Recent Advances (from Munich) in Dealing with Process Variations

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Outline

- Timing Analysis of Digital Circuits
- Statistical Waveform Variation Propagation
- Current Source Models (Transfer System Models)
- Summary

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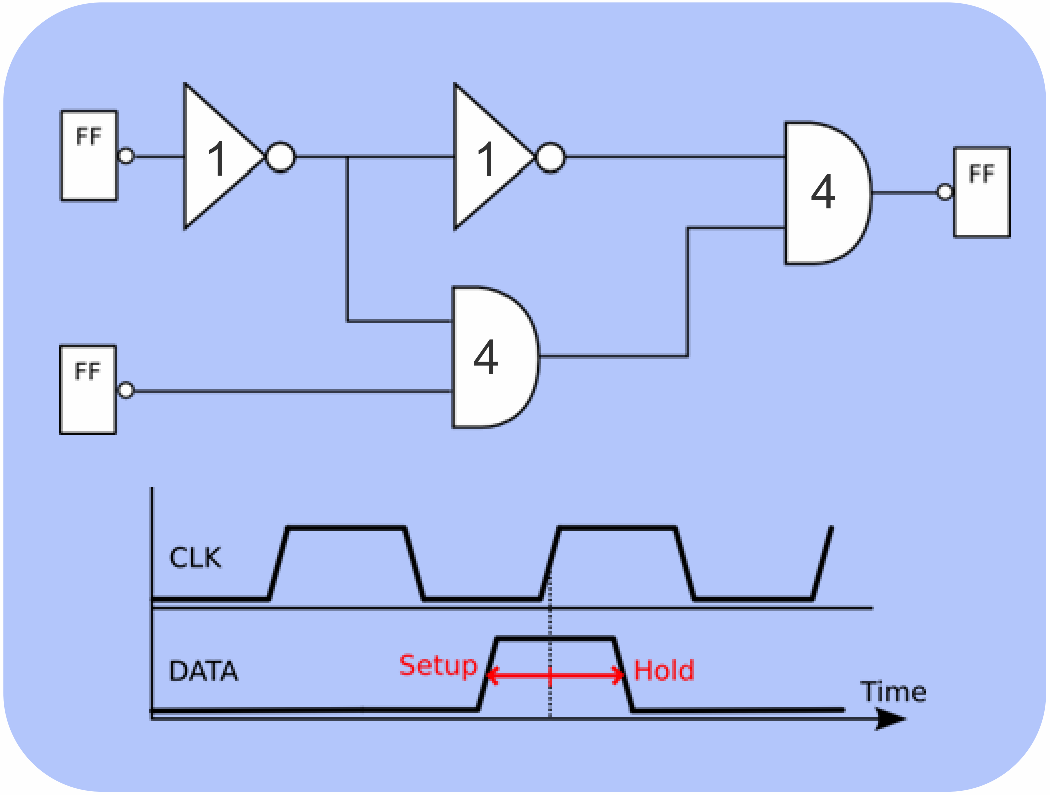
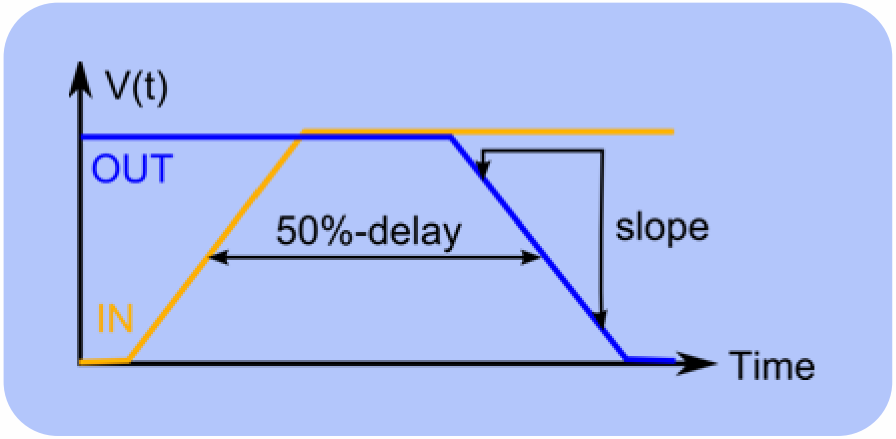
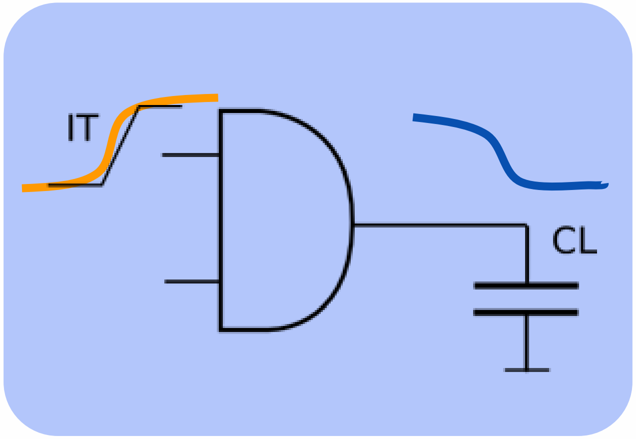
Static Timing Analysis in a Nutshell



- neglect logic function
- find longest/shortest path
- check for setup and hold time violations

