Electromigration-aware Interconnect Design

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Acknowledgments
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ISPD 2002

International Symposium on Physical Design

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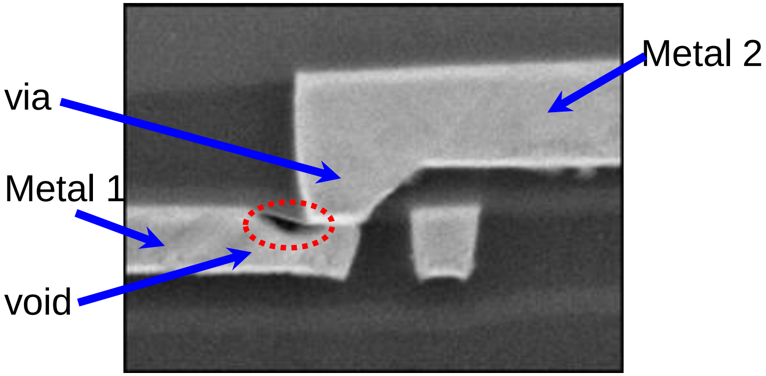
San Francisco, California, USA

Outline

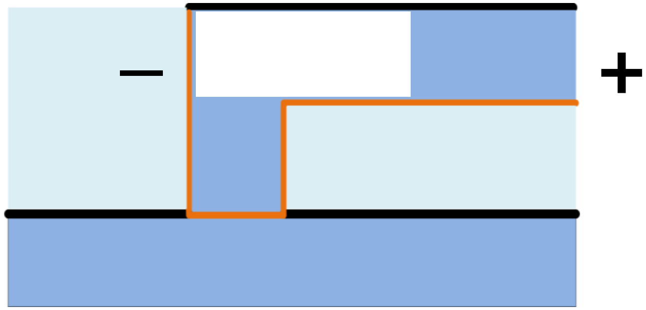
- Overview of electromigration
- EM modeling
- The weakest-link model (and why it's problematic)

Interconnect aging

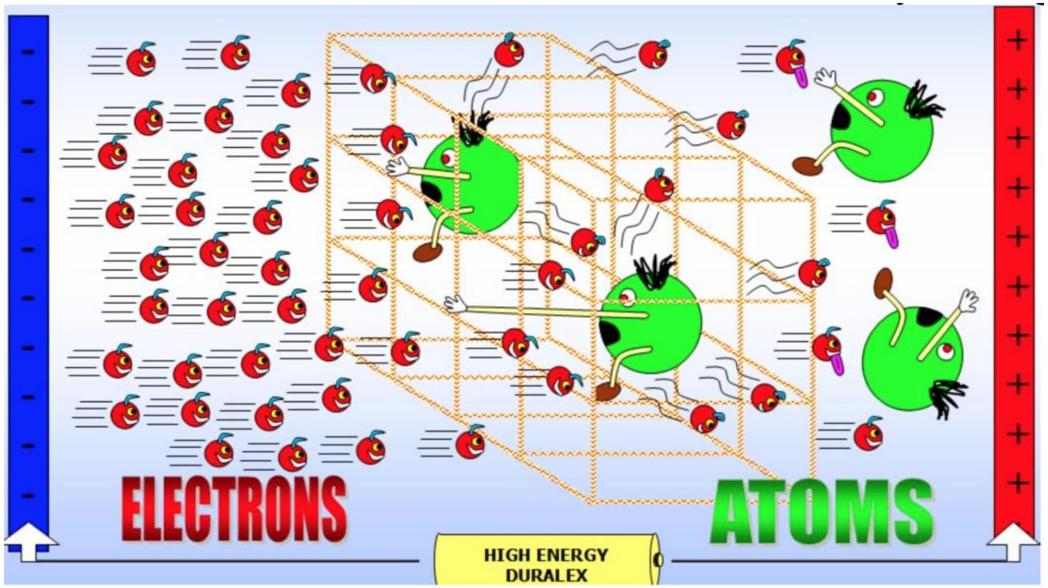
- Electromigration (EM)



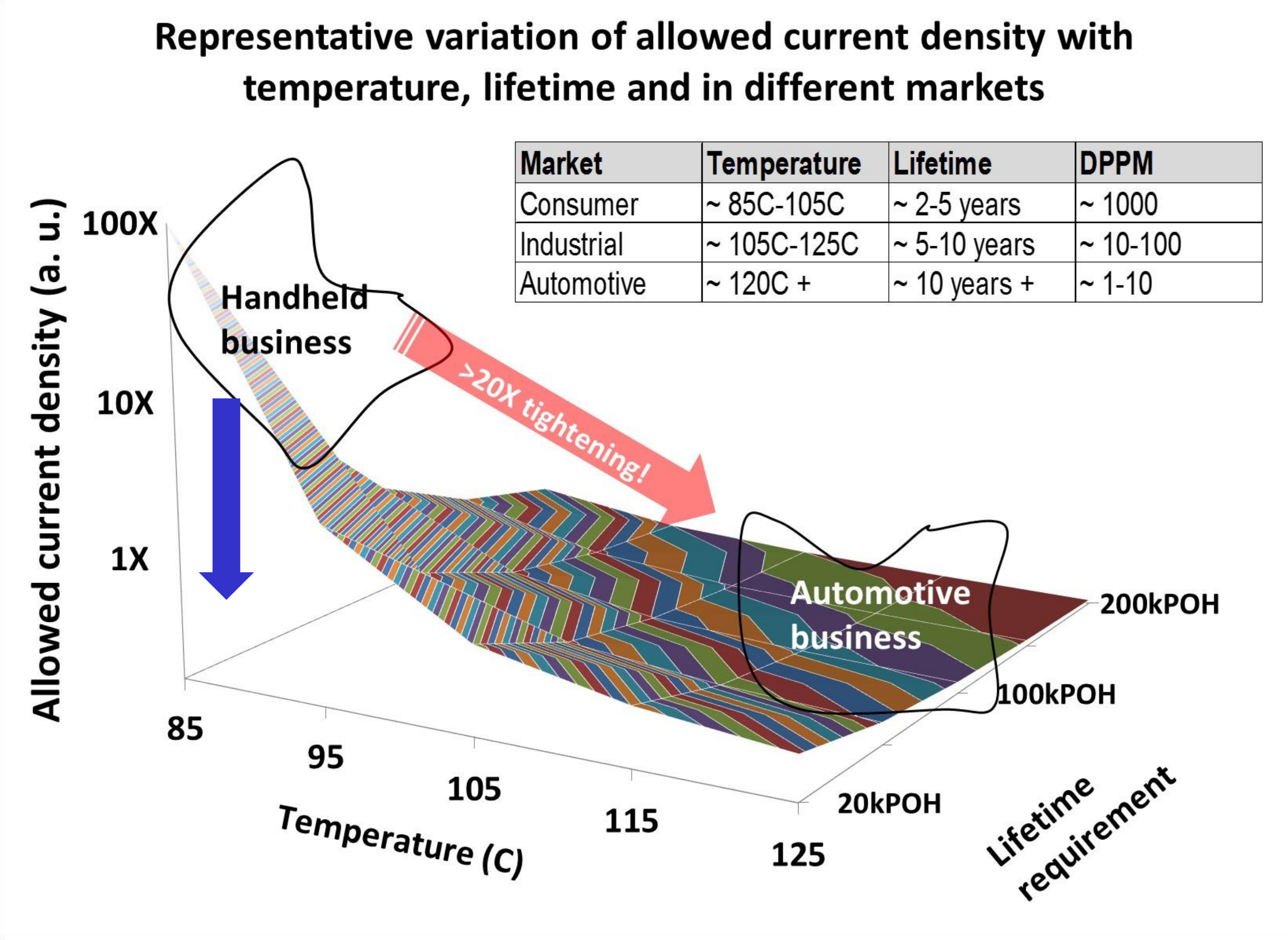
Cross-section TEM image



[Li, IRPS ’09]



Traditional view of EM



Market	Temperature	Lifetime	DPPM
Consumer	~ 85C-105C	~ 2-5 years	~ 1000
Industrial	~ 105C-125C	~ 5-10 years	~ 10-100
Automotive	~ 120C +	~ 10 years +	~ 1-10

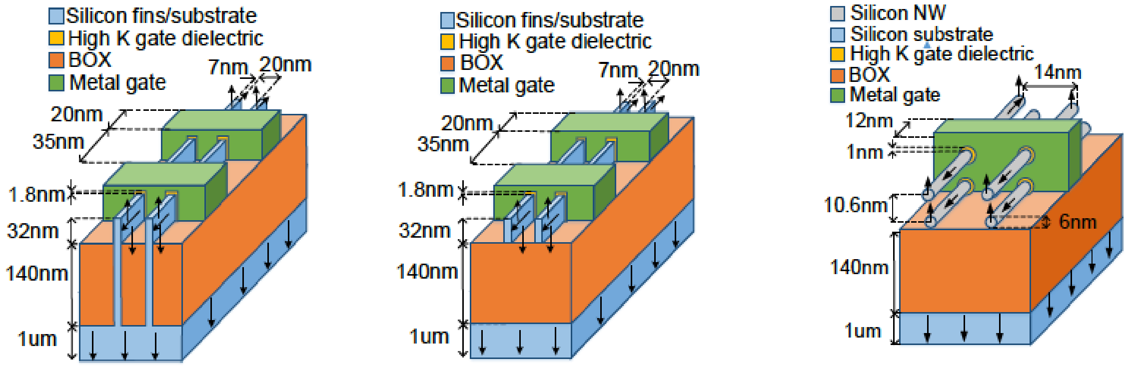
+ I/O drivers

+FinFETs,GAAFETs

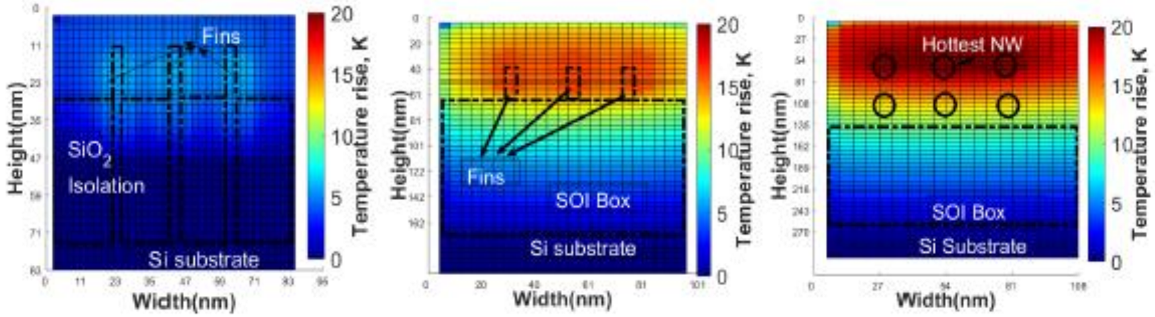
[Jain, TVLSI June 16]

Self heating

- Joule heating in wires
- Multigate FETs make things worse
  - Larger degrees of self-heating, worse paths to the ambient



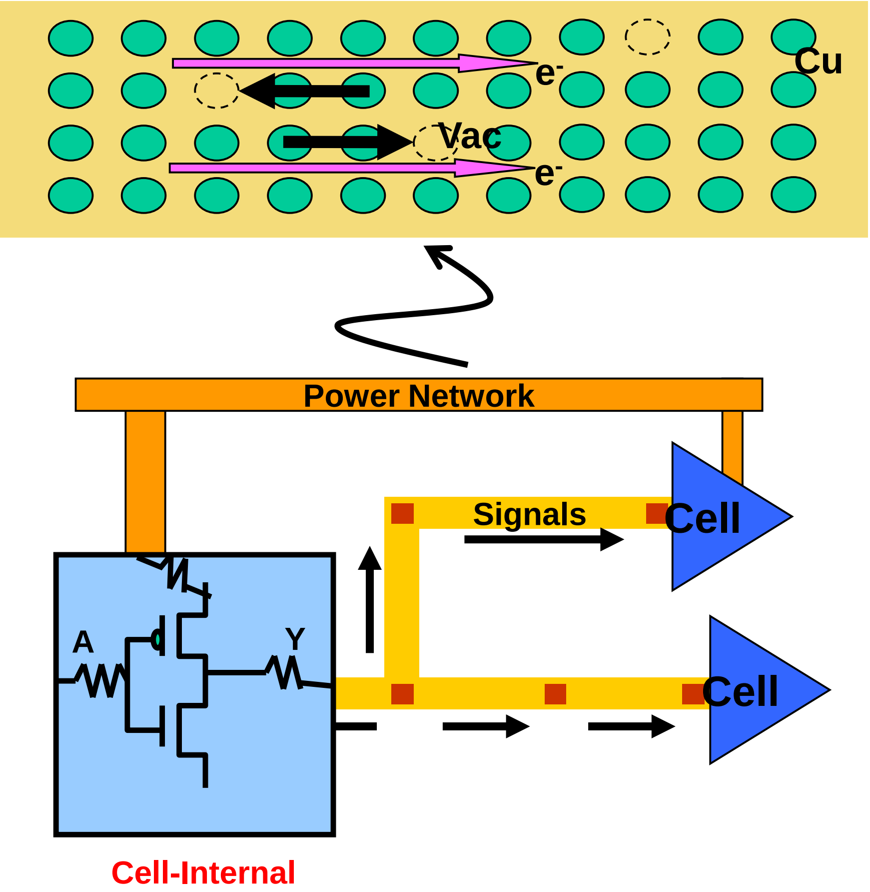
Bulk FinFET SOI FinFET GAAFET

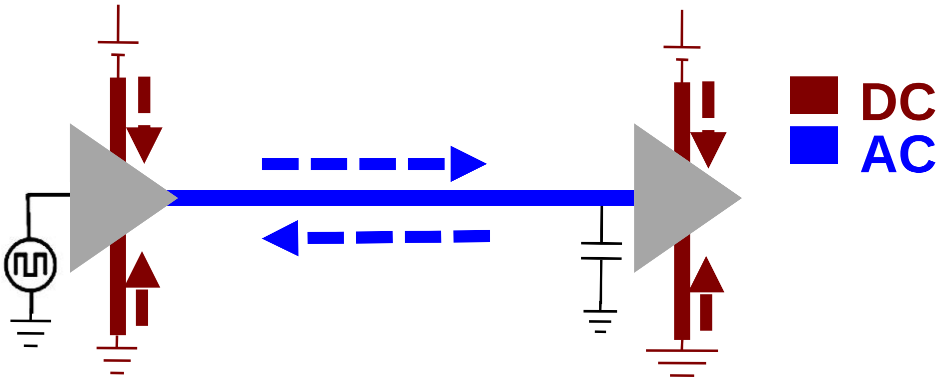


[Chhabria, ISQED 19]

Which interconnects?

