

Logic Synthesis and Verification

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Technology Mapping

Reading:

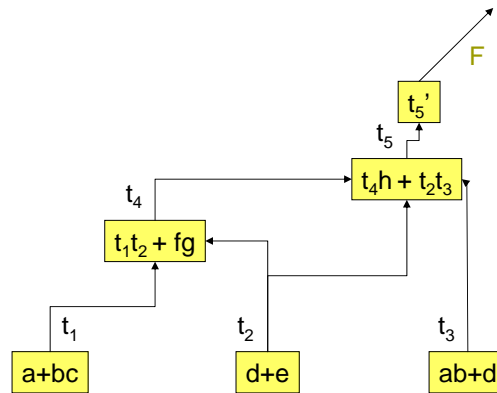
Logic Synthesis in a Nutshell
Section 4

most of the following slides are by
courtesy of Andreas Kuehlmann

Technology Independent Optimization

Example

$$\begin{aligned} t_1 &= a + bc \\ t_2 &= d + e \\ t_3 &= ab + d \\ t_4 &= t_1 t_2 + fg \\ t_5 &= t_4 h + t_2 t_3 \\ F &= t_5' \end{aligned}$$

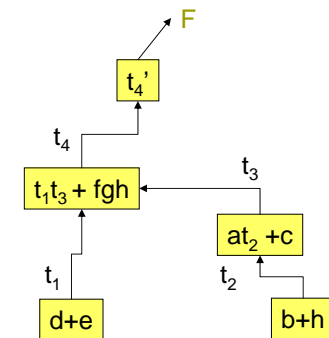


An unoptimized set of logic equations consisting of 17 literals

Technology Independent Optimization

Example (cont'd)

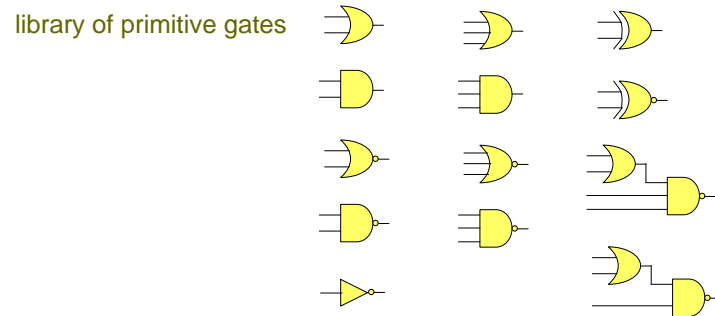
$$\begin{aligned} t_1 &= d + e \\ t_2 &= b + h \\ t_3 &= at_2 + c \\ t_4 &= t_1 t_3 + fgh \\ F &= t_4' \end{aligned}$$



An optimized set of logic equations consisting of 13 literals

Technology Mapping

- Implement an optimized Boolean network using a set of pre-designed and pre-characterized gates from a *library*
 - Each gate has a *cost* (e.g. area, delay, power, etc.)



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Technology Mapping

- Two approaches:
 - Rule based: LSS
 - Algorithmic: DAGON
 - Represent the netlist to be mapped in terms of a selected set of base functions, e.g., {NAND2, INV}
 - Base functions from a *functionally complete* set
 - Such a netlist is called the *subject graph*
 - Each gate in the library is likewise represented using the base functions
 - Represent each gate in *all possible* ways
 - This generates *pattern graphs*

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Algorithmic Technology Mapping

- A *cover* is a collection of pattern graphs such that
 - every node of the subject graph is *contained* in one (or more) pattern graphs
 - each *input* required by a pattern graph is actually an *output* of some other pattern graph (i.e. the inputs of one gate must exist as outputs of other gates)
- For area minimization, the cost of the cover is the *sum of the areas* of the gates in the cover
- Technology mapping problem:

Find a *minimum cost covering* of the subject graph by choosing from the collection of pattern graphs for all the gates in the library

