Libraries and Mapping

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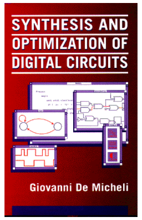

Module 1

- **Objective**
  - **Libraries**
  - **Problem formulation and analysis**
  - **Algorithms for library binding based on structural methods**

Library binding

- Given an unbound logic network and a set of library cells
  - Transform into an interconnection of instances of library cells
  - Optimize delay
    - (under area or power constraints)
  - Optimize area
    - Under delay and/or power constraints
  - Optimize power
    - Under delay and/or area constraints
- Library binding is called also technology mapping
  - Redesigning circuits in different technologies

Major approaches

- **Rule-based systems**
  - Generic, handle all types of cells and situations
  - Hard to obtain circuit with specific properties
  - Data base:
    - Set of pattern pairs
    - Local search: detect pattern, implement its best realization
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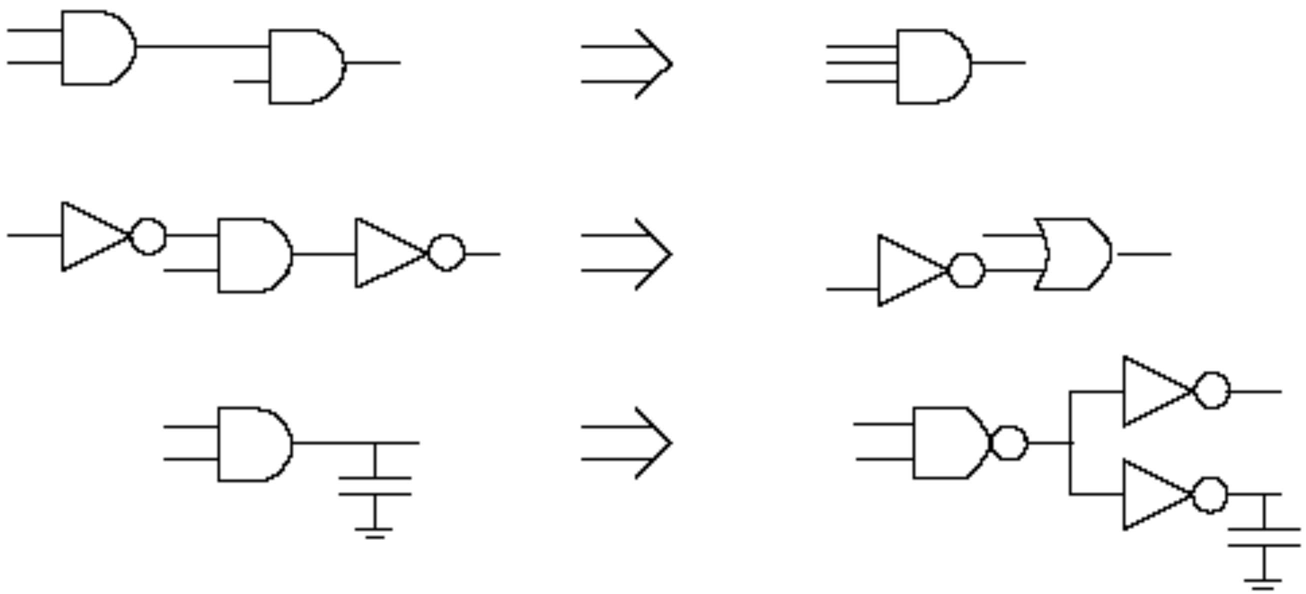


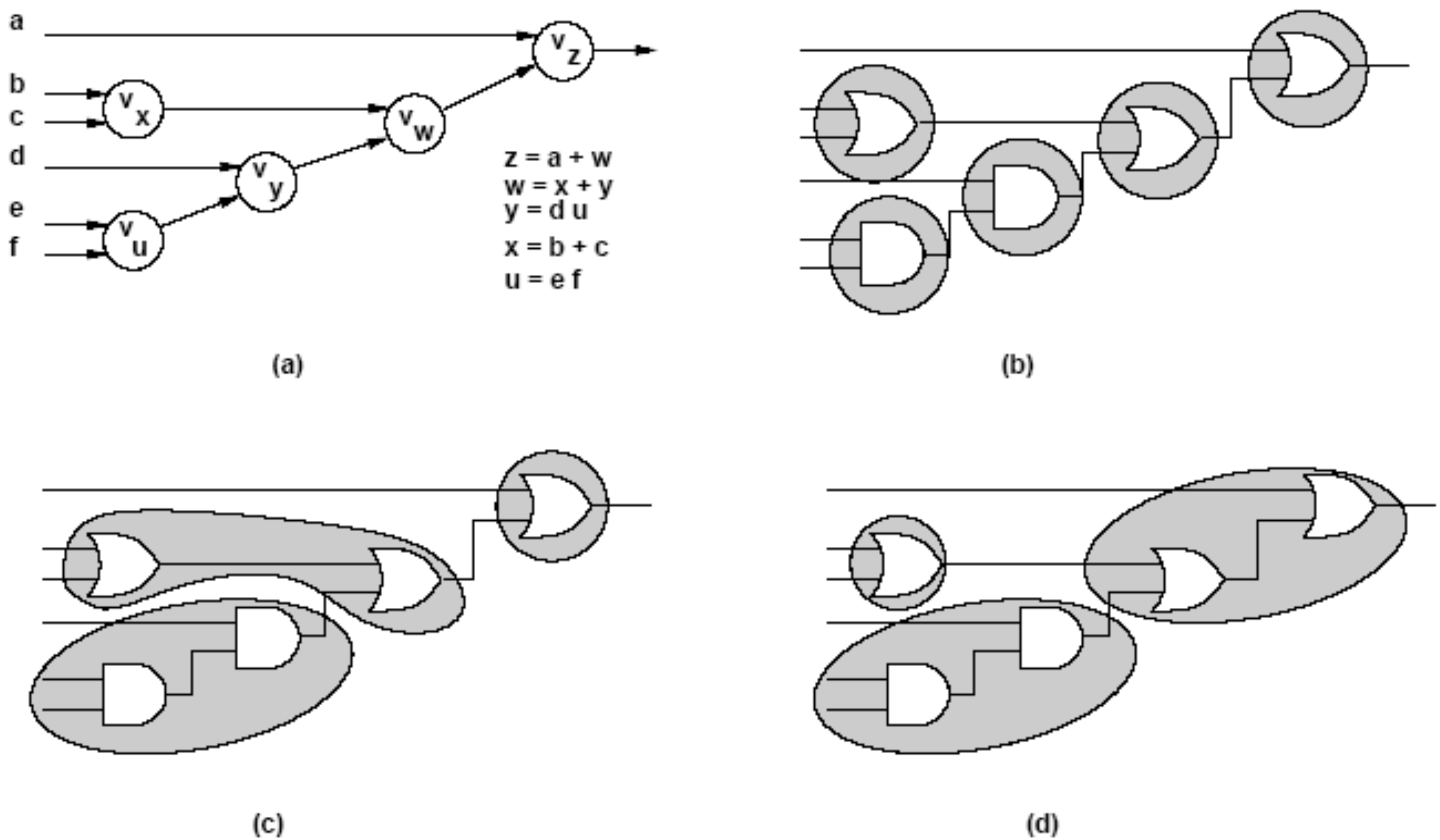
Library binding: issues

- **Matching**:
  - A cell matches a sub-network when their terminal behavior is the same
  - Tautology problem
  - *Input-variable* assignment problem
- **Covering**:
  - A cover of an unbound network is a partition into sub-networks which can be replaced by library cells
  - Binate covering problem

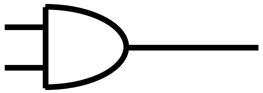
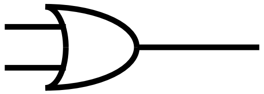
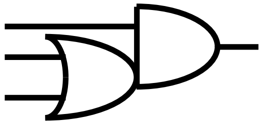
Assumptions

- Network granularity is fine
  - Decomposition into base functions:
  - 2-input AND, OR, NAND, NOR
- Trivial binding
  - Use base cells to realize decomposed network
  - There exists always a trivial binding:
    - Base-cost solution…