- Power grids
  - Largely unidirectional current
- Signal interconnects
  - Bidirectional current flow
  - Recovery effects seen





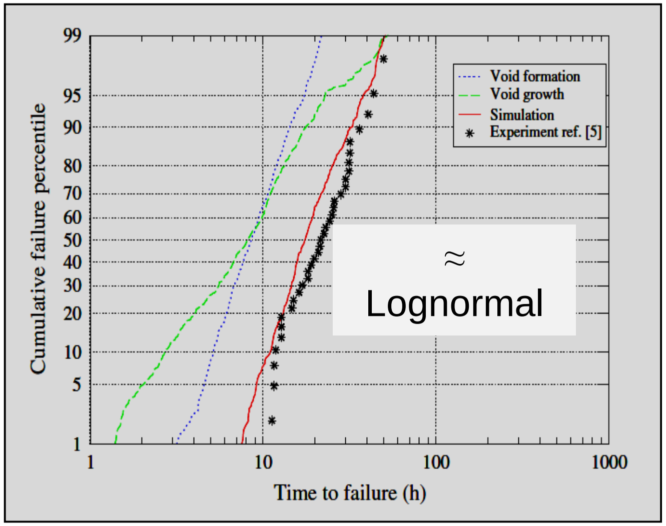
Outline

- Overview of electromigration
- EM modeling
- The weakest-link model (and why it's problematic)

Black's law

- Black's law
  - Predicts mean time to failure

$$t_{50} = A j_{AVG}^{-n} exp\left(\frac{Q_{EM}}{k_B T}\right); \Delta T \propto j_{RMS}^2$$



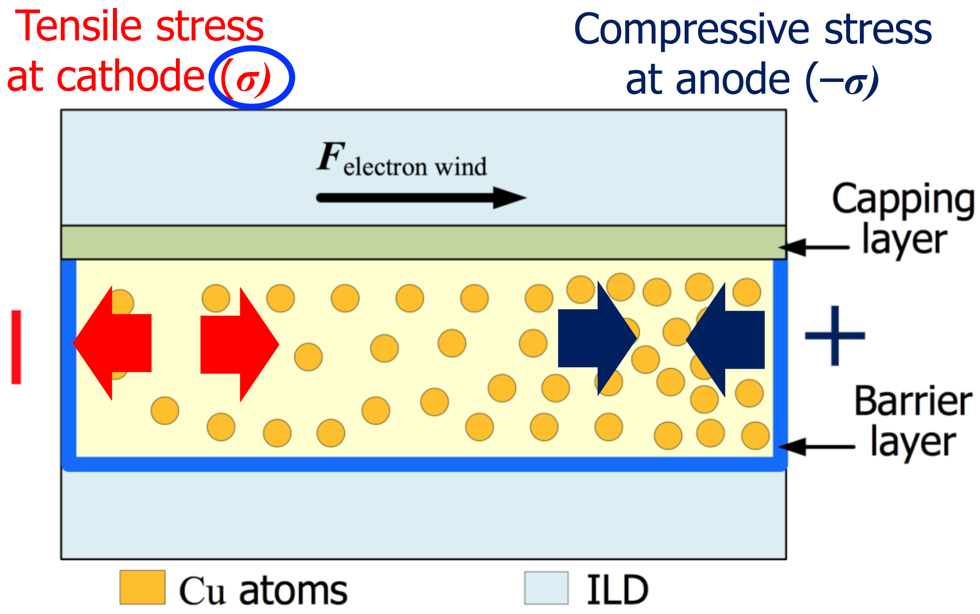
≈ Lognormal

- TTF follows a lognormal distribution
  - For a fail fraction FF, defects in parts per million (DPPM)

$$t_z = t_{50} e^{z/\sigma} \qquad FF = \int_{-\infty}^{z} \frac{e^{-x^2/2}}{\sqrt{2\pi}} dx$$

  - Constraint on t_z → Constraint on t_{50} → Constraint on j_{AVG}
  - Joule heating → Constraint on j_{RMS}
- Circuit-level EM constraint:
  - For each wire, stay within $j_{RMS,max}$, $j_{AVG,max}$

Physics of mortality and the Blech criterion



Atomic diffusion creates stress gradient that causes $F_{\text{back-stress}}$

Blech criterion

At steady state,
$F_{\text{electron wind}} = F_{\text{back-stress}}$

If: At steady state, $\sigma < \sigma_{\text{critcal}}$
then: wire is immortal!
(voids never form)

$\sigma < \sigma_{\text{critcal}} \Rightarrow J \times L < K_1$ (Blech criterion)

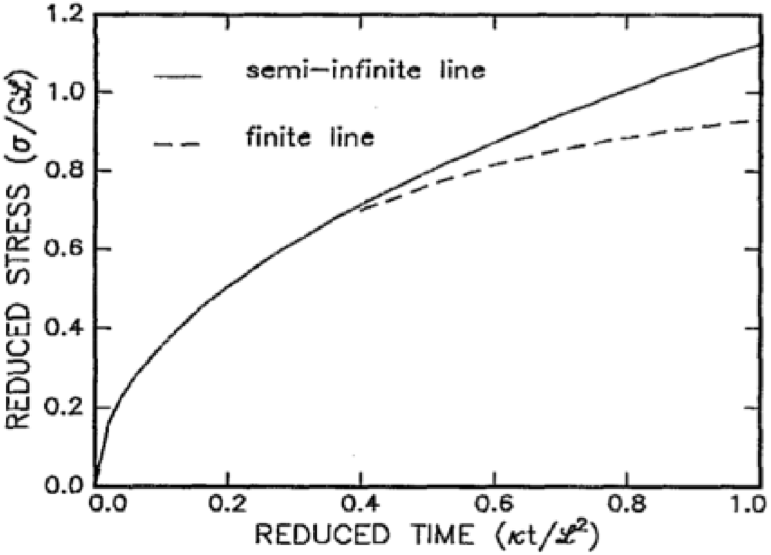
σ_{critcal}: Critical stress needed for void formation

Physics-based EM analysis

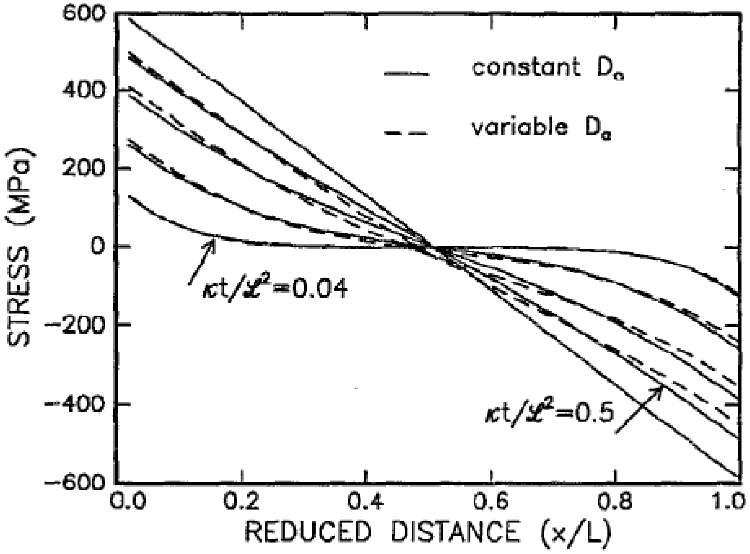
- Korhonen model
  - Void nucleation

$$\frac{\partial \sigma_H}{\partial t} = \frac{\partial}{\partial x}\left[\kappa\left(\frac{\partial \sigma_H}{\partial x} + G\right)\right]$$

$$\frac{\partial \sigma}{\partial t} = \frac{\partial}{\partial x}[\kappa\,(F_{\text{back-stress}} + F_{\text{electron wind}}\ )]$$



Stress at a blocking boundary (cathode)



Stress evolution along the wire

[Korhonen, JAP 1993]

EM mortality: Issues with classical approach

Blech criterion

if: $J \times L < K_1$
Wire immortal to EM
else: wire is
potentially mortal

Steady state approach for mortality

Black's equation

For potential mortal wires:

$$\mathrm{TTF} = \frac{K_2}{J^n} \exp\left(\frac{K_3}{T}\right)$$

Empirical model, issues for Cu

[Lloyd, MER '07]

EM mortality: Classical vs. filtering approach

Blech criterion

if: $J \times L < K_1$
Wire immortal to EM
else: wire is
potentially mortal

Steady state approach for mortality

Black's equation

For potential mortal wires:

$$\mathrm{TTF} = \frac{K_2}{J^n} \exp\left(\frac{K_3}{T}\right)$$

Empirical model, issues for Cu

[Lloyd, MR '07]

Filtering approach

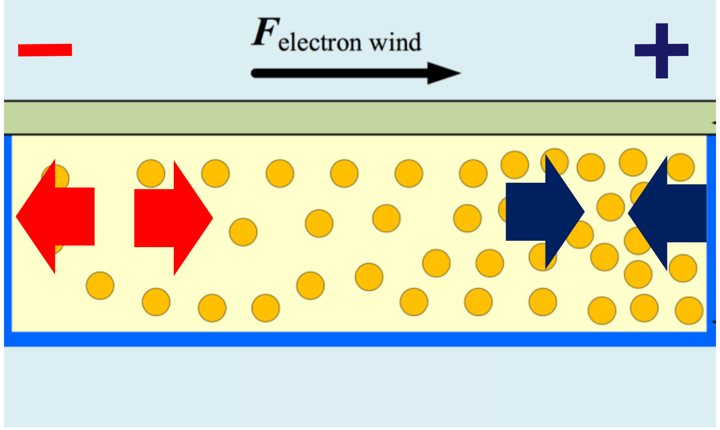
Transient state approach for mortality

Physics-based, applicable for Cu

EM mortality: Mechanical stress evolution

Tensile stress at cathode (σ)

Compressive stress at anode ($-\sigma$)

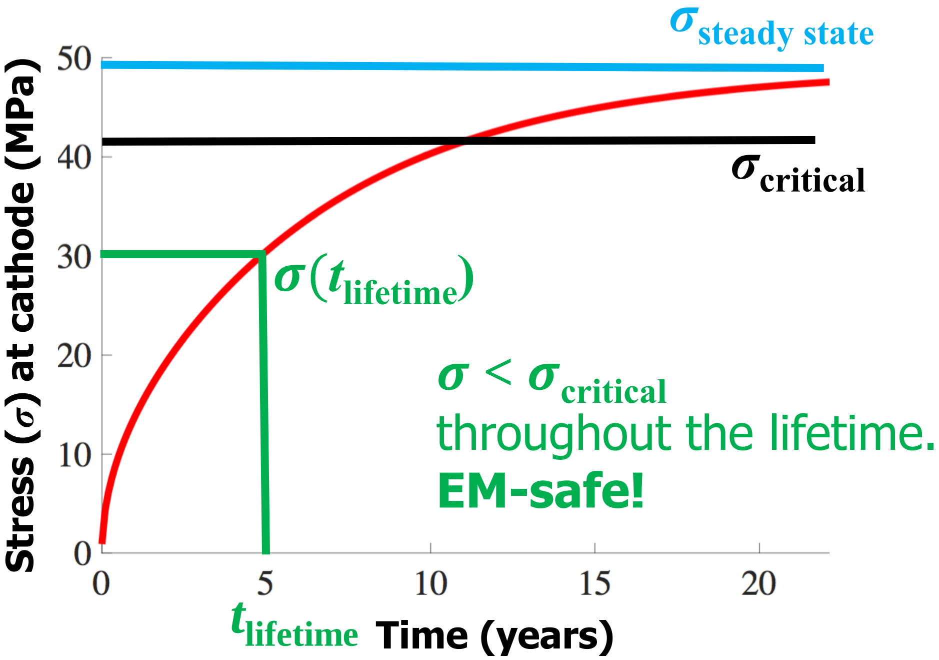


● Cu atoms

Atomic diffusion creates stress gradient that causes $F_{\text{back-stress}}$

Blech criterion presumes **steady state** between $F_{\text{electron wind}}$ and $F_{\text{back-stress}}$

Potentially mortal by Blech criterion



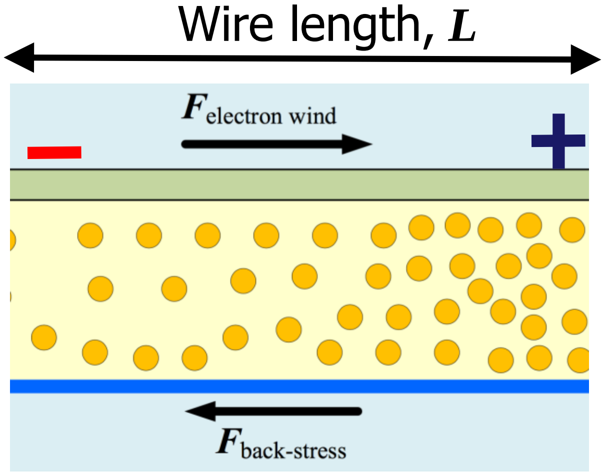
$\sigma < \sigma_{\text{critical}}$ throughout the lifetime.
EM-safe!

