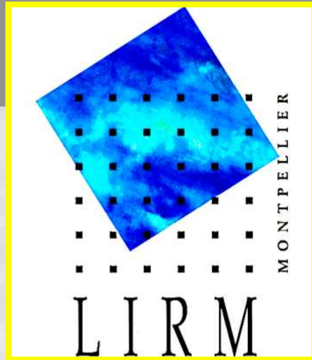
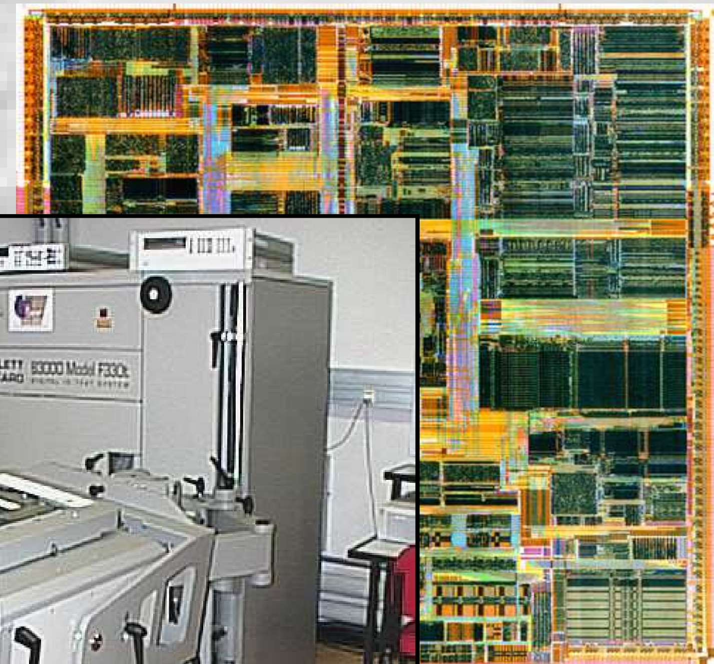
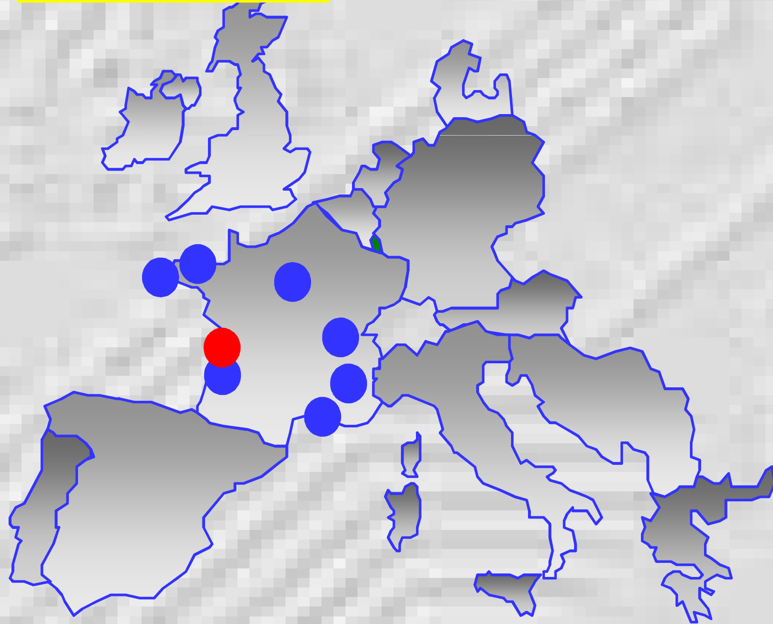
Fundamentals of Digital & Analog System Testing



Michel Renovell





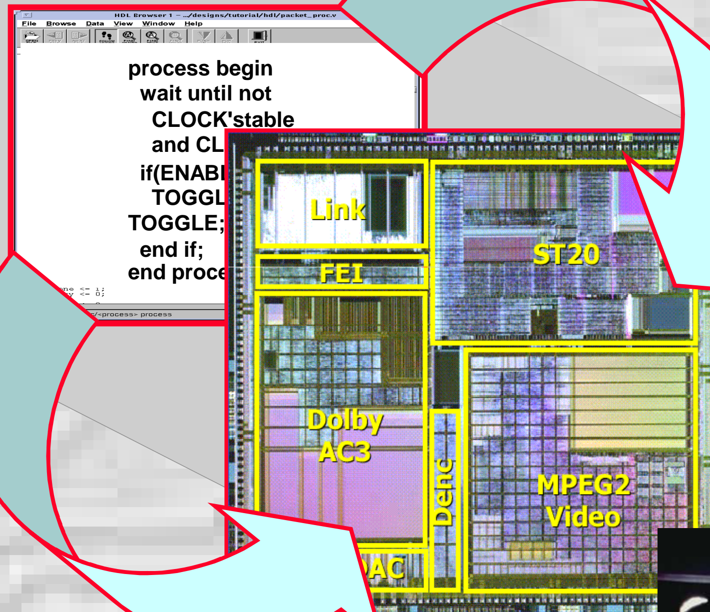
Ecole Numérique IN2P3

Introduction

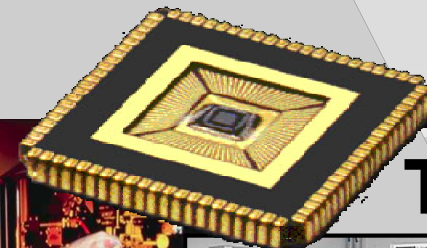
IN2P3

Application

Test (preparation)



Technology



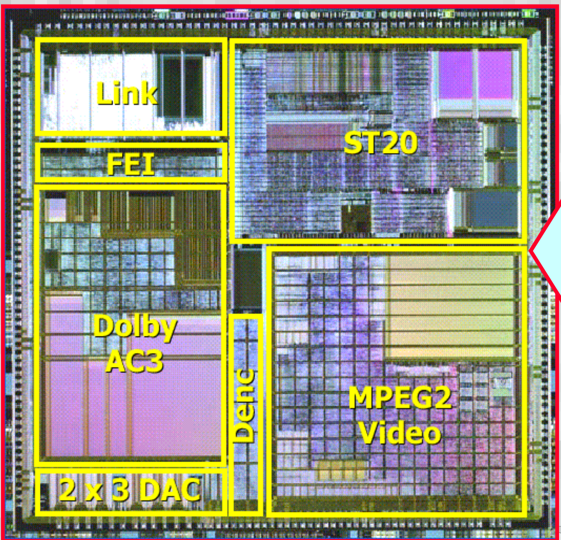
Test

Design

Introduction


```
process begin
  wait until not
    CLOCK'stable
    and CLOCK=1;
  if(ENABLE='1') then
    TOGGLE<= not
TOGGLE;
  end if;
end process;
```

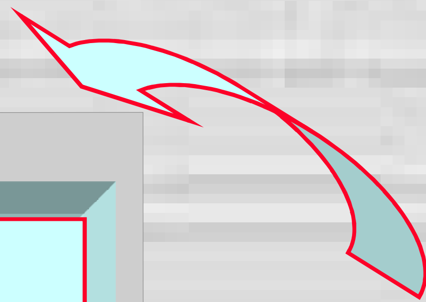
Design Error



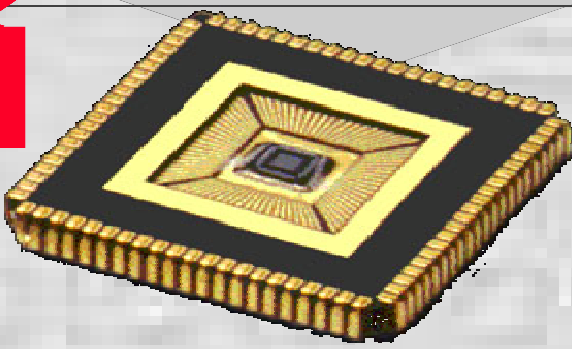
Design

Layout

Manufacturing

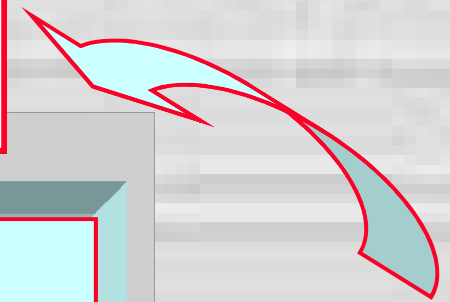


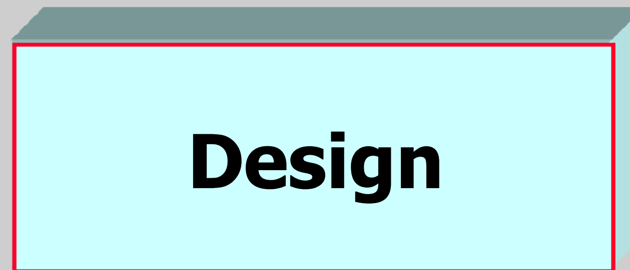
Deviation & Spot

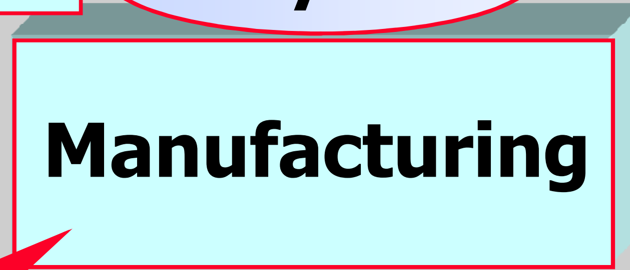


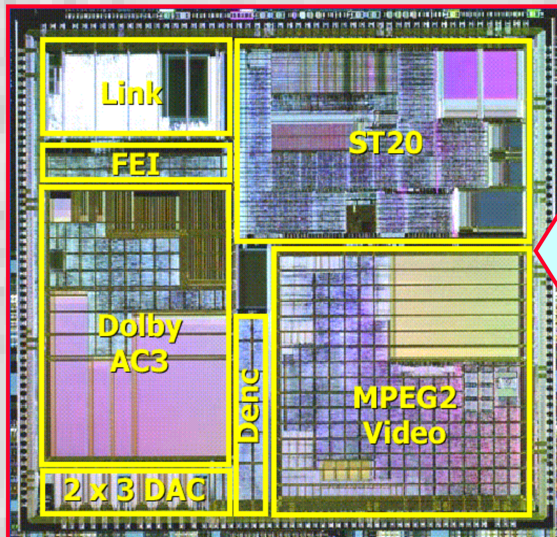
Introduction

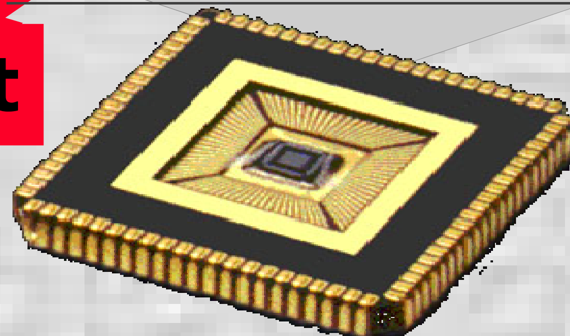
IN2P3





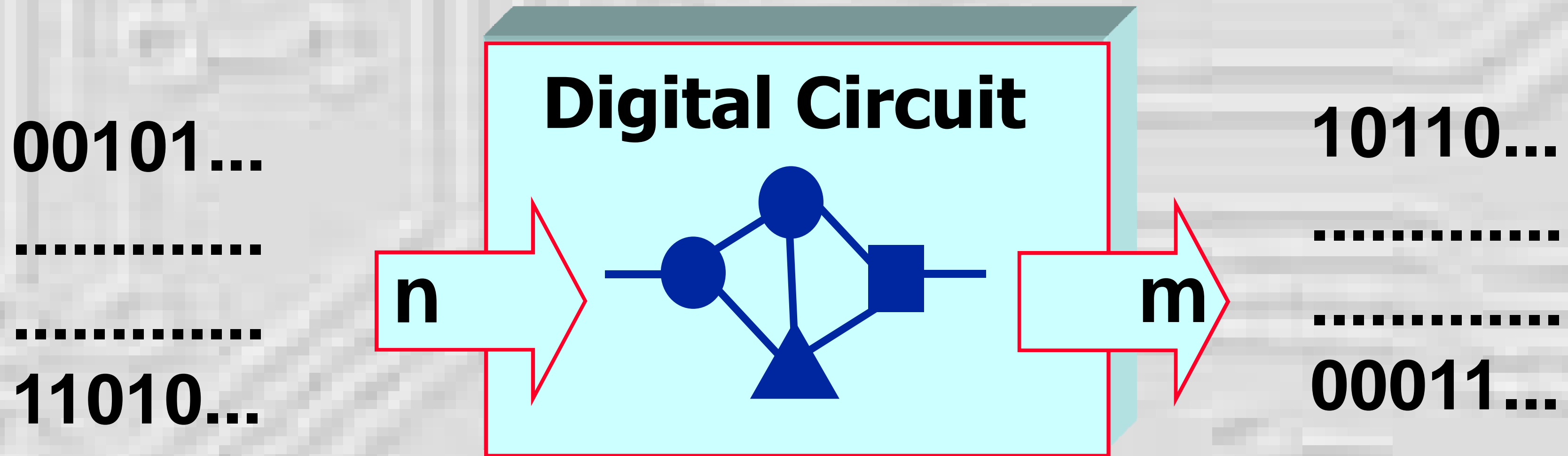






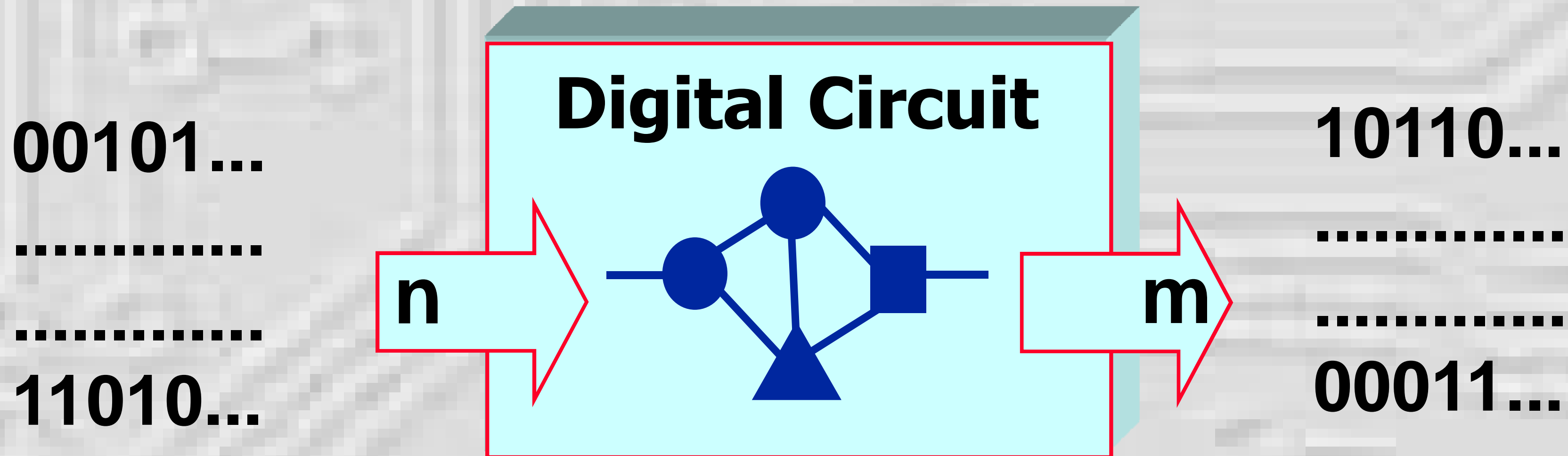
Deviation & Spot

Introduction



- Boolean Testing
- Test Patterns
- Go/NoGo

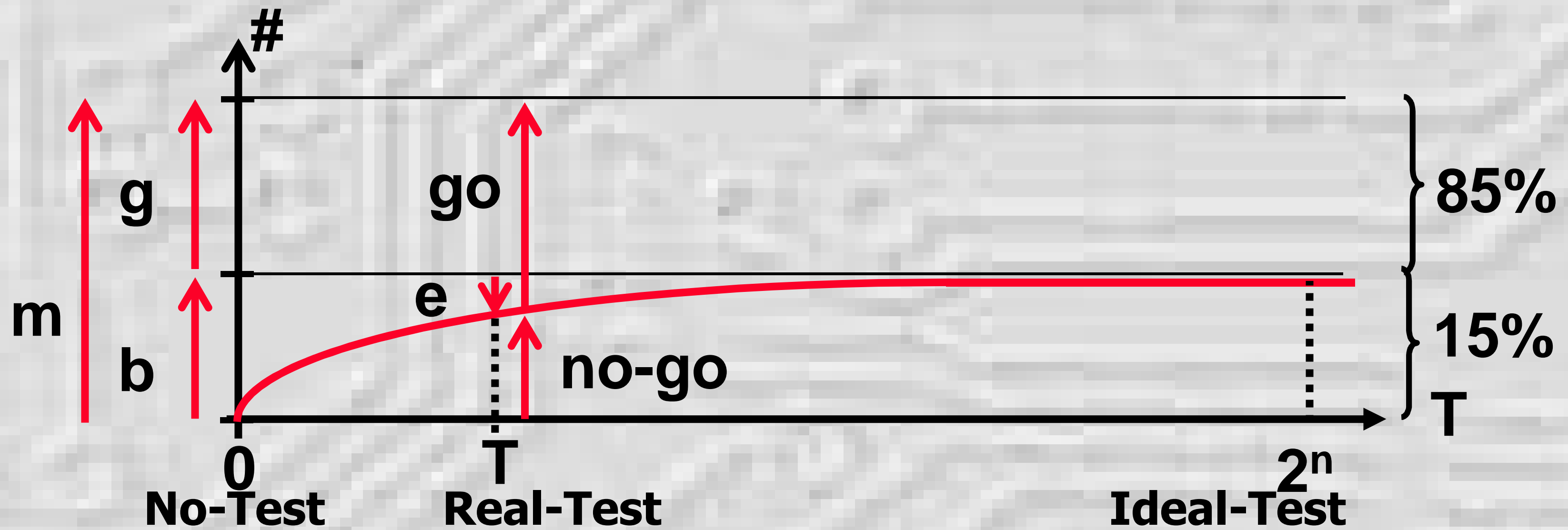
Introduction



- Exhaustive Testing
- 2^{64} patterns
- 10^{20}/100MHz = 10^{12}s
- => 5850 years

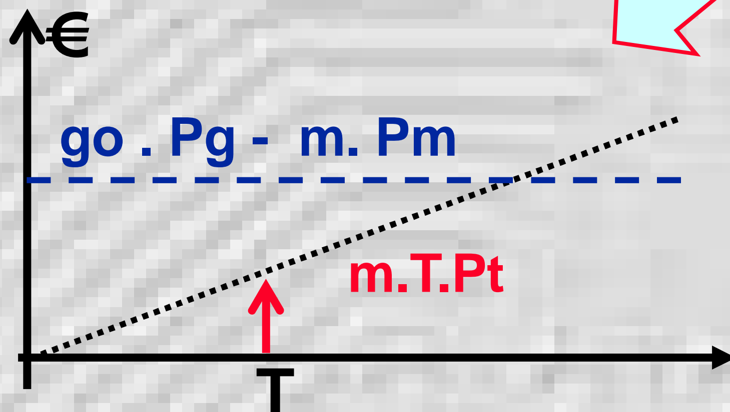
- Realistic Test
- 10s / 100MHz
- 10^{9}
- 1 / 10^{11}

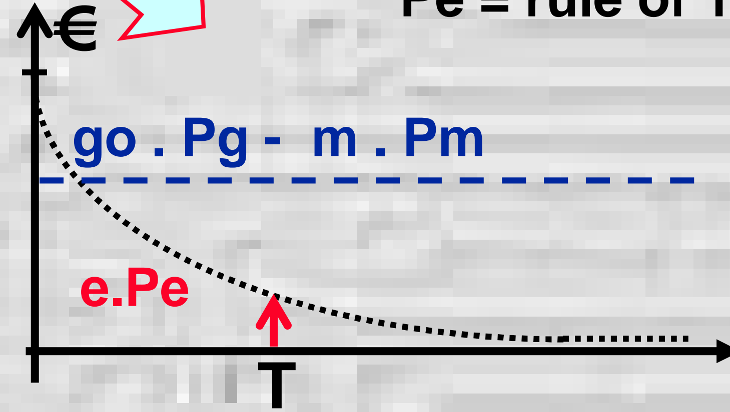
Introduction



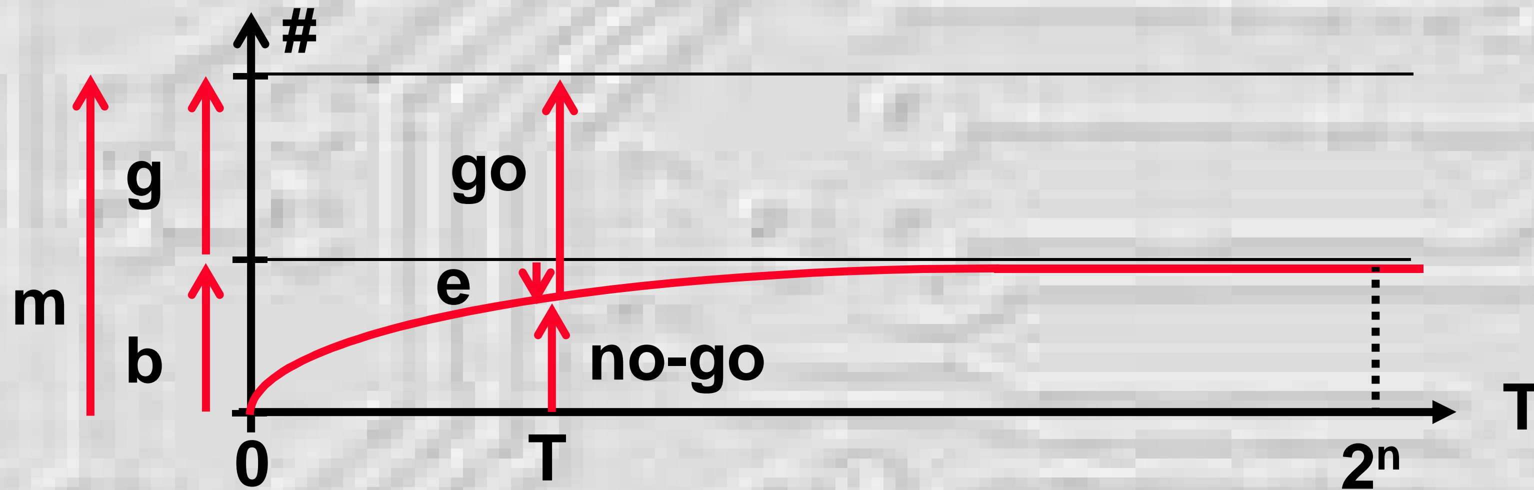
go . Pg - m . Pm > Margin

Y = 75%
e = 500 ppm
Pe = rule of 10

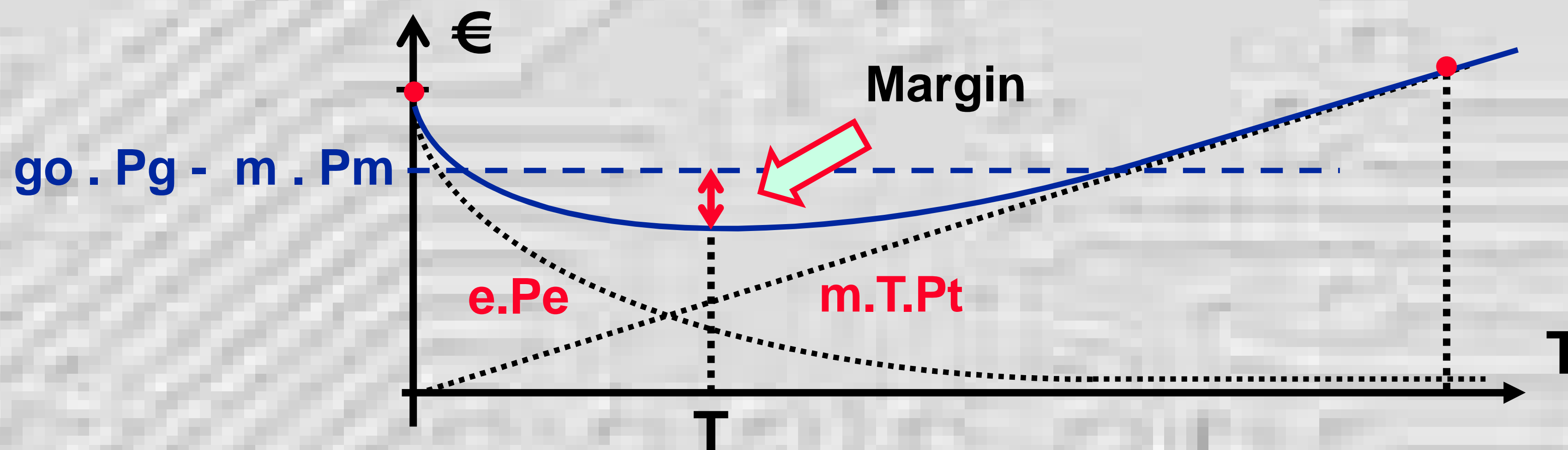




Introduction

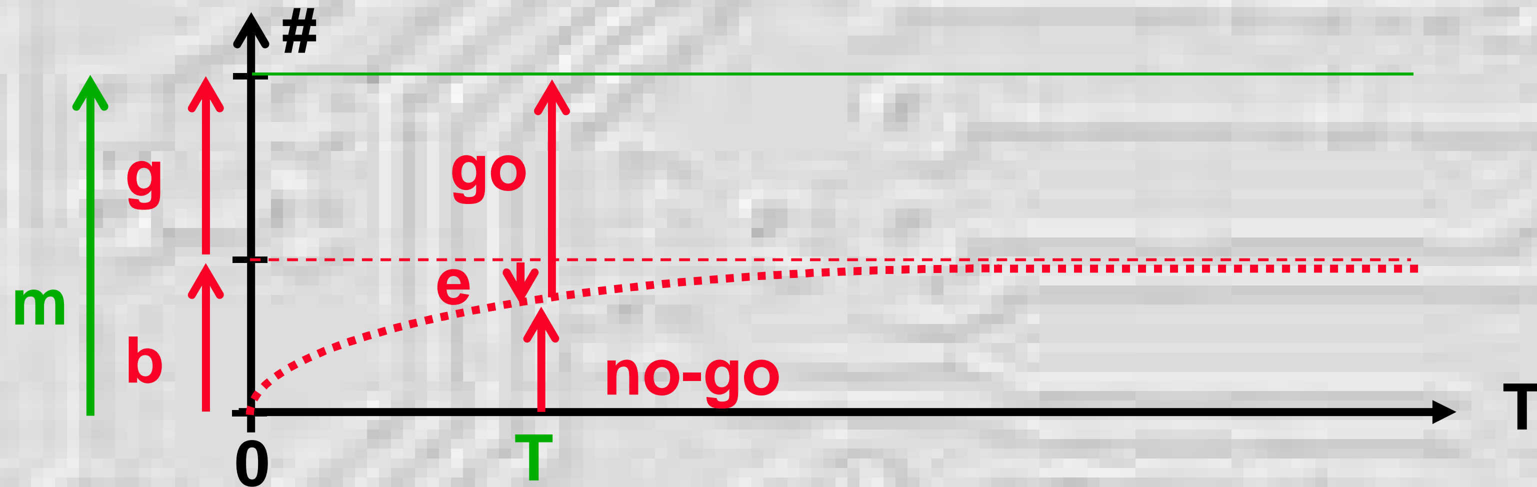


$$go \, . \, Pg - m \, . \, Pm \geq m \, . \, T \, . \, Pt + e \, . \, Pe$$



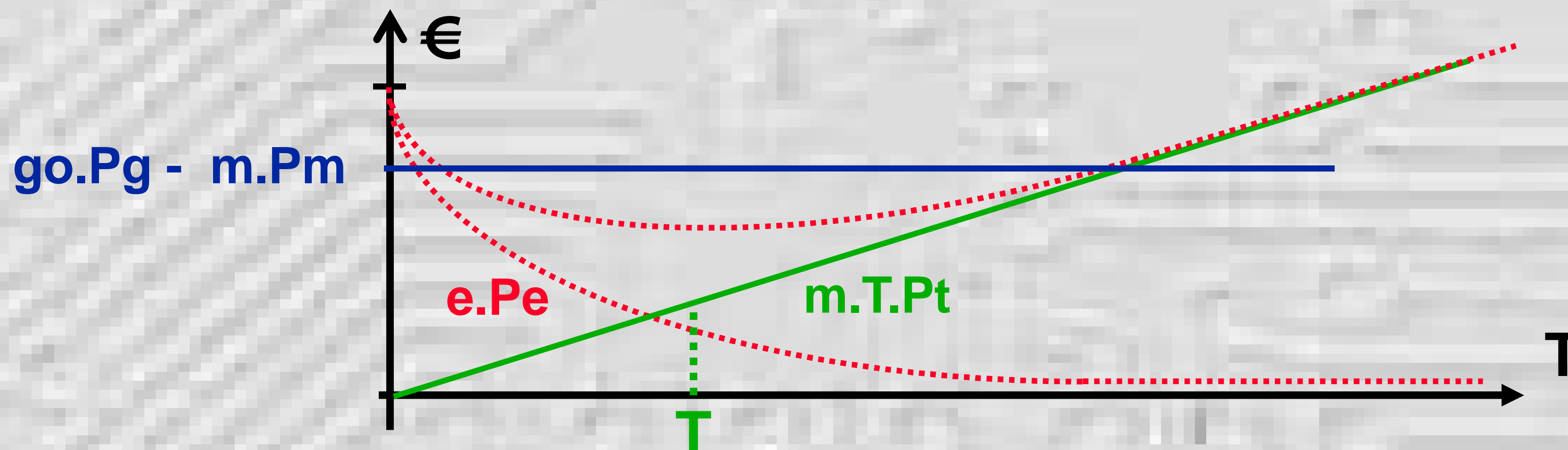
Introduction

IN2P3



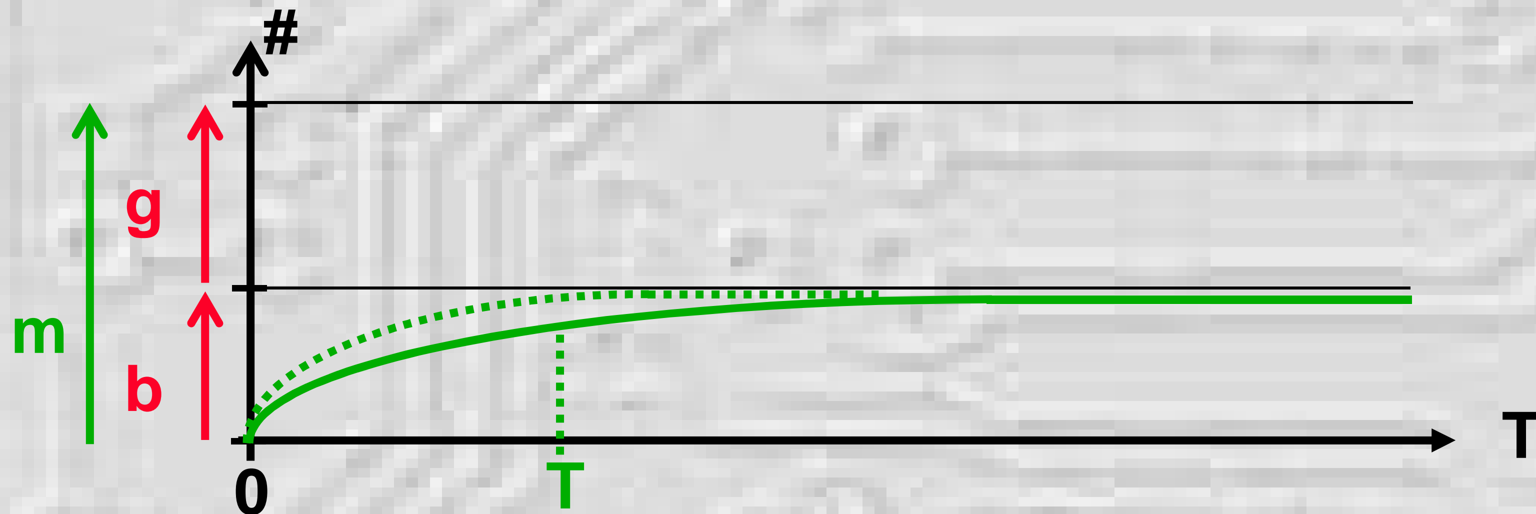
I) Criteria to stop the test generation

=> Estimate how many faulty circuits not yet detected (e?)



