Delay Faults

Delays along every path from PI to PO or between internal latches must be *less than* the operational system clock interval.

We have already discussed a number of defects that can cause delay faults:

- GOS defects
- Resistive shorting defects between nodes and to the supply rails
- Parasitic transistor leakages, defective pn junctions and incorrect or shifted threshold voltages
- Certain types of opens
- Process variations can also cause devices to switch at a speed lower than the specification.

An *SA0* or *SA1* can be modeled as a delay fault in which the signal takes an **infinite** amount of time to change to *1* or *0*, respectively.

Passing stuck fault tests is usually not sufficient however for systems that operate at any appreciable speed.

Running stuck-at fault tests at higher speed can uncover some delay faults.

Delay Tests

- Delay tests consist of *vector-pairs*.
- All input transitions occur at the same time.
- The longest delay combinational path is referred to as the **critical path**, which determines the shortest clock period.

  A delay fault means that the delay of one or more paths (not necessarily the critical path) exceeds the clock period.

Test Definition:

- At time t_1, the initializing vector of the two-pattern test, V_1, is applied through the input latches or PIs and the circuit is allowed to stabilize.
- At time t_2, the second test pattern, V_2, is applied.
- At time t_3, a logic value measurement (a sample) is made at the output latches or POs.

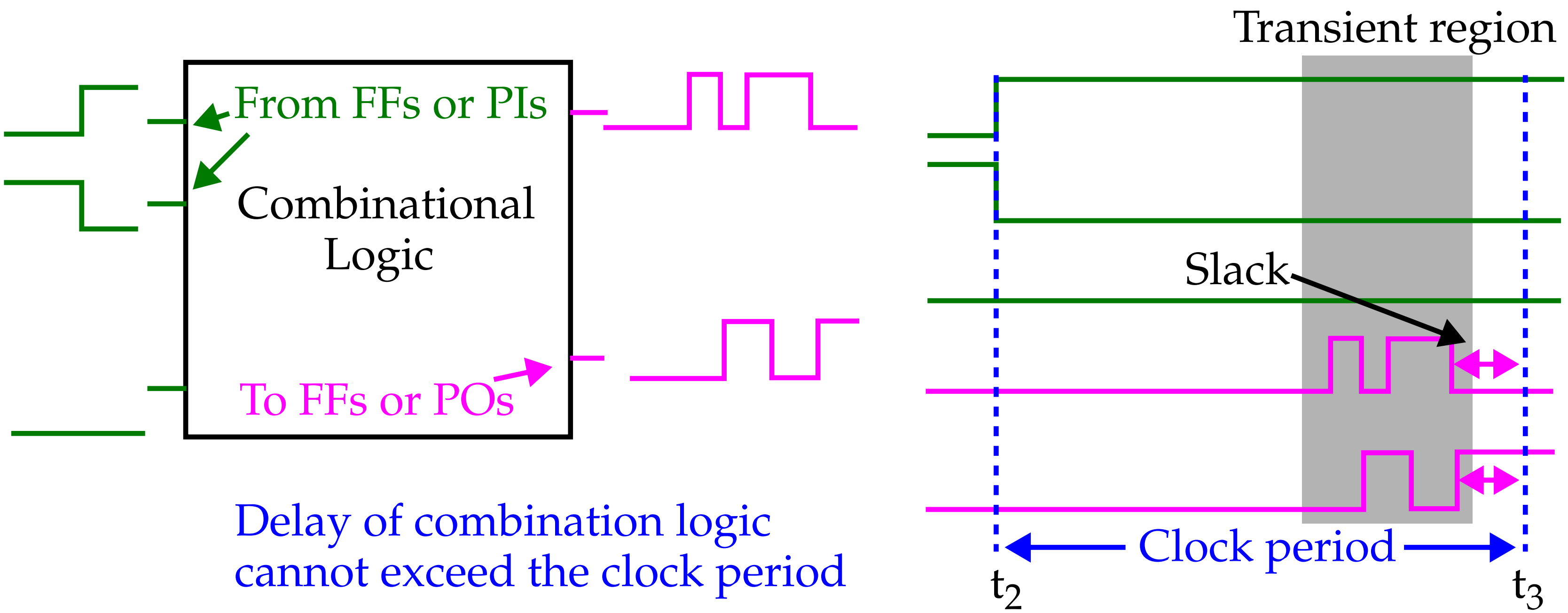
The delay test vectors V_1 and V_2 may sensitize one or more paths, p_i.

Delay Tests

Let:

- $T_C = (t_3 - t_2)$ represent the time interval between the application of vector V_2 at the PIs and the sampling event at the POs
- The *nominal delay* of each of these paths be defined as pd_i.
- The **slack** of each path be defined as $sd_i = T_C - pd_i$.

This is the difference between the propagation delay of each of the sensitized paths in the nominal circuit and the test interval.



Delay Fault Test Generation

Difficulties with delay fault test generation:

- Test generation requires a sensitized path that extends from a PI to a PO.

- Path selection heuristics must be used because the total number of paths is *exponentially* related to the number of inputs and gates in the circuit.

- The application of the test set must be performed at the *rated speed* of the device.

  This requires test equipment that is capable of accurately timing two-vector test sequences.

- The *detection* of a defect that introduces an additional delay, ad_i, along a sensitized path is dependent on satisfying the condition:

  $ad_i > sd_i$ (or $pd_i + ad_i > T_C$)

Hazards

A path sensitized by a delay test consists of *on-path* nodes and *off-path* nodes.

The nodes along the *sensitized path* are referred to as *on-path* nodes.

Static sensitization defines the case when all *off-path* nodes settle to non-controlling values (0 for OR/NOR, 1 for AND/NAND) following app. of V_2.

This is a necessary condition to test a path for a delay fault.

The gates along the sensitized path have exactly **one** on-path input and zero or more non-controlling off-path inputs.

