A brief introduction to Compact Model Technology Computer Aided Design

(CMT CAD)

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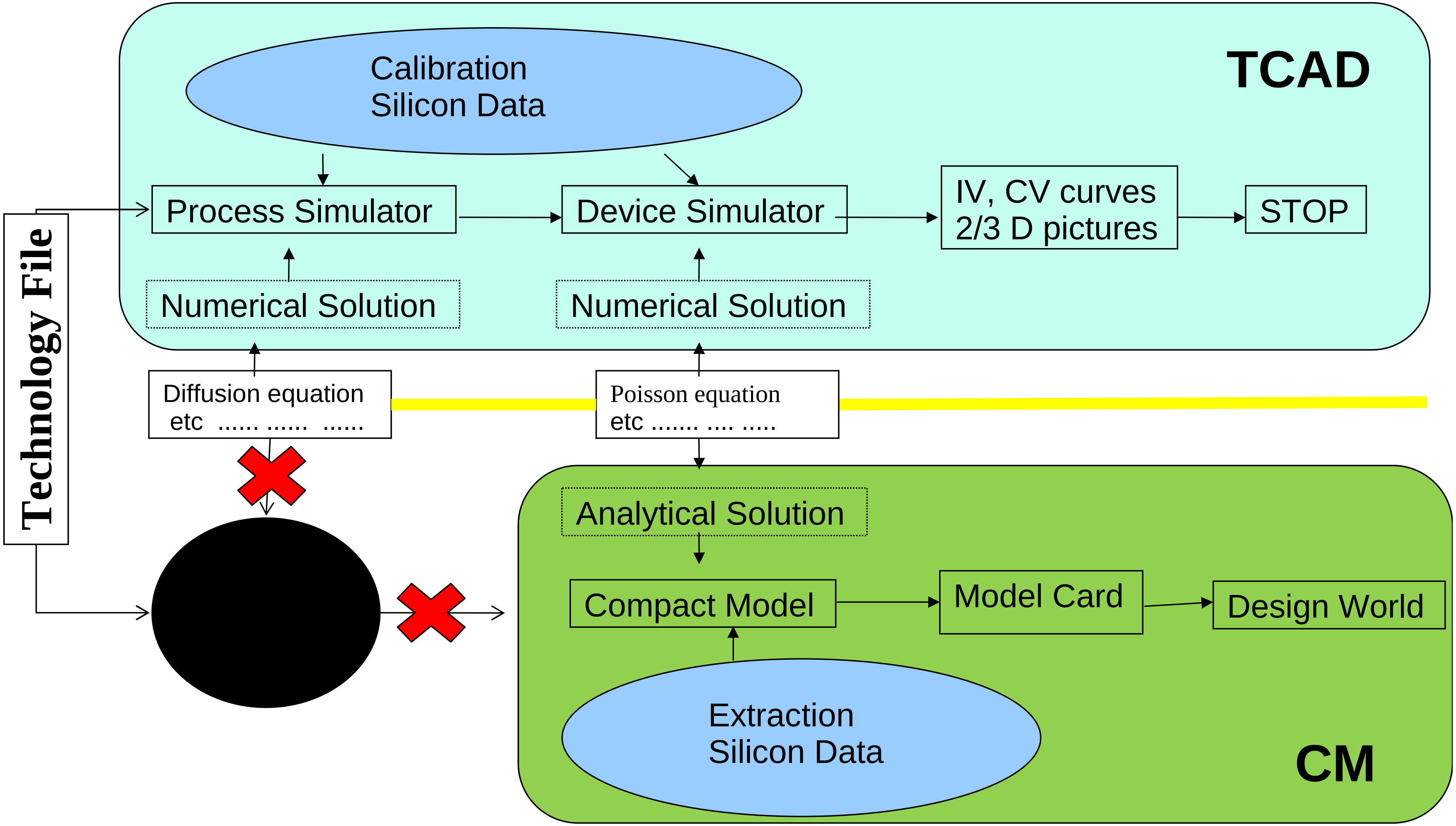
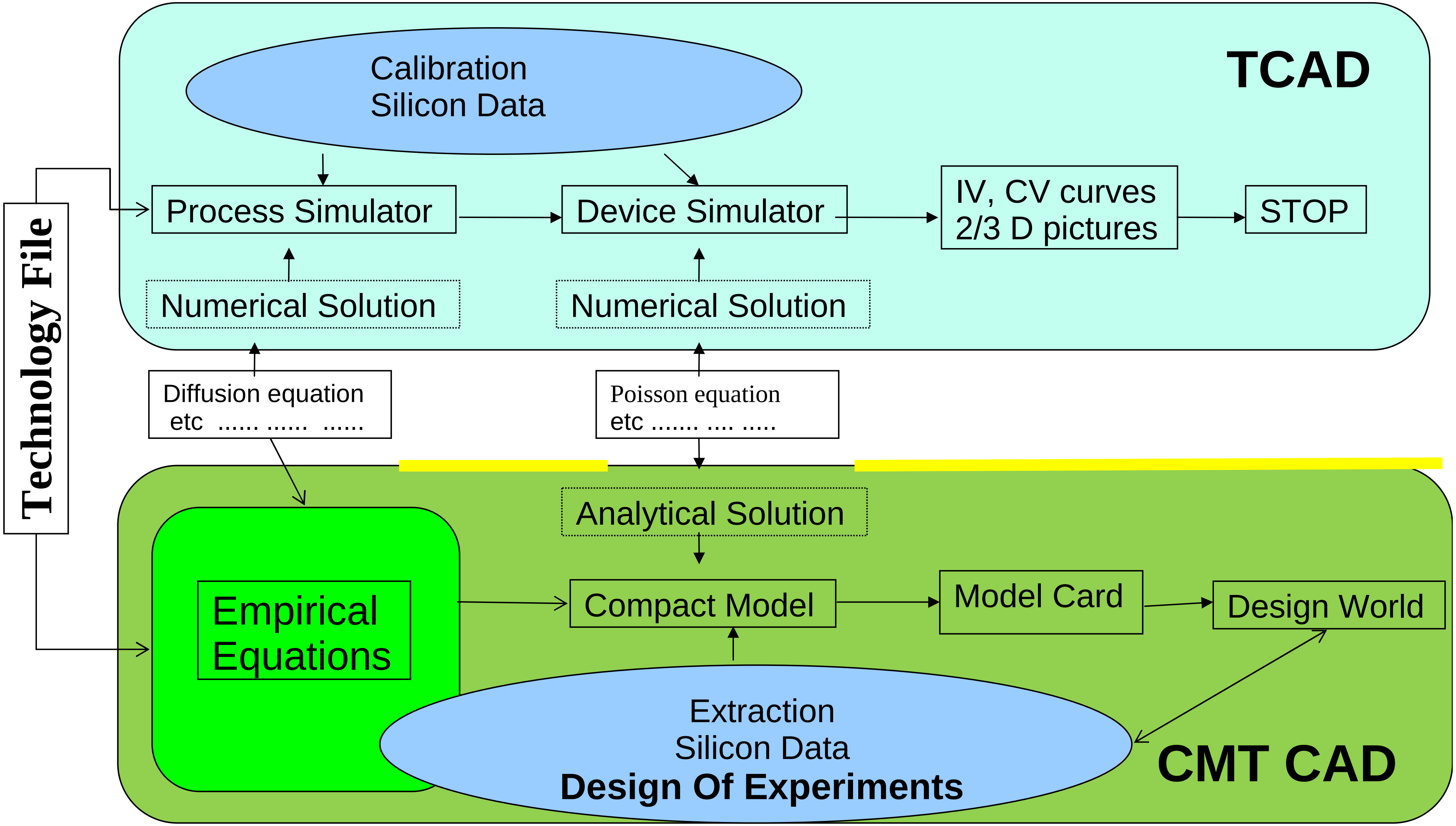
Agenda

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

TCAD vs. Compact Models



TCAD vs. CMT CAD



TCAD

Calibration
Silicon Data

Process Simulator

Device Simulator

IV, CV curves
2/3 D pictures

STOP

Numerical Solution

Numerical Solution

Diffusion equation
etc ....

