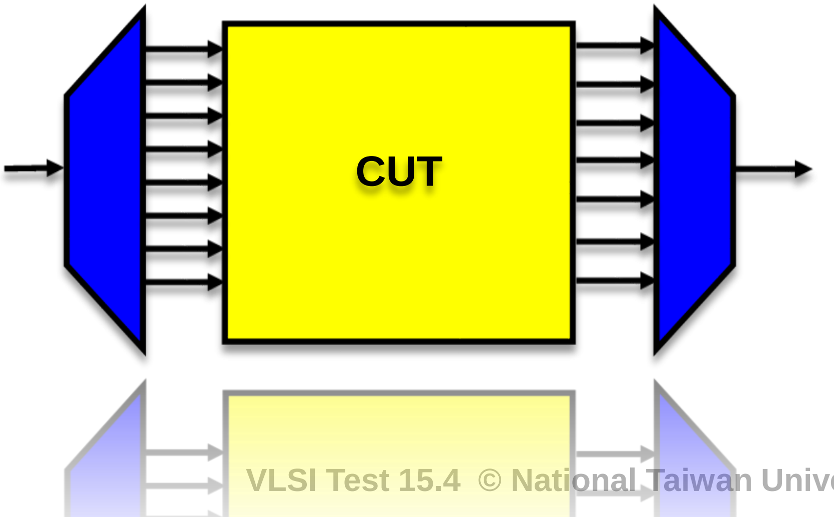
Test Compression

- Introduction
- Software Techniques
- **Hardware Techniques**
  - Test Stimulus Compression
  - **Test Response Compaction(TRC)***
- Industry Practices
- Conclusion

* NOTE
Test stimulus compression is lossless
Test response compaction can be lossy



What is Good TRC?

1. **High Compaction Ratio (CR)**

$$CR = \frac{Original\ \ Data\ Volume}{Compacted\ \ Data\ Volume}$$

2. **Low Aliasing**

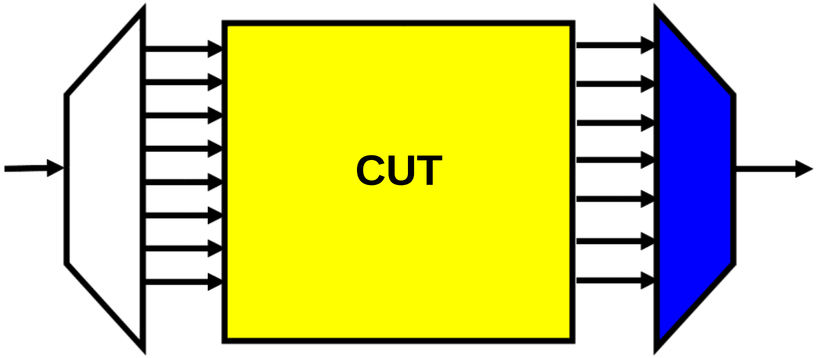
$$PAL = \frac{number\ of\ \ faulty\ \ outputs\ \ that\ \ generate\ gold\ \ signature}{total\ number\ of\ \ faulty\ outputs}$$

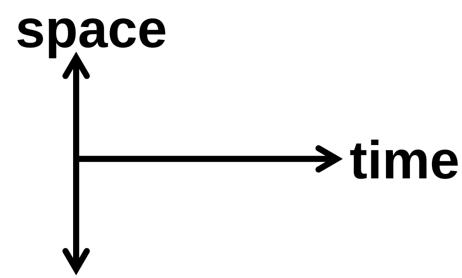
3. **Tolerate/mask unknown (X) outputs**
   - **Unknown outputs come from memory or non-scan flip-flop**
   - **NOTE: this is different from *unspecified bit (X)* during ATPG**

4. **Diagnosis support (not in this lecture)**

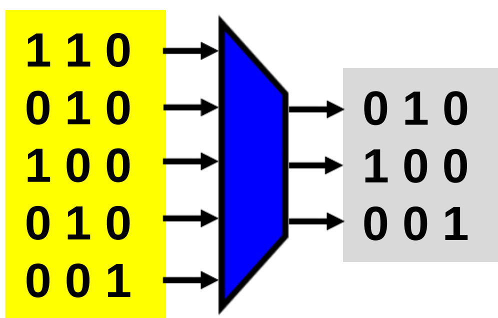
   Compacted test responses of a fault is different from those of another fault

Test Response Compactor (TRC)



