

DIGITAL SYSTEM TESTING COE -545

Lecture – 08

Testability Measures

Objective

- Regrettably, Decisions in the D-ALG are *Arbitrary*
- **PODEM** Uses the Testability of Nodes to help Choose among alternative Choices.
- *Derive* an *Approximate Measure* Of How Easy/Hard it is to Test a Given CUT
- **Usage:**
 - Analyze the Difficulty of Testing a given CUT → *Redesign or Add Special Test Hardware*
 - Guidance for Algorithms Computing Test Patterns → *Make Better Informed Decisions in the D-Drive and Line-Justification Steps*
 - Estimation of Fault Coverage
 - Estimation of Test Vector Length

Testability Measures

- Generally 2 Measures are Used:
 1. Controllability (CY), and
 2. Observability (OY),
- No Agreed-Upon Standard for measuring CY or OY {SCOAP, CAMELOT, VICTOR, etc.}

Controllability (CY):

Defined for Both Logic 1 & 0; as a measure for the Ability to Control the State of a Given Line (node) from PIs → Thus, Every Line Has a 1-Controllability and a 0-Controllability

Observability (OY):

A measure of the Ease/Difficulty with which the State of a given Line can be Observed at one or more PO

- CY & OY May be Normalized Between 0 & 1.

Testability Analysis

- Involves Circuit *Topological analysis*, but no test vectors and *no search* algorithm
 - *Static analysis*
- **Linear** computational complexity
 - Otherwise, is pointless – might as well use automatic test-pattern generation and calculate:
 - Exact fault coverage
 - Exact test vectors

SCOAP – Sandia Controllability and Observability Analysis Program

- Computes Combinational & Sequential CY & OY
- Combinational measures:
 - *CC0* – Difficulty of setting circuit line to logic 0
 - *CC1* – Difficulty of setting circuit line to logic 1
 - *CO* – Difficulty of observing a circuit line
- Sequential measures – analogous:
 - *SC0*
 - *SC1*
 - *SO*

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Range of SCOAP Measures

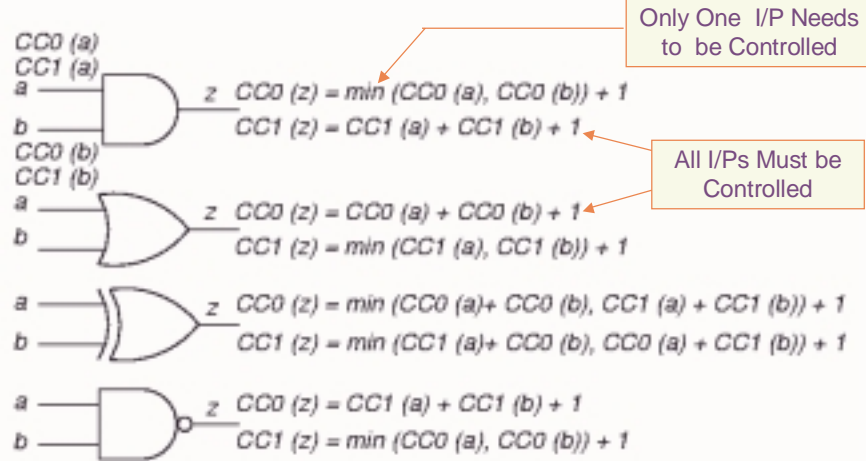
- Each Line is Assigned Controllability & Observability *Numeric* Values
- **Controllability** – **1** (easiest to control) to **infinity** (**hardest**)
- **Observability** – **0** (easiest to observe) to **infinity** (**hardest**)
- Combinational measures:
 - Roughly Proportional to # Circuit Lines that must be Set to Control or Observe the Given Line
 - Line Controllabilities are Computed **Starting** at the **PIs** moving *Forward* to **POs**
 - Line Observabilities are Computed **Starting** at the **POs** moving *Backwards* to **PIs**
- Sequential measures:
 - Roughly proportional to # times a flip-flop must be clocked to control or observe given line

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Controllability Examples

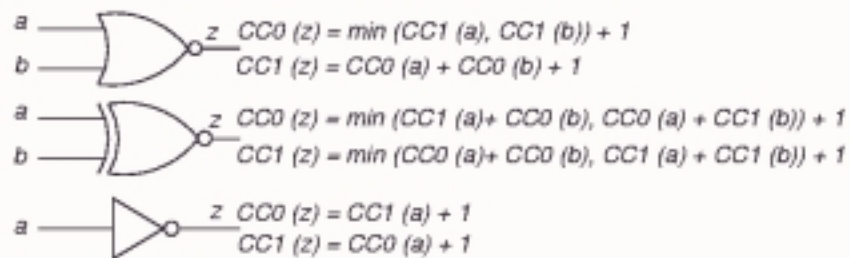


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Controllability Examples (Contd)



