Electrothermal Analysis and Optimization Techniques for Nanoscale Integrated Circuits

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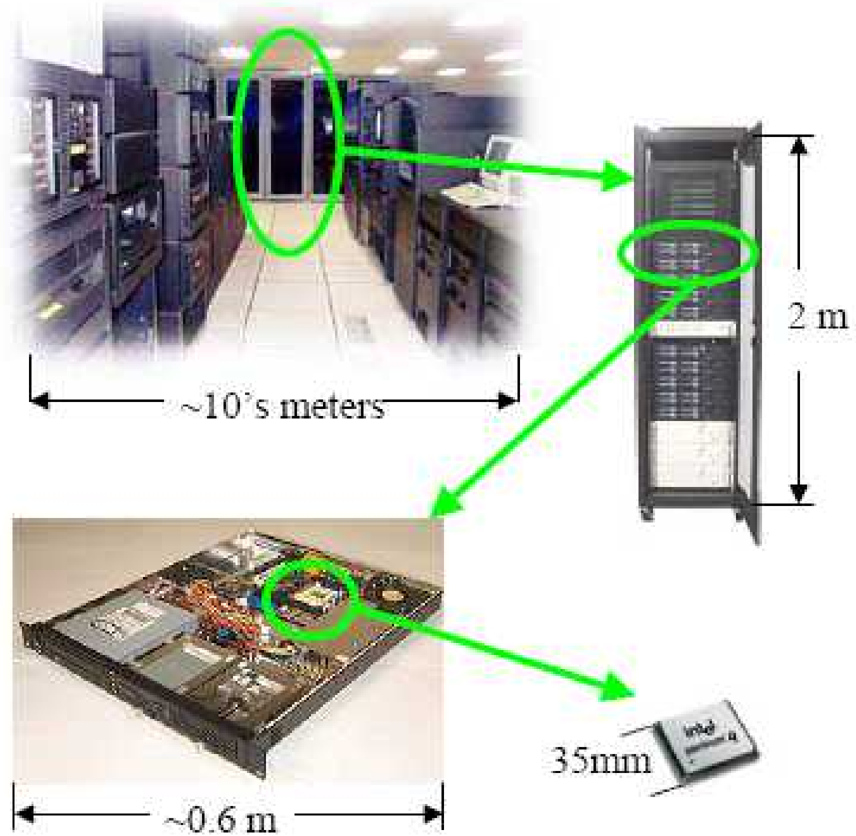
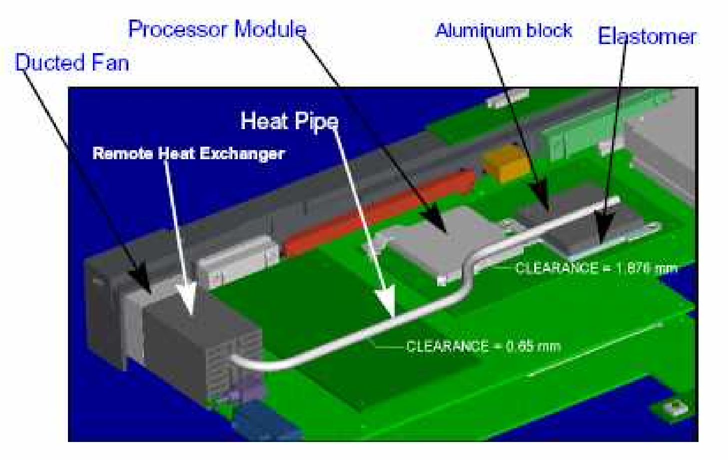
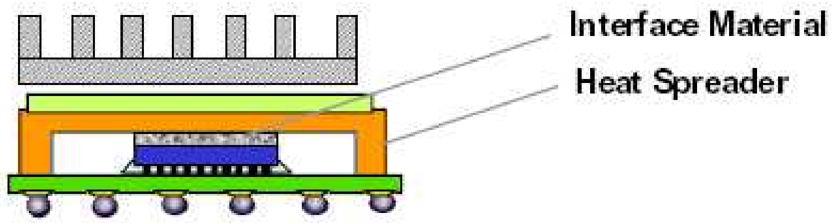
Motivation: Temperature problems

The problem of heat removal



[Joshi, Georgia Tech]





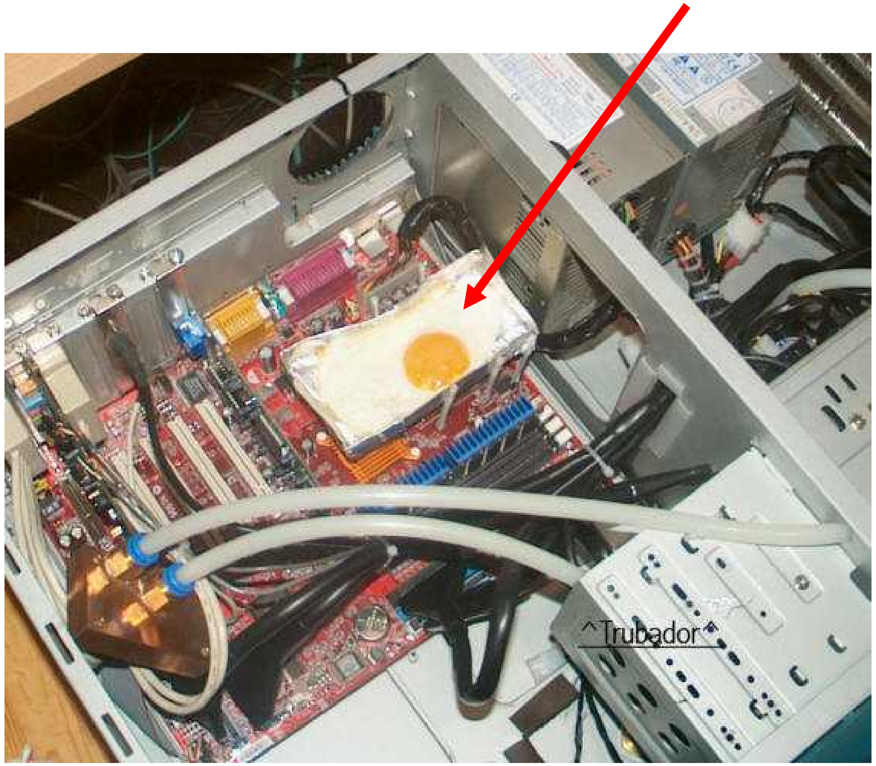
[Viswanath *et al.*, Intel]

Interesting (certainly novel) approaches to cooling

Cooking oil as a coolant

[http://www.tomshardware.com/2006/01/09/strip_out_the_fans]

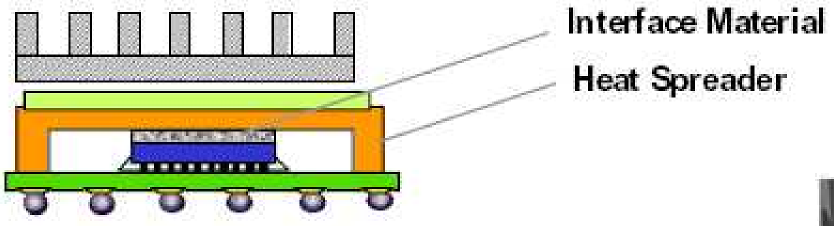
Multitasking



Fried egg

By Trubador, available at
http://www.phys.ncku.edu.tw/~htsu/humor/fry_egg.html

Chip cooling technologies
("Cooling a 200W Light Bulb that is the Size of a Postage Stamp")

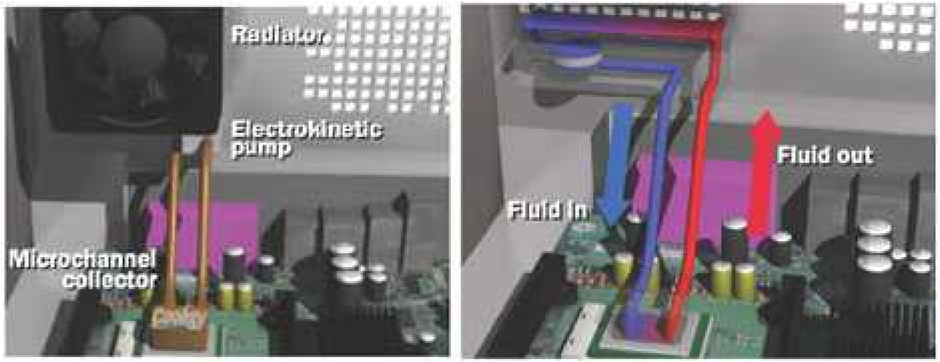


[Viswanath *et al.*, Intel]

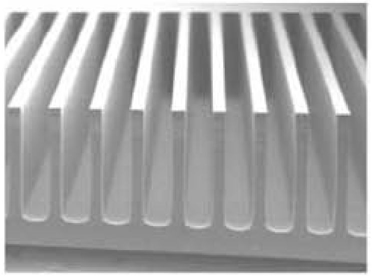
- Air cooling (passive or active)
- Heat sink
- Thermal interface materials (TIMs), heat spreaders
  - Next generation TIMs shows much better thermal conductivity
- Thermal vias

Exotic cooling techniques

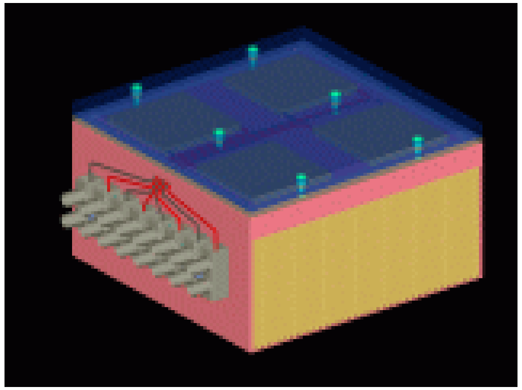
- Microchannels

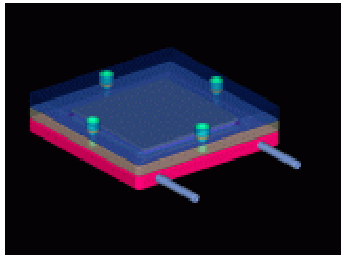


[www.cooligy.com]

