ECE 538

VLSI System Testing

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Testability Measures

Testability Measures

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

Purpose

- Need approximate measure of:
  - Difficulty of setting internal circuit lines to 0 or 1 by setting primary circuit inputs
  - Difficulty of observing internal circuit lines by observing primary outputs
- Uses:
  - Analysis of difficulty of testing internal circuit parts – redesign or add special test hardware
  - Guidance for algorithms computing test patterns – avoid using hard-to-control lines
  - Estimation of fault coverage
  - Estimation of test vector length

Origins

- Control theory
- Rutman 1972 -- First definition of controllability
- Goldstein 1979 -- SCOAP
  - First definition of observability
  - First elegant formulation
  - First efficient algorithm to compute controllability and observability
- Parker & McCluskey 1975
  - Definition of probabilistic controllability
- Brglez 1984 -- COP
  - 1^{st} probabilistic measures
- Seth, Pan & Agrawal 1985 – PREDICT
  - 1^{st} exact probabilistic measures

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

Types of Measures

- SCOAP – Sandia Controllability and Observability Analysis Program
- 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*

Range of SCOAP Measures

- Controllabilities – 1 (easiest) to infinity (hardest)
- Observabilities – 0 (easiest) to infinity (hardest)
- Combinational measures:
  - Roughly proportional to # circuit lines that must be set to control or observe given line
- Sequential measures:
  - Roughly proportional to # times a flip-flop must be clocked to control or observe given line

Goldstein's SCOAP Measures

- AND gate O/P 0 controllability:

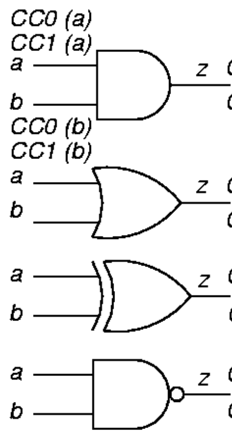
  output_controllability = min (input_controllabilities) + 1
- AND gate O/P 1 controllability:

  output_controllability = S (input_controllabilities) + 1
- XOR gate O/P controllability

  output_controllability = min (controllabilities of each input set) + 1
- Fanout Stem observability:

  S or min (some or all fanout branch observabilities)

Controllability Examples



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

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

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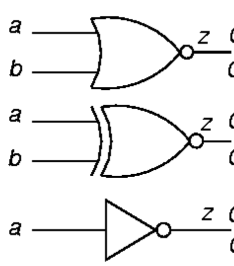
$CC1(z) = \min(CC1(a) + CC0(b), CC0(a) + CC1(b)) + 1$

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

More Controllability Examples



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

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

$CC0(z) = CC1(a) + 1$
$CC1(z) = CC0(a) + 1$

Observability Examples

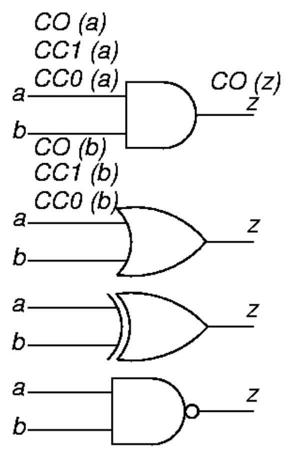
To observe a gate input:
Observe output and make other input values non-controlling

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

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

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

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



More Observability Examples

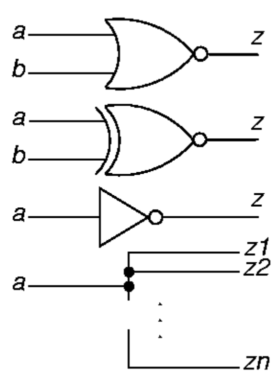
To observe a fanout stem:
Observe it through branch with best observability

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

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

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

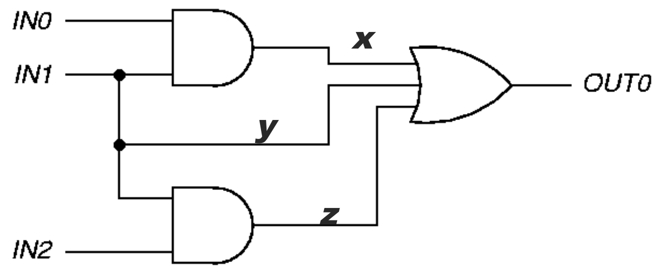
$CO(a) = \min(CO(z1), CO(z2), ..., CO(zn))$



