

DfX for Nanoelectronic Circuits and Systems

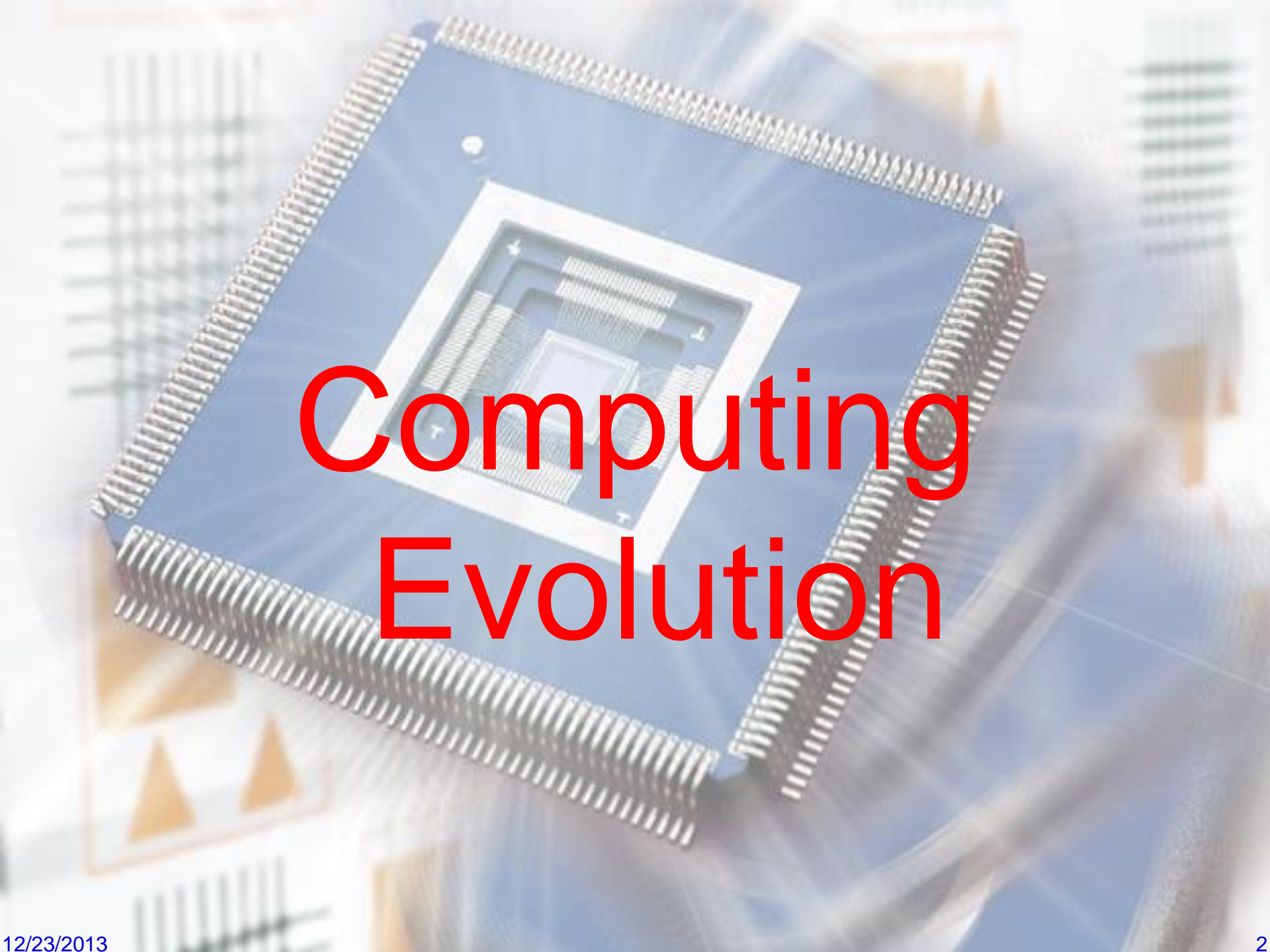
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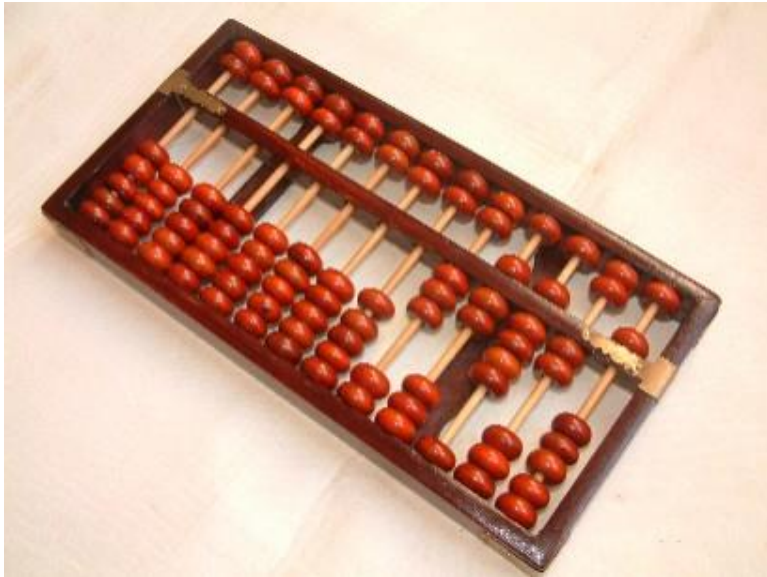
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Computing Evolution

Ancient Computing Machines -- Mechanical



2400 BC

- The abacus
- The first known calculator
- Invented in Babylonia

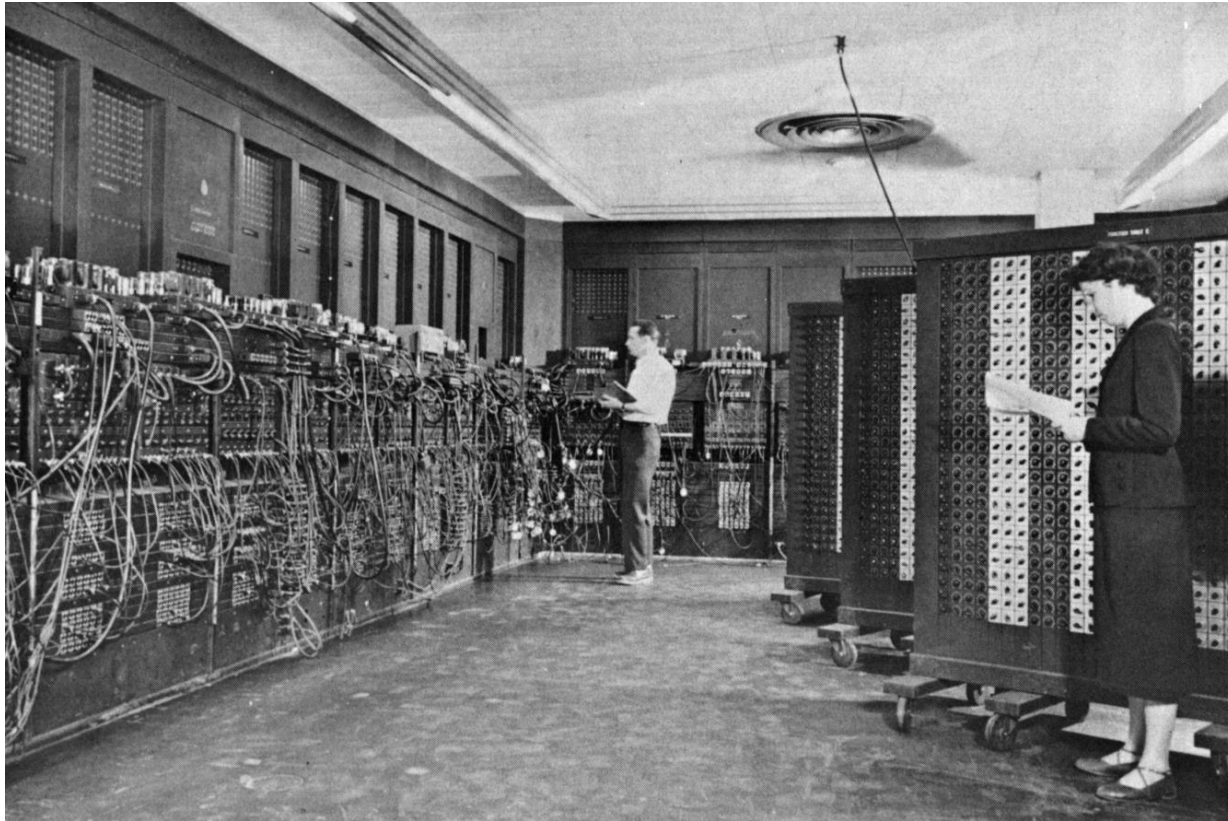


1832 AD

- The Babbage Difference Machine
- Tabulated polynomial functions
- Invented in Britain

A green light to greatness.

The First Electronic Computer



1946

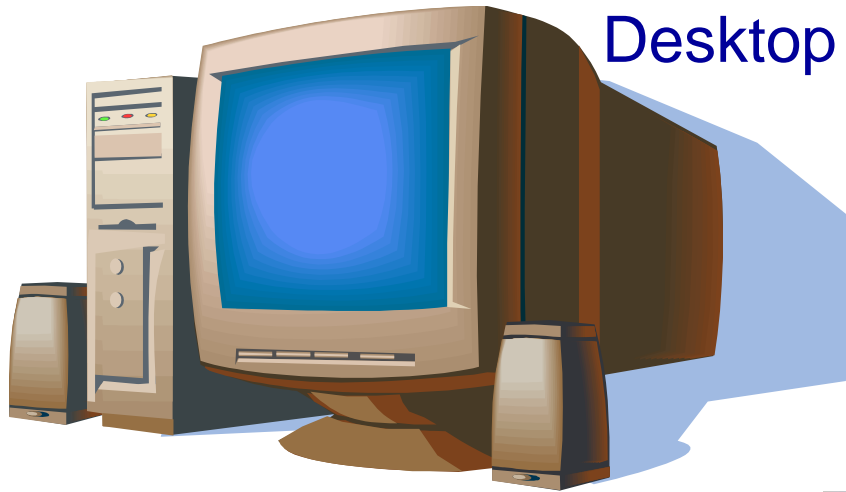
- **ENIAC** -- The first electronic general-purpose computer.
- Turing-complete, digital, and programmable.
- Invented in USA.

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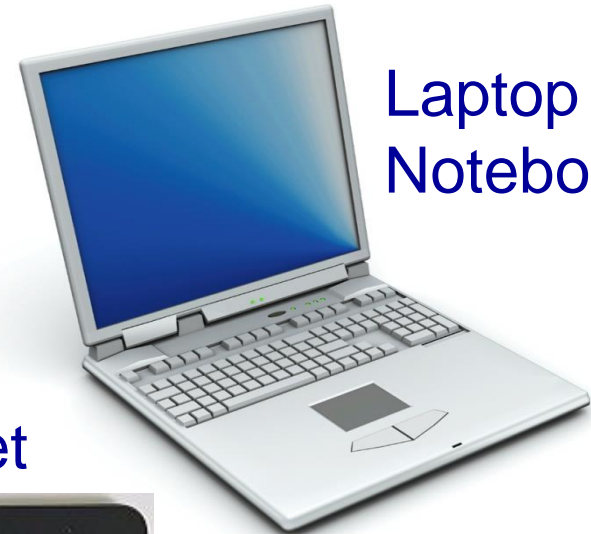


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Current Computing Systems



Desktop PC



Laptop or
Notebook PC

Tablet



Slate PC



Smart
Phone

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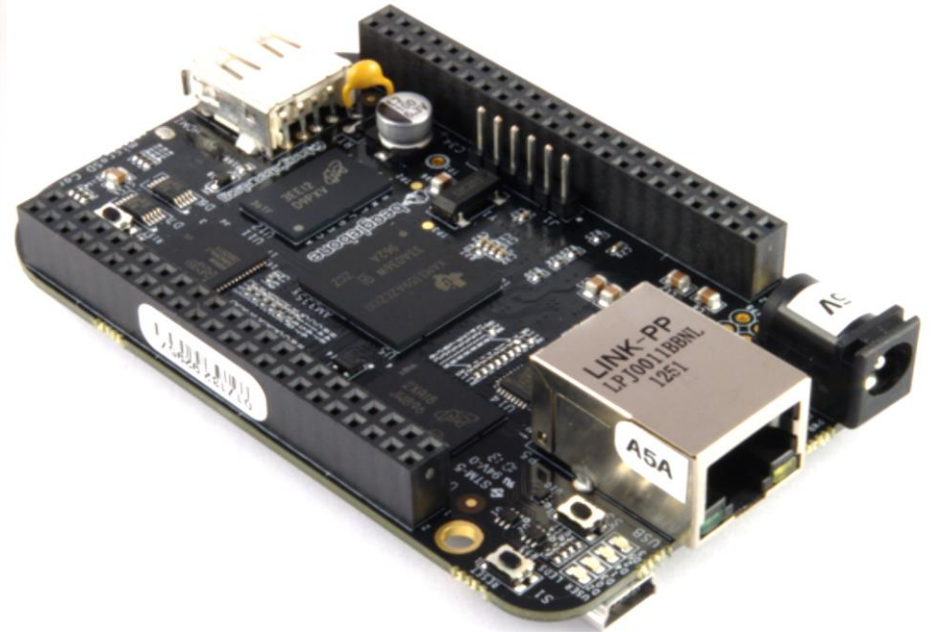


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Smallest Single-Board Computers



Raspberry Pi



BeagleBone

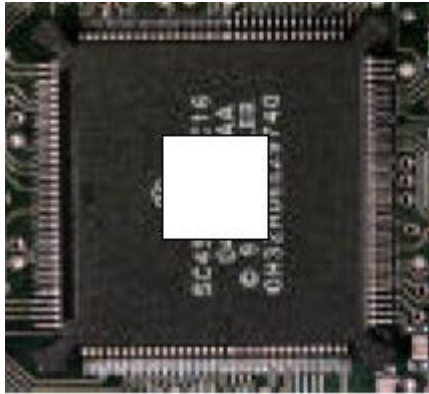
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The Workhorses

Variety of Integrated Circuits or Chips?



Low-Cost ASIC



Communication Chip



Secure Media Processor



Intel Core i7 LGA1366 processor has 1366 pins.



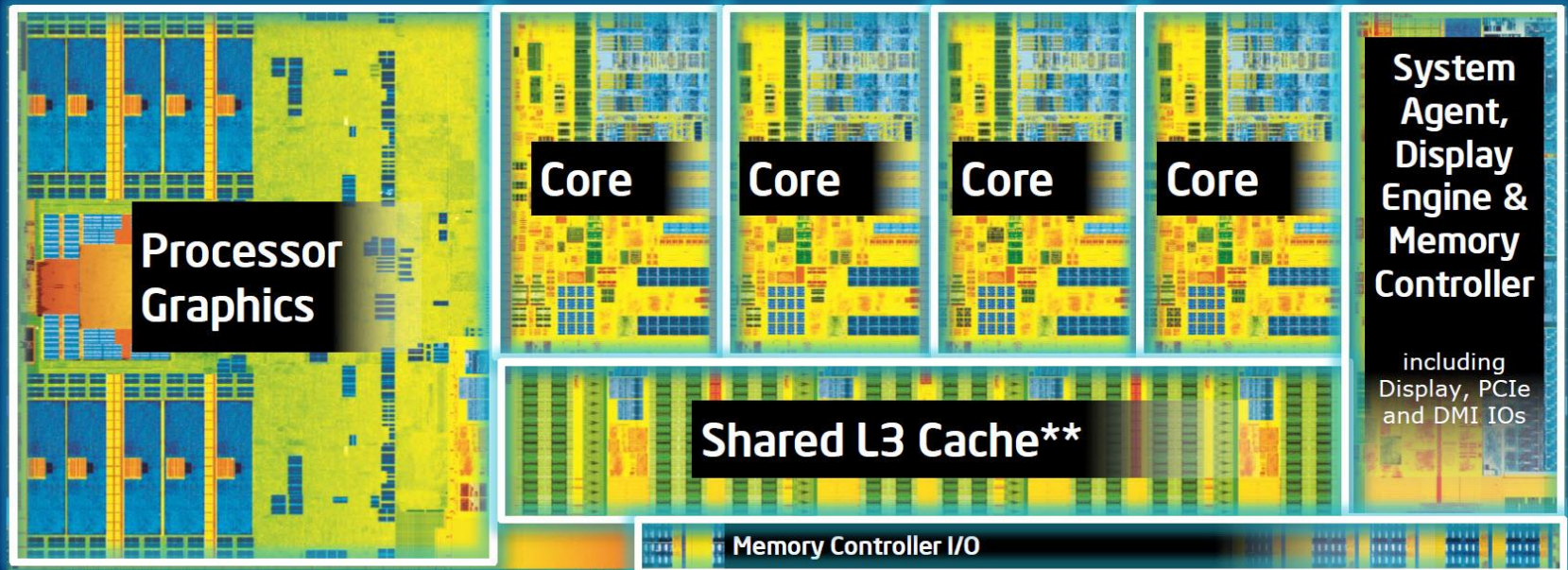
ADC Chip

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Intel Haswell Chip -- 2013

4th Generation Intel® Core™ Processor Die Map *22nm Tri-Gate 3-D Transistors*



Quad core die shown above

Transistor count: 1.4 Billion

Die size: 177mm²

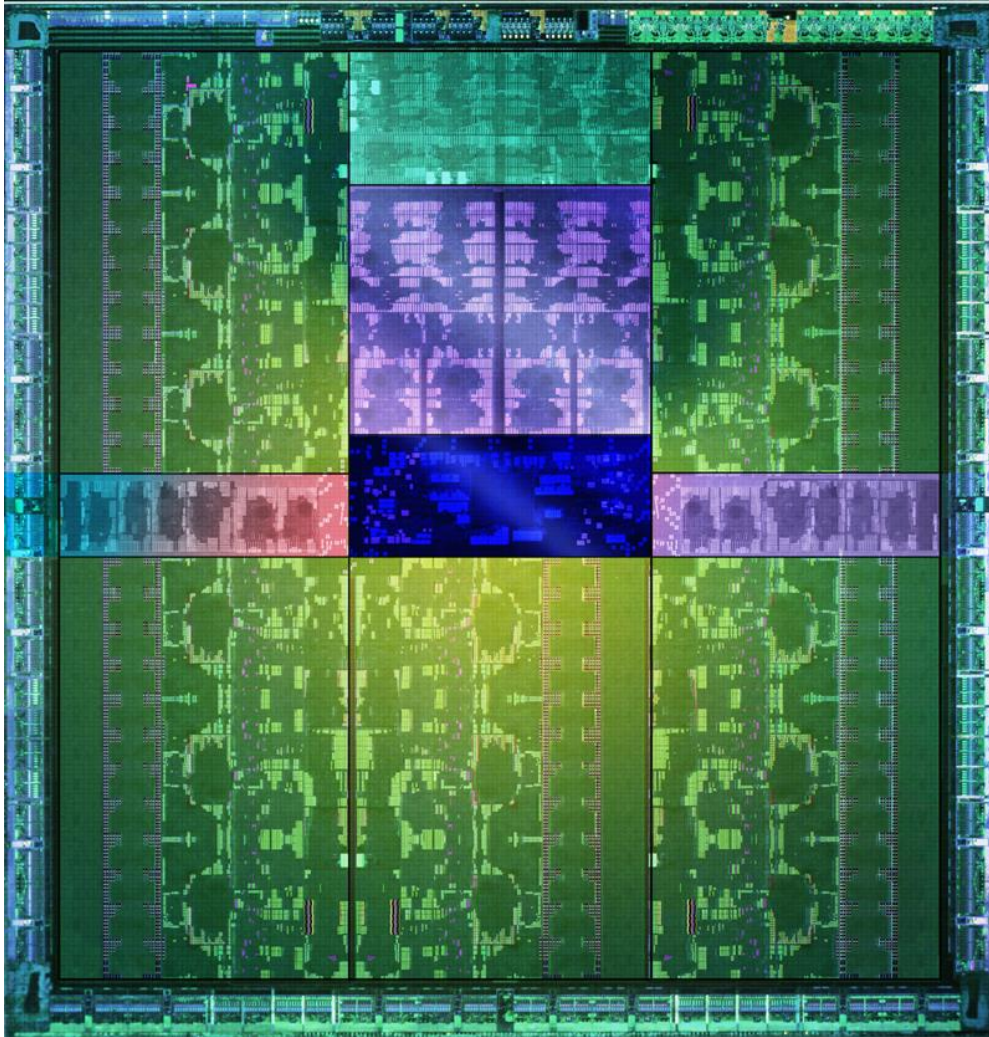
** Cache is shared across all 4 cores and processor graphics

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GPU with Highest Transistor Count



Nvidia GK110 has
7.1 billion
transistors of a
28nm technology.

