# VE527

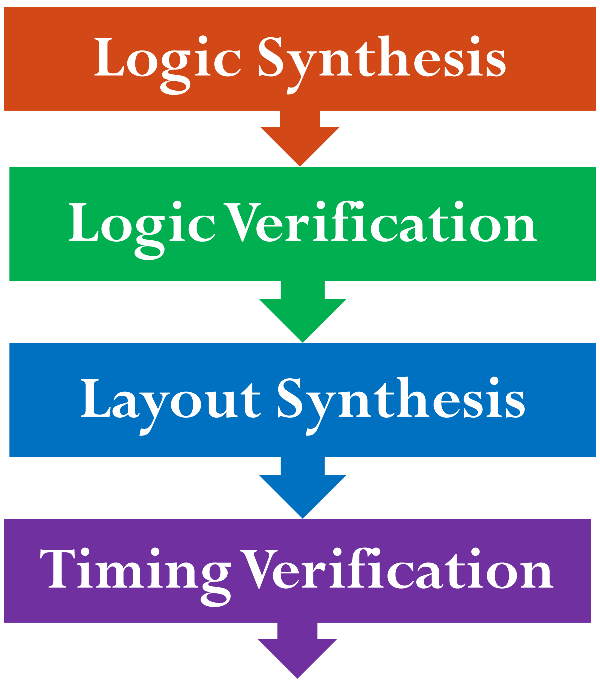
## Computer-Aided Design of Integrated Circuits

Technology Mapping

# Outline

- Technology mapping
  - Problem
  - Background on the Solution -- Tree Covering Algorithm
  - Details of Tree Covering Algorithm

# The Focus of Our Course




- Start with some Boolean / logic design description …
- …end with gates+wires, located at (x,y) coordinates on chip

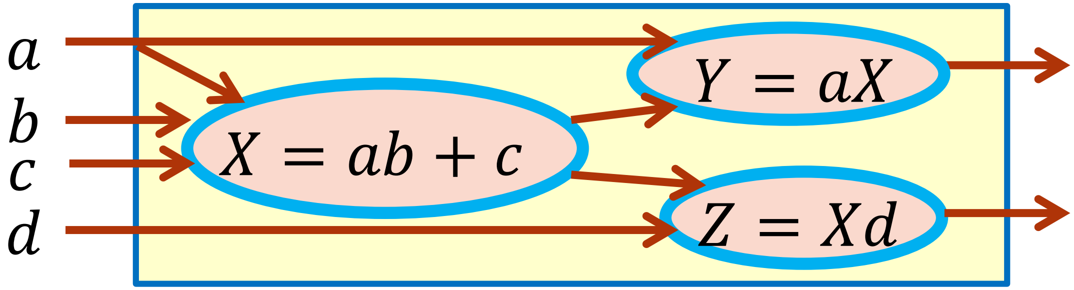
# Logic Synthesis

High-level design description → Logic Synthesis → Connected gates + wires in your technology. Called "netlist"

- Two steps in logic synthesis:
  - Technology-independent synthesis
  - Technology mapping

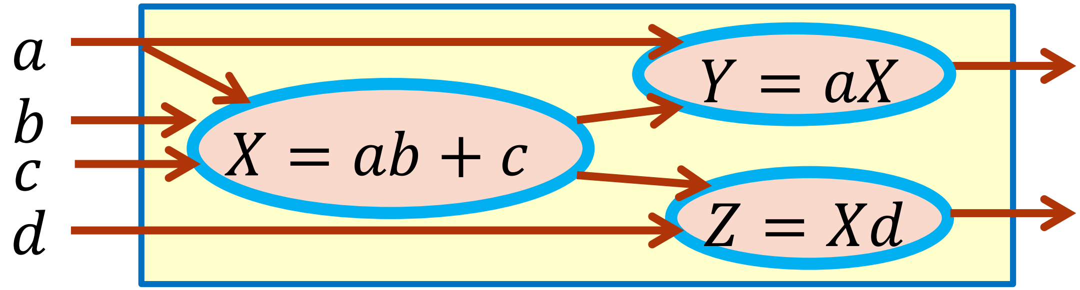
# Technology-Independent Synthesis

- Output: **Boolean Logic Network**
  - A graph of connected blocks with each block being a 2-level Boolean functions in **sum-of-product (SOP) form**.
  - It is **not** the actual **gate-level netlist**.
  - The result is called: "**uncommitted**" logic, or "**technology independent**" logic.



# Tech Mapping: The Problem

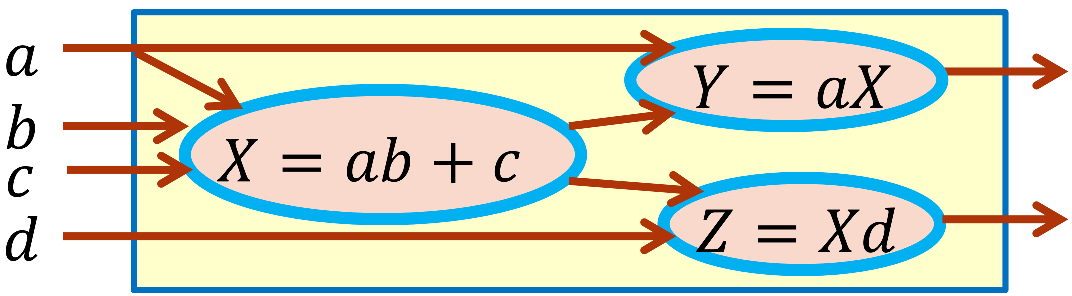
- Boolean logic network is still a little **abstract**.
  - We know the network structure and the Boolean function of each node.
  - … but that still does **not** give us the actual **gate-level netlist**.



# Tech Mapping: The Problem

- Usually, we are given a gate library, from which we can pick gates. Suppose we have these gates in our "**library**".

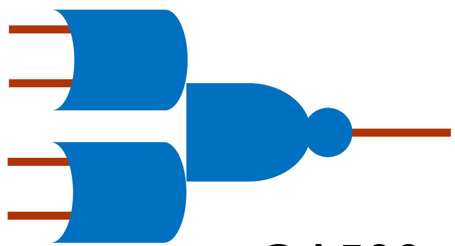

  - This is called "**the technology**" we are allowed to use to build the netlist.
  - Note: OA21 is an OR-AND, a so-called **complex gate** in our library.




