Testability Measures

An attempt to *quantify* testability by Goldstein '79 and Grason '79 resulted in two testability measures, **controllability** and **observability**.

Controllability is defined as the difficulty of setting a particular logic signal to a 0 or a 1.

PIs are free (usually assigned a value of 1).

Output 1 values for AND gates are more expensive than OR gates.

Observability defined as the difficulty of observing the state of a logic signal.

Purpose:

- Analysis of difficulty of testing internal circuit nodes.
  May need to modify circuit, add observation points or test hardware.
- Can be used to guide ATPG algorithms, i.e., to help them make decisions by providing information about the difficulty of setting lines.
- Can be used to estimate fault coverage.
- Can be used to estimate test vector length.

Testability Measures

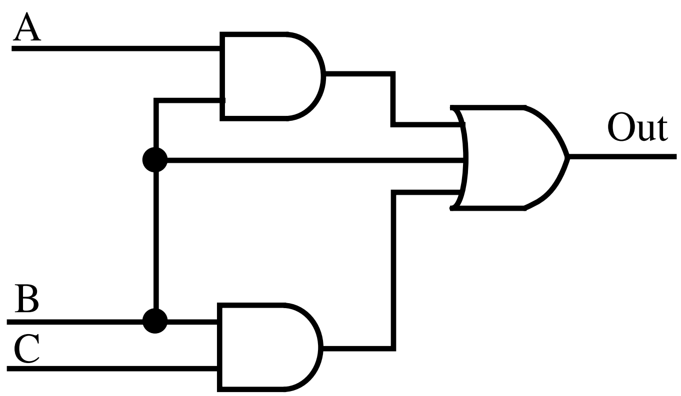
Testability analysis attributes:

- Requires topological analysis (but no test vectors).
- It is linear in complexity.

Otherwise it's pointless, i.e., might as well use ATPG to compute **exact** fault coverage.

Goldstein developed SCOAP testability measures and describes a linear complexity algorithm to compute them.

The algorithm has significant inaccuracies because it assumes that signals at reconvergent fanout stems are independent.



B fans out to 3 gates, the outputs of these gates *reconverge* at the OR gate.

Testability Measures

The assumption of signal independence is the key behind SCOAP's linear time algorithm.

However, this reduces its accuracy in predicting which individual faults will remain *undetected* and which will be detected.

SCOAP testability measures:

- *Controllability*: From 1 (easiest) to infinity (hardest).
- *Observability*: From 0 (easiest) to infinity (hardest).

Combinational measures are related to the number of signals that may be manipulated to control or observe *l*.

Sequential measures are related to the number of times a FF must be clocked to control or observe a line.

Testability Measures

Another approach is to make them probability based, i.e., they range between 0 and 1.

Here, the *1-controllability*, **C1**, is the probability of a signal value on line *l* being set to 1 by a random vector.

W.r.t. **fault detection** probability, we can cast the problem as the C1 of a signal line that is the XOR of the good and faulty circuit outputs.

Problem: Almost doubles the size of the circuit to be analyzed.

Alternatively, it can be cast (incorrectly) as the probability of detecting a SA0 fault on line *l* by a random input, e.g., C1(*l*) * OB(*l*).

Problem: control and observability of a line are NOT independent.

Jain and Agrawal address this problem in PREDICT using *conditional probabilities* for observability.

PREDICT computes **exact** probabilities but has exponential complexity for some circuits.

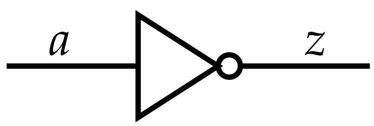
SCOAP Testability Measures

Goldstein's algorithm: SCOAP

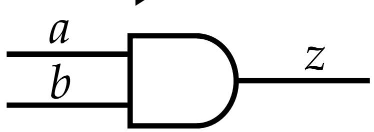
Consists of 6 numerical measures for each signal (l) in the circuit:

- Combin. *0-controllability*, **CC0(l)**; Sequential *0-controllability*, **SC0(l)**
- Combin. *1-controllability*, **CC1(l)**; Sequential *1-controllability*, **SC1(l)**
- Combin. *observability*, **CO(l)**; Sequential *observability*, **SO(l)**

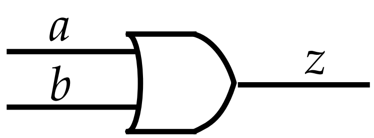
Controllabilities:The basic process: Set PIs to 1, progress from PIs to POs, add 1 to account for logic depth.