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Subject Graph

- Example

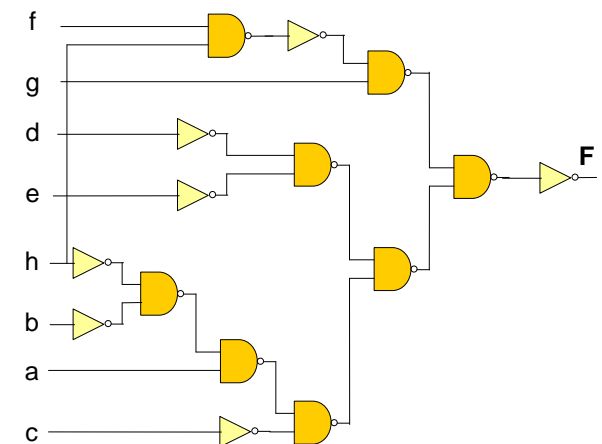
$$t_1 = d + e$$

$$t_2 = b + h$$

$$t_3 = at_2 + c$$

$$t_4 = t_1 t_3 + fgh$$

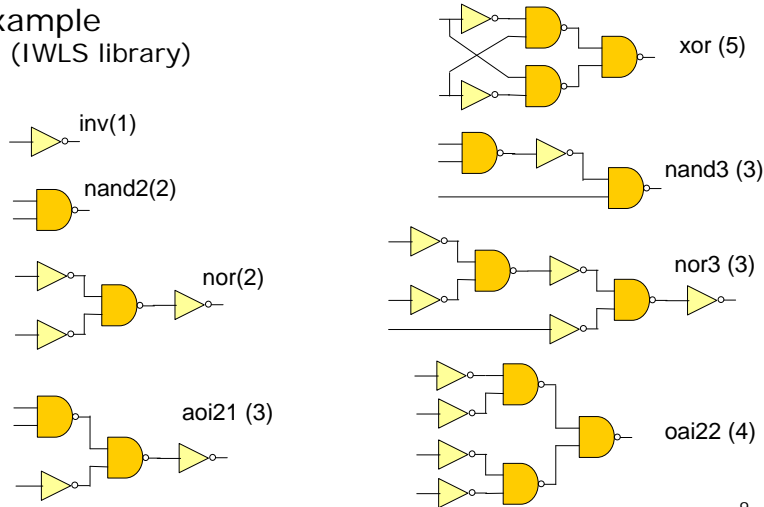
$$F = t_4'$$



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Pattern Graphs

- Example
 - (IWLS library)

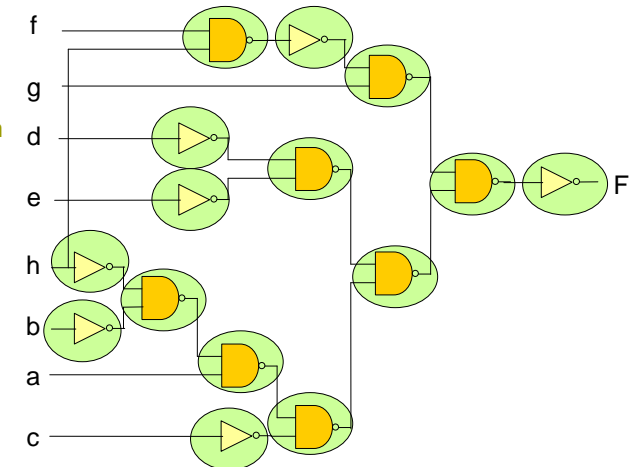


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Subject Graph Covering (1)

- Example

$$\begin{aligned}
 t_1 &= d + e \\
 t_2 &= b + h \\
 t_3 &= at_2 + c \\
 t_4 &= t_1t_3 + fgh \\
 F &= t_4'
 \end{aligned}$$



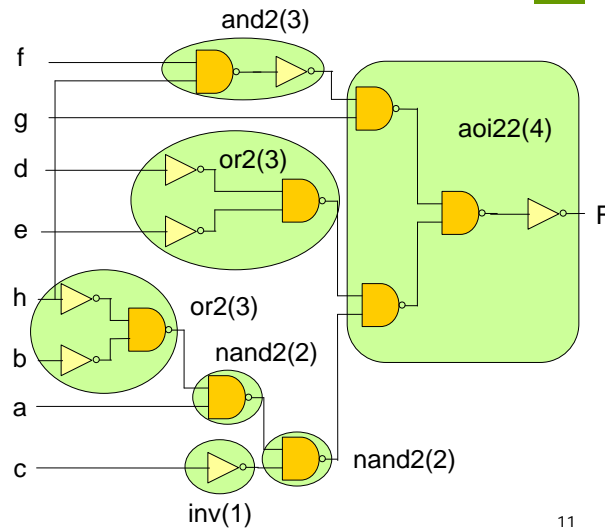
Total cost = 23

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Subject Graph Covering (2)

- Example

$$\begin{aligned}
 t_1 &= d + e \\
 t_2 &= b + h \\
 t_3 &= at_2 + c \\
 t_4 &= t_1t_3 + fgh \\
 F &= t_4'
 \end{aligned}$$



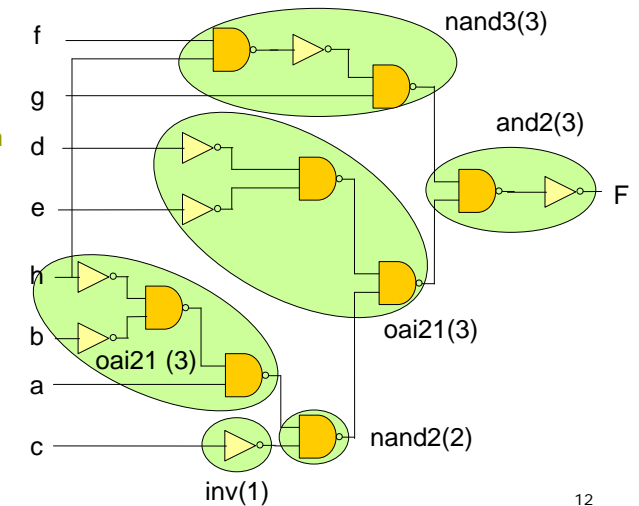
Total cost = 18

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Subject Graph Covering (3)

