Spectral Testing

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Basic Idea

- **Meaningful inputs (e.g., test vectors) of a circuit are *not* random.**
- **Input signals must have spectral characteristics that are different from *white noise* (random vectors).**

History of this Work

- Class project, Spring 1999:
  - Develop an ATPG program using vector compaction.
  - Determination of input weights had limited success for combinational circuits and no success for sequential circuits.
  - Combinational ATPG improved when input correlations were considered (space correlation).
  - Sequential ATPG required both spatial and time correlation.

References: Books

- **A. V. Oppenheim, R. W. Schafer and J. R. Buck,** *Discrete-Time Signal Processing*, **Englewood Cliffs, New Jersey, Prentice Hall, 1999.**
- **M. A. Thornton, R. Drechsler and D. M. Miller,** *Spectral Techniques in VLSI CAD*, **Boston: Kluwer Academic Publishers, 2001.**

References: Papers

- A. K. Susskind, “Testing by Verifying Walsh Coefficients,” *IEEE Trans. Comp*., vol. C-32, pp. 198-201, Feb. 1983.
- T.-C. Hsiao and S. C. Seth, “The Use of Rademacher-Walsh Spectrum in Random Compact Testing,” *IEEE Trans. Comp*., vol. C-33, pp. 934-937, Oct. 1984.
- S. Sheng, A. Jain, M. S. Hsiao and V. D. Agrawal, “Correlation Analysis for Compacted Test Vectors and the Use of Correlated Vectors for Test Generation,” *IEEE International Test Synthesis Workshop*, 2000.
- A. Giani, S. Sheng, M. S. Hsiao and V. D. Agrawal, “Efficient Spectral Techniques for Sequential ATPG,” *Proc. IEEE Design & Test (DATE) Conf*., March 2001, pp. 204-208.
- A. Giani, S. Sheng, M. S. Hsiao and V. D. Agrawal, “Novel Spectral Methods for Built-In Self-Test in a System-on-a-Chip Environment,” *Proc. 19th IEEE VLSI Test Symp*., Apr.-May 2001, pp. 163-168.
- A. Giani, S. Sheng, M. Hsiao and V. D. Agrawal, “Compaction-Based Test Generation Using State and Fault Information,” *J. Electronic Testing: Theory and Applic*., vol. 18, no. 1, pp. 63-72, February 2002.
- O. Khan and M. L. Bushnell, “Spectral Analysis for Statistical Compaction During Built-In Self-Testing,” *Proc. International Test Conf*., Oct. 2004, pp. 67-76.
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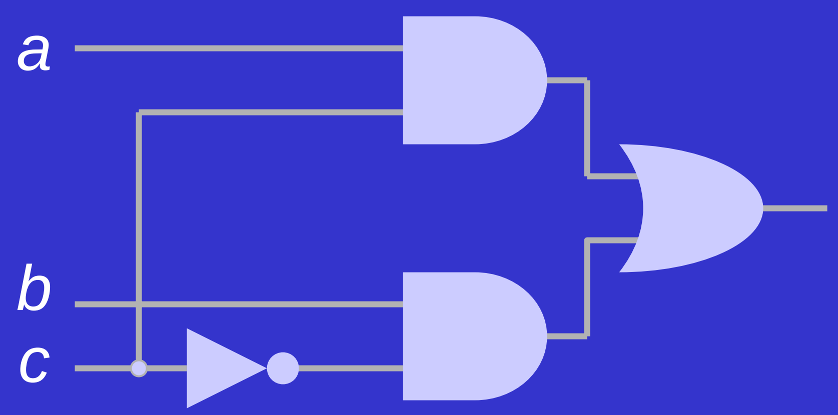
Statistics of Test Vectors