Delay fault tests are classified according to the voltage behavior of the *off-path* nodes.

Such tests can be **invalidated** under certain conditions.

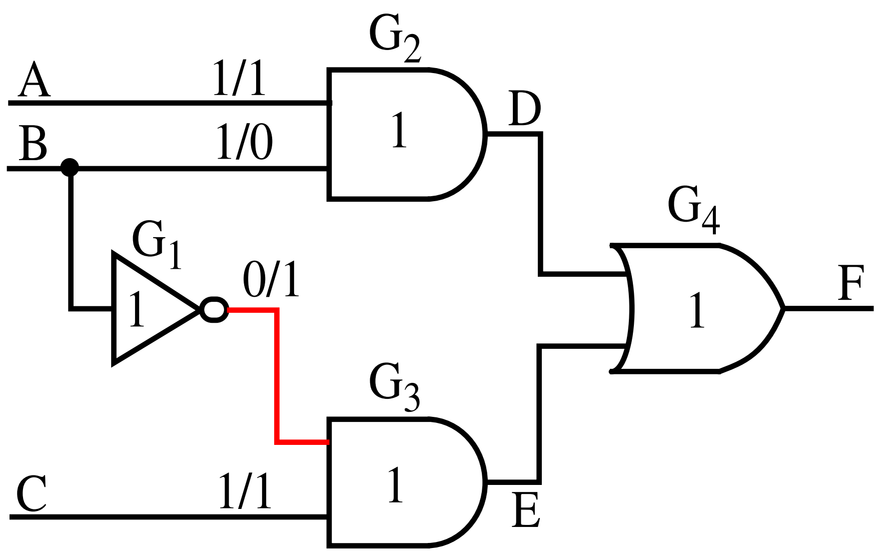
Hazards can invalidate tests:

- **Static hazard**: describes a circuit condition where *off-path* nodes change momentarily when they are supposed to remain constant.
- **Dynamic hazard**: describes a circuit condition where *off-path* nodes make several transitions when they are supposed to make a single transition.

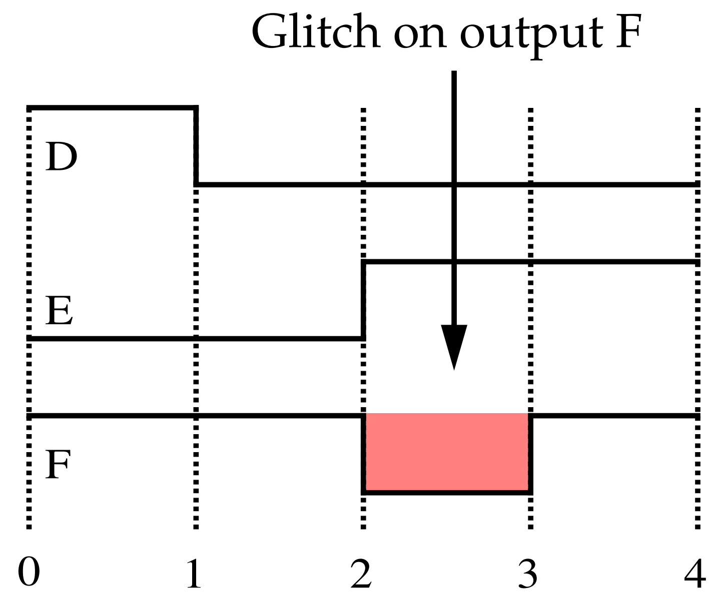
Hazards

Static Hazards:

$$F = (A \bullet B) + (C \bullet \bar{B})$$



Gate delays are circled.



Time line starting when vector *ABC* = (*101*) is applied.

Two vector sequence is *ABC* = (*111*), (*101*).

Gate G_1 introduces an additional delay of 1 unit.

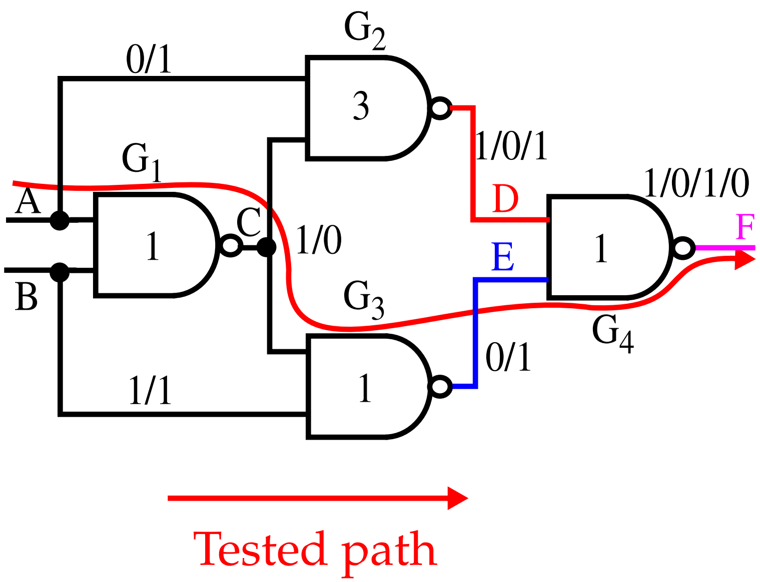
Output *E* of gate G_3 is driven to a logic *1*, one time unit behind *D -> 0*.