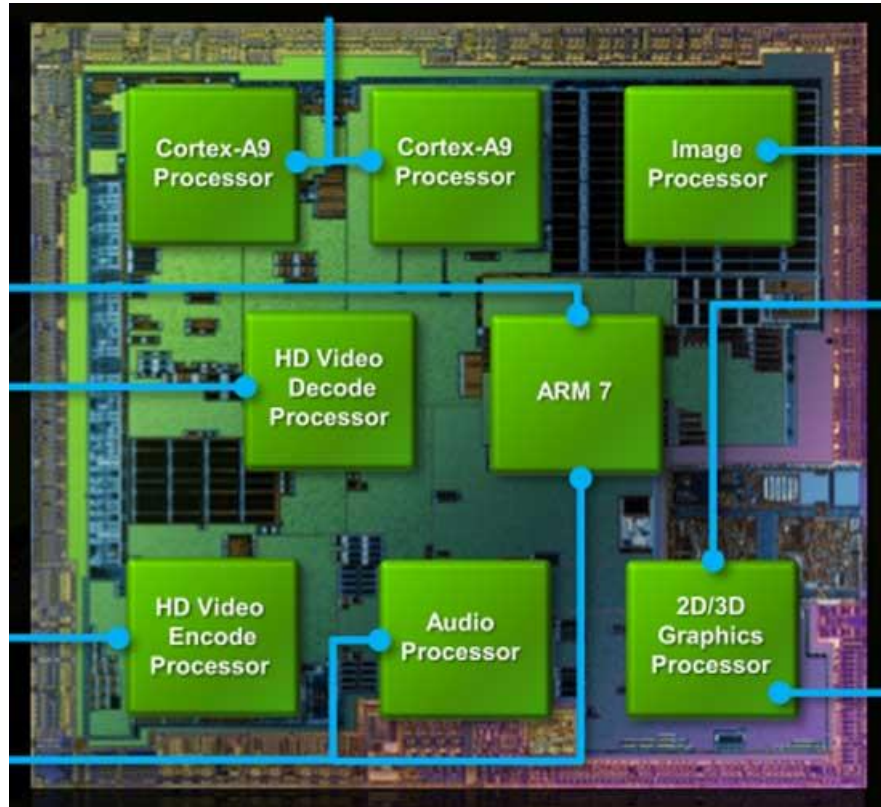
Source: <http://www.tomshardware.com/news/nvidia-tesla-k20-gk110-gpu,15683.html>

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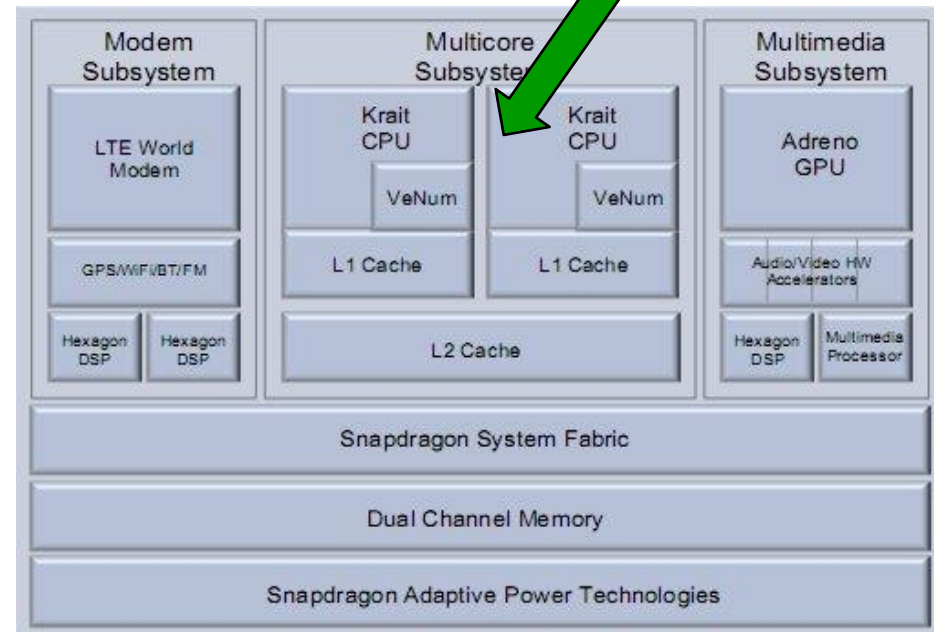
Processor for Mobile Systems: Essentially AMS-SoCs



NVIDIA's Tegra 2 die

Source: <http://www.anandtech.com>

ARM-based
from Qualcomm



Snapdragon S4 Block Diagram

Source: <http://www.cnx-software.com>

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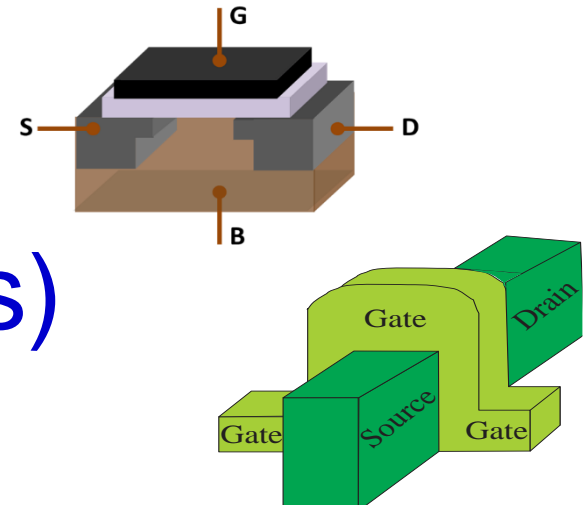


The Drivers

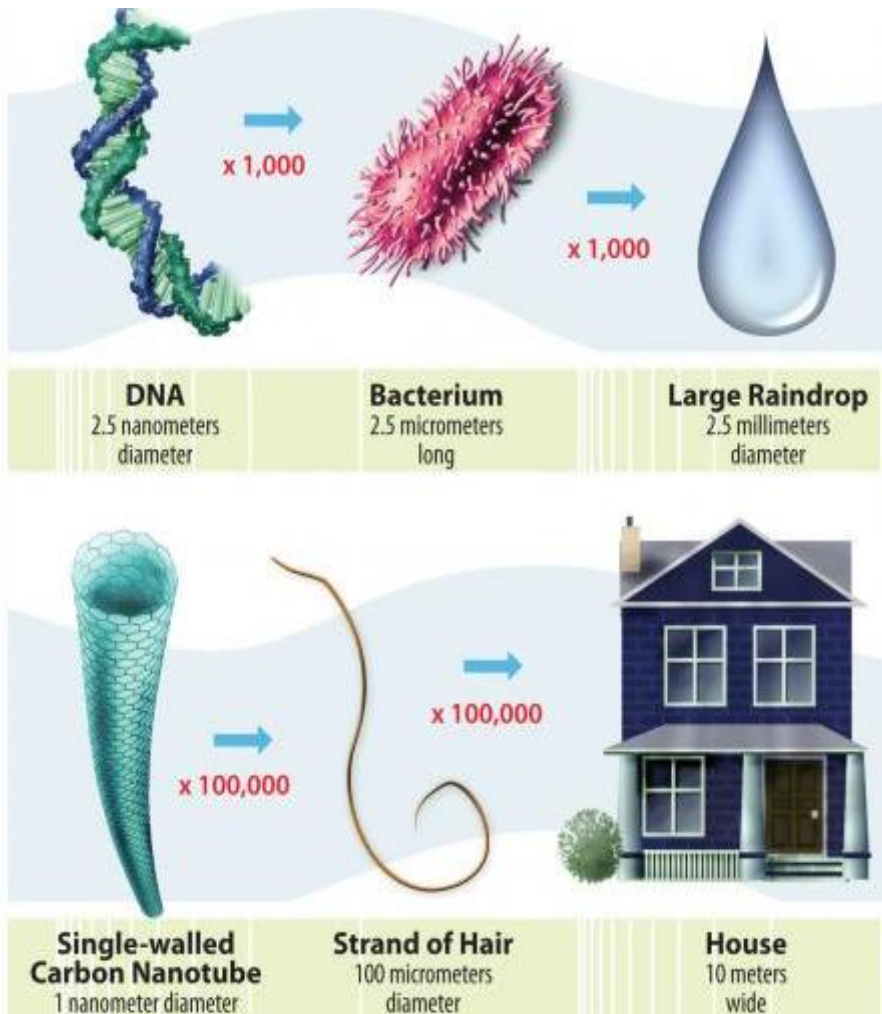
■ Technology Miniaturization (aka Technology Scaling)

Nano

■ New Technology (Alternative Devices)



How Small in Nano??

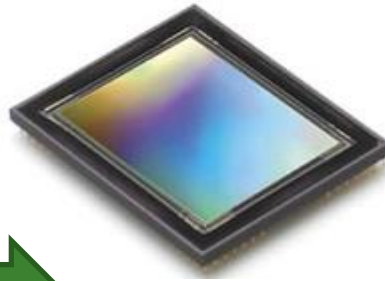


- "nano" means one-billionth, or 10^{-9}
- A sheet of paper is about 100,000 nanometers thick
- A human hair is approx. 100,000 nanometers wide

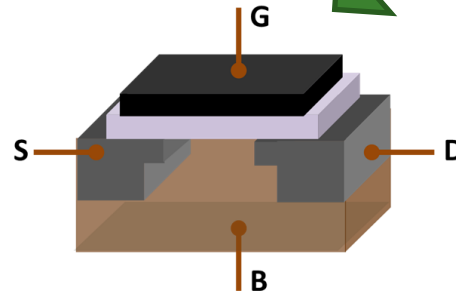
Source: <http://www.nano.gov/nanotech-101/what/nano-size>

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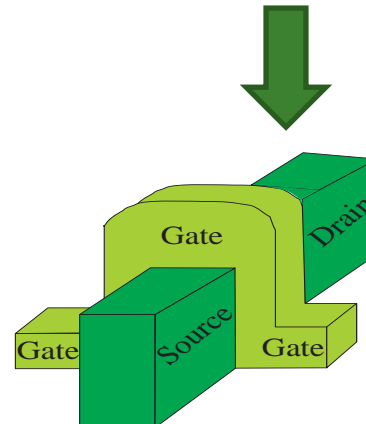
A Typical Nanoelectronic System



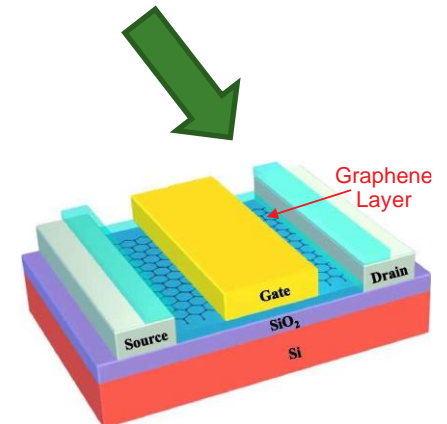
Heterogeneous components with
millions of nanoscale devices.



High-K
nano-CMOS



Triple Gate



Graphene
Nanoribbon

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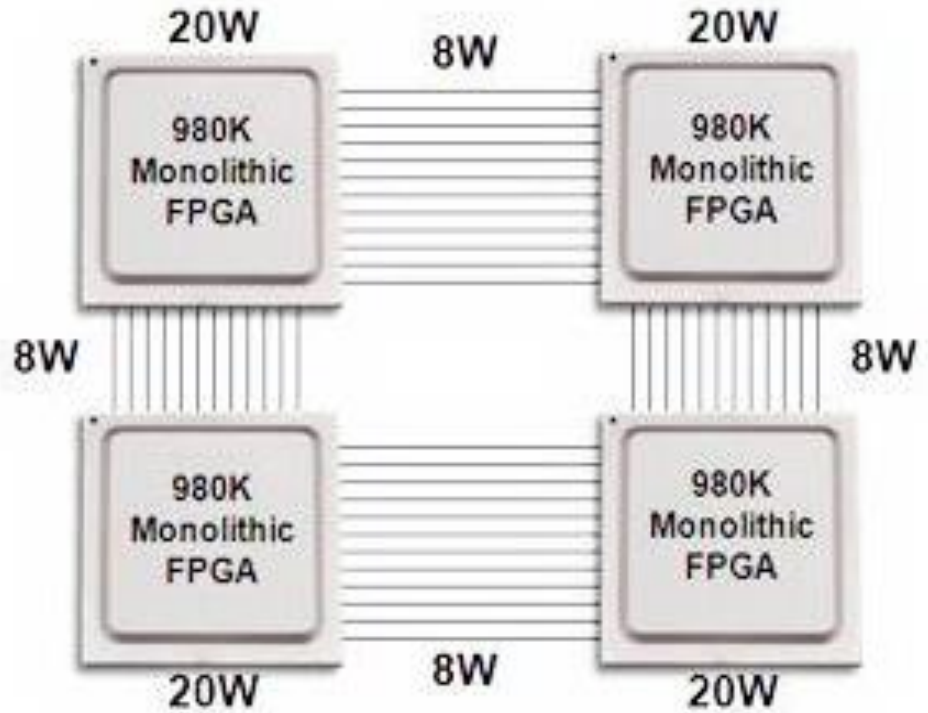


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Good and Bad, and DFX

Scaling Reduces Power Dissipation



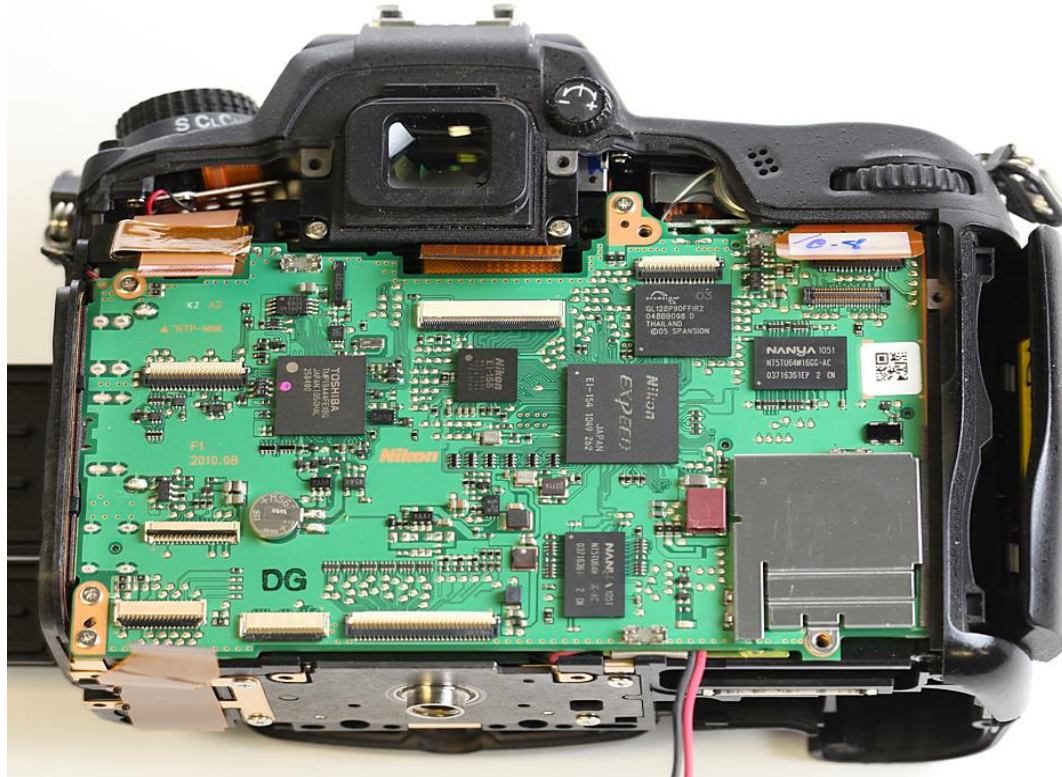
1 Virtex-7 2000T = 4 Largest Monolithic FPGAs

19 Watts 112 Watts

Source: <http://low-powerdesign.com/sleibson>

Scaling Reduces Cost of Electronics

In 1986: 1.3 megapixels CCD sensor Kodak camera was \$13,000. You can buy now for few dollars.