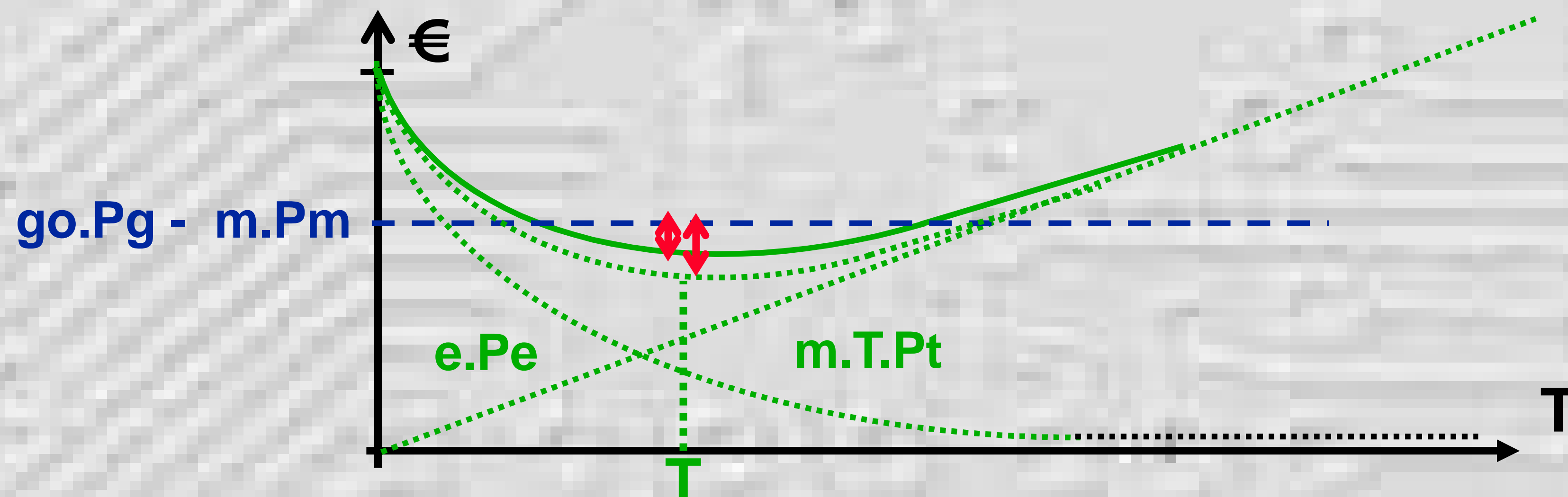
Introduction

IN2P3

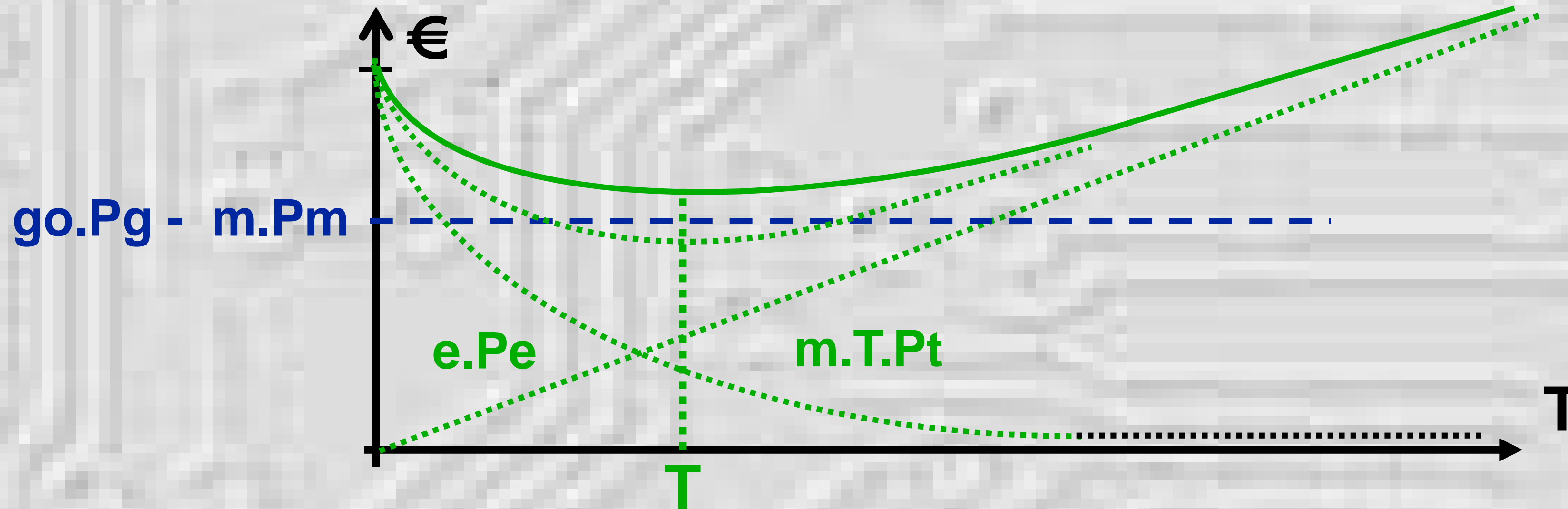


II) Criteria to optimize the test generation

=> Estimate how many faulty circuits are detected by each vector



Introduction



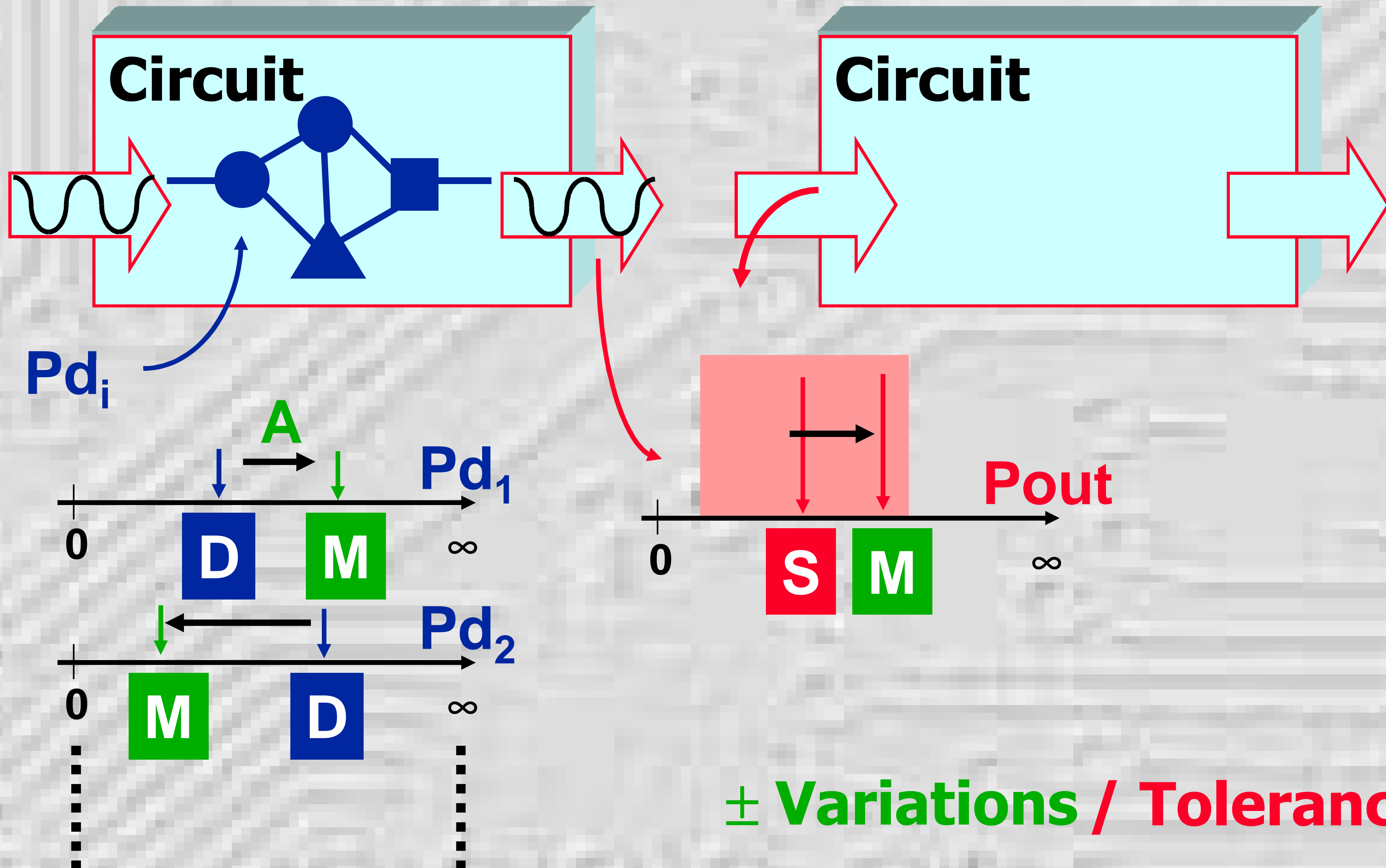
III) Criteria to make circuit Testable

=> Propose circuit modifications

Fundamental Properties

Fund. Props

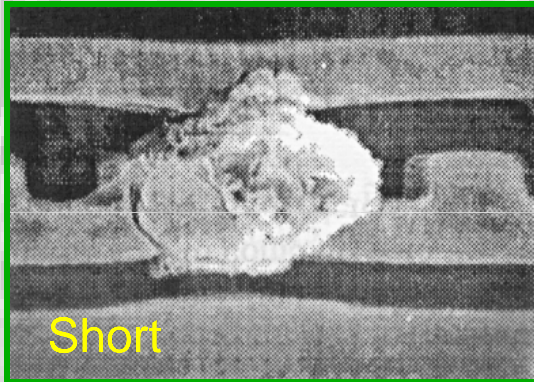
IN2P3

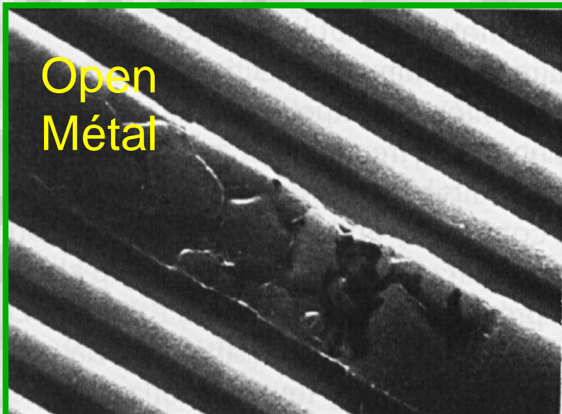


± Variations / Tolerance

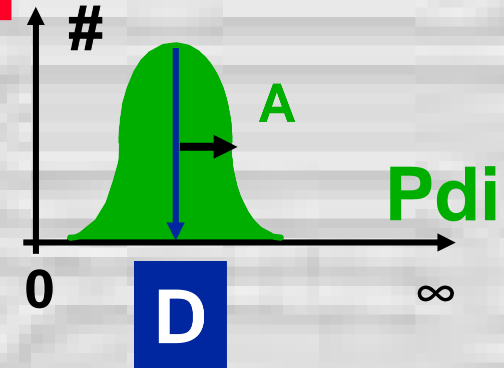
Fund. Props

± Variations ?



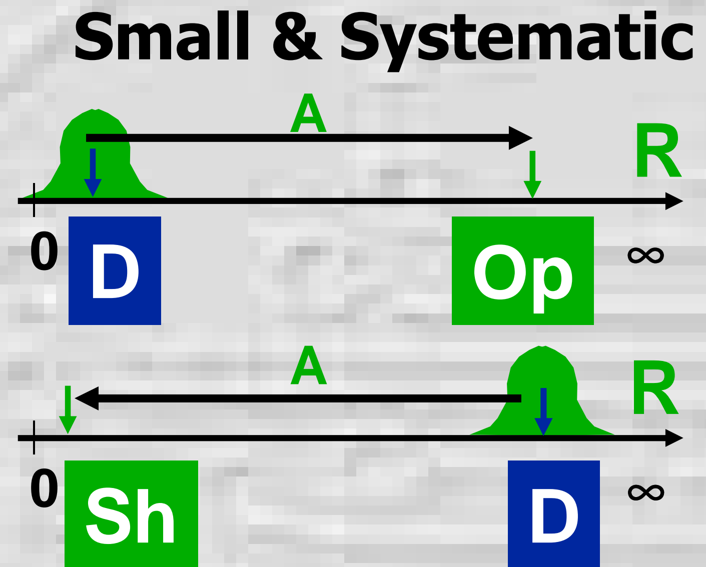


Deviation



Small & Systematic

Spot

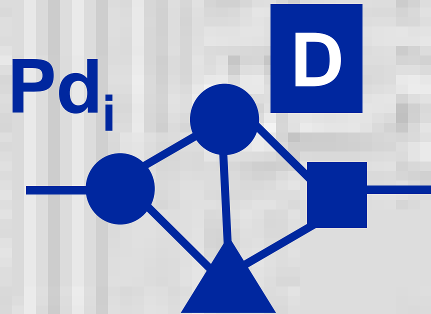


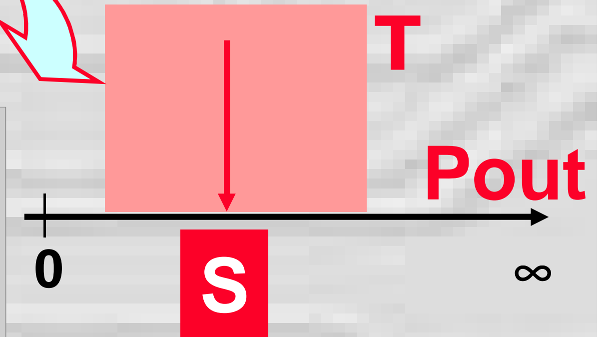
Large & Scarce

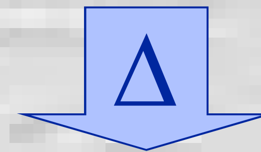
Fund. Props

IN2P3

```
process begin
  wait until not
    CLOCK'stable
    and CLOCK=1;
  if(ENABLE='1') then
    TOGGLE<= not
TOGGLE;
  end if;
end process;
```



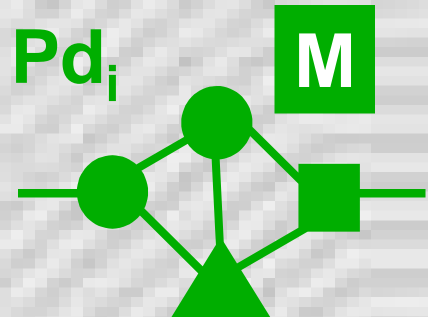


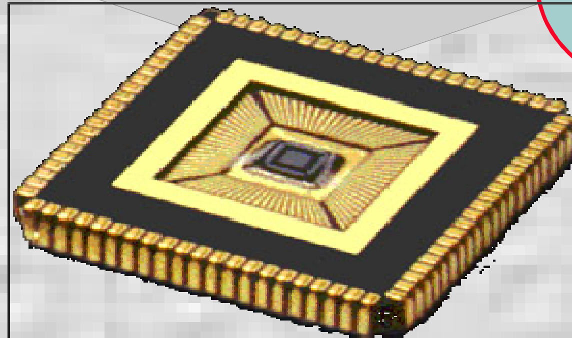


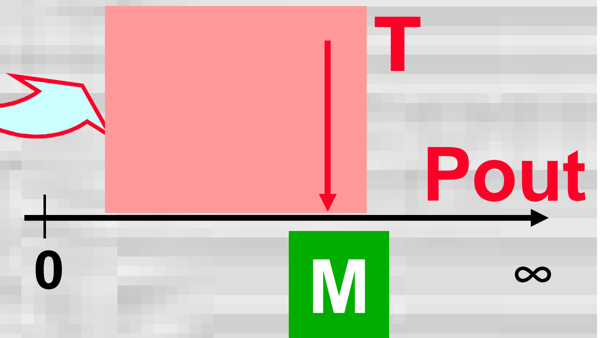
Design

Se=Δ Pout/ΔPdi

Manufacturing



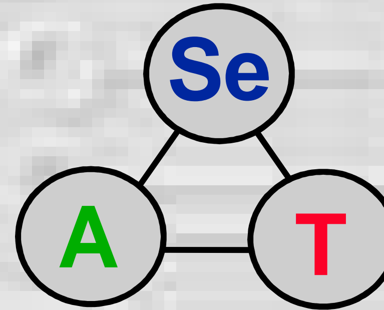




Fund. Props

Specification ?

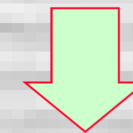
```
process begin
 wait until not
  CLOCK'stable
  and CLOCK=1;
 if(ENABLE='1') then
  TOGGLE<= not
TOGGLE;
 end if;
end process;
```



- **Amplitude : A / D $\Rightarrow$ F**
- **Tolerance : Po / S $\pm$ T**
- **Sensitivity : Se =** $\dfrac{\Delta Ps}{\Delta Pdi}$

A * Se < T ?

A < T / Se ?



Robustness

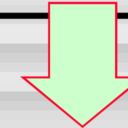
Fund. Props

IN2P3

```
process begin
  wait until not
    CLOCK'stable
    and CLOCK=1;
  if(ENABLE='1') then
    TOGGLE<= not
TOGGLE;
  end if;
end process;
```

Specification ?

A < T / Se ?



Robustness

Low T/Se	**High T/Se**

<u>Deviations</u>

- **Small**
- **Systematic**

<u>Spot</u> (Low T/Se)

- **Large**
- **Scarce**

<u>Spot</u> (High T/Se)

- **Large**
- **Scarce**

Fund. Props

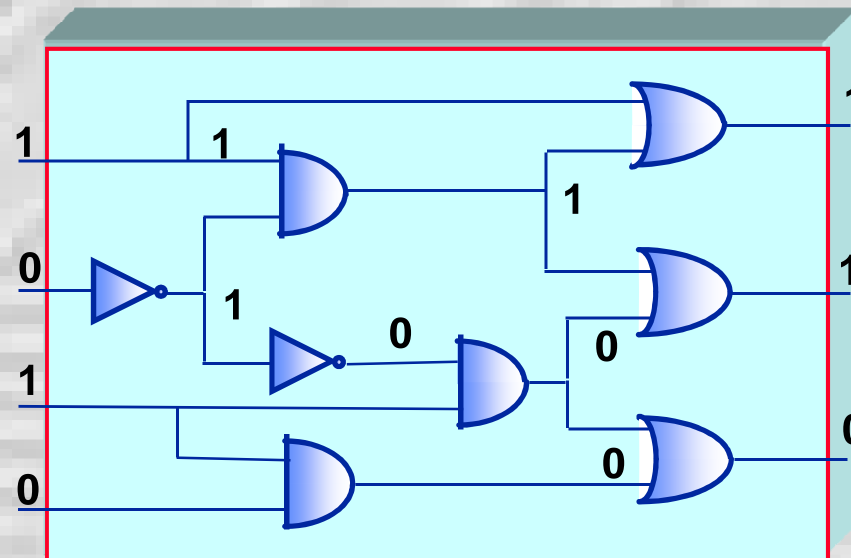
IN2P3

Digital

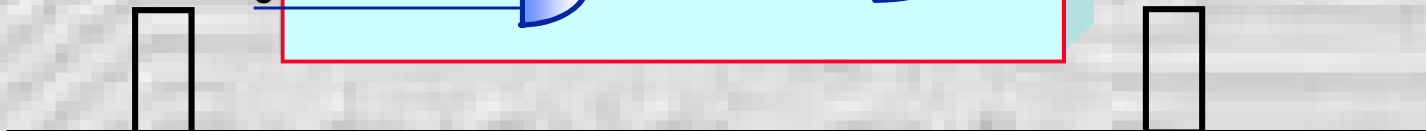
```
process begin
  wait until not
    CLOCK'stable
    and CLOCK=1;
  if(ENABLE='1') then
    TOGGLE<= not
TOGGLE;
  end if;
end process;
```

Specification ?

- Logic
- Timing



Cl



Fund. Props

Digital

```
process begin
  wait until not
    CLOCK'stable
    and CLOCK=1;
  if(ENABLE='1') then
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TOGGLE;
  end if;
end process;
```
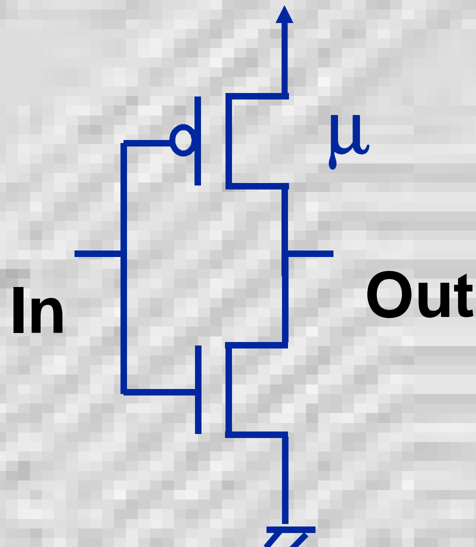
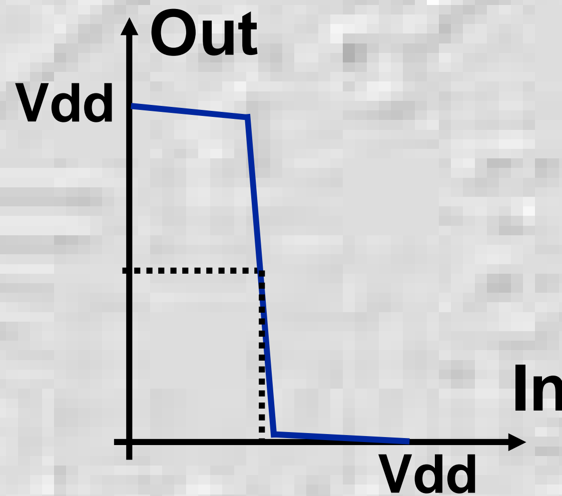
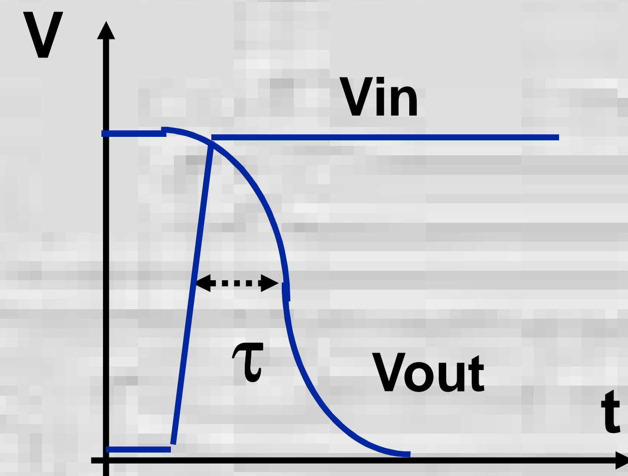

Specification ?

- Logic
- Timing



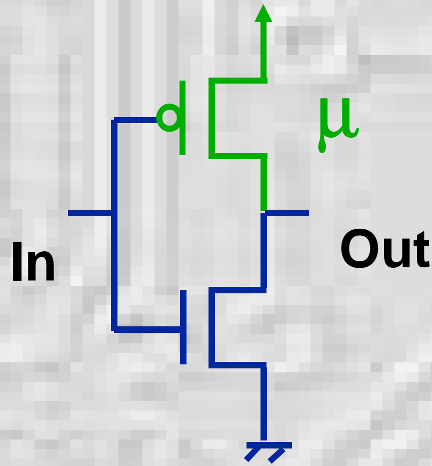


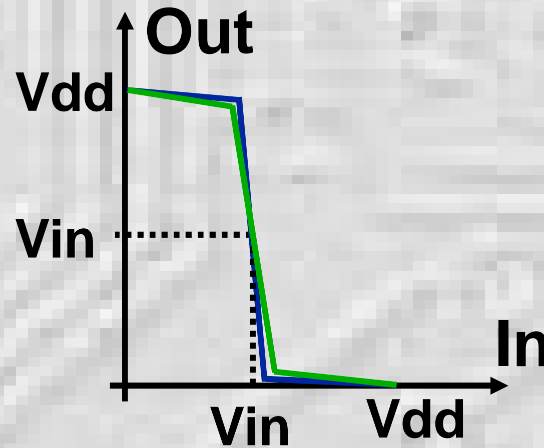


Fund. Props

IN2P3

Digital

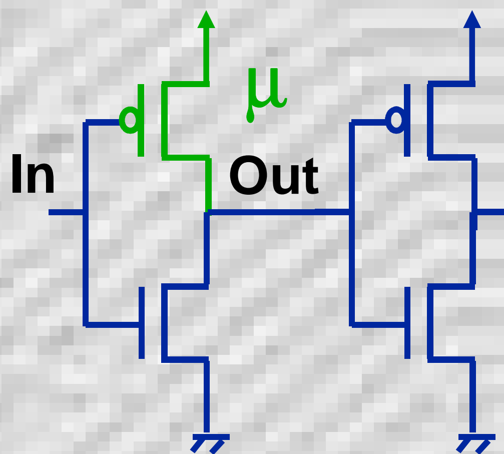


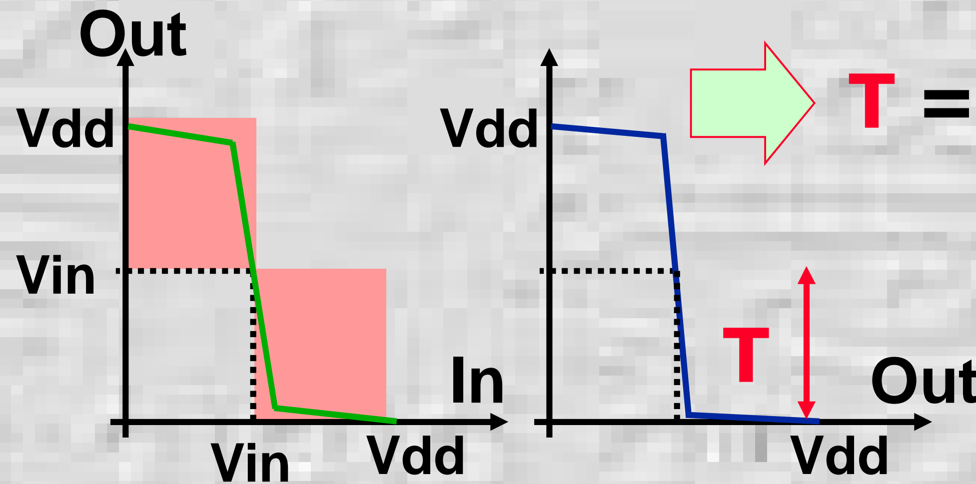


$$Se = \frac{\Delta Ps}{\Delta Pdi}$$

Very High T/Se

Circuit Indpt





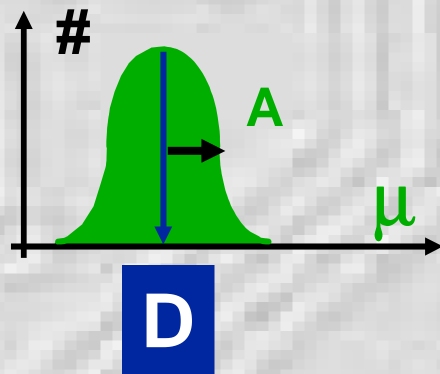
T = 50%

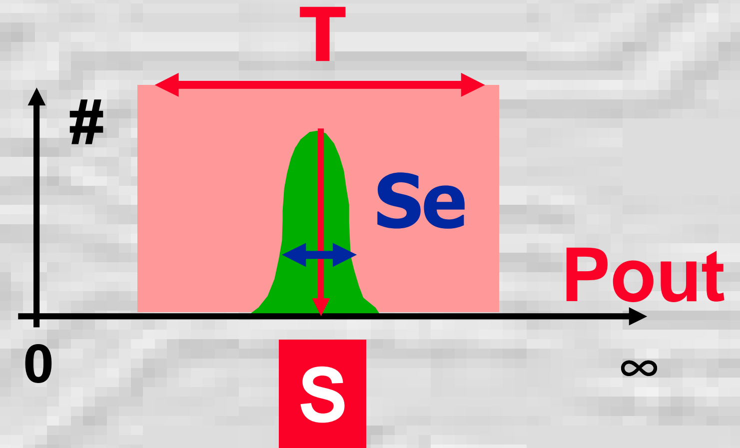
Fund. Props

IN2P3

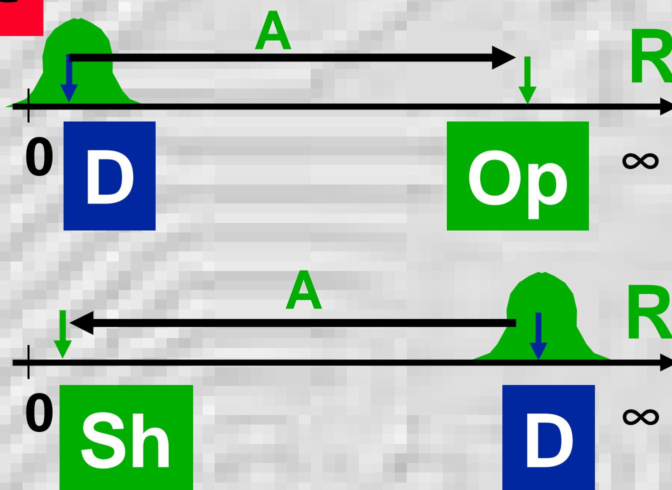
Digital

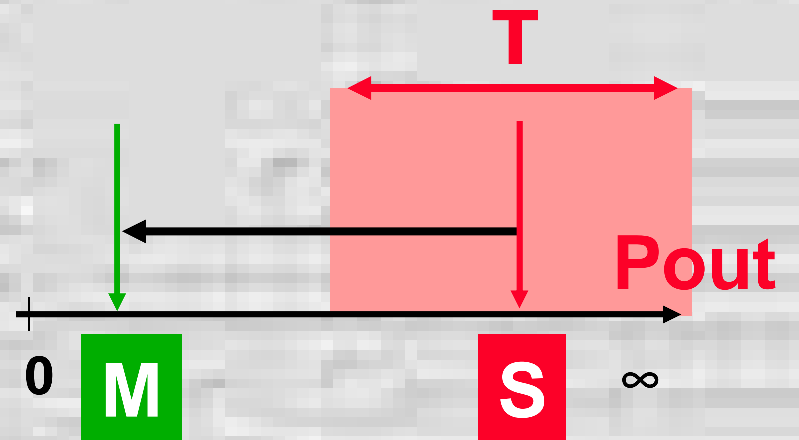
Deviation





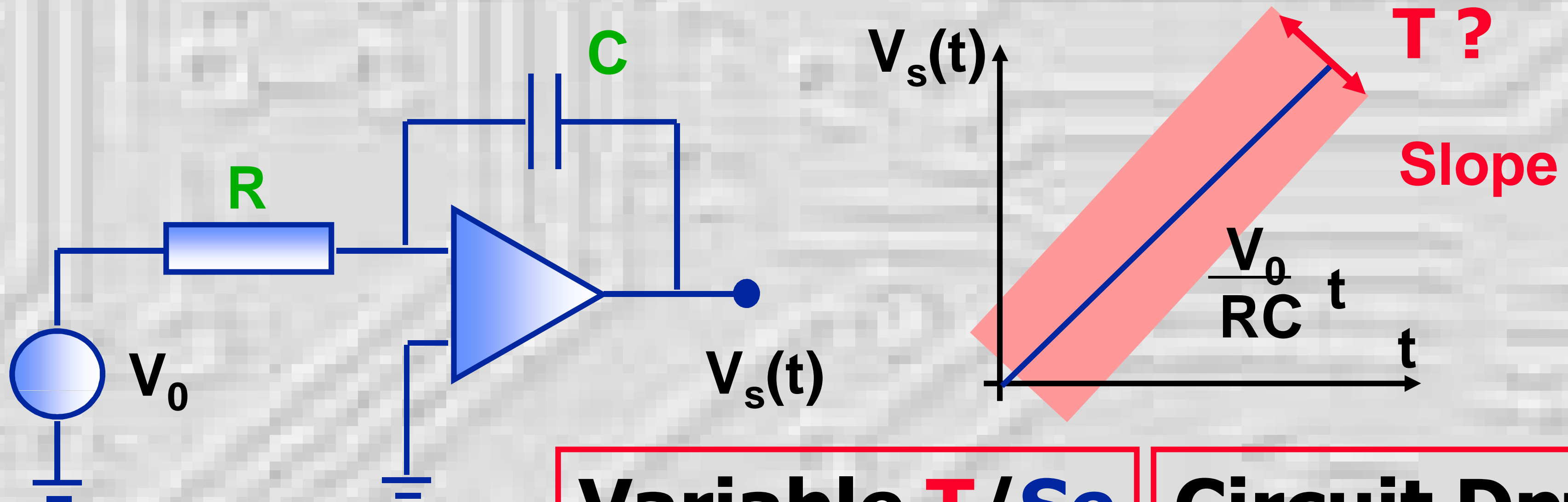
Spot

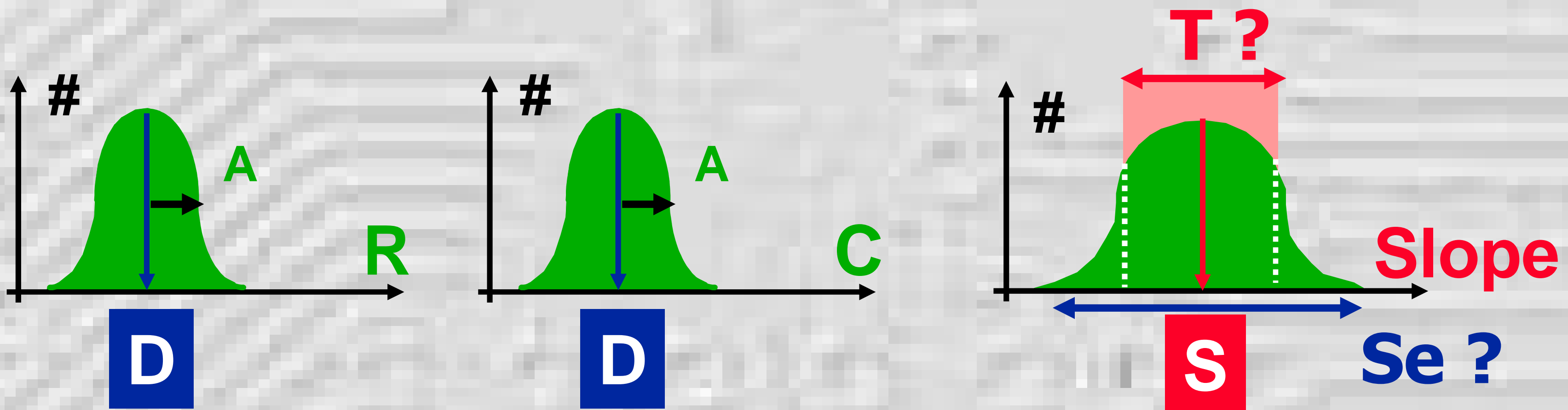




Fund. Props

IN2P3

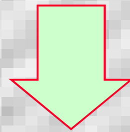
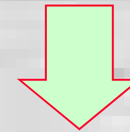


