Institut
Mines-Télécom

Design of Reliable Processors Based on Unreliable Devices

Séminaire COMELEC

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Outline

What is Reliability ?

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

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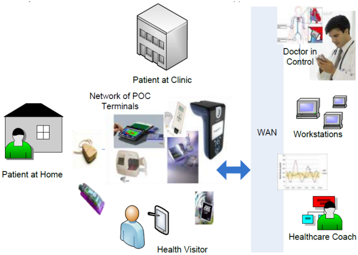
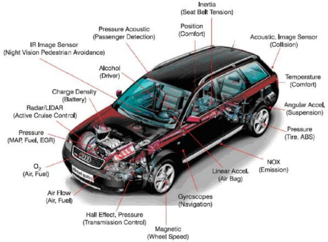
Reliability is the ability of a system or component to perform its required functions under **stated conditions** for a **specified period of time**.

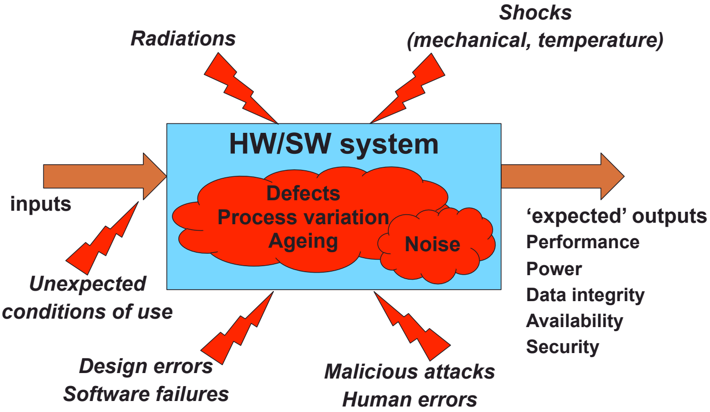
When is Reliability Important ?

- Safety critical applications
  - Biomedical
  - Transport
  - Spatial
  - Energy
  - Security
  - ...
- But today also for
  - Computer
  - Communications
  - Consumer





Is the Electronics Reliable ?



Radiations

Shocks
(mechanical, temperature)

HW/SW system

Defects
Process variation
Ageing

Noise

inputs

Unexpected
conditions of use

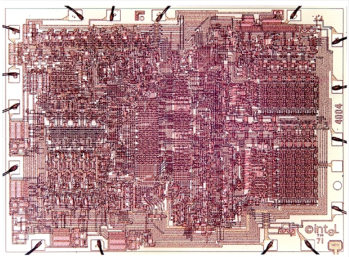
Design errors
Software failures

Malicious attacks
Human errors

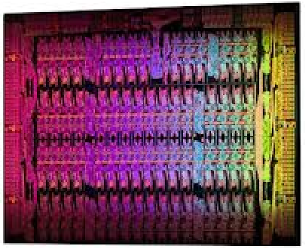
‘expected’ outputs
Performance
Power
Data integrity
Availability
Security