Poisson equation
etc ....

Technology File

Analytical Solution

Empirical
Equations

Compact Model

Model Card

Design World

Extraction
Silicon Data
Design Of Experiments

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 < vth0 < 1
- $$0 < vth = vth0 + \frac{lvth0}{L_{eff}} + \frac{wvth0}{W_{eff}} + \frac{pvth0}{L_{eff} \times W_{eff}} < 1$$
- where: $$L_{eff} = L_{drawn} + XL - 2\left(LINT + \frac{LL}{L^{LLN}} + \frac{LW}{W^{LWN}} + \frac{LWL}{L^{LLN}W^{LWN}} \right)$$
- $$Penalty(vth) = \begin{cases} 0 & vth < 1 \\ \infty \times (vth - 1)^2 & vth > 1 \end{cases}$$

Automatic BSIM3/4 Model Parameter Extraction with Penalty Function

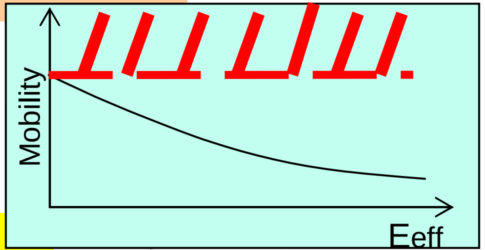
Example of Penalty Function

Mobility model for mobMod=2 (BSIM3)

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

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

P_μ - Function of more than 100 model parameters

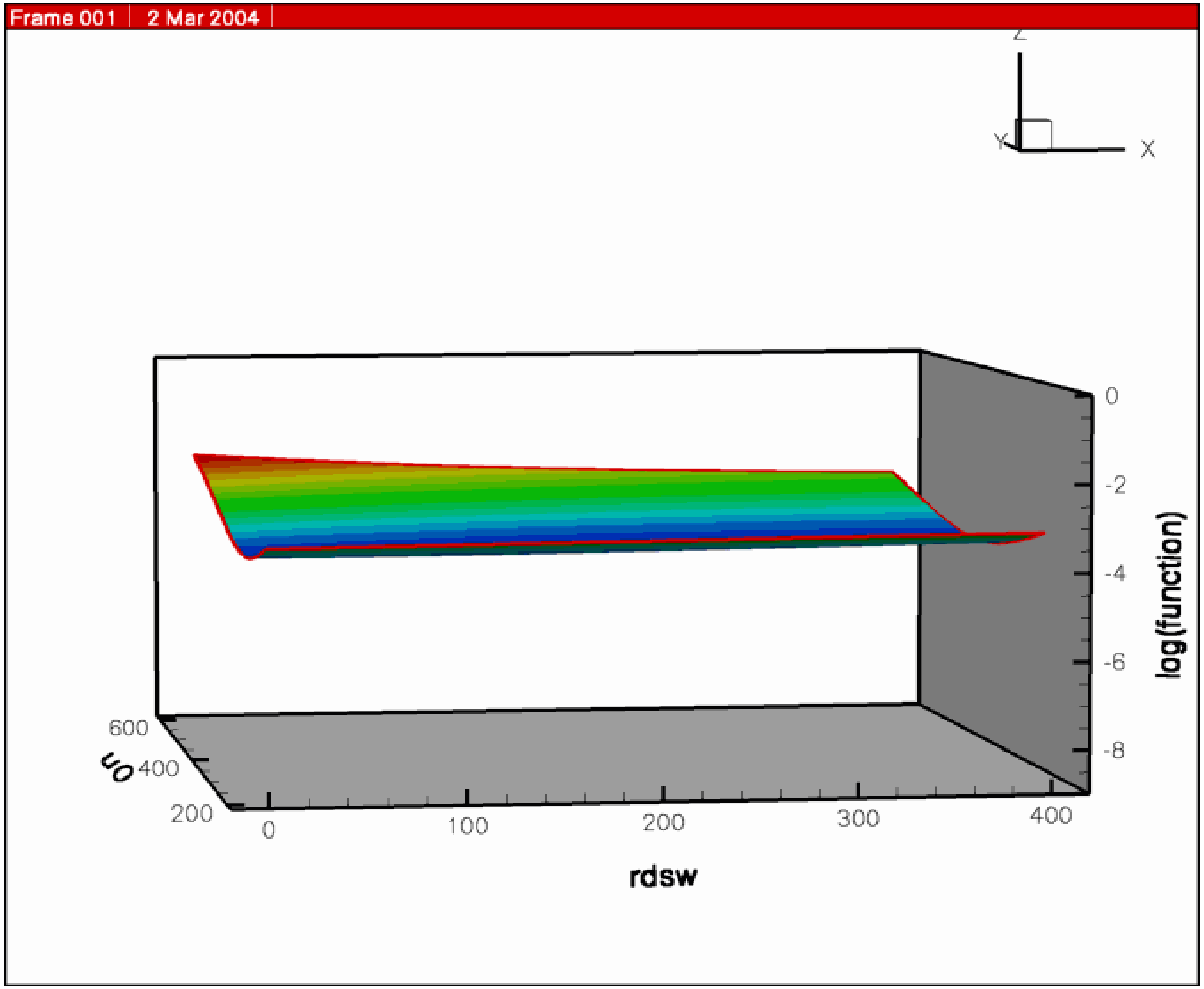


BSIM3 Constraint $P_\mu > 0$

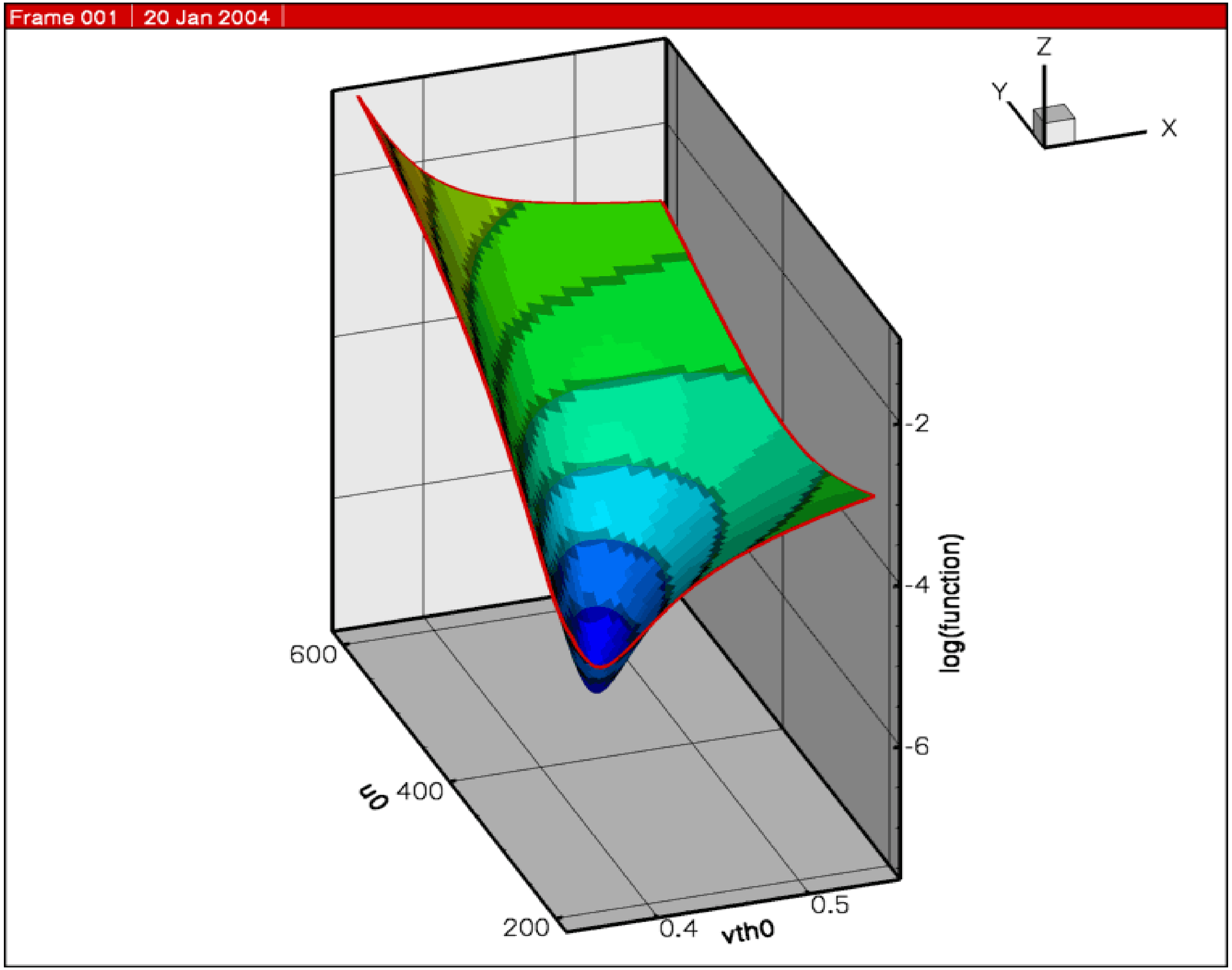
Penalty Function $$\psi(P_\mu) = \begin{cases} 0 & P_\mu > 0 \\ (-P_\mu)^2 & P_\mu \le 0 \end{cases}$$