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

# Aside: Complex Gates

**OR-AND-Inverter**



**OAI22**

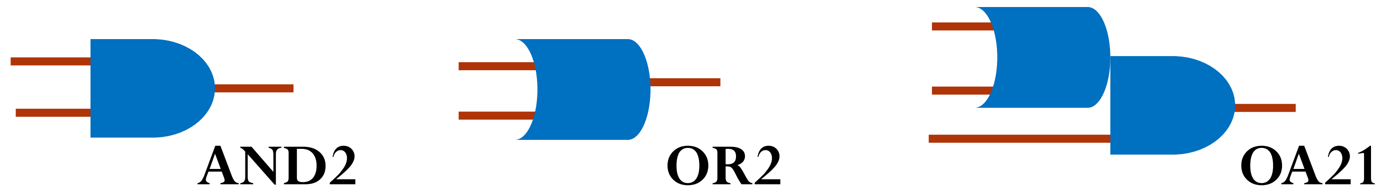
**AND-OR-Inverter**

**AOI221**

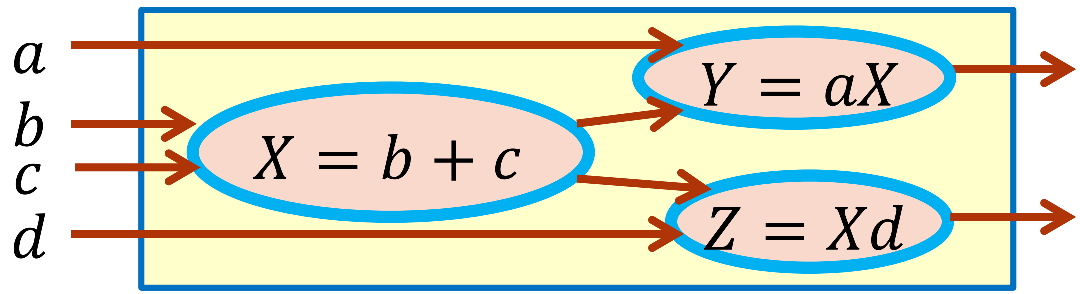
- In CMOS, OAI and AOI gate structures are **efficient** at transistor level.

