

A brief introduction to
Compact Model Technology
Computer Aided Design

(CMT CAD)

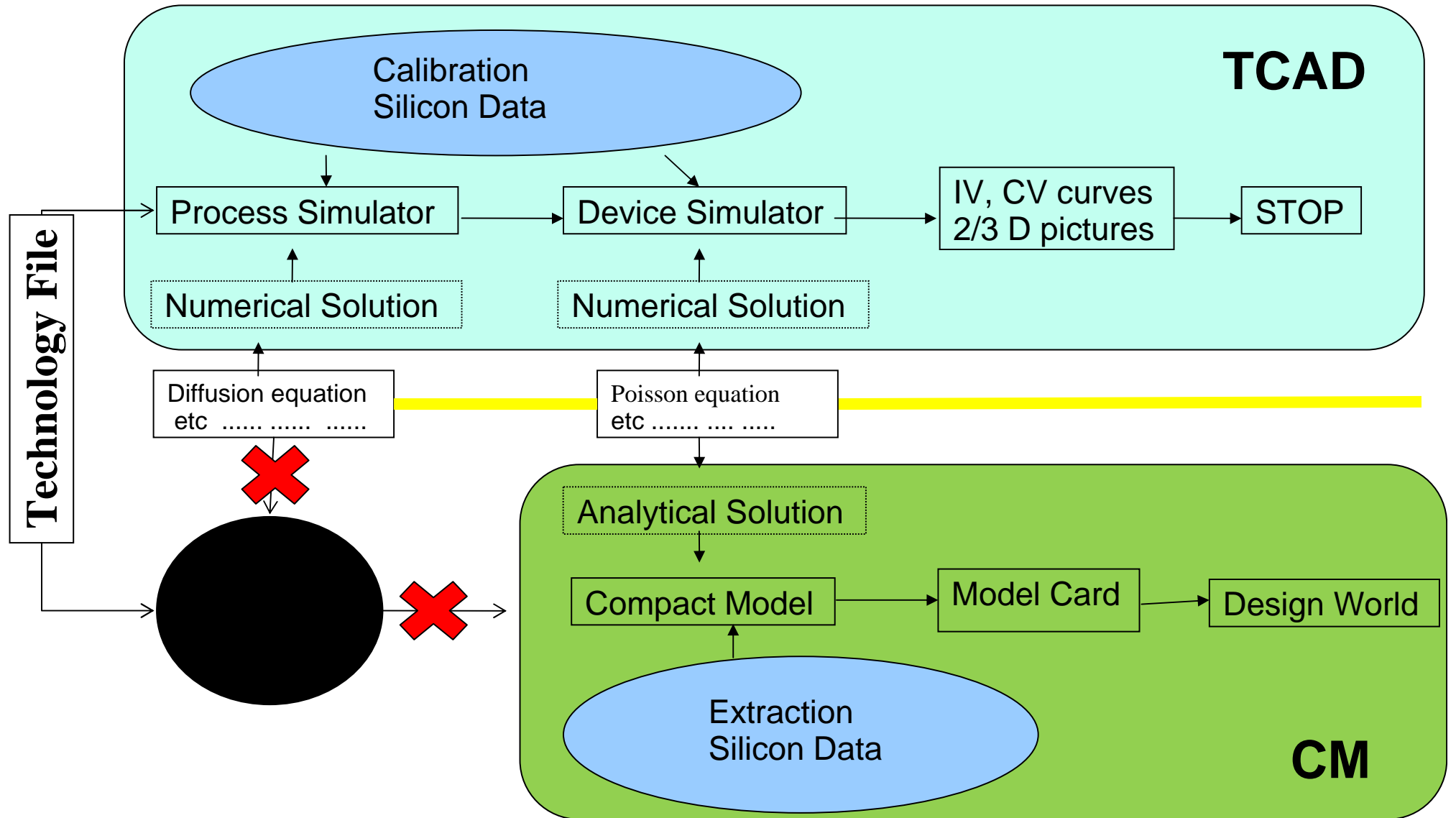
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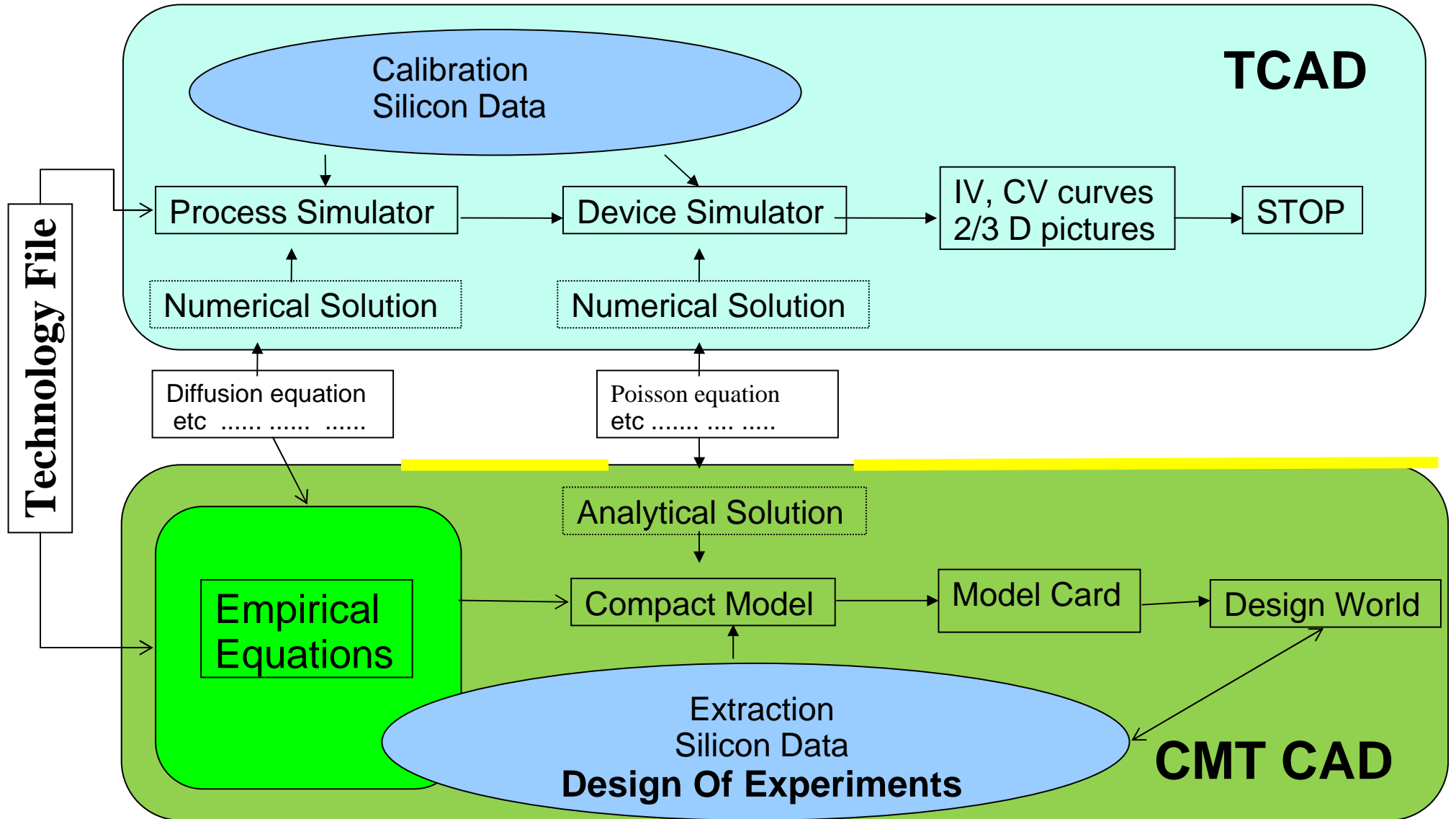
Agenda

- CMT CAD and TCAD
- Nonlinear Programming
- Penalty Functions
- Prior Works
- Applications
- Realization

TCAD vs. Compact Models



TCAD vs. CMT CAD



Nonlinear Programming

A branch of applied mathematics concerned with finding the minimum of a function of several variables, subject to constraints or restrictions on the variables.