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Observability Examples

To observe a gate input: *Observe output and make other input values non-controlling*

$$CO(a) = CO(z) + CC1(b) + 1$$

$$CO(b) = CO(z) + CC1(a) + 1$$

$$CO(a) = CO(z) + CC0(b) + 1$$

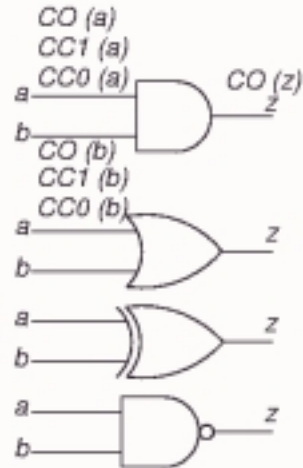
$$CO(b) = CO(z) + CC0(a) + 1$$

$$CO(a) = CO(z) + \min(CC0(b), CC1(b)) + 1$$

$$CO(b) = CO(z) + \min(CC0(a), CC1(a)) + 1$$

$$CO(a) = CO(z) + CC1(b) + 1$$

$$CO(b) = CO(z) + CC1(a) + 1$$



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More Observability Examples

To observe a *fanout stems*:

Observe it through branch with best observability

$$CO(a) = CO(z) + CC0(b) + 1$$

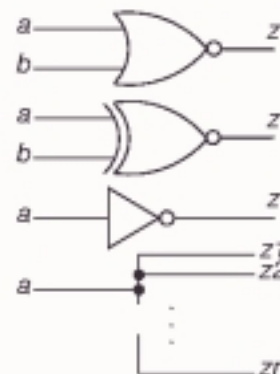
$$CO(b) = CO(z) + CC0(a) + 1$$

$$CO(a) = CO(z) + \min(CC0(b), CC1(b)) + 1$$

$$CO(b) = CO(z) + \min(CC0(a), CC1(a)) + 1$$

$$CO(a) = CO(z) + 1$$

$$CO(a) = \min(CO(z1), CO(z2), \dots, CO(zn))$$



Min → Independent Branches
Max → Dependent Branches

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Goldstein's SCOAP Measures

- **AND gate 0-Controllability:**

$$\text{Output_Controllability} = \text{Min} (\text{Input_Controllability}) + 1$$
- **AND gate 1-Controllability:**

$$\text{Output_Controllability} = \Sigma (\text{Input_Controllability}) + 1$$

- **XOR gate O/P Controllability**

$$\text{Output_Controllability} = \text{min} (\text{controllabilities of each input set}) + 1$$

- **Fanout Stem Observability:**

$$\Sigma \text{ or min (some or all fanout branch observabilities)}$$

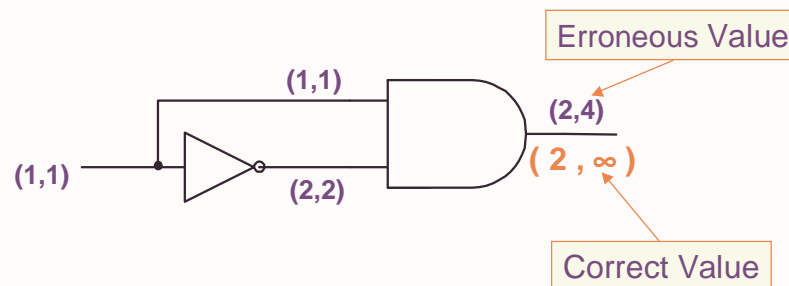
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Error Due to Stems & Reconverging Fanouts

SCOAP measures Incorrectly Computes Controllabilities
 Assuming that Fanout Branches to Be Independent →
 Untrue for Reconvergent Branches



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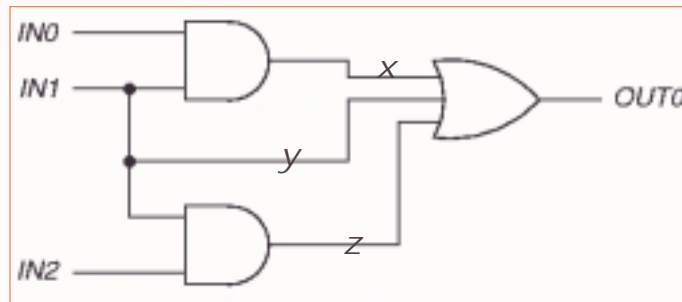
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Error Due to Stems & Reconverging Fanouts

SCOAP measures Incorrectly assume that controlling or observing x, y, z are *independent* events

- $CC0(x), CC0(y), CC0(z)$ correlate
- $CC1(x), CC1(y), CC1(z)$ correlate
- $CO(x), CO(y), CO(z)$ correlate