100% coverage
Tests:

a	**00011**
b	**01100**
c	**10101**

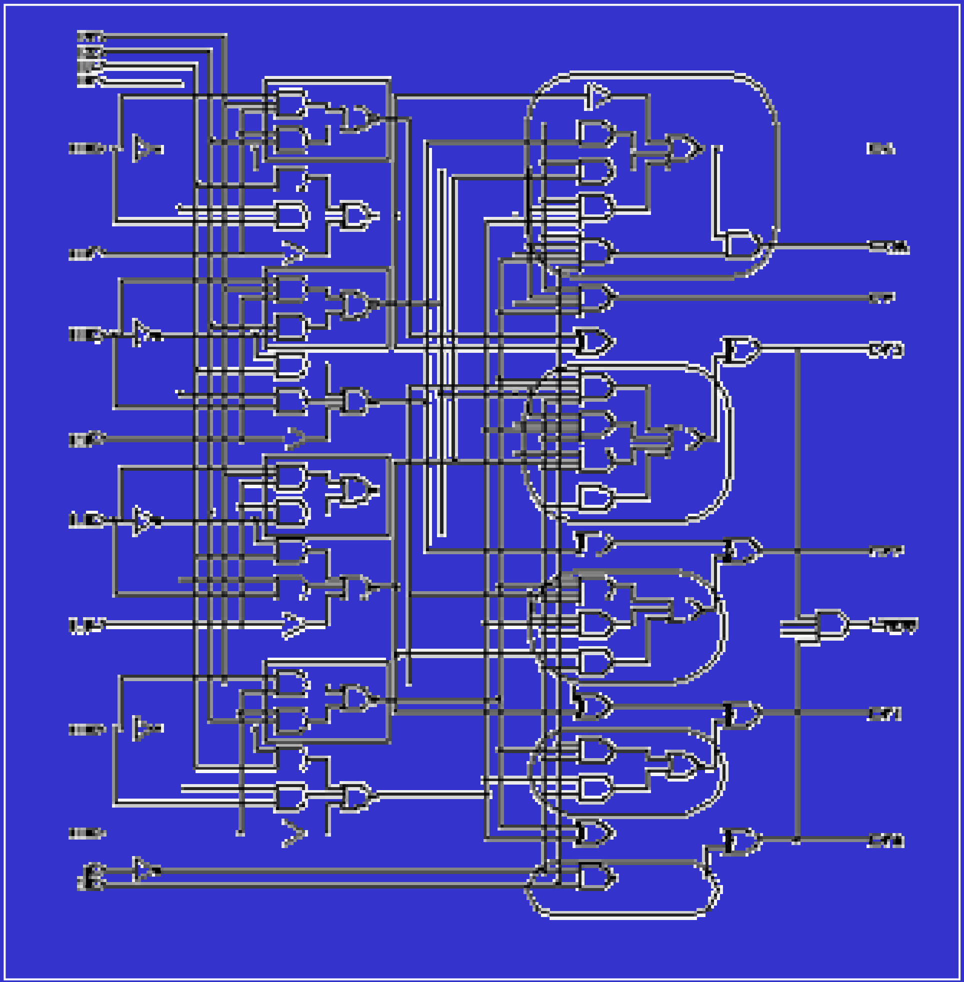


Test vectors are no<u>t</u> random:

1. **Correlation:** $a = \bar{b}$**, frequently.**
2. **Weighting:** *c* **has more 1s than** *a* **or** *b***.**

Vectors for 74181 ALU

Twelve vectors:
01010000111101
01011111111100
01010001111001
01010010110001
01011000000011
01010100100001
10100000000100
10101100001000
10100011010100
10101111111010
01010011000000
10100011101111
46% 1's



TLC Circuit: s298

Test vector sequence:

000 repeat 3 times
001 repeat 8 times
000 repeat 39 times
010 repeat 17 times
000 repeat 24 times
001 repeat 5 times
000
100 repeat 3 times
000 repeat 17 times

Spectrum of a Bit-Stream

- **Hadamard matrix of order k gives bases for bit-streams of length 2^k.**
- **Example: k=2**