Minimize $f(x)$ with respect to x

subject to constraints:

$q_i(x) \leq 0$ - inequality constraints

$h_j(x) = 0$ - equality constraints

Penalty Functions (Example)

- $0 < v_{th0} < 1$

- $0 < v_{th} = v_{th0} + \frac{lv_{th0}}{L_{eff}} + \frac{wv_{th0}}{W_{eff}} + \frac{pv_{th0}}{L_{eff} \times W_{eff}} < 1$

- where: $L_{eff} = L_{drawn} + XL - 2 \left(LINT + \frac{LL}{L^{LLN}} + \frac{LW}{W^{LWN}} + \frac{LWL}{L^{LLN}W^{LWN}} \right)$

- $Penalty(v_{th}) = \begin{cases} 0 & v_{th} < 1 \\ \infty \times (v_{th} - 1)^2 & v_{th} > 1 \end{cases}$

Example of Penalty Function

Mobility model for mobMod=2 (BSIM3)

$$\mu_{eff} = \frac{\mu_0}{1 + P_\mu}$$

$$P_\mu = (U_A + U_C \cdot Vbs_{eff}) \left(\frac{Vgs_{eff}}{Tox} \right) + U_B \cdot \left(\frac{Vgs_{eff}}{Tox} \right)^2$$

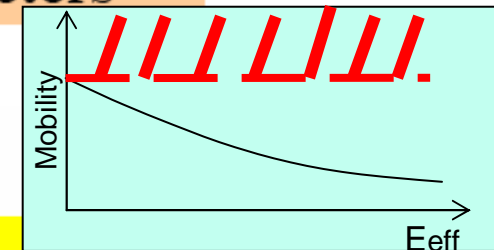
P_μ - Function of more than 100 model parameters