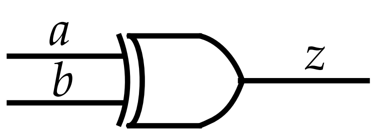
$$CC0(z) = CC1(a) + 1$$
$$CC1(z) = CC0(a) + 1$$



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



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



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

SCOAP Testability Measures

In general, if only one input sets gate's output:

output controllability = *min*(input controllabilites) + 1

If all inputs set gate output:

output controllability = *sum*(input controllabilities) + 1

If gate output is determined by multiple input sets, e.g., XOR:

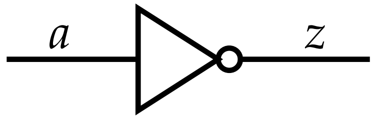
output controllability = *min*(controllabilities of input sets) + 1

Remember that reconverging signals may correlate and therefore this procedure becomes inaccurate at the reconvergence point.

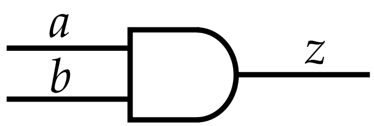
Observabilities: The basic process: After controllabilities computed, set P0s to 0, progress from PO to PIs, add 1 to account for logic depth.

For example, the difficulty of observing a designated input to a gate is the sum of (1) the output observability (2) the difficulty of setting all other inputs to *non-dominant* values (3) plus 1 for logic depth.

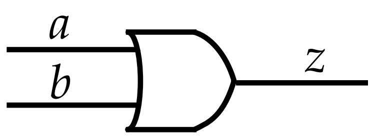
SCOAP Testability Measures



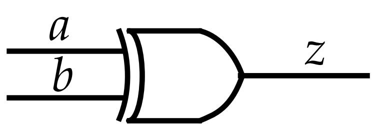
$CO(a) = CO(z) + 1$



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



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



$CO(a) = \mathrm{CO}(z) + \min\{CC0(b) + CC1(b)\} + 1$

The accuracy problem occurs for the computation of the observability of a fanout **stem** with *n* branches.

One attempt is to bound the stem probability by:

- *min*(all fanout branch observabilities)

  The events of observing a signal through each branch are **independent.**
- *max*(all fanout branch observabilities)

  They are all **dependent**, therefore branch that's hardest to observe is correct choice.

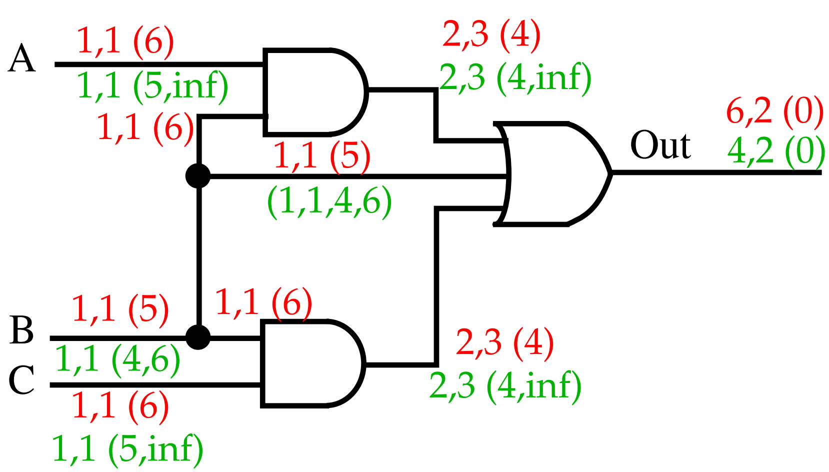
SCOAP Testability Measures

Problem: These ignore the possibility that observing a signal may require its propagation through *some* or *all* fanout branches.