1. **Practical EM mortality: relative to the product lifetime**
2. **Transient stress evolution instead of steady state**

EM mortality: Modeling transient stress

EM equation

$$\frac{\partial \sigma}{\partial t} = \frac{\partial}{\partial x}\left[\kappa\left(F_{\text{back-stress}} + F_{\text{electron wind}}\right)\right]$$



Stress at cathode, $\sigma(t)$, 2 options:

1. **Semi-infinite *(SI)*:**

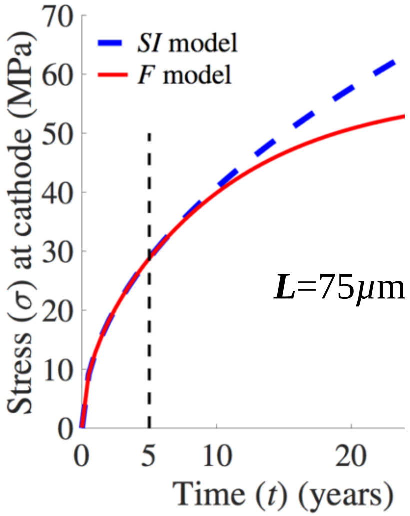
$$\sigma(t) = \alpha_1 J \sqrt{t}$$

Efficient, but overestimates stress

2. **Finite *(F)*:**

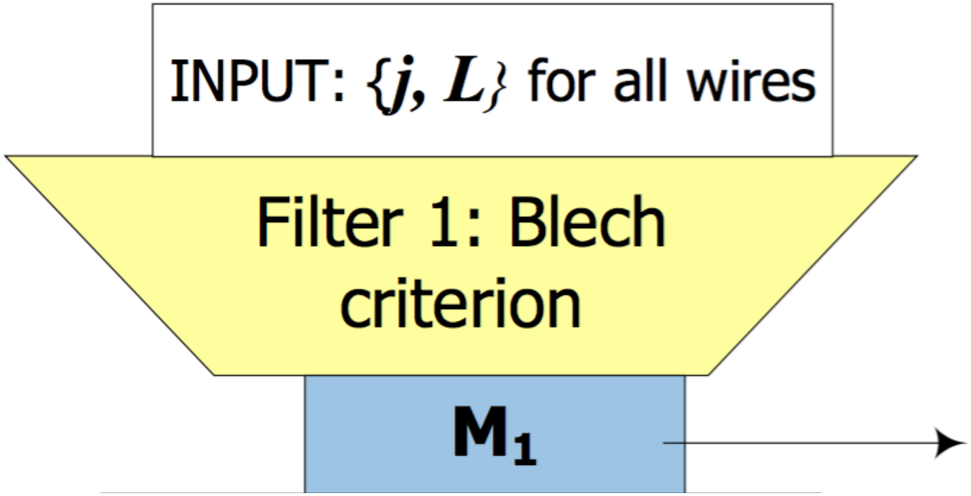
$$\sigma(t) = J\,L\,\alpha_2\left(\frac{1}{2} - \sum_{n=0}^{\infty}\frac{e^{-m_n^2\frac{t\,\alpha_3}{L^2}}}{m_{n^2}}\right)$$

Inefficient, but accurate prediction



Extension to interconnect trees using [Park, IRPS10]

Sequential mortal wire filtration



INPUT: $\{j, L\}$ for all wires

Filter 1: Blech criterion

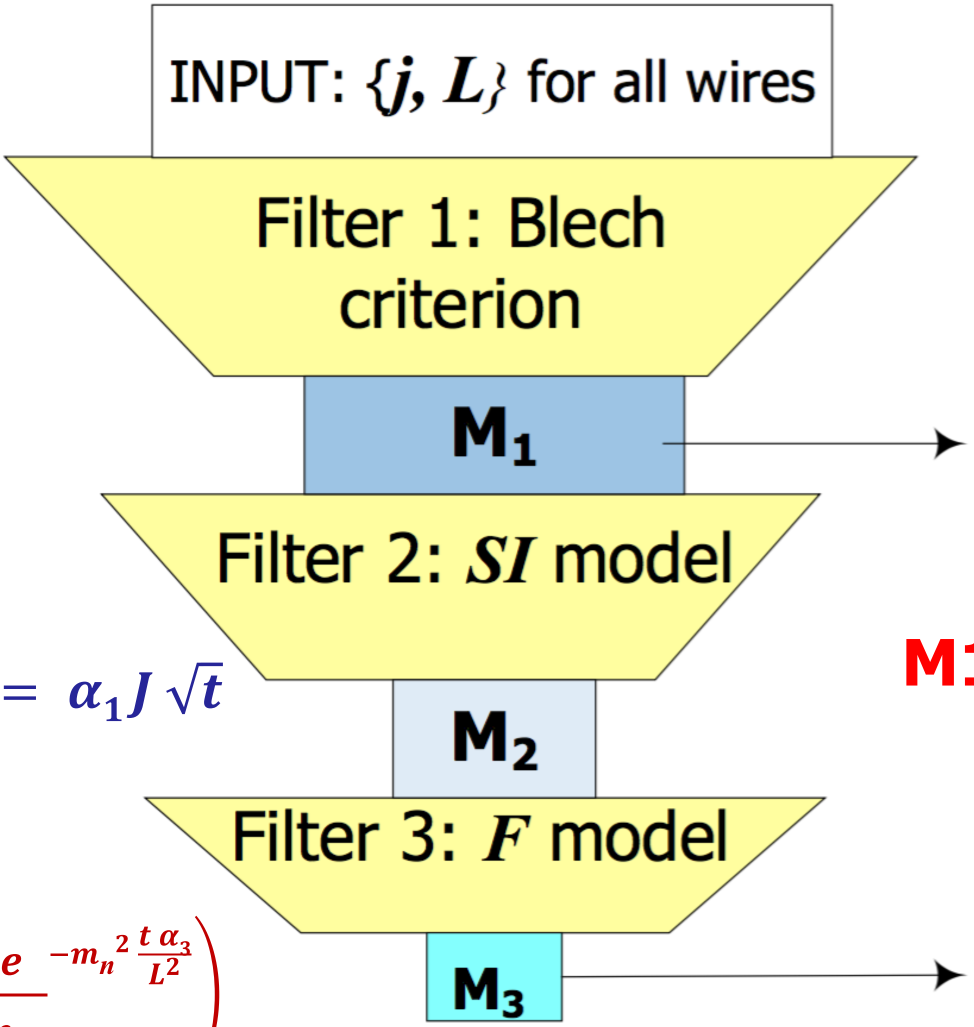
$\mathbf{M_1}$

M$_1$: OUTPUT of the Blech criterion

M$_N$: Mortal wires after Filter$_N$

Sequential mortal wire filtration

M_N: Mortal wires after Filter_N



INPUT: $\{j, L\}$ for all wires

Filter 1: Blech criterion

M_1

M_1: OUTPUT of the Blech criterion

Filter 2: SI model

$$\sigma(t) = \alpha_1 J \sqrt{t}$$

M_2

M1 ⊃ M2 ⊃ M3

Filter 3: F model

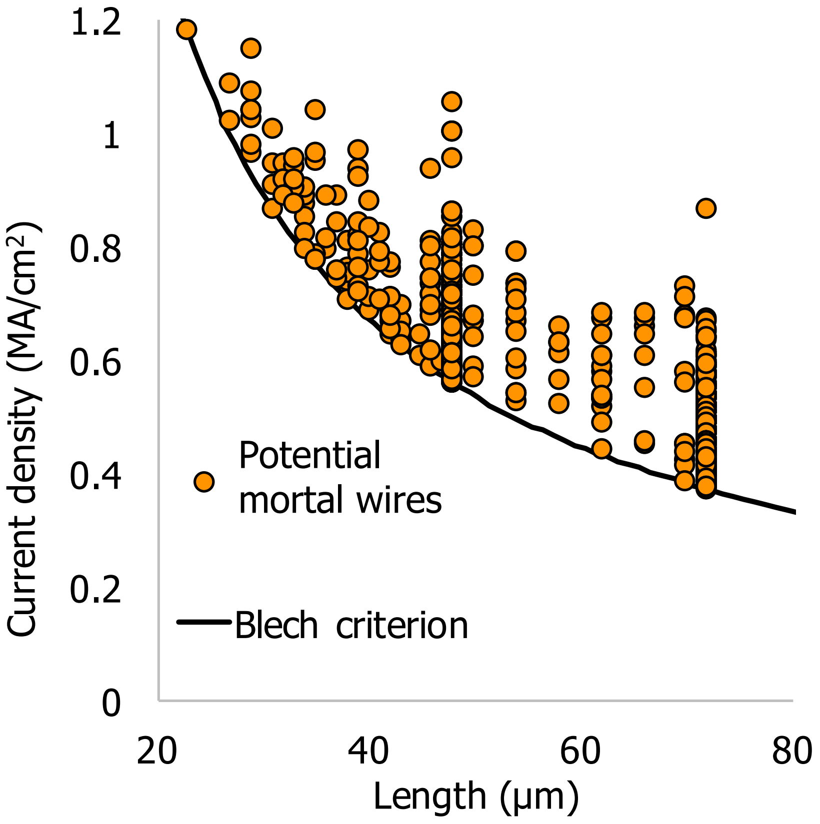
M_3

M_3: OUTPUT of our mortality criterion

$$\sigma(t) = J\,L\,\alpha_2\left(\frac{1}{2} - \sum_{n=0}^{\infty}\frac{e^{-m_n^2\frac{t\,\alpha_3}{L^2}}}{m_n^2}\right)$$

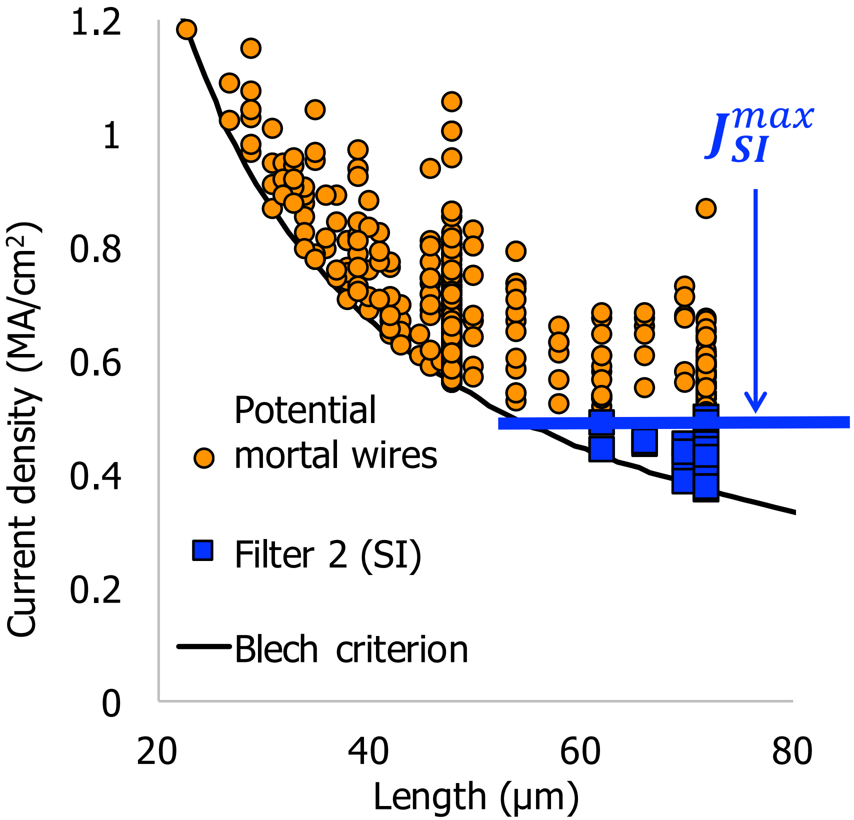
IBMPG case study: PG2 mortal wire distribution

Potential Mortal wires from the Blech criterion



IBMPG case study: PG2 mortal wire distribution

Immortal wires filtered out using pessimistic Filter 2 (SI)

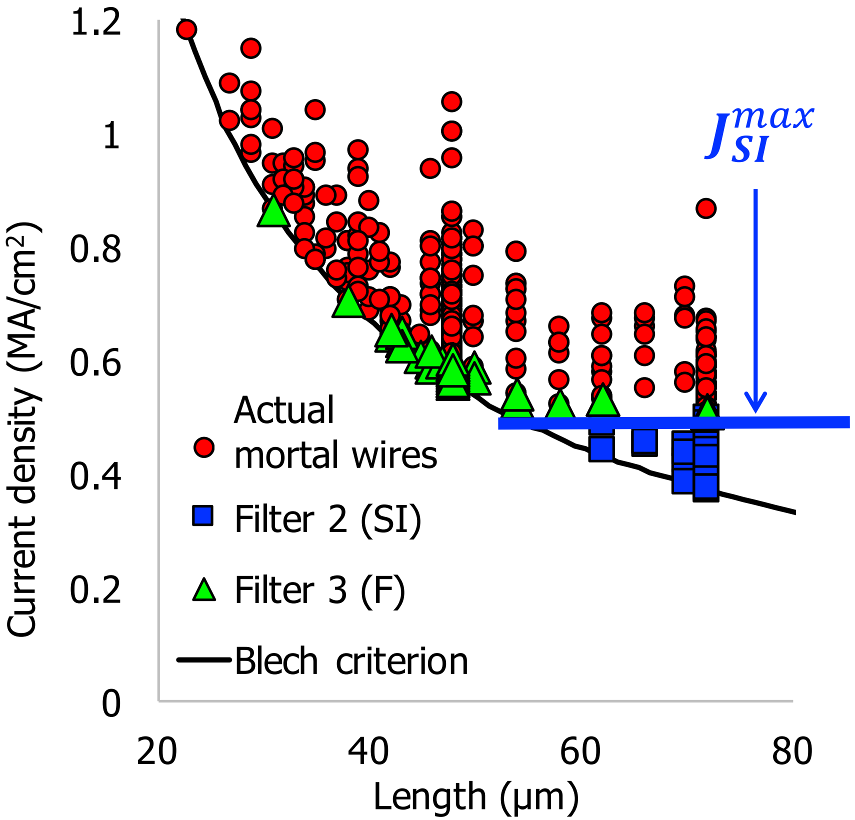


Product lifetime = 10 years

Temperature (T) = 105C

IBMPG case study: PG2 mortal wire distribution

Immortal wires filtered out using pessimistic Filter 2 (SI) & accurate Filter 3 (F)

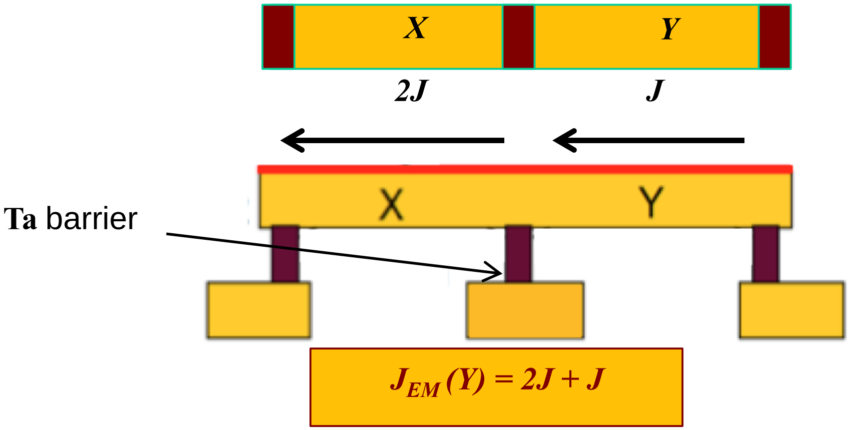


Product lifetime = 10 years

Temperature (T) = 105C

What about lines with branches? Vias?

