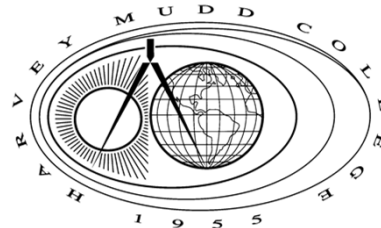


# Introduction to CMOS VLSI Design

## Lecture 17: Design for Testability

David Harris



Harvey Mudd College

Spring 2004

# Outline

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- ❑ Testing
  - Logic Verification
  - Silicon Debug
  - Manufacturing Test
- ❑ Fault Models
- ❑ Observability and Controllability
- ❑ Design for Test
  - Scan
  - BIST
- ❑ Boundary Scan

# Testing

- ❑ Testing is one of the most expensive parts of chips
  - Logic verification accounts for > 50% of design effort for many chips
  - Debug time after fabrication has enormous opportunity cost
  - Shipping defective parts can sink a company
  
- ❑ Example: Intel FDIV bug
  - Logic error not caught until > 1M units shipped
  - Recall cost \$450M (!!!)

# Logic Verification

- ❑ Does the chip simulate correctly?
  - Usually done at HDL level
  - Verification engineers write test bench for HDL
    - Can't test all cases
    - Look for corner cases
    - Try to break logic design
- ❑ Ex: 32-bit adder
  - Test all combinations of corner cases as inputs:
    - 0, 1, 2,  $2^{31}-1$ , -1,  $-2^{31}$ , a few random numbers
- ❑ Good tests require ingenuity

# Silicon Debug

- ❑ Test the first chips back from fabrication
  - If you are lucky, they work the first time
  - If not...
- ❑ Logic bugs vs. electrical failures
  - Most chip failures are logic bugs from inadequate simulation
  - Some are electrical failures
    - Crosstalk
    - Dynamic nodes: leakage, charge sharing
    - Ratio failures
  - A few are tool or methodology failures (e.g. DRC)
- ❑ Fix the bugs and fabricate a corrected chip

# Shmoo Plots

## ❑ How to diagnose failures?

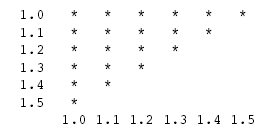
- Hard to access chips
  - Picoprobes
  - Electron beam
  - Laser voltage probing
  - Built-in self-test

## ❑ Shmoo plots

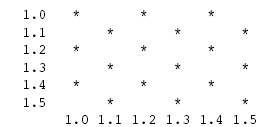
- Vary voltage, frequency
- Look for cause of electrical failures

*Clock period in ns on the left, frequency increases going up  
Voltage on the bottom, increase left to right*

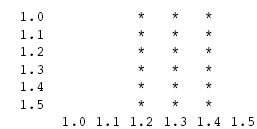
*\* indicates a failure*



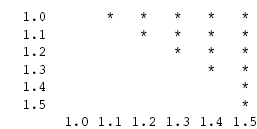
Normal  
Well-behaved shmoo  
Typical Speedpath



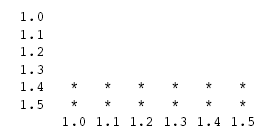
"Brick Wall"



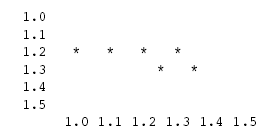
"Wall"  
Fails at a certain voltage



"Reverse speedpath"  
Increase in voltage reduces frequency



"Floor"  
Works at high but not low frequency



"Finger"  
Fails at a specific point in the shmoo

# Shmoo Plots

## ❑ How to diagnose failures?

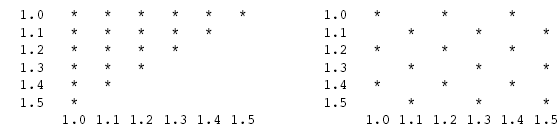
- Hard to access chips
  - Picoprobes
  - Electron beam
  - Laser voltage probing
  - Built-in self-test

## ❑ Shmoo plots

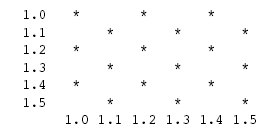
- Vary voltage, frequency
- Look for cause of electrical failures

*Clock period in ns on the left, frequency increases going up  
Voltage on the bottom, increase left to right*

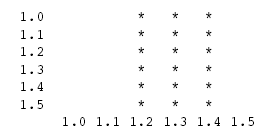
*\* indicates a failure*



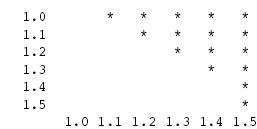
Normal  
Well-behaved shmoo  
Typical Speedpath



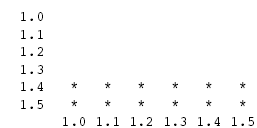
“Brick Wall”  
Bistable  
Initialization



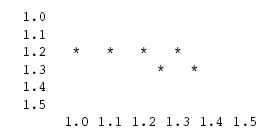
“Wall”  
Fails at a certain voltage  
Coupling, charge share, races



