VLSI CAD: Logic to Layout

Lecture 10.1

From Logic to Layout: Technology Mapping Basics

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From Logic… To Layout…

- **What you know...**
  - Computational Boolean algebra, representation, some verification, some synthesis
  - This is what happens in the **"front end"** of the ASIC design process

High-level design description → Synthesis, verification → Connected gates + wires in your technology: called a **netlist**

- **One key missing step:**
  - How to **transform** result of multi-level synthesis into real gates for layout task
  - Called: **Technology Mapping**. Or **Tech Mapping**. Or **Mapping, Fitting, Binding**
    - Reference: Giovanni DeMicheli, *Synthesis and Optimization of Digital Circuits*, McGraw Hill, 1994, Chapter 10

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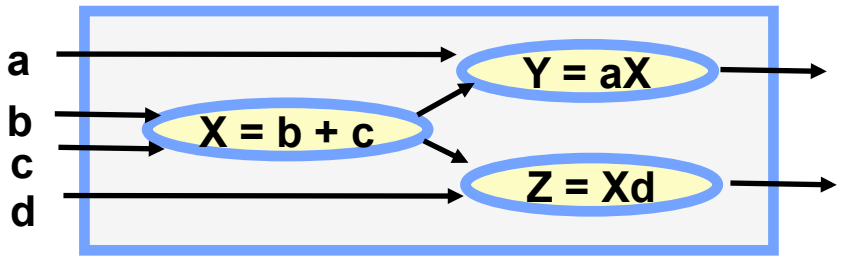
Tech Mapping: The Problem

- **Multi-level model is still a little abstract**
  - Structure of the Boolean logic network is fixed
  - ESPRESSO-style 2-level simplification done on each node of network...
  - But that still does **not** give us the actual gate-level netlist
- **Trivial example**



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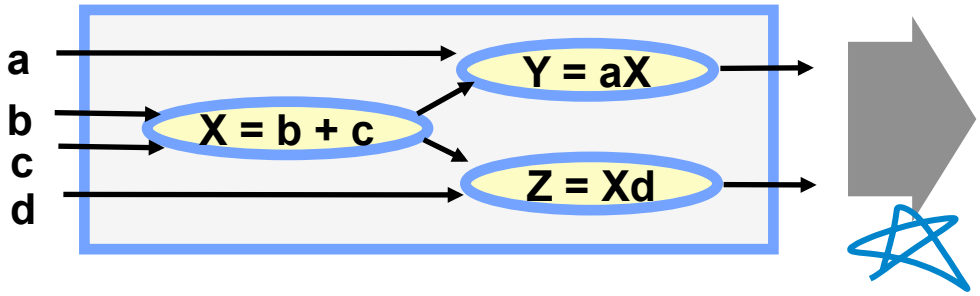
Tech Mapping: Problem

- **Suppose we have these gates in our "library"**
  - This is called "**the technology**" we are allowed to use to build this optimized netlist

  - **OA21** is an OR-AND, a so-called **complex gate** in our library



How do we build the 2 functions specified in this Boolean Logic Network using **only** these gates from **our library**?

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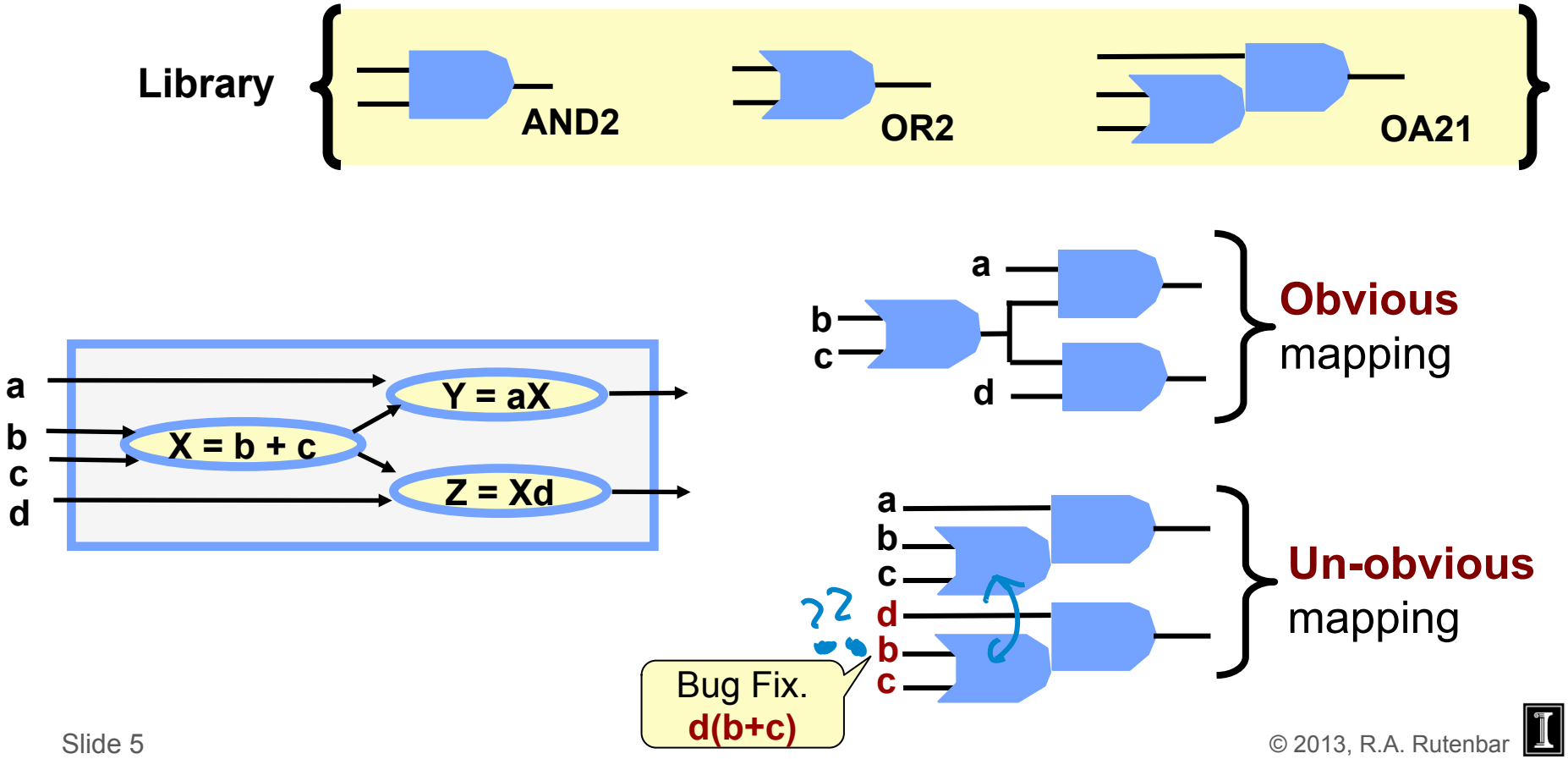
Tech Mapping: Simple Example



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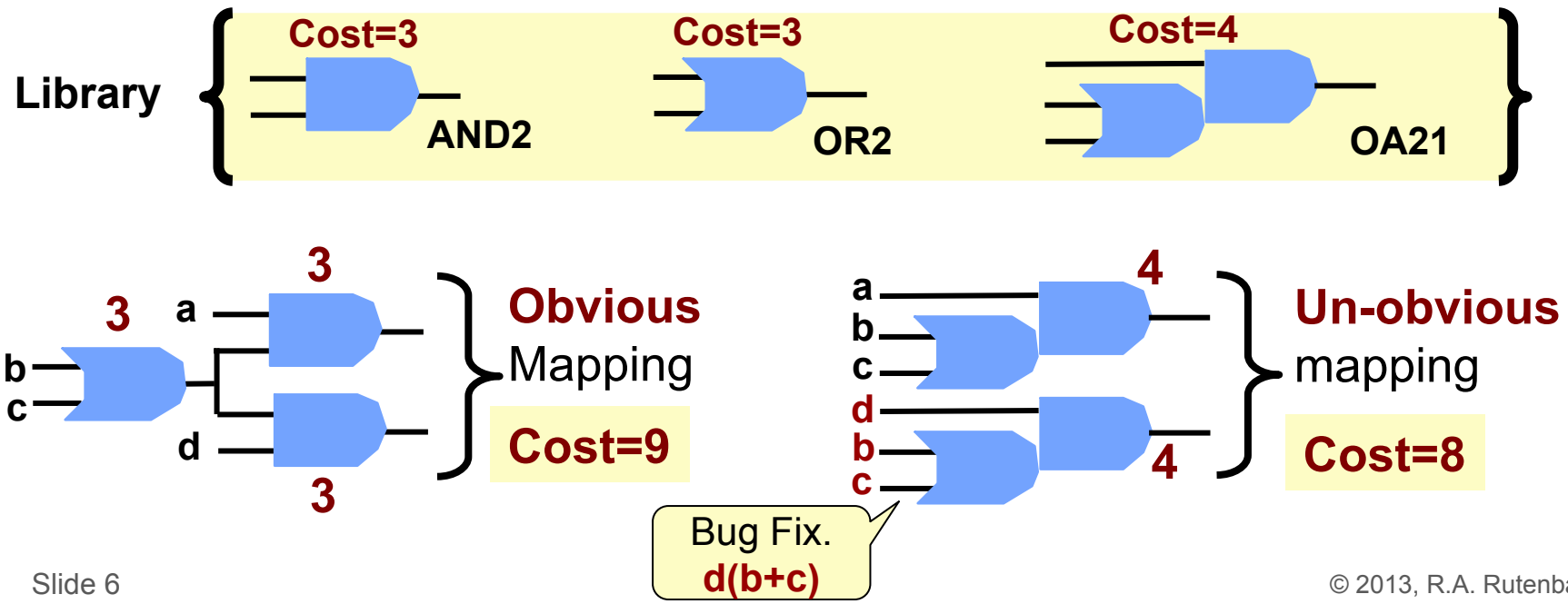
Tech Mapping: Simple Example

- **Why choose a non-obvious mapping?**
  - **Answer 1: Cost**. Suppose each gate in library has a cost associated with it.
  - Think of this as, eg, the **silicon area** of the standard cell gate



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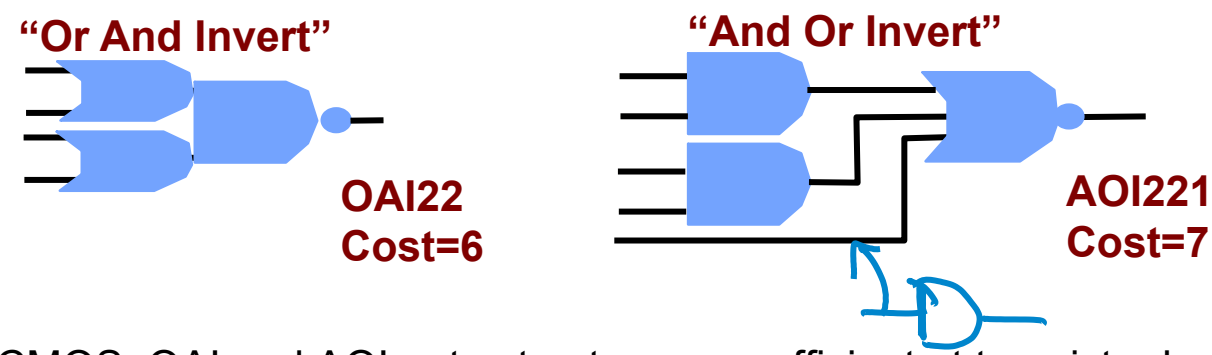
Tech Mapping

- **Why choose a non-obvious mapping?**
  - **Answer 2:** **Complexity** (which really is just cost, in a *different* way)
  - Your library might have complex gates that are hard to map "by eye"



  - In CMOS, OAI and AOI gate structures are efficient at transistor level

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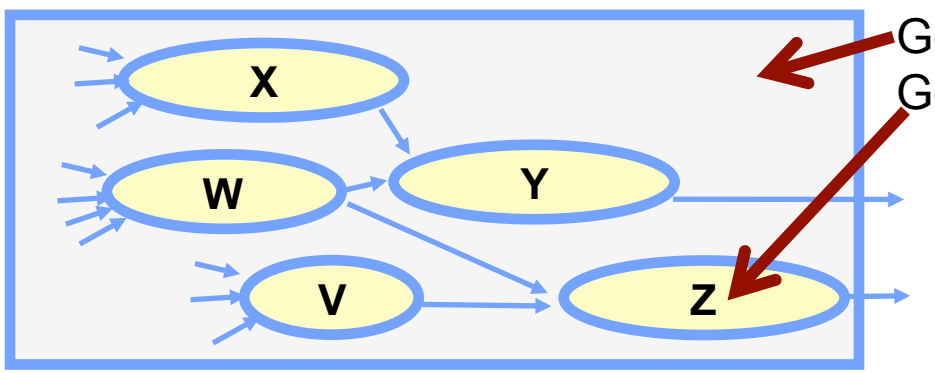
What “Multilevel Synthesis” Does…

- **Helpful “mental” model to use: Multi-level synthesis does this...**
  - **Structures** the multiple-vertex Boolean logic network **“well”**
  - **Minimizes SOP** contents of each vertex in the network **“well”**, ie, # of literals
  - But it does **not create real logic gates**
  - This result is called: **“uncommitted”** logic, or **“technology independent”** logic



Good **global** structure (nodes)
Good **local** structure (SOP in nodes)

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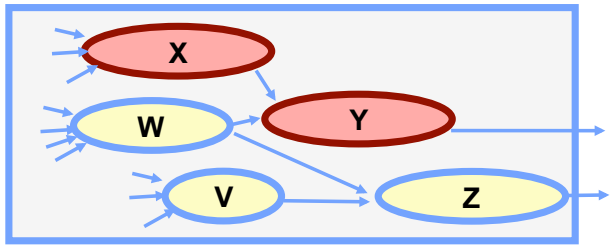
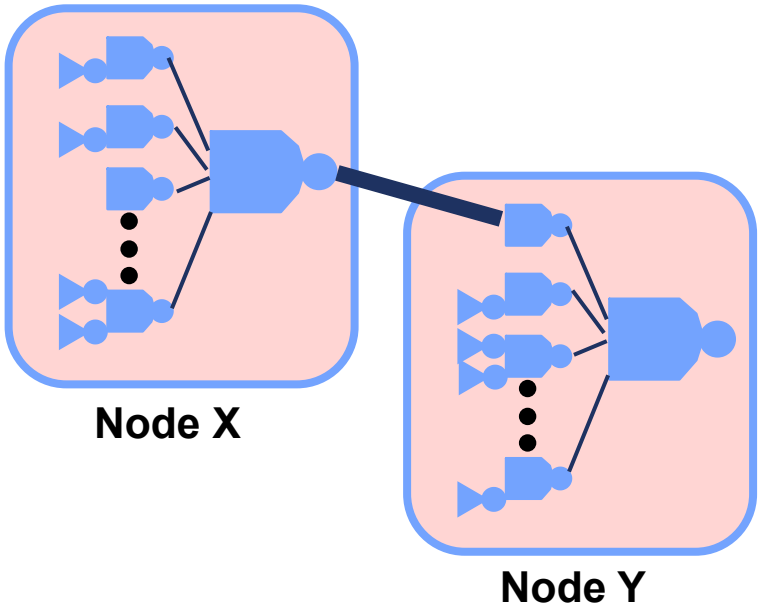
What “Technology Mapping” Does

- **Model**
  - First, we transform uncommitted logic into simple, **real** gates
  - We transform **every** SOP form in **each** node into **NAND** & **NOT** gates. Nothing else!