Y.Mahotin … Automatic BSIM3/4 Model Parameter Extraction with Penalty Function, Nanotech 2004

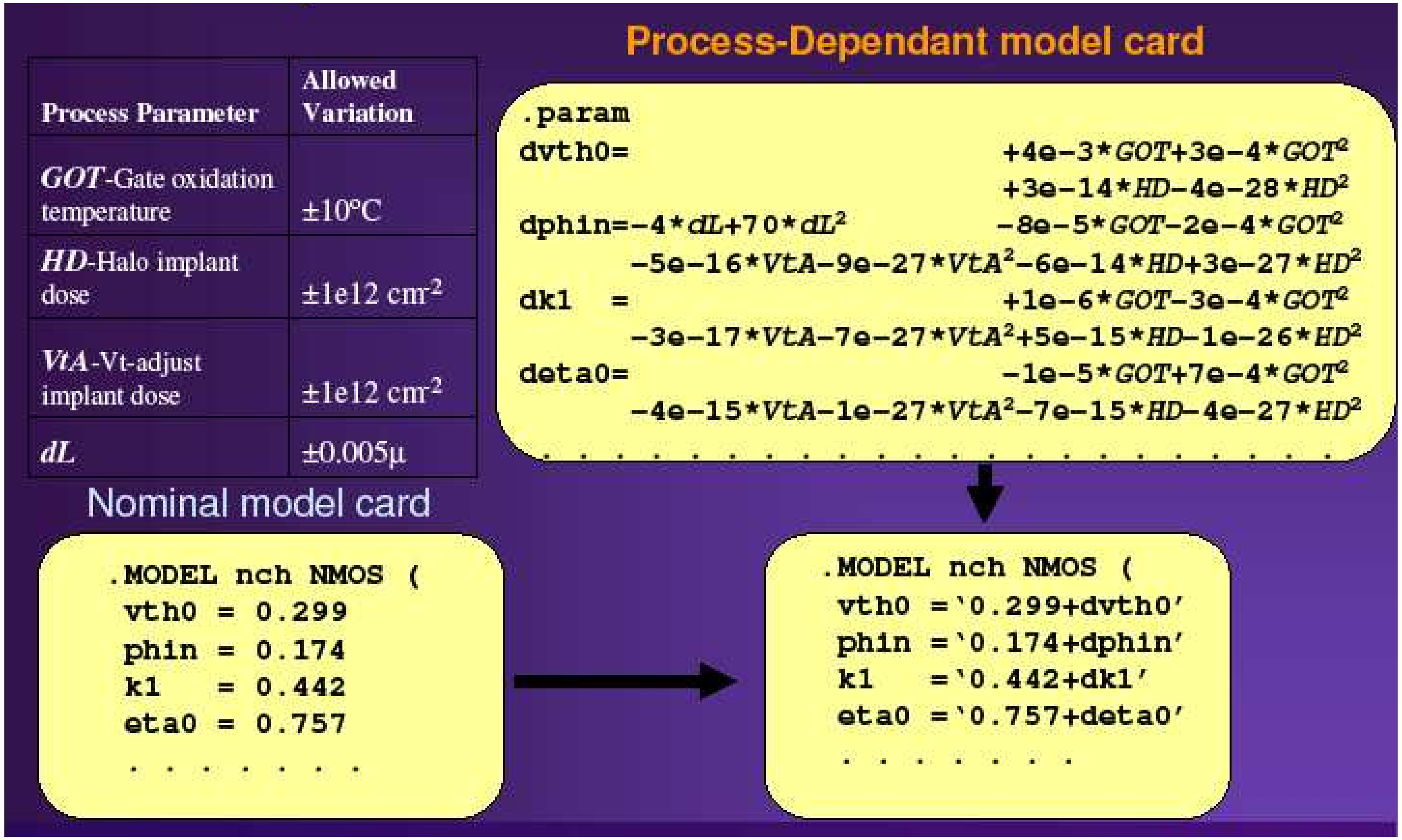
Penalty Function in Work



Penalty Function in Work



Process-aware SPICE models



Process Parameter	Allowed Variation
GOT-Gate oxidation temperature	±10°C
HD-Halo implant dose	±1e12 cm^{-2}
VtA-Vt-adjust implant dose	±1e12 cm^{-2}
dL	±0.005μ

Nominal model card

```
.MODEL nch NMOS (
 vth0 = 0.299
 phin = 0.174
 k1   = 0.442
 eta0 = 0.757
 . . . . . . .
```

Process-Dependant model card

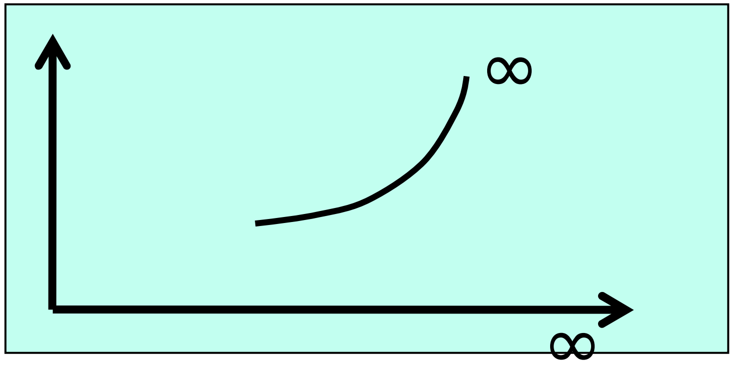
```
.param
dvth0=                         +4e-3*GOT+3e-4*GOT^2
                               +3e-14*HD-4e-28*HD^2
dphin=-4*dL+70*dL^2           -8e-5*GOT-2e-4*GOT^2
      -5e-16*VtA-9e-27*VtA^2-6e-14*HD+3e-27*HD^2
dk1  =                         +1e-6*GOT-3e-4*GOT^2
      -3e-17*VtA-7e-27*VtA^2+5e-15*HD-1e-26*HD^2
deta0=                         -1e-5*GOT+7e-4*GOT^2
      -4e-15*VtA-1e-27*VtA^2-7e-15*HD-4e-27*HD^2
 . . . . . . . . . . . . . . . . . . . . . .
```

```
.MODEL nch NMOS (
 vth0 ='0.299+dvth0'
 phin ='0.174+dphin'
 k1   ='0.442+dk1'
 eta0 ='0.757+deta0'
 . . . . . . .
```