“Reverse speedpath”  
Increase in voltage reduces frequency  
Speedpath, leakage



“Floor”  
Works at high but not low frequency  
Leakage



“Finger”  
Fails at a specific point in the shmoo  
Coupling

# Manufacturing Test

- ❑ A speck of dust on a wafer is sufficient to kill chip
- ❑ *Yield* of any chip is  $< 100\%$ 
  - Must test chips after manufacturing before delivery to customers to only ship good parts
- ❑ Manufacturing testers are very expensive
  - Minimize time on tester
  - Careful selection of *test vectors*





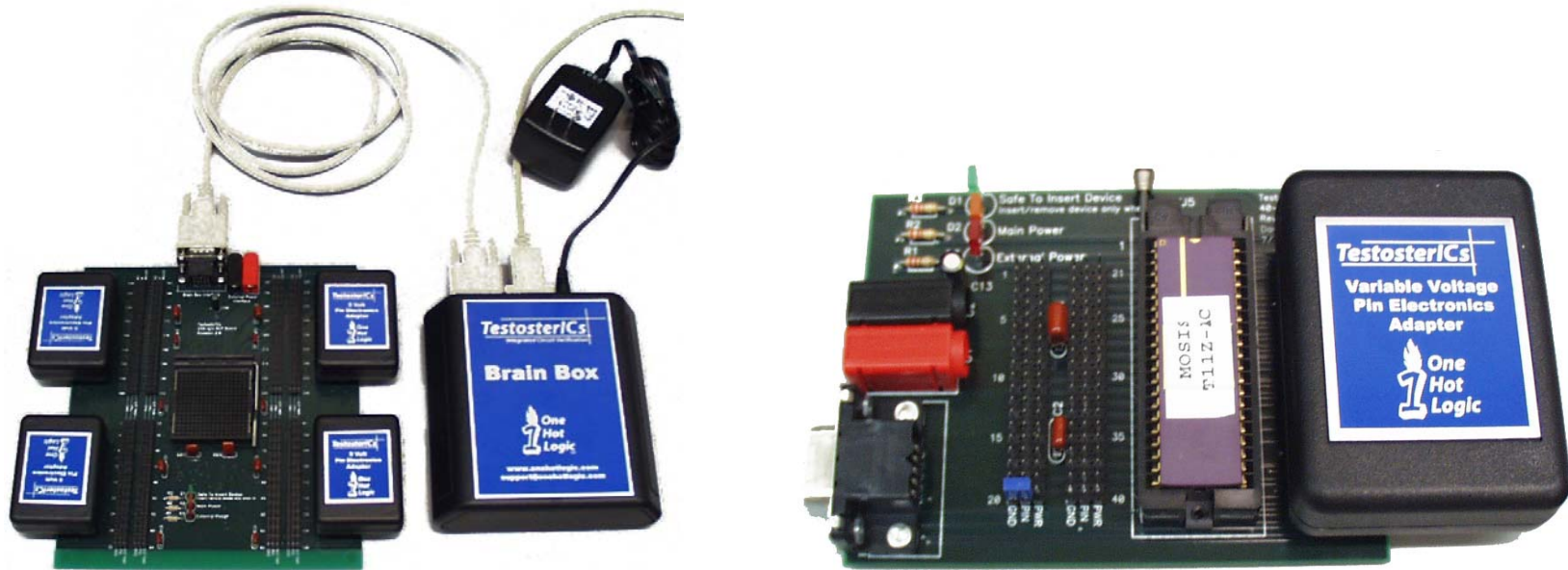
# Testing Your Chips

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- ❑ If you don't have a multimillion dollar tester:
  - Build a breadboard with LED's and switches
  - Hook up a logic analyzer and pattern generator
  - Or use a low-cost functional chip tester

# TestosterICs

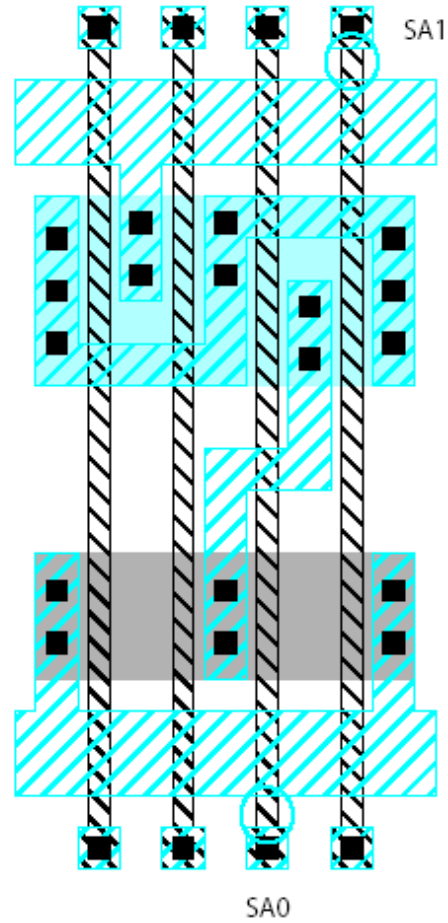
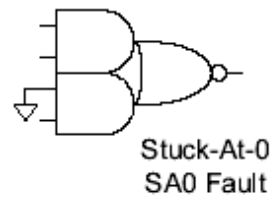
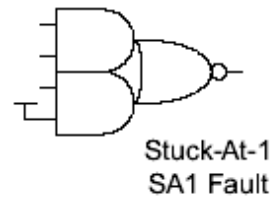
- ❑ Ex: TestosterICs functional chip tester
  - Designed by clinic teams and David Diaz at HMC
  - Reads your IRSIM test vectors, applies them to your chip, and reports assertion failures



