Modeling of IC Variability

Simulation and Characterization of Statistical CMOS Variability and Reliability

SISPAD 2010 Workshop

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Introduction

- IC variability originates from interacting layout components, manufacturing imperfections, and randomness at the atomistic scale.

- IC variability has a hierarchical & hybrid character
  - Its hierarchy reflects the nature of production (*device*, *chip*, *field*, *wafer*, and *wafer-lot*)
  - It is *hybrid*, because at each levels variability consists of *systematic (deterministic)* and *random* components.

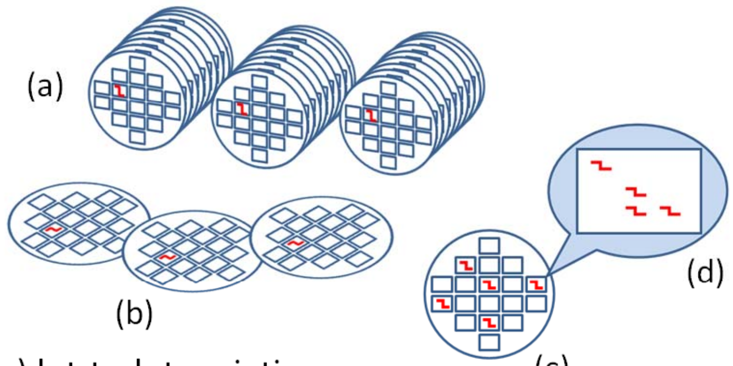
- A <u>complete</u>, yet *parsimonious* statistical model is needed to capture and describe variability.

Outline

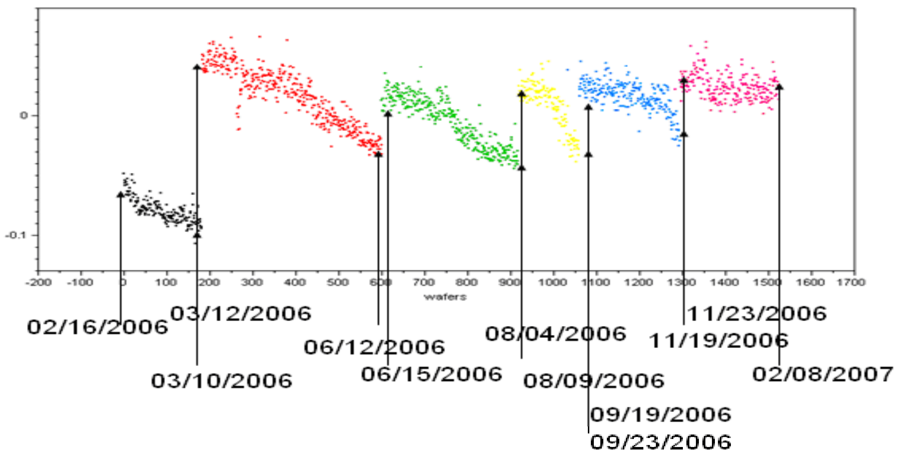
- Introduction
- Modeling and Case Studies
  - Random Variability
  - Systematic (Deterministic) Variability
  - Global Hierarchical Variability Model
- Future

Why is it such a hard problem?

- Dual Nature: Random vs. Systematic
- Various levels of *Hierarchy*
  - die, field, wafer, lot
- Various *consumers* of variability information
  - device, process, circuit engineers
- A large portion of variability is ***not stationary***



a) lot-to-lot variation
b) wafer-to-wafer variation
c) die-to-die or across-wafer variation
d) within-die variation



Model Hierarchy (lot, wafer, within wafer, within die)

$$p_{ijkl} = \eta + \lambda_i + \sigma_j + \alpha_{ij} + \beta_k + \omega_{ijk} + \gamma_l + \tau_{kl} + \epsilon_{ijkl}$$

Model Estimator	Description
$\hat{\eta} = \bar{p}_{....}$	Global Mean
$\hat{\lambda}_i = \bar{p}_{i...} - \bar{p}_{....}$	Lot Factor
$\hat{\sigma}_j = \bar{p}_{.j..} - \bar{p}_{....}$	Wafer or Slot Factor
$\hat{\alpha}_{ij} = \bar{p}_{ij..} - \bar{p}_{i...} - \bar{p}_{.j..} + \bar{p}_{....}$	Lot-Wafer Interaction Factor
$\hat{\beta}_k = \bar{p}_{..k.} - \bar{p}_{....}$	Average Wafer
$\hat{\omega}_{ijk} = \bar{p}_{ijk.} - \bar{p}_{ij..} - \bar{p}_{..k.} + \bar{p}_{....}$	Deviation from Average Wafer
$\hat{\gamma}_l = \bar{p}_{...l} - \bar{p}_{....}$	Average Die
$\hat{\tau}_{kl} = \bar{p}_{..kl} - \bar{p}_{..k.} - \bar{p}_{...l} + \bar{p}_{....}$	Die-Site Interaction
$\hat{\epsilon}_{ijkl} = p_{ijkl} - \bar{p}_{ijk.} + \bar{p}_{..k.} - \bar{p}_{..kl}$	Residual