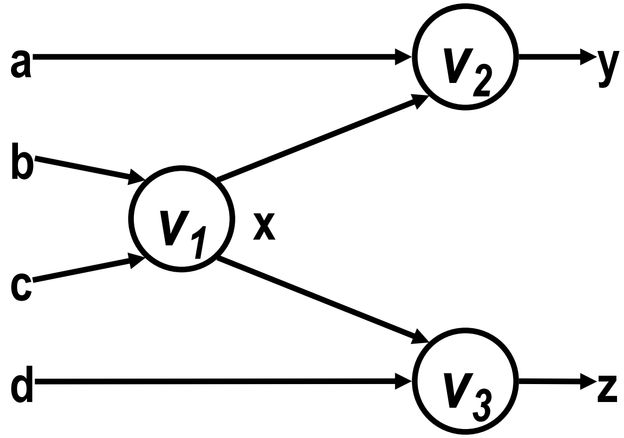
Example

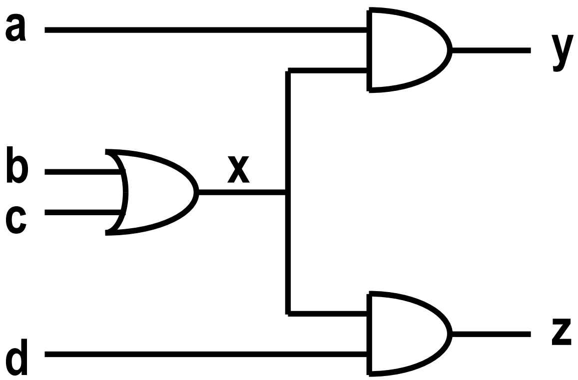


Example

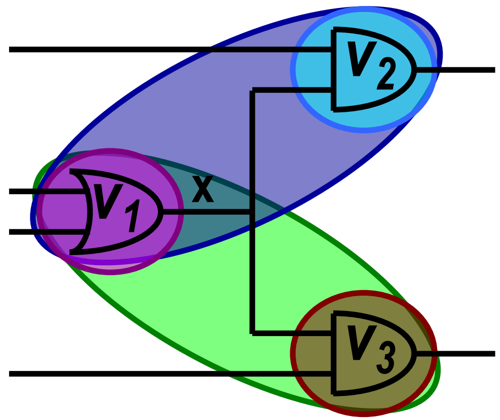
Library		Cost
	AND2	4
	OR2	4
	OA21	5

$x = b + c$
$y = ax$
$z = xd$



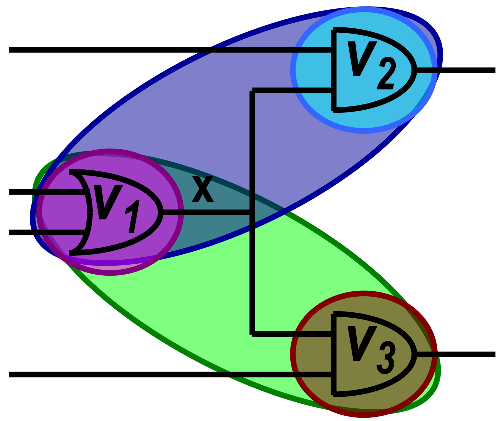


m_1: $\{v_1, OR2\}$
m_2: $\{v_2, AND2\}$
m_3: $\{v_3, AND2\}$
m_4: $\{v_1, v_2, OA21\}$
m_5: $\{v_1, v_3, OA21\}$



Example

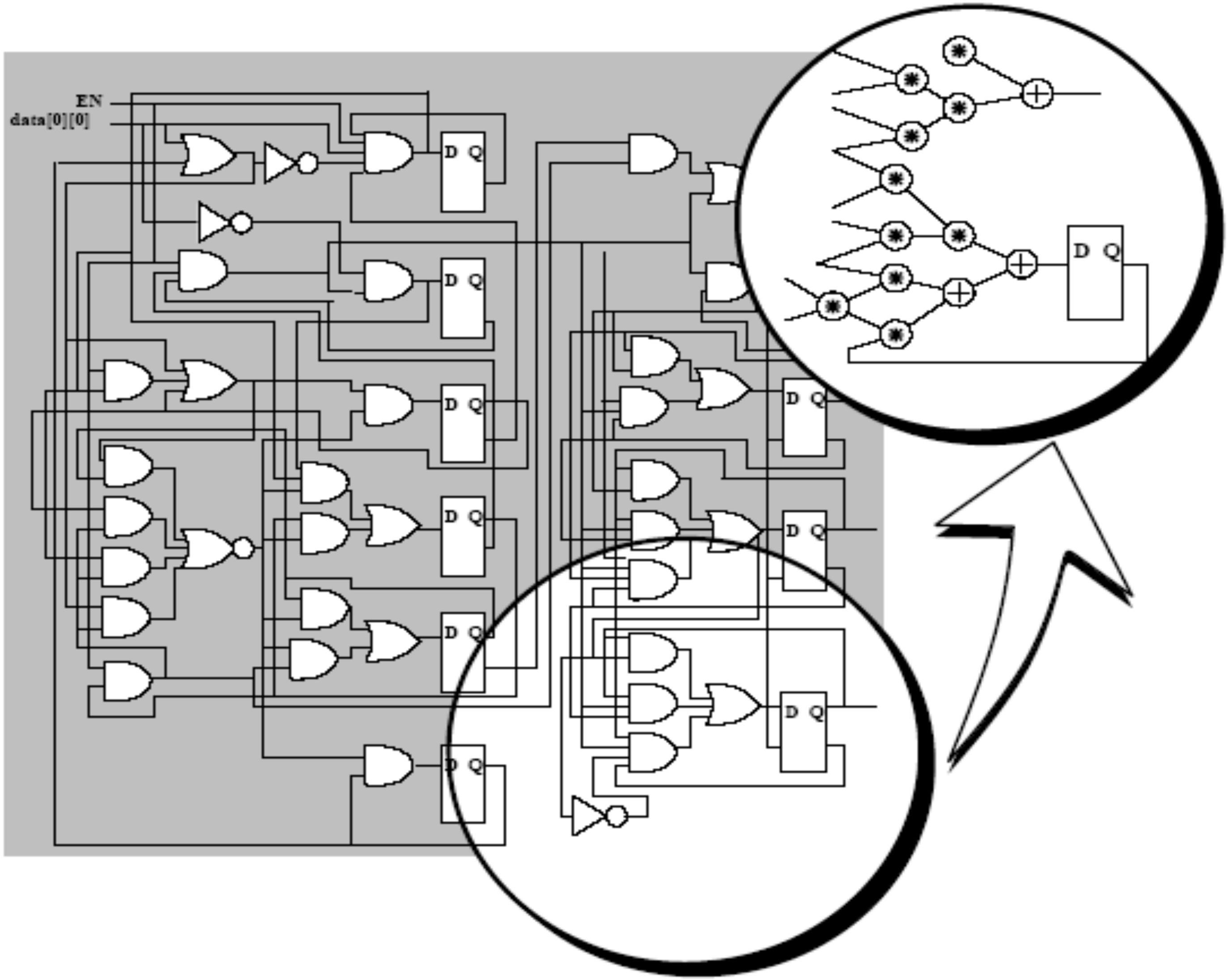
- **Vertex covering:**
  - Covering v_1 : $(m_1 + m_4 + m_5)$
  - Covering v_2 : $(m_2 + m_4)$
  - Covering v_3 : $(m_3 + m_5)$
- **Input compatibility:**
  - Match m_2 requires m_1
    - $(m'_2 + m_1)$
  - Match m_3 requires m_1
    - $(m'_3 + m_1)$
- **Overall binate covering clause**
  - $(m_1+m_4+m_5)(m_2+m_4)(m_3+m_5)(m'_2+m_1)(m'_3+m_1) = 1$



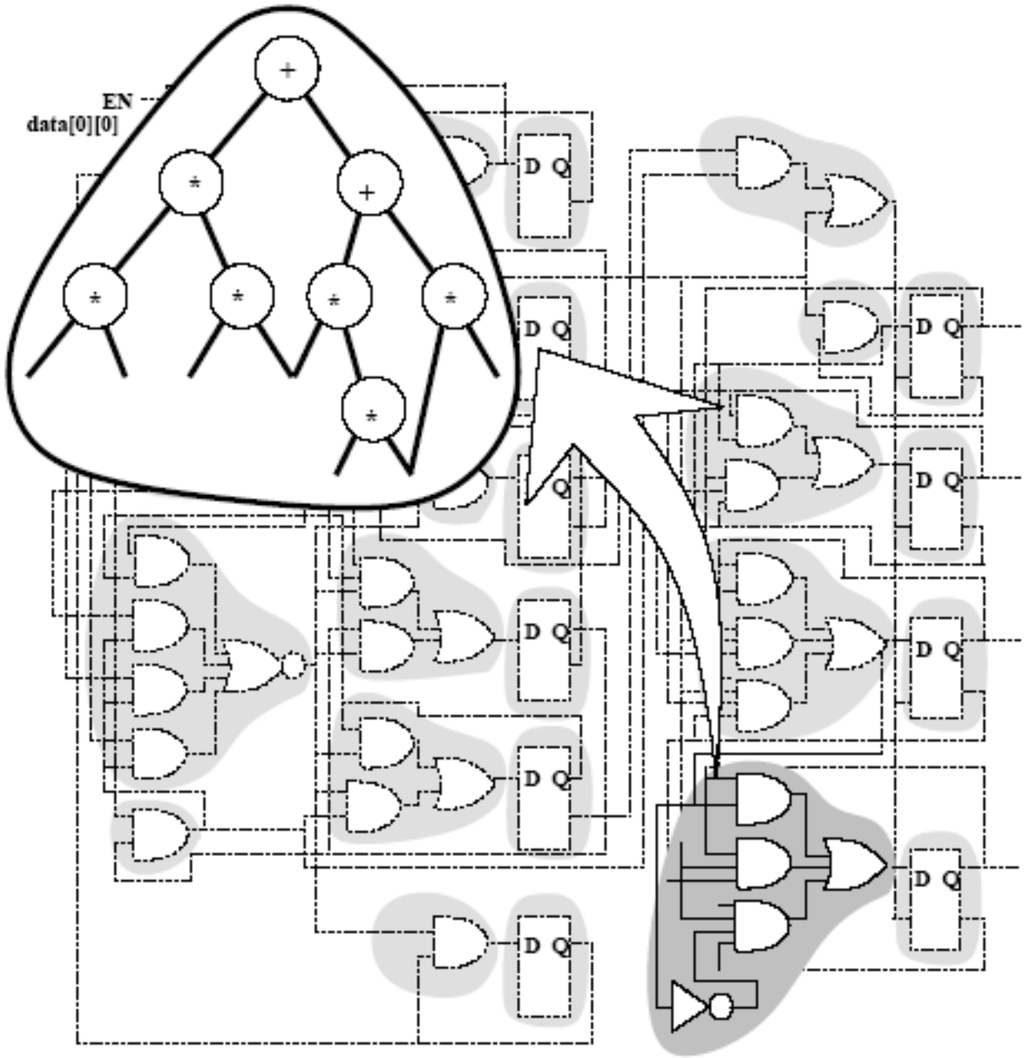
Heuristic approach to library binding

- Split problem into various stages:
  - Decomposition
    - Cast network and library in standard form
    - Decompose into base functions
    - Example, NAND2 and INV
  - Partitioning
    - Break network into cones
    - Reduce to many multi-input, single-output networks
  - Covering
    - Cover each sub-network by library cells
- Most tools use this strategy
  - Sometimes stages are merged