Nikon D7000
DSLR camera.

16 MP → \$700

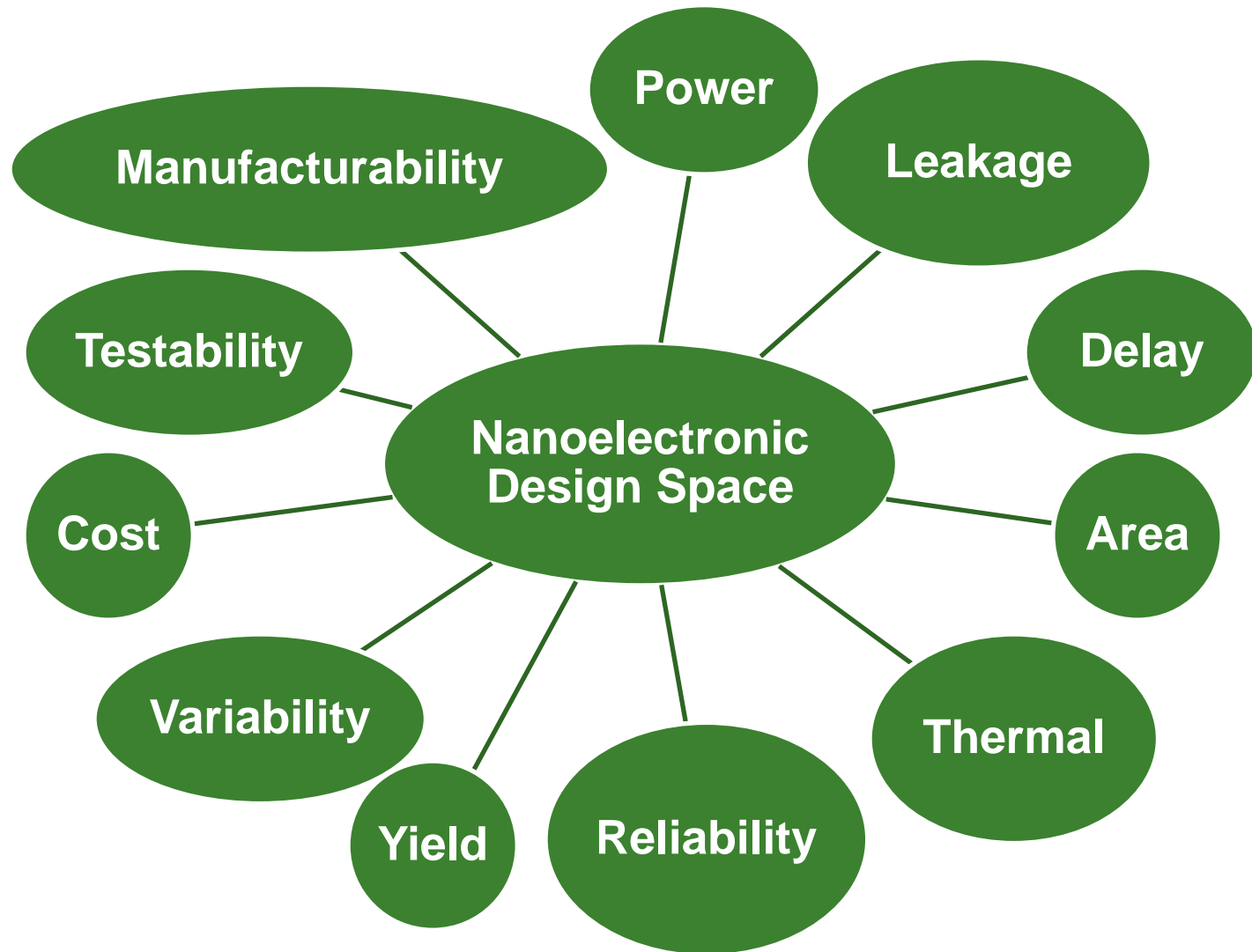
Source: <http://www.lensrentals.com/blog/2012/04/d7000-dissection>

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Nanoelectronics : Challenges

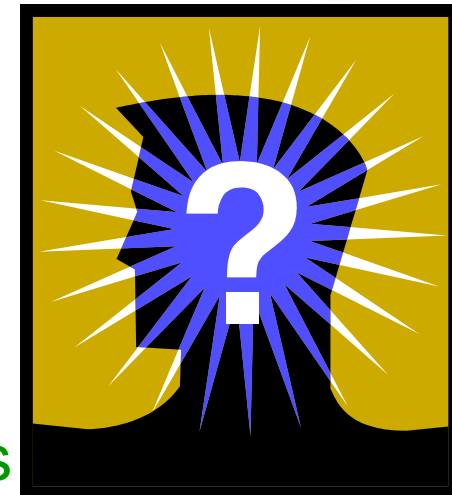


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DfX -- Design for X (aka Design for Excellence)

X = set of IC design challenges

- ❑ **M**anufacturability
- ❑ **P**ower
- ❑ **V**ariability
- ❑ **C**ost
- ❑ **Y**ield
- ❑ **R**eliability
- ❑ **T**est
- ❑ **D**ebug



Designers

Source: ISVLSI 2012 Andrew Kahng Keynote

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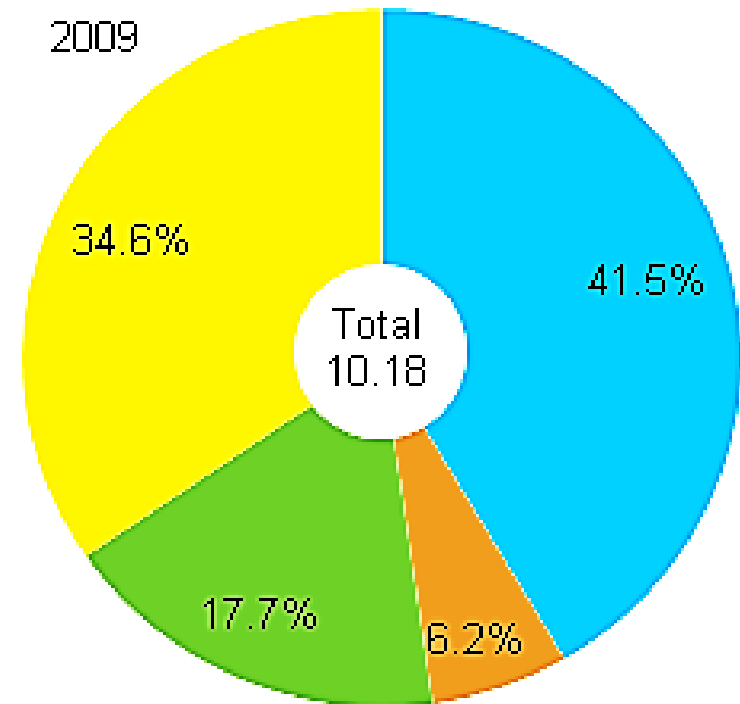
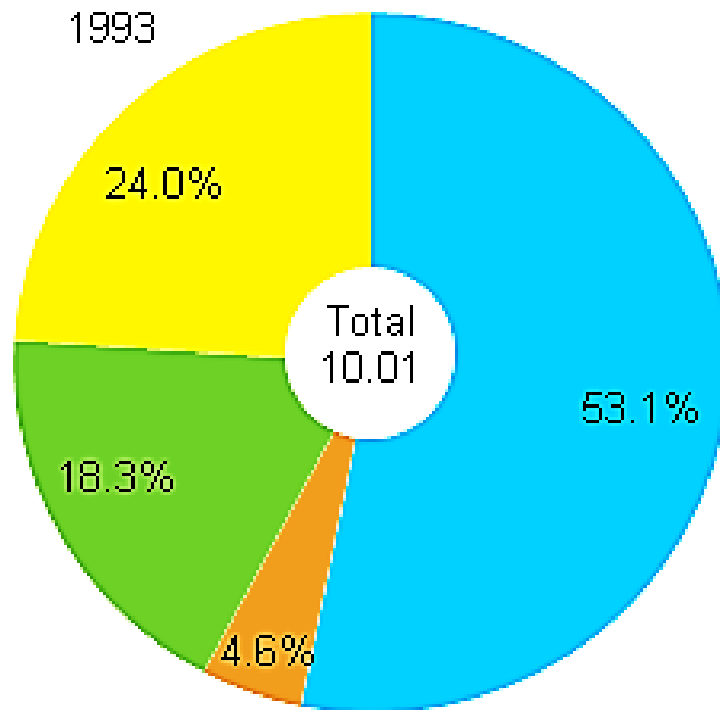
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Design for Power (DfP)

Consumer Electronics Demand More and More Energy

Energy consumption in homes by end uses
quadrillion Btu and percent



■ space heating ■ air conditioning ■ water heating ■ appliances, electronics, and lighting

Quadrillion BTU (or quad): 1 quad = 10^{15} BTU = 1.055 Exa Joule (EJ).

Source: U.S. Energy Information Administration.

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Different Electronic Systems: Common Story



- Smarter ... Faster ... High Throughput ...
→ Power Hungry !! Battery Hungry !!

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Battery Dependency: Not Overstated



One 787 Battery:
12 Cells / 32 V DC



- Boeing 787's across the globe were grounded in early 2013.

Source: <http://www.newairplane.com>

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Battery Dependency: Not Overstated



- Great idea: Smartwatch with functioning like smartphone.
- **Big Problem:** Battery life of one time charging is **only 1 day**.

Source: <http://www.businessinsider.com>

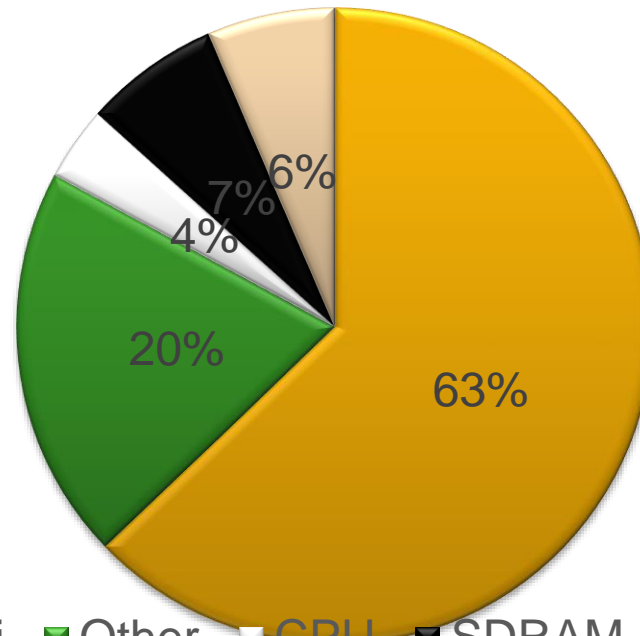
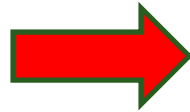
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A Typical Electronic System: Where Energy Consumed??

Power of a Mobile System



■ WiFi ■ Other ■ CPU ■ SDRAM ■ Bluetooth

Power dissipation breakdown in idle
mode of a connected mobile device

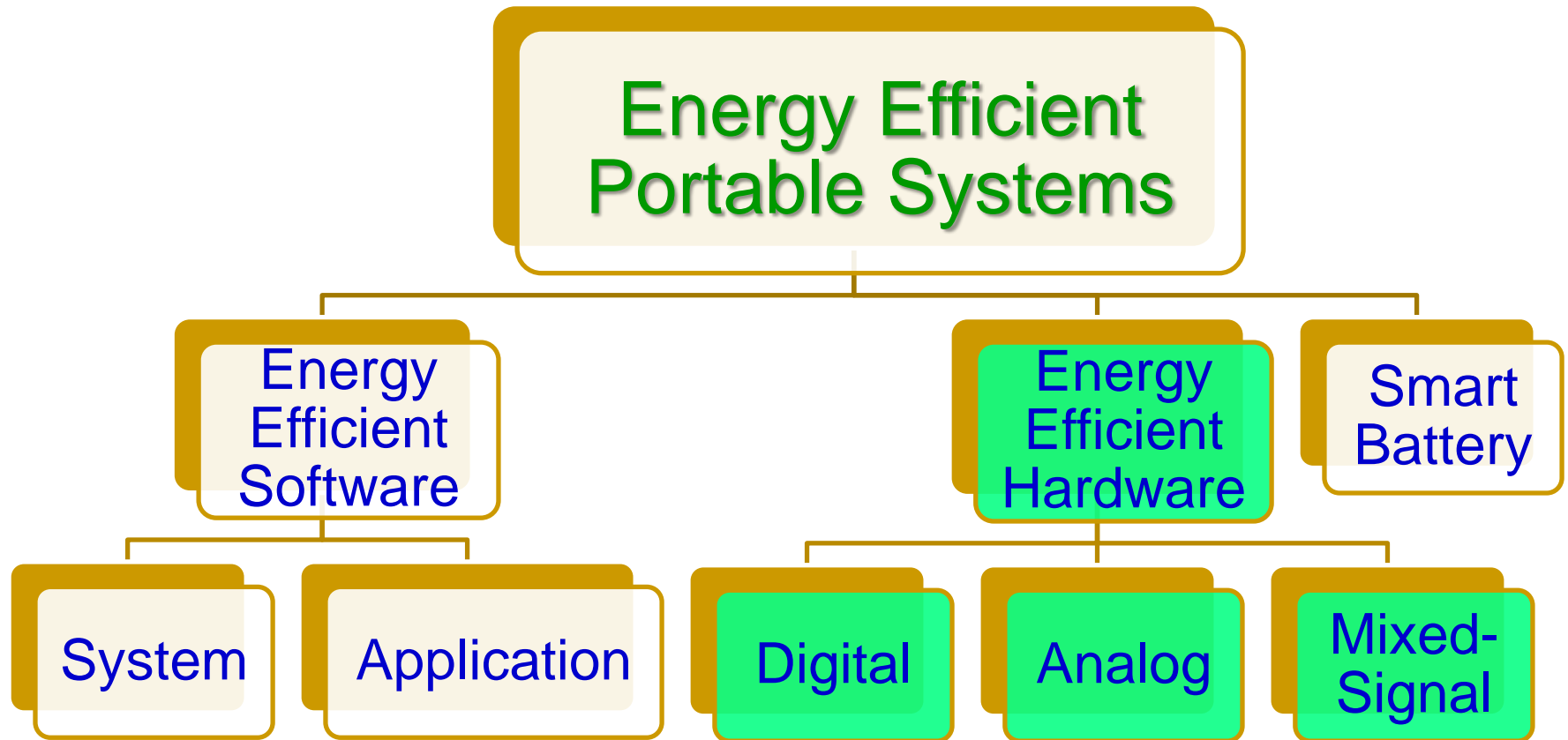
Source: Pering MobiSys 2006

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DfP: Possible Solution Fronts