Advances in CMOS

- Moore's law (popular form) : $2\times\ N_{tr}/mm^2$ every 18 months



Intel 4004 (1971) : 10μm and 2.3×10^3 tr

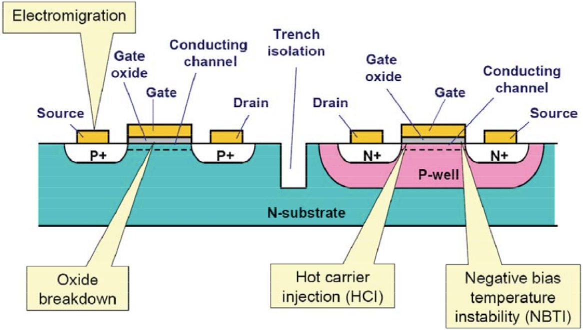


Intel Xeon Phi (2012) : 22nm and 5×10^9 tr

More Moore

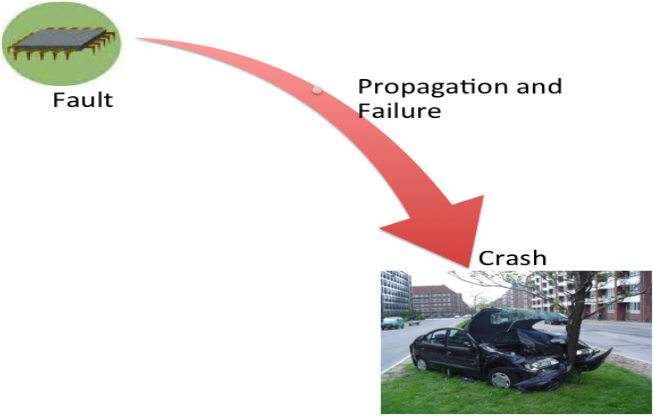
- Scaling issues
  - Design complexity, test challenge, low power voltage
  - Variability – Modelling
  - Sensitivity to unscaled environmental disturbances
- Scaling effects
  - Yield decrease
  - **Reliability decrease**

Scaling and Reliability



ageing, single and multiple transient faults

Fault Propagation

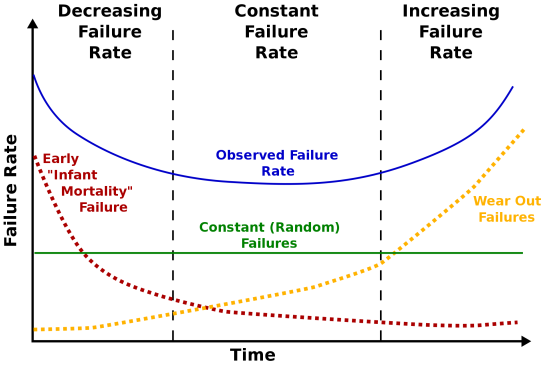


Fault

Propagation and Failure

Crash

Bathtub Curve



Some Metrics

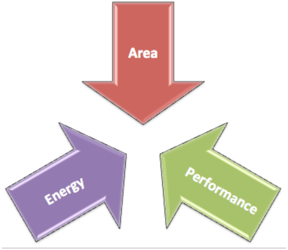
- Mean Time To Failures *MTTF*
- Mean Time To Repair *MTTR*
- **Mean Time Between Failures *MTBF***
- **Failures In Time *FIT***
- **Failure Rate**

$$R = e^{-\frac{Time}{MTBF}}$$

$$R = Prob(exact)$$

Research at Telecom ParisTech

How to get **optimized** design of processors ?



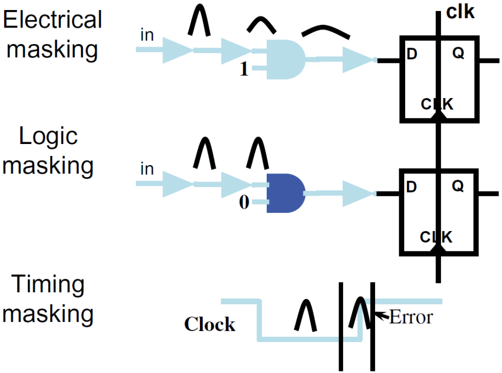
Research at Telecom ParisTech

How to get **optimized** design of **reliable** processors based on **unreliable** devices ?

- Risk minimization
- More (than) Moore
- Fabless generalization

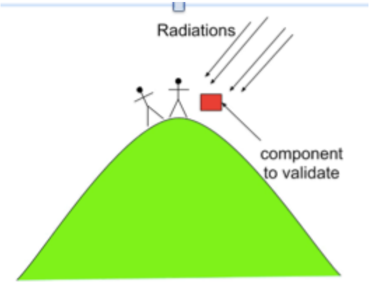
Reliability improvement
⇒ penalties !

