Digitally Assisted Analog Circuits

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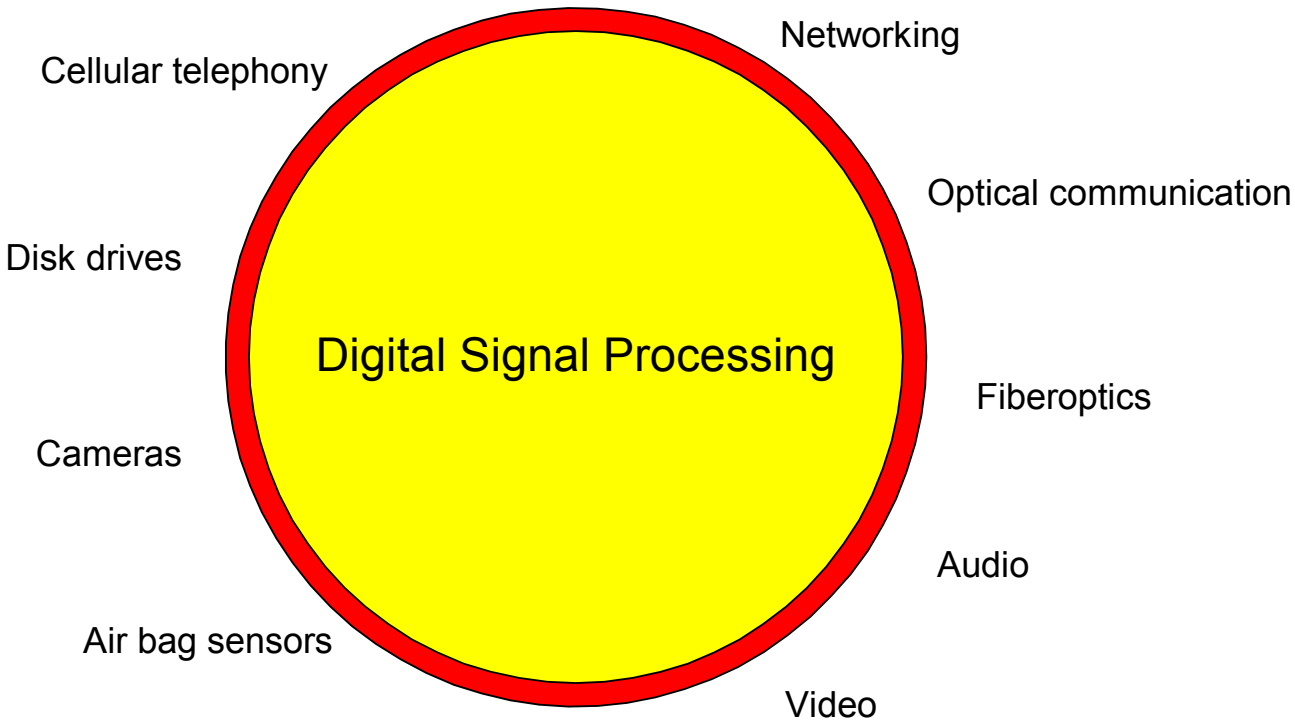
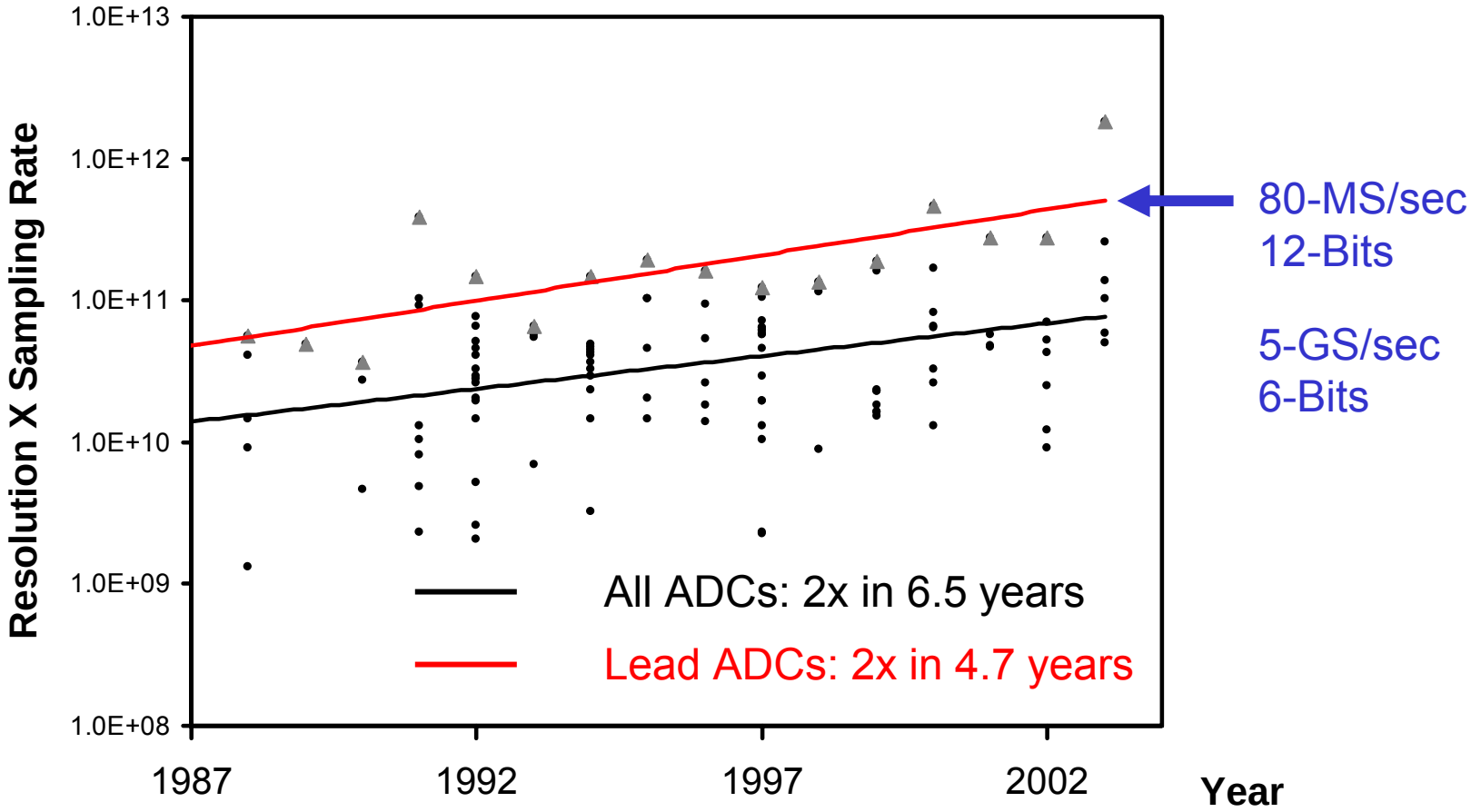
Integrated Circuit Trends

- Moore's Law
  - Transistor count doubles every 2 years
- Rapidly improving circuit performance:
  - E.g. microprocessors:
    - Clock rate doubles in 2.3 years
    - Performance doubles every 1.5 years
  - Enables new functions, e.g.
    - digital video,
    - wireless LAN, WAN, 3G, …
- Analog circuit performance trends?
  - Present trends
  - Challenges
  - Opportunities