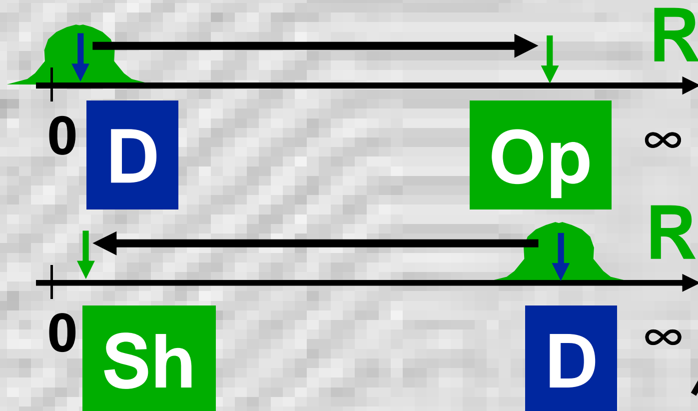


Fund. Props

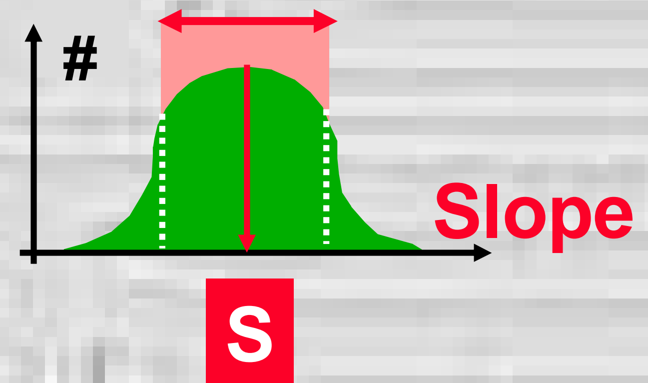
IN2P3

Digital	Analog
High T/Se	Low T/Se
	Deviations Small & Syst.
Spots Large & Sc.	Spots Large & Sc.
Defect Oriented Test	Spec Oriented Test



Timing

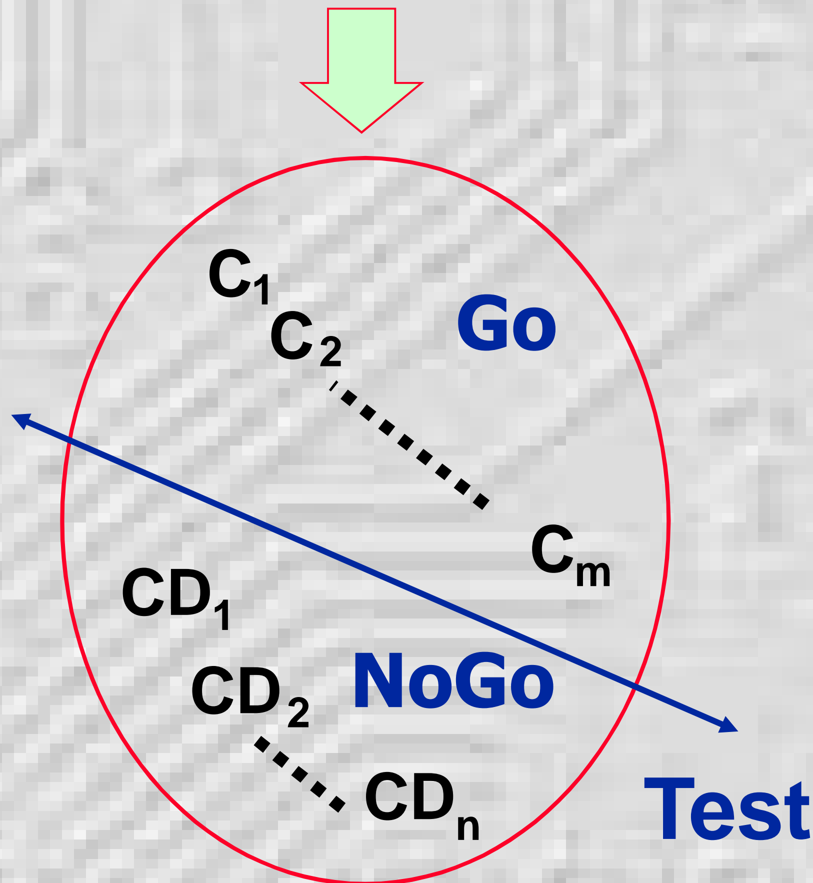


Fund. Props

IN2P3

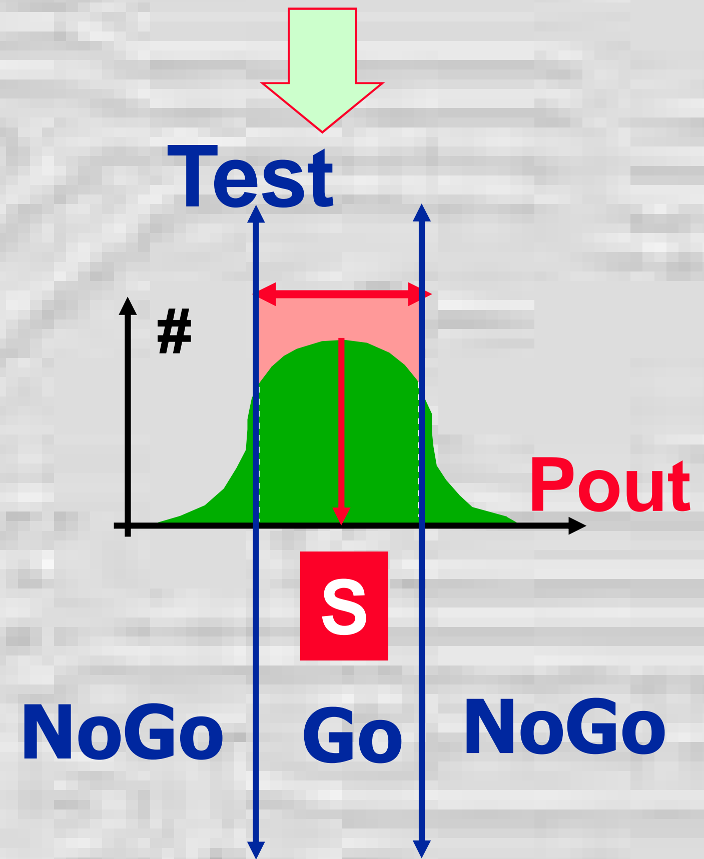
Digital

Defect Oriented Test



Analog

Spec Oriented Test

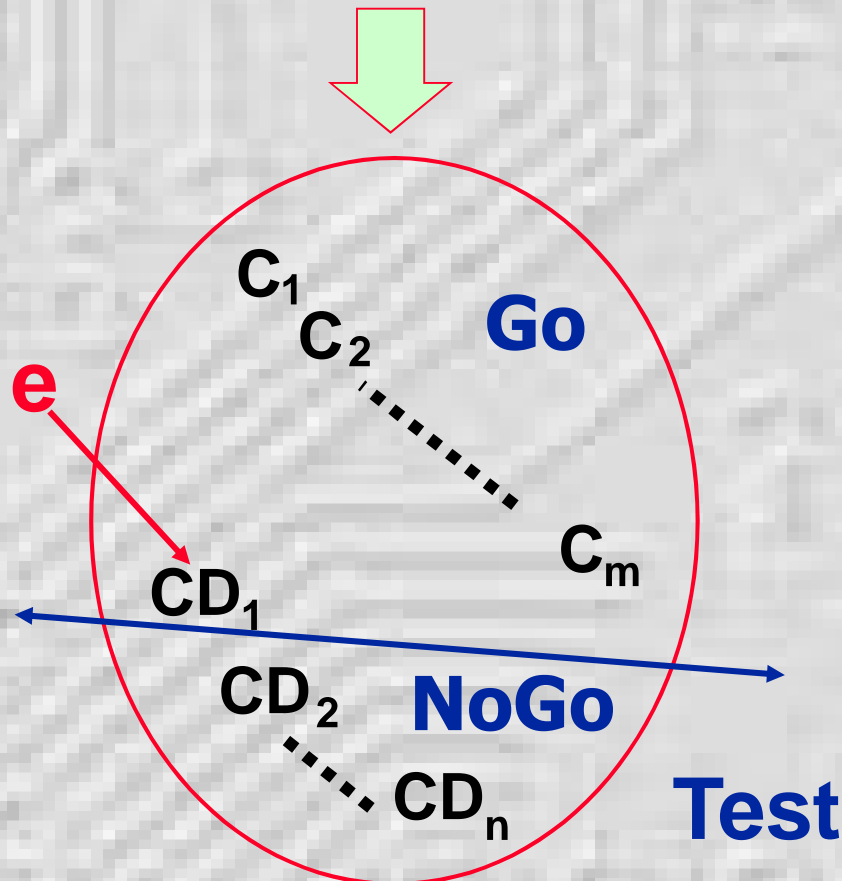


Fund. Props

IN2P3

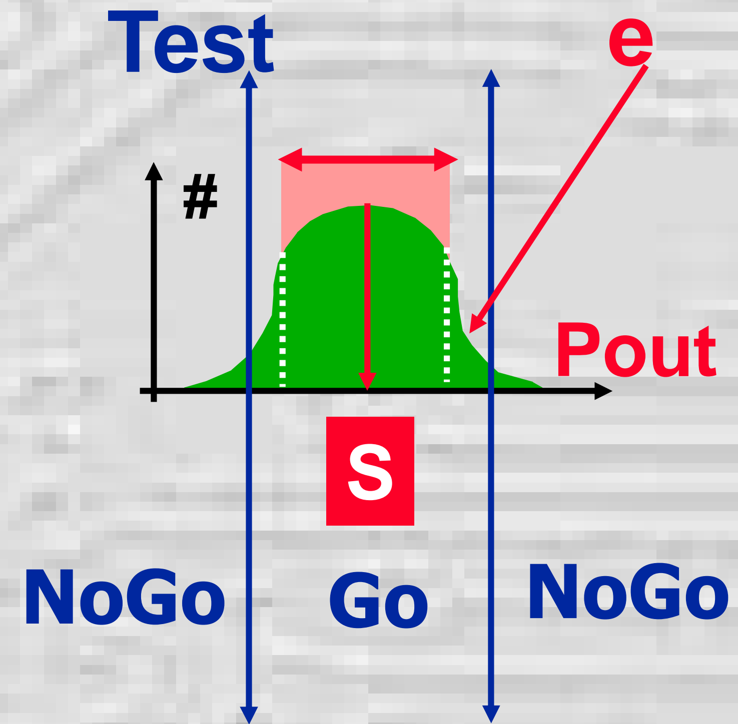
Digital

Defect Oriented Test



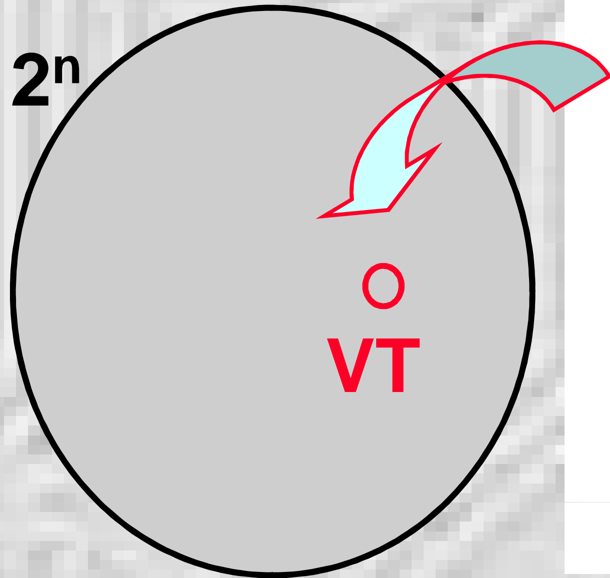
Analog

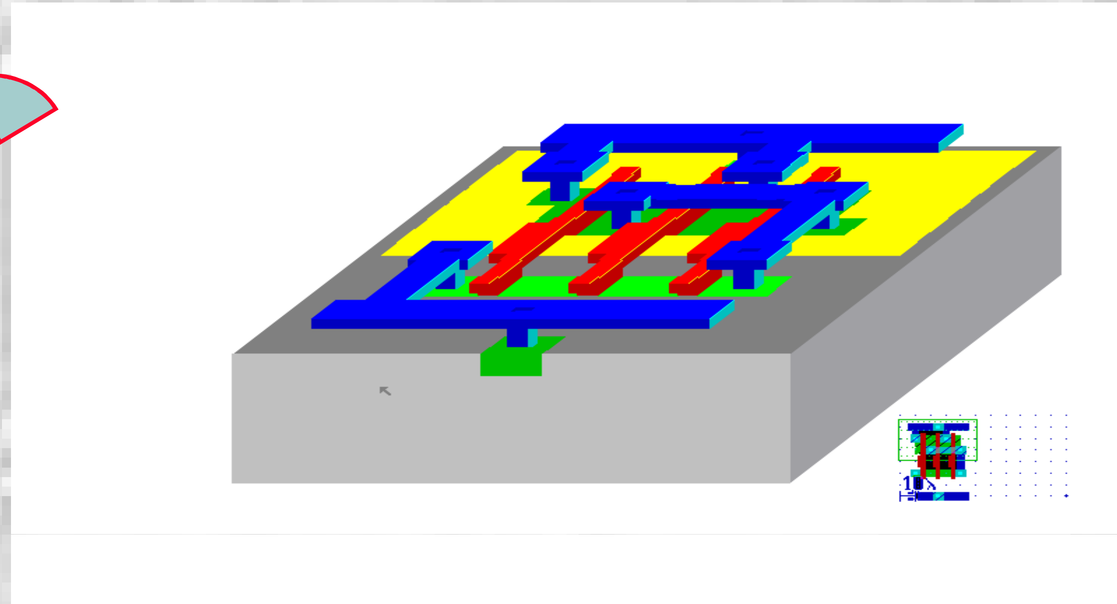
Spec Oriented Test



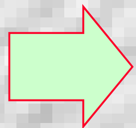
Digital Approach

Digital Approach

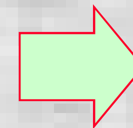




Spot-Free Digital Circuit <=> In Specification

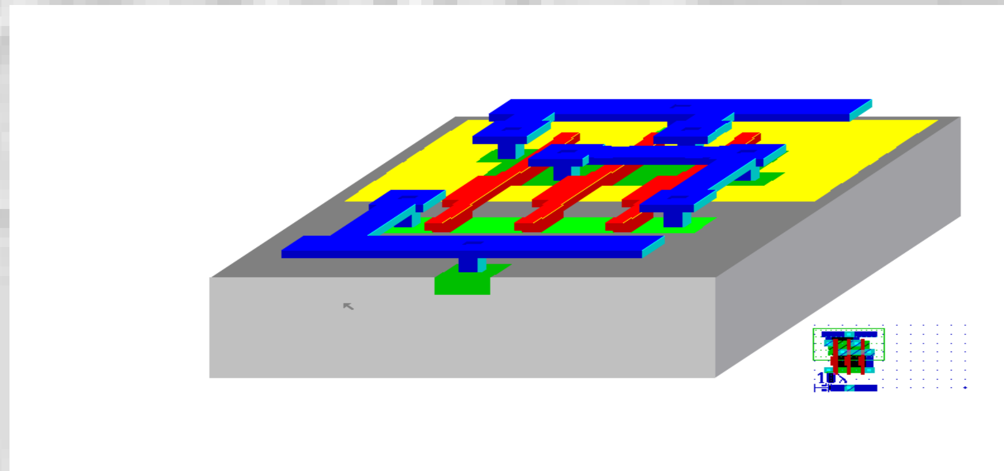


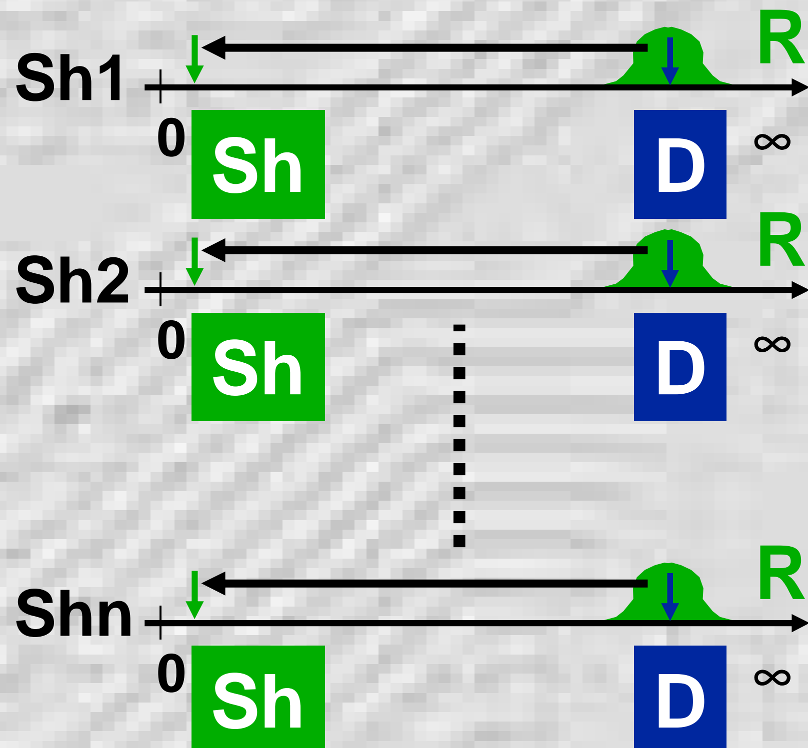
For *each possible spot*
Compute a stimuli
that reveals its presence

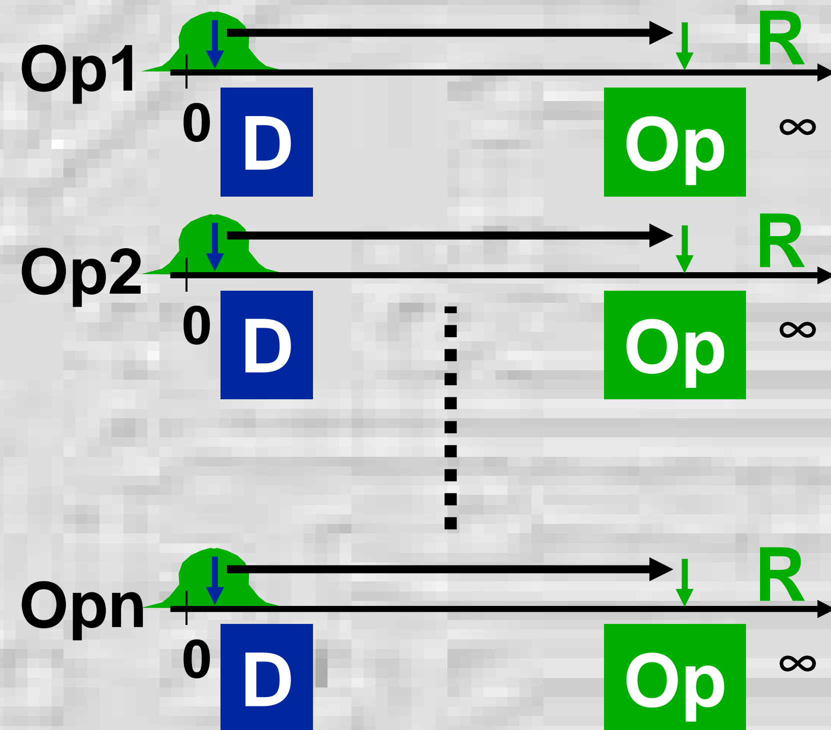


Test Pattern List

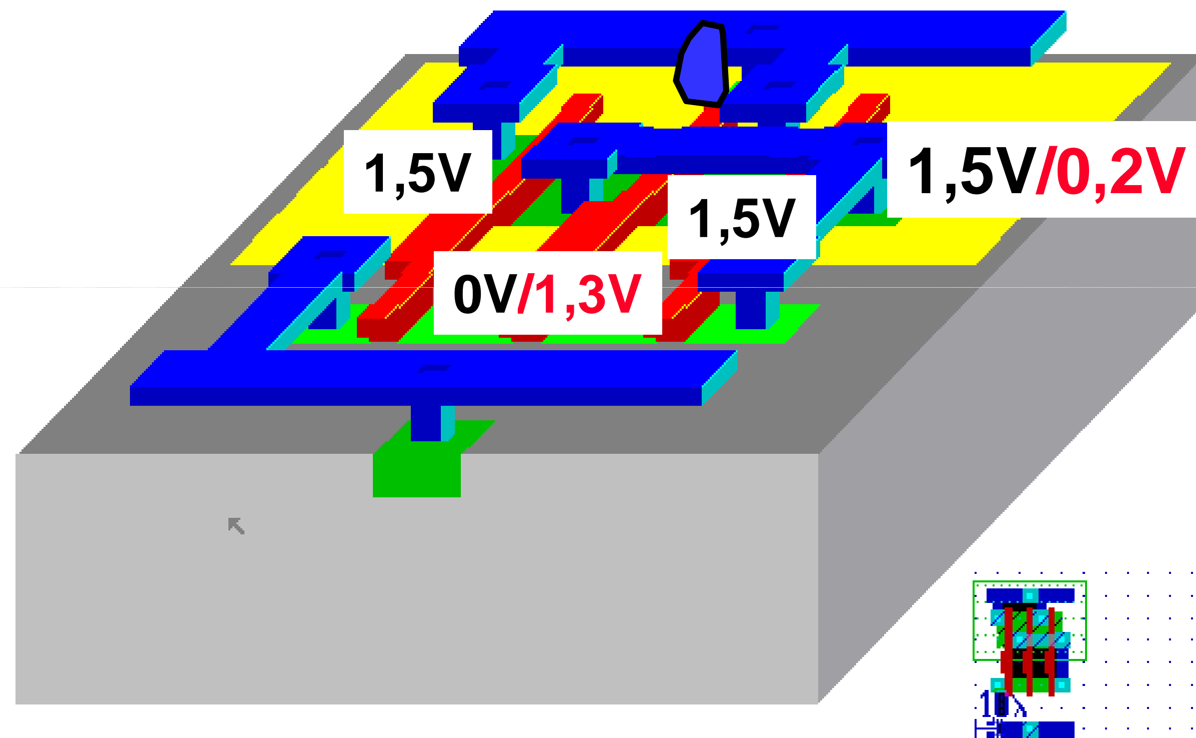
Digital Approach



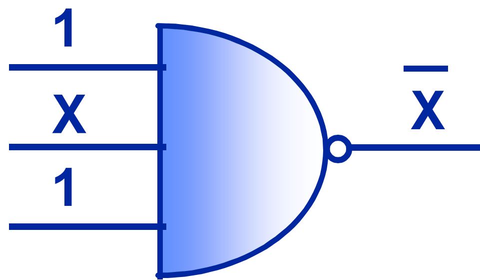


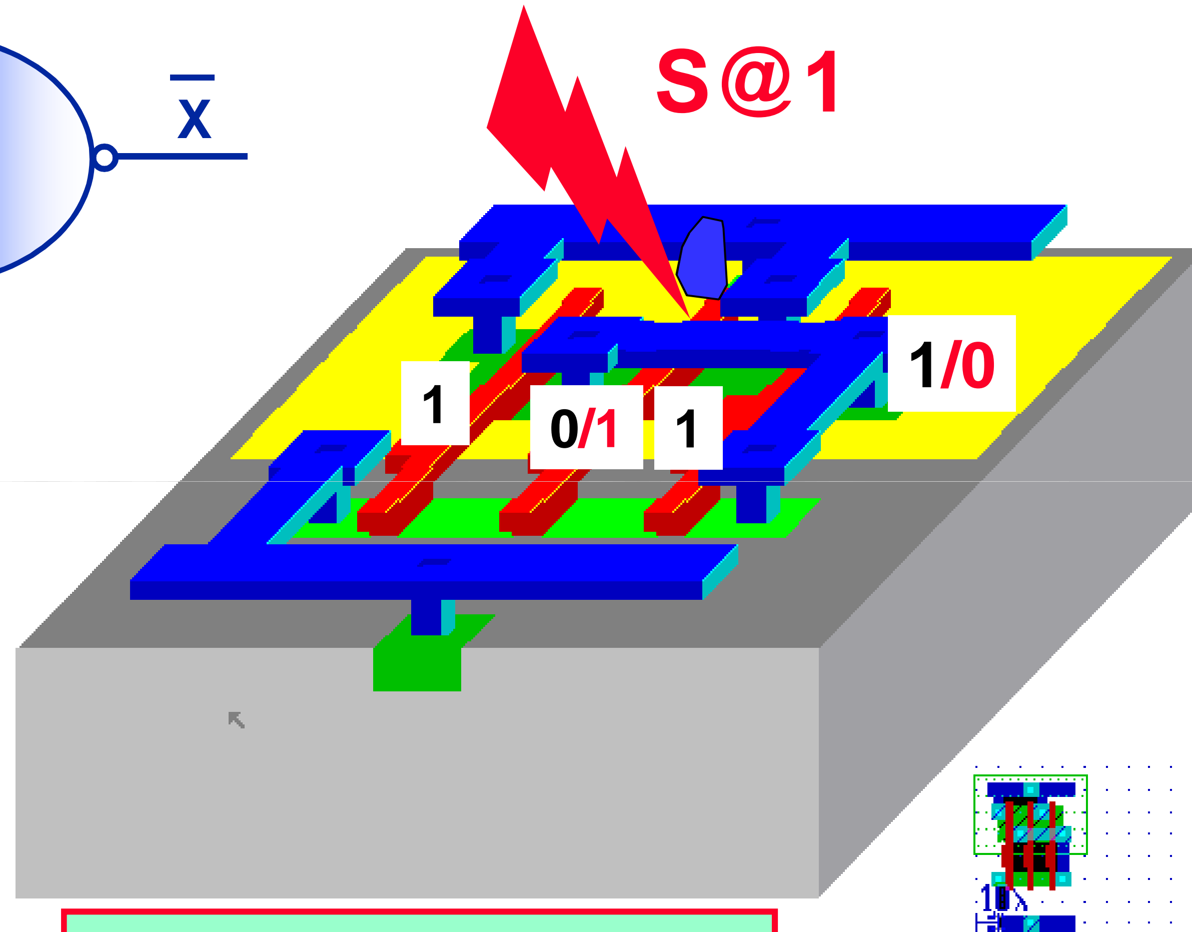


Digital Approach



Digital Approach

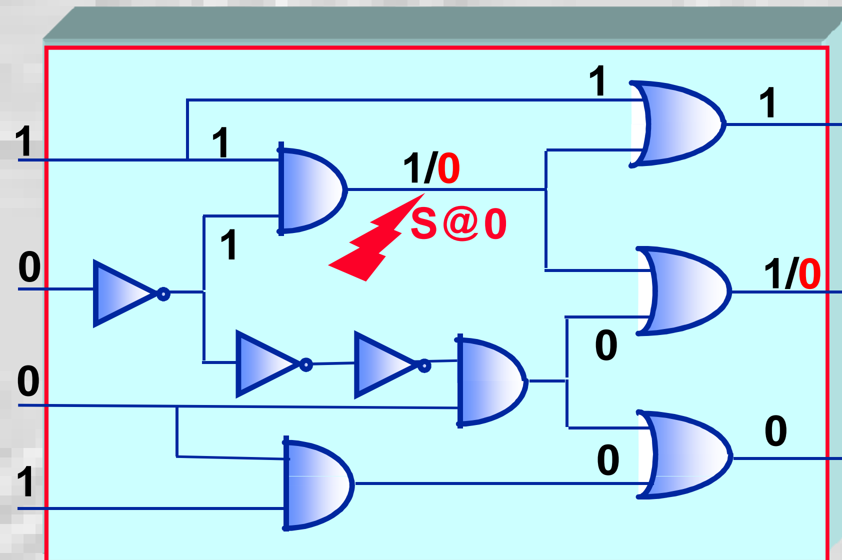




Spot <=> Fault Model
- S@0
- S@1

Digital Approach

IN2P3



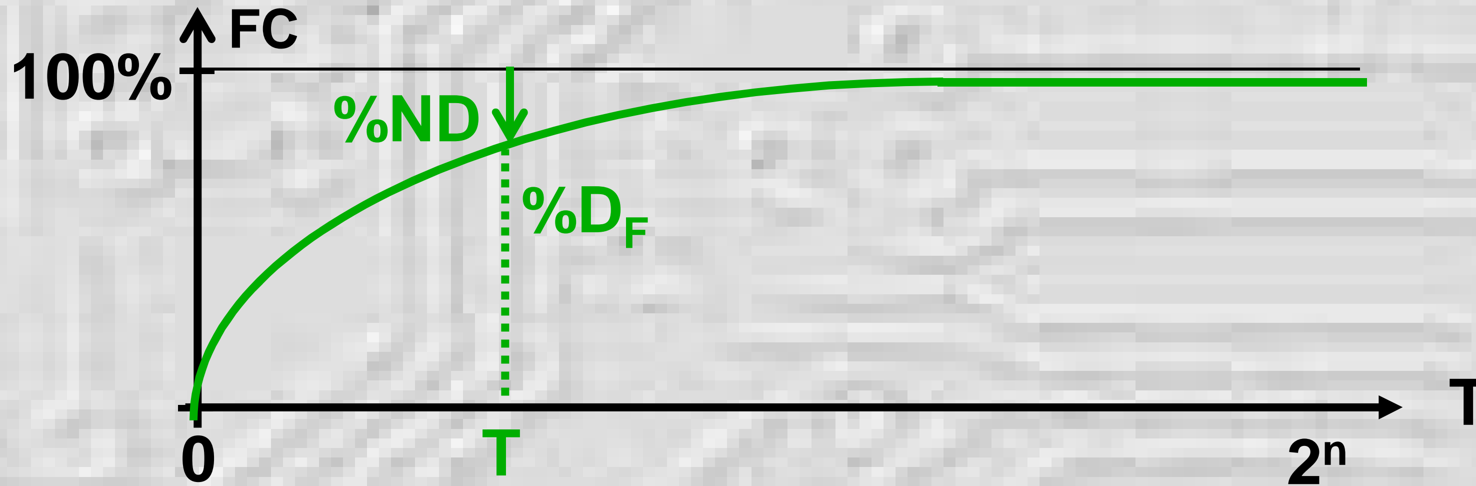
Cost

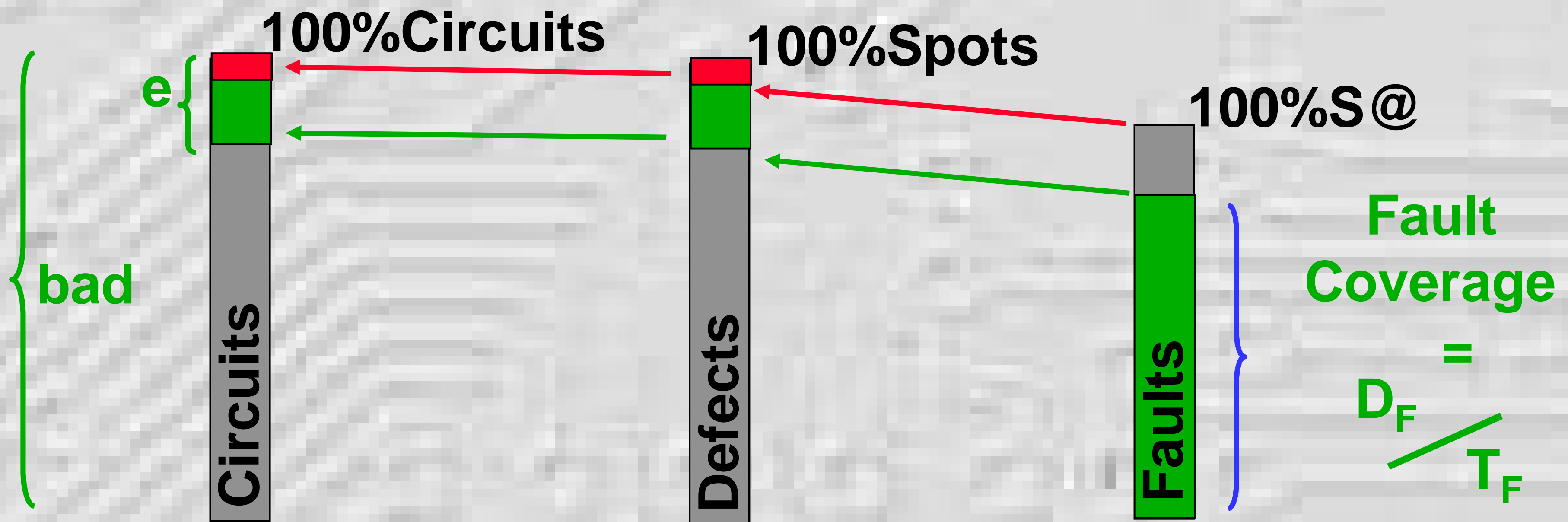
- 10^6 gates
- 10^6 nodes
- 10^6 S@0
- 10^6 S@1
- 2.10^6 vectors
- 100Mhz