DfP: Design of an Universal Level Converter for Dynamic Power Management

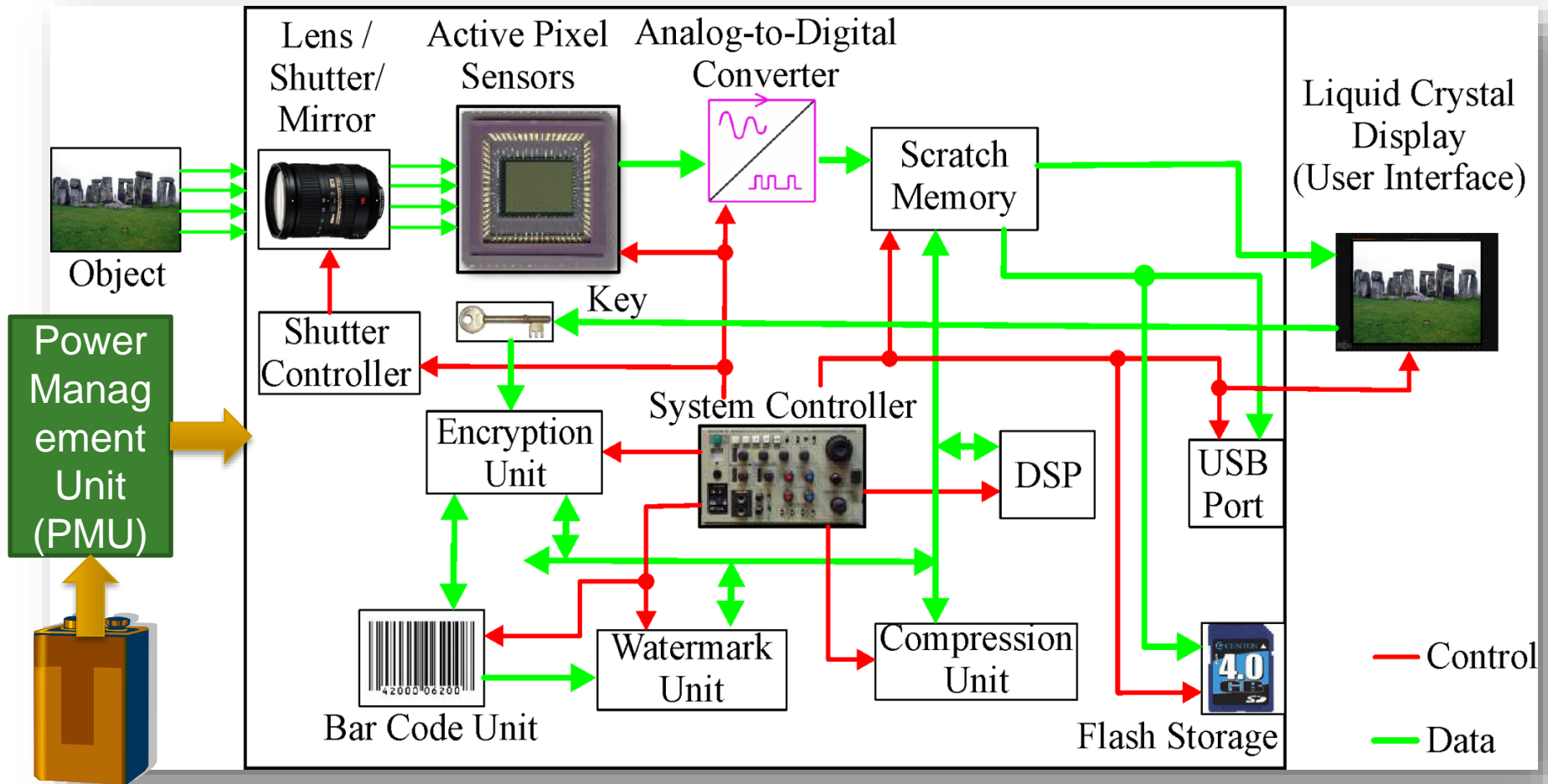
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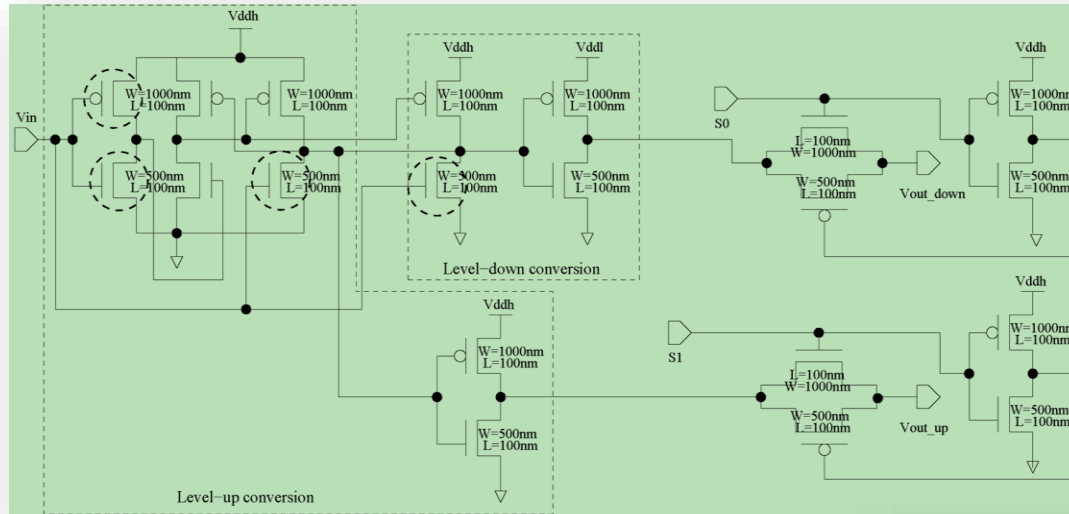
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One Example Electronic System: Secure Digital Camera



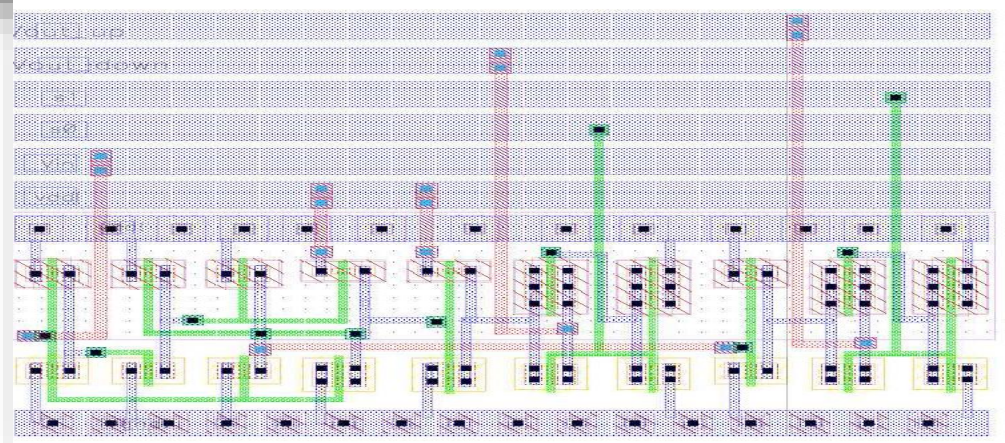
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Universal Voltage-Level Converter: One Topology



- 20 transistor area efficient design.
- Energy hungry transistors are circled.

- Energy hungry transistors have thicker oxide.
- 90nm CMOS dual-oxide physical design of ULC.



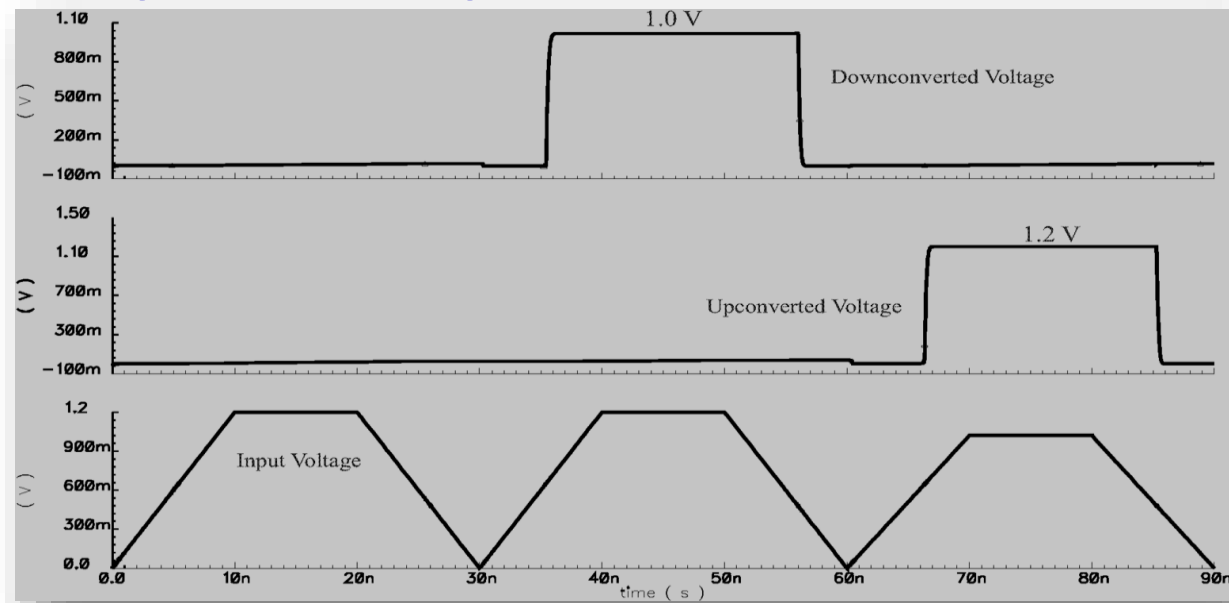
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Universal Voltage-Level Converter: Operations

Operations of the ULC:

- ❑ Level-up conversion
- ❑ Level-down conversion
- ❑ Blocking of input signal

Select Signal		Type of Operation
0	0	Block Signal
0	1	Up Conversion
1	0	Down Conversion



Output

Input

Universal Voltage-Level Converter: Has Minimal Overhead

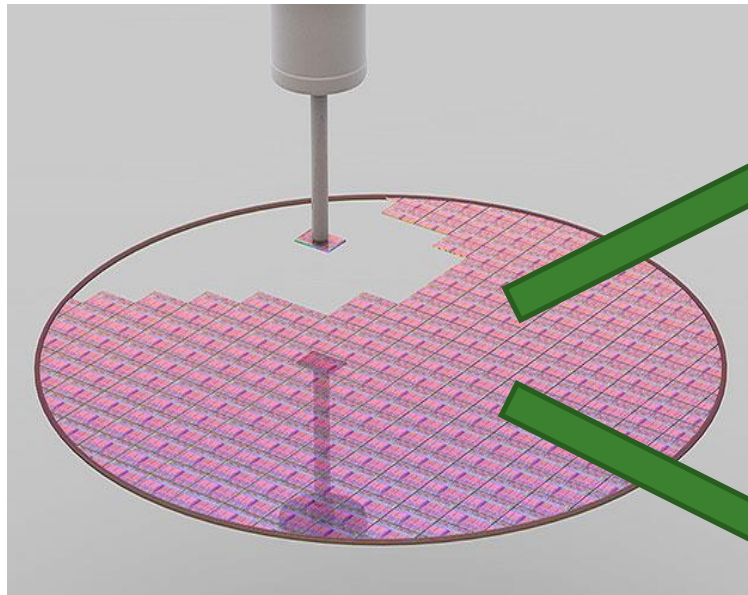
Designs	Technology (nm)	Power	Delay	Conversion	Design Approach
Ishihara 2004	130nm	---	127 ps	Level-up and down	Level converting flip flops
Yu 2001	350nm	220.57 μ W	---	Level-up	SDCVS
Sadeghi 2006	100nm	10 μ W	1 ns	Level-up	Pass transistor and Keeper transistor
ULC	90 nm	12.26 μ W	113.8 ps	Level-up/down and block	All conversion types and Programmable



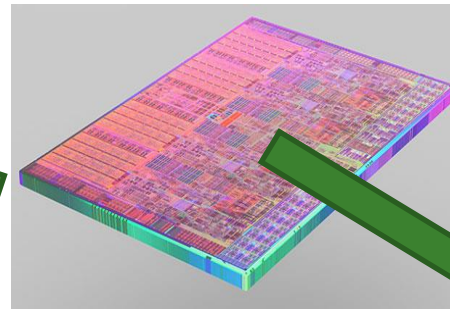
Design for Variability (DfV)

Nanoelectronics Variability ?

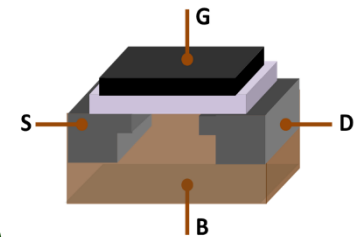
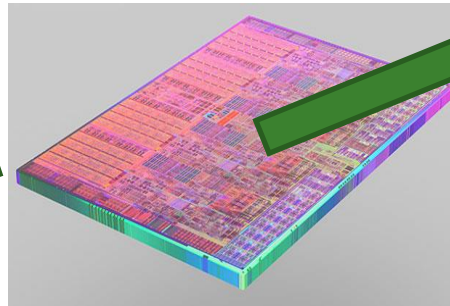
- Discrepancy between the chip parameters --
Design Time versus Actual Post Fabrication



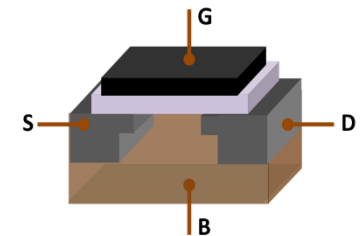
Same Design Fabricated



Each Chip has
Different Performance

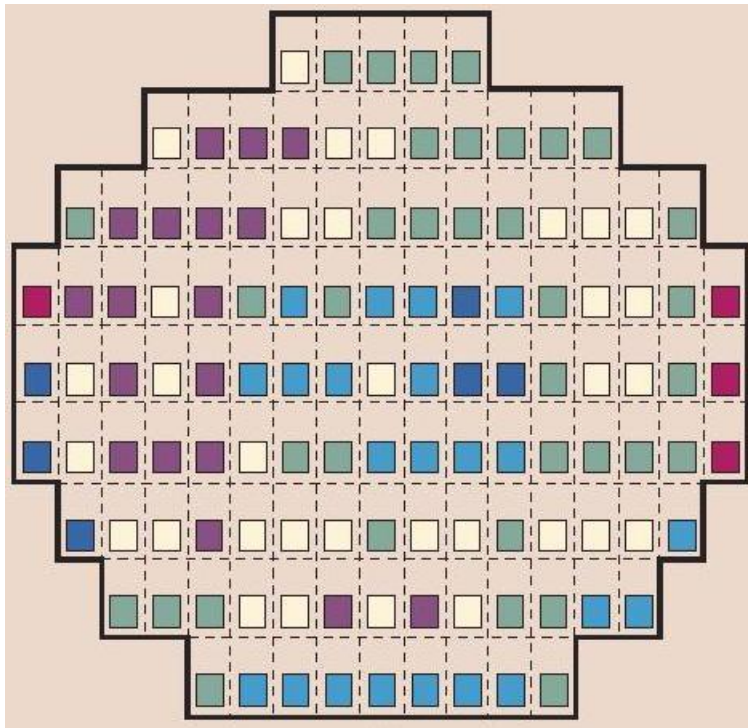


Each Transistor
is Different

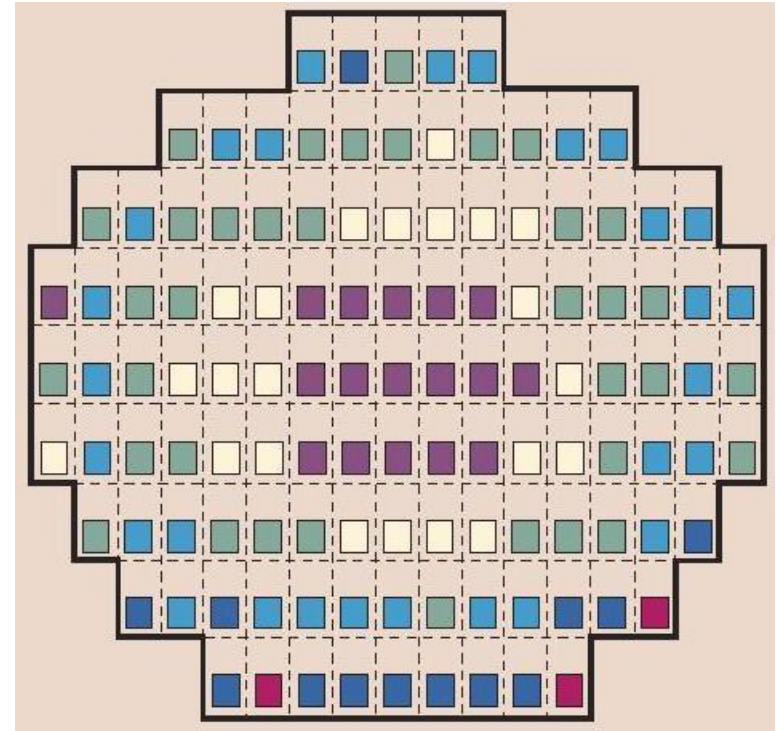


Source: <http://apcmag.com/picture-gallery-how-a-chip-is-made.htm>

Process Variation: Parameters



Source-drain resistance is different for different chips in a same die.



Gate-to-source and gate-to-drain overlap capacitance is different for different chips in a same die.

Source: Bernstein et al., IBM J. Res. & Dev., July/Sep 2006.

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Process Variation: The Impact