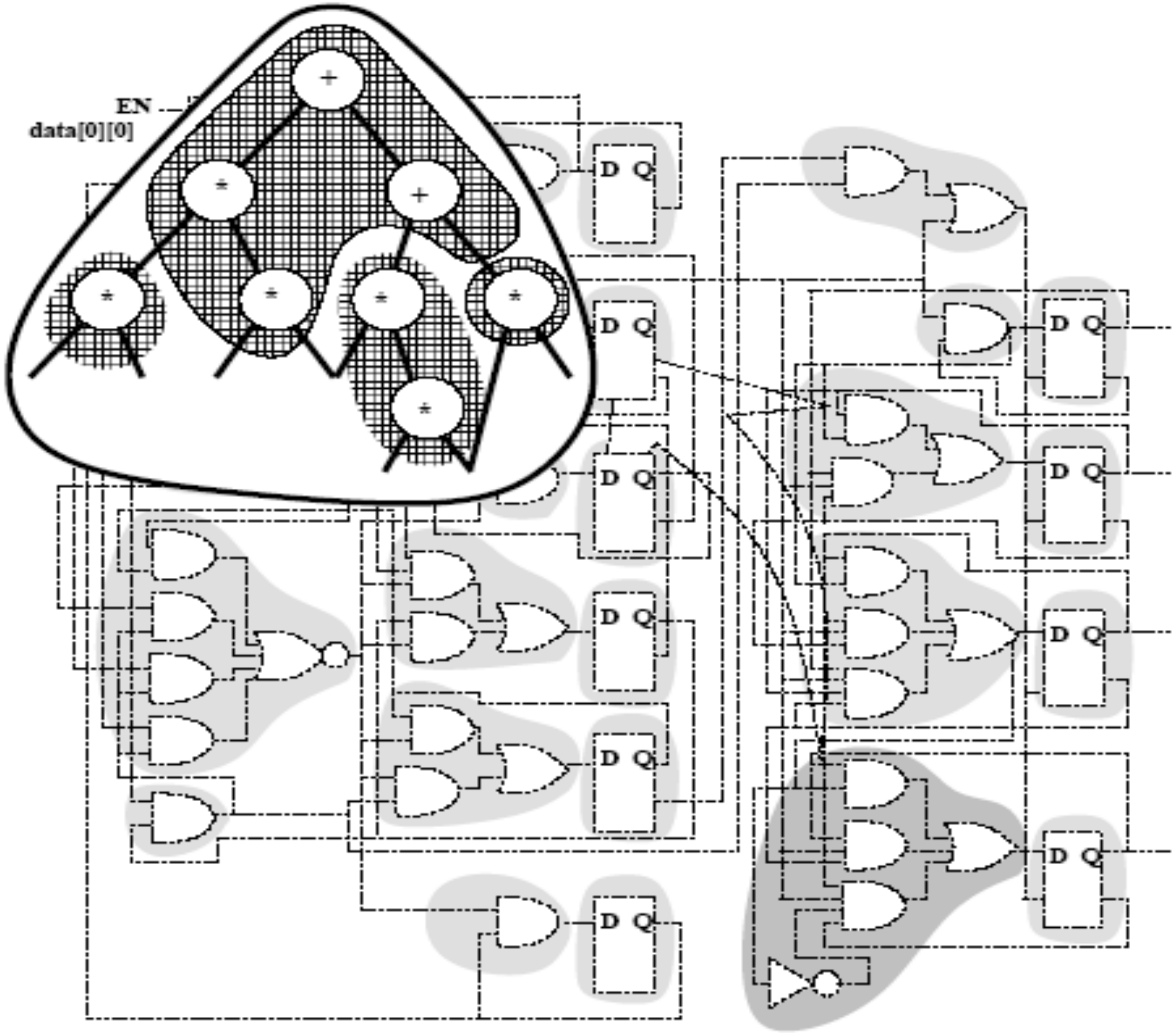
Decomposition



Partitioning



Covering

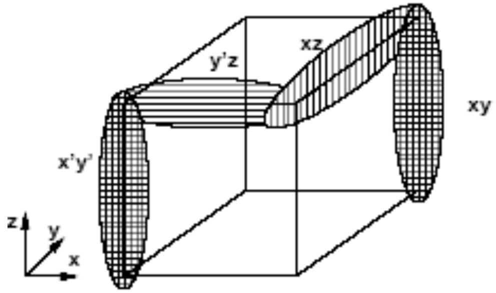


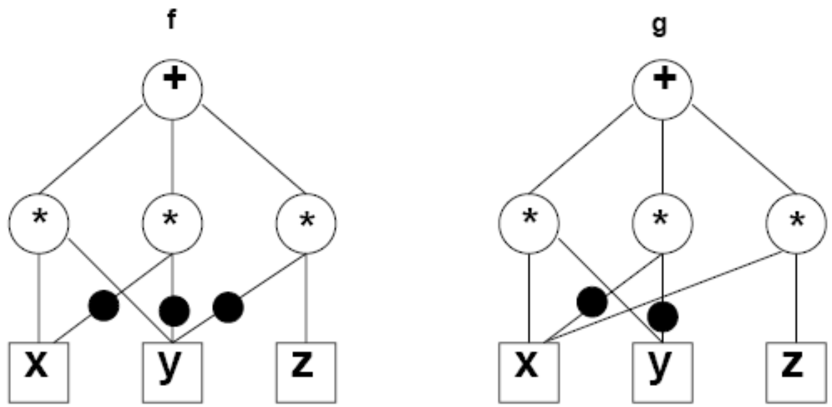
Heuristic algorithms

- Structural approach
  - Model functions by patterns
    - Example: tree, dags
  - Rely on pattern matching techniques
- Boolean approach
  - Use Boolean models
  - Solve the tautology problem
    - Use BDD technology
  - More powerful

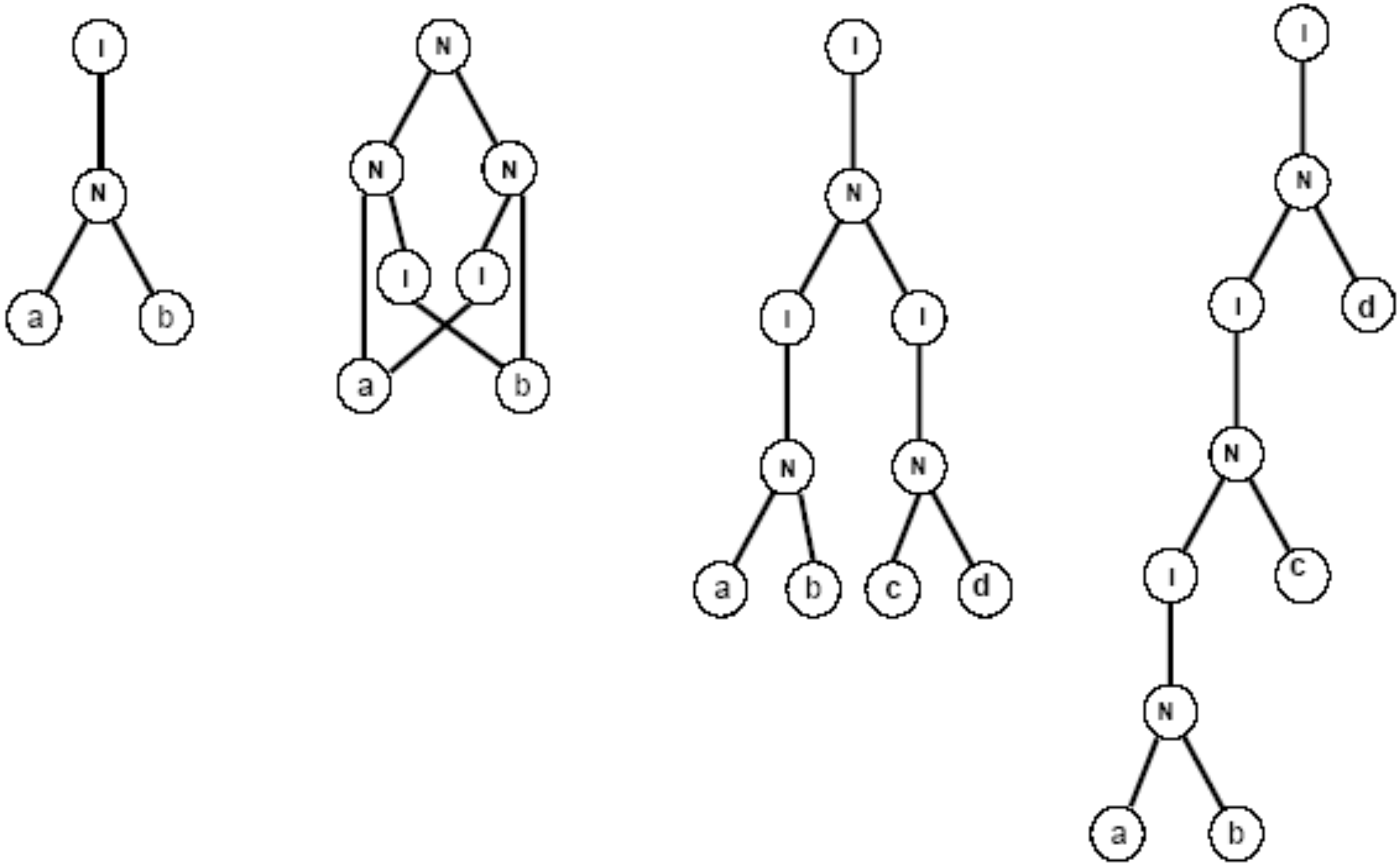
Example

- Boolean vs. structural matching
- $f = xy + x'y' + y'z$
- $g = xy + x'y' + xz$
- Function equality is a tautology
  - Boolean match
- Patterns may be different
  - Structural match may not exist