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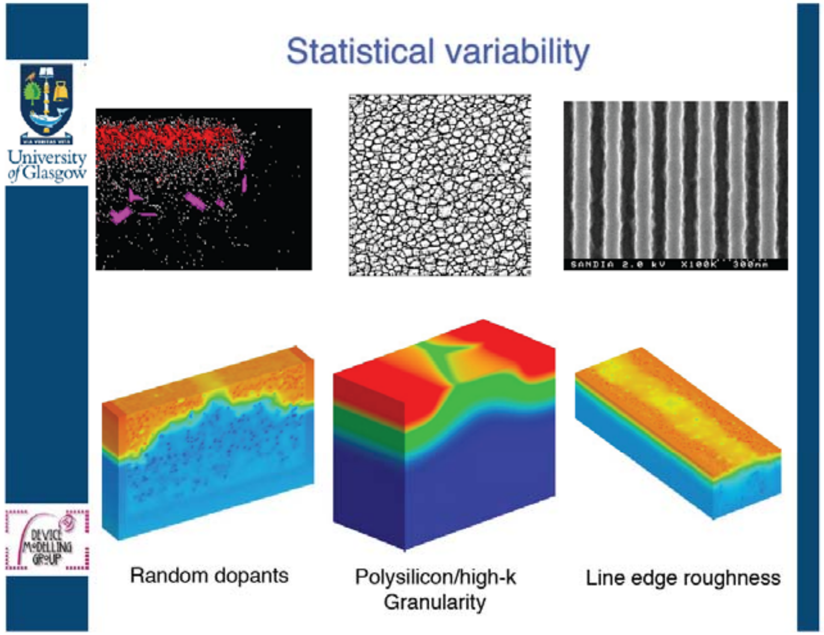
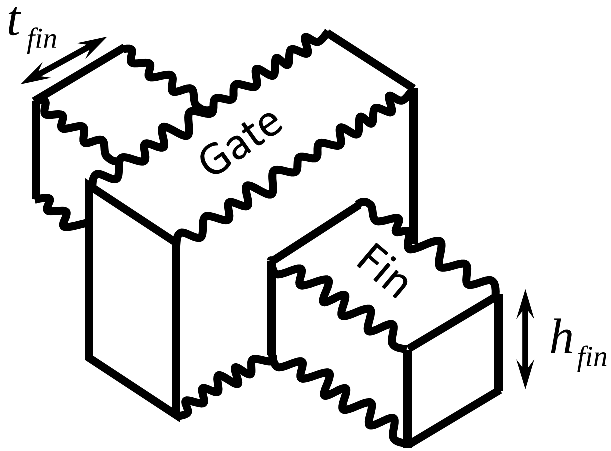
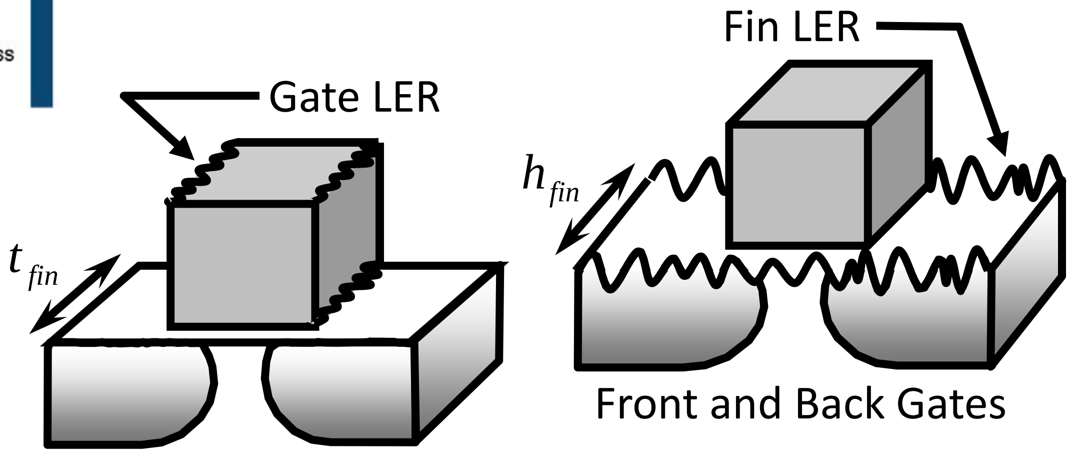
Intrinsic (Random) Variability



IEEE/ACM Workshop on Variability Modeling and Characterization
ICCAD 2009
Scott Roy (Univ. of Glasgow): *Atomistic Simulation of Variability*

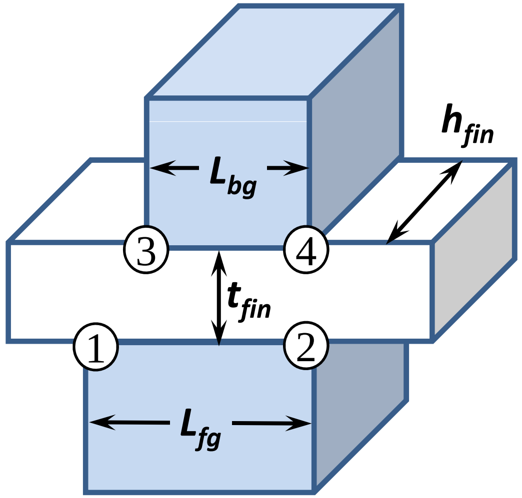


(Patel, Spanos and King-Liu, TED 2009)



Top Gate

Front and Back Gates

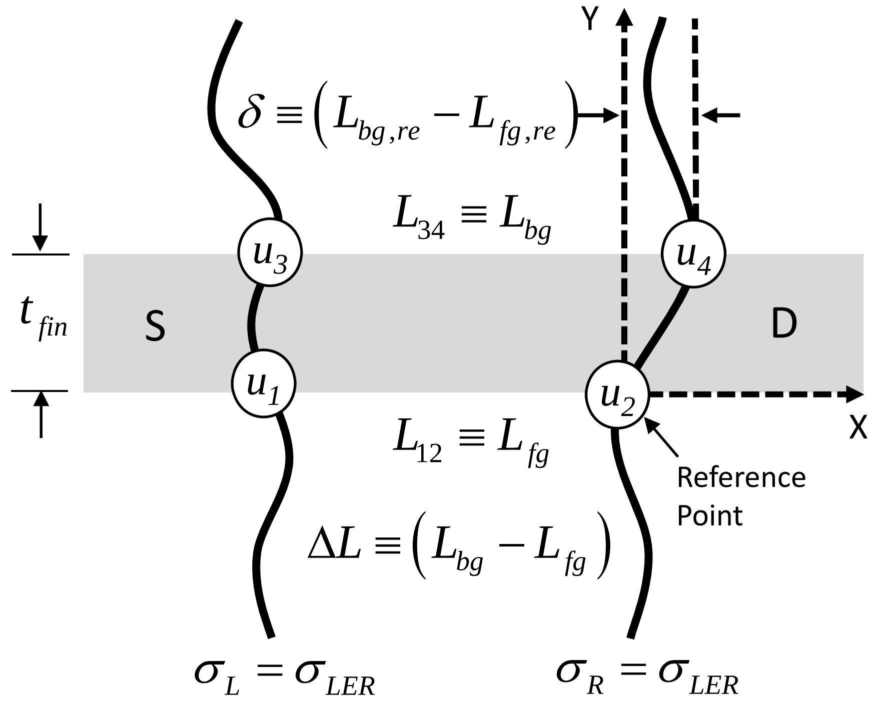


LER Model Description

(Patel, Spanos and King-Liu, TED 2009)