# Stuck-At Faults

- How does a chip fail?
  - Usually failures are shorts between two conductors or opens in a conductor
  - This can cause very complicated behavior
- A simpler model: *Stuck-At*
  - Assume all failures cause nodes to be “stuck-at” 0 or 1, i.e. shorted to GND or  $V_{DD}$
  - Not quite true, but works well in practice

# Examples



# Observability & Controllability

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- ❑ *Observability*: ease of observing a node by watching external output pins of the chip
- ❑ *Controllability*: ease of forcing a node to 0 or 1 by driving input pins of the chip
  
- ❑ Combinational logic is usually easy to observe and control
- ❑ Finite state machines can be very difficult, requiring many cycles to enter desired state
  - Especially if state transition diagram is not known to the test engineer

# Test Pattern Generation

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- ❑ Manufacturing test ideally would check every node in the circuit to prove it is not stuck.
- ❑ Apply the smallest sequence of test vectors necessary to prove each node is not stuck.
- ❑ Good observability and controllability reduces number of test vectors required for manufacturing test.
  - Reduces the cost of testing
  - Motivates design-for-test

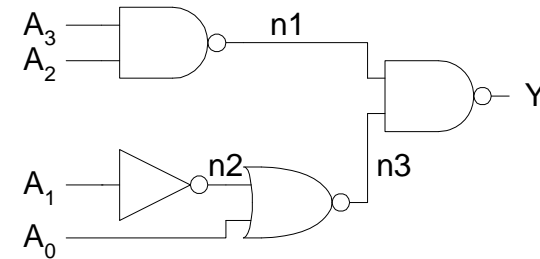
# Test Example

SA1

SA0

- $A_3$
- $A_2$
- $A_1$
- $A_0$
- $n1$
- $n2$
- $n3$
- $Y$

- Minimum set:

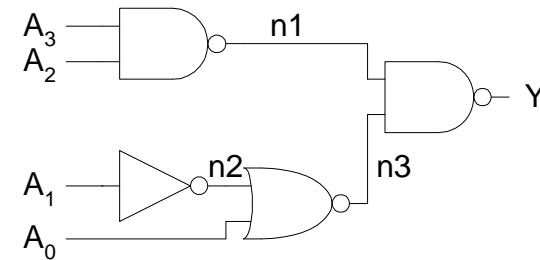


# Test Example

- $A_3$
- $A_2$
- $A_1$
- $A_0$
- $n1$
- $n2$
- $n3$
- $Y$

SA1  
{0110}

SA0  
{1110}

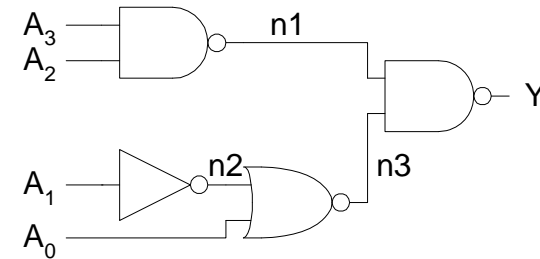


- Minimum set:



# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$		
<input type="checkbox"/> $A_0$		
<input type="checkbox"/> n1		
<input type="checkbox"/> n2		
<input type="checkbox"/> n3		
<input type="checkbox"/> Y		

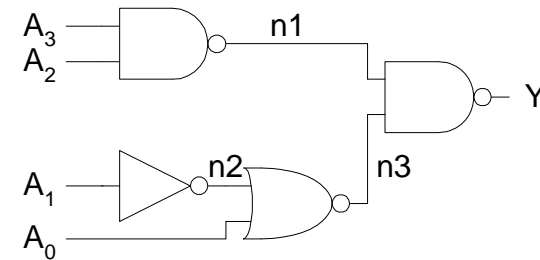


Minimum set:

# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$		
<input type="checkbox"/> n1		
<input type="checkbox"/> n2		
<input type="checkbox"/> n3		
<input type="checkbox"/> Y		