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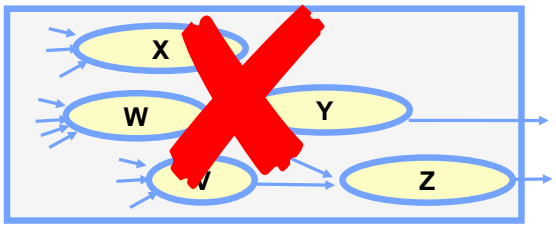
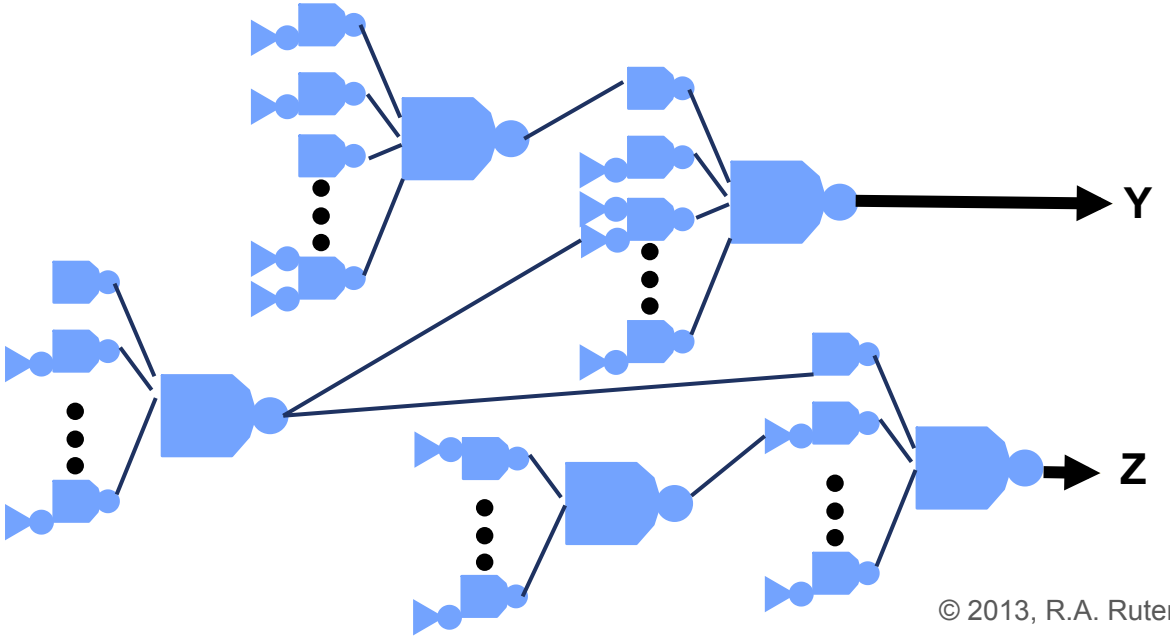
What "Technology Mapping" Does

- **Model**
  - **Final result:** Boolean logic network **disappears**. **X, Y, W, V, Z** boundaries go away
  - We have one **BIG** "flat" network of **NANDs** and **NOTs**. This is what we map.





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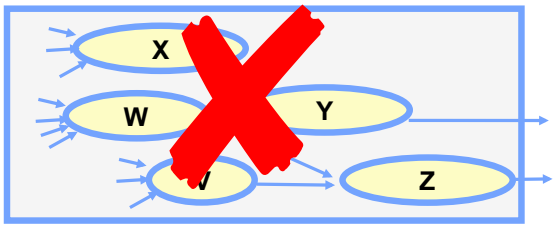
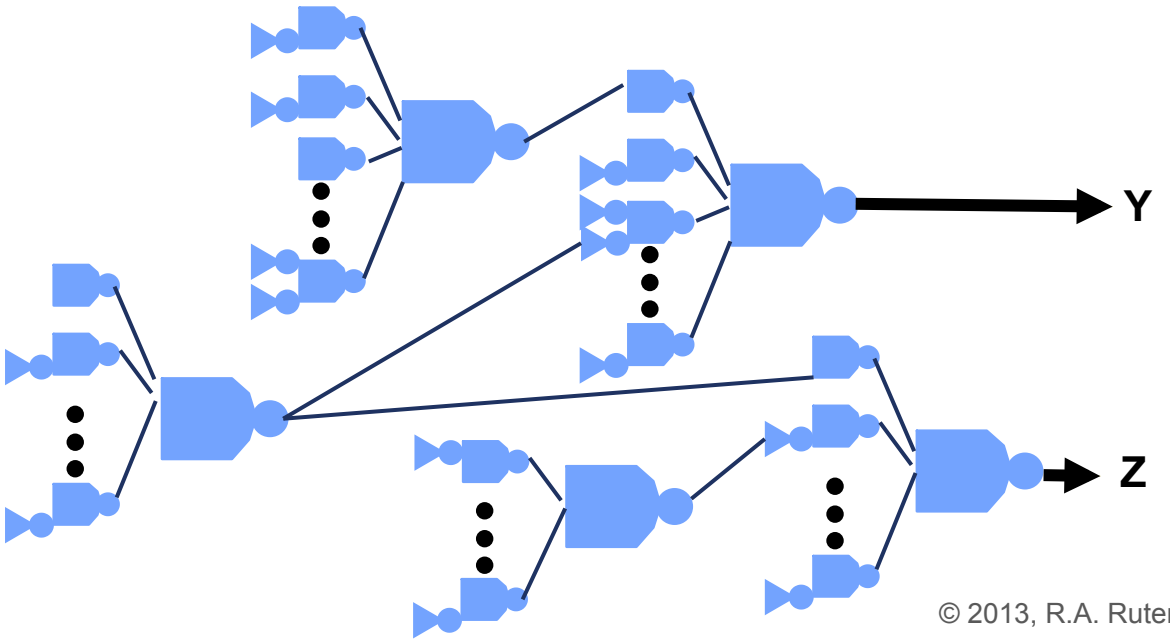
This is Our Starting Point…

- **Multi-level synthesis produces this big network of simple gates**
- **How to transform – map – this onto standard cells in our library?**





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VLSI CAD: Logic to Layout

Lecture 10.2

From Logic to Layout: Technology Mapping as Tree Covering

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Technology Mapping as *Tree Covering*

- **One famous, simple model of problem**
  - Your logic network to be mapped is a **tree of simple gates**
    - Easiest to assume absolutely minimal gate types
    - For us: uncommitted form is 2 input **NAND** ("**NAND2"**) and **NOT** gates, only
  - Your library of available "real" gate types is also **"represented"** in this form
    - Each gate is represented as a **tree** of **NAND2** and **NOT** gates, with associated **cost**

- **Method is surprisingly simple and optimal**
  - Original reference: Kurt Keutzer, "DAGON: Technology Binding and Local Optimization by DAG Matching," Proc. ACM/IEEE Design Automation Conference (DAC), 1987

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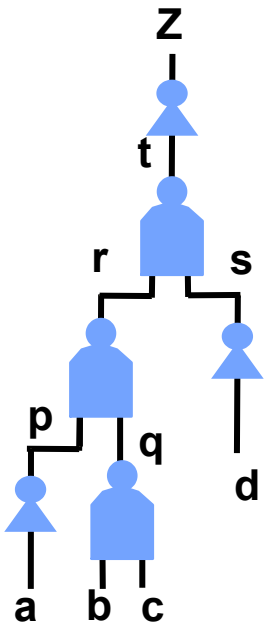
Tree Covering Example: Start with…

- **Here is your uncommitted logic to be tech mapped**
  - This is what results from our multilevel synthesis optimization…
  - … after replacing all SOP forms in the network nodes with **NAND/NOT**
  - Called the **subject tree.**
  - (Restrict to NAND2 to keep this simple, to map this example in detail. Also label not only inputs but all internal wires too.)



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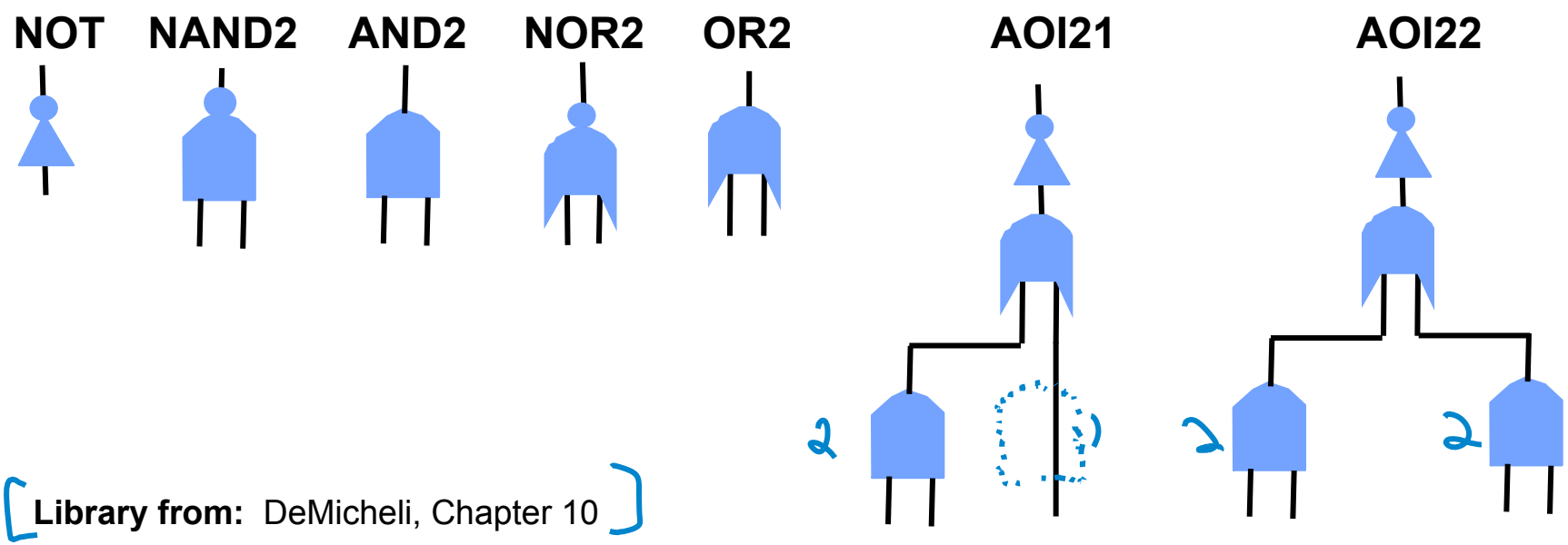
Tree Covering: Your Technology Library

- **And, here is a very simple technology library**
  - **First problem:** this is **not** in the required **NAND2/NOT-only** form. Must **transform**