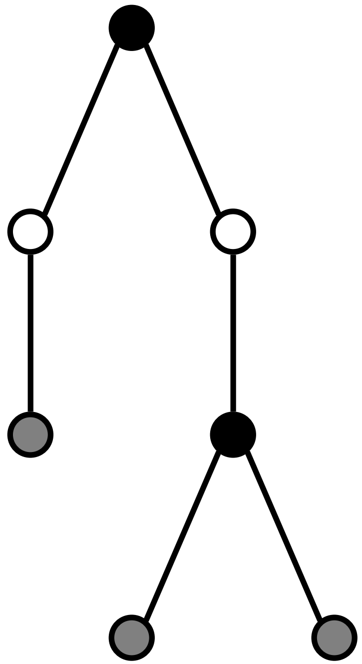


Example

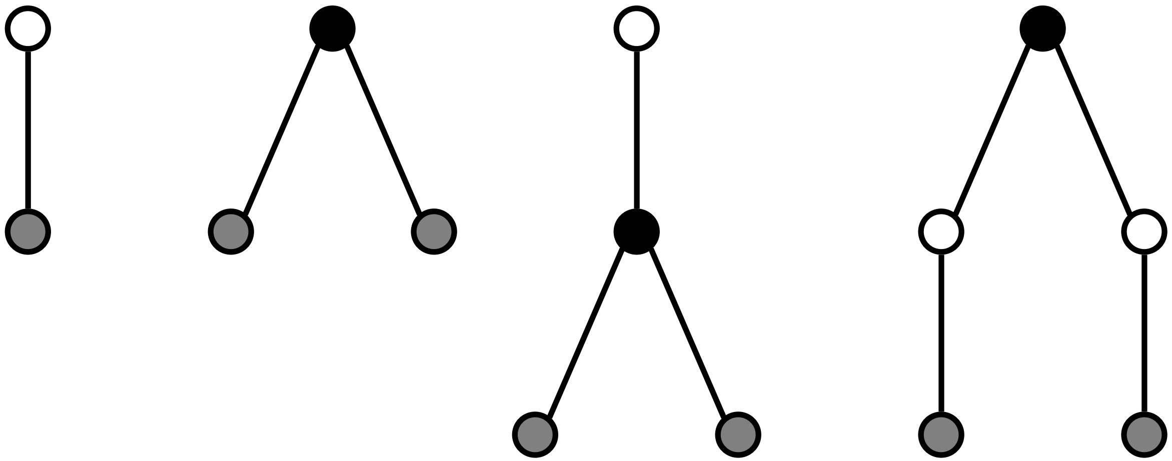


Example

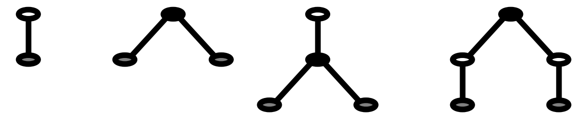
SUBJECT TREE



PATTERN TREES



cost = 2	cost = 3	cost = 4	cost = 5
INV	NAND	AND	OR

Example: Lib 

Match of s: t1
cost = 2

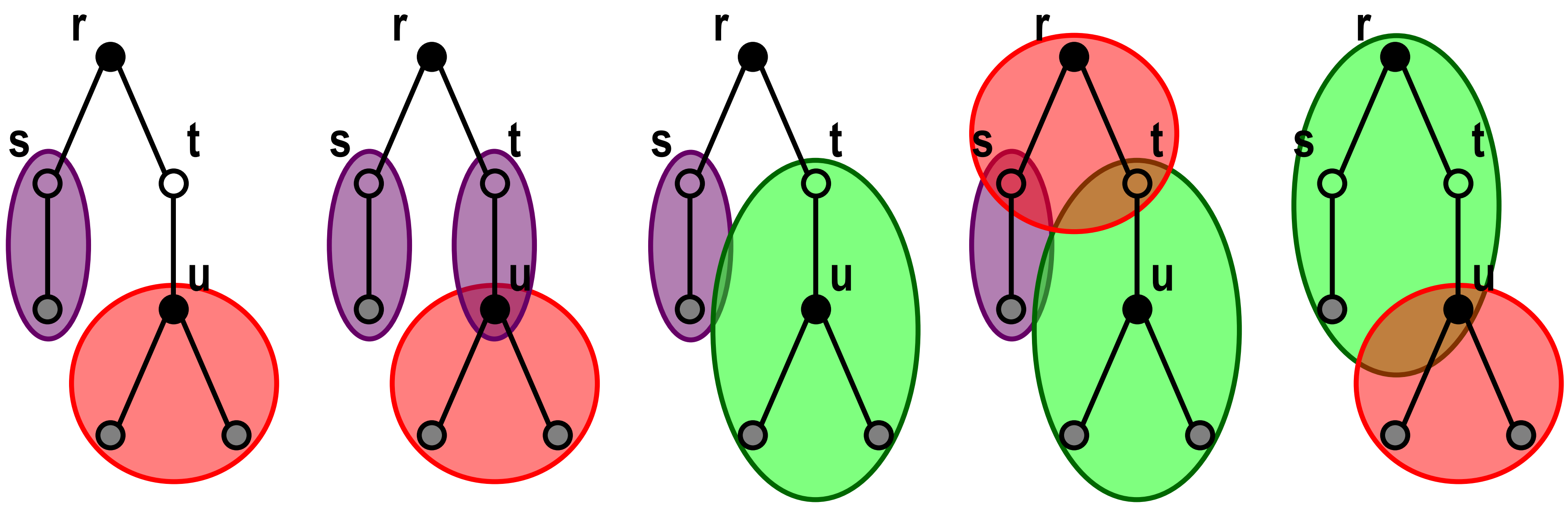
Match of u: t2
cost = 3

Match of t: t1
cost = 2+3 = 5

Match of t: t3
cost = 4

Match of r: t2
cost = 3+2+4 =9

Match of r: t4
cost = 5+3 =8



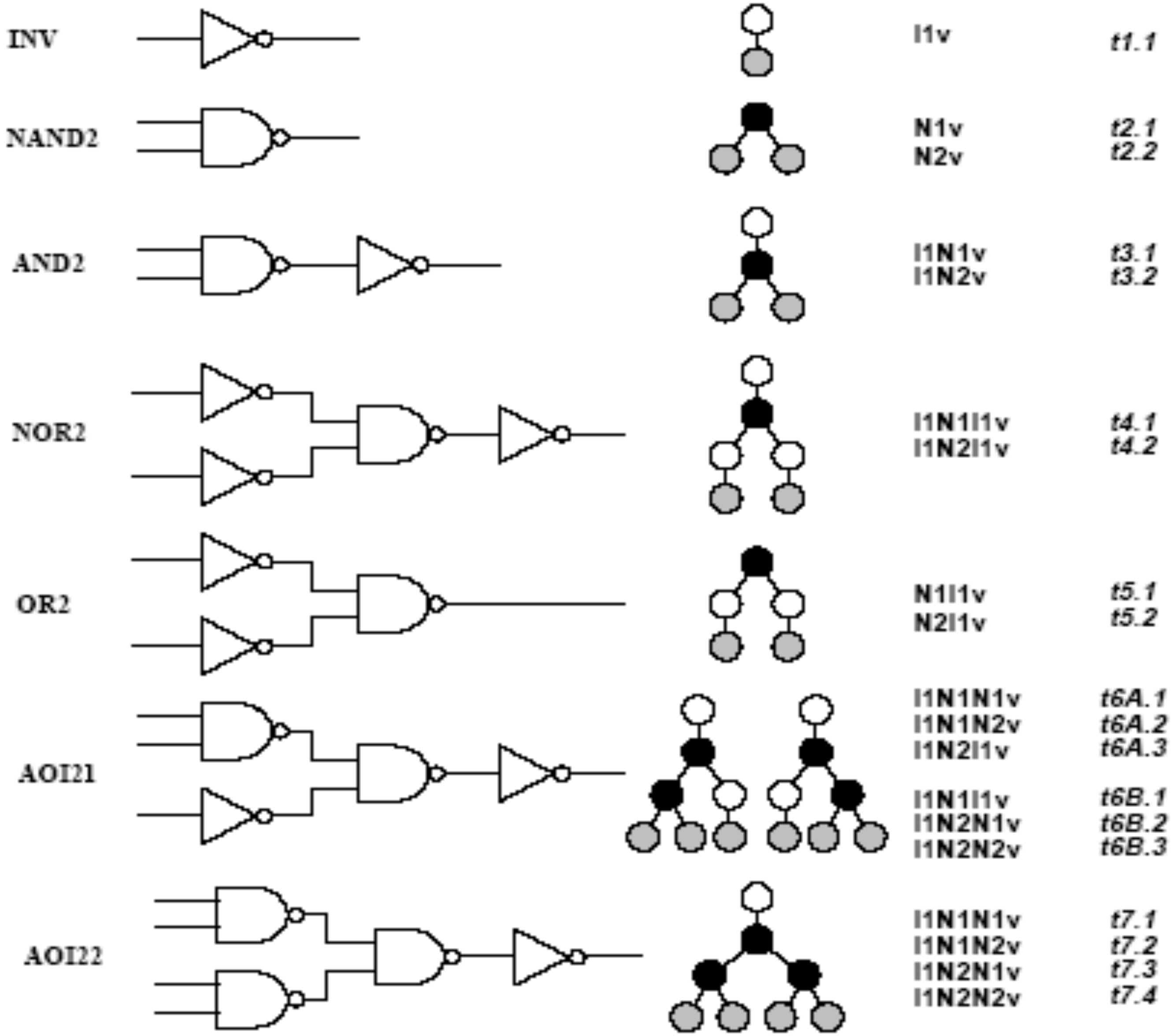
Tree covering

- Dynamic programming
  - Visit subject tree bottom up
- At each vertex
  - Attempt to match:
    - Locally rooted subtree to all library cell
    - Find best match and record
  - There is always a match when the base cells are in the library
- Bottom-up search yields and optimum cover
- Caveat:
  - Mapping into trees is a distortion for some cells
  - Overall optimality is weakened by the overall strategy of splitting into several stages

Different covering problems

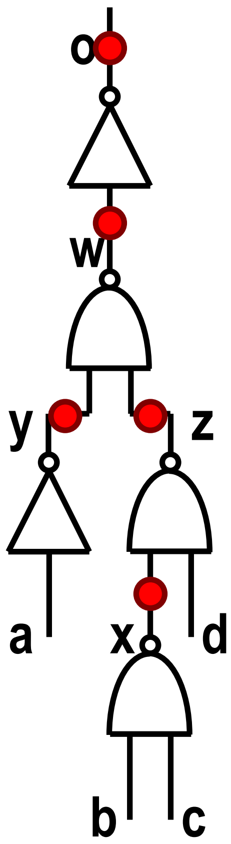
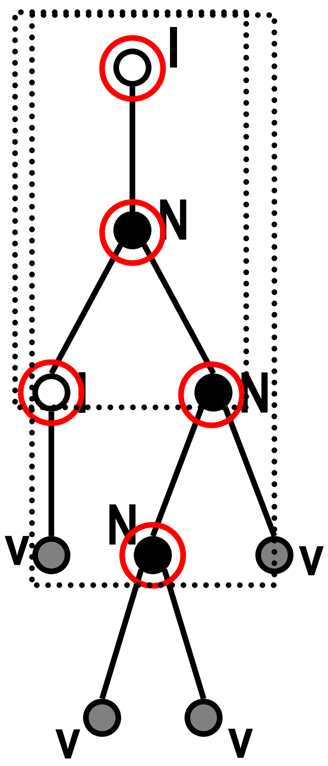
- **Covering for minimum area:**
  - Each cell has a fixed area cost (label)
  - Area is additive:
    - Add area of match to cost of sub-trees
- **Covering for minimum delay:**
  - Delay is fanout independent
    - Delay computed with (max, +) rules
    - Add delay of match to highest cost of sub-trees
  - Delay is fanout dependent
    - Look-ahead scheme is required

Simple library



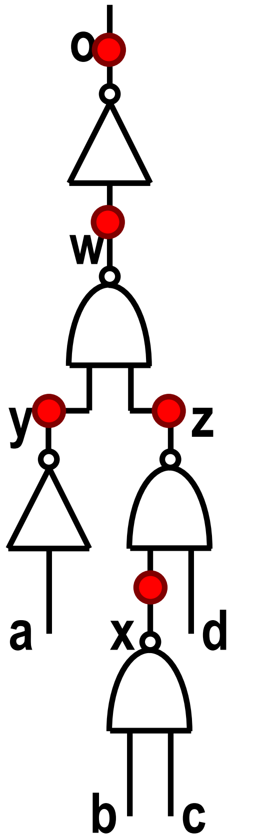
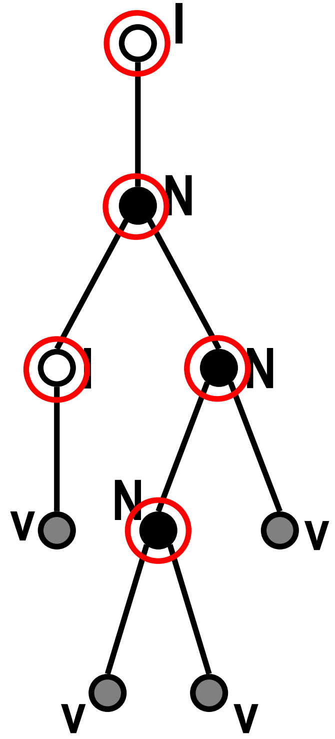
Example – minimum area cover