# Tech Mapping: Simple Example

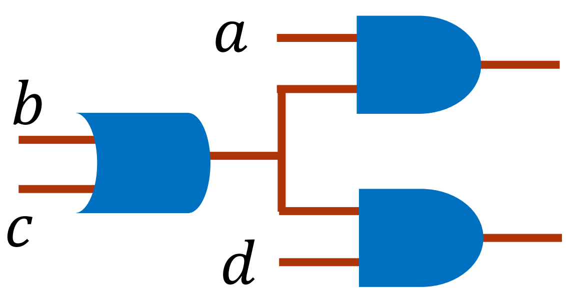
**Library**



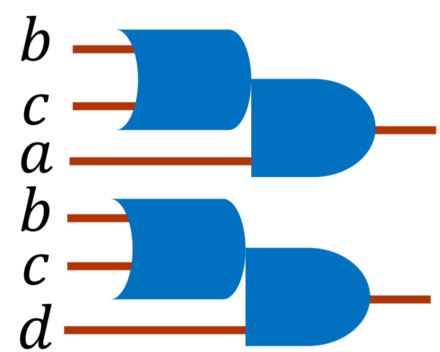

**Target**




**Obvious Mapping**



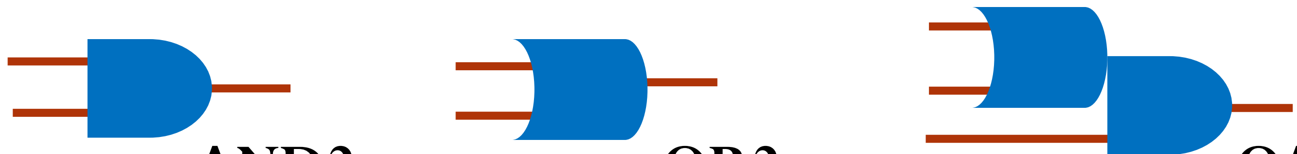

**Non-obvious Mapping**



# Tech Mapping

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

**Library**

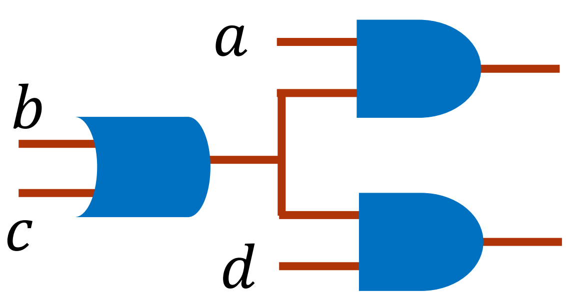


**AND2** — **Cost 3**

**OR2** — **Cost 3**

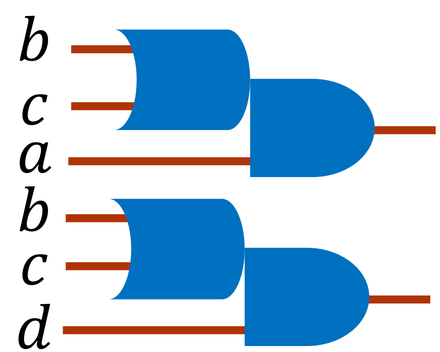
**OA21** — **Cost 4**

**Obvious Mapping**




**Cost 9**

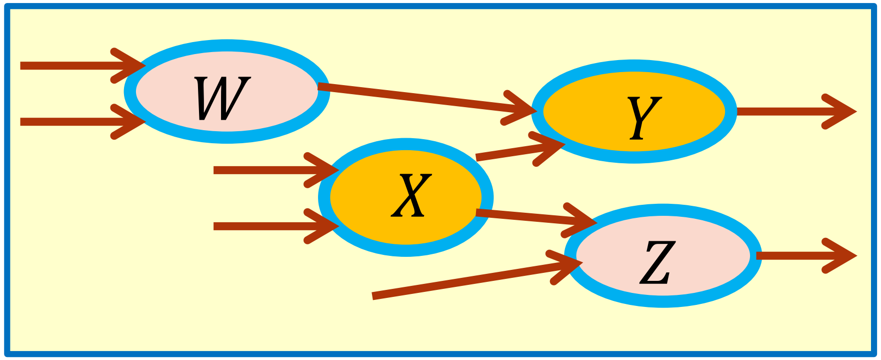
**Non-obvious Mapping**

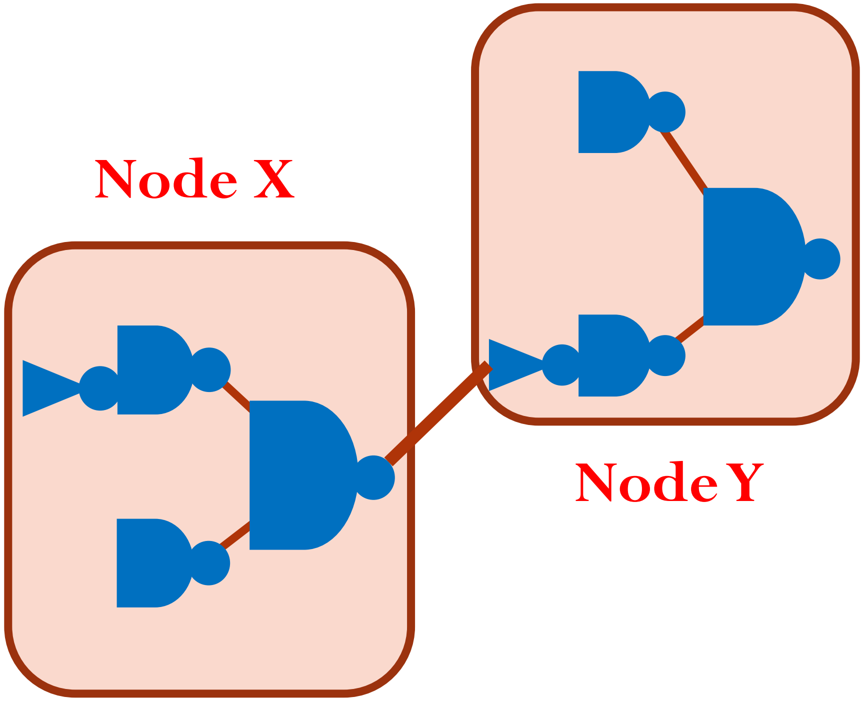



**Cost 8**

# The Starting Point of Tech Mapping

- First, we transform **uncommitted logic** into simple, **real** gates.
  - We transform **every** SOP form in **each** node into **2-input NAND (NAND2)** & **NOT** gates. Nothing else!



# How to Map SOP into NAND2s & NOTs?

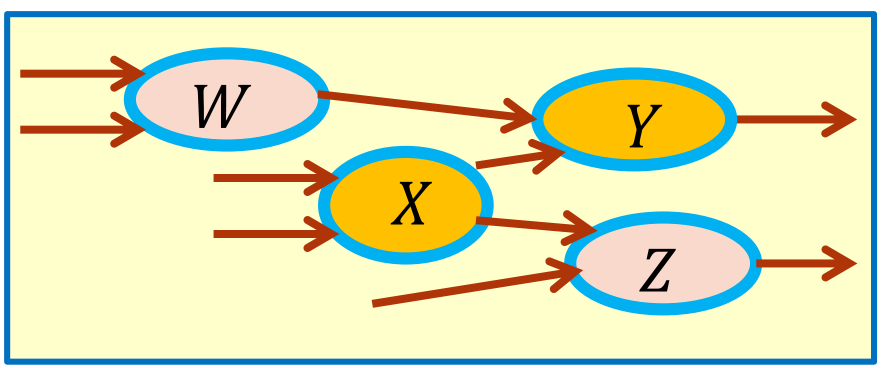
- Multi-input AND gate to multiple 2-input AND gates
- Multi-input OR gate to multiple 2-input OR gates
- 2-input AND gate

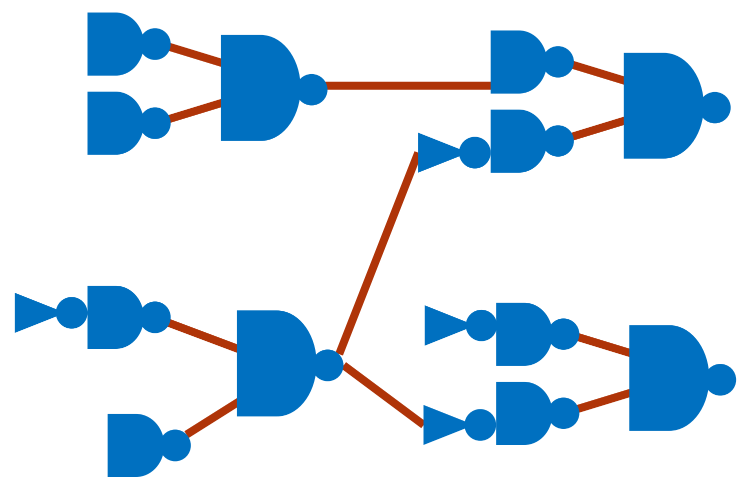

- 2-input OR gate


**By De Morgan's Law**

# The Starting Point of Tech Mapping

- By transforming every SOP form in each node into NAND & NOT gates …
  - … Boolean logic network **disappears**.
  - We have one BIG "**flat**" network of **NAND2s** and **NOTs**. This is what we are going to map.



# Outline

- Technology mapping
  - Problem
  - Background on the Solution -- Tree Covering Algorithm
  - Details of Tree Covering Algorithm

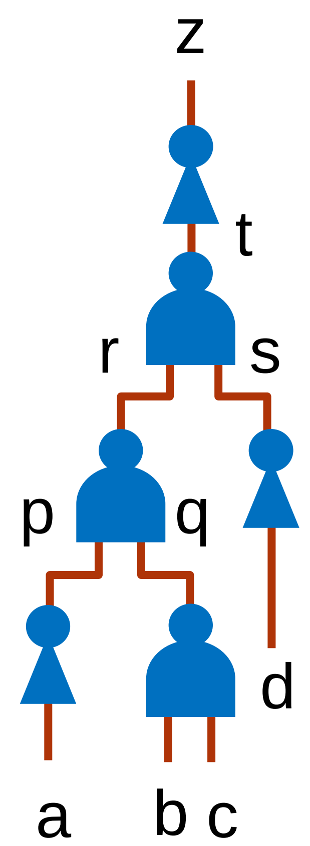
# Technology Mapping as Tree Covering

- One famous, simple model of problem:
  - Your logic network to be mapped is **a tree of simple gates**.
    - We assume uncommitted form has **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**.
  - Reference: Kurt Keutzer, "DAGON: Technology Binding and Local Optimization by DAG Matching," Proc. ACM/IEEE Design Automation Conference (DAC), 1987.