Goldstein uses: CO(*stem*) = *min*(CO(*branches*))

Therefore, observability calculation errors occur and ATPG algorithms which use them may be misled.

Goldstein's algorithm has only O(2**n*) or O(*n*) complexity.



Format:
CC0, CC1 (CO)

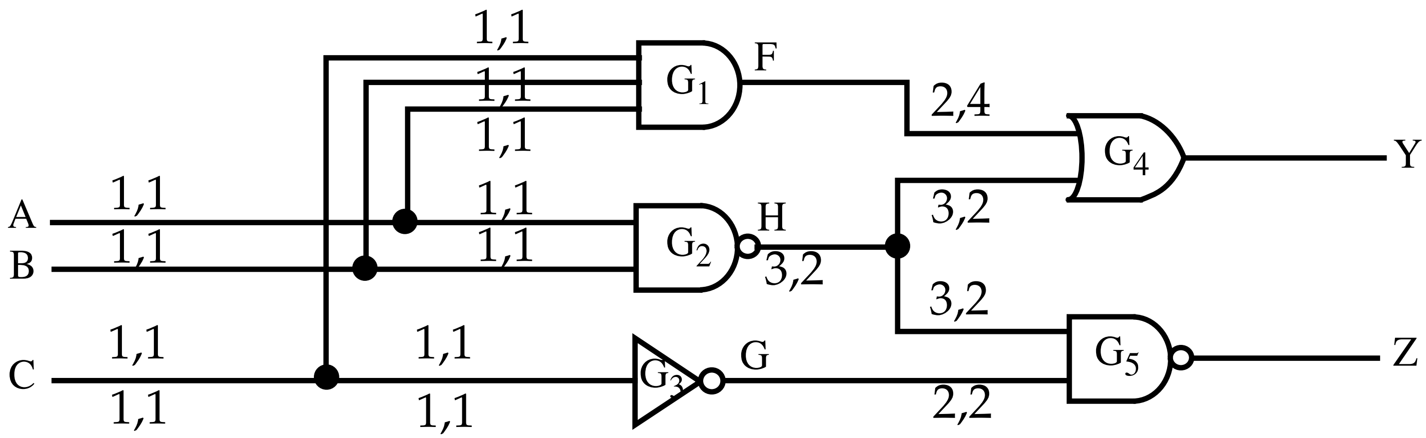
SCOAP in red
Correct in green

Observability
0 1
CC0, CC1 (CO, CO)

Note that the red numbers are given by the SCOAP algorithm and the green number are the exact values.

SCOAP Testability Measures

An example with multiple outputs:



Let's refer to the branches using the gate index, e.g., A_1, A_2 and H_4, H_5, etc.

For nodes *F*, *H* and *G*:

$CC0(\mathrm{F}) = \min\{CC0(\mathrm{A}), CC0(\mathrm{B}), CC0(\mathrm{C})\} + 1 = 2$