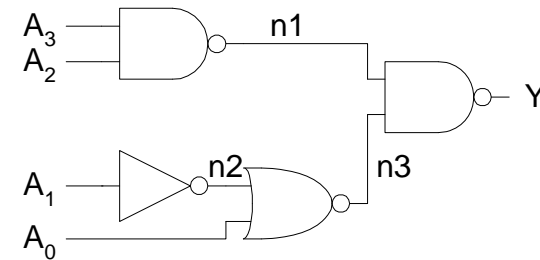
Minimum set:



# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$	{0110}	{0111}
<input type="checkbox"/> n1		
<input type="checkbox"/> n2		
<input type="checkbox"/> n3		
<input type="checkbox"/> Y		

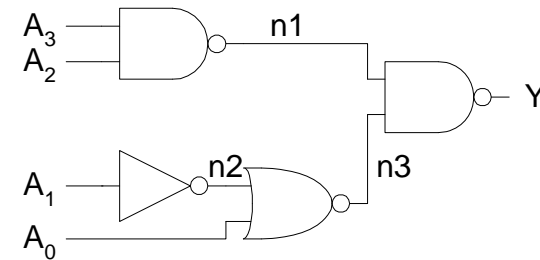
Minimum set:



# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$	{0110}	{0111}
<input type="checkbox"/> n1	{1110}	{0110}
<input type="checkbox"/> n2		
<input type="checkbox"/> n3		
<input type="checkbox"/> Y		

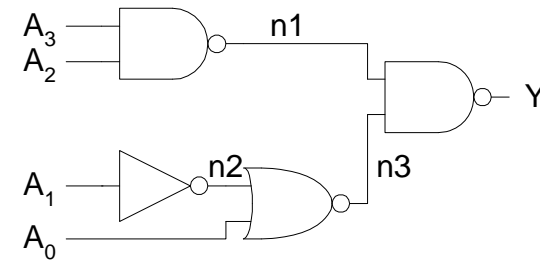
Minimum set:



# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$	{0110}	{0111}
<input type="checkbox"/> n1	{1110}	{0110}
<input type="checkbox"/> n2	{0110}	{0100}
<input type="checkbox"/> n3		
<input type="checkbox"/> Y		

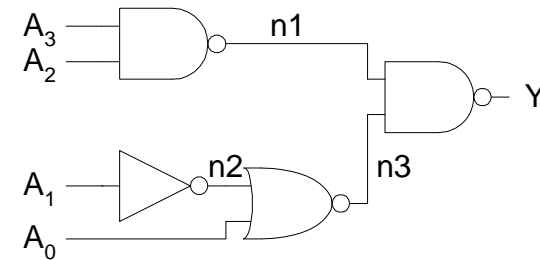
Minimum set:



# Test Example

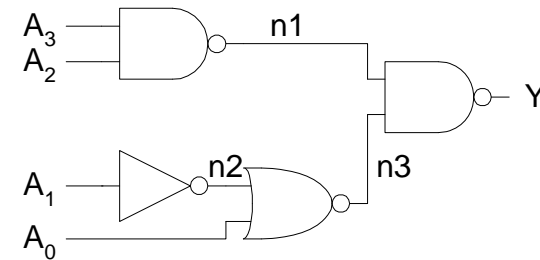
	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$	{0110}	{0111}
<input type="checkbox"/> n1	{1110}	{0110}
<input type="checkbox"/> n2	{0110}	{0100}
<input type="checkbox"/> n3	{0101}	{0110}
<input type="checkbox"/> Y		

Minimum set:



# Test Example

	SA1	SA0
<input type="checkbox"/> $A_3$	{0110}	{1110}
<input type="checkbox"/> $A_2$	{1010}	{1110}
<input type="checkbox"/> $A_1$	{0100}	{0110}
<input type="checkbox"/> $A_0$	{0110}	{0111}
<input type="checkbox"/> $n1$	{1110}	{0110}
<input type="checkbox"/> $n2$	{0110}	{0100}
<input type="checkbox"/> $n3$	{0101}	{0110}
<input type="checkbox"/> $Y$	{0110}	{1110}



- Minimum set: {0100, 0101, 0110, 0111, 1010, 1110}

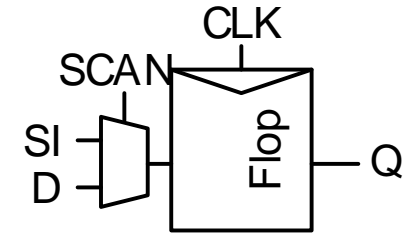
# Design for Test

- ❑ Design the chip to increase observability and controllability
- ❑ If each register could be observed and controlled, test problem reduces to testing combinational logic between registers.
- ❑ Better yet, logic blocks could enter test mode where they generate test patterns and report the results automatically.

