Matching, Segmentation and Linearity in Data Converters

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IEEE, CAS Seminar

October 30th, 2001

THE WORLD LEADER IN DSP AND ANALOG
TEXAS INSTRUMENTS

Presentation Contents

Part 1: Data Converters

- **Nonlinearity.**
- **Segmentation.**

Part 2: Mismatch

- **Random.**
- **Systematic.**

Part 3: Measurement

- **Resistors String DACs**
- **Capacitors SAR ADCs**

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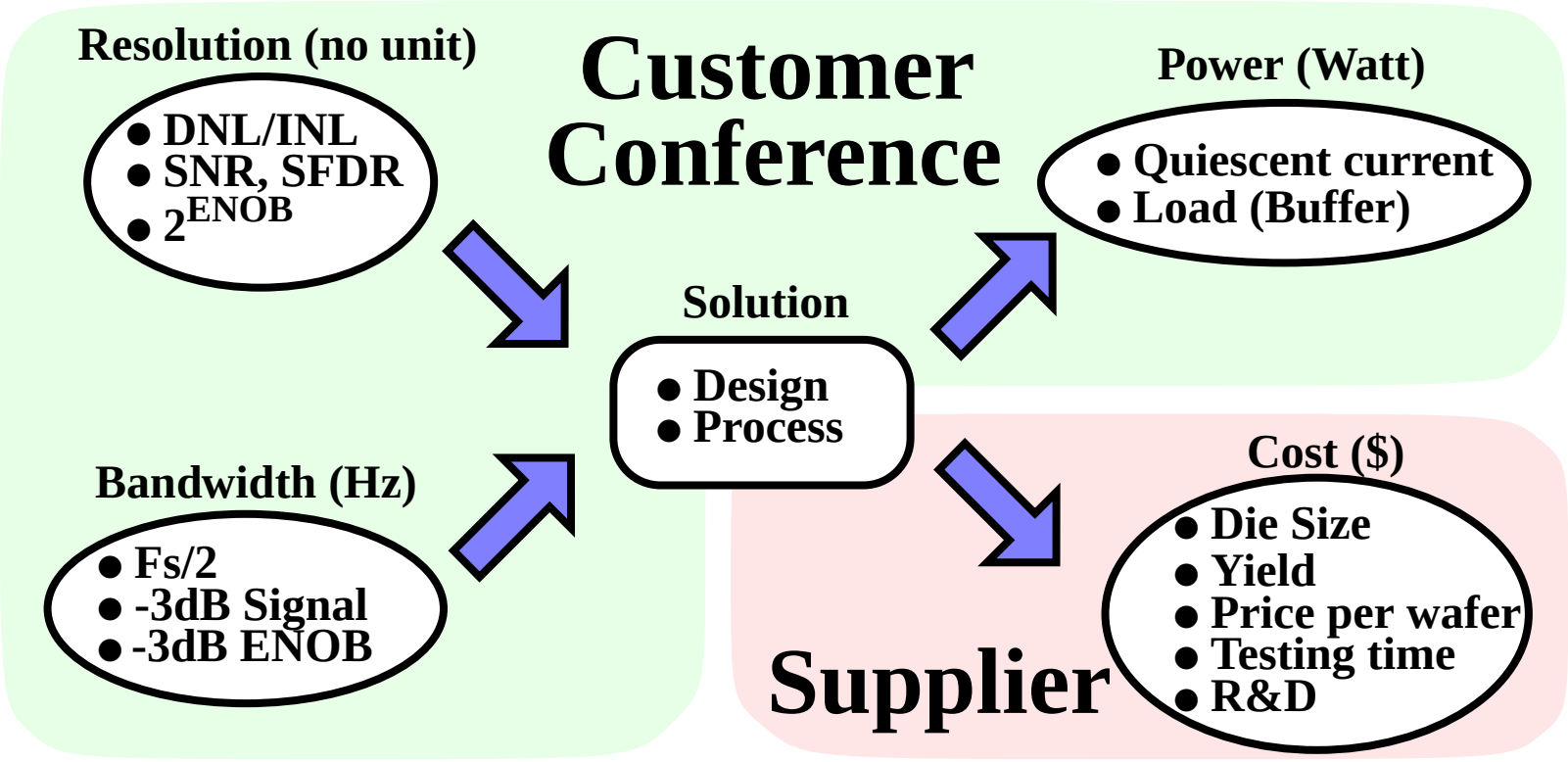
Data Converter Figure of Merit

✔ **Segmentation is an important part of the design solution. Drastic impact on the FOM of the converter.**



$$FOM = \frac{Power \bullet Cost}{Resolution \bullet Bandwidth} (J\$)$$

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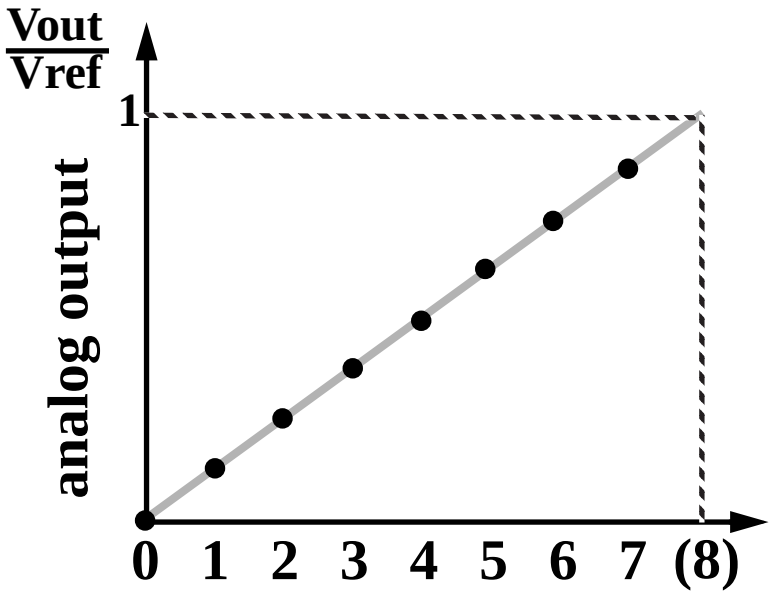
Converter Fundamentals

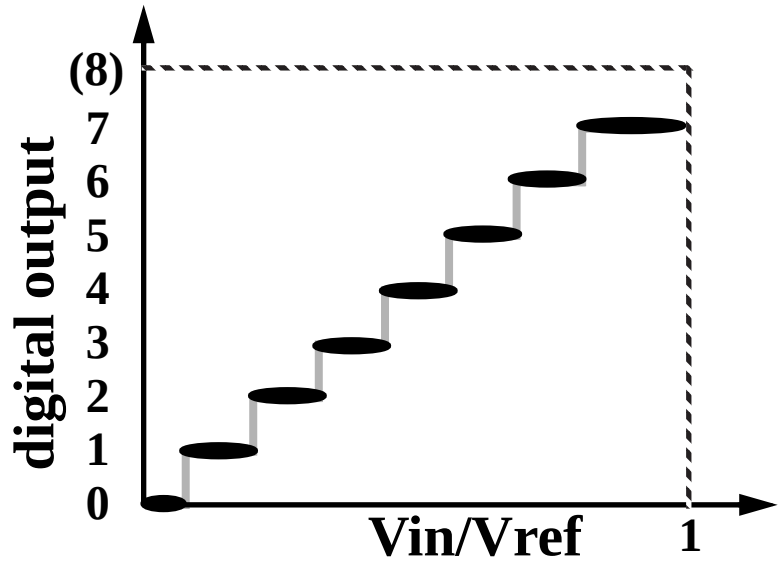
✔ Digital to Analog



$$SQNR = 20\log\left(\frac{V_{ref}}{2\sqrt{2}} \Big/ \frac{V_{ref}}{2^n\sqrt{12}}\right) = 6n + 1.7$$

- $Vout=(b_2 2^{-1}+b_1 2^{-2}+b_0 2^{-3})Vref$
- $Vlsb = Vref/2^n$.

✔ Analog to Digital



- $Vin+Eq=(b_2 2^{-1}+b_1 2^{-2}+b_0 2^{-3})Vref$
- $-Vlsb/2 < Eq < Vlsb/2$

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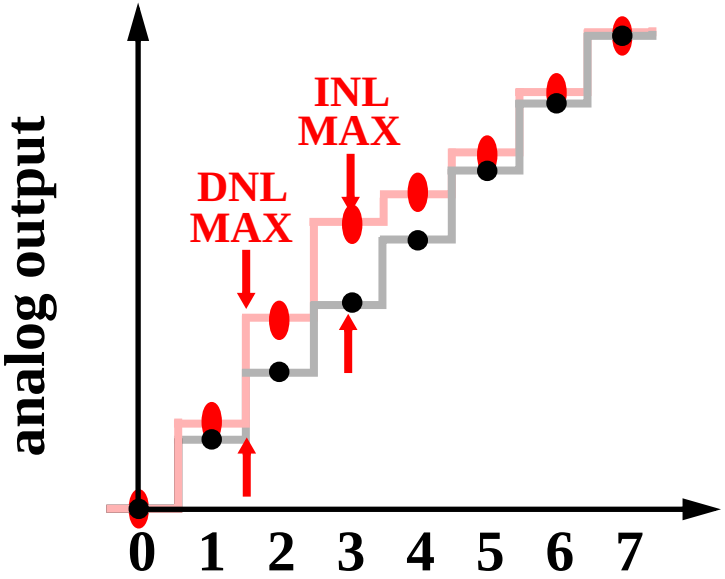
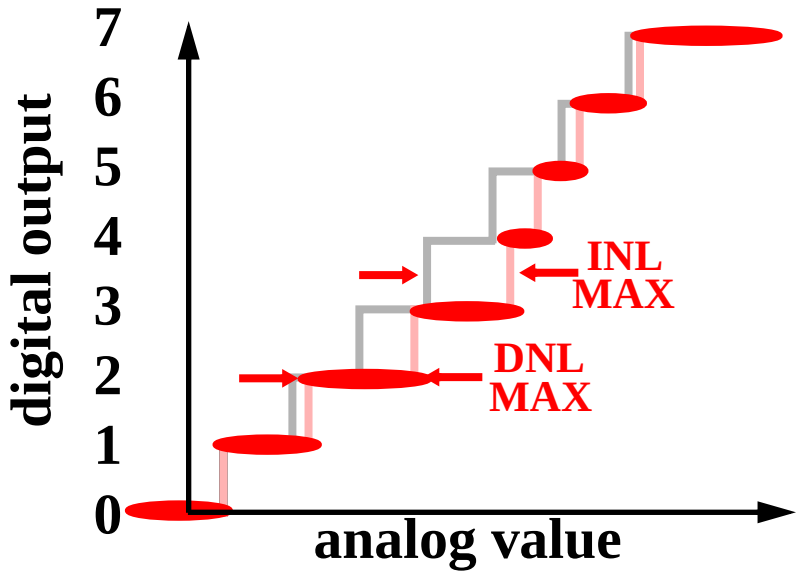
Nonlinearity Fundamentals

✔ Digital to Analog



- Ramp the 2^n codes.
- 1 conversion per code.
- Linearity based on step size

✔ Analog to Digital



- Ramp from Vrefm to Vrefp
- several conversions per code
- Number of hits per code.

The linear transfer function is obtained by a fit (end-points, RMS)

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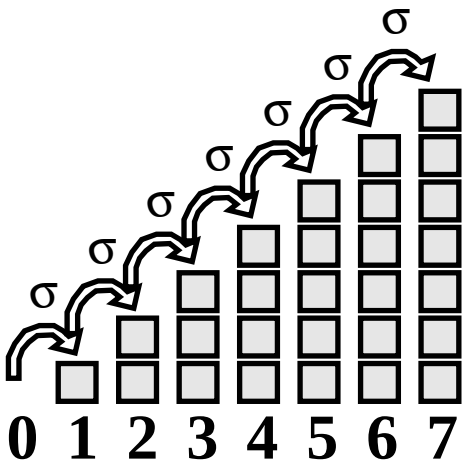
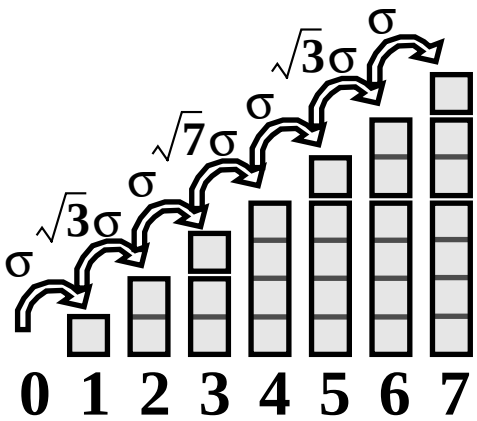
Binary versus Thermometer

✔ **Thermometer Code**



3 bits converter
Monotonicity
(+/-1 LSB DNL)

✔ **Binary Code**



- 7 elements (7 units)
- Same weight
- Same DNL for all code
- Mismatch 3σ<99%
- Decoding&routing

- 3 elements (7 units)
- Weight is power of 2
- Worst DNL at MSB code
- Mismatch 3σ<37%
- Straigth adressing

Note: For both examples, the DNL σ is an approximation.