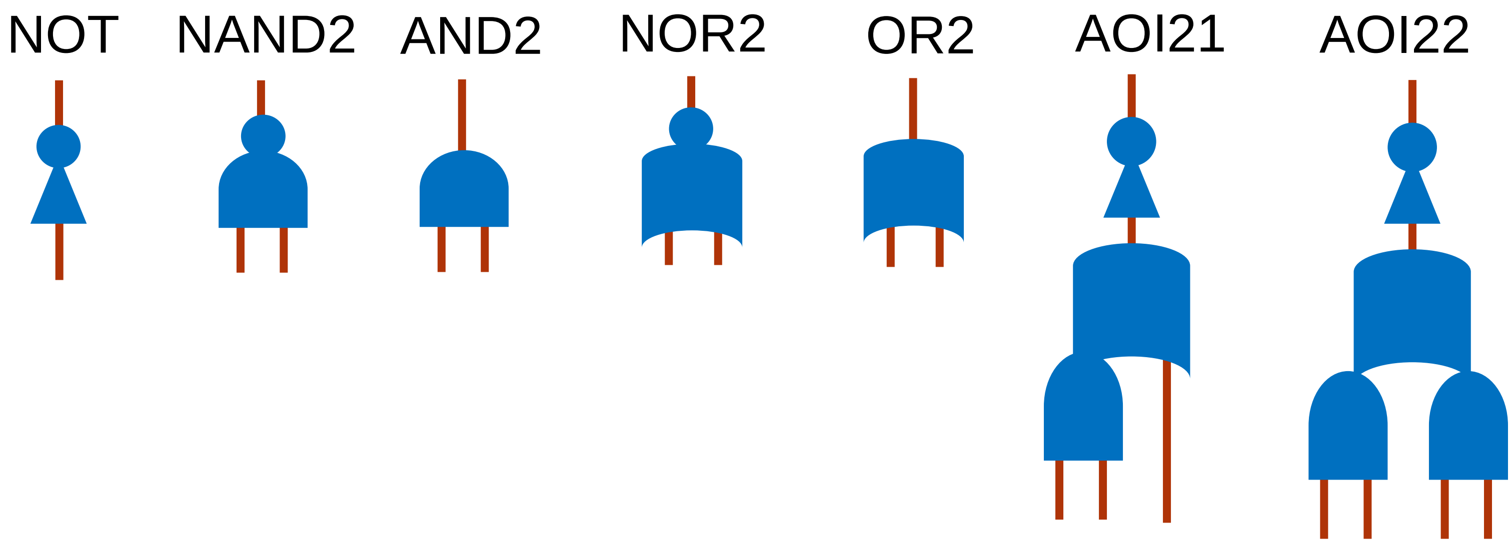
# Tree Covering Example: Start with…

- Here is your uncommitted logic to be **tech mapped**.
  - This is the result from our technology independent synthesis, after replacing all SOP forms in the network nodes with **NAND2/NOT**.
  - Called the **subject tree**.
  - Label not only inputs but also all internal wires too.



# Tree Covering: Your Technology Library

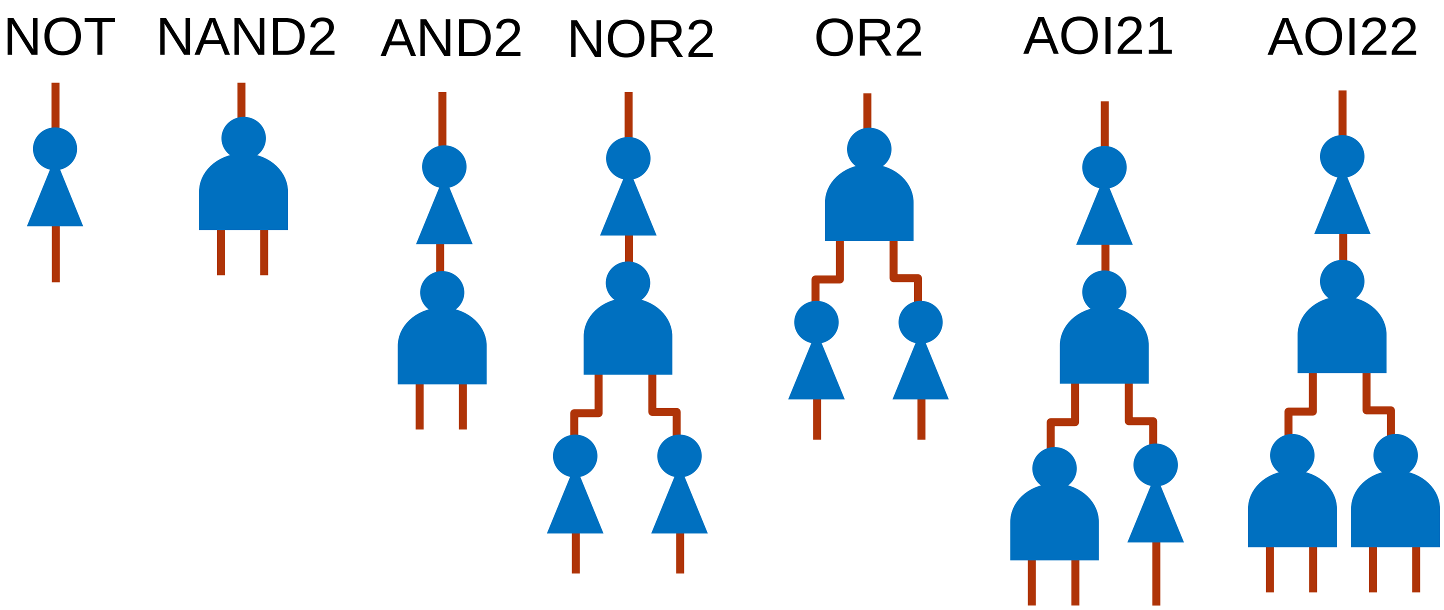
- And, here is a very simple **technology library**.




- First problem: this is **not** in the required **NAND2/NOT-only** form. **Must transform**.