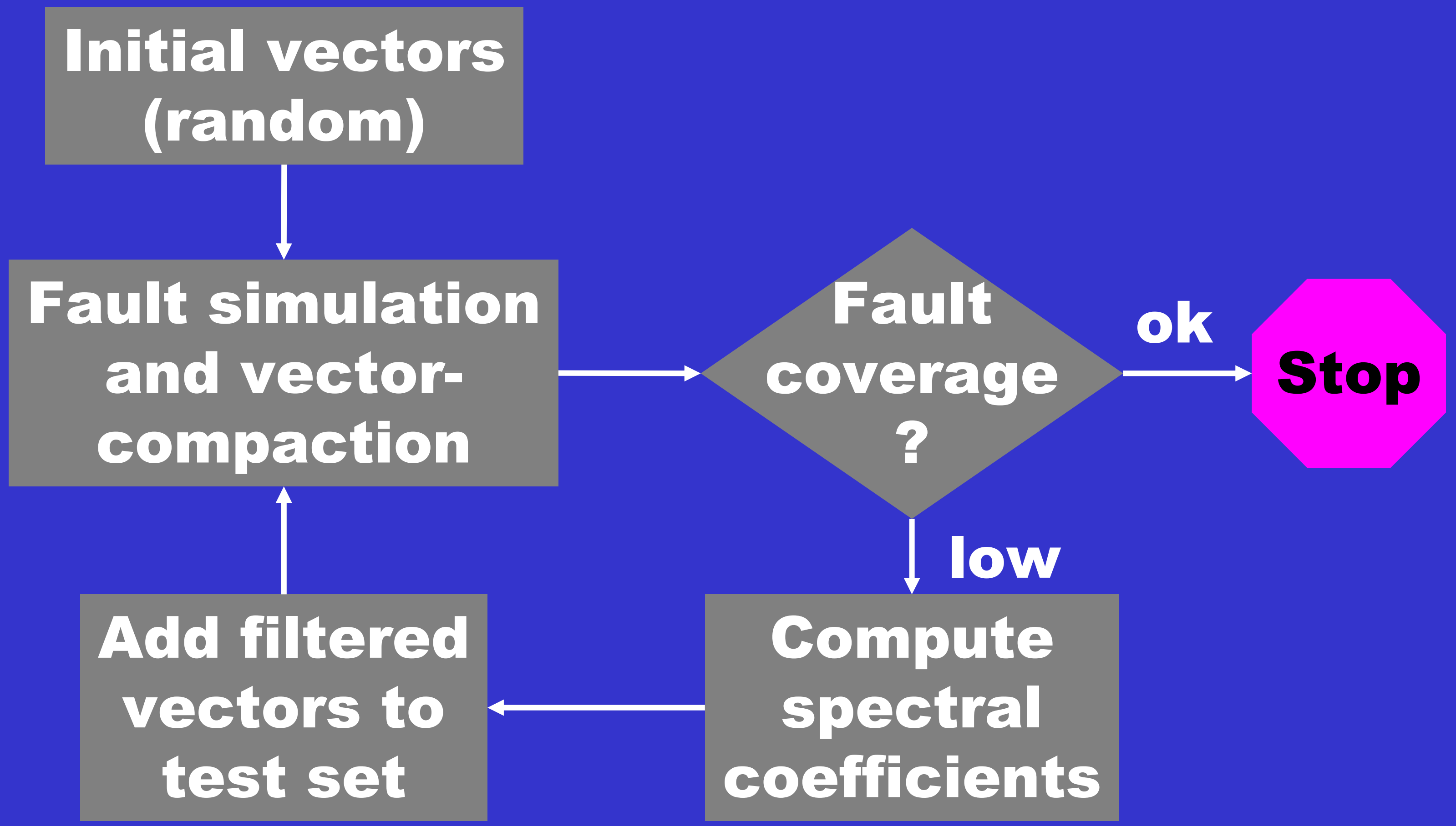
$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} -1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ -2 \\ -2 \\ -2 \end{bmatrix} \longrightarrow \begin{matrix} 1 \\ 0 \\ 0 \\ 0 \end{matrix}$$

$$H(k) \times C = k.B$$

Filtering Noise

- Determine coefficient matrices for the input bit-streams.
- Eliminate minor (small) coefficients.
- Multiply modified coefficients with Hadamard matrix to obtain the filtered bit-streams.