- **Area cost:** INV:2 NAND2:3 AND2: 4 AOI21: 6

Network	Subject graph	Vertex	Match	Gate	Cost
		x	t2	NAND2(b,c)	3
		y	t1	INV(a)	2
		z	t2	NAND2(x,d)	3+3 = 6
		w	t2	NAND2(y,z)	3+6+ 2 = 11
		o	t1	INV(w)	2+11 = 13
			t3	AND2(y,z)	6 + 4 + 2 = 12
			t6B	AOI21(x,d,a)	6 + 3 = $\boxed{9}$

Example – minimum delay cover

- Fixed delays: INV:2 NAND2:4 AND2: 5 AOI21: 10
- All inputs are stable at time 0, except for $t_d = 6$

Network	Subject graph	Vertex	Match	Gate	Cost
		x	t2	NAND2(b,c)	4
		y	t1	INV(a)	2
		z	t2	NAND2(x,d)	6+4 = 10
		w	t2	NAND2(y,z)	10 + 4 = 14
		o	t1	INV(w)	14 + 2 = 16
			t3	AND2(y,z)	10 + 5 = $\boxed{15}$
			t6B	AOI21(x,d,a)	10 + 6 = 16

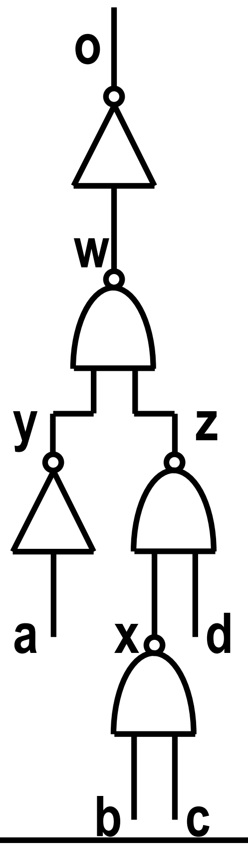
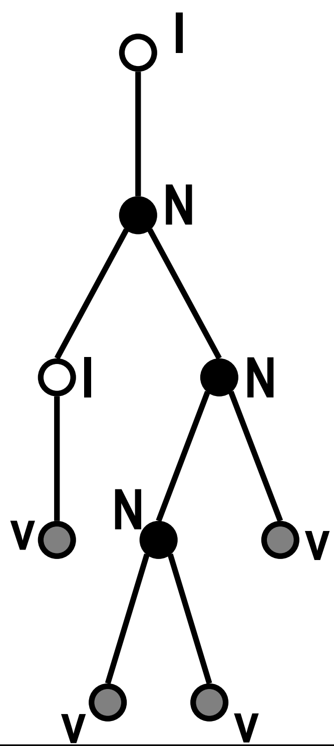
Minimum-delay cover for load-dependent delays

- **Model**
  - Gate delay is $d = \alpha + \beta$ cap_load
  - Capacitive load depends on the driven cells (fanout cone)
  - There is a finite (possibly small) set of capacitive loads
- **Algorithm**
  - Visit subject tree bottom up
  - Compute an array of solutions for each possible load
  - For each input to a matching cell, the best match for the corresponding load is selected
- **Optimality**
  - Optimum solution when all possible loads are considered
  - Heuristic: group loads into bins

Example – minimum delay cover

- Delays: INV:1+load NAND2: 3+load AND2: 4+load AOI21: 9+load
- All inputs are stable at time 0, except for $t_d = 6$
- All loads are 1

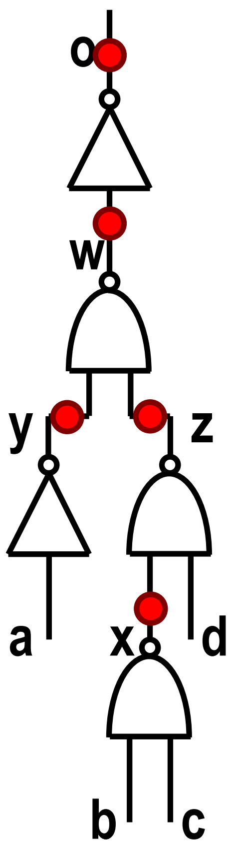
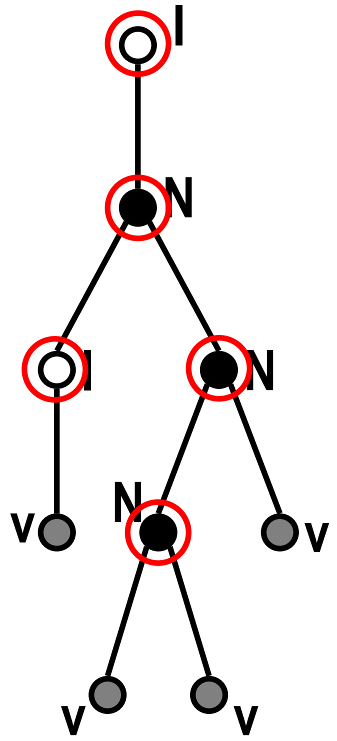
Same as before !