- Flux Divergence
  - Current flow in neighboring wire affects EM flux
  - Use effective current for EM



- The above is approximate
  - There's a physics-based version for this too

[Park, IRPS10]

Outline

- Overview of electromigration
- EM modeling
- The weakest-link model (and why it's problematic)

Circuit impact

- Conventional way to overcome EM

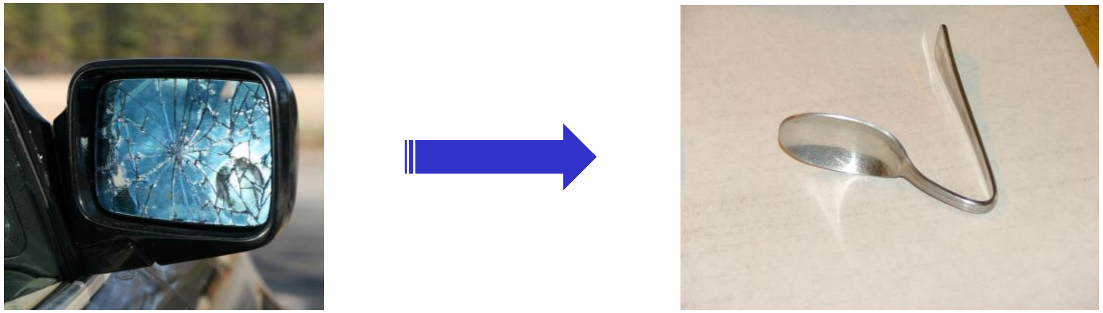
$$t_z = t_{50} e^{z/\sigma} \qquad t_{50} = A j_{AVG}^{-n} exp\left(\frac{Q_{EM}}{k_B T}\right)$$

  - Constraint on t_z → Constraint on t_{50} → Constraint on j_{AVG}
  - Joule heating → Constraint on j_{RMS}

- Circuit-level EM constraint:
  - For each wire, stay within $j_{RMS,max}$, $j_{AVG,max}$

- Weakest-link model

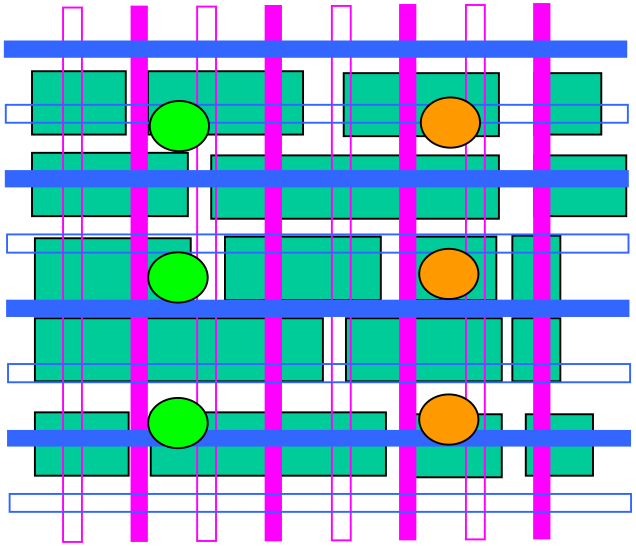
Handling catastrophic errors



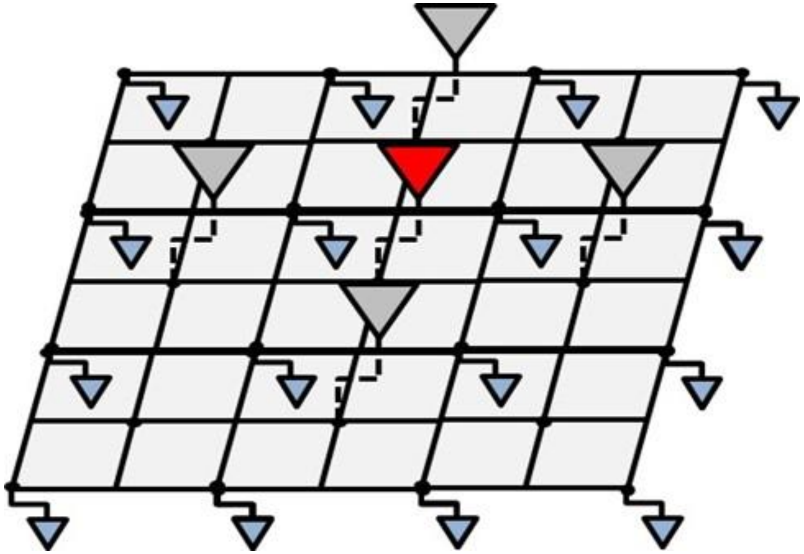
- A simple analysis of an n-component system
  - F_i = probability of failure of the i^{th} component
  - $1 - F_i$ = probability that the i^{th} component works
  - n = number of components in the system
  - $(1 - F_i)^n$ = probability that all n components work
  - Probability of system failure = $1 - (1 - F_i)^n$
- Implicit assumptions
  - All failures are catastrophic
  - All failures are equally serious
  - All failures are independent

Interconnect redundancy

- Several on-chip interconnect systems are built to be redundant



Power grids

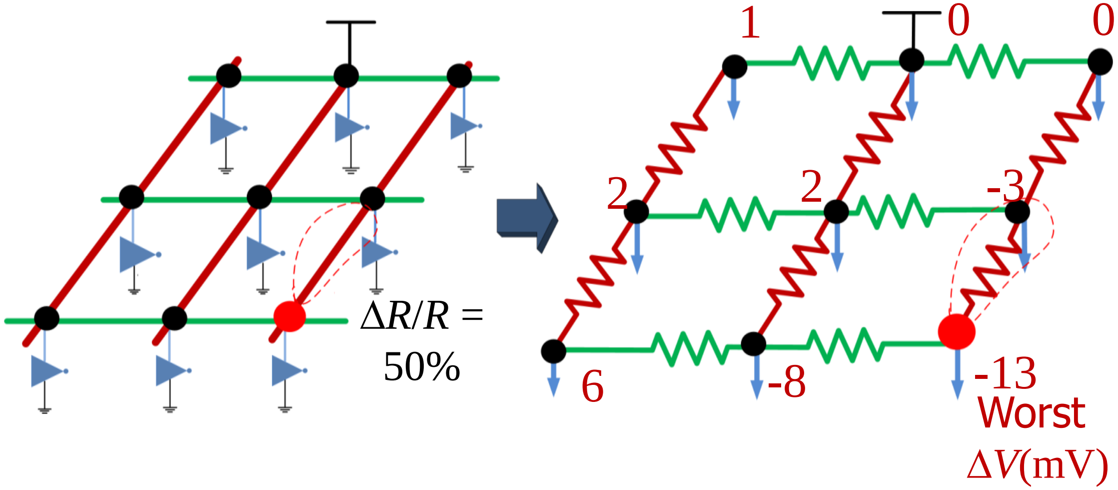


Clock grids

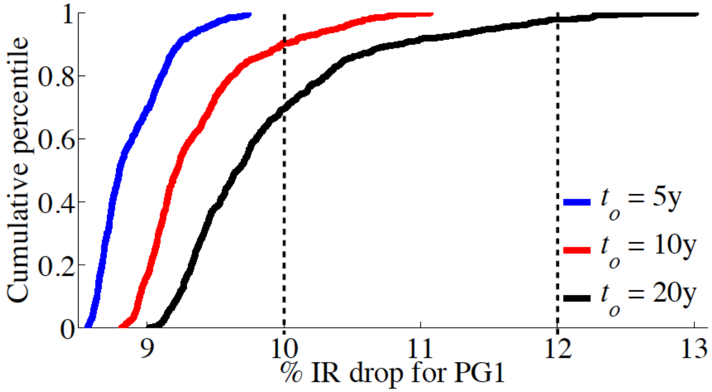
- A system fails when it’s key parameters fail – and NOT at first failure!

Electromigration in power grids

- Power grids are built to contain redundancies!

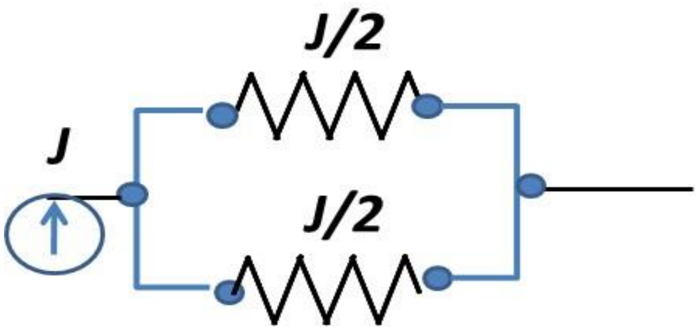


A better failure criterion:

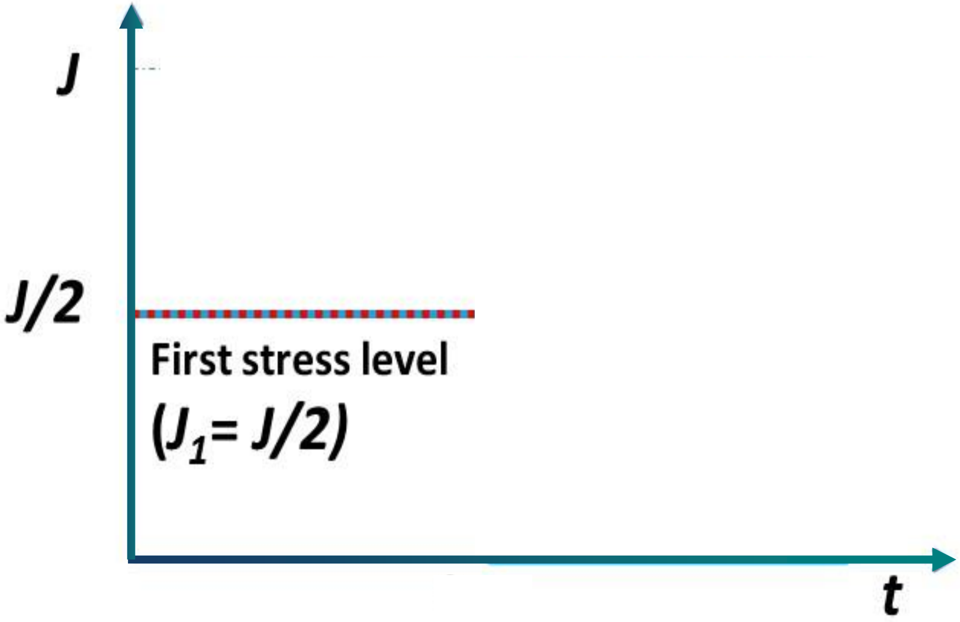


[Mishra, DAC13]

Analyzing redundancy

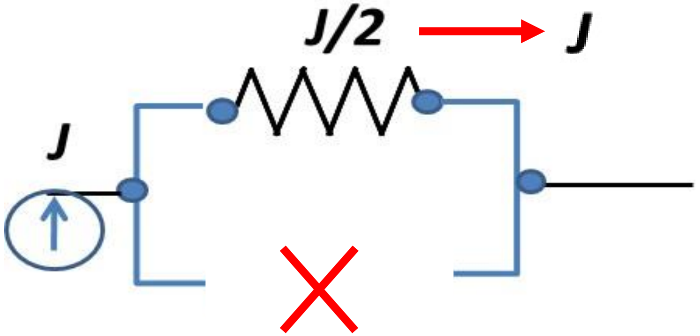


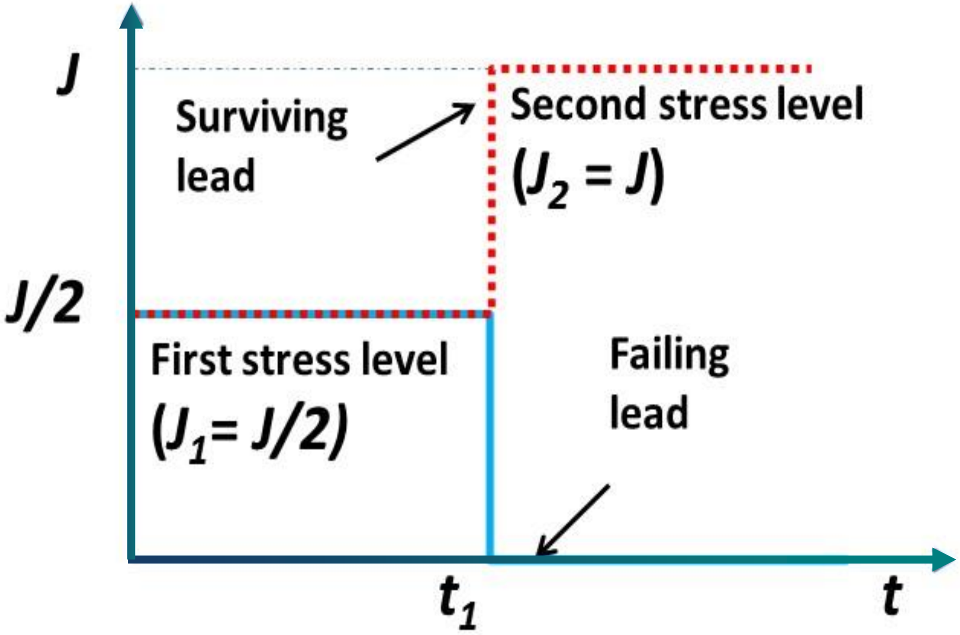
- Two component system: one of the two fails first



[Jain, IRPS15]