Spectral ATPG



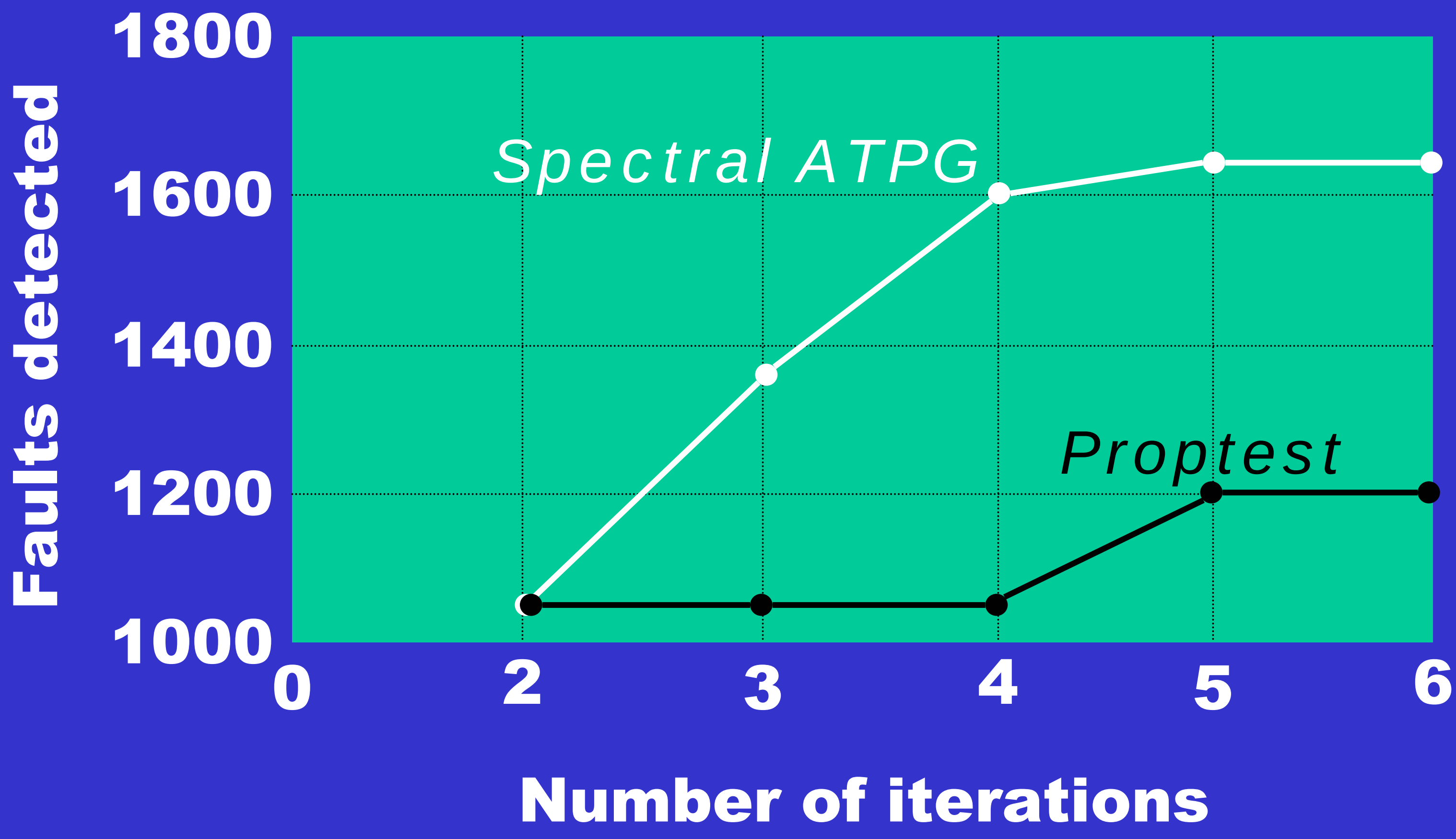
ATPG RESULTS

Circuit name	HITEC			Strategate			Proptest			Spectral ATPG		
	Det	vec	CPU s	Det	vec	CPU s	Det	vec	CPU s	Det	vec	CPU s
s5378	3231	912	1104	3639	11571	2268	3643	672	36	3643	734	44
b12	-	-	-	1488	33113	9659	1470	3697	28	1645	4464	24

Ref: Giani *et al.*, *DATE* **'02**

CPU: Ultra Sparc 10
HITEC: Nierman and Patel, *EDAC***'91**
Strategate: Hsiao et al., *ACMTDAES***'00**
Proptest: Guo et al., *DAC***'99**

ATPG for b12


1800
1600
1400
1200
1000
Faults detected
Spectral ATPG
Proptest
0
2
3
4
5
6
Number of iterations

Spectral Self-Test TPG

- Compute spectral coefficients for given test vectors.
- Save major coefficients.
- Generate tests by multiplying saved coefficients with Hadamard matrix.
- TPG may be implemented in software or hardware.

SOC Self-Test Application

Circuit name	Total faults	Detected faults: Weighted-random patterns Ideal	Detected faults: Weighted-random patterns Rounded	Detected faults: Spectral patterns
s5378	4603	3127	3083	3596
b12	3102	663	636	1621

