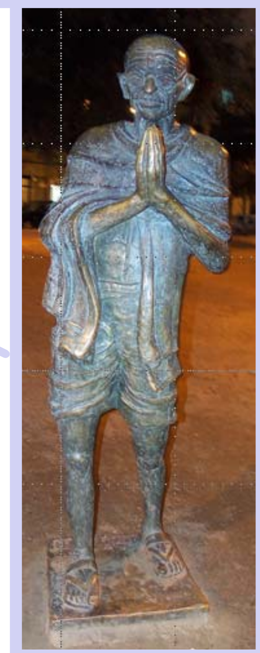
Design Tools for Beyond CMOS

Sandip Tiwari
st222@cornell.edu



Jardin
Gandhi

Acknowledgements: Collaborators, students, peers, funders (NSF, DARPA, Mellowes Endowment, Hosts), ...

My View

1. Greatest new technologies find entirely new applications of their own.
   NP complete, robust decision making in the midst of uncertainty in devices, information input, incomplete description of the problem.

2. For new technologies, design systems are certainly very important, but robust design systems will nearly always be insufficient for the purpose of comparing to an entrenched 50 year technology infrastructure. (bipolar, nmos, cmos, …).
   New technology in entrenched spaces finds an application – digital watch for CMOS – to slowly penetrate and evolve.

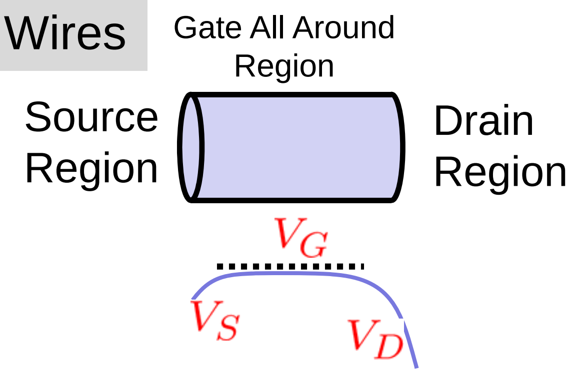
3. But, it is possible to make reasonable judgment *when some characteristic is truly inappropriate for a replacement task*.

4. If we really want to have the freedom to explore architectures, new devices in some design context, functions, …, it must be open so different expertise can come together. This needs interfaces and all the necessary attributes specified in a defined format that are required by fiat. Robustness, variabilities, functional description, … all need to be part of the framework's design and this is something those who give money can enforce.

Example: Characteristics *Charge*

Problem of today:
Variability(Control), Off-state current, Turn-on sharpness, Drive Current

Wires



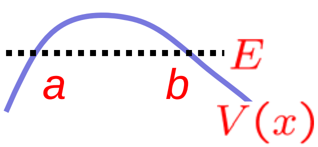
$$\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial y^2} = 0$$

Scaling: $r' = \lambda r, y' = \lambda y$

$$\frac{1}{r'}\frac{\partial}{\partial r'} r' \frac{\partial \psi}{\partial r'} + \frac{\partial^2 \psi}{\partial y'^2} = 0$$

If aspect ratio retained (scaling), potential profile invariant

How small? Tunneling – off-state in traditional, on-state in tunnel FETs



$$I \propto T \approx \frac{\exp(-2\Gamma_{ba})}{\left[1 + \frac{1}{4}\exp(-2\Gamma_{ba})\right]^2} \approx \exp(-2\Gamma_{ba}) = \exp\left[-2\int_a^b \gamma(y)dy\right]$$

$$\exp\left(-2\int\sqrt{\frac{2m^*}{\hbar^2}}\,[V(y)-E]dy\right) \approx \exp\left|-2\sqrt{\frac{2m^*}{\hbar^2}}\left(\sqrt{V}L - \frac{EL}{2\sqrt{V}} + \cdots\right)\right|$$

1st order term:

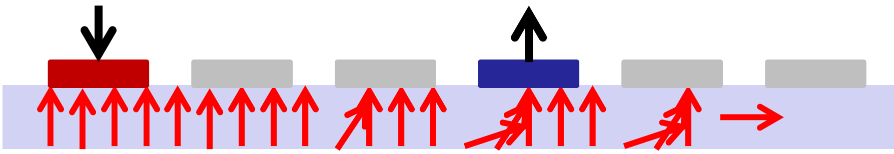
Current proportional to square root of potentials in barrier. Slow swing
Variance inversely proportional to length scale – tunneling.