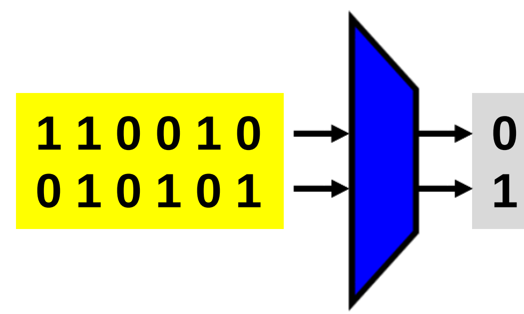


- ***Space compaction***
  - reduces output pins



$$Compaction\ \ Ratio = \frac{5}{3}$$

- ***Time compaction***
  - reduces output length



$$Compaction\ \ Ratio = \frac{6}{1}$$

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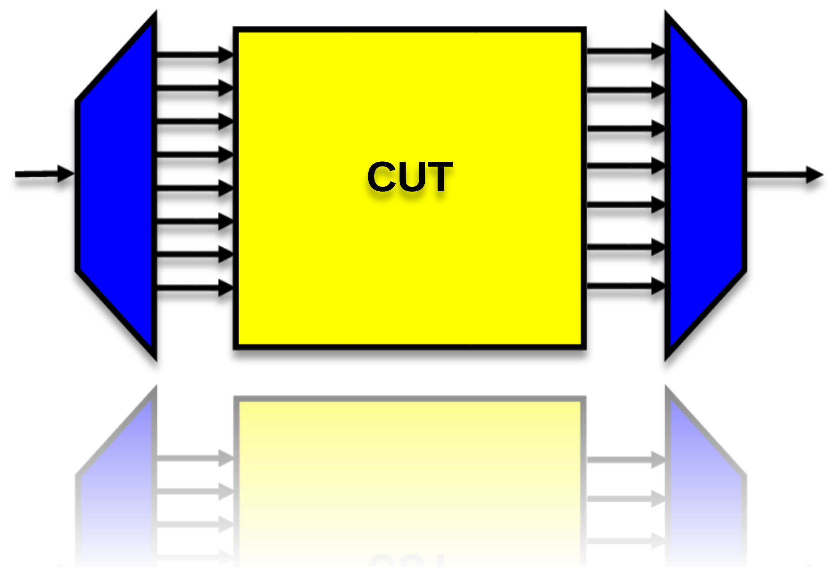
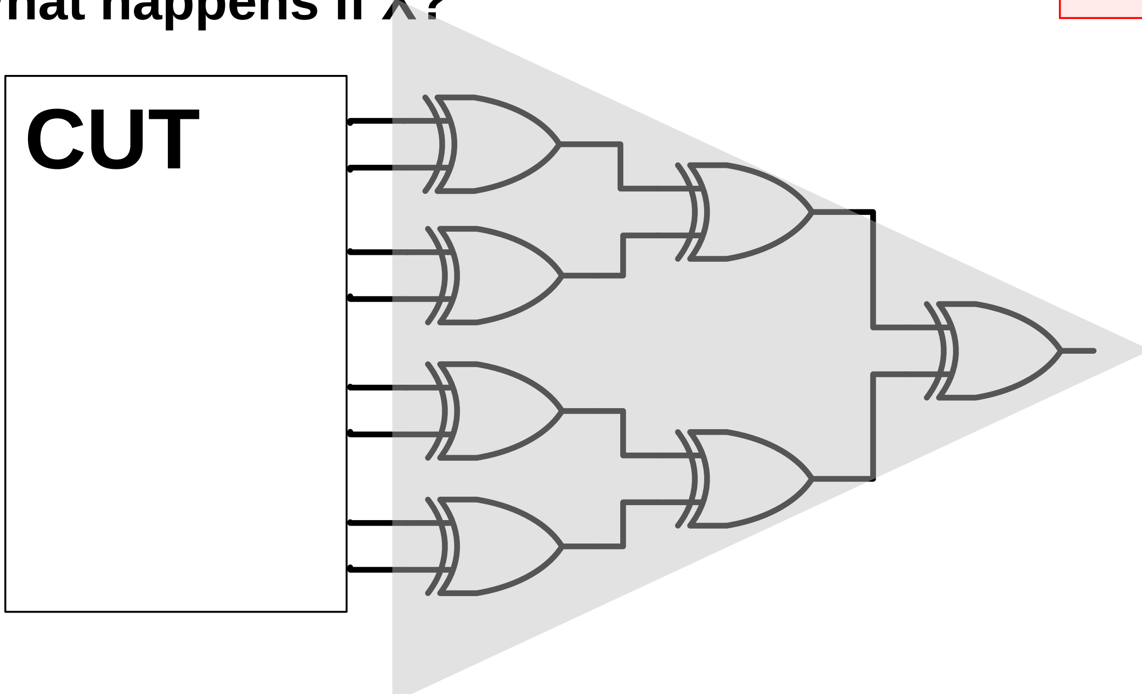


Single XOR-Tree

- 1. High CR
- 2. Bad PAL
  - Detects odd number of errors, not even
- 3. What happens if X?

$$CR = \# CUT \ \ outputs$$

$$PAL = \frac{1}{2}$$

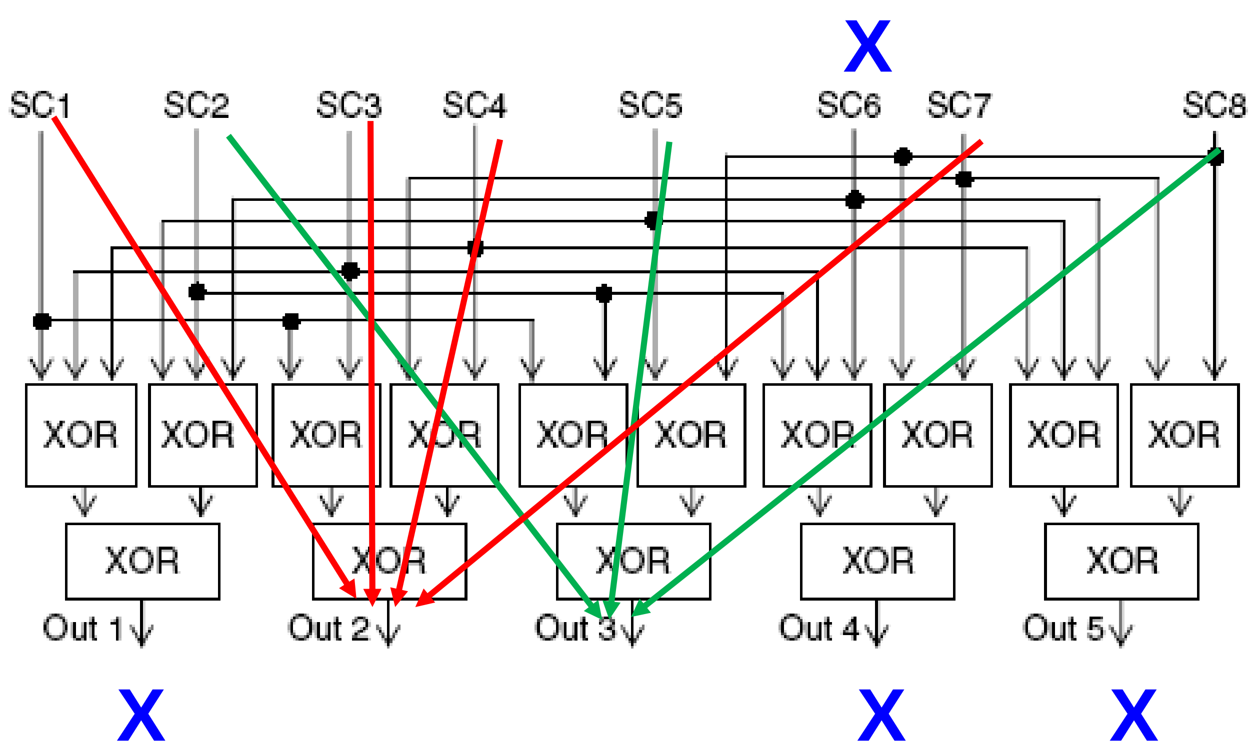


Single XOR Tree Can NOT Tolerate X

Idea: can we add more trees?