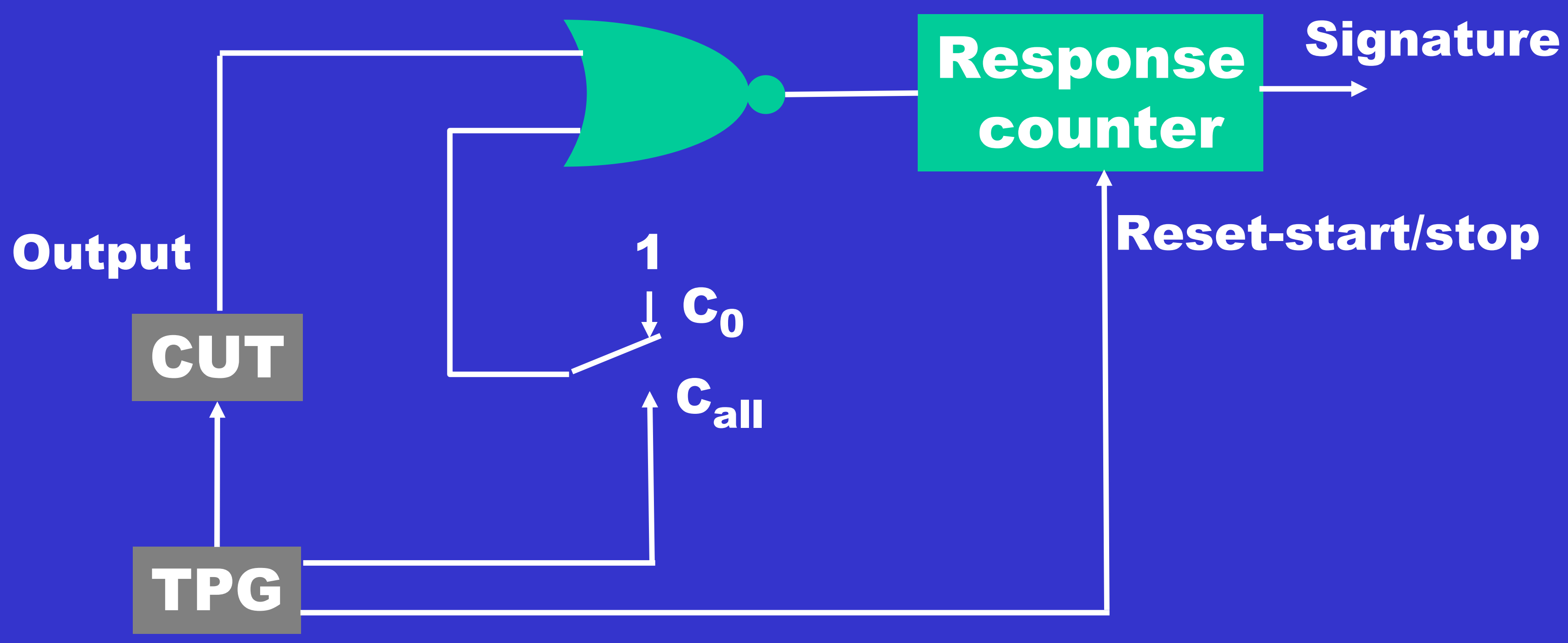
Ref: Giani et al., *VTS* **'01**

Number of patterns **= 70,000**

Self-Test Signature

- Susskind, FTCS ’81, IEEETC ’83
- Match Walsh coefficient of input vector with output.
- Compute number of times output matches minus #mismatches for
  - C_0 – first Walsh coefficient (counting 1’s or syndrome)
  - C_{all} – highest order Walsh coefficient, 0(1) for odd(even) number of zeros in the input vector

Susskind's Response Compactor