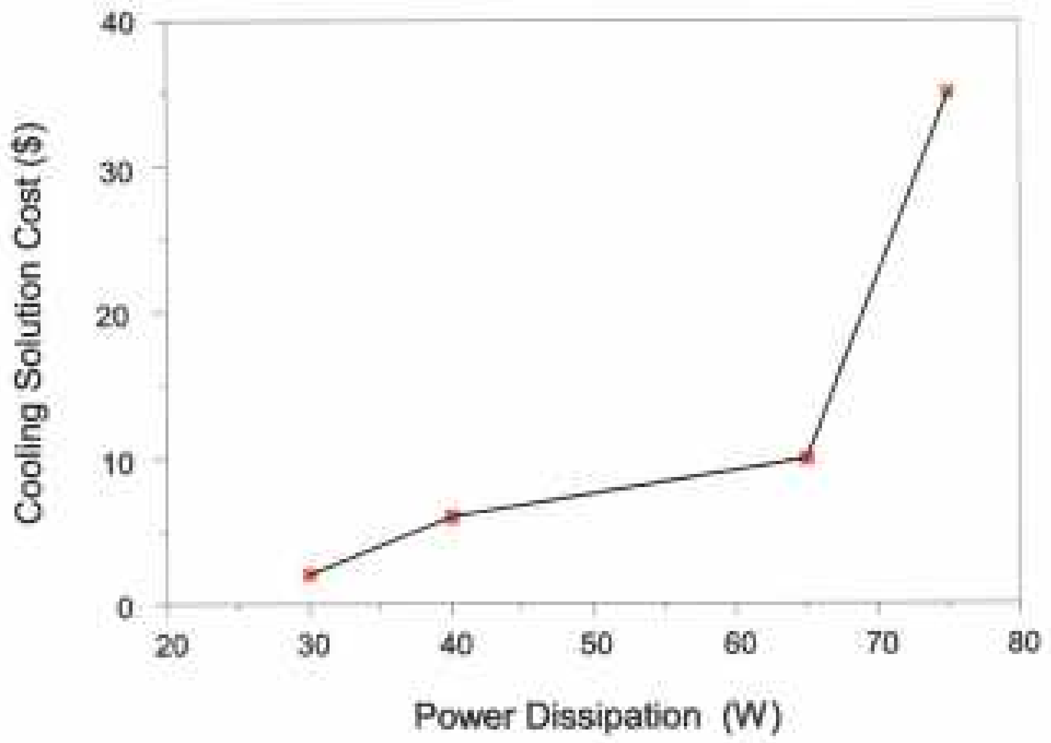


- Peltier elements



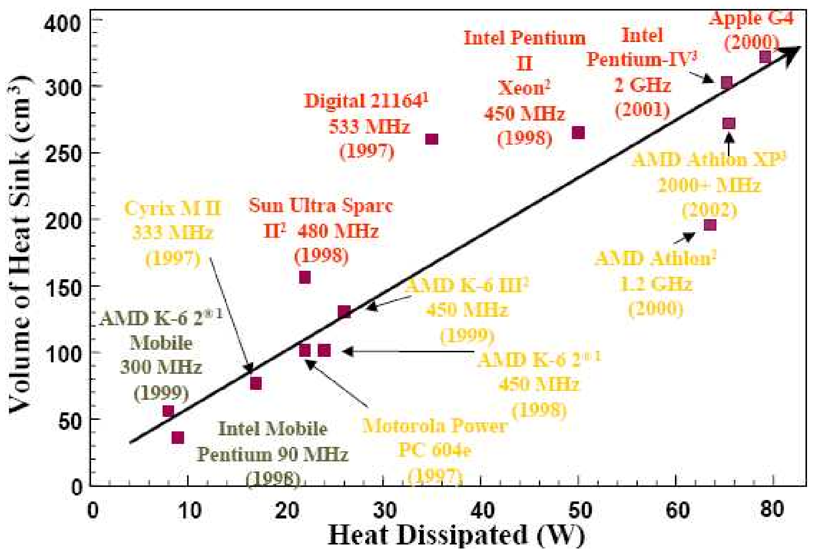


Cost of cooling a microprocessor

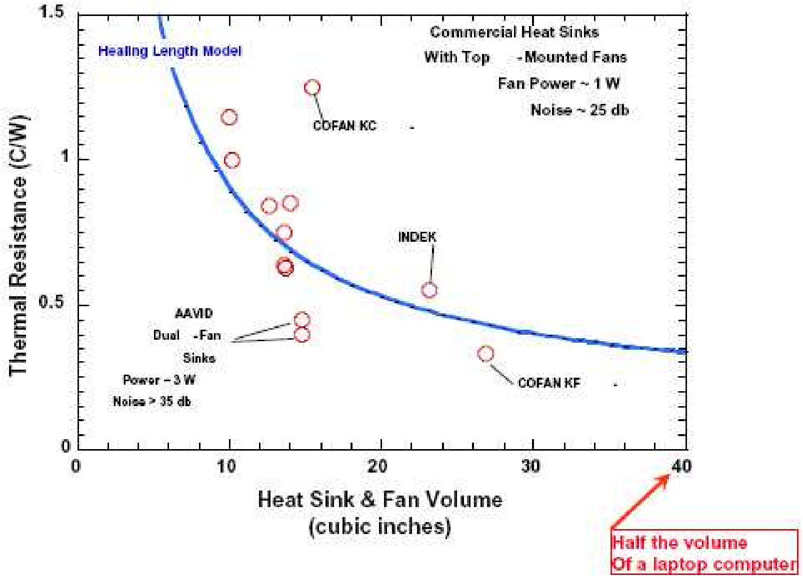


[Intel, via Hannemann]

Physical limitations on heat sinks



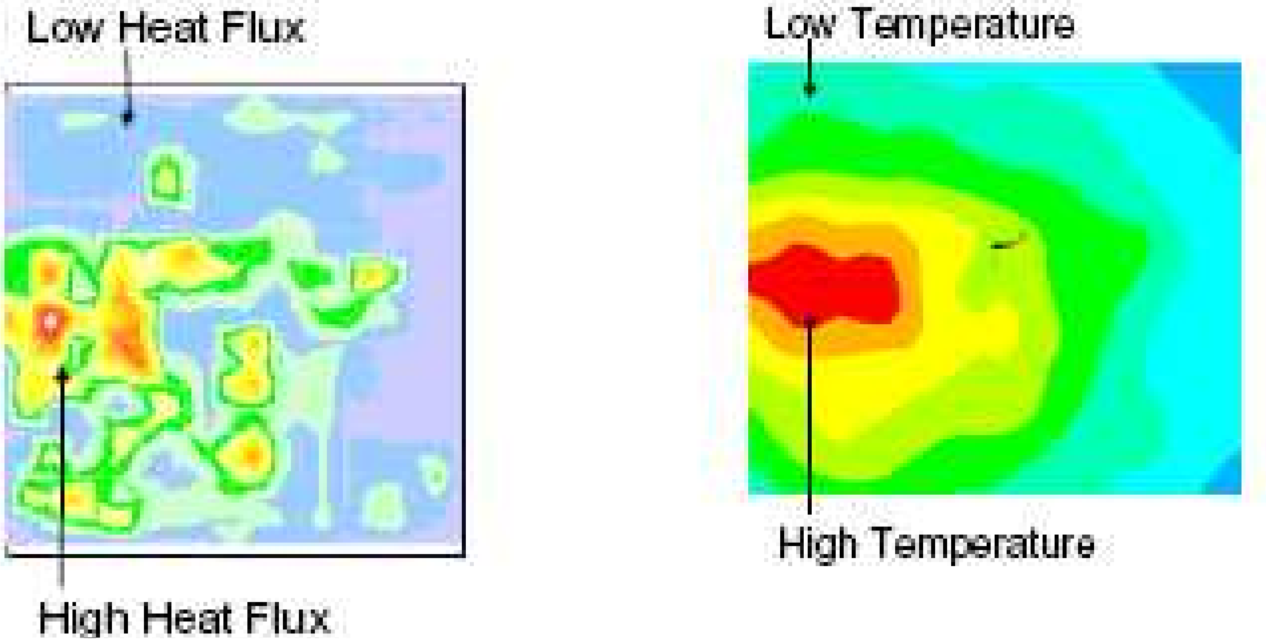
[Joshi, Georgia Tech]



[Goodson, Stanford]

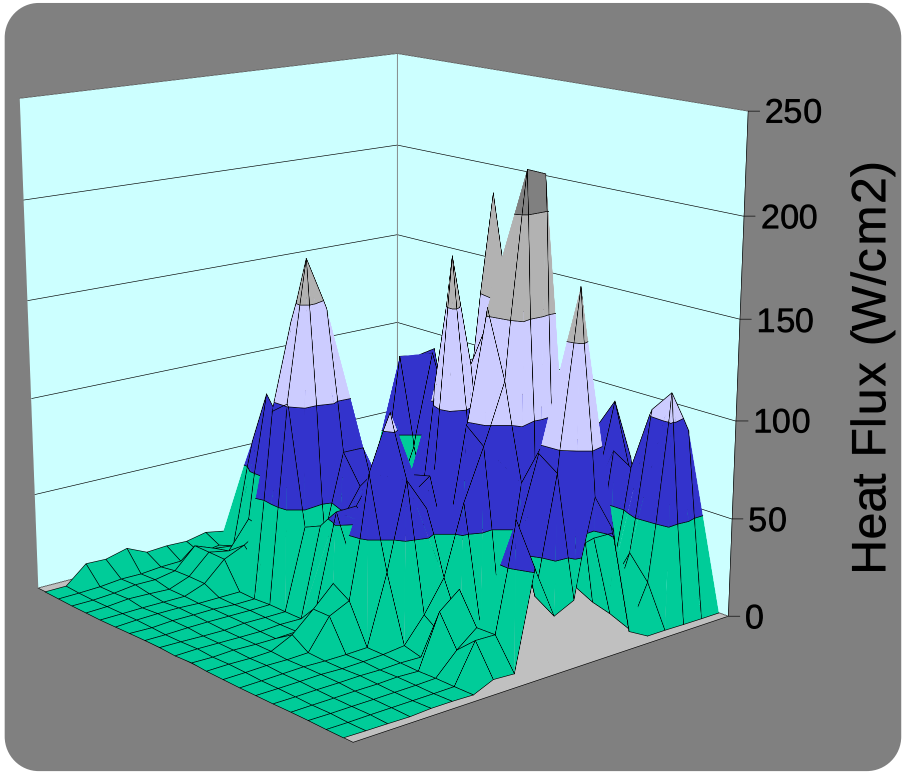
Motivation: Electrothermal effects

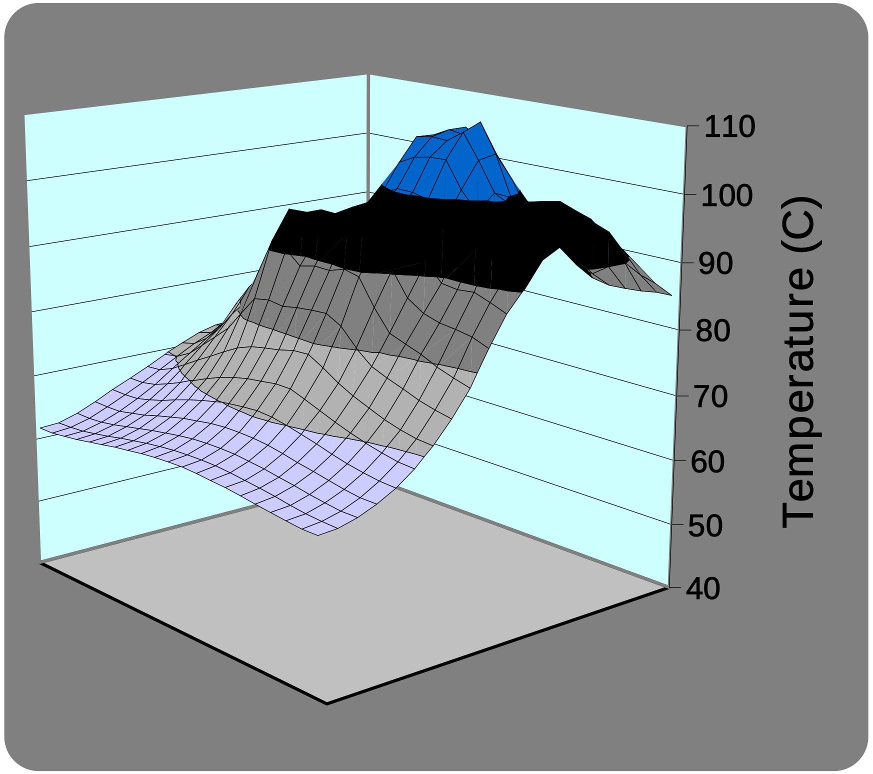
Heat flux maps vs. temperature maps



[Viswanath *et al.*, Intel]