- Example

$$\begin{aligned}
 t_1 &= d + e \\
 t_2 &= b + h \\
 t_3 &= at_2 + c \\
 t_4 &= t_1t_3 + fgh \\
 F &= t_4'
 \end{aligned}$$



Total cost = 15

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DAG Covering

- Input:
 - Logic network after technology independent optimization
 - A library of gates with their costs
- Output:
 - A netlist of gates (from library) which minimizes total cost
- General Approach:
 - Construct a subject DAG (directed acyclic graph) for the network
 - Represent each gate in the target library by pattern DAG's
 - Find an optimal-cost covering of subject DAG using the collection of pattern DAG's

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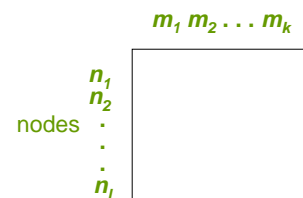
DAG Covering

- Complexity
 - NP-hard
 - Remains NP-hard even when the nodes have out-degree ≤ 2
 - If subject DAG and pattern DAG's are trees, efficient algorithms exist

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DAG Covering Binate Covering Approach

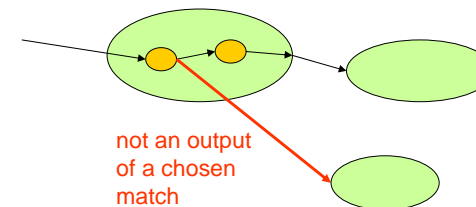
- Compute all possible matches $\{m_k\}$ of pattern graphs for each node in the subject graph
- Using a variable m_i for each match of a pattern graph in the subject graph, ($m_i = 1$ if match is chosen)
- Write a clause for each node of the subject graph indicating which matches cover this node (each node has to be covered)
 - e.g., if a subject node is covered by matches $\{m_2, m_5, m_{10}\}$, then the clause would be $(m_2 + m_5 + m_{10})$
- Repeat for each subject node and take the product over all subject nodes (CNF)



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DAG Covering Binate Covering Approach

- Any satisfying assignment guarantees that all subject nodes are covered, but does not guarantee that other matches chosen create outputs needed as inputs for a given match



- Resolve this problem by adding additional clauses

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DAG Covering Binate Covering Approach

- Let match m_i have subject nodes v_{i1}, \dots, v_{in} as its n inputs. If m_i is chosen, one of the matches that realizes v_{ij} must also be chosen for each input j (if j not a primary input).

- Let S_{ij} be the disjunctive expression in the variables m_k giving the possible matches which realize v_{ij} as an output node. Selecting match m_i implies satisfying each of the expressions S_{ij} for $j = 1 \dots n$. This can be written

$$(m_i \Rightarrow (S_{i1} \dots S_{in})) \Leftrightarrow (\bar{m}_i + (S_{i1} \dots S_{in})) \Leftrightarrow ((\bar{m}_i + S_{i1}) \dots (\bar{m}_i + S_{in}))$$

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DAG Covering Binate Covering Approach

- Also, one of the matches for each primary output of the circuit must be selected
- An assignment to variables m_i that satisfies the above covering expression is a legal graph cover
- For area optimization, each match m_i has a cost c_i that is the area of the gate the match represents
- The goal is a satisfying assignment with the least total cost
 - Find a least-cost prime:
 - if a variable $m_i = 0$ its cost is 0, else its cost is c_i
 - $m_i = 0$ means that match i is not chosen

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DAG Covering Binate Covering Approach

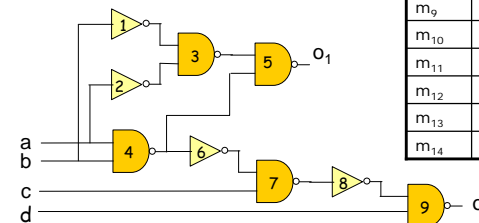
- Binate covering is more general than unate covering

- Unlike unate covering, variables are present in both their true and complemented forms in the covering expression
- The covering expression is a binate function, and the problem is referred to as the *binate-covering problem*

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DAG Covering Binate Covering Approach

- Example



Match	Gate	Cost	Inputs	Root	Covers
m_1	inv	1	b	g_1	g_1
m_2	inv	1	a	g_2	g_2
m_3	nand2	2	g_1, g_2	g_3	g_3
m_4	nand2	2	a, b	g_4	g_4
m_5	nand2	2	g_3, g_4	g_5	g_5
m_6	inv	1	g_4	g_6	g_6
m_7	nand2	2	g_6, c	g_7	g_7
m_8	inv	1	g_7	g_8	g_8
m_9	nand2	2	g_8, d	g_9	g_9
m_{10}	nand3	3	g_6, c, d	g_9	g_7, g_8, g_9
m_{11}	nand3	3	a, b, c	g_7	g_4, g_6, g_7
m_{12}	xnor2	5	a, b	g_5	g_1, g_2, g_3, g_4, g_5
m_{13}	nand4	4	a, b, c, d	g_9	g_4, g_6, g_7, g_8, g_9
m_{14}	oai21	3	a, b, g_4	g_5	g_1, g_2, g_3, g_5