Library from: DeMicheli, Chapter 10

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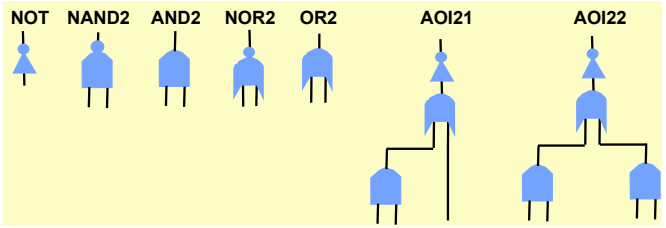
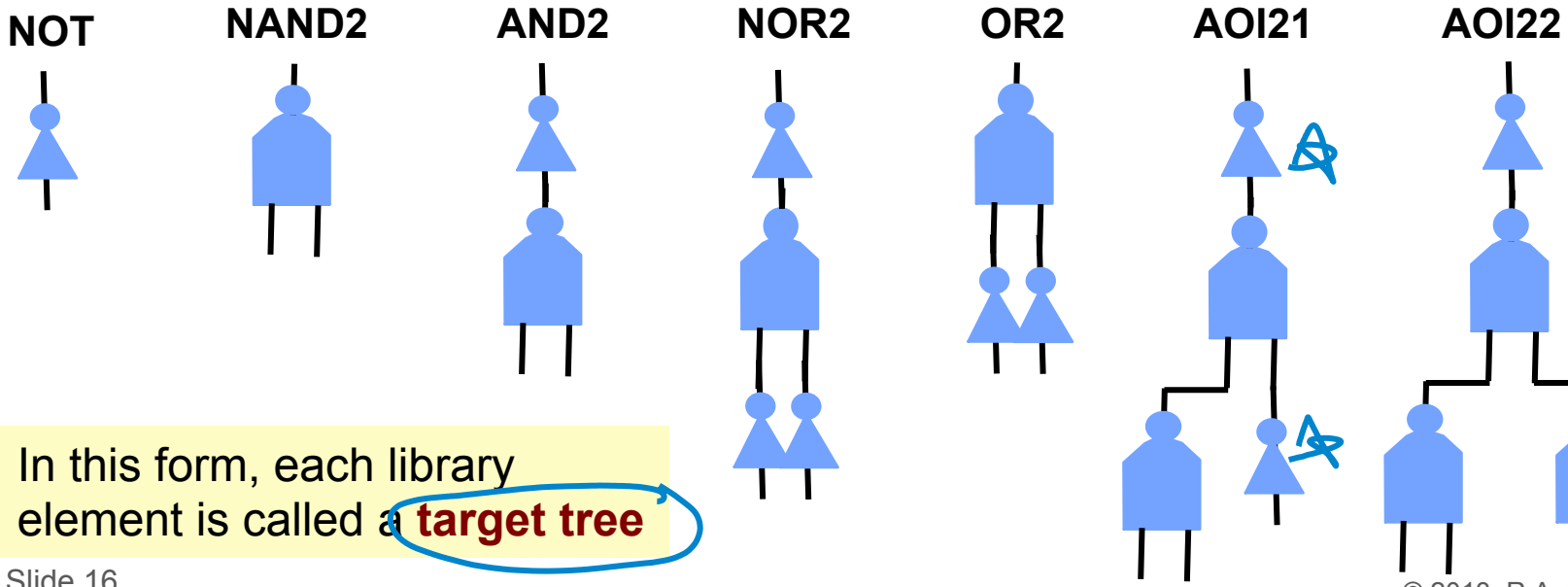
Tree Covering: Representing Library

- **Transforming to NAND2/NOT form is easy**
  - Just some DeMorgan law Boolean algebra.





In this form, each library element is called a **target tree**

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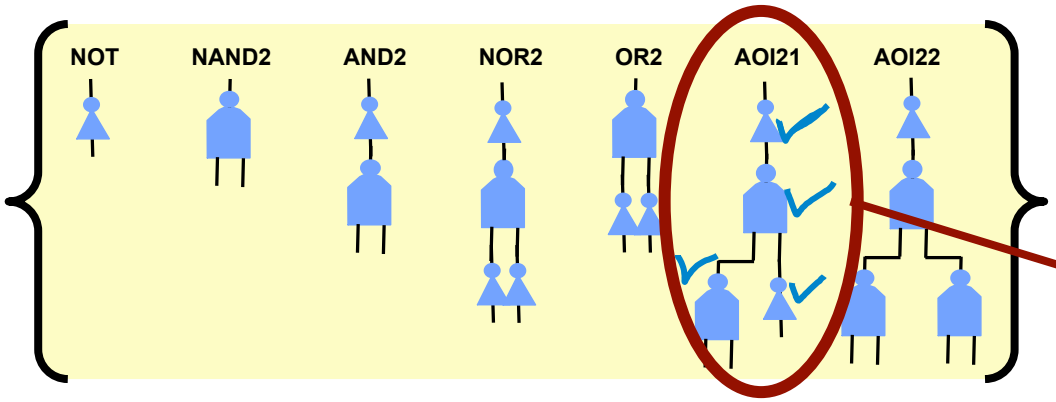
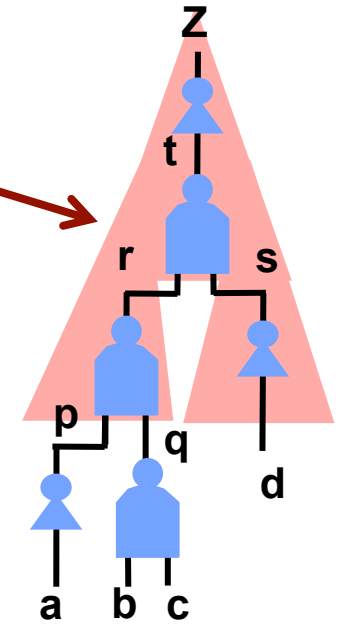
Essential Idea in "Tree Covering"





- **No Boolean algebra here!**
- **This is called: structural mapping**
  - Find where, in subject graph, the library pattern "matches" everywhere
  - NAND matches NAND, NOT matches NOT, etc

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The General Tree Cover Representation

- **Again: this is called a structural tech mapper**
- **Why?**
  - Because there is no Boolean algebra anywhere in here!
  - We just match the gates, wires in a simple **pattern-match** way
- **Result**
  - Surprisingly simple covering algorithm for cost-optimal cover
  - But first, lets simplify the way we draw these, to emphasize “structural” match

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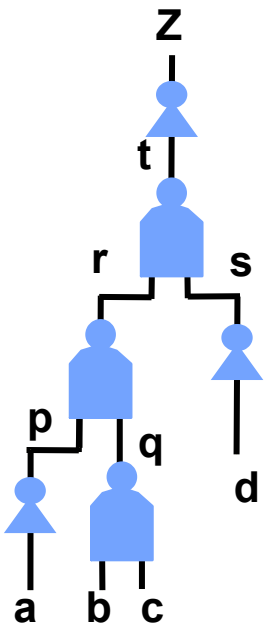
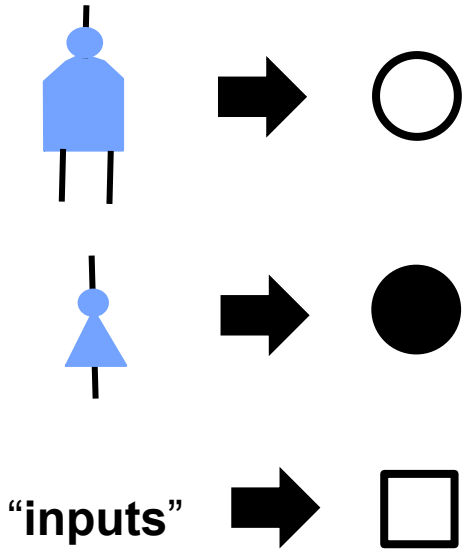
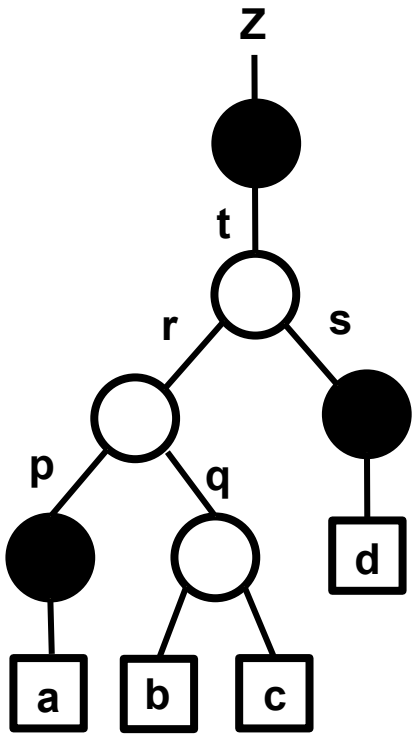
Representing Trees for Covering



Only **three** kinds of structures that we need **match** in any tree





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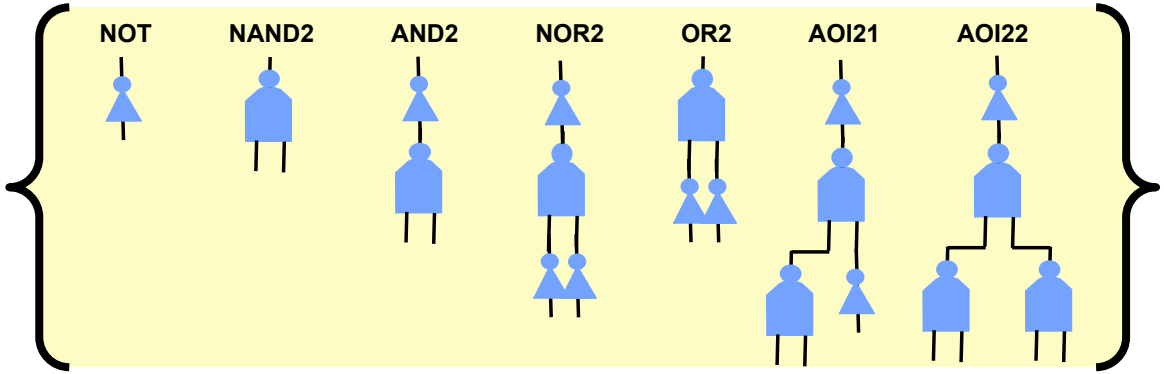
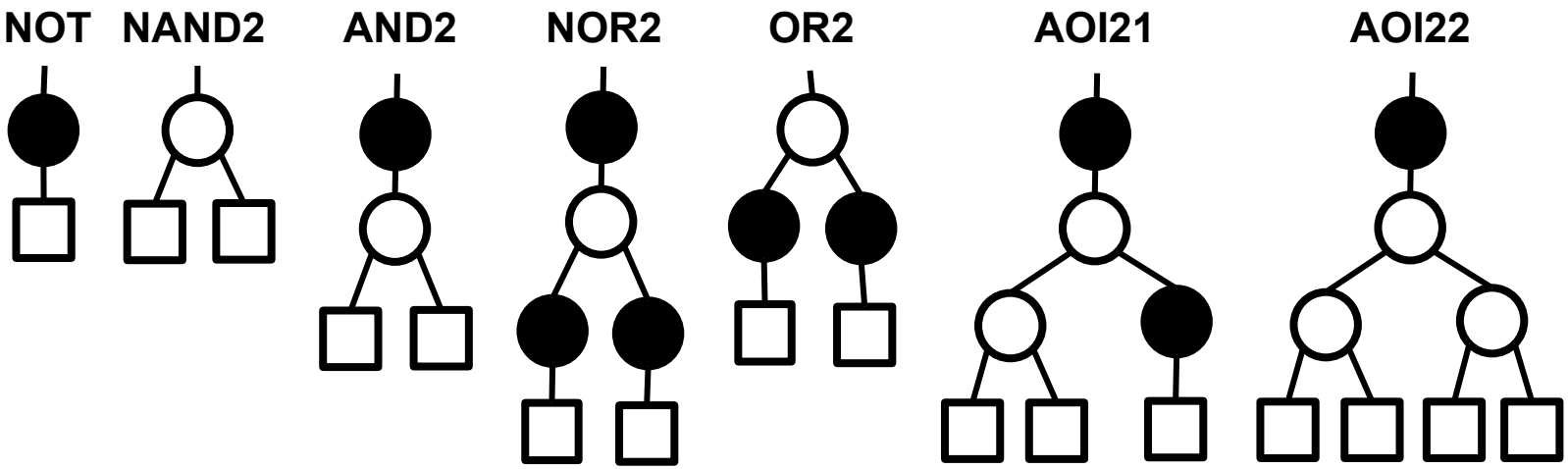
Represent Library in this *Same* Style





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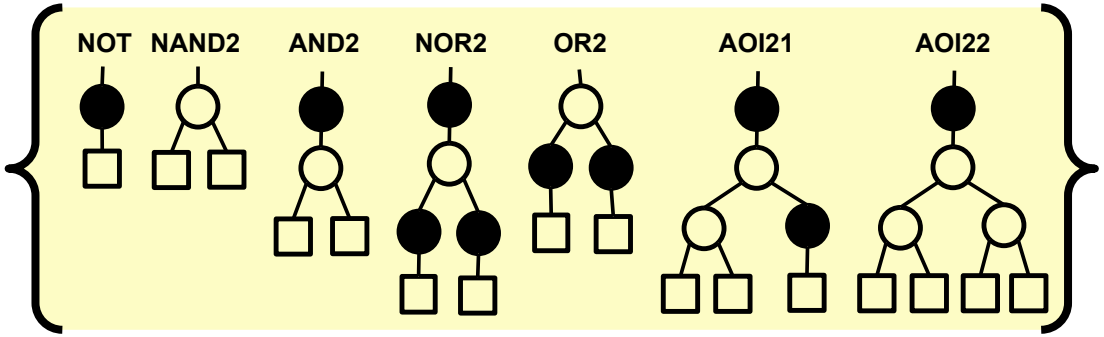
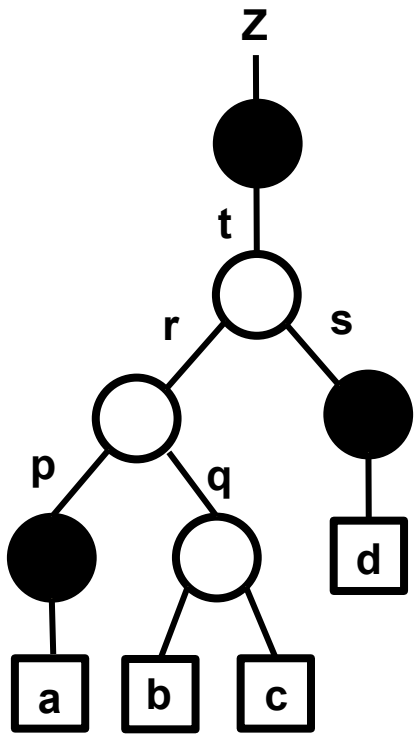
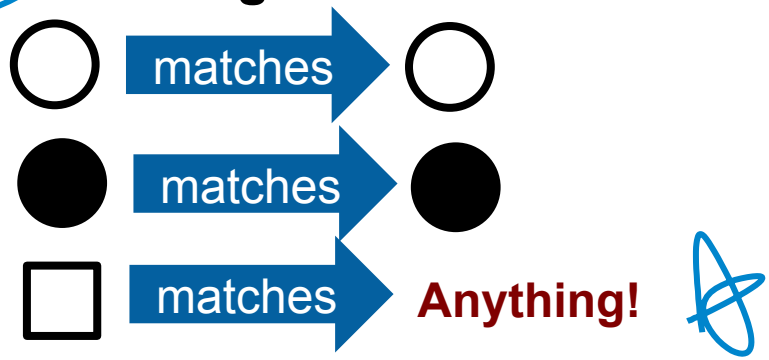
Structural Mapping Problem: Revisited