BSIM3 Constraint

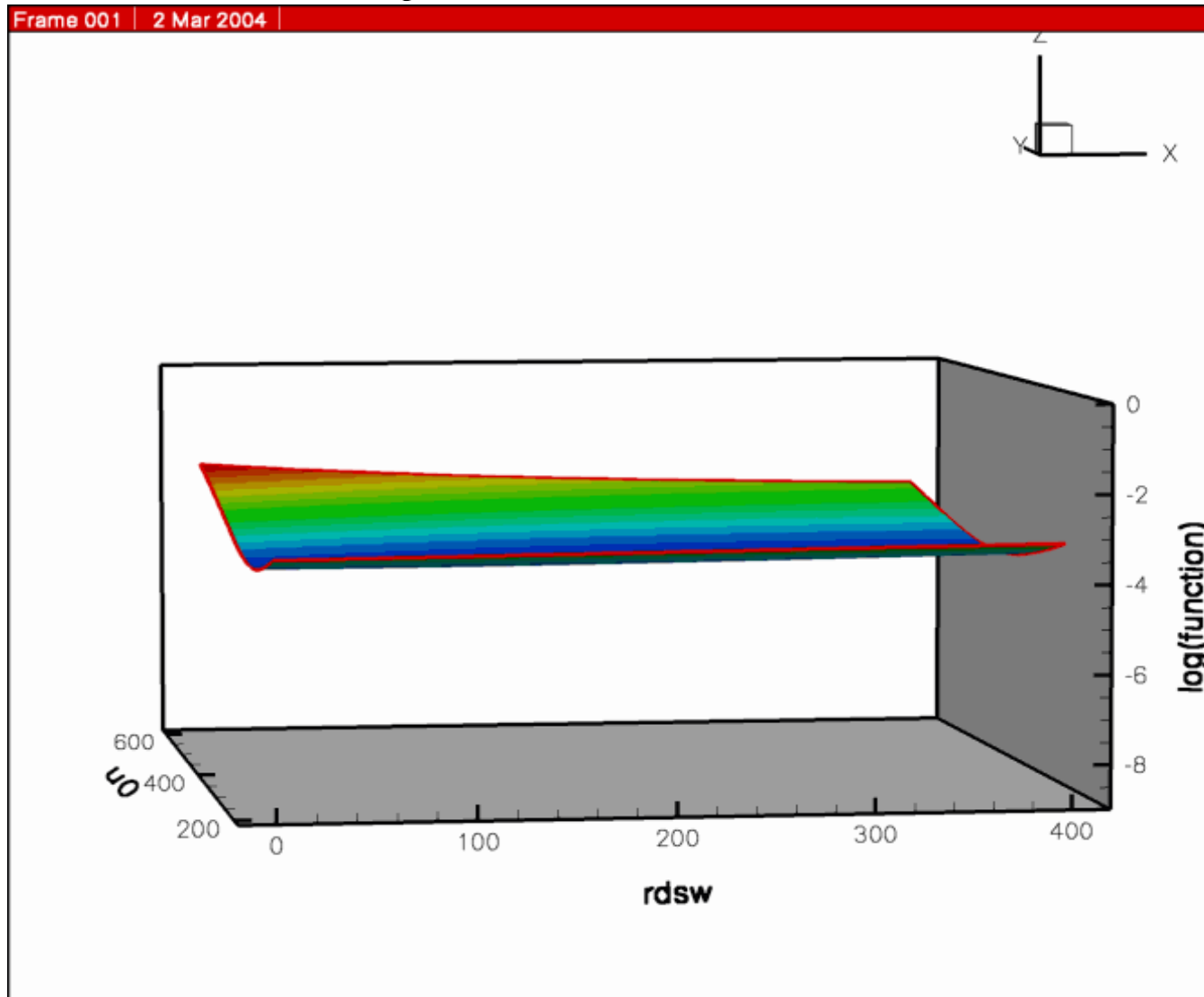
$$P_\mu > 0$$

Penalty Function

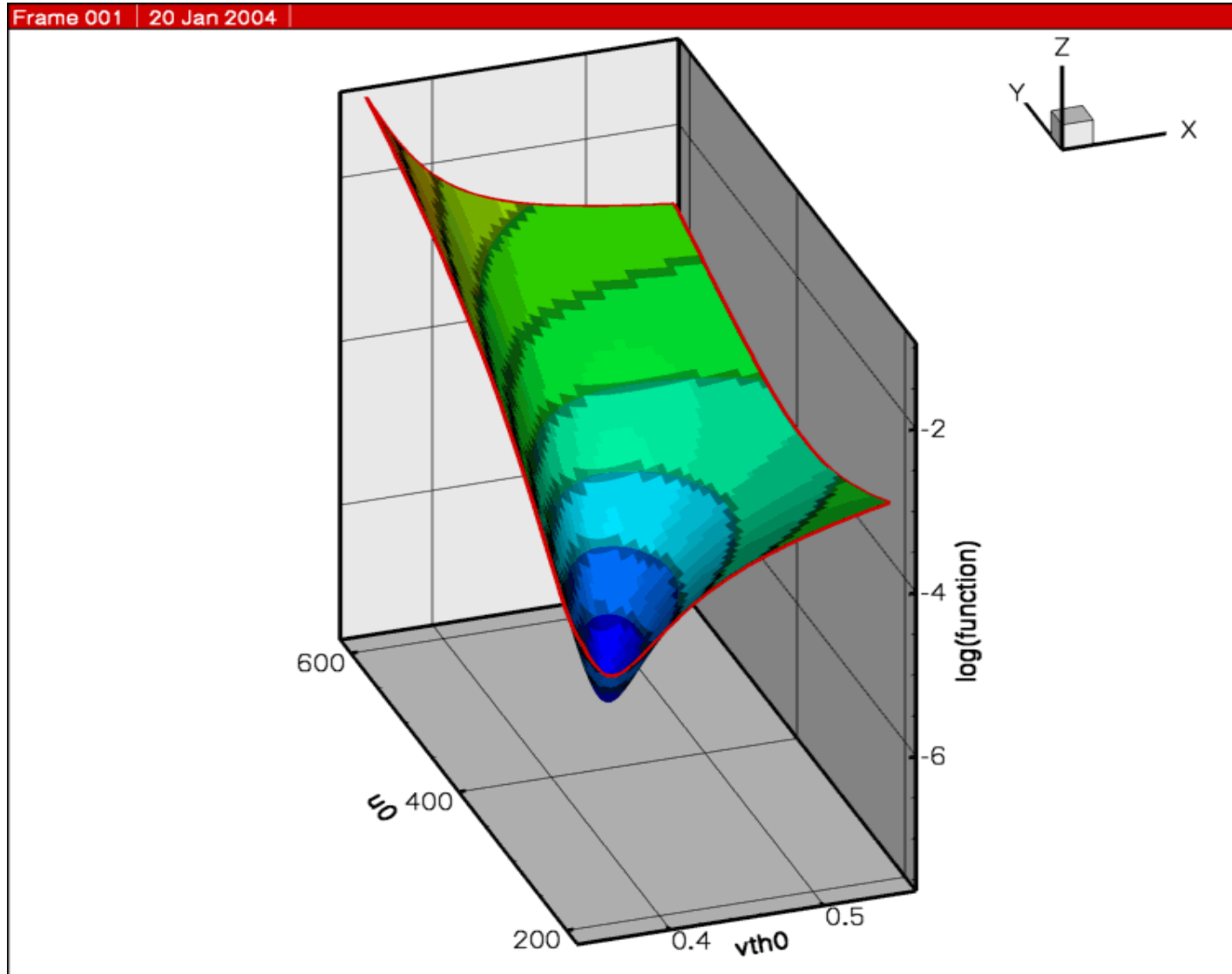
$$\psi(P_\mu) = \begin{cases} 0 & P_\mu > 0 \\ (-P_\mu)^2 & P_\mu \leq 0 \end{cases}$$