On-chip temperature variations



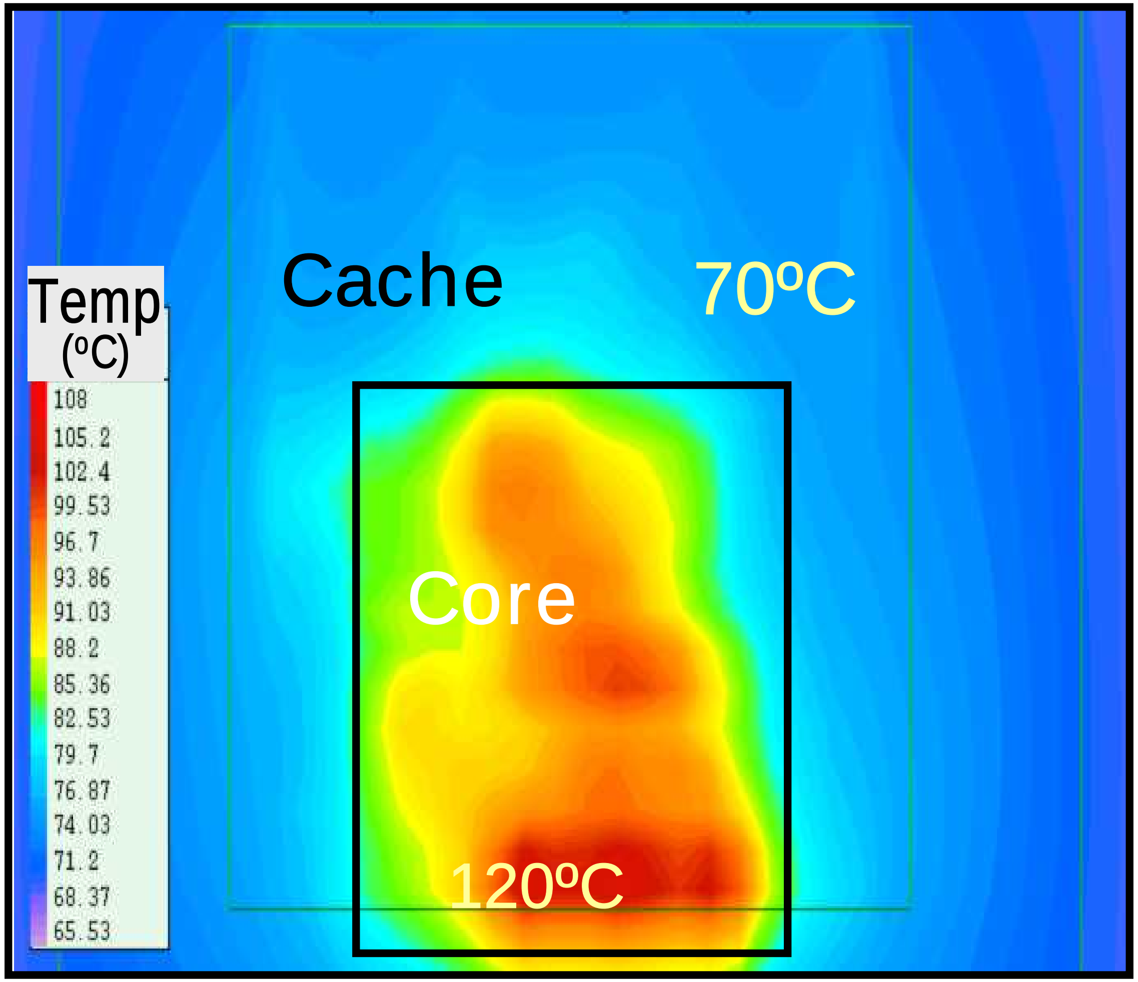


Heat Flux (W/cm^2)
Results in V_{cc} variation

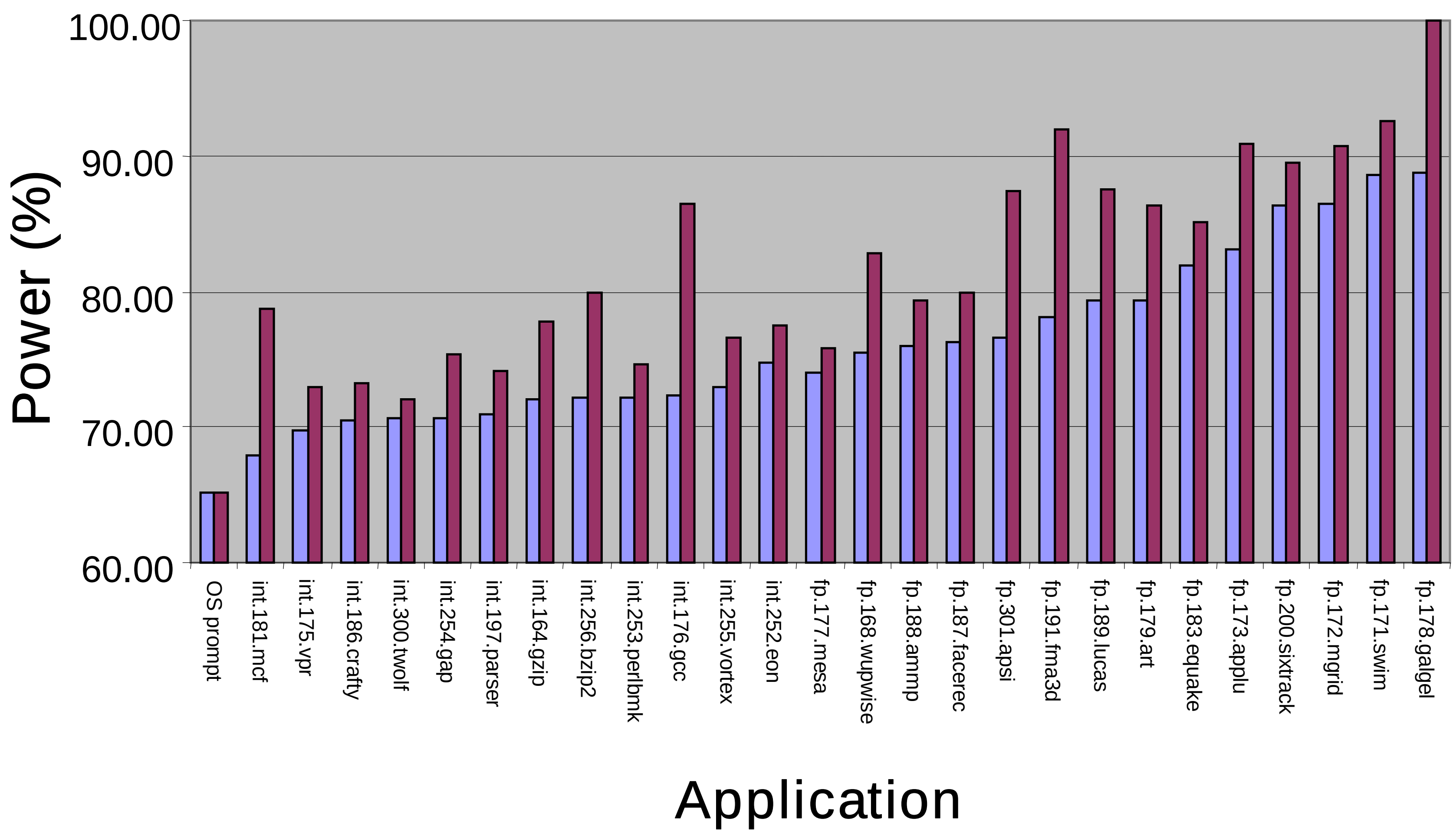
Temperature Variation (° C)

[Borkar, Intel]

Temperature contours: Core vs. cache



Power as a function of application

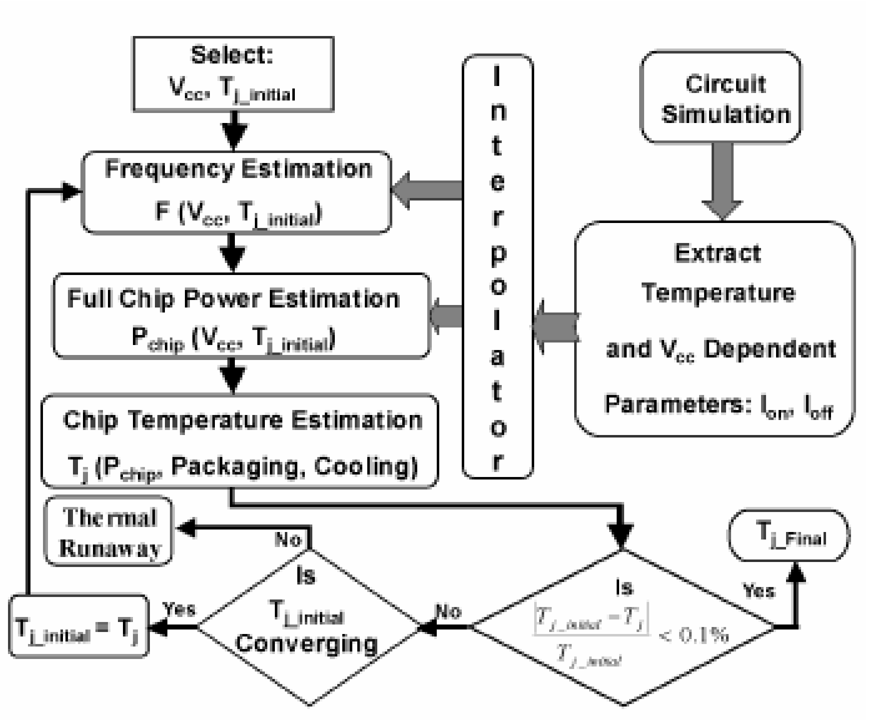


[McGowen, Intel]

Leakage current effects

- Leakage current varies exponentially with temperature

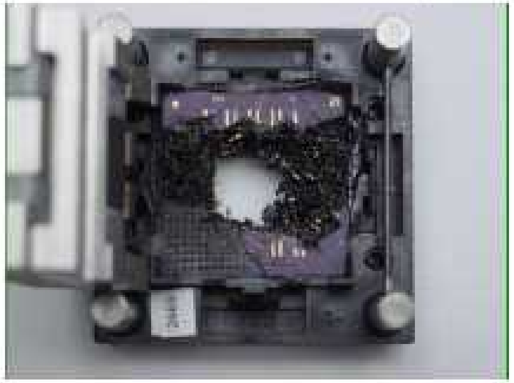
- Self-consistent solutions



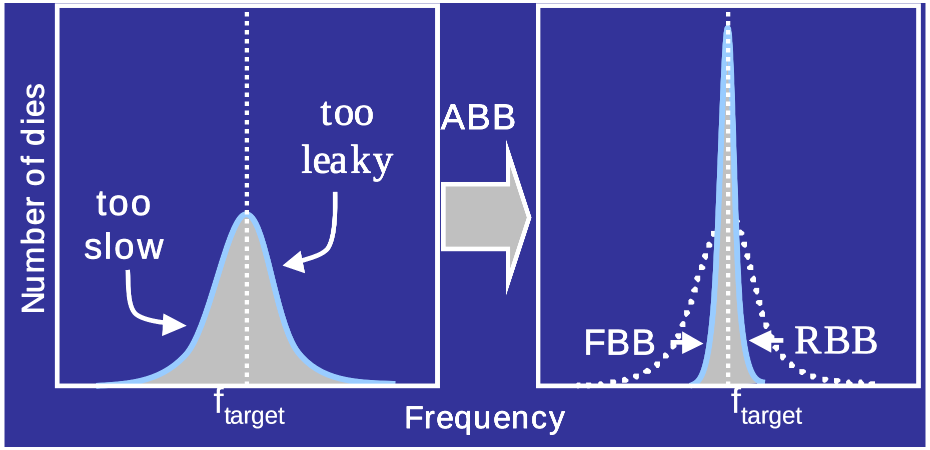
[Vassighi, Intel]