- **No Boolean algebra here at all!**
- **Structural matching rules:**



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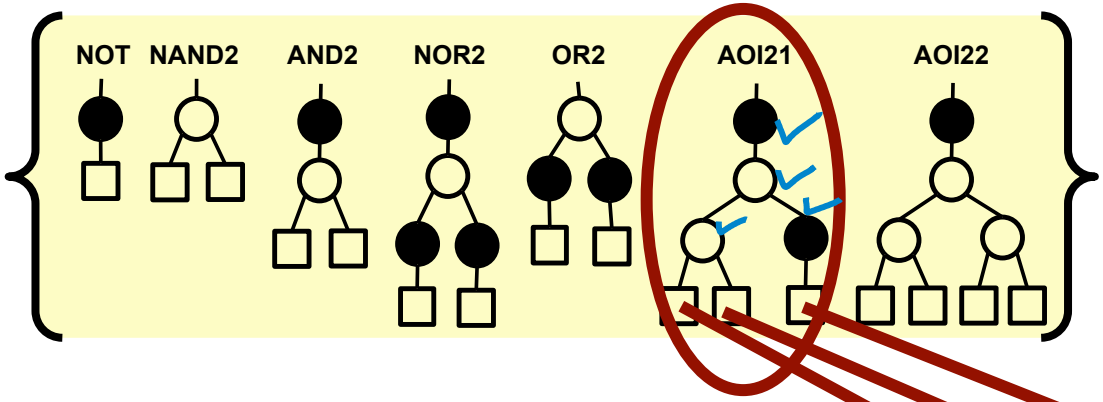
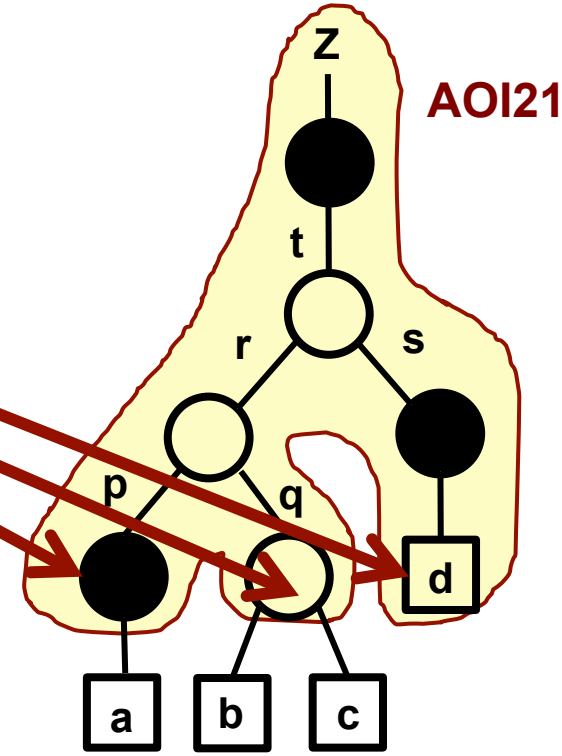
How a “Target Gate” Matches Subject Tree





- **The AOI21 matches at Z**
  - Because all internal nodes match exactly
  - **And the inputs match “anything”**

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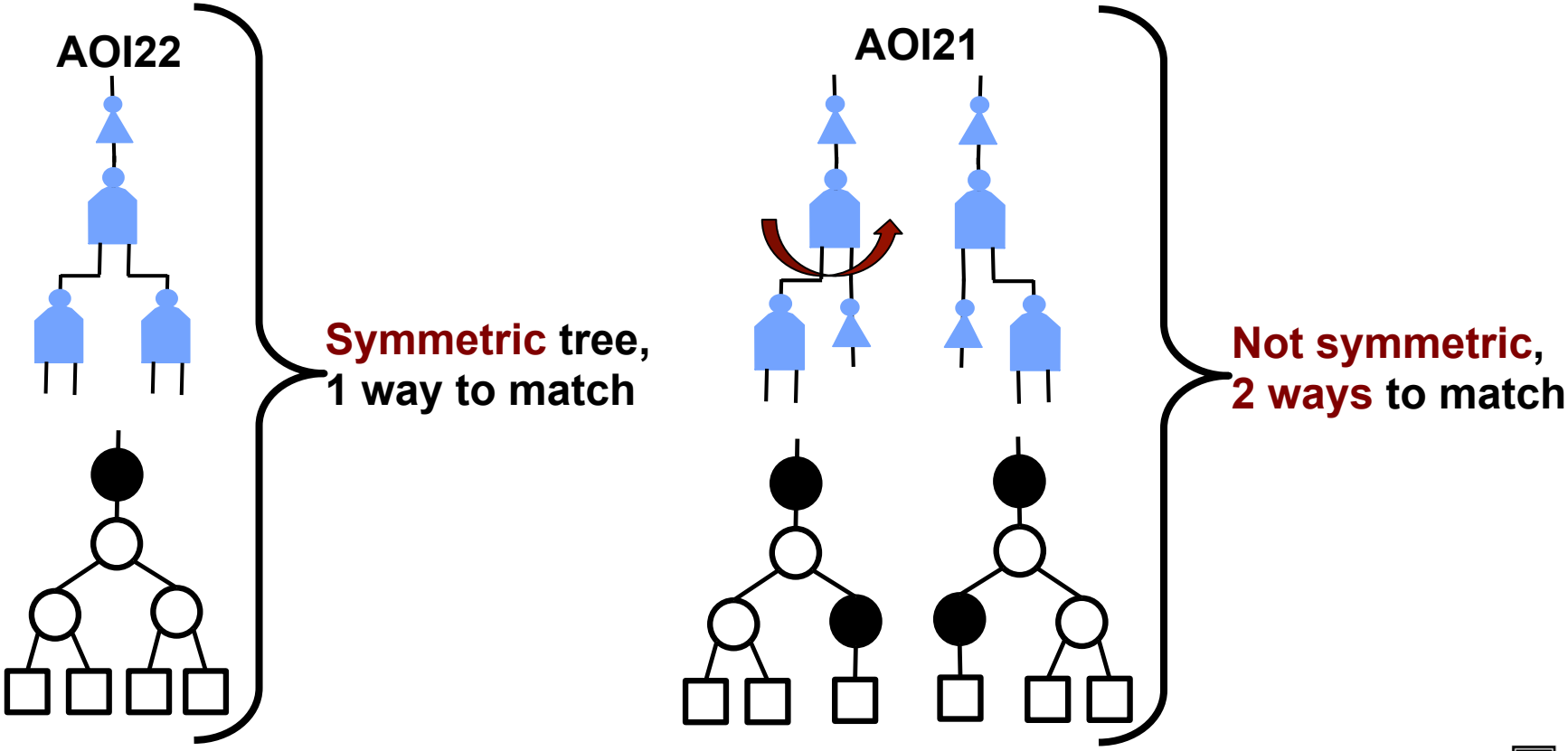
Be Careful: Symmetries Matter!



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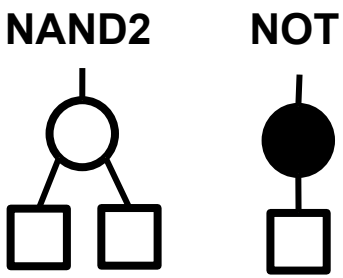
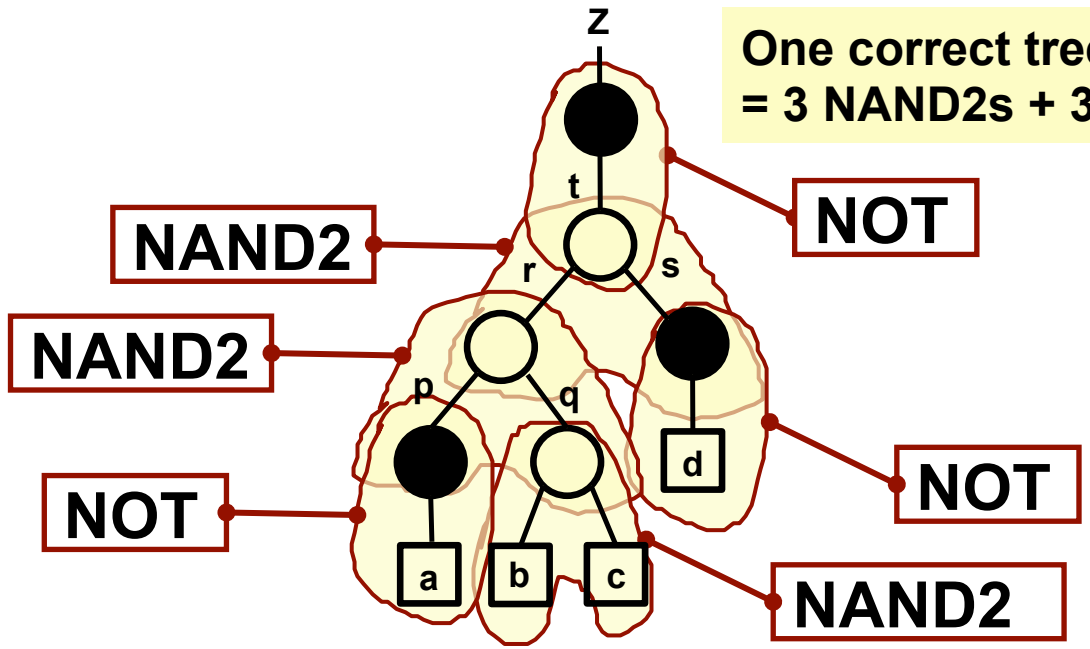
Rules for a *Complete* Tree Cover

- **Every node in subject tree is covered some library tree**
- **Output of every library gate overlaps input of next library pattern**





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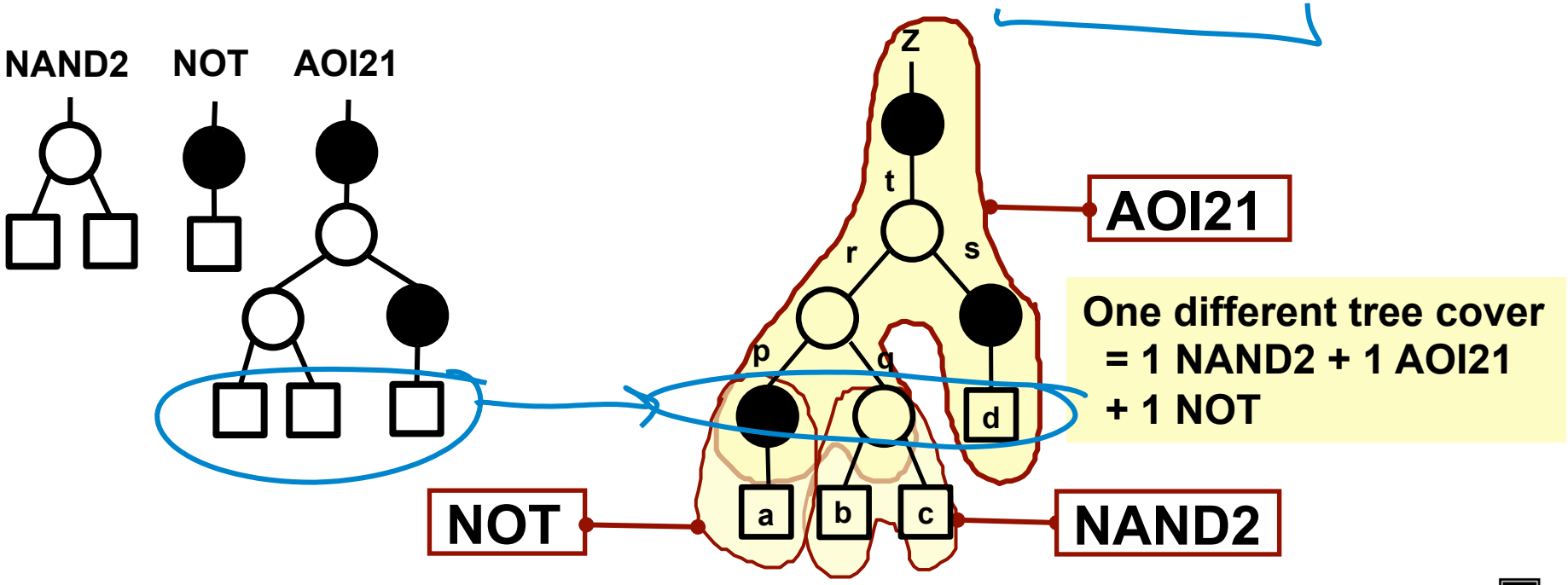
Rules for a *Complete* Tree Cover

- **Note: usually there are many different legal covers**
- **Which one do we choose? The one with minimum cost**



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VLSI CAD: Logic to Layout

Lecture 10.3

From Logic to Layout: Technology Mapping—Tree-ifying the Netlist

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Tech Mapping via Tree Covering

- **What do we need for a complete algorithm?**

- **Tree-ifying the input netlist**
  - One key assumption needs discussion
- **Tree matching**
  - For each node in your subject tree, find the target pattern trees in library match here
- **Minimum-cost covering**
  - Assume you know what can match at each node of subject tree
  - ..so, which ones do you pick for a minimum cost cover?