Error Due to Stems & Reconverging Fanouts

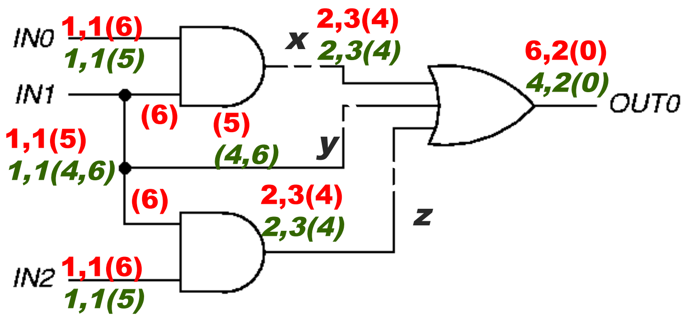
SCOAP measures wrongly assume that controlling or observing *x*, *y*, *z* are independent events

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

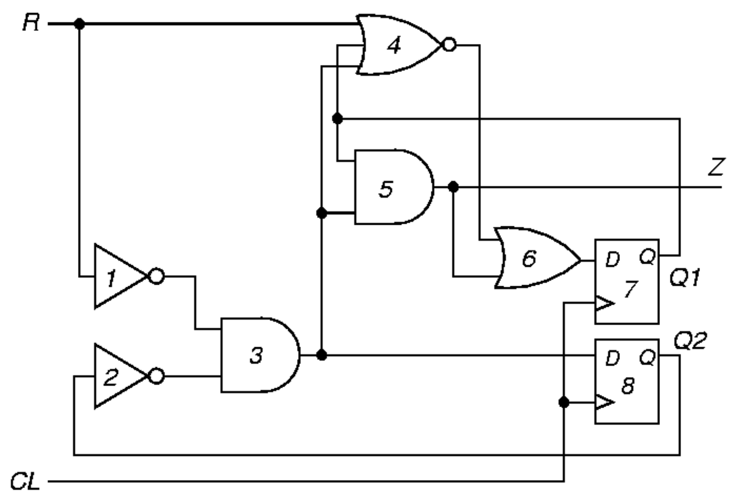


Correlation Error Example

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



Sequential Circuit Example

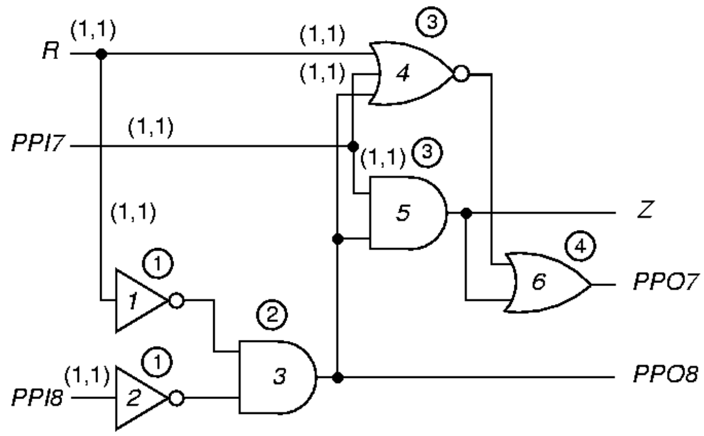


Levelization Algorithm 6.1

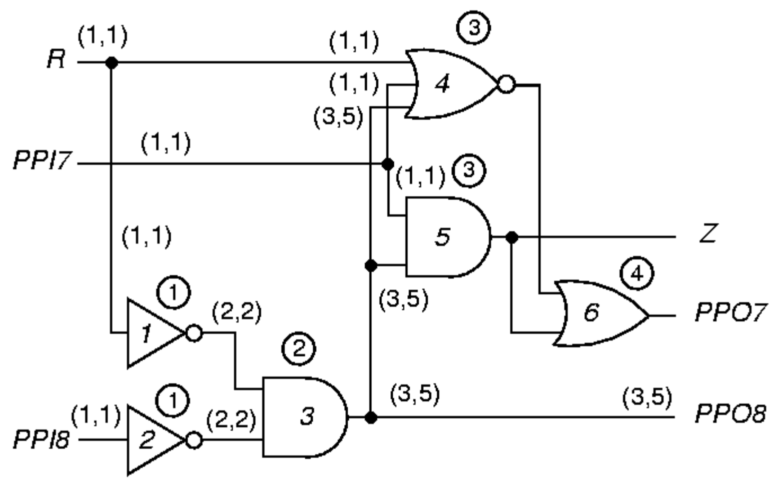
- Label each gate with max # of logic levels from primary inputs or with max # of logic levels from primary output
- Assign level # 0 to all *primary inputs* (PIs)
- For each PI fanout:
  - Label that line with the PI level number, &
  - Queue logic gate driven by that fanout
- While queue is not empty:
  - Dequeue next logic gate
  - If all gate inputs have level #'s, label the gate with the maximum of them + 1;
  - Else, requeue the gate