Physical Structure <=> Logical Structure

- Each Logic node S@0
- Each Logic node S@1
- TPG

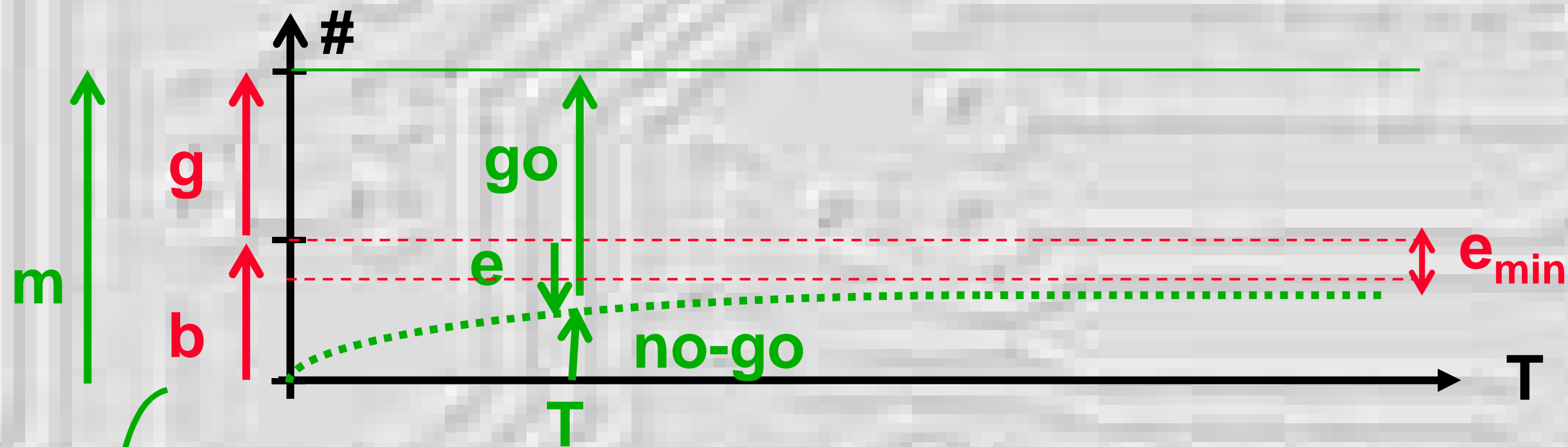
Digital Approach



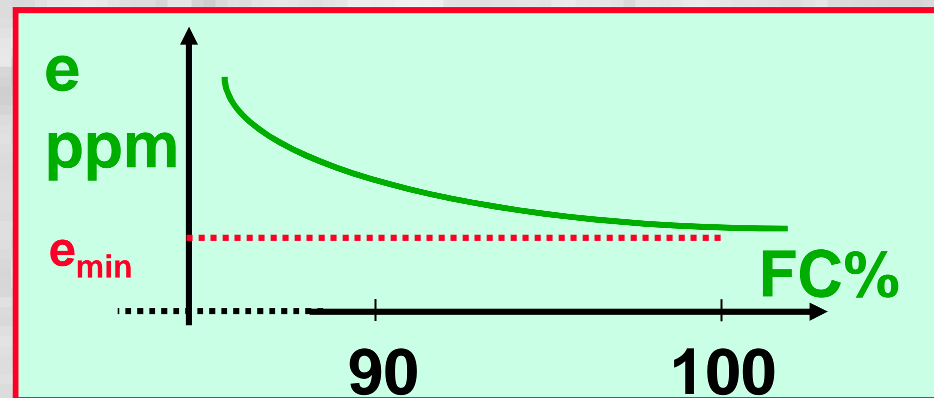


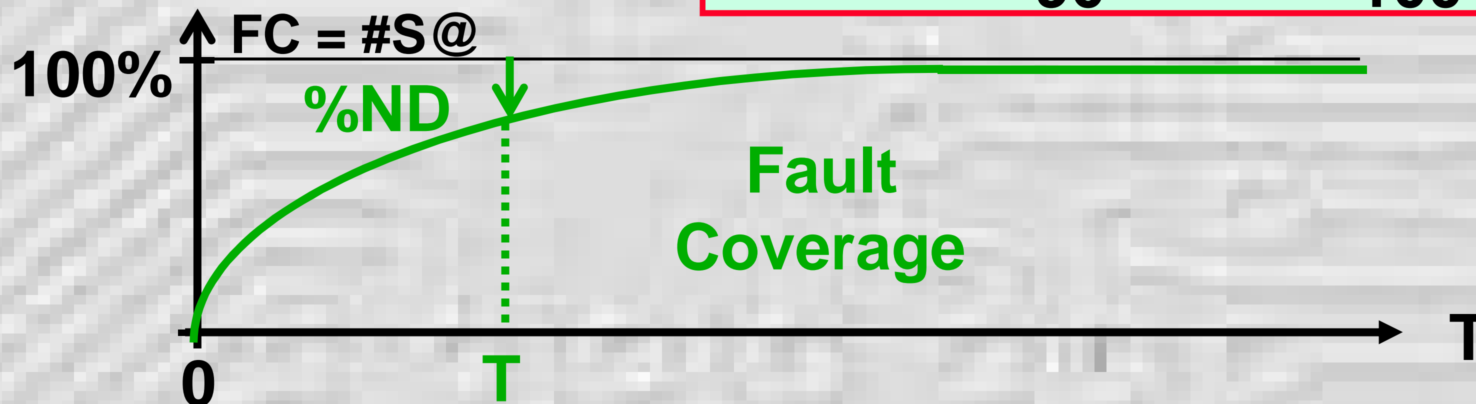
Digital Approach

IN2P3

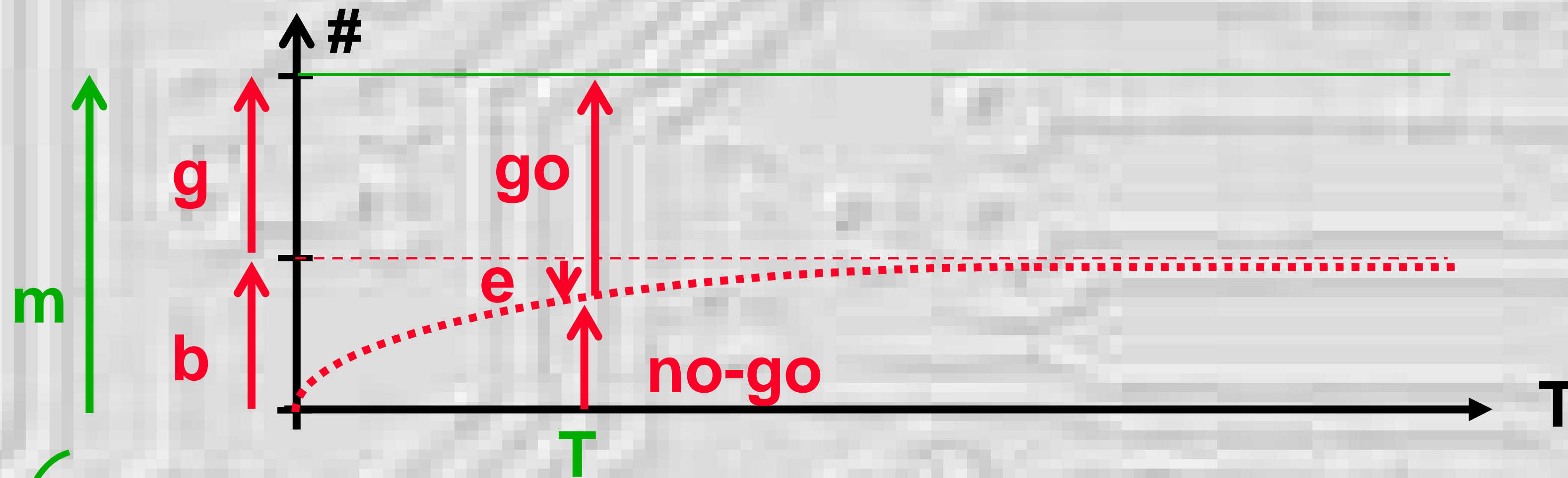


Quality



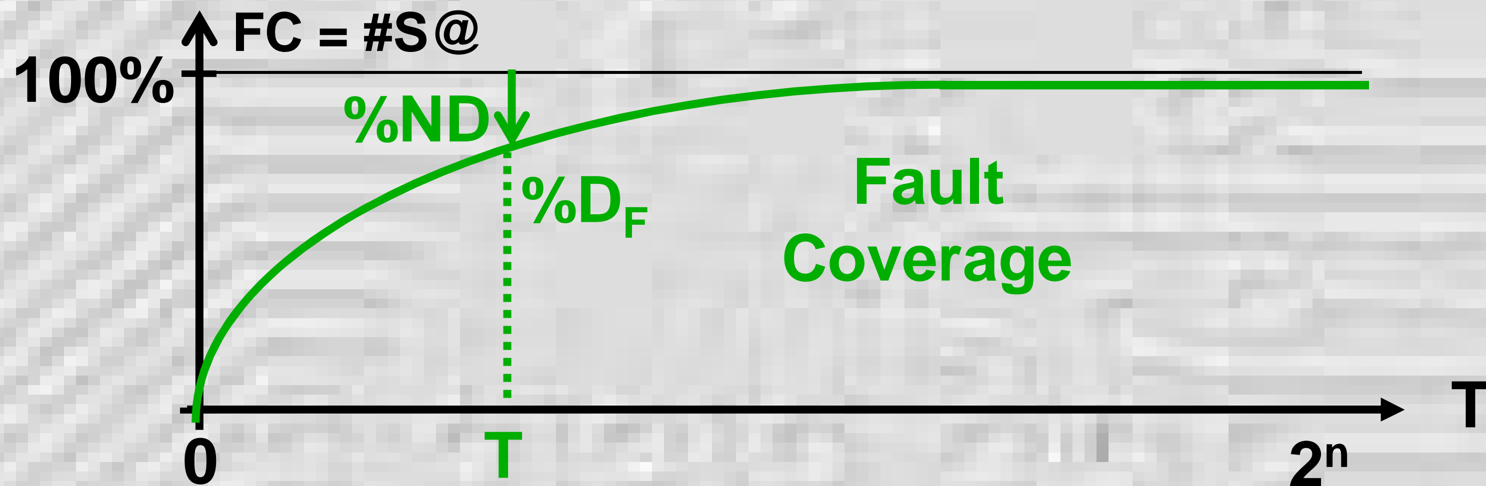


Digital Approach



I) Criteria to stop the test generation

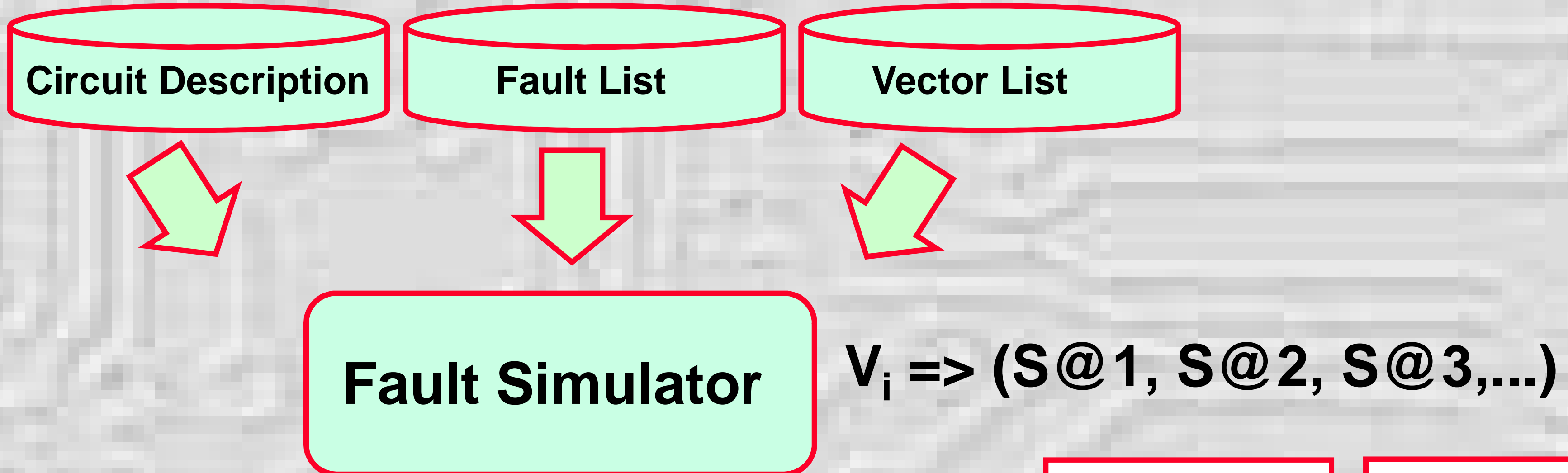
=> Estimate how many faulty circuits not yet detected (e?)



Test Generation

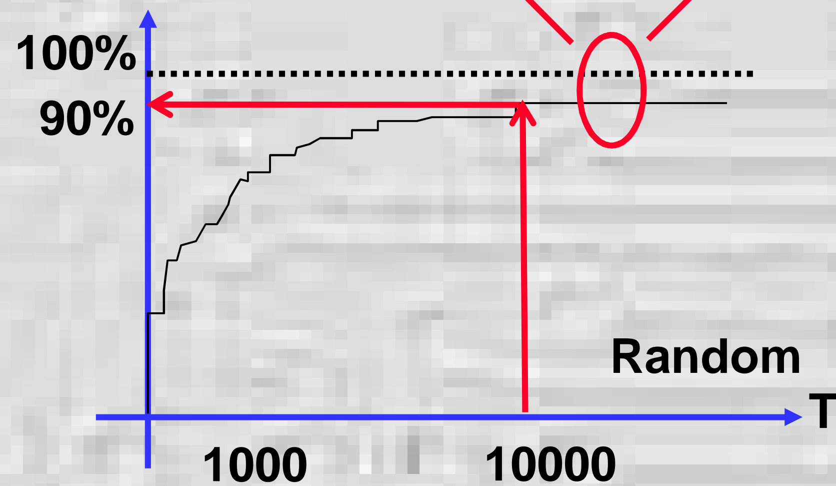
Test Generation

IN2P3

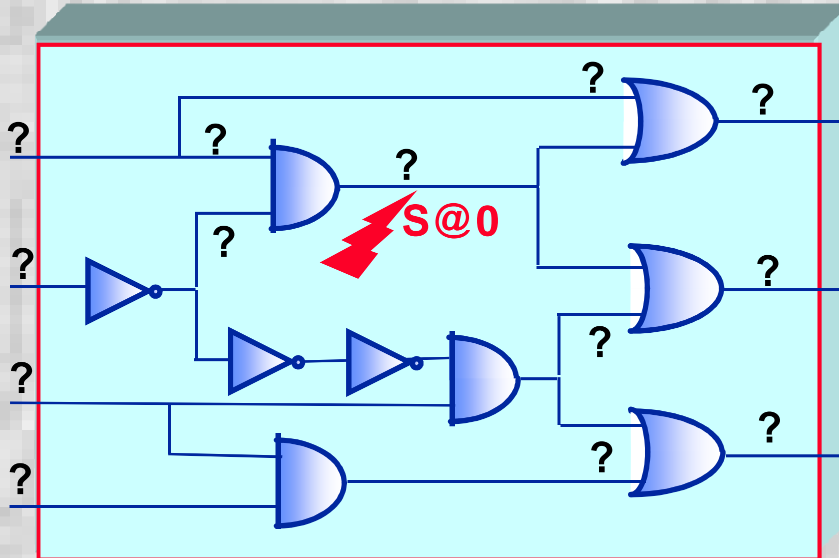


V_i => (S@1, S@2, S@3,...)

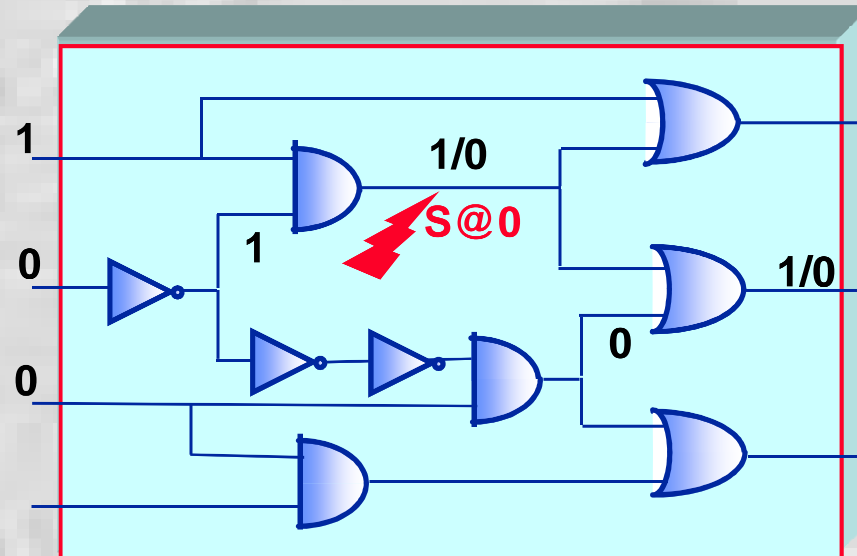
$FC = D_F / T_F$



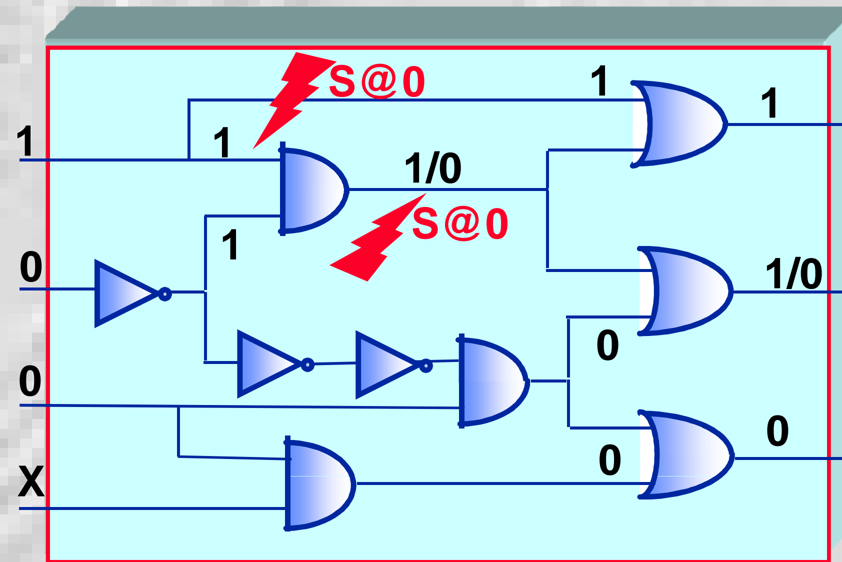
Test Generation



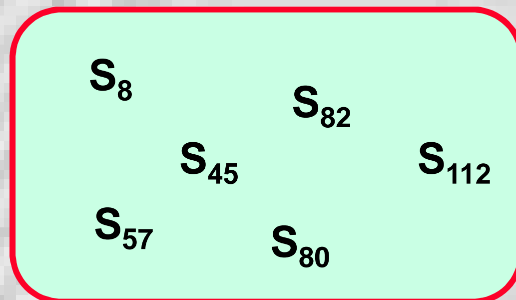
Compute <=> ATPG



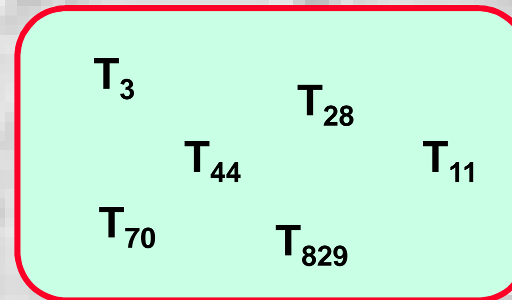
Test Generation



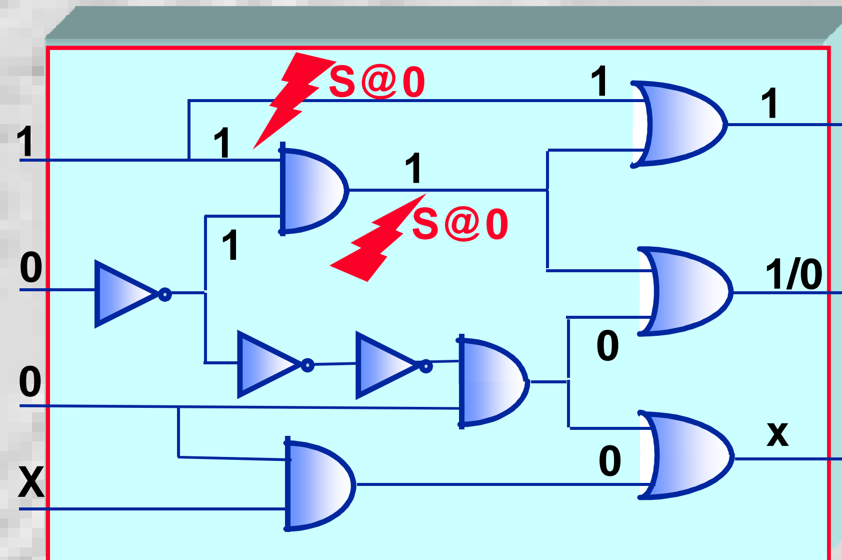
T_9



S_{13}

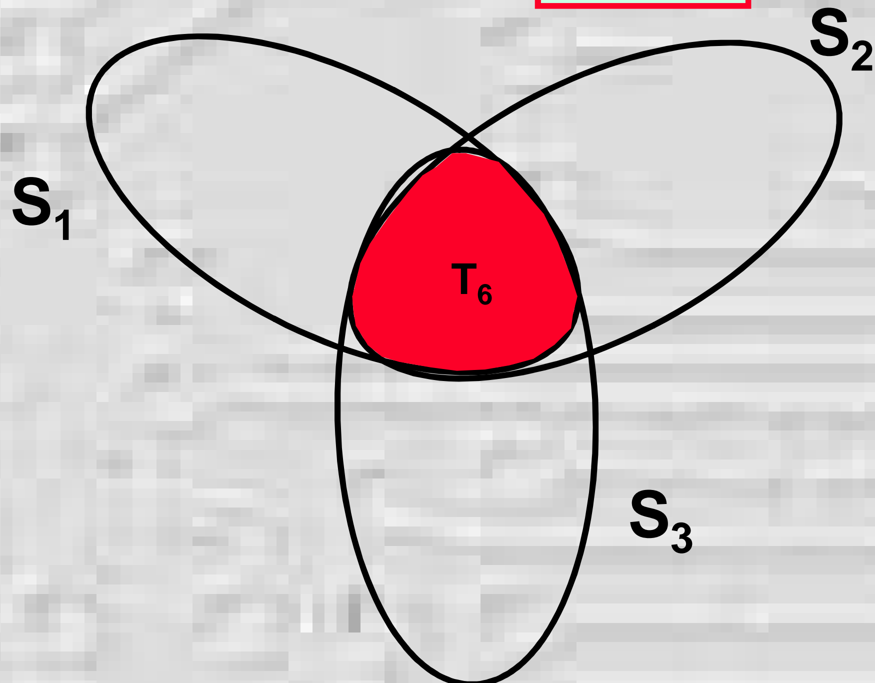


Test Generation

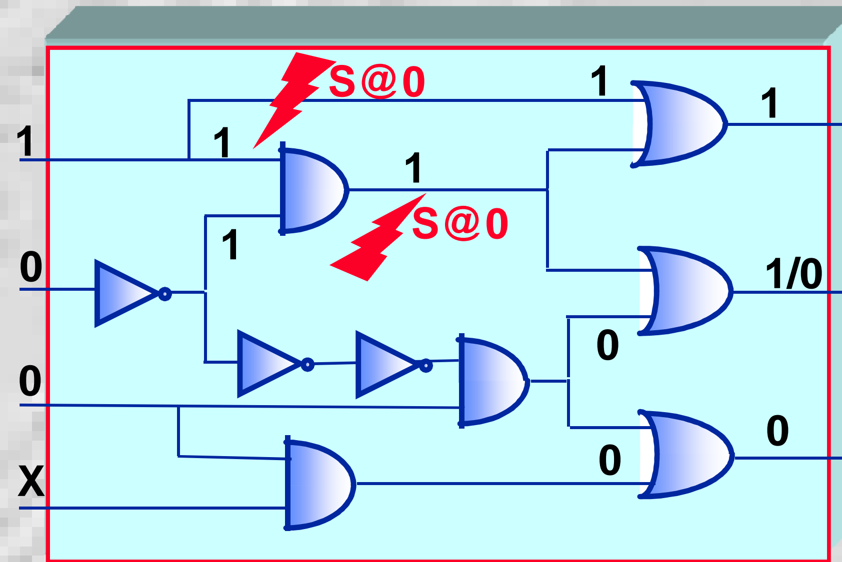


Cost

- Desired e (Application)
- Desired FC%
- Structural ATPG => Vectors
- Minimal number



Test Generation



FC 90%

- S@1 => S1=(T_{11} or T_{12} or T_{13} ...)
- S@2 => S2=(T_{21} or T_{22} or T_{23} ...)
- S@3 => S3=(T_{31} or T_{32} or T_{33} ...)
- ....

FC 98%

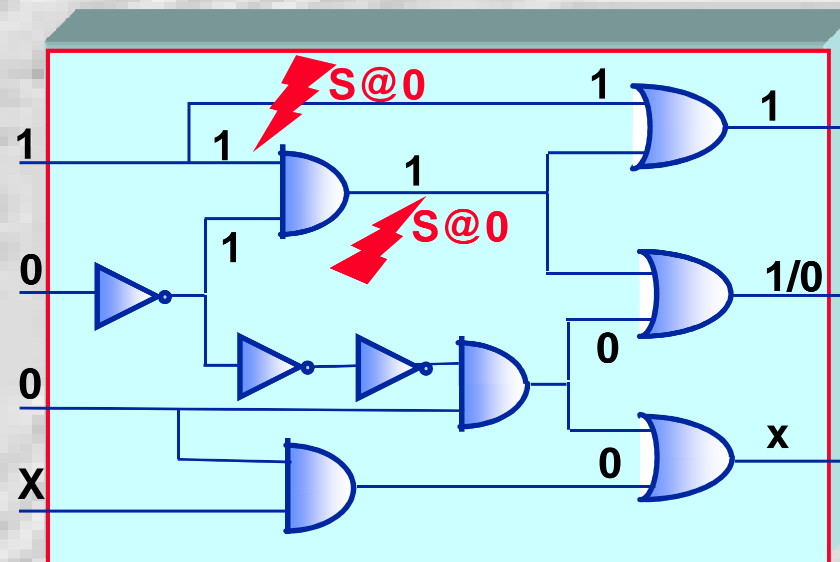
S1 and S2 and S3 and ..

$$T=(T_1+T_2+T_3)(T_1)(T_2+T_4)$$

$$T=T_1T_2+T_1T_2T_3+T_1T_4 +T_1T_2T_4+T_1T_3T_4$$

Test Generation

IN2P3



Cost

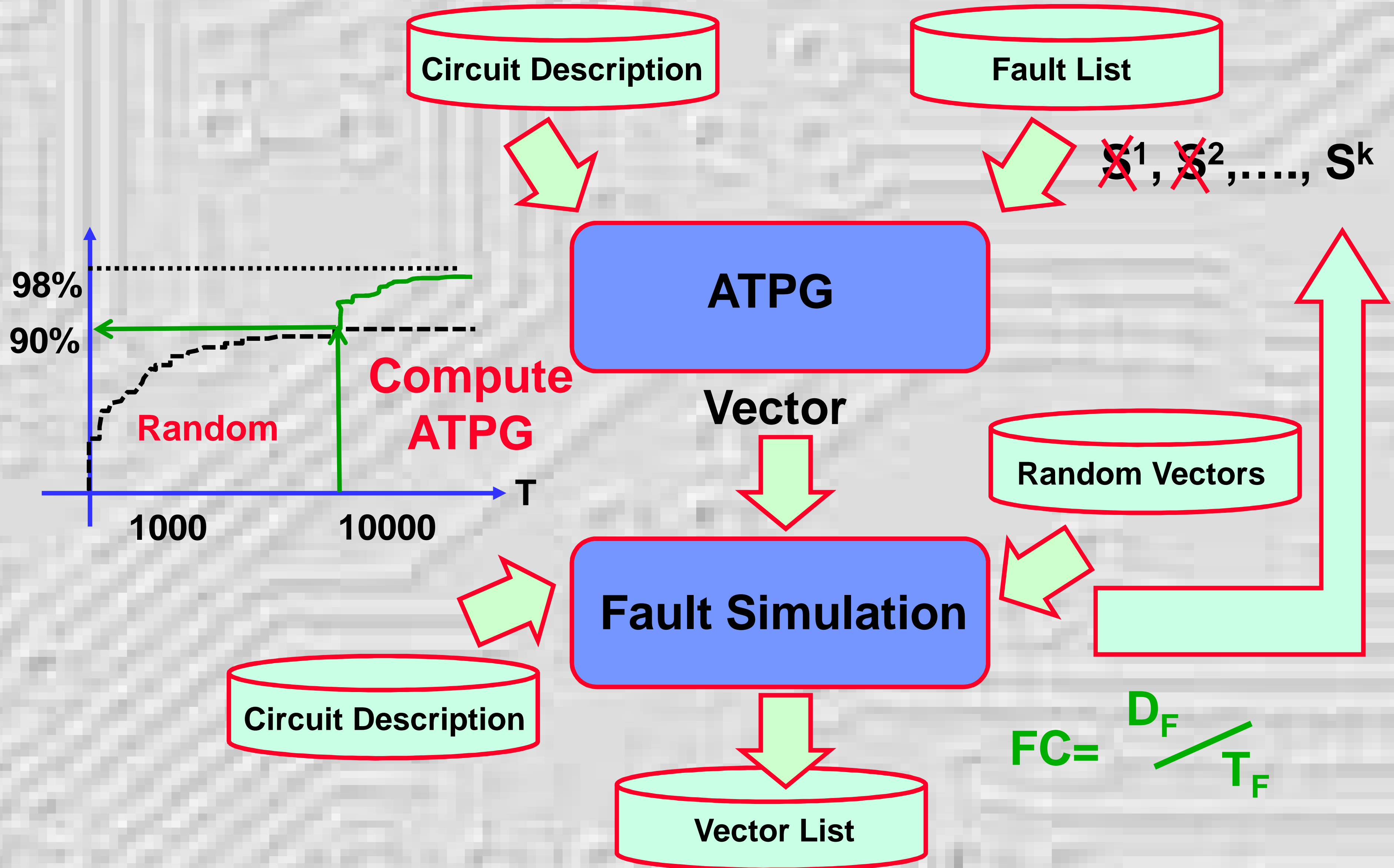
- **ATPG :**

  S@1 => T_{11} (np)

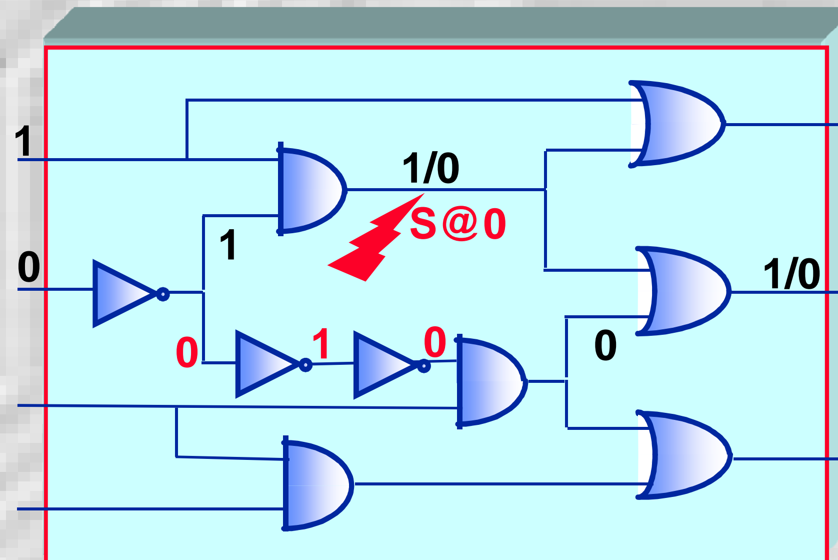
- **Fault Simulation :**

  V_{ij} => (S@1, S@2, S@3, S@4 ...)(ok)

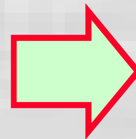
Test Generation



Test Generation



- Backward justification
- Conflict
- Backtrack

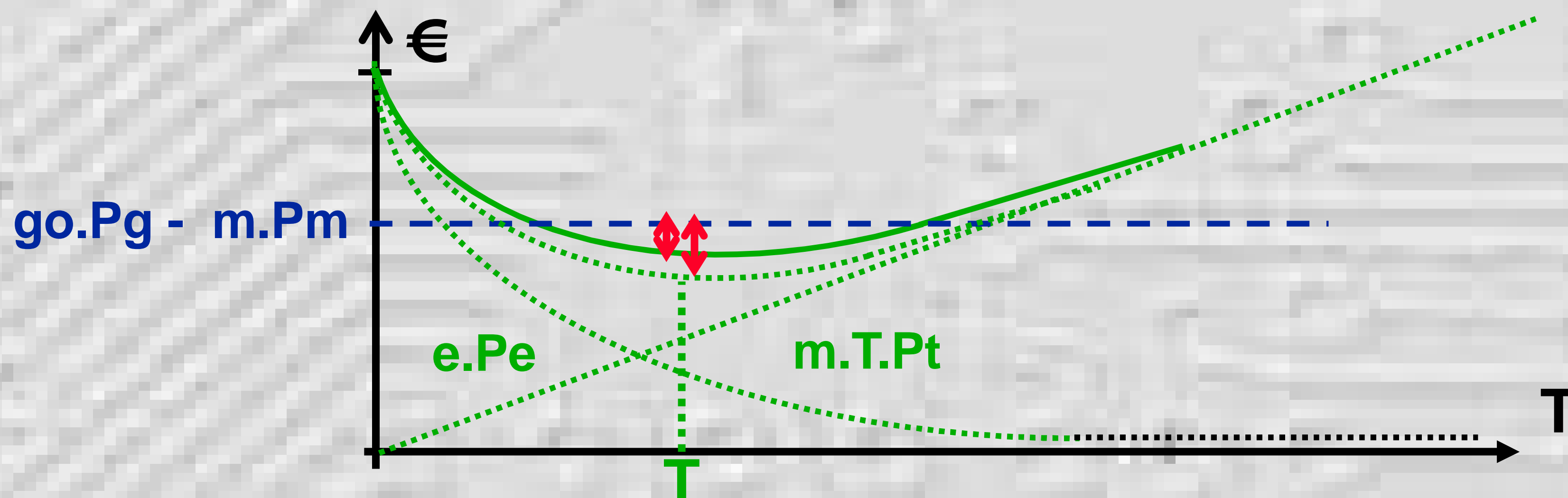


- Limited number Backtrack
-

Test Generation

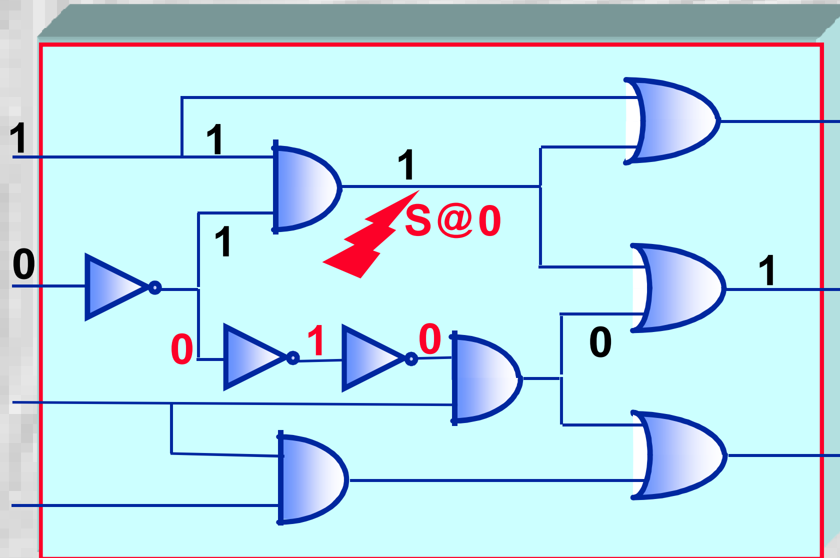
II) Criteria to optimize the test generation