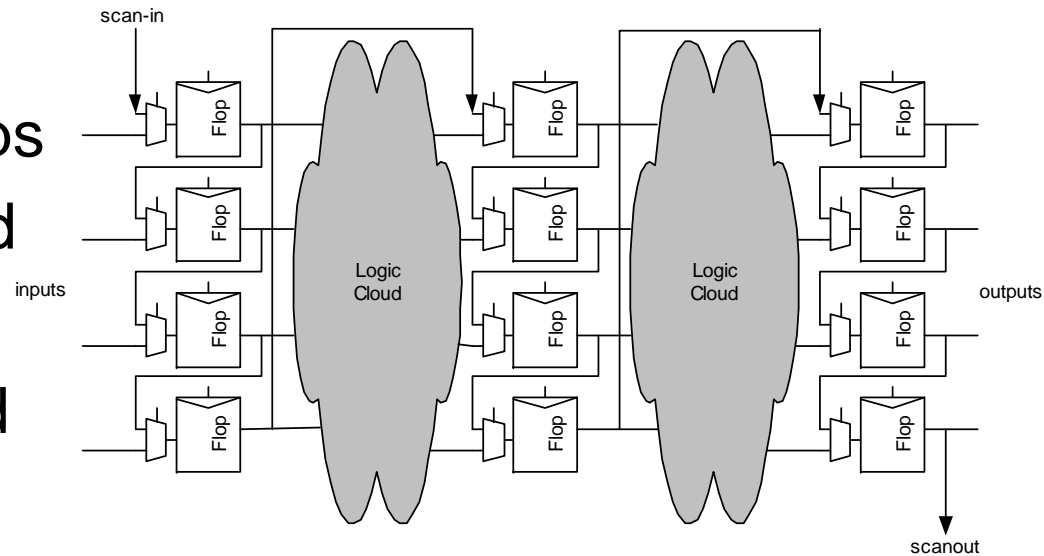


# Scan

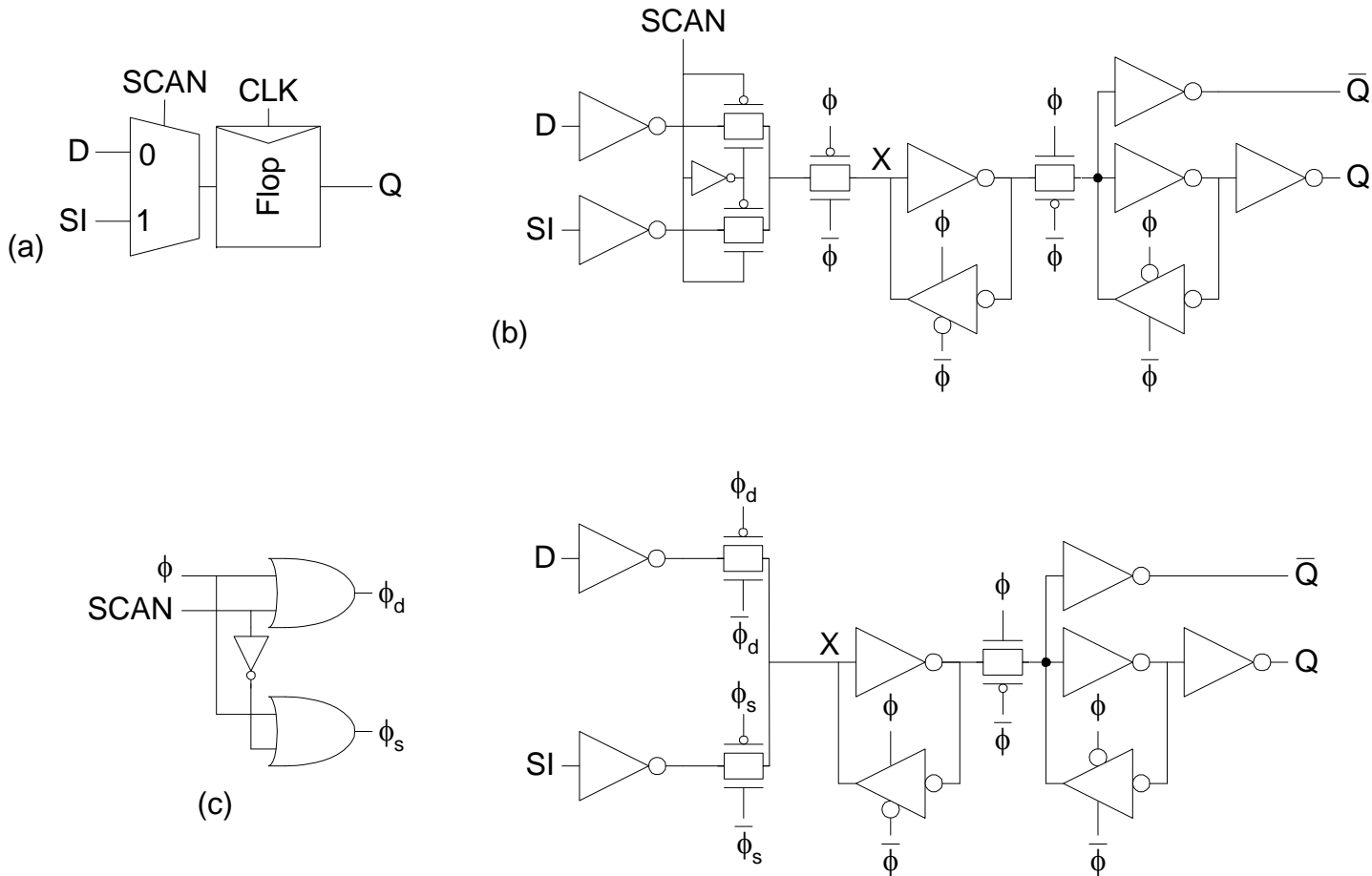
- ❑ Convert each flip-flop to a scan register
  - Only costs one extra multiplexer
- ❑ Normal mode: flip-flops behave as usual
- ❑ Scan mode: flip-flops behave as shift register



