Logic Synthesis and Verification

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Timing Analysis & Optimization

Reading:

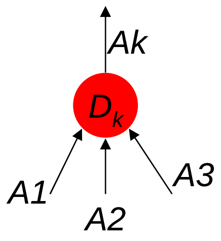
Logic Synthesis in a Nutshell

Sections 5 & 6

part of the following slides are by courtesy of Andreas Kuehlmann

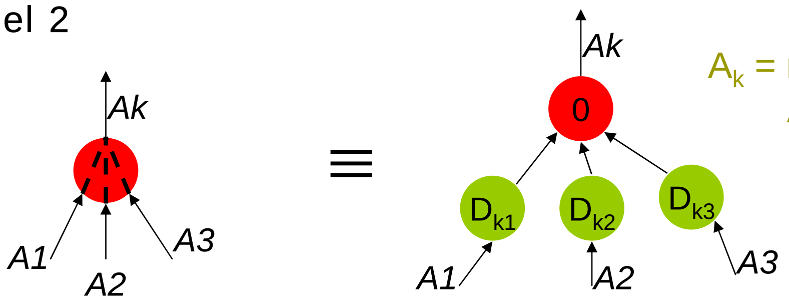
Delay Models

- Model 1



A_k = arrival time = $\max\{A_1,A_2,A_3\} + D_k$, where D_k is the delay at node k, parameterized according to function f_k and fanout node k

- Model 2

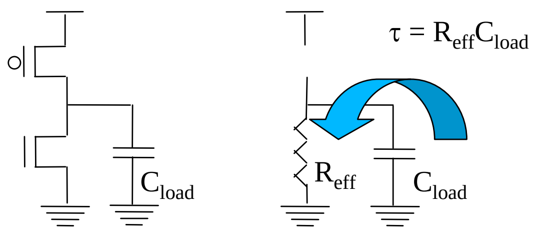


$A_k = \max\{A_1+D_{k1}, A_2+D_{k2}, A_3+D_{k3}\}$

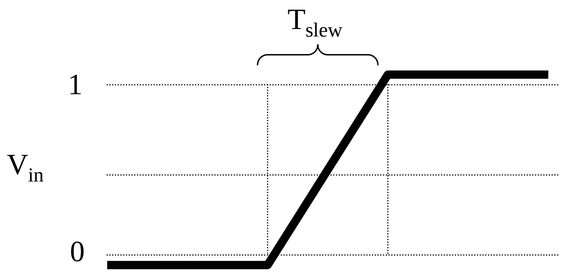
Can also have different times for rise time and fall time

Gate Delay

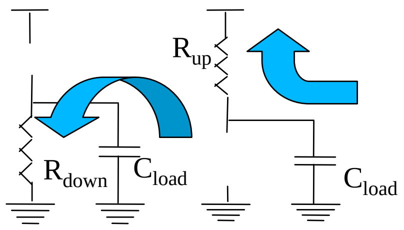
- The delay of a gate depends on its circuit context, and in particular:
  1. Output Load
     - Capacitive loading ∝ the charges that a gate must move to swing the output voltage
     - Due to interconnect and logic fanout
  2. Input Slew
     - Slew = transition time
     - Slower transistor switching → longer delay, longer output slew



An inverter *e.g. output 1→0*



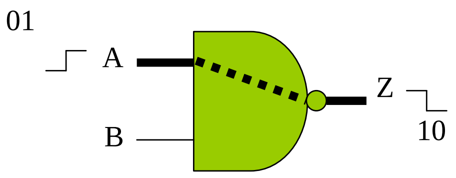
Rising and Falling Edges



- Driving strengths of pull-up and pull-down networks may not be equivalent
  - Rising and falling outputs may have different delays
- *Idea*: maintain the latest/earliest arrival time of rising and falling transitions independently
  - Unateness of each input/output pair is encoded in the library
    - Positively unate inputs: only trigger output transitions in the same direction (e.g. an AND gate)
    - Negatively unate inputs: only trigger output transitions in the opposite direction (e.g. a NOR gate)
    - A transition on a binate input could trigger either direction on an output (e.g. an XOR gate)
  - Only considers local functionality, but allows a less conservative analysis

Timing Library

- Timing library contains all relevant information about each standard cell
  - E.g., pin direction, clock, pin capacitance, etc.
- Delay (fastest, slowest, and often typical) and output slew are encoded for each input-to-output path and each pair of transition directions
- Values typically represented as 2 dimensional look-up tables (of output load and input slew)
  - Interpolation is used



```
Path(
   inputPorts(A),
   outputPorts(Z),
   inputTransition(01),
   outputTransition(10),
   “delay_table_1”,
   “output_slew_table_1”
);
```

“delay_table_1”

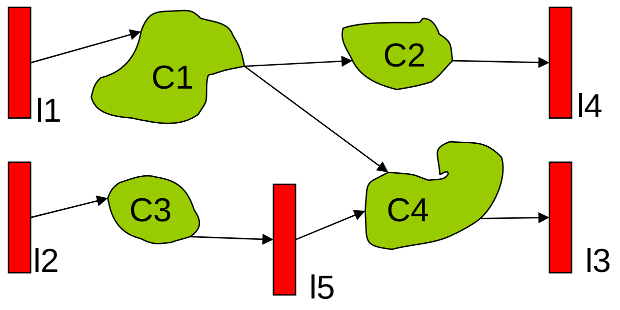
Output load (nF)

Input slew (ns)

	1.0	2.0	4.0	10.0
0.1	2.1	2.6	3.4	6.1
0.5	2.4	2.9	3.9	7.2
1.0	2.6	3.4	4.0	8.1
2.0	2.8	3.7	4.9	10.3

Sequential Circuit

- Arrival times known at l_1, l_2, and l_5
- Required times known at l_3, l_4, and l_5
- Delay analysis gives arrival and required times (hence slacks) for C_1, C_2, C_3, C_4



Arrival Time Calculation

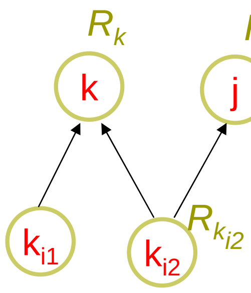
```
// level of PI nodes initialized to 0,
// the others are set to -1.
// Invoke LEVEL from PO
Algorithm LEVEL(k) { // levelize nodes
  if( k.level != -1)
    return(k.level)
  else
    k.level = 1+max{LEVEL(k_i)|k_i ∈ fanin(k)}
  return(k.level)
}

// Compute arrival times:
// Given arrival times on PI's
Algorithm ARRIVAL() {
  for L = 1 to MAXLEVEL
    for {k|k.level = L}
      A_k = MAX{A_ki} + D_k
}
```

Required Time Calculation

- Required time:
  - Given required times on primary outputs
  - Traverse in reverse topological order (i.e. from POs to PIs)
  - If (k_i, k) is an edge between k_i and k, the required time of this edge is $R_{k_i,k} = R_k - D_k$
  - The required time of output of node k is $R_k = \min \{ R_{k,k_j} \mid k_j \in \text{fanout}(k) \}$

```
// Compute required times:
// Given required times on PO's
Algorithm REQUIRED() {
  for L = MAXLEVEL-1 to 0
    for {k|k.level = L}
      $R_k = \text{MIN}\{R_{k,ki}\} - D_k$
}
```