Gate delays from pre-characterized Look-up Table



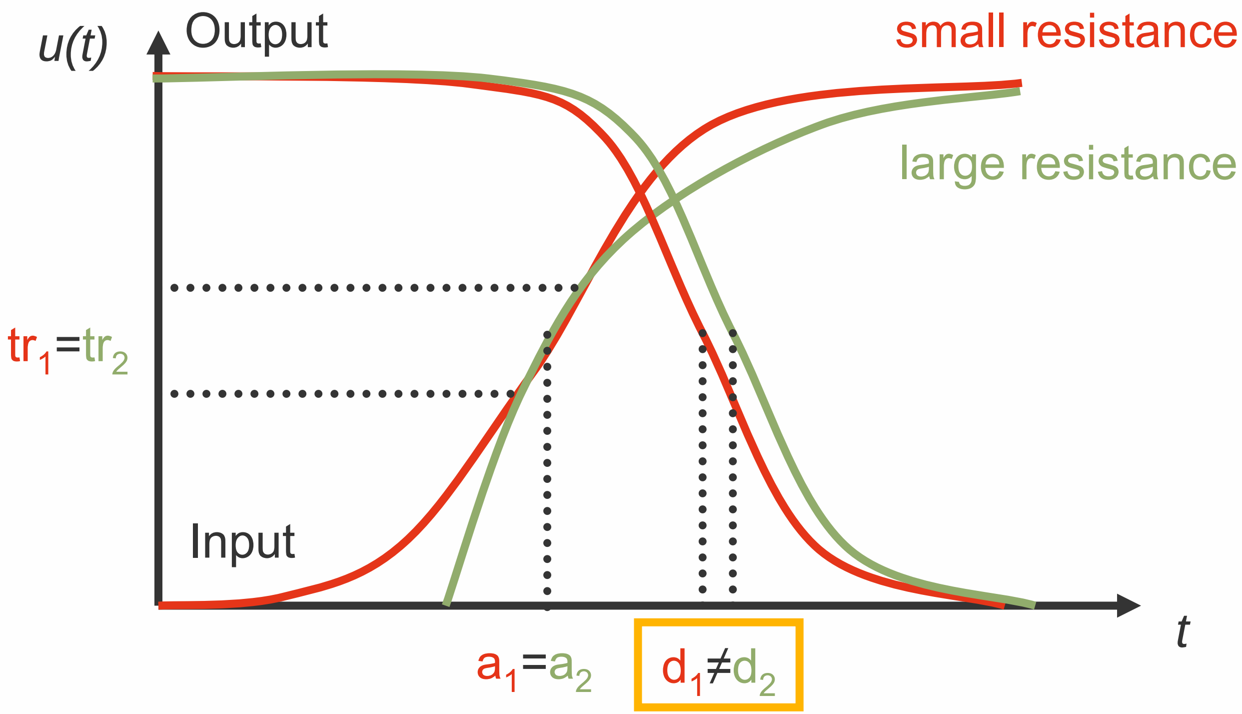


$$\text{Delay/OT} = \begin{bmatrix} & \text{CL} & \rightarrow & & \\ \text{IT} & 1.0 & 2.0 & 4.0 & 6.0 \\ \downarrow & 1.2 & 2.1 & 4.2 & 6.0 \\ & 1.4 & 2.3 & 4.3 & 6.1 \\ & 1.6 & 2.5 & 4.4 & 6.2 \end{bmatrix}$$

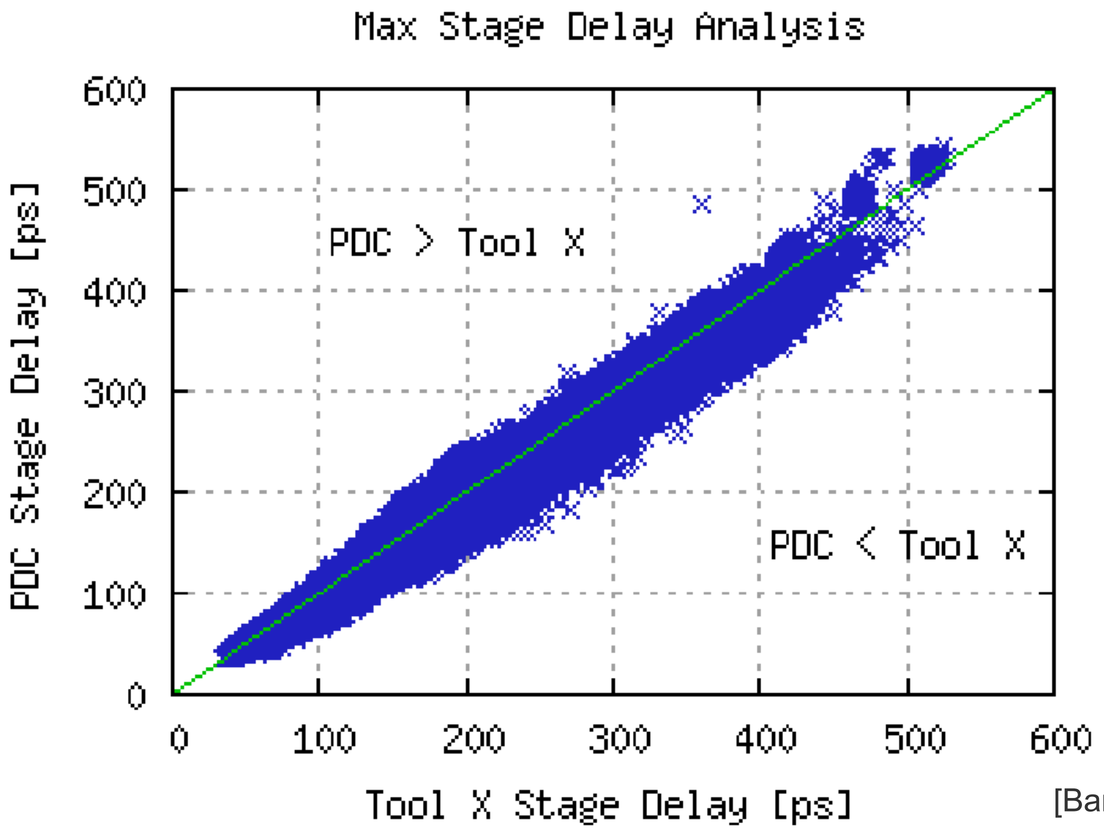
- Parameters:
  Slope (IT),
  Load Capacitance (CL)