- ❑ Contents of flops can be scanned out and new values scanned in



# Scannable Flip-flops



# Built-in Self-test

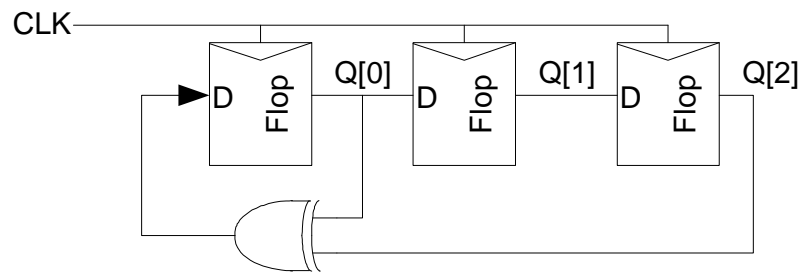
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- ❑ Built-in self-test lets blocks test themselves
  - Generate pseudo-random inputs to comb. logic
  - Combine outputs into a *syndrome*
  - With high probability, block is fault-free if it produces the expected syndrome

# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

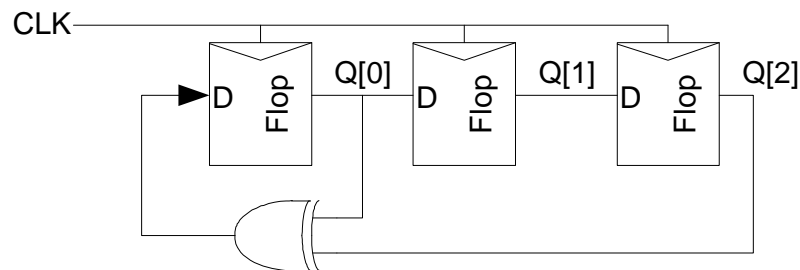


Step	Q
0	111
1	
2	
3	
4	
5	
6	
7	

# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

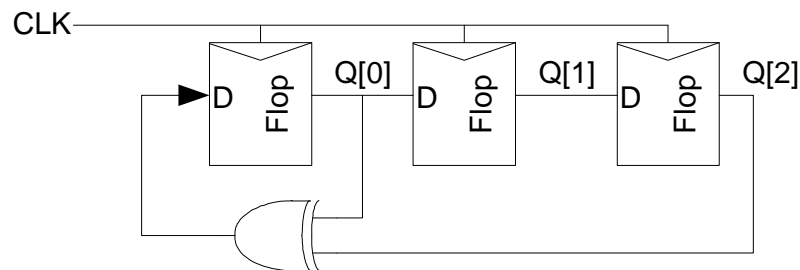


Step	Q
0	111
1	110
2	
3	
4	
5	
6	
7	

# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

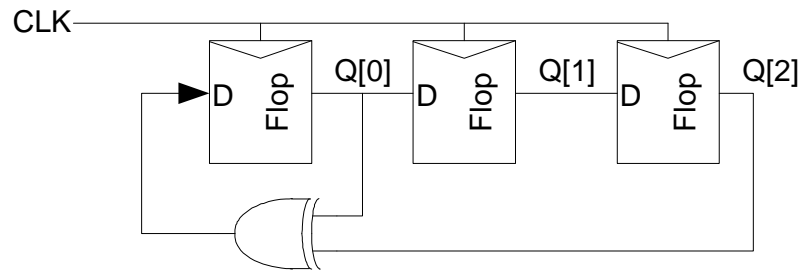


Step	Q
0	111
1	110
2	101
3	
4	
5	
6	
7	