Slack

- Slack:
  - Slack at the output of node k is $S_k = R_k - A_k$

    Since $R_{ki,k} = R_k - D_k$

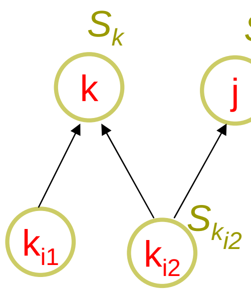
    $S_{ki,k} = R_{ki,k} - A_{ki}$

    $S_{ki,k} + A_{ki} = R_k - D_k = S_k + A_k - D_k$

    Since $A_k = \max \{A_{kj}\} + D_k$

    $S_{ki,k} = S_k + \max \{A_{kj}\} - A_{ki}$ $\quad k_j, k_i \in \text{fanin}(k)$

    $S_{ki} = \min\{S_{ki,j}\}$ $\quad j \in \text{fanout}(k_i)$



- Note:
  - Each edge of a circuit graph has a slack and required time
  - Negative slack is bad

Static Timing Analysis

- A static critical path of a Boolean network is a path P = $\{n_1, n_2, \dots, n_p\}$, where $S_{n_k, n_{k+1}} < 0$
  - Note:
    - If a node *n* is on a static critical path, then at least one of the fanin edges of *n* is critical. Hence, all critical paths reach from an input to an output.
    - There may be several critical paths

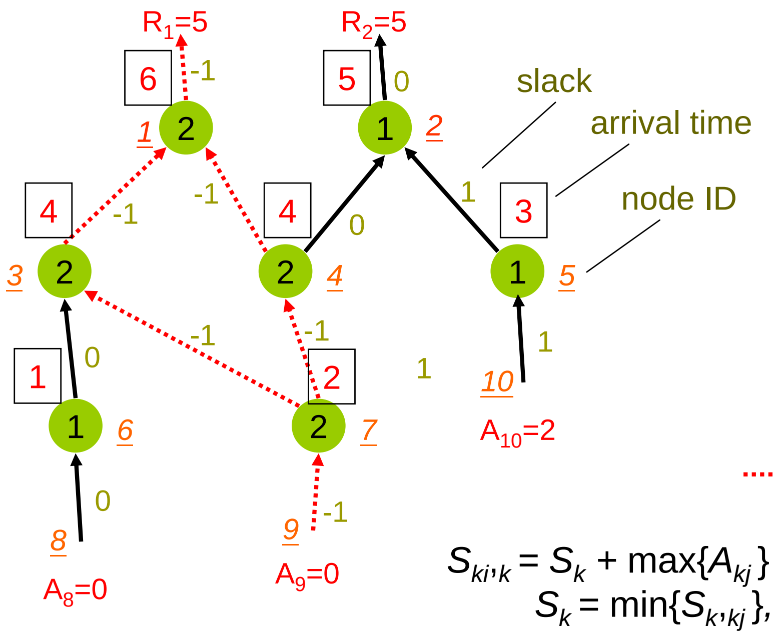
- Timing optimization is a min-max problem: minimize $\max\{-S_i, 0\}$

Static Timing Analysis

- Example

$A_1 = 6$ $R_1 = 5$
$A_2 = 5$ $R_2 = 5$

$S_1 = -1$	$R_3 = 3$
$S_2 = 0$	$R_7 = 1$
$S_{3,1} = -1$	$R_9 = -1$
$S_{4,1} = -1$	
$S_{4,2} = 0$	
$S_{5,2} = 1$	
$S_{6,3} = 0$	
$S_{7,3} = -1$	
$S_{7,4} = -1$	
$S_{7,5} = 1$	
$S_{8,6} = 0$	
$S_{9,7} = -1$	



······ critical path edges

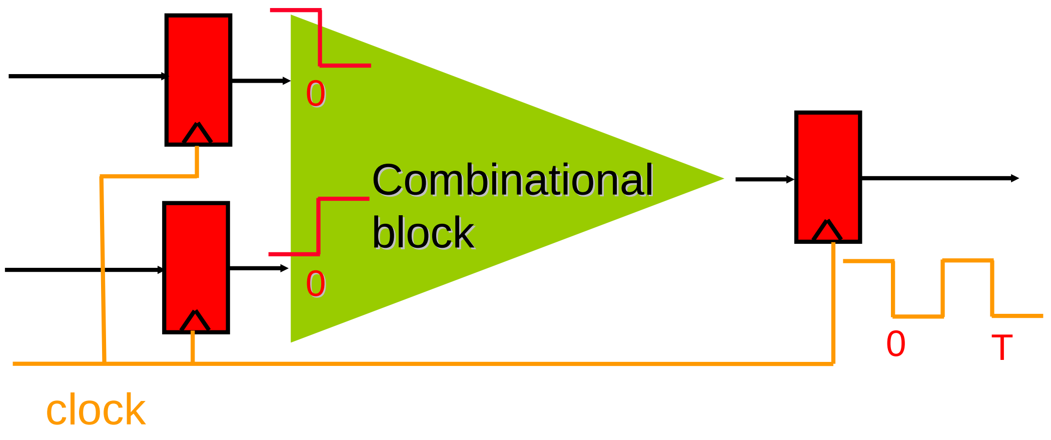
$$S_{k_i,k} = S_k + \max\{A_{k_j}\} - A_{k_i},\ k_j, k_i \in \text{fanin}(k)$$
$$S_k = \min\{S_{k,k_j}\},\ k_j \in \text{fanout}(k)$$

Static Timing Analysis

- Problems
  - We want to determine the true critical paths of a circuit in order to:
    - determine the minimum cycle time that a circuit will function correctly
    - identify critical paths for performance optimization - don't want to try to optimize wrong (non-critical) paths
  - Implications:
    - Don't want false paths (produced by static delay analysis)
    - Delay model is a worst case model
      - Need to ensure correctness for case where ith gate delay ≤ D_i^{Max}

Functional Timing Analysis

- Functional timing analysis estimates when the output of a given circuit gets stable



Functional Timing Analysis

- Motivation
  - Timing verification
    - Verifies whether a design meets a given timing constraint
      - E.g., cycle-time constraint
  - Timing optimization
    - Needs to identify critical portion of a design for further optimization
    - Critical path identification
  - In both applications, accurate analysis is desirable

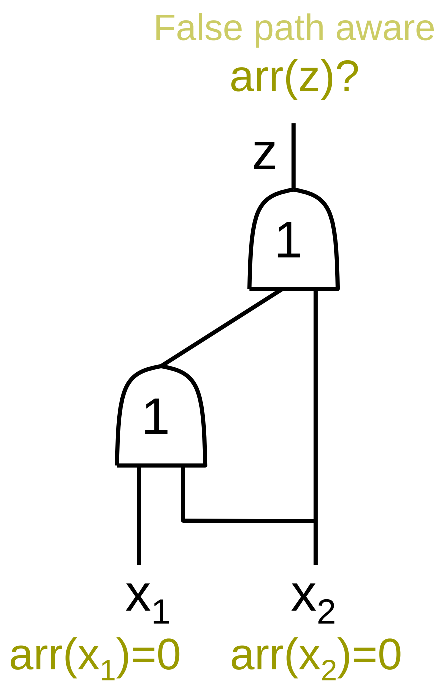
Gate-Level Timing Analysis

- Naïve approach - Simulate all input vectors with SPICE
  - Accurate, but too expensive