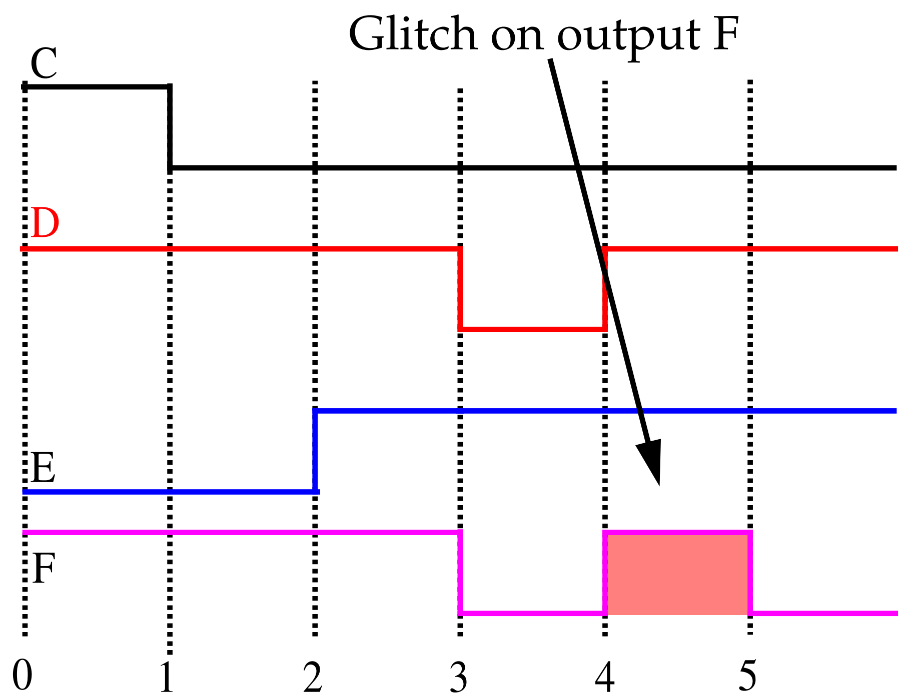
Produces a glitch on *F*.

Hazards

Dynamic Hazards:

$$F = (A \bullet \bar{B}) + (\bar{A} \bullet B)$$





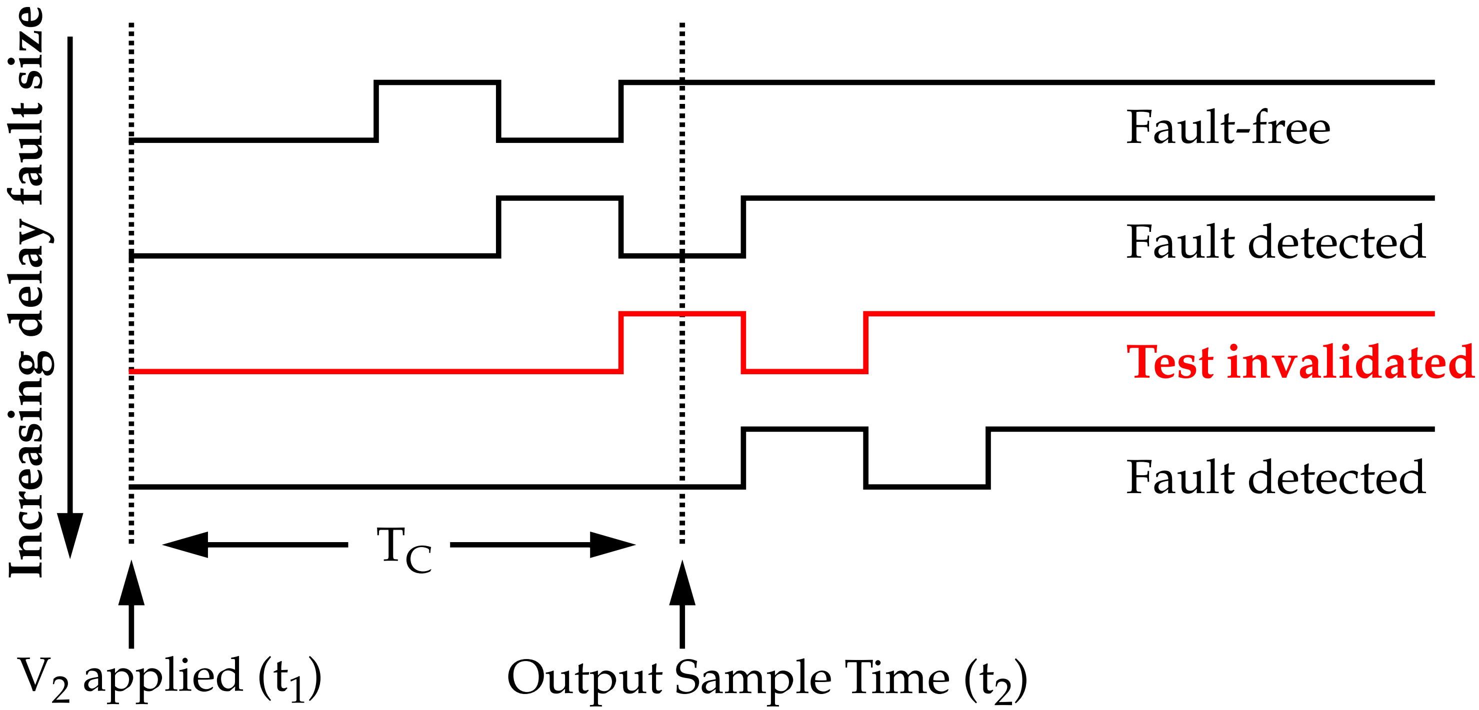
Time line starting when vector $AB = (11)$ is applied.

Two vector sequence is $AB = (01), (11)$.

Gate G_2 has a delay value of 3 time units.

Hazards and Invalidation

Static hazards can create *dynamic hazards* along tested paths and need to be considered during test generation.