$$\sigma_{\delta}^{2} = 2\sigma_{LER}^{2}\left(1-\rho_{A}(t_{fin})\right)$$

$$\rho(y) = e^{-\left(|y|/\xi\right)^{2\alpha}}$$ Auto-correlation function



For a resist-defined gate electrode,

$$\sigma_{\Delta L}^{2} = 4\sigma_{LER}^{2}\left[1-\rho_{A}(t_{fin})\right].$$

For a spacer-defined gate electrode ,

$$\sigma_{\Delta L}^{2} = 0$$

LER Simulation Details

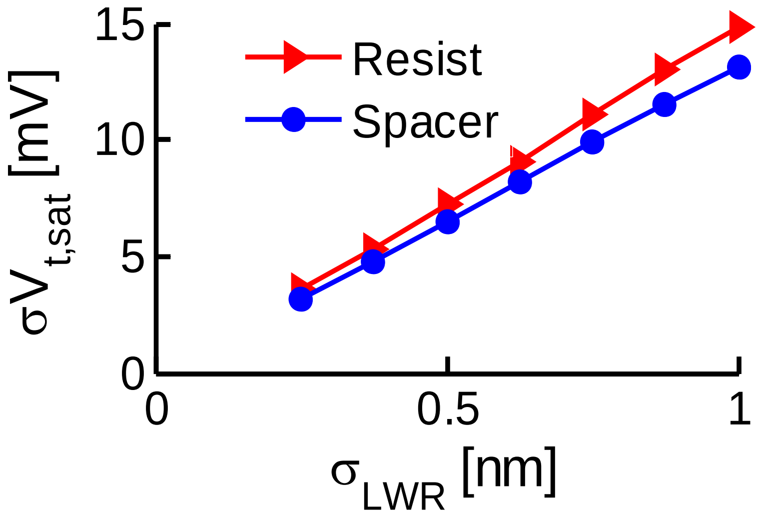
TABLE 1: 2-D DEVICE SIMULATION PARAMETERS

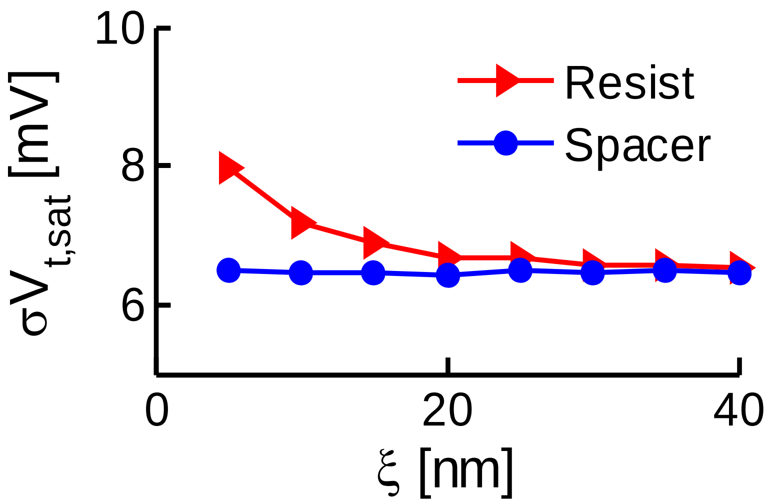
Electrical/Doping	Structural
V_{dd}=0.9V	L_g=13nm
ϕ_m=4.62eV	t_{ox}=6A
N_B=1e15 cm^{-3}	L_{sp}=7.2nm
$N_{s/d}$=1e20 cm^{-3}	t_{fin}=7.5nm
$\sigma_{s/d}$=4nm/dec	t_{poly}=13nm

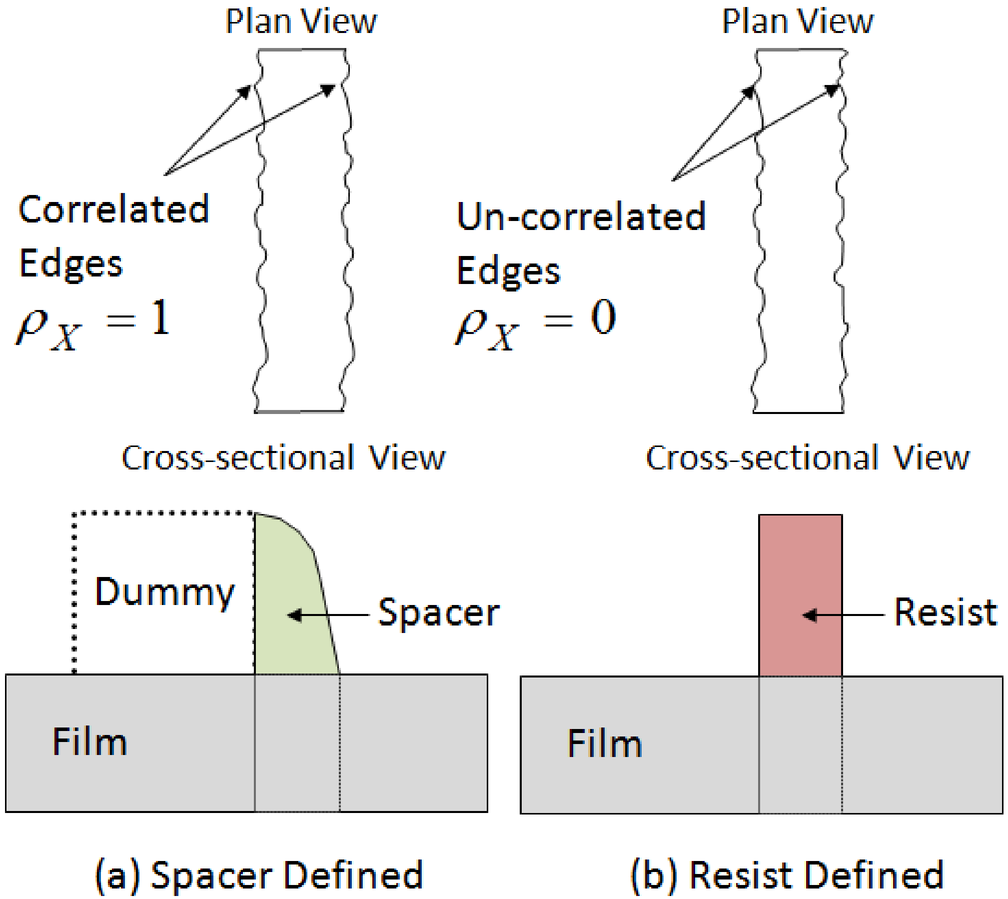
TABLE 2: 2-D NOMINAL DEVICE PERFORMANCE PARAMETERS.