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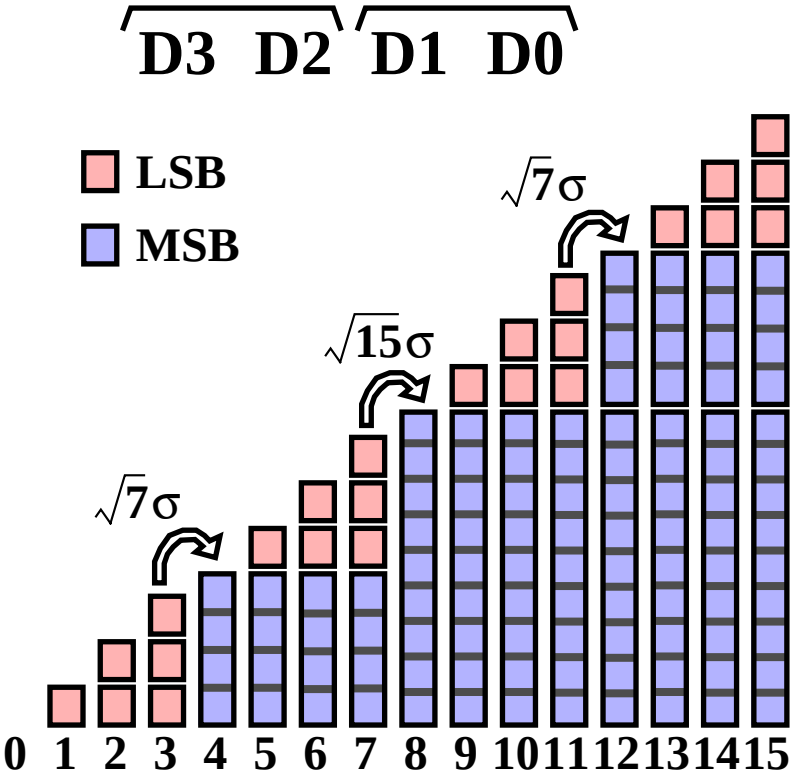
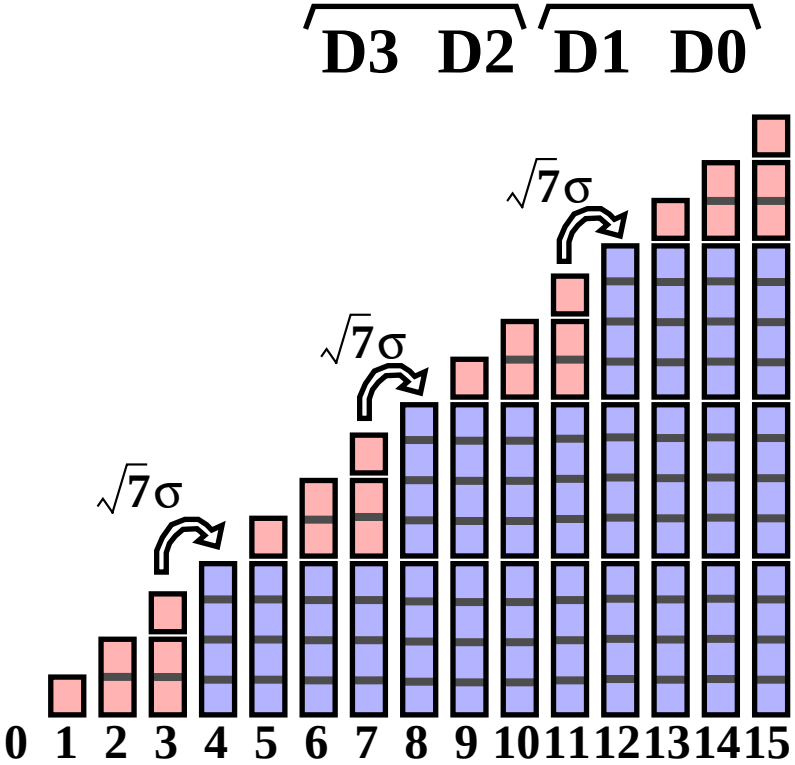
Segmentation (MSB/LSB)

✔ **Binary-Thermometer**



- 5 elements (15 units)
- all units switched at MSB

✔ **Thermometer-Binary**



- 5 elements (15 units)
- minimize switched units
- good for linearity and glitch

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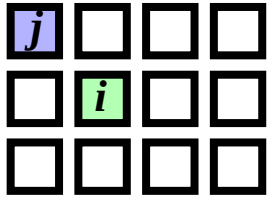
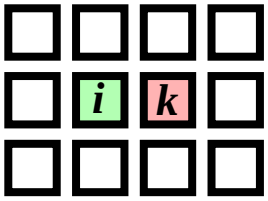
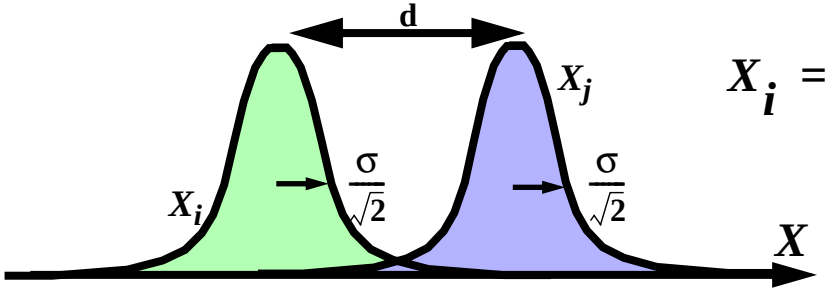
Random or Systematic Errors

✔ **Total mismatch is the sum of random and systematic errors.**
Inter-die statistical study splits systematic *d* from random σ.
Layout&design optimum minimizes overall mismatch: d+3σ.

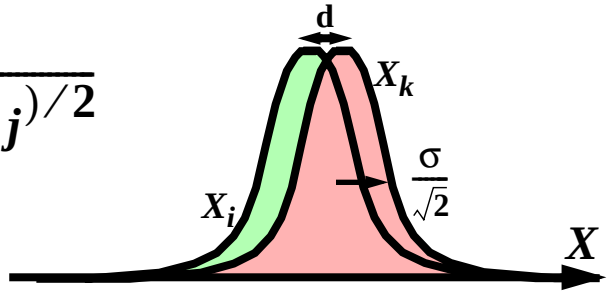


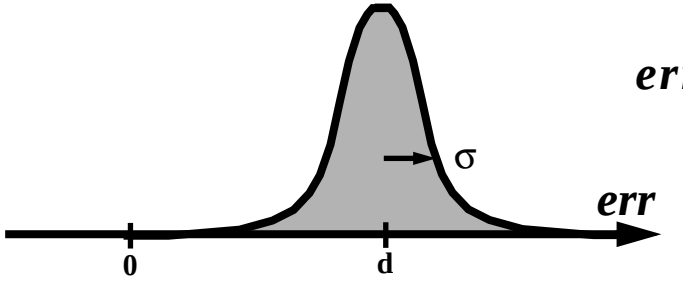
C_i is the measured characteristic of the element i.



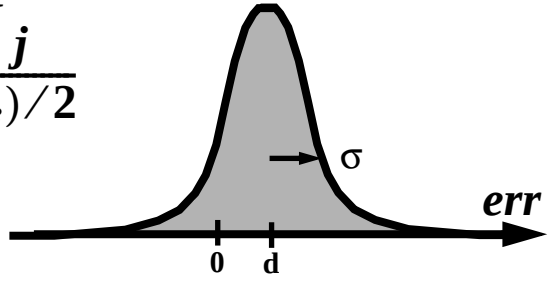


$$X_i = \frac{C_i}{(C_i + C_j)/2}$$





$$err_{ij} = \frac{X_i - X_j}{(X_i + X_j)/2}$$



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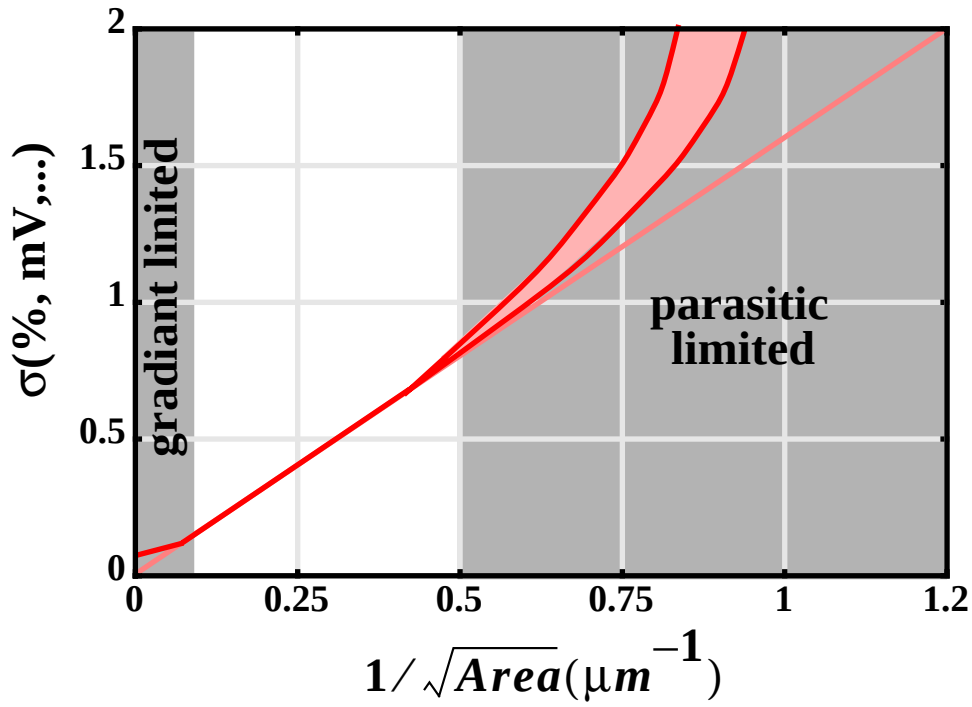
Device Random Mismatch

✔ **Random mismatch is due to microscopic process fluctuations.**

These variations are ruled by statistical law: $\sigma^2 = \sum_i \sigma_i^2$

The equation $\sigma = \alpha / \sqrt{WL}$ **is only valid in a certain range.**



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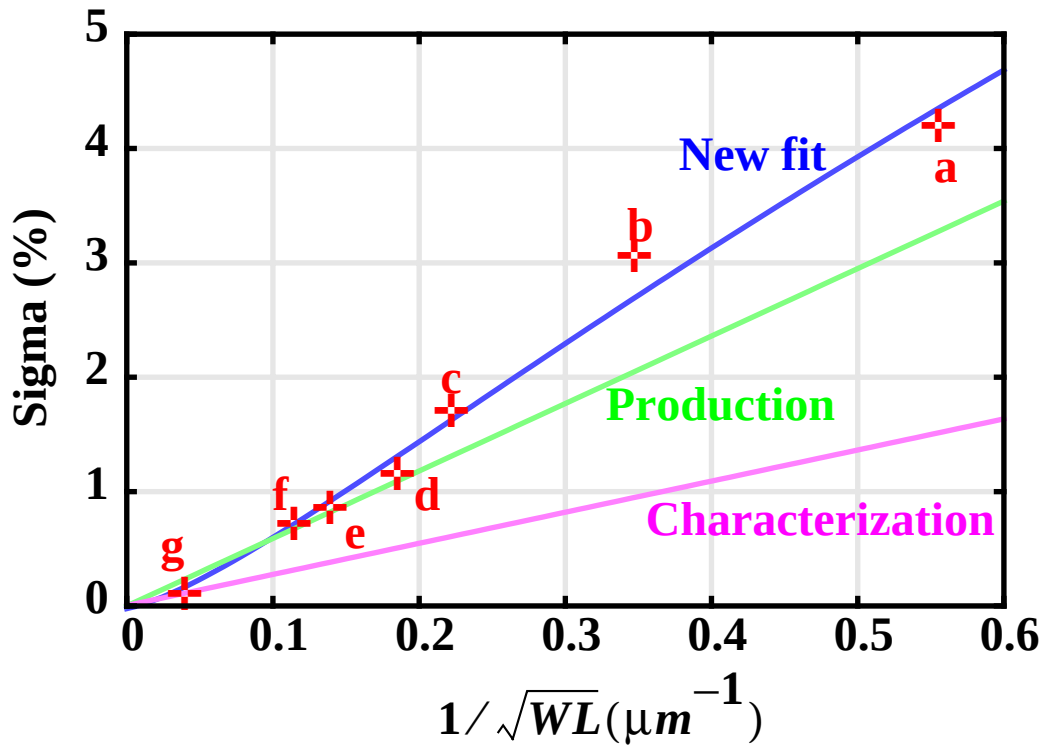
Parasitics Random Mismatch