Analyzing redundancy

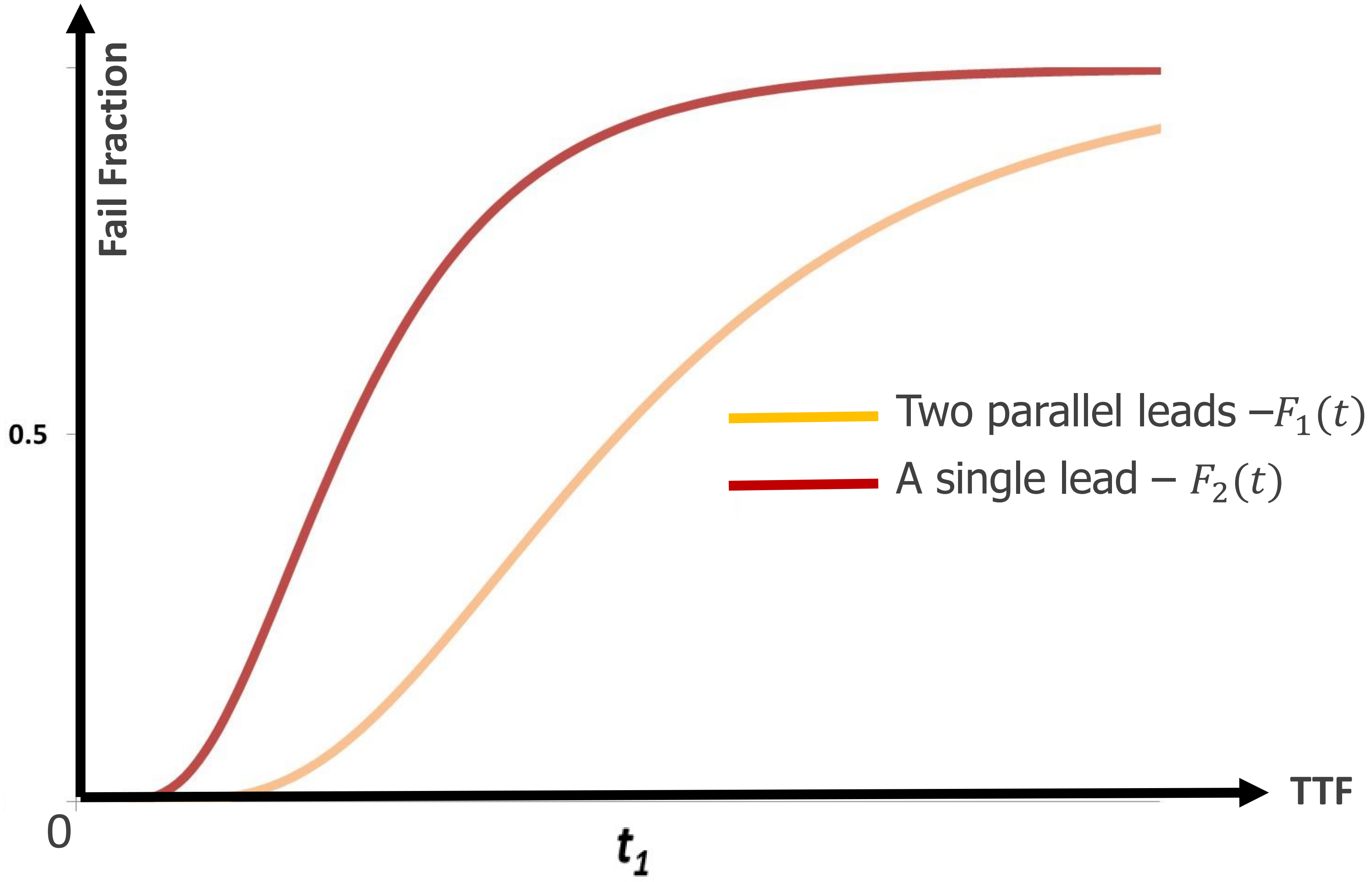




[Jain, IRPS15]

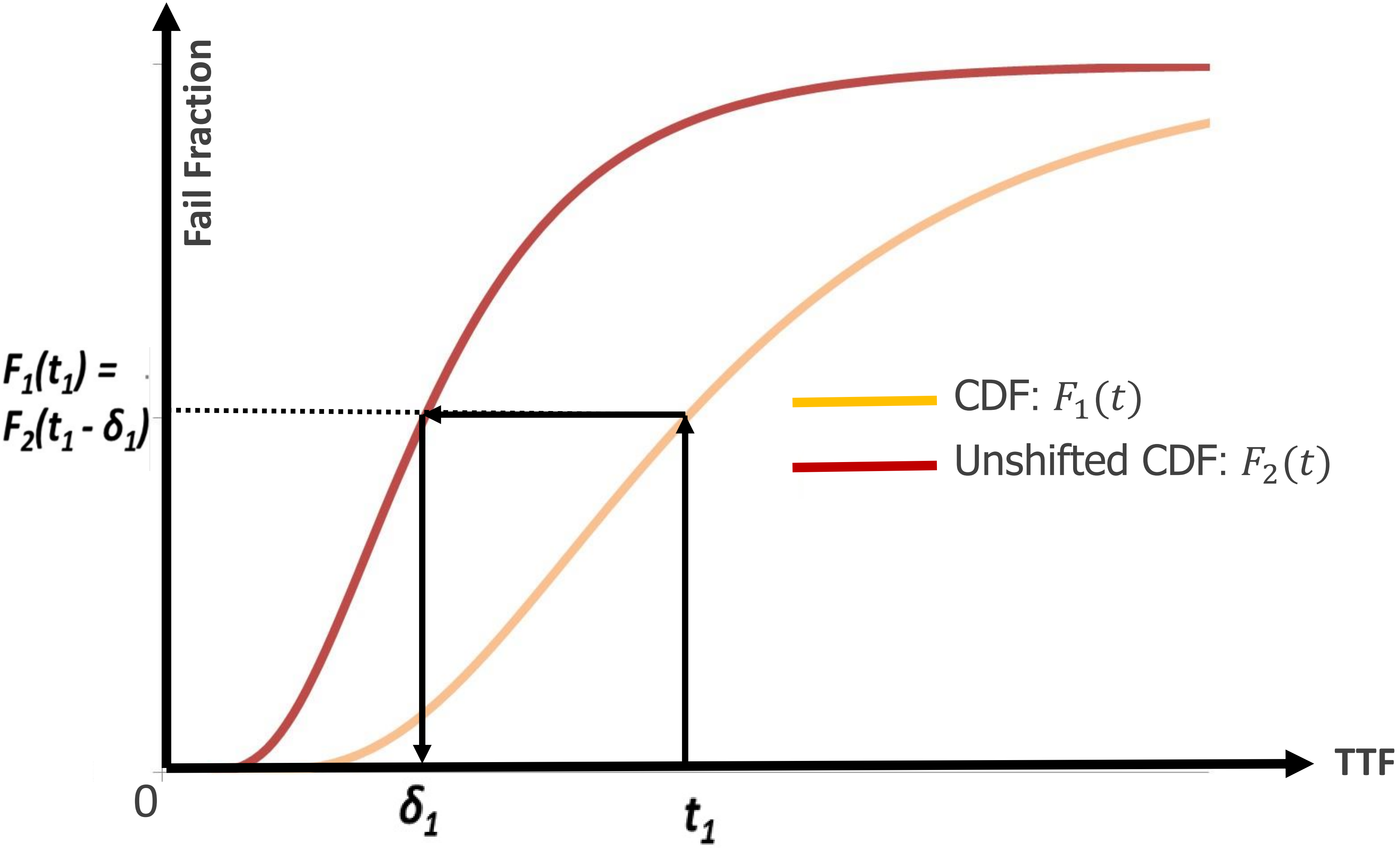
- Two-component system: one of the two fails first
- Post-failure: current goes through intact component

Reliability under changing stress



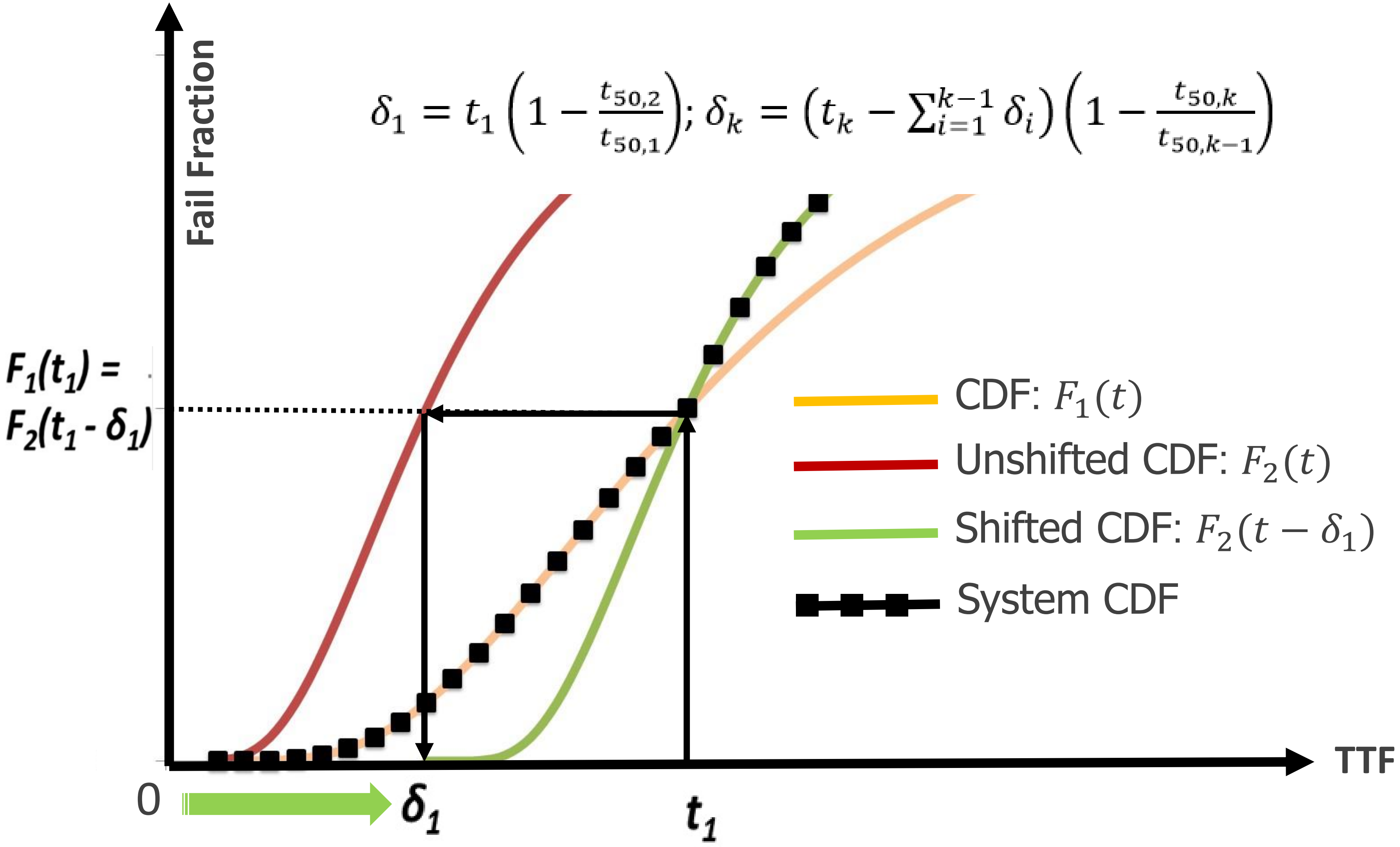
[Jain, IRPS15]

Reliability under changing stress



[Jain, IRPS15]