Parameter	Units	Value
$V_{t,sat}$	mV	210
SS	mV/dec	69
DIBL	mV/V	30
$g_{m,sat}$	mA/V	6.75
$I_{d,sat}$	mA/μm	2.48
I_{off}	pA/μm	94.4

Spacer v. Resist







$$\boxed{\sigma^2_{LWR} = 2\sigma^2_{LER}\left(1-\rho_X\right)} \quad \sigma_L = \sigma_R \equiv \sigma_{LER}$$

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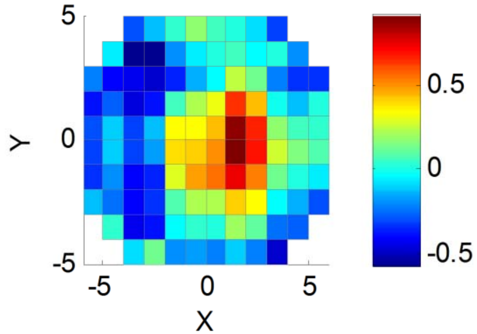
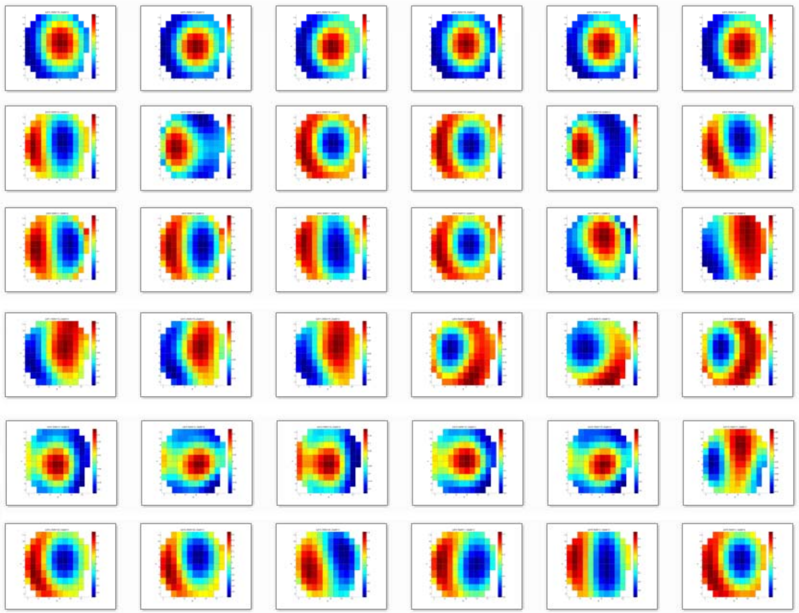
The Statistics of Spatial Variability