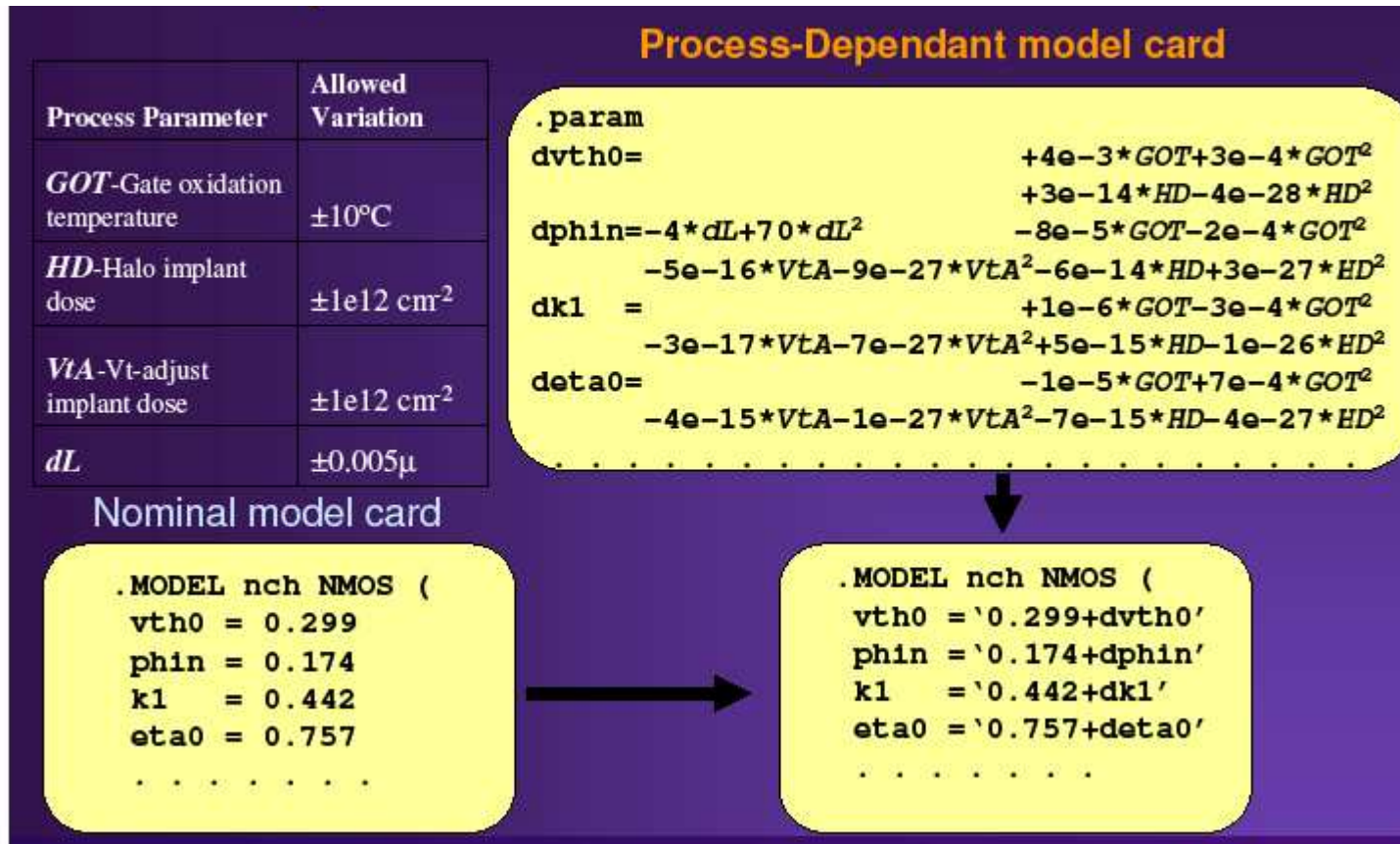
Penalty Function in Work



Penalty Function in Work



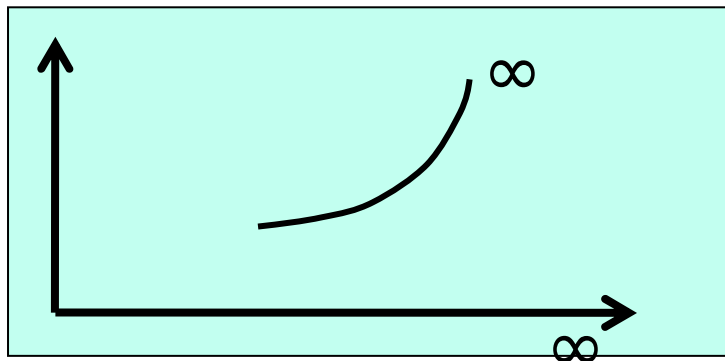
Process-aware SPICE models



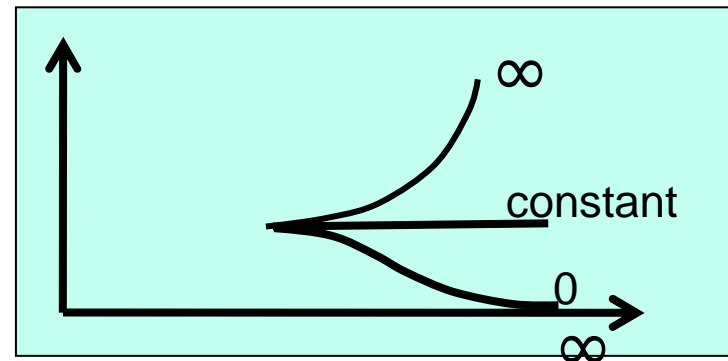
. Mahotin ..., TCAD-based Process Dependant HSPICE Model Parameter Extraction, Nanotech2006

Process-aware SPICE model Problems

- Based on TCAD simulations
- Limited mathematical possibilities
- Small process variations
- Incorrect asymptotic behavior



Quadratic function



Special mathematical functions

CMT CAD

Extract a Process Dependent SPICE Model (from Silicon)

Example

Assume this is a BSIM4 model

Drain Current

$$I_d = F(\vec{P})$$

Vector of Process Parameters = (HALO implantation dose, HALO implantation energy, Annealing temperature, Gate oxidation temperature, ...) /up to 100 parameters/

CMT CAD (continue)

- **Problem** (digital applications): Find \mathcal{P} to maximize \mathbf{I}_{on} and minimize \mathbf{I}_{off} **simultaneously**

- **Nonlinear Programming Problem:**

$$\max_{\mathcal{P}} \left(I_{on}(\mathcal{P}) - \alpha \times I_{off}(\mathcal{P}) \right)$$

- **Solution:** Optimal Values of :

CMT CAD (continue)

- **Problem** (analog applications) : Find \vec{P}
to maximize the maximum of : $Gm = \frac{\partial Id}{\partial Vg}$
- **Nonlinear Programming Problem:**
$$\max_{\vec{P}} (Gm_{\max}(\vec{P}))$$
- **Solution:** Optimal values of \vec{P} to maximize the maximum of Gm

Mathematical abstractions to model process variations

Model Parameters

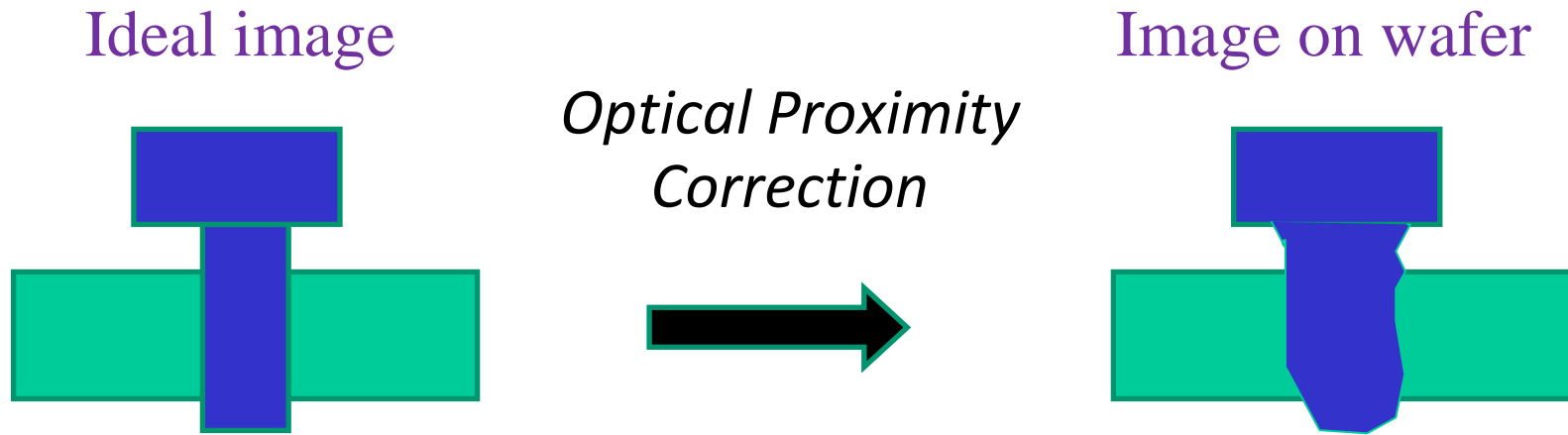
$$1: M_i = M_{i0} + \sum_j \sum_n a_{ijn} \tilde{P}_j^n$$