✔ **Parasitic matching are not controlled and usually poor.**

Mismatch equation $\sigma_{\%} = \dfrac{\sqrt{(R_m \cdot \sigma_{\%m})^2 + (R_p \cdot \sigma_{\%p})^2}}{R_m + R_p}$



a: TXQ ($1.8*1.8\mu m^2$)
b: TXI ($2.9*2.9\mu m^2$)
c: AFC ($4.5*4.5\mu m^2$)
d: AFC ($5.4*5.4\mu m^2$)
e: TXI ($7.2*7.2\mu m^2$)
f: DAC3 ($3.6*20.5\mu m^2$)
g:TestChips ($>300\mu m^2$)

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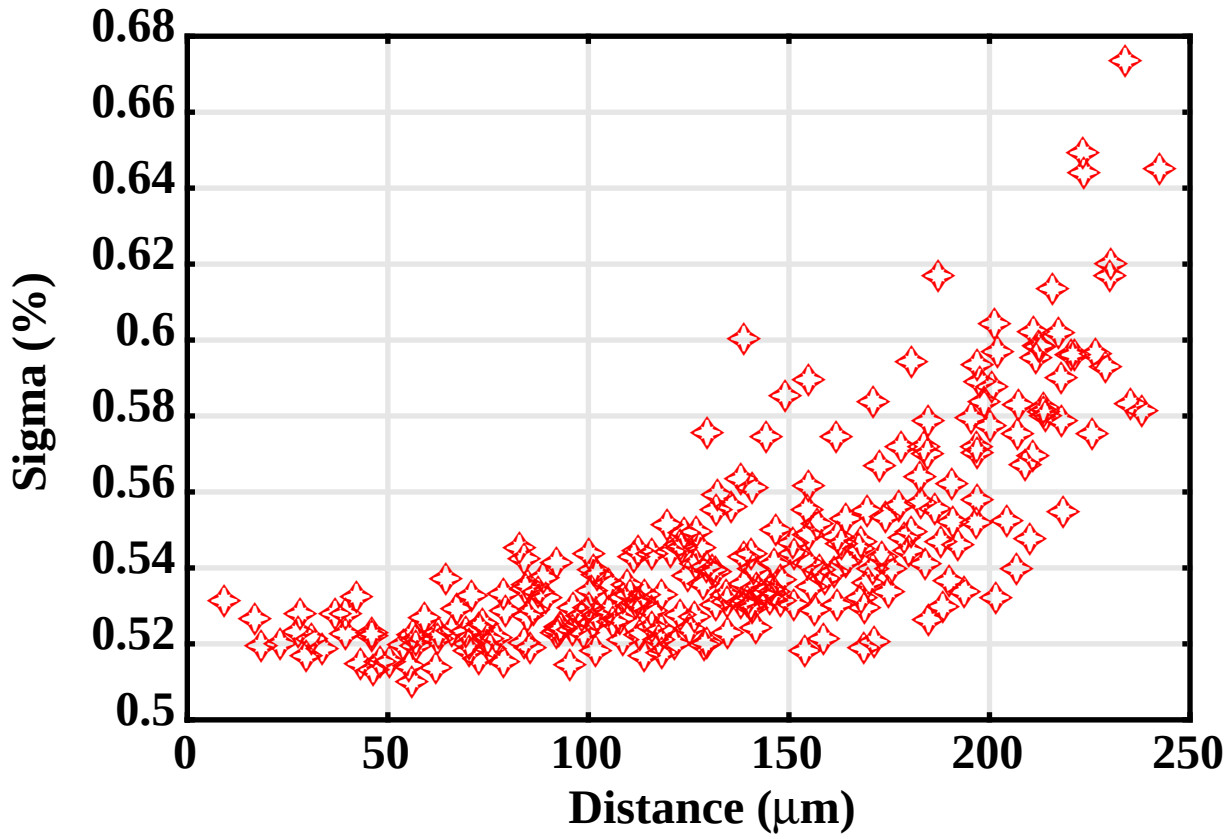
Gradiant Random Mismatch

✔ **Distance between devices degrades their matching properties.**

Mismatch equation $\sigma_{\%}^2 = \alpha^2 / WL + \beta^2 d^2$



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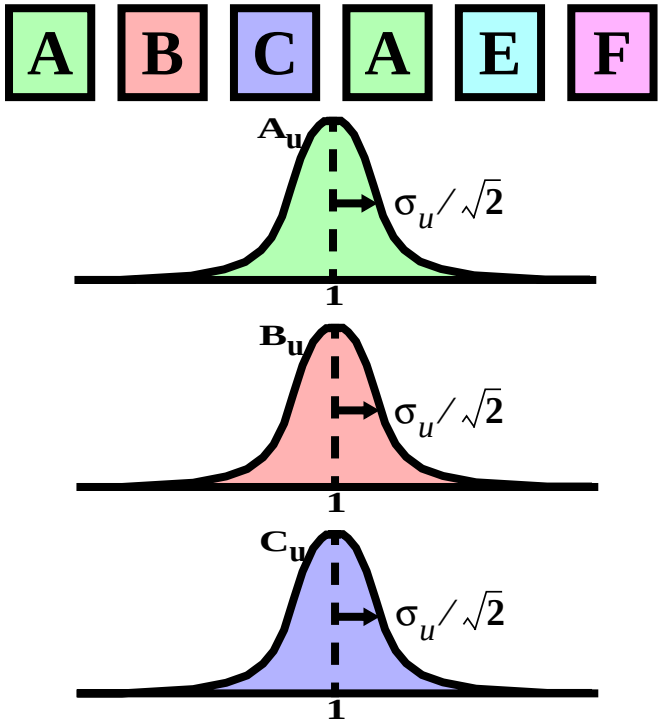
Matching within a group

- ✔ Mismatch of a device and the average value of it's group
- ✔ The device to match is part of the average ensemble!
- ✔ The correlation will skew the matching probability.



$$X_{avg} = \frac{1}{N}\sum_{i=1}^{N} X_i$$

$$M_A = \frac{X(A)/M - Xavg}{X_{avg}}$$

$$\sigma_A = \sqrt{\frac{M(N-M)}{N}}\ \frac{\sigma_u}{\sqrt{2}}$$

Device A has M units in a N units ensemble

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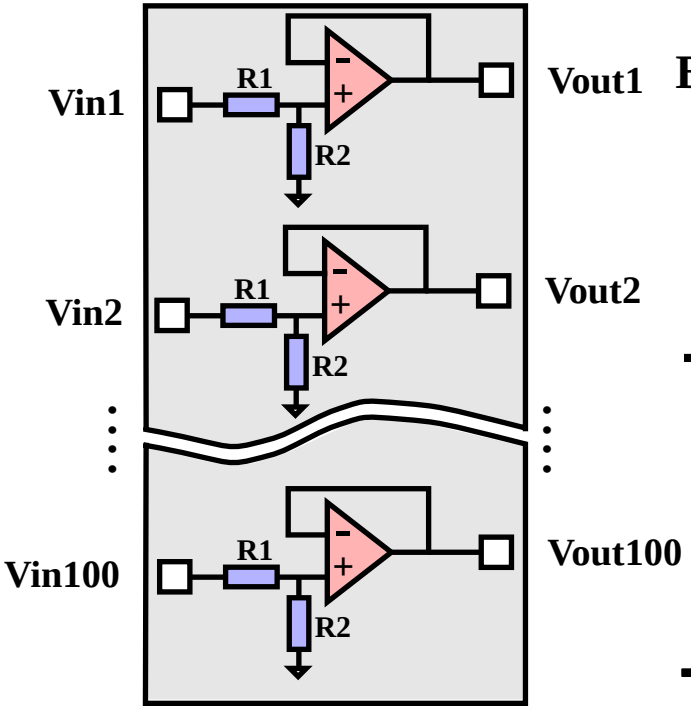
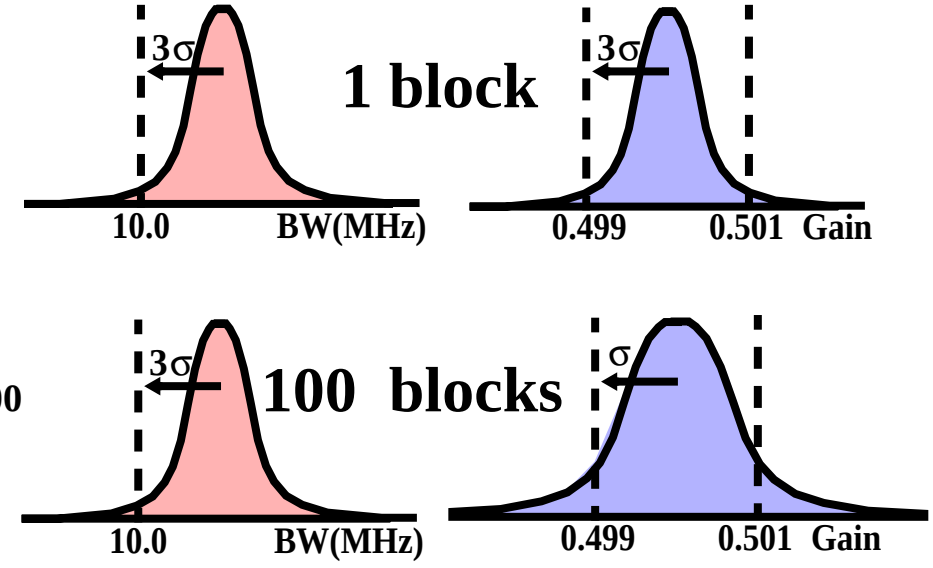
Random Matching and Yield

✔ **How many sigma mismatch are needed for yield?**
Most IC parameters (Gain, BW,..) are correlated within a die.
Mismatch is not! $\sigma_{CHIP} = \sqrt{N}\ \sigma_{BLOCK}$



Chip Specification:

Bandwidth> 10MHz **Gain=0.5 +/-1%**



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Systematic Mismatch

✔ A systematic mismatch is an error, caused by a macroscopic phenomenon which repeats itself identically on every circuits (layout), on one circuit of the reticle (photo-errors or particles).

✔ Relative error $\Delta P/P$ usually not proportional to $1/\sqrt{WL}$

✔ Can be corrected when related to layout or design.
Designer can minimize the causes or cancel the effects.

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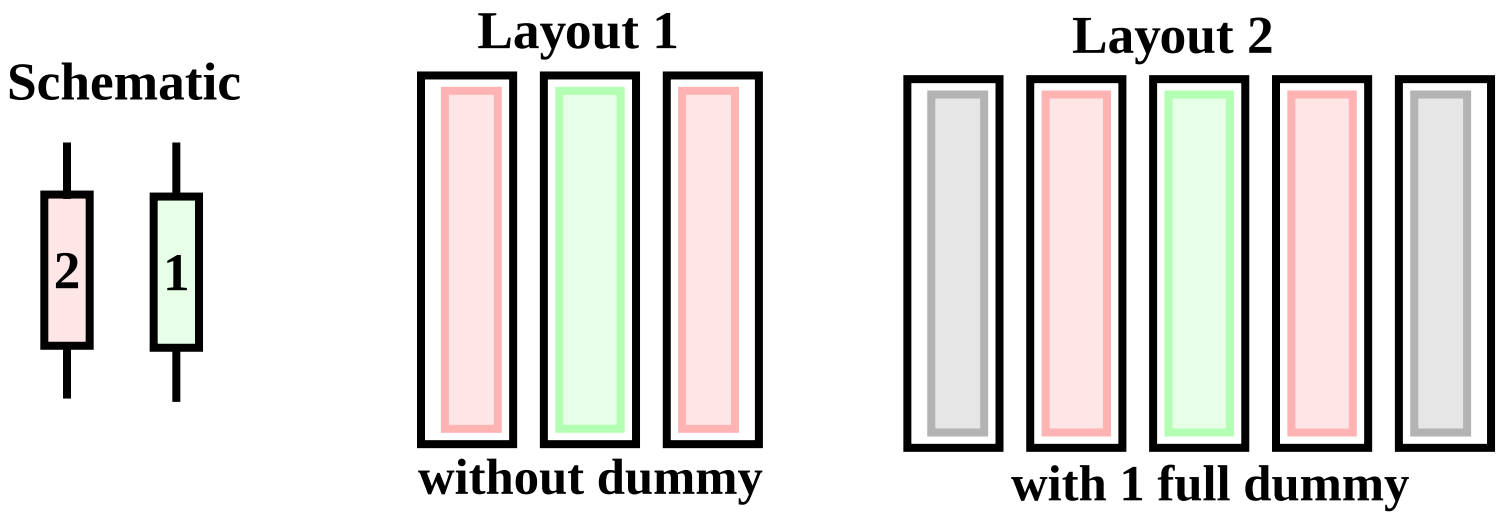
Etch Rate Variation

- ✔ Etching rate depends upon geometry of layer opening. Large opening grants more access to the etchant.