- Gate-level timing analysis (our focus)
  - Less accurate than SPICE due to the level of abstraction, but much more efficient
  - Scenario:
    - Gate/wire delays are pre-characterized (accuracy loss)
    - Perform timing analysis of a gate-level circuit assuming the gate/wire delays

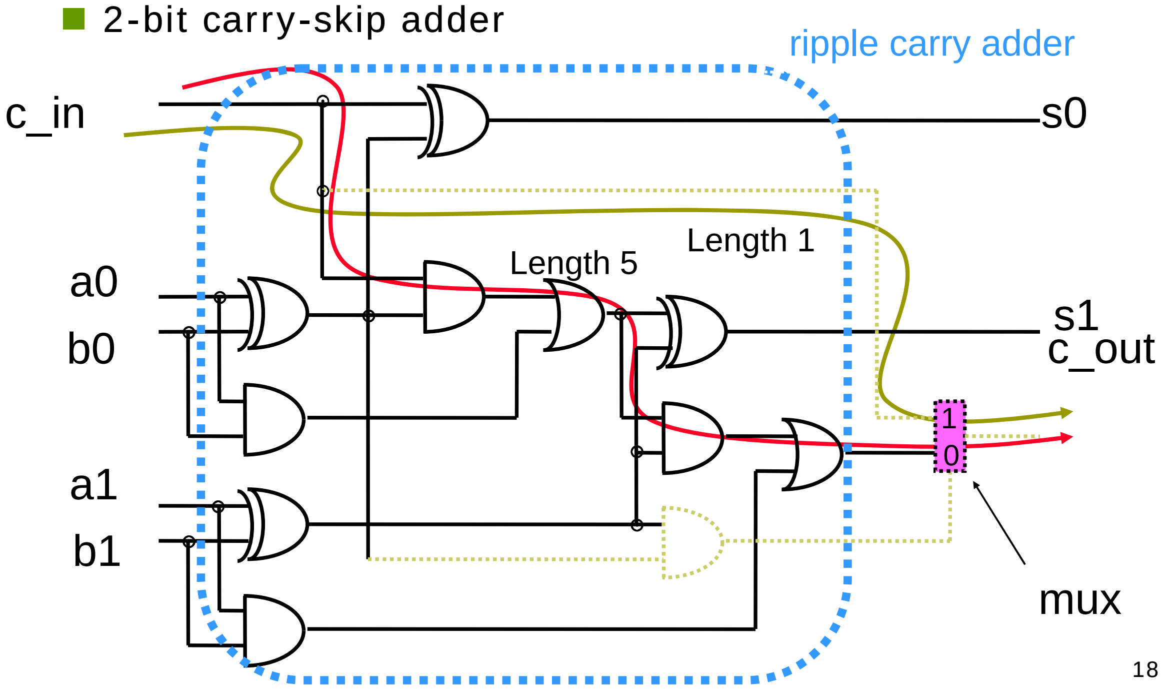
Gate-Level Timing Analysis

- A naive approach is topological analysis
  - Easy longest-path problem
  - Linear in the size of a network
- Not all paths can propagate signal events
  - False paths
  - If all longest paths are false, topological analysis gives delay over-estimation
- Functional timing analysis = false-path-aware timing analysis
  - Compute false-path-aware arrival time



Gate-Level Timing Analysis

- Example
  - 2-bit carry-skip adder

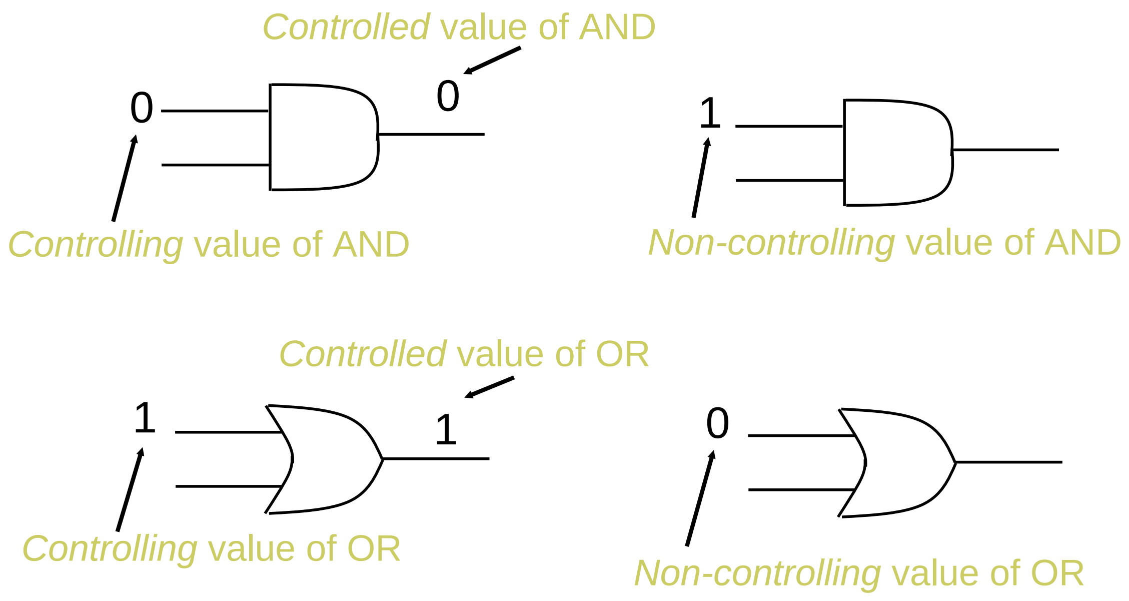


False Path Analysis

- Is a path responsible for circuit delay?
  - If the answer is no, can ignore the path for delay computation
- Check the falsity of long paths until we find the longest true path
  - How can we determine whether a path is a false path?
- Delay under-estimation is unacceptable
  - Can lead to overlooking timing violation
- Delay over-estimation is acceptable, but not desirable
  - Topological analysis may yield over-estimation, but never under-estimation