Relevance of Waveforms

- increasing resisitive shielding from wiring
- today‘s standard modeling does not capture resulting effects



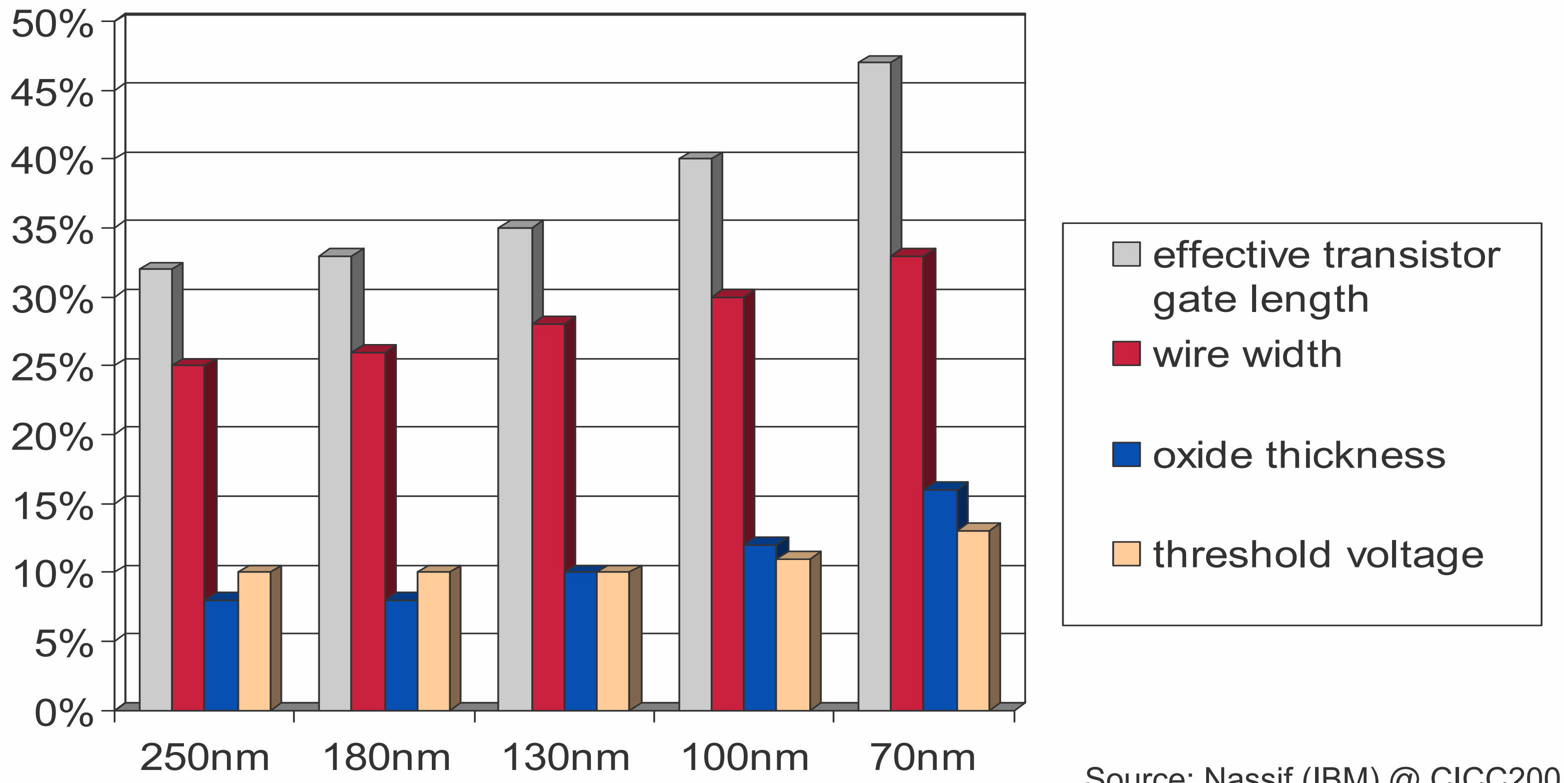
Effects of too simplistic modeling: inaccuracy



[Bargfrede, Mirbeth 06]

3-Sigma Variations of Technology Parameters

variations relative to nominal values



Source: Nassif (IBM) @ CICC2001

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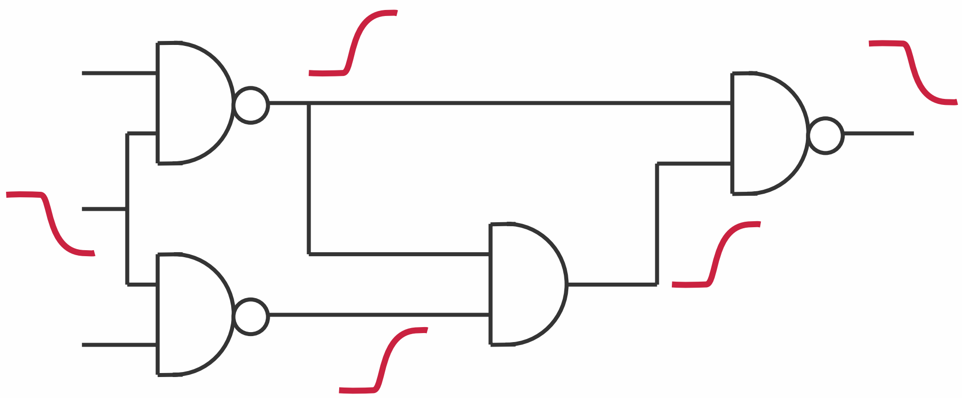
Path Delay Calculator (Infineon) [Bargfrede, Mirbeth 06]