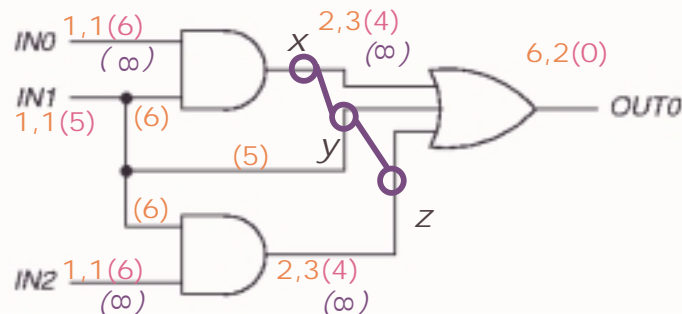
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Correlation Error Example

- **Exact** computation of measures is NP-Complete and impractical
- SCOAP measures are in red or bold $CC0, CC1 (CO)$ -- Italicized (Blue) measures show correct values



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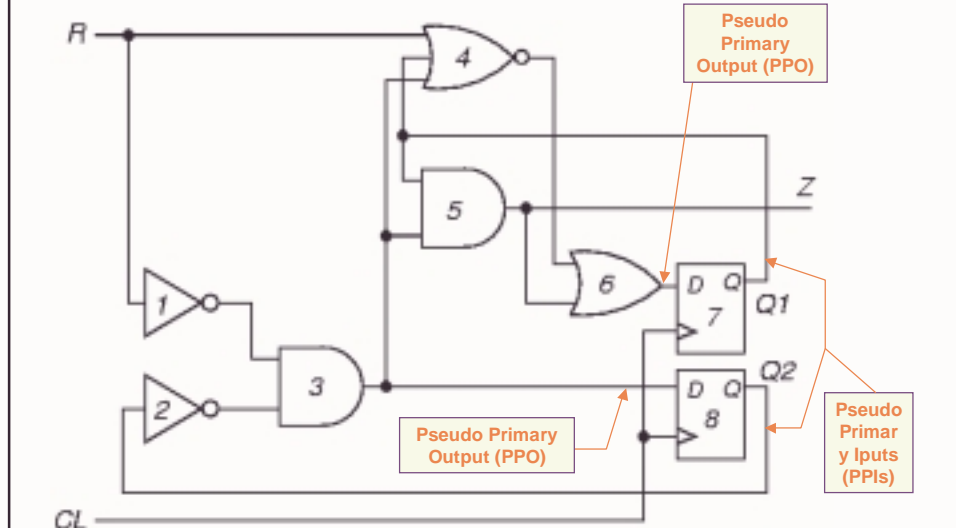
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Sequential Example

Assumption: Fully Controllable (Scannable) FFs→

- FF Inputs → Pseudo POs of Combinational Logic
- FF Outputs → Pseudo PIs for Combinational Logic



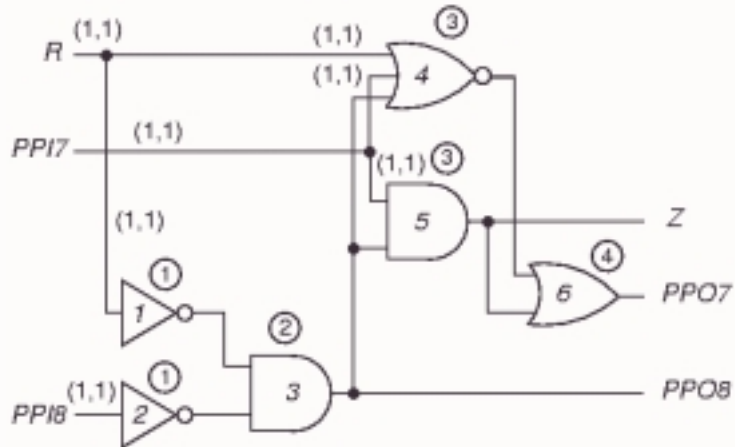
Levelization Algorithm 6.1

- **Label** each gate with max # of logic levels from primary inputs or with max # of logic levels from primary output
- **Assign** level # 0 to all *primary inputs* (PIs)
- **For each PI fanout:**
 - Label that line with the PI level number, &
 - Queue logic gate driven by that fanout
- **While queue is not empty:**
 - Dequeue the next logic gate
 - **IF** all gate inputs have level #'s,
 - label the gate with the highest of them + 1;
 - Label O/P Line & its Fanout Lines with the same level number, &
 - Queue logic gates driven by the fanout lines
 - **Else**, requeue the gate

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Controllability Through Level 0

Circled numbers → level number.
Parenthesized Numbers → (CC0, CC1)