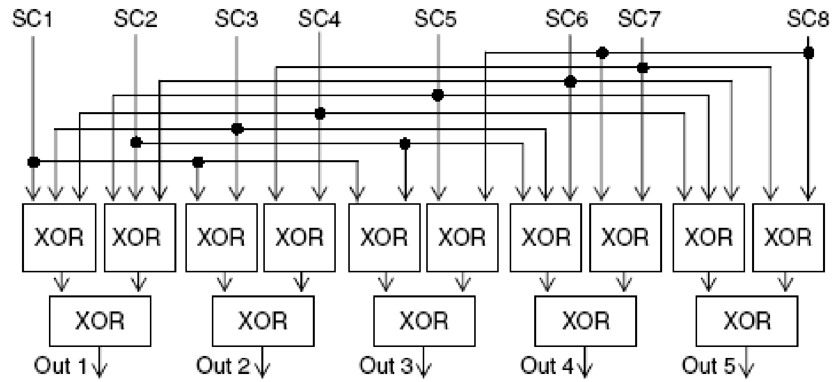
X-compact [Mitra 04]

- Multiple XOR trees can detect errors in presence of X
- Example (WWW. Fig. 6.24)
  - Scan chain (SC) 6 produces unknown 'X'
  - The other 7 scan chains are not contaminated



X-compact Matrix, *M*

- **Each row represents a scan chain**
- **Each column represents an compactor output**
- $M_{i,j}$ **= 1 means** j_{th} **compactor outputs depends on** i_{th} **scan output**



$$S = \begin{bmatrix} SC1 \\ SC2 \\ SC3 \\ SC4 \\ SC5 \\ SC6 \\ SC7 \\ SC8 \end{bmatrix} \quad M = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \quad O = \begin{bmatrix} Out1 \\ Out2 \\ Out3 \\ Out4 \\ Out5 \end{bmatrix}$$

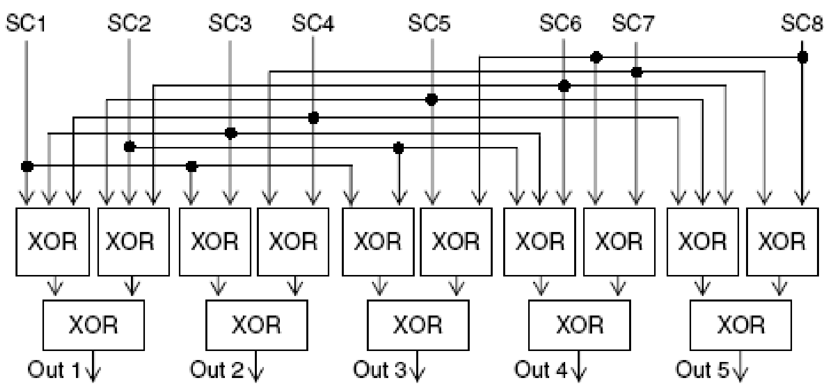
$$\boxed{S^T \times M = O^T}$$

X-compact Matrix, *M*

(WWW Theorem 6.4) Any 1, 2 or odd number of errors at same cycle are detected if every row in *M* has *distinct odd number of 1's.*

1) **Single error is detected because no row is all zeros**
2) **Two errors are detected because adding any two rows produces non-zero results since no two rows are the same**
3) **Odd number of errors are detected because adding odd number of rows produces non-zero results (since all rows has odd 1's)**

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

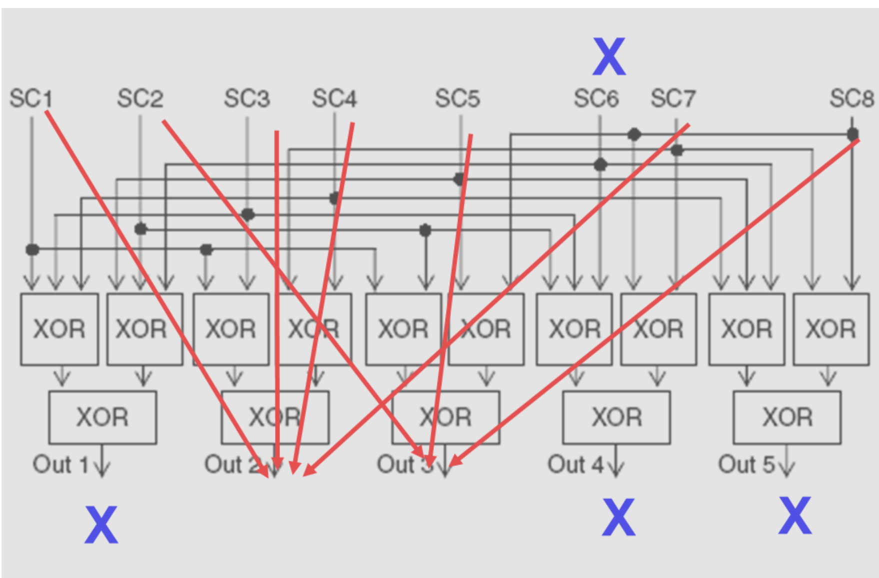


every row has 3 ones

Theorem for X-tolerance

- X-compact guarantees to detect 1 error from any scan chain with 1 unknown (X) from any other scan chain at same cycle
  - If and only if submatrix obtained by removing that row and columns having 1's
  - does not contain a row of all 0s

- Example: SC 6 produces X



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

What is CR?