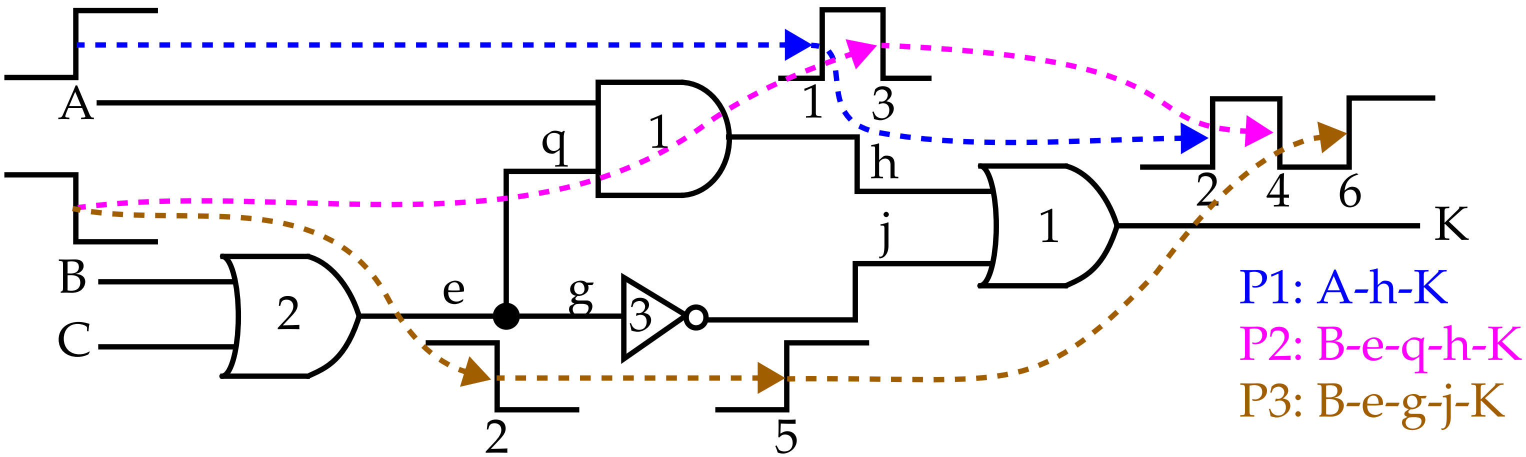


Note, unlike the previous example, the glitch occurs **before** the intended transition, and can invalidate the test (e.g. fault is not detected).

Delay Tests and Invalidation

The critical path(s) of this circuit is 6 time units.

Let's set the clock period $T = 7$.



Assume only one faulty path.

No delay fault is detected if path delay along P3 is less than 7 units.

This test will **not** detect single delay faults along paths P1 or P2.

Assume there can be **multiple faulty** paths.

Assume P2 and P3 are faulty and P2 extends the "static glitch" at the output beyond 7 units, then it masks P3's delay fault.

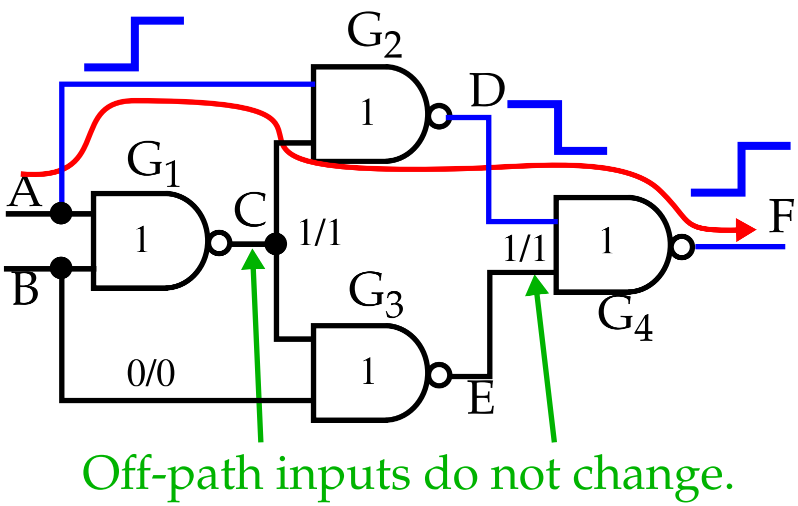
This test is called a **non-robust** test for delay fault P3.

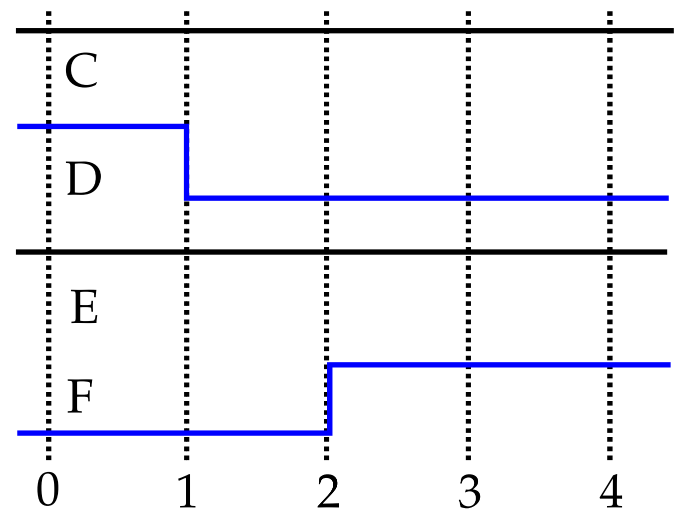
Delay Fault Path Classification

Most paths in a circuit can be classified as:

- *Hazard-free robust testable*
- *Robust testable*
- *Non-robust testable*

Hazard-free robust test





Off-path inputs are stable and **hazard-free** throughout the test interval, T_C.

This is the most desirable test since *invalidation* is not possible.

Robust Test

Hazard-free robust tests are desirable but it's not possible in many cases to generate them.

Transitions that occur at fan-out points often *reconverge* as off-path inputs along the tested path.

However, **robust** tests are still possible even when static hazards are present on the off-path inputs.

Static hazards are *necessary but not sufficient* to make a delay test non-robust.