$CC1(\mathrm{F}) = CC1(\mathrm{A}) + CC1(\mathrm{B}) + CC1(\mathrm{C}) + 1 = 4$

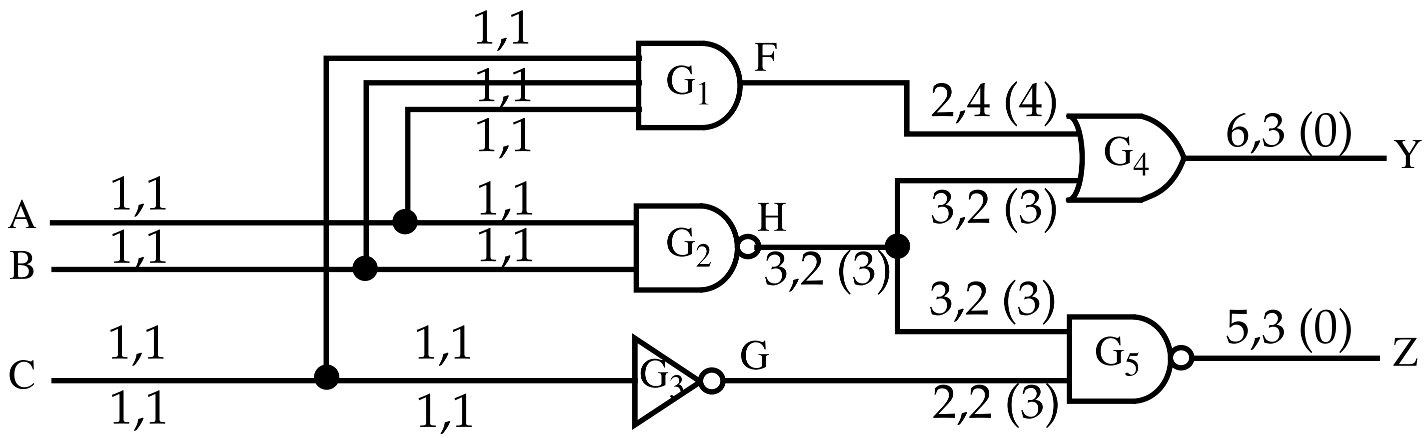
$CC0(\mathrm{H}) = CC1(\mathrm{A}) + CC1(\mathrm{B}) + 1 = 3$

$CC1(\mathrm{H}) = \min\{CC0(\mathrm{A}), CC0(\mathrm{B})\} + 1 = 2$

$CC0(\mathrm{G}) = CC1(\mathrm{C}) + 1 = 2$

$CC1(\mathrm{G}) = CC0(\mathrm{C}) + 1 = 2$

SCOAP Testability Measures



$CC0(\mathrm{Y}) = CC0(\mathrm{F}) + CC0(\mathrm{H}) + 1 = 6$

$CC1(\mathrm{Y}) = \min\{CC1(\mathrm{F}), CC1(\mathrm{H})\} + 1 = 3$

$CC0(\mathrm{Z}) = CC1(\mathrm{H}) + CC1(\mathrm{G}) + 1 = 5$

$CC1(\mathrm{Z}) = \min\{CC0(\mathrm{H}), CC0(\mathrm{G})\} + 1 =3$

In order to **observe** node F on PO Y, it is necessary to control H to 0.

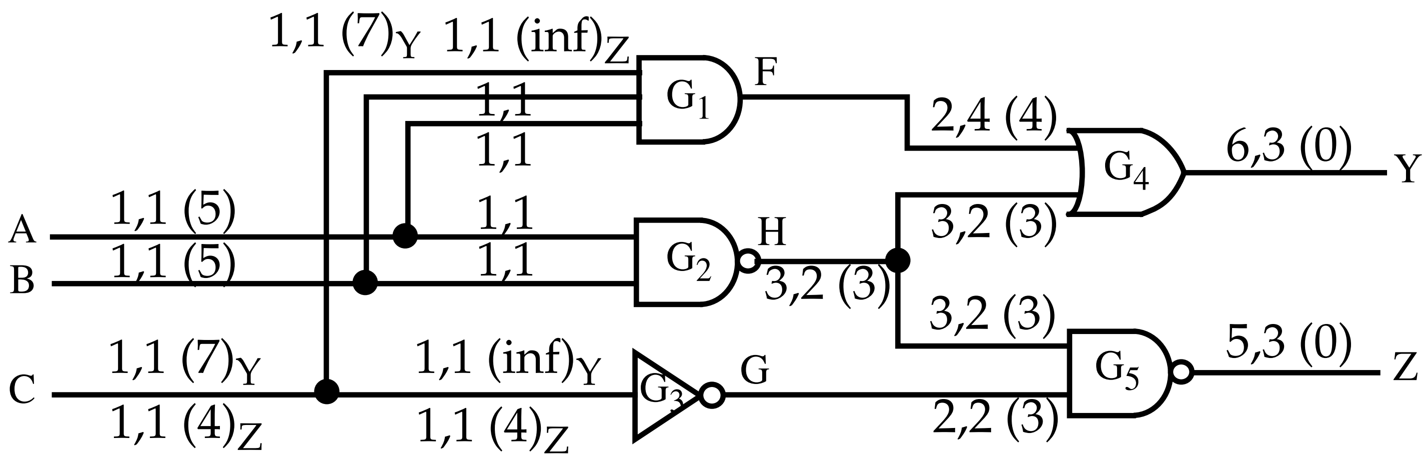
$CO_{\mathrm{Y}}(\mathrm{F}) = CO(\mathrm{Y}) + CC0(\mathrm{H}) + 1 = 4$