- Yield Loss
- Reliability Issue
- Higher Cost

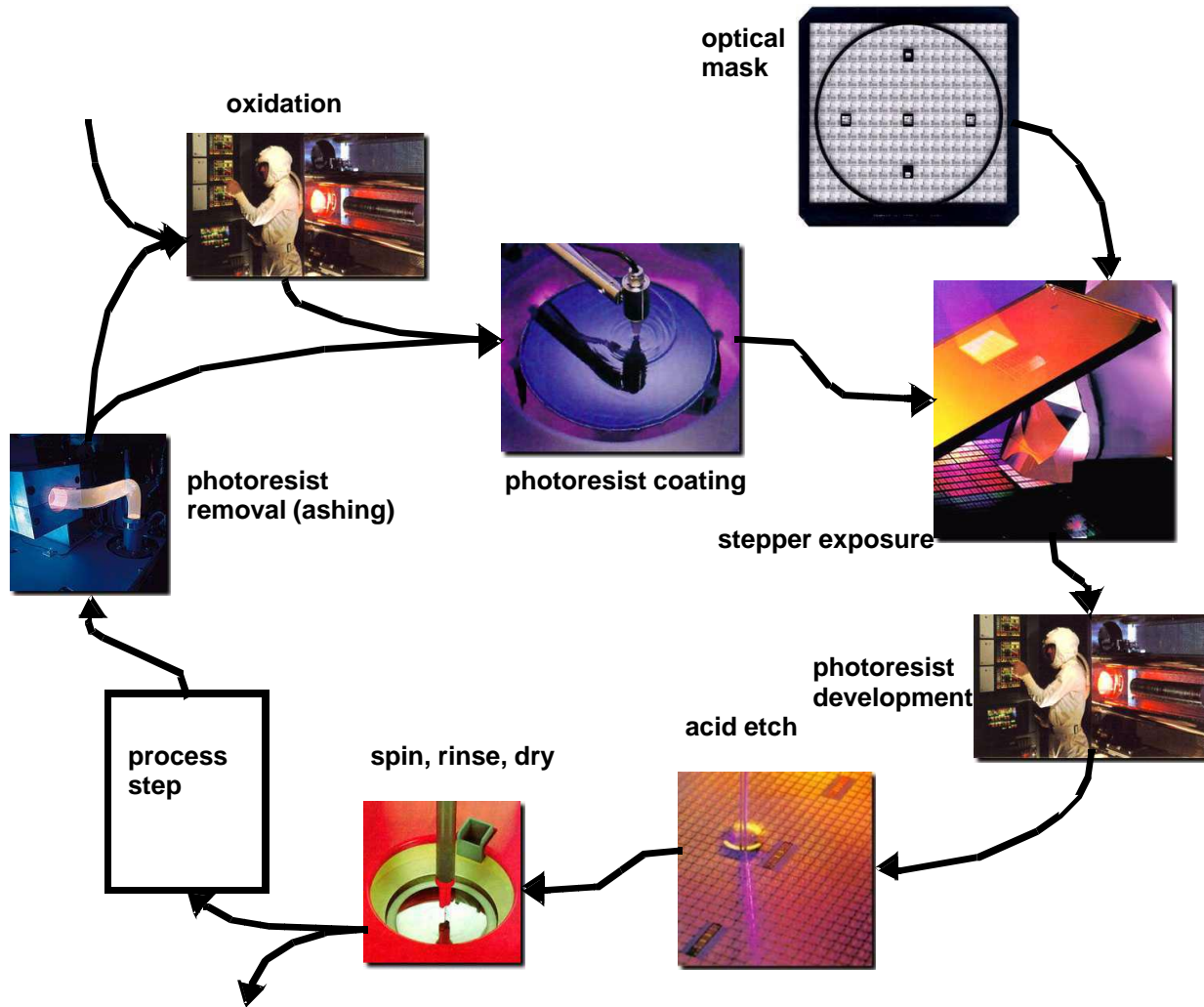
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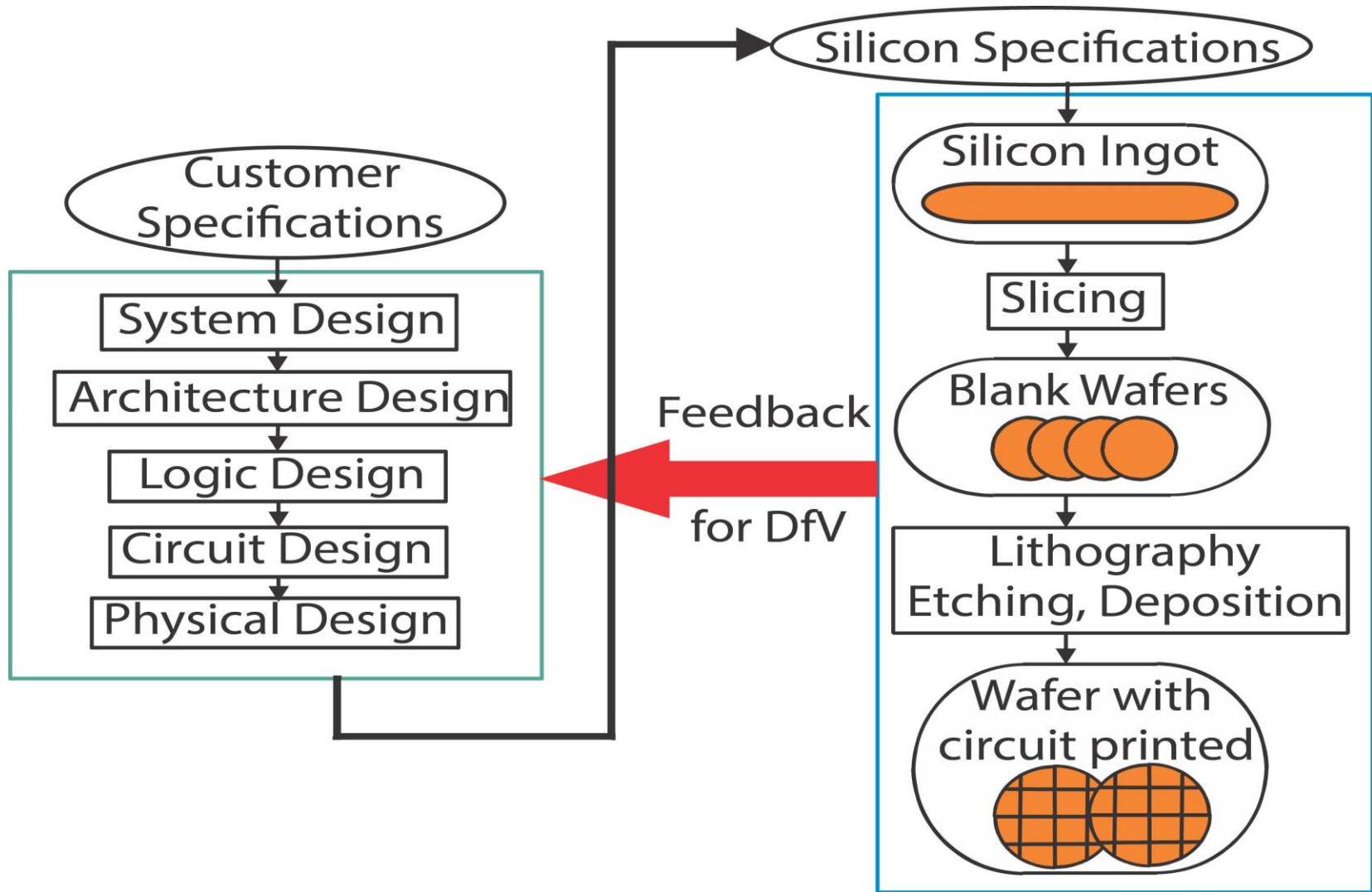
Process Variation: Sources



**Sophisticated
Lithography**

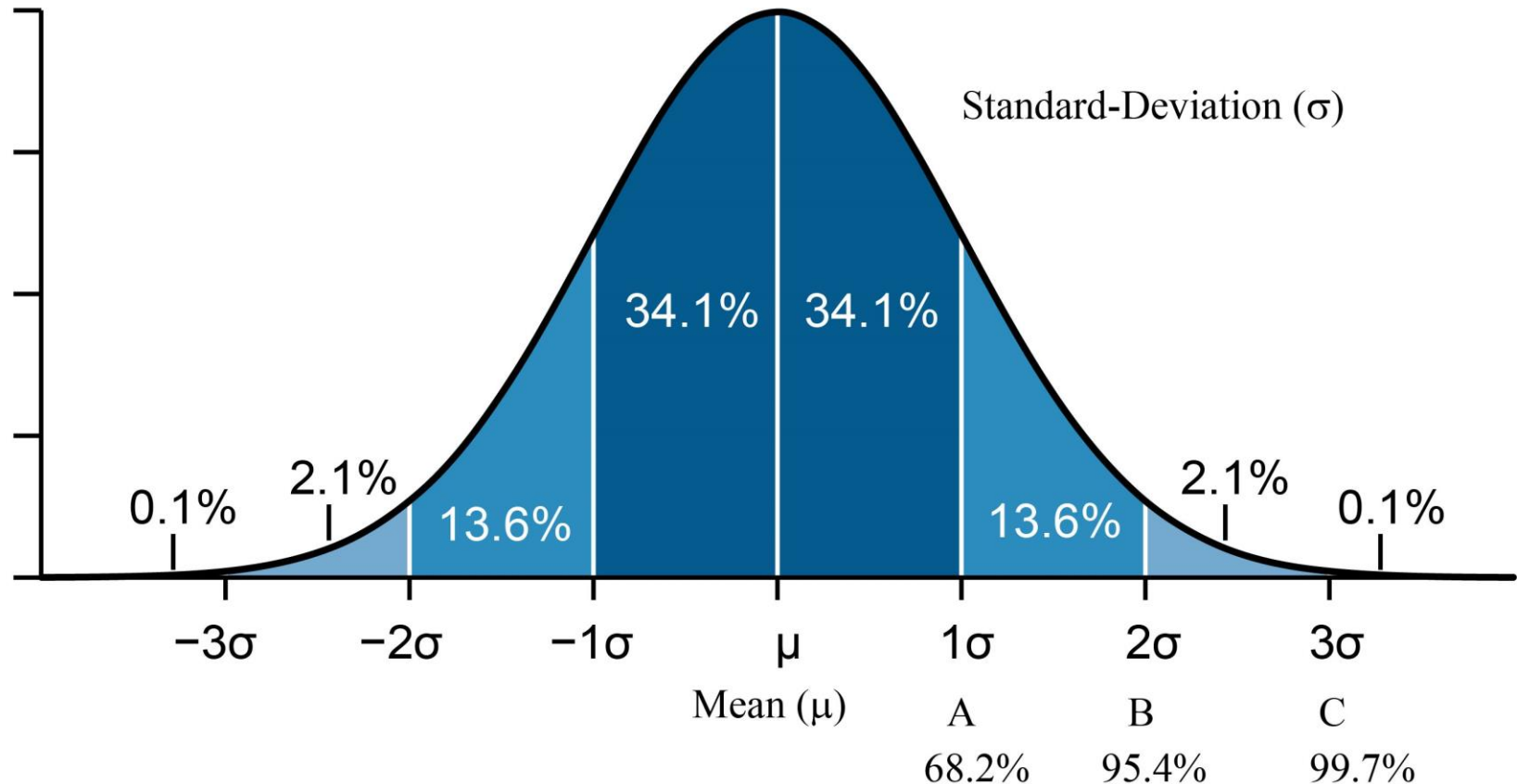
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Process Variations : Solution



Process Variations Aware Optimization: Key Idea

Histograms



Power / Performance Values



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DfV: Statistical Nano-CMOS RTL Optimization for Power

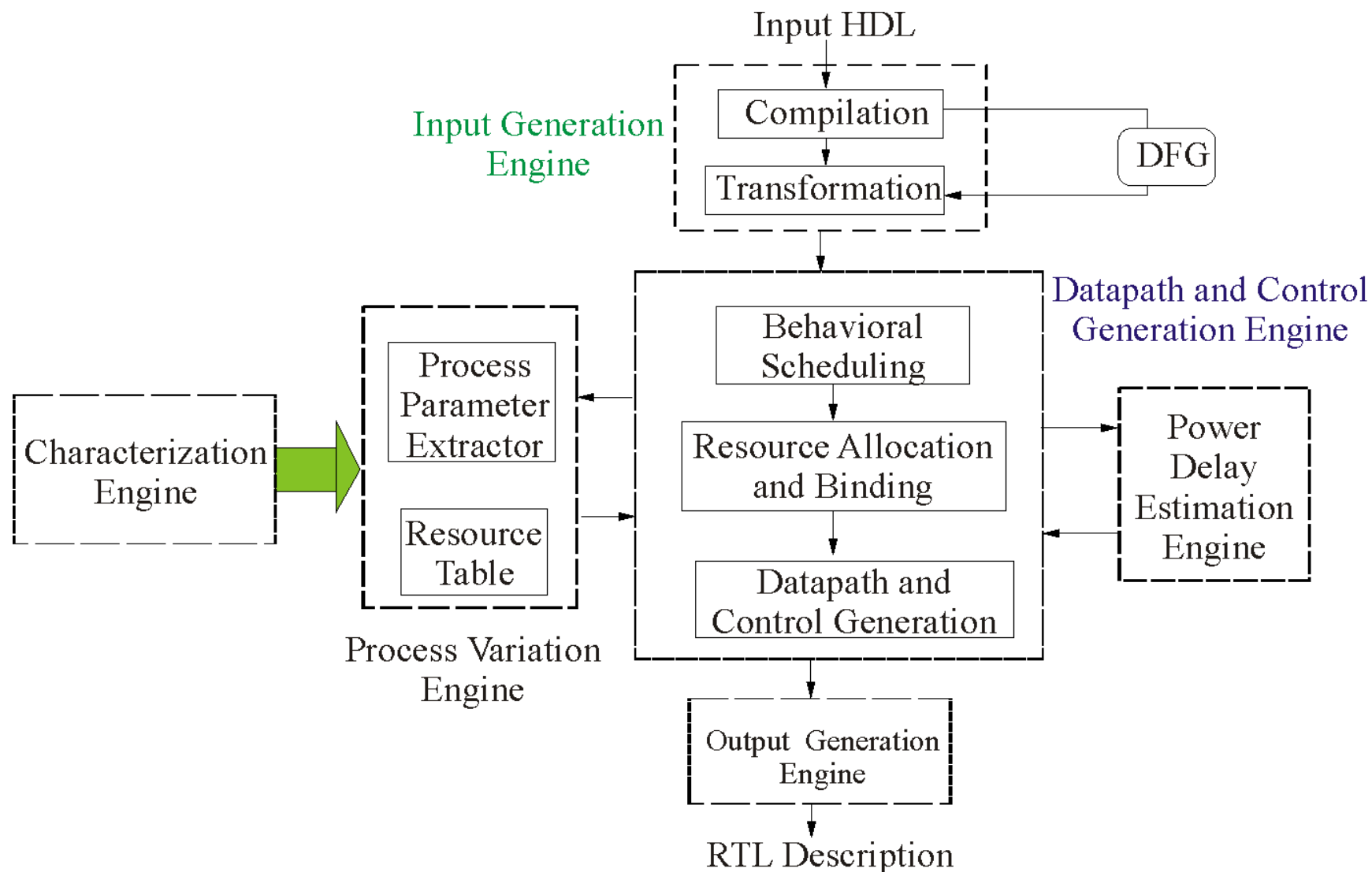
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Nano-CMOS RTL Statistical Optimization



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Statistical RTL Optimization: Formulation

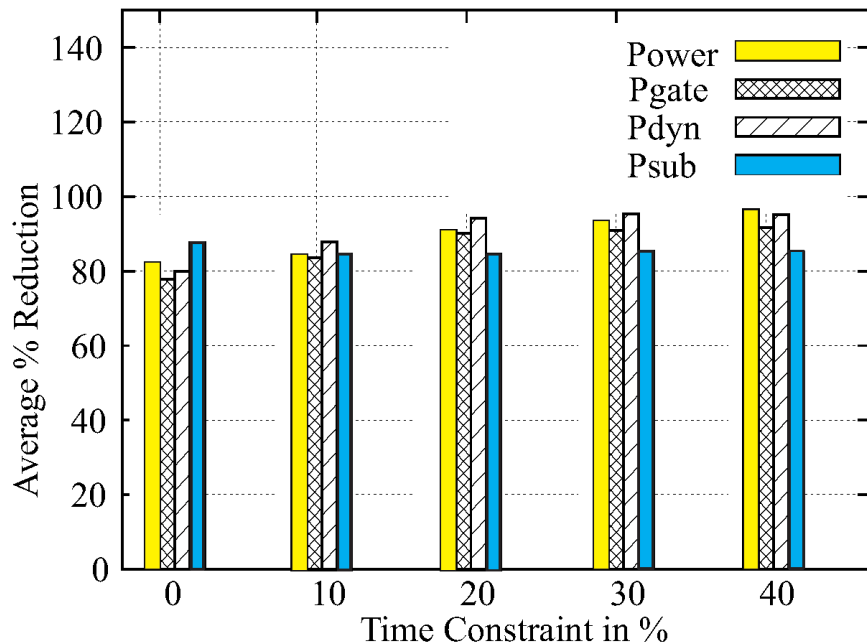
Minimize: $FoM_{Total}^{DFG} \left(\mu_I^{DFG}, \sigma_I^{DFG} \right)$

Subjected to (Resource/Time Constraints):

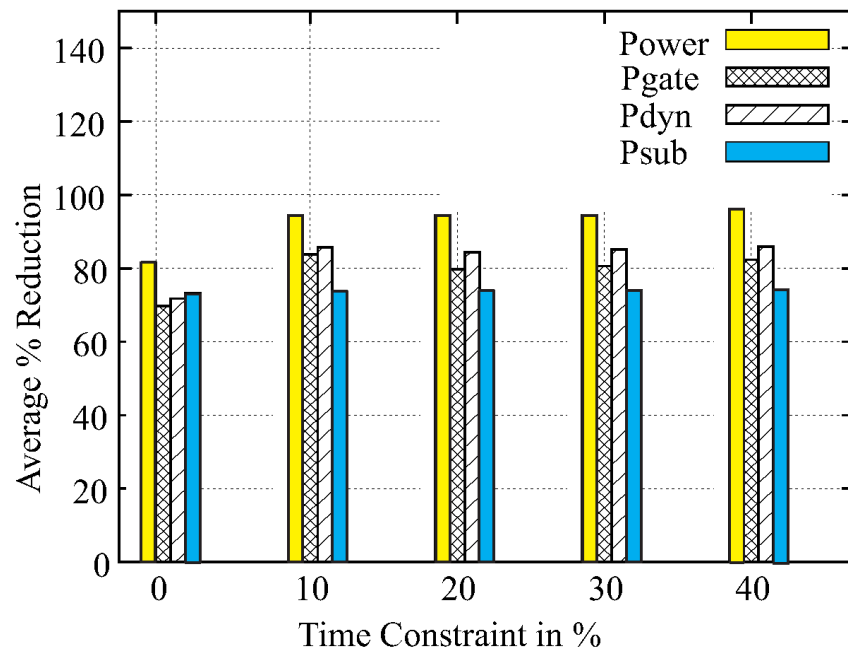
$Allocated(FU_{k,i}) \leq Available(FU_{k,i}), \forall cycle c$

$D_{CP}^{DFG} \left(\mu_D^{DFG}, \sigma_D^{DFG} \right) \leq D_{Con} \left(\mu_D^{Con}, \sigma_D^{Con} \right)$

Statistical RTL Optimization: Results on DSP Benchmarks



(For ARF Benchmark)



(For BPF Benchmark)

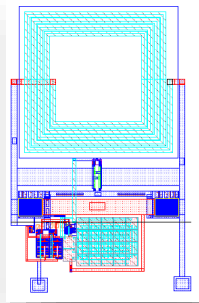
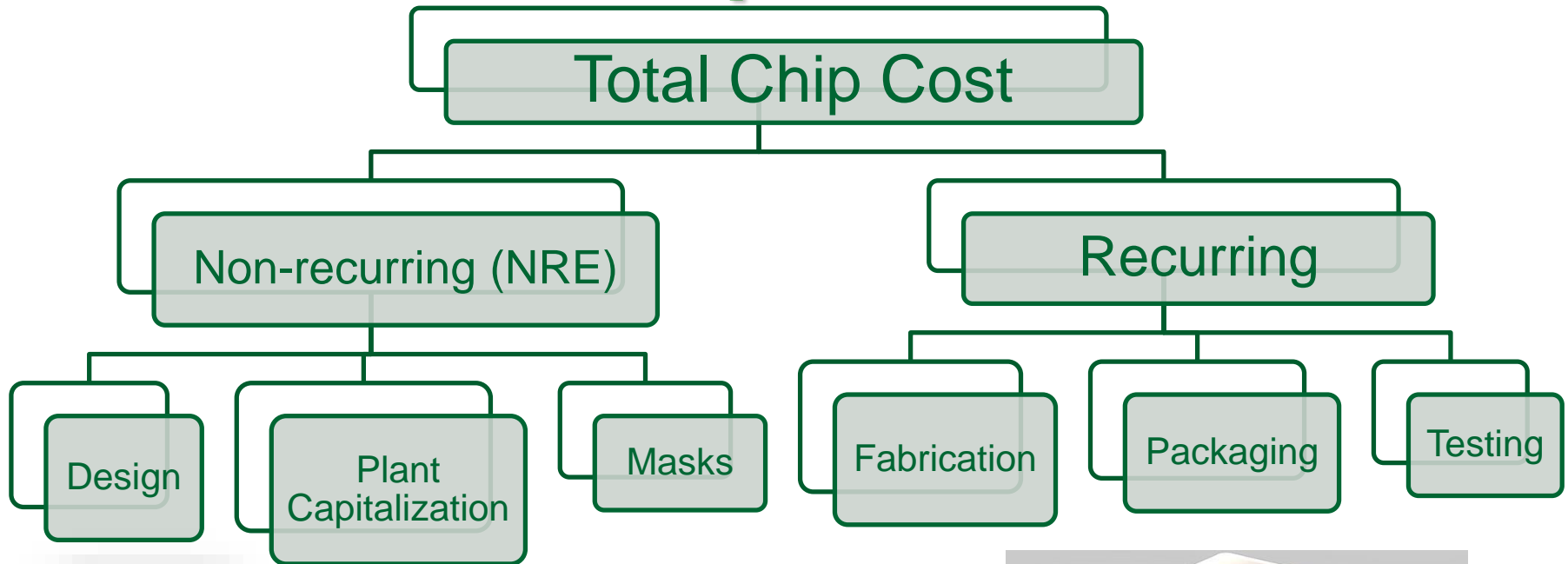
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Design for Cost (\$) (DfC)