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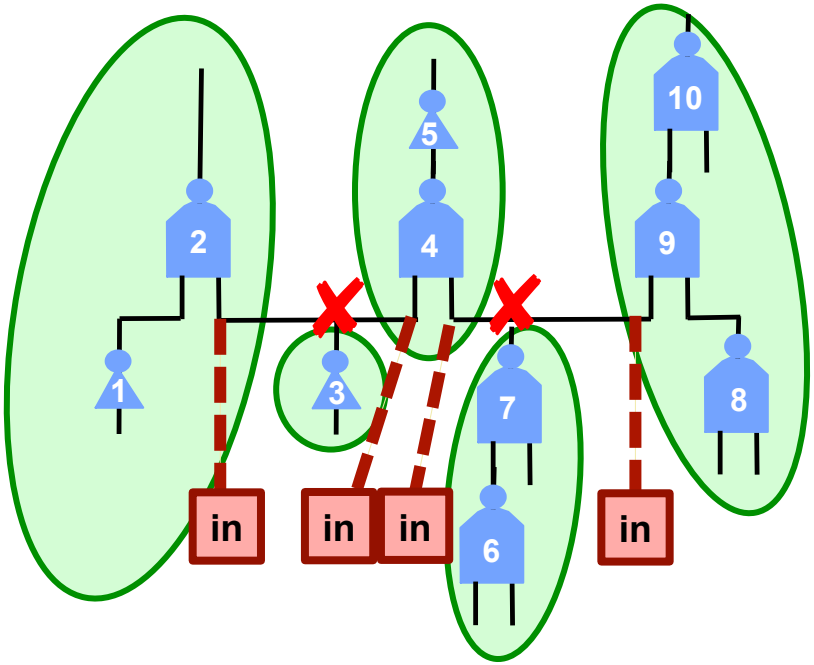
Tree-ifying the Netlist

- **These algorithms only work on trees, not more general graphs**
  - Gate netlists are **Directed Acyclic Graphs** (DAGs): directed edges, no loops DAGs
  - Every place you see a gate with fanout (> 1 other gate), you **need to split**



Rules:

1. **Every** gate with fanout > 1 becomes the **root** of a new sub-tree
2. **Each** connected fanout becomes a **new input** to a new tree

So, we **split** this DAG with fanouts into **5 separate trees**, map each separately

This entails some clear loss of optimality, since cannot map across trees

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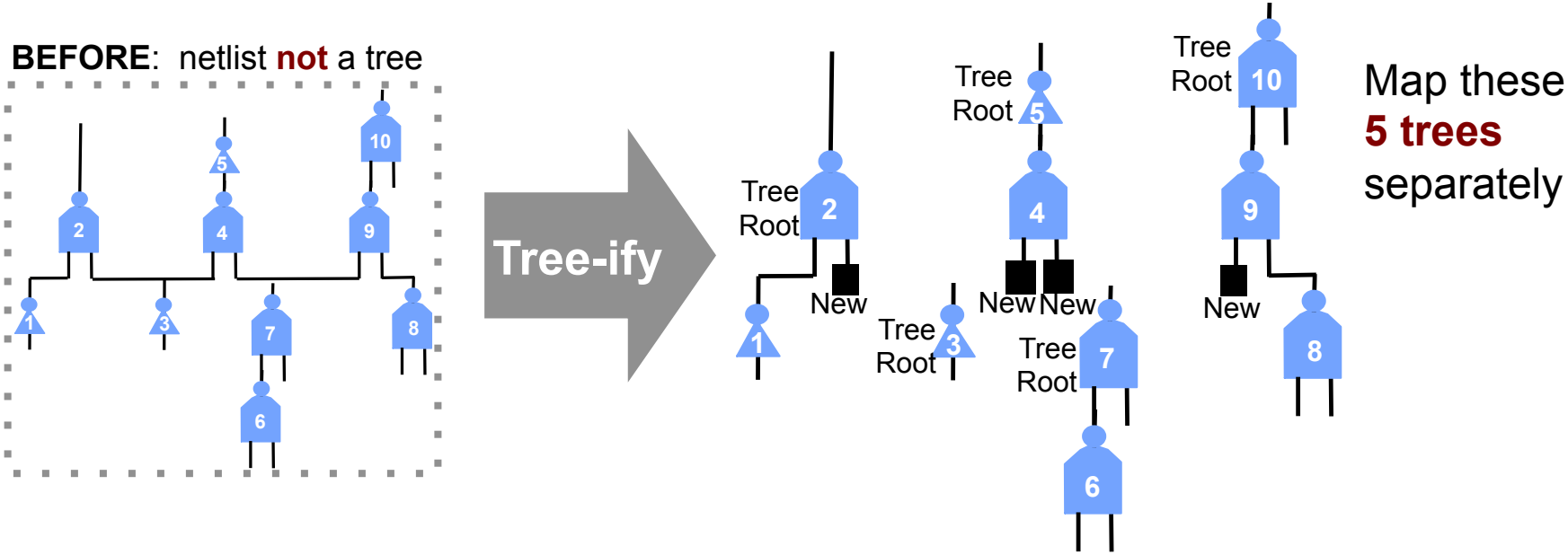
Tree-ifying Netlist: Result

- **Our algorithms mandate trees, not DAGs**
  - Every place there is fanout from gate output > 1, you have to cut
  - Loses some optimality. There are ways around these, but we won't discuss these



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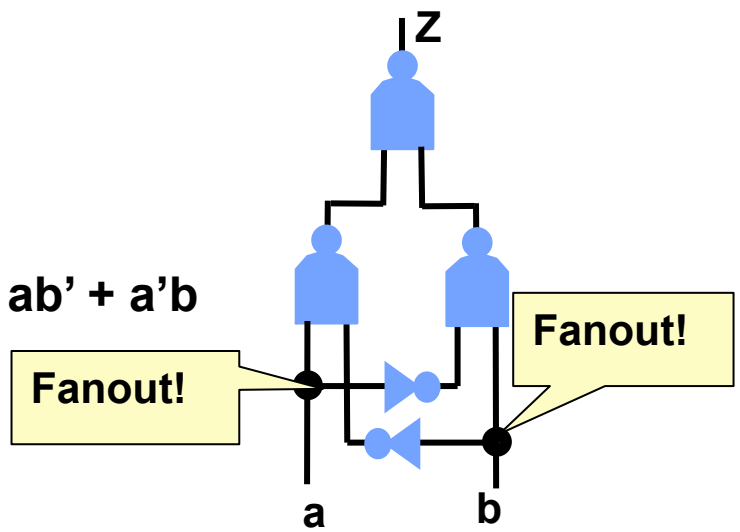
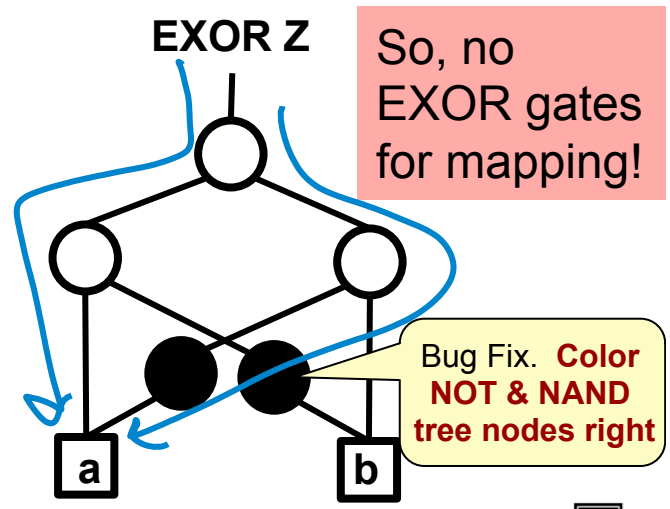
Aside: How Restrictive is "Tree" Assumption?

- **Subject graph and each pattern graph must be trees**
  - Subject tree must be tree-ify-ed. **What about pattern trees?**
  - Are there ordinary, common – useful-- 'gates' that cannot be trees?
  - Yes! There are tricks to deal with this – but for us, these are forbidden!

EXOR gate

Z= ab' + a'b





So, no EXOR gates for mapping!

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VLSI CAD: Logic to Layout

Lecture 10.4

From Logic to Layout: Technology Mapping—Recursive Matching

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Tech Mapping via Tree Covering

- **What do we need for a complete algorithm?**

- **Tree-ifying the input netlist**
  - One key assumption needs discussion
- **Tree matching**
  - For each node in your subject tree, find the target pattern trees in library match here
- **Minimum-cost covering**
  - Assume you know what can match at each node of subject tree
  - ..so, which ones do you pick for a minimum cost cover?

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Tree Matching

- **Goal:**
  - Determine, for every node in subject tree, what library gate can **match** (structurally)

- **Straightforward approach: Recursive matching**
  - Simple idea is to just try **every library gate** at **every node of subject tree**
  - Library gates are small patterns – this is not too much work
  - **Recursive means:** match **root** of subject with **root** of pattern, and then recursively match **children** of subject to children of pattern

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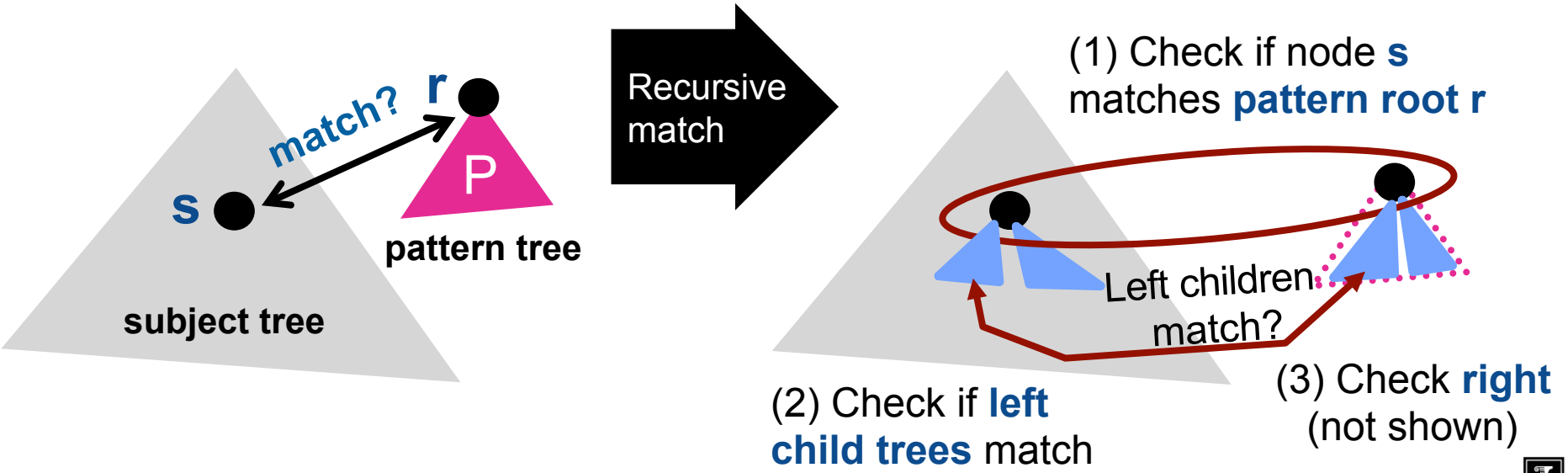
Recursive Tree Matching

- **Does library pattern tree P match node s in our subject tree?**
  - First, check if node **s** matches **r=root(P)** node of pattern **P**
  - If so, **recursively** match **left child tree** of **s** and **r**, and then **right child trees**



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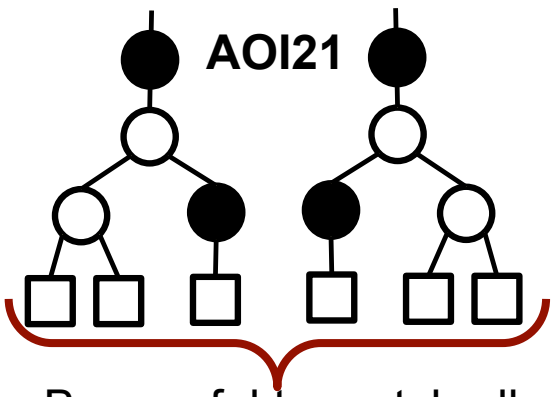
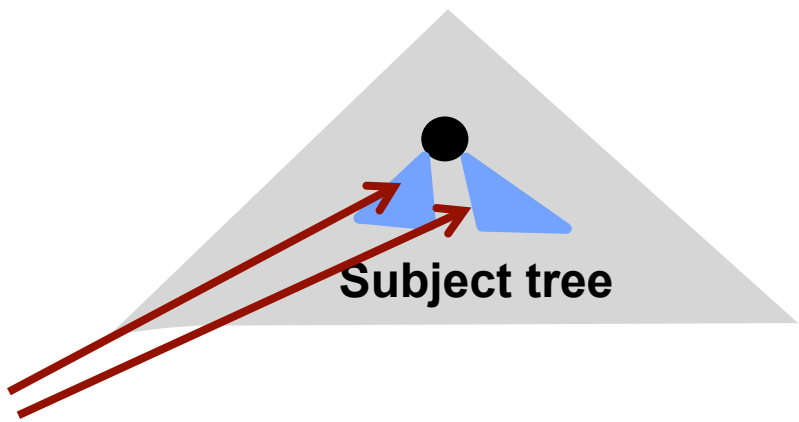
Tree Matching: One Subtlety

- **Be careful matching asymmetric library patterns**
  - Our example was AOI21. Need to remember to check all possible match possibilities by "**rotating**" the pattern tree



Be careful to match all **possible orientations** of these asymmetric patterns



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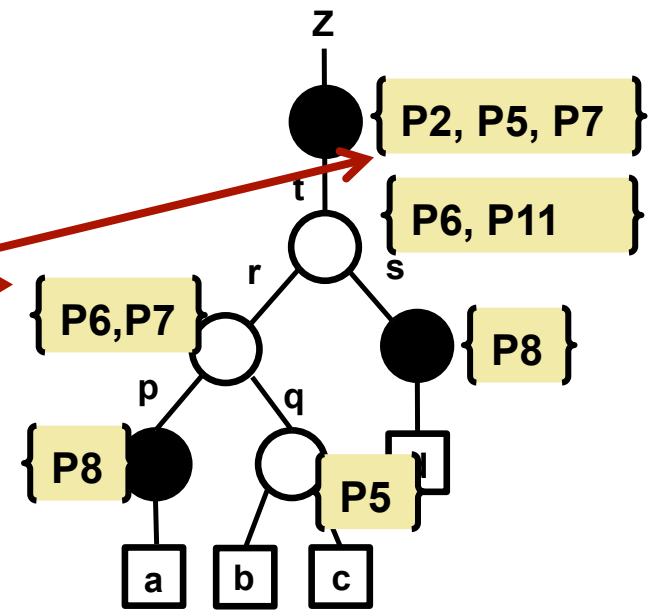
Result After Matching

- **Where are we?**
  - For each "gate type" node of subject tree, we know which library pattern trees **match** that node.
  - We **annotate** each such node in the tree with this **matching information**



- **Next problem:**
  - What is the ***best cover*** of the subject tree with patterns from target library?

