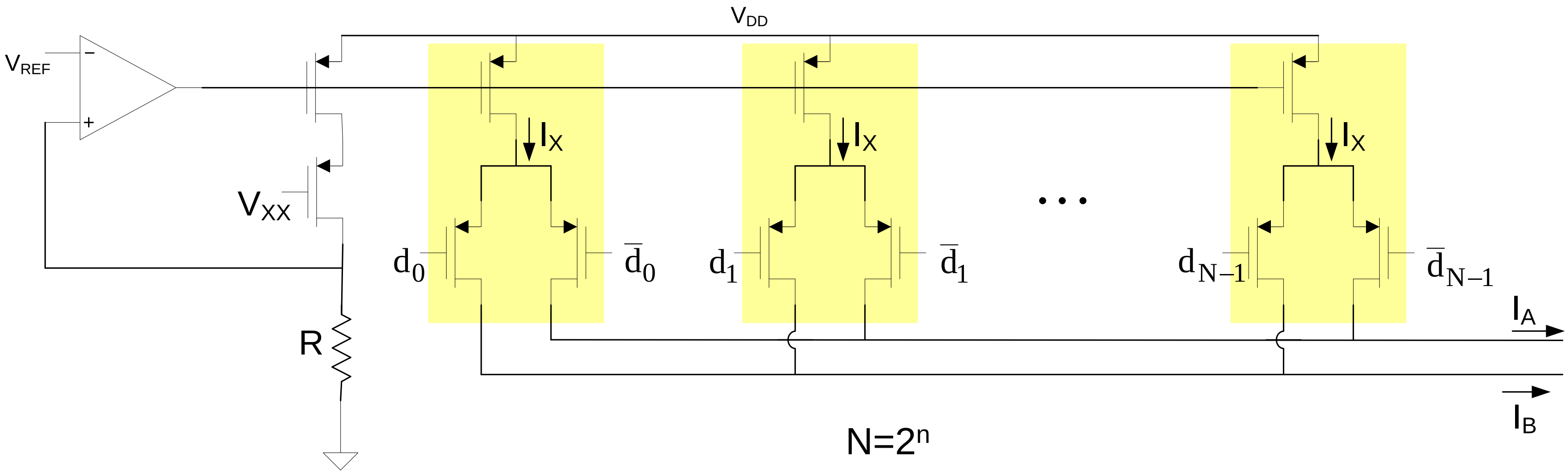




Do current-source bit cells also introduce code-dependent β in the feedback amplifier and thus code-dependent op amp settling?

No! β=1 for all codes with current-source bit cell.

Current Steering DAC with Supply Independent Biasing



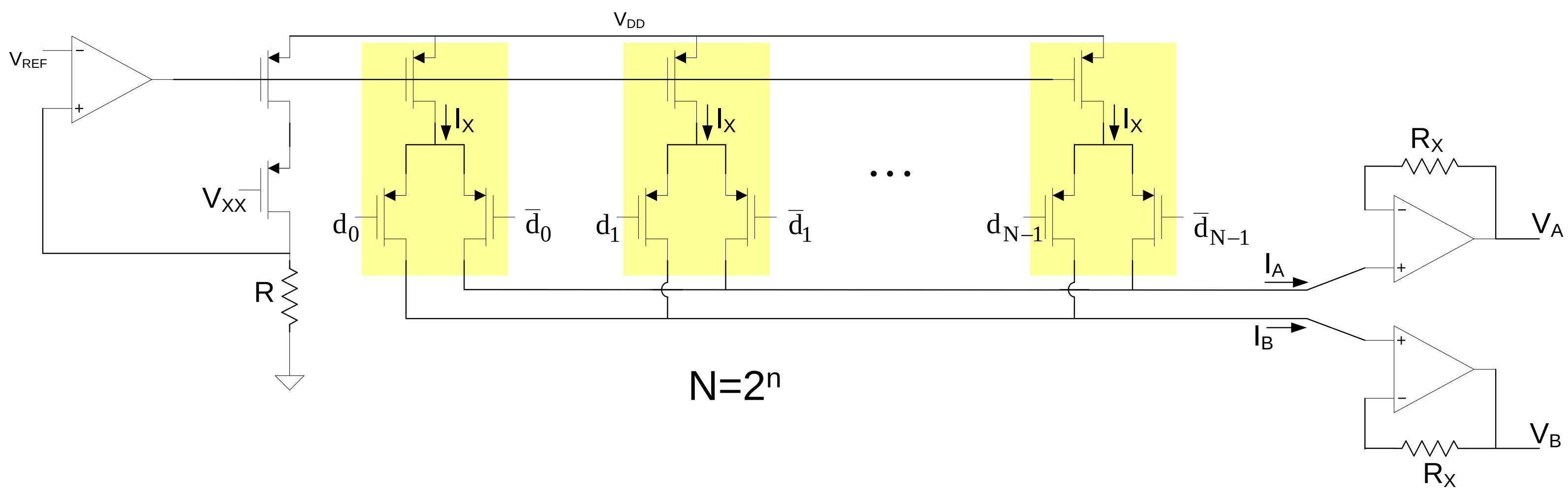
If transistors on top row are all matched, $I_X = V_{REF}/R$