- ✔ Use dummy to ensure uniform etching
  Minimum dummy size is process dependant (~10µm Si)



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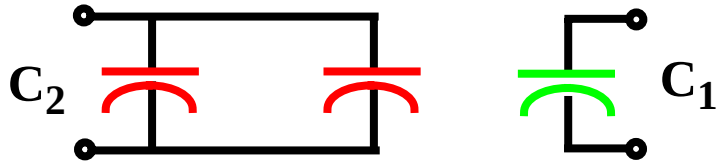
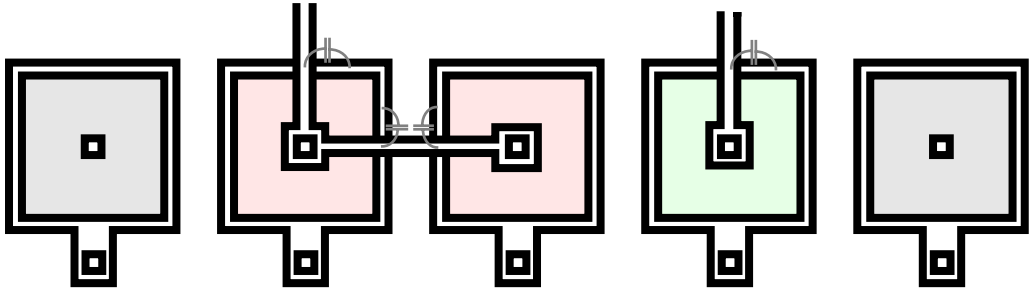
Interconnect Capacitance

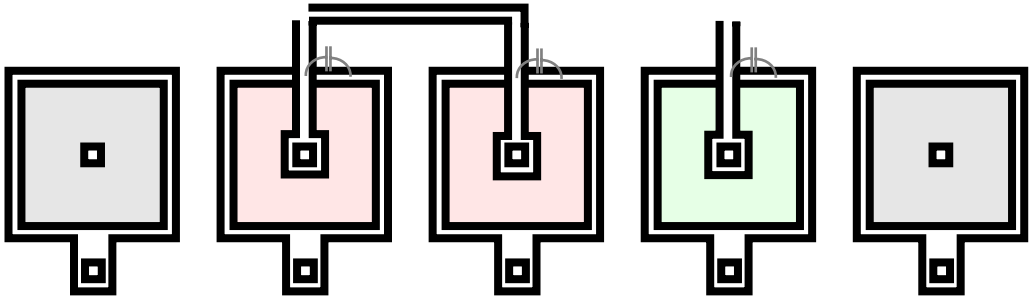
✔ **The interconnect line interacts with the bottom plate. Make uniform connection(bottom-top plates mask shift)**



Schematic
$C_1 = C$
$C_2 = 2C$



Layout 1
$C_1 = C + C_{p1}$
$C_2 = 2C + C_{p1,2,3}$



Layout 2
$C_1 = C + C_{p1}$
$C_2 = 2C + 2C_{p1}$

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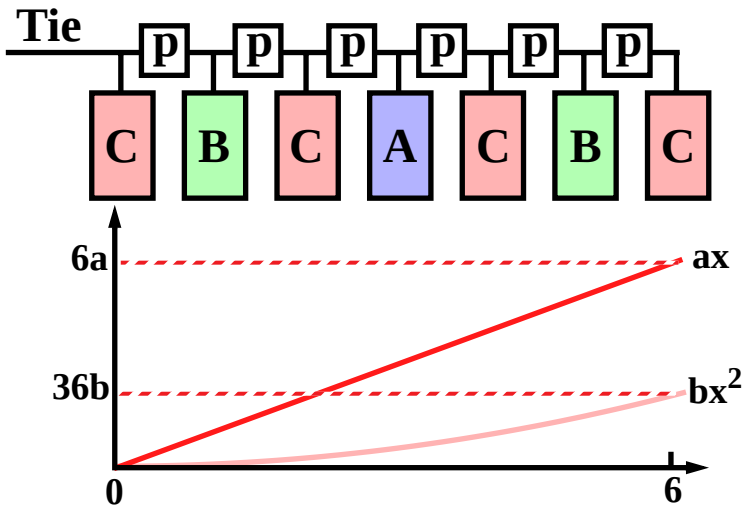
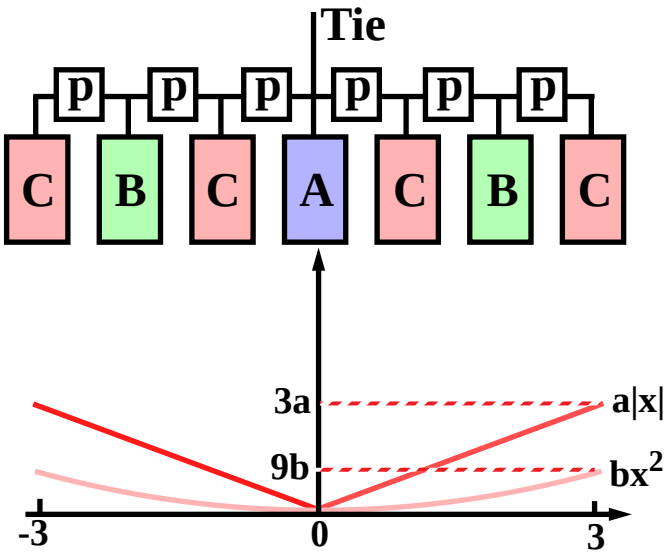
Distributed Parasitics

✔ **Importance of the connection location in the array**
Centering tie transform gradiant from 1st to 2nd order.
2nd order gradiant not cancelled on single unit elements





unit	(A,B,C)	A	B	C
x	3	3	3	3
x^2	13	9	13	14

unit	(A,B,C)	A	B	C
|x|	1.7	0	2	2
x^2	4	0	4	5

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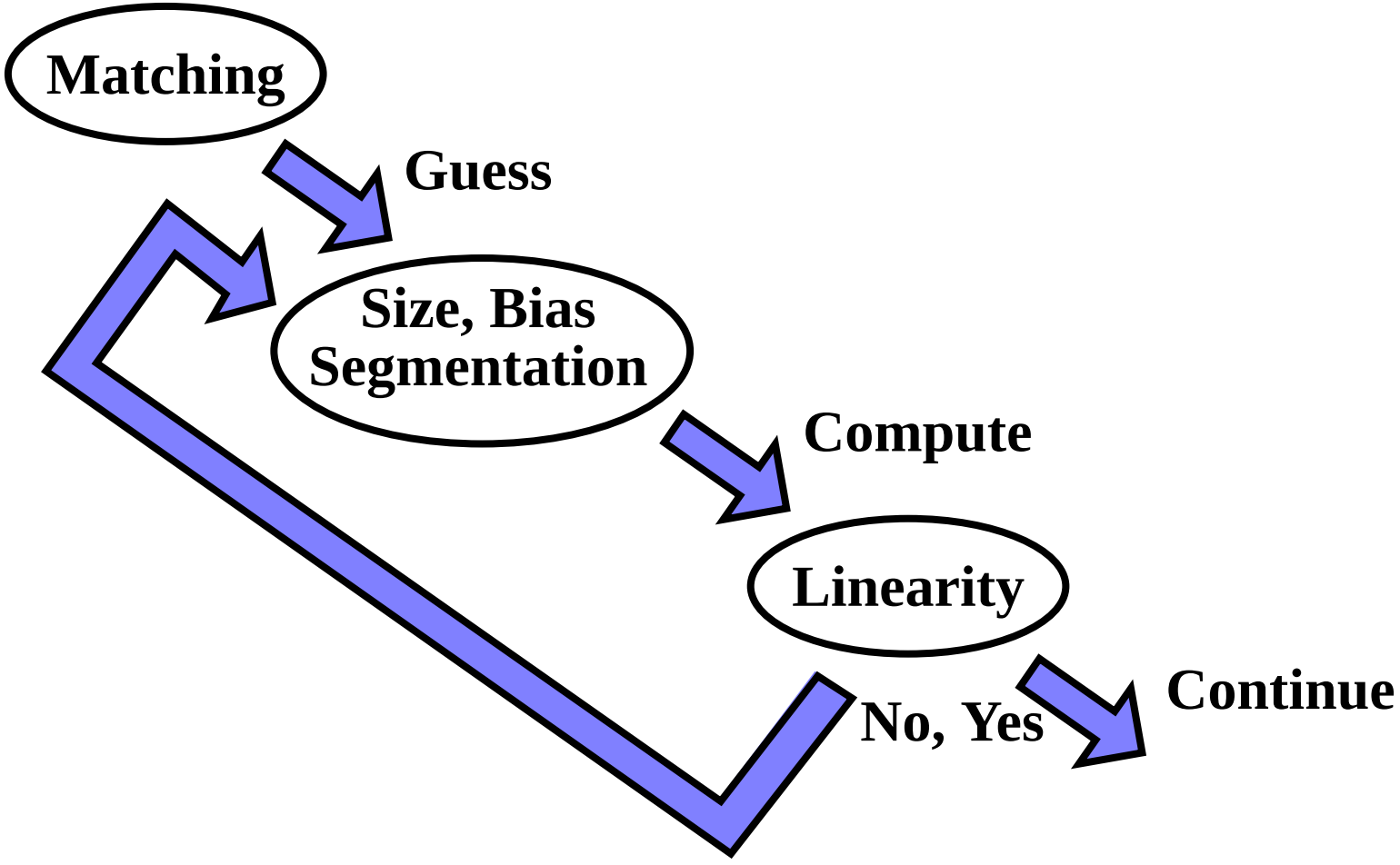
Data Converter Design

✔ Iterative method to determine Size, Bias and Segmentation. Good knowledge of mismatch allows a correct convergence



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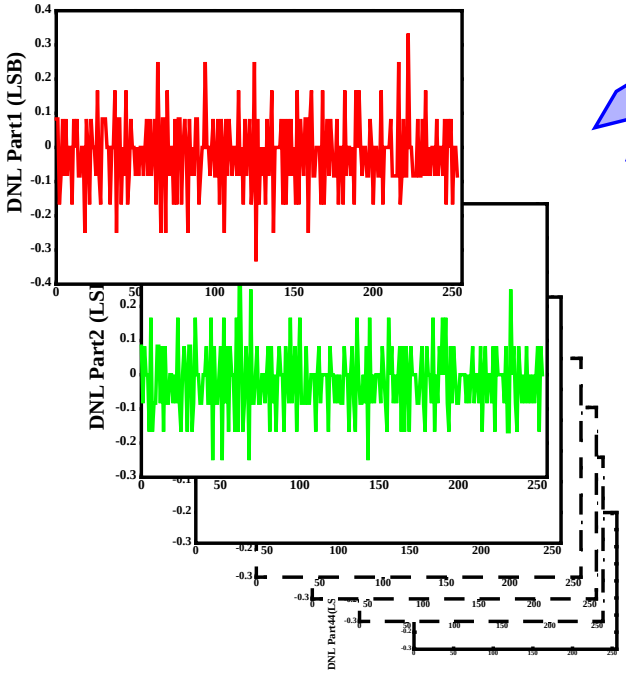
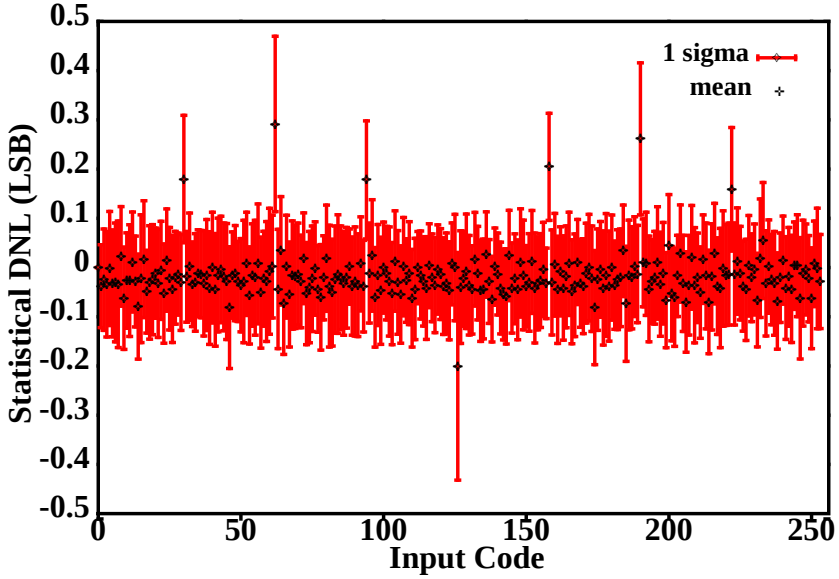
Data Converter Measurements

✔ **Mismatch must dominate measured non-linearities .**
(Segmentation will prove we measure mismatch)
Enough parts to narrow confidence intervals.