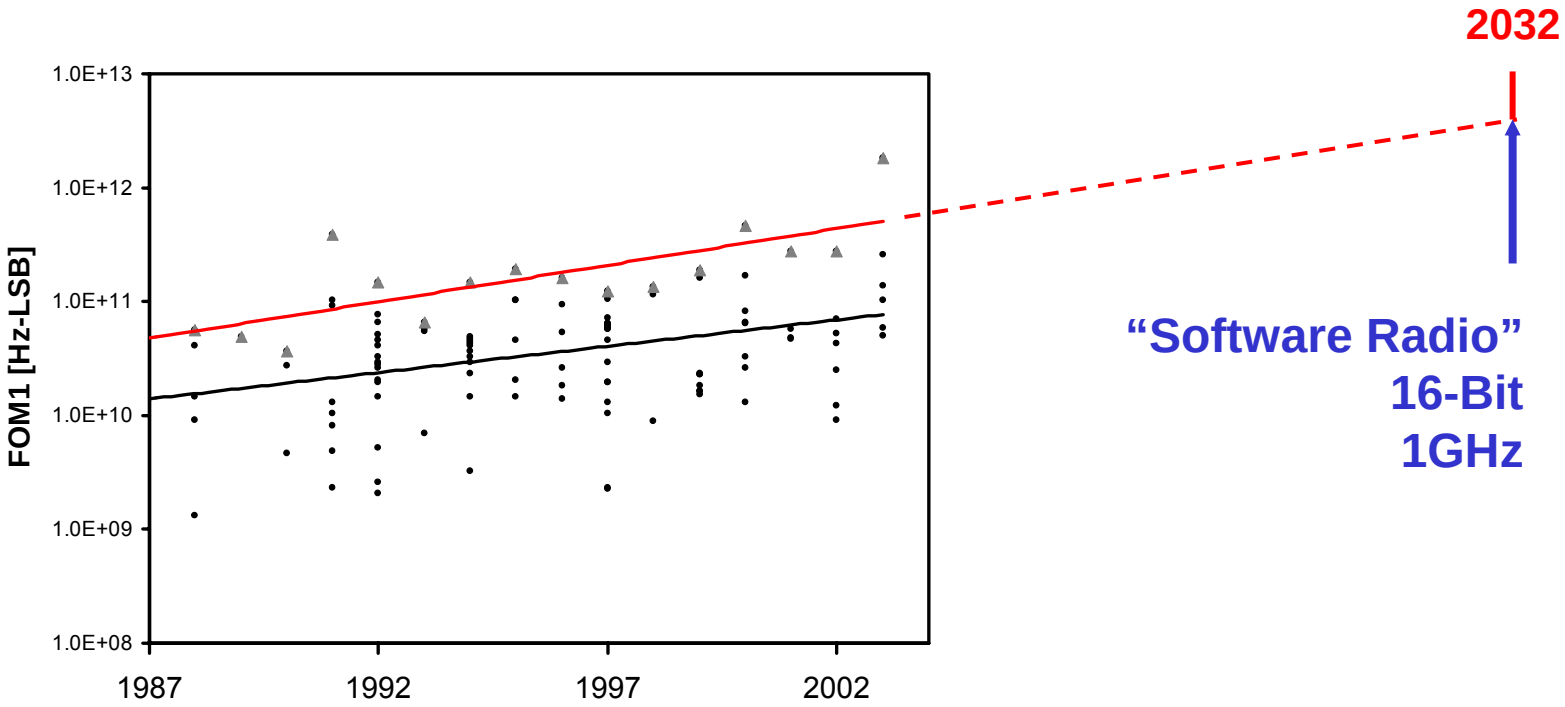
Analog Circuit Applications



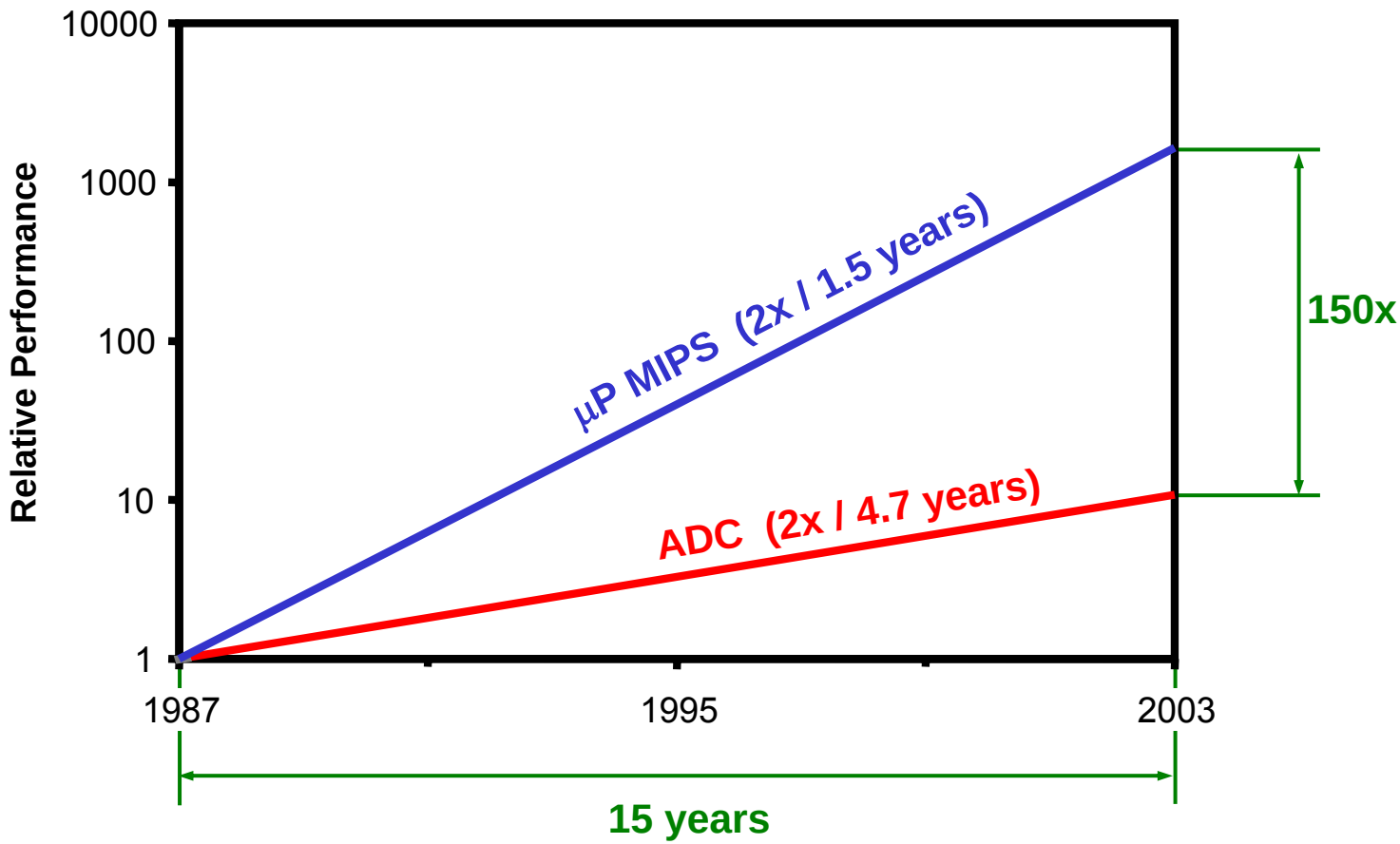
Analog Circuit Performance (ADC)



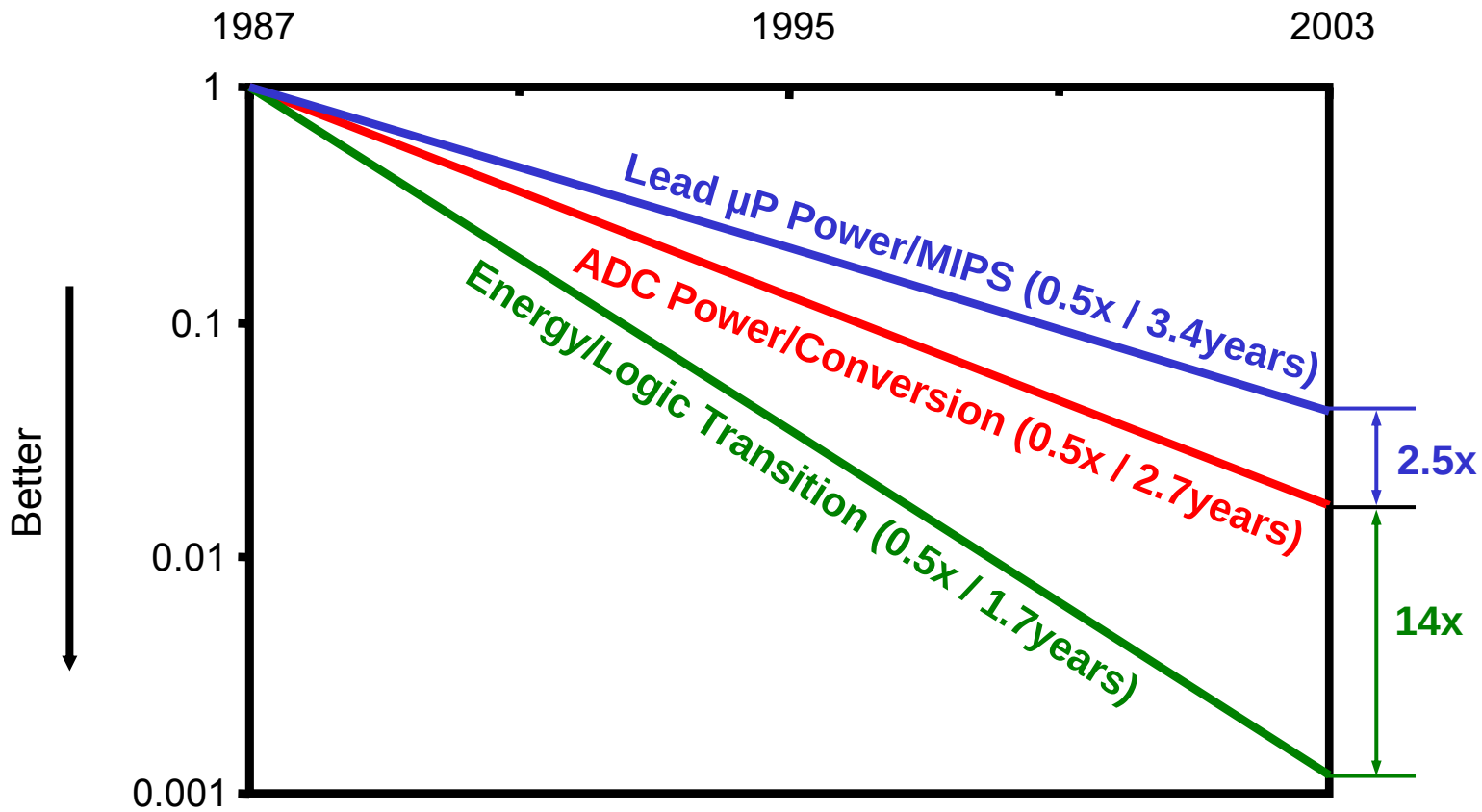
ADC Performance Projection



Analog-Digital Performance Comparison



Analog-Digital Power Comparison



Analog-Digital Power Comparison

Digital

$$P_{dig} \propto CV_{DD}^2 f_{CLK}$$

C	gate, wiring capacitance
V_{DD}	supply voltage
f_{CLK}	clock speed

- Reducing V_{DD} ***lowers*** power
- Power = f(***scaling***, C)