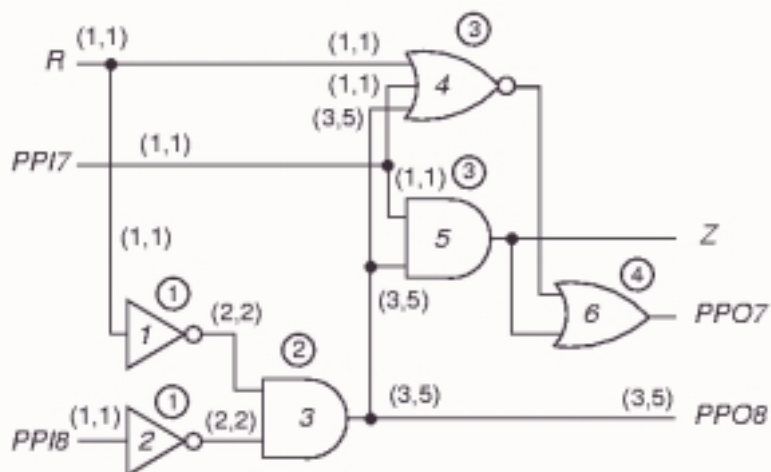


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Controllability Through Level 2

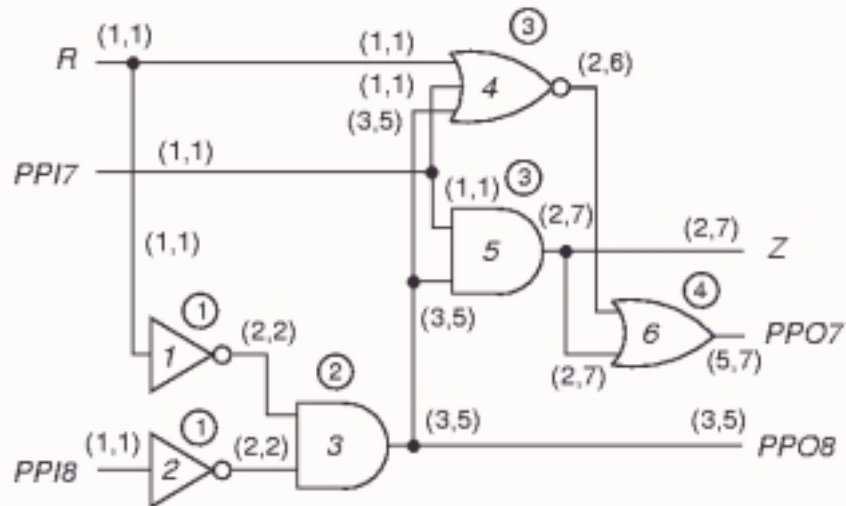


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Final Combinational Controllability



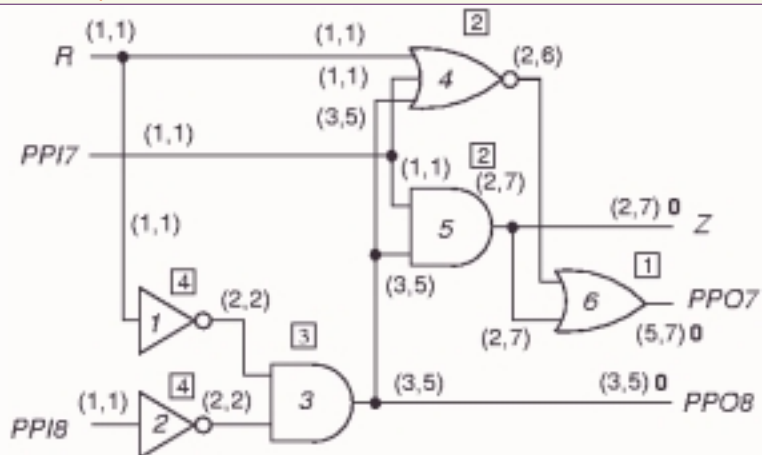
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Combinational Observability for Level 1

Number in square box → level from *primary outputs* (POs).
(CC0, CC1) CO

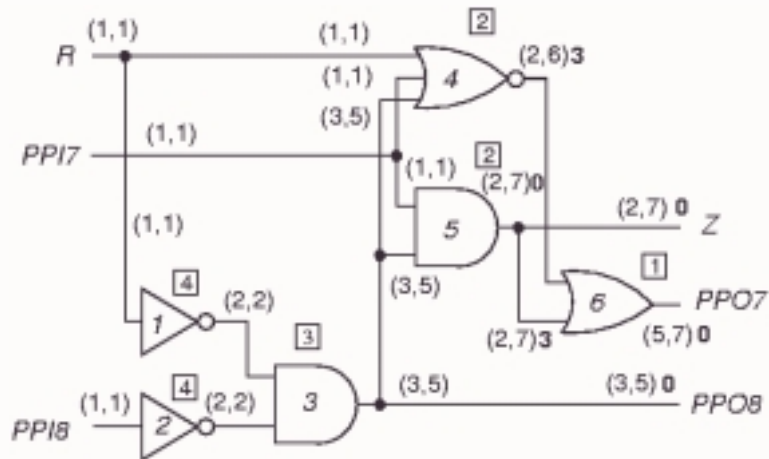


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Combinational Observabilities for Level 2