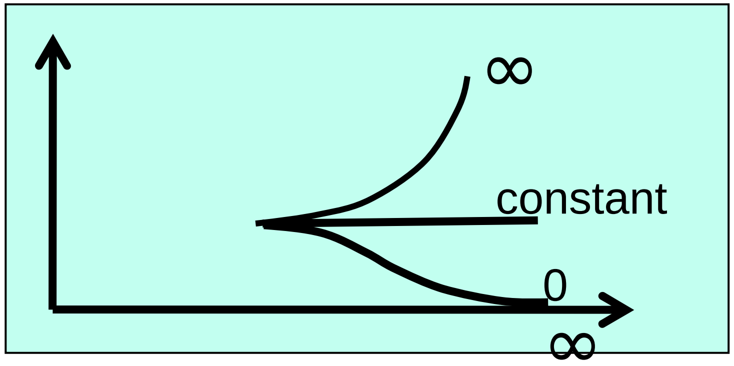
. Mahotin …, TCAD-based Process Dependant HSPICE Model Parameter Extraction, Nanotech2006

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)

Assume this is a BSIM4 model

Example

Drain Current

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

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 $\vec{P}$ to maximize $\mathbf{I_{on}}$ and minimize $\mathbf{I_{off}}$

  simultaneously

- Nonlinear Programming Problem:

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

- Solution: Optimal Values of : $\vec{P}$

CMT CAD (continue)

- Problem (analog applications) : Find $\vec{P}$

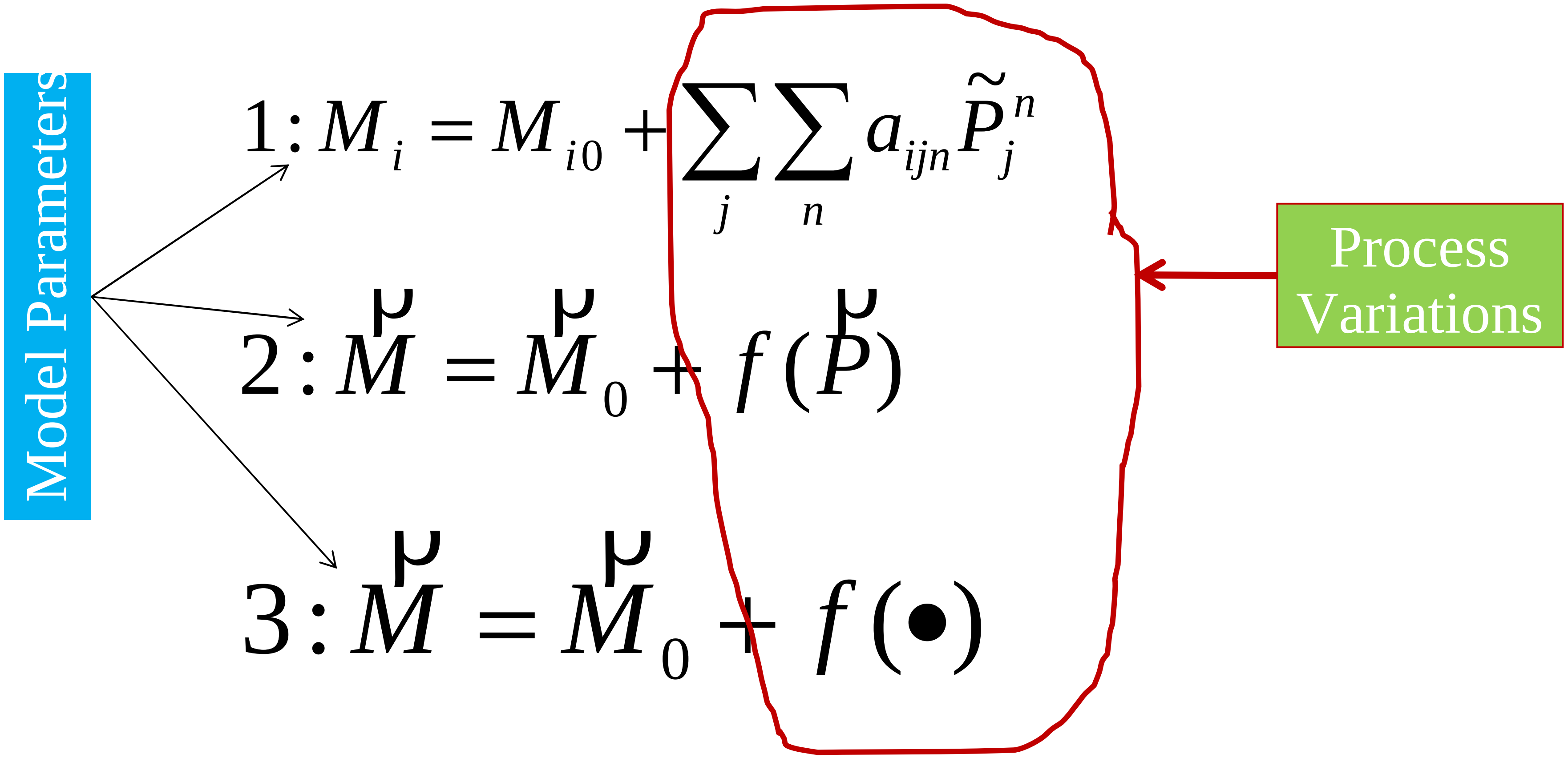
  to maximize the maximum of : $Gm = \frac{\partial Id}{\partial Vg}$

- Nonlinear Programming Problem:

$$\max_{\vec{P}}\left(Gm_{\max}\left(\vec{P}\right)\right)$$

- Solution: Optimal values of $\vec{P}$ to maximize the maximum of Gm

Mathematical abstractions to model process variations



Model Parameters

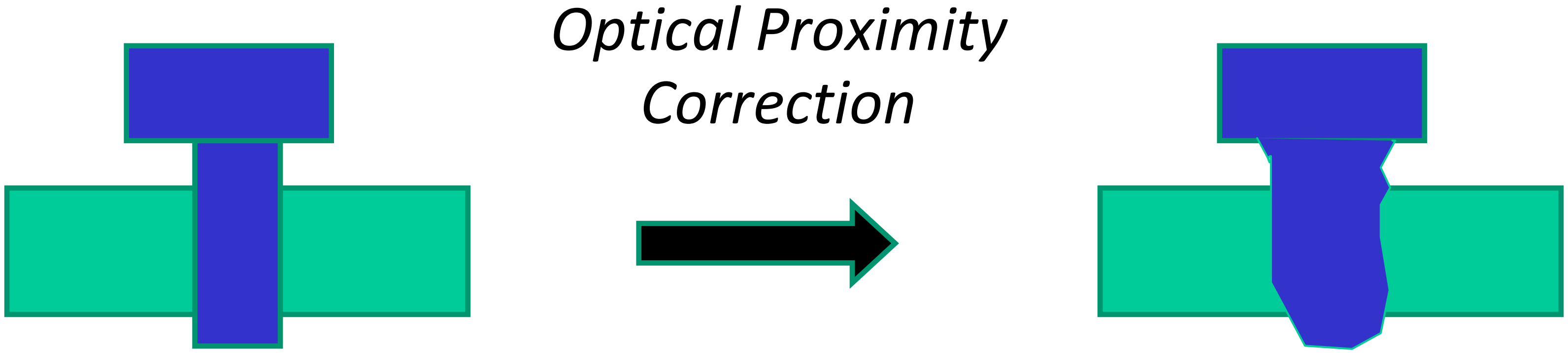
$$1: M_i = M_{i0} + \sum_j \sum_n a_{ijn} \tilde{P}_j^n$$