Problem is law of large numbers in its Poisson limit.

Problems of graphene, nanotubes, are much worse because of additional size, energy and its line width effects .

Example: Characteristics *Spin*

Magnetization switching with spin current, spin qubits, …, spin-torque flipping limits



Spin transport, Signal loss⇔failure rate

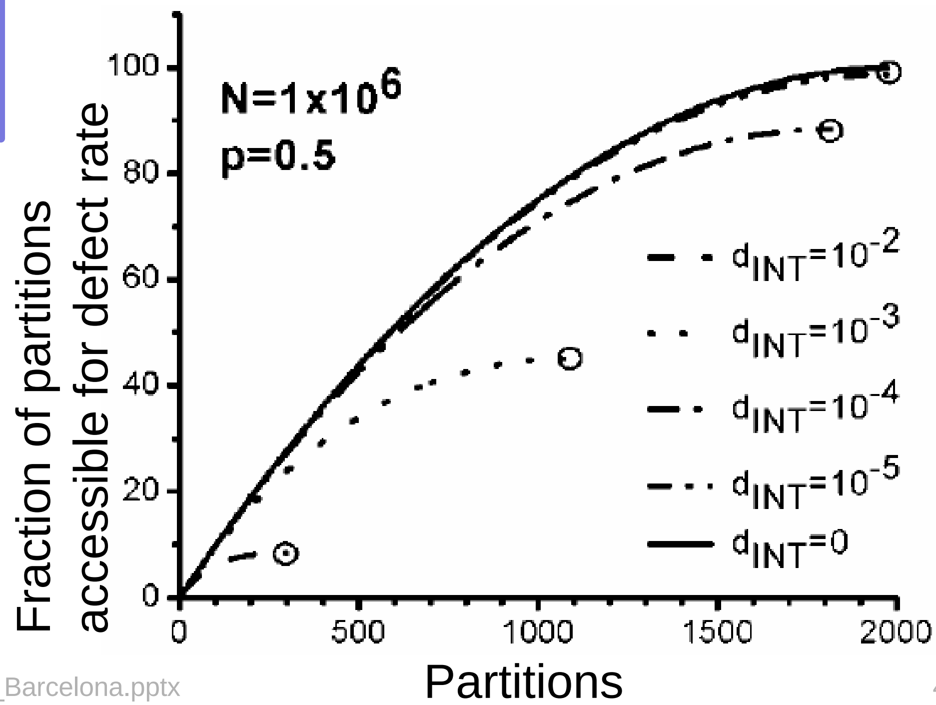
$$q = 1 - \exp\left(-\frac{\ell}{\lambda_c}\right)$$