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DAG Covering Binate Covering Approach

Example (cont'd)

- Generate constraints that each node g_i be covered by some match

$$(m_1 + m_{12} + m_{14}) (m_2 + m_{12} + m_{14}) (m_3 + m_{12} + m_{14})$$

$$(m_4 + m_{11} + m_{12} + m_{13}) (m_5 + m_{12} + m_{14})$$

$$(m_6 + m_{11} + m_{13}) (m_7 + m_{10} + m_{11} + m_{13})$$

$$(m_8 + m_{10} + m_{13}) (m_9 + m_{10} + m_{13})$$

- To ensure that a cover leads to a valid circuit, extra clauses are generated
 - For example, selecting m_3 requires that
 - a match be chosen which produces g_2 as an output, and
 - a match be chosen which produces g_1 as an output
- The only match which produces g_1 is m_1 , and the only match which produces g_2 is m_2

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DAG Covering Binate Covering Approach

Example (cont'd)

- The primary output nodes g_5 and g_9 must be realized as an output of some match

- The matches which realize g_5 as an output are m_5, m_{12}, m_{14}

- The matches which realize g_9 as an output are m_9, m_{10}, m_{13}

Note:

- A match which requires a primary input as an input is satisfied trivially
- Matches $m_1, m_2, m_4, m_{11}, m_{12}, m_{13}$ are driven only by primary inputs and do not require additional clauses

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DAG Covering Binate Covering Approach

Example (cont'd)

- Finally, we get

$$(\bar{m}_3 + m_1) (\bar{m}_3 + m_2) (m_3 + \bar{m}_5) (\bar{m}_5 + m_4) (\bar{m}_6 + m_4)$$

$$(\bar{m}_7 + m_6) (\bar{m}_8 + m_7) (m_8 + m_9) (\bar{m}_{10} + m_6)$$

$$(\bar{m}_{14} + m_4) (m_5 + m_{12} + m_{14}) (m_9 + m_{10} + m_{13})$$

- The covering expression has 58 implicants
- The least cost prime implicant is $m_3 m_5 m_6 m_7 m_8 m_9 m_{10} m_{12} m_{13} \bar{m}_{14}$
- This uses two gates for a cost of 9 gate units. This corresponds to a cover which selects matches m_{12} (xor2) and m_{13} (nand4).

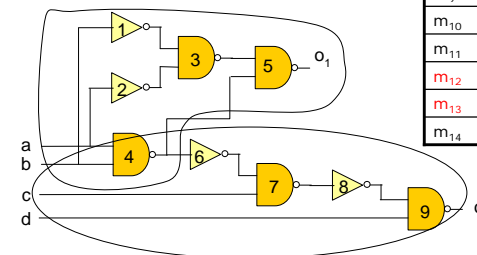
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DAG Covering Binate Covering Approach

Example (cont'd)

Match	Gate	Cost	Inputs	Root	Covers
m_1	inv	1	b	g_1	g_1
m_2	inv	1	a	g_2	g_2
m_3	nand2	2	g_1, g_2	g_3	g_3
m_4	nand2	2	a, b	g_4	g_4
m_5	nand2	2	g_3, g_4	g_5	g_5
m_6	inv	1	g_4	g_6	g_6
m_7	nand2	2	g_6, c	g_7	g_7
m_8	inv	1	g_7	g_8	g_8
m_9	nand2	2	g_8, d	g_9	g_9
m_{10}	nand3	3	g_6, c, d	g_9	g_7, g_8, g_9
m_{11}	nand3	3	a, b, c	g_7	g_4, g_6, g_7
m_{12}	xnor2	5	a, b	g_5	g_1, g_2, g_3, g_4, g_5
m_{13}	nand4	4	a, b, c, d	g_9	g_4, g_6, g_7, g_8, g_9
m_{14}	oai21	3	a, b, g_4	g_5	g_1, g_2, g_3, g_5

$$m_3 \bar{m}_5 \bar{m}_6 \bar{m}_7 \bar{m}_8 \bar{m}_9 \bar{m}_{10} m_{12} m_{13} \bar{m}_{14}$$



Note: g_4 is covered by both matches

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DAG Covering Binate Covering Approach

- Complexity
 - DAG-covering: **covering + implication** constraints
 - More general than unate covering
 - Finding least cost prime of a *binate* function
 - Even finding a feasible solution is NP-complete (SAT)
 - For unate covering, finding a feasible solution is easy
 - Given a *subject graph*, the binate covering provides the **exact** solution to the technology-mapping problem
 - **However**, better results may be obtained with a different initial decomposition into 2-input NANDs and inverters
 - Methods to solve the binate covering formulation:
 - Branch and bound, BDD-based
 - Expensive even for moderate-size networks