# Tree Covering: Representing Library

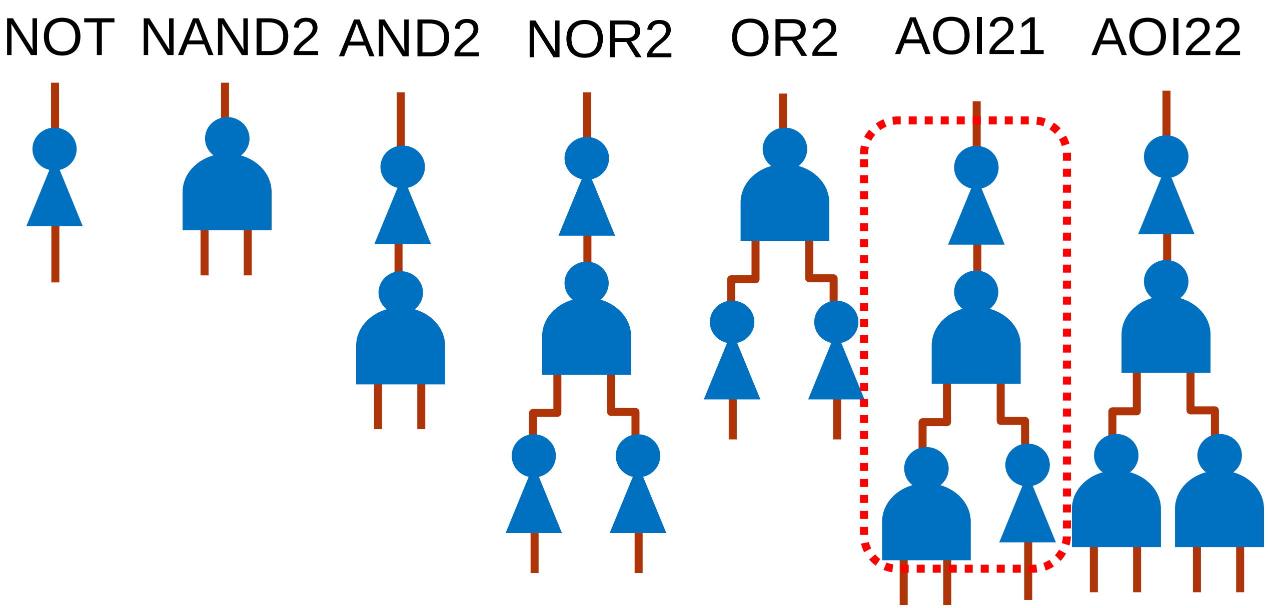
- Transforming to NAND2/NOT form is **easy**.
  - Just apply **De Morgan's law**.

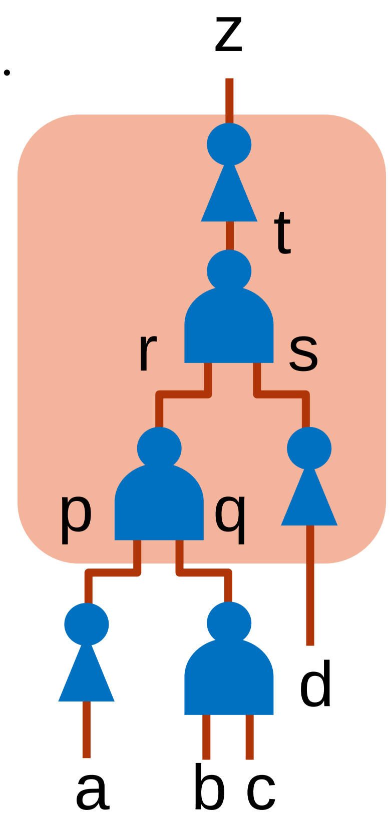



- Each library element in this form is called a **pattern tree**.

# Essential Idea in “Tree Covering”

- **Avoid** any **Boolean algebra**!
- Just do “**pattern matching**”.
  - Find where, in subject graph, the library pattern “matches”.
  - NAND matches NAND, NOT matches NOT, etc.
  - This is called: **structural mapping**.



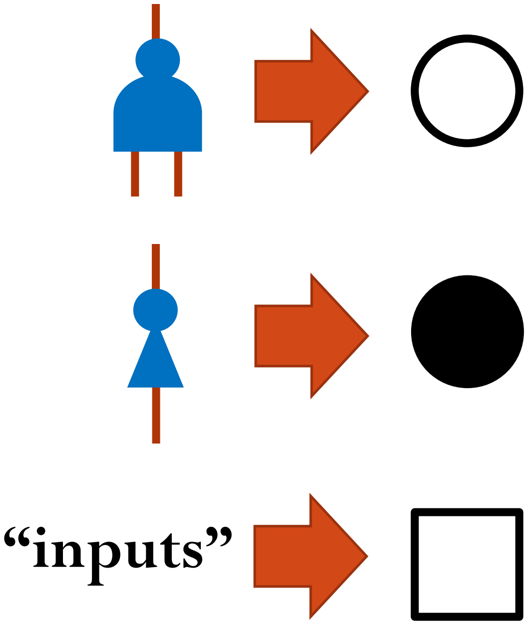



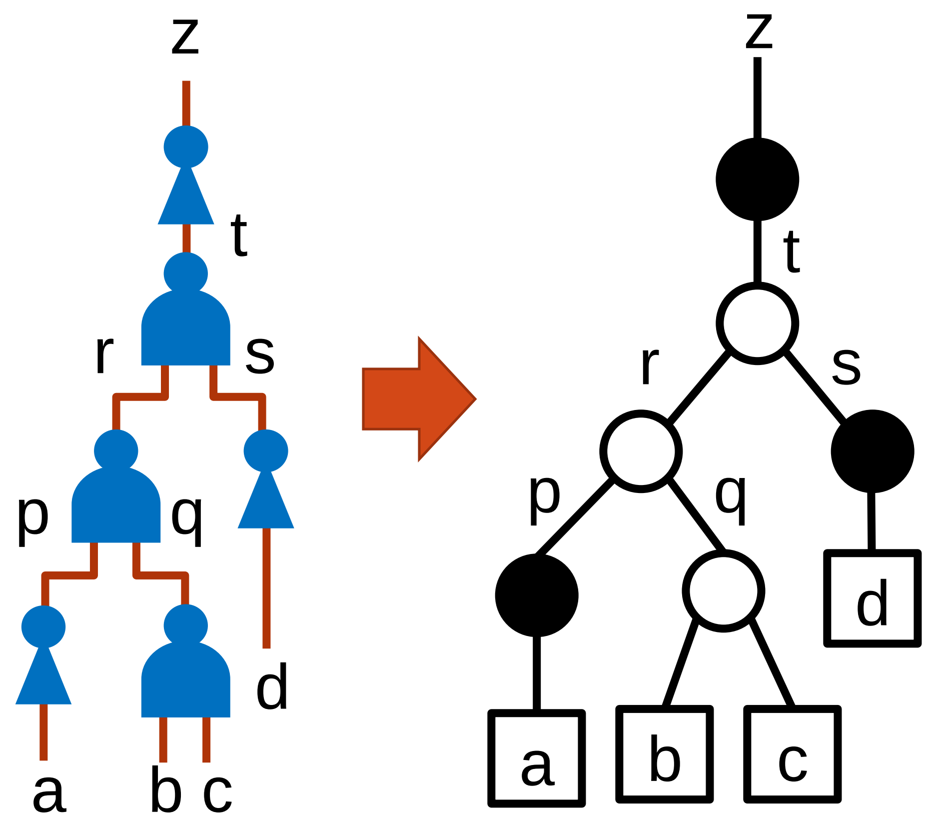
# The General "Tree Covering"

- This is called a **structural tech mapper**.
- Why?
  - Because there is no Boolean algebra here!
  - We just match the gates and 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.