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

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

Process Variations

Gate shape variations



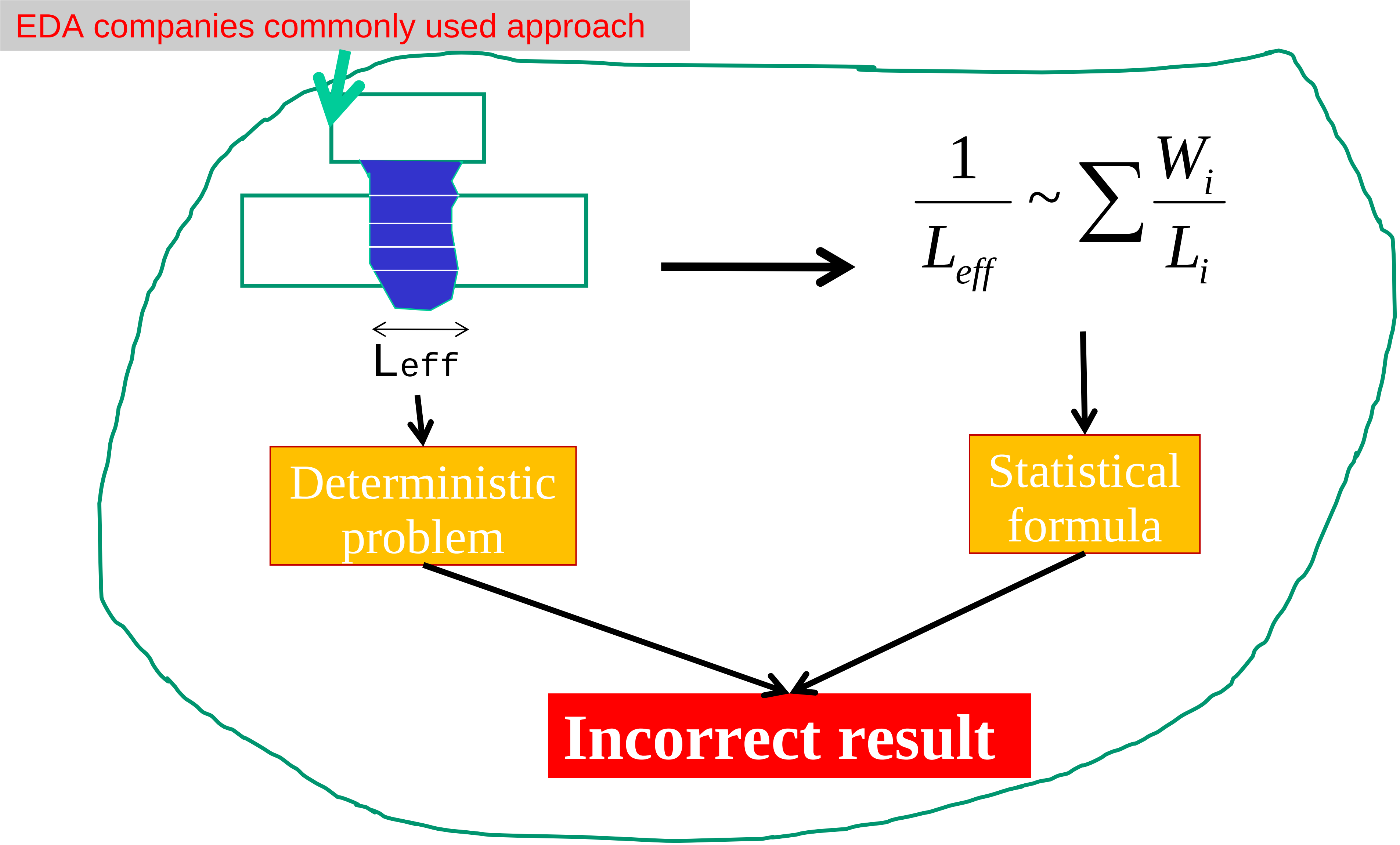
Ideal image

Optical Proximity Correction

Image on wafer

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

Is the problem solved?



EDA companies commonly used approach

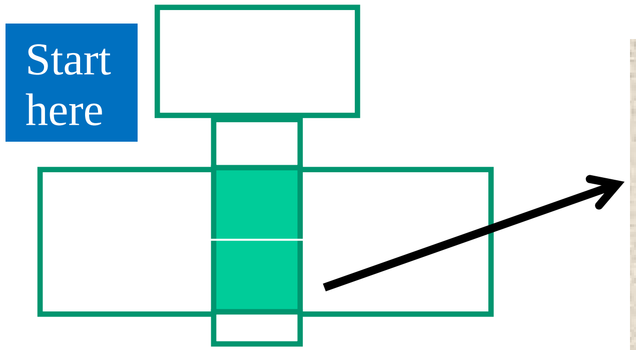
$$\frac{1}{L_{eff}} \sim \sum \frac{W_i}{L_i}$$

Deterministic problem

Statistical formula

Incorrect result

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



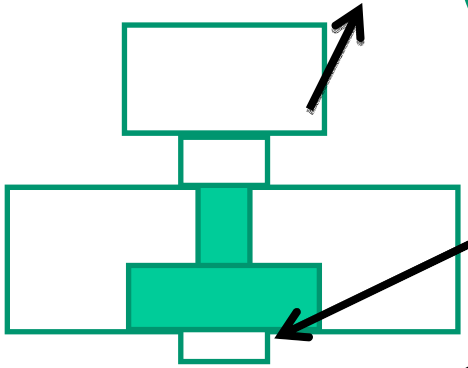
Id = Id ?

$$\frac{1}{L}=0.5*\left(\frac{1}{L}+\frac{1}{L}\right)=0.5*\left(\frac{1}{L}+\frac{2}{2*L}\right)=0.5*\left(\frac{1}{L}+\frac{1+1}{2*L}\right)=$$

$$=0.5*\left(\frac{1}{L}+\frac{1}{2*L}+\frac{1}{2*L}\right)=0.5*\left(\frac{2+1}{2*L}+\frac{1}{2*L}\right)=$$

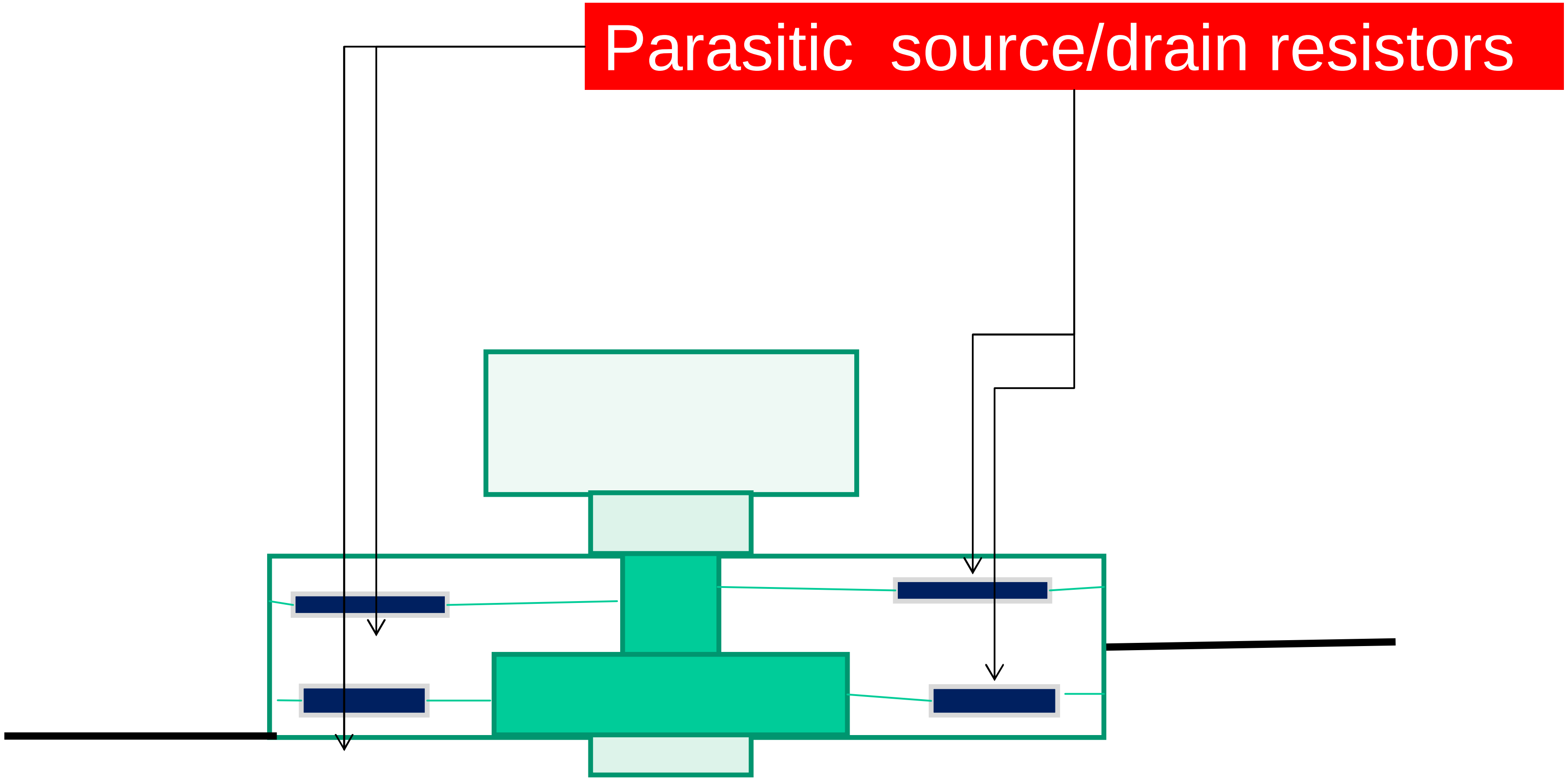
$$=0.5*\left(\frac{1}{\frac{2}{3}*L}+\frac{1}{2*L}\right)$$