Masking Effects

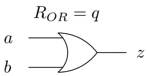


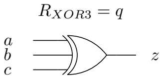
⇒ **Reliability assessment !**

Hardware Fault Injection



Probabilistic Transfer Matrices (PTM)


$R_{OR} = q$


$R_{XOR3} = q$

$$inputs\; \begin{array}{cc} & \begin{array}{cc} \multicolumn{2}{c}{outputs} \\ 0 & 1 \end{array} \\ \begin{array}{c}00\\01\\10\\11\end{array} & \left[\begin{array}{cc}1&0\\0&1\\0&1\\0&1\end{array}\right]\end{array}$$

ITM_{OR}

$$inputs\; \begin{array}{cc} & \begin{array}{cc} \multicolumn{2}{c}{outputs} \\ 0 & 1 \end{array} \\ \begin{array}{c}00\\01\\10\\11\end{array} & \left[\begin{array}{cc}q&1-q\\1-q&q\\1-q&q\\1-q&q\end{array}\right]\end{array}$$

PTM_{OR}

$$inputs\; \begin{array}{cc} & \begin{array}{cc} \multicolumn{2}{c}{outputs} \\ 0 & 1 \end{array} \\ \begin{array}{c}000\\001\\010\\011\\100\\101\\110\\111\end{array} & \left[\begin{array}{cc}1&0\\0&1\\0&1\\1&0\\0&1\\1&0\\1&0\\0&1\end{array}\right]\end{array}$$

ITM_{XOR3}

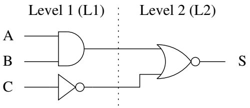
$$inputs\; \begin{array}{cc} & \begin{array}{cc} \multicolumn{2}{c}{outputs} \\ 0 & 1 \end{array} \\ \begin{array}{c}000\\001\\010\\011\\100\\101\\110\\111\end{array} & \left[\begin{array}{cc}q&1-q\\1-q&q\\1-q&q\\q&1-q\\1-q&q\\q&1-q\\q&1-q\\1-q&q\end{array}\right]\end{array}$$

PTM_{XOR3}

[1] S. Krishnaswamy, G.F Viamontes, I.L. Markov, I.L and J.P Hayes, Accurate reliability evaluation and enhancement via probabilistic transfer matrices, DATE'2005

⋆

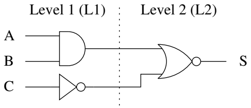
PTM Computation



$$PTM_{NOT} = \begin{bmatrix} p & q \\ q & p \end{bmatrix} \qquad PTM_{AND} = \begin{bmatrix} q & p \\ q & p \\ q & p \\ p & q \end{bmatrix} \qquad PTM_{NOR} = \begin{bmatrix} p & q \\ q & p \\ q & p \\ q & p \end{bmatrix}$$

$$PTM_{L1} = PTM_{AND} \otimes PTM_{NOT} = \begin{bmatrix} q \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} & p \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} \\ q \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} & p \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} \\ q \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} & p \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} \\ p \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} & q \cdot \begin{bmatrix} p & q \\ q & p \end{bmatrix} \end{bmatrix} = \begin{bmatrix} pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ p^2 & pq & pq & q^2 \\ pq & p^2 & q^2 & pq \end{bmatrix}$$

PTM Computation



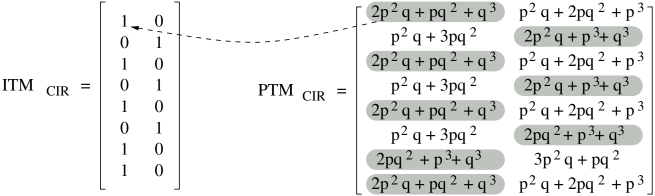
$$PTM_{NOT} = \begin{bmatrix} p & q \\ q & p \end{bmatrix} \qquad PTM_{AND} = \begin{bmatrix} q & p \\ q & p \\ q & p \\ p & q \end{bmatrix} \qquad PTM_{NOR} = \begin{bmatrix} p & q \\ q & p \\ q & p \\ q & p \end{bmatrix}$$

$$PTM_{CIR} = PTM_{L1} \cdot PTM_{NOR} = \begin{bmatrix} pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ pq & q^2 & p^2 & pq \\ q^2 & pq & pq & p^2 \\ p^2 & pq & pq & q^2 \\ pq & p^2 & q^2 & pq \end{bmatrix} \cdot \begin{bmatrix} p & q \\ q & p \\ q & p \\ q & p \end{bmatrix} = \begin{bmatrix} 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2p^2q + p^3 + q^3 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2p^2q + p^3 + q^3 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2pq^2 + p^3 + q^3 \\ 2pq^2 + p^3 + q^3 & 3p^2q + pq^2 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \end{bmatrix}$$