STAT



code	mean(LSB)	sigma(LSB)
1st MSB	-0.20	0.23
2nd MSB	0.29	0.18
3rd MSB	0.18	0.13
others avg	0.05	0.10

SUM-UP

MISMATCH

Mismatch	Random	Systematic
1 unit	-0.3%	0.5%

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What kind of resistors ?

✔ **Analog Baseband (LBC, A21, A12) and RF (RFBC, SiGe)**

- **Type: High or Medium (ZTC) Sheet Polysilicon.**
- **Resistivity: 50Ω/❑ to 2kΩ/❑.**
- **Matching: 2.7%.µm (HSR) up to 13.2%.µm (MSR).**
- **Temperature coefficient: 0 to -1400ppm/C**
- **Voltage coefficient: 55ppm/V and 1pmm/V^2**

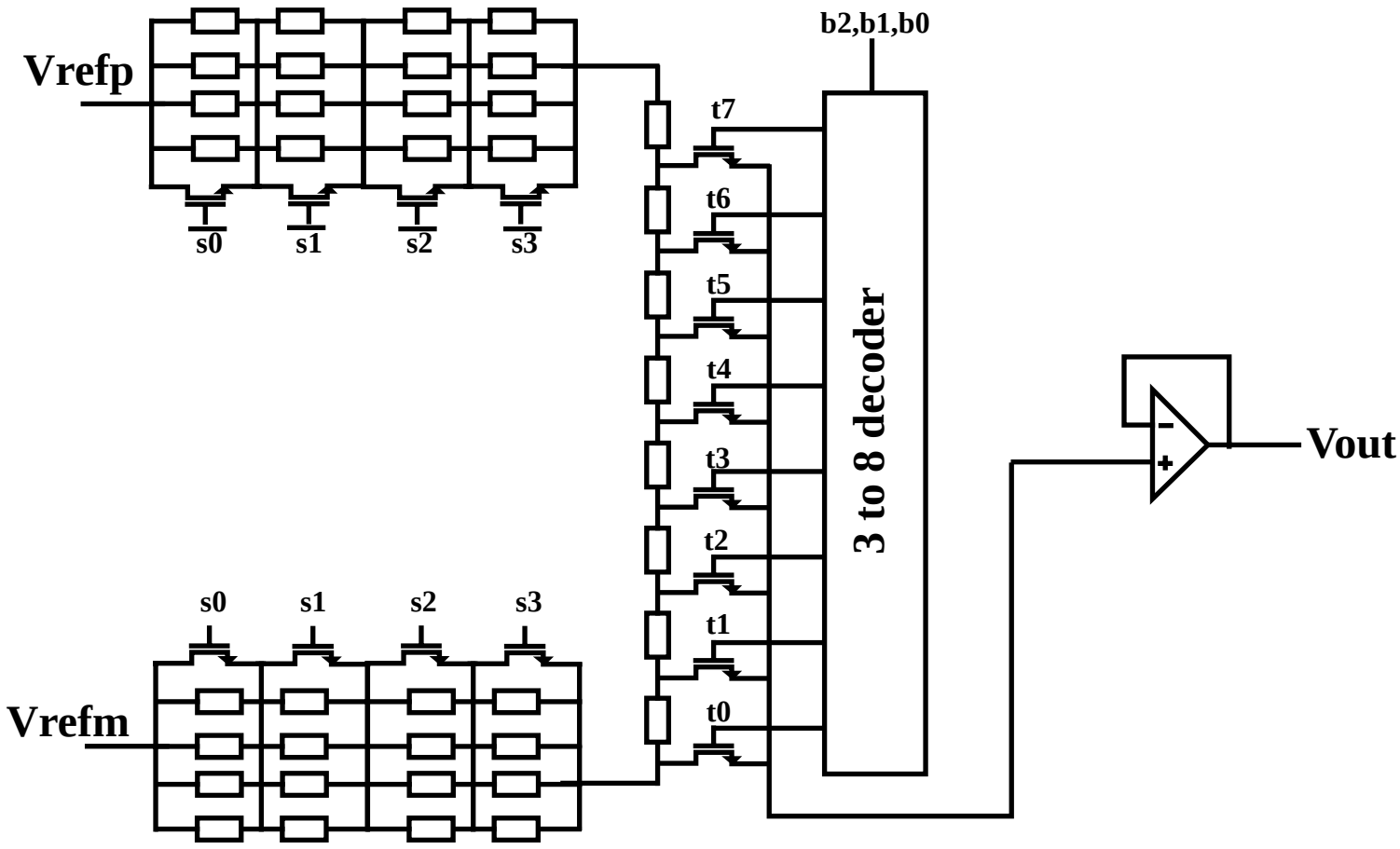
✔ **Deep-Submicron CMOS (C07, C05, C035, ...)**

- **Type: Silicided N-moat, Silicided Polysilicon or Metal.**
- **Resistivity: 20mΩ/❑ to 5Ω/❑.**
- **Matching: 6.5%.µm (N-moat).**
- **Temperature coefficient: 3000 to 4400ppm/C**
- **Voltage coefficient: 100 to 10k ppm/V and 300 to 7kppm/V^2**

R-DAC Block Diagram

✔ Output is tapped from MSB resistor string.

✔ LSB resistors are shorted to shift the string up and down.



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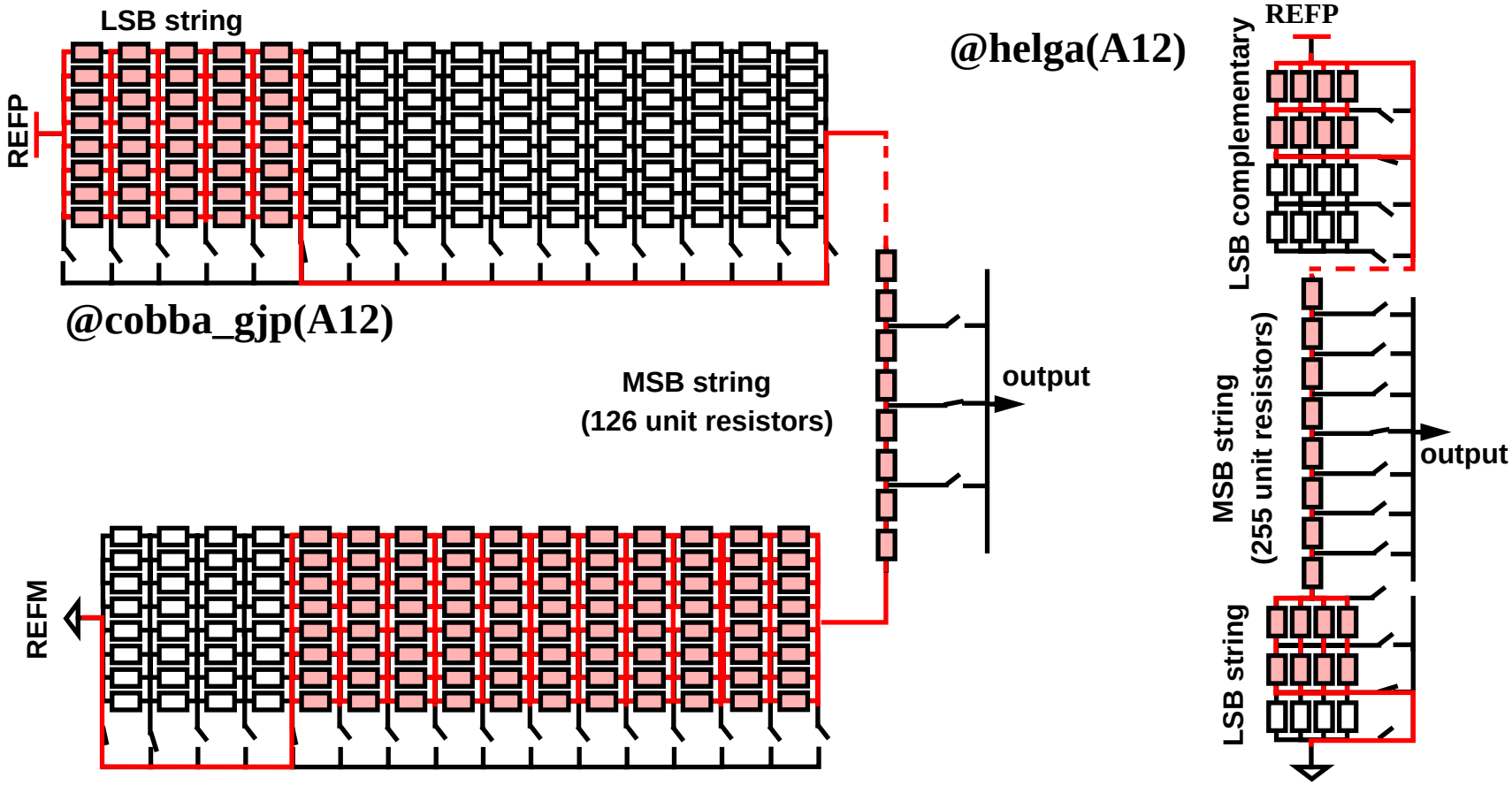
10 bits R-DAC Trial: Schematic

✔ Implementation "A"

✔ Implementation "B"



- 6-4 segmentation
- Full decode

- 8-2 segmentation
- Folded decode

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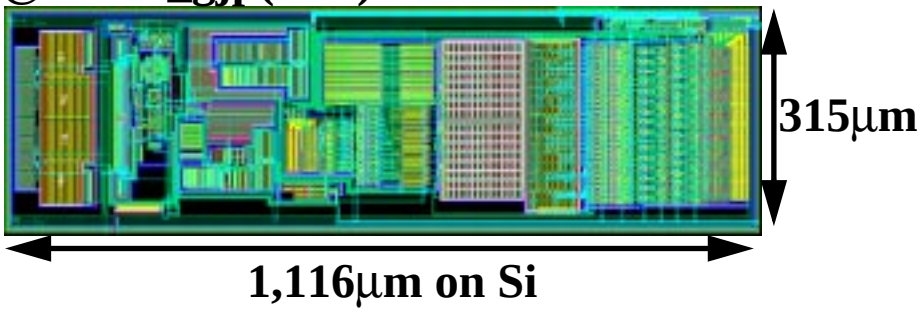
10 bits R-DAC Trials: Layout

✔ Implementation “A”

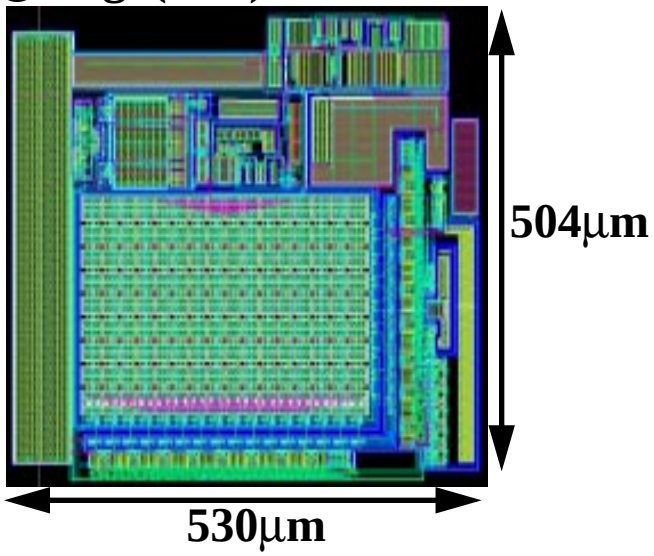
@cobba_gjp(A12)



- Resistors: 67,860µm^2
- Decode: 98,560µm^2
- Switches: 36,740µm^2
- Total: 203,160µm^2

✔ Implementation “B”

@helga(A12)



- Resistors: 110,700µm^2
- Decode: 67,420µm^2
- Switches:14,780µm^2
- Total: 192,900µm^2