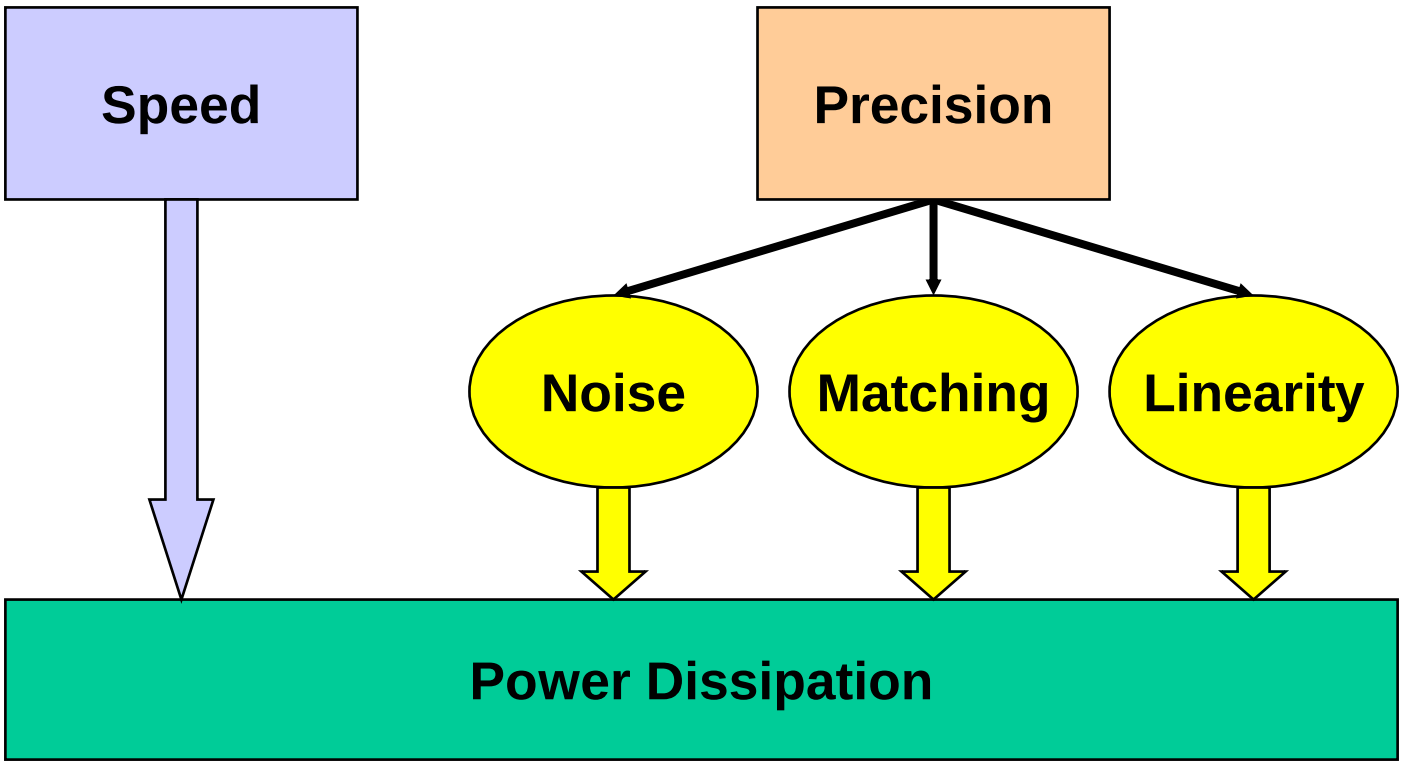
Analog

$$P_{ana} \propto \frac{2^{2B}}{V_{DD}} f_{CLK}$$

B	resolution [Bits]
V_{DD}	supply voltage
f_{CLK}	clock speed

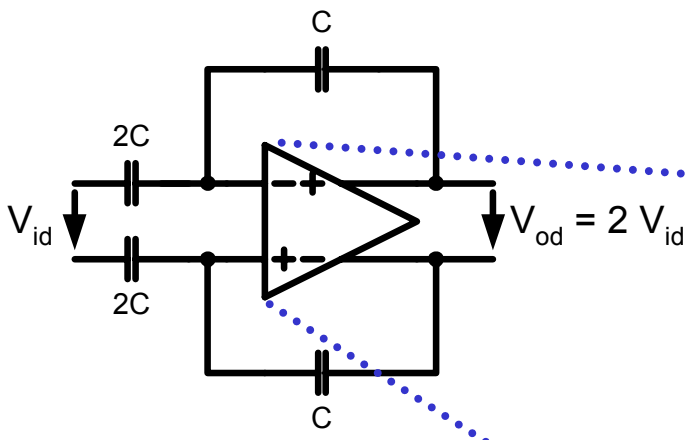
- Reducing V_{DD} ***inreases*** power
- Power = f(***resolution***, B)

Analog Circuit Challenges

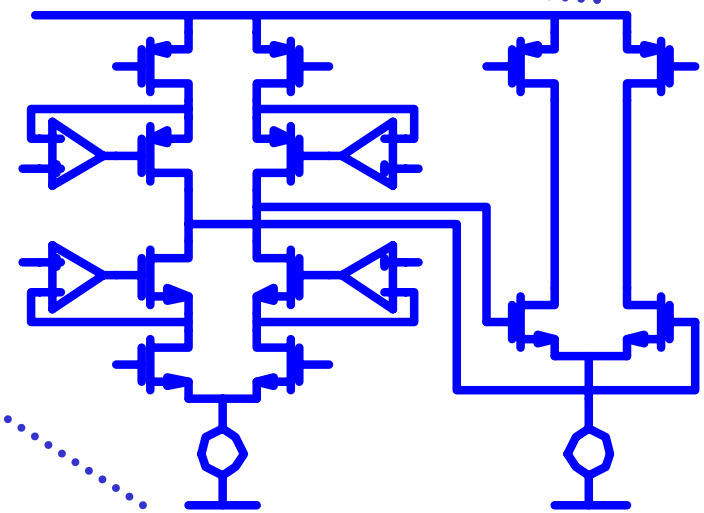


Analog Precision Techniques

Feedback

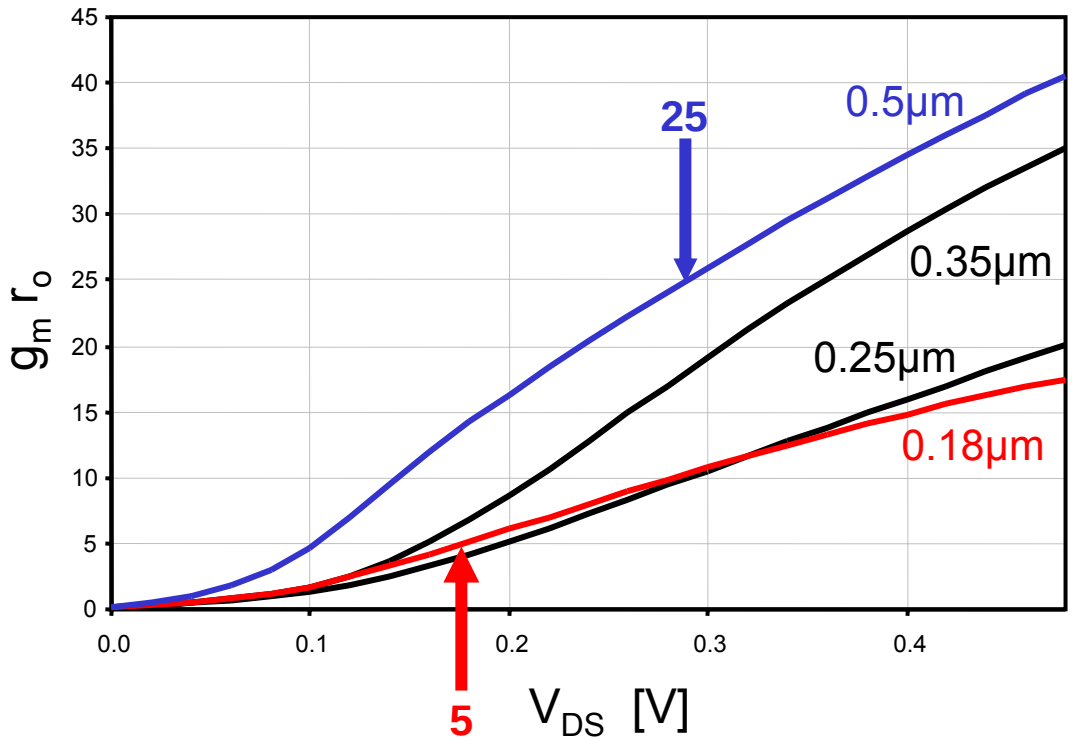


Gain = 2



Gain = 100,000

Intrinsic Transistor Gain



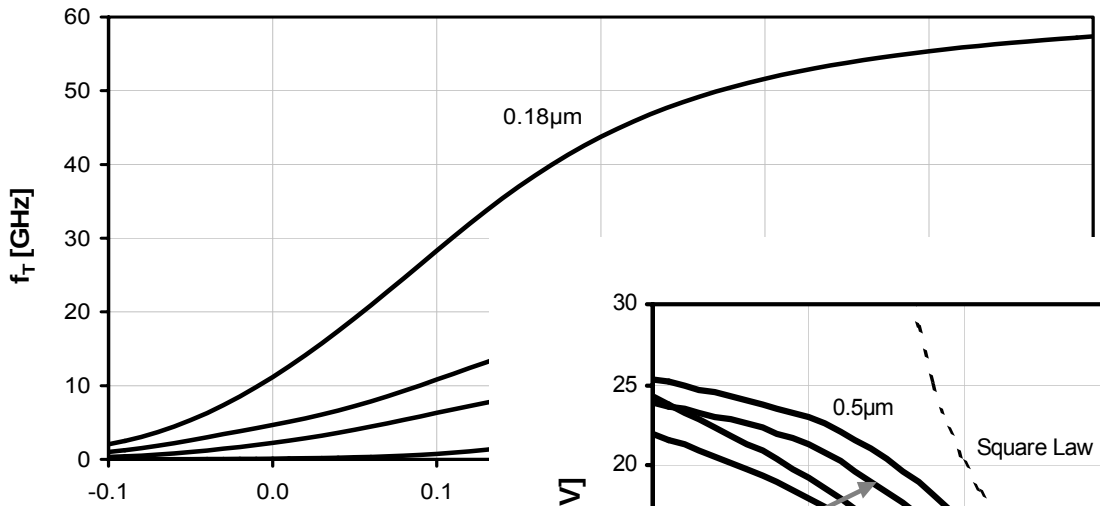
Channel length L ↓
Gain ↓

Scaling “hurts”

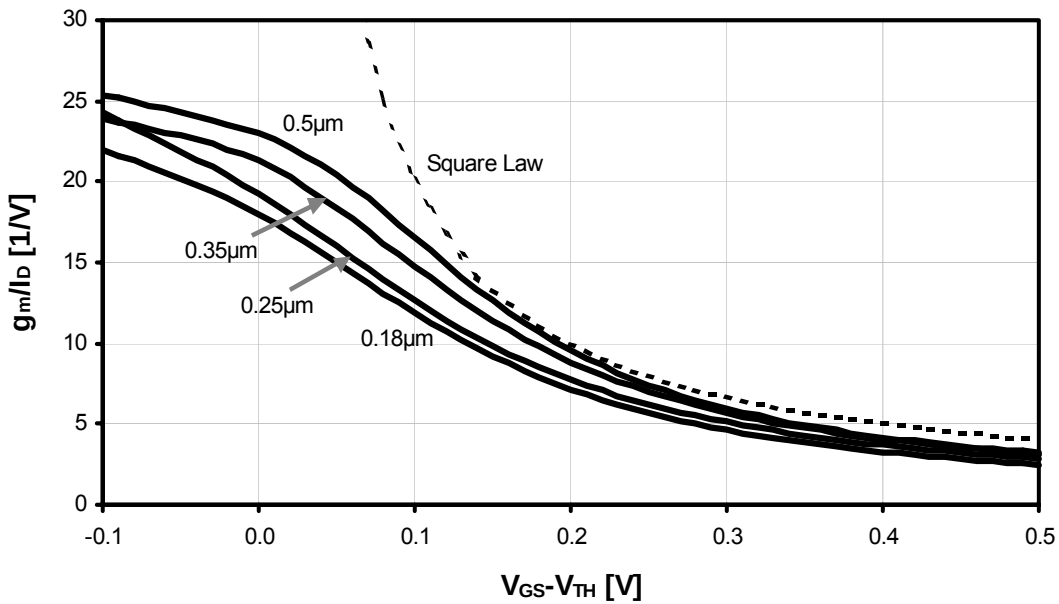
Consequences …

- [Annema, TCAS99]:
  - "The overall effect is that power consumption decreases with newer CMOS processes down to about 0.25 or 0.35 μm."
  - "The trend that power consumption increases with decreasing supply voltage was shown to be fundamental …"
- [Annema, PlanetAnalog, 2004, http://www.planetanalog.com/printableArticle.jhtml?articleID=17701355]
  - "In conclusion, analog circuits can benefit from technology scaling if the supply voltages are not scaled down, unlike in their digital counterparts."
- [Bult, ISSCC99]:
  - "Power dissipation generally increases if a circuit operates under reduced signal swing conditions to maintain performance."
- Scaling has no benefits?