Network	Subject graph	Vertex	Match	Gate	Cost
		x	t2	NAND2(b,c)	4
		y	t1	INV(a)	2
		z	t2	NAND2(x,d)	6+4 = 10
		w	t2	NAND2(y,z)	10 + 4 = 14
		o	t1	INV(w)	14 + 2 = 16
			t3	AND2(y,z)	10 + 5 = $\boxed{15}$
			t6B	AOI21(x,d,a)	10 + 6 = 16

Example – minimum delay cover

- Delays: INV: 1+load   NAND2: 3+load   AND2: 4+load   AOI21: 9+load
- All inputs are stable at time 0, except for $t_d = 6$
- All loads are 1 (for cells seen so far)
- Add new cell SINV with delay 1 + ½ load and load 2
- The sub-network drives a load of 5

Example – minimum delay cover

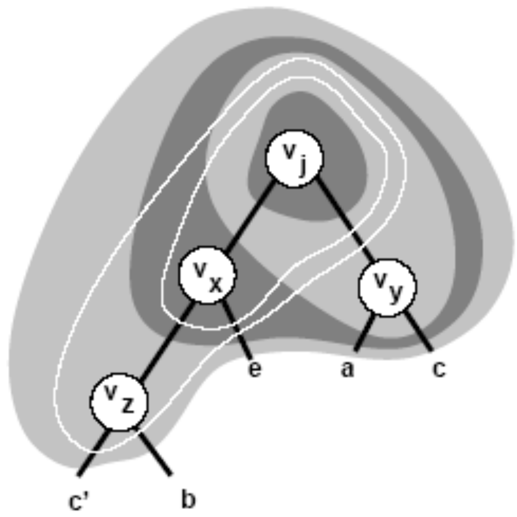
Network	Subject graph	Vertex	Match	Gate	Cost		
					Load=1	Load=2	Load=5
		x	t2	NAND2(b,c)	4	5	8
		y	t1	INV(a)	2	3	6
		z	t2	NAND2(x,d)	10	11	14
		w	t2	NAND2(y,z)	14	15	18
		o	t1	INV(w)			20
			t3	AND2(y,z)			19
			t6B	AOI21(x,d,a)			20
				SINV(w)			$\boxed{18.5}$

Module 2

- **Objectives**
  - **Boolean covering**
  - **Boolean matching**
  - **Simultaneous optimization and binding**
  - **Extensions to Boolean methods**

Boolean covering

- Decompose network into base functions
- Partition network into cones
- Apply bottom-up covering to each cone
  - When considering vertex v:
    - Construct clusters by local elimination
    - Limit the depth of the cluster by limiting the support of the function
    - Associate several functions with vertex v
    - Apply matching and record cost



$$
\begin{aligned}
f_{j,1} &= xy; \\
f_{j,2} &= x(a+c); \\
f_{j,3} &= (e+z)y; \\
f_{j,4} &= (e+z)(a+c); \\
f_{j,5} &= (e+c'+d)y; \\
f_{j,6} &= (e+c'+d)(a+c);
\end{aligned}
$$

Boolean matching
P-equivalence

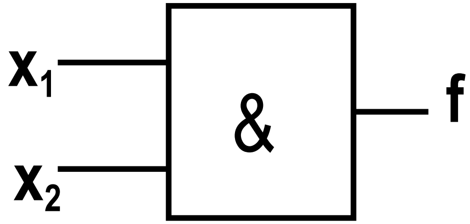
- **Cluster function f(x)**
  - Sub-network behavior
- **Pattern function g(y)**
  - Cell behavior
- ***P*-equivalence**
  - Is there a permutation operator P, such that $f(x) = g(P\,x)$ is a tautology?
- **Approaches:**
  - Tautology check over all input permutations
  - Multi-rooted pattern ROBDD capturing all permutations

Input/output polarity assignment

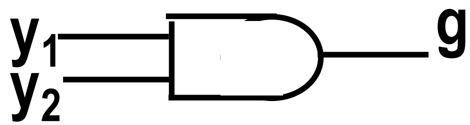
- ***NPN*** **classification of logic functions**
- ***NPN*-equivalence**
  - There exist a permutation operator P and complementation operators N_i and N_o, such that $f(x) = N_o\, g\, (\, P\, N_i\, x\,)$ is a tautology
- **Variations:**
  - ***N*-equivalence**
  - ***PN*-equivalence**

Boolean matching

- **Pin assignment problem:**
  - Map cluster variables x to pattern variables y
  - Characteristic equation: $A(x,y) = 1$

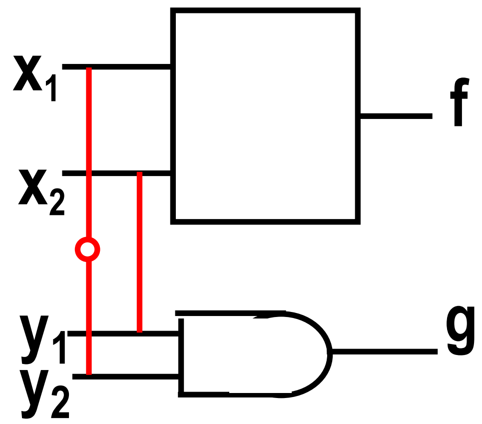


- **Pattern function under variable assignment:**
  - $g_A(x) = S_y\ (\ A(x,y)\ g(y)\ )$



- **Tautology problem**
  - $f(x) = g_A(x)$
  - $\forall_x\ f(x) = S_y\ (\ A(x,y)\ g(y)\ )$

Example



- Cluster terminals: x -- cell terminals: y
- Assign x_1 to y'_2 and x_2 to y_1
- Characteristic equation
  - $A\ (x_1, x_2, y_1, y_2) = (x_1 \oplus y_2)\ (x_2 \overline{\oplus}\ y_1)$
- AND pattern function
  - $g = y_1\ y_2$
- Pattern function under assignment
  - $S_{y1y2}\ A\ g = S_{y1y2}\ ((x_1 \oplus y_2)\ (x_2 \overline{\oplus}\ y_1)\ y_1\ y_2\ ) = x_2\, x'_1$

Signatures and filters

- Capture some properties of Boolean functions
- If signatures do not match, there is no match
- Signatures are used as filters to reduce computation
- Signatures:
  - Unateness
  - Symmetries
  - Co-factor sizes
  - Spectra

Filters based on unateness and symmetries

- Any pin assignment must associate:
  - Unate variables in $f(x)$ with unate variables in $g(y)$
  - Binate variables in $f(x)$ with binate variables in $g(y)$
- Variables or group of variables:
  - That are interchangeable in $f(x)$ must be interchangeable in $g(y)$