- Thermal runaway

Ref: M Miller, NGBI, 2001



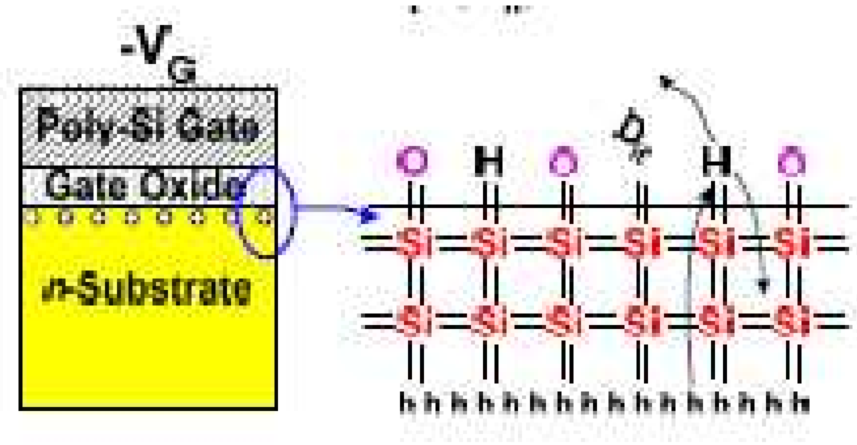
- Variability effects



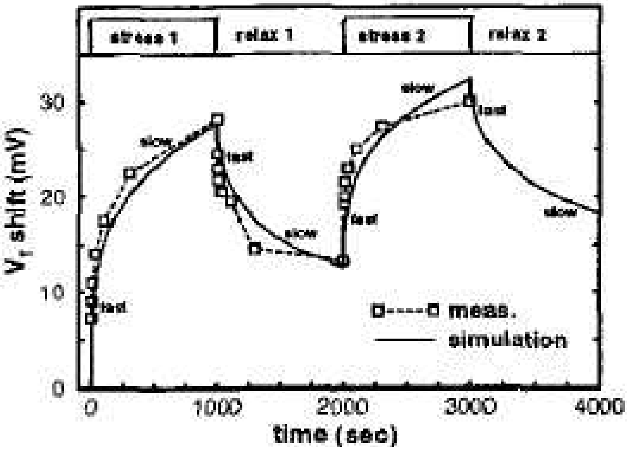
[Borkar, Intel]

Reliability impact

- Electromigration
  - Black's equation: increased temperature reduces mean time to failure
  - MTTF = $A_0 (J - J_{crit})^{-n} e^{-Ea/kT}$
- Hot carrier injection
- Negative bias temperature instability (NBTI)



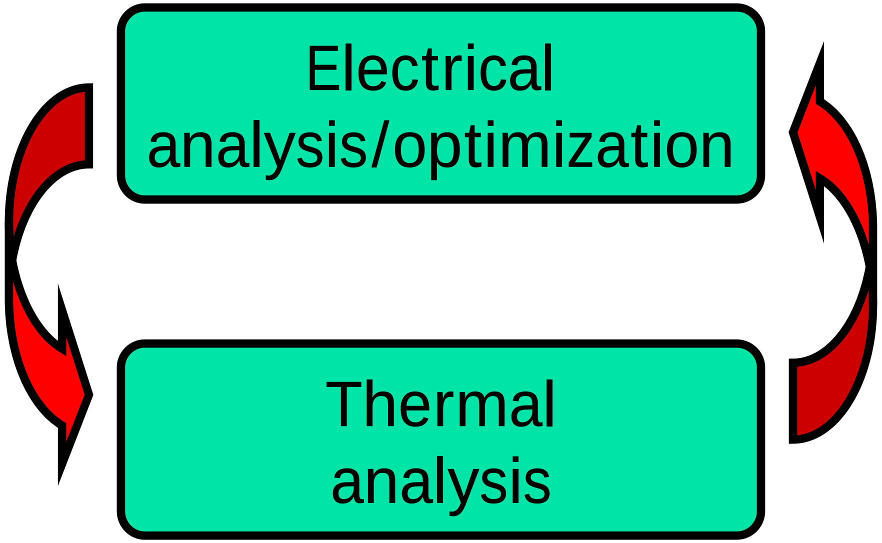
[Schroder]



[Alam]

Electrothermal design

- Simple approach



Electrical analysis/optimization

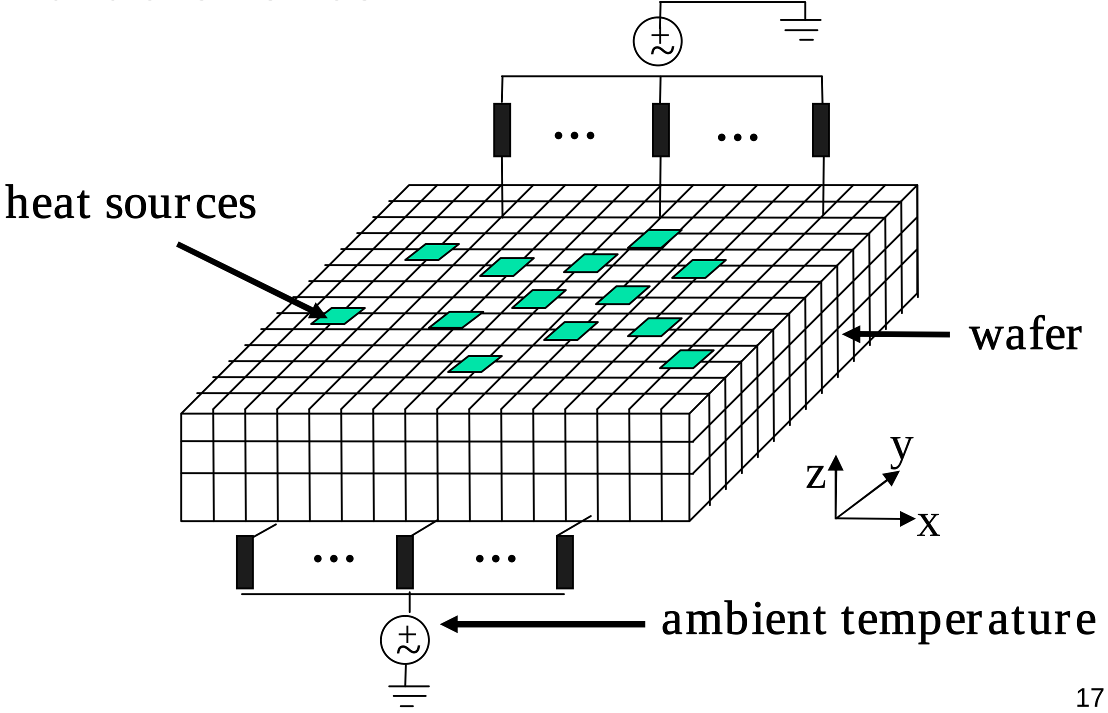
Thermal analysis

- Integrated approach
  - Include thermal effects during analysis, optimization
  - Tightly coupled analysis/optimization
- Temperature affects
  - Leakage power
  - Timing
    - Higher temperatures reduce V_T, reduce mobility
- Temperature is affected by
  - Leakage power
  - Timing

Thermal analysis

Thermal analysis

- Heat generation
  - Switching gates/blocks act as heat sources
  - Time constants for heat of the order of ms or more
- Temperature alters device behavior, switching speeds
- Strong local spatial characteristics



Thermal analysis

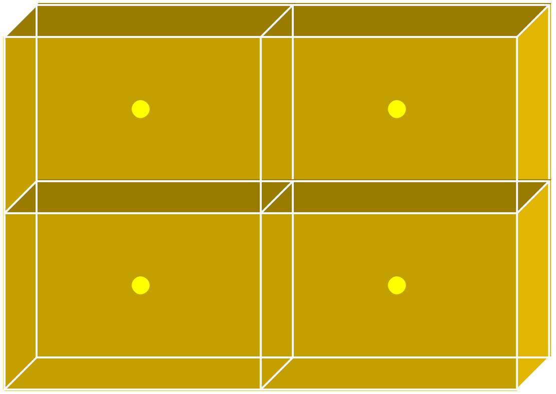
- Thermal equation: partial differential equation

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} + Q(x, y, z) = 0$$

- Boundary conditions corresponding to the ambient, heat sink, etc.
- Self-consistency
  - Power is a function of temperature, which is a function of power!
  - Often handled using iterations
- Some solution techniques
  - Numerical: solve large, sparse systems of linear equations
    - Finite difference method
    - Finite element method
  - System structure is similar to power grid systems
  - Semi-analytical
    - Green functions

The finite difference approach

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} + Q(x, y, z) = 0$$



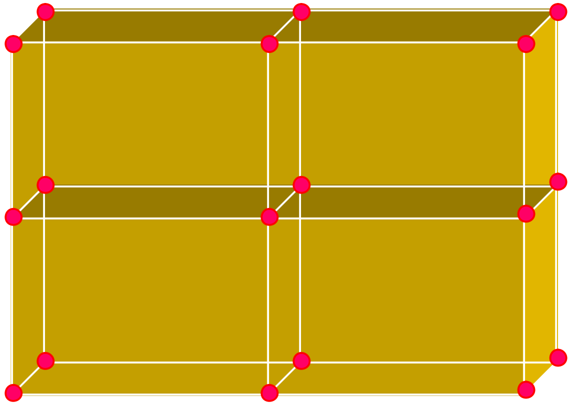
- Finite difference method
  - Discretize into elements; assume element temp. constant
  - Thermal-electrical analogy
    - Can find "thermal resistance" values between element centers
- Eliminate internal mesh nodes to get

$$G\,T = P$$

  - G is the thermal conductance matrix
  - T and P are the temperature and power density vector over mesh nodes on the top surface of the wafer

The finite element approach

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} + Q(x,y,z) = 0$$



- Also a discretization methods
    - Discretize into elements; use polynomial interpolation based on values at nodes
    - Use “element stamps” and assemble these into a larger matrix
    - Apply boundary conditions to get

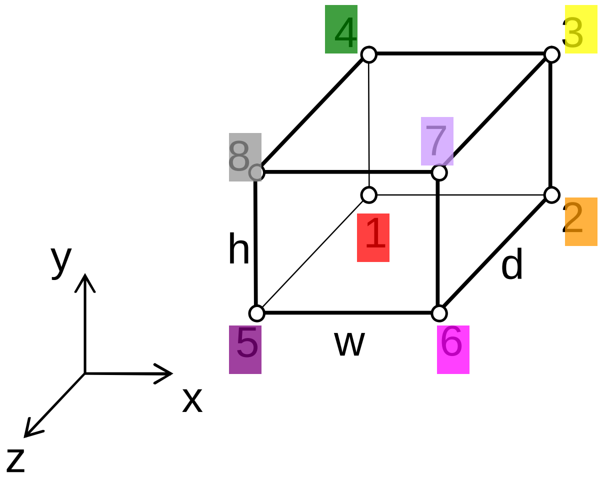
$$G\,T = P$$

    - (G here is denser and smaller than for FDM)

Element stiffness matrix

- Stamp for a hexahedral element
  - Rows and columns correspond to nodes 1 - 8

$$[k]=\begin{bmatrix} +A & +B & +C & +D & +E & +F & +G & +H \\ +B & +A & +D & +C & +F & +E & +H & +G \\ +C & +D & +A & +B & +G & +H & +E & +F \\ +D & +C & +B & +A & +H & +G & +F & +E \\ +E & +F & +G & +H & +A & +B & +C & +D \\ +F & +E & +H & +G & +B & +A & +D & +C \\ +G & +H & +E & +F & +C & +D & +A & +B \\ +H & +G & +F & +E & +D & +C & +B & +A \end{bmatrix}\quad \begin{array}{l} 1 \leftarrow \text{nodes} \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{array}$$



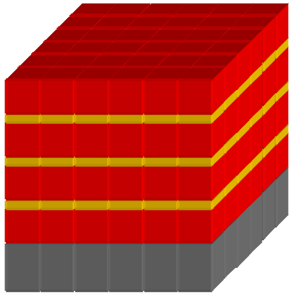
$$\text{where}\quad A=\frac{K_x hd}{9w}+\frac{K_y wd}{9h}+\frac{K_z wh}{9d},\quad B=-\frac{K_x hd}{9w}+\frac{K_y wd}{18h}+\frac{K_z wh}{18d}$$

$$C=-\frac{K_x hd}{18w}-\frac{K_y wd}{18h}+\frac{K_z wh}{36d},\quad D=\frac{K_x hd}{18w}-\frac{K_y wd}{9h}+\frac{K_z wh}{18d}$$

$$F=\frac{K_x hd}{18w}+\frac{K_y wd}{18h}-\frac{K_z wh}{9d},\quad E=-\frac{K_x hd}{18w}+\frac{K_y wd}{36h}-\frac{K_z wh}{18d}$$

$$G=-\frac{K_x hd}{36w}-\frac{K_y wd}{36h}-\frac{K_z wh}{36d},\quad H=\frac{K_x hd}{36w}-\frac{K_y wd}{18h}-\frac{K_z wh}{18d}$$