Thermometer coded structure (requires binary to thermometer decoder)

$$I_A = \left(\frac{V_{REF}}{R}\right)\sum_{i=0}^{N-1} d_i$$

Provides Differential Output Currents

Current Steering DAC with Supply Independent Biasing

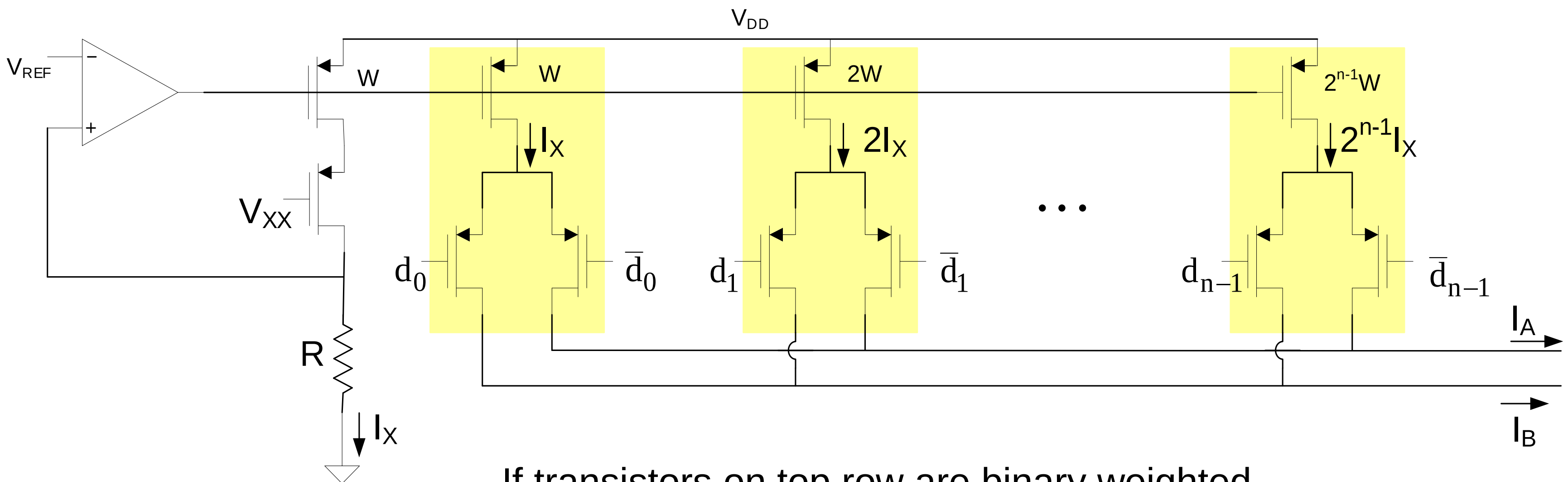


If transistors on top row are all matched, $I_X = V_{REF}/R$

$$V_A = \left(-V_{REF}\frac{R_A}{R}\right)\sum_{i=0}^{N-1} d_i$$

Provides Differential Output Voltages

Current Current Steering DAC with Supply Independent Biasing



If transistors on top row are binary weighted

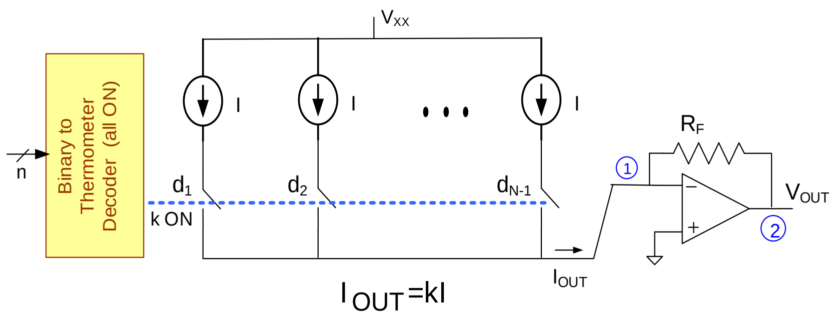
$$I_A = \left(\frac{V_{REF}}{R}\right)\sum_{i=0}^{n-1} \frac{d_i}{2^{n-i}}$$

Provides Differential Output Currents

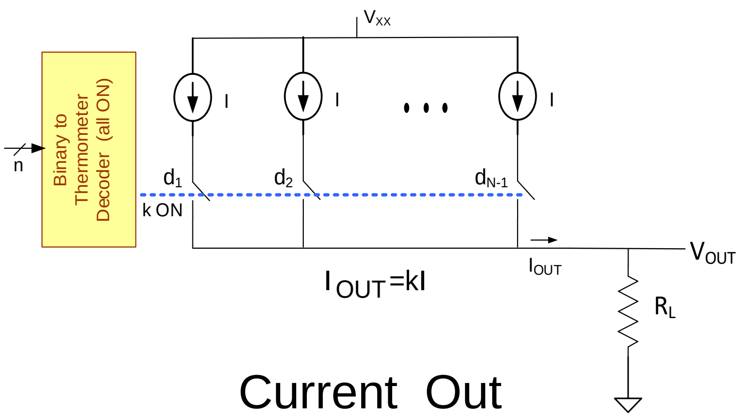
Will usually use parallel connections of unary transistor cells to increase effective W

Does this serve as an MDAC?

Current Steering DAC



Voltage Out



Current Out

- Many current steering DACs have an output current instead of an output voltage
- Output voltage is often established by steering current to a fixed external resistor (50Ω or 100 Ω)
- Most basic current steering architectures with a high output impedance can be used by simply removing the op amp
- Whereas output impedance of current sources was not of major concern when driving a null-port, it can be of major concern for current output
- Speed may improve and power dissipation may decrease in internal circuitry if output is current