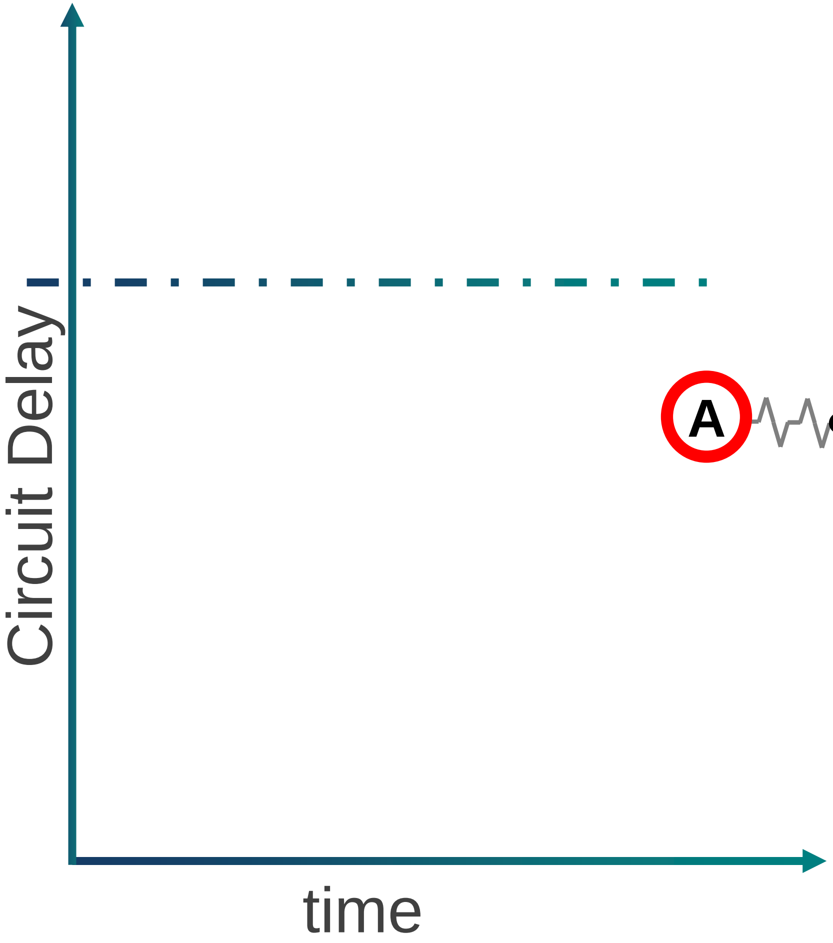
Reliability under changing stress

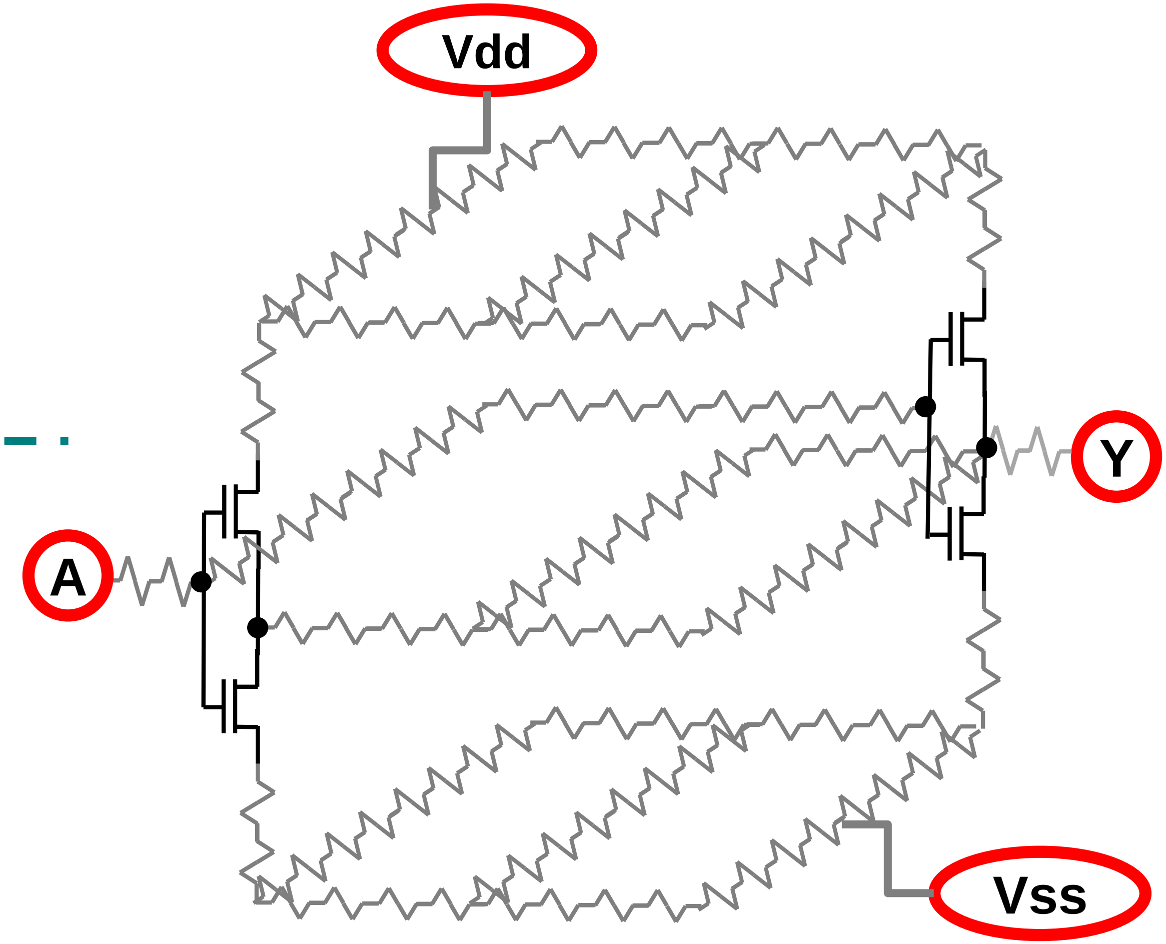


$$\delta_1 = t_1\left(1 - \frac{t_{50,2}}{t_{50,1}}\right);\ \delta_k = \left(t_k - \sum_{i=1}^{k-1}\delta_i\right)\left(1 - \frac{t_{50,k}}{t_{50,k-1}}\right)$$

[Jain, IRPS15]

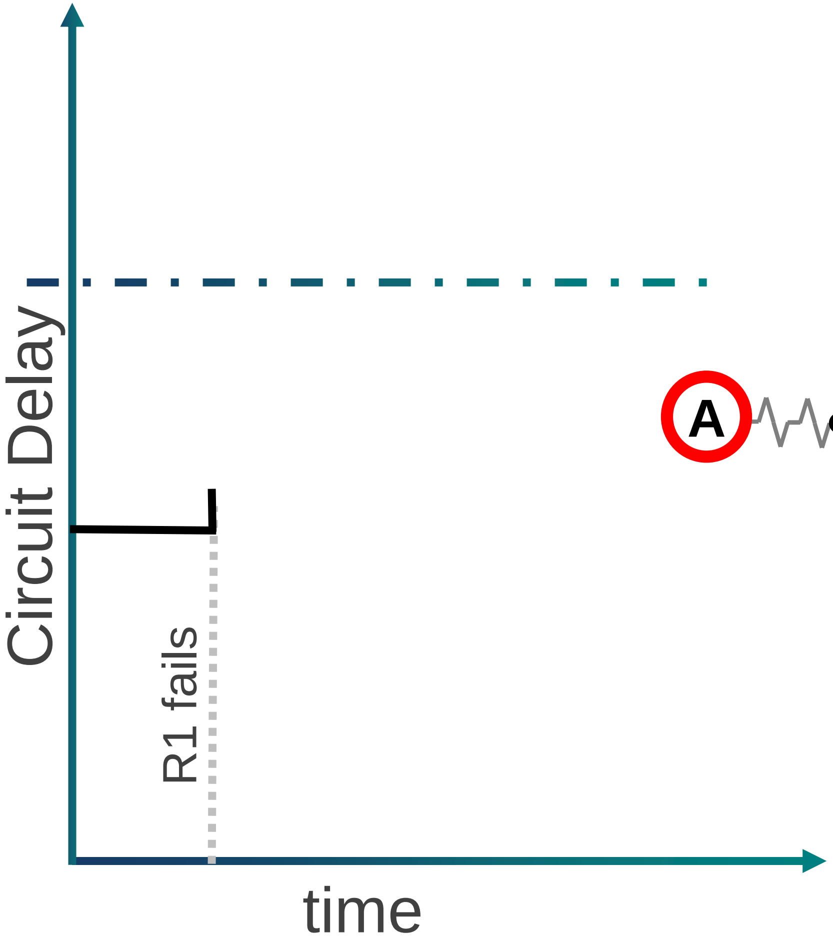
System impact for a clock grid

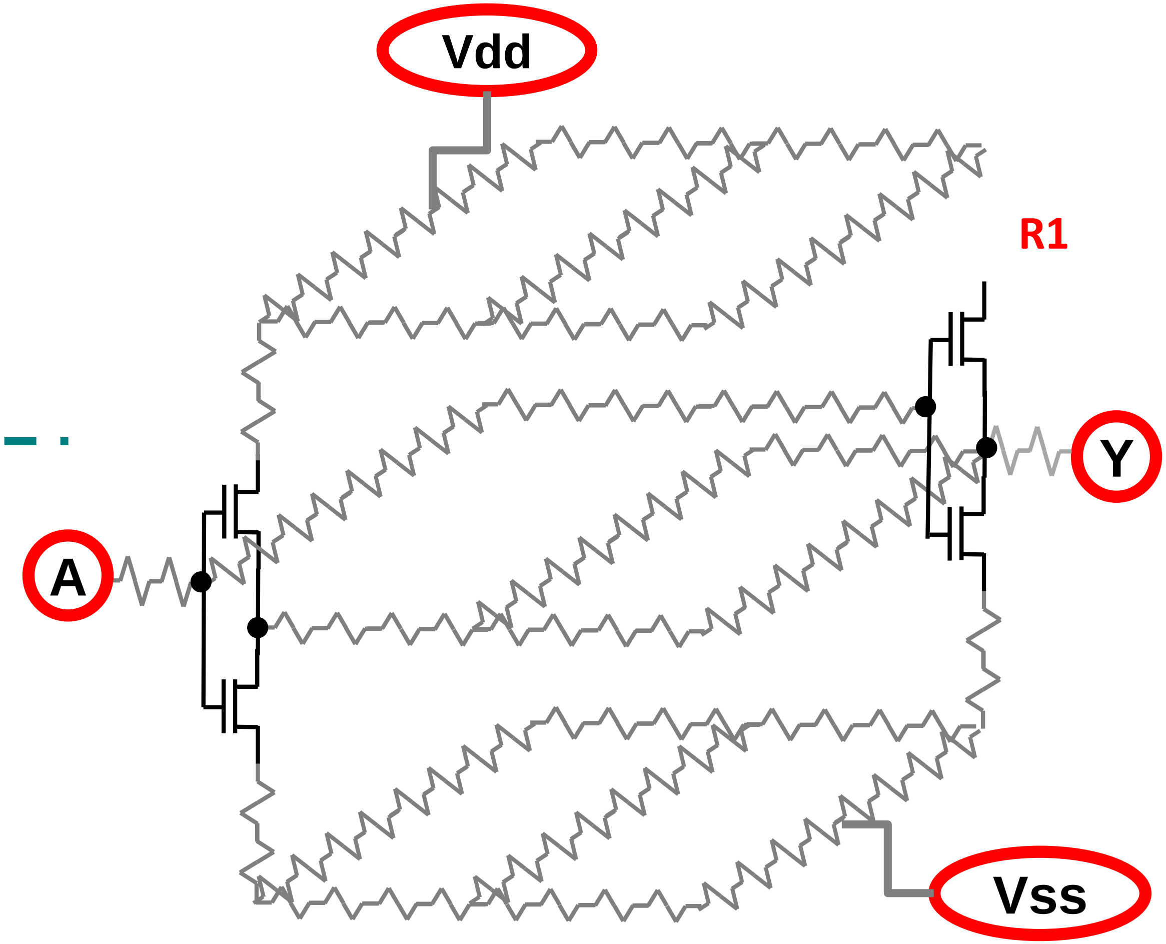




[Jain, IRPS15]

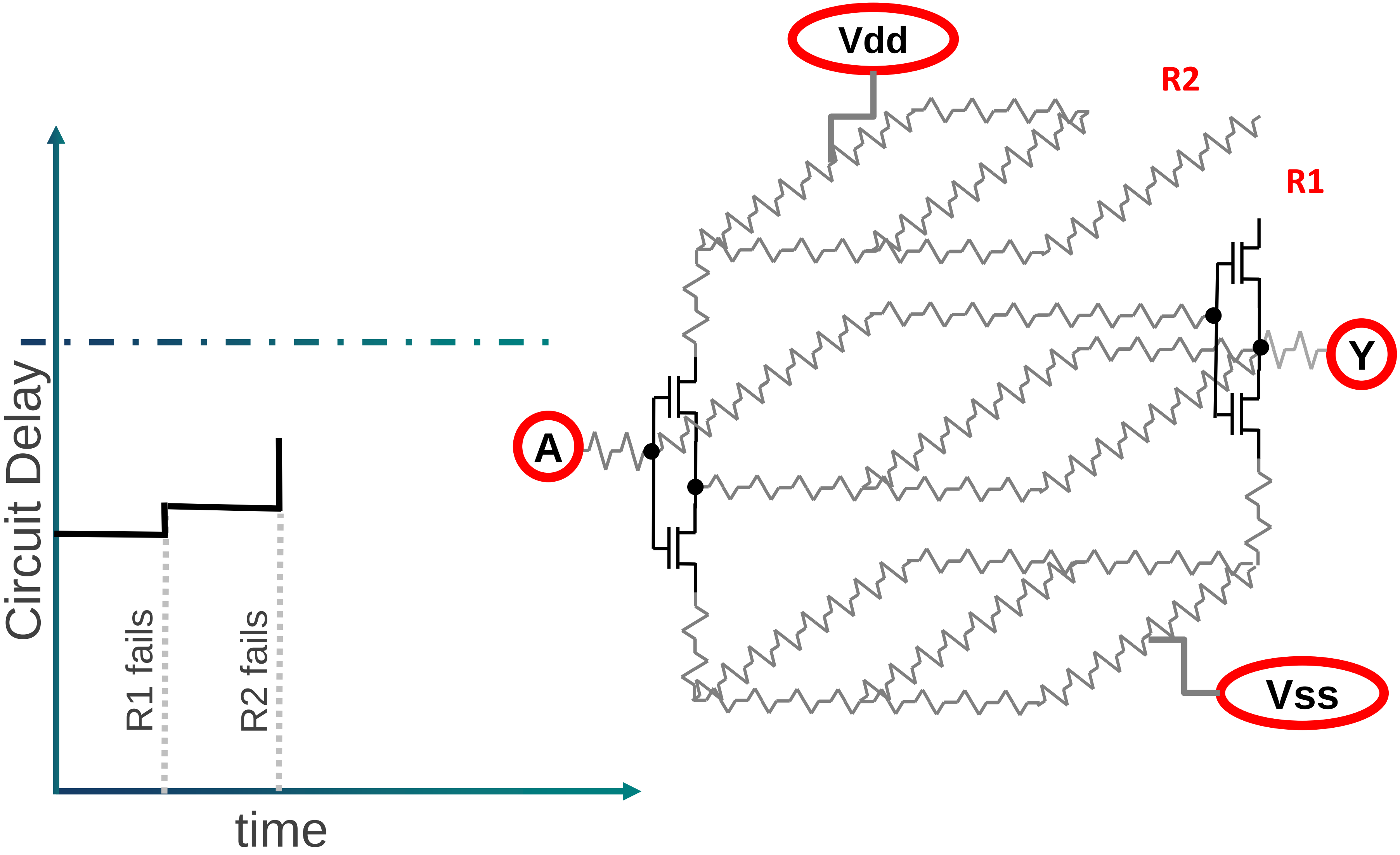
System impact for a clock grid





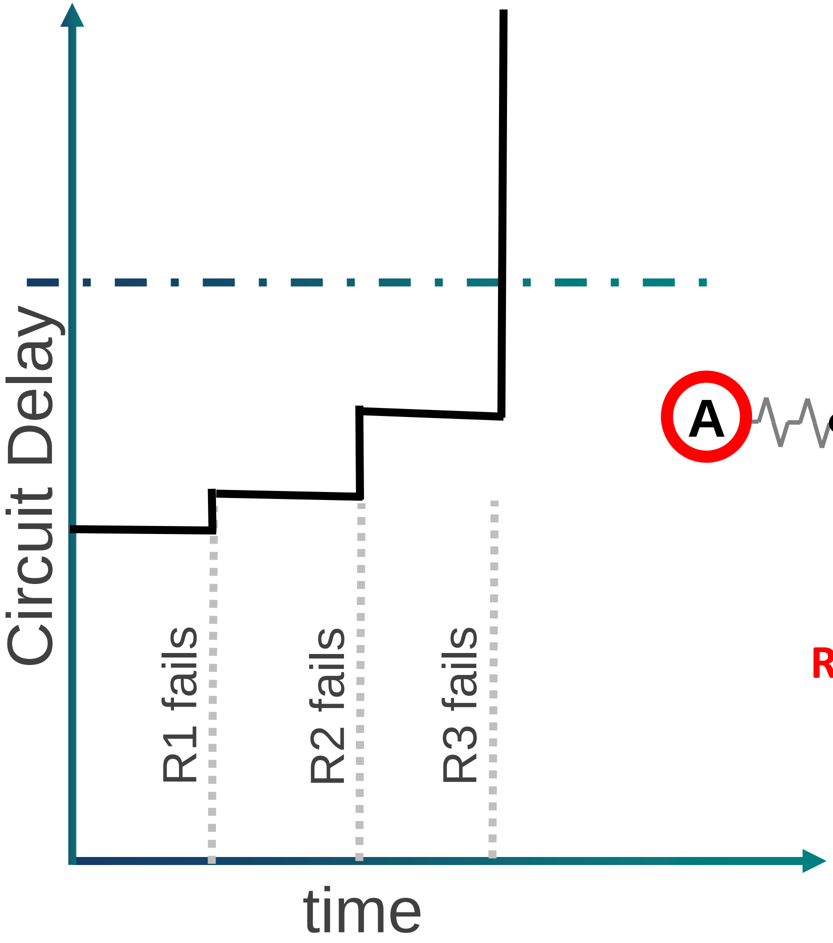
[Jain, IRPS15]