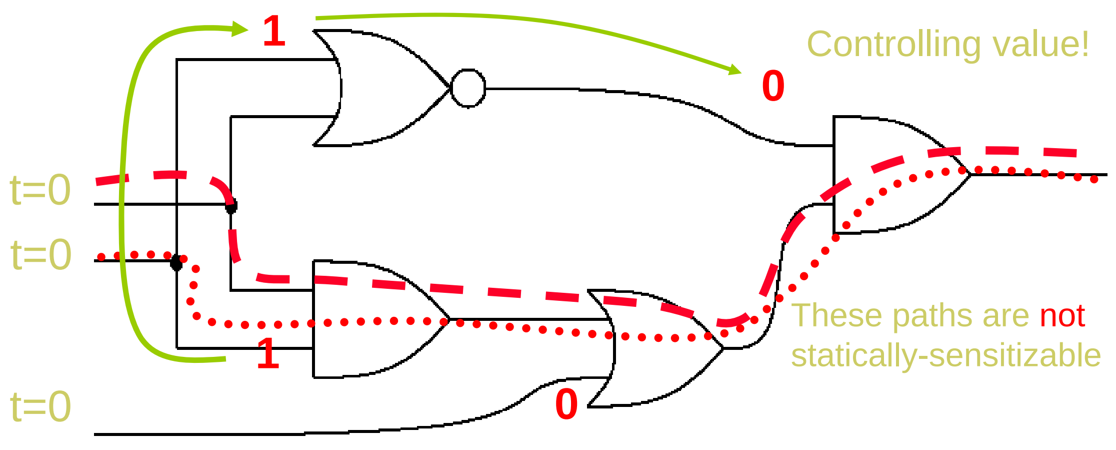
False Path Analysis

- Controlling and non-controlling values



False Path Analysis
Static Sensitization

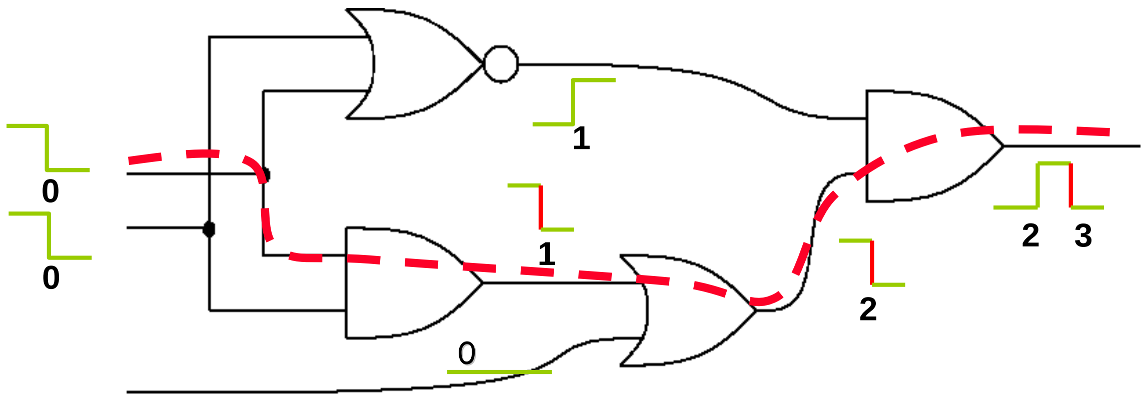
- Static sensitization
  - A path is *statically-sensitizable* if there exists an input vector such that all the side-inputs to the path are of non-controlling values
    - This is independent of gate delays



The longest true path is of length 2?

False Path Analysis
Static Sensitization

- Example
  - The (dashed) path is responsible for delay!
  - Delay under-estimation by static sensitization (delay = 2 when true delay = 3)
    - incorrect condition

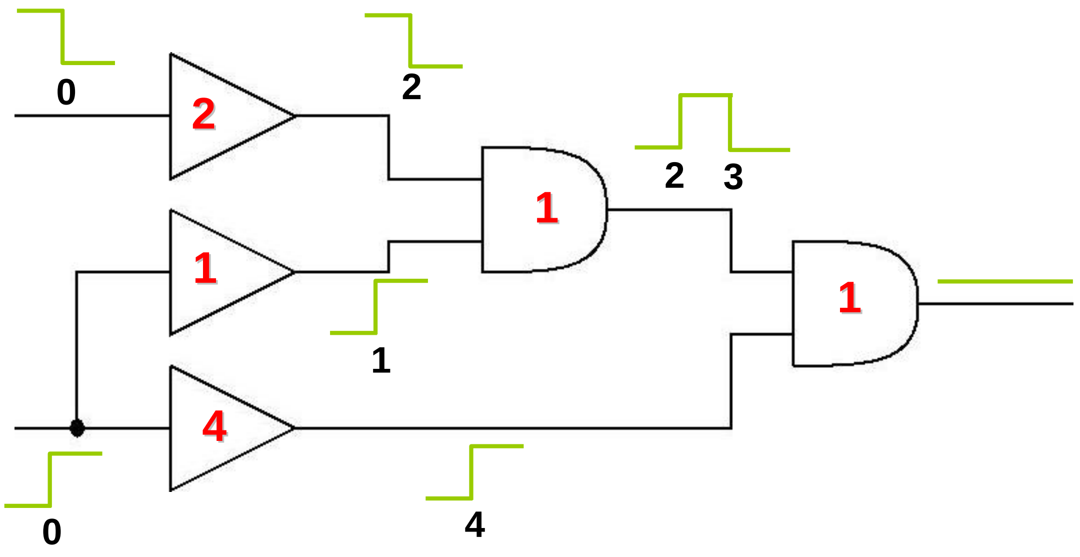


False Path Analysis
Static Sensitization

- Problem: The idea of forcing non-controlling values to side inputs is okay, but timing was ignored
  - The same signal can have a controlling value at one time and a non-controlling value at another time

- How about timing simulation as a correct method?

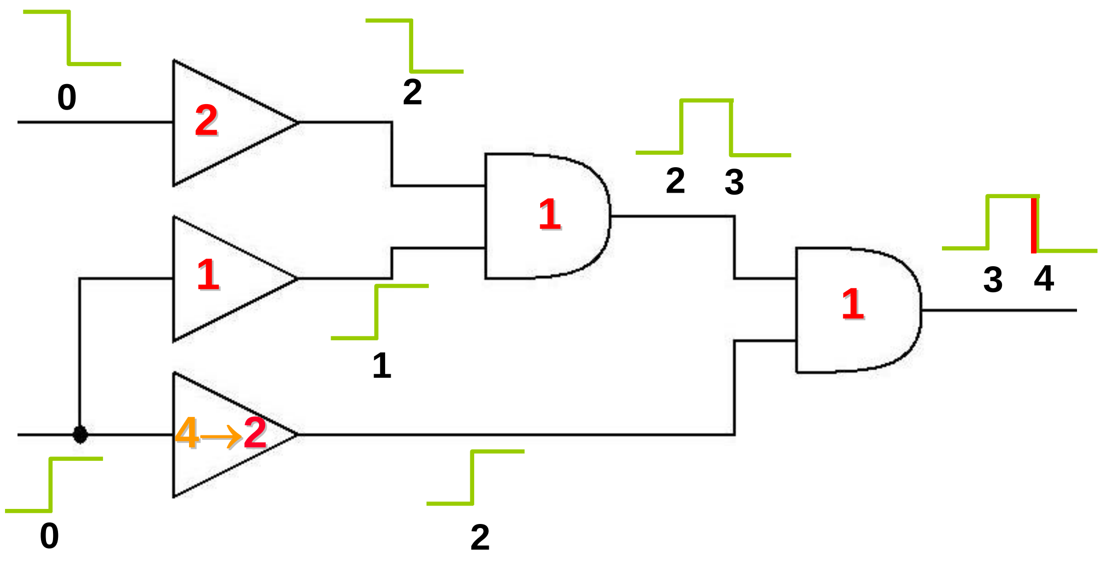
False Path Analysis
Timing Simulation



Implies delay = 0 under input vector (0,1)

BUT!