Incorrect



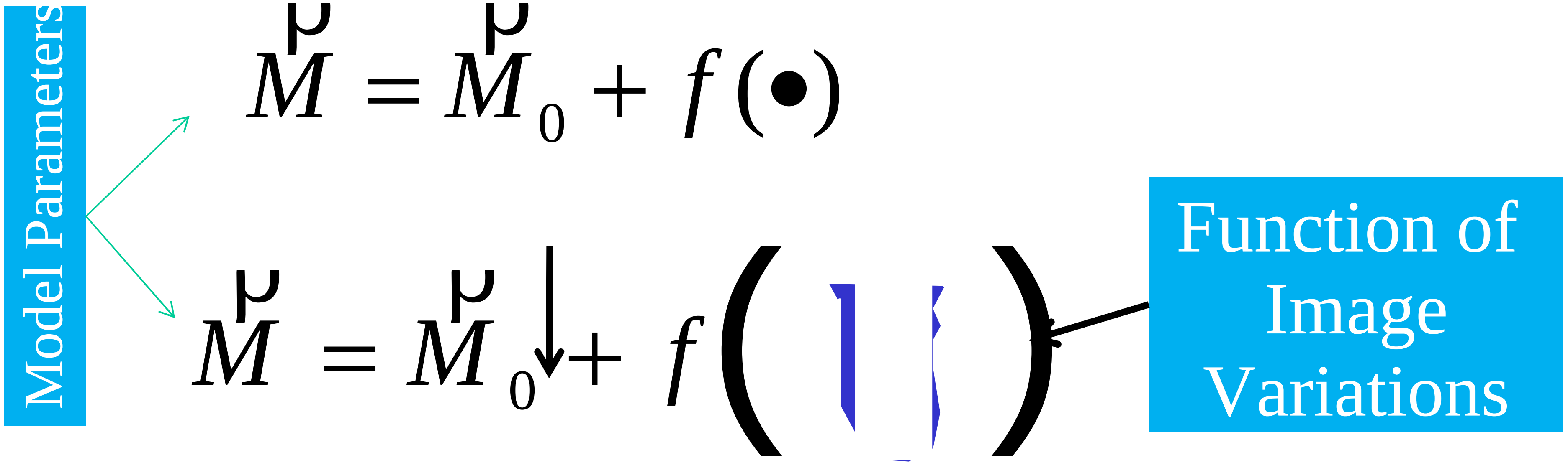
A thought experiment is a proposal for an experiment that would test or ***illuminate* a hypothesis or theory**.
From Wikipedia, the free encyclopedia

One of the reasons of incorrectness



Parasitic source/drain resistors

Image Variation



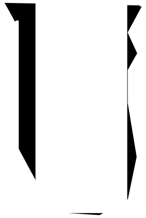
Model Parameters

$$\vec{M} = \vec{M}_0 + f(\bullet)$$

$$\vec{M} = \vec{M}_0 \downarrow + f\left(\quad\right)$$

Function of Image Variations

Modeling of Gate Shape Variations

1. 

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

2. Geometrical Moments -

$$m_{ij} = \iint x^i y^j f\left(x,y\right) dxdy \qquad i,j:0 \rightarrow \infty$$

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

Result:

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

Development of Technologies
less sensitive to OPC variations

Process Parameters

Gate Shape

- Assumption: $Id = F(\vec{P}, \text{[illegible]})$ is available
- Problem definition:

Assume this is a BSIM4 model

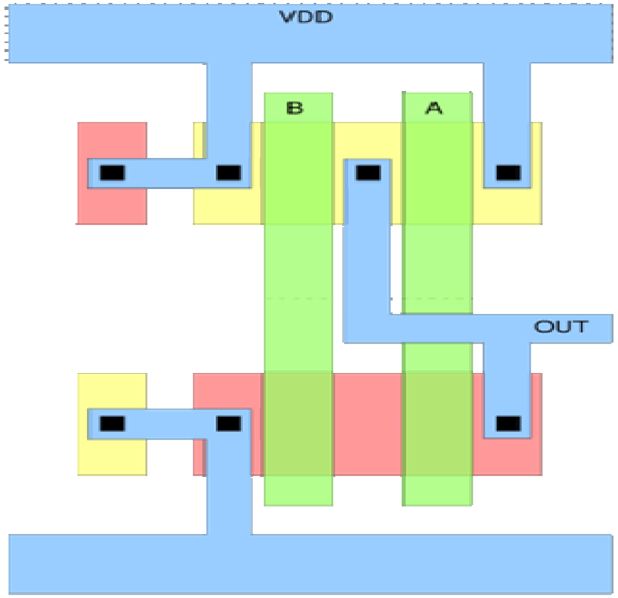
$$\min_{\vec{P}} \sum_{i} \left(Id_{\text{target}} - F\left(\vec{P}, \text{[illegible]}\right)\right)^2$$