for $q = .001$ $\ell = 0.001\lambda_c$

if $\lambda_c = 100\ \mu m, \Rightarrow \ell = 100\ nm$

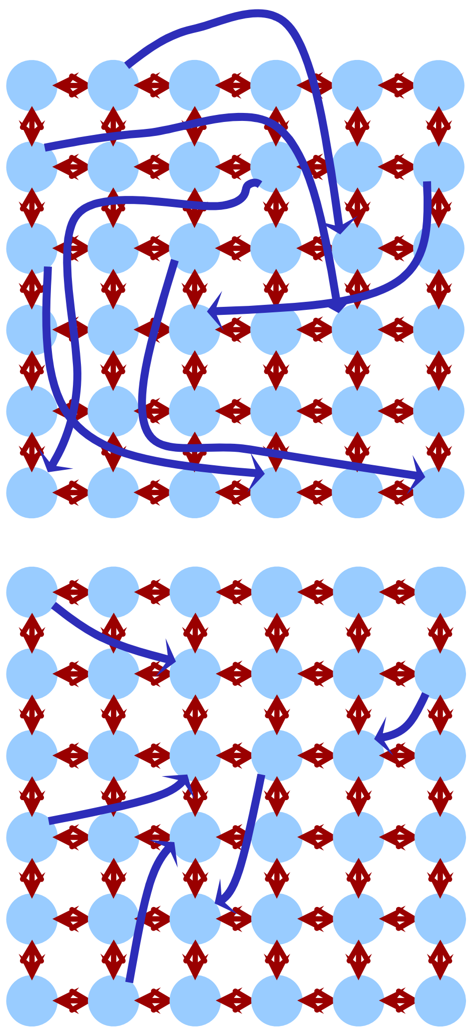
Signal recoverable up to q of ½. If $\lambda_c/2 = 50\ \mu m$, energy of $\approx 1\ V \times 10\ \mu A = 10\ \mu W$ needed per recovery, or $400\ mW/cm^2$+ area. I think these are quite optimistic numbers.

For normal distribution of errors, fraction of usability.
This in turn raises power for error correction, and devices that cannot be used.