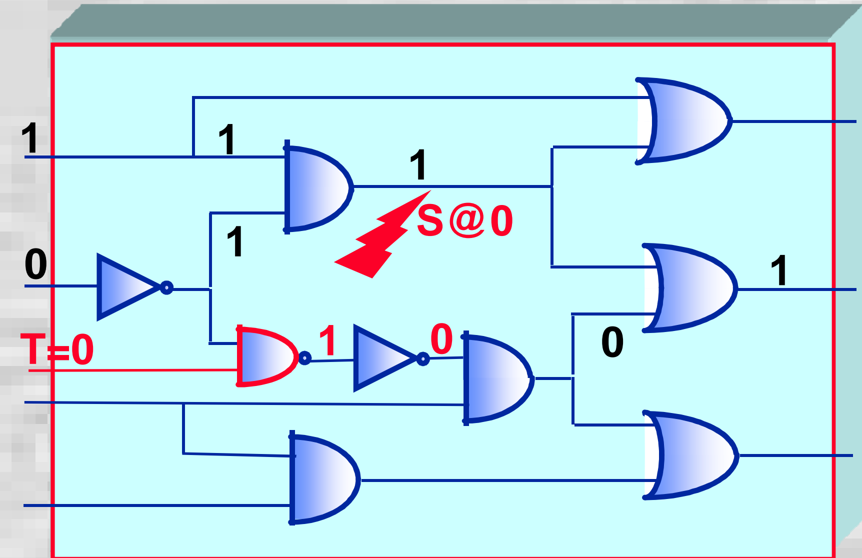
=> Estimate how many faulty circuits are detected by each vector



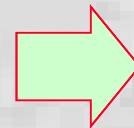
Design For Testability

DFT





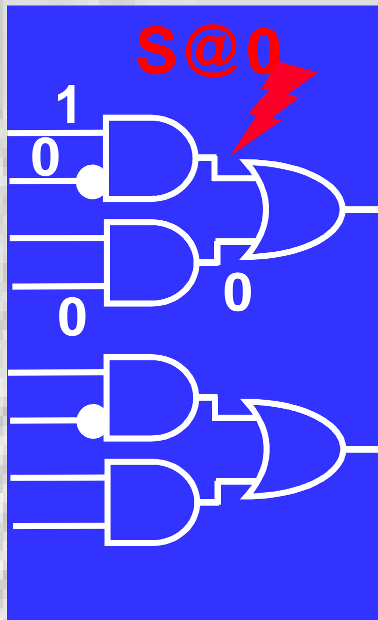
- ATPG / Backtrack
- FC < Desired FC (98%)
- Modify the Structure



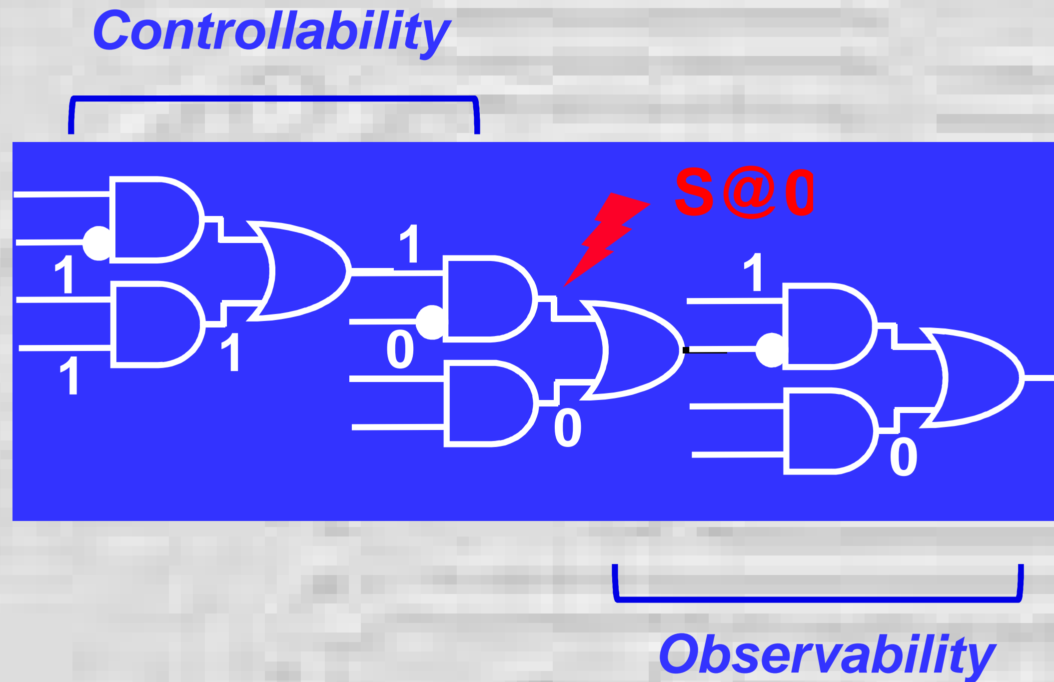
Design For Test

Structured DFT

Combinational Logic



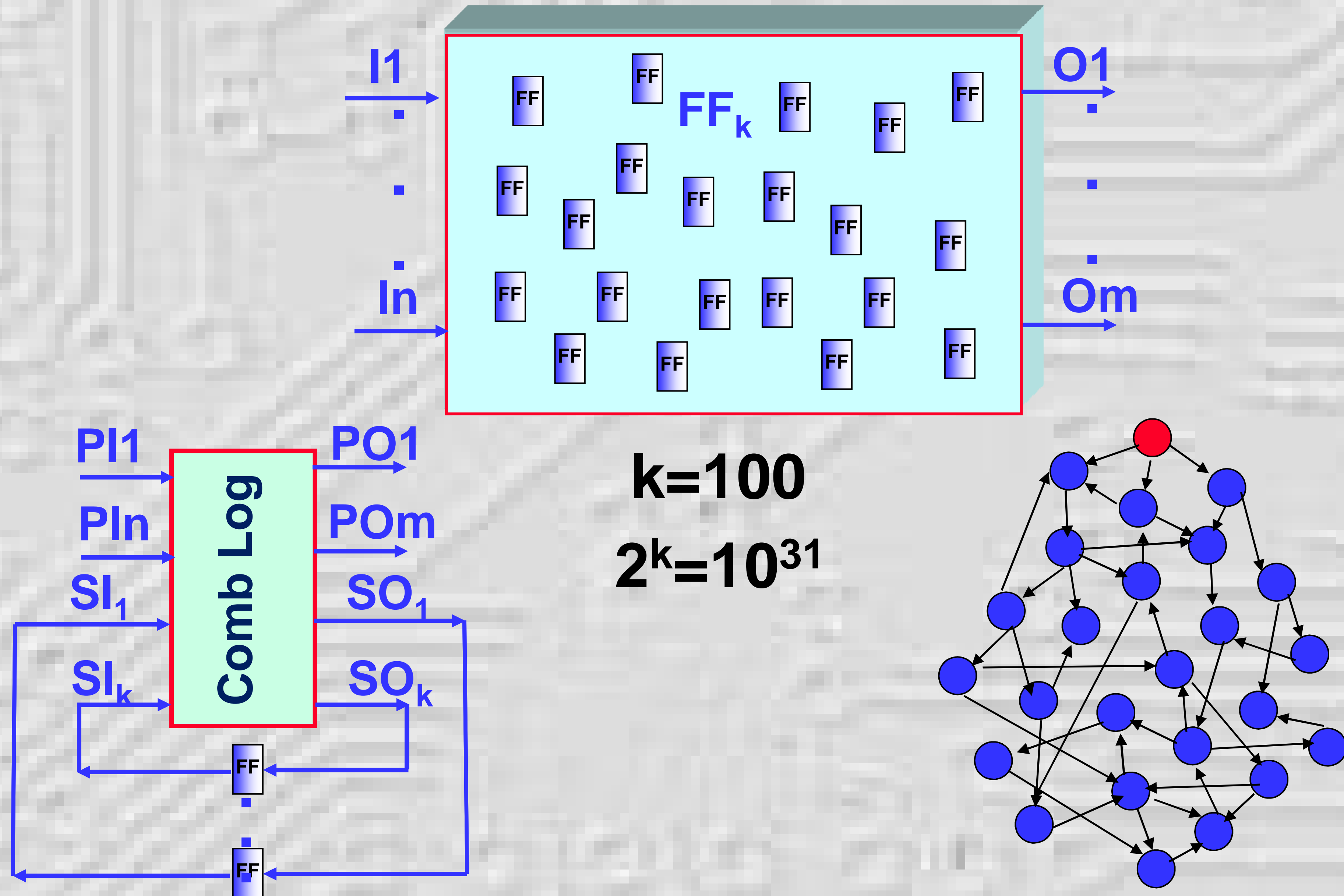
Controllability



Observability

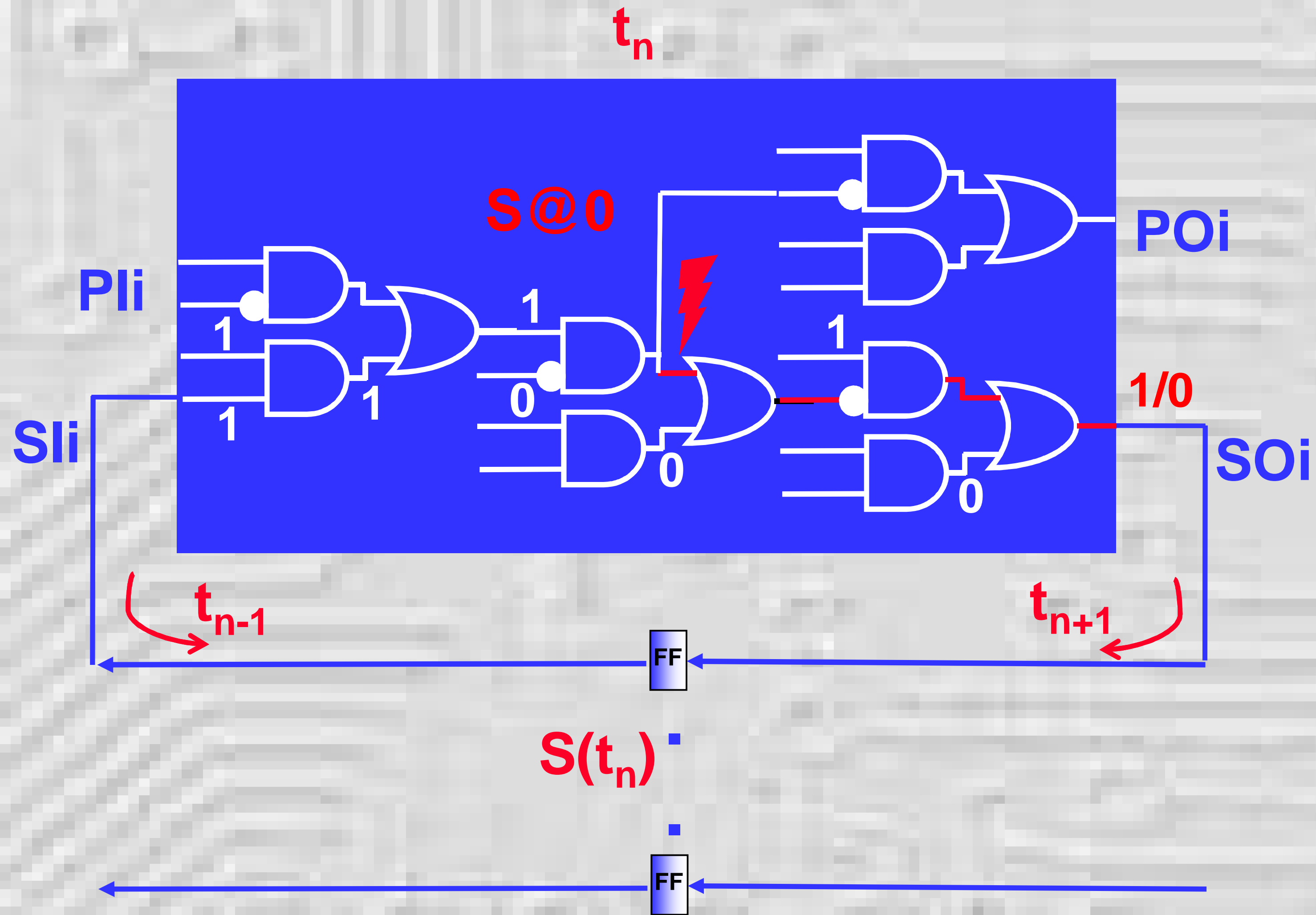
Structured DFT

IN2P3

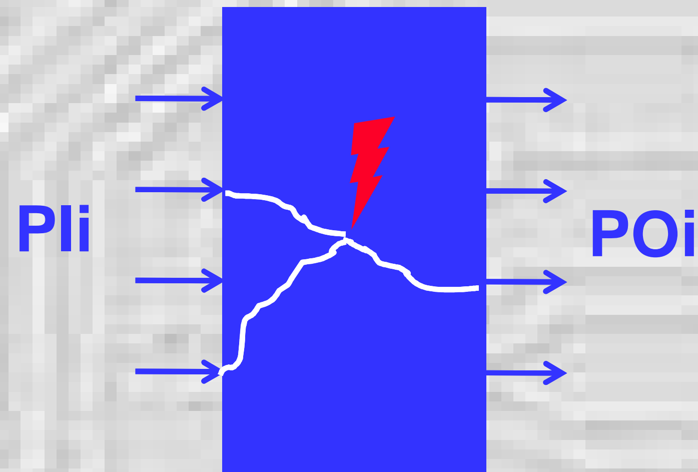


Structured DFT

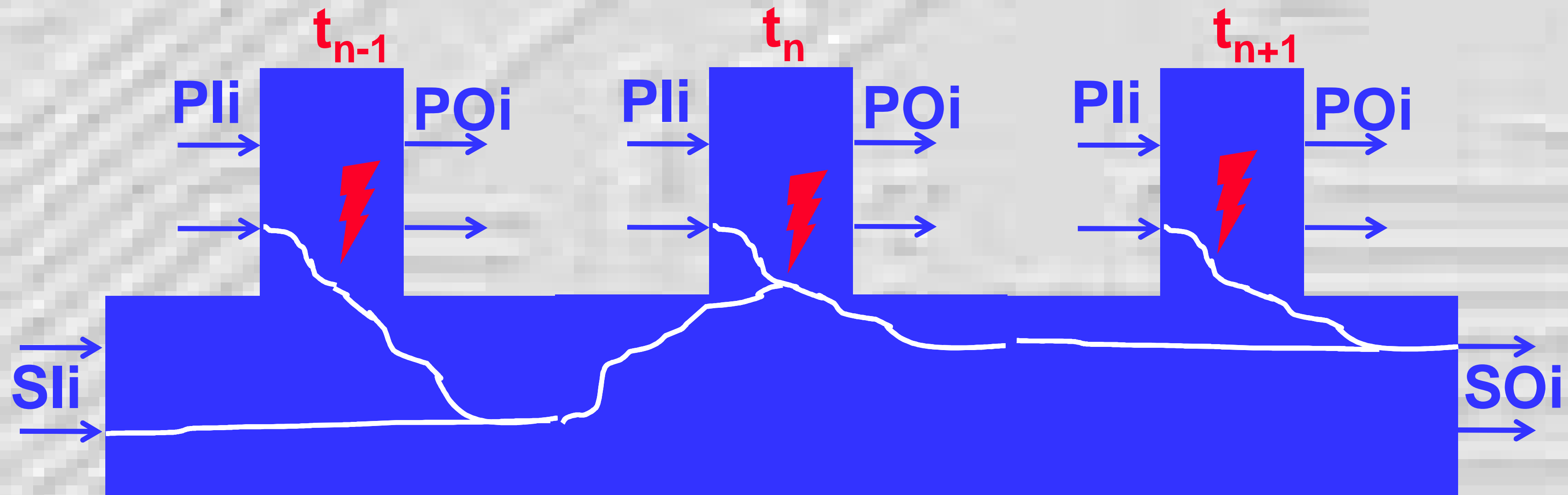
Sequential Logic



Structured DFT

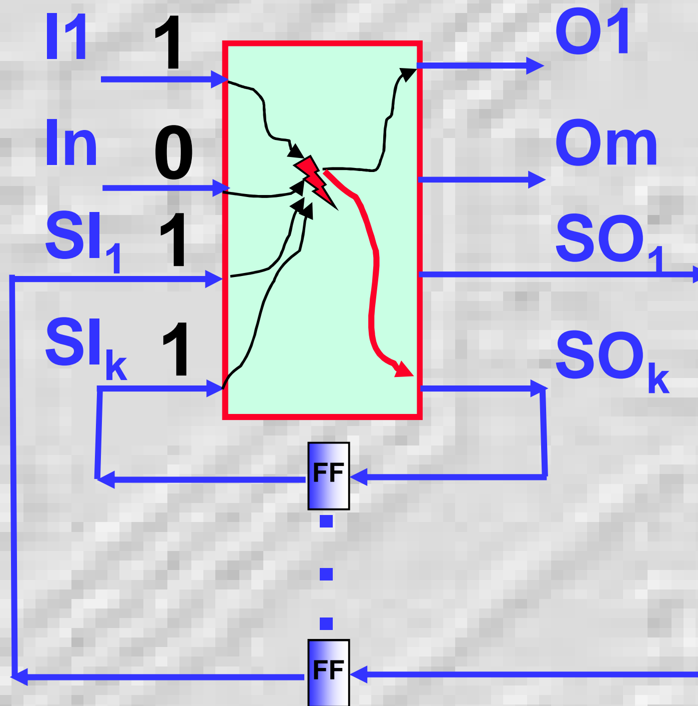


Sequential Logic



ATPG unfeasible

Structured DFT

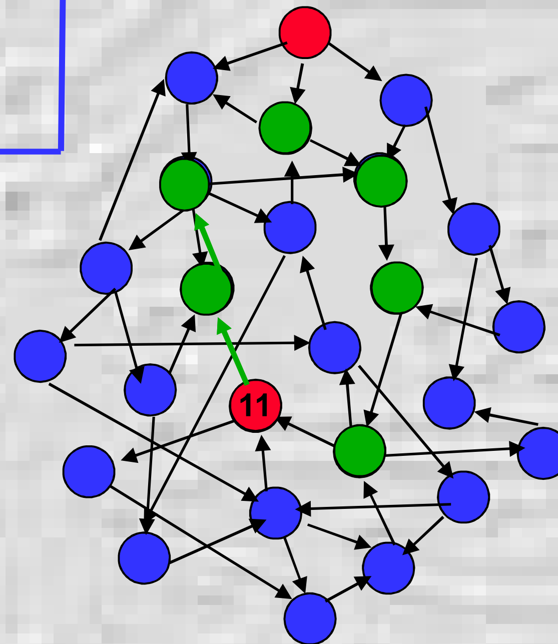


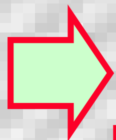
$k=100$

$2^k=10^{31}$

$N_T=2^{k/4}$

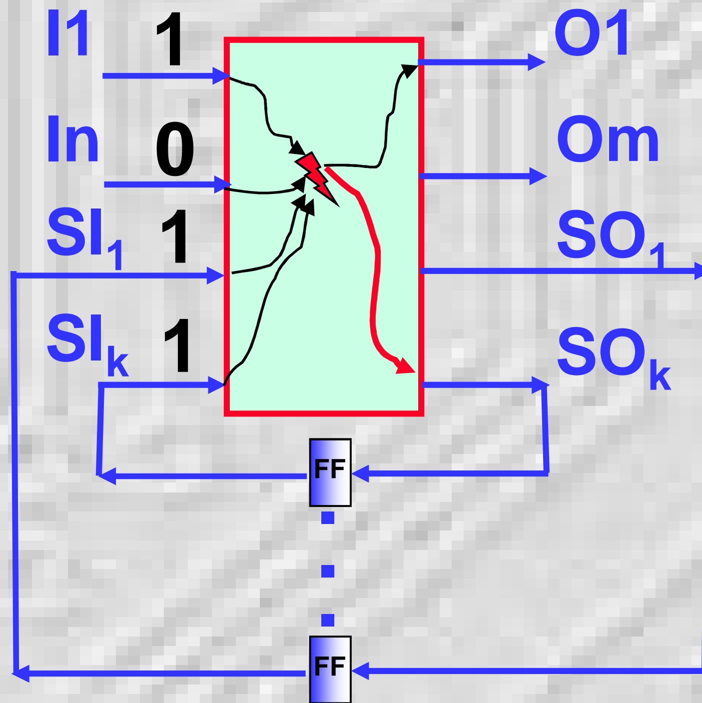
$\sim 10^7$



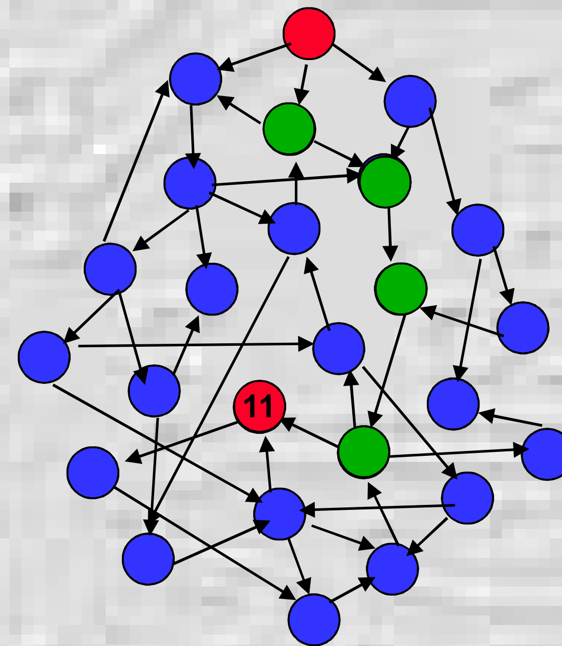


Lseq = 10^7 x Lcomb

Structured DFT



Combinational ATPG

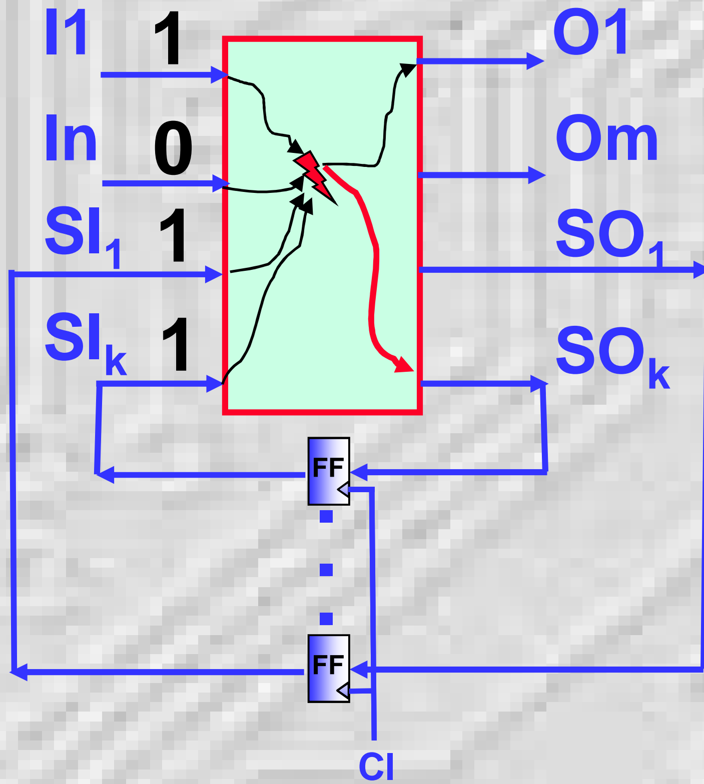


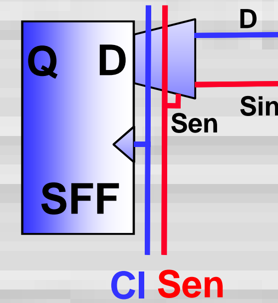
$k=100$

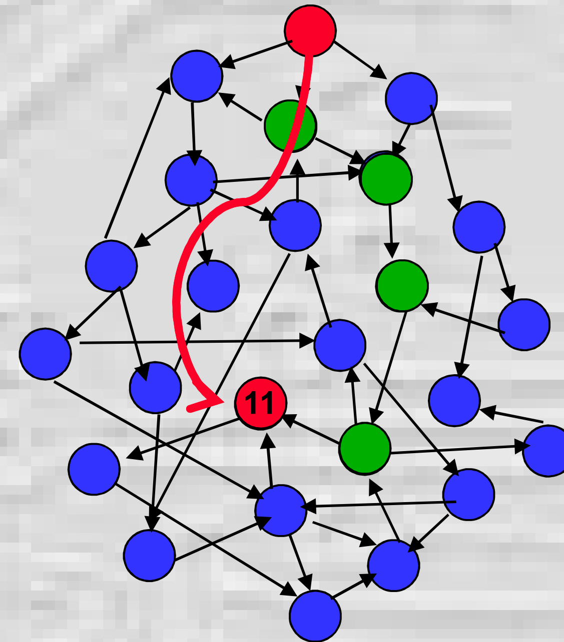
$2^k=10^{31}$

$N_T=2^{k/4}$
$\sim 10^7$

Structured DFT







Structured DFT

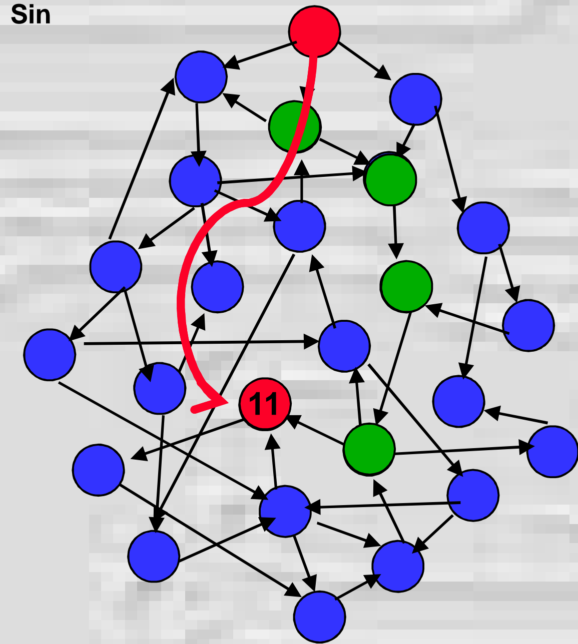
I1 1
In 0
SI_1 1
SI_k 1
O1
Om
SO_1
SO_k

Q D
SFF
D
Sin
Sen
Sout1
Sin1

Q D
SFF
D
Sin
Sen
Sout2
Sin2

CI Sen

Q D
SFF
D
Sin
Sen
CI Sen

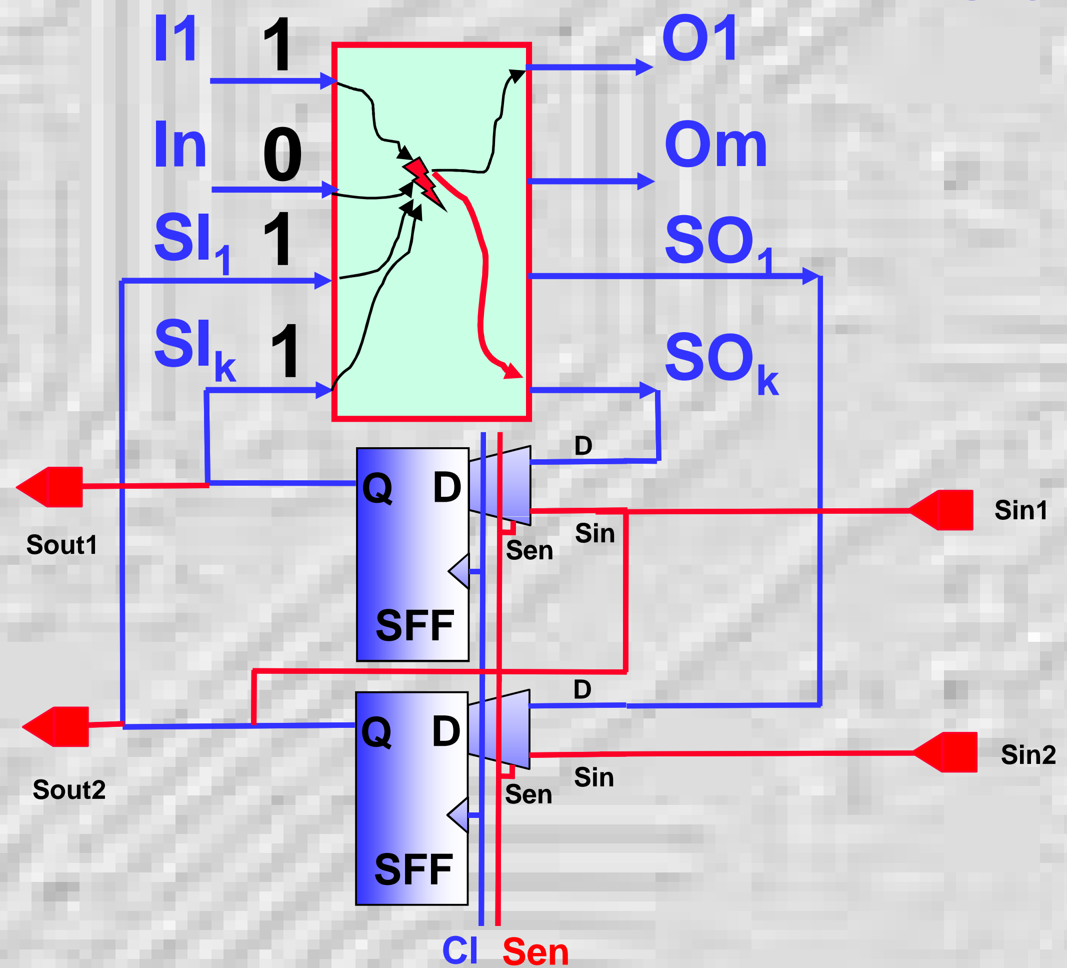


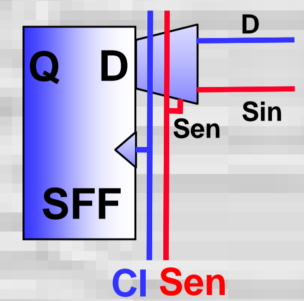
Sen
CI
Bits Sini
Bits Ii
Bits Oi
Bits Souti

- Lseq = 2 x Lcomb
- Npin = 2k+1

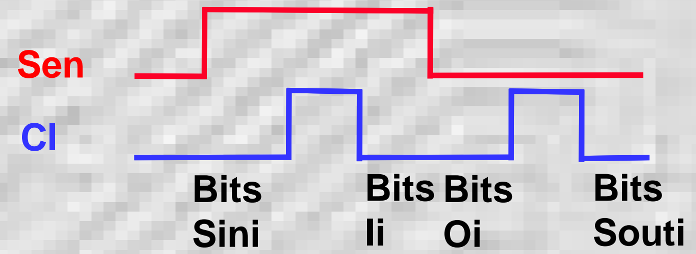
Structured DFT

SCAN Design



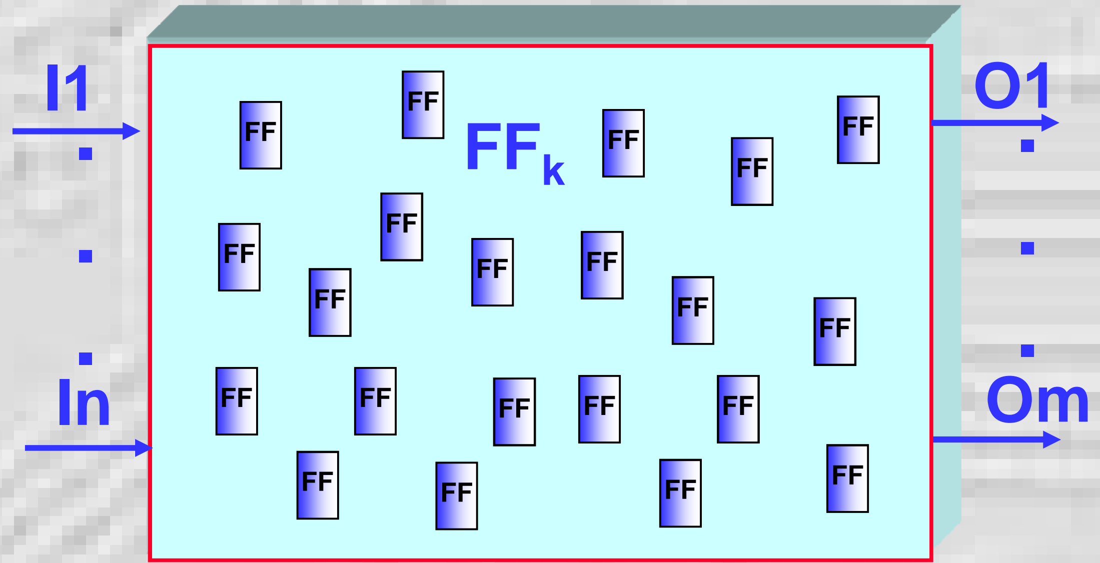


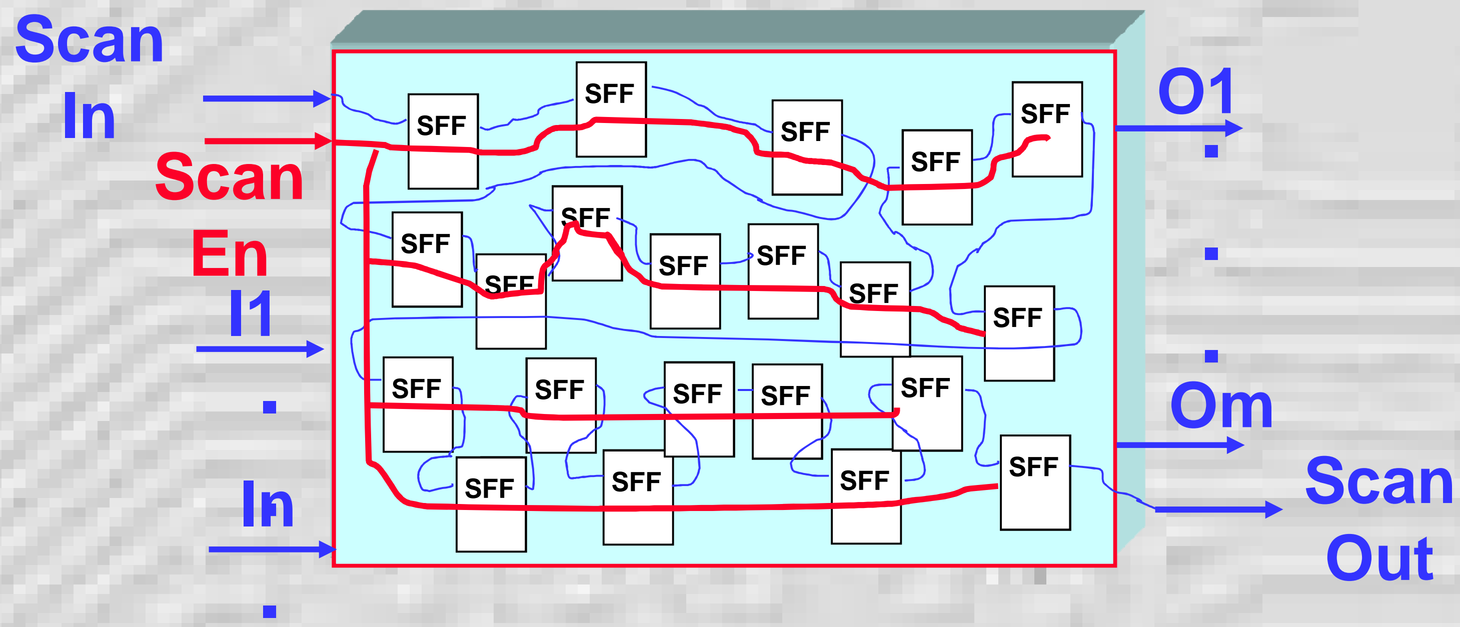
- $L_{seq} = k \times L_{comb}$
- $N_{pin} = 2+1$