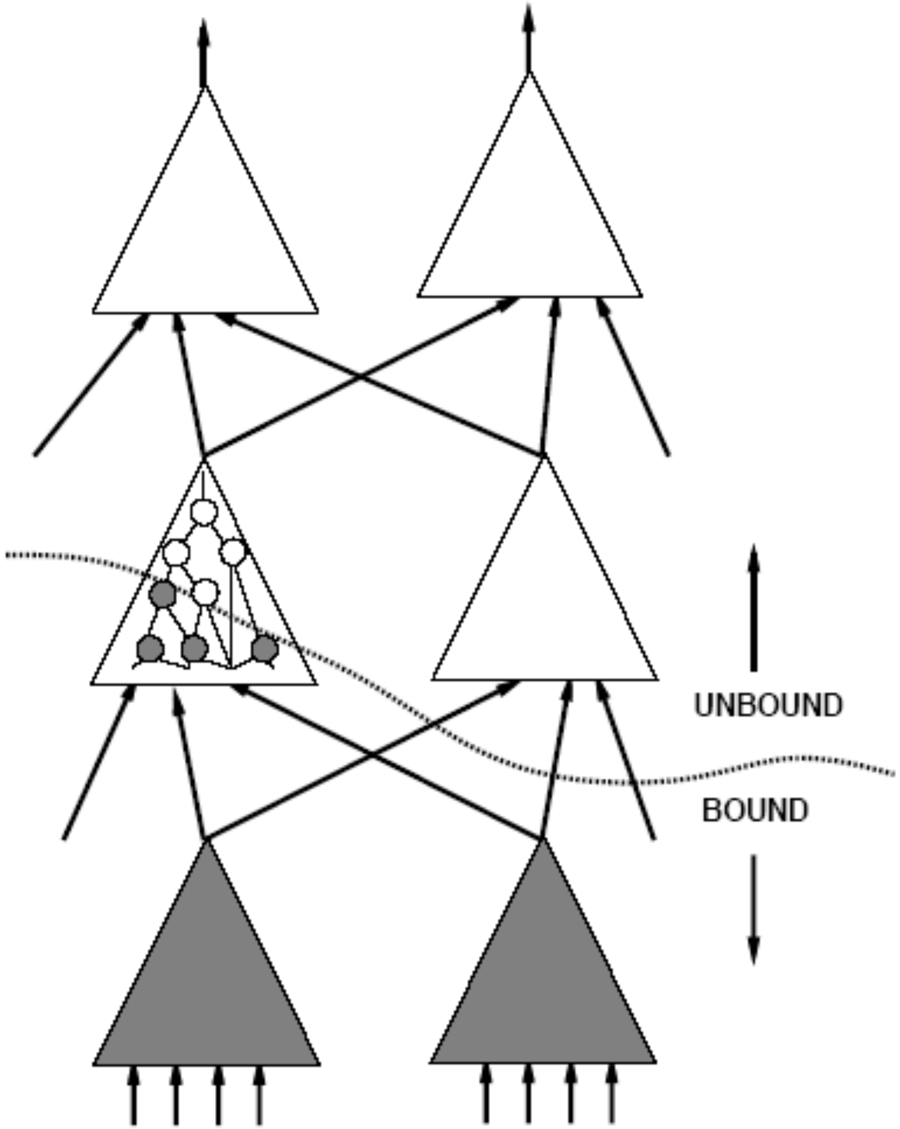
Example

- **Cluster function:** $f = abc$
  - Symmetries { { a,b,c} }
  - Unate
- **Pattern functions**
  - $g_1 = a + b + c$
    - Symmetries { { a,b,c} }
    - Unate
  - $g_2 = ab + c$
    - Symmetries { {a,b}, {c} }
    - Unate
  - $g_3 = abc' + a'b'c$
    - Symmetries { {a,b,c} }
    - Binate

Concurrent optimization and library binding

- **Motivation**
  - **Logic simplification is usually done prior to binding**
  - **Logic simplification and substitution can be combined with binding**
- **Mechanism**
  - **Binding induces some *don't care* conditions**
  - **Exploit *don't cares* as degrees of freedom in matching**

Example



Boolean matching with *don't care* conditions

- Given $f(x)$, $f_{DC}(x)$ and $g(y)$
  - g matches f, if g is equivalent to h, where:

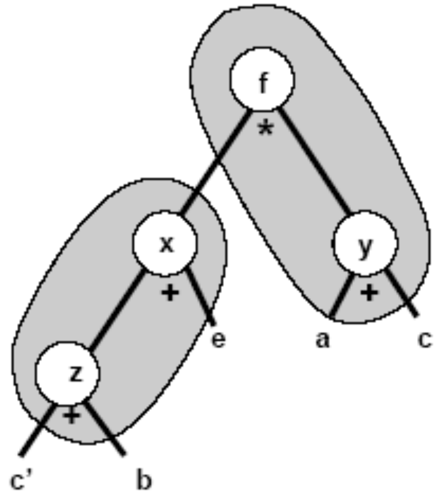
$$f \; f'_{DC} \le h \le f + f_{DC}$$

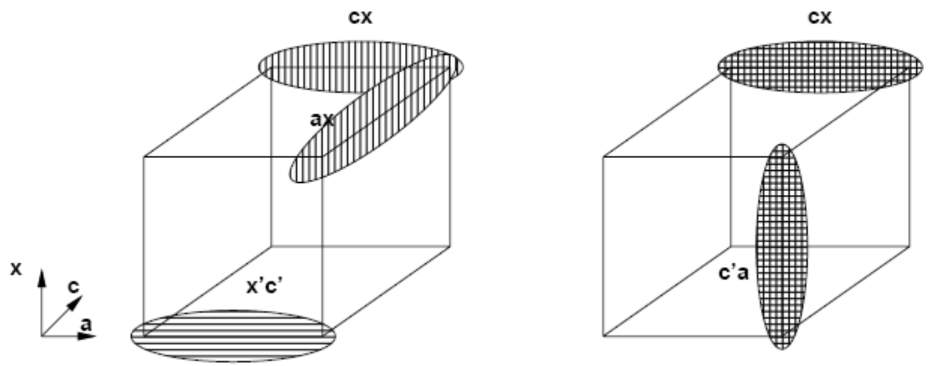
- Matching condition:

$$\forall_x \left(f_{DC}(x) + f(x) \;\overline{\oplus}\; S_y \left(A(x,y)\, g(y) \right) \right)$$

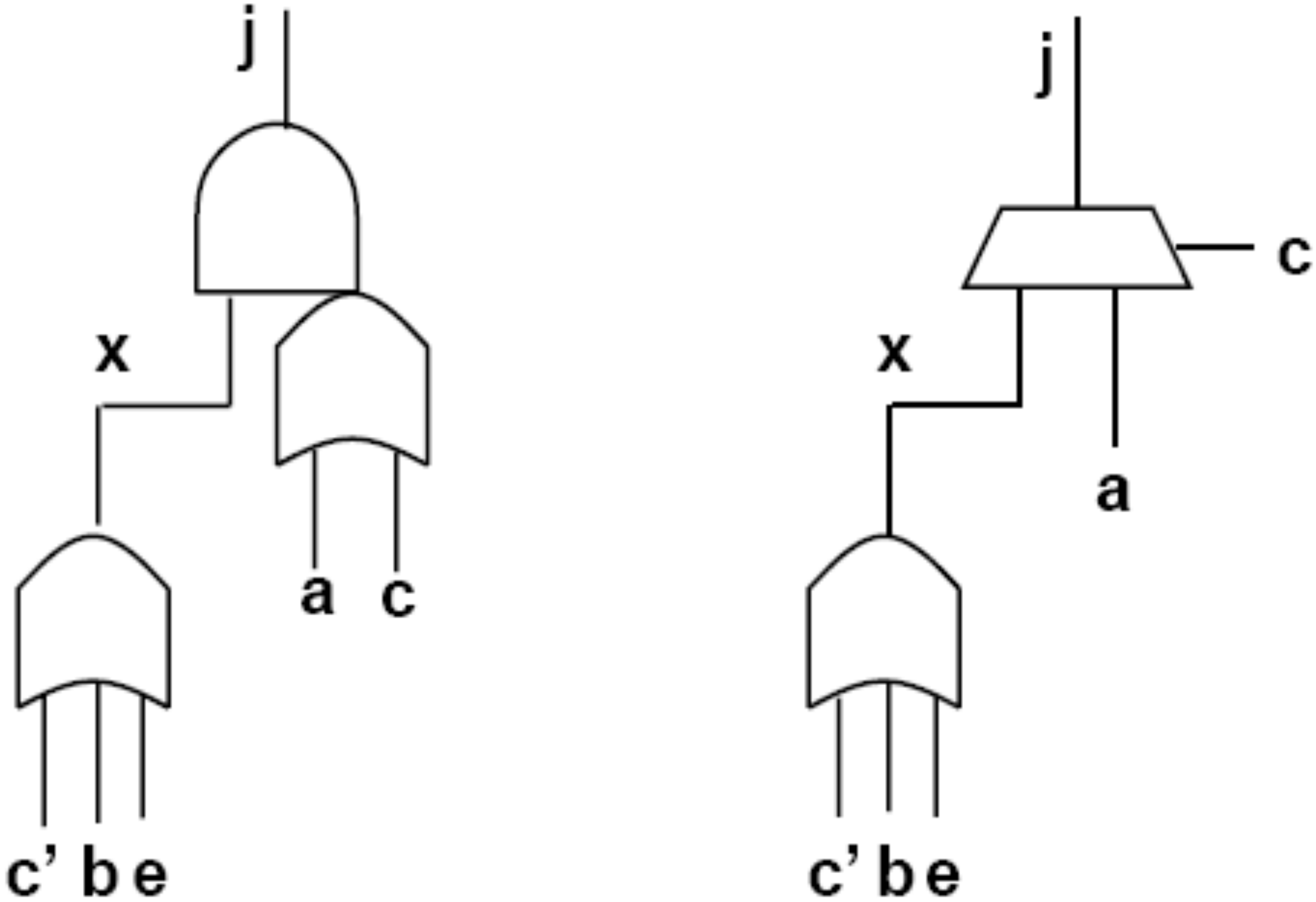
Example

- Assume v_x is bound to an OR3(c' ,b,e)
- Don' t care set includes $x \oplus (c' + b + e)$
- Consider $f_j = x(a+c)$ with CDC = $x' c'$
- No simplification.
  - Mapping into AOI gate.
- Matching with DCs.
  - Map to a MUX gate.