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VLSI CAD: Logic to Layout

Lecture 10.5

From Logic to Layout: Technology Mapping—Minimum Cost Covering

Rob A. Rutenbar
University of Illinois

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Tech Mapping via Tree Covering

- **What do we need for a complete algorithm?**

- **Tree-ifying the input netlist**
  - One key assumption needs discussion
- **Tree matching**
  - For each node in your subject tree, find the target pattern trees in library match here
- **Minimum-cost covering**
  - Assume you know what can match at each node of subject tree
  - ..so, which ones do you pick for a minimum cost cover?

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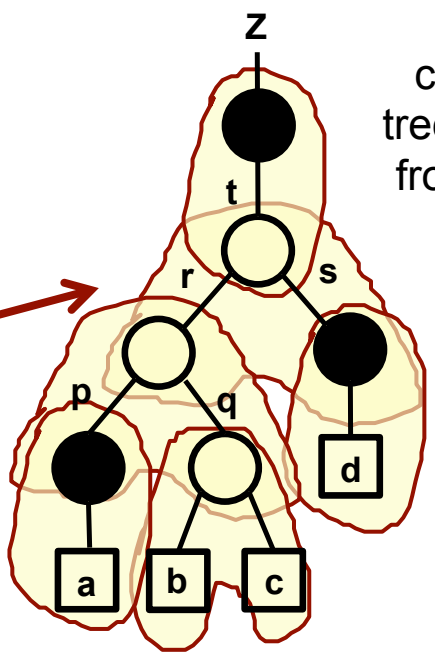
Minimum Cost Tree Covering

- **Where are we?**
  - We **tree-ified** subject tree
  - For each node of subject tree, we know which library pattern trees **match** it
- **Next problem:**
  - What is the ***best cover*** of the subject tree with patterns from target library?



One possible cover of subject tree with 6 patterns from target library

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Minimum Cost Covering of Subject Tree

- **What cover do we choose?**
  - We assign a **cost** to each library pattern
  - We choose the (or, a) **minimum cost** ("**mincost**") cover of the subject tree

- **One big idea makes this easy (!) to do:**
  - If pattern **P** is a mincost match at some node **s** of subject tree, then...
  - … each leaf of pattern tree must also be the root of some mincost matching pattern
  - Leads to a nice recursive algorithm for **mincost(node in subject tree)**
    - (This is actually a ***dynamic programming*** algorithm, if you know that term...)

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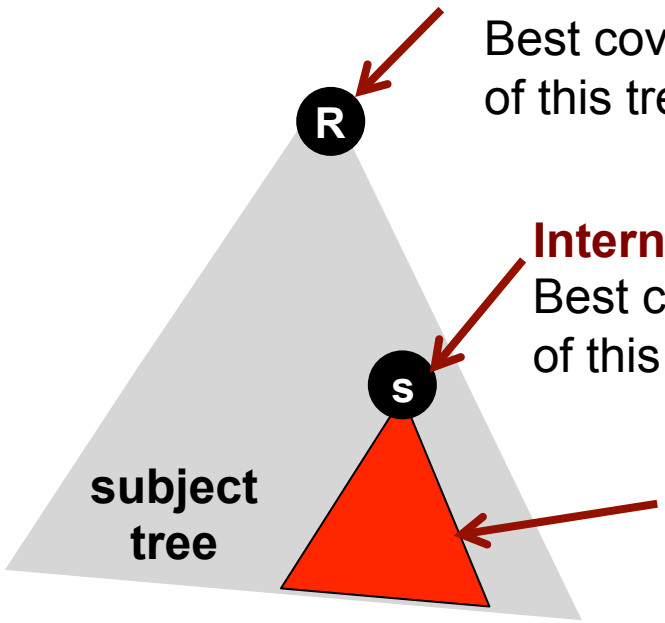
Some Terminology First



Root R of subject tree.
Best cover – mapping –
of this tree has cost=**mincost(R)**

Internal node s in subject tree.
Best cover – mapping –
of this **sub**-tree has cost=**mincost(s)**

Remember: we **tree-ified** the netlist.
This is a **tree**. Indeed, every internal node
is the **root** of another, **smaller tree.**
This is crucial for our mapping algorithm.

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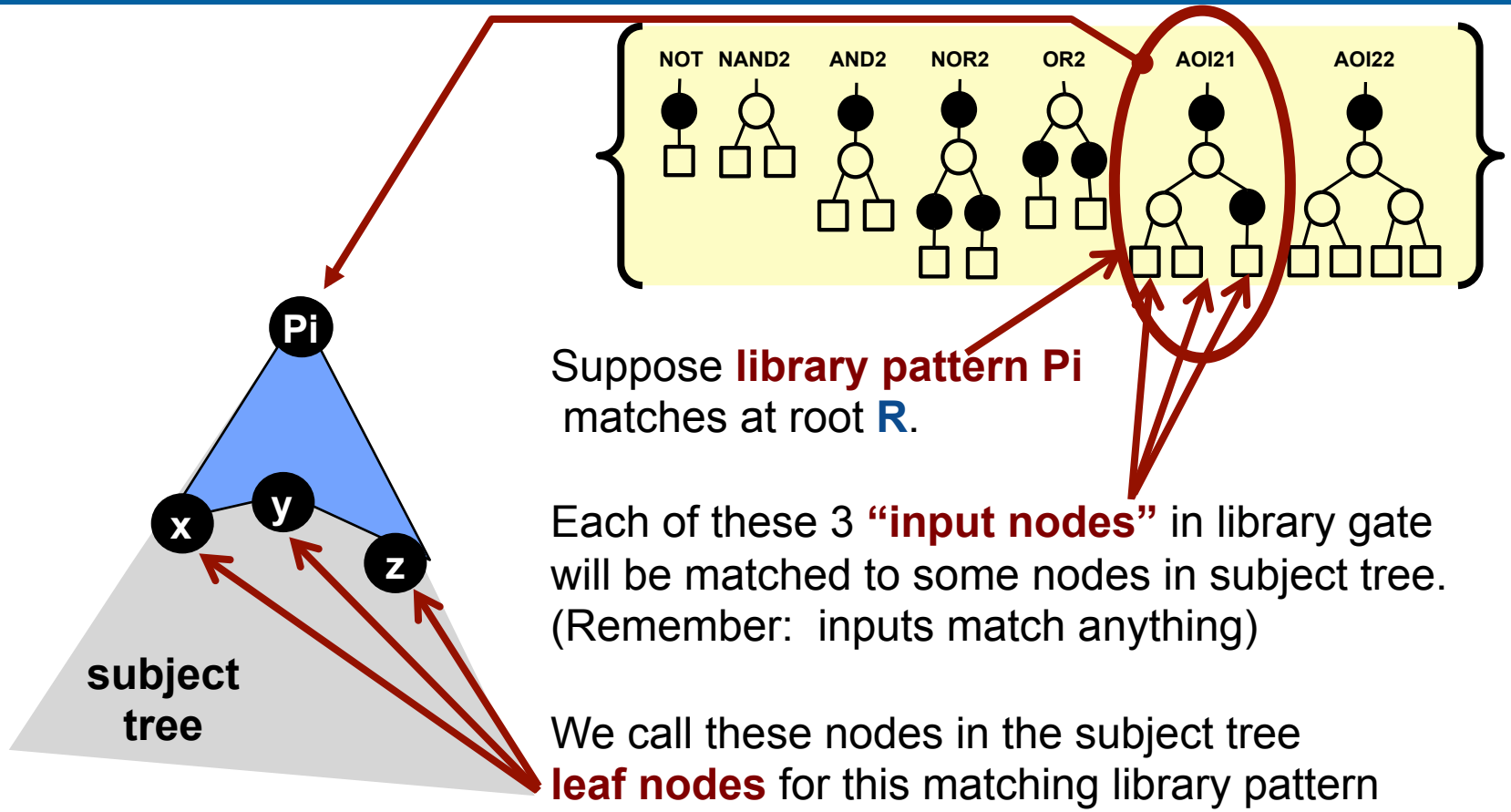
More Terminology …



Suppose **library pattern Pi** matches at root **R**.

Each of these 3 **"input nodes"** in library gate will be matched to some nodes in subject tree. (Remember: inputs match anything)

We call these nodes in the subject tree **leaf nodes** for this matching library pattern

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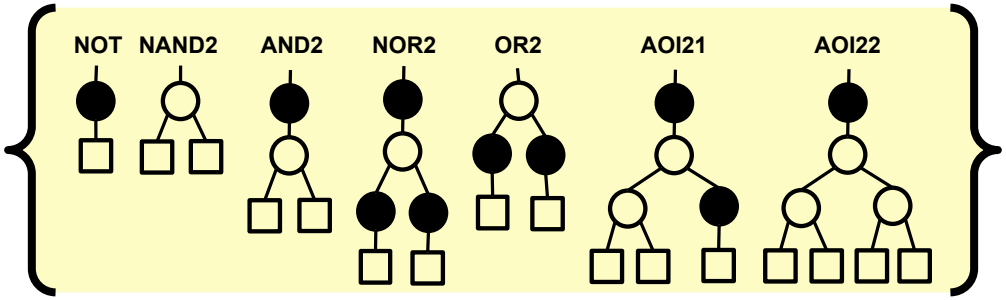
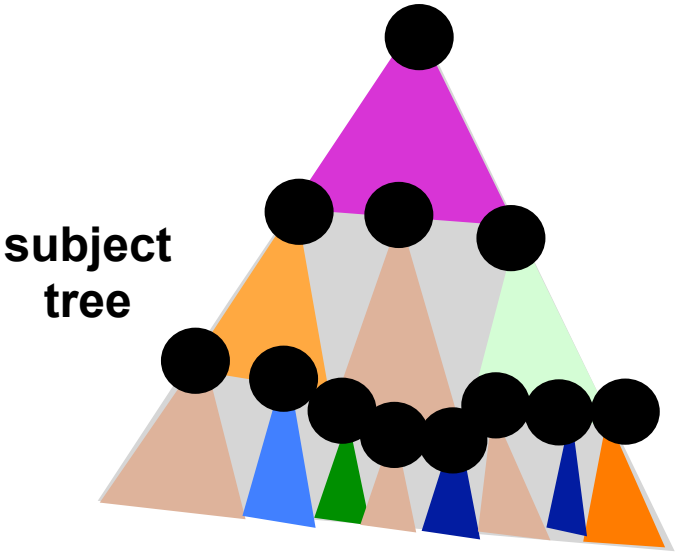
Final Terminology …





Every gate pattern in target library has a **cost**

Gate pattern **Pi** has **cost(Pi)**

We use library costs to calculate cost to map our complete subject netlist

We add up **cost(node)** for each node where a pattern matches, for all patterns covering subject