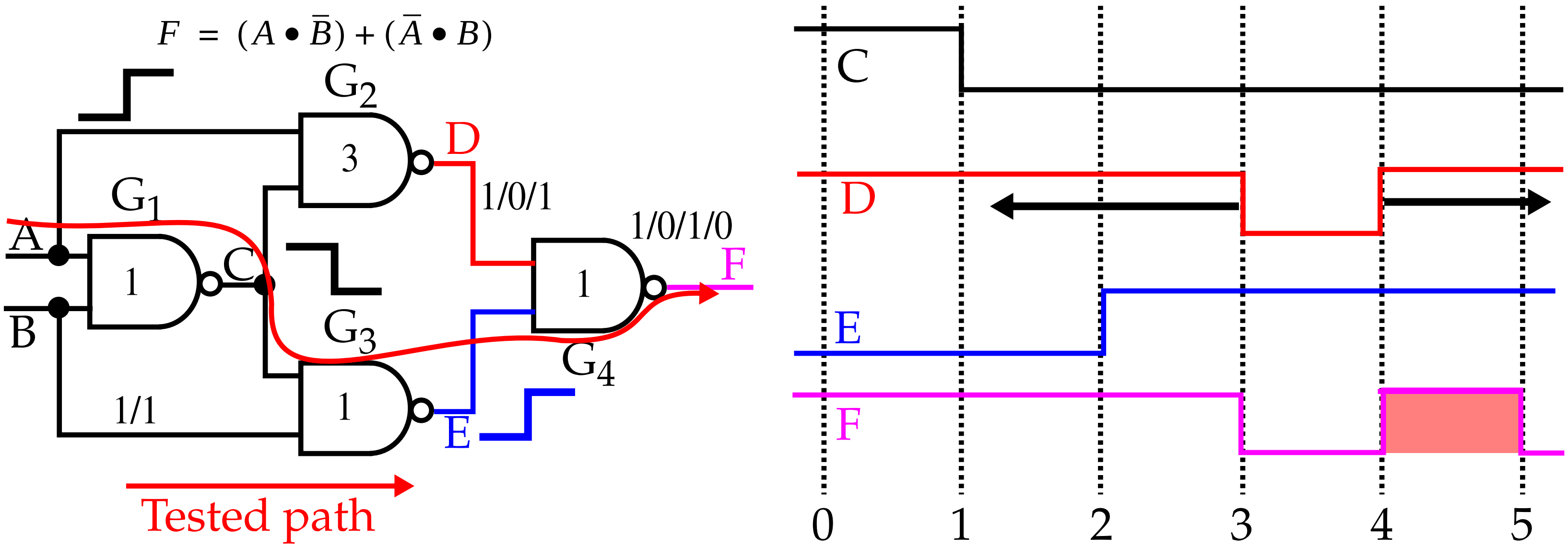
A delay test is a *robust* test if the **on-path** nodes control the *first* occurrence of a transition through all gates along the tested path.

This ensures that a delay test is not *invalidated* or a path delay fault *masked* by delay characteristics of gates not on the tested path.

A **robust path-delay test** guarantees to produce an incorrect value at the output if the delay of the path exceeds the clock period, irrespective of other path delays.

Robust Test

Robust delay test:



This test is robust since *F* will not change state until the transition on *E* has occurred.

In other words, any assignable delay to *D* can never mask a delay fault that may occur on the tested path.

This is true because the on-path node *E* holds the **dominant** input value on gate G_4, and therefore determines the *earliest* transition possible on *F*.

Therefore, *D* is allowed to delay the transition on *F* but not speed it up.

Robust Test

It is possible that:

- *D* can cause a **transition** to occur on *F* after the transition on-path node *E* has occurred.
- *D* may **further delay** the transition of *F* since it too can hold the dominant input value on gate G_4.

The former condition is sufficient to cause a glitch on *F* (as shown).

The latter condition implies that a robust test does not require the sensitized path to *dominate the timing*, or, to be the **last** transition to occur on all gates along the sensitized path.

An *on-input* node will make the transition either:

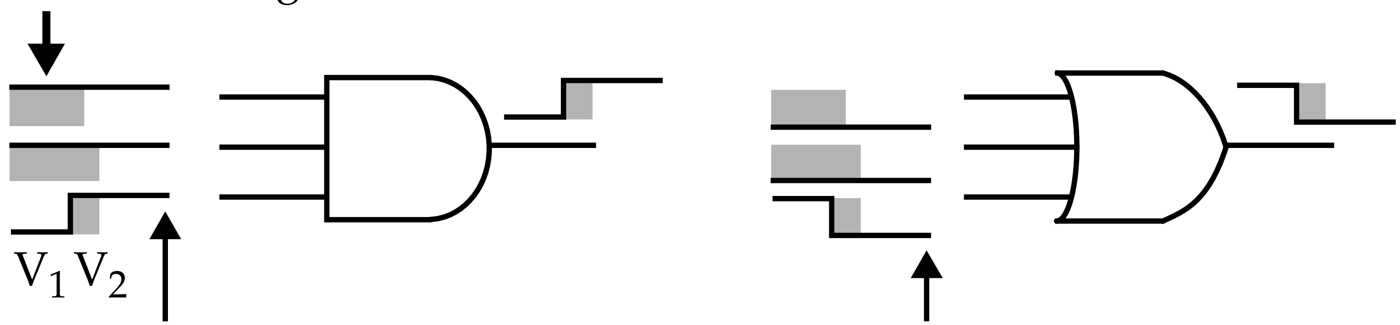
- From the *dominant* input state of the gate to the *non-dominant* input state.
- From the *non-dominant* input state of the gate to the *dominant* input state.

Robust Test

For the first case, the **off-path** inputs of the gate must behave in either one of two ways.