Scaling Benefits

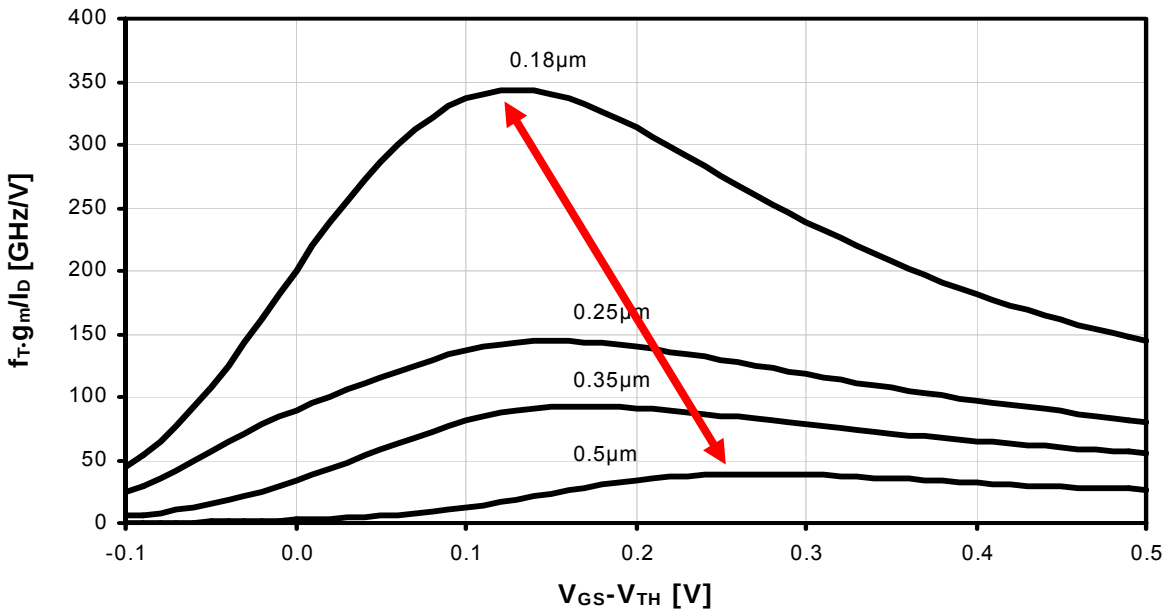


Intrinsic speed (f_T)



Efficiency g_m/I_D

Transistor Performance

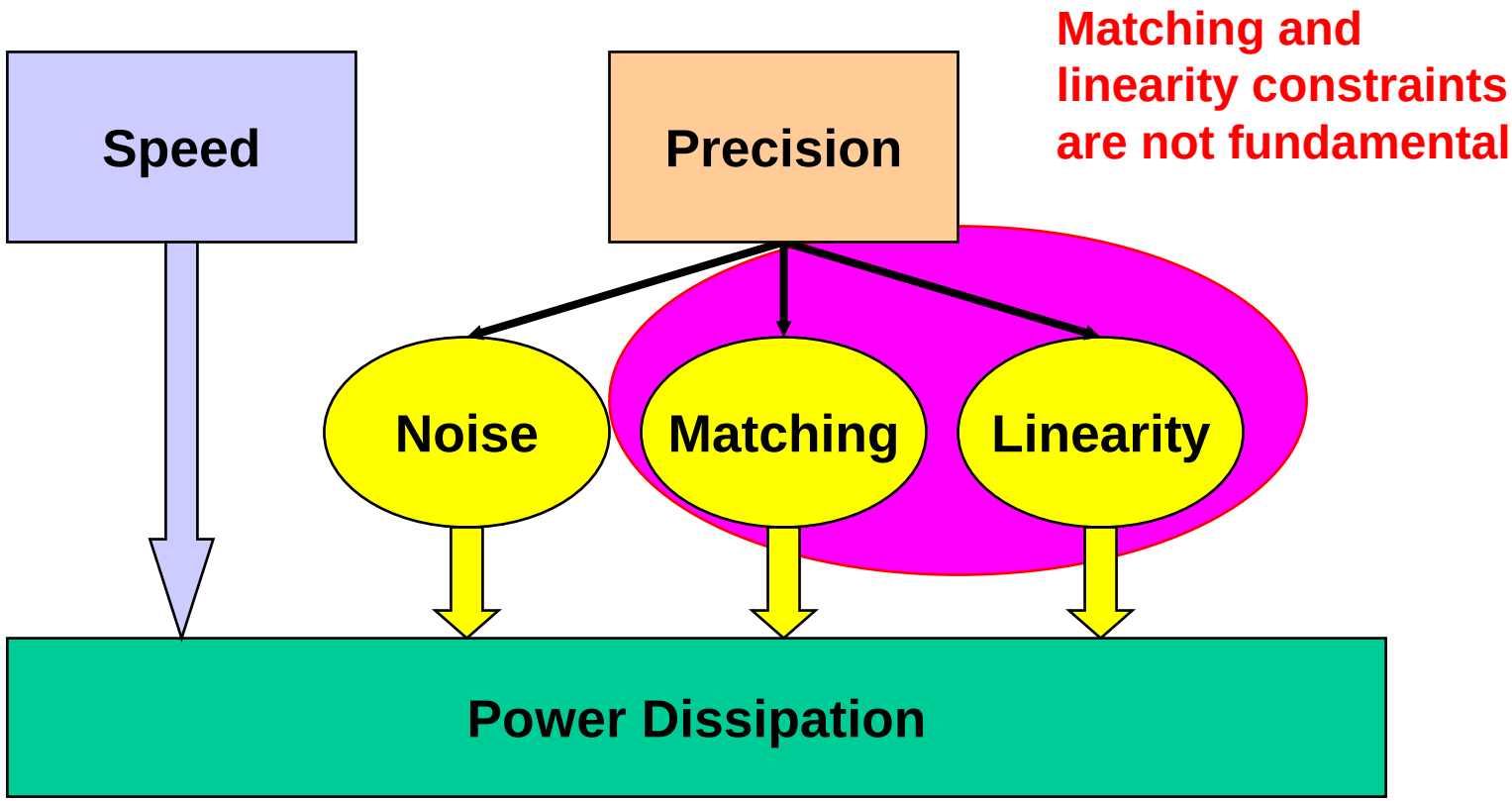


Scaled transistor:
Significantly better performance at lower voltage

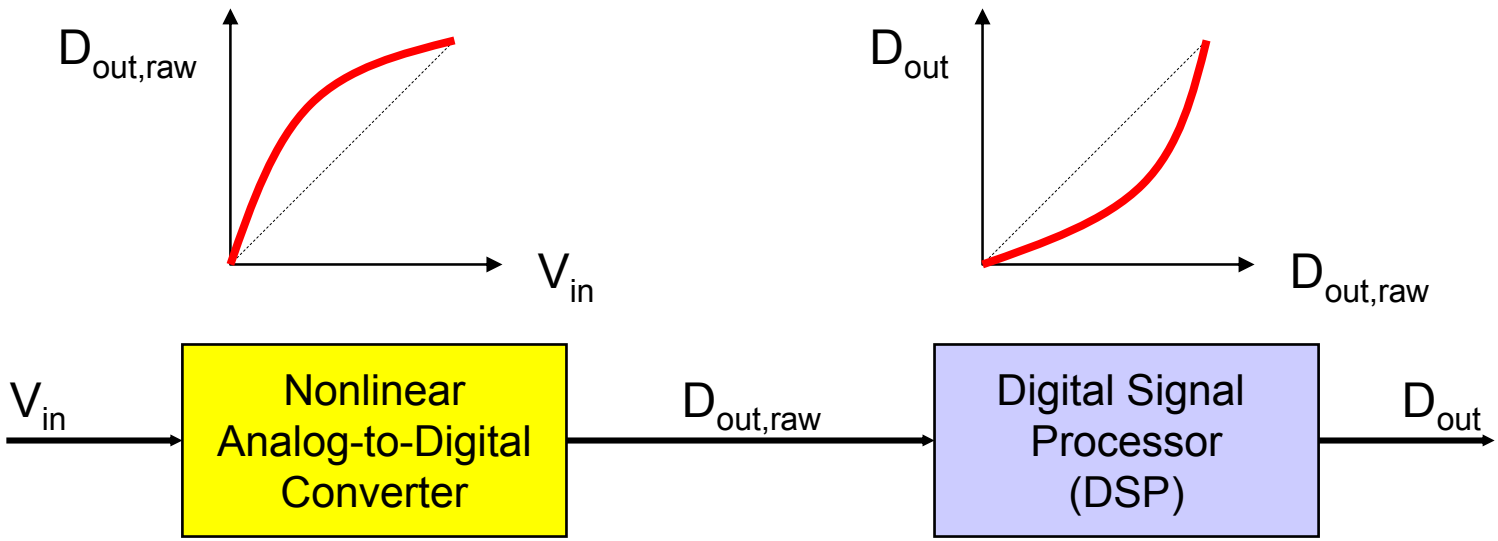
Technology Scaling

- Device performance improves
  - Speed (f_T)
  - Power efficiency (g_m / I_D)
- Digital circuits
  - Capitalize on improved devices
  - Clock rate doubles every 2.3 years
  - Performance (MIPS, SPECint) doubles every 1.5 years
- Analog circuits
  - Low supply, intrinsic device gain negatively impacts precision
  - Relative performance increasingly lags that of digital circuits
  - Performance doubles in 5 years
  - Over 15 years, analog/digital performance gap is ~ 150x
- Is this also a “law”