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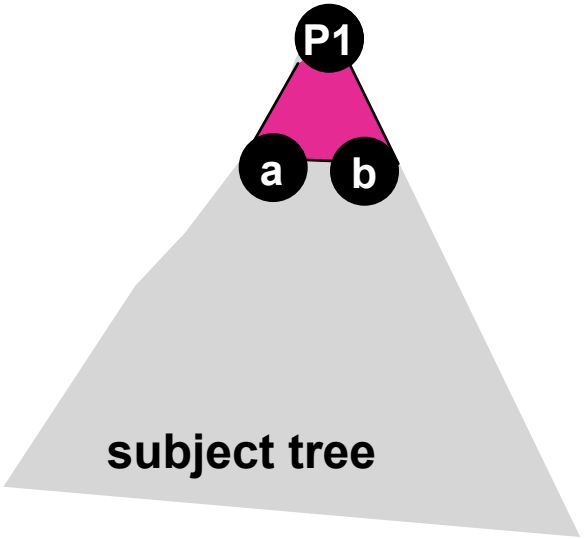
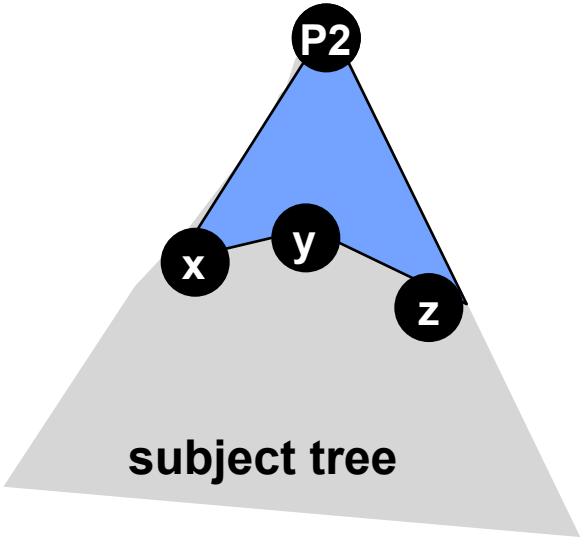
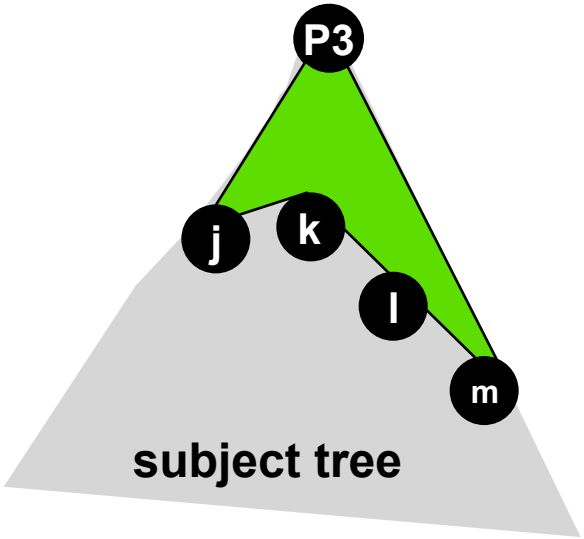
Mincost Tree Covering: The Idea

- **Assume 3 different library patterns match at root R of subject tree**
  - Pattern **P1** has **2** leaf nodes: **a b**
  - Pattern **P2** has **3** leaf nodes: **x y z**
  - Pattern **P3** has **4** leaf nodes: **j k l m**

  Which of these gates produces the smallest value of **mincost(R)**?







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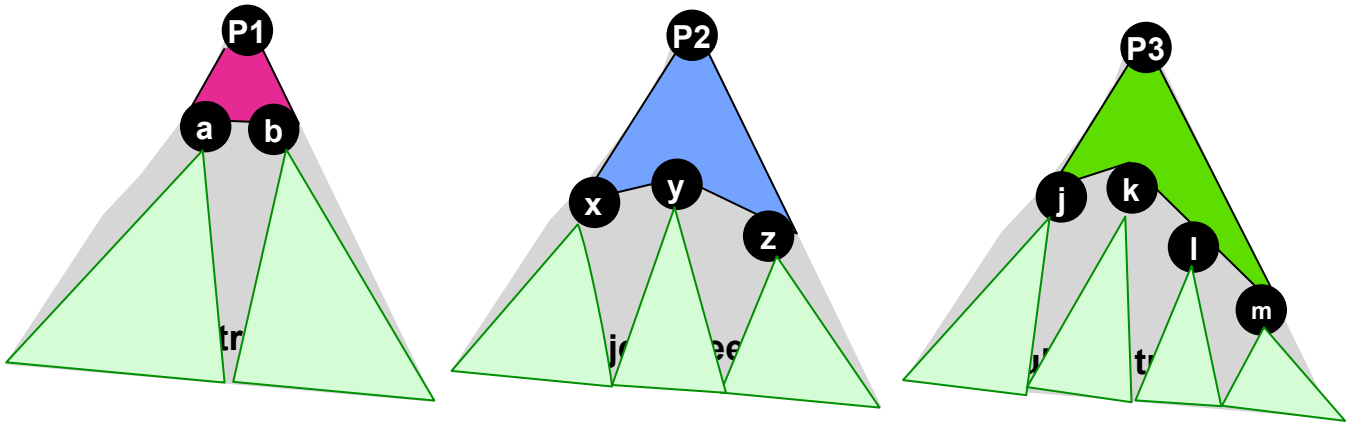
Mincost Tree Cover: Recursive Formula



- **Cheapest cover of root of subject has mincost(root) =**

Minimum over patterns that match at root R

$$\left\{ \begin{array}{l} \text{cost(P1)} + \text{mincost(a)} + \text{mincost(b)}, \\ \text{cost(P2)} + \text{mincost(x)} + \text{mincost(y)} + \text{mincost(z)}, \\ \text{cost(P3)} + \text{mincost(j)} + \text{mincost(k)} + \text{mincost(l)} + \text{mincost(m)} \end{array} \right\}$$

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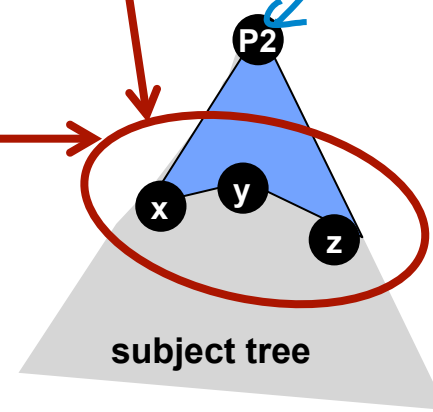
Mincost Cover: Basic Recursive Algorithm

```
mincost( treenode) {
   cost = ∞
   foreach( pattern P matching at subject treenode) {

      let L = {nodes in subject tree corresponding to leaf nodes in P
               when P is placed with its root at treenode }

      newcost = cost(P)
      foreach( node n in L } {
         newcost = newcost +  mincost( n );
      }
      if ( newcost < cost )
      then  {
         cost = newcost;
         treenode.BestLibPattern = P;
      }
   }
```



subject tree nodes "under" **x, y, z**

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Min Cost Tree Cover

- **One useful optimization we must note:**
  - This algorithm will **revisit** same treenode many times during recursions...
  - ...and it will **recompute** the mincost cover for that node each time.

- **Can we do better...?**
  - Yes, just keep a table with min cost value for each node
  - Starts with value ∞ and then when node's cost get computed, this value gets updated
  - Check first to see if node has been visited before computing it--saves computing again

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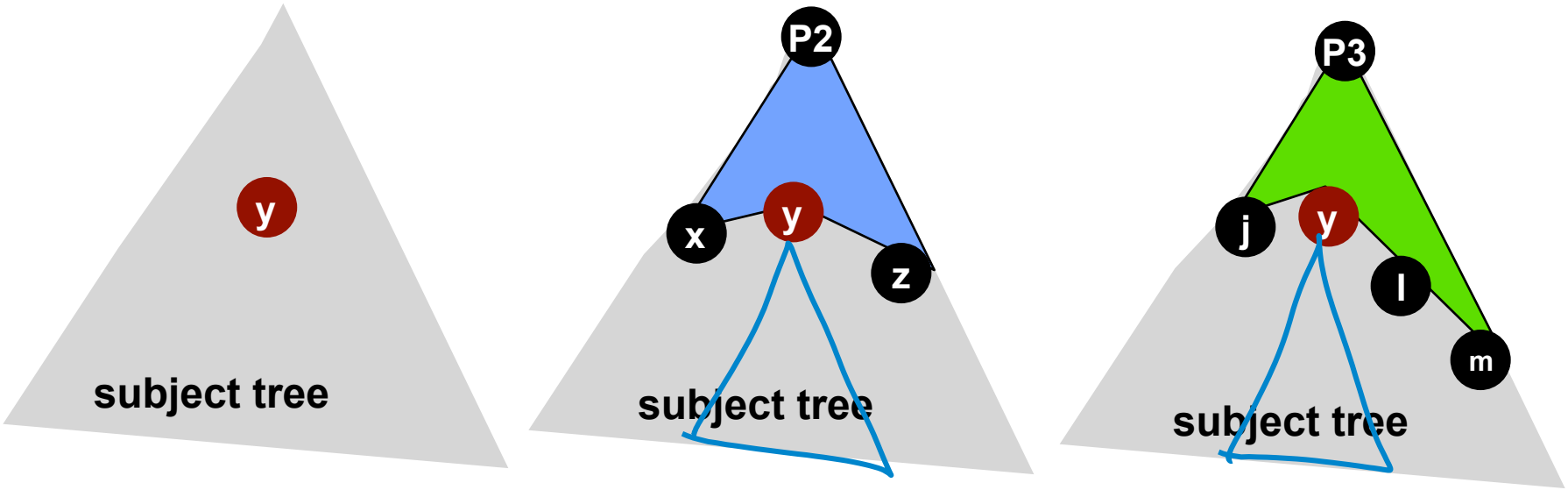
Illustration

- **Node "y" in this subject tree**
  - Will get its **mincost(y)** cover computed when we put **P2** at root of subject tree...
  - ...and again when we put **P3** at the root
  - **Better solution:** just compute it **once**, first time, **save** it, and **look it up** later!



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VLSI CAD: Logic to Layout

Lecture 10.6

From Logic to Layout: Technology Mapping—Detailed Covering Example

Rob A. Rutenbar
University of Illinois

Chris Knapton/Digital Vision/Getty Images

Tech Mapping via Tree Covering

- **What do we need for a complete algorithm?**

- **Tree-ifying the input netlist**
  - One key assumption needs discussion
- **Tree matching**
  - For each node in your subject tree, find the target pattern trees in library match here
- **Minimum-cost covering**
  - Assume you know what can match at each node of subject tree
  - ..so, which ones do you pick for a minimum cost cover?

EXAMPLE

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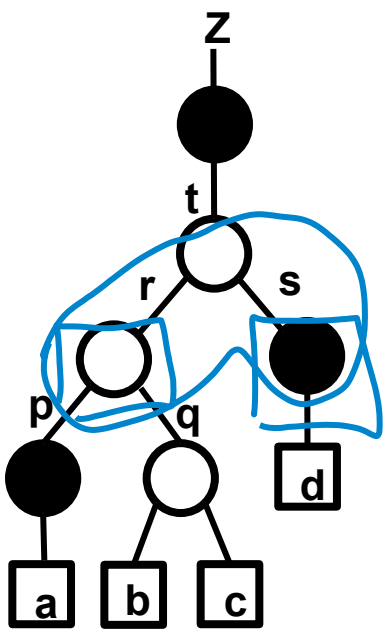
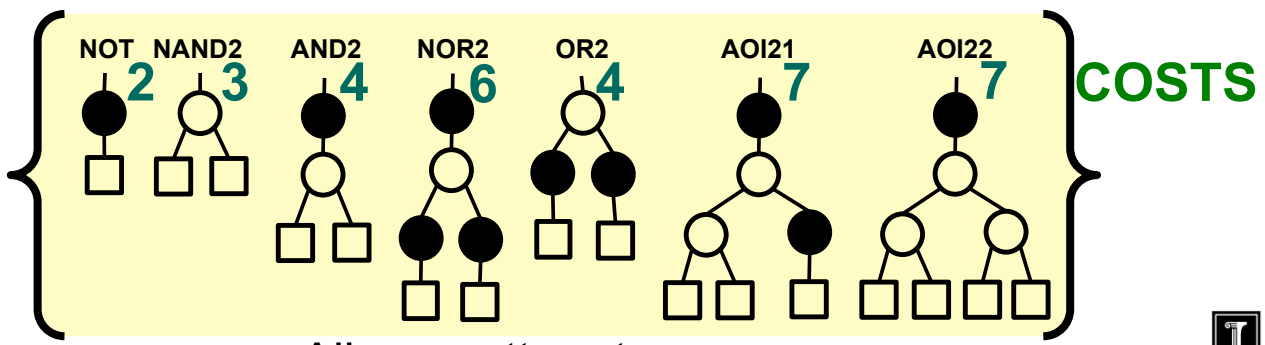
Min Cost Tree Cover Example

Subject tree



At node	Can Match	With min cost
z	NOT	2 + mincost(**t**)
	AOI21	7 + mincost(**p**) + mincost(**q**)
t	NAND2	3 + mincost(**r**) + mincost(**s**)
r	NAND2	3 + mincost(**p**) + mincost(**q**)
p	NOT	2
q	NAND2	3
s	NOT	2

Minimum



All our pattern trees

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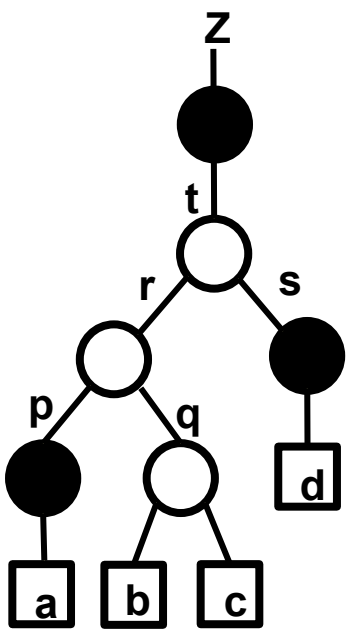
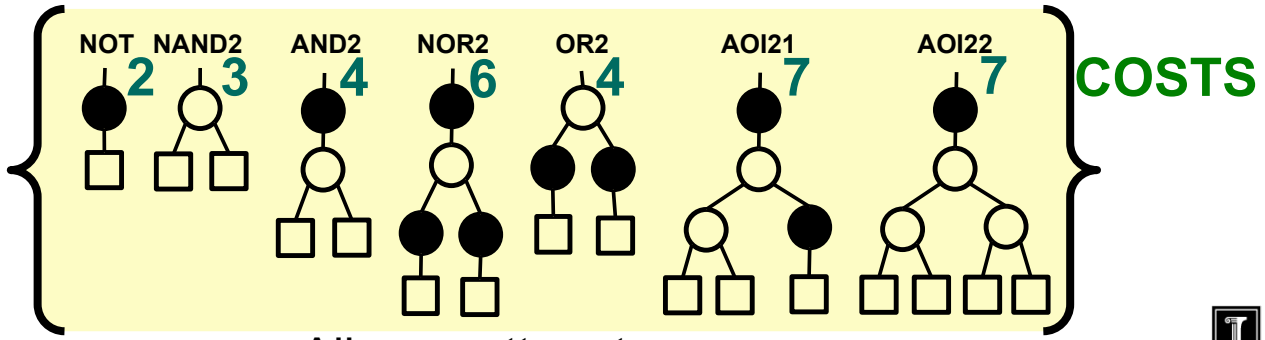
Min Cost Tree Cover Example