- If the *off-path* input node changes state, then it must make a transition from the **dominant** to the **non-dominant** input state of the gate.
- If it does *not* change state, then it must remain in steady-state at the **non-dominant** value during the entire test interval.

"don't care" regions are shaded



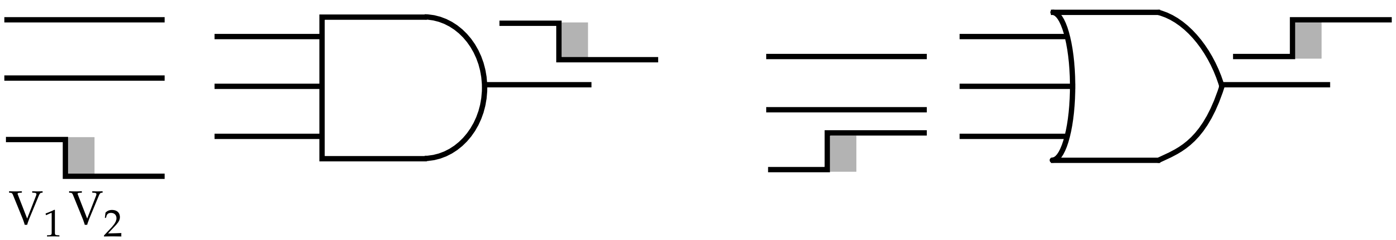
All must settle to non-controlling values otherwise the path is not sensitized.

When all *off-path* inputs honor these constraints, the outputs of the gates along the test path will **not** make the transition until the *last* of all transitioning input lines have toggled.

Robust Test

For the second case, the *off-path* inputs must remain at their **non-dominant** states during the entire test interval.

No off-path transition is allowed.



In either case, hazards will **not** be visible at the output until after the desired transition has propagated along the tested path.

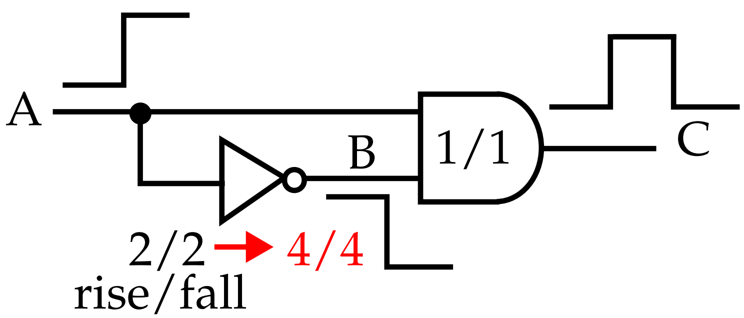
However, for many circuits, even this weaker set of constraints permits only a small percentage of path delay faults to be robust tested.

Non-Robust Test

A **non-robust** tests allow the output to change **before** the *on-path* transition propagates along the tested path.

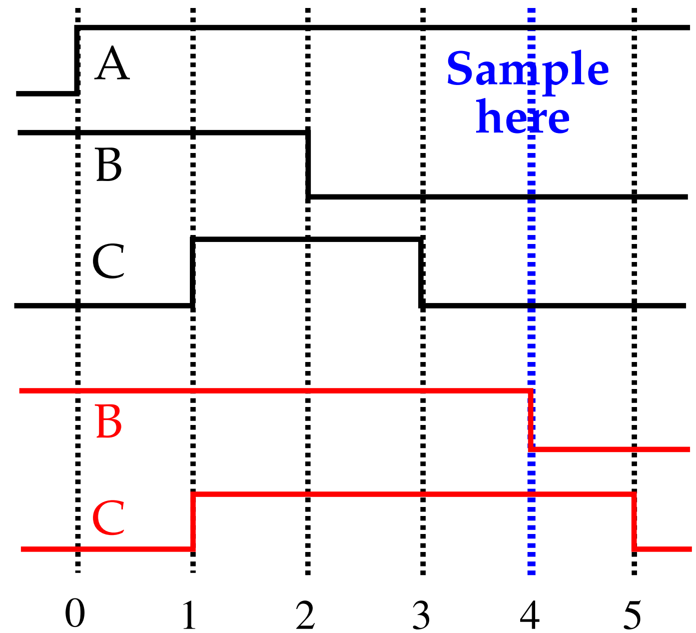
A non-robust test **cannot** guarantee the detection of a delay fault along a test path in the presence of *other faults*.

Non-robust test for path delay fault ↑ A-B-C



Pulse Generator circuit

Note that the steady-state output is always 0.