Element and global matrices



- Elements are aligned in a grid pattern
- Element matrices, *k*, are calculated for each element
- Similar to the Modified Nodal Formulation:
  - These stamps, *K*, are added to the global matrix, K_{global}
- Now solve

$$K_{global}\,T = P$$

- P = power vector, T = temperature vector

Reducing the global matrices using fixed temperatures (“ground nodes”)

- Starting with a global system of equations
  - X_1 are the unknown values
  - X_2 are fixed values

$$\left[\begin{array}{c:c} K_{11} & K_{12} \\ \hdashline K_{21} & K_{22} \end{array}\right] \left\{\begin{array}{c} X_1 \\ \hdashline X_2 \end{array}\right\} = \left\{\begin{array}{c} F_1 \\ \hdashline F_2 \end{array}\right\}$$

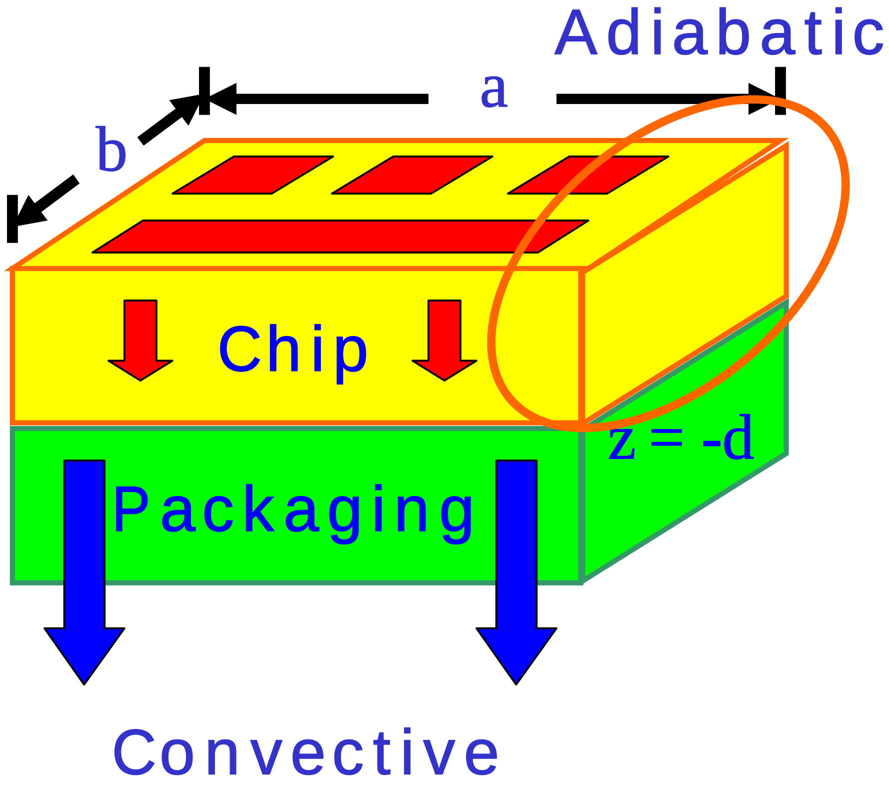
- Eliminate rows and columns corresponding to fixed values

$$[K_{11}]\{X_1\} = \{F_1\} - [K_{12}]\{X_2\}$$

- Results in a reduced system of equation
- Applicable to both FEA and force-directed methods

The Green function method

- Problem definition



$$\nabla^2 T(x,y,z) = 0$$

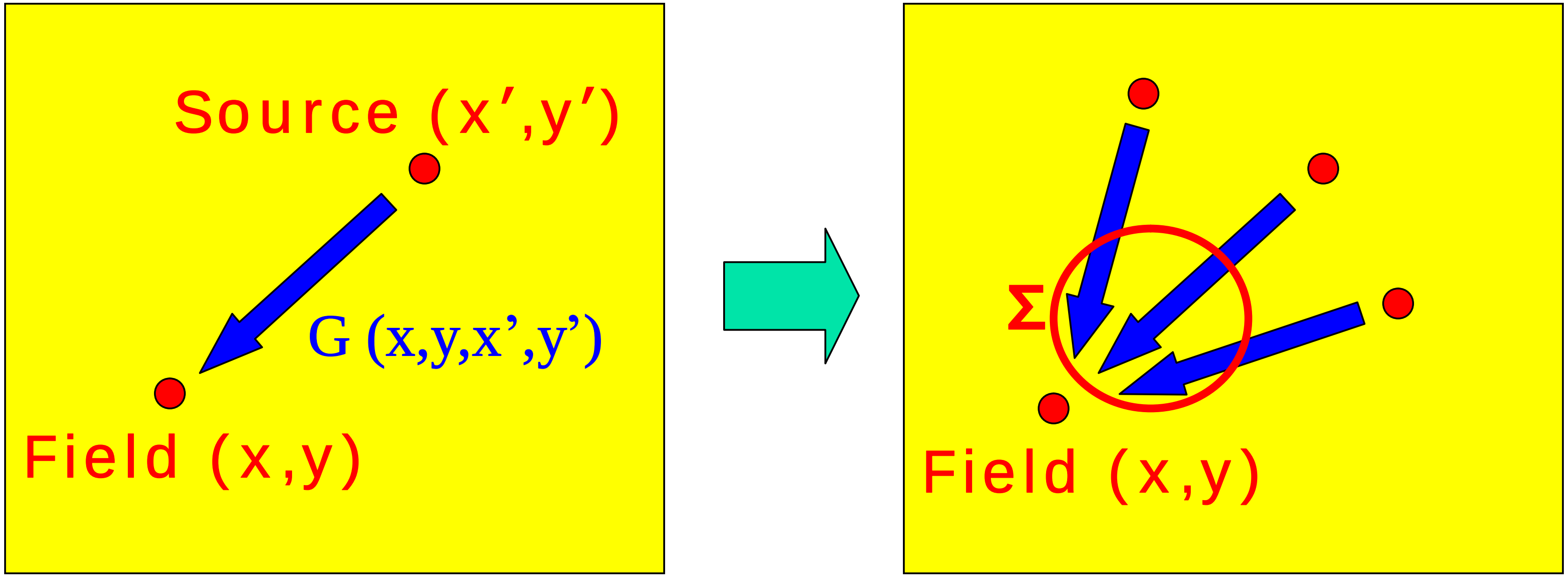
$$\left.\frac{\partial T(x,y,z)}{\partial x}\right|_{x=0,a} = \left.\frac{\partial T(x,y,z)}{\partial y}\right|_{y=0,b} = 0$$

$$k\left.\frac{\partial T(x,y,z)}{\partial z}\right|_{z=0} = P_d(x,y)$$

$$k\left.\frac{\partial T(x,y,z)}{\partial z}\right|_{z=-d} = hT(x,y,z)\big|_{z=-d}$$

P_d – power density, k – thermal conductivity, h – heat transfer coefficient

The Green function method (contd.)



Source (x',y')

$G\,(x,y,x',y')$

Field (x,y)

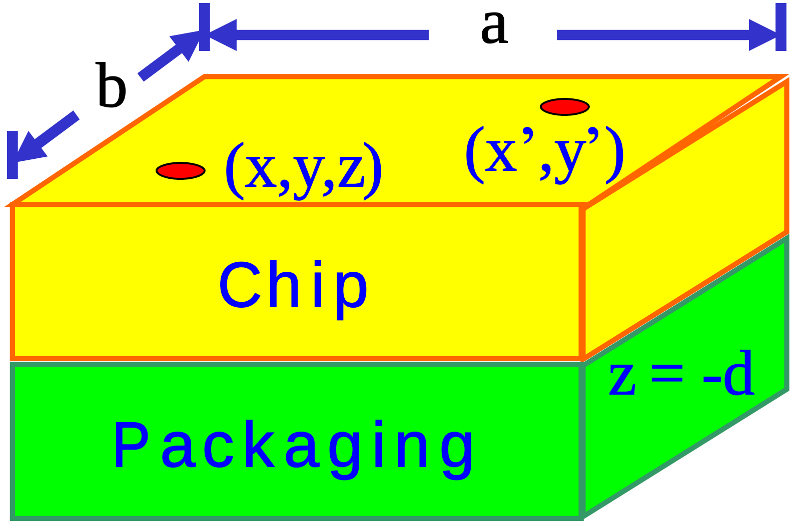
Σ

Field (x,y)

Advantages:

- no 3D meshing necessary
- can do localized solve efficiently

The Green function method (contd.)



$$\nabla^2 G(x, y, z, x', y') = 0$$

$$\left.\frac{\partial G(x, y, z, x', y')}{\partial x}\right|_{x=0,a} = \left.\frac{\partial G(x, y, z, x', y')}{\partial y}\right|_{y=0,b} = 0$$

$$k\left.\frac{\partial G(x, y, z, x', y')}{\partial z}\right|_{z=0} = \delta(x - x')\delta(y - y')$$

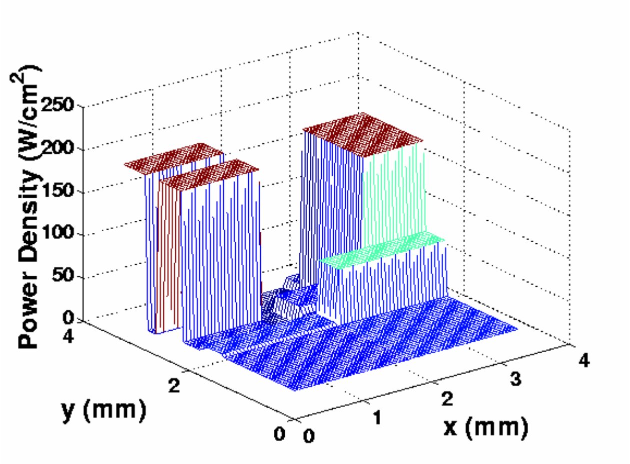
$$k\left.\frac{\partial G(x, y, z, x', y')}{\partial z}\right|_{z=-d} = hG(x, y, z, x', y')\big|_{z=-d}$$

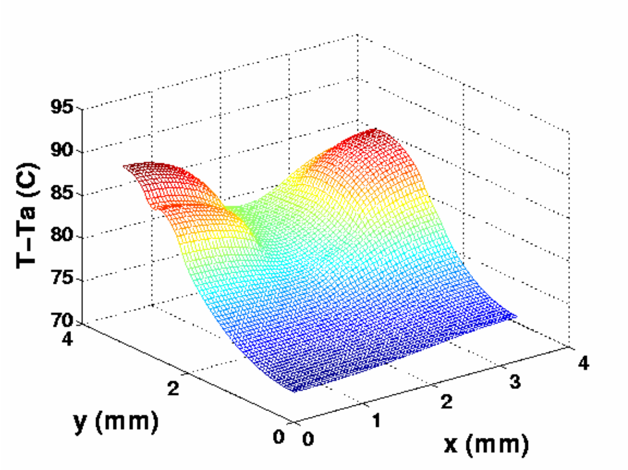
$$G(x, y, x', y') = G(x, y, z = 0, x', y') = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} C_{mn}\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)\cos\left(\frac{m\pi x'}{a}\right)\cos\left(\frac{n\pi y'}{b}\right)$$