Matching Output to Tone

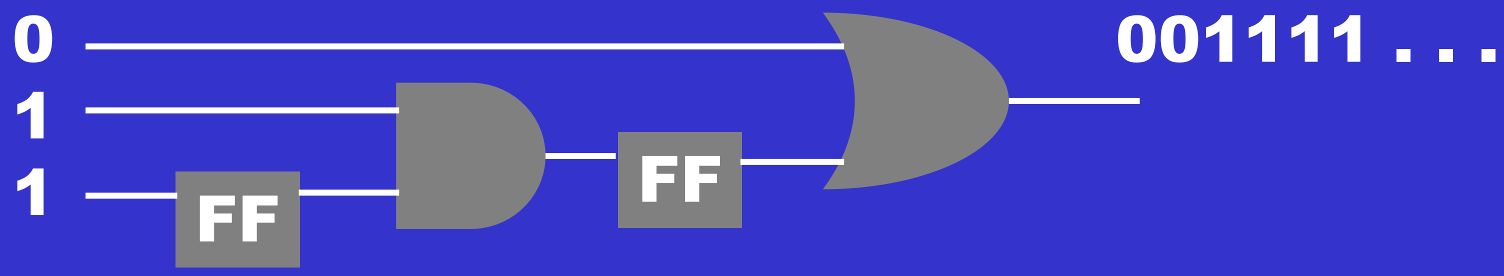
- Khan and Bushnell, ITC '04
- Susskind's C0 is DC, 111111 . . .
- Tones are:
  - 01010101010 . . .
  - 10101010101 . . .
  - 001100110011 . . .
  - 110011001100 . . .
  - . . . . .
- Empirical result: Zero aliasing in benchmark circuits when two tones are matched separately for each output.

Transfer Function

- Characterize digital circuit in frequency domain by a transfer function.