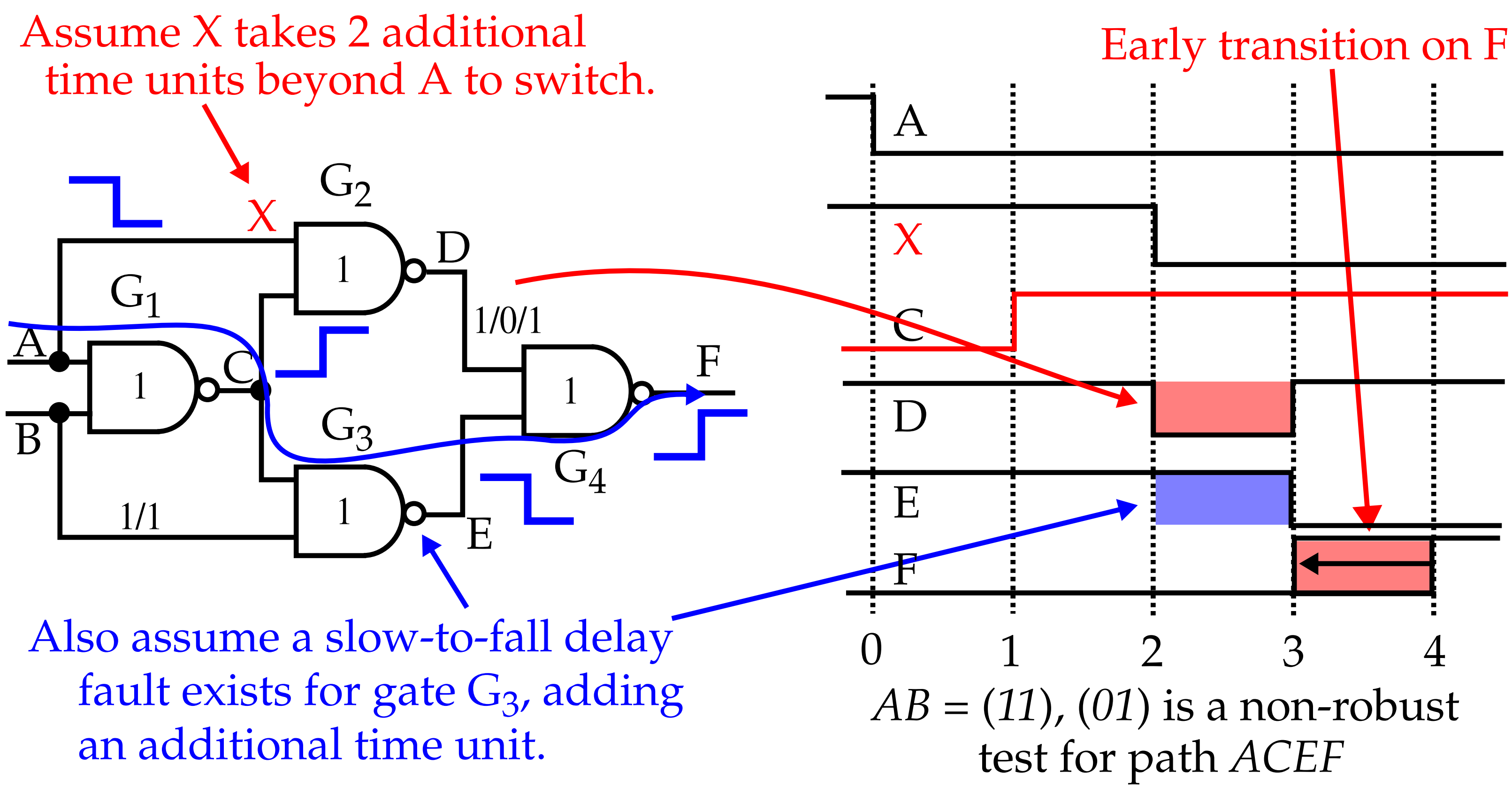


Although the delay fault introduced by the inverter is detected (as shown), a delay fault along *A-C* may cause the output to remain at 0 or it may push the pulse beyond $T = 4$ -- which invalidates it.

Non-Robust Test

A **non-robust** path delay test guarantees the detection of a path-delay fault only when *no other path delay fault* is present.

Single fault assumption (similar to the Stuck-At fault model).