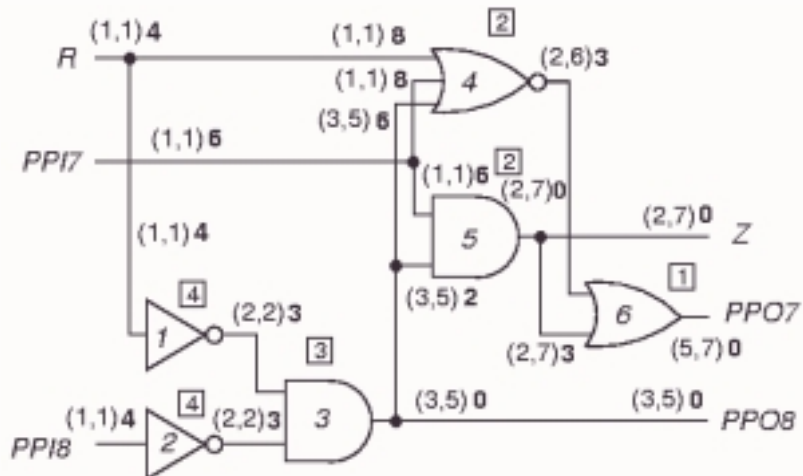


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Final Combinational Observabilities



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Sequential Measure Differences

- **Combinational**
 - **Increment** $CC0$, $CC1$, CO when **passing through a Gate**, either forwards (Controllability) or backwards (Observability)
 - CCi , CO *are not incremented when passing through FFs*, ($CC0(Q)$, $CC1(Q)$, $CO(D)$) either forwards or backwards
- **Sequential**
 - **Increment** SCi , SO only when **Passing through a FF**, either forwards or backwards, to Q , \bar{Q} , D , C , SET , or $RESET$
 - SCi & SO *are not incremented when passing through Combinational Gates*, either forwards or backwards.
- **Both**
 - Must iterate on feedback loops until controllabilities stabilize

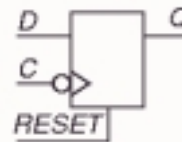
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D Flip-Flop Equations

- **Assume a Synchronous RESET line.**
- $CC1(Q) = CC1(D) + CC1(C) + CC0(C) + CC0(RESET)$
- $SC1(Q) = SC1(D) + SC1(C) + SC0(C) + SC0(RESET) + 1$
- $CC0(Q) = \min \{ CC1(RESET) + CC1(C) + CC0(C), CC0(D) + CC1(C) + CC0(C) \}$
- $SC0(Q) = \min \{ SC1(RESET) + SC1(C) + SC0(C), SC0(D) + SC1(C) + SC0(C) \} + 1$
- $CO(D) = CO(Q) + CC1(C) + CC0(C) + CC0(RESET)$
- $SO(D) = SO(Q) + SC1(C) + SC0(C) + SC0(RESET) + 1$



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D Flip-Flop Clock and Reset

- $CO(RESET) = CO(Q) + CCI(Q) + CCI(RESET) + CCI(C) + CC0(C)$
- $SO(RESET) = SO(Q) + SCI(Q) + SCI(RESET) + SCI(C) + SC0(C) + 1$
- **Three ways to observe the clock line:**
 1. Set Q to 1 and clock in a 0 from D
 2. Set the flip-flop and then reset it
 3. Reset the flip-flop and clock in a 1 from D
- $CO(C) = \min \{ CO(Q) + CCI(Q) + CC0(D) + CCI(C) + CC0(C), CO(Q) + CCI(Q) + CCI(RESET) + CCI(C) + CC0(C), CO(Q) + CC0(Q) + CC0(RESET) + CCI(D) + CCI(C) + CC0(C) \}$
- $SO(C) = \text{Similar to } CO(C) + 1$

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Algorithm: Testability Computation

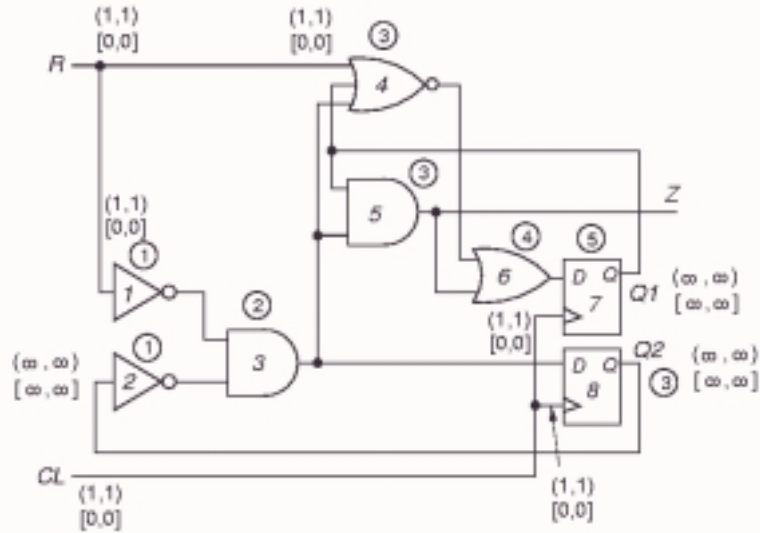
1. For all **PIs**, $CC0 = CCI = 1$ and $SC0 = SCI = 0$
2. Initialize all other nodes, $CC0 = CCI = SC0 = SCI = \infty$
3. Go from **PIs** to **POs**, using CC and SC equations to get controllabilities -- *Iterate* on loops *until SC stabilizes* → Convergence Guaranteed {Monotonically Decreasing Values, (initially ∞)} → 2-3 Iterations are Typical.
4. For all **POs**, set $CO = SO = 0$, For **Other Nodes** $CO=SO=\infty$
5. Work from **POs** to **PIs**, Use CO , SO , and *Precomputed controllabilities* to map O/P Node Observabilities of Gates & FFS into I/P observabilities
6. Fanout stem $(CO, SO) = \min \{ \text{branch } (CO, SO) \}$
7. If a CC or SC (CO or SO) is ∞ , that node is uncontrollable or unobservable.