$CO_{\mathrm{Z}}(\mathrm{G}) = CO(\mathrm{Z}) + CC1(\mathrm{H}) + 1 = 3$

$CO_{\mathrm{Y}}(\mathrm{H}) = CO(\mathrm{Y}) + CC0(\mathrm{F}) + 1 = 3$

$CO_{\mathrm{Z}}(\mathrm{H}) = CO(\mathrm{Z}) + CC1(\mathrm{G}) + 1 = 3$

SCOAP Testability Measures



Inputs are observable on *Y* or *Z*.

Consider observability of C via Y:

$$CO_Y(C) = CO_Y(F) + CC1(A) + CC1(B) + 1 = 7$$

Consider observability of C via Z:

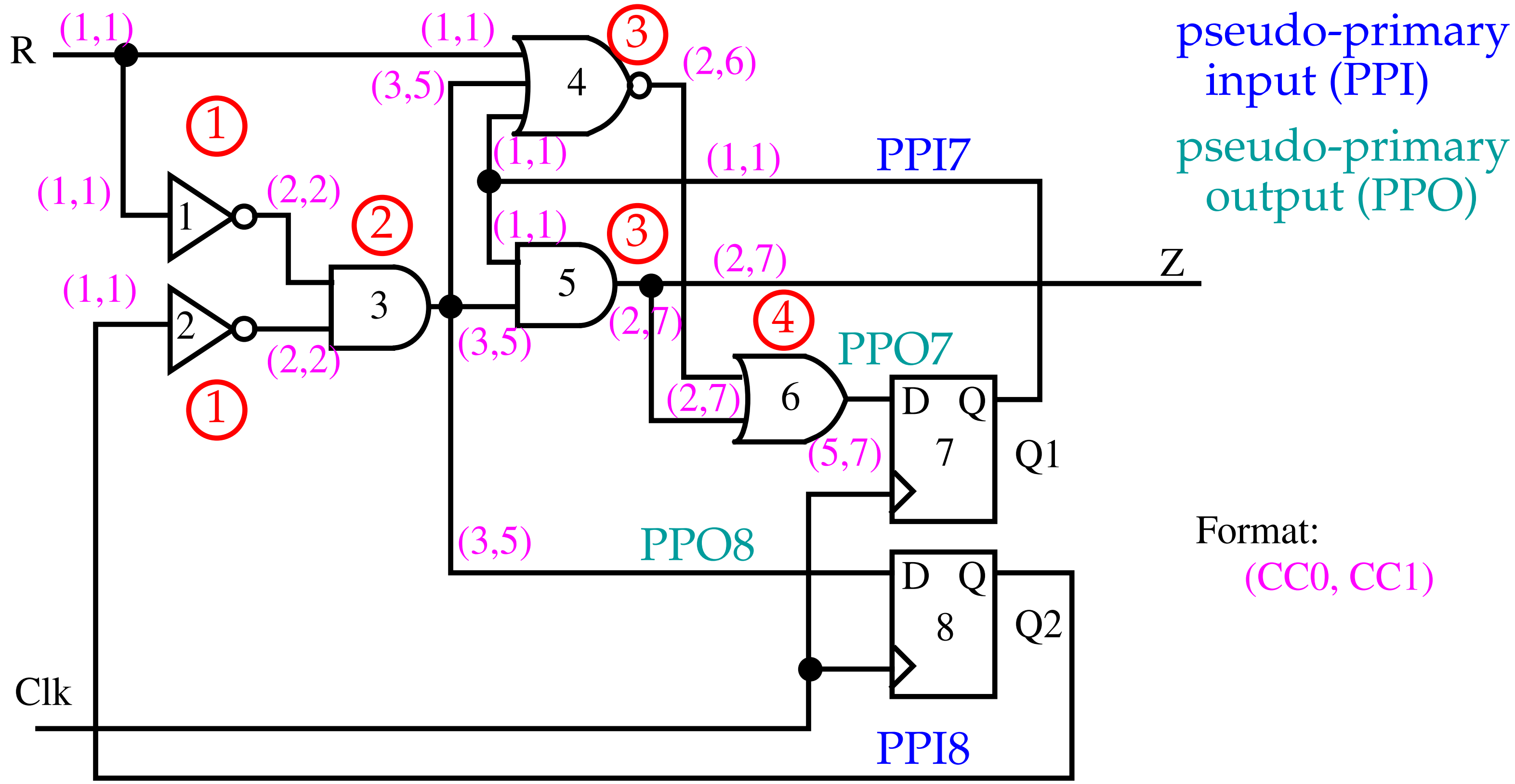
$$CO_Z(C) = CO_Z(G) + 1 = 4$$

Note that C_1 is not observable, (inf), on Z and C_3 is not observable on Y.

Also, SA1 faults on A_1 and B_1 are not observable because of the redundancy but they are still assigned finite values (left as an exercise).

SCOAP Testability Measures

Sequential circuit with scannable FFs (treat as combinational):



Eliminate FFs and assign pseudo-primary inputs/outputs, PPIx and PPOx.

Levelize the circuit, as shown by the circled numbers in the circuit, for the forward pass.

See text for observabilities and more details.

SCOAP Testability Measures

Sequential SCOAP measures differences:

- Increment the sequential measure by 1 only when:

  Signals propagate from FF inputs to Q or $\overline{\text{Q}}$, or

  Signals propagate from FF outputs backwards to D, Clk, SET or RESET inputs.

- One must iterate on feedback loops until controllabilities stabilize.

SC0, SC1 and SO formulas differ from CC0, CC1 and C0 only in that you do NOT add one when moving from one level to another.