Analog Circuit Challenges



Analog Circuit Nonlinearity

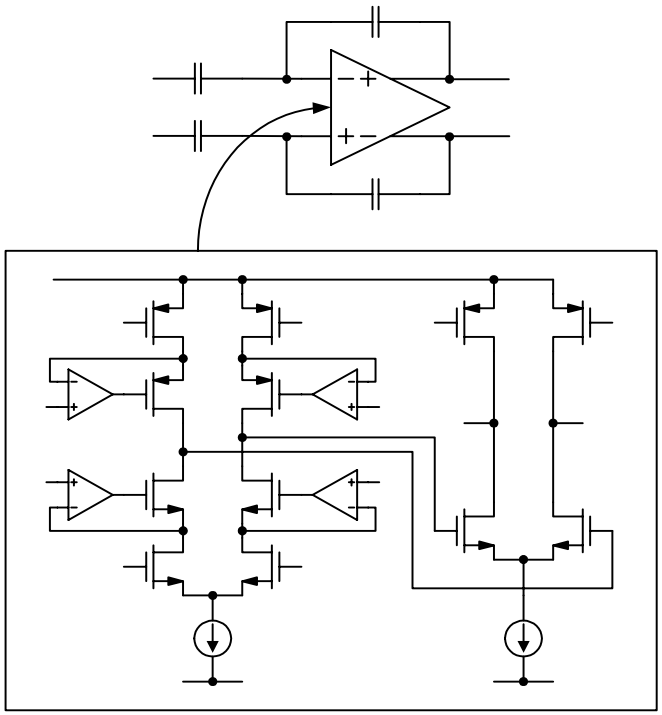


$$D_{out,raw} = f(V_{in})$$

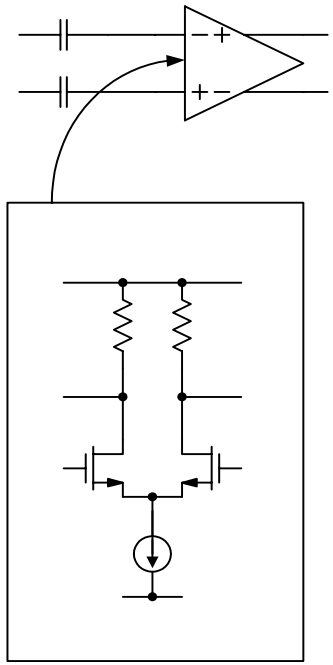
$$\begin{aligned} D_{out} &= f^{-1}(D_{out,raw}) \\ &= f^{-1}(f(V_{in})) \\ &= V_{in} \end{aligned}$$

Open-Loop Amplification

Precision Amplifier

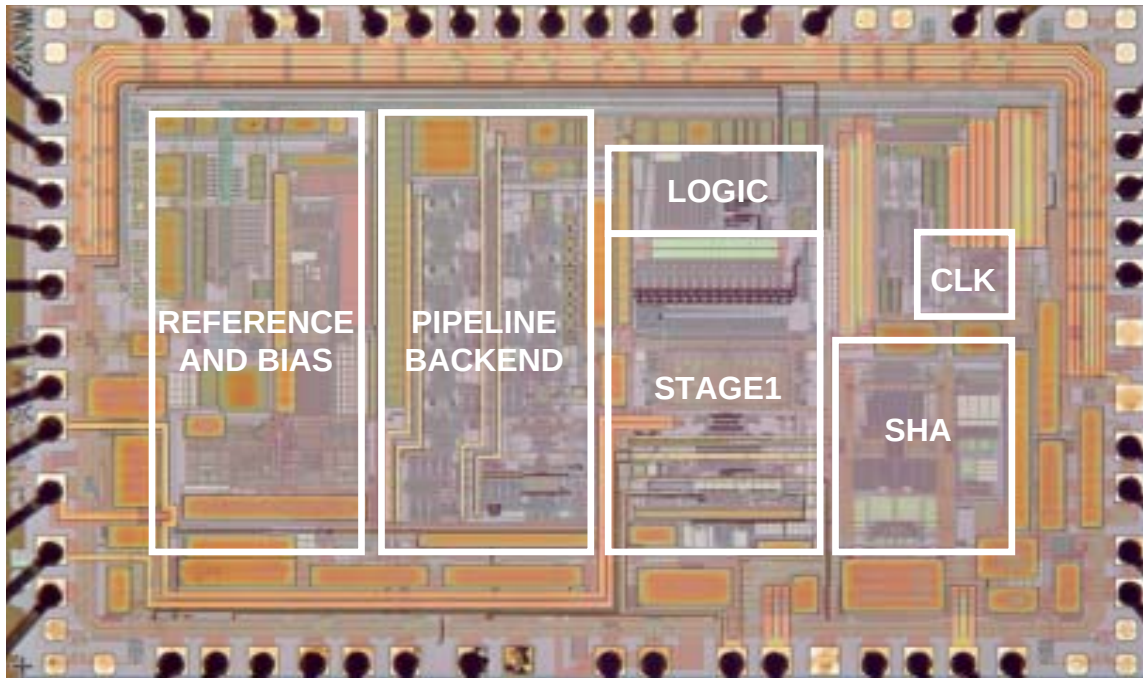


“Open loop“



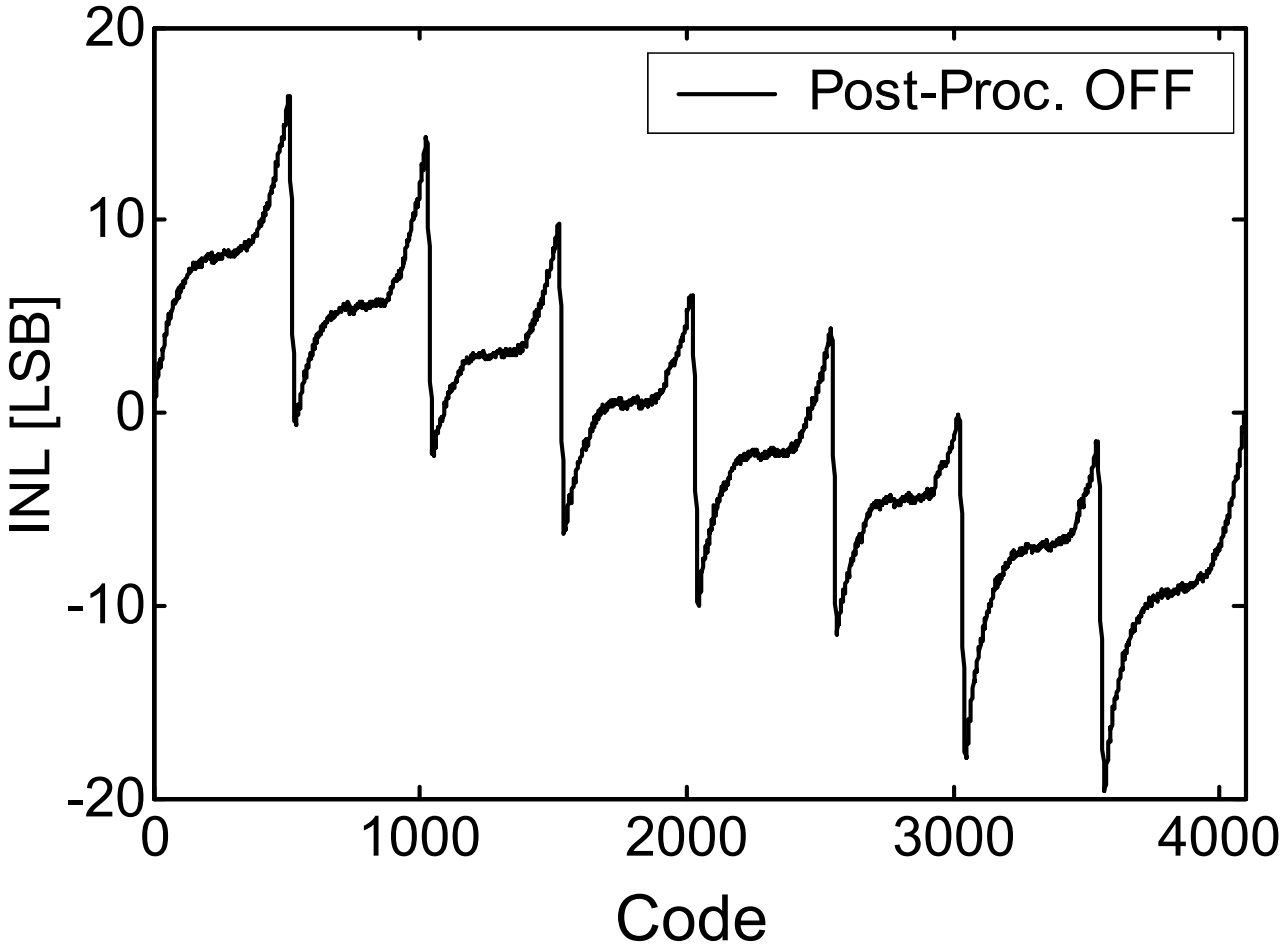
- \+ Faster
- \+ Lower Power
- \+ Lower Noise
- \+ Increased Signal Range
- – Nonlinear
  - ➢ Use DSP to linearize!
- ***Practical?***