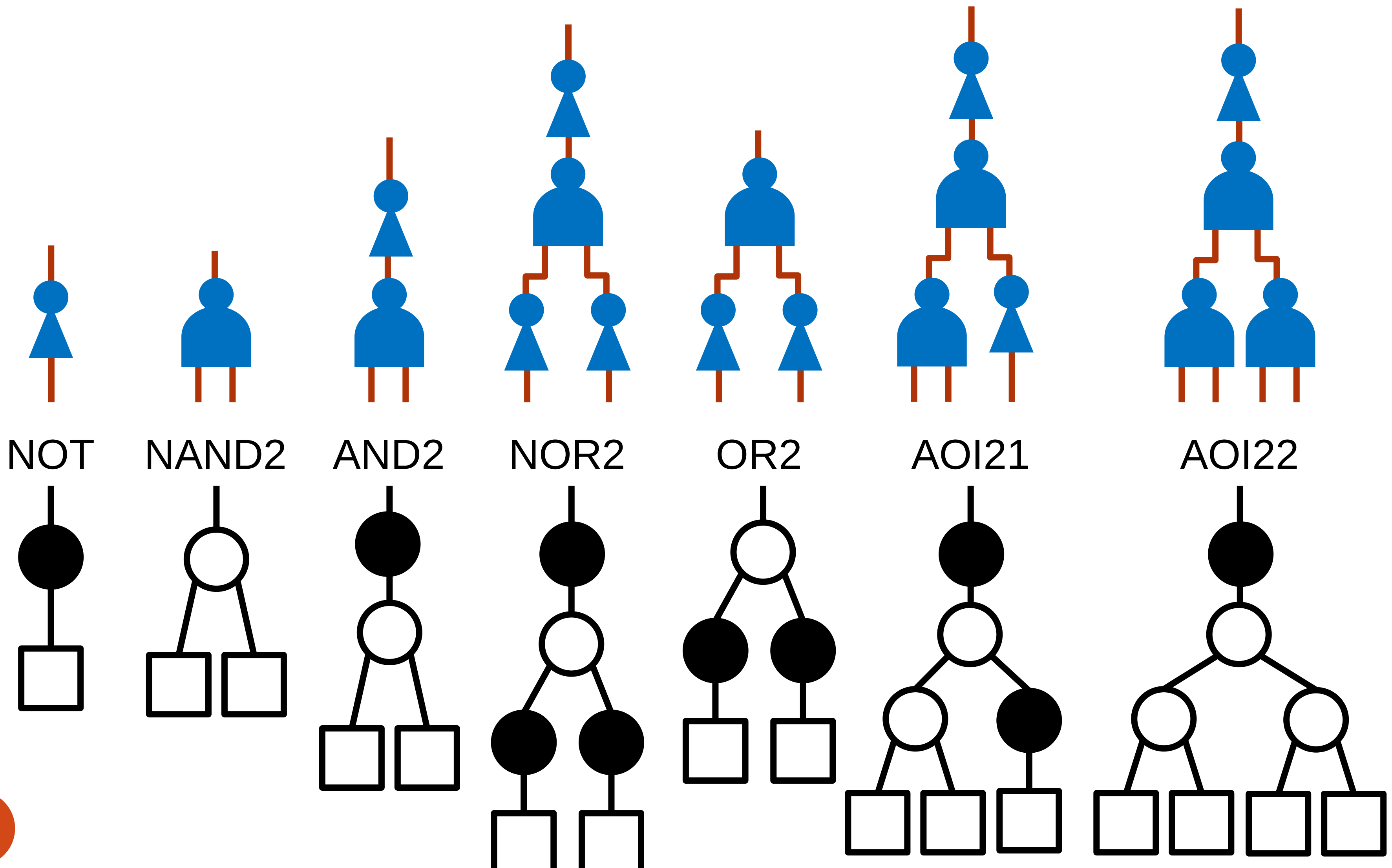
# Representing Trees for Covering

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

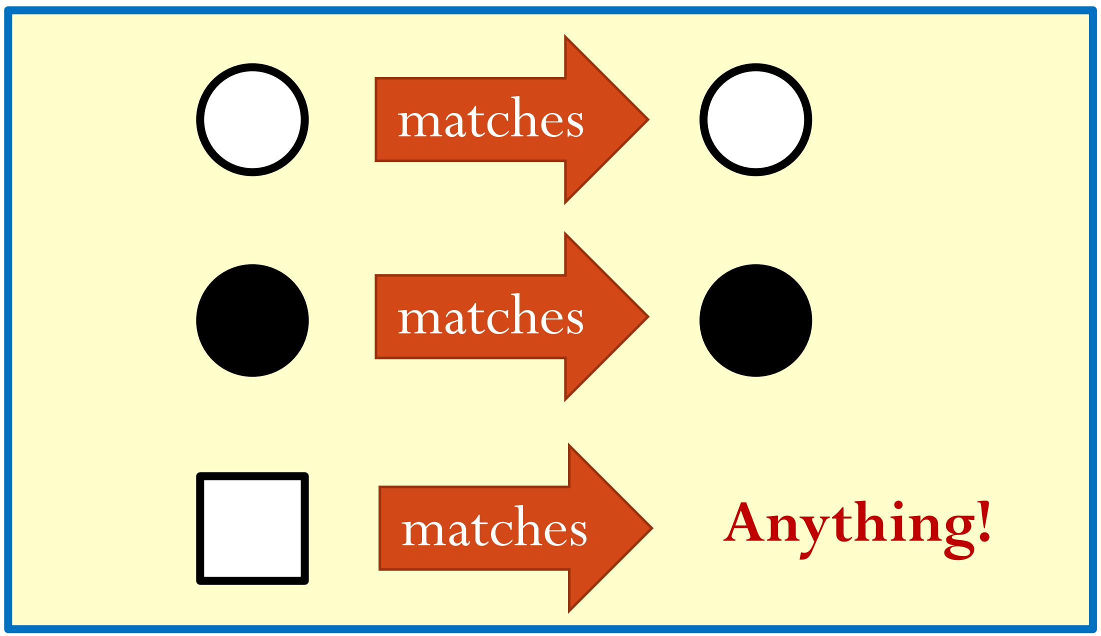


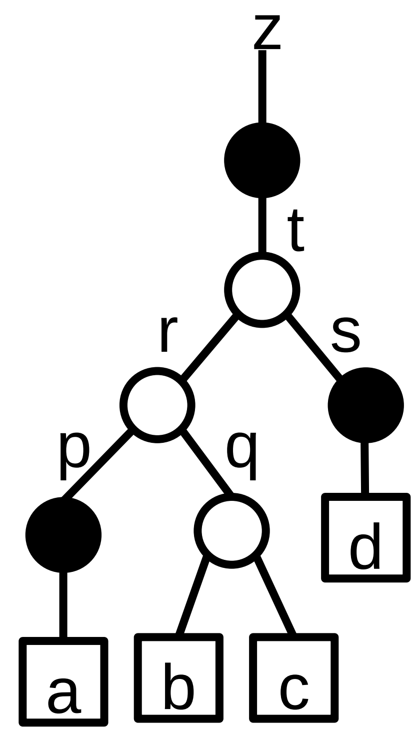



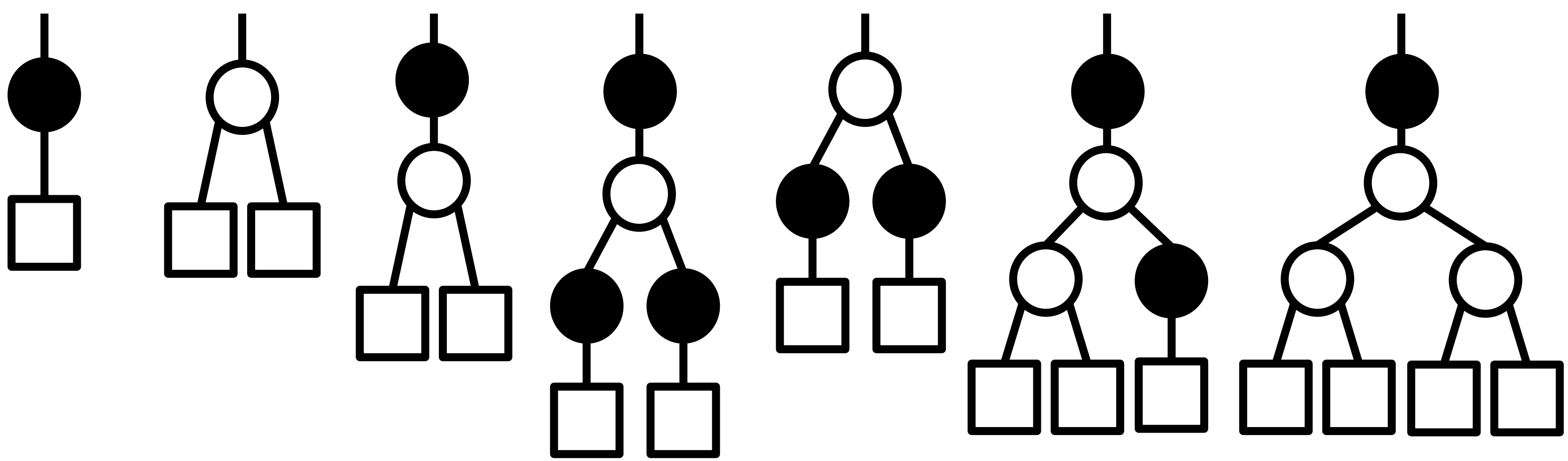