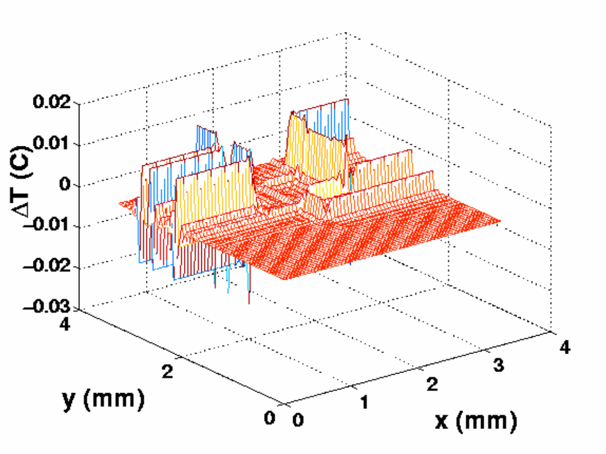
Fast computation techniques

- Algorithm I: Table look-up approach [Zhan, ASPDAC05]
  - Solve the double infinite summation issue
  - Suitable for sensitivity analysis and incremental calculation
- Algorithm II: Frequency domain computation approach [Zhan, ICCAD05]
  - Solve the pair-wise calculation issue
  - Suitable for full-chip temperature profiling
- Algorithm III: Precorrected FFT approach
  - Solve problems with local high accuracy requirements

Sample results





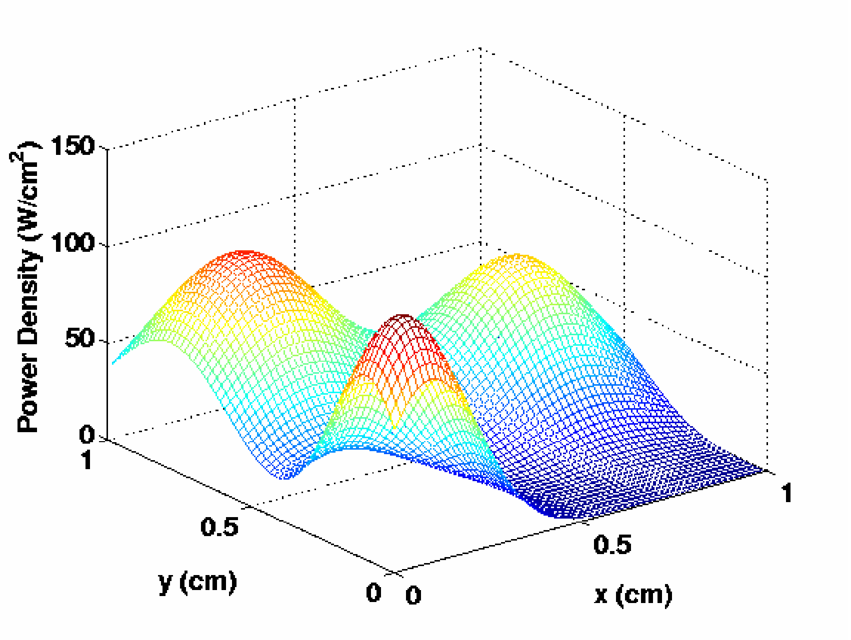


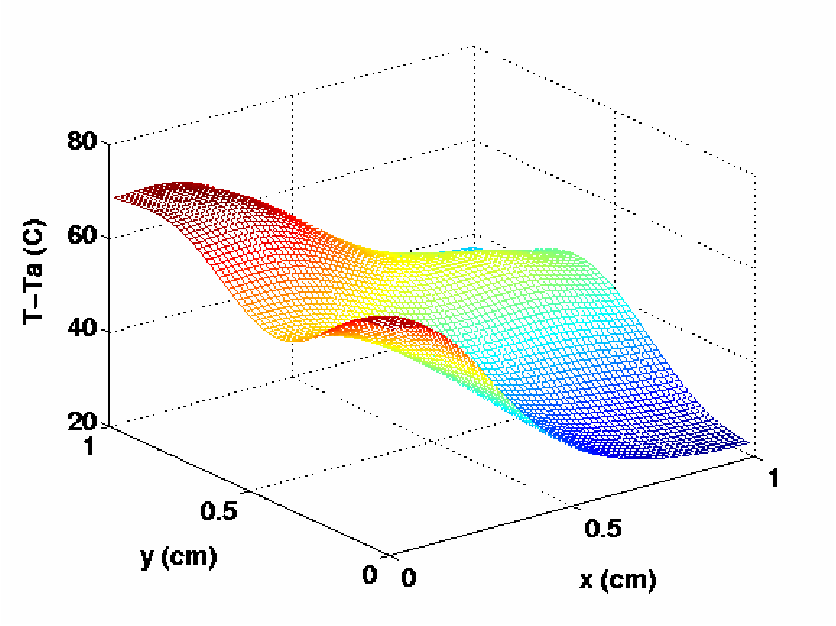
Runtime comparison

Algorithm I: 30msec

Algorithm II: 10msec

Another example





1024x1024 grid cells

Electrothermal Optimization/Mitigation

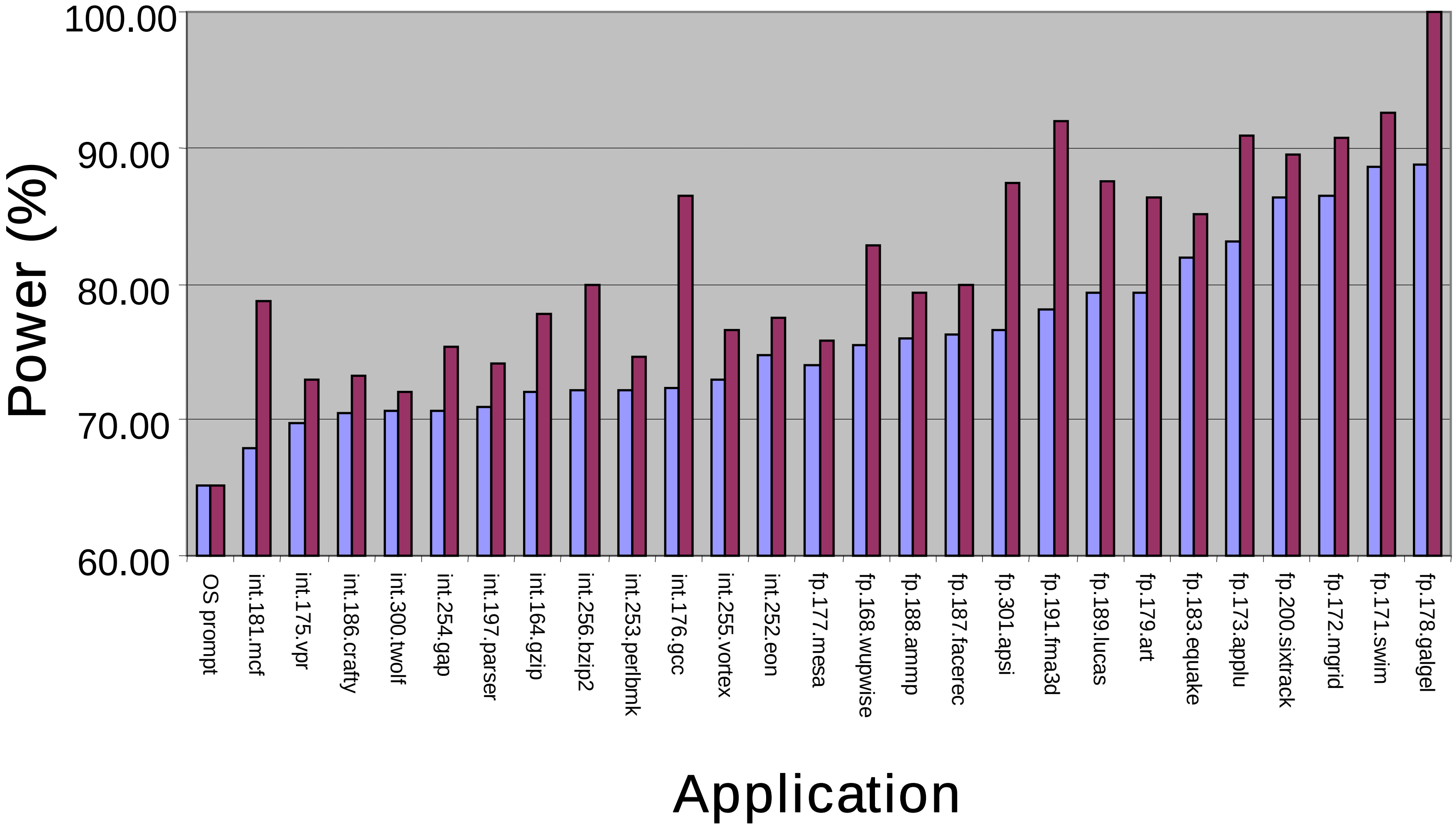
Electrothermal optimization

- Various techniques at all levels of design

- Some examples
  - Architectural optimizations
  - Thermal mitigation
    - Placement
    - Application of body biases

Recall: Power as a function of application

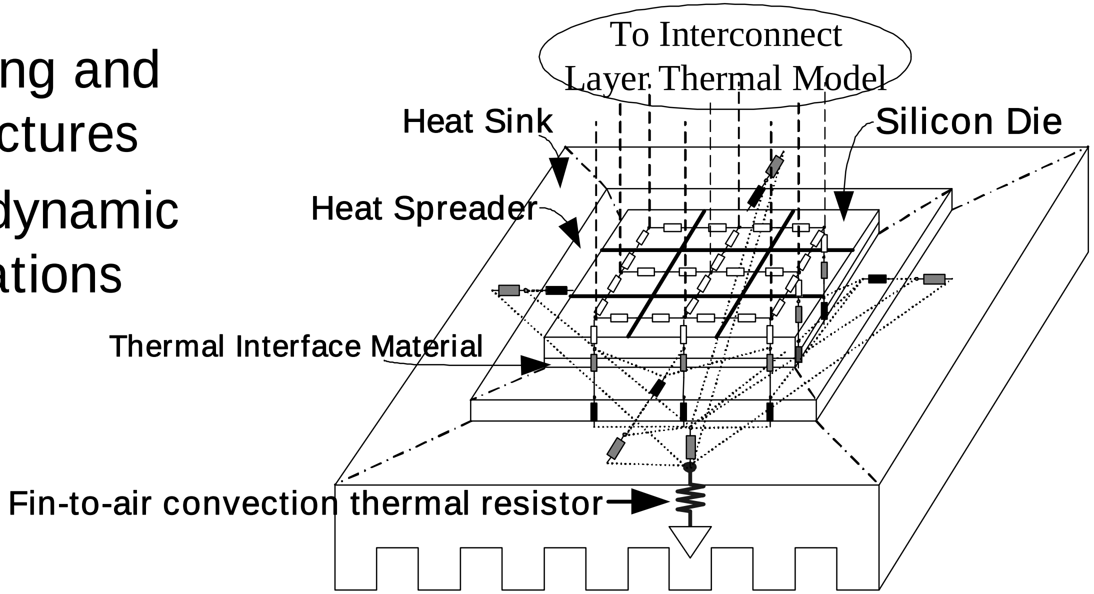
Average and Peak Power as a % of Max Peak



[McGowen, Intel]