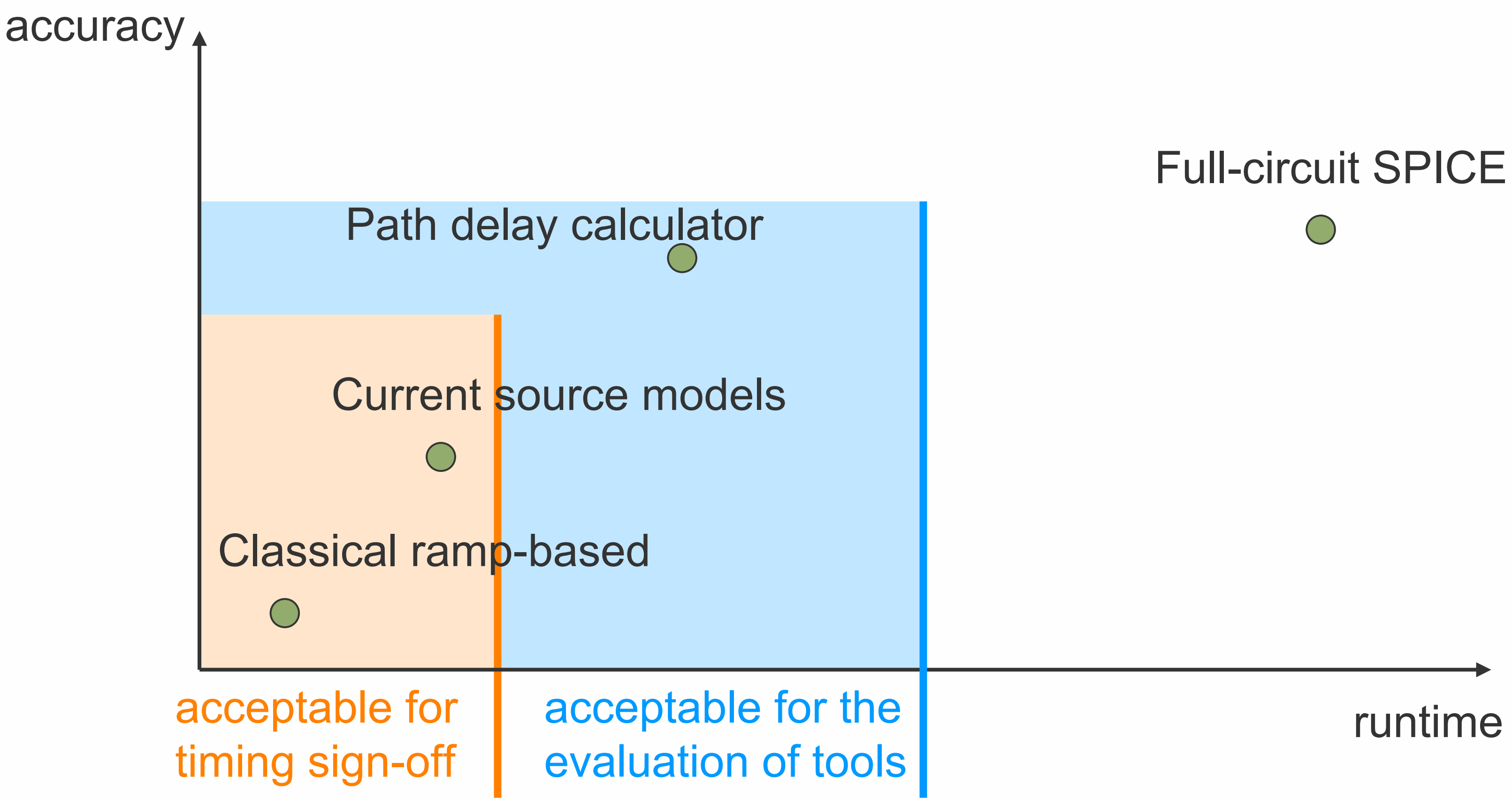
- Block-based timing reference tool
- Successive analog simulations
- Entire dynamic load taken into account
- Propagation of analog waveforms



Static timing analysis

- SPICE-like accuracy
- much faster

Trade-off between Runtime and Accuracy



Considering Variations

Assumptions:

•Gaussian distributions

•Linear dependence on global and local process parameters

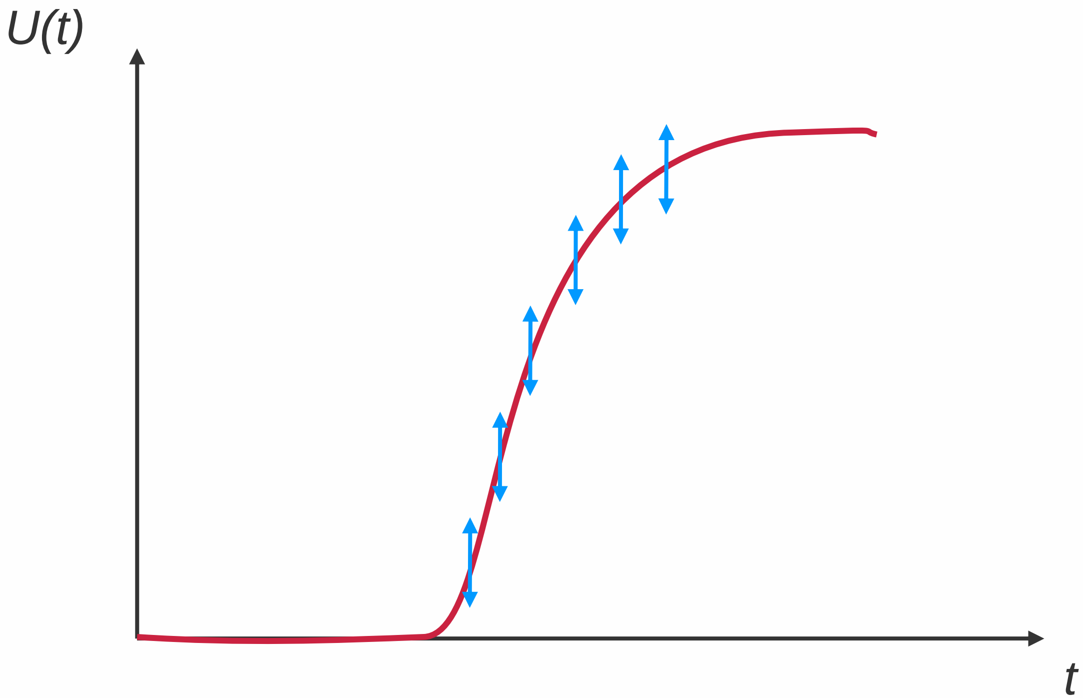
→ Canonical sum: $d = d_0 + \sum_i a_i \cdot \delta p_i$