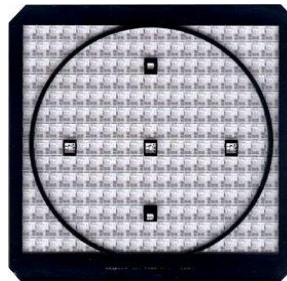
Chip Cost



\$ 0.5B



\$ 5B



\$ 2M



Source: http://www.ami.ac.uk/courses/ami4202_mdesign/u02/

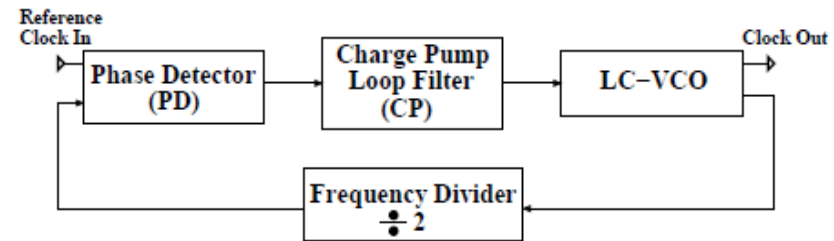
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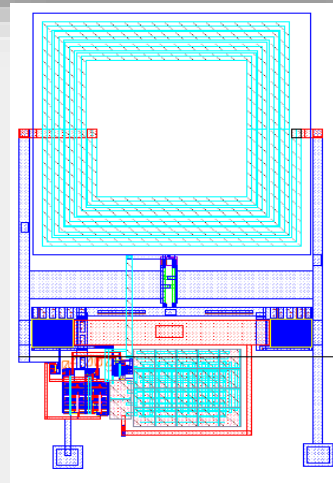
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One of the Key Issues: Time/Effort

- The simulation time for a Phase-Locked-Loop (PLL) lock on a full-blown (RCLK) parasitic netlist is of the **order of many days!** → **High NRE cost.**



PLL

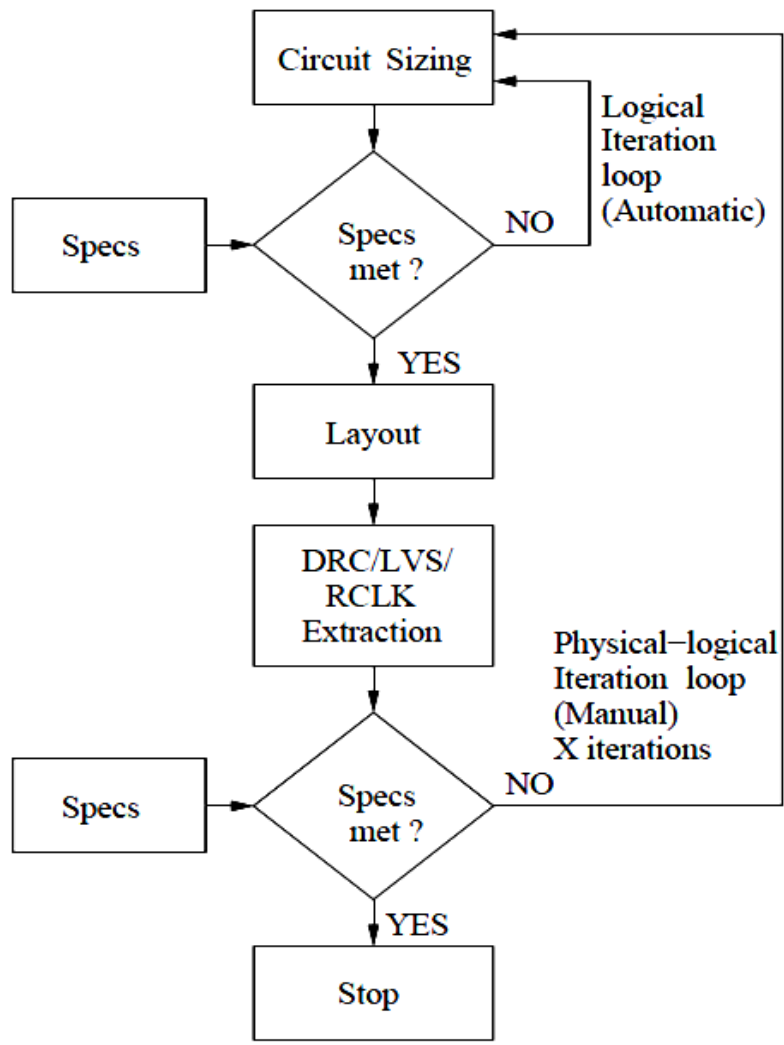


- **Issues for AMS-SoC components:**

- How fast can design space exploration be performed?
- How fast can layout generation and optimization be performed?

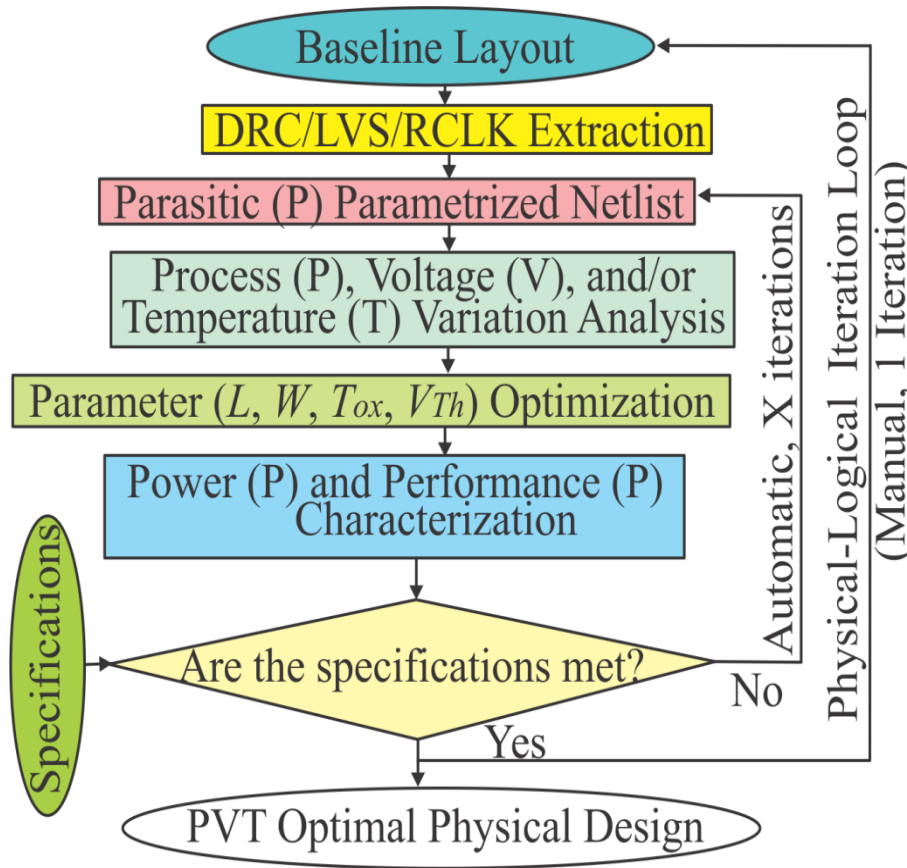
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Standard Design Flow – Very Slow



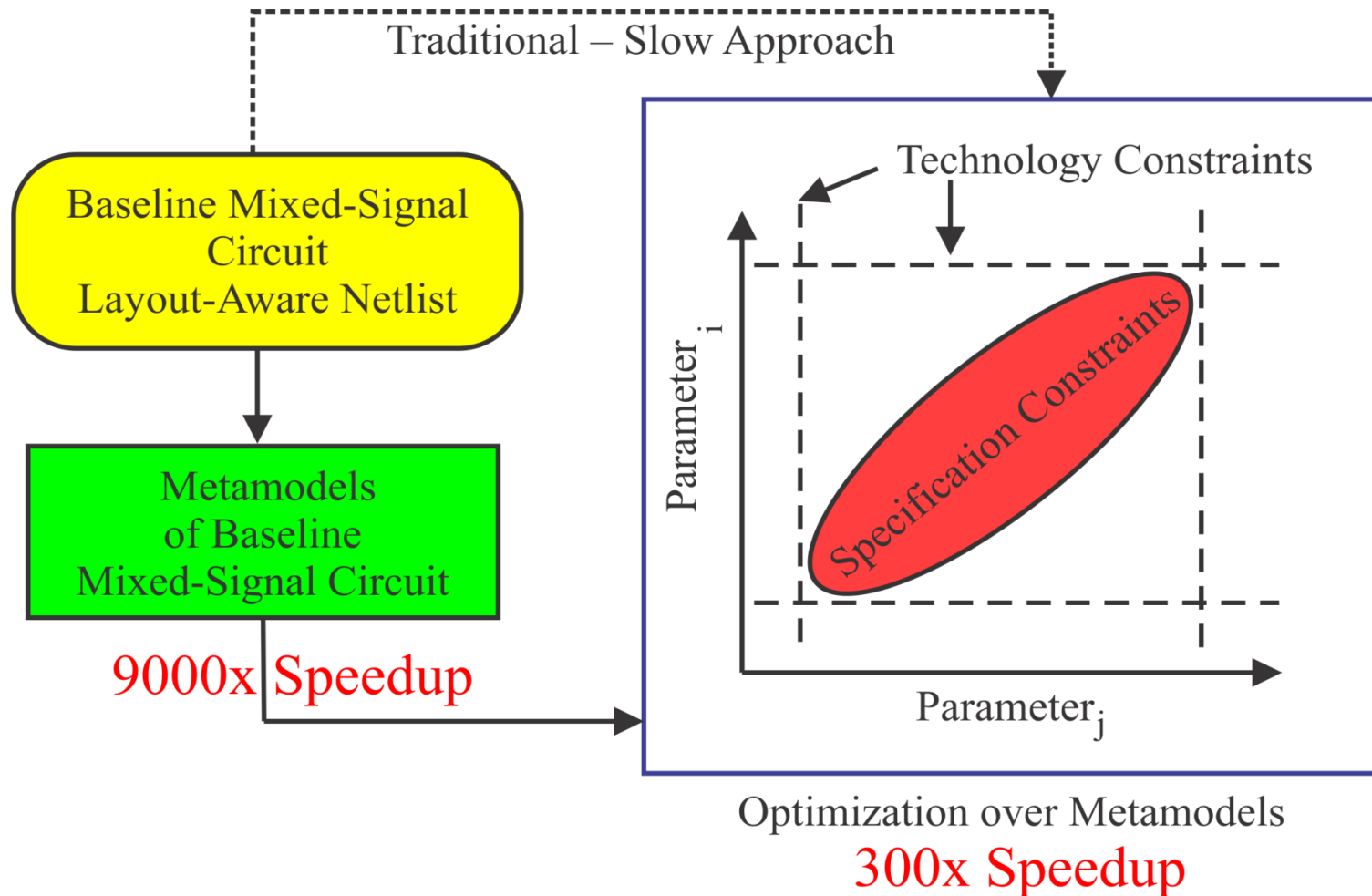
- Standard design flow requires multiple manual iterations on the back-end layout to achieve parasitic closure between front-end circuit and back-end layout.
- Longer design cycle time.
- Error prone design.
- Higher non-recurrent cost.
- Difficult to handle nanoscale challenges.

Automatic Optimization on Netlist (Faster than manual flow; still slow)



- Automatic iteration over netlist improves design optimization.
- Still needs multiple simulations using analog simulator (SPICE).
- SPICE is slow.

Two Tier Speed Up Through Metamodel

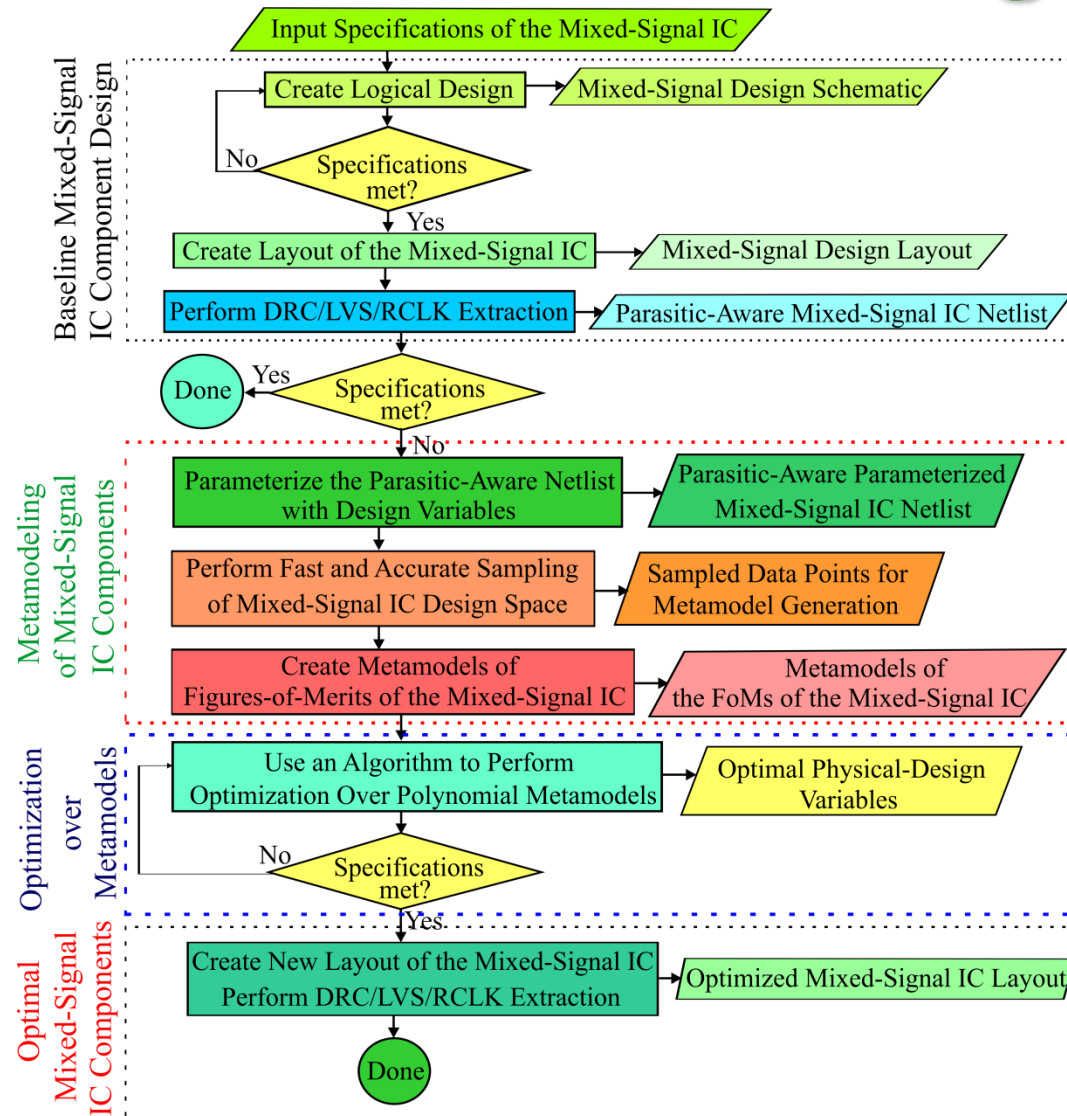


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Proposed Flow: Key Perspective

- Novel design and optimization methodology that will produce robust AMS-SoC components using **ultra-fast automatic iterations over metamodels** (instead of netlist) and two manual layout steps.
- The methodology easily accommodates multidimensional challenges, reduces design cycle time, improves circuit yield, and reduces chip cost.