- **Every row in the X-compact matrix is *nonzero, distinct***
  - **contains *odd number* of 1's**

number of compactor outputs (#out)	**max number of scan chains (#sc)**	**CR**
5	$C^5{}_3=10$	2
6	$C^6{}_3=20$	3.3
7	$C^7{}_3=35$	5
8	$C^8{}_3=56$	7
9	$C^9{}_5=126$	14
10	$C^{10}{}_5=252$	25.2

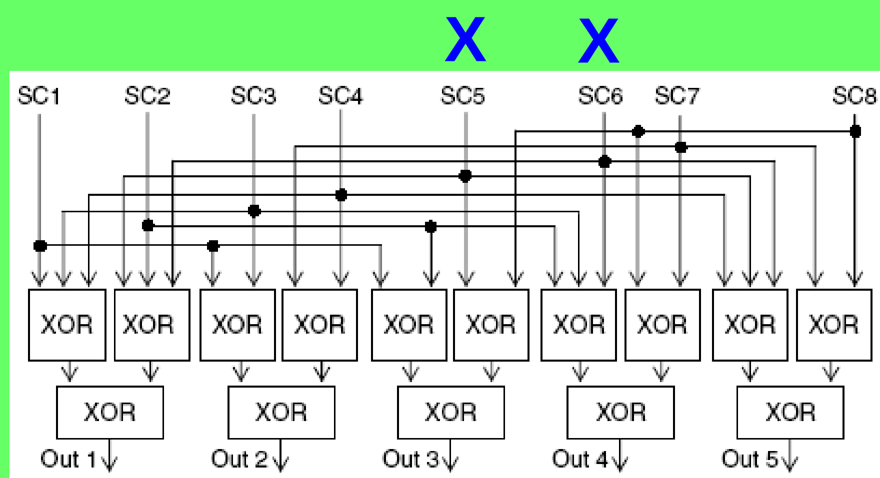
$$M = \left.\begin{array}{ccccc} \multicolumn{5}{c}{\begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}} \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \end{array}\right\} C_3^5 = 10$$

$$CR = \frac{Original\ \ Data}{Compacted\ \ Data} = \frac{\#SC}{\#Out}$$

QUIZ

Q: Which scan chain error we can NOT detect, when there are 2 X's from SC5 and SC6?

ANS:



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

Cannot Tolerate Many X at Same Time

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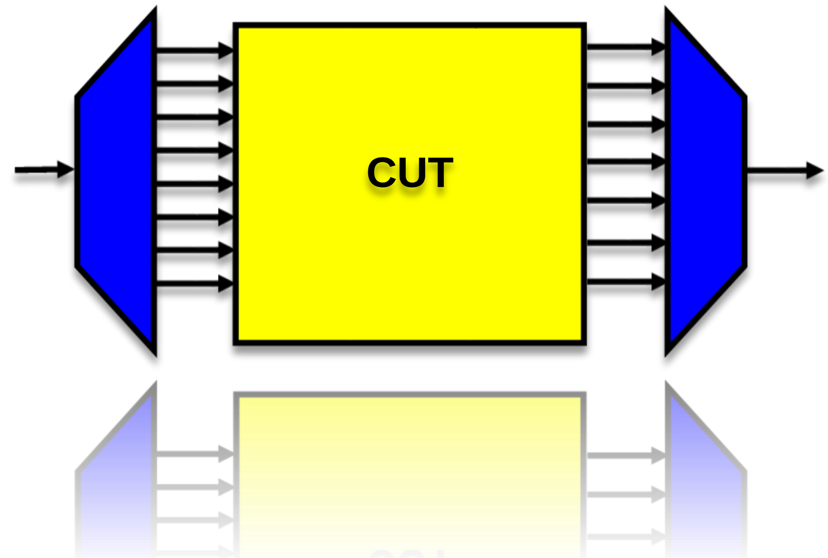
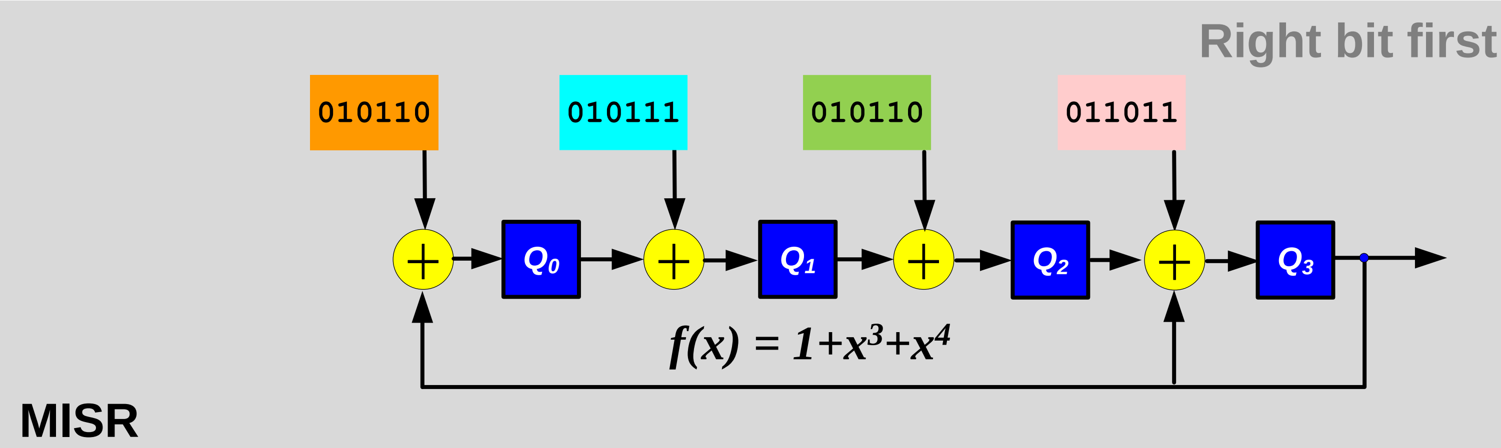
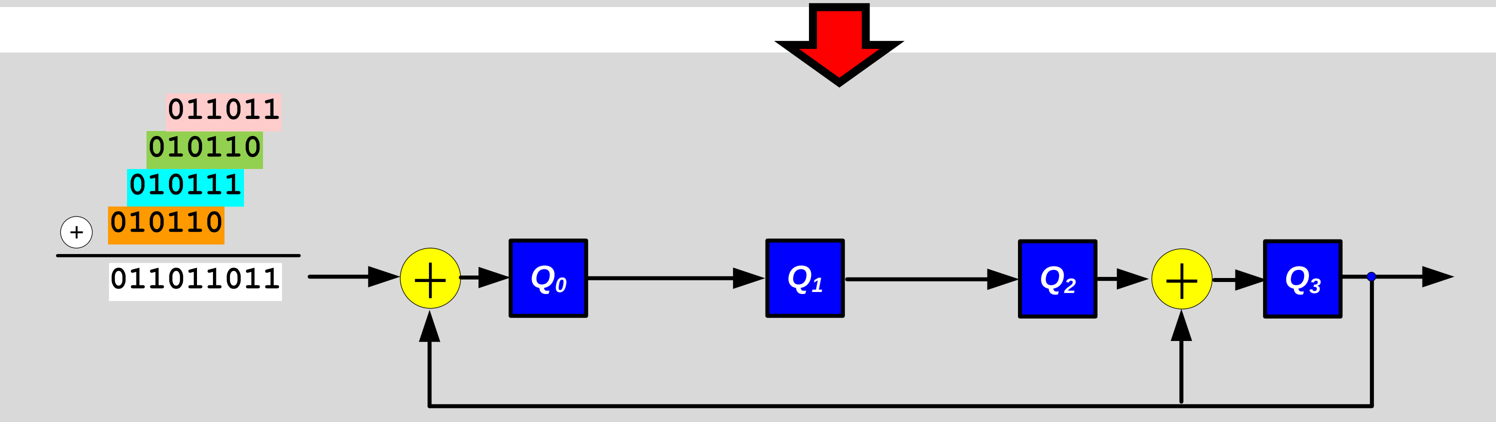