Reliability Calculation with PTM

$$R_{cir} = \sum_{ITM_{cir}(i,j)=1} p(j|i)p(i)$$

- $p(i)$ is the probability of input value i
- $p(j|i)$ is the $(i,j)th$ element in PTM_{cir}



$$ITM_{CIR} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 1 & 0 \end{bmatrix} \qquad PTM_{CIR} = \begin{bmatrix} 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2p^2q + p^3 + q^3 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2p^2q + p^3 + q^3 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \\ p^2q + 3pq^2 & 2pq^2 + p^3 + q^3 \\ 2pq^2 + p^3 + q^3 & 3p^2q + pq^2 \\ 2p^2q + pq^2 + q^3 & p^2q + 2pq^2 + p^3 \end{bmatrix}$$

Signal Probability and Reliability (SPR)

$$S = \begin{bmatrix} 0_c & 1_i \\ 0_i & 1_c \end{bmatrix}$$

$$SPR_S = \begin{bmatrix} p(s = 0_c) & p(s = 1_i) \\ p(s = 0_i) & p(s = 1_c) \end{bmatrix} = \begin{bmatrix} s_0 & s_1 \\ s_2 & s_3 \end{bmatrix}$$

$$R_S = p(s = 0_c) + p(s = 1_c) = s_0 + s_3$$

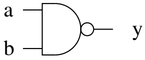
[1] **D. Franco, M. Vasconcelos, L. Naviner et J.-F. Naviner, Signal Probability for Reliability Evaluation of Logic Circuits, Microelectronics Reliability Journal, Septembre 2008, vol. 48, pp. 1586-1591**

Signal Reliability Propagation

$$A_4 = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix}$$

$$B_4 = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix}$$

$$q_{NAND} = 0.92$$



$$ITM_{NAND}$$

$$y_0 \longleftarrow \begin{bmatrix} 0 & 1 \\ 0 & 1 \\ 0 & 1 \\ 1 & 0 \end{bmatrix} \longrightarrow y_3$$

$$\underbrace{\begin{bmatrix} 0.25 & 0 & 0 & 0 \\ 0 & 0.25 & 0 & 0 \\ 0 & 0 & 0.25 & 0 \\ 0 & 0 & 0 & 0.25 \end{bmatrix}}_{I_{NAND} = A_4 \otimes B_4} \times \underbrace{\begin{bmatrix} 0.08 & 0.92 \\ 0.08 & 0.92 \\ 0.08 & 0.92 \\ 0.92 & 0.08 \end{bmatrix}}_{PTM_{NAND}} = \underbrace{\begin{bmatrix} 0.02 & 0.23 \\ 0.02 & 0.23 \\ 0.02 & 0.23 \\ 0.23 & 0.02 \end{bmatrix}}_{p(y)}$$

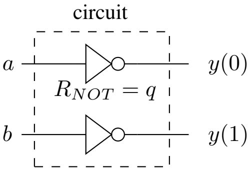
$$\underbrace{\begin{bmatrix} 0.23 & 0.02 \\ 0.06 & 0.69 \end{bmatrix}}_{Y_4}$$

★

Reconvergent Signals

$$a = b$$

$$A_4 = \begin{bmatrix} a_0 & 0 \\ 0 & a_3 \end{bmatrix} \qquad B_4 = \begin{bmatrix} b_0 & 0 \\ 0 & b_3 \end{bmatrix}$$



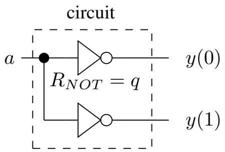
$$Y(0)_4 = \begin{bmatrix} a_3 q & a_3 \bar{q} \\ a_0 \bar{q} & a_0 q \end{bmatrix} \qquad Y(1)_4 = \begin{bmatrix} b_3 q & b_3 \bar{q} \\ b_0 \bar{q} & b_0 q \end{bmatrix}$$

$$R(circuit) = R_{y(0)} R_{y(1)} = a_3 b_3 q^2 + a_3 b_0 q^2 + a_0 b_3 q^2 + a_0 b_0 q^2$$