Subject tree



At node	Can Match	With min cost
z	NOT	2 + mincost(**t**)
	AOI21	7 + ~~mincost(**p**)~~ 2 + ~~mincost(**q**)~~ 3
t	NAND2	3 + mincost(**r**) + ~~mincost(**s**)~~ 2
r	NAND2	3 + ~~mincost(**p**)~~ 2 + ~~mincost(**q**)~~ 3
p	NOT	2
q	NAND2	3
s	NOT	2

Minimum



All our pattern trees

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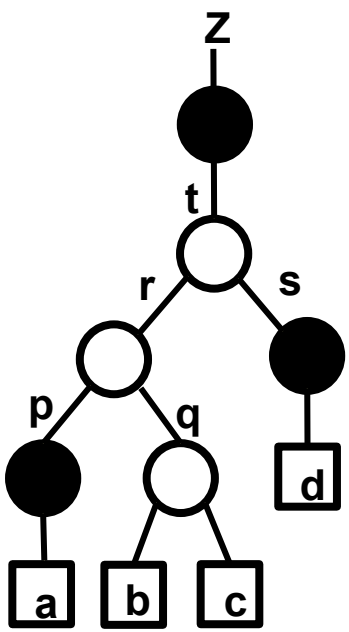
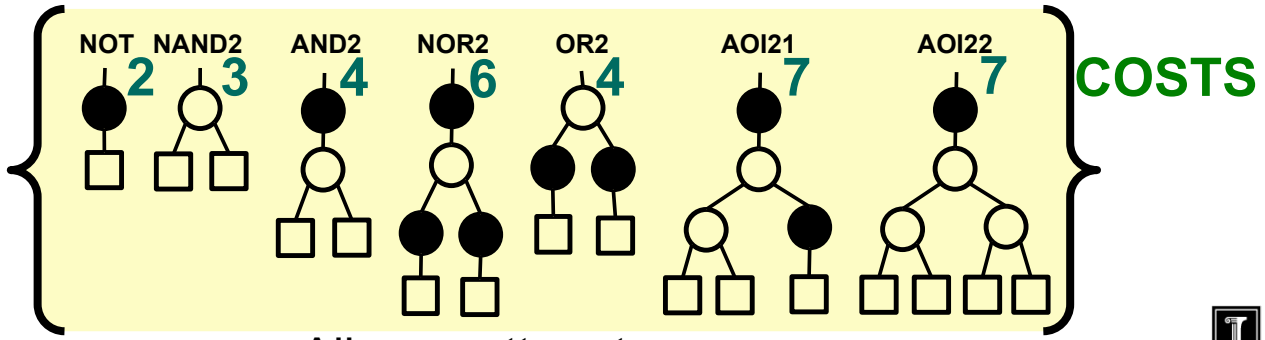
Min Cost Tree Cover Example

Subject tree



At node	Can Match	With min cost
z	NOT	2 + mincost(**t**)
	AOI21	7 + 2 + 3 = **12**
t	NAND2	3 + ~~mincost(**r**)~~ 8 + 2
r	NAND2	3 + 2 + 3 = **8**
p	NOT	2
q	NAND2	3
s	NOT	2

Minimum



All our pattern trees

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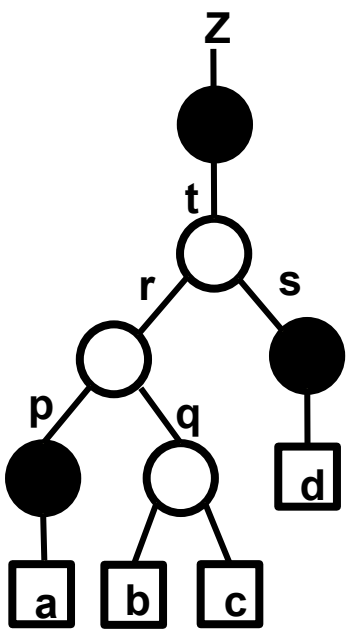
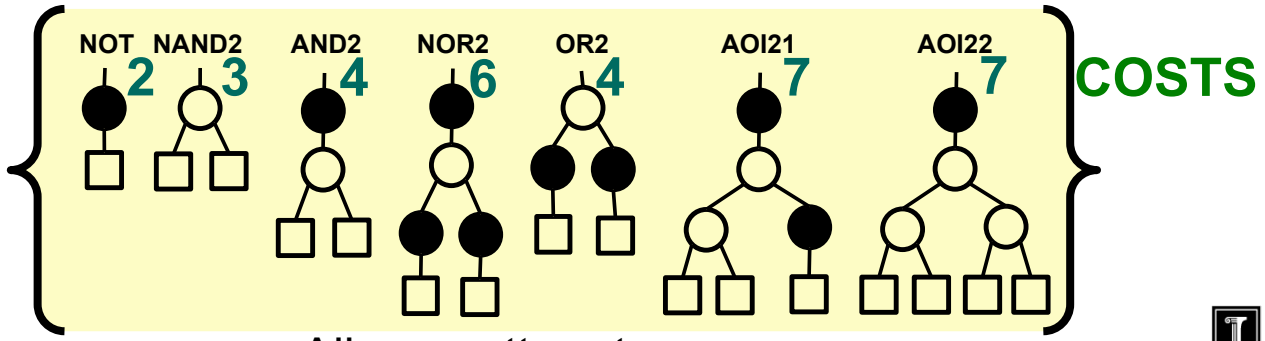
Min Cost Tree Cover Example

Subject tree



At node	Can Match	With min cost
z	NOT	~~2 + mincost(t)~~ 13
	AOI21	7 + 2 + 3 = 12
t	NAND2	3 + 8 + 2 = 13
r	NAND2	3 + 2 + 3 = 8
p	NOT	2
q	NAND2	3
s	NOT	2

Minimum



All our pattern trees

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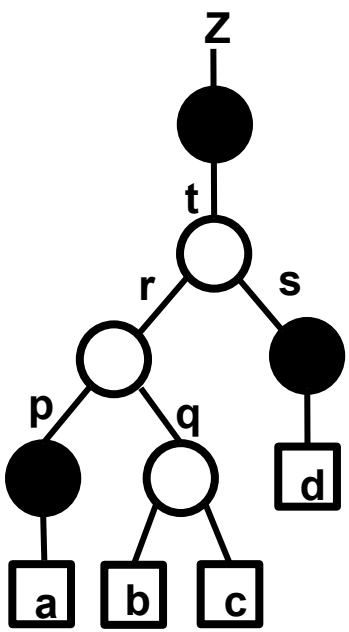
Min Cost Tree Cover Example

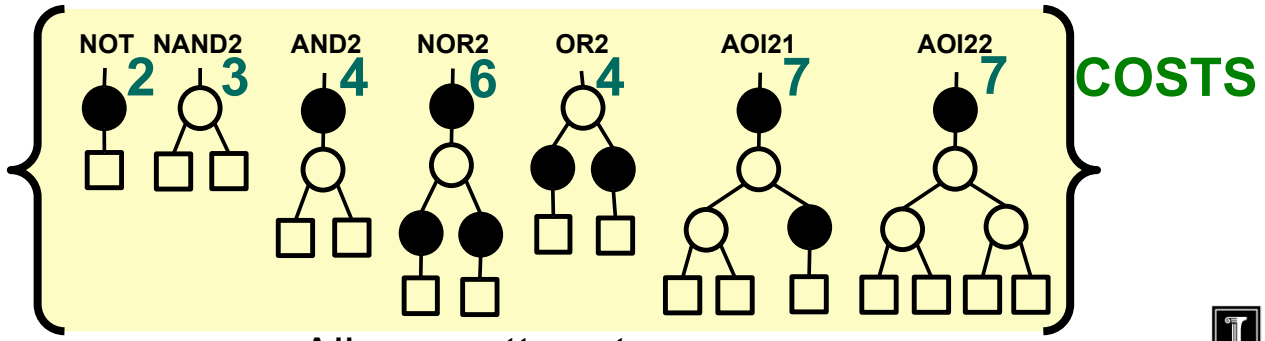
Subject tree



At node	Can Match	With min cost
z	NOT	2 + 13 = 15
	AOI21	7 + 2 + 3 = 12
t	NAND2	3 + 8 + 2 = 13
r	NAND2	3 + 2 + 3 = 8
p	NOT	2
q	NAND2	3
s	NOT	2

Minimum

Best! AOI21 @ Z



All our pattern trees

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Min Cost Cover: How To Get Final Cover?

- **Look at best cost at subject root. Find pattern P with that cost.**
  - In our example: this is **cost=12** associated with AOI21 at node **Z**
- **Find the leaf nodes in the subject tree with P at the root**
  - In our example: this is nodes **p** and **q**
  - Look at the **best cost** at each of these leaf nodes
  - Find the pattern **Pi** that is associated with each of these best costs at leaf nodes
  - Choose best cost pattern **Pi** for each leaf node, that look again at **leaf nodes** inside each of these patterns **Pi**, placed inside the subject tree
  - **Repeat**…

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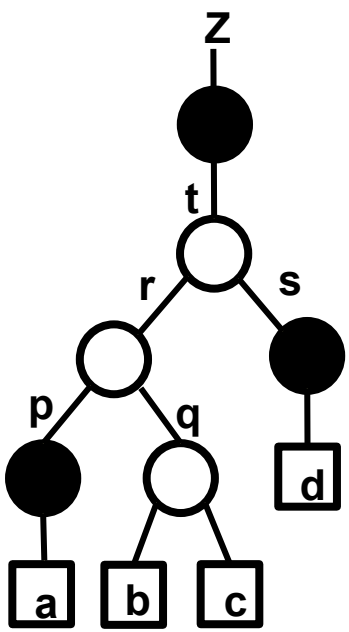
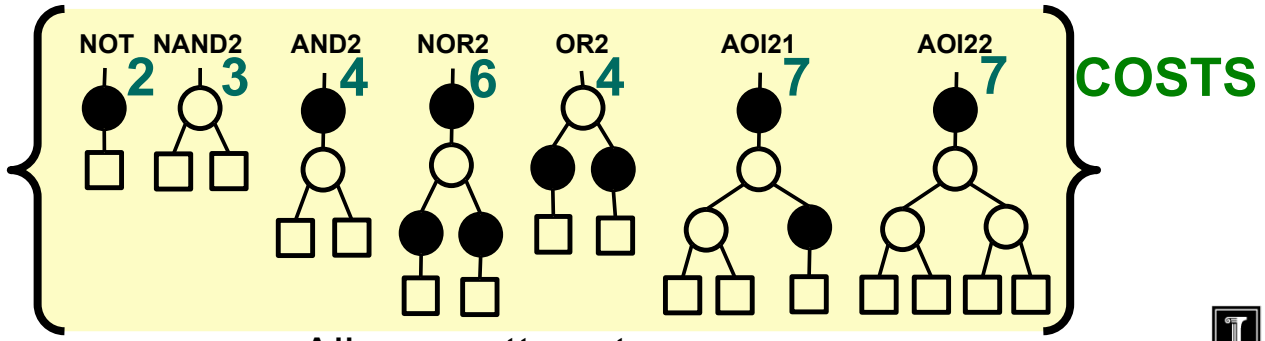
Min Cost Tree Cover Example

Subject tree



	At node	Can Match	With min cost
	z	NOT	**15** = **2** + mincost(**t**)
Best!		AOI21	**12** = **7** + mincost(**p**) + mincost(**q**)
	t	NAND2	**13** = **3** + mincost(**r**) + mincost(**s**)
	r	NAND2	**8** = **3** + mincost(**p**) + mincost(**q**)
Choose	p	NOT	**2**
Choose	q	NAND2	**3**
	s	NOT	**2**

Min



All our pattern trees

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Min Cost Tree Cover

- **Example**
  - If costs for NOT, NAND2, AND2, AOI21 are as shown...
  - Best cover is to use one AOI21 (@ Z), one NAND2 (@ q), and one NOT (@ p)

- **Turns out to be several nice extensions possible**
  - Can modify algorithm a little to minimize **delay** instead of cost
  - Need to deal with some technical issues associated with capacitive loads for driven gates, but some simple discrete loads can be modeled and handled
  - Many interesting and useful variations, starting from this algorithm skeleton

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Summary

- **Technology mapping ...**
  - Synthesis gives you “uncommitted” or “technology independent” design, eg, NAND2 and NOT
  - **Mapping turns this into real gates in your own library**
  - Can determine difference between good implementation and a bad one

- **Tree covering**
  - One nice, simple, elegant approach to the problem
  - 3 parts: tree-ify input, match all lib patterns, find min cost cover
  - Yes, there are other ways to do this. Some work with real Boolean algebra in mapping. Other applications, like for Lookup-Table (LUT) FPGA, are yet different

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