False Path Analysis
Timing Simulation



Implies delay = 4 under the same input (0,1) as before

False Path Analysis
Timing Simulation

- Problem: If gate delays are reduced, delay estimates can increase
- Not acceptable since
  - Gate delays are just upper-bounds, actual delay is in [0,d]
    - Delay uncertainty due to manufacturing
  - We are implicitly analyzing a family of circuits where gate delays are within the upper-bounds

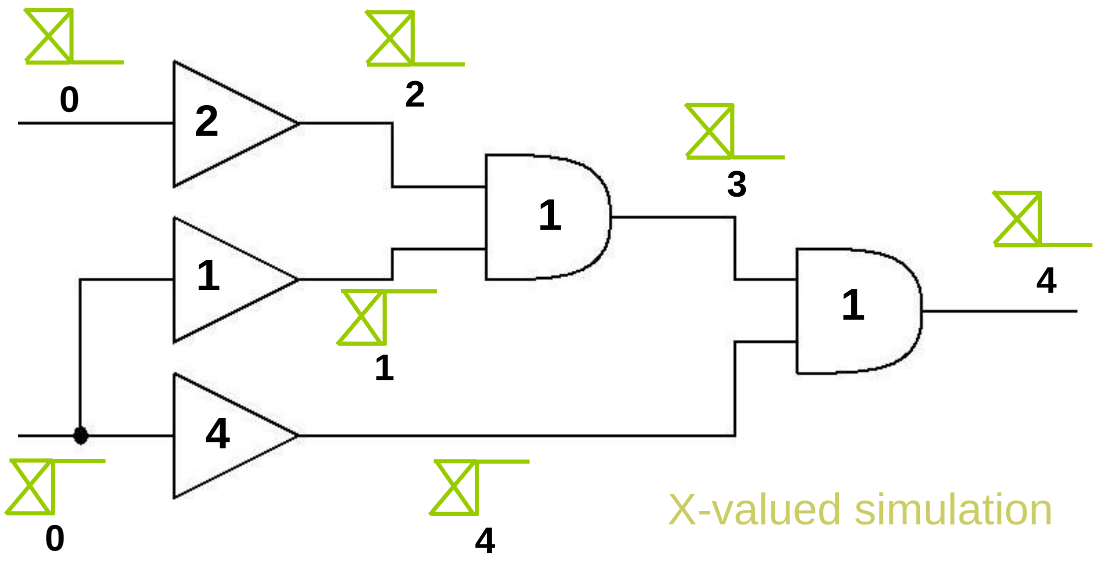
False Path Analysis
Timing Simulation

- Definition: Given a circuit C and a delay estimation method delay_estimate, if
  - C* is obtained from C by reducing some gate delays, and
  - delay_estimate(C*) ≤ delay_estimate(C),

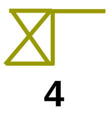
  then delay_estimate has *monotone speedup*

- Timing simulation does not have such a property

False Path Analysis
Timing Simulation



X-valued simulation



means that the rising signal occurs anywhere between $t = -\infty$ and $t = 4$.

False Path Analysis
Timing Simulation

- Timed 3-valued (0,1,X) simulation
  - called X-valued simulation
  - monotone speedup property is satisfied
- Underlying model of
  - floating mode condition
    - Applies to “simple gate” networks only
  - viability
    - Applies to general Boolean networks

False Path Analysis
Timing Simulation

- Checking the falsity of every path explicitly is too expensive due to the exponential number of paths
- Modern approach:
  1. Start:
     $L = L_{top}$ = topological longest path delay
     $L_{old} = 0$
  2. Binary search:

```
if (Delay(L)) (*)     $L_d = |L - L_{old}|/2$, $L_{old} = L$, $L = L + L_d$
else                  $L_d = |L - L_{old}|/2$, $L_{old} = L$, $L = L - L_d$
if ($L > L_{top}$ or  $L_d <$ threshold)      $L = L_{old}$, done
```

(*) Delay(L) = 1 if there is an input vector under which an output gets stable only at time *t* where $L \le t$?
Can be reduced to
- a SAT or timed-ATPG problem

SAT-Based False Path Analysis

- Decision problem:

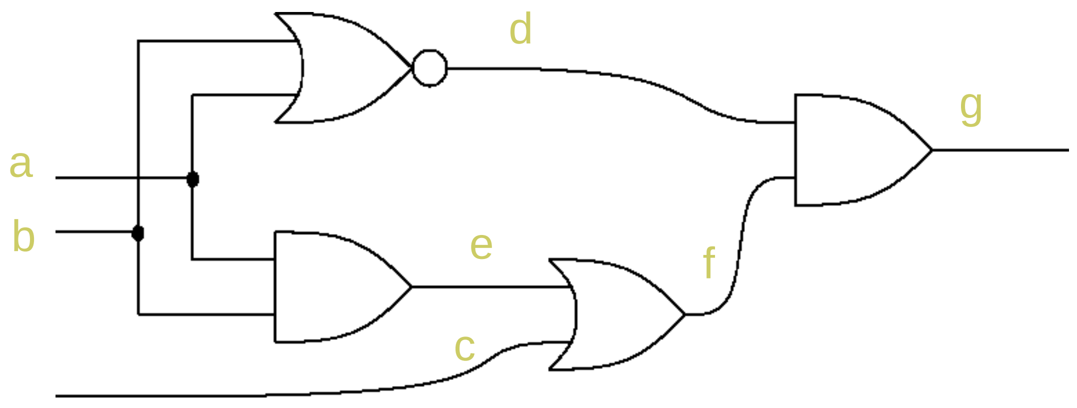
  Is there an input vector under which the output gets stable only after t = T ?
- Idea:
  1. Characterize the set of all input vectors S(T) that make the output stable no later than t = T
  2. Check if S(T) contains S (all possible input vectors)

  Can be solved as a SAT problem:

  Is S \ S(T) empty? - set difference + emptiness checking
  - Let F and F(T) be the characteristic functions of S and S(T)
  - Is F $\wedge\neg$F(T) satisfiable?

SAT-Based False Path Analysis

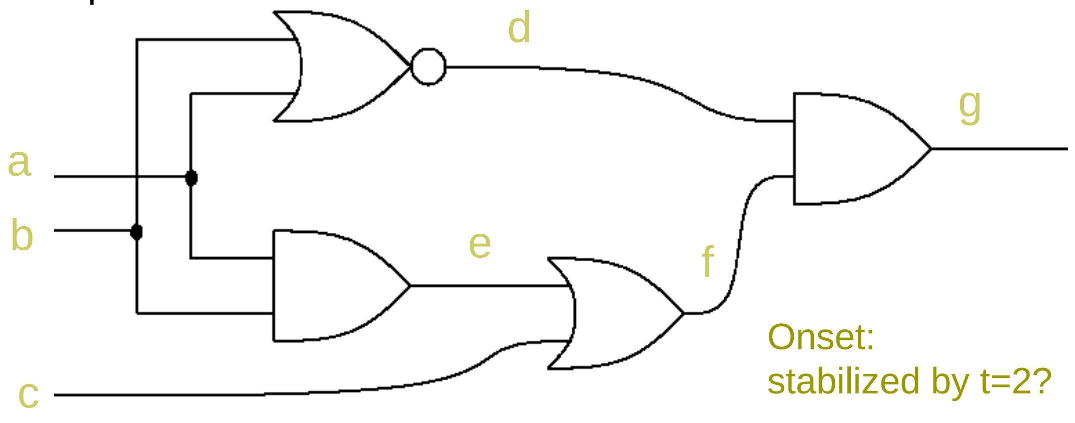
- Example



Assume all the PIs arrive at t = 0, all gate delays = 1
Is the output stable time t > 2?