Multipath SPR

$Pass\ 1\ :$

$$A_4 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$



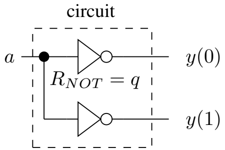
$$Y(0)_4 = \begin{bmatrix} 0 & 0 \\ \bar{q} & q \end{bmatrix}$$

$$Y(1)_4 = \begin{bmatrix} 0 & 0 \\ \bar{q} & q \end{bmatrix}$$

$$R(circuit, a_0) = R_{y(0)} R_{y(1)} a_0 = a_0 q^2$$

$Pass\ 2\ :$

$$A_4 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$



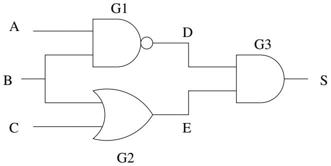
$$Y(0)_4 = \begin{bmatrix} q & \bar{q} \\ 0 & 0 \end{bmatrix}$$

$$Y(1)_4 = \begin{bmatrix} q & \bar{q} \\ 0 & 0 \end{bmatrix}$$

$$R(circuit, a_3) = R_{y(0)} R_{y(1)} a_3 = a_3 q^2$$

$$R(circuit) = R(circuit, a_0) + R(circuit, a_3) = a_0 q^2 + a_3 q^2$$

Multipath SPR



$$SPR_{D_i} = ITM_{G_1} \times (SPR_A \otimes SPR_{B_i}) \times PTM_{G_1} \quad (1)$$

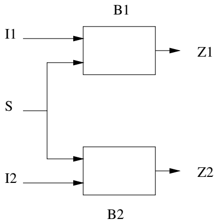
$$SPR_{E_i} = ITM_{G_2} \times (SPR_{B_i} \otimes SPR_C) \times PTM_{G_2} \quad (2)$$

$$SPR_{S_i} = ITM_{G_3} \times (SPR_{D_i} \otimes SPR_{E_i}) \times PTM_{G_3} \quad (3)$$

$$SPR_S = \sum_{i=1}^{4} SPR_{S_i} \times w_i \quad (4)$$

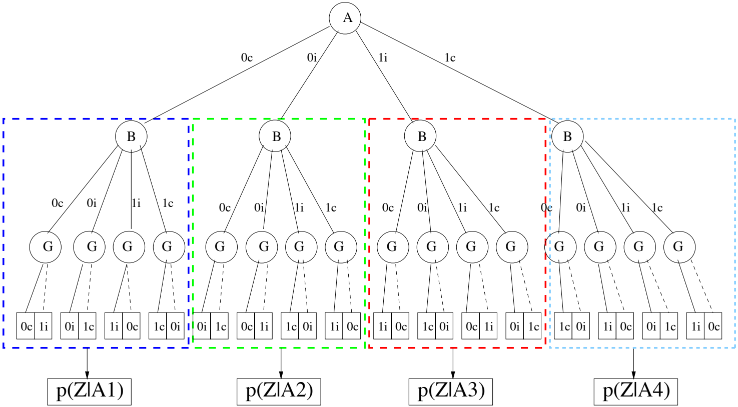
[1] D. Teixeira Franco, M. Rabelo de Vasconcelos, L. A. B. de Naviner, and J. cois Naviner, "A Tool for Signal Reliability Analysis of Logic Circuits," DATE'09

Conditional Probability



$$p(Z1 = i) = f1(S, I1, B1) \Rightarrow p(Z1 = i|S = k) = f1(I1, B1)$$
$$p(Z2 = j) = f2(S, I2, B2) \Rightarrow p(Z2 = j|S = k) = f2(I2, B2)$$

Conditional Probability



Logic XOR

Conditional Probability Matrices (CPM)

$$CPM_Z = \begin{pmatrix} p(z_1/a_1) & p(z_1/a_2) & p(z_1/a_3) & p(z_1/a_4) \\ p(z_2/a_1) & p(z_2/a_2) & p(z_2/a_3) & p(z_2/a_4) \\ p(z_3/a_1) & p(z_3/a_2) & p(z_3/a_3) & p(z_3/a_4) \\ p(z_4/a_1) & p(z_4/a_2) & p(z_4/a_3) & p(z_4/a_4) \end{pmatrix}$$