The sum over different gate shapes

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

Layout Variations

Example: CMOS NAND

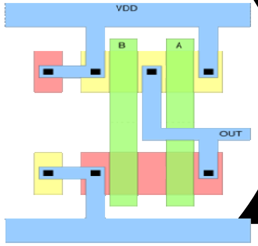


From Wikipedia, the free encyclopedia

Layout-dependent SPICE model

Model Parameters

$$\vec{M} = \vec{M}_0 + f\Big(\quad \Big)$$

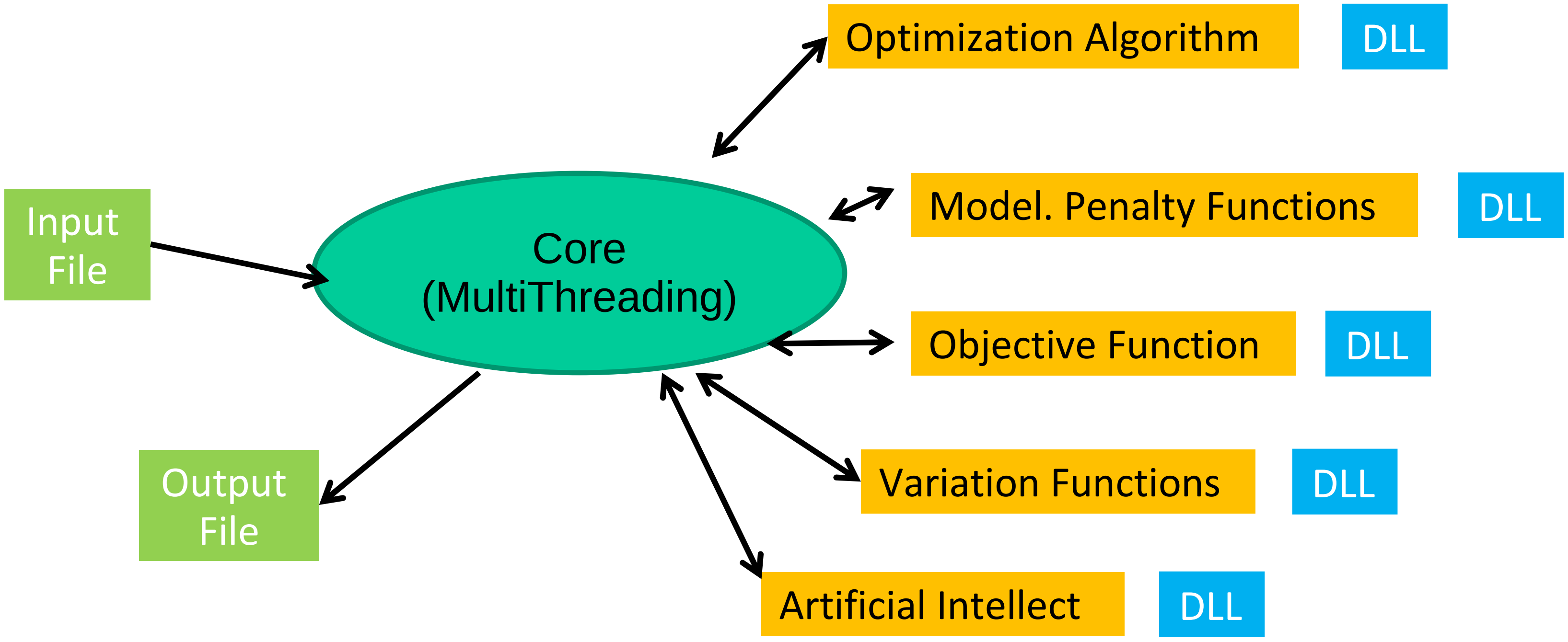


Function of layout

$$\boxed{\vec{M} = \vec{M}_0 + \sum_{ij} a_{ij} m_{ij} + \sum_{ij} b_{ij} m_{ij}^2}$$

Realization

- Modern C/C++ programming techniques



Optimization Algorithm DLL

Input File

Core (MultiThreading)