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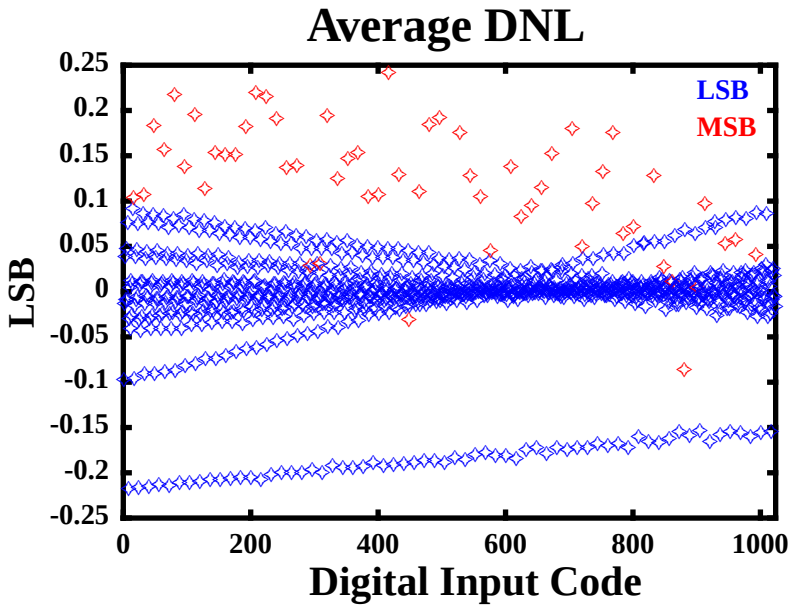
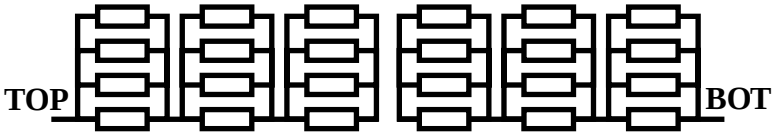
10 bits R-DAC Trial: Linearity

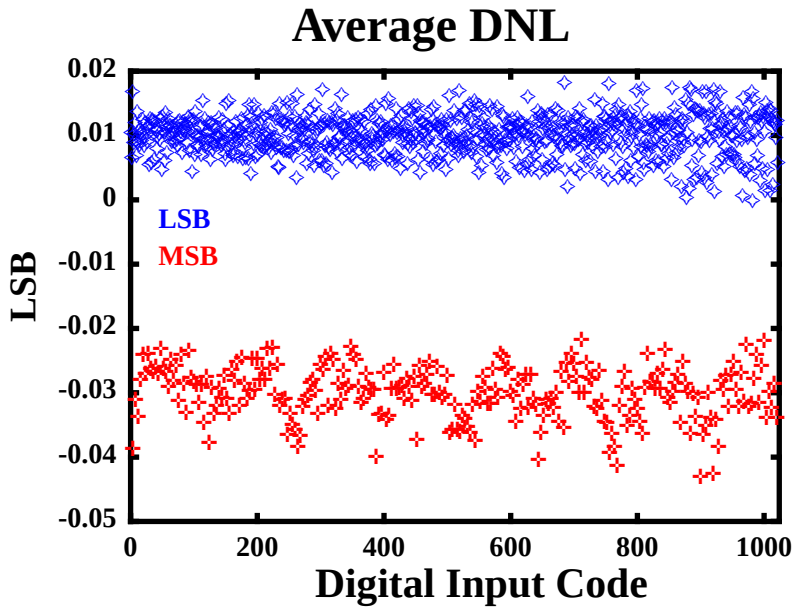
✔ Implementation "A"



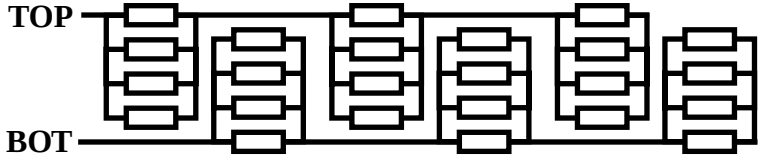
- DNL sys: +/-0.25 LSB
- no LSB superposition
- ΔI due to LSB mismatch



✔ Implementation "B"



- DNL sys: +/-0.05 LSB
- LSB/MSB mismatch
- Interleaved LSB



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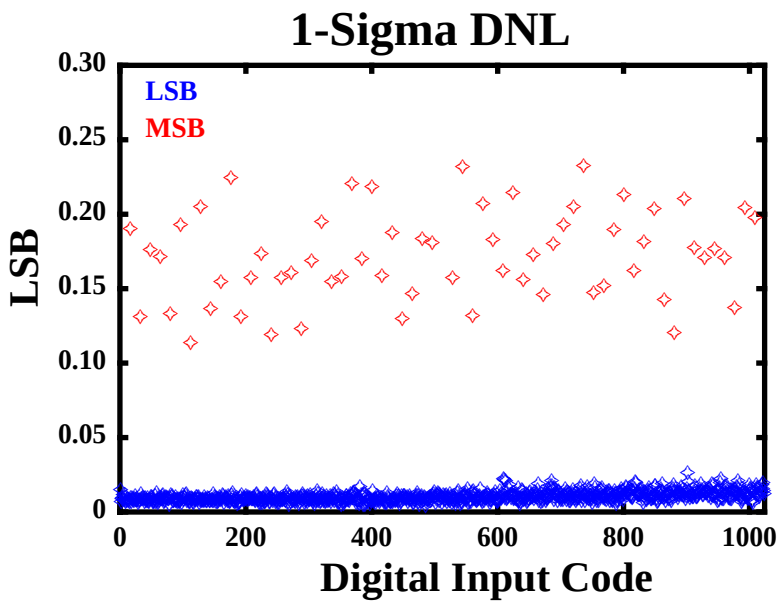
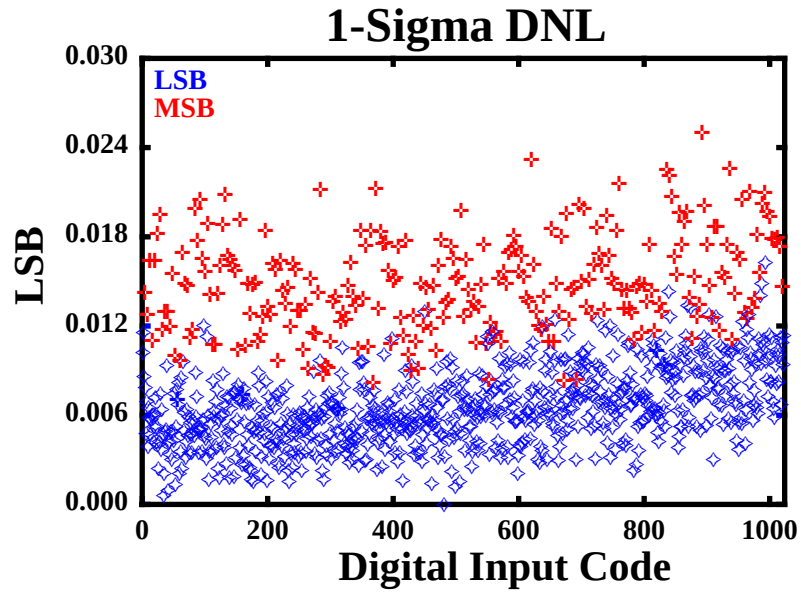
10 bits R-DAC Trial: Linearity

✔ Implementation "A"



- DNL σ: 0.17 LSB
- 6-4 segmentation σ_{dnl}~12 σ_u
- 117μm^2 MSR σ_u=1.2%

✔ Implementation "B"



- DNL σ: 0.015 LSB
- 8-2 segmentation σ_{dnl}~3 σ_u
- 148μm^2 HSR σ_u=0.23%

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R-DAC Trial: Conclusion

✔ Implementation “A”

- Don’t use A12 medium-sheet
- Interleave your LSB
- Keep a safe segmentation

✔ Implementation “B”

- Units are oversized
- Match LSB/MSB units
- Match interconnects

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Presentation Contents

Part 1: Data Converters

- **Nonlinearity.**
- **Segmentation.**

Part 2: Mismatch

- **Random.**
- **Systematic.**

Part 3: Measurements

- **Resistors String DACs**
- **Capacitors SAR ADCs**

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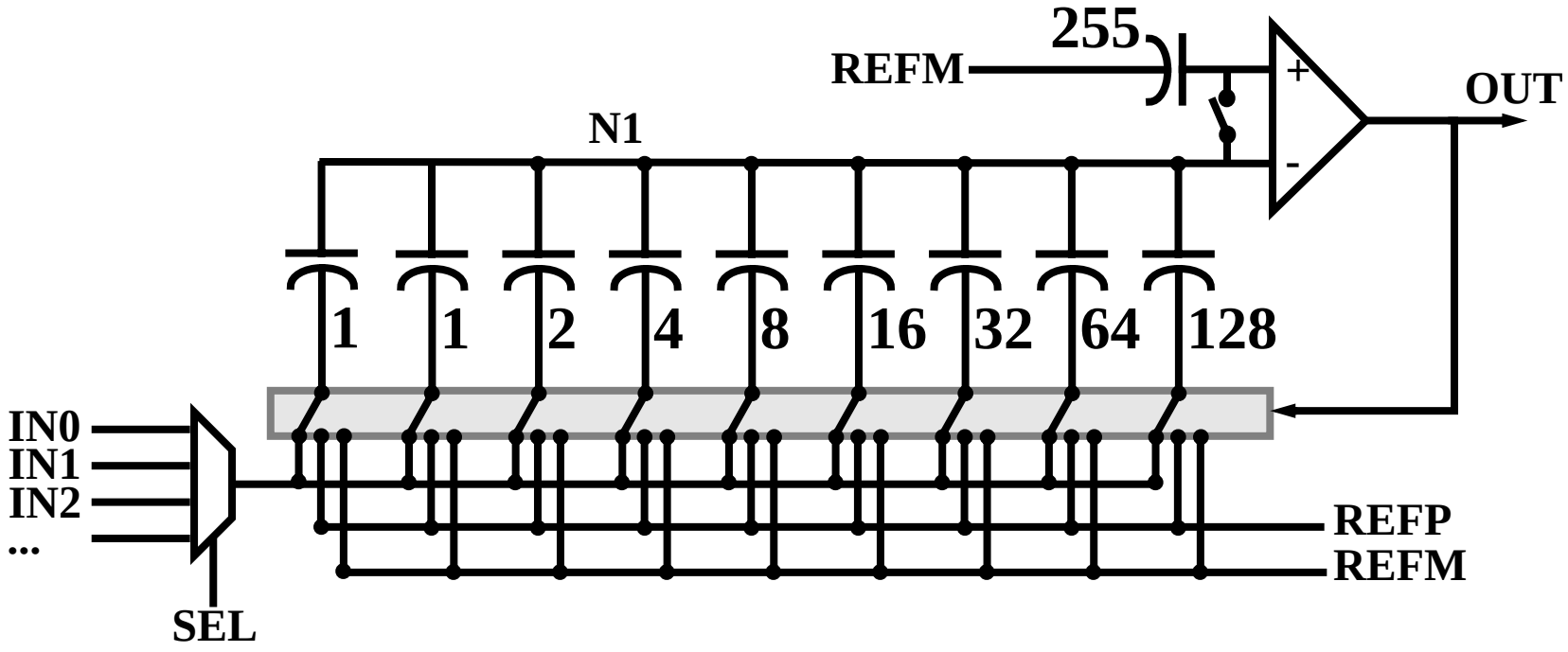
Capacitors SAR ADC

✔ 8-bits Succesive Approximation Register ADC



- Sampling: Charge stored on node N1 (fixed at Vmid)
- Open switch at comparator inputs.
- Connect MSB capacitor to REFP, other bits to REFM.
- Compare MSB downto LSB.

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What kind of capacitors ?