Experimental Verification

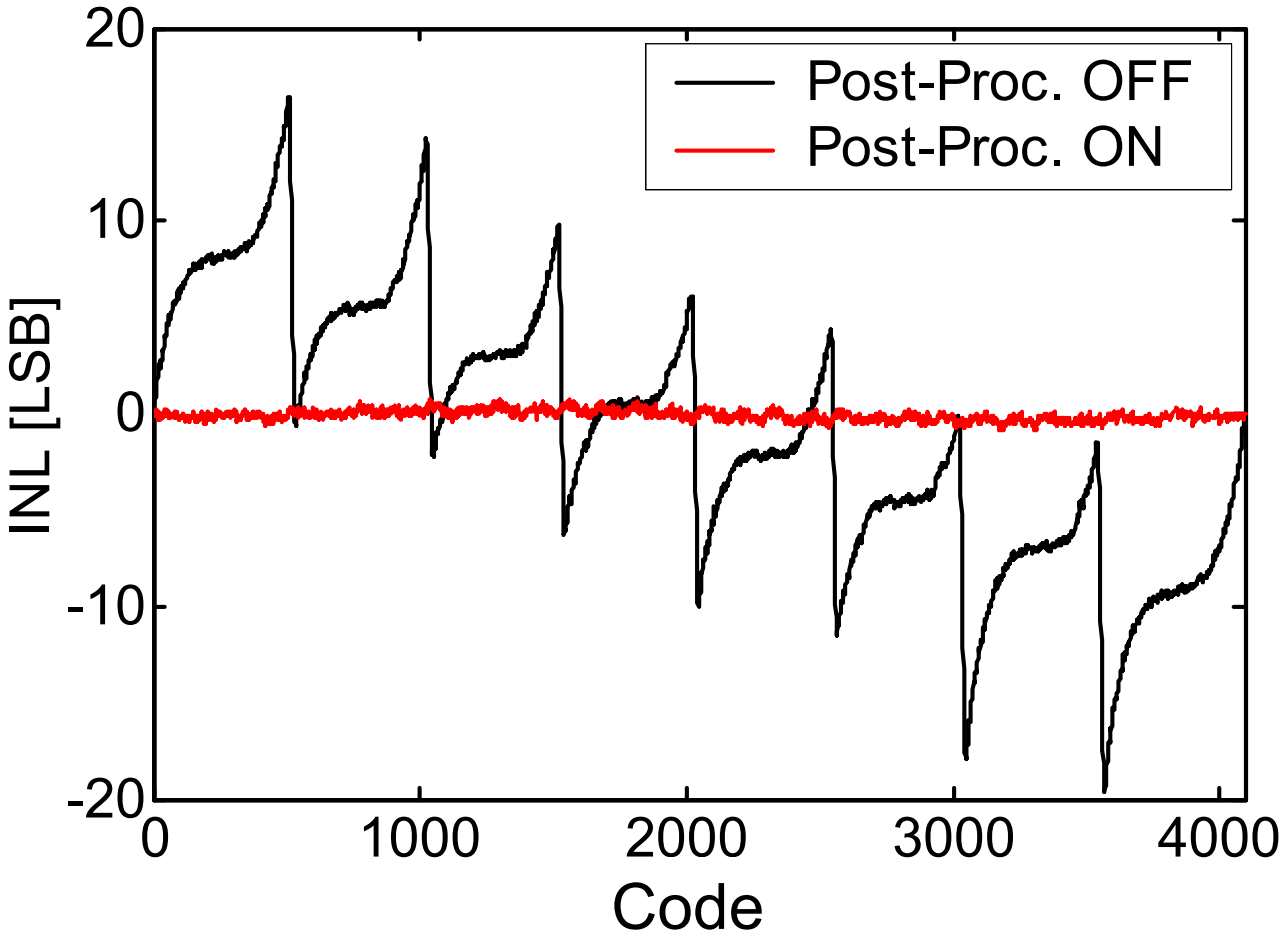


- 12bit, 75MHz, 0.35µm, post-processor off chip
- Based on commercial part (Analog Devices AD9235)