# PRSG

## □ Linear Feedback Shift Register

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

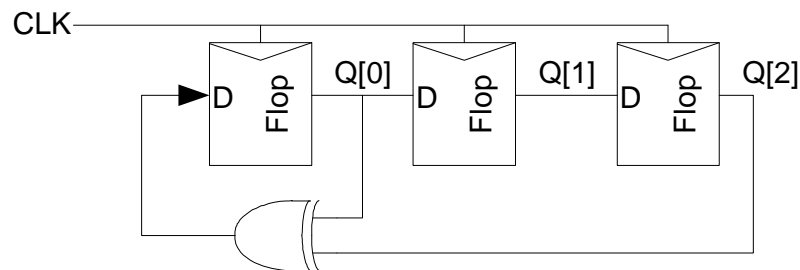


Step	Q
0	111
1	110
2	101
3	010
4	
5	
6	
7	

# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*



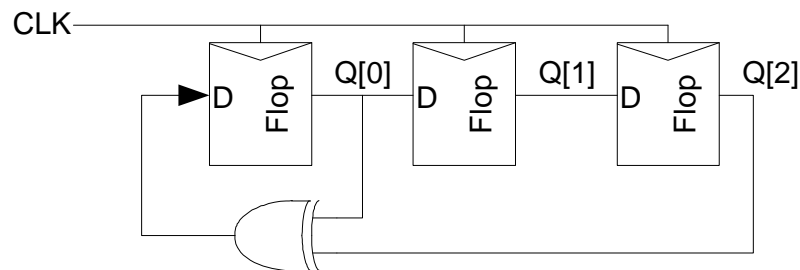
Step	Q
0	111
1	110
2	101
3	010
4	100
5	
6	
7	



# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

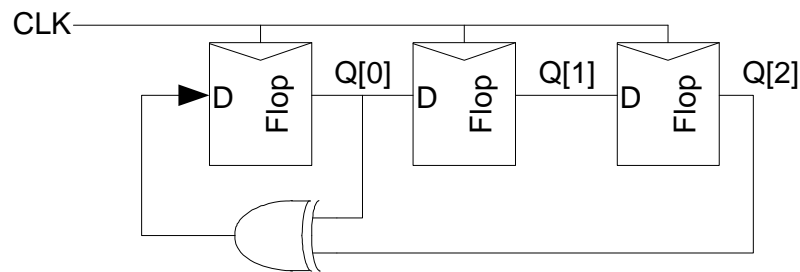


Step	Q
0	111
1	110
2	101
3	010
4	100
5	001
6	
7	

# PRSG

## ❑ *Linear Feedback Shift Register*

- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*

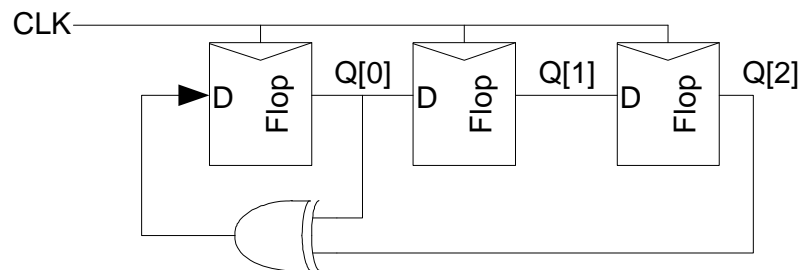


Step	Q
0	111
1	110
2	101
3	010
4	100
5	001
6	011
7	

# PRSG

## ❑ *Linear Feedback Shift Register*

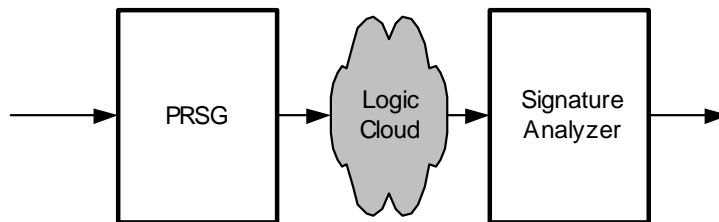
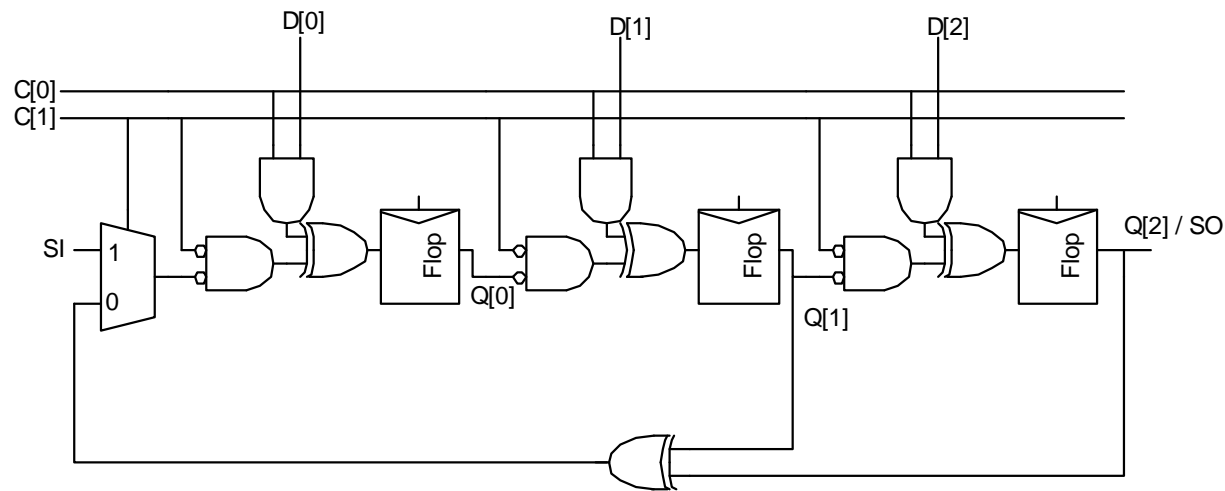
- Shift register with input taken from XOR of state
- *Pseudo-Random Sequence Generator*