$\star$

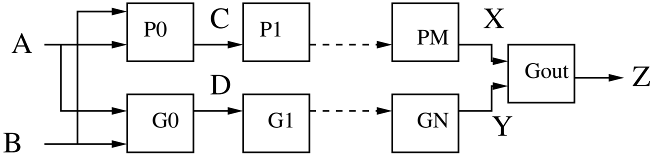
[1] J. Torras Flaquer, J.-M. Daveau, L. Naviner and Ph. Roche, Handling reconvergent paths using conditional probabilities in combinatorial logic netlists reliability estimation, IEEE ICECS'10.

Conditional Probability Matrices (CPM)

$$CPM_Y = \begin{pmatrix} p(y_1/s_1^1 \cap \ldots \cap s_1^N) & \ldots & p(y_1/s_4^1 \cap \ldots \cap s_4^N) \\ p(y_2/s_1^1 \cap \ldots \cap s_1^N) & \ldots & p(y_1/s_4^1 \cap \ldots \cap s_4^N) \\ p(y_3/s_1^1 \cap \ldots \cap s_1^N) & \ldots & p(y_1/s_4^1 \cap \ldots \cap s_4^N) \\ p(y_4/s_1^1 \cap \ldots \cap s_1^N) & \ldots & p(y_1/s_4^1 \cap \ldots \cap s_4^N) \end{pmatrix}$$

[1] **J. Torras Flaquer, J.-M. Daveau, L. Naviner and Ph. Roche, Handling reconvergent paths using conditional probabilities in combinatorial logic netlists reliability estimation, IEEE ICECS'10.**

Reliability based on CPM



$$SPR_Z = ITM^T_{G_{out}} \cdot M_{XY} \cdot PTM^T_{G_{out}}$$

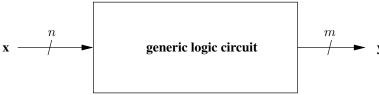
$$CPM_{X/A\cap B} = \prod_{i=0}^{M} CPM_{Pi} \qquad CPM_{Y/A\cap B} = \prod_{i=0}^{N} CPM_{Gj}$$

$$p(x_i \cap y_j) = \sum_{k=1}^{4} \sum_{l=1}^{4} p(x_i/a_k \cap b_l) \cdot p(y_j/a_k \cap b_l) \cdot p(a_k) \cdot p(b_j)$$

Probabilistic Binomial Reliability Model

$$R = \sum_{j=0}^{2^{ne}-1} \prod_{fault-free} q_i \prod_{faulty} (1-q_i) \sum_{i=0}^{2^{nx}-1} p(\mathbf{x}_i) \left(\overline{\mathbf{y}(\mathbf{x}_i, \mathbf{e}_0) \oplus \mathbf{y}(\mathbf{x}_i, \mathbf{e}_j)} \right)$$

- Logical masking features
- Technology/profile aspects
- Relevant faults
- Relevant input vectors



[1] **M. Correia De Vasconcelos, D. Teixeira Franco, L. Alves de Barros Naviner and J. F. Naviner, Reliability Analysis of Combinational Circuits Based on a Probabilistic Binomial Model, IEEE-NEWCAS and TAISA Conference, Montréal, Canada, June 2008.**

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- **Logical masking features**
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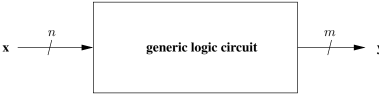

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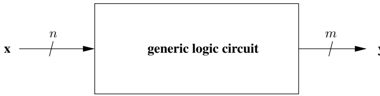
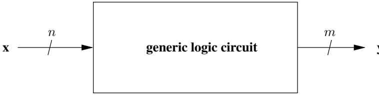


[1] M. Correia De Vasconcelos, D. Teixeira Franco, L. Alves de Barros Naviner and J. F. Naviner, Reliability Analysis of Combinational Circuits Based on a Probabilistic Binomial Model, IEEE-NEWCAS and TAISA Conference, Montréal, Canada, June 2008.