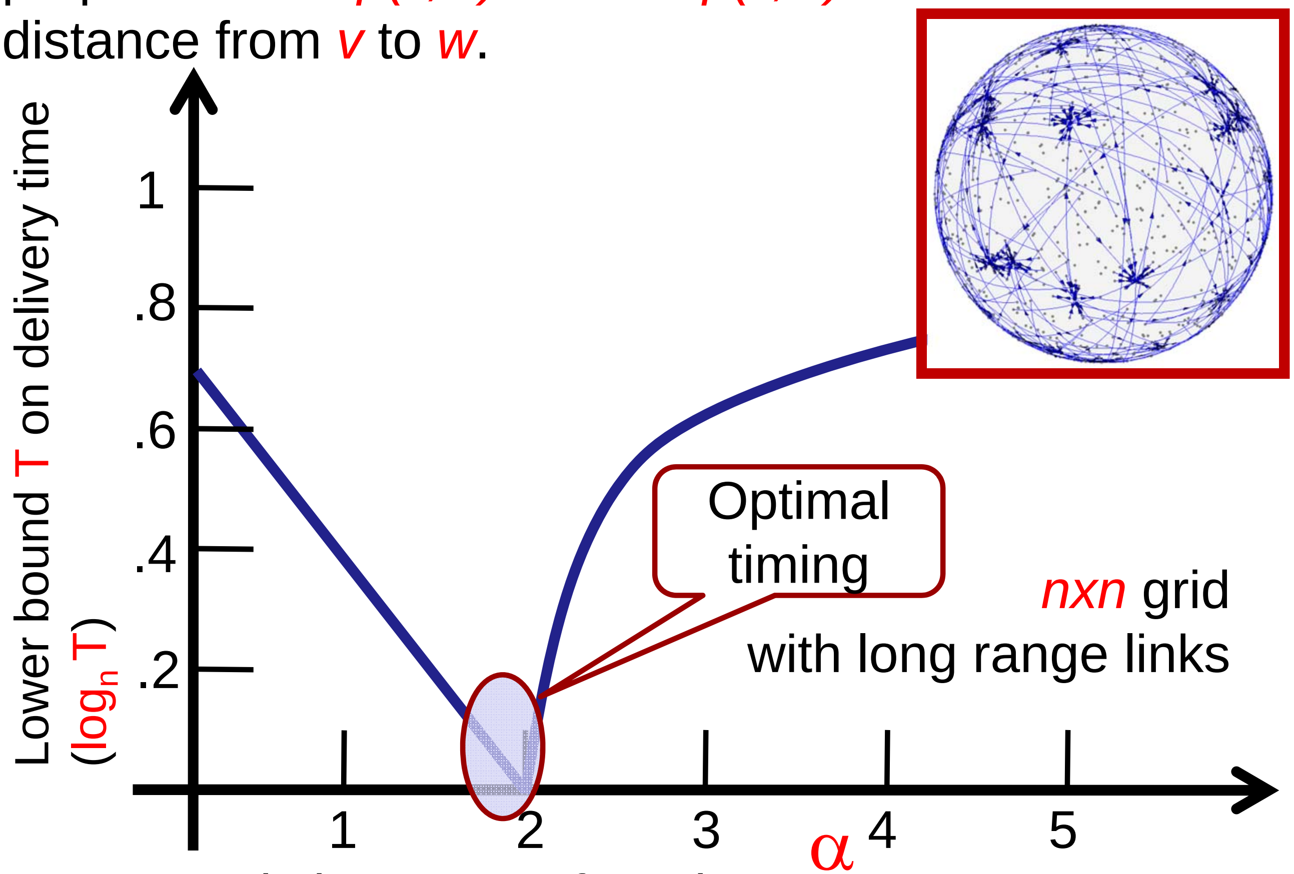


An Important Issue We Forget:
Networks – Timing in Large Integration

Small World Network: A class of networks with orderly local structure and small diameter
Watts-Strogatz (1998)



Long range percolation model: For each node *v*, add directed link to random node *w* with probability proportional to $p(v,w)^{-\alpha}$ where *p(v,w)* is the lattice distance from *v* to *w*.



Build a mixture of long range and short range for robustness

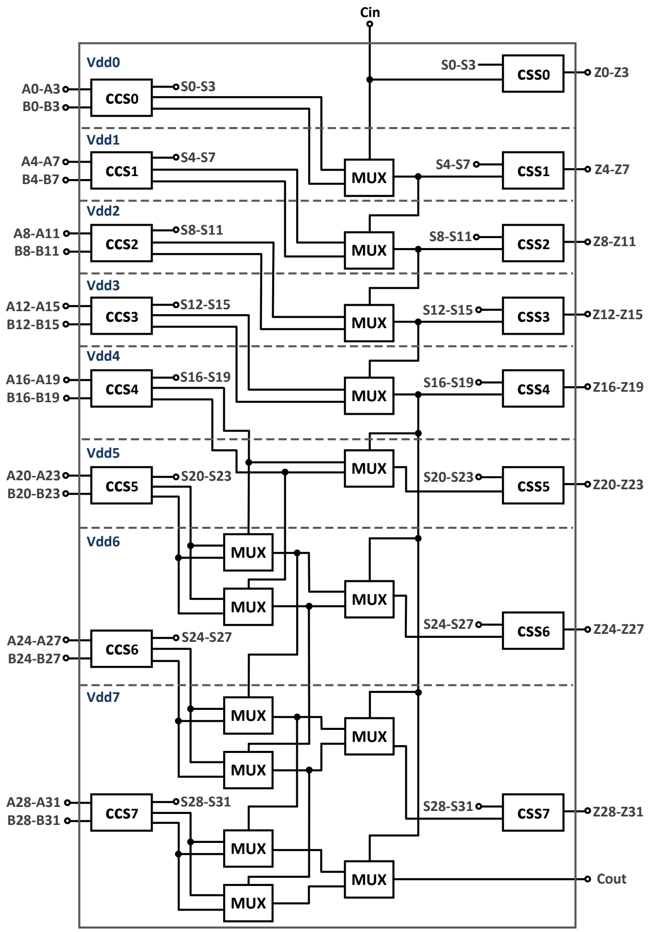
New Computing Models

Learn to live with errors.