SAT-Based False Path Analysis

- Example

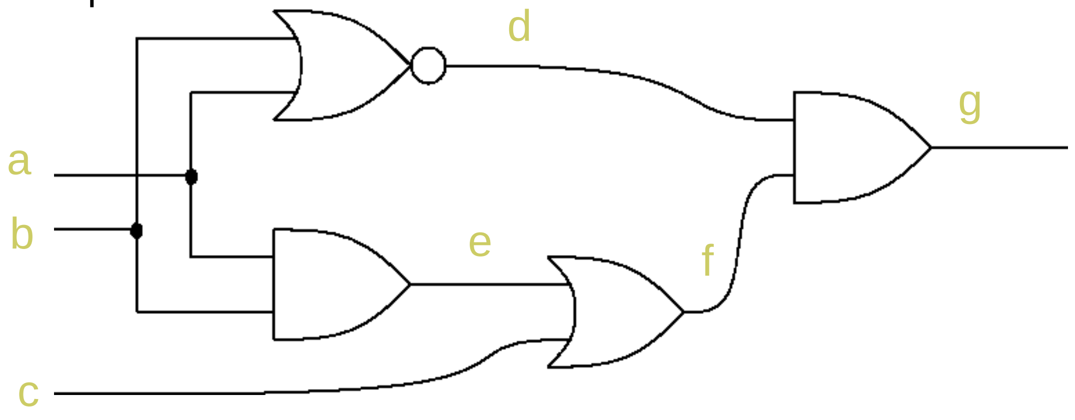


Onset:
stabilized by t=2?

- g(1,t=2) : the set of input vectors under which g gets stable to value = 1 no later than t =2
- g(1,t=2) = d(1,t=1) ∩ f(1,t=1) = (a(0,t=0) ∩ b(0,t=0)) ∩ (c(1,t=0) ∪ e(1,t=0)) = ¬a ¬b (c ∪ ∅) = ¬a ¬b c = S1(t=2)
- g(1,t=∞) = onset = ¬a ¬b c = g(1,t=2) = S1

SAT-Based False Path Analysis

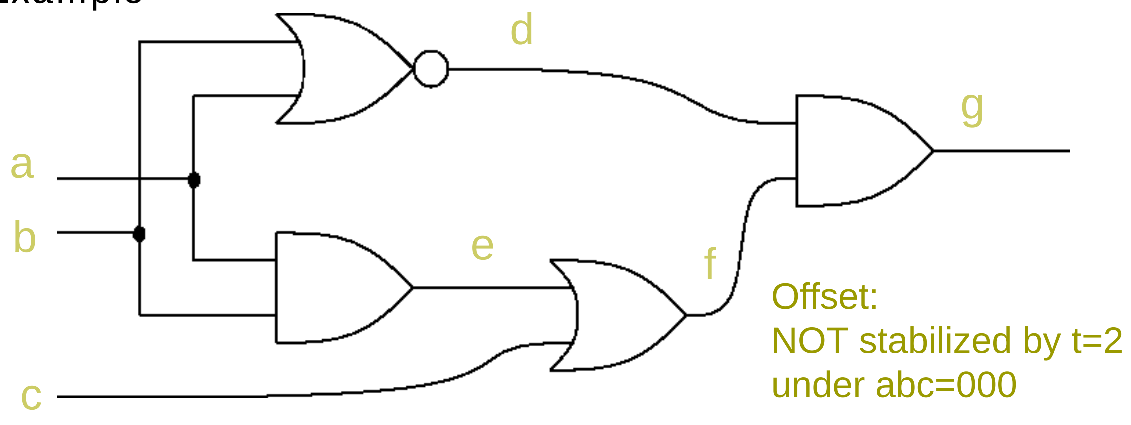
- Example



- g(0,t=2) : the set of input vectors under which g gets stable to value = 0 no later than t=2
- g(0,t=2) = d(0,t=1) ∪ f(0,t=1) = (a(1,t=0) ∪ b(1,t=0)) ∪ (c(0,t=0) ∩ e(0,t=0)) = (a+b) + (¬c ∩ ∅) = a+b = S0(t=2)
- g(0,t=∞) = offset = a+b+¬c = S0

SAT-Based False Path Analysis

- Example



- g(0,t=2) : the set of input vectors under which g gets stable to 0 no later than t=2
- g(0,t=2) = a+b
- g(0,t=∞) = offset = a+b+¬c
- g(0,t=∞) \ g(0,t=2) = (a+b+¬c) ¬(a+b) = ¬a¬b¬c satisfiable

Timing Analysis

- Summary
  - False-path-aware arrival time analysis is well-understood
    - Practical algorithms exist
  - Remaining problems
    - Incremental analysis (make it so that a small change in the circuit does not make the analysis start all over)
    - Integration with logic optimization
    - DSM issues such as cross-talk-aware false path analysis

Timing Optimization

Several factors affecting circuit delay:

- Technology
  - Design type (e.g. domino, static CMOS, etc.)
  - Gate type
  - Gate size
- Circuit structure
  - Length of computation paths
  - False paths
  - Buffering
- Electrical parasitics
  - Wire loads
  - Layout

Timing Optimization

- Problem statement

  Given:
  - Initial circuit function description
  - Library of primitive functions
  - Performance constraints (arrival/required times)

  Generate:
  - An implementation of the circuit using the primitive functions, such that:
    - performance constraints are met
    - circuit area is minimized