Review: MISR (video 14.3)

- ***MISR (multiple input signature register)*** **is similar to LFSR**
  - **except parallel inputs feed XOR between stages**





Equivalent LFSR

$M(x)=x+x^2+x^4+x^5+x^7+x^8$

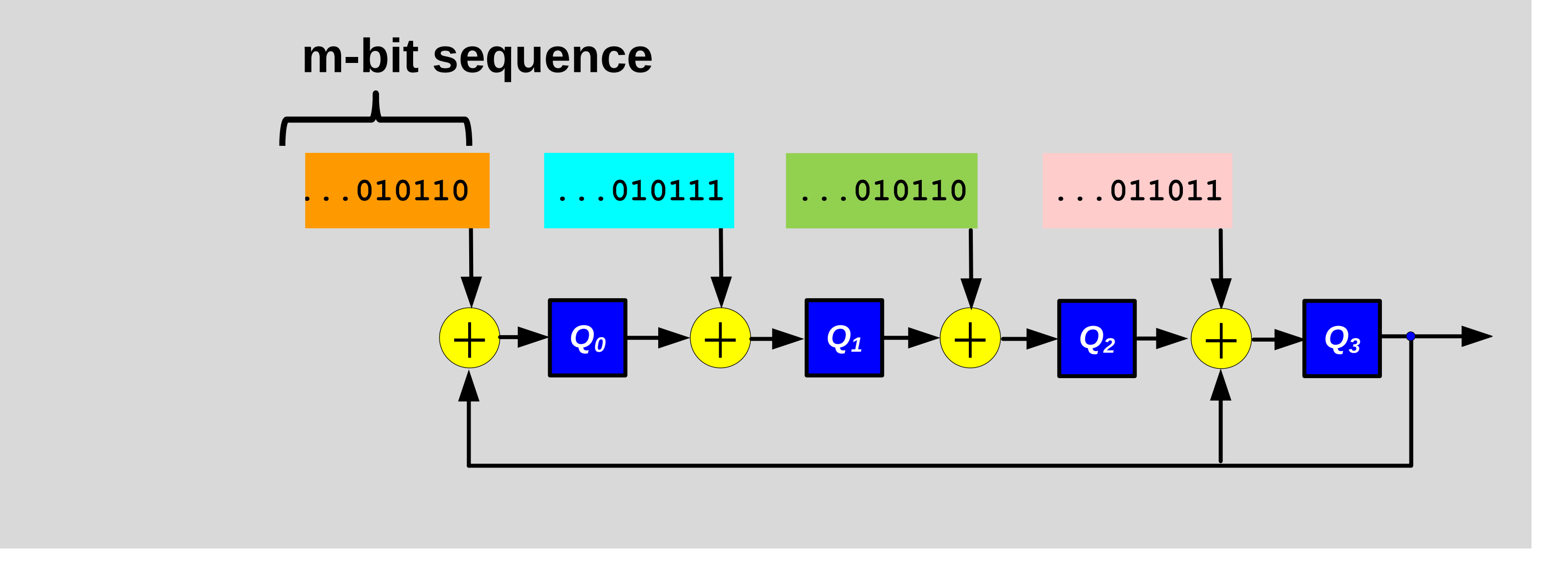
$R(x)=M(x) \bmod f(x) = 1+x^2+x^3$

CR=? Aliasing=?

- MISR degree = *N*, input bit sequence length = *m*
  - Signature is *N* bits

$$CR = \frac{Original\ \ Data}{Compacted\ \ Data} = \frac{N \times m}{N} = m$$

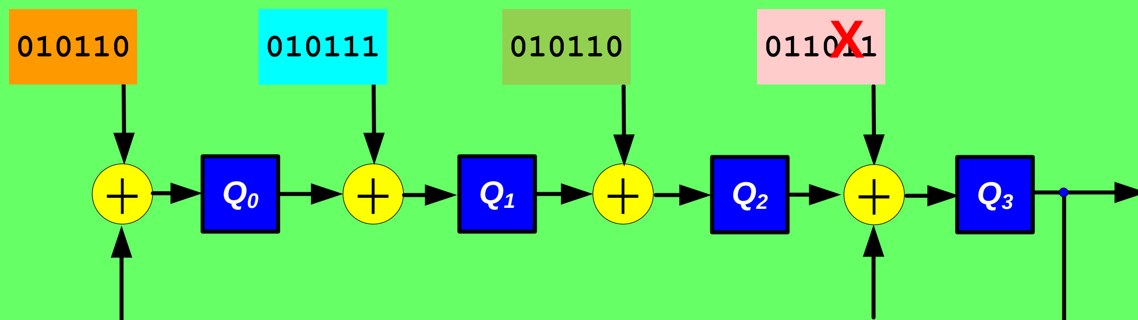
$$PAL \approx 2^{-N} \quad \text{(see 14.3)}$$