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Tree Covering

- When the subject graph and pattern graphs are **trees**, an efficient algorithm to find the best cover exists
- Solvable with **dynamic programming**

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Tree Covering

1. **Partition** subject graph into **forest** of trees
2. **Cover** each tree optimally using dynamic programming
 - Given:
 - Subject trees (networks to be mapped)
 - Forest of patterns (gate library)
 - For each node *N* of a subject tree
 - **Recursive Assumption**: for all children of *N*, a **best** cost match (**which implements the node**) is known
 - Compute cost of each pattern tree which matches at *N*, Cost = SUM of best costs of implementing each **input** of pattern **plus** the cost of the pattern
 - Cost of a **leaf** of the tree is 0
 - Choose least cost matching pattern for implementing *N*

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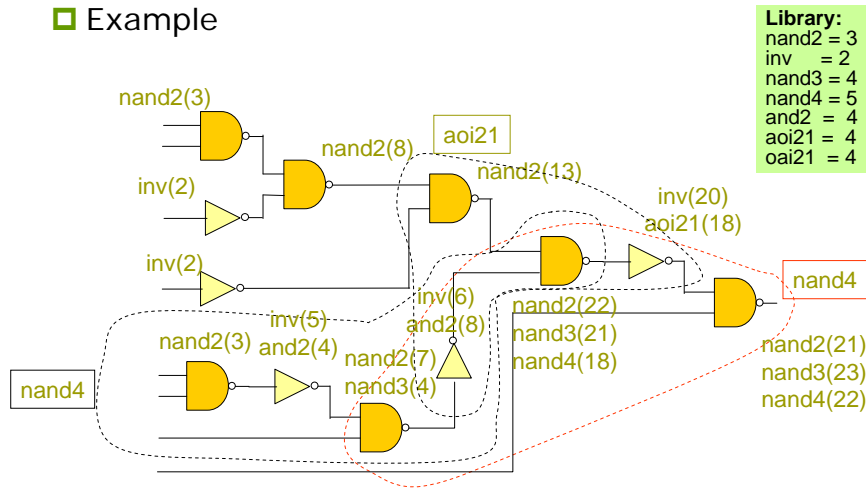
Tree Covering

```
□ Algorithm OPTIMAL_AREA_COVER(node) {
  foreach input of node {
    OPTIMAL_AREA_COVER(input); //satisfies recur. assumption
  }
  // Using these, find the best cover at node
  node->area = INFINITY;
  node->match = 0;
  foreach match at node {
    area = match->area;
    foreach pin of match {
      area = area + pin->area;
    }
    if (area < node->area) {
      node->area = area;
      node->match = match;
    }
  }
}
```

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Tree Covering

Example



Tree Covering

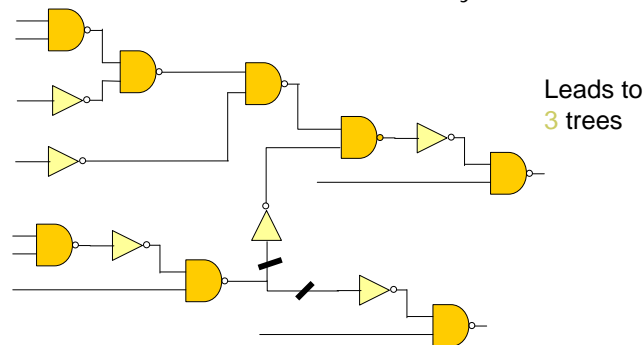
Complexity

- Complexity is controlled by finding **all** sub-trees of the subject graph which are isomorphic to a pattern tree
- Linear** complexity in both size of subject tree and size of collection of pattern trees

Tree Covering

Partition subject DAG into trees

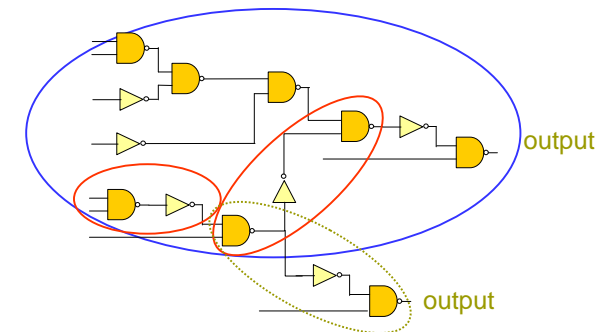
- Trivial partition:** break the graph at all multiple-fanout points
 - no duplication or overlap in the resulting trees
 - drawback - sometimes results in many **small** trees



Tree Covering

Partition subject DAG into trees

- Single-cone partition:** from a single output, form a large tree back to the primary inputs
 - map successive outputs until they hit match output formed from mapping previous primary outputs
 - Duplicates some logic (where trees overlap)
 - Produces much larger trees, potentially better area results