✔ **Analog Baseband (LBC, A21, A12) and RF (RFBC, SiGe)**

- **Type: Silicided Poly1-Poly2 or Silicided Poly-Tinitride.**
- **Density: 0.7fF/μm^2 to 2.0fF/μm^2.**
- **Mismatch: 0.37%.μm up to 1.9%.μm.**
- **Voltage coefficient: 9ppm/V and 9pmm/V^2**

✔ **Deep-Submicron CMOS (C07, C05, C035, ...)**

- **Sandwich or Flux Metal-Insulator-Metal (MIM).**
- **Density: 0.1fF/μm^2 to 1.2fF/μm^2 (max).**
- **Mismatch: 1.0%.μm up to 2.0%.μm.**
- **Voltage coefficient: 4 ppm/V and 1pmm/V^2**

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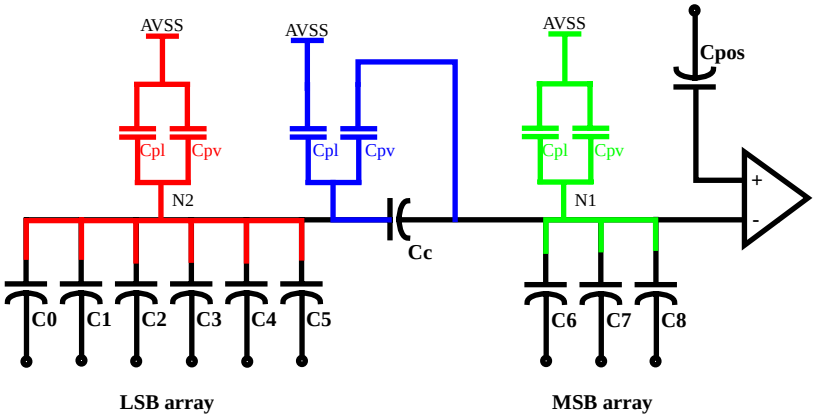
8 bits SAR ADC Trial: Schematic

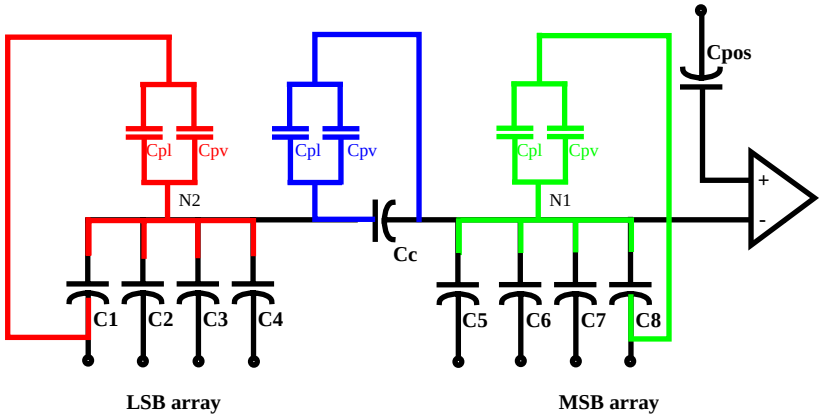
✔ Implementation “A”



Cap	C0	C1	C2	C3	C4	C5	Cc	C6	C7	C8
Units	1/2	1/2	1	2	4	8	16/15	1	2	4

- 3-5 coupled array
- Non-integer capacitor
- Parasitic dependant

✔ Implementation “B”



C1	C2	C3	C4	Cc	C5	C6	C7	C8
1	2	4	8	1	1	2	4	8

- 4-4 coupled array
- Integer capacitor
- Parasitic independant

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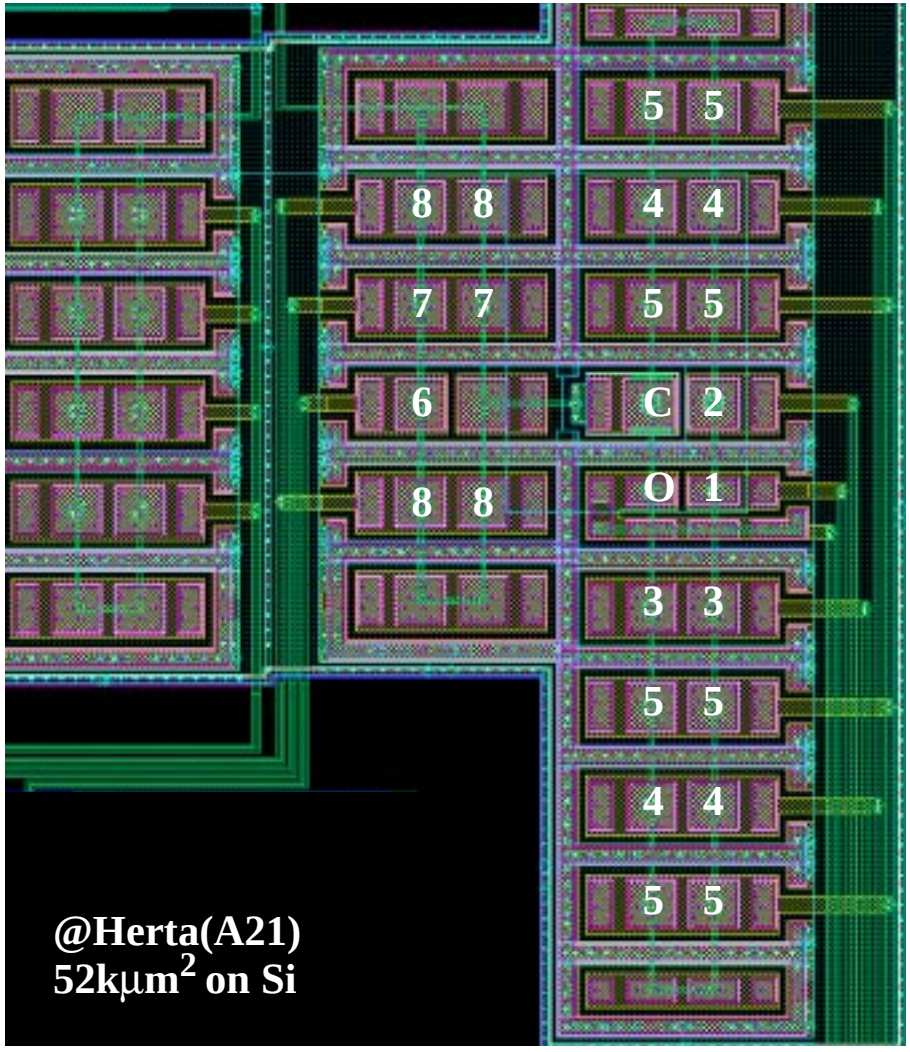
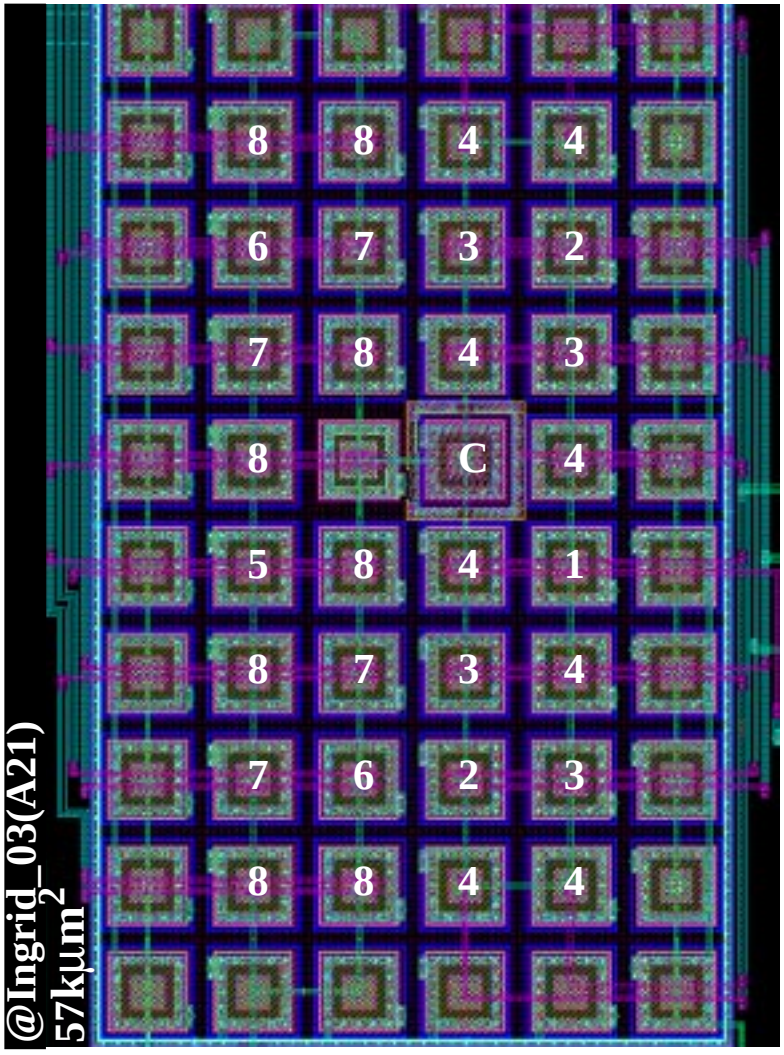
8 bits SAR ADC Trial: Layout

✔ Implementation “A”



✔ Implementation “B”



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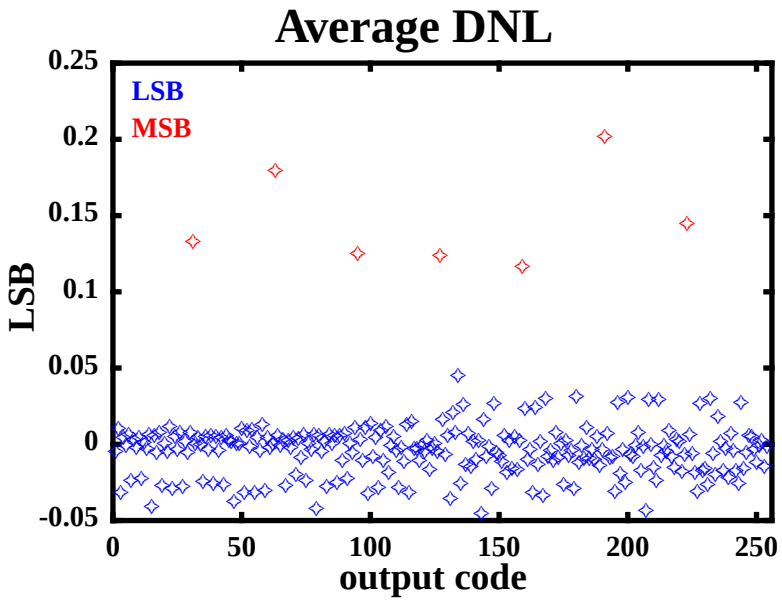
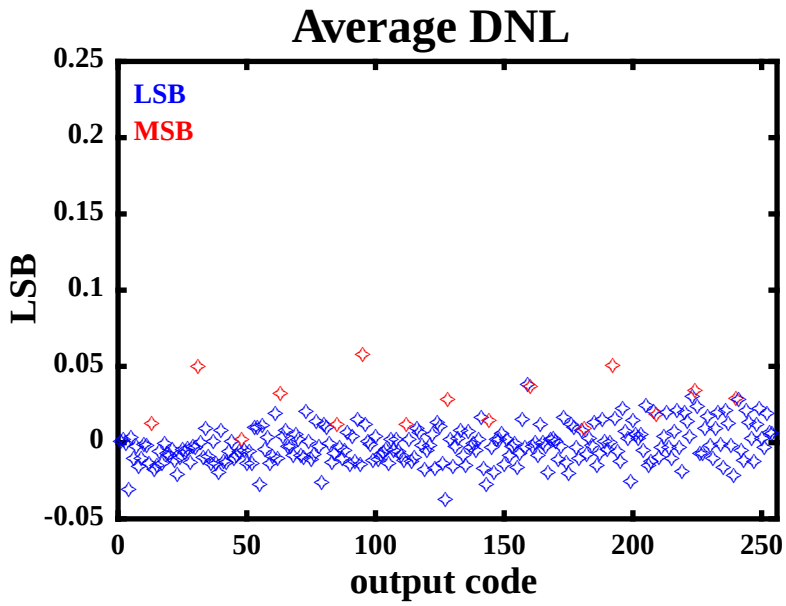
8 bits SAR ADC Trial: Linearity

✔ Implementation "A"



- Systematic<0.25 LSB.
- Parasitic dependant.
- Vary with Fabs and time.

✔ Implementation "B"



- Systematic<0.075 LSB.
- Parasitic independant.
- Robust to variations.