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Sequential Example Initialization

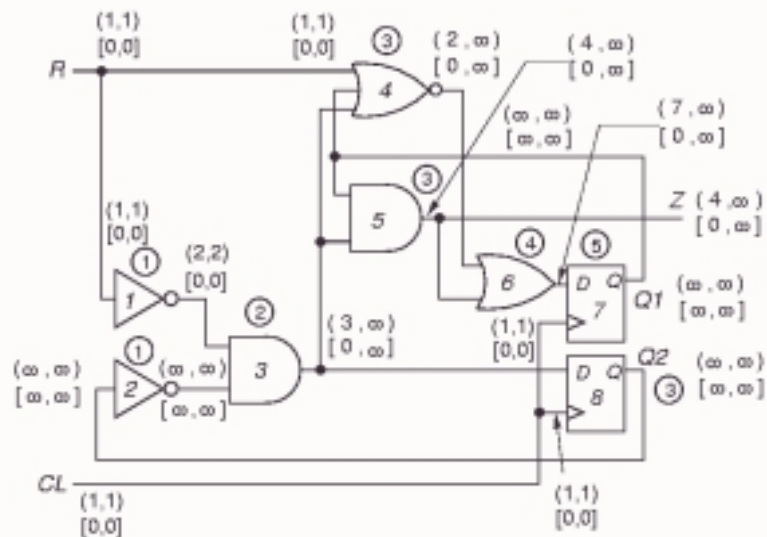


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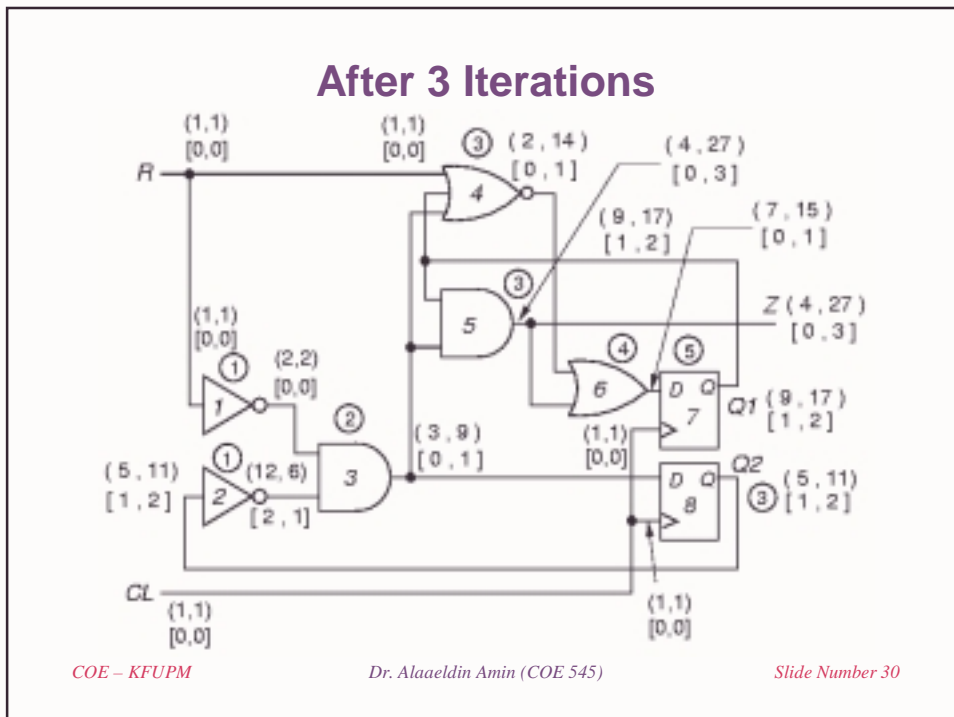
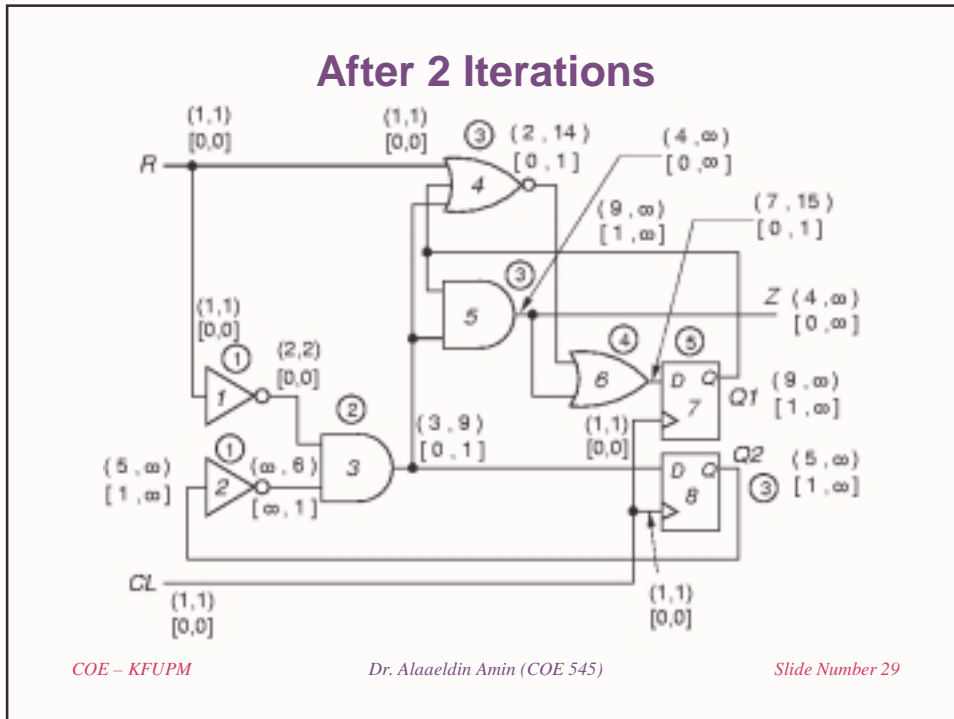
After 1 Iteration