Probabilistic Binomial Reliability Model

$$R = \sum_{j=0}^{2^{n_e}-1} \prod_{fault-free} q_i \prod_{faulty} (1-q_i) \sum_{i=0}^{2^{n_x}-1} p(\mathbf{x}_i) \left(\overline{\mathbf{y}(\mathbf{x}_i, \mathbf{e}_0) \oplus \mathbf{y}(\mathbf{x}_i, \mathbf{e}_j)} \right)$$

- Logical masking features
- Technology/profile aspects
- **Relevant faults**
- Relevant input vectors



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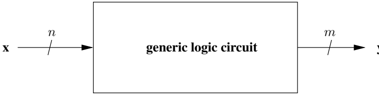
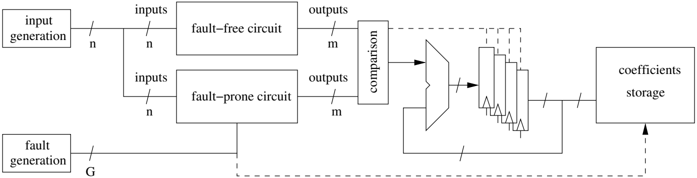


[1] **M. Correia De Vasconcelos, D. Teixeira Franco, L. Alves de Barros Naviner and J. F. Naviner, Reliability Analysis of Combinational Circuits Based on a Probabilistic Binomial Model, IEEE-NEWCAS and TAISA Conference, Montréal, Canada, June 2008.**

PBR Implementation

- Simulate (or emulate) errors and then compare outputs
- FIFA : Fault-Injection Fault-Analysis platform[1,2]
  - Acceleration of fault injection and functional simulation

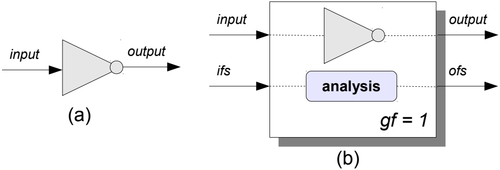


[1] E. Marques, N. Maciel, L. Naviner and J. F. Naviner, A New Fault Generator Suitable for Reliability Analysis of Digital Circuits, IEEE CUMTA'10.

[2] L. Alves de Barros Naviner, J. F. Naviner, G. Gonçalves dos Santos Jr, E. Crespo Marques and N. Maciel, FIFA : A Fault-Injection-Fault-Analysis-based tool for reliability assessment at RTL level, ES-REF'11.

SNAP Approach

- Fault source and fault propagation

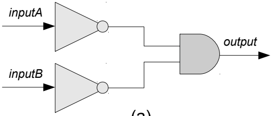


$$ofs = f(ifs, gf, input, gate)$$

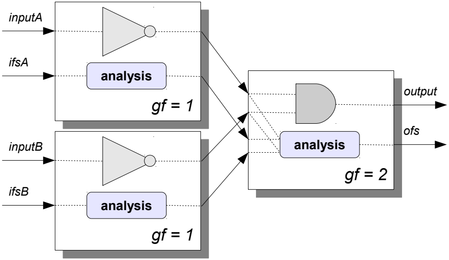
[1] S. Pagliarini, A. Ben Dhia, L. Naviner and J. F. Naviner, SNaP : a Novel Hybrid Method for Circuit Reliability Assessment Under Multiple Faults, ESREF'13.

Reliability Calculation based on SNAP

- $R = q^{ofs}$



(a)



(b)

Comparisons

	Accuracy	Complexity	Trade-off	FPGA
PTM	☺☺☺	☹☹☹	-	-
SPR	☺☹	☺☺☺	-	-
SPR-MP	☺☺☺	☺☺☹	Yes	-
CPM	☺☺☺	☺☺☹	Yes	-
PBR	☺☺☺	☺☺☹	Yes	Yes
SNAP	☺☺☹	☺☺☺	-	Yes

Conclusions

- Reliability issues and challenges

- Need of cost-effective fault tolerant architectures
- Need of efficient assessment approaches

- Some Telecom ParisTech contributions (models, methods and tools)
  - SPR, SPR-MP, CPM, SPR-DWAA
  - PBR, FIFA, SNAP, ...

Conclusions

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To know more about ...

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