Controllability Through Level 0

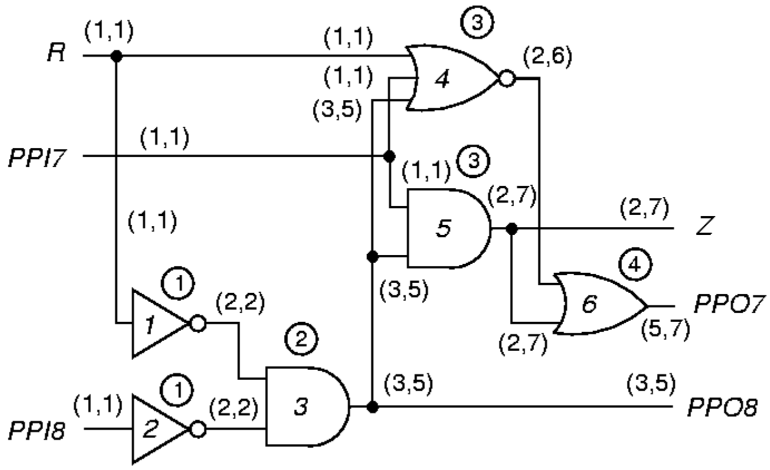
Circled numbers give level number (CC0, CC1)



Controllability Through Level 2



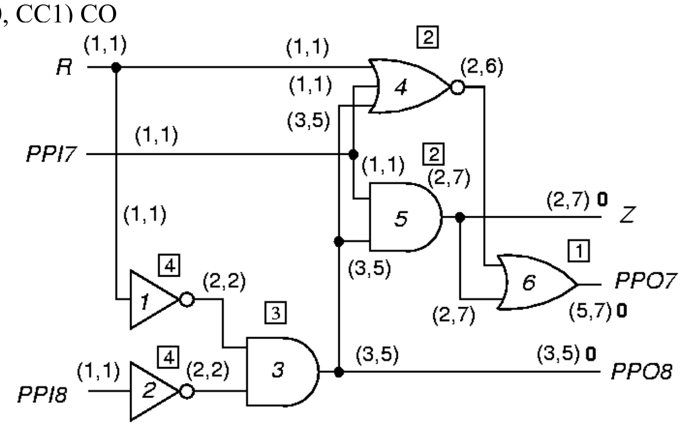
Final Combinational Controllability



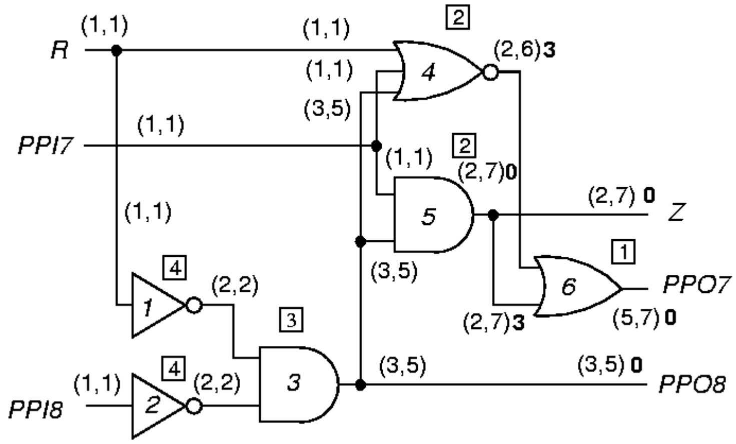
Combinational Observability for Level 1

Number in square box is level from *primary outputs* (POs).

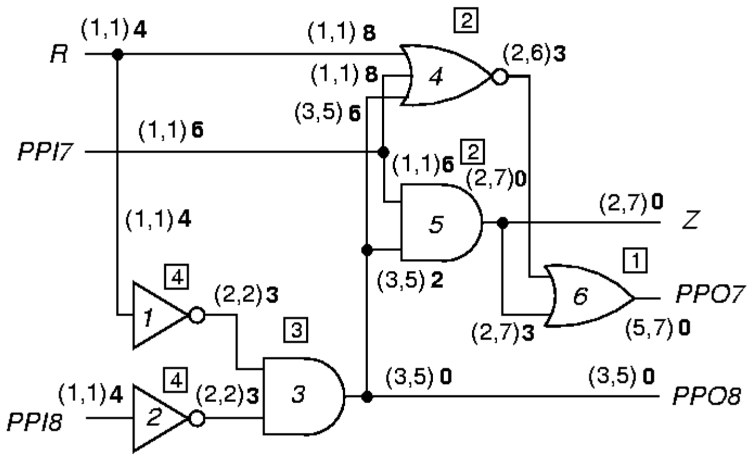
(CC0, CC1) CO



Combinational Observabilities for Level 2



Final Combinational Observabilities



Sequential Measure Differences

- Combinational
  - Increment *CC0, CC1, CO* whenever you pass through a gate, either forwards or backwards
- Sequential
  - Increment *SC0, SC1, SO* only when you pass through a flip-flop, either forwards or backwards, to *Q*, $\overline{Q}$, *D, C, SET*, or *RESET*
- Both
  - Must iterate on feedback loops until controllabilities stabilize
- *See details in the text*

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