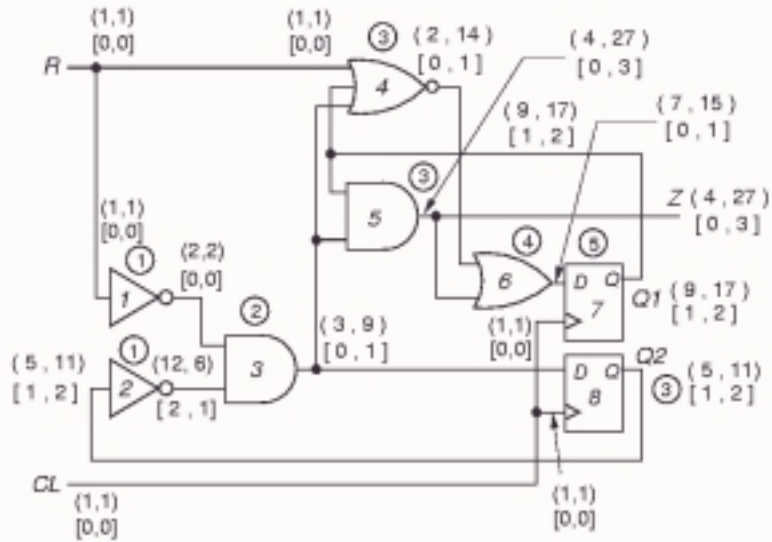
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Stable Sequential Measures

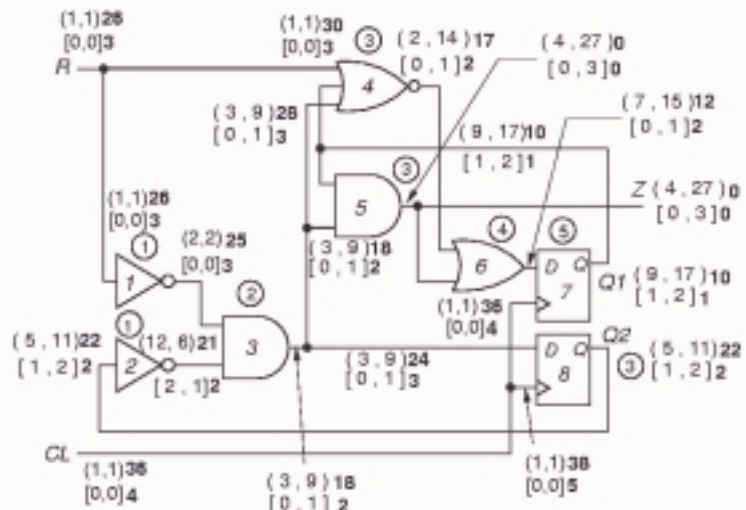


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Final Sequential Observabilities