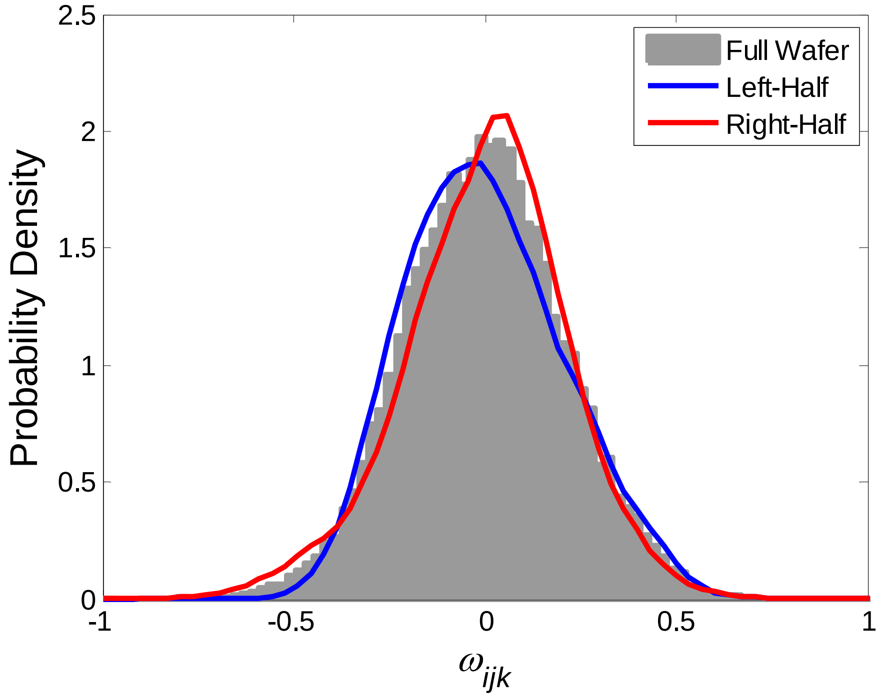
Ring Oscillator Frequency, 65nm node

Average Wafer

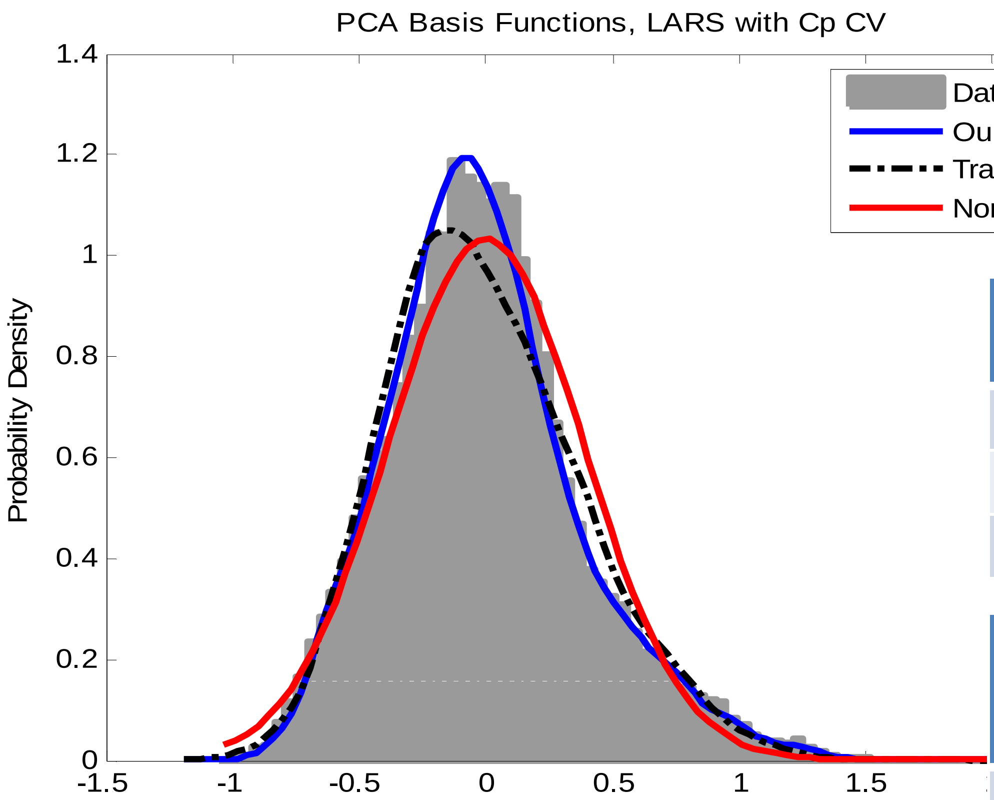


Residuals





Results using PCA Basis Functions



Statistical Moment	Data	Traditional Model	Our Model
Variance	0.149	0.147	0.142
Skewness	0.545	0.401	0.563
Kurtosis	3.555	3.002	3.544

Metric	% Actual Data [95% CI]	% Traditional Model	% Our Model
Upper Tail	1.47 [1.34, 1.61]	1.00	1.45
Lower Tail	0.02 [0.00, 0.03]	0.09	0.02
Out of Spec [-1, 1]	1.49 [1.35, 1.62]	1.00	1.45

Traditional Method:

$$\hat{\beta} + \varepsilon_{\hat{\omega}}$$

$$\varepsilon_{\hat{\omega}} \sim \mathrm{N}\left(0, \mathrm{var}(\hat{\omega}_{ijk})\right)$$

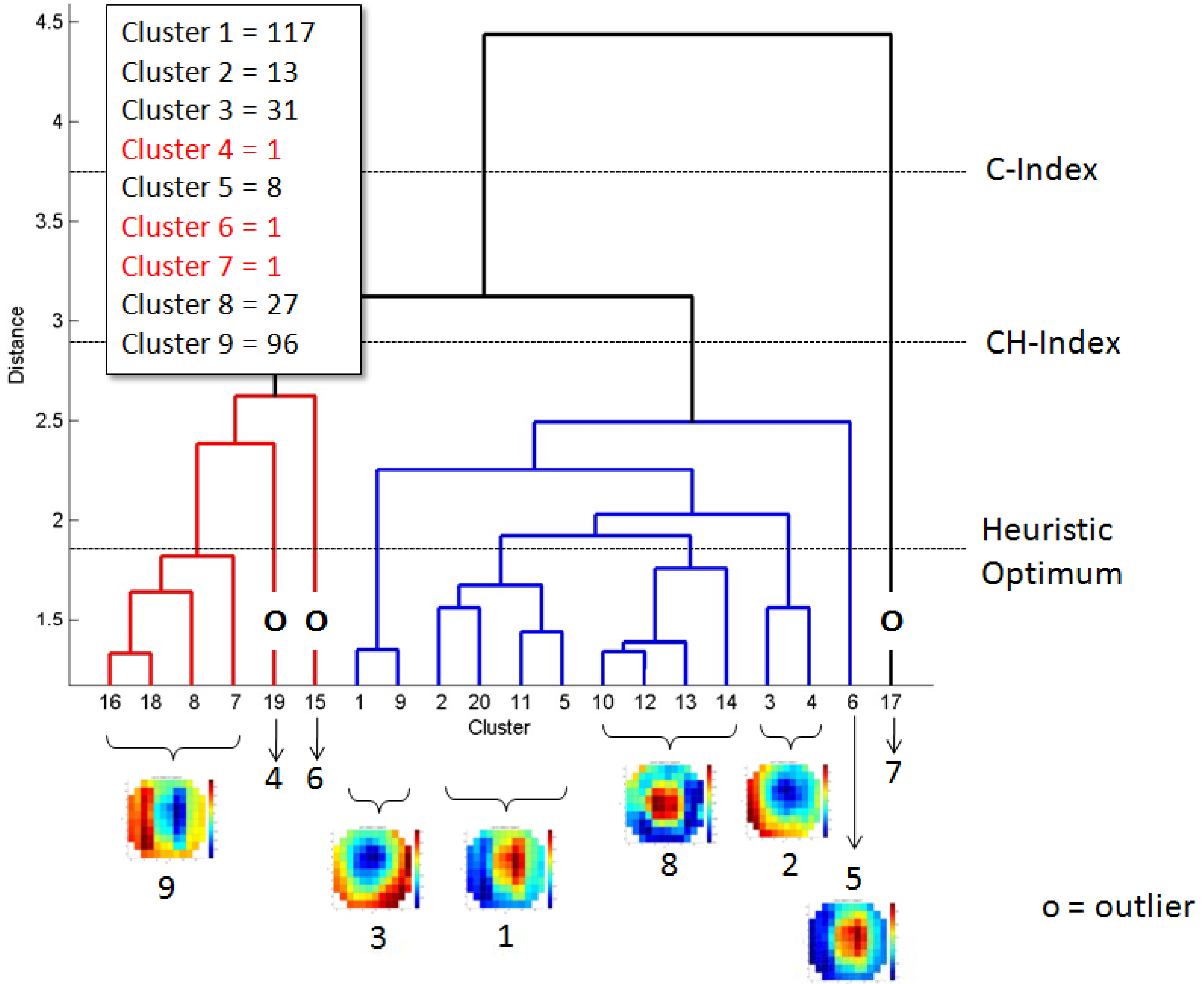
Proposed Method:

$$\hat{\beta} + \tilde{\omega} + \varepsilon_R$$

$$\varepsilon_R \sim \mathrm{N}\left(0, \sigma_R^2\right)$$

$$R = \hat{\omega}_{ijk} - \tilde{\omega}$$

A Bonus Application: Cluster Analysis



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Within-die Variation

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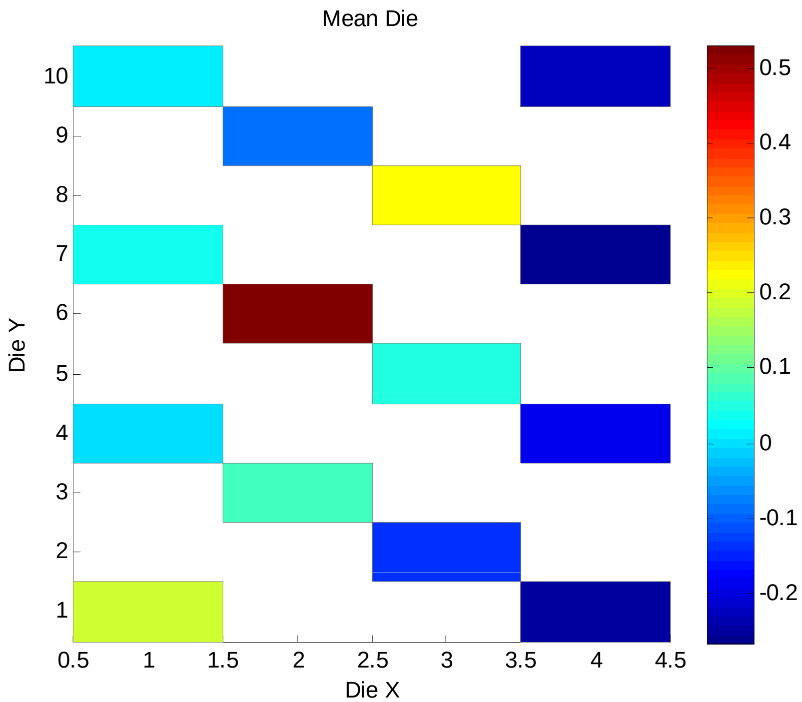
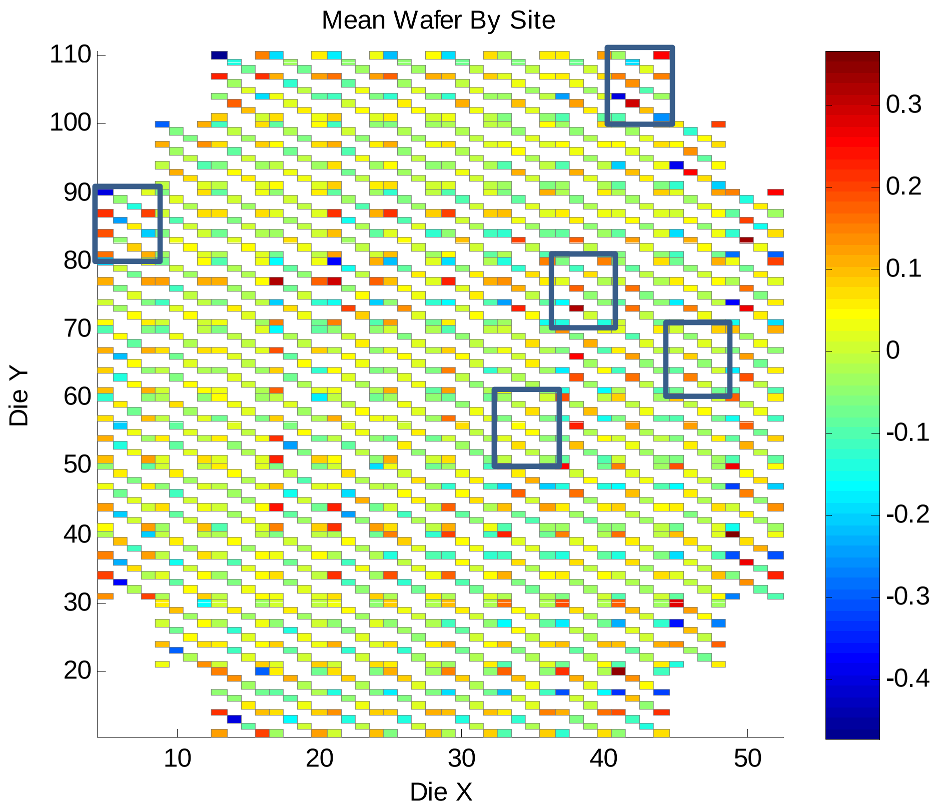
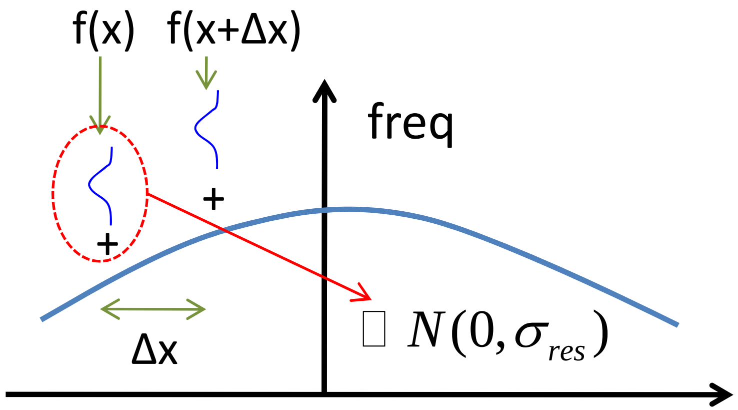