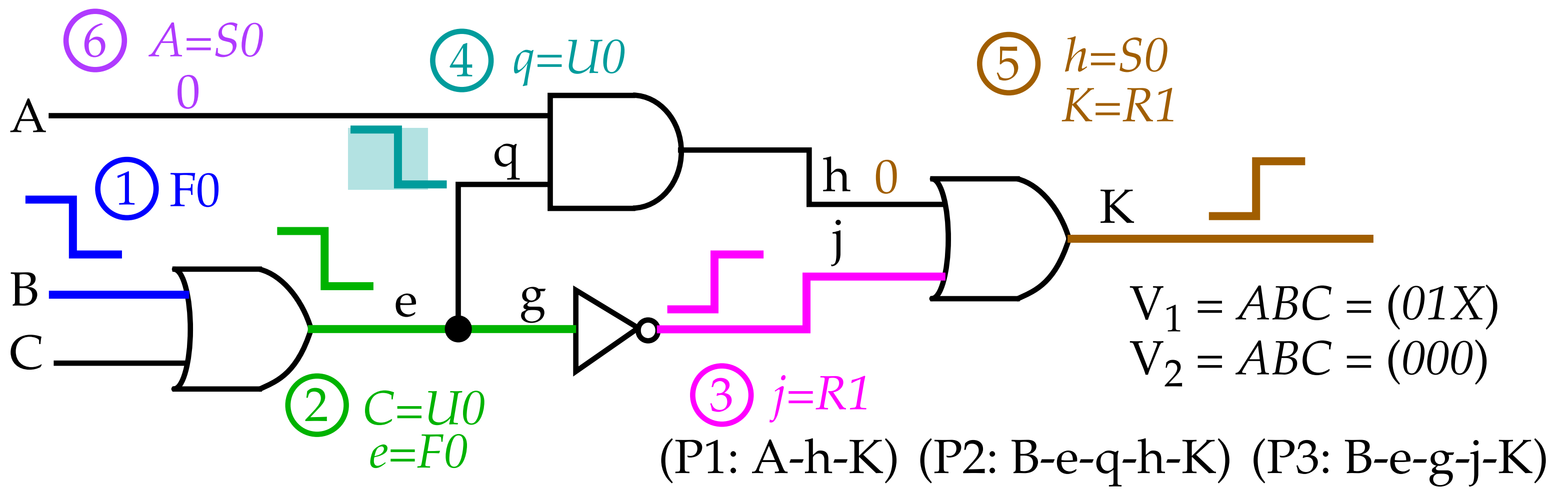


AB = (*11*), (*01*) is a non-robust test for path *ACEF*

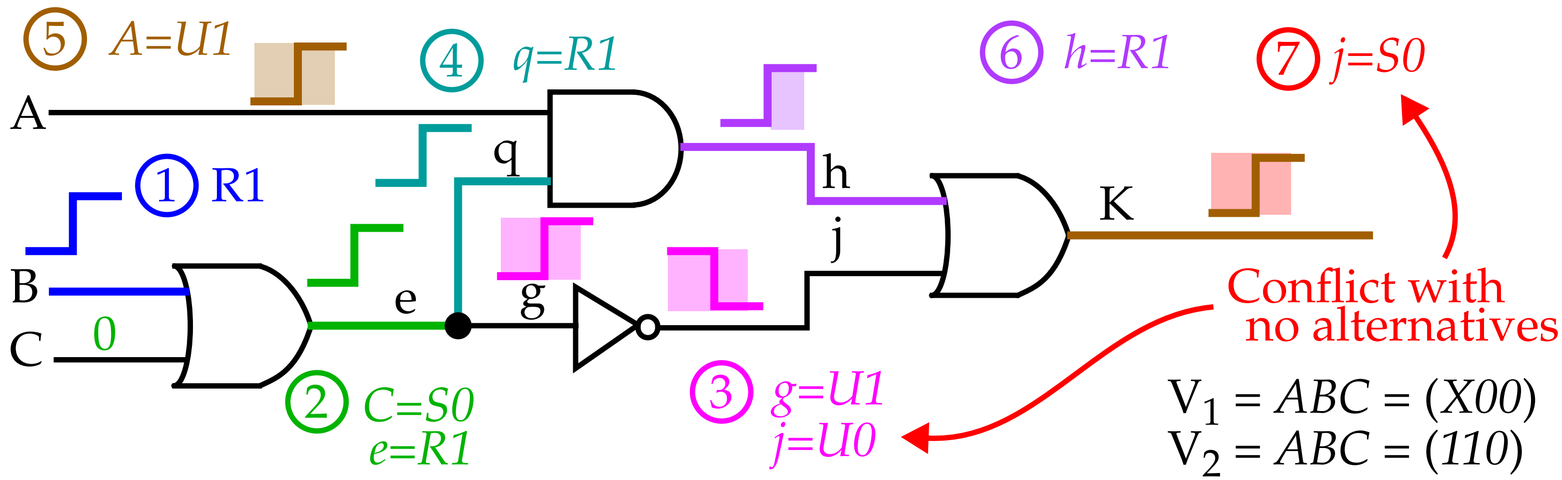
The fault is called a *singly-testable path-delay fault* in cases where a test exists.

Path Delay Fault Test Generation

To generate test for falling transition on path P3:



P3's falling test is **robust**, i.e., it cannot be invalidated by P2's delay.



P2's rising test is **non-robust**, delay along P3 can invalidate.

Path Delay Fault Test Generation

Previous procedure terminates showing no **robust** test is possible, so we are stuck with a non-robust test for the rising transition of P2.

Single input change (SIC): a simpler method of generating **non-robust** tests.

Use a combinational ATPG algorithm to *statically sensitize* the entire path for V_2.

V_1 is obtained by changing one bit in V_2 that corresponds to the origin of the path.

Validatable non-robust tests

It is desirable to find as many robust tests as possible.

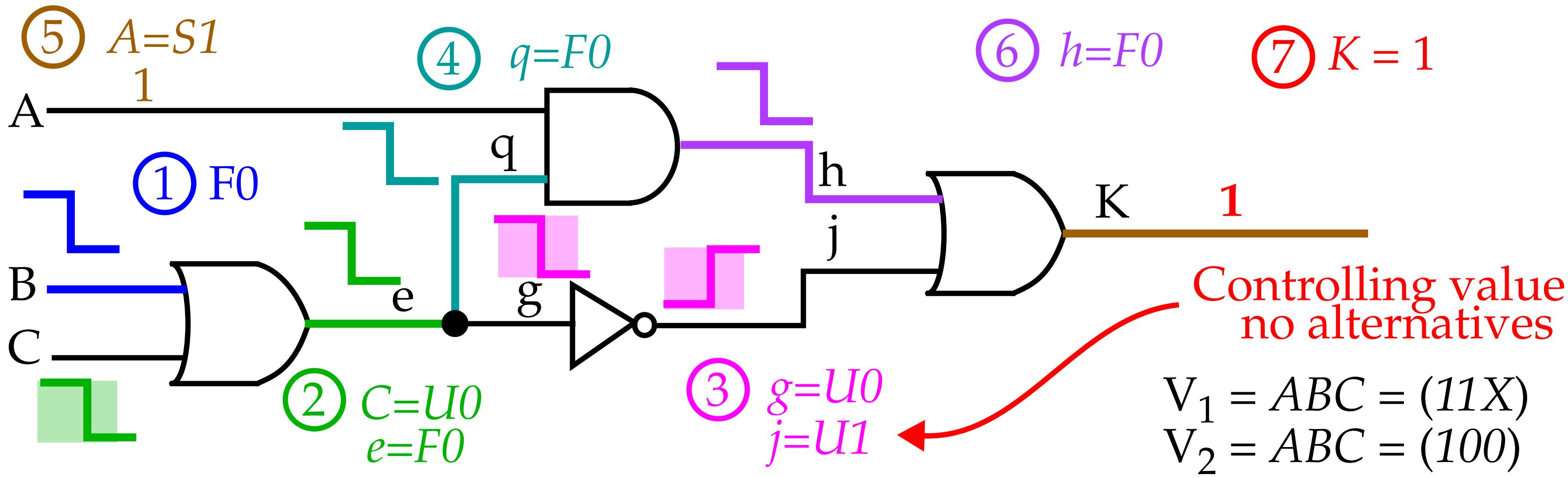
The presence of robust tests for some paths *improves* the reliability of non-robust tests for other paths.

For example, there are 6 robustly testable paths in the previous circuit.

With these tests, the rising transition test of P2 is as good as a robust test.

Untestable

Some paths are not even **non-robust testable**.



(P2: B-e-q-h-K)

P2 falling has no delay test.