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Test Vector Length Prediction

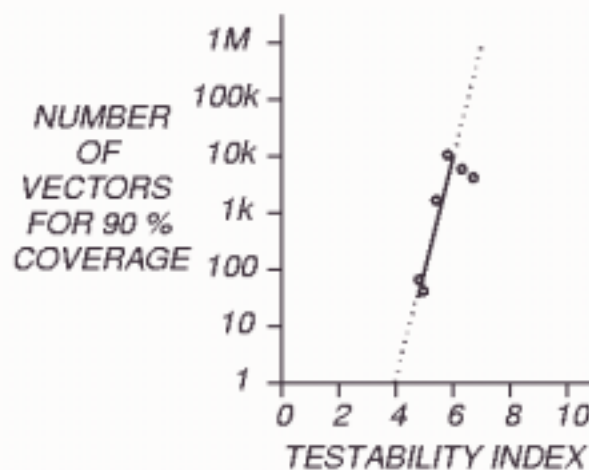
- **Testability for node x stuck-at faults**
 - $T(x_{sa_0}) = CCI(x) + CO(x)$
 - $T(x_{sa_1}) = CC0(x) + CO(x)$
- **Compute testabilities for all stuck-at faults $T(f_i)$**
- **Define the Testability Index of a Circuit as Follows**
 - $Testability\ index = \text{Log} \sum_{\forall f_i} T(f_i)$
- **An Almost Linear Relation was found to Exist between The Testability Index of a Circuit and the Number of TVs for 90% Fault Coverage**

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Number Test Vectors vs. Testability Index



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High Level Testability

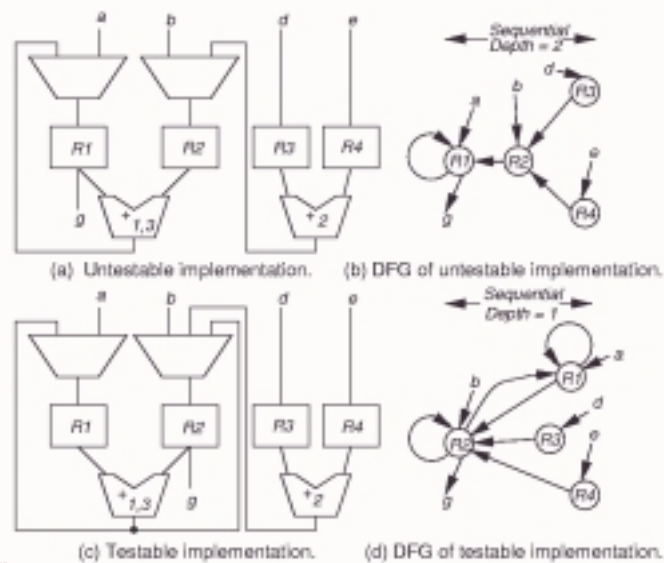
- Build *data path control graph (DPCG)* for circuit
- Compute *sequential depth* -- # arcs along path between PIs, registers, and POs
- Improve Register Transfer Level Testability with redesign

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Improved RTL Design



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Summary

- **Testability approximately measures:**
 - Difficulty of setting circuit lines to 0 or 1
 - Difficulty of observing internal circuit lines
- **Uses:**
 - Analysis of difficulty of testing internal circuit parts
 - Redesign circuit hardware or add special test hardware where measures show bad controllability or observability
 - Guidance for algorithms computing test patterns – avoid using hard-to-control lines
 - Estimation of fault coverage – 3-5 % error
 - Estimation of test vector length

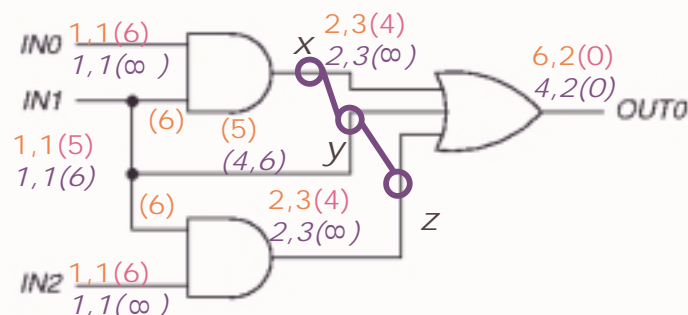
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Correlation Error Example

- **Exact** computation of measures is NP-Complete and impractical
- **SCOAP** measures are in red or bold **CC0,CC1 (CO)** -- **Italicized (Blue)** measures show correct values



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Lecture 8 Testability Measures

- **Controllability and observability**
- **SCOAP measures**
 - Sources of correlation error
 - Combinational circuit example
 - Sequential circuit example
- **Test vector length prediction**
- **High-Level testability measures**
- **Summary**