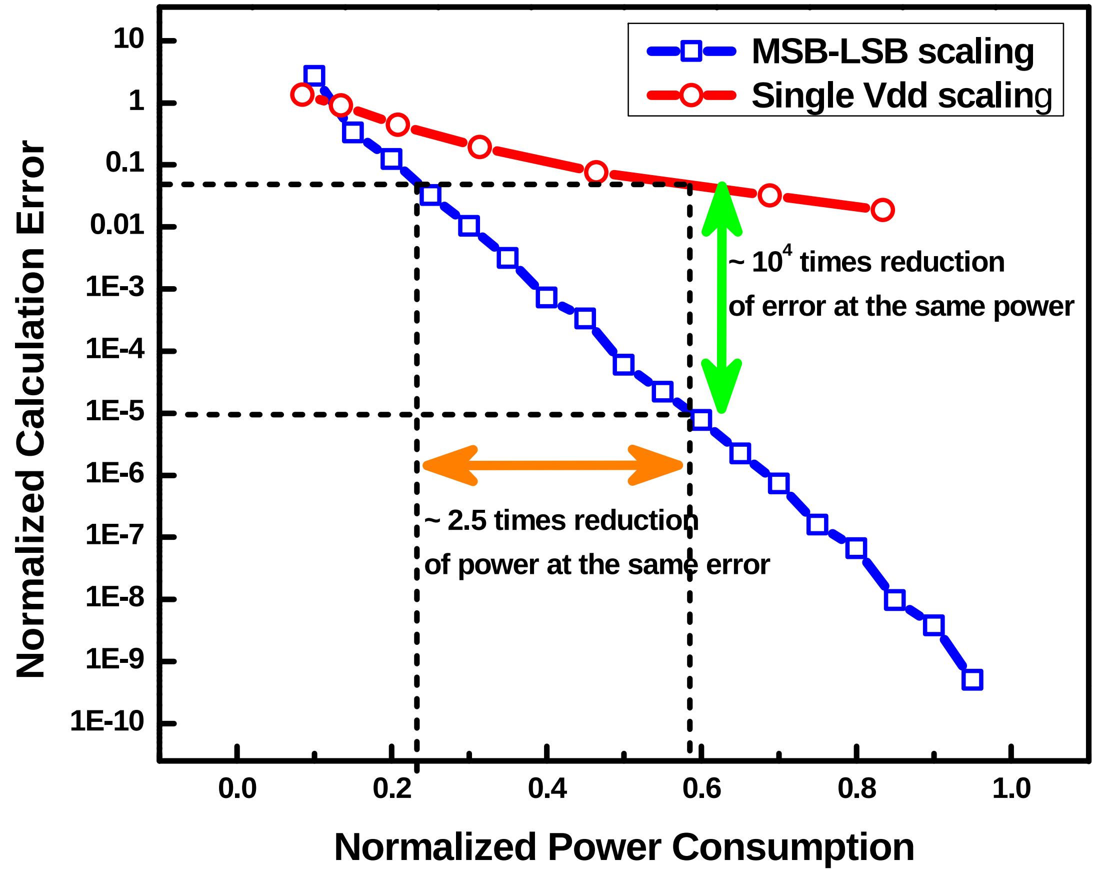
Indeed, take advantage of it to get robustness in presence of uncertainty from all the different sources.