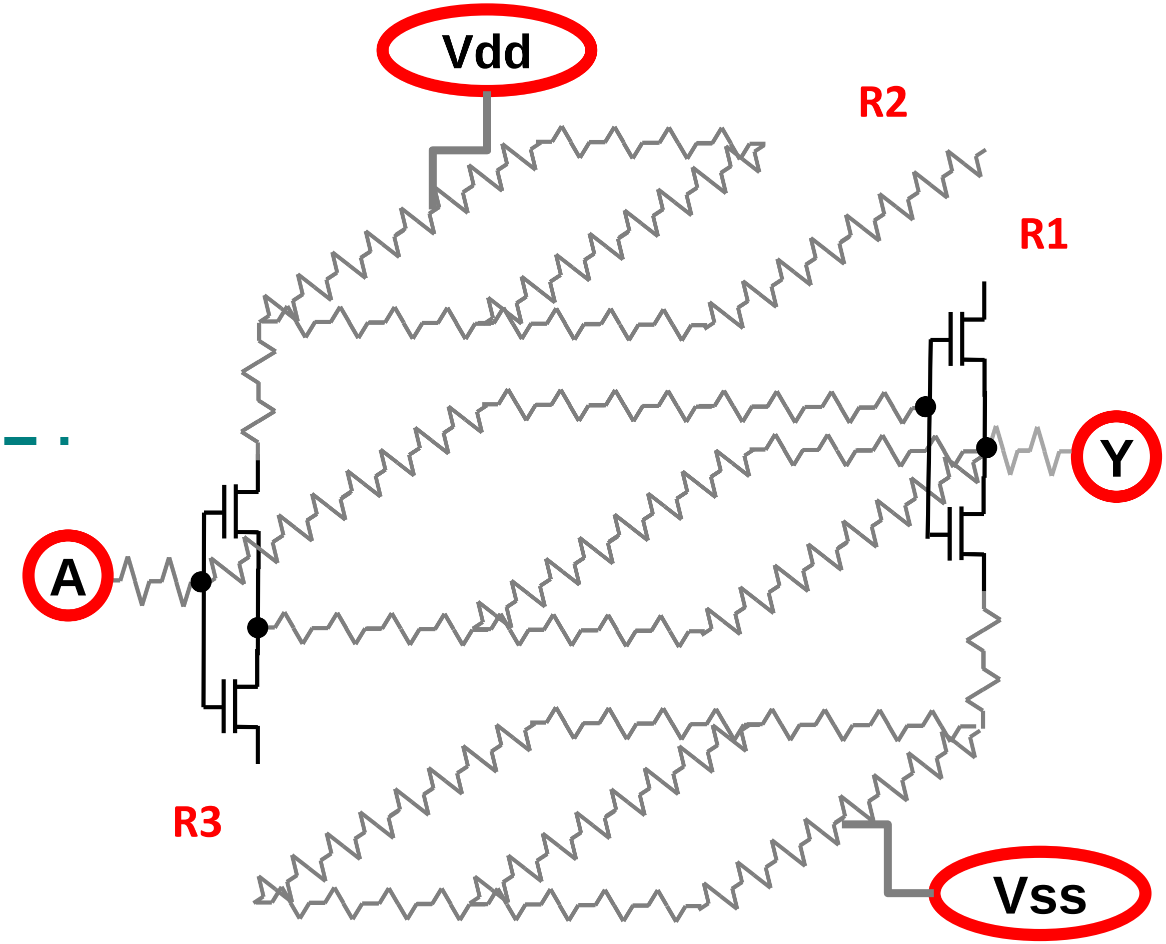
System impact for a clock grid



[Jain, IRPS15]

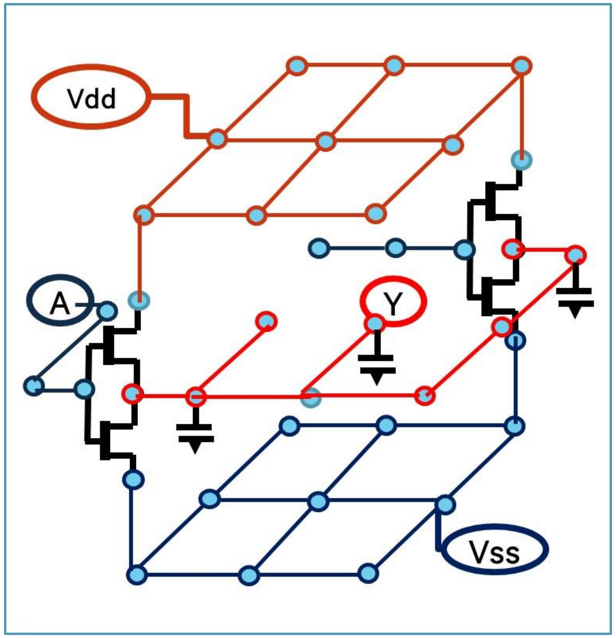
System impact for a clock grid

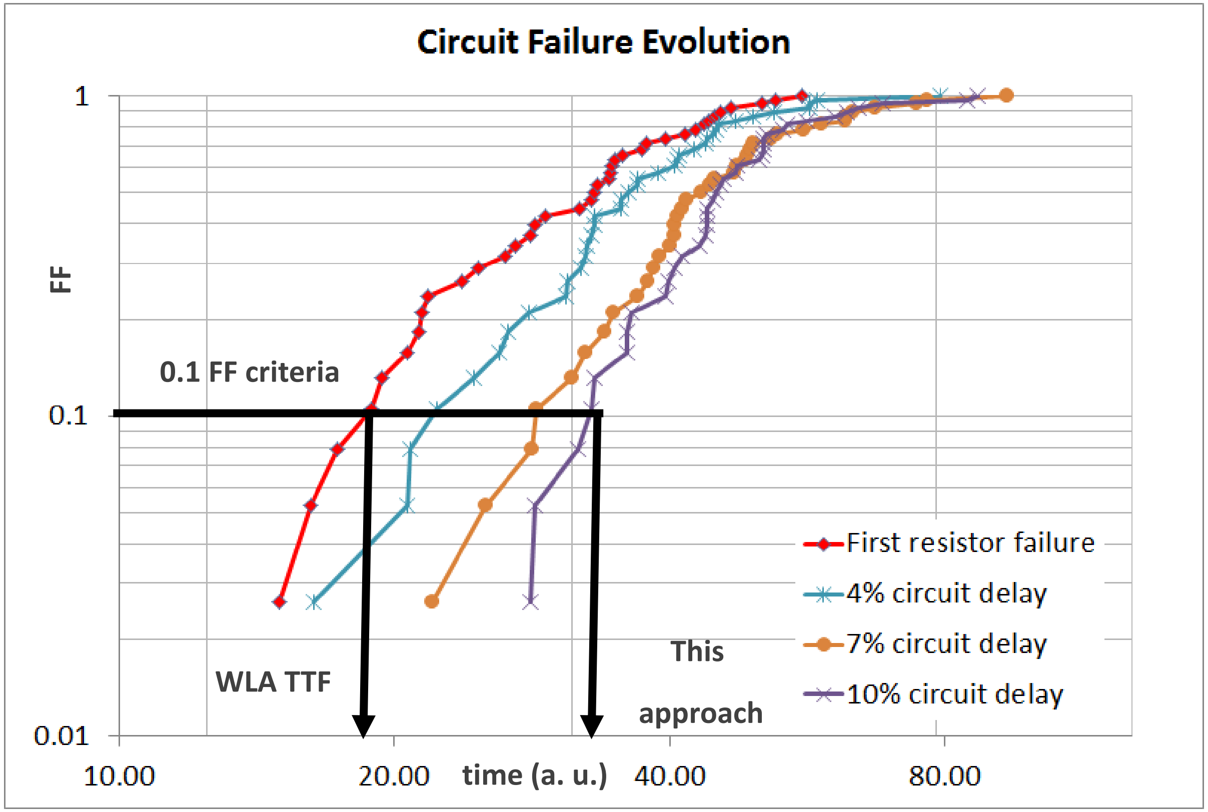




[Jain, IRPS15]

Quantitative evaluation



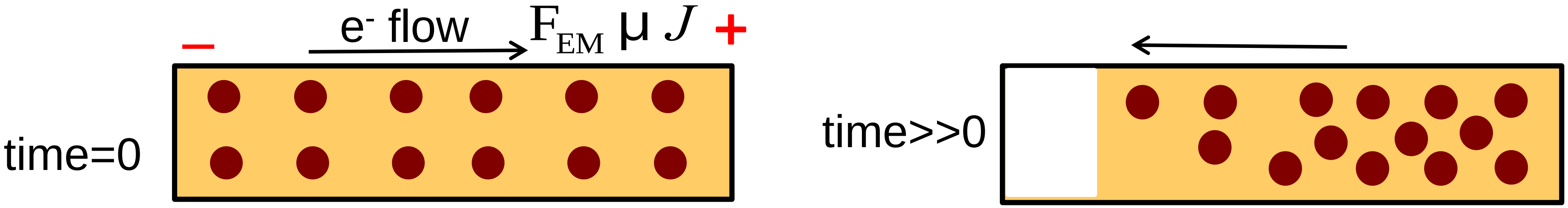


[Jain, IRPS15]

EM and stress

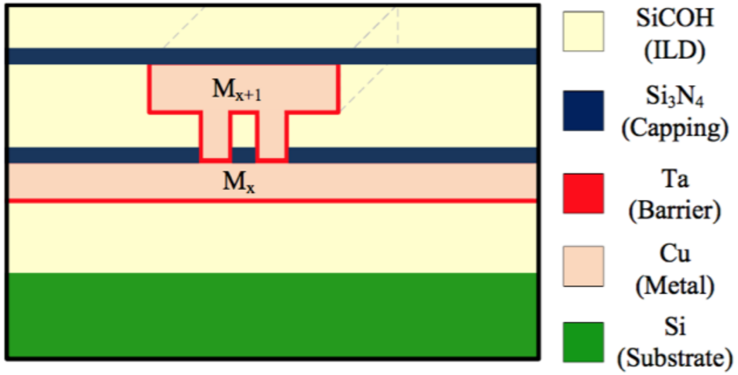
- Blech effect
  - Back stress opposes electron wind
  - Some wires are "immortal" due to back-stress

$(jL) < (jL)_{critical}$ → "immortal wire"



- Other sources of stress – thermomechanical stress

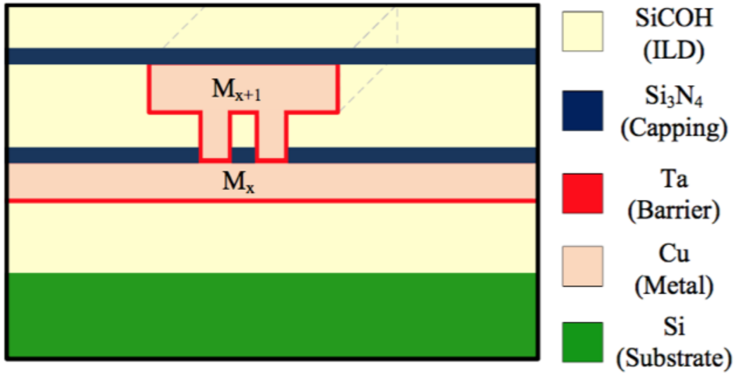
Typical Cu interconnect



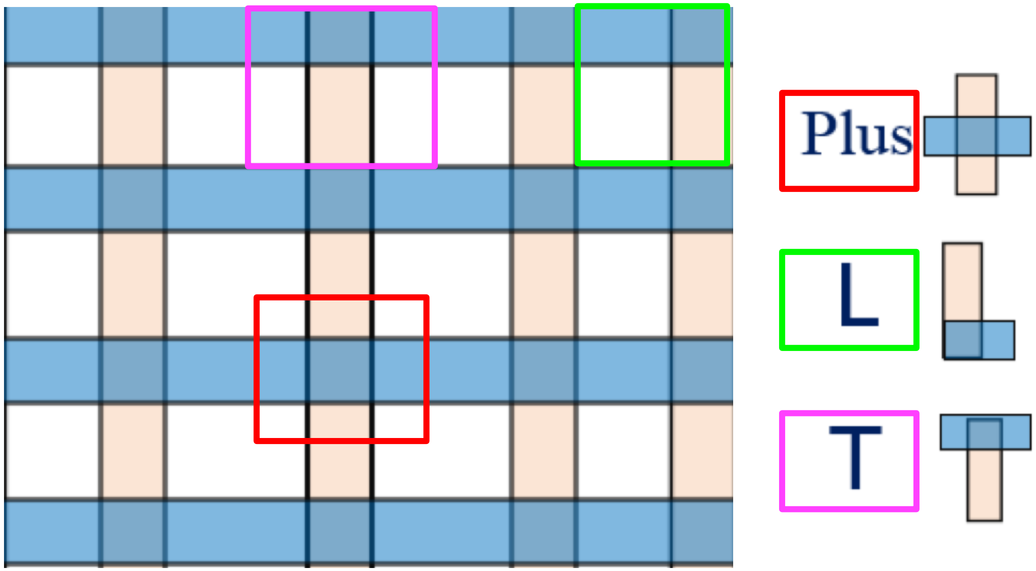
[Mishra, DAC16]

Thermomechanical stress in power grid

- Caused by thermal expansion mismatch between various layers of the interconnect system
- Evaluate using Finite Element Method (**FEM**)
- FEM: Numerical, computationally expensive



Various layers in typical copper interconnect

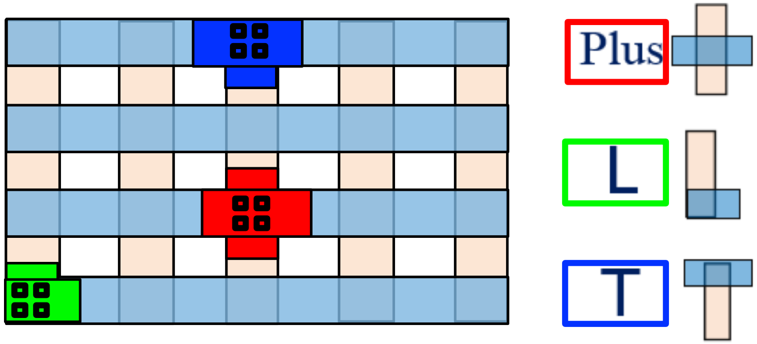


[Mishra, DAC16]

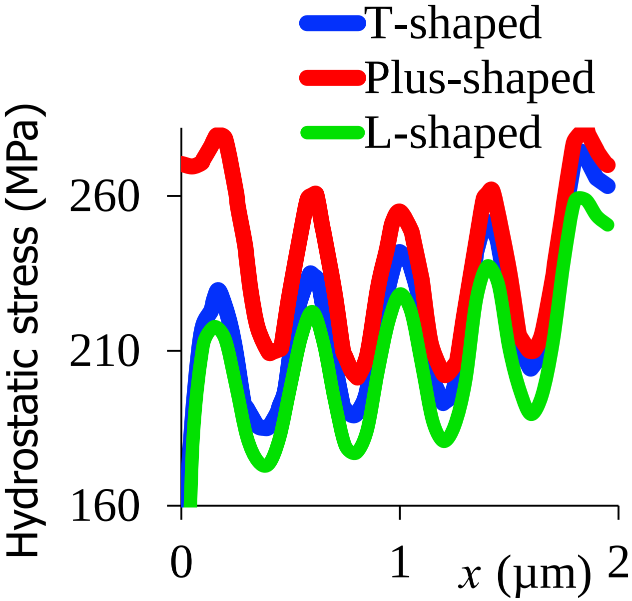
Stress analysis of power grid vias (contd.)