Architectural mitigation

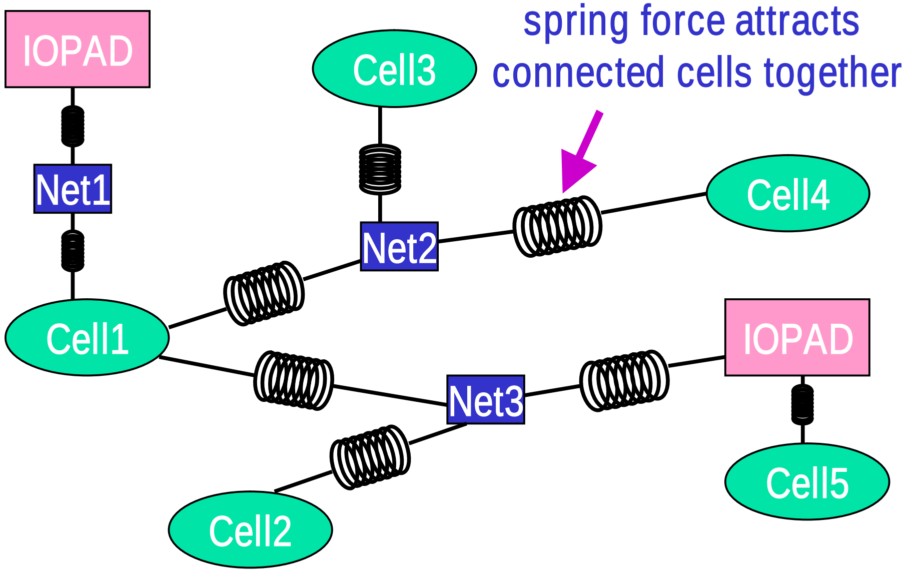
- Work by Skadron, Stan *et al.* at Virginia
- Coarse FDM model (HotSpot)
- Coupled with microarchitectural simulator
- Can be used for analyzing and optimizing microarchitectures
- Integrate clock gating/dynamic voltage scaling optimizations



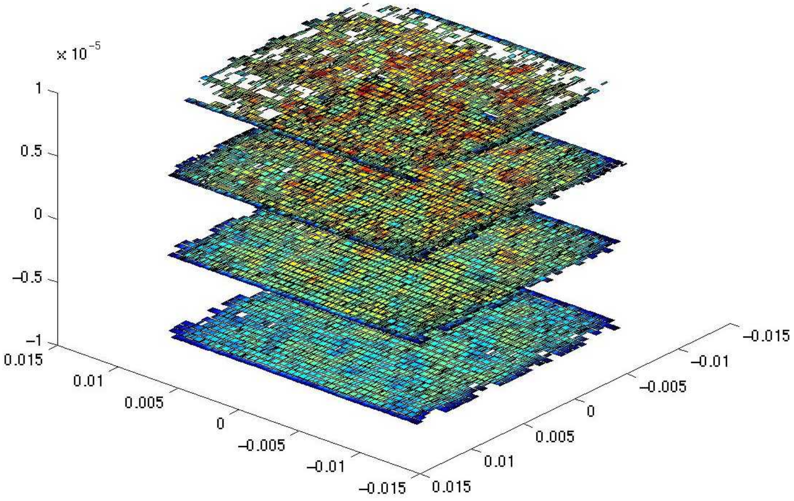
[Stan]

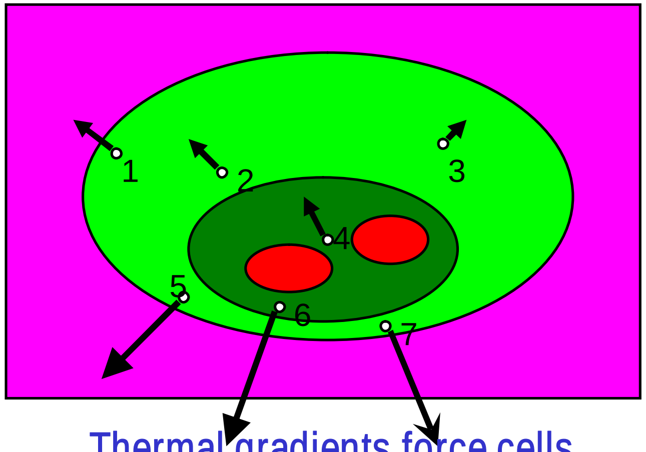
Placement

- Spatial distribution of cells can affect temperature distributions
- 3D circuits: thermal issues are much stronger
- Force-directed approach



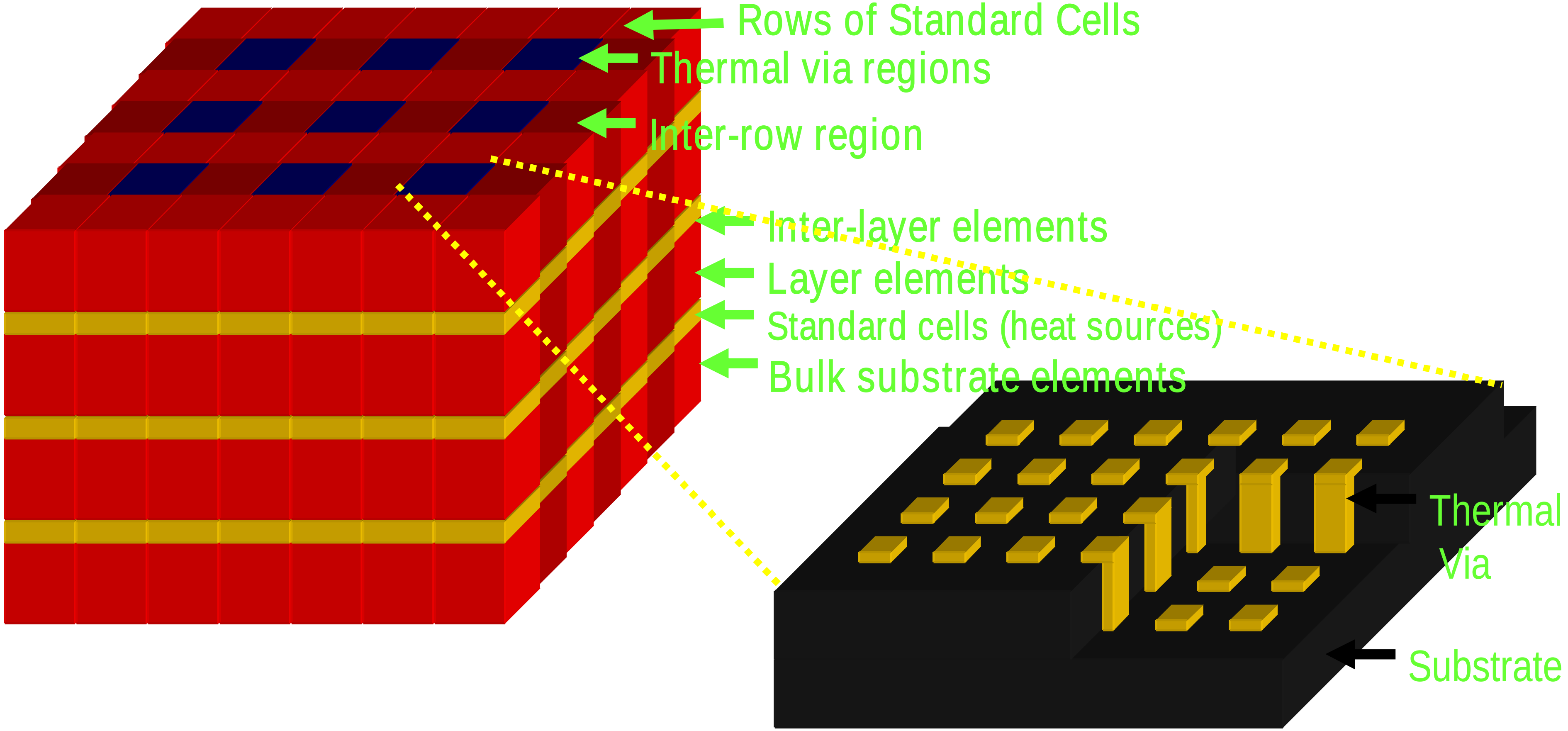
spring force attracts connected cells together



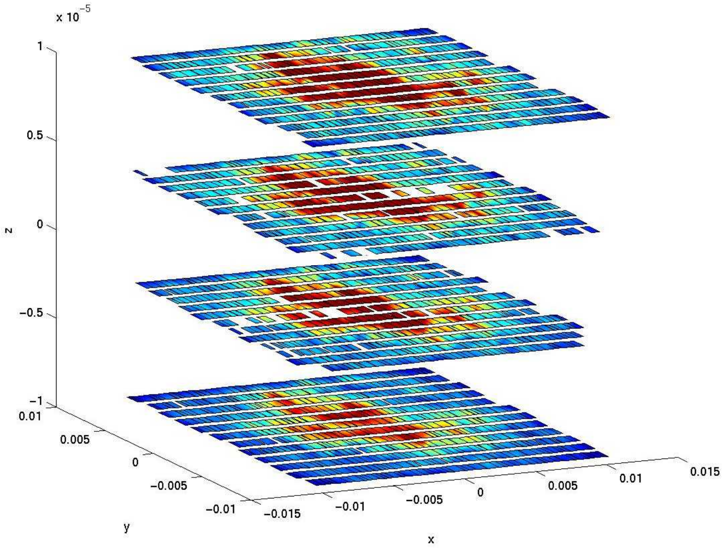


Thermal gradients force cells away from hot spots

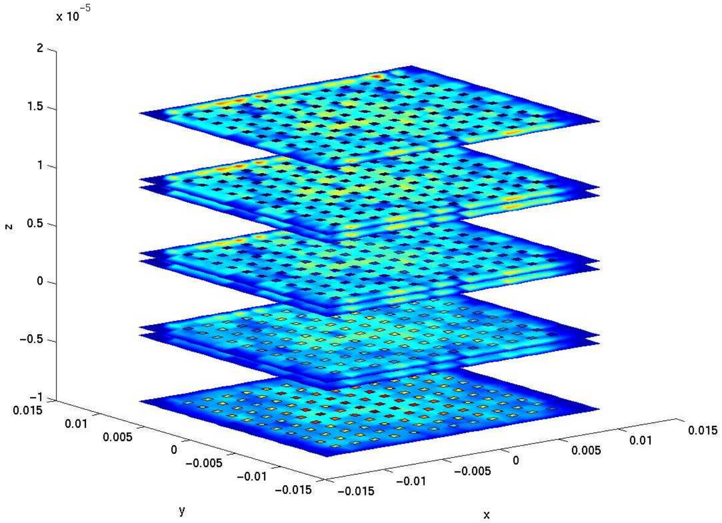
Heat removal through thermal vias (3D)



Heat removal through thermal vias (3D)