Min-Delay Technology Mapping

- For trees:
 - identical to min-area covering
 - use optimal delay values within the dynamic programming paradigm
- For DAGs:
 - if delay does not depend on number of fanouts: use dynamic programming as presented for trees
 - leads to optimal solution in polynomial time
 - Assume logic replication is okay
- Combined objective
 - e.g. apply delay as first criteria, then area as second
 - combine with static timing analysis to focus on critical paths

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Decomposition and Technology Mapping

Common Approach:

- Phase 1: Technology independent optimization
 - commit to a particular Boolean network
 - algebraic decomposition used
- Phase 2: AND2/INV decomposition
 - commit to a particular decomposition of a general Boolean network using **2-input ANDs and inverters**
- Phase 3: Technology mapping (**tree-mapping**)

Drawbacks:

Procedures in each phase are **disconnected**:

- Phase 1 and Phase 2 make **critical decisions** without knowing much about constraints and library
- Phase 3 knows about constraints and library, but solution space is **restricted** by decisions made earlier

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Combined Decomposition and Technology Mapping

- Incorporate technology independent procedures (Phase 1 and Phase 2) into technology mapping
- Lehman-Watanabe Algorithm:
 - **Key Idea:**
 - Efficiently encode a **set** of AND2/INV decompositions into a **single** structure called a **mapping graph**
 - Apply a modified tree-based technology mapper while **dynamically performing algebraic logic decomposition** on the mapping graph

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Combined Decomposition and Technology Mapping

□ Outline

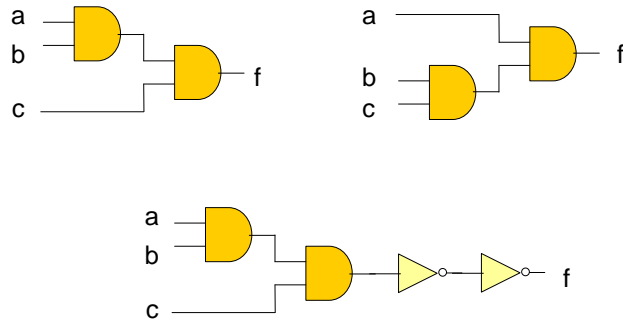
- Mapping Graph
 - Encodes a set of AND2/INV decompositions
- Tree-mapping on a mapping graph: **graph-mapping**
- **Δ -mapping:**
 - **without** dynamic logic decomposition
 - solution space: Phase 3 + Phase 2
- **Δ -mapping:**
 - **with** dynamic logic decomposition
 - solution space: Phase 3 + Phase 2 + Algebraic decomposition (Phase 1)

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Combined Decomposition and Technology Mapping

AND2/INV decomposition

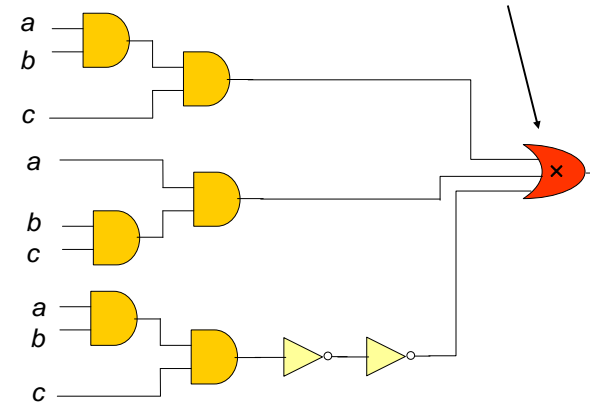
- E.g., $f = abc$ can be represented in various ways



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Combined Decomposition and Technology Mapping

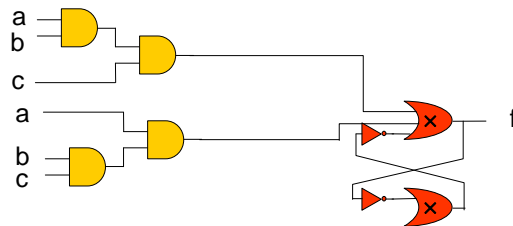
Combine different AND2/INV decompositions with a choice node



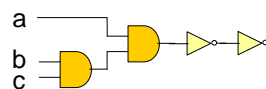
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Combined Decomposition and Technology Mapping

- The previous AND2/INV decompositions can be represented more compactly as:



- This representation encodes even more decompositions, e.g.,

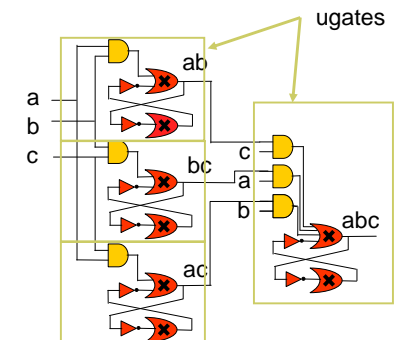


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Combined Decomposition and Technology Mapping

- Mapping graph** is a Boolean network containing the following four modifications:

- Choice node**: choices on different decompositions
- Cyclic**: functions written in terms of each other, e.g. inverter chain with an arbitrary length
- Reduced**: No two choice nodes with same function. No two AND2s with same fanin. (like BDD node sharing)
- Ugates**: just for efficient implementation - do not explicitly represent choice nodes and inverters
 - For CHT benchmark (MCNC'91), there are 2.2×10^{10} AND2/INV decompositions. All are encoded with only 400 ugates containing 59% AND2s in total.