Structured DFT

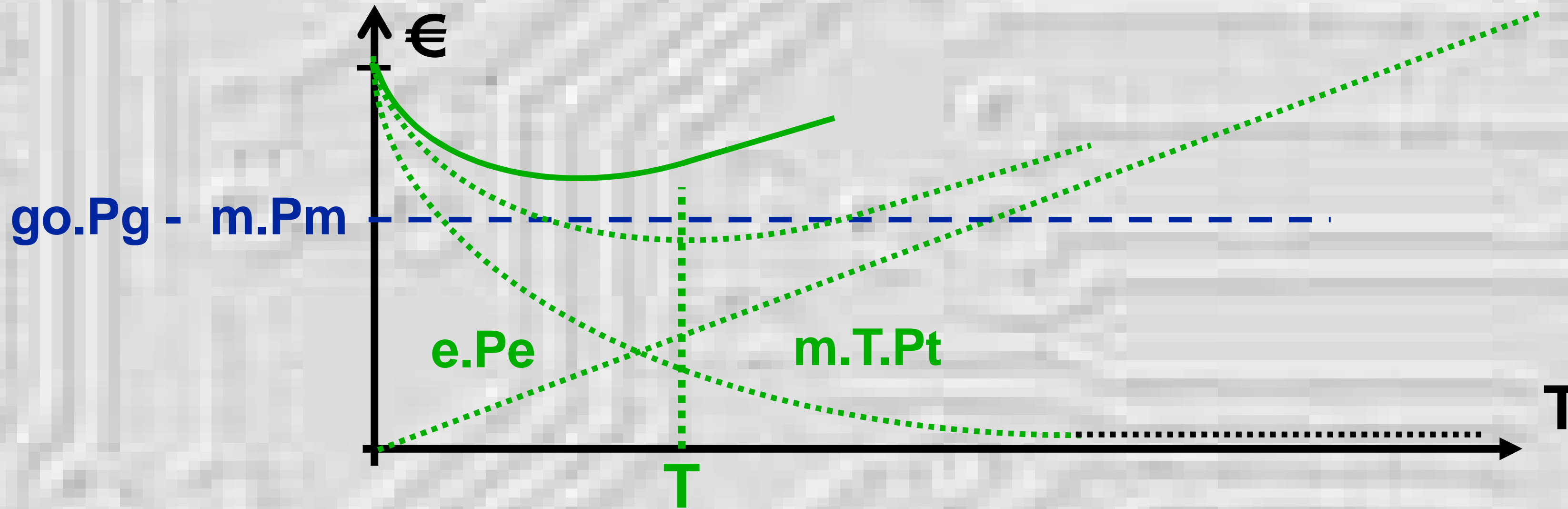
Sequential Logic





DFT

IN2P3

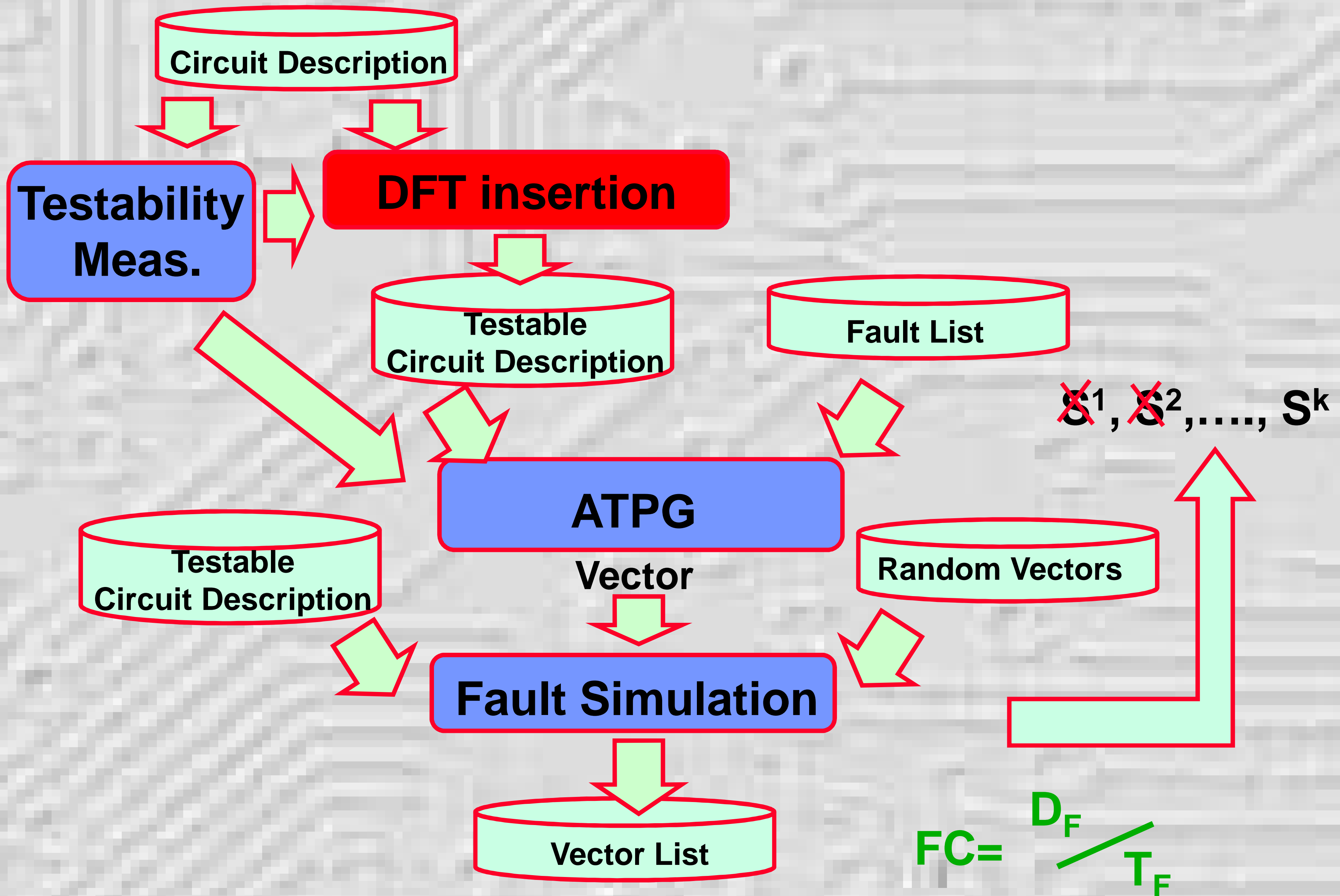


III) Criteria to make circuit Testable

=> Propose circuit modifications

DFT

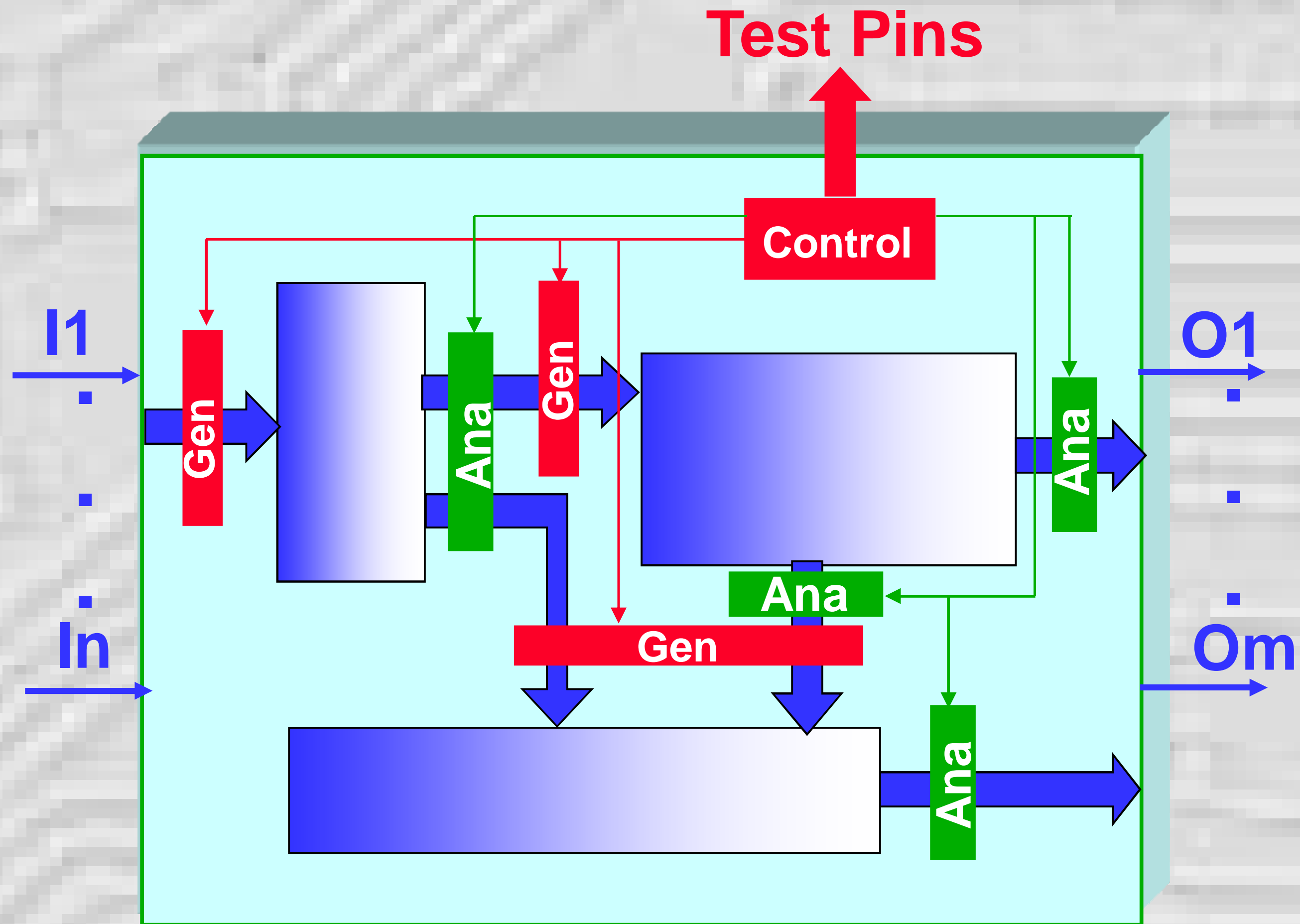
IN2P3



Built –In Self-Test

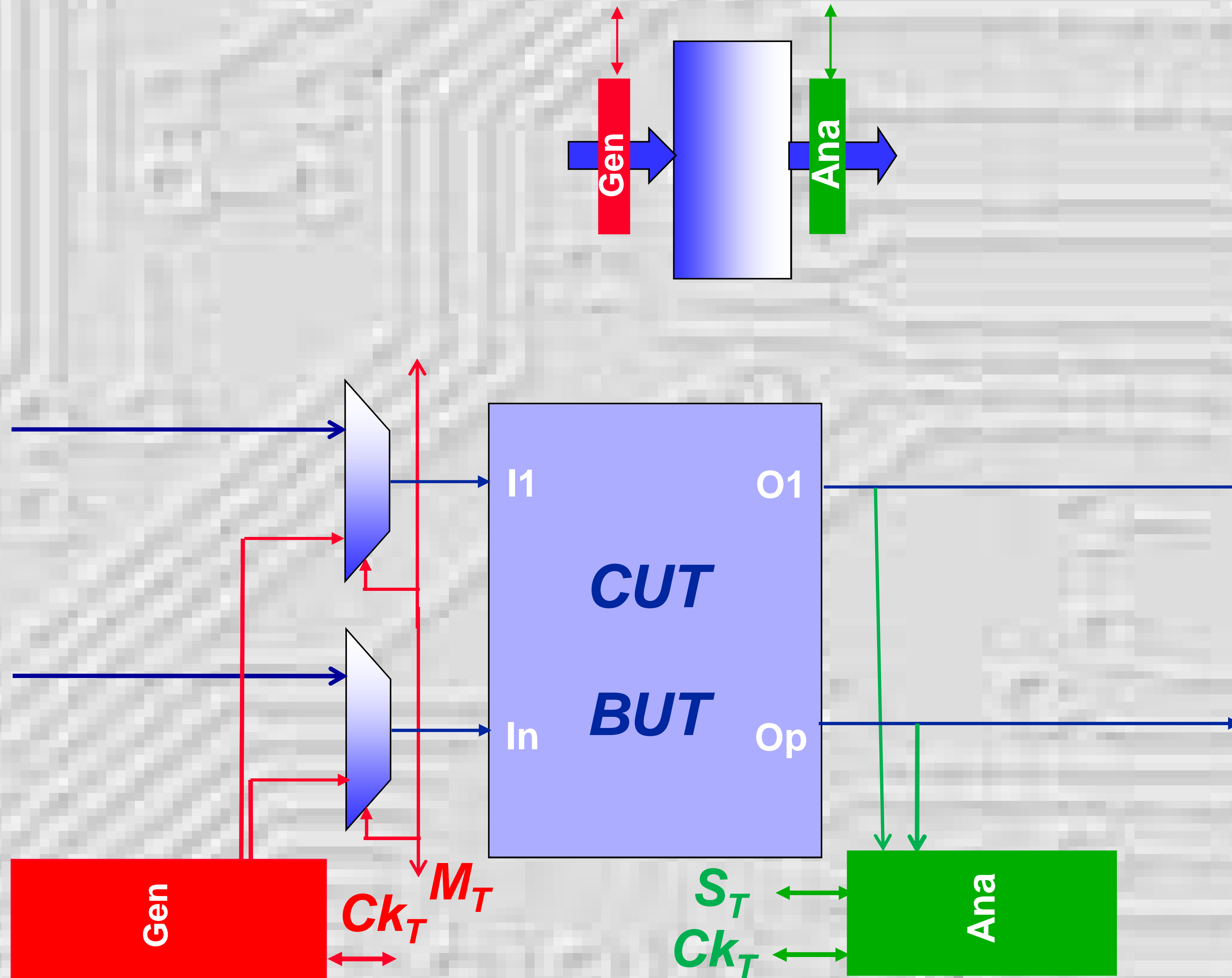
BIST

IN2P3



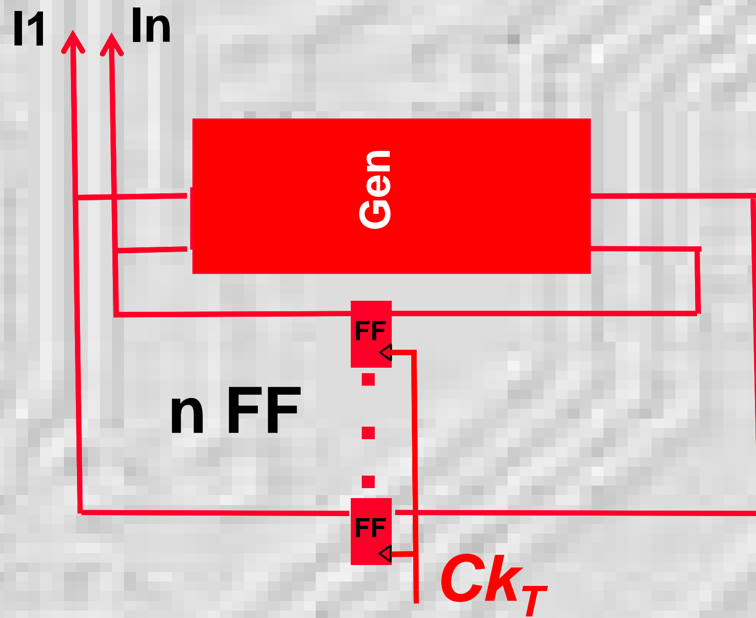
BIST

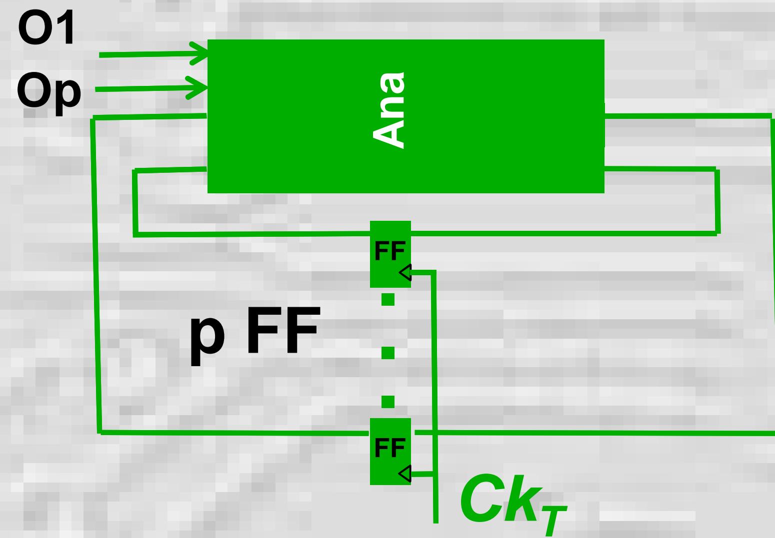
IN2P3

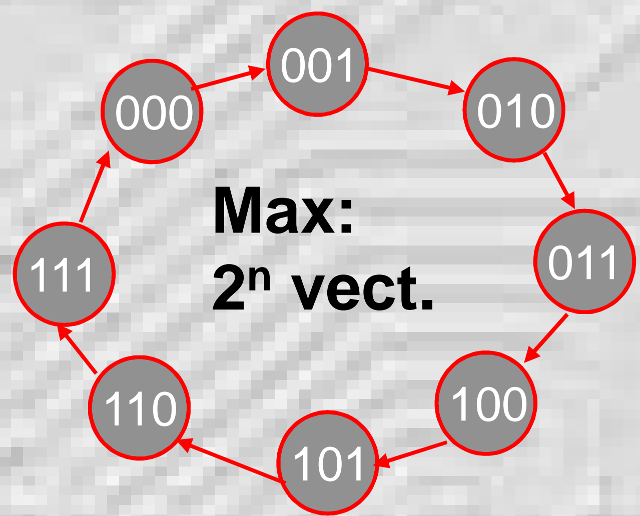


BIST

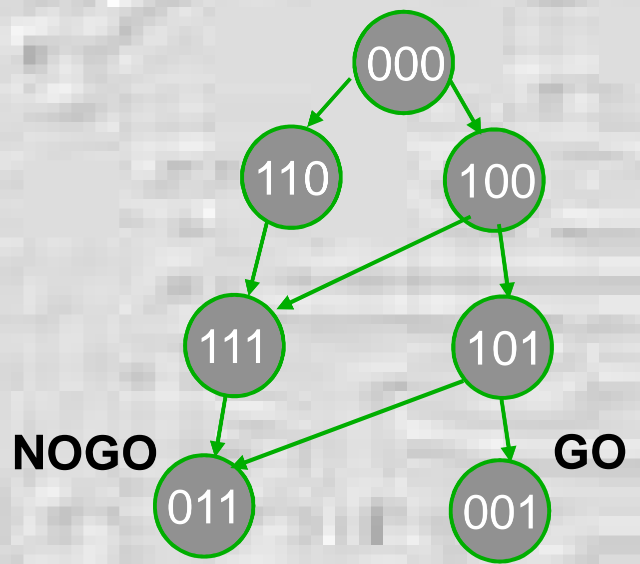
IN2P3





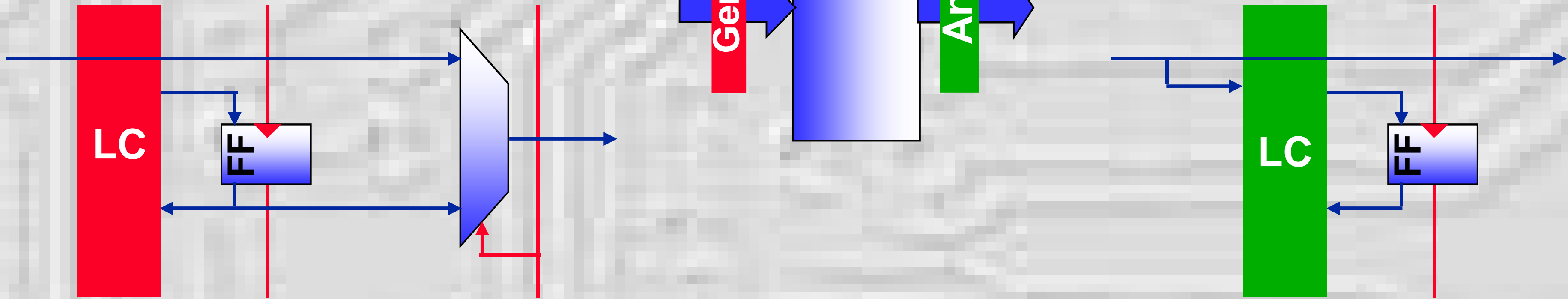


Max:
2^n vect.



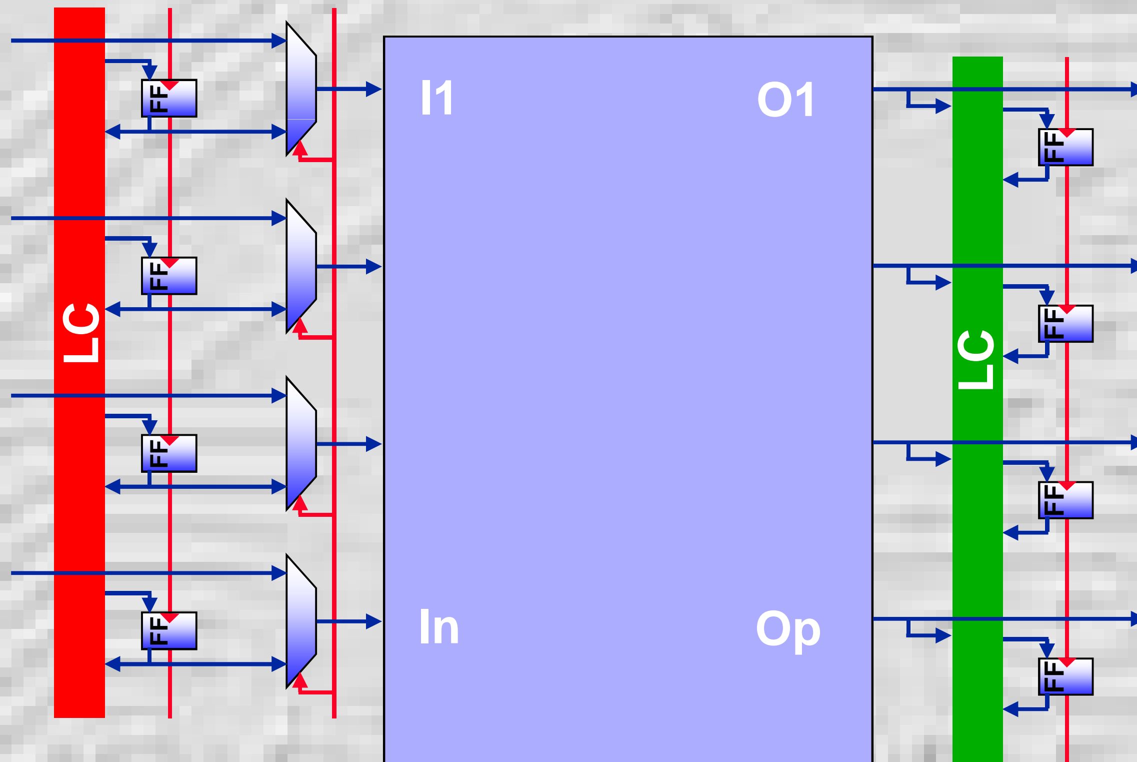
BIST

IN2P3



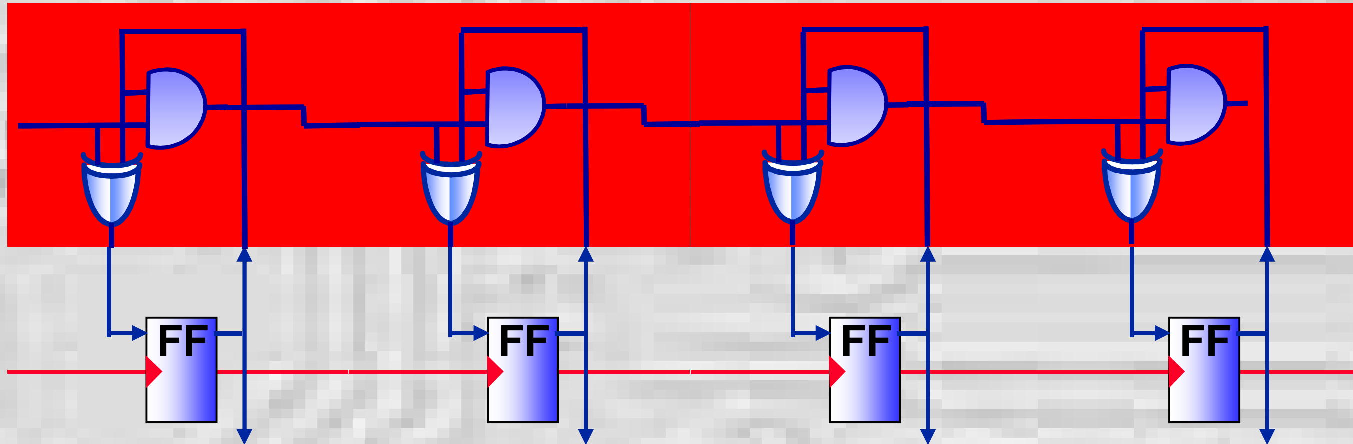
n FF

Max:
2^n vect.



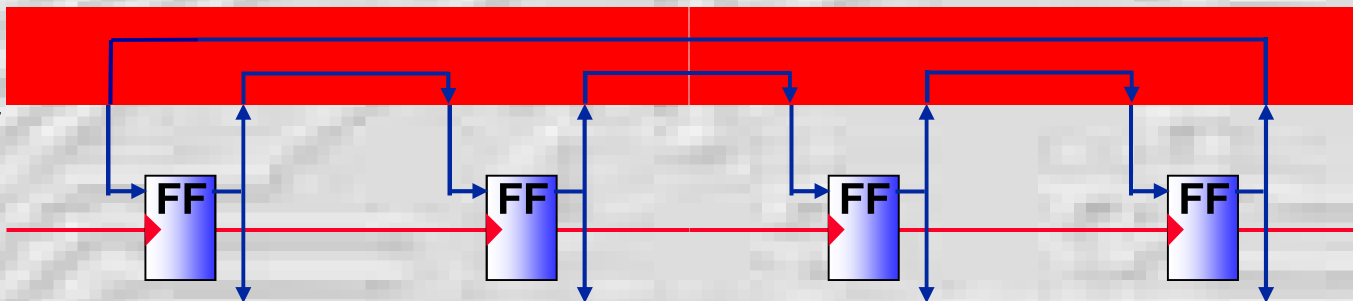
BIST

Counter



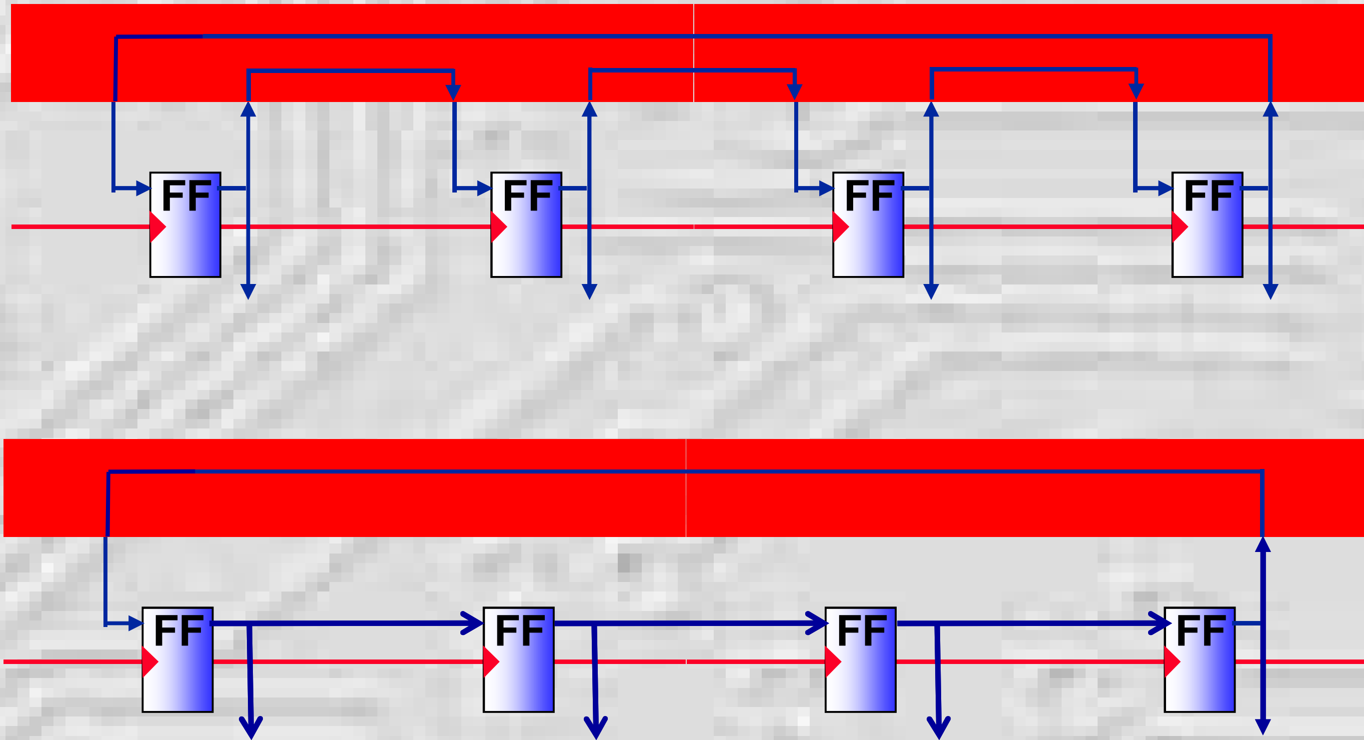
Max:
2^4 vect.