Questions:

•How to model waveform variations ?

•How to obtain sensitivities a_i for these waveform variations?

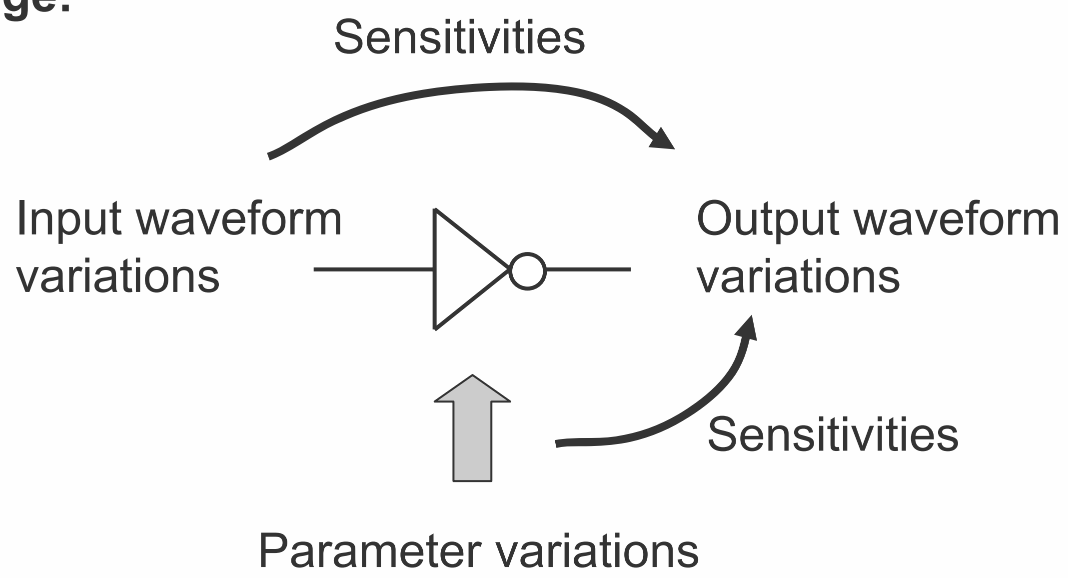
Modeling Waveform Variations: Voltage Variations



$$V(t) = V_0(t) + \sum_i \chi_i(t) \cdot \delta p_i$$

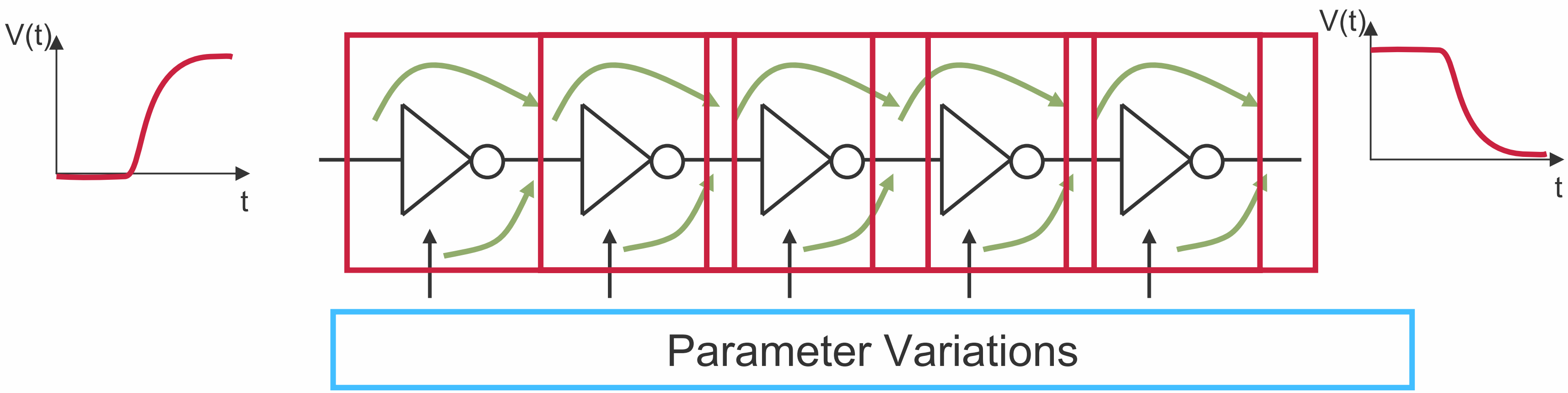
Path-Based Propagation of Variations: Single Stage

Single Stage:

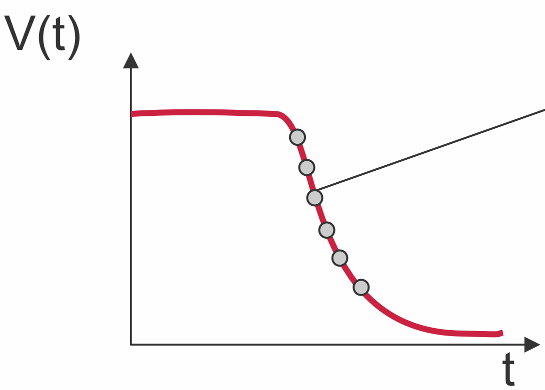


- Nominal simulation
- Sensitivities w.r.t. the input variations
- Sensitivities w.r.t. the gate parameter variations
- Addition of both influences

Successive Path-based Propagation of Variations



Result: nominal waveform



$$v_2 = v_{2,0} + \sum \chi_{2,i} \cdot \delta p_i$$

Results: Industrial Design

Paths with extracted post-layout parasitics including interconnects
(4 global, 2 local parameters)

#gates	#res/#cap	error σ_d	runtime	runtime 10,000 Monte Carlo	speedup
35	237/215	3%	15m23s	7d2h33m	665X
35	241/219	5%	15m27s	7d0h53m	655X
34	225/204	4%	15m7s	6d4h53m	590X
50	108/44	5%	23m20s	13d21h20m	857X

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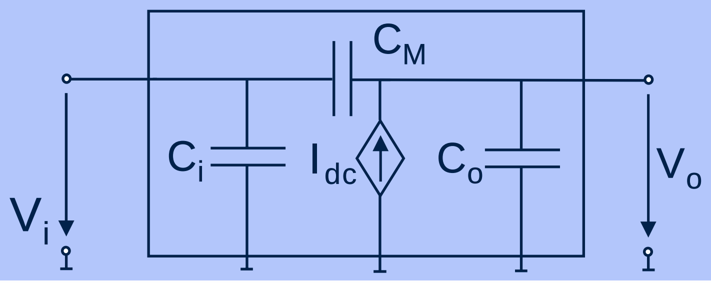
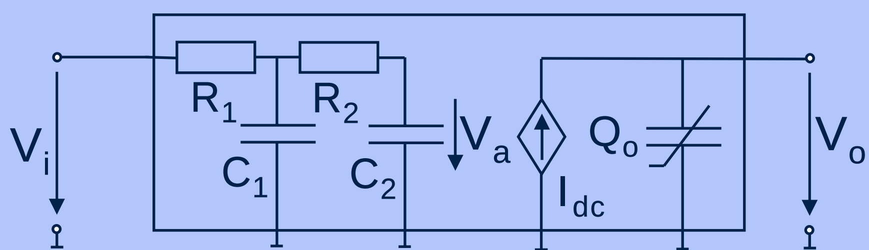
Evolution of Current Source Models



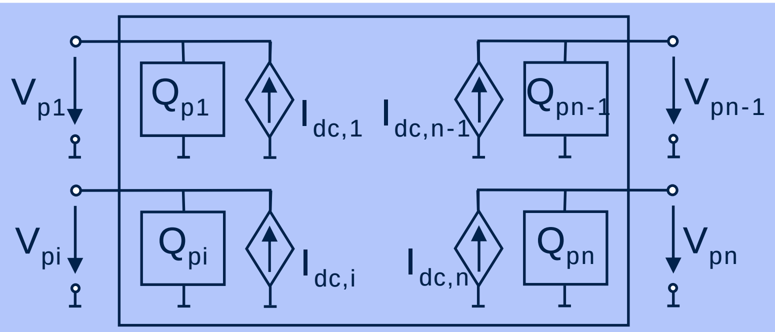
$Idc = f(Vi,Vo)$, $Ci,Co,CM = const.$

DAC 2003, Croix, Wong:
Blade and razor: cell and interconnect delay analysis using current-based models



$Idc = f(Va,Vo)$, $Q_o = f(Va,Vo)$

2007 Transactions on VLSI, Li, Feng, Acar:
Characterizing Multistage Nonlinear Drivers and Variability for Accurate Timing and Noise Analysis



$Idc,i=f(Vp1,Vp2,...,Vpn)$
$Qpi=f(Vp1,Vp2,...,Vpn)$

DAC 2006, Amin et.al.:
A multi-port current source model for multiple-input switching effects in CMOS library cells

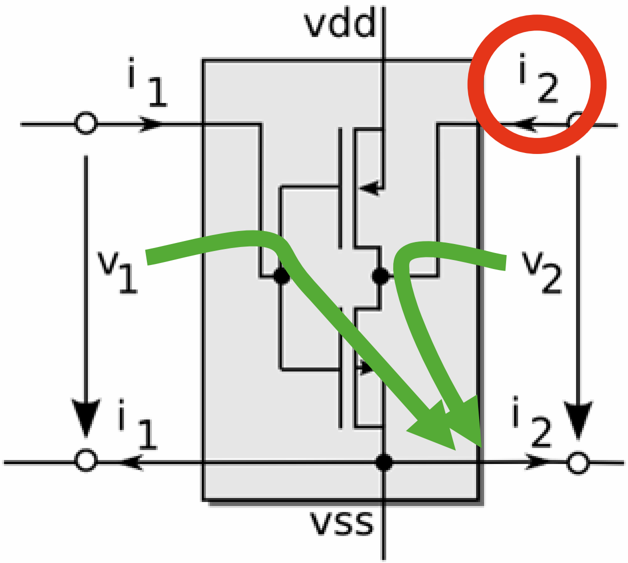
Figures drawn by Dr. Petra Nordholz, IFX Munich

What do we really want …?

$$i_2 = f(v_1, v_2)$$

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} j_1 \\ j_2 \end{bmatrix}$$