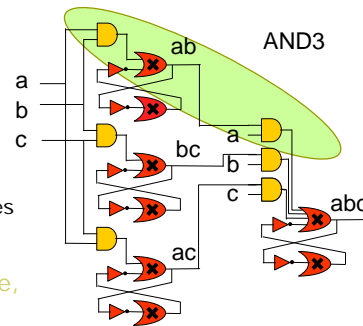
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Combined Decomposition and Technology Mapping

Graph-Mapping on Trees*:

Apply dynamic programming from primary inputs:

- find matches at each AND2 and INV, and
- retain the cost of a best cover at each node
 - a match may contain choice nodes
 - the cost at a choice node is the minimum of fanin costs
- fixed-point iteration on each cycle, until costs of all the nodes in the cycle become stable



- Run-time is typically linear in the size of the mapping graph

* mapping graph may not be a tree, but any multiple fanout node just represents several copies of same function.

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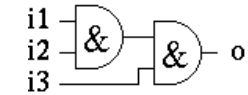
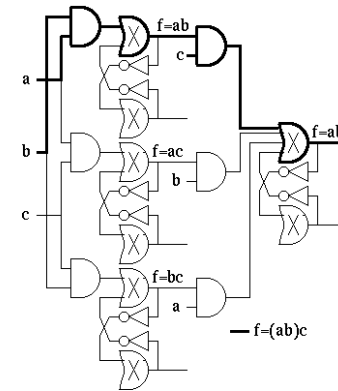
Combined Decomposition and Technology Mapping

Example

- Graph mapping on trees for min delay
 - best choice if c is later than a and b.

subject graph

library pattern graph



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Combined Decomposition and Technology Mapping

Graph mapping

Graph-mapping(μ) = $\min_{\theta \in \mu} \{ \text{tree-mapping}(\theta) \}$

μ : mapping graph

θ : AND2/INV decomposition encoded in μ

- Graph-mapping finds an optimal tree implementation for each primary output over all AND2/INV decompositions encoded in μ
- Graph-mapping is as powerful as applying tree-mapping exhaustively, but is typically exponentially faster

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Combined Decomposition and Technology Mapping

Λ -mapping

Given a Boolean network η ,

- Generate a mapping graph μ :
- For each node of η ,
 - encode all AND2 decompositions for each product term
 - E.g., $abc \Rightarrow 3$ AND2 decompositions: $a(bc)$, $c(ab)$, $b(ca)$
 - encode all AND2/INV decompositions for the sum term
 - E.g., $p+q+r \Rightarrow 3$ AND2/INV decompositions: $p+(q+r)$, $r+(p+q)$, $q+(r+p)$
 - In practice, η is preprocessed so each node has at most 10 product terms and each term has at most 10 literals
- Apply graph-mapping on μ

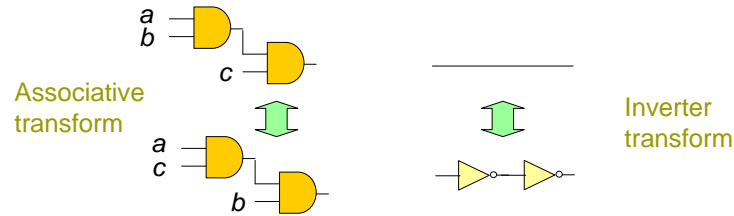
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Combined Decomposition and Technology Mapping

Λ-mapping

For the mapping graph μ generated for a Boolean network η , let

- L_η be the set of AND2/INV decompositions encoded in μ
- Λ_η be the closure of the set of AND2/INV decompositions of η under the associative and inverter transformations:

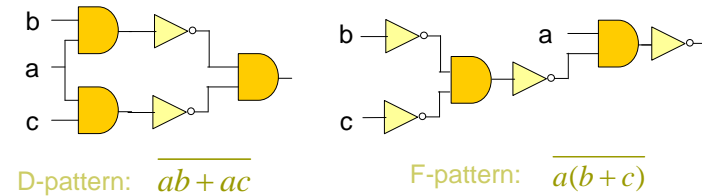


■ Theorem: $\Lambda\eta = L\eta$

Combined Decomposition and Technology Mapping

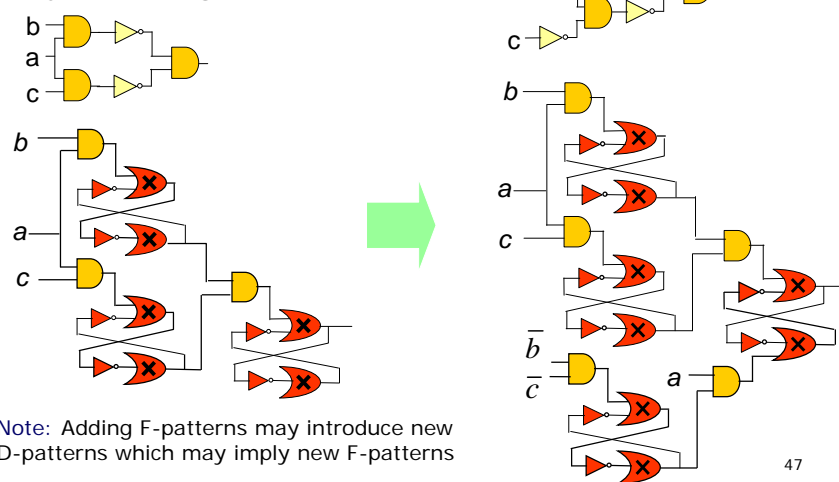
Dynamic logic decomposition

- During graph-mapping, dynamically modify the mapping graph: find D-patterns and add F-patterns



Combined Decomposition and Technology Mapping

Dynamic logic decomposition

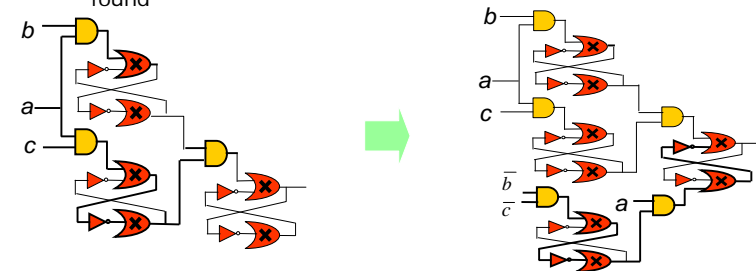


Combined Decomposition and Technology Mapping

Δ-mapping

Given a Boolean network η ,

- Generate a mapping graph μ
- Iteratively apply graph mapping on μ , while performing dynamic logic decomposition until nothing changes in μ
 - Before finding matches at an AND2 in μ , check if D-pattern matches at the AND2. If so, add the corresponding F-pattern
 - In practice, terminate the procedure when a feasible solution is found

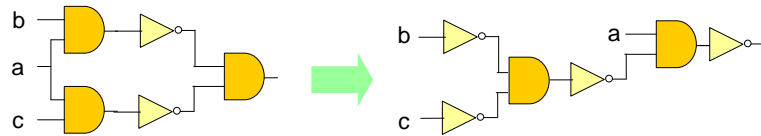


Combined Decomposition and Technology Mapping

□ Δ -mapping

For the mapping graph μ generated for a Boolean network η , let

- D_η be the set of AND2/INV decompositions encoded in the resulting mapping graph.
- Δ_η be the closure of Λ_η under the distributive transformation:



□ Theorem: $\Delta_\eta = D_\eta$

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Combined Decomposition and Technology Mapping

□ Theorem: If

1. η^* is an arbitrary Boolean network obtained from η by algebraic decomposition, and
2. θ is an arbitrary AND2/INV decomposition of η^*

then $\theta \in D_\eta$

- The resulting mapping graph encodes all the AND2/INV decompositions of all algebraic decompositions of η

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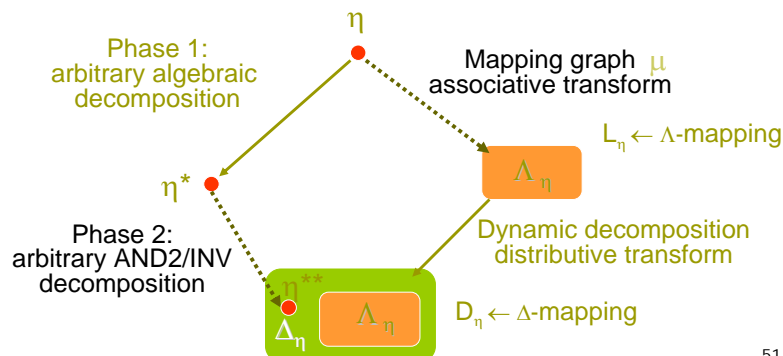
Combined Decomposition and Technology Mapping

- Λ -mapping captures all AND2/INV decompositions of η :

Phase 2 (subject graph generation) is subsumed

- Δ -mapping captures all algebraic decompositions:

Phase 2 and Phase 1 are subsumed



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Combined Decomposition and Technology Mapping

□ Summary

- Logic decomposition during technology mapping
 - Efficiently encode a set on AND2/INV decompositions
 - Dynamically perform logic decomposition
- Two mapping procedures
 - Λ -mapping: optimal over all AND2/INV decompositions (associative rule)
 - Δ -mapping: optimal over all algebraic decompositions (distributive rule)
- Was implemented and used for commercial design projects (in DEC/Compac alpha)
- Extended for sequential circuits:
 - considers all retiming possibilities (implicitly) and algebraic factors across latches

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