Feedback
Shift
Register



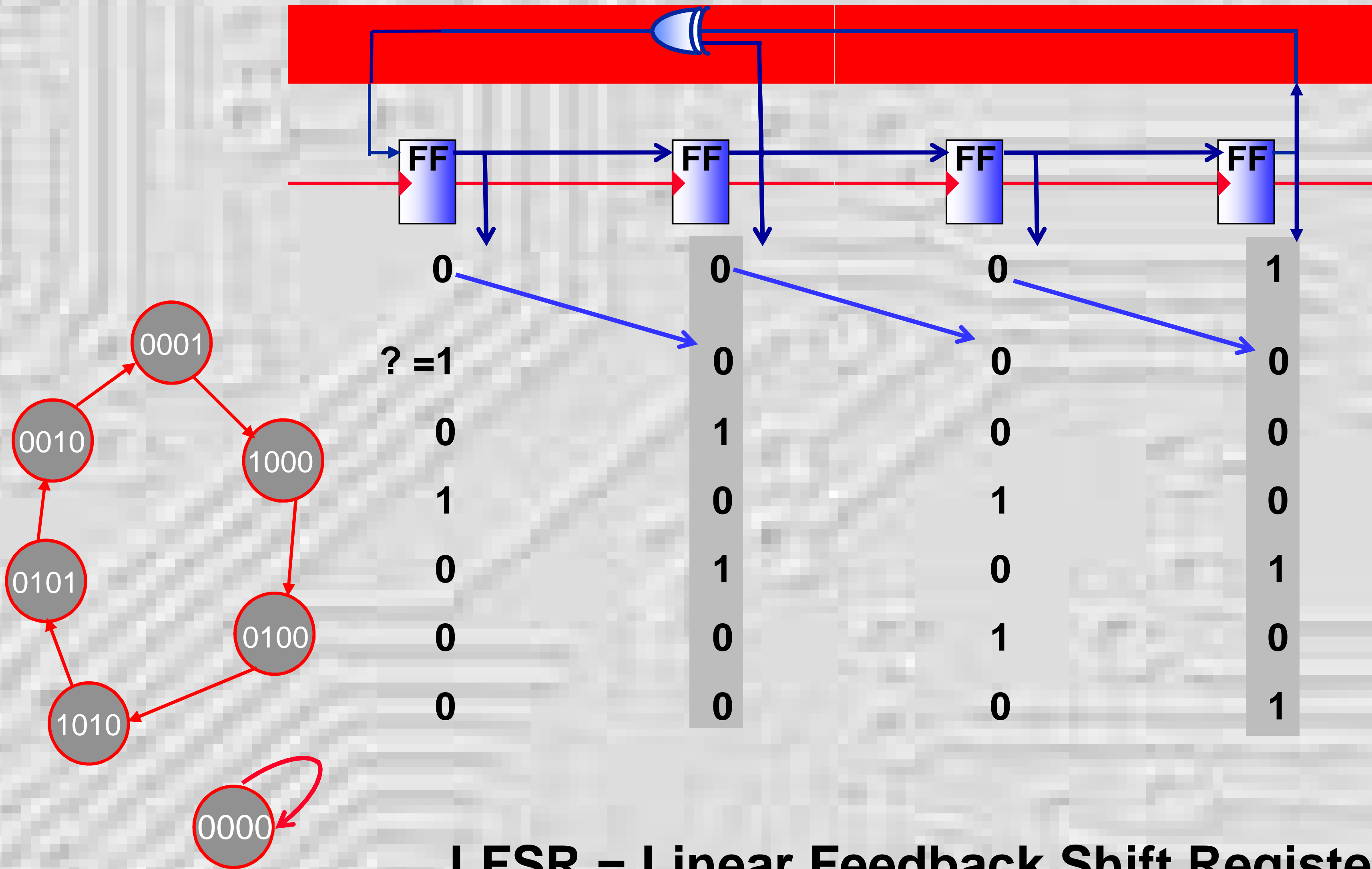
BIST

Feedback Shift Register



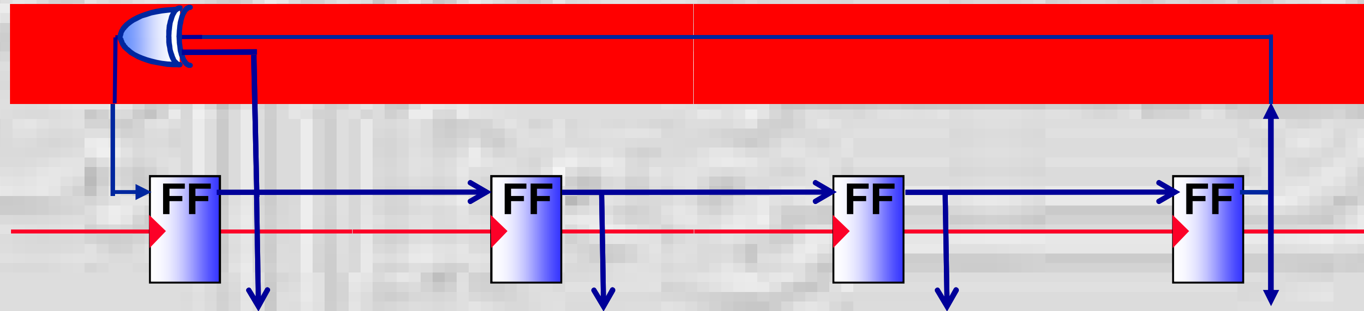
BIST

IN2P3



LFSR = Linear Feedback Shift Register

BIST



$2^4 - 1$ Vectors !

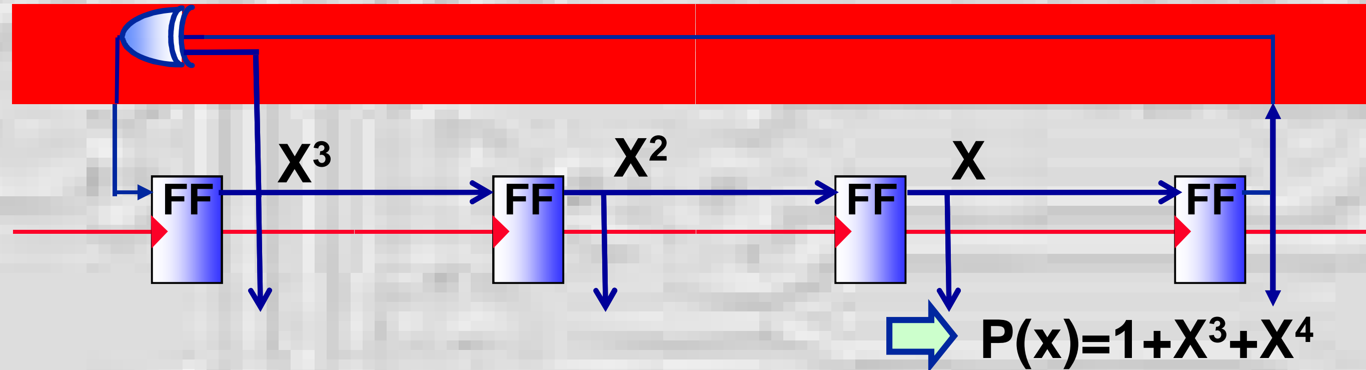
0	0	0	1
1	0	0	0
1	1	0	0
1	1	1	0
1	1	1	1
0	1	1	1
1	0	1	1
0	1	0	1
1	0	1	0
1	1	0	1
0	1	1	0
0	0	1	1
1	0	0	1
0	1	0	0
0	0	1	0
0	0	0	1

BIST

IN2P3

LFSR2

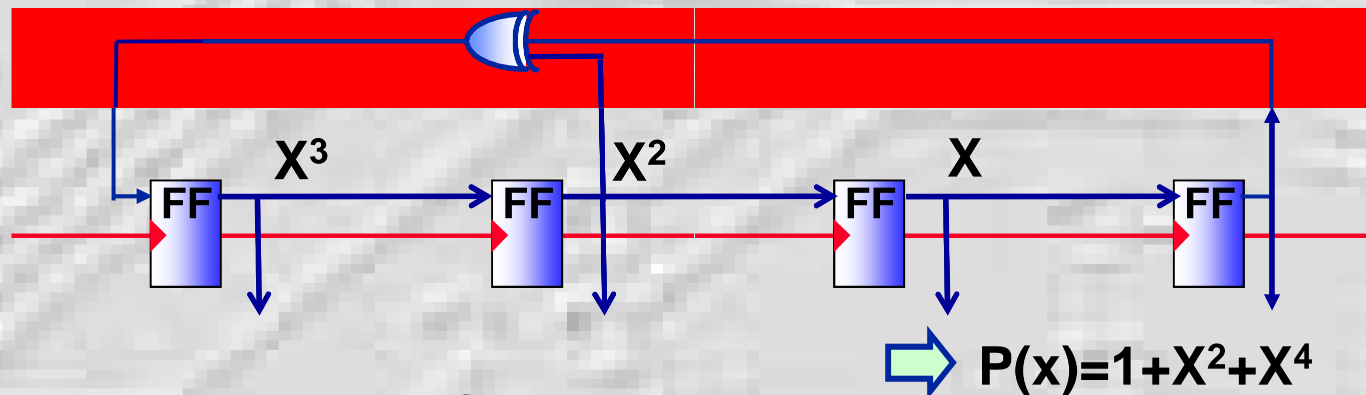
15 vect.



$P(x)=1+X^3+X^4$

LFSR1

6 vect.



$P(x)=1+X^2+X^4$

$P(X)= \sum Xi$ with X in $B=\{0,1\}$

XOR, AND

Galois Field

$$
\begin{array}{r|l}
X^4 + X^2 + 1 & X^2 + X + 1 \\
\underline{X^4 + X^3 + X^2} & \overline{X^2 + X + 1} \\
X^3 + 1 & \\
\underline{X^3 + X^2 + X} & \\
X^2 + X + 1 & \\
\underline{X^2 + X + 1} & \\
0 &
\end{array}
$$

Primitive P(x) ⇨ 2^n-1

BIST

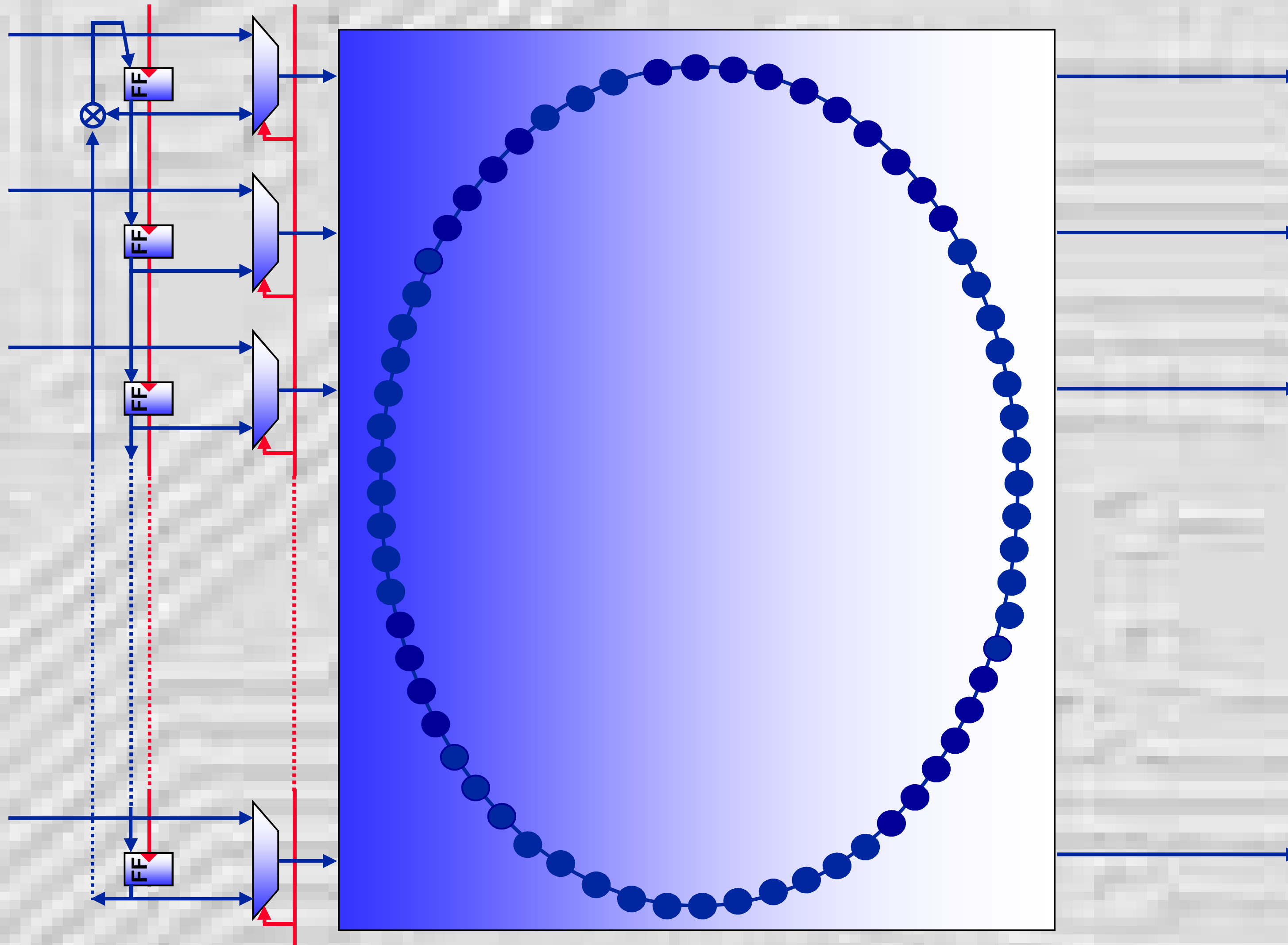
degré					degré					degré				
1	0				13	4	3	1	0	25	3	0		
2	1	0			14	12	11	1	0	26	8	7	1	0
3	1	0			15	1	0			27	8	7	1	0
4	1	0			16	5	3	2	0	28	3	0		
5	2	0			17	3	0			29	2	0		
6	1	0			18	7	0			30	16	15	1	0
7	1	0			19	6	5	1	0	31	3	0		
8	6	5	1	0	20	3	0			32	28	27	1	0
9	4	0			21	2	0			33	13	0		
10	3	0			22	1	0			34	15	14	1	0
11	2	0			23	5	0			35	2	0		
12	7	4	[illegible]	0	24	4	3	1	0	36	11	0		

$$P(x) = x^{34} + x^{15} + x^{14} + x + 1$$

$$P(x) = x^{22} + x + 1$$

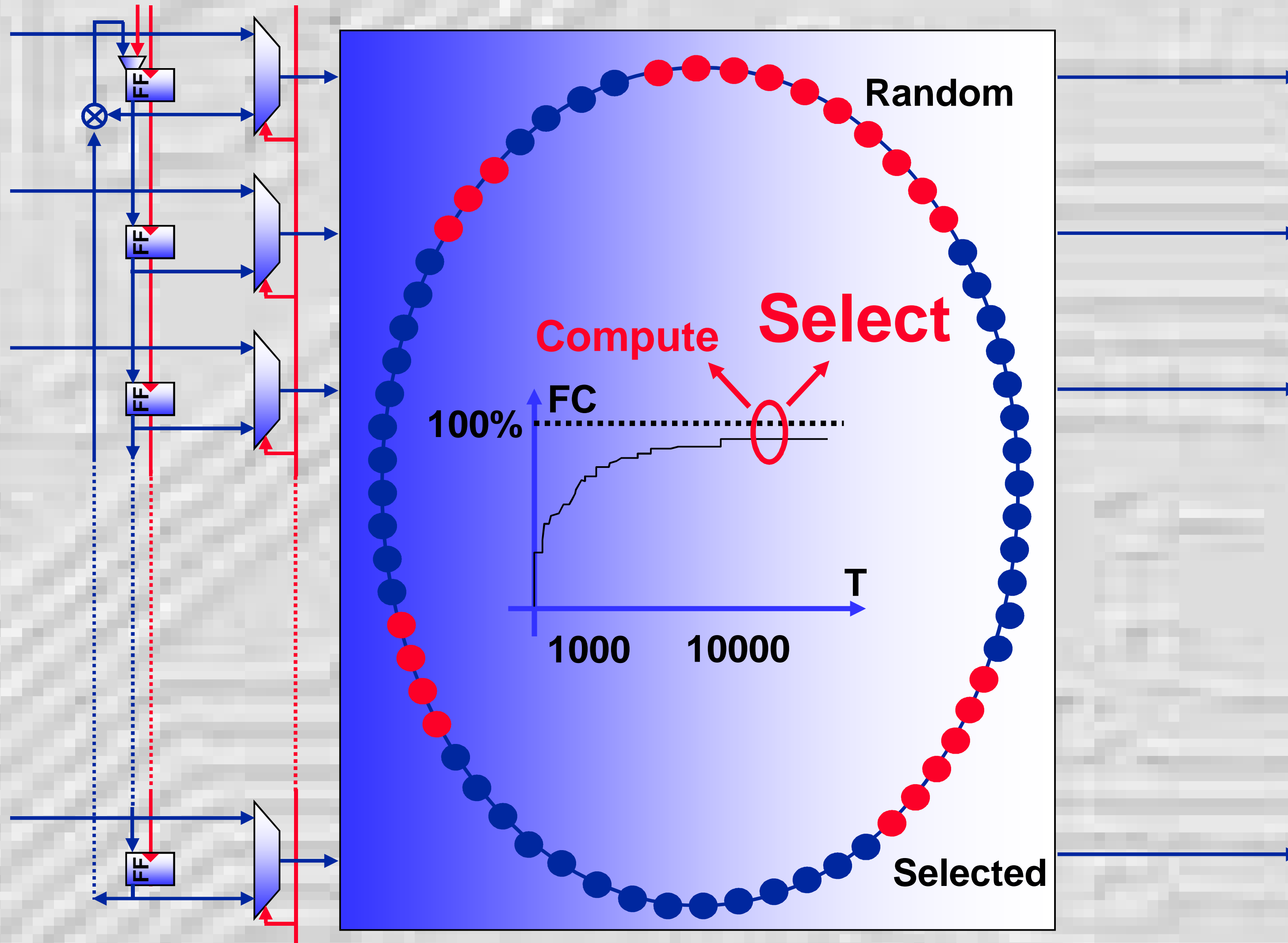
BIST

IN2P3



BIST

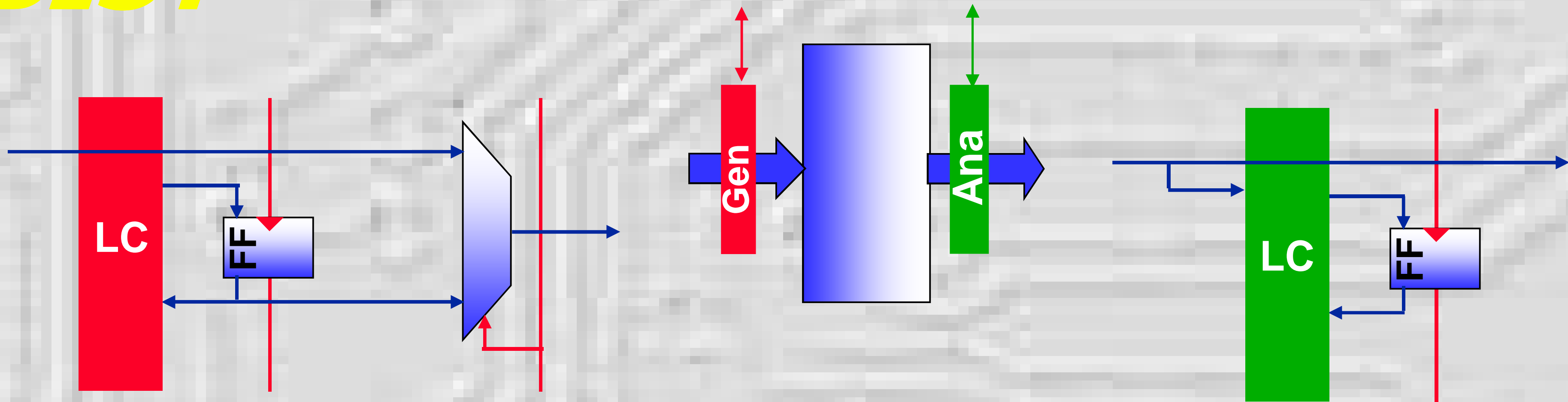
IN2P3



- Test Length²
- Seed/Clock
- Reconf Polyn

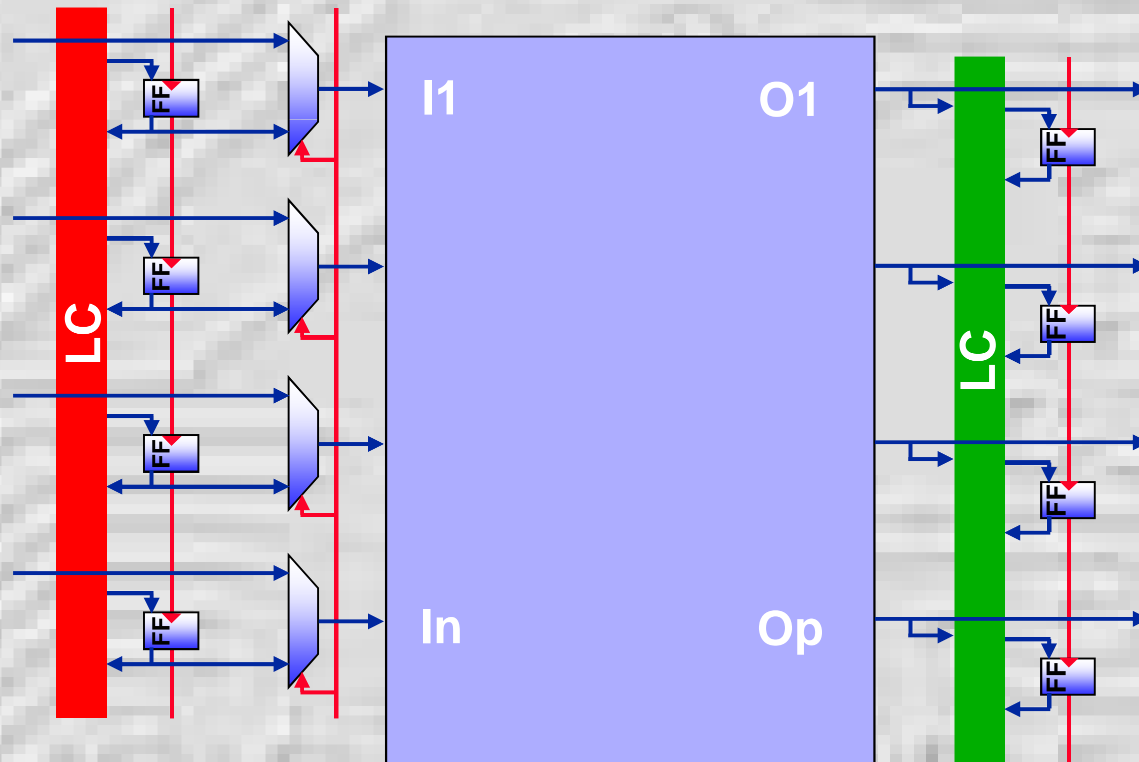
BIST

IN2P3



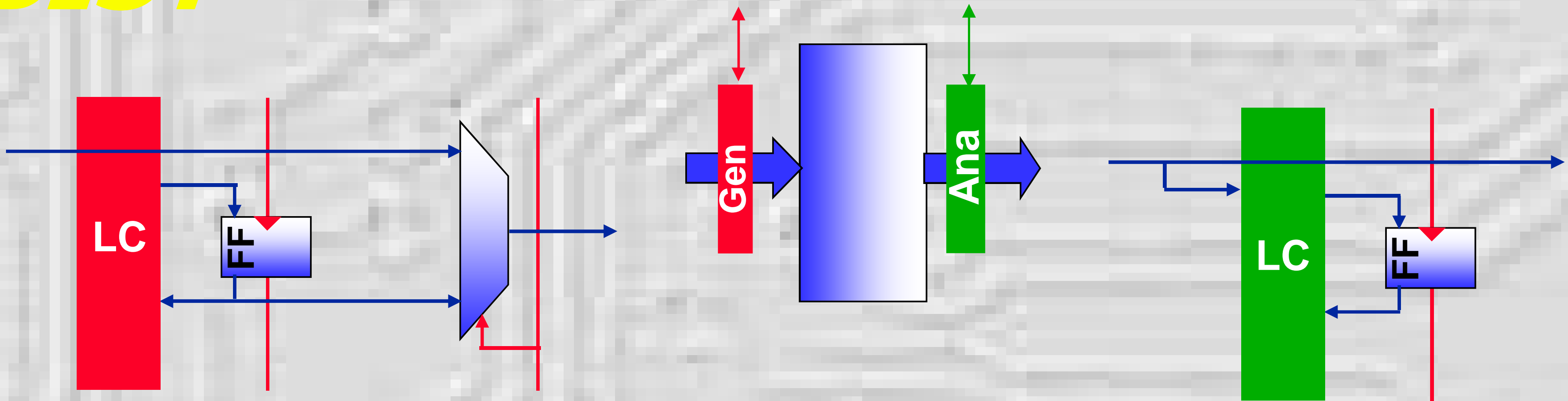
n FF

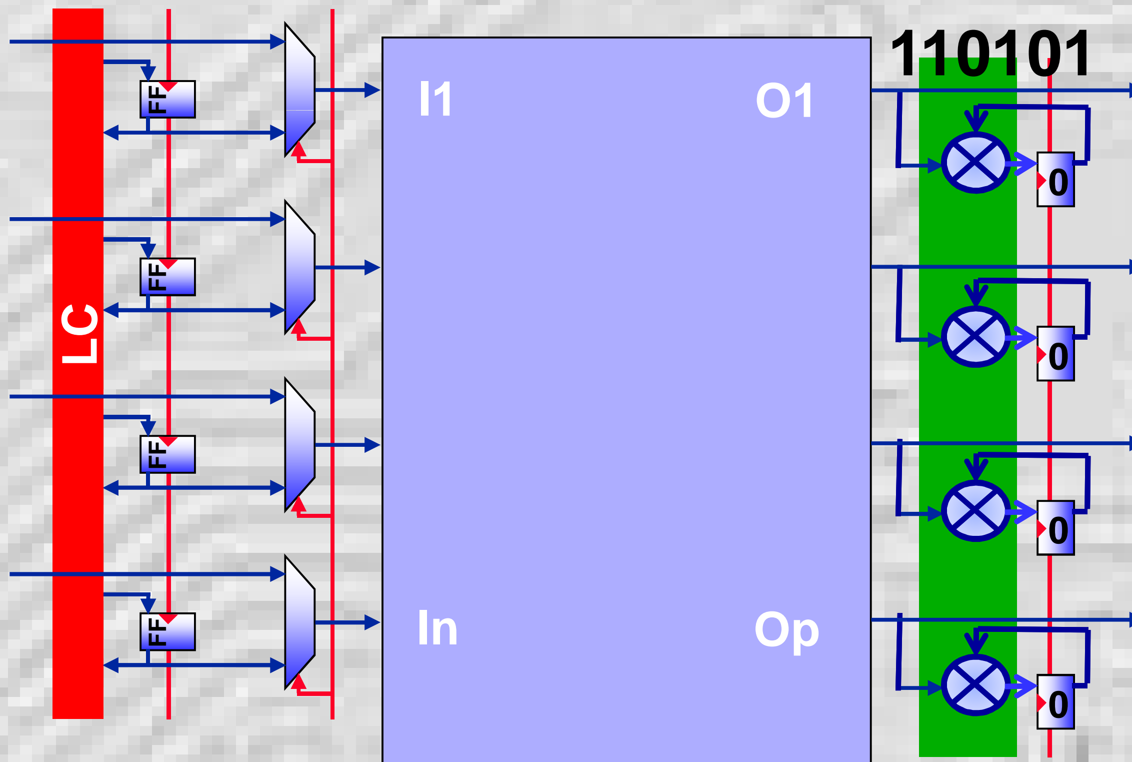
Max:
2^n vect.