MISR has High CR and Low PAL

QUIZ

Q: What is signature if one bit is changed to X 'unknown' ?
ANS:



MISR is NOT X-tolerant

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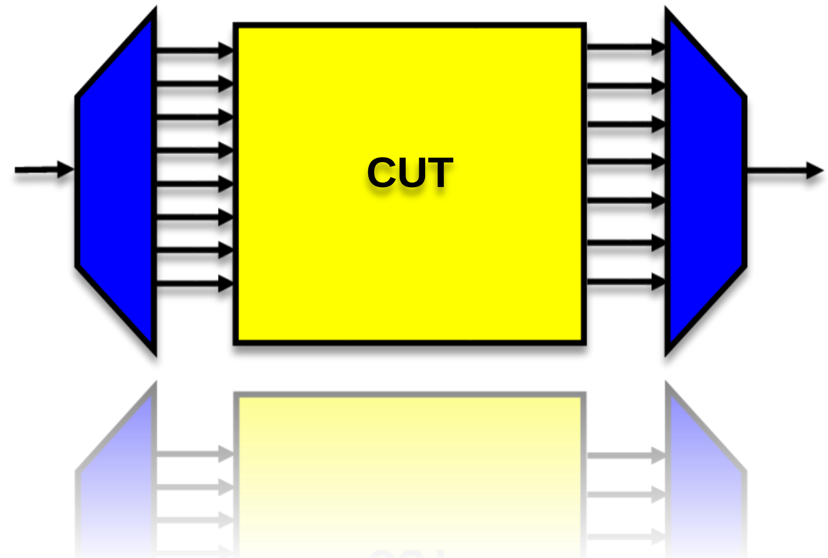
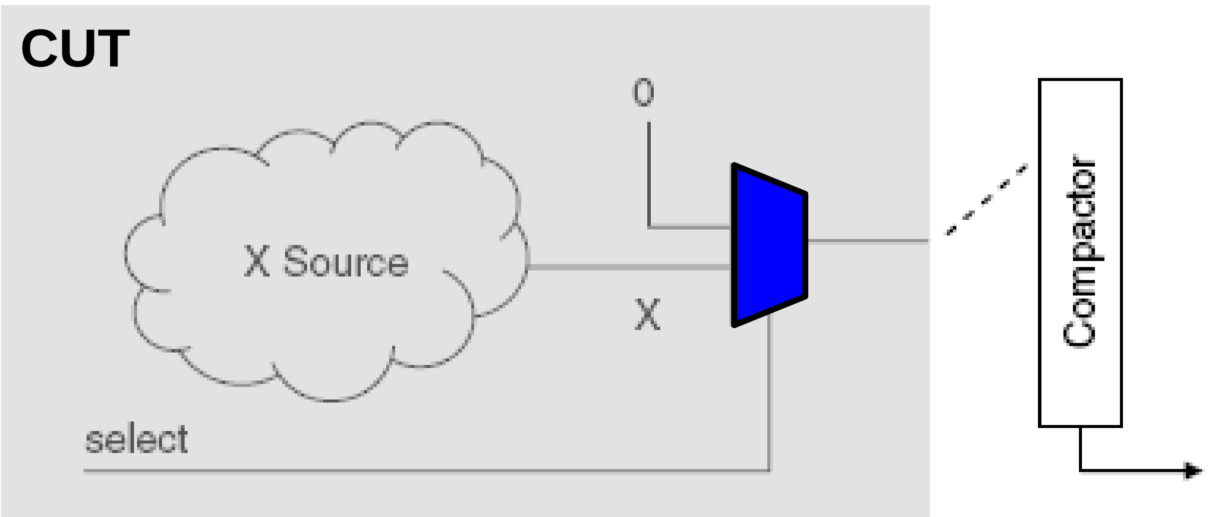


X-blocking (or X-bounding)

- Add extra DFT inside CUT to block X before reaching compactor
  - Area overhead and extra delay
- X source can be
  - non-scan FF, memory, multi-cycle paths, false paths*…



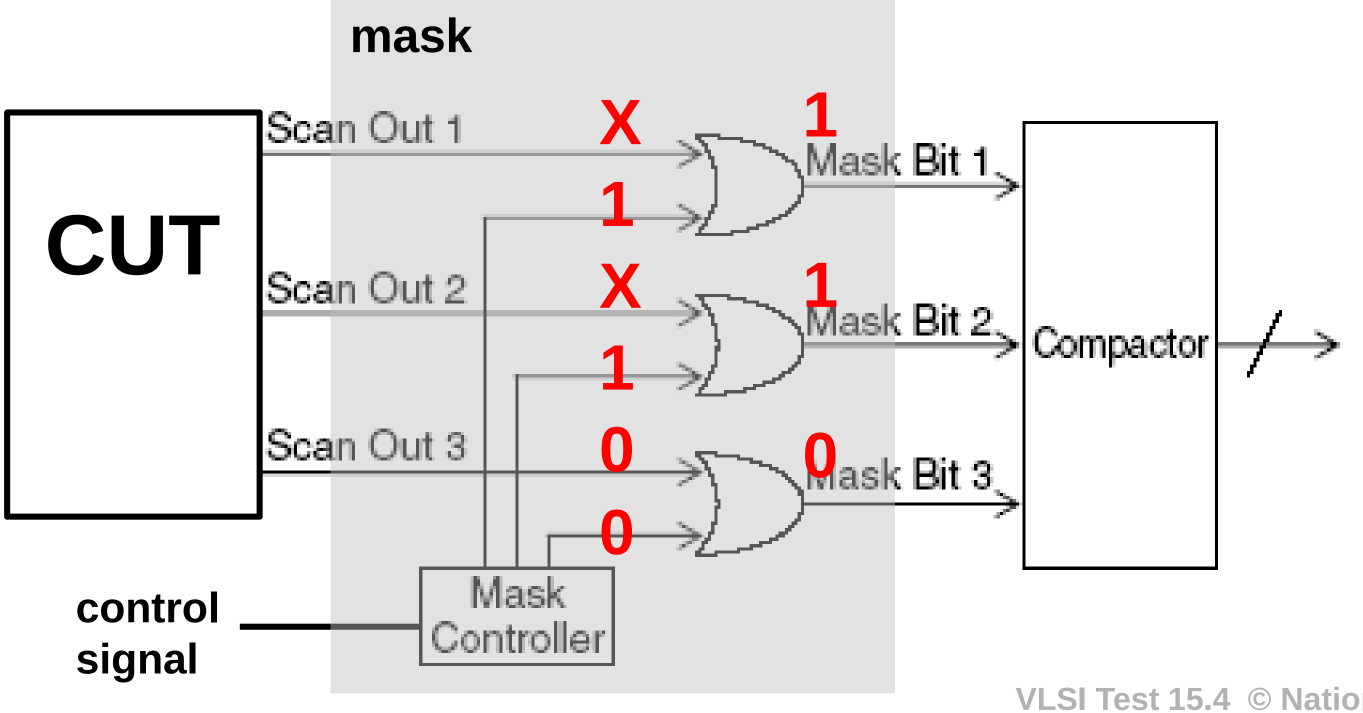
(WWW Fig. 6.25)