$$2: \overset{\mu}{M} = \overset{\mu}{M}_0 + f(\overset{\mu}{P})$$

$$3: \overset{\mu}{M} = \overset{\mu}{M}_0 + f(\bullet)$$

Process
Variations

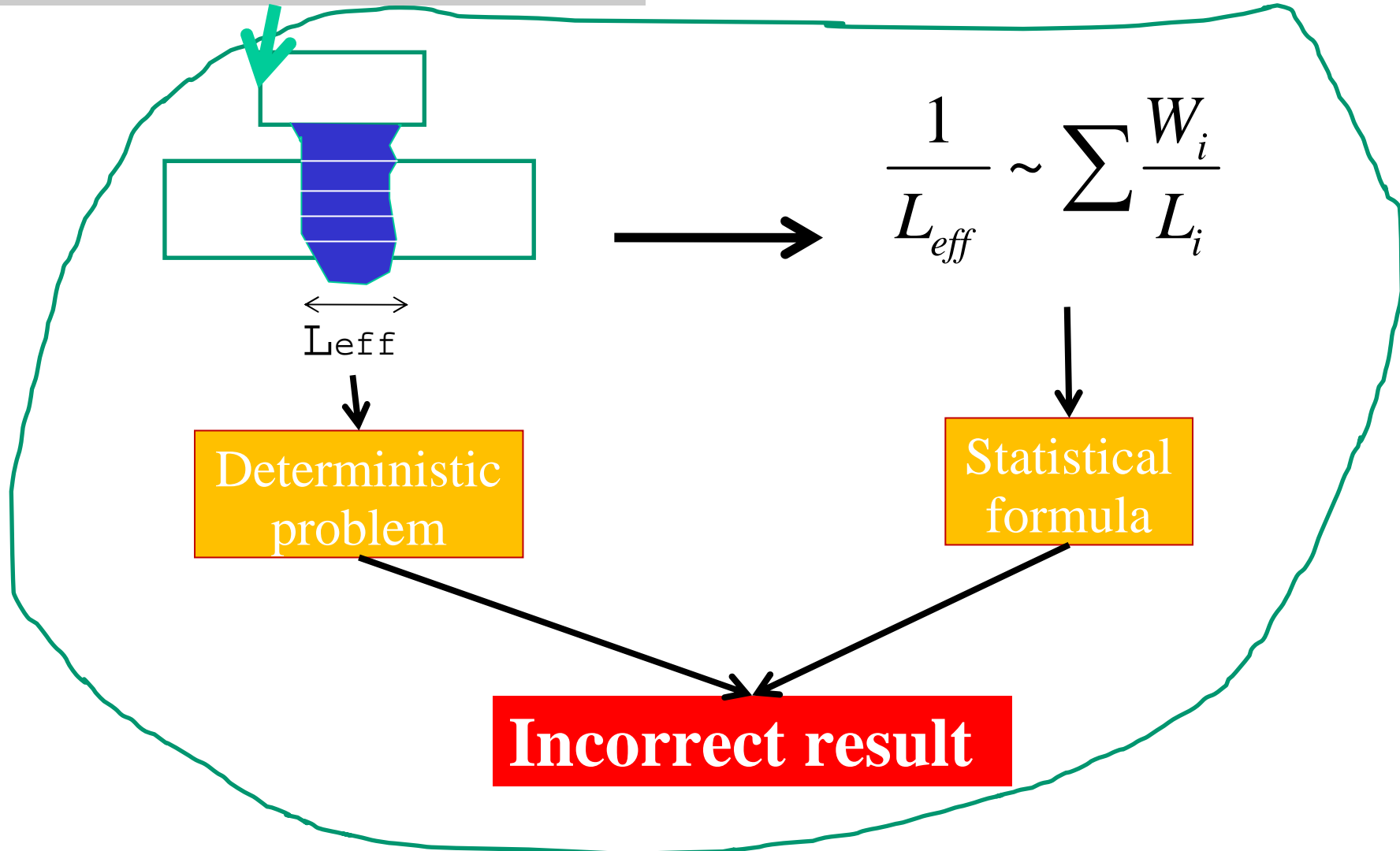
Gate shape variations



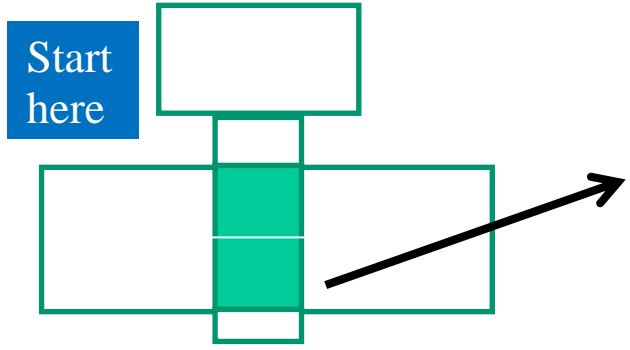
1. How to model ?
2. Is the problem solved?
3. No

Is the problem solved?

EDA companies commonly used approach



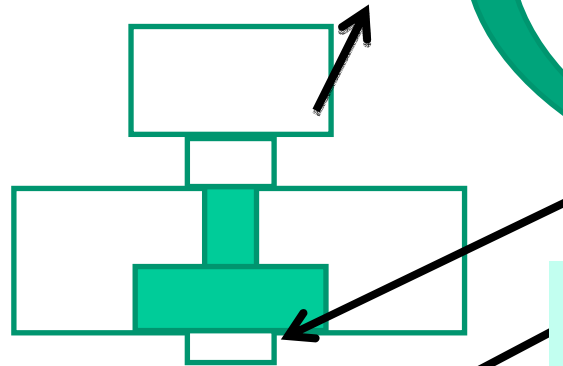
The statement that the problem has been solved is a myth (*thought experiment*)



$$\begin{aligned} \frac{1}{L} &= 0.5 * \left(\frac{1}{L} + \frac{1}{L} \right) = 0.5 * \left(\frac{1}{L} + \frac{2}{2 * L} \right) = 0.5 * \left(\frac{1}{L} + \frac{1+1}{2 * L} \right) = \\ &= 0.5 * \left(\frac{1}{L} + \frac{1}{2 * L} + \frac{1}{2 * L} \right) = 0.5 * \left(\frac{2+1}{2 * L} + \frac{1}{2 * L} \right) = \\ &= 0.5 * \left(\frac{1}{\frac{2}{3} * L} + \frac{1}{2 * L} \right) \end{aligned}$$

Id = Id ?

Incorrect



A thought experiment is a proposal for an experiment that would test or *illuminate* a hypothesis or theory.
From Wikipedia, the free encyclopedia