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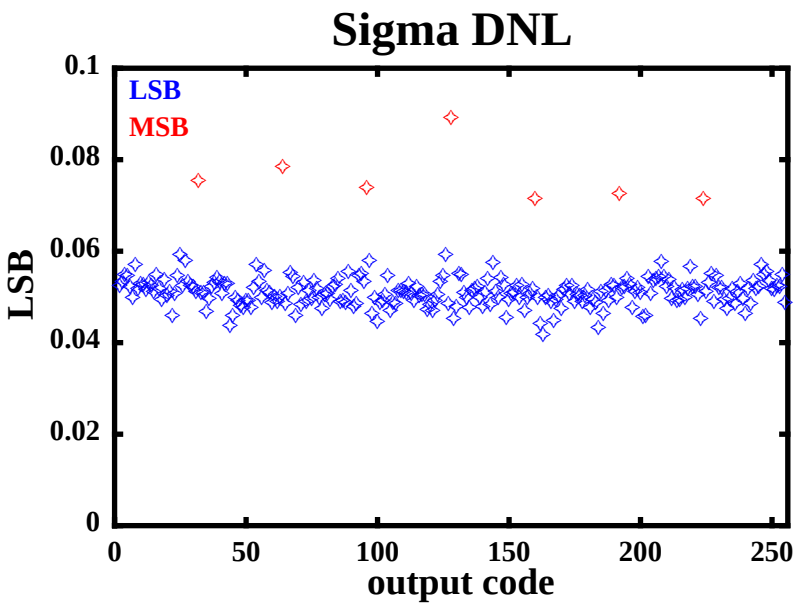
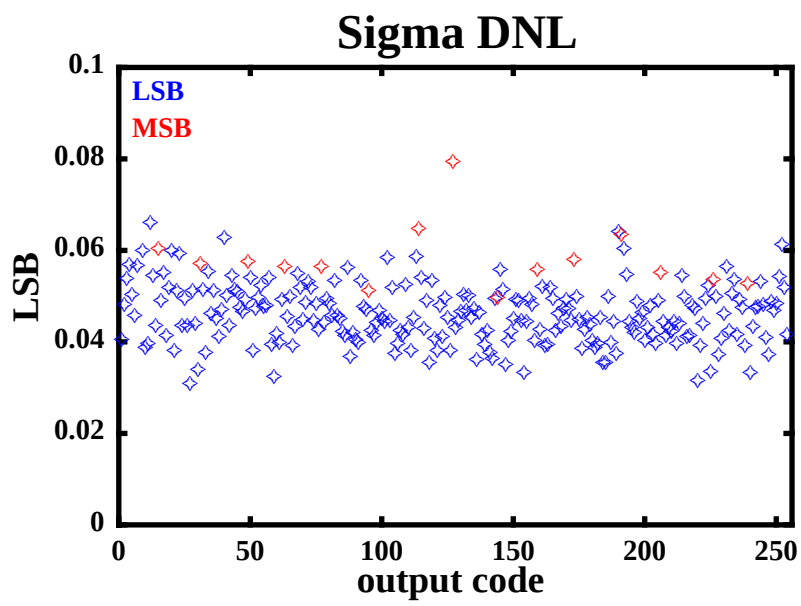
8 bits SAR ADC Trial: Linearity

✔ Implementation "A"



- Random σ_{dnl}~0.09 LSB.
- Unit size:15.6*18μm^2 (319fF).
- Unit matching σ_u~0.13%.
- MSB made of 4 units.

✔ Implementation "B"



- Random σ_{dnl}~0.08 LSB.
- Unit size:16*16μm^2 (290fF)
- Unit matching σ_u~0.14%.
- MSB made of 8 units.

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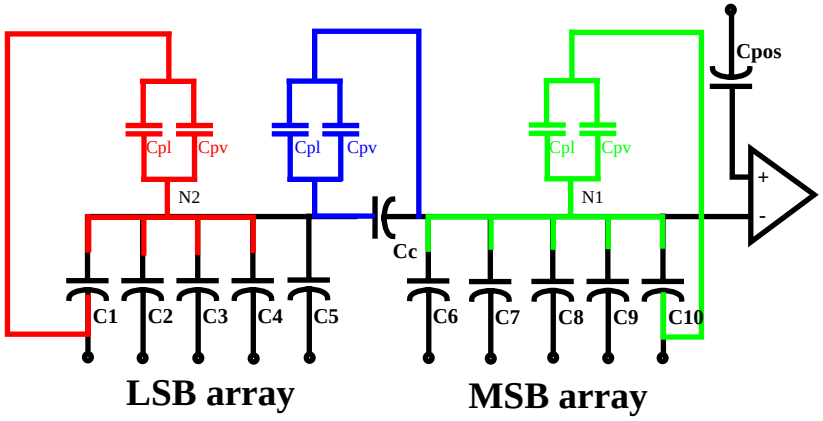
10 bits SAR ADC Trial: Schematic

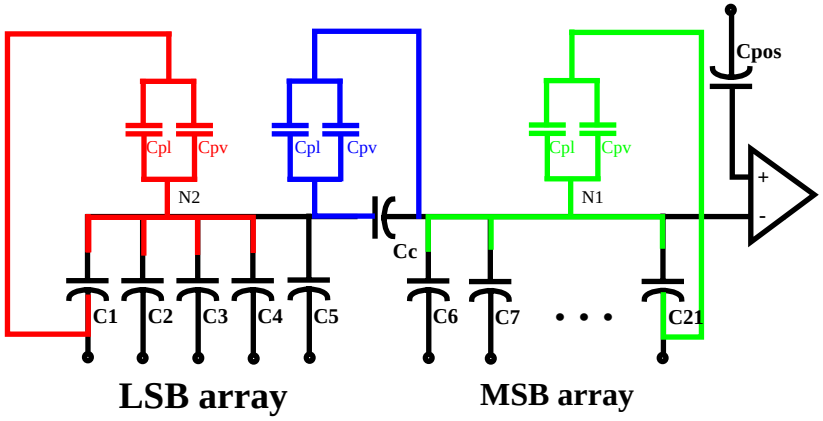
✔ Implementation "A"



C1	C2	C3	C4	C5	Cc	C6	C7	C8	C9	C10
1	2	4	8	16	1	1	2	4	8	16

- 5-5 coupled, fully binary.
- 11 elements, 63 units.

✔ Implementation "B"



C1	C2	C3	C4	C5	Cc	C6	C7..21
1	2	4	8	16	1	1	2

- 5-5 coupled, 4-6 segmented.
- 22 elements, 63 units.

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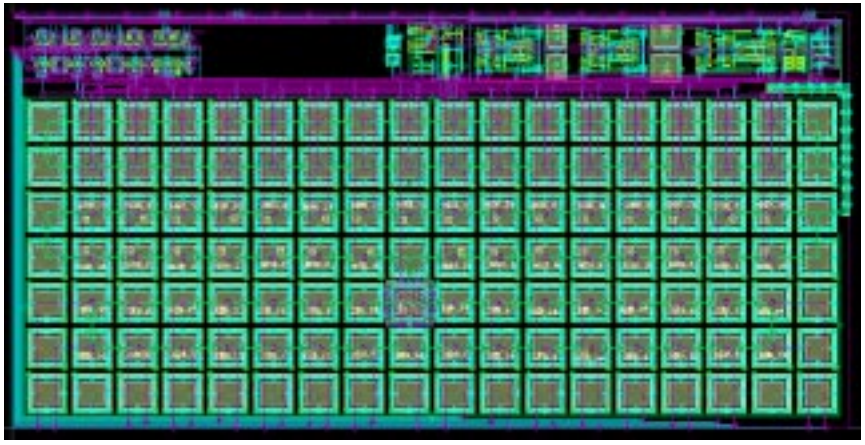
10 bits SAR ADC Trial: Layout

✔ Binary implementation

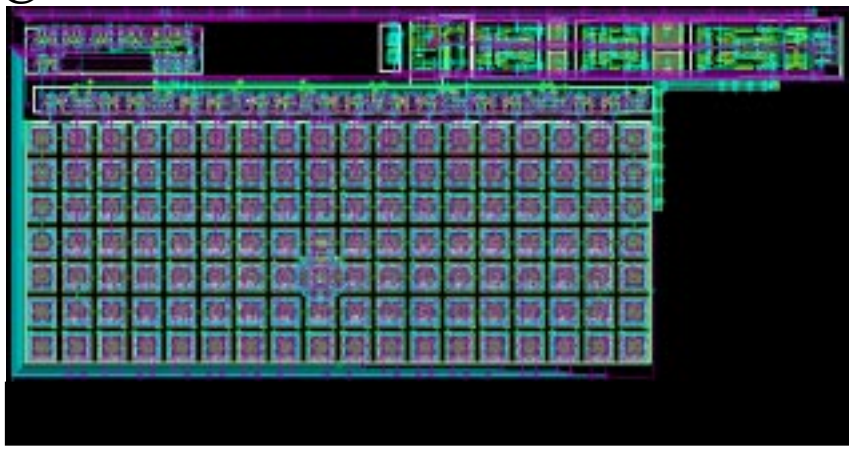
@GCAP3 v0.0



- 5-5 coupled, fully binary.
- 11 elements, 63 units.
- unit size:18*18μm^2 on Si.

✔ Segmented implementation

@GCAP3 v1.0



- 5-5 coupled, 4-6 segmented.
- 22 elements, 63 units.
- unit size:10.8*10.8μm^2 on Si.
- Capacitor array shrink.
- Capacitive load reduction.

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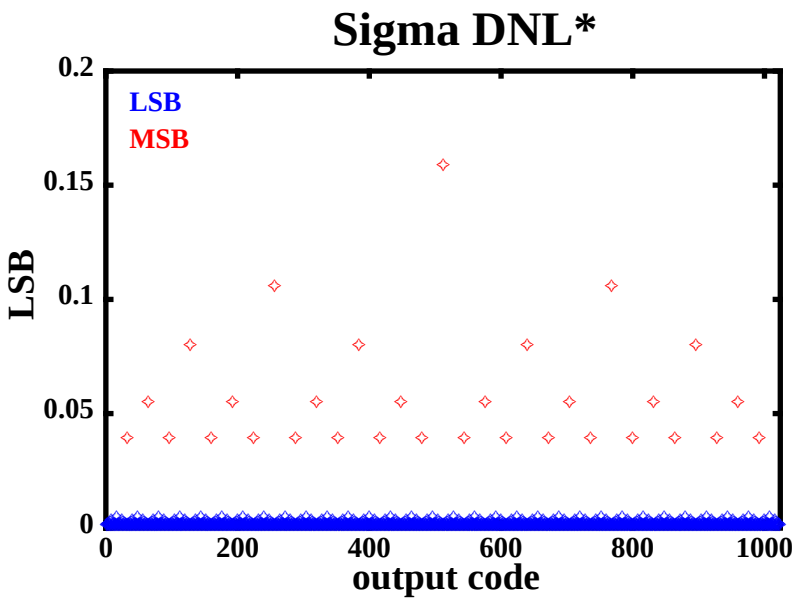
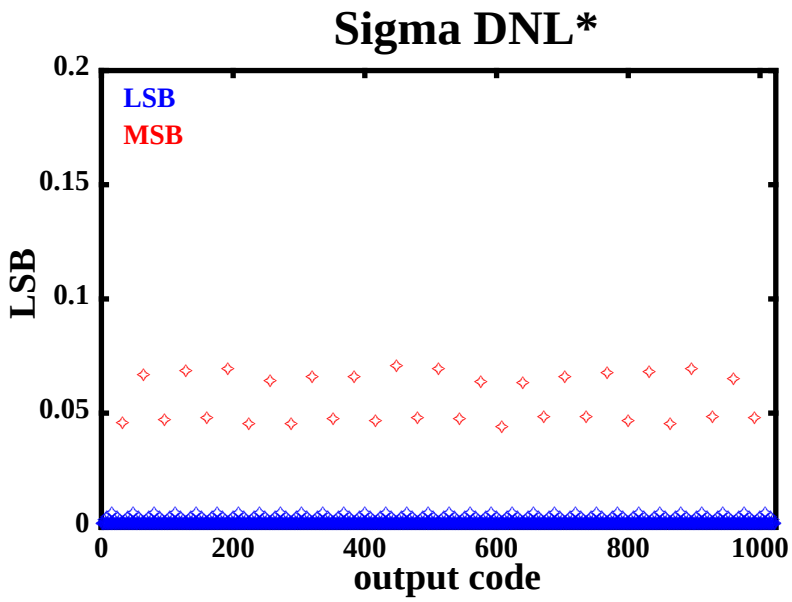
10 bits SAR ADC Trial: Linearity

✔ Implementation "A"



- unit size: $(18\mu m)^2$ on Si
- σ_u~0.11%
- σ_{dnl}~0.16 LSB

✔ Implementation "B"



- unit size: $(10.8\mu m)^2$
- σ_u~0.18%
- σ_{dnl}~0.07 LSB

* Simulated data

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SAR ADC Trial: Conclusion

✔ Classical Implementation

- Take care of parasitics
- Be cautious with MSB
- Large systematic error

✔ Improved Implementation

- Reduced systematic error
- Be more agressive in sizing
- Use thermometer code

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Conclusion

- ✔ **Segmentation choice is driven by matching data (process), specifications (customer) and targeted area/yield ($).**

- ✔ **Carefull study of measured DNL gives insight in systematic (layout related) and random (process related) mismatches, allowing refinements in the next converter design.**

- ✔ **This method can be used to extract systematic and random mismatch from the characterization of data converters used in production parts.**

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