# Represent Library in this Same Style



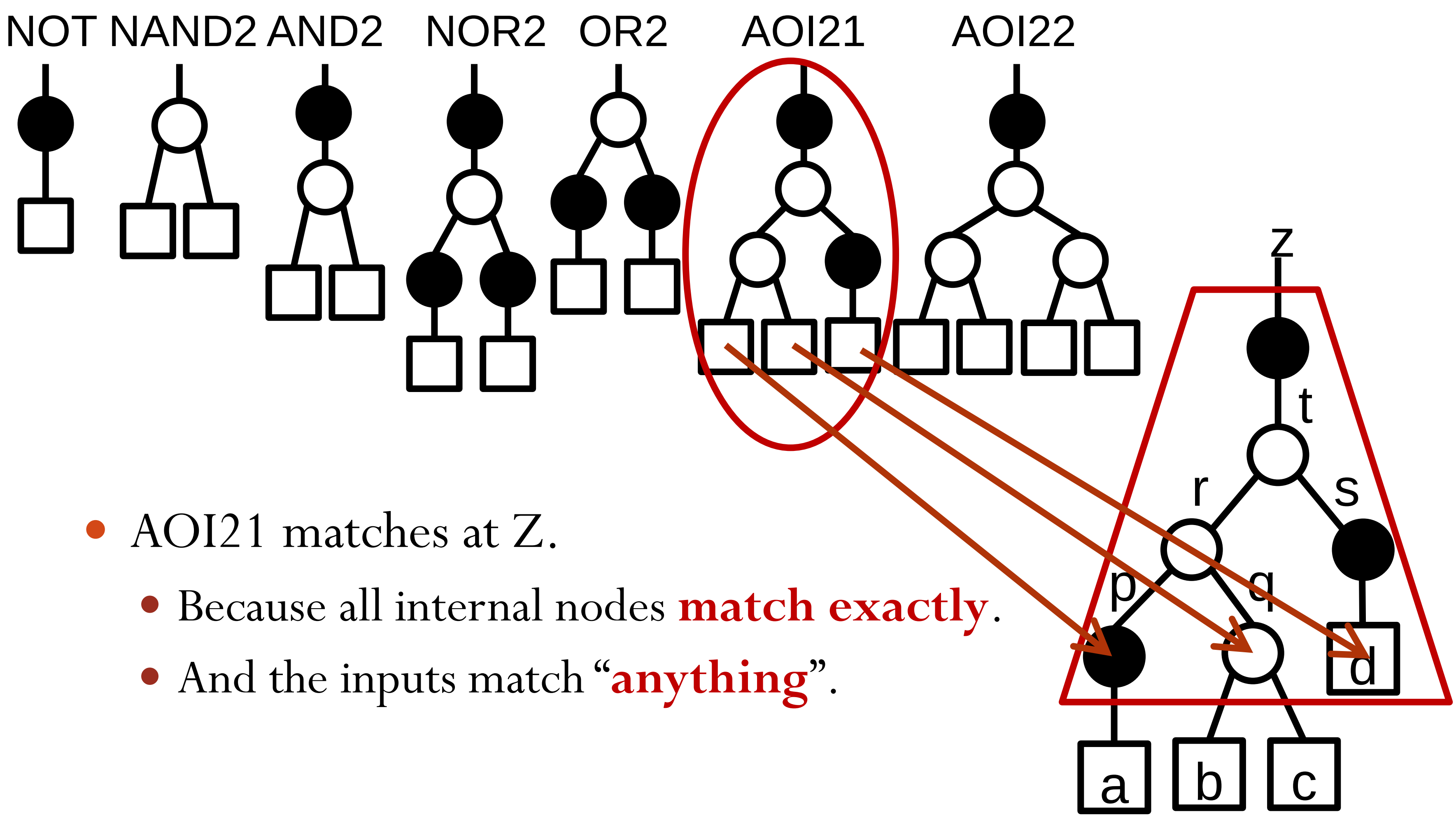
# Structural Mapping Rules



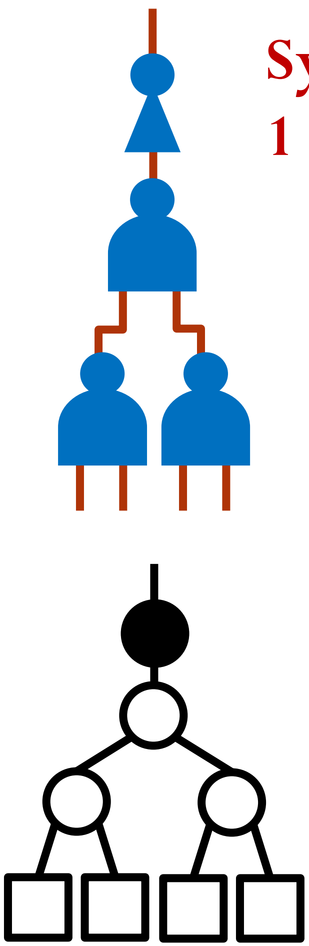
# How a “Target Gate” Matches Subject Tree




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

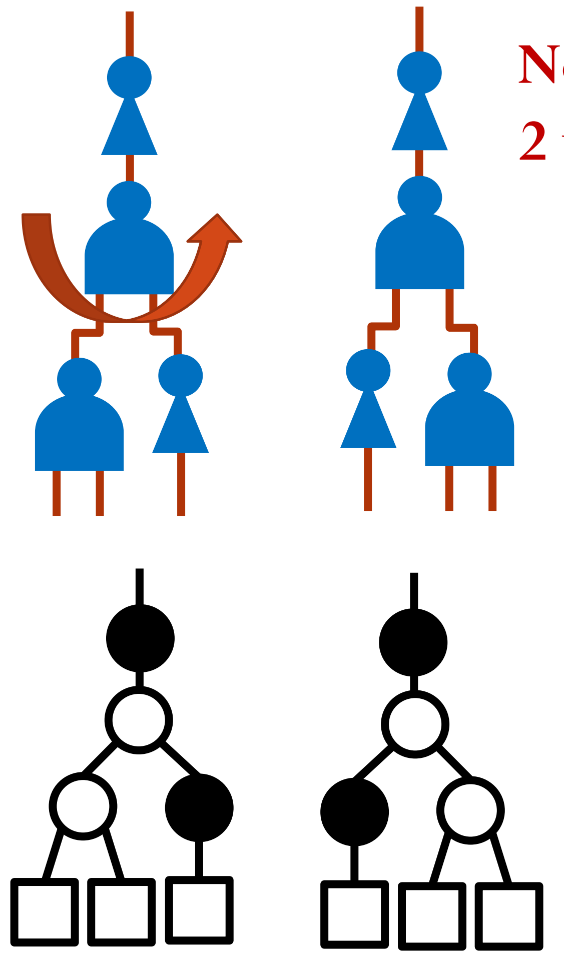