SC0 and SC1 roughly measure the number of times various FFs must be clocked to control a signal.

If line l can only be set to 1 but clocking FF a twice and FF b three times, SC1(l) should be 5.

SO correspondingly measure the number of times a FF must be clocked to observe a combinational signal.

(Read sections in text).

Testability Measures

SCOAP can be used to predict the length of a test set.

Testabilities of SA faults at node x given by:

$T(x\ SA0) = CC1(x) + CO(x)$

$T(x\ SA1) = CC0(x) + CO(x)$

These indicate in order to detect a fault at x, one must set x to the opposite value from the fault and observe x at a PO.

A testability index can be computed as:

Testability index = log (sum over all faults f_i of $T(f_i)$).

How are Testability Measures useful?

- In ATPG during *backtracing* (controllabilities) and *propagating* the fault effect (observabilites) since they give the path of least resistance.

  Some caution is necessary since reconvergent fanout introduce error in controllabilites and fanout stems introduce error in observabilities.

Testability Measures

How are Testability Measures useful?

- Tell designer which parts of the design are extremely hard-to-test.

  Either redesign or special-purpose test hardware is needed to achieve high fault coverage.

- Extremely useful for estimating fault coverage and test vector length.

  Fault coverage estimation via testability can reduce CPU time by orders of magnitude over fault simulation (and has only a 3-5% error).