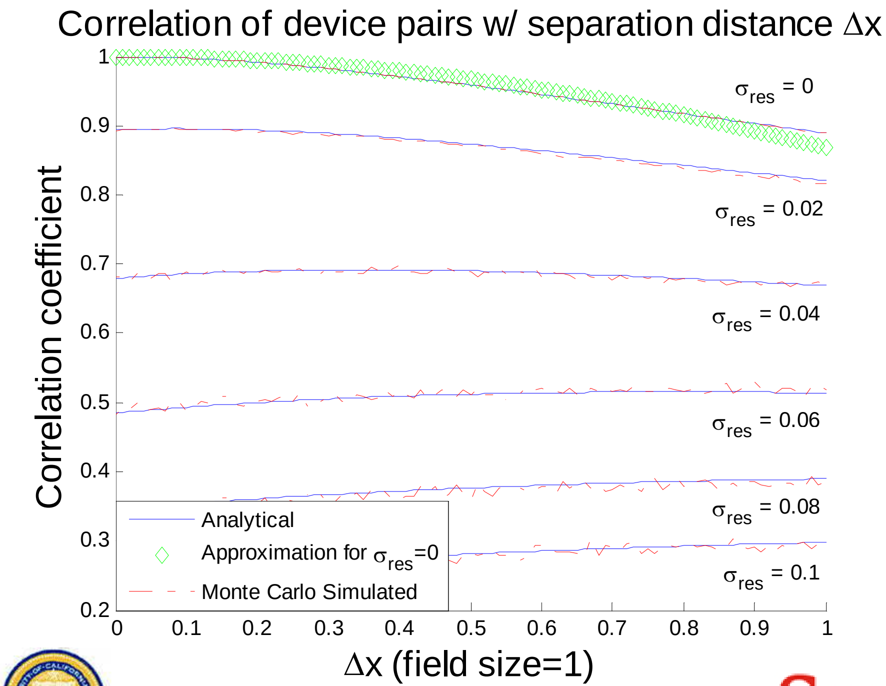
Average die



Die-level residuals

Apparent Spatial Correlation





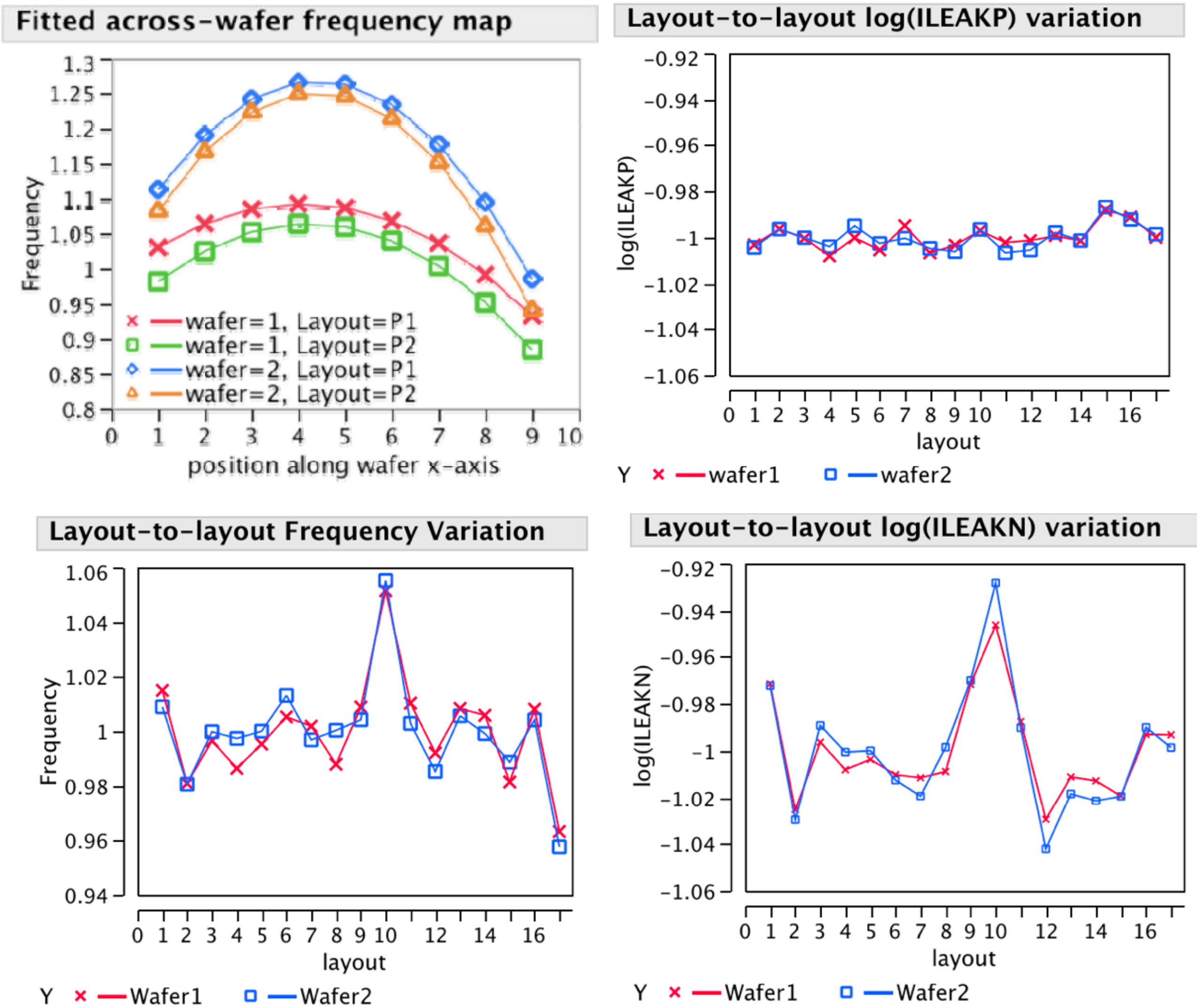
$$Z_1 = f(x,y) + e_1$$

$$Z_2 = f(x+\Delta x, y) + e_2$$

$$\approx f(x,y) + \frac{\partial f(x,y)}{\partial x}\Delta x + e_2$$

>> ***Unmodeled*** Systematic Variation Exhibits Spatial Correlation

Layout Effect Analysis



Global Hierarchical Variability Model

Data (metrology & electrical) → Global Hierarchical Variability Model

On-demand custom variability "views":

- Circuit Simulation (physical process corners)
- Statistical Timing Analysis (die-level, apparent "spatial" correlation)
- Parametric Yield Targeting ("total" variability)
- Process Fingerprinting (Fault diagnosis through clustering)

$$p_{ijkl} = \eta + \lambda_i + \sigma_j + \alpha_{ij} + \beta_k + \omega_{ijk} + \gamma_l + \tau_{kl} + \epsilon_{ijkl}$$