Transfer Conductance



- Replace nonlinear elements by equivalent circuits
- Calculate output current

Calculate transfer function on equivalent circuit

$$(\mathbf{G} + p\mathbf{C})\mathbf{x} = \mathbf{w}$$

$$\mathbf{T}\mathbf{x} = \mathbf{w}$$

$$x_i = \frac{\begin{vmatrix} \mathbf{T} & \mathbf{w} \\ -\mathbf{d}_i^t & 0 \end{vmatrix}}{\begin{vmatrix} \mathbf{T} & 0 \\ -\mathbf{d}_i^t & 1 \end{vmatrix}} = \frac{N(v_1, v_2, p)}{D(p)}$$

$$x_i = \frac{N(v_1, p)}{D(p)} + \frac{N(v_2, p)}{D(p)} + \frac{N_{DC}}{D(p)}$$

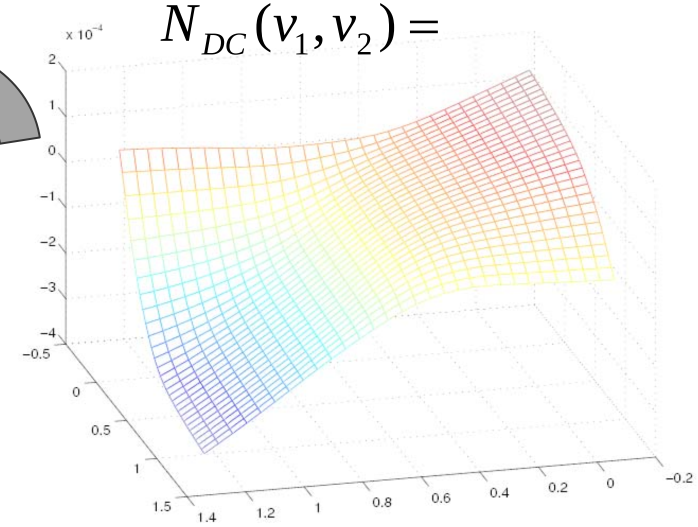
- Symbolically Solved
- Generally applicable
- Symbolic function independent of bias conditions
- Truncation

Account for nonlinearities by LUTs

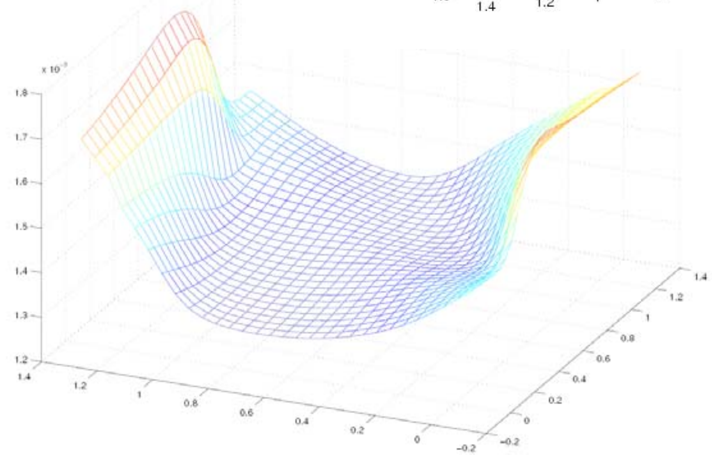
$$i_2 = \frac{N(v_1, p)}{D(p)} + \frac{N(v_2, p)}{D(p)} + \frac{N_{DC}}{D(p)}$$