Step	Q
0	111
1	110
2	101
3	010
4	100
5	001
6	011
7	111 (repeats)

# BILBO

- Built-in Logic Block Observer
  - Combine scan with PRSG & signature analysis

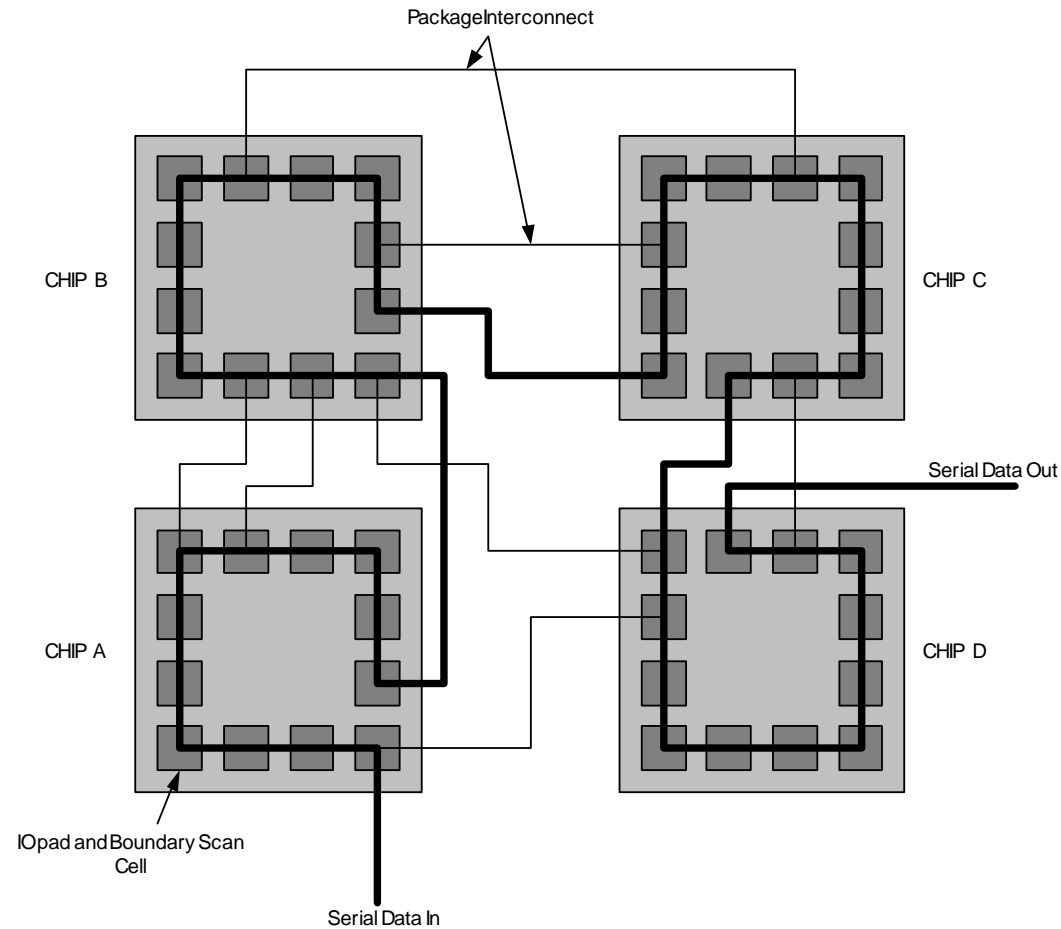


MODE	C[1]	C[0]
Scan	0	0
Test	0	1
Reset	1	0
Normal	1	1

# Boundary Scan

- ❑ Testing boards is also difficult
  - Need to verify solder joints are good
    - Drive a pin to 0, then to 1
    - Check that all connected pins get the values
- ❑ Through-hole boards used “bed of nails”
- ❑ SMT and BGA boards cannot easily contact pins
- ❑ Build capability of observing and controlling pins into each chip to make board test easier

# Boundary Scan Example



# Boundary Scan Interface

- ❑ Boundary scan is accessed through five pins
  - TCK: test clock
  - TMS: test mode select
  - TDI: test data in
  - TDO: test data out
  - TRST\*: test reset (optional)
  
- ❑ Chips with internal scan chains can access the chains through boundary scan for unified test strategy.

# Summary

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- ❑ Think about testing from the beginning
  - Simulate as you go
  - Plan for test after fabrication
  
- ❑ “If you don’t test it, it won’t work! (Guaranteed)”