Metamodel-Based Design Flow



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Metamodels : Selected Types

Nanoscale-CMOS Circuit Metamodels

Polynomial

Regular
Polynomial

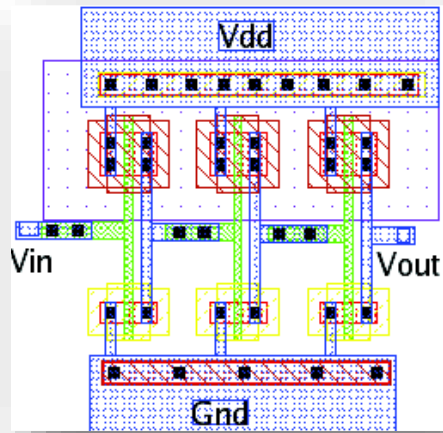
Piece-wise
Polynomial

Nonpolynomial

Artificial
Neural
Networks

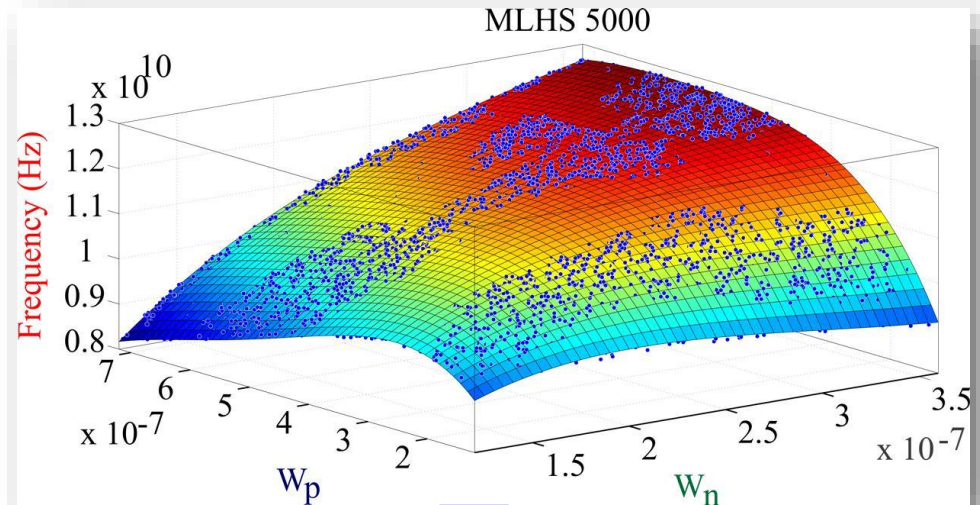
Kriging
Methods

Metamodels : Polynomial Example



**Actual
Circuit
(SPICE
netlist) of
AMS-SoC
Components**

**Statistical
Sampling**



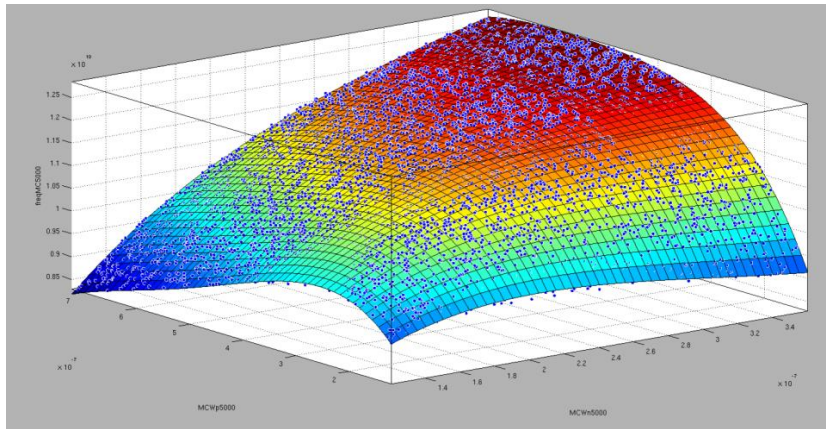
**Polynomial
Function
Fitting**

$$f(W_n, W_p) = 7.94 \times 10^9 + 1.1 \times 10^{16} W_n + 1.28 \times 10^{15} W_p.$$

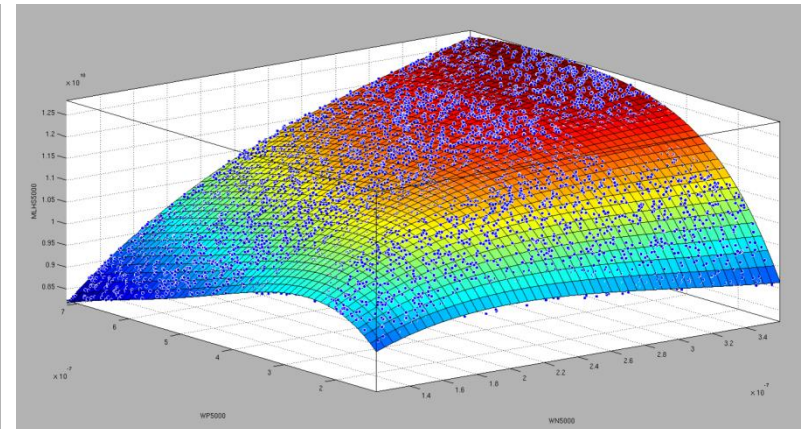
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Sampling Techniques: 45nm Ring Oscillator Circuit (5000 points)

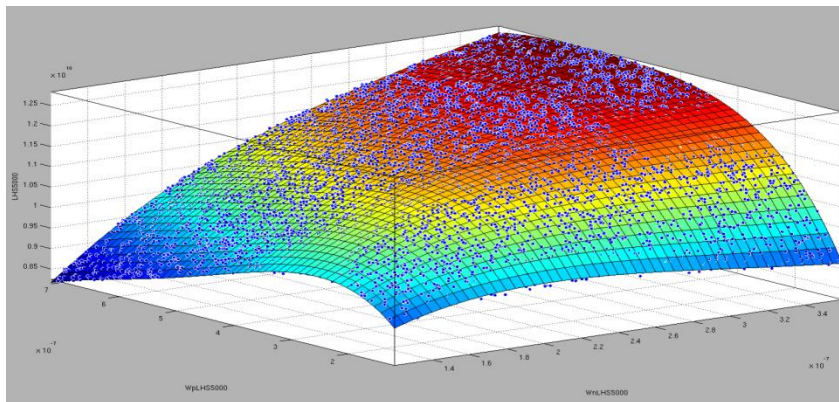
Monte Carlo



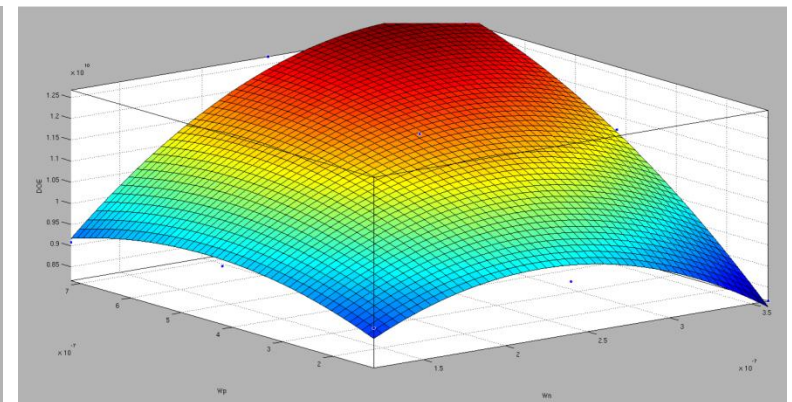
MLHS



LHS



DOE



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Polynomial Metamodels

- The generated sample data can be fitted in many ways to generate a metamodel.
- The choice of fitting algorithm can affect the accuracy of the metamodel.
- A simple metamodel has the following form:

$$y = \sum_{i,j=0}^k \left(\alpha_{ij} \times x_1^i \times x_2^j \right)$$

- y is the response being modeled (e.g. frequency), $x = [W_n, W_p]$ is the vector of variables and α_{ij} are the coefficients.

Metamodel: Polynomial Comparison

Case Study Circuits	Polynomial Order	μ error (in MHz)	σ error (in MHz)
Ring Oscillator 45nm CMOS Target f : 10GHz	1	571.0	286.7
	2	195.4	78.1
	3	37.2	18.0
	4	20.0	10.7
	5	17.1	9.6
LC-VCO 180nm CMOS Target f : 2.7GHz	1	42.3	40.1
	2	39.4	37.8
	3	35.4	33.9
	4	30.5	29.3
	5	26.5	25.2

Ring oscillator – Order 1

$$f(W_n, W_p) = 7.94 \times 10^9 + 1.1 \times 10^{16} W_n + 1.28 \times 10^{15} W_p.$$

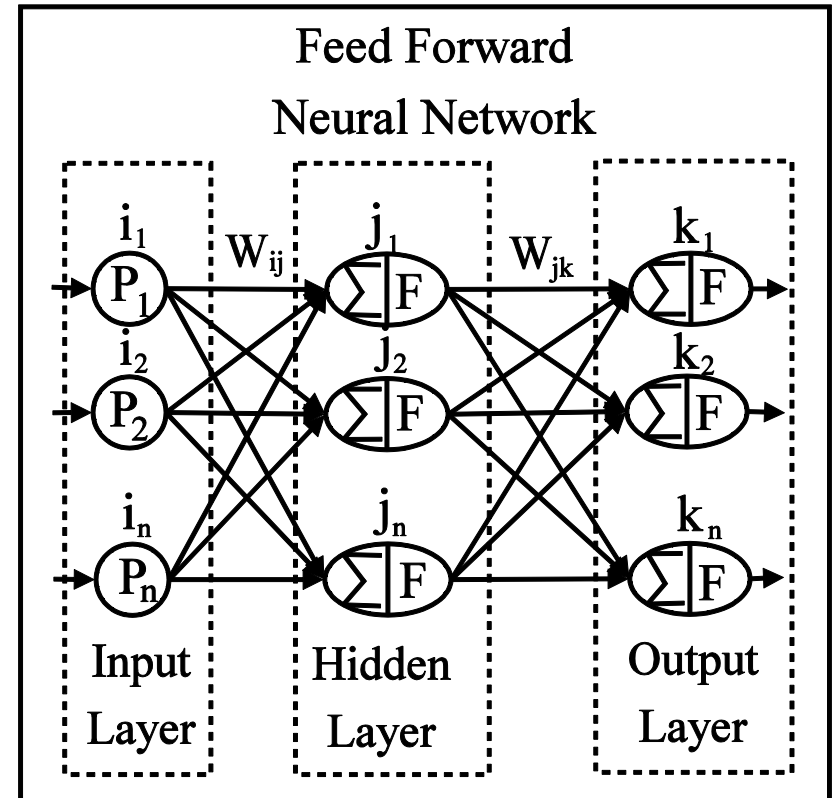
LC-VCO – Order 1

$$f(W_n, W_p) = 2.38 \times 10^9 - 3.49 \times 10^{12} W_n - 6.66 \times 10^{12} W_p.$$

Artificial Neural Network (ANN) Metamodeling

- Feed-forward dual layer (FFDL) ANNs are considered.
- FFDL ANN created for each FoM:
 - Nonlinear hidden layer functions are considered each varying hidden neurons 1-20:

$$b_j(v_j) = \tanh(\lambda v_j)$$



Metamodel Comparison: Polynomial Vs Nonpolynomial

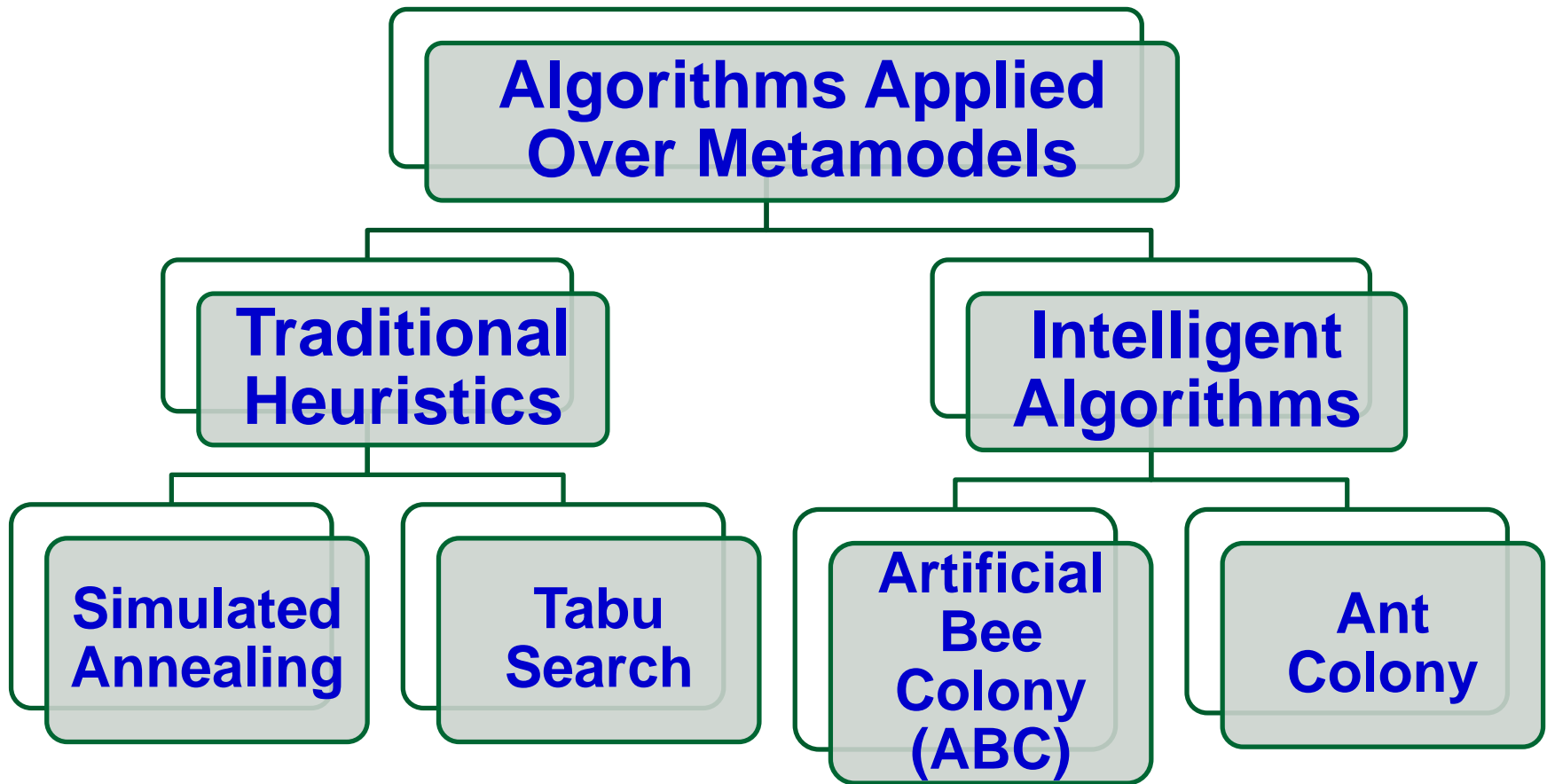
- Nonpolynomial (Artificial Neural Network) is more suitable large circuits.

180nm CMOS PLL with Target Specs: $f = 2.7\text{GHz}$, $P = 3.9\text{mW}$, $8.5\mu\text{s}$.

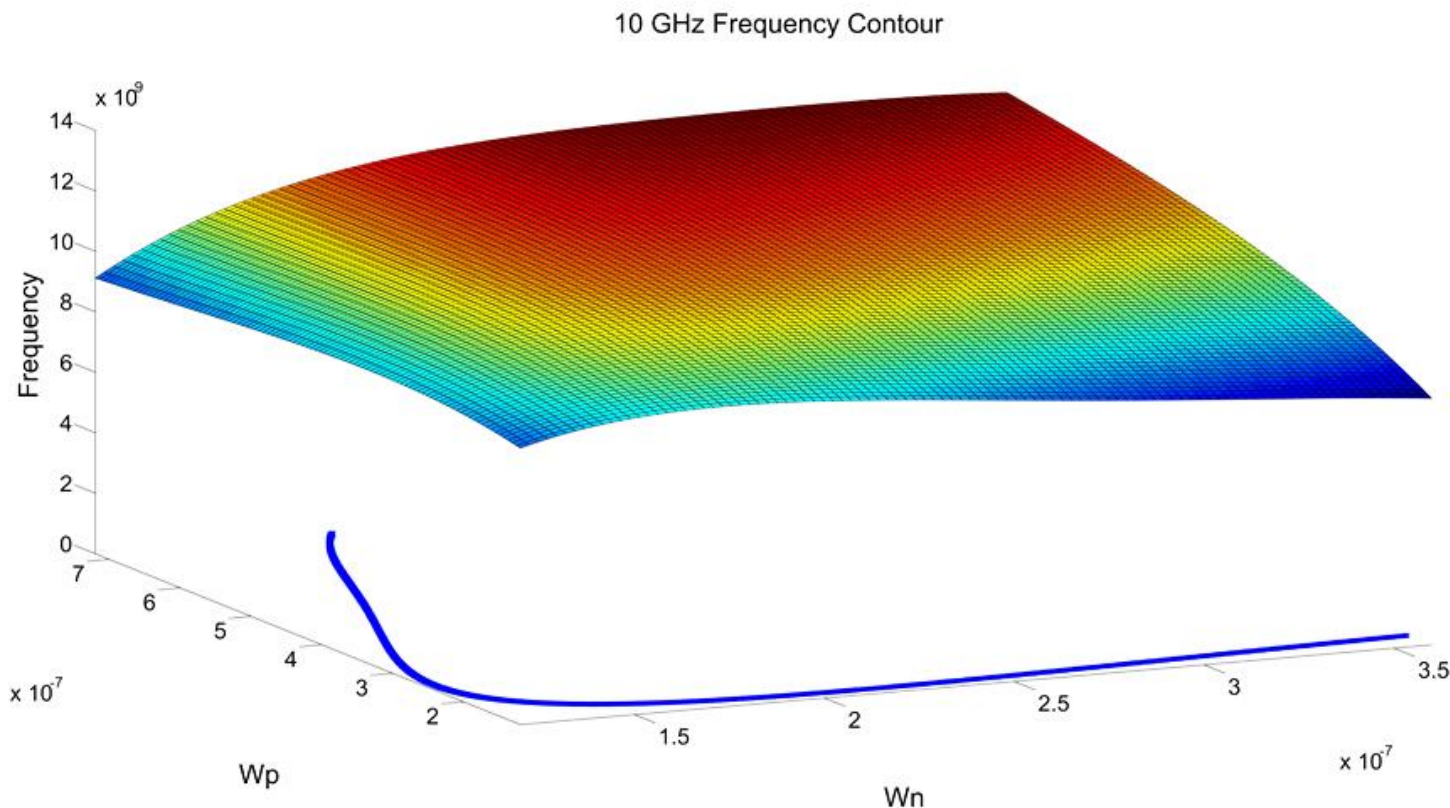
Figures-of-Merits (FoM)	Polynomial # of Coefficients	RMSE	Nonpolynomial (Neural Network)
Frequency	48	77.96 MHz	48MHz
Power	50	2.6mW	0.29mW
Locking Time	56	1.9 μs	1.2 μs

- 56% increase in accuracy over polynomial metamodels.
- On average 3.2% error over golden design surface.