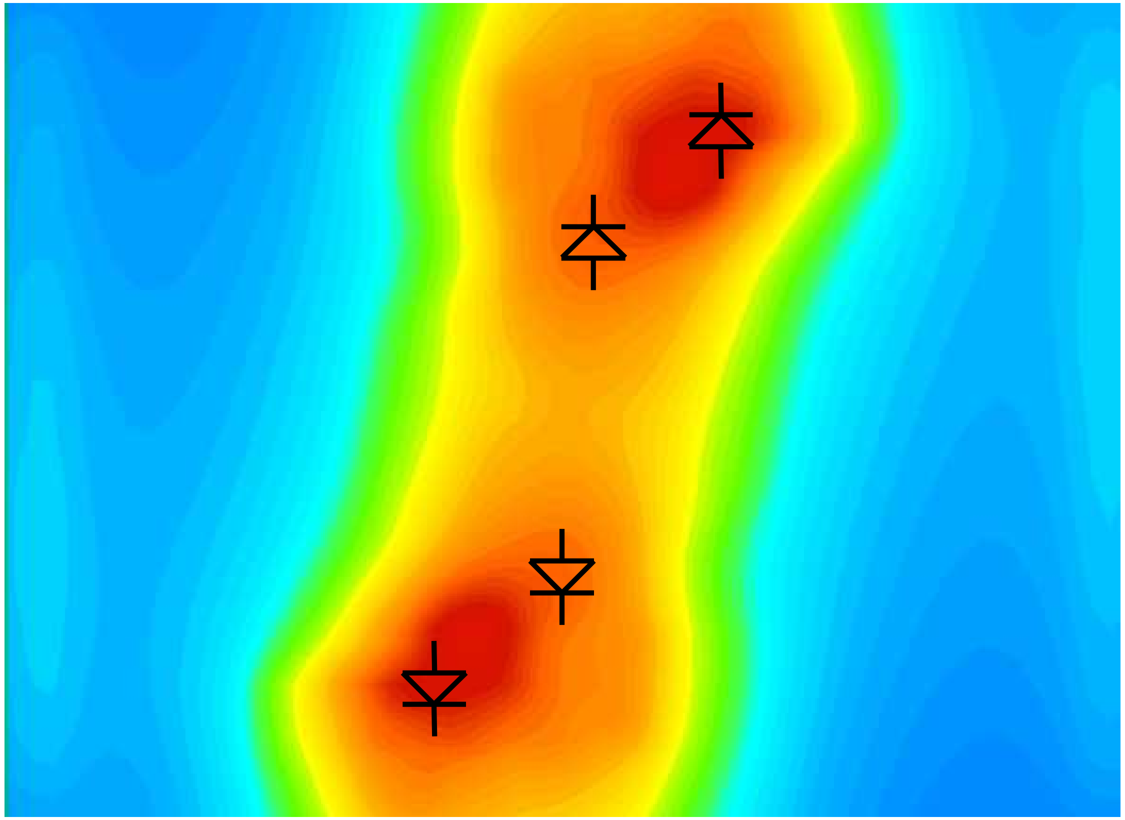


Before



After

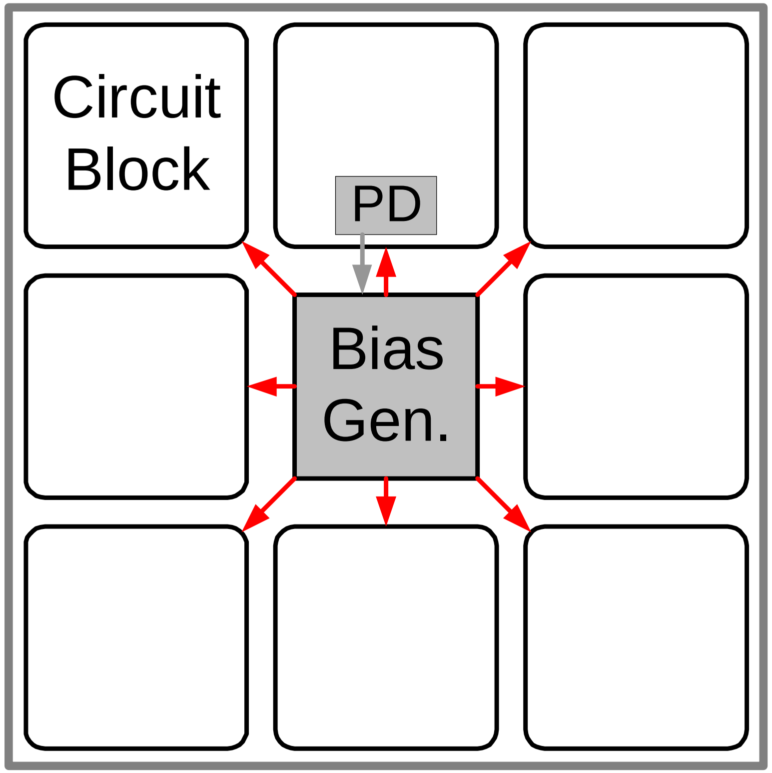
Measuring temperature



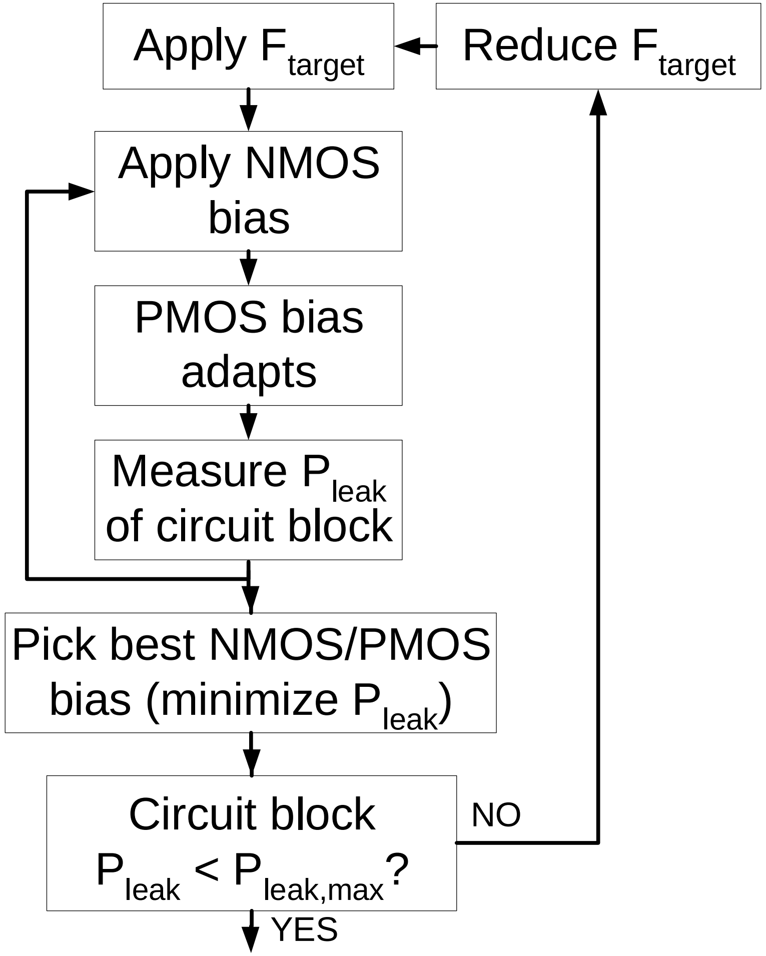
- Place thermal sensors (diodes) at various points

[McGowen, Intel]

Adaptive body bias



PD = Phase detector and critical path



Apply F_{target}

Reduce F_{target}

Apply NMOS bias

PMOS bias adapts

Measure P_{leak} of circuit block

Pick best NMOS/PMOS bias (minimize P_{leak})

Circuit block $P_{leak} < P_{leak,max}$?

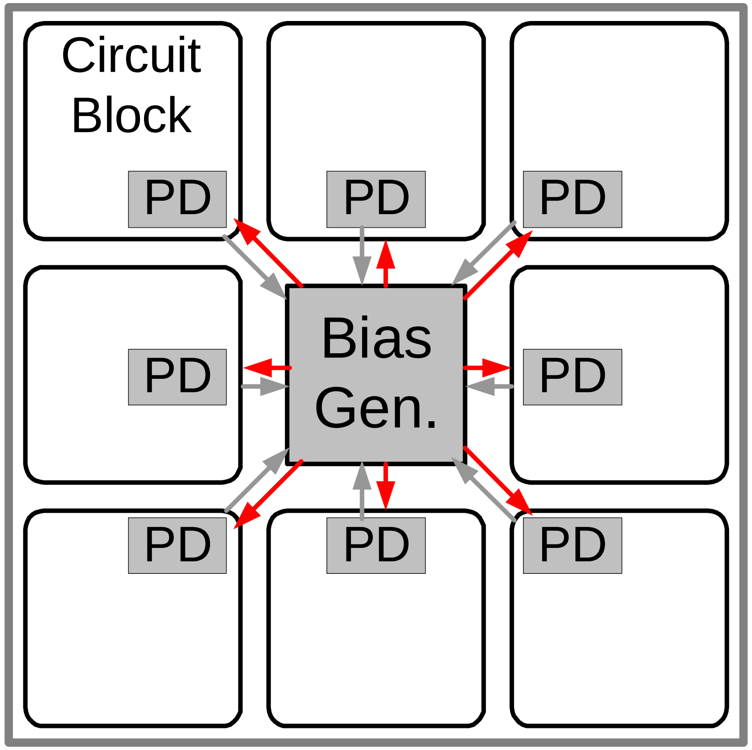
NO

YES

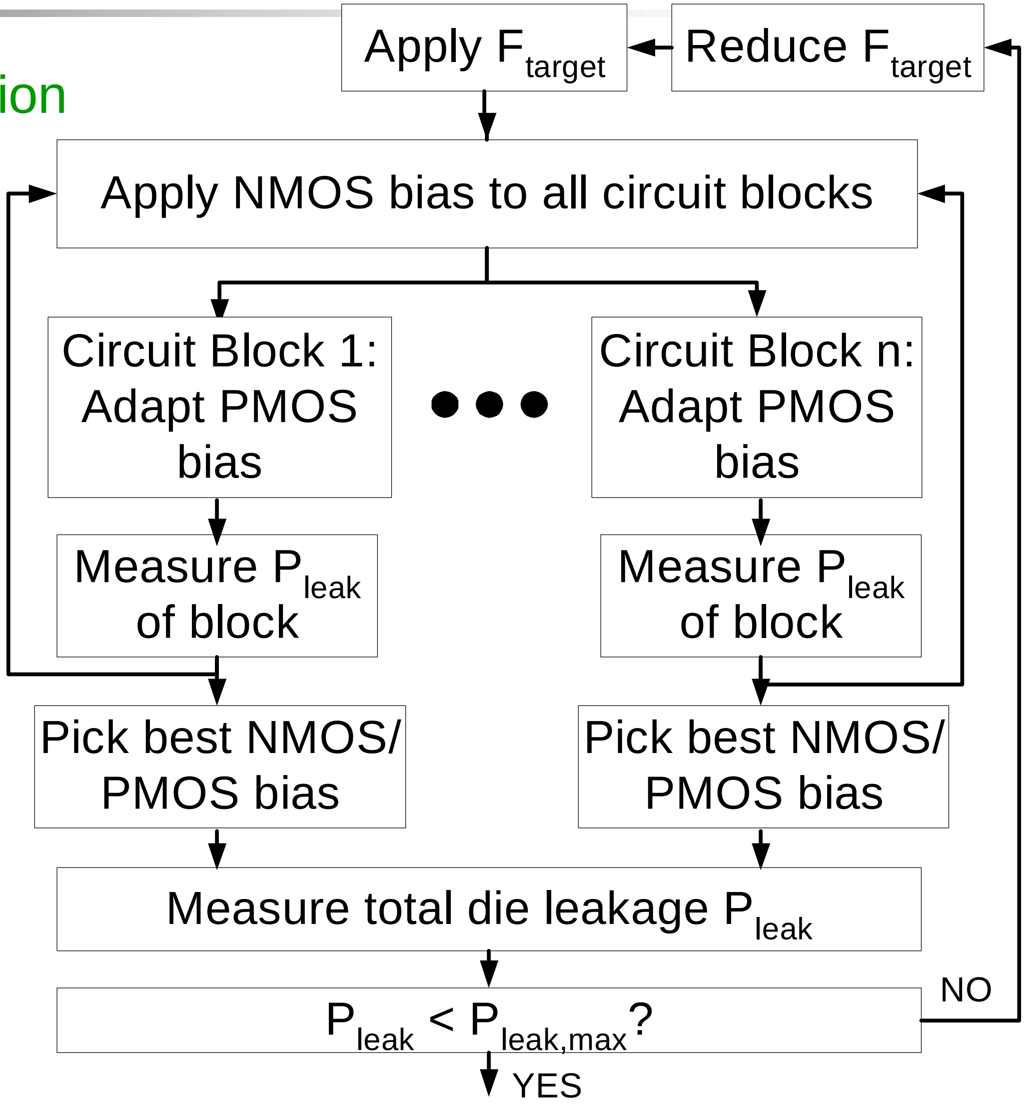
[J. Tschanz, ISSCC02]

Within-die adaptive body bias

Compensating for within-die variation



Area overhead:
Similar to ABB



Apply F_{target}

Reduce F_{target}

Apply NMOS bias to all circuit blocks

Circuit Block 1: Adapt PMOS bias

●●●

Circuit Block n: Adapt PMOS bias

Measure P_{leak} of block

Measure P_{leak} of block

Pick best NMOS/ PMOS bias

Pick best NMOS/ PMOS bias

Measure total die leakage P_{leak}

$P_{leak} < P_{leak,max}$?

NO

YES

Conclusion

- Temperature issues are vital for nanometer-scale designs
- Old metrics (power, etc.) aren’t good enough
- A coordinated electrothermal design strategy is essential