One of the reasons of incorrectness

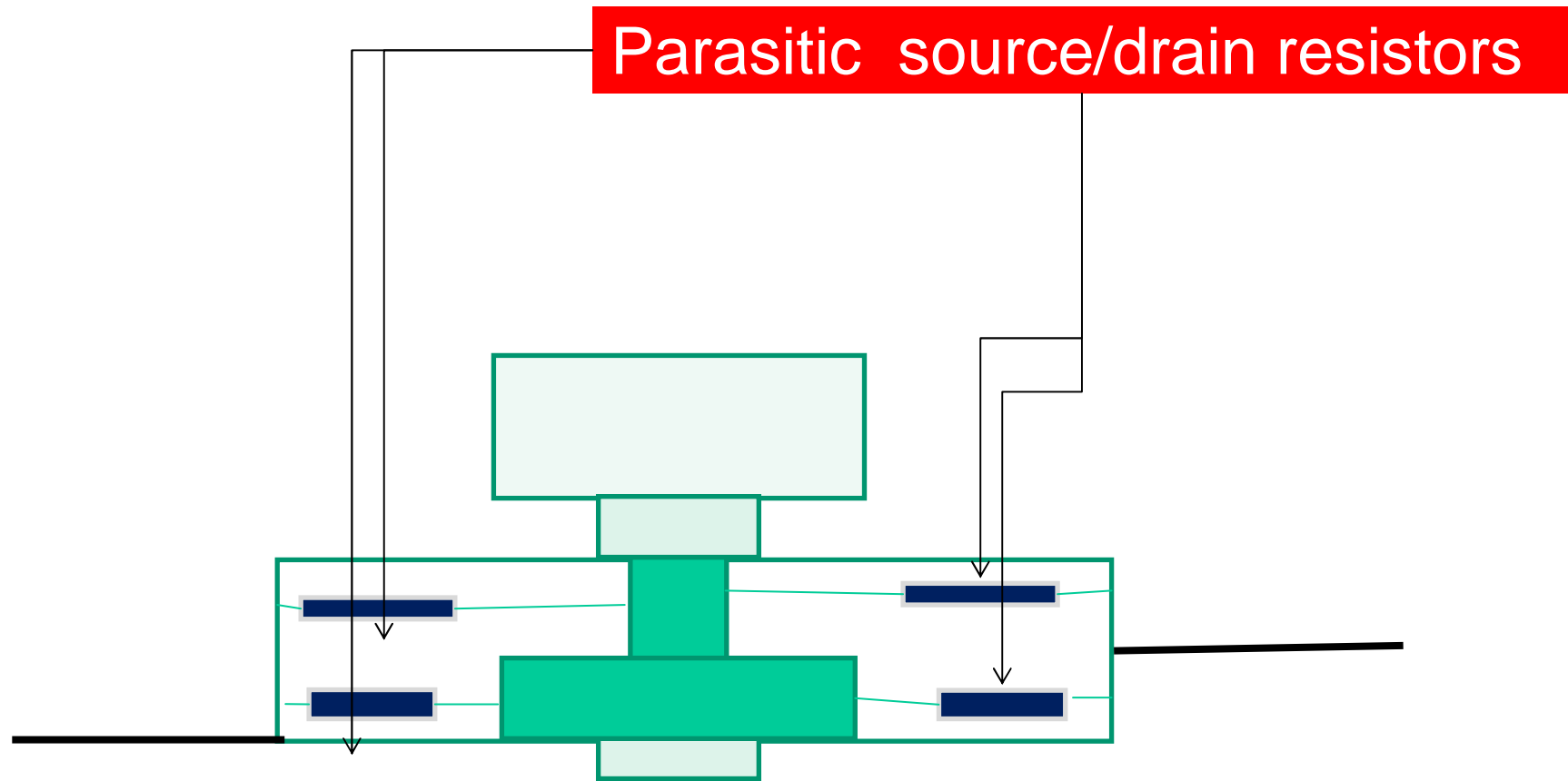


Image Variation



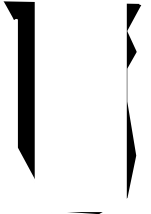
Model Parameters

$$\mathbf{M}^{\mu} = \mathbf{M}_0^{\mu} + f(\bullet)$$

$$\mathbf{M}^{\mu} = \mathbf{M}_0^{\mu} \downarrow + f\left(\begin{array}{c} \text{Image Variation} \end{array}\right)$$

Function of Image Variations

Modeling of Gate Shape Variations

1.  $= f(x, y) = \begin{cases} 1 & \text{black} \\ 0 & \text{white} \end{cases}$

2. Geometrical Moments–

$$m_{ij} = \iint x^i y^j f(x, y) dx dy \quad i, j : 0 \rightarrow \infty$$

3. $f(x, y) \Leftrightarrow m_{ij} \quad i, j : 0 \rightarrow \infty$

Result:

$$\overset{p}{M} = \overset{p}{M}_0 + \sum_{ij} a_{ij} m_{ij}$$

Development of Technologies less sensitive to OPC variations

Process Parameters

Gate Shape

- Assumption: $I_d = F(\mathcal{P}, \mathcal{I})$ is available
- Problem definition:

Assume this is a BSIM4 model

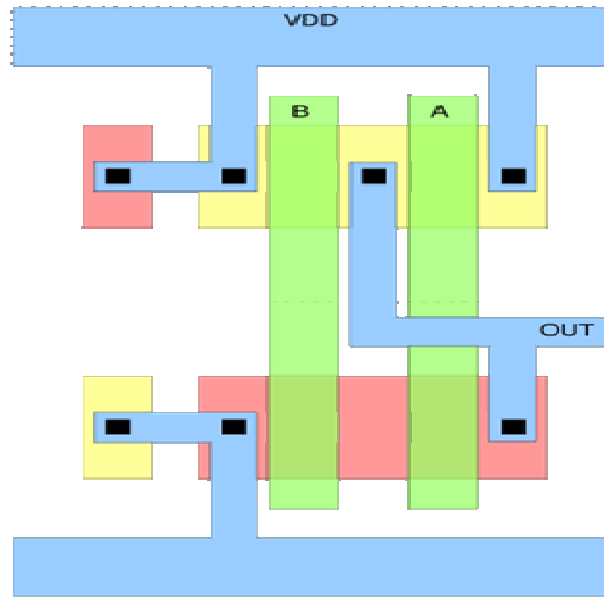
$$\min_{\mathcal{P}} \sum_i \left(I_{d_{\text{target}}} - F(\mathcal{P}, \mathcal{I}_i) \right)^2$$

The sum over different gate shapes

- **Result:** Optimal Process Parameters \mathcal{P}_{of}
Technology less sensitive to Gate Shape Variations