Selected Algorithms for Optimization over Metamodels



Exhaustive Search : 45nm RO



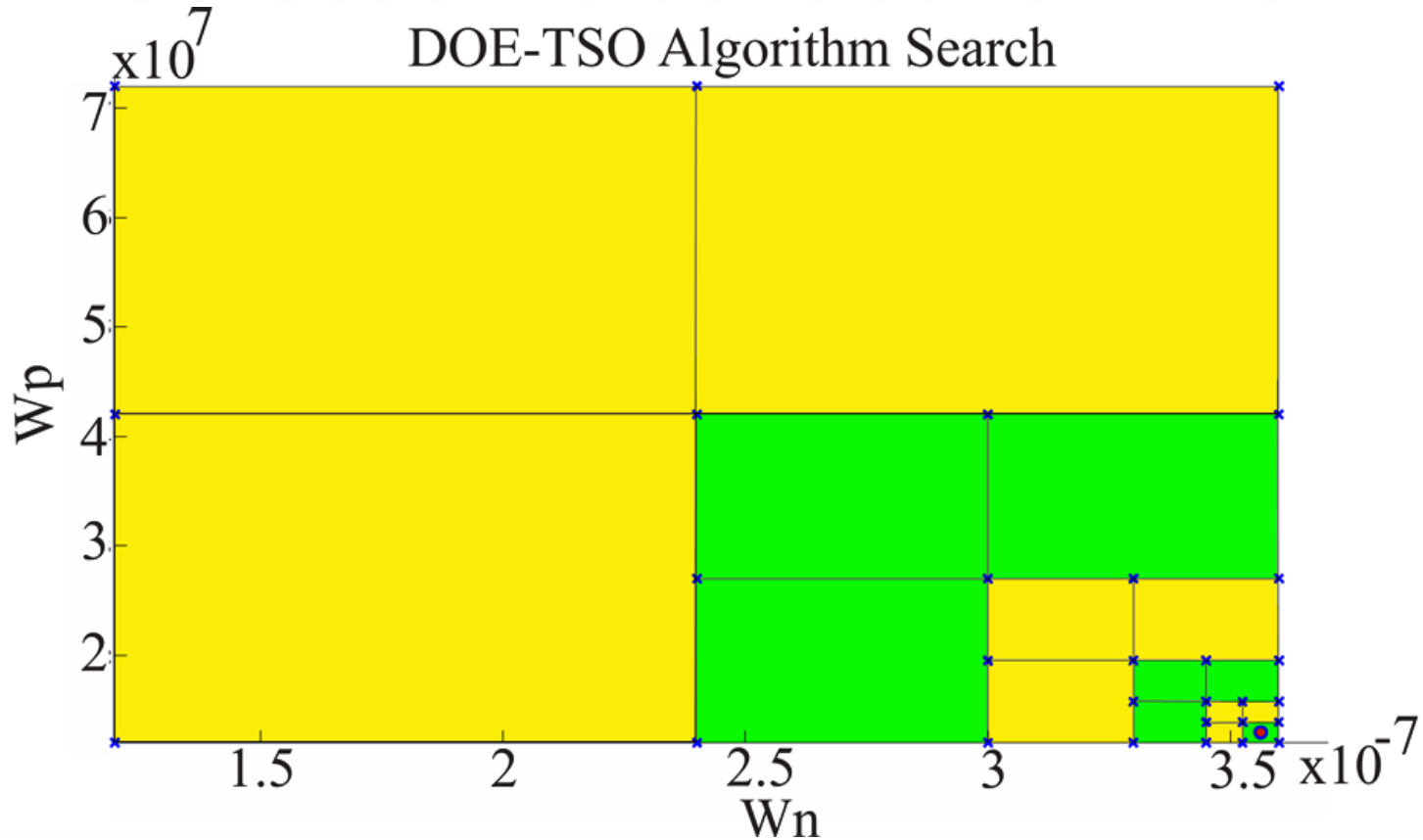
- Searches over two parameter space.
- Parameters incremented over specified steps.

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DOE Assisted Tabu Search: 45nm RO



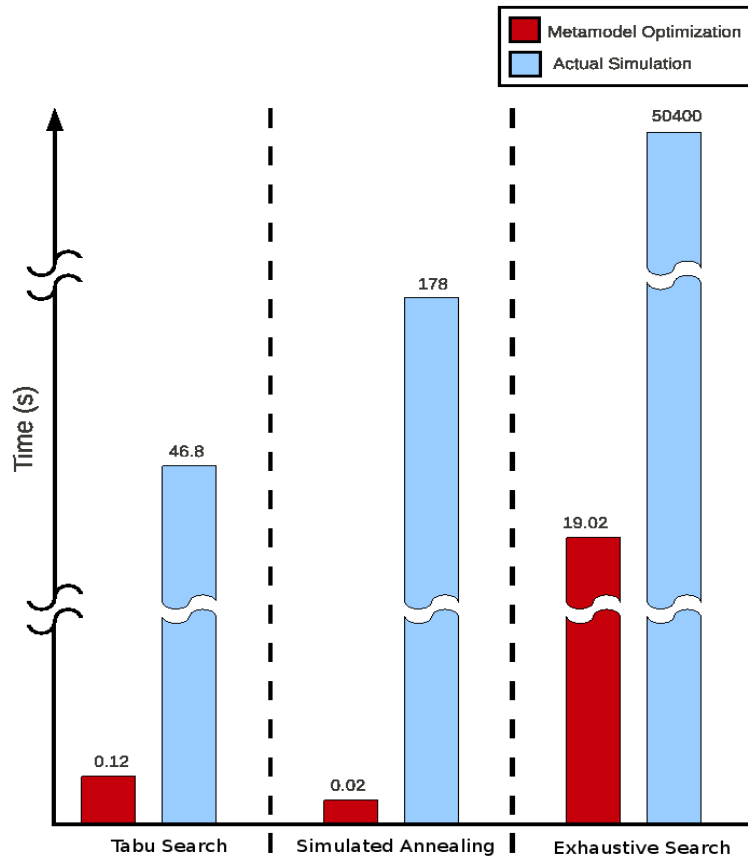
- Search space is recursively divided into rectangles and each time the rectangle with superior result is selected.

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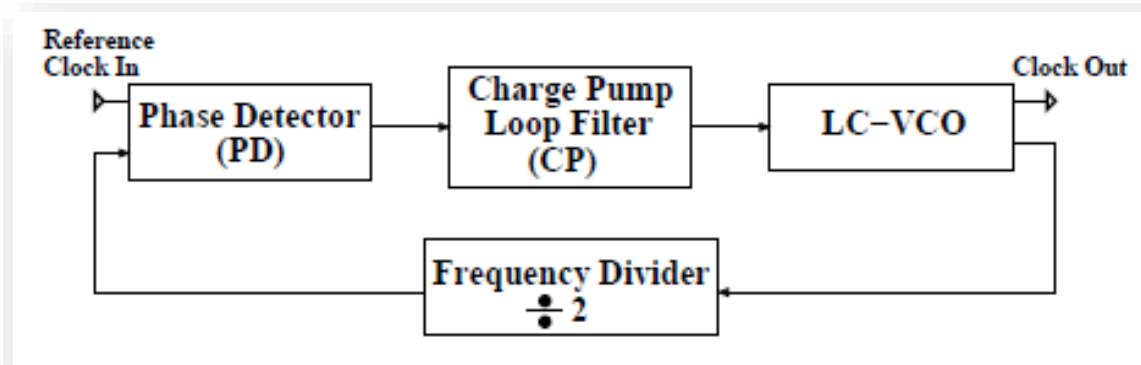
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Comparison of the Running Time of Heuristic Algorithms: 45nm RO



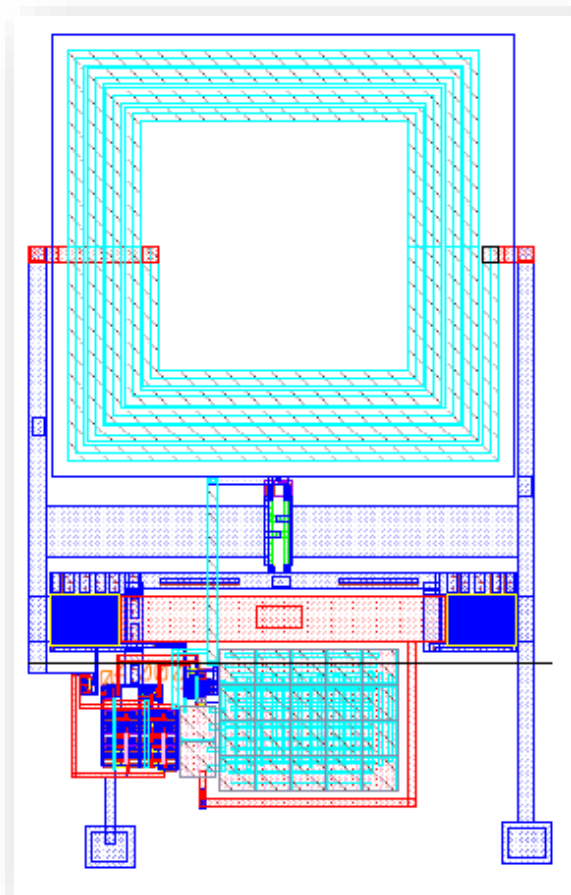
- **Optimization without metamodels:** the tabu search optimization is faster by $\sim 1000\times$ than the exhaustive search and $\sim 4\times$ faster than the simulated annealing optimization.
- **Optimization with metamodels:** the simulated annealing optimization is faster by $\sim 1000\times$ than the exhaustive search and $\sim 6\times$ faster than the tabu search optimization.

Case Study Circuit: 180nm PLL



Block diagram of a PLL.

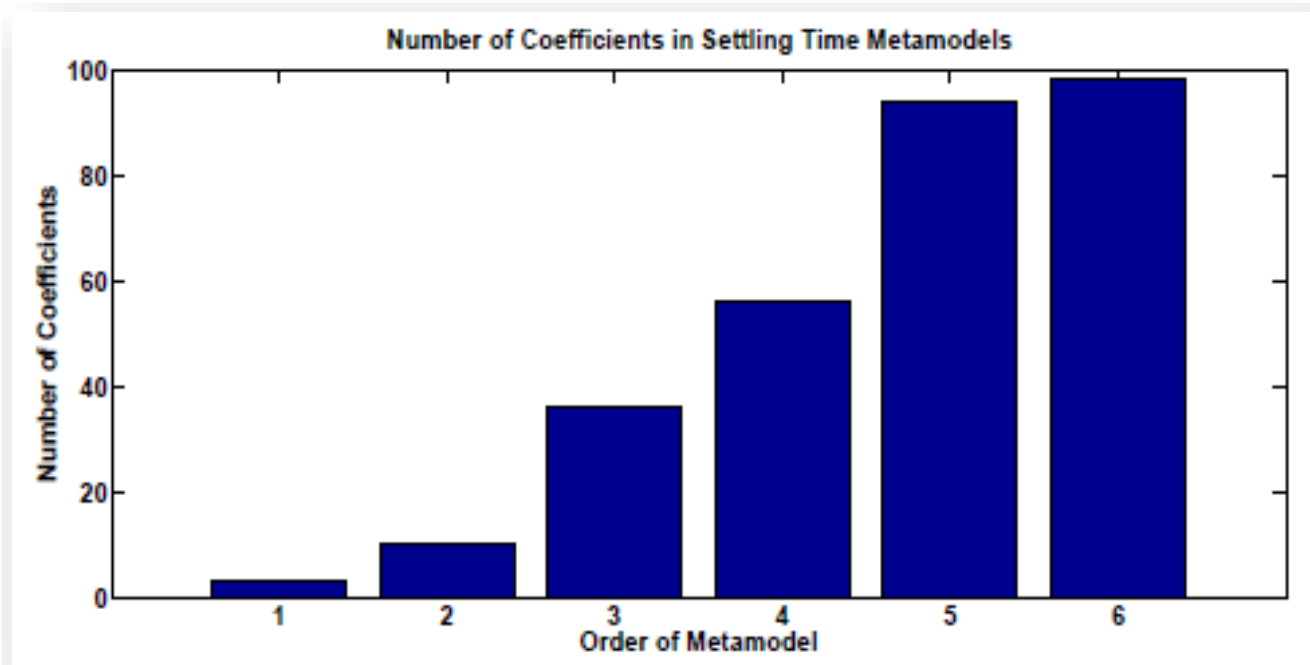
- PLL circuit is characterized for frequency, power, vertical and horizontal jitter (for simple phase noise), and locking time.
- Metamodels are created for each FoM from same sample set.



PLL for 180nm.

PLL: Polynomial Metamodels ...

- The number of coefficients corresponding to the order of the generated metamodel for settling time.
- This means that the model is over fitted, therefore for the metamodel that represents settling time, a polynomial order of 4 will be used.



Artificial Bee-Colony : Overview

1. **Initial** food sources are produced for all worker bees.
2. **Do**
 - 1) Each worker bee goes to a food source and evaluates its nectar amount.
 - 2) Each onlooker bee watches the dance of worker bees and chooses one of their sources depending on the dances and evaluates its nectar amount.
 - 3) Determine abandoned food sources and replace with the new food sources discovered by scout bees.
 - 4) Best food source determined so far is recorded.
3. **While** (requirements are met)

A food source → a solution; A position of a food source → a design variable set; Nectar amount → Quality of a solution; Number of worker bees → number of quality solutions.

PLL: ABC over Poly. Metamodels

PLL parameters with constraints and optimized values.

Circuit	Parameter	Min (m)	Max (m)	Optimal Value (m)
Phase Detector	W_{ppd1}	400n	2μ	1.66μ
	W_{npd1}	400n	2μ	1.11μ
	W_{ppd2}	400n	2μ	784n
	W_{npd2}	400n	2μ	689n
	W_{ppd3}	400n	2μ	1.54μ
	W_{npd3}	400n	2μ	737n
Charge Pump	W_{nCP1}	400n	2μ	1.24μ
	W_{pCP1}	400n	2μ	1.35μ
	W_{nCP2}	1μ	4μ	1.35μ
	W_{pCP2}	1μ	4μ	2.88μ
LC-VCO	W_{nLC}	3μ	20μ	18.62μ
	W_{pLC}	6μ	40μ	37.48μ
Divider	W_{p1Div}	400n	2μ	1.65μ
	W_{p2Div}	400n	2μ	1.54μ
	W_{p3Div}	400n	2μ	1.38μ
	W_{p4Div}	400n	2μ	1.96μ
	W_{n1Div}	400n	2μ	1.09μ
	W_{n2Div}	400n	2μ	1.17μ
	W_{n3Div}	400n	2μ	1.29μ
	W_{n4Div}	400n	2μ	1.95μ
	W_{n5Div}	400n	2μ	536n

- An exhaustive search of the design space of 21 parameters with 10 intervals per parameter requires 10^{21} simulations.
- 10^{21} SPICE simulations is slow; 10min per one.
- 10^{21} simulations using polynomial metamodels is fast.
- Time savings: $\approx 10^{20} \times$ SPICE simulation time.

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PLL: ABC Optimization: Poly Vs ANN

Optimization Results

FoM	Poly. Metamodel	ANN Metamodel
Average Power	3.9 mW	3.9 mW
Frequency	2.6909 GHz	2.7026 GHz

Optimization Time Comparison

Algorithm	Circuit Netlist	Poly. Metamodel	ANN Metamodel
ABC (100 iterations)	#bees(20) * 5 min * 100 iteration = 10,000 minutes = 7 days (worst case)	5 mins	0.12 mins
Metamodel Generation	0	11 hours for LHS + 1 min creation	11 hours for LHS + 10mins training and verification.

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Conclusions

- Nanoelectronic circuits and systems have multifold design challenges.
- DfX is design for X – Power, Variability, Cost ...
- DfP:
 - 35% of total energy in USA is consumed by electronics.
 - Battery is an critical constraint for portable systems.
 - Energy efficient hardware, software at the same time better battery design needed for effective solutions.
- DfV: Reduce the variability in chip and enhance yield.
- DfC: Reduce NRE, yield, and time to market.
- Much more research is needed for combined consideration of issues, e.g. $X \leftarrow \text{Variability and Cost}$

References

- **S. P. Mohanty** and E. Kougianos, "Incorporating Manufacturing Process Variation Awareness in Fast Design Optimization of Nanoscale CMOS VCOs", *IEEE Transactions on Semiconductor Manufacturing*, Accepted on 12 Nov 2013, DOI: <http://libproxy.library.unt.edu:2083/10.1109/TSM.2013.2291112>.
- **S. P. Mohanty**, M. Gomathisankaran, and E. Kougianos, "Variability-Aware Architecture Level Optimization Techniques for Robust Nanoscale Chip Design", *Elsevier International Journal on Computers and Electrical Engineering (IJCEE)*, 2014, DOI: <http://dx.doi.org/10.1016/j.compeleceng.2013.11.026>.
- O. Okobiah, **S. P. Mohanty**, and E. Kougianos, "Geostatistical-Inspired Fast Layout Optimization of a Nano-CMOS Thermal Sensor", *IET Circuits, Devices & Systems (CDS)*, Volume 7, No. 5, September 2013, pp. 253--262.
- O. Garitselov, **S. P. Mohanty**, and E. Kougianos, "A Comparative Study of Metamodels for Fast and Accurate Simulation of Nano-CMOS Circuits", *IEEE Trans. on Semiconductor Manufacturing*, Vol. 25, No. 1, Feb 2012, pp. 26--36.
- S. P. Mohanty, E. Kougianos, and O. Okobiah, "Optimal Design of a Dual-Oxide Nano-CMOS Universal Level Converter for Multi-V_{dd} SoCs", *Springer Analog Integrated Circuits & Signal Processing J.*, Vol. 72, No. 2, 2012, pp. 451--467.
- O. Garitselov, **S. P. Mohanty**, and E. Kougianos, "Accurate Polynomial Metamodeling-Based Ultra-Fast Bee Colony Optimization of a Nano-CMOS PLL", *Journal of Low Power Electronics*, Vol. 8, No. 3, June 2012, pp. 317--328.

A close-up, slightly blurred image of a blue microchip with a central square area containing a smaller chip and various circuit patterns. The chip is surrounded by a dense array of gold pins.

Thank You !!!

Slides Available at:

<http://www.cse.unt.edu/~smohanty>