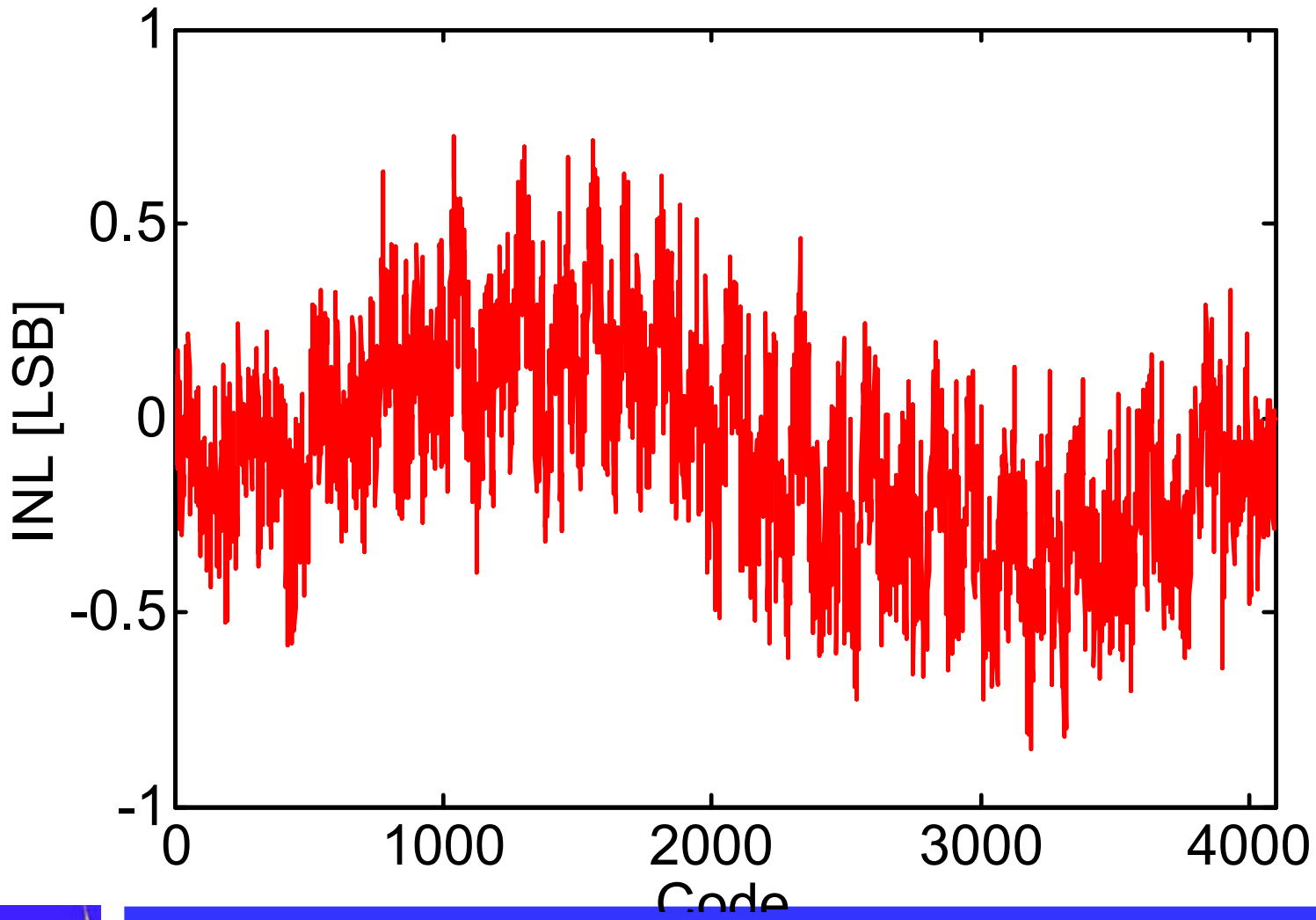
Measured INL



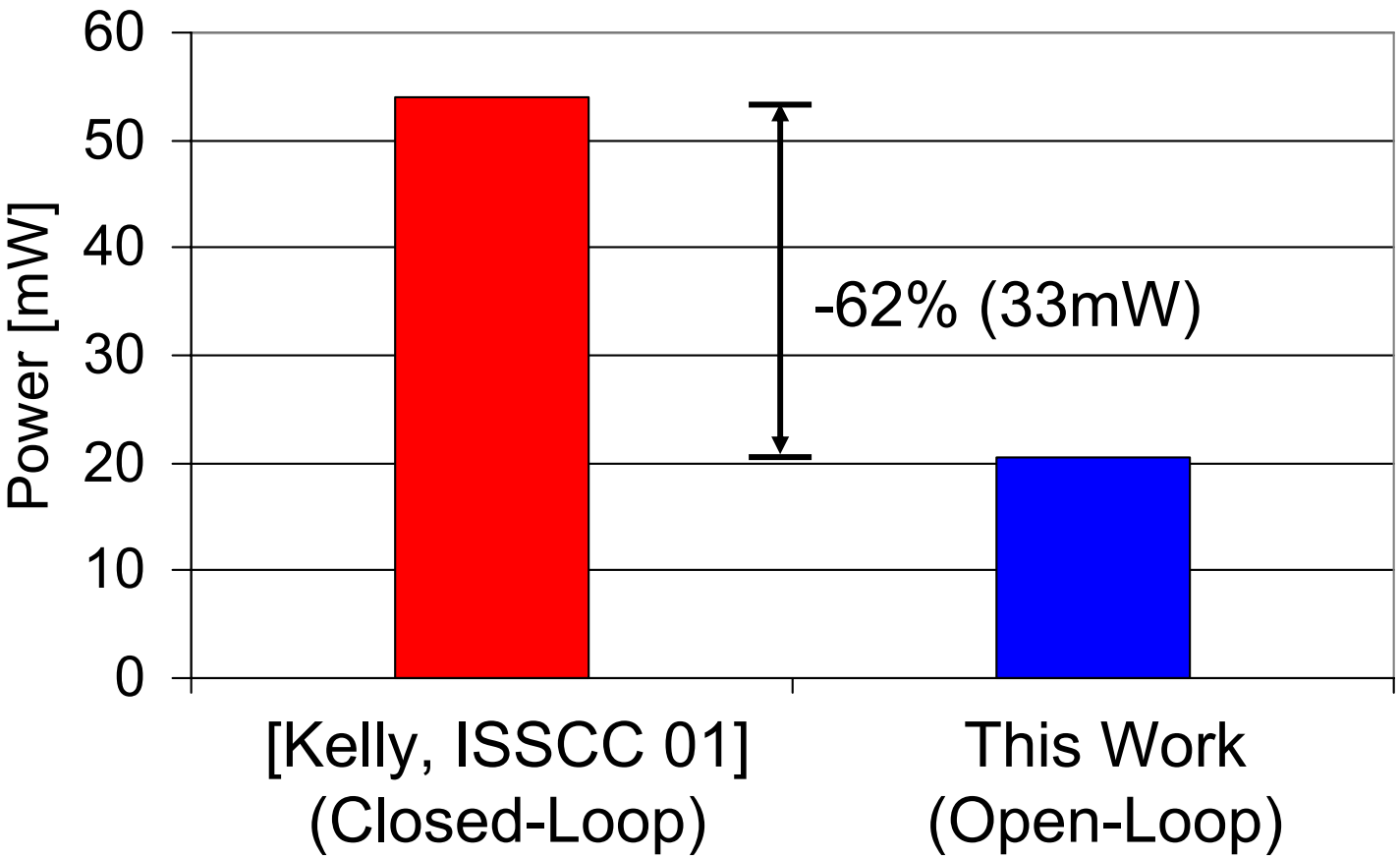
Measured INL



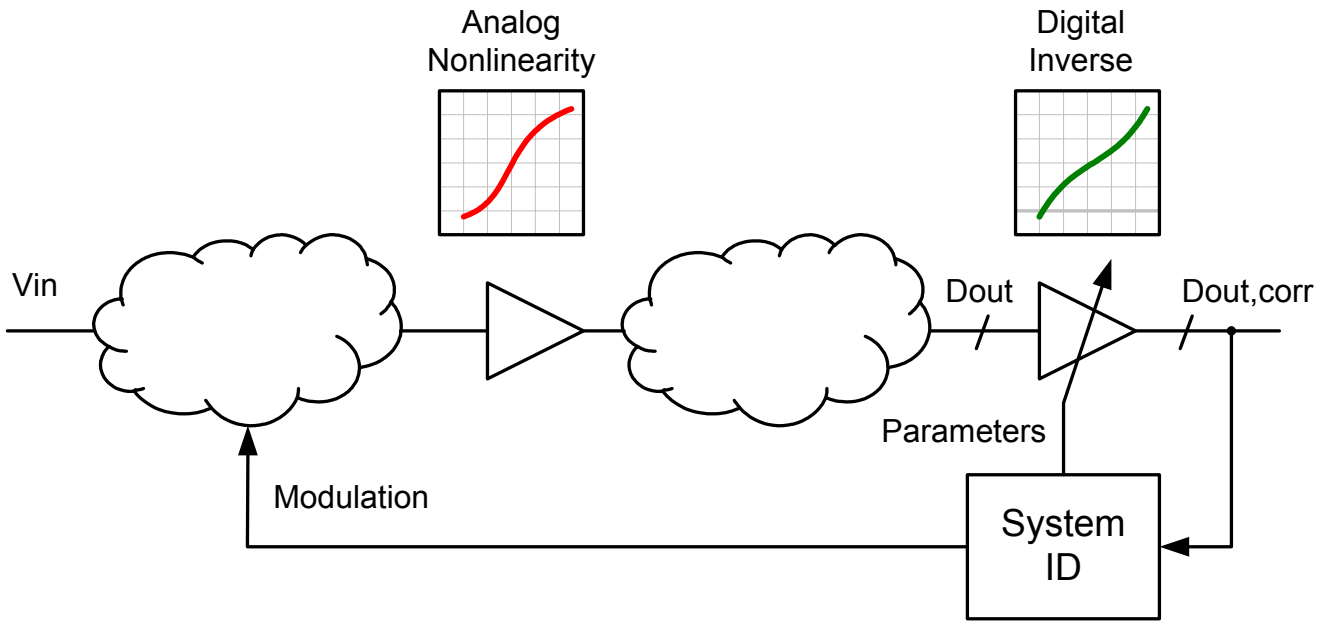
INL Zoom (Post-Proc. ON)



Stage1 Amplifier Power



Digital Nonlinearity Correction



- System ID determines optimum post distortion
- Background operation tracks variations over time without interrupting normal circuit operation

Digital Post-Processor

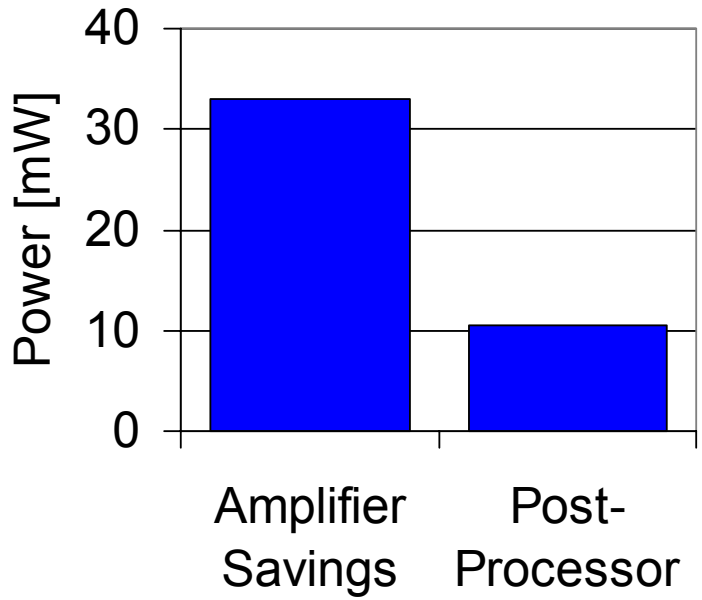
- 8400 Gates, 64 bytes RAM, 64kBit ROM
- Implementation in 0.35µm technology

Area=1.4mm^2 (18%)

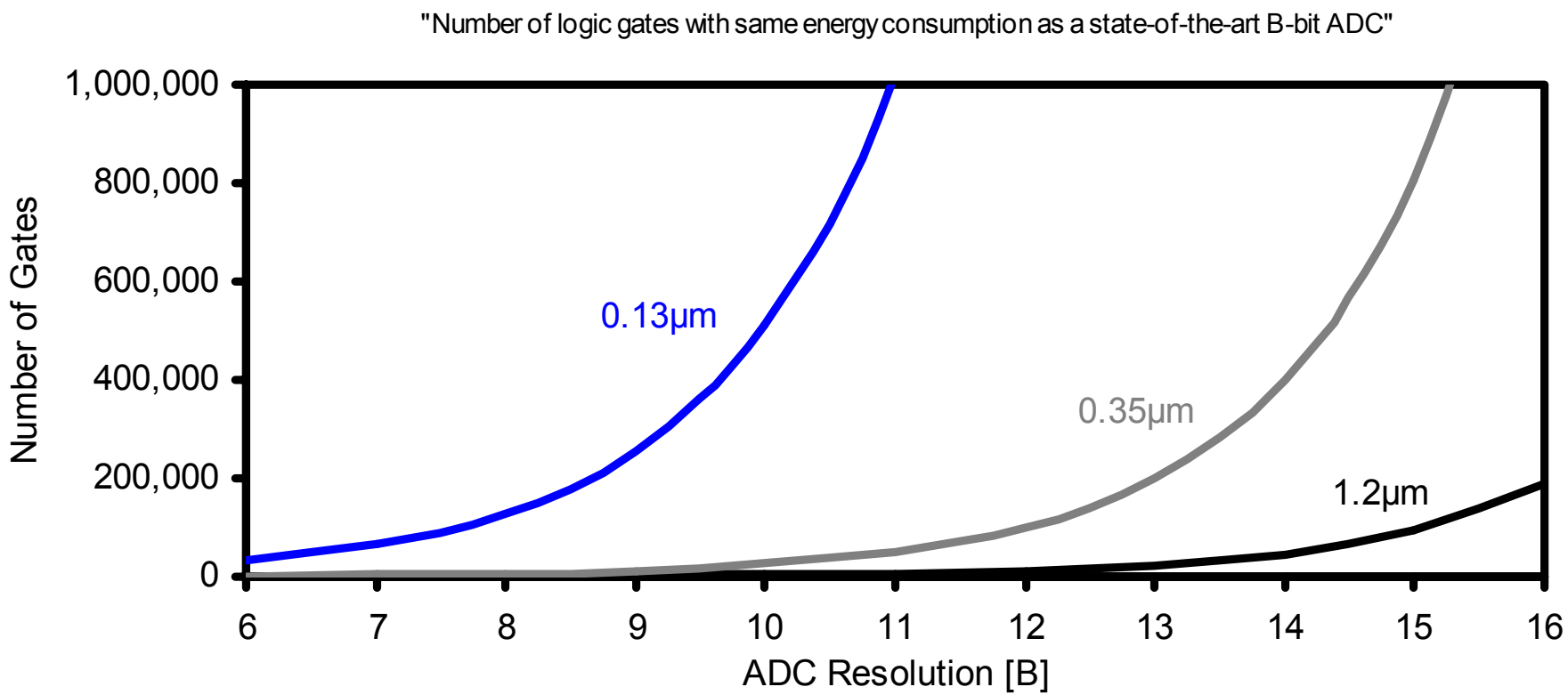
Power=10.5mW (3.6%)

Pipelined ADC
(7.9 mm^2)