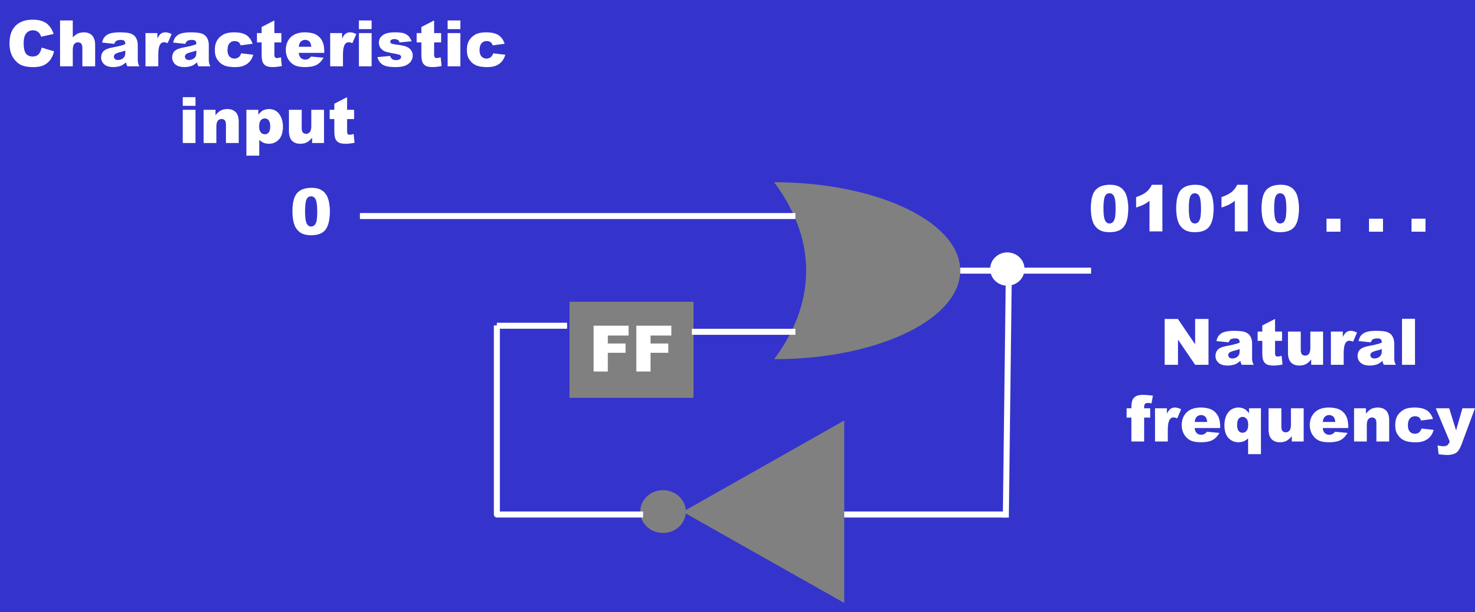
$$Y(\omega) = H(\omega)\,X(\omega)$$

Circuit 1: Non-Oscillatory Behavior



Non-oscillatory steady-state output is due to a feedback free structure.

Circuit 2: Oscillatory Behavior



Oscillatory steady-state output is due to the feedback structure.

Some Observations

- Feedback free circuit
  - Like simple filter. May pass some frequencies and block others.
  - Fixed inputs produce a transient output followed by a fixed steady state output.
  - Maximum duration of transient is determined by the sequential depth of the circuit.
  - Combinational circuit is similar.
  - Testing or verification may be possible by examining the pass and stop bands.
  - A complete characterization of transfer function may lead to new methods of synthesis.

More Observations

- Circuit with feedback
  - Like a complex filter may pass some frequencies and block others.
  - Fixed input can produce either a transient or oscillatory (natural frequency) output (poles in the transfer function?)
  - Fixed inputs (characteristic vectors) that produce output oscillation may have test and verification significance.
  - Natural frequencies can be determined from the lengths of feedback cycles.

Conclusion

- A vector sequence is efficiently represented by its spectral coefficients.
- Spectral analysis is useful in ATPG and BIST.
- Spectral TPG synthesis is an open problem.
- A digital circuit is a filter:
  - Output spectrum for random inputs is the impulse response.
  - Analysis of impulse response may lead to suitable input spectrum for test and verification.
  - Useful (?) characteristics are natural or resonance frequencies, characteristic vectors, transient behavior.