Thermal stress for every via can vary depending on:

- Position of the via array in the power grid
- Position of the via in the via array
- Via array configuration (e.g., 4x4, 8x8 via array)



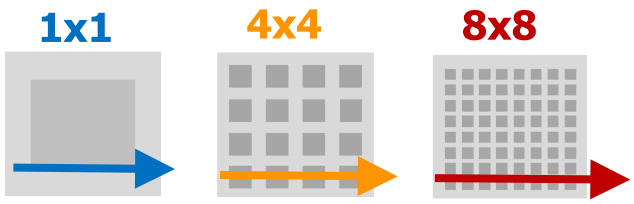
Plus-shaped, **T-shaped**, and **L-shaped** **4x4 via array**



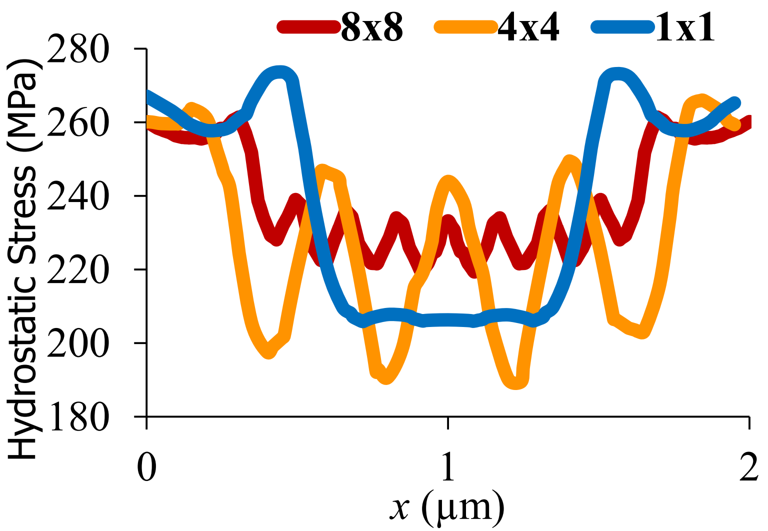
Stress analysis of power grid vias (contd.)

Thermal stress for every via can vary depending on:

- Position of the via array in the power grid
- Position of the via in the via array
- Via array configuration (e.g., 4x4, 8x8 via array)



Three configurations
with the same area

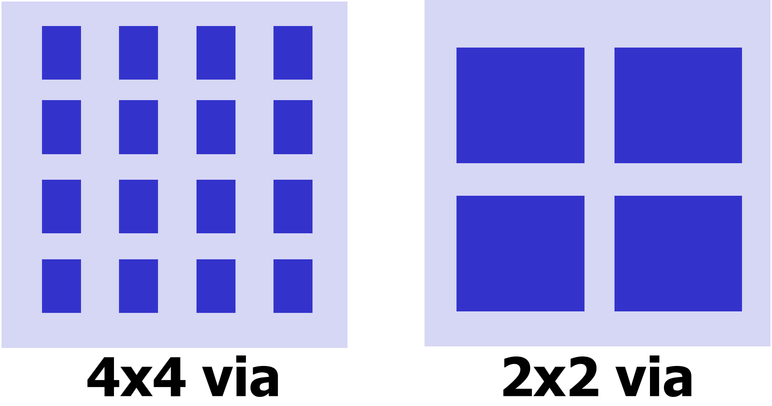


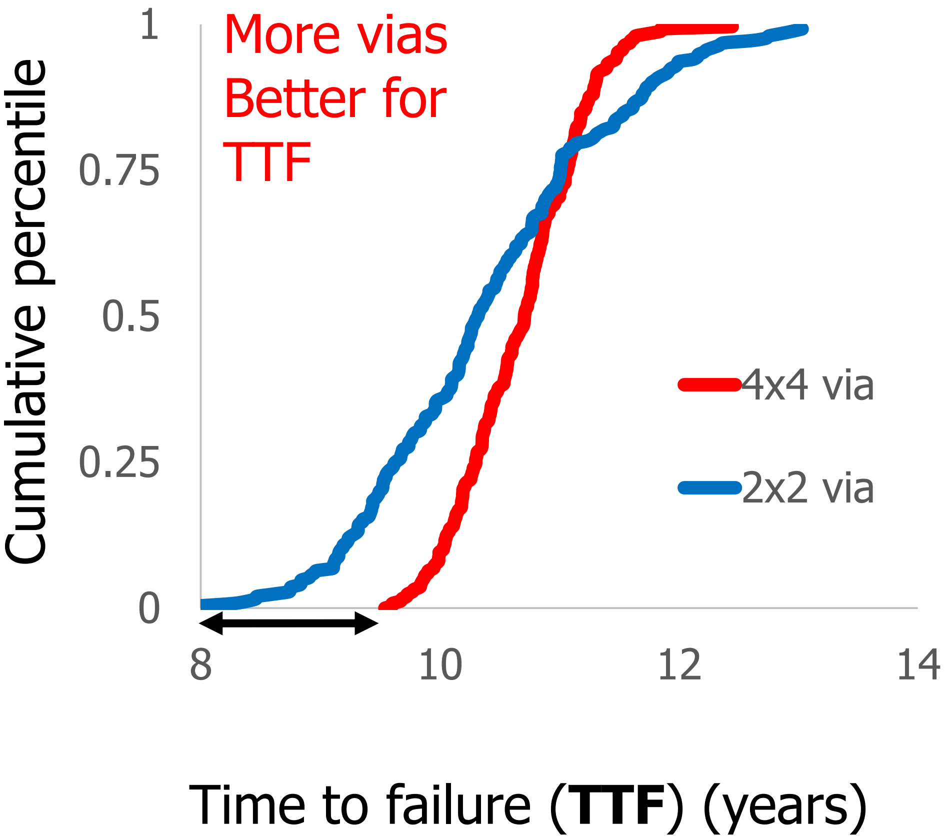
30MPa stress difference = ~30% change in lifetime

Via array performance and redundancy

When does the via array fail?

Via arrays with same resistance





More vias Better for TTF

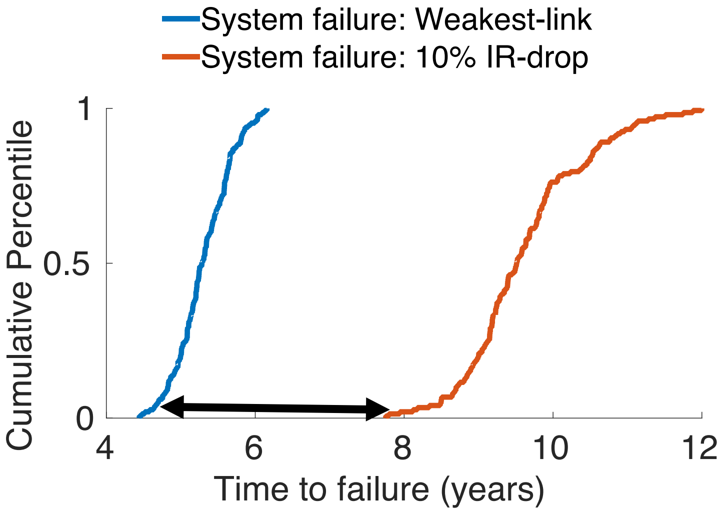
Time to failure (**TTF**) (years)

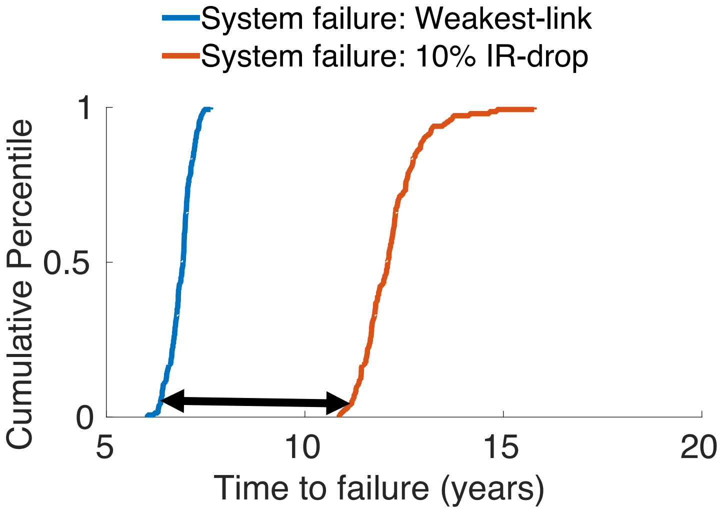
[Mishra, DAC16]

IMBPG1: TTF for various failure criteria

Failure criteria for:

1. **System (power grid) failure**
   - Weakest-link: Conventional method, implies 1st failure
   - Our criterion: 10% IR-drop
2. **Sub-system (via array) failure**
   - Weakest-link: 1st via failure
   - Our criterion: 8th via failure





[Mishra, DAC16]

Conclusion

- EM is an important problem for current/future technologies

- Critical issue in high-current density scenarios
  - Lower metal levels
  - Analog blocks
  - Potential within-cell issues
  - Higher on-chip temperatures exacerbate the challenge

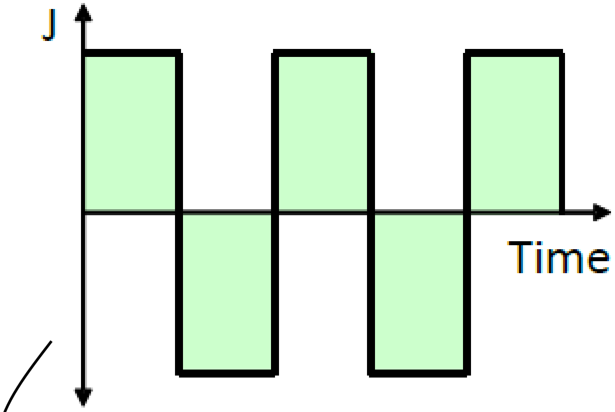
- Leveraging redundancy for EM mitigation is essential

Thank you!

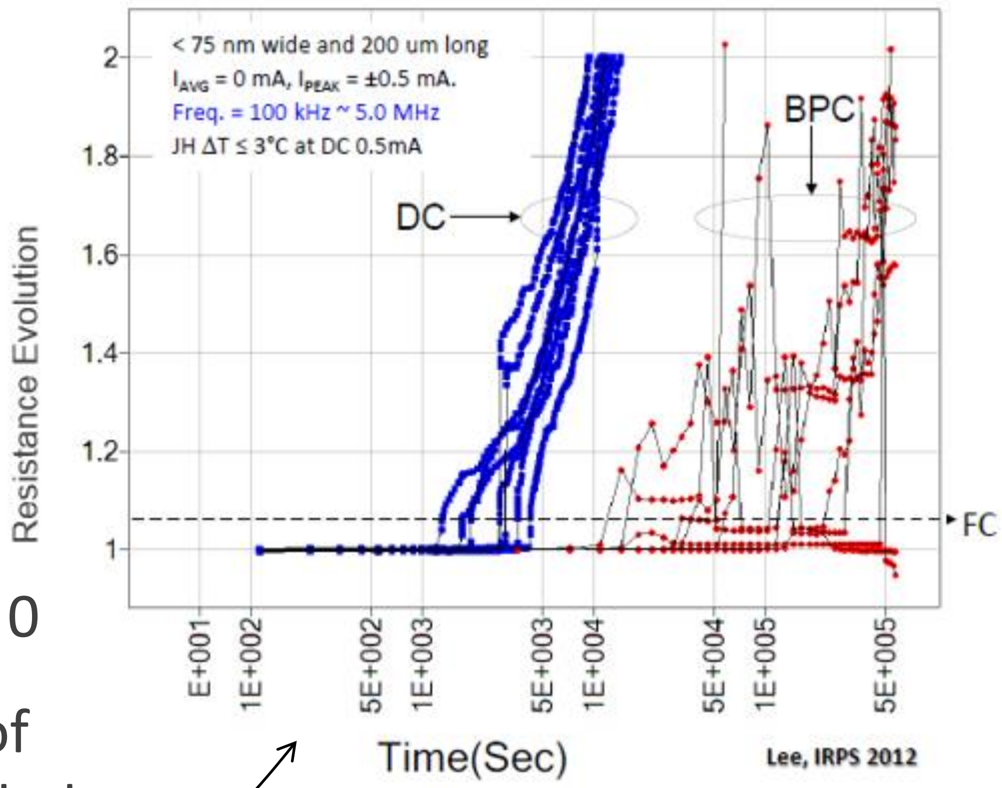
Backup

"AC EM"

Bidirectional pulsed current



- Mathematical average = 0
- Electromigration point of view, failures are seen, but at much higher lifetime
- Define a new 'recovered' current criteria:



Lee, IRPS 2012

$$J = J_{avg}^{+} - \Re J_{avg}^{-}$$