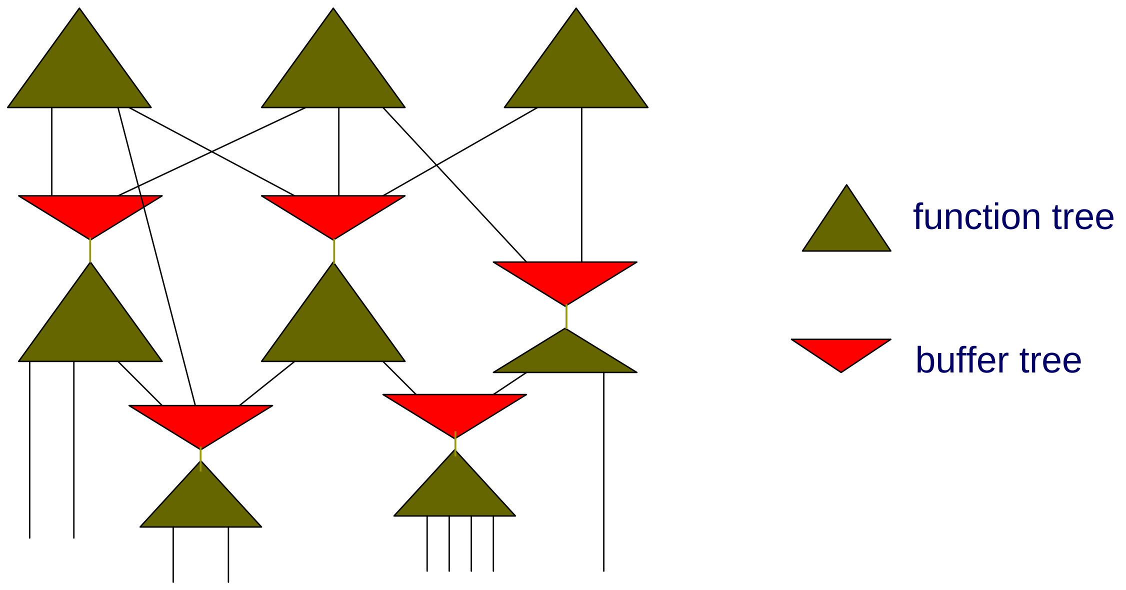
Timing Optimization

- Design flow

Behavioral description	Behavior optimization (scheduling)
Logic and latches	RTL synthesis
Logic equations	Logic synthesis •Technology independent •Technology mapping
Gate netlist	•Gate library •Timing constraints •Delay models
Layout	Timing-driven place and route

Timing Optimization

- Buffered circuit structure



Timing Optimization

- Circuit restructuring
  - Reschedule operations to reduce computation time
- Timing-driven technology mapping
  - Selection of gates from library
    - Minimum delay
      - Similar to area minimization under the load independent model
    - Minimize delay and area
- Implementation of buffer trees
- Gate/wire sizing
- Constant delay synthesis

Timing Optimization

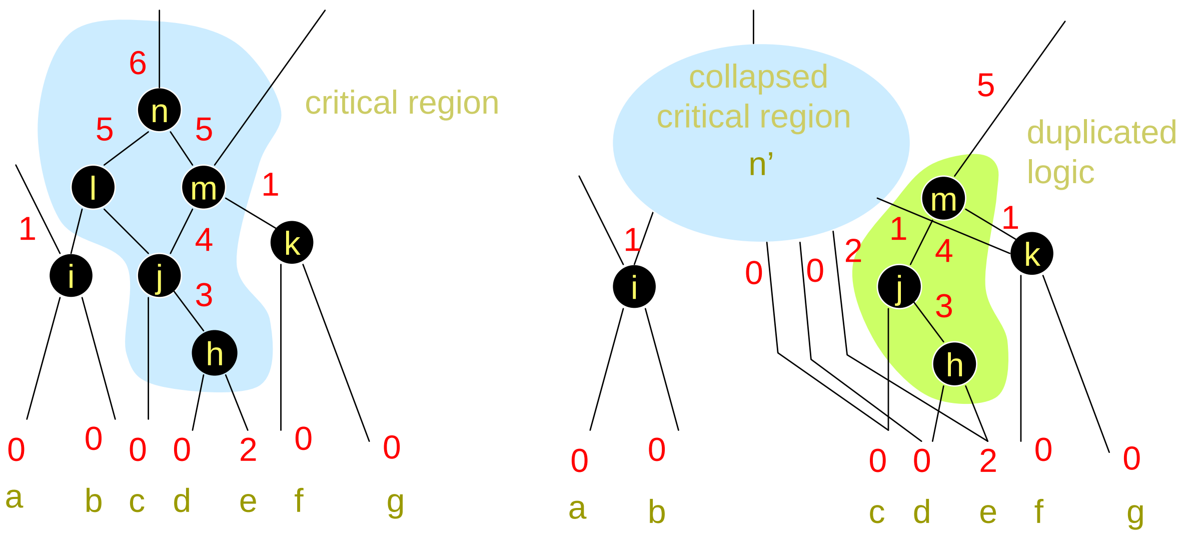
- Circuit restructuring
  - Global: Reduce depth of entire circuit
    - Partial collapsing
    - Boolean simplification
  - Local: Mimic optimization techniques in adders
    - Carry lookahead (THR tree-height reduction)
    - Conditional sum (GST transformation)
    - Carry bypass (GBX transformation)

Timing Optimization

- Circuit restructuring
  - Performance measured by logic levels, sensitisable paths, technology-dependent delays
  - Level-based optimization
    - Tree height reduction
    - Partial collapsing and simplification
    - Generalized select transform
  - Sensitisable path based optimization
    - Generalized bypass transform