Inexact Addition

MSB-LSB weighted scaling of supply voltages for 32-bit CCS-CSS adders



Adder Block

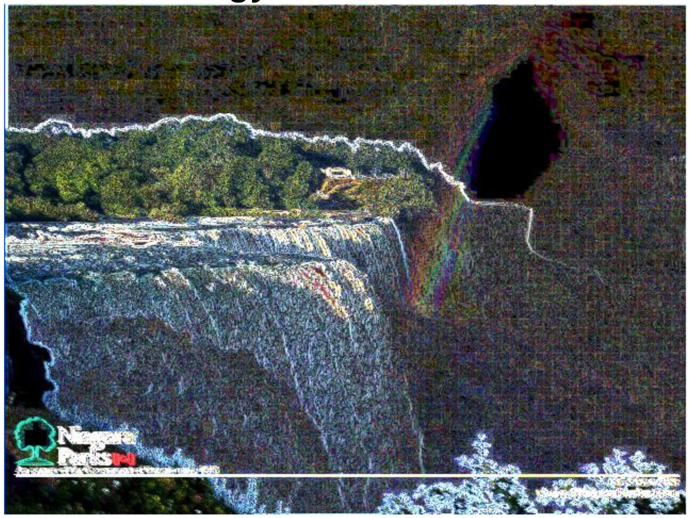


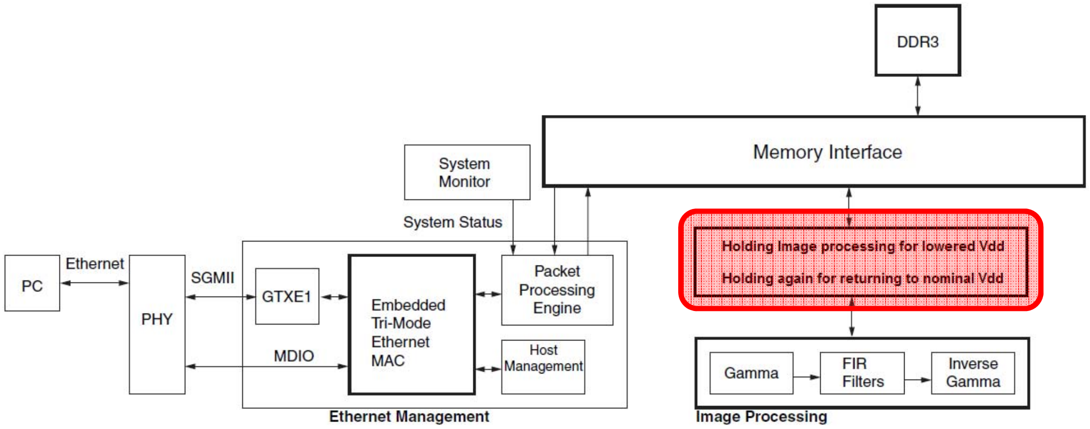
Kim & Tiwari, NanoAch ACM (2011)

Image Processing through Inexactness from DSP Lower Voltages

Kim & Tiwari (2011)

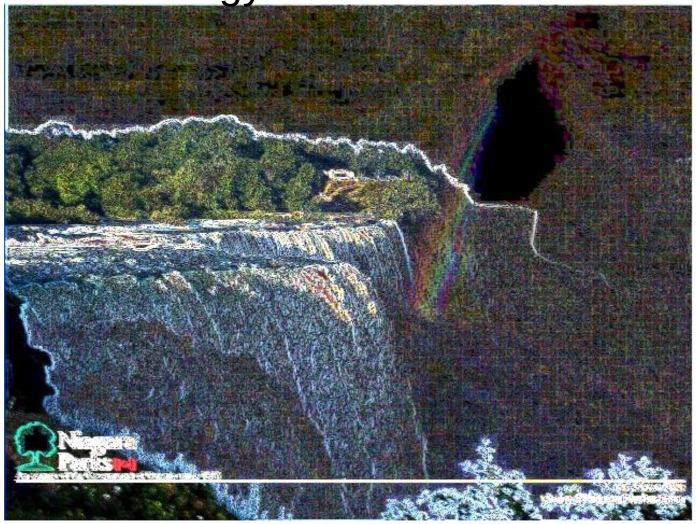
x0.52 Energy





x0.66 Energy

x1.0 Energy



Bayesian Engines

Machine learning models – hidden Markov, neural nets, … Bayesian/Belief networks

Such Bayesian probabilistic networks for AI, signal processing, data mining, …. in dedicated hardware.

Acyclic Graphs:

$$p(X_1, \cdots, X_n) = \prod_{i=1}^{n} p[X_i | Parent_i]$$

Outgoing: Sum-product normalized
Incoming: Max-sum normalized

Basic Computational Blocks

Dedicated evolving networked hardware using suitable electronic devices. High FI, High FO

Probabilistic gates of Inexact approaches

This opens up thinking about new devices in an entirely new way.

Tiwari, Lin, Weijia, Palem, …