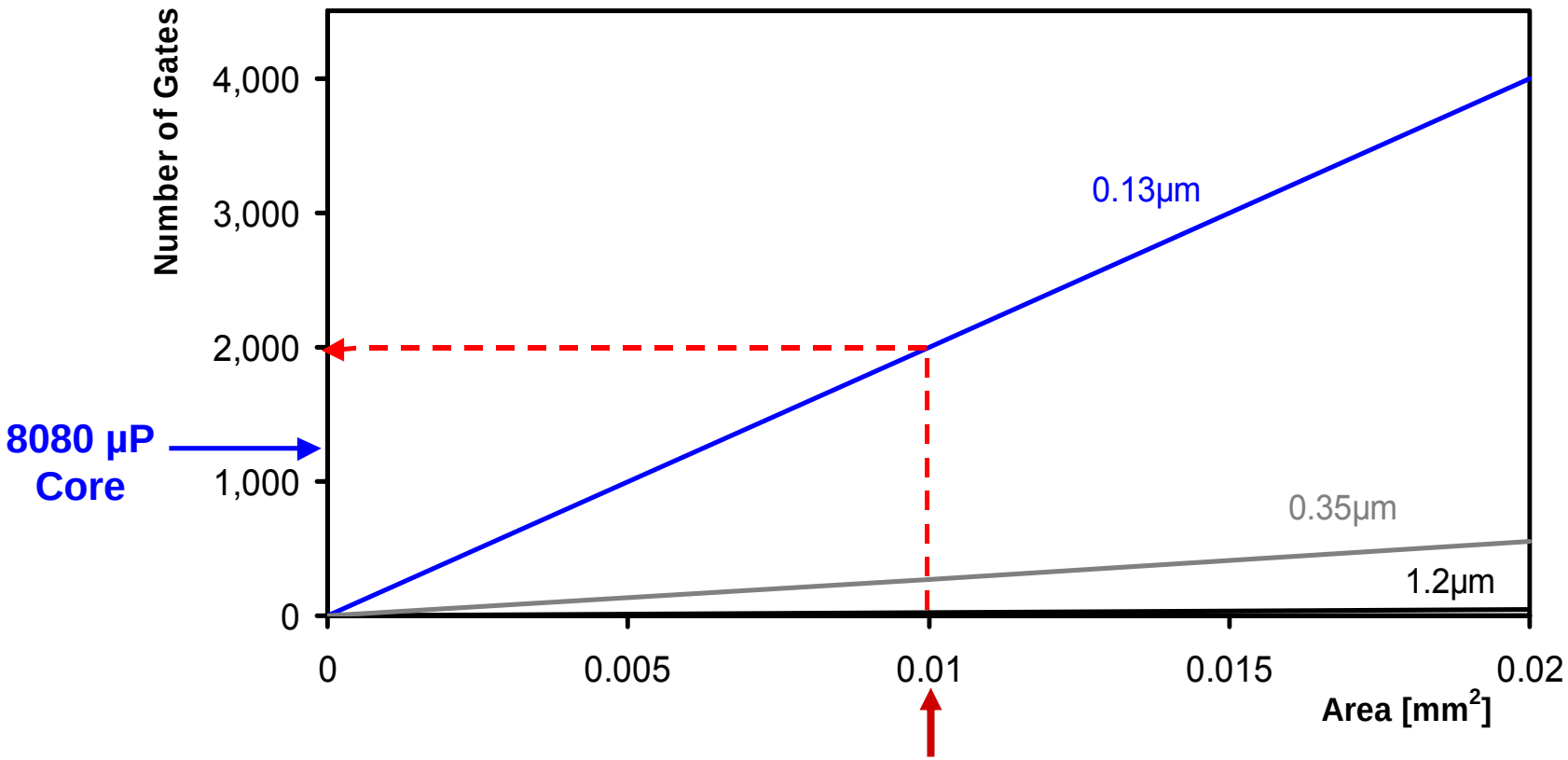
Post-Processor



Analog / Digital Power Comparison

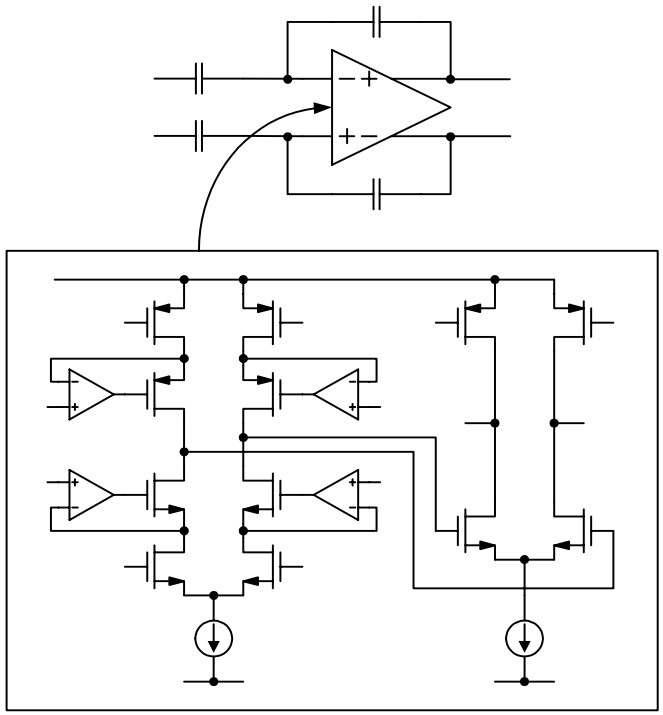


Analog / Digital Area Comparison

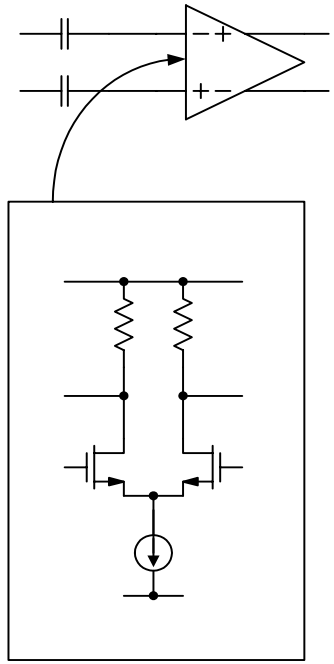


Circuit Issues

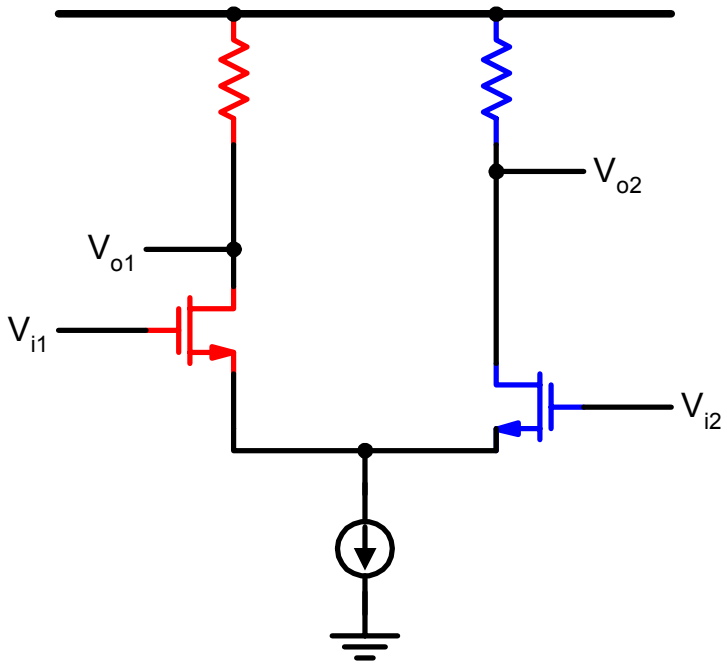
Precision Amplifier



“Open loop“

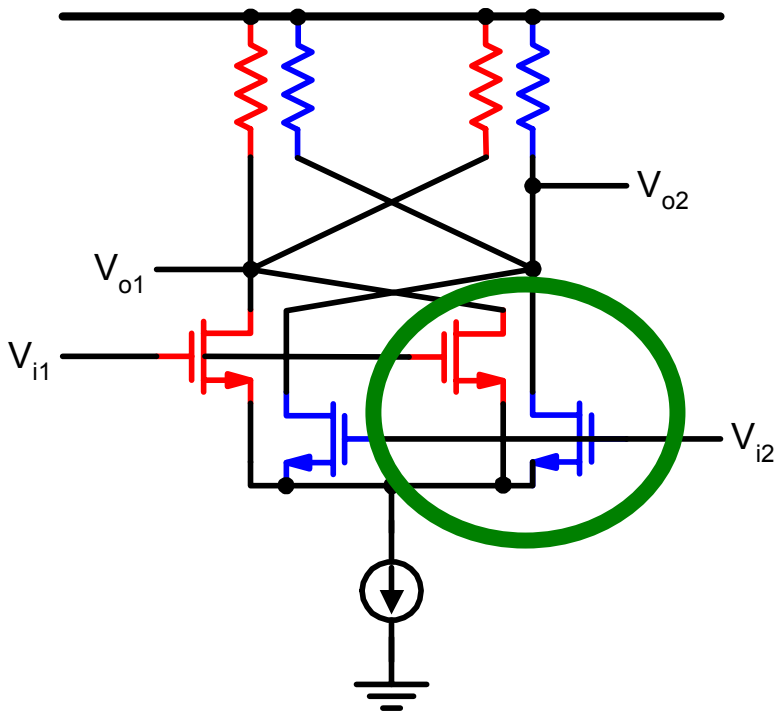


Self-Heating



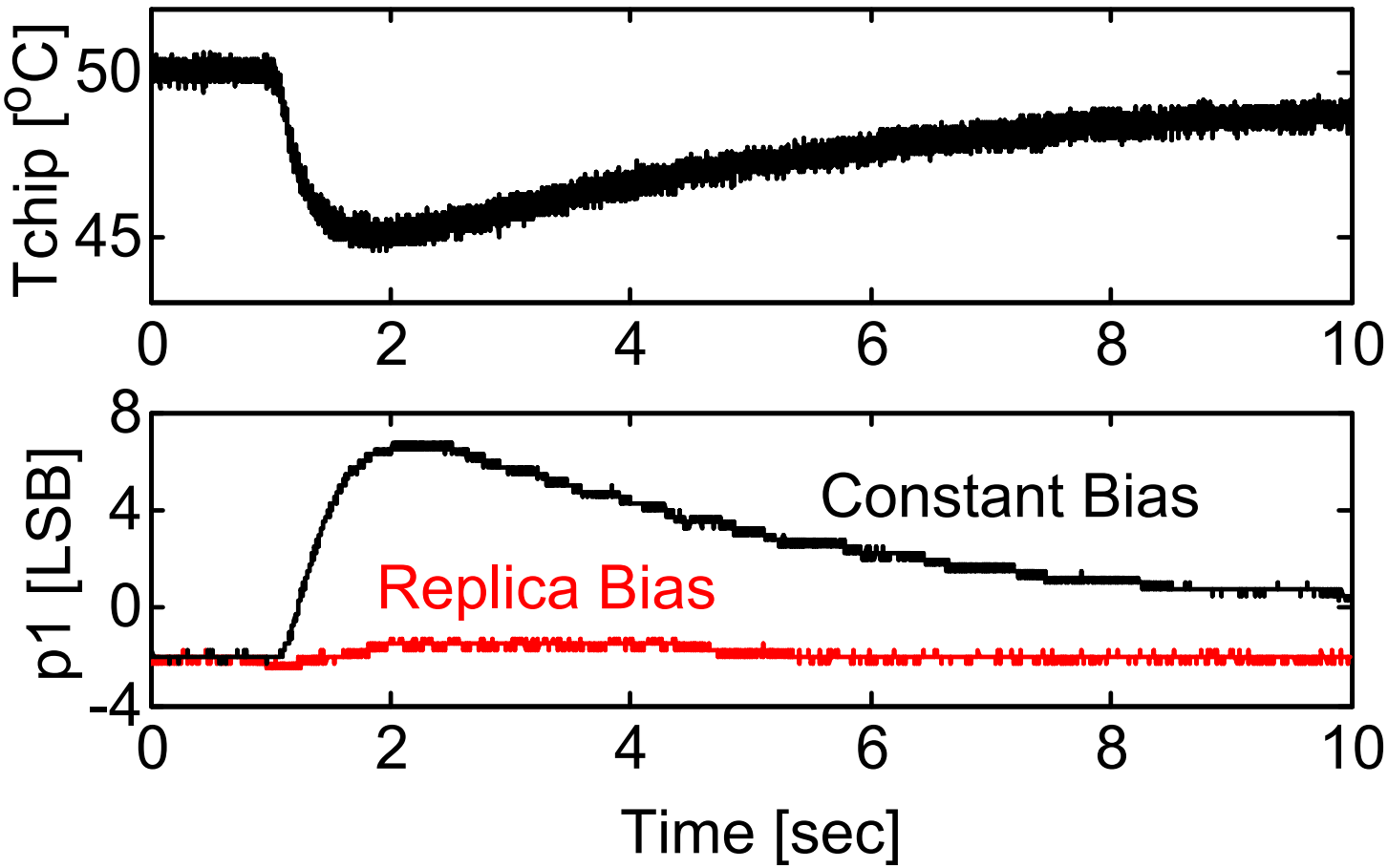
- Signal dependent current
- Signal dependent device temperature & characteristics
- Background calibration too slow to track changes

Device Interleaving



Interleaved layout
→ uniform temperature distribution

Reduced Temperature Sensitivity



Conclusion

- Technology scaling trends are only conditionally beneficial for analog circuit performance
- Analog circuit improvements lag progress of digital functions
- Digitally assisted analog circuits offload accuracy constraints to digital processor
- Benefits:
  - Improved analog circuit performance
  - Profit from future technology scaling

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Book

kluwer
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