Layout Variations

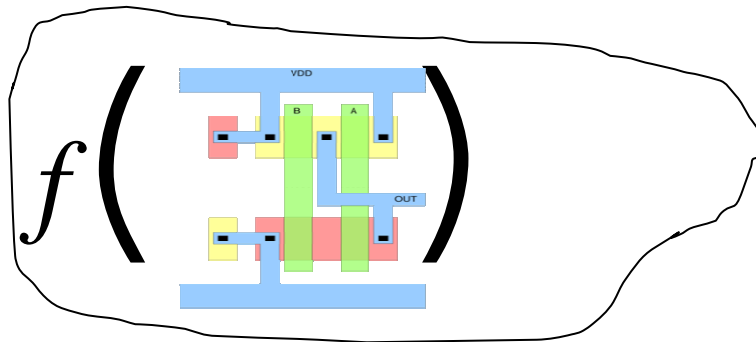
Example: CMOS NAND



From Wikipedia, the free encyclopedia

Layout-dependent SPICE model

$$\overset{p}{M} = \overset{p}{M}_0 +$$



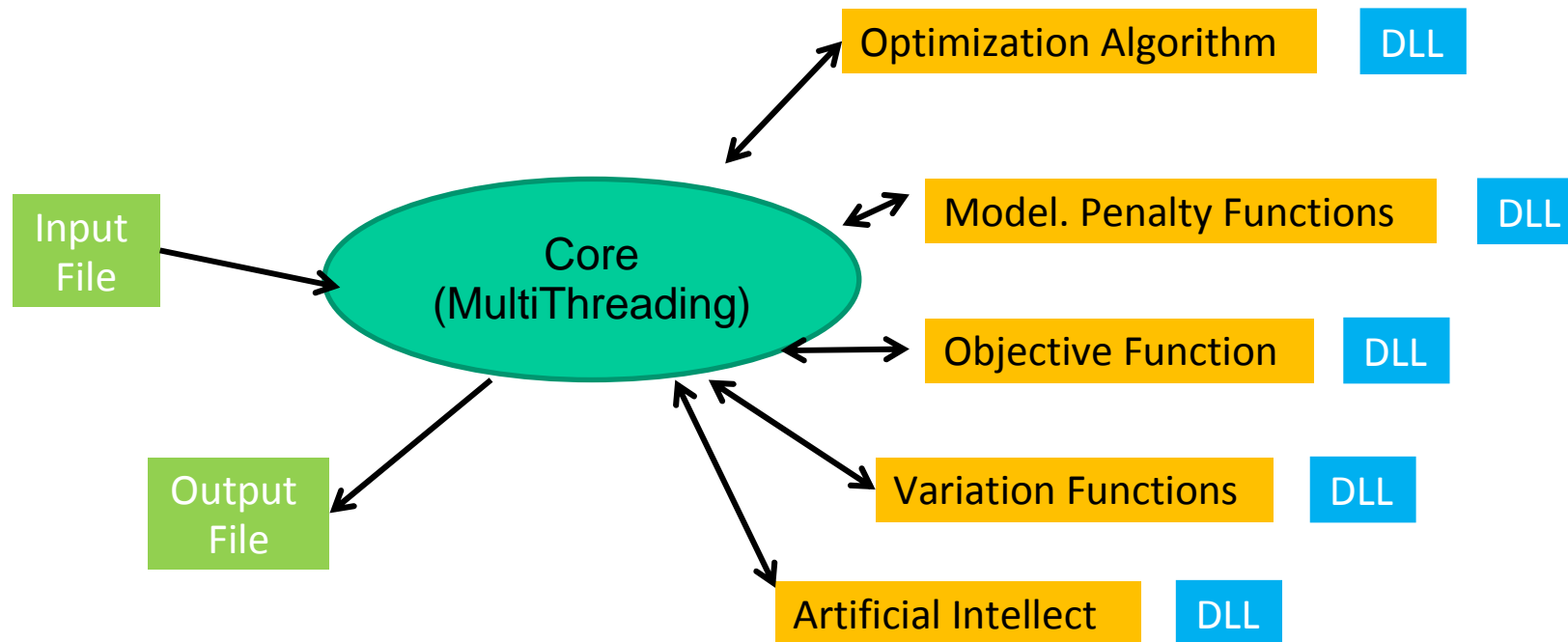
Function
of layout

Model Parameters

$$\overset{p}{M} = \overset{p}{M}_0 + \sum_{ij} a_{ij} m_{ij} + \sum_{ij} b_{ij} m_{ij}^2$$

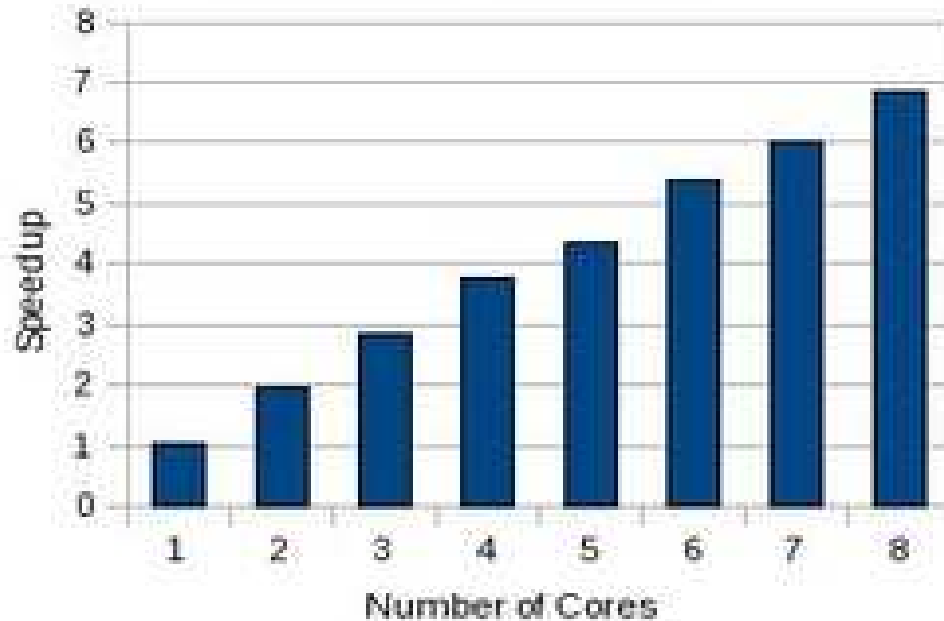
Realization

- Modern C/C++ programming techniques



Multi-threaded scalability

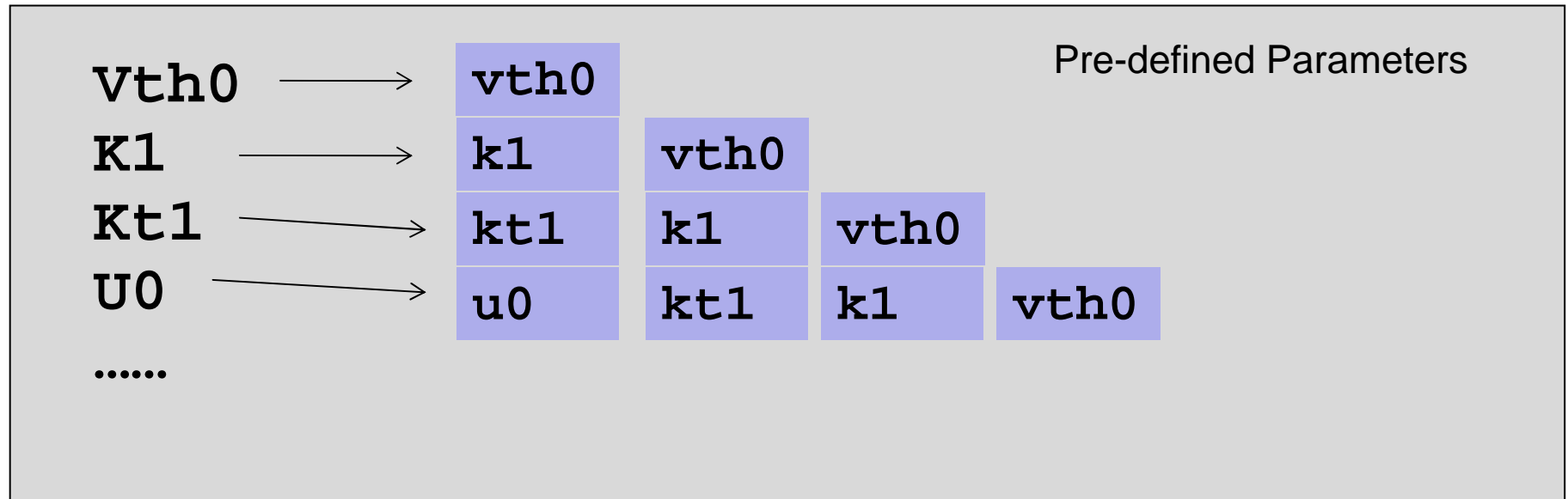
Speedup as a function of number of Cores