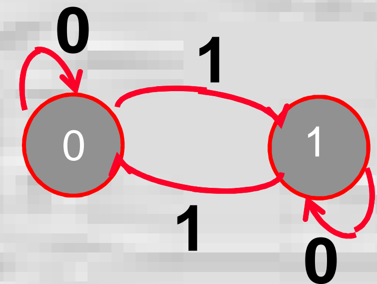


BIST

IN2P3







Aliasing

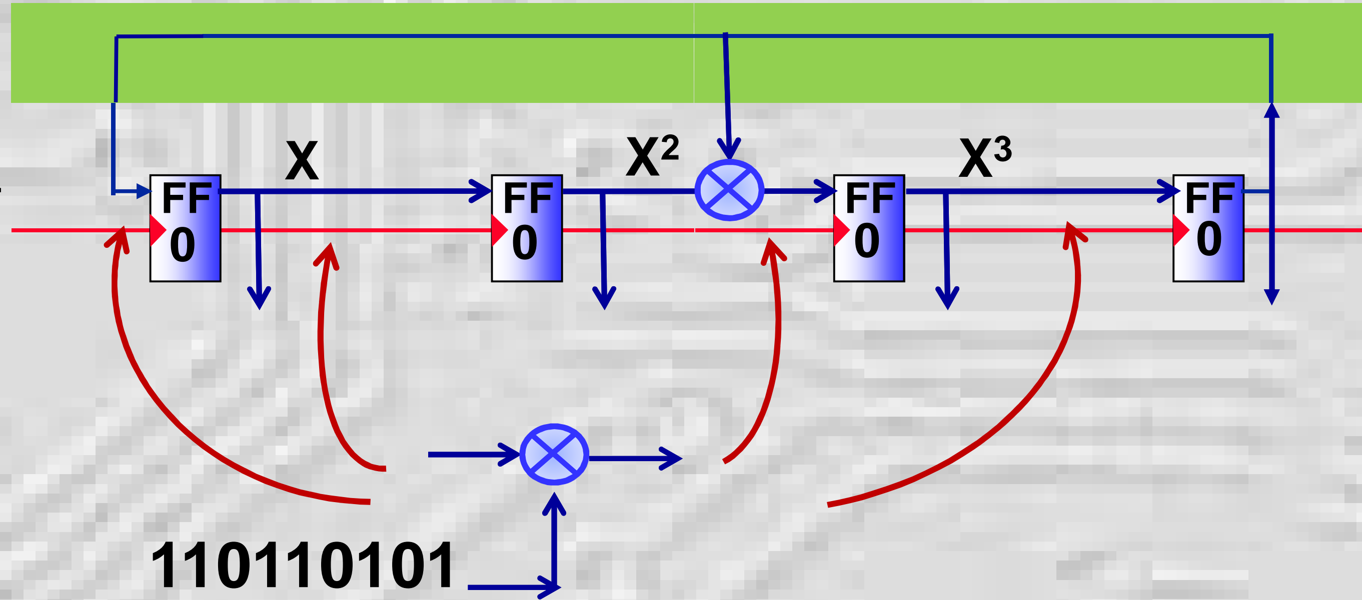
P=1/2

BIST

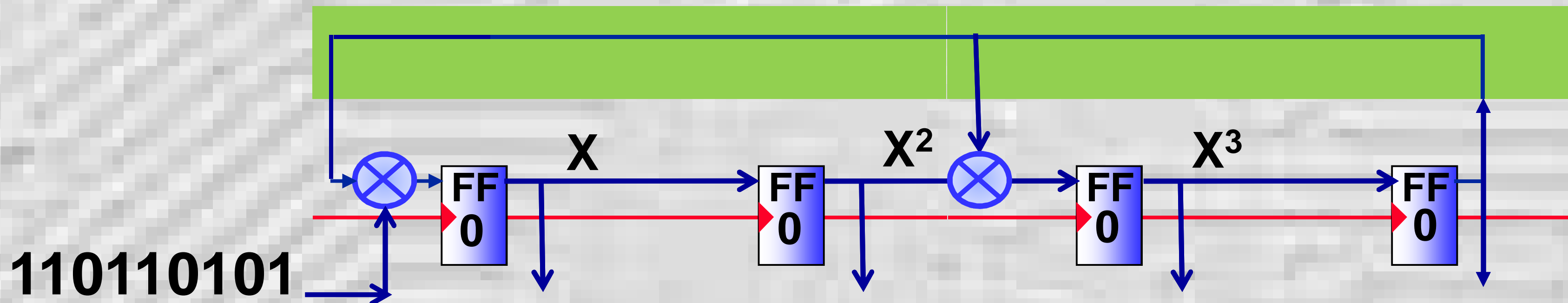
IN2P3

Internal LFSR

$P(x)=1+X^2+X^4$



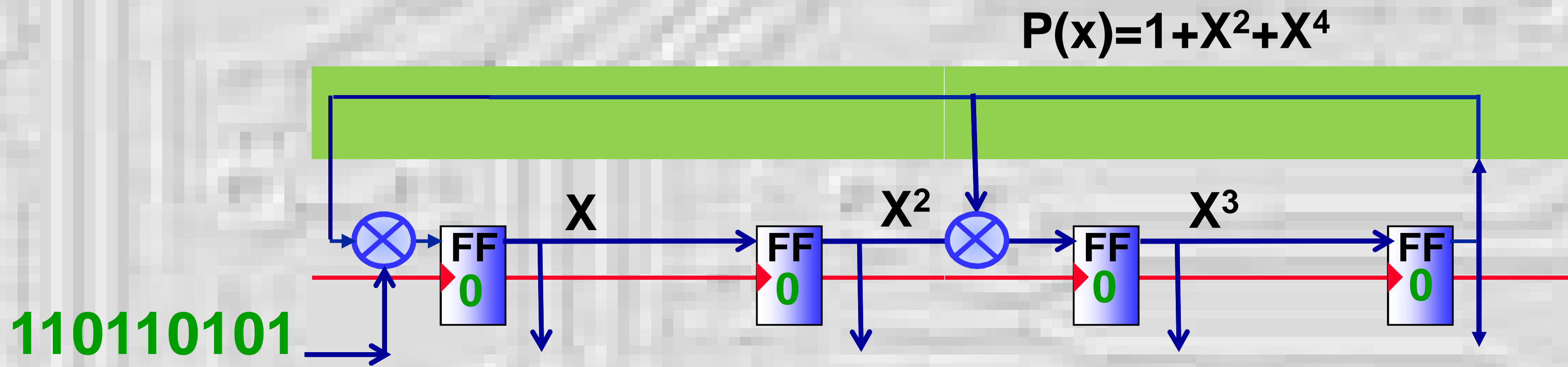
$P(x)=1+X^2+X^4$



BIST

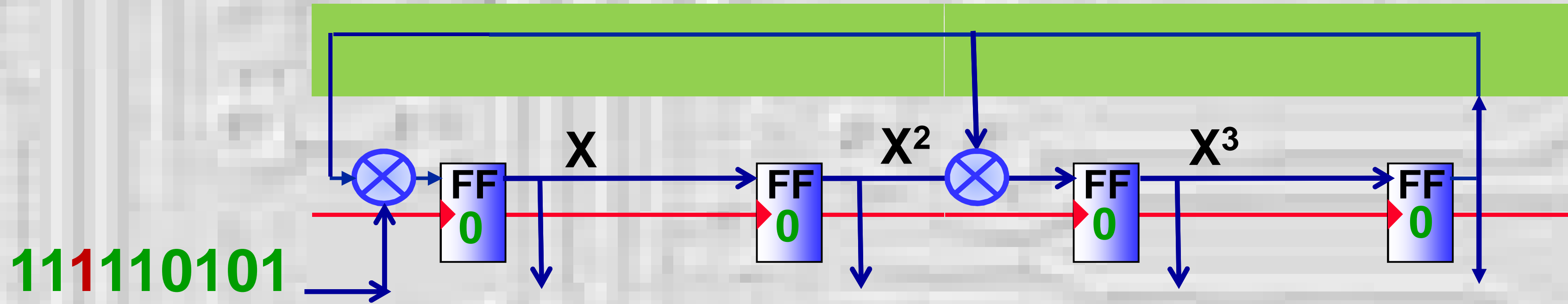
IN2P3

$P(x)=1+X^2+X^4$

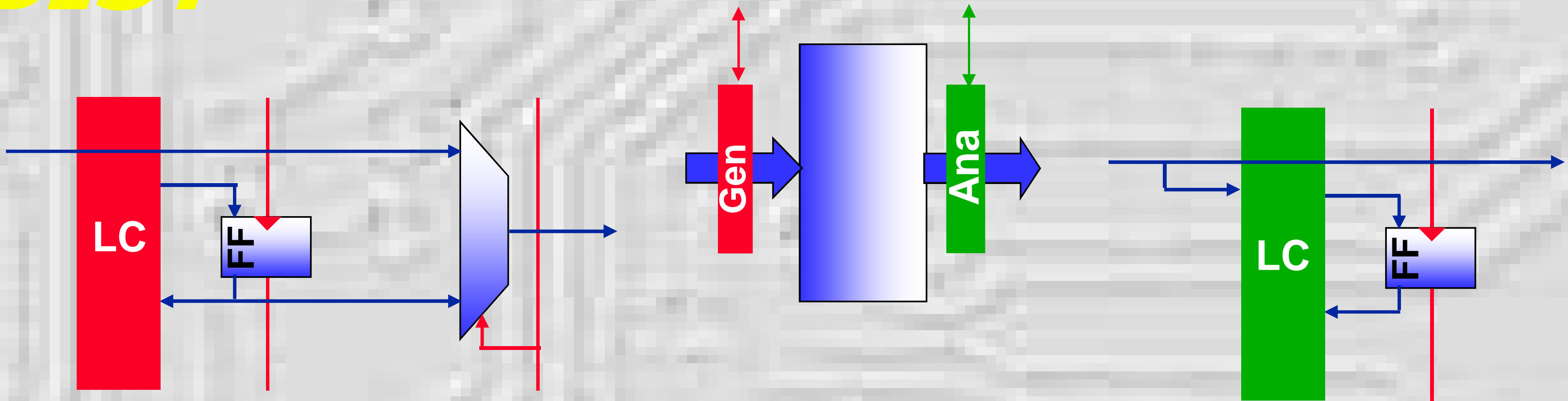


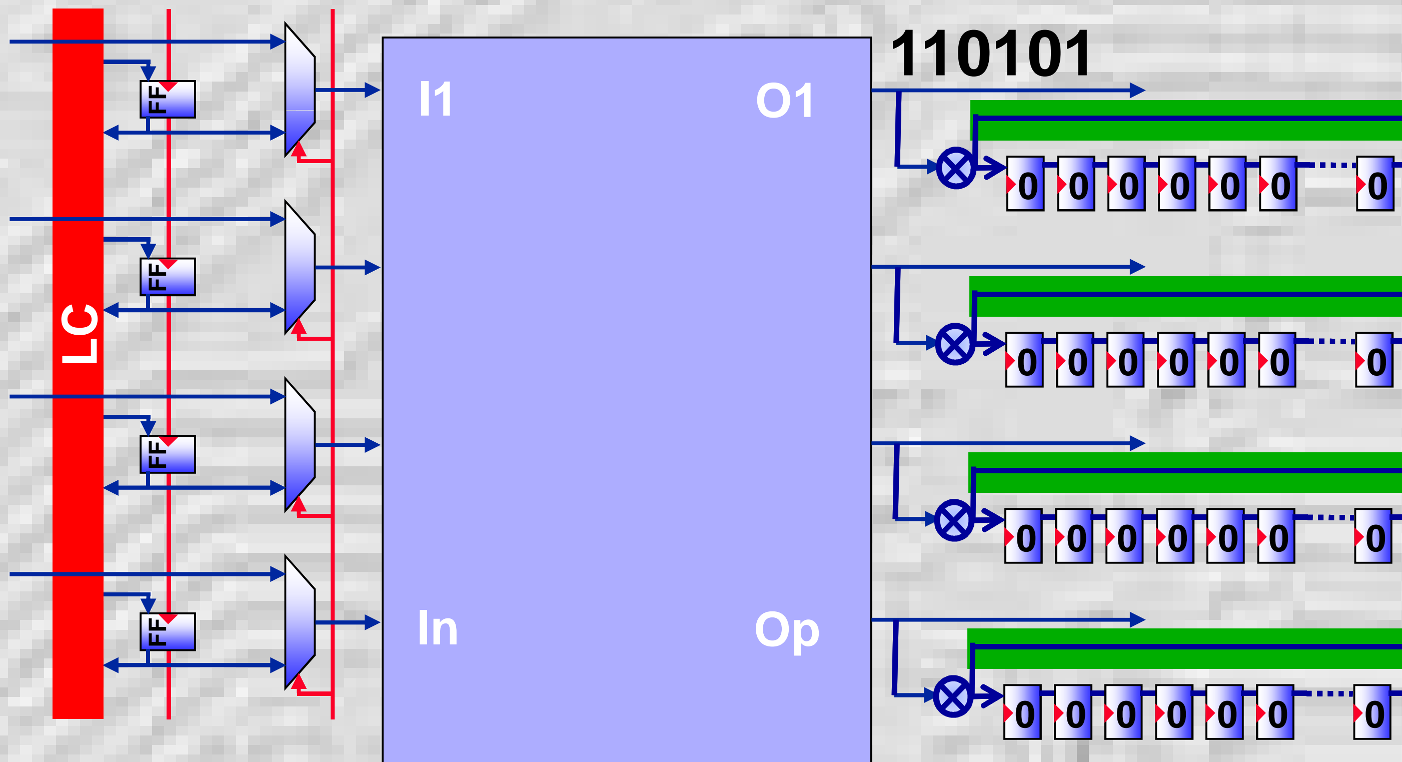
BIST

IN2P3



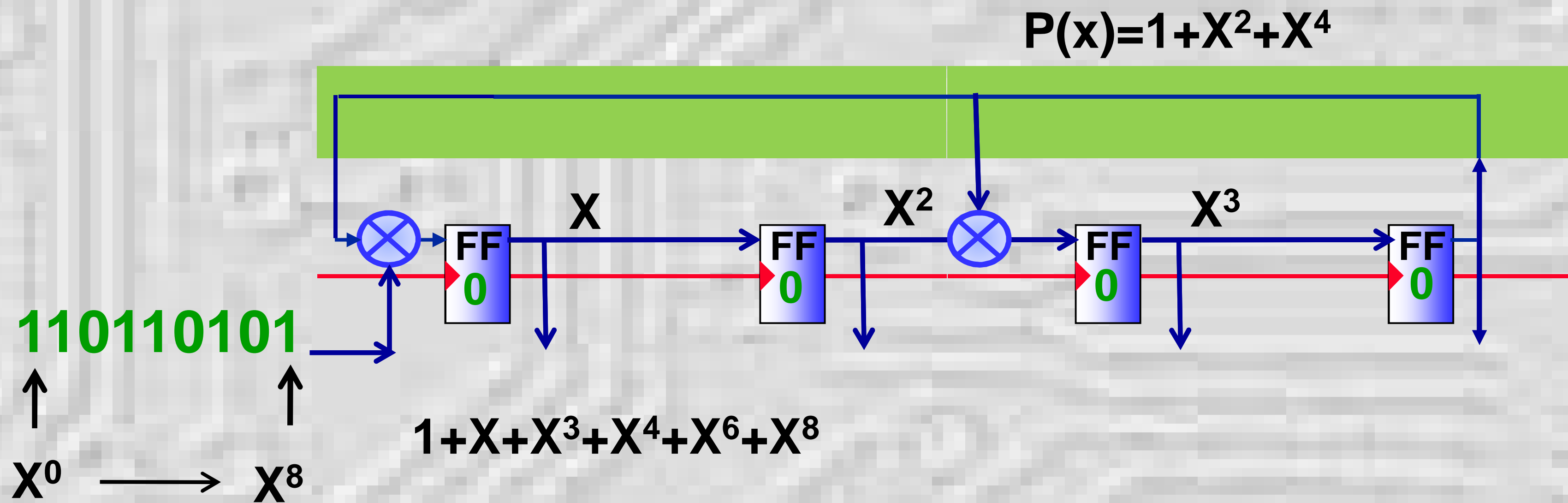
BIST





BIST

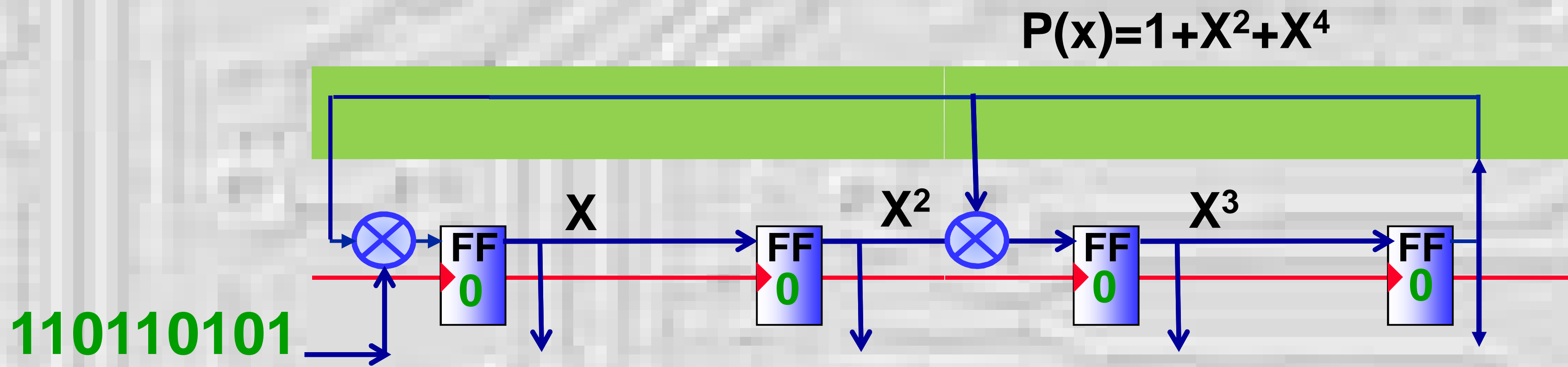
IN2P3



$$
\begin{array}{l|l}
X^8 + X^6 + X^4 + X^3 + X + 1 & X^4 + X^2 + 1 \\
X^8 + X^6 + X^4 & \overline{X^4} \\
\hline
0X^8+0X^6+0X^4+X^3 & \\
\quad 0 & \\
\hline
X^3 + X & \\
\quad 0 & \\
\hline
X^3 + X + 1 &
\end{array}
$$

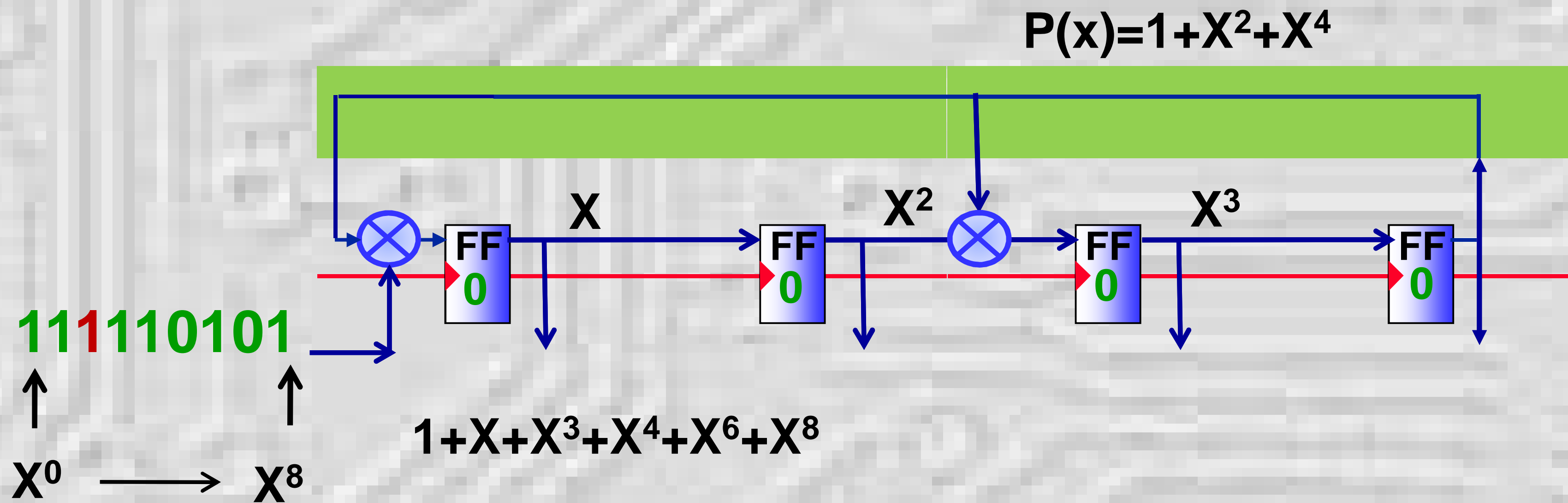
$$
\begin{array}{l|l}
101011011 & 10101 \\
10101 & \overline{10000} \\
\hline
000001 & \\
0 & \\
\hline
10 & \\
00 & \\
\hline
101 & \\
000 & \\
\hline
1011 &
\end{array}
$$

BIST



BIST

IN2P3



$$X^8 + X^6 + X^4 + X^3 + X^2 + X + 1 \;\Big|\; X^4 + X^2 + 1$$

$X^8 + X^6 + X^4$

$0X^8+0X^6+0X^4+X^3$

0

$X^3 + X^2$

0

$X^3 + X^2 + X$

0

$X^3 + X^2 + X + 1$

Quotient: X^4

101011111 | 10101

10101

000001

0

11

00

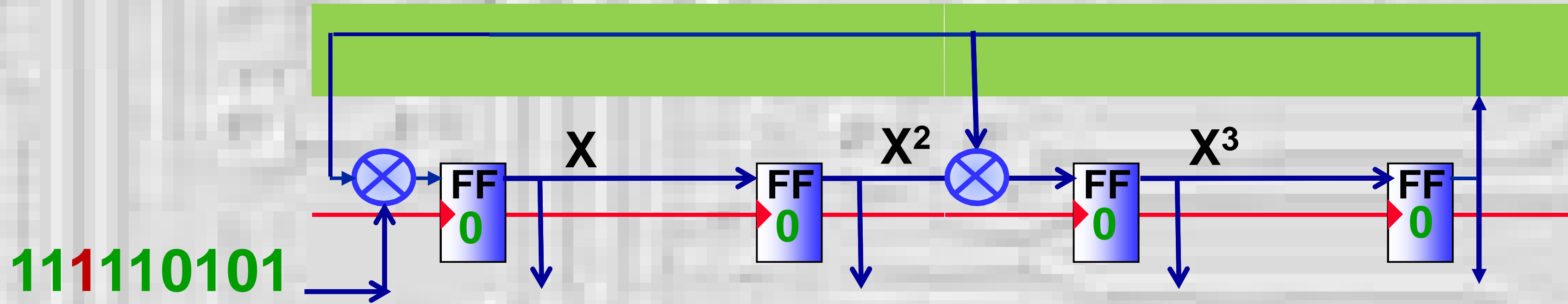
111

000

1111

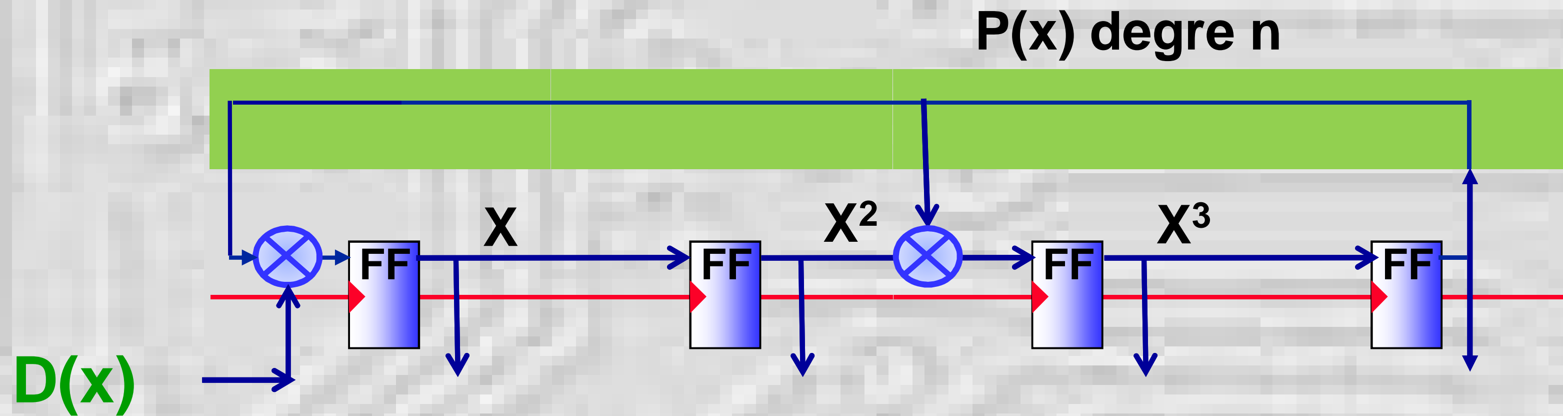
Quotient: 10000

BIST



BIST

IN2P3



D(x) = P(x) . Q(x) + R(x)

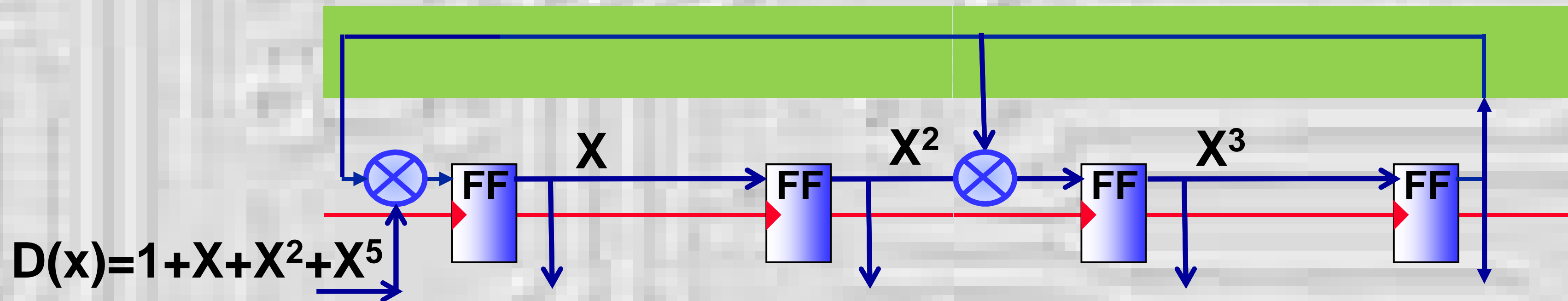
D'(x) = P(x) . Q'(x) + R'(x)

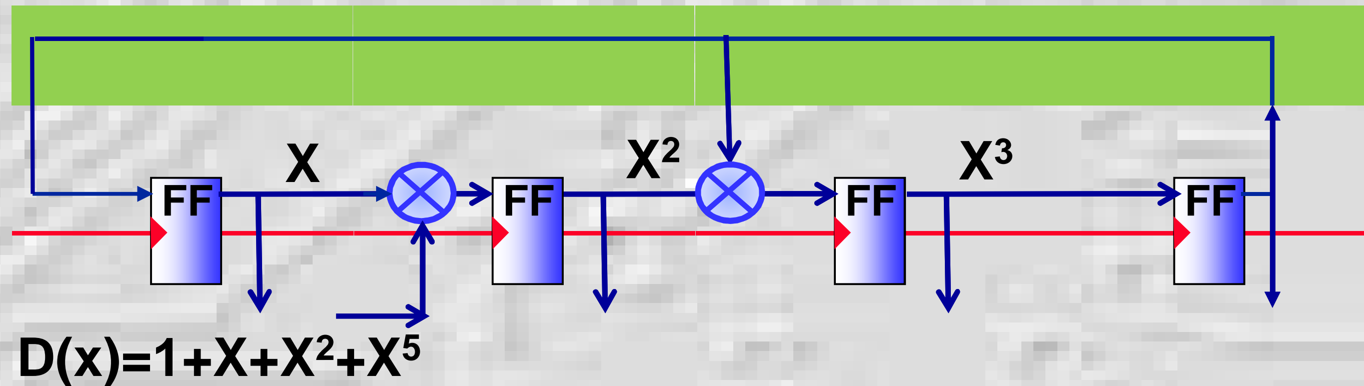
Probability R(x) = R'(x)

Aliasing

Prob=$1/2^n$

BIST





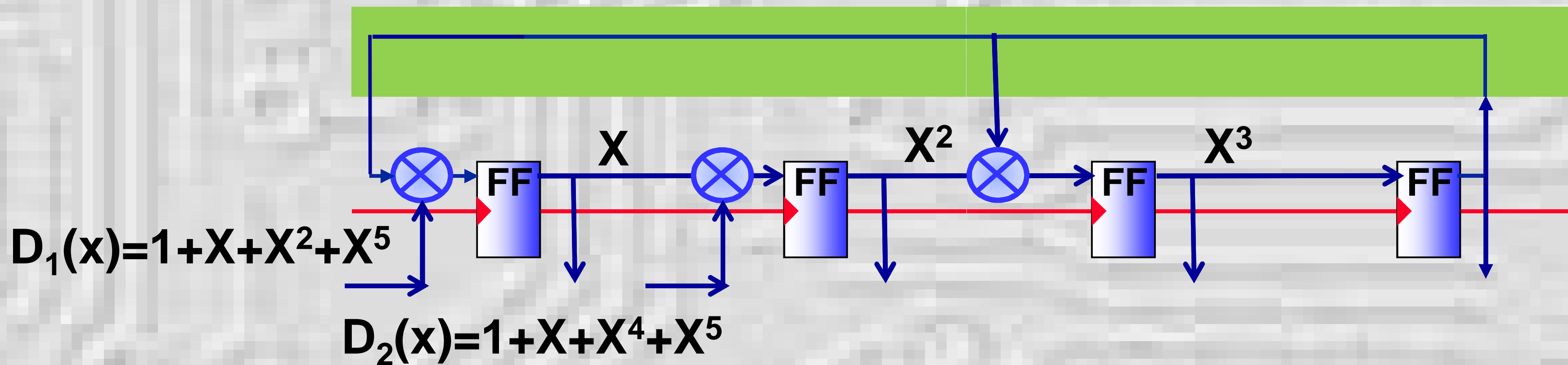
$$
\begin{array}{l|l}
X^5 + X^2 + X + 1 & X^4 + X^2 + 1 \\
X^5 + X^3 + X & \hline
\hline
1X^3 + 1X^2 + 0X + 1 & X
\end{array}
$$

Aliasing

$P = 1/2^n$

IN2P3

BIST



$D_1(x) = P(x) \,.\, Q_1(x) + R_1(x)$

$D_2(x) = P(x) \,.\, Q_2(x) + R_2(x)$

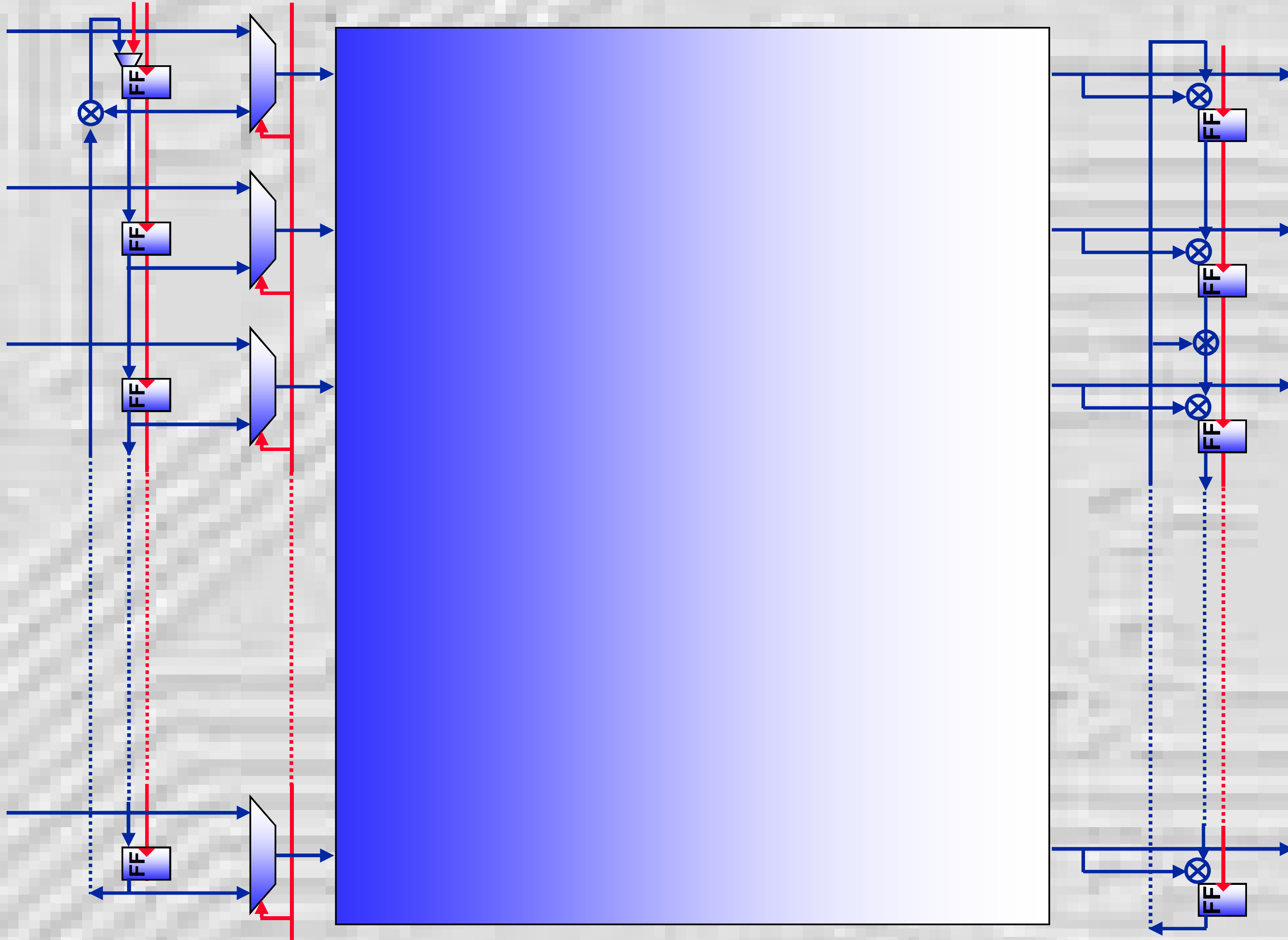
- $R(x) = R_1(x) \otimes R_2(x)$
- $R'(x) = R'_1(x) \otimes R_2(x)$
- $R'(x) = R_1(x) \otimes R'_2(x)$

Aliasing

$P=1/2^n$

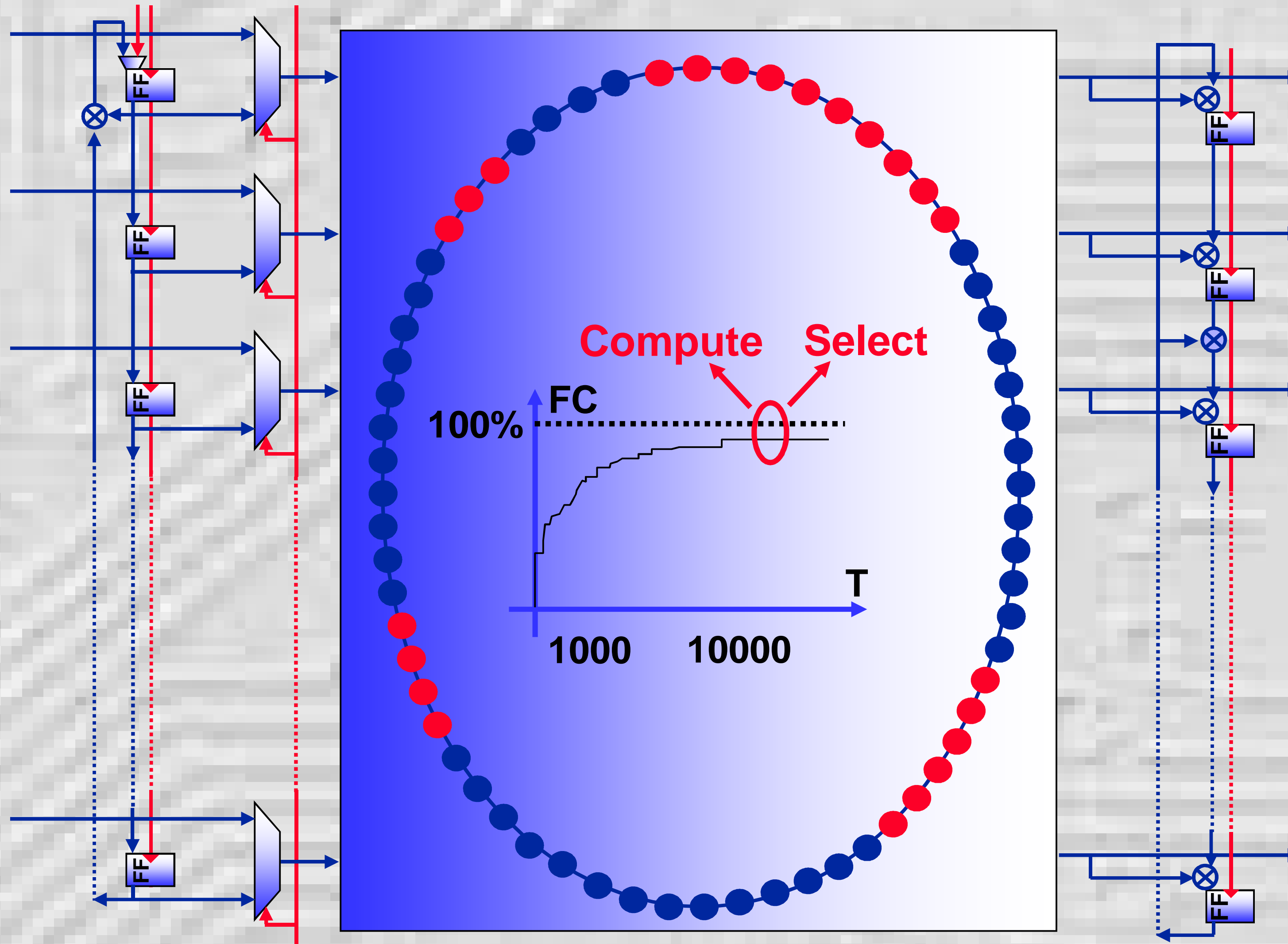
BIST

IN2P3



BIST

IN2P3

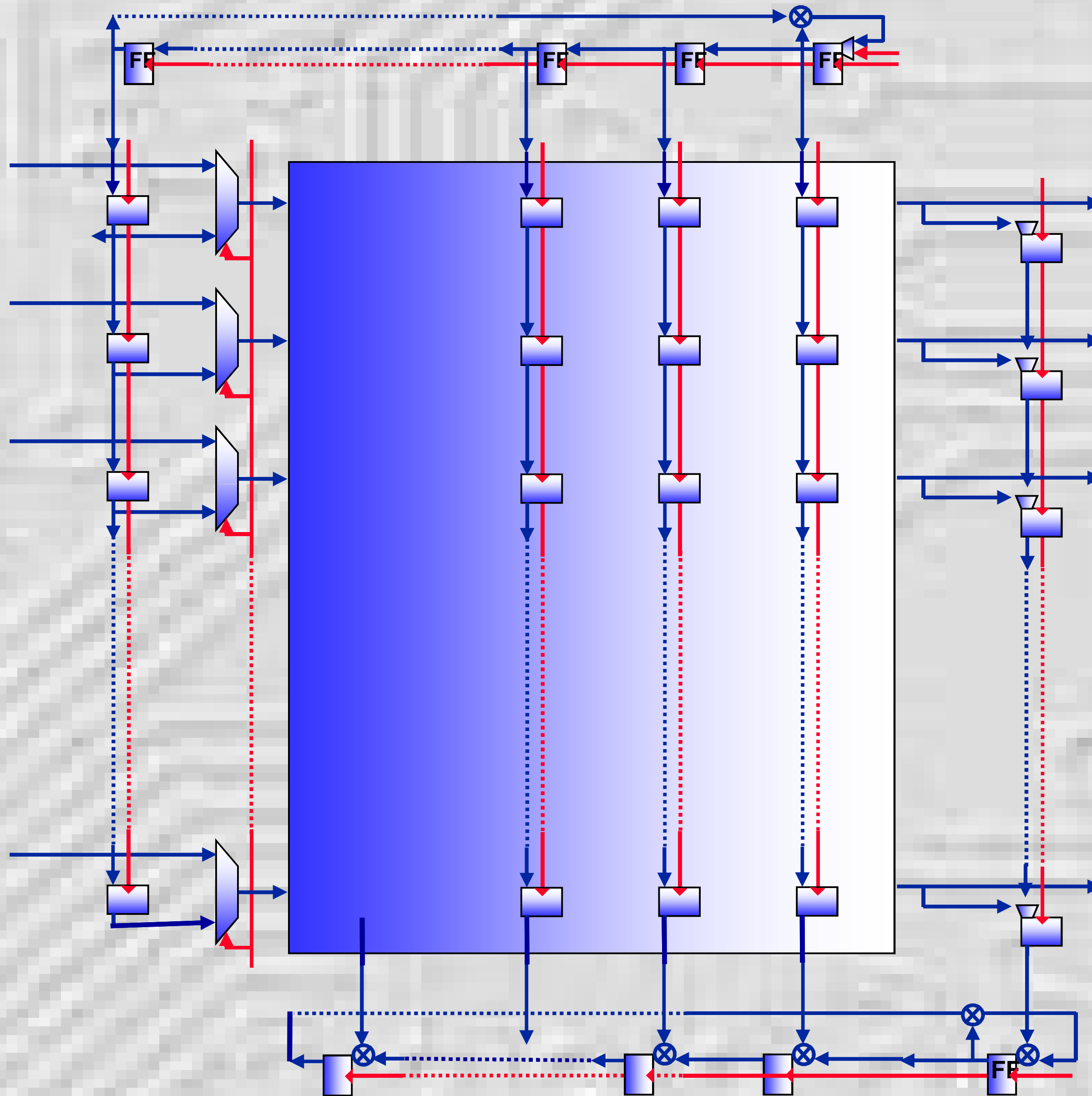


- Test Length^2
- Seed/Clock
- Reconf Polyn

BIST

IN2P3

IBM STUMPS



BIST