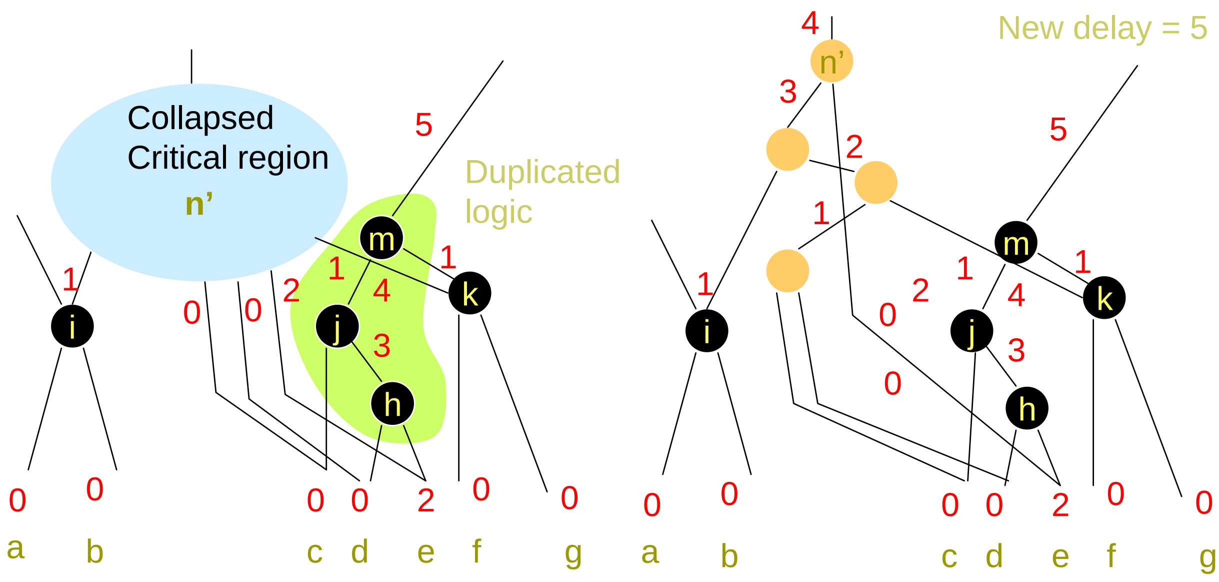
Timing Optimization

- Tree height reduction



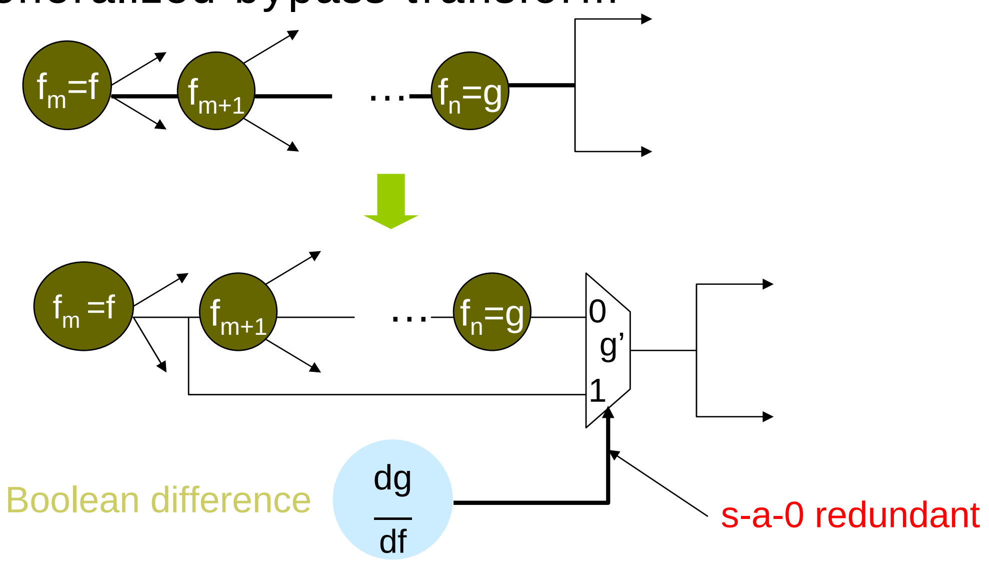
Timing Optimization

- Tree height reduction



Timing Optimization

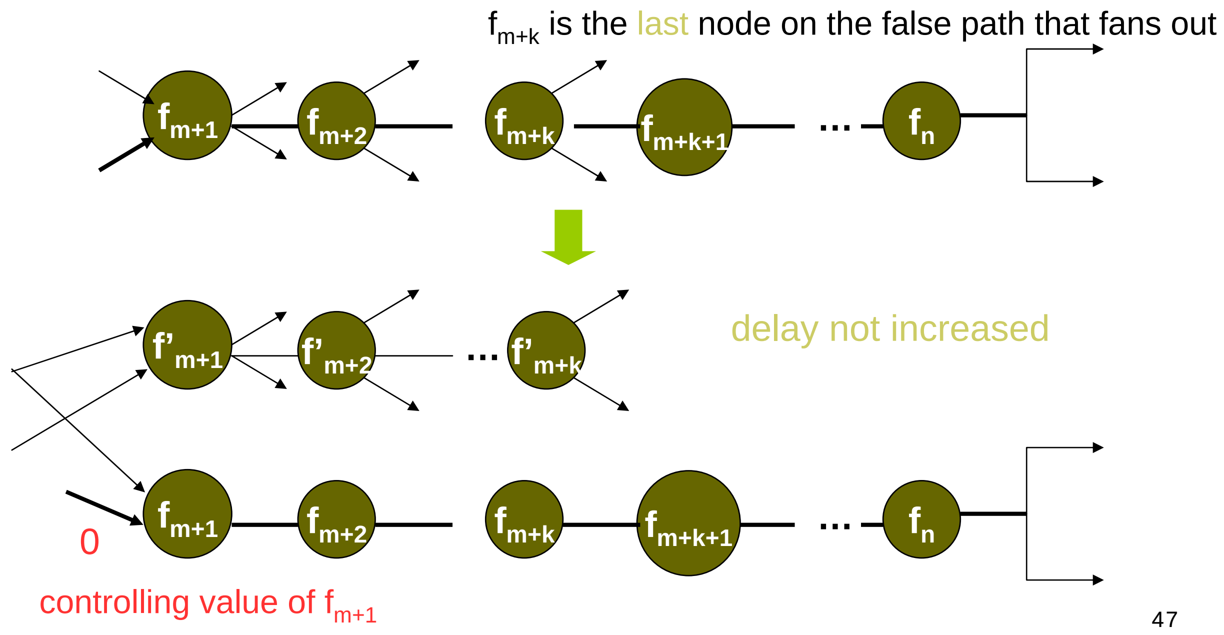
- Generalized bypass transform



- Make critical path false to bypass critical logic and speed up circuit

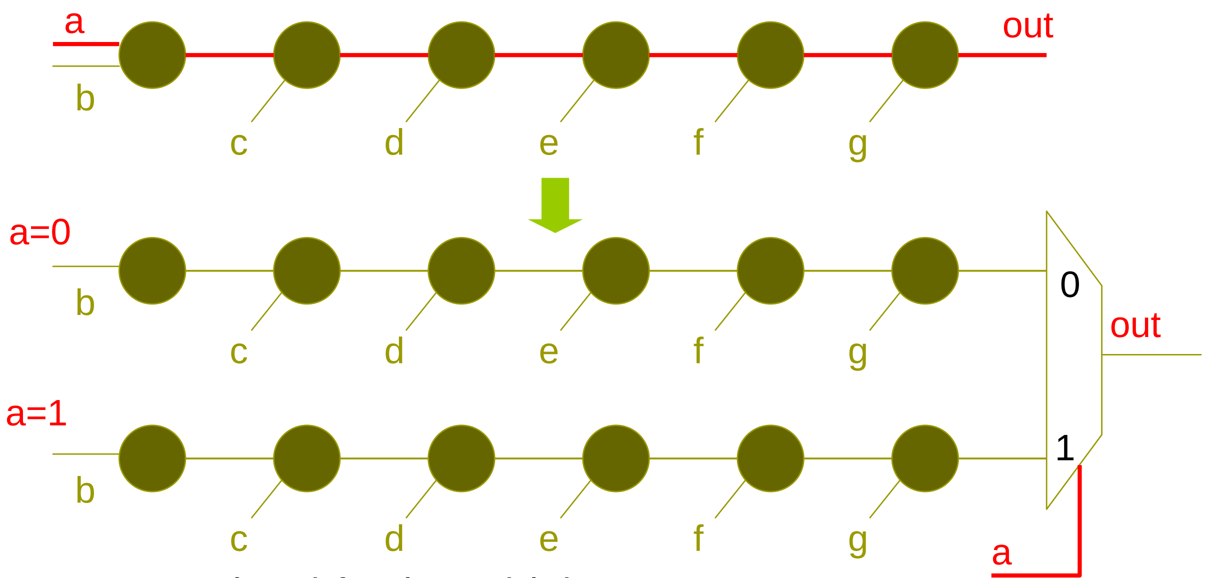
Timing Optimization

- False path removal by logic duplication



Timing Optimization

- Generalized select transform



- Late signal feeds multiplexor

Timing Optimization

- Summary
  - There are various methods for delay optimization at different synthesis stages
    - No single technique dominates
    - Most techniques (except false path removal by logic duplication) ignore false paths when assessing the delay and critical regions