*multi-cycle paths needs more than 1 cycle to finish computation so test responses can be X
*false paths are not activated by normal operation so test responses can be X

X-masking

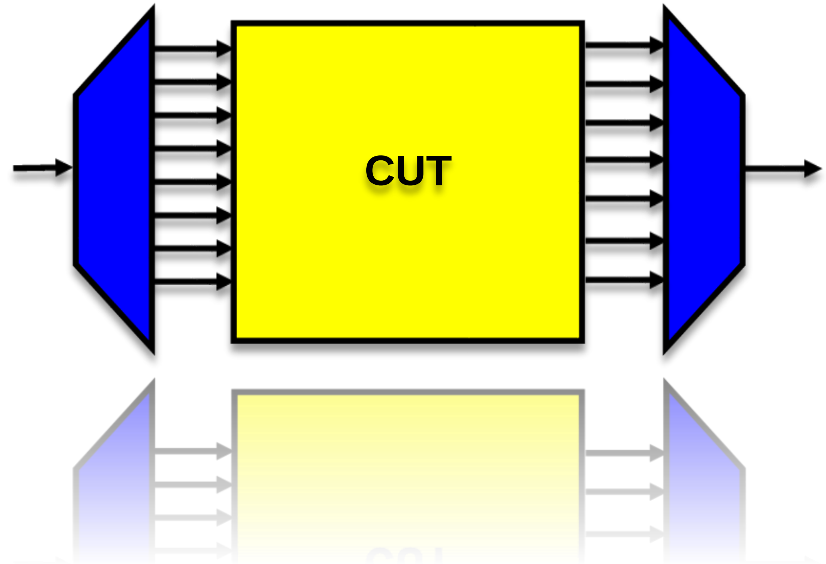
- Add extra mask between CUT and compactor

- Example: mask outputs by OR gates
  - 1 = mask
  - 0 = pass through



Summary

- Test Response Compaction
  - Space Compaction
    - XOR-tree, X-compact
  - Time Compaction
    - MISR
      - High CR, Low PAL
      - Cannot tolerate X
  - X-bounding, X-masking
      - Can mask many X