Example

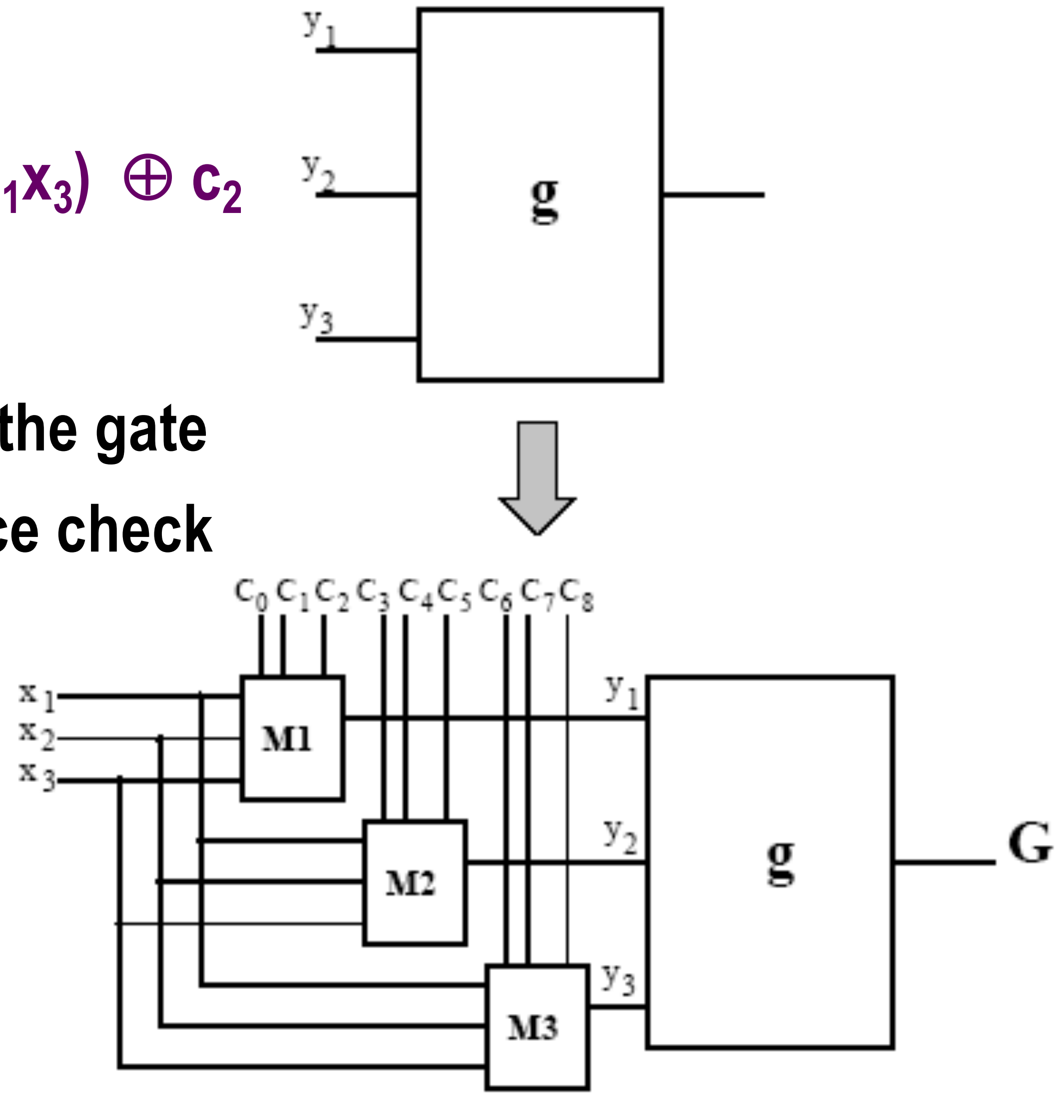


Extended matching

- Motivation:
  - Search implicitly for best pin assignment
  - Make a single test, determining matching and assignment
- Technique:
  - Construct BDD model of cell and assignments
- Visual intuition:
  - Imagine to place MUX function at cell inputs
  - Each cell input can be routed to any cluster input (or voltage rail)
  - Input polarity can be changed:
    - NP-equivalence (extensible to NPN)
  - Cell and cluster may differ in size
- Cell and multiplexers are described by a composite function $G(x,c)$
  - Pin assignment is determining c

Example

- $g = y_1 + y_2 y'_3$
- $y_1(c,x) = (c_0c_1x_1 + c_0c'_1x_2 + c'_0c_1x_3) \oplus c_2$
- $G = y_1(c,x) + y_2(c,x)\, y_3(c,x)'$
- An EXOR gate can be placed at the gate output to support NPN-equivalence check



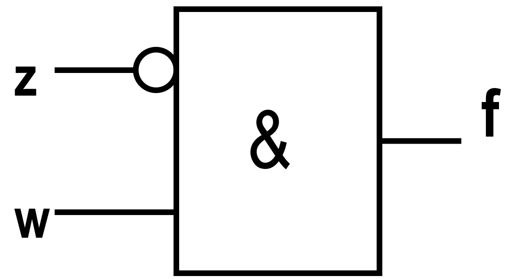
Extended matching modeling

- **Model composite functions with ROBDDs**
  - Assume n-input cluster and m-input cell
  - For each cell input:
    - $\lceil \log_2 n \rceil$ variables for pin permutation
    - One variable for input polarity
  - Total size of c: $m(\lceil \log_2 n \rceil + 1)$
  - One additional variable for output polarity
- **A match exists if there is at least one value of c satisfying**

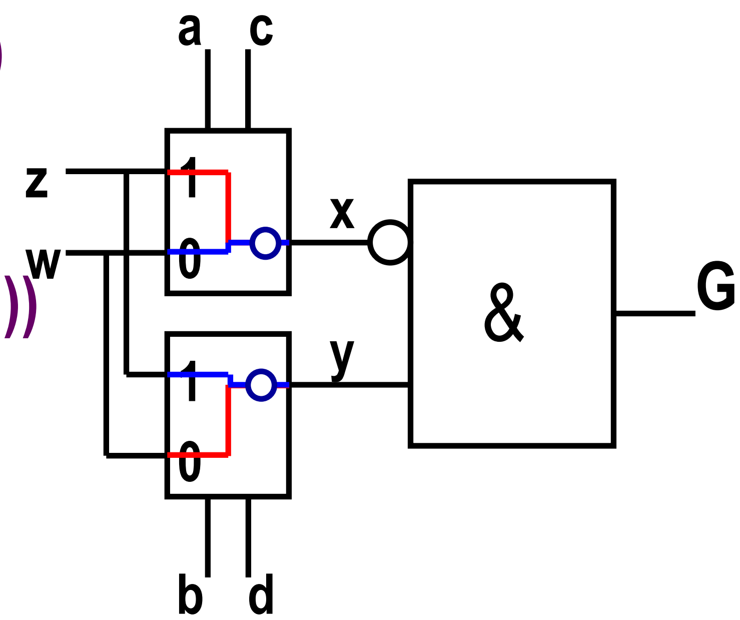
$$M(c) = \forall_x [\, G(x,c) \,\overline{\oplus}\, f(x) \,]$$

Example

- Cell: $g = x' y$
- Cluster: $f = wz'$



- $G(a,b,c,d) = (c \oplus (za + wa'))' (d \oplus (zb + wb'))$



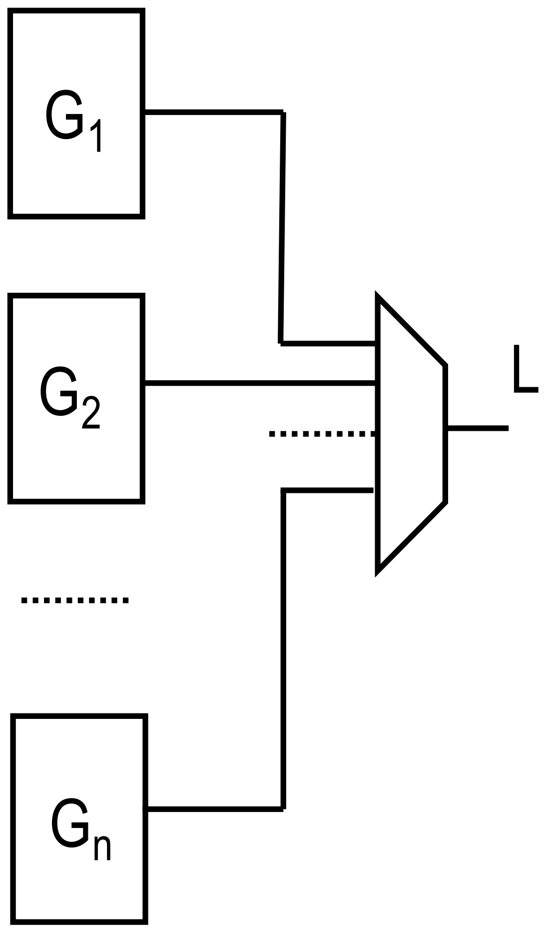
- $F \overline{\oplus} G = (wz) \overline{\oplus} (c \oplus (za + wa'))' (d \oplus zb + wb'))$
- $M(c) = ab' c' d' + a' bcd$

Extended matching

- Extended matching captures implicitly all possible matches
- No extra burden when exploiting *don't care* sets
- $M(c) = \forall_x [\, G(x,c) \overline{\oplus} f(x) + f_{DC}(x) \,]$
- Efficient BDD representation
- Extensions:
  - Support multiple-output matching
  - Full library representation

Full library model

- Represent full library with $L(x,c)$
  - One single (large) BDD
- Visual intuition
  - All composite cells connected to a MUX
- Compare cluster to library $L(x,c)$
  - $M(c) = \forall_x [\, L(x,c) \overline{\oplus} f(x) + f_{DC}(x) \,]$
  - Vector c determines:
    - Feasible cell matches
    - Feasible pin assignments
    - Feasible output polarity



Summary

- Library binding is a key step in synthesis
- Most systems use some rules together with heuristic algorithms that concentrate on combinational logic
  - Best results are obtained with Boolean matching
  - Sometimes structural matching is used for speed
- Library binding is tightly linked to buffering and to physical design