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Of Further Interest

- What about Statistical Circuit Simulation?
  - Propagating Gaussian and Mixture of Gaussian (MOG) distributions through interval representation
- What about temporal non-stationarity?
  - Can be modeled or “collapsed” depending on the needed “view”
- What about SRAM variability?
  - Nothing special other than we really must capture <u>extreme</u> tails of distribution <u>extremely</u> well (see above)

Acknowledgements

- Graduate Students at UC Berkeley: Yu Ben, Jason Cain, Paul Friedberg, Justin Ghan, Kun Qian, Ying Qiao, Anand Subramanian, QianYing Tang, Dekong Zeng
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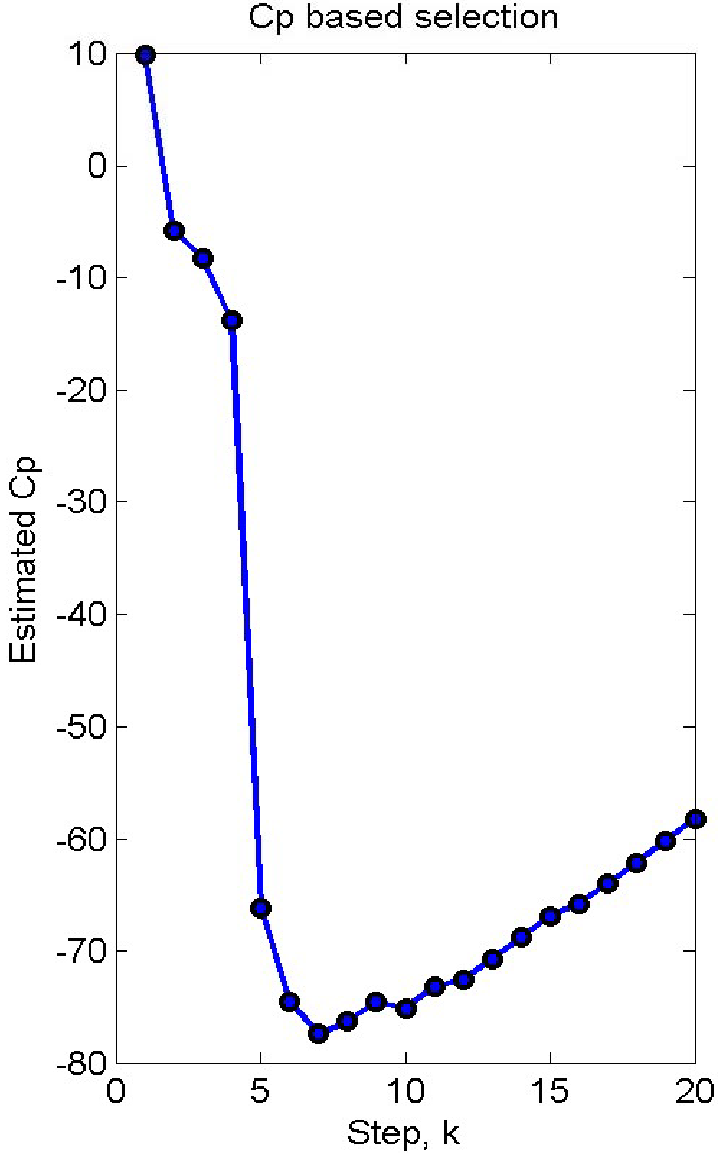
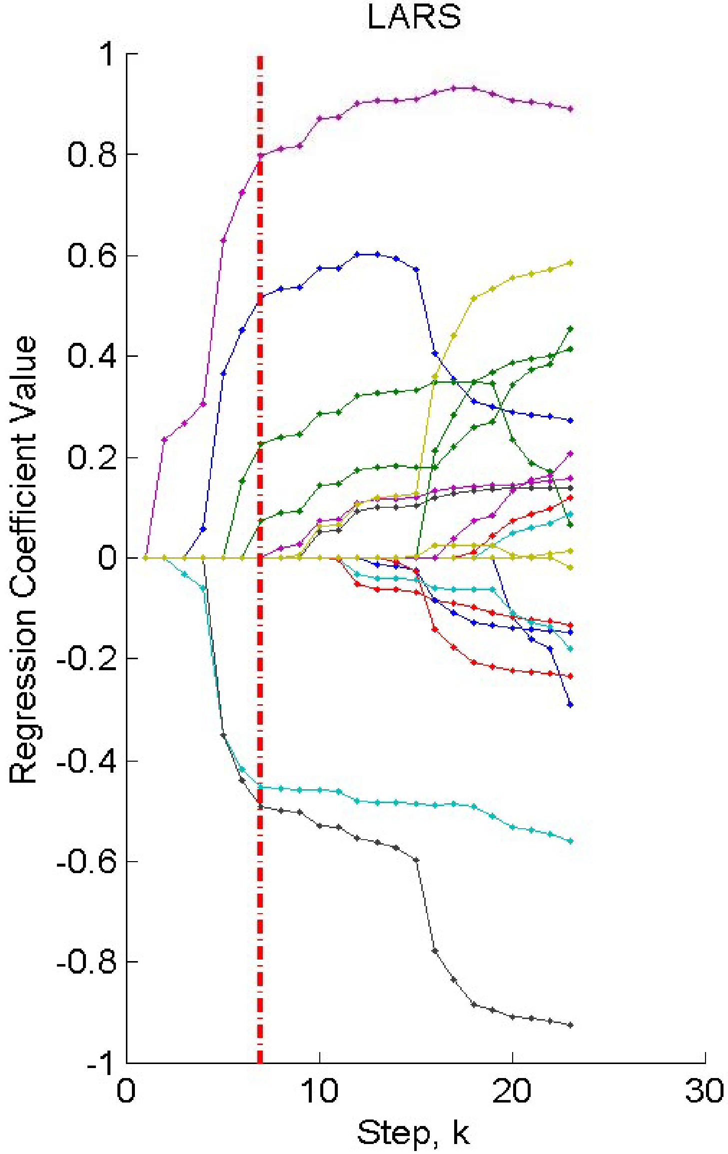
- Datasets from IBM (Dr. Sani Nassif) and BWRC/ST (through Professor Bora Nikolic)
- Funding from SRC, IMPACT/UC Discovery, C2S2 and TSMC

Thank you for your attention!

Questions?

Least Angle Regression with Cp Selection





Lot 7, Wafer 9, Terms = 1, 2, 4, 7, 9, 12