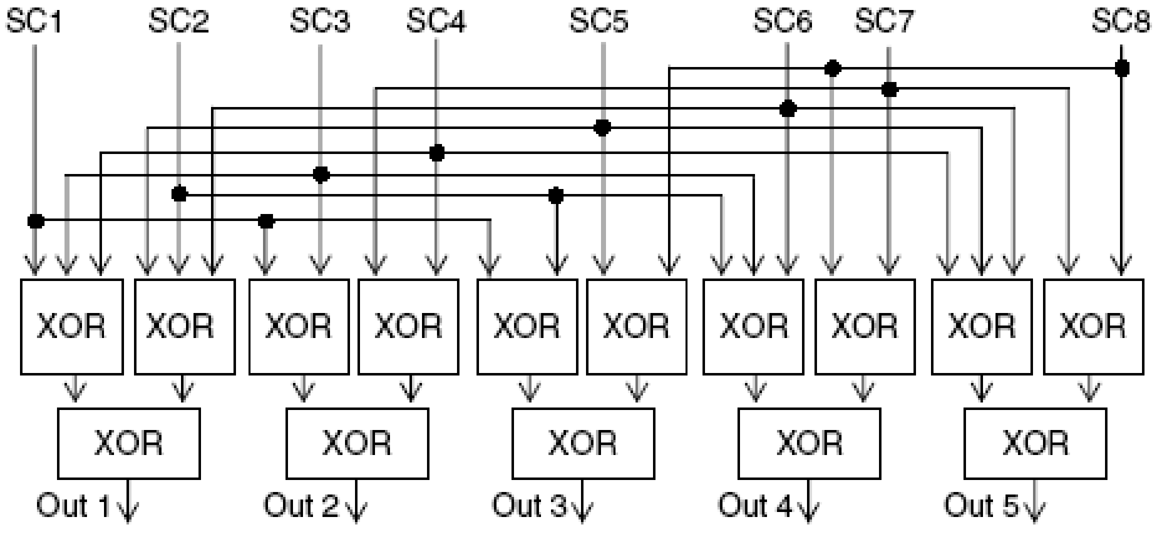


X-Masking + MISR/XOR-tree is Most Popular Solution

FFT

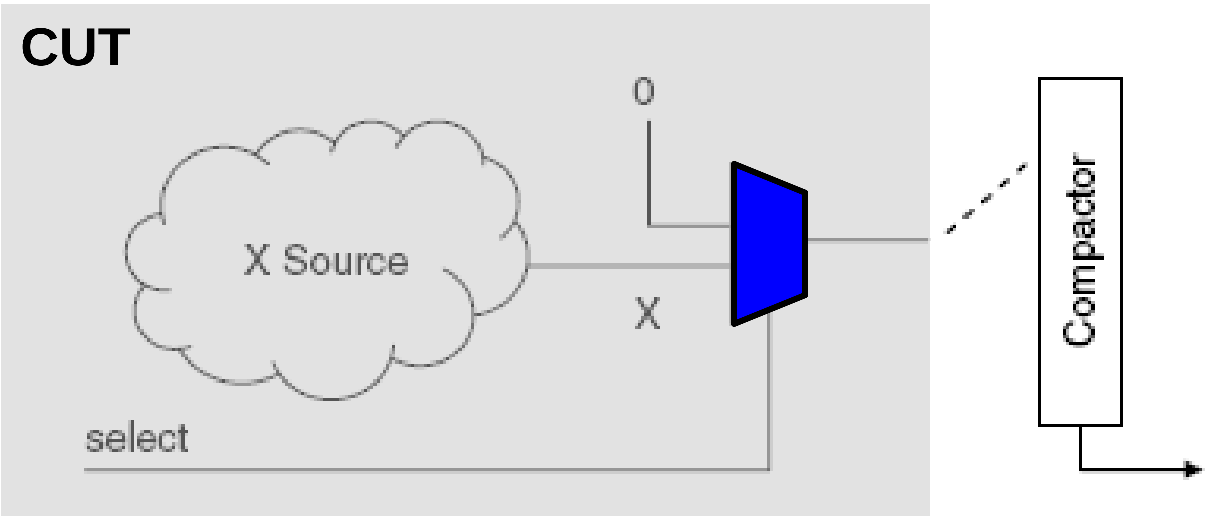
- **What is Prob. of Aliasing for X-compactor?**

(Theorem 6.4) Any 1, 2 or odd number of errors at same scan-out cycle are detected if *every row in M has distinct odd number of 1's.*



FFT

- X source can be multi-cycle paths, false paths
- Q: why multi-cycle paths generate X in test mode?
- Q: why false paths generate X in test mode?

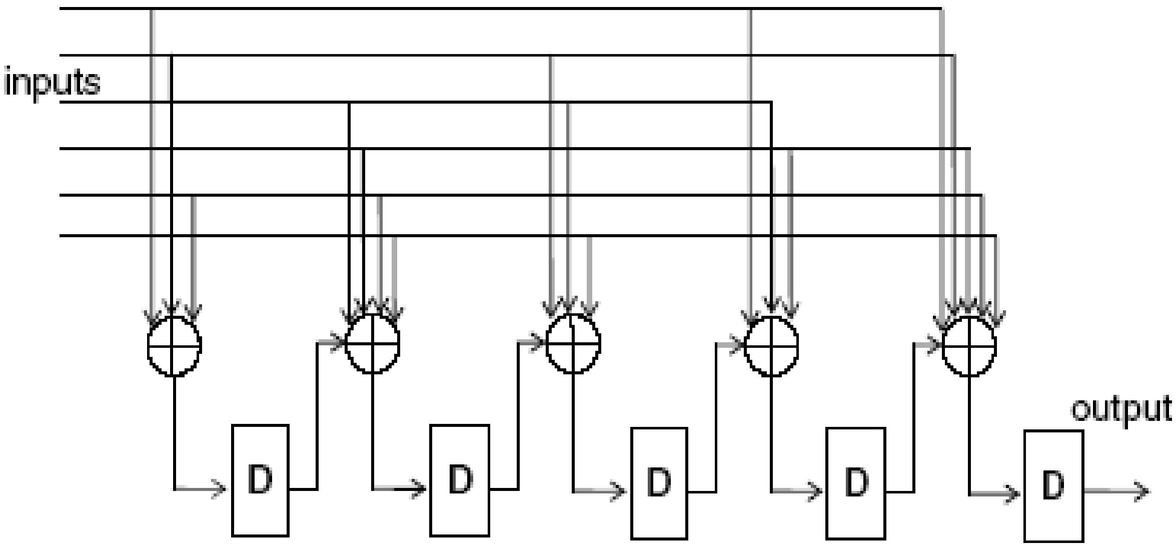


(WWW Fig. 6.25)

*multi-cycle paths needs more than 1 cycle to finish computation so test responses can be X
*false paths are not activated by normal operation so test responses can be X

FFT

- This is a **hybrid space-time compactor**
- Q: What are advantages and disadvantages ?



FFT

- Q: In X-compact matrix, why cannot we have even number of 1's in each row?

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

Theorems for Error Detection

- **(WWW Theorem 6.3)**
  - **If only a single scan chain produces an error at any scan-out cycle (scan slice), the X-compactor is guaranteed to produce errors if and only if *no row of the X-compact matrix contains all 0's.***
- **(WWW Theorem 6.4)**
  - **Errors from any one , two or an odd number of scan chains at the same scan-out cycle are guaranteed to be detected**
    - **if every row in the X-compact matrix is *nonzero, distinct and contains an odd number of 1's.***

How to Design X-compactor?

- **(WWW Theorem 6.4)**
  - **Errors from any one , two or an odd number of scan chains at the same scan-out cycle are guaranteed to be detected**
  - **if every row in the X-compact matrix is *nonzero, distinct and contains an odd number of 1's.***

max number of scan chains (#sc)	number of compactor outputs (#out)
C^5_3=10	5
C^6_3=20	6
C^7_3=35	7
C^8_3=56	8
C^9_5=126	9
C^{10}_5=252	10

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

$$CR = \frac{Original\ \ Data}{Compressed\ \ Data} = \frac{\#SC}{\#Out}$$

Time v.s. Space Compaction

- D: original test responses
- C: compacted test responses
- Compactor converts *D* matrix (*m x n*) to *C* matrix (*p x q)*
  - Column index referred to as time dimension
  - Row index referred to as space dimension
- Space compression: *p < m, q=n*
- Time compression: *q < n*

$$C = \Phi(D)$$