Model. Penalty Functions DLL

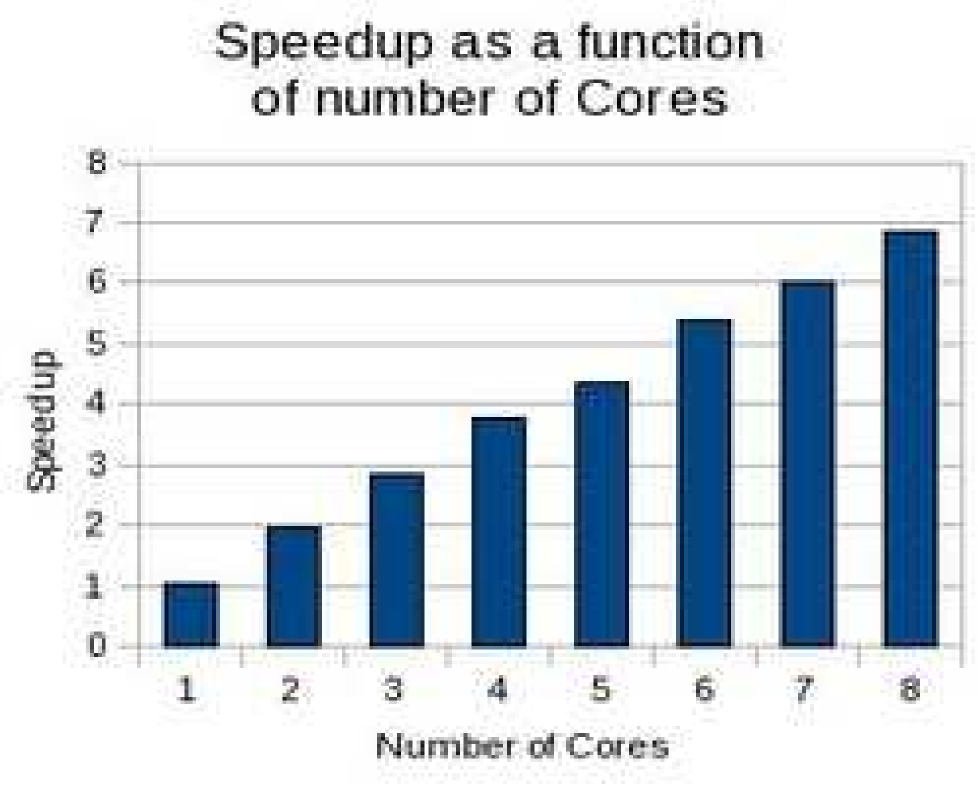
Objective Function DLL

Output File

Variation Functions DLL

Artificial Intellect DLL

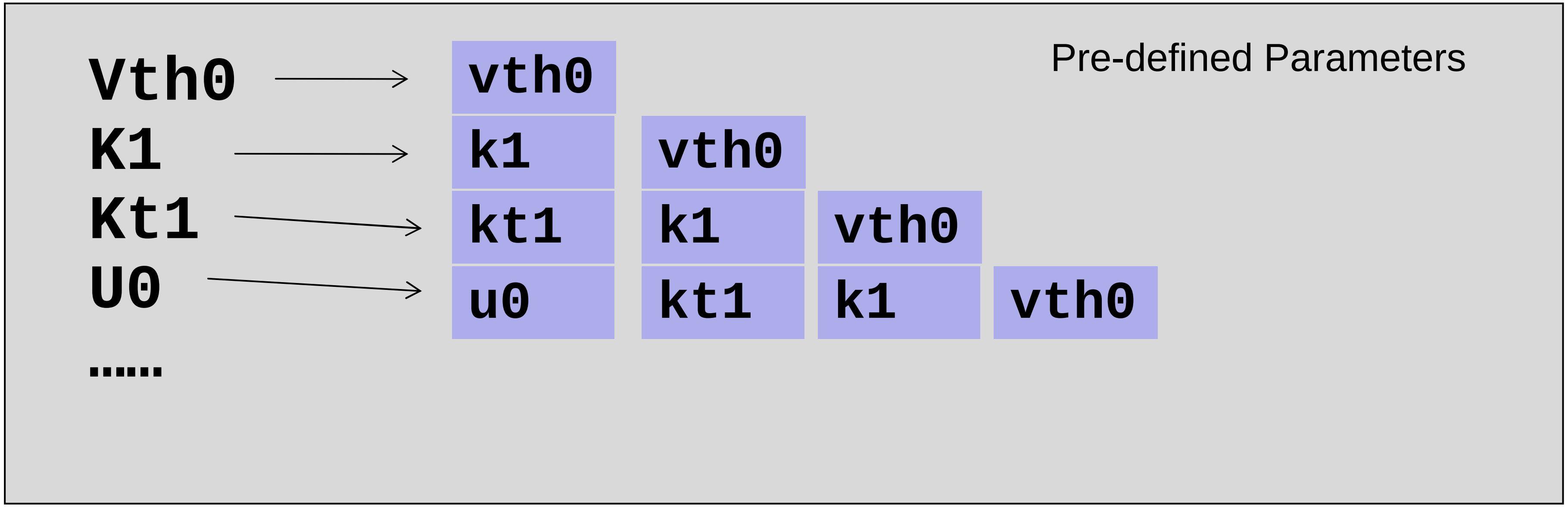
Multi-threaded scalability



- 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



Pre-defined Parameters

Vth0 → vth0

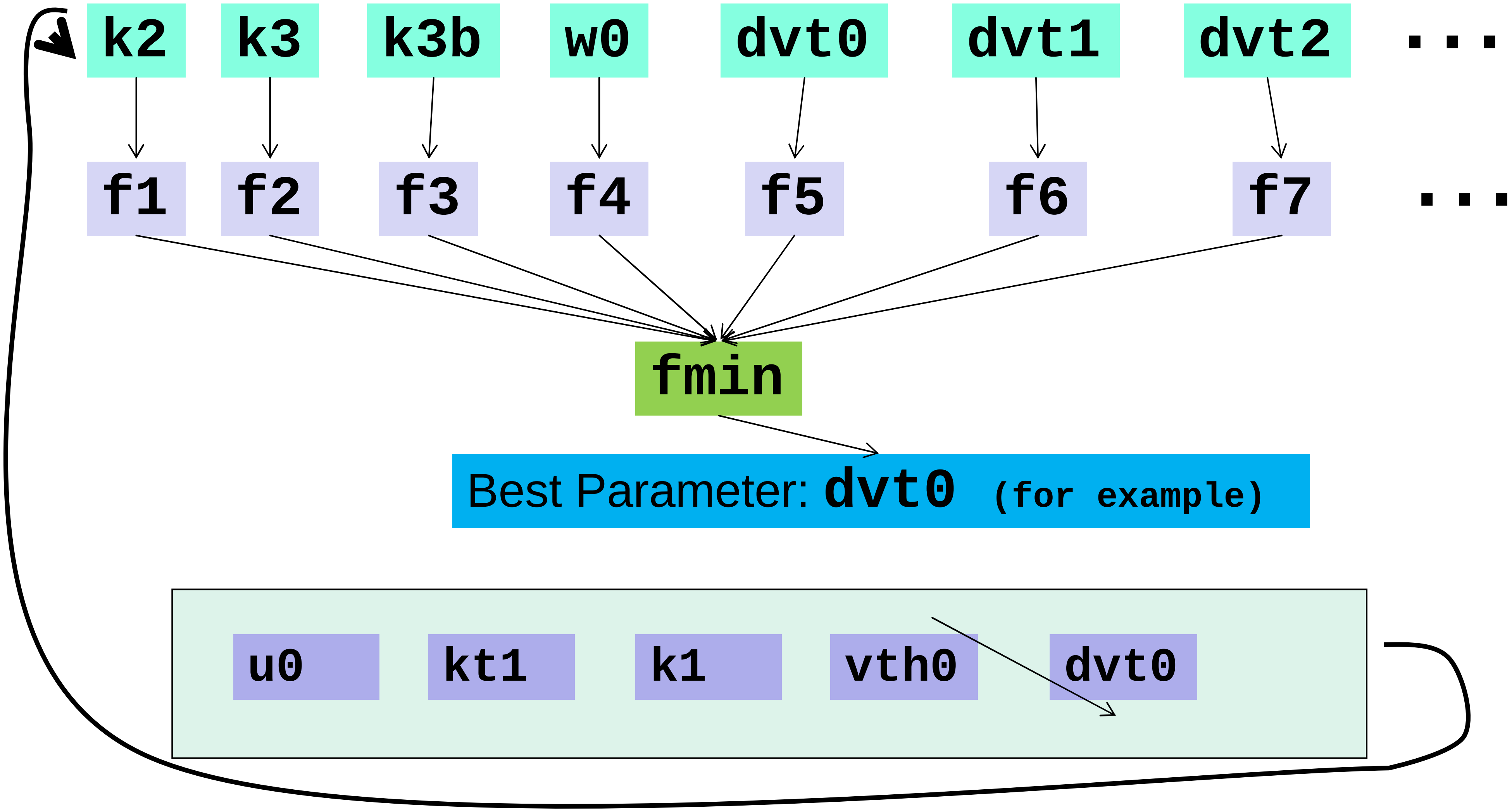
K1 → k1 vth0

Kt1 → kt1 k1 vth0

U0 → u0 kt1 k1 vth0

……

Automatic Parameter Extraction



`k2` `k3` `k3b` `w0` `dvt0` `dvt1` `dvt2` `...`

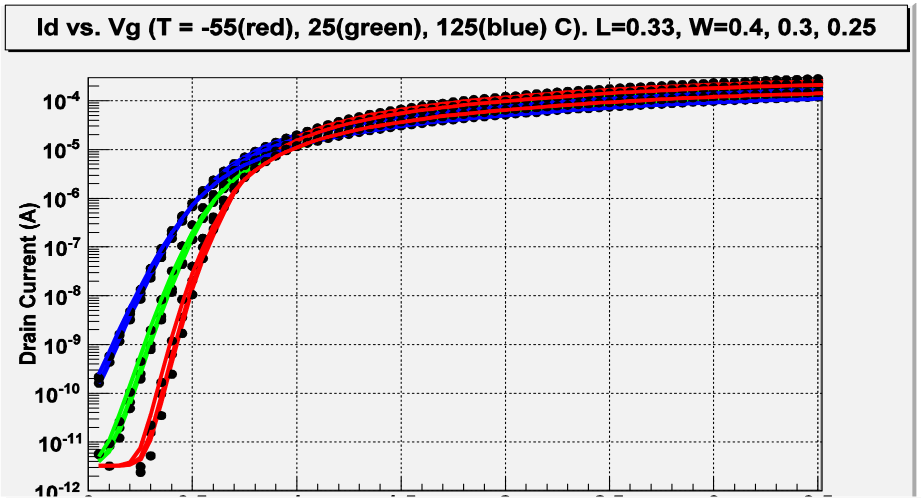
`f1` `f2` `f3` `f4` `f5` `f6` `f7` `...`

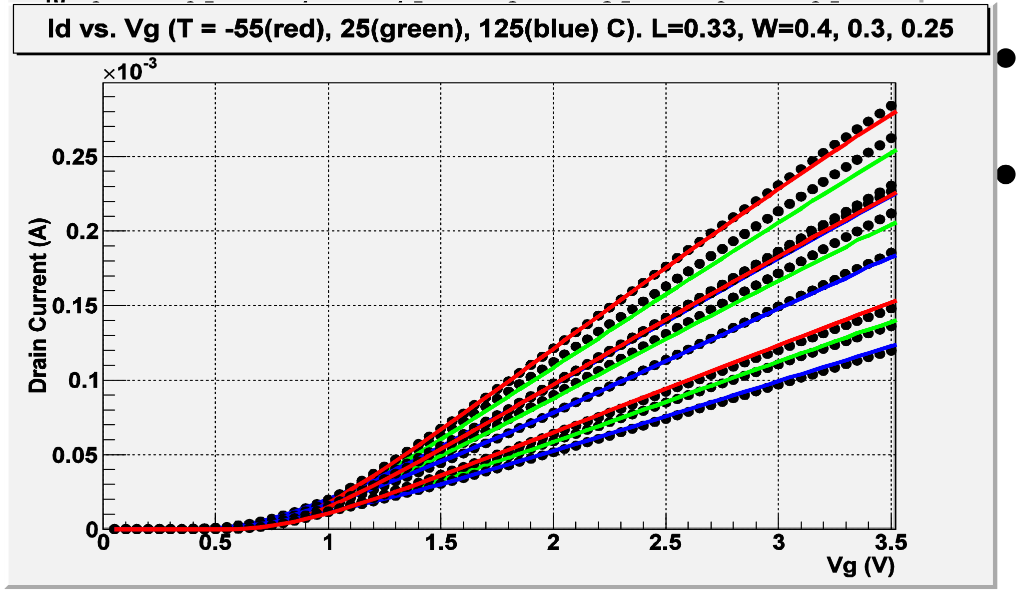
`fmin`

Best Parameter: **`dvt0`** `(for example)`

`u0` `kt1` `k1` `vth0` `dvt0`

Automatic Parameter Extraction





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