$$i_2 = \frac{\cdots}{a \cdot p^2 + b \cdot p + c}$$

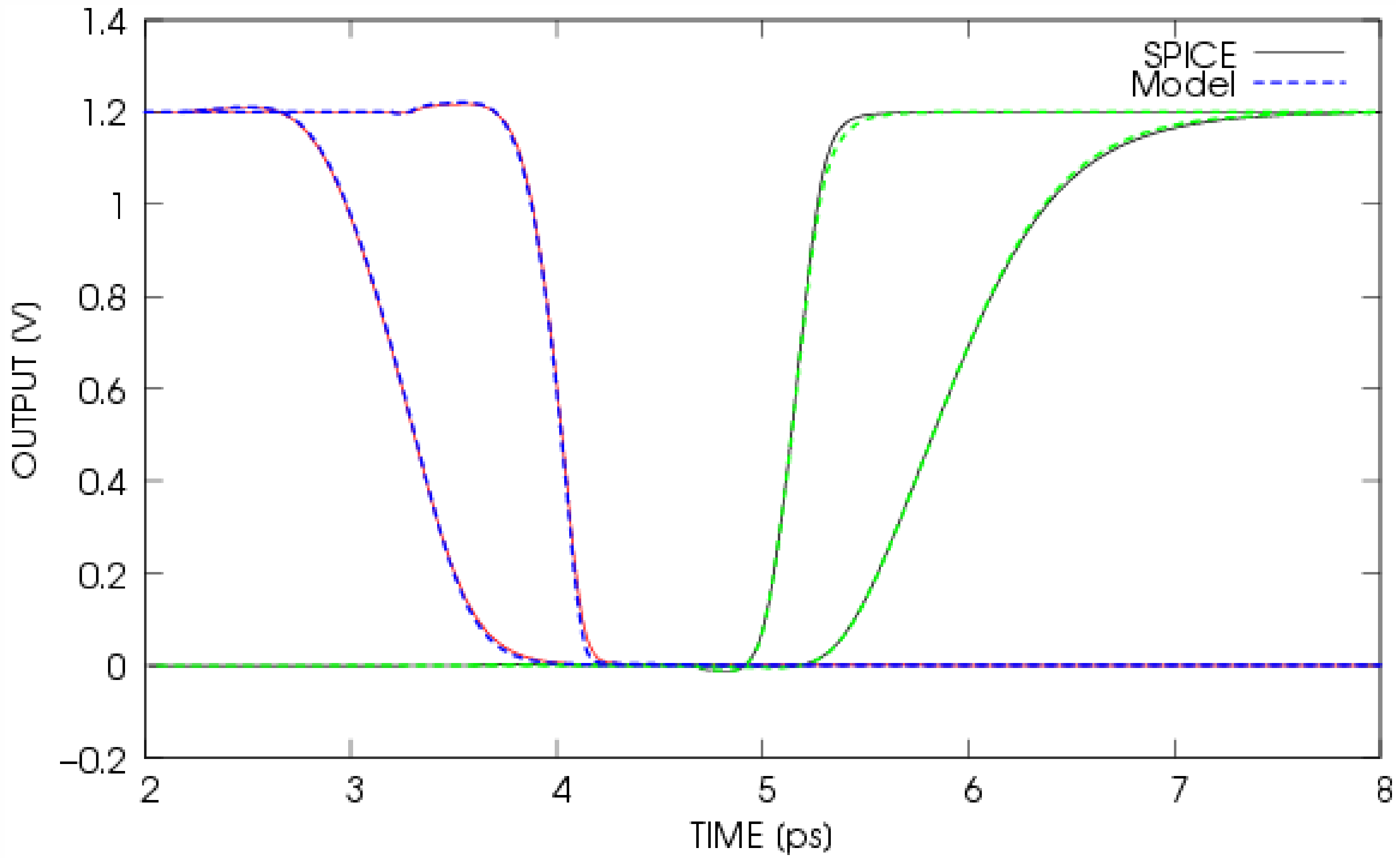
$N_{DC}(v_1, v_2) =$



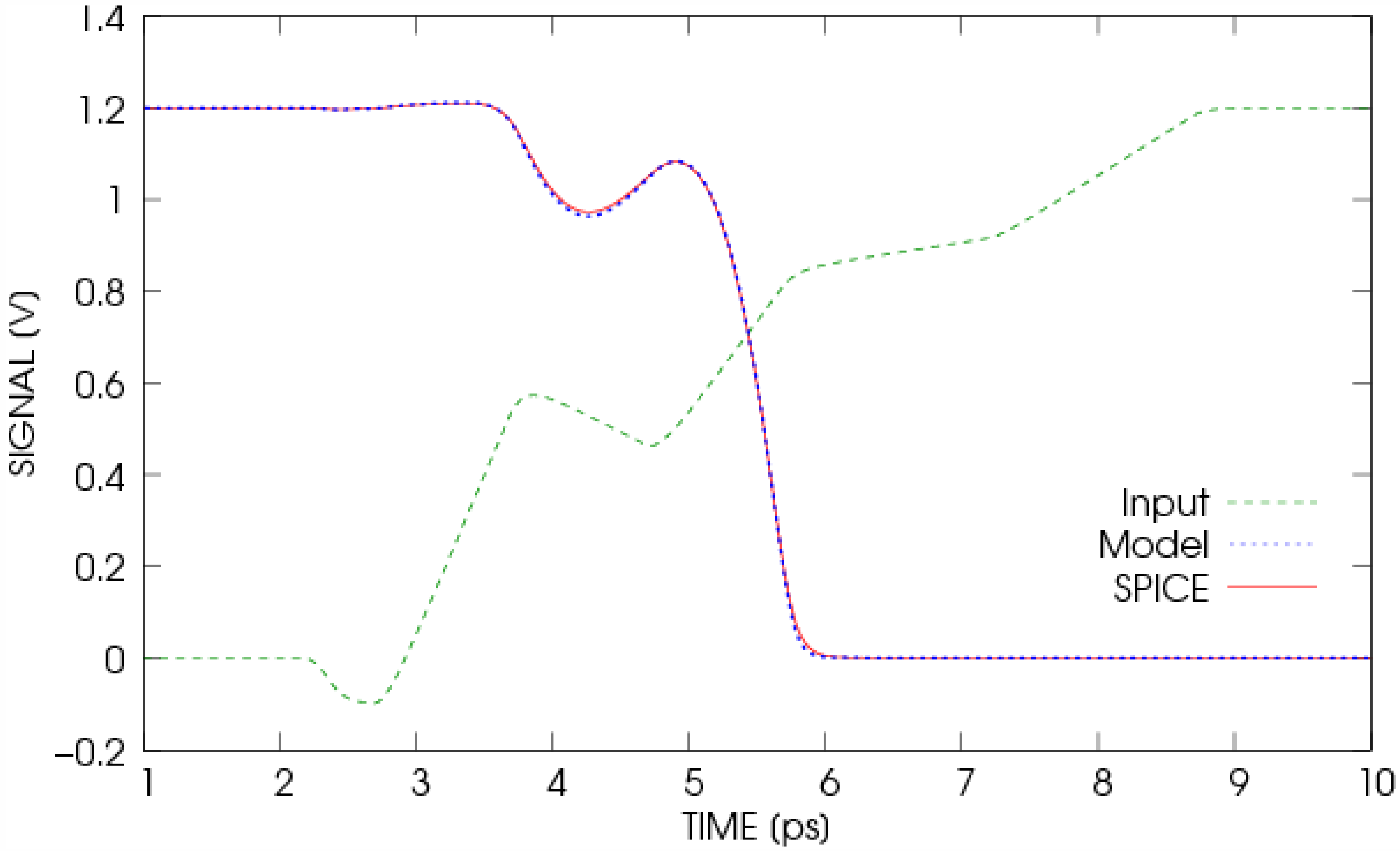
$b(v_1, v_2) =$



Comparison to SPICE shows almost identical waveforms



Noisy input waveform also handled very accurately



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Summary

- More detailed modeling for timing analysis required!
- Statistical modeling of waveform variations
- Structure-based Current Source Model
  - Symbolic (linear) transfer conductance function
  - Look-up Tables for coefficients
  - Simple to characterize (only DC measurements)

$$i_2 = \frac{N(v_1, p)}{D(p)} + \frac{N(v_2, p)}{D(p)} + \frac{N_{DC}}{D(p)}$$