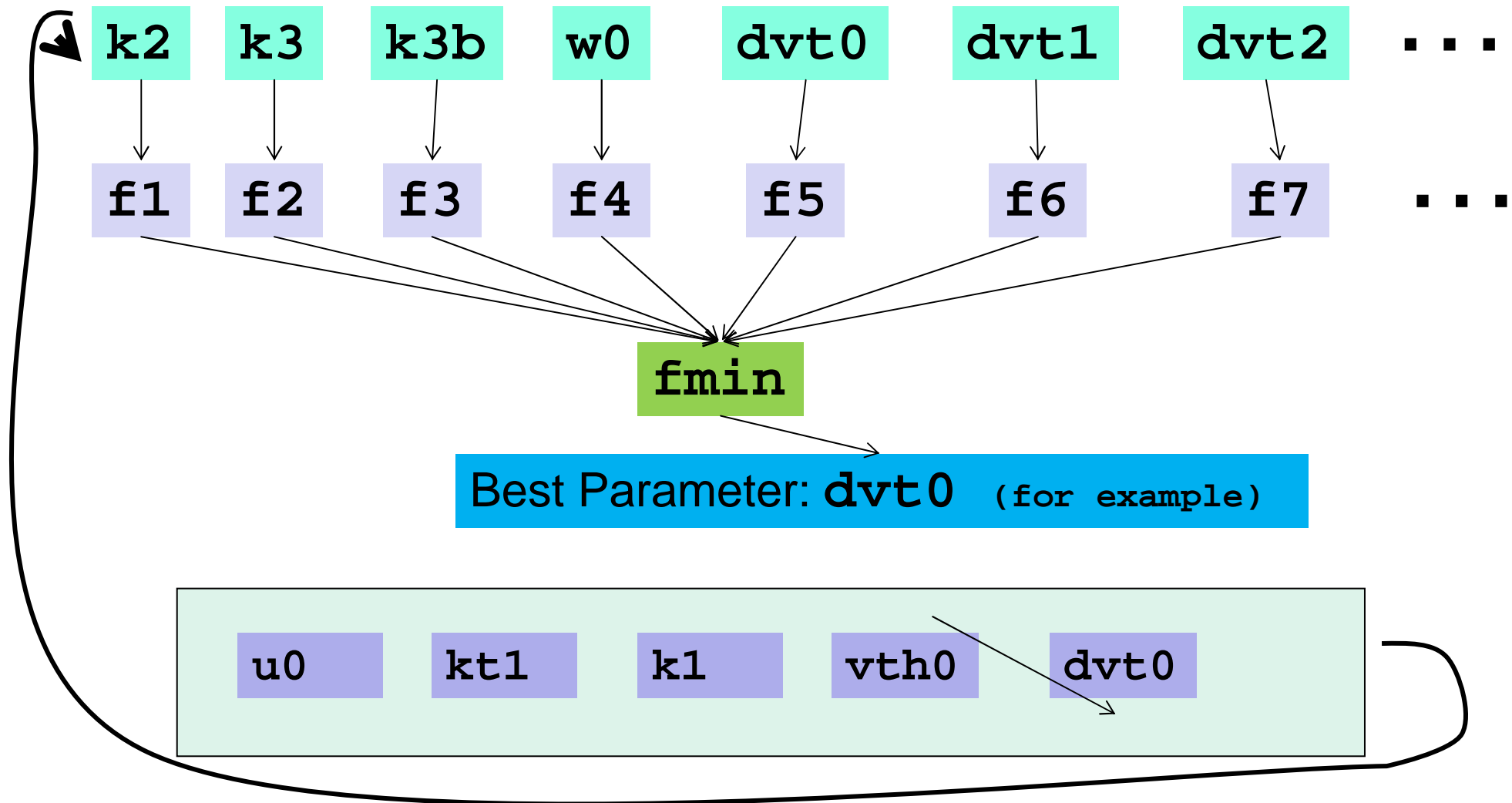
- AMD single chip, 8 Cores (Opteron 6128)
- 50 BSIM3 model parameters
- 22 devices
- 30,000 measured points

Automatic Parameter Extraction

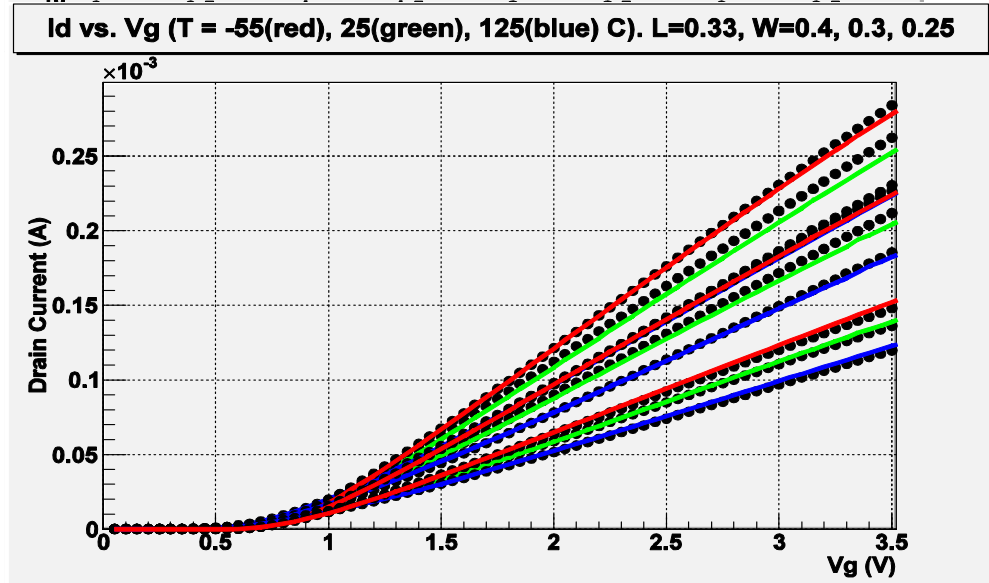
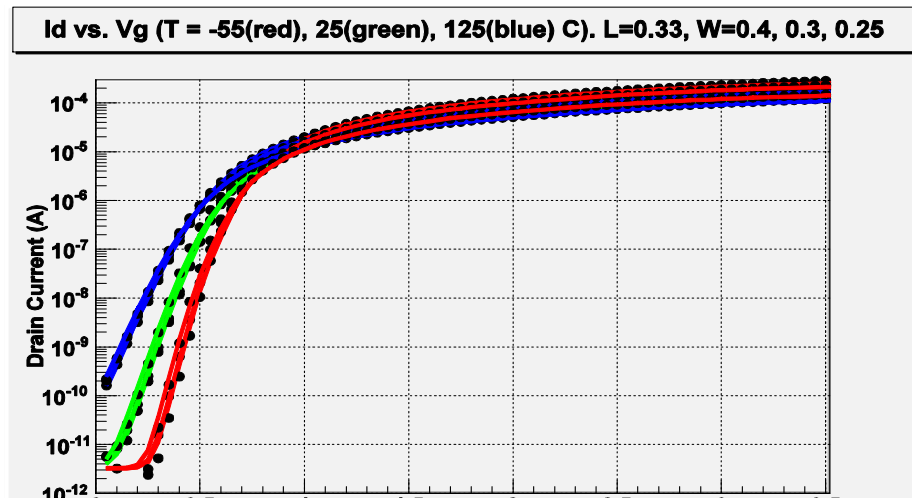
1. Pre-defined Model Parameters
2. Non-binning Parameters
3. Binning Parameters



Automatic Parameter Extraction



Automatic Parameter Extraction



- 115 Model Parameters
- 25 devices
- -55, 25, 125 °C
- 100,000 points
- 8 Cores, 40 hours
- 5% accuracy