# Be Careful: Symmetries Matter!

AOI22



**Symmetric** tree,
**1 way** to match

AOI21

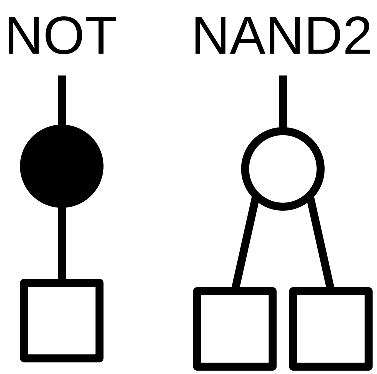


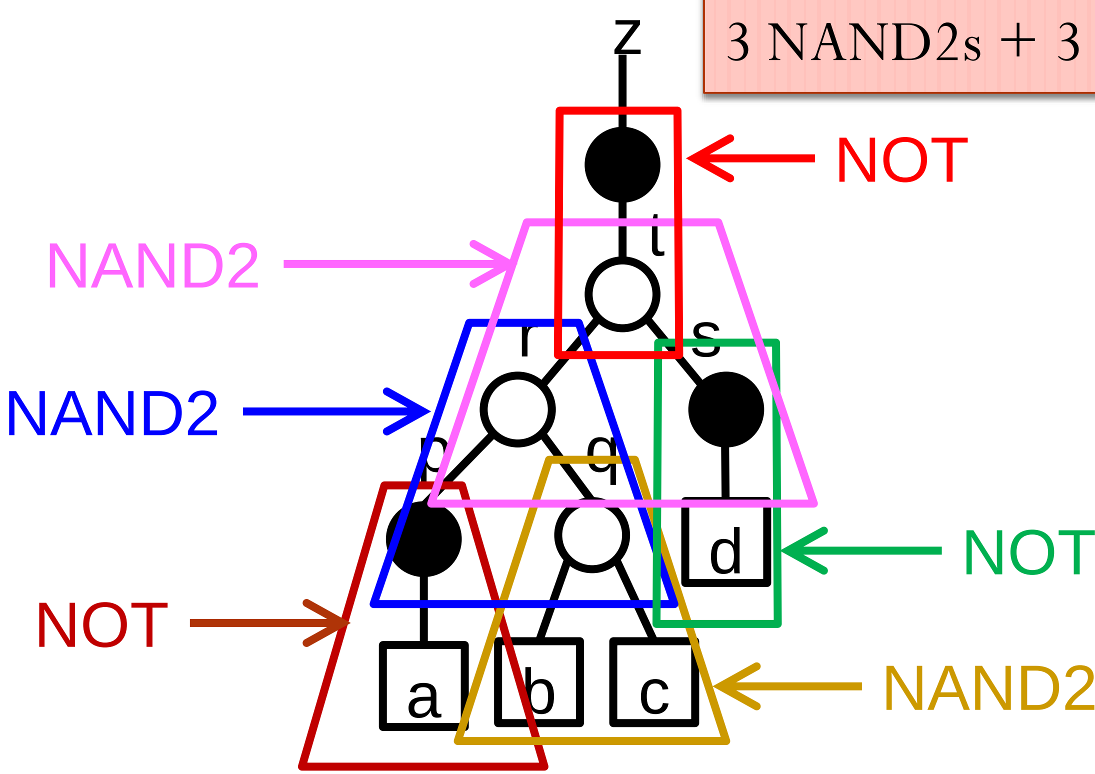
**Not symmetric**,
**2 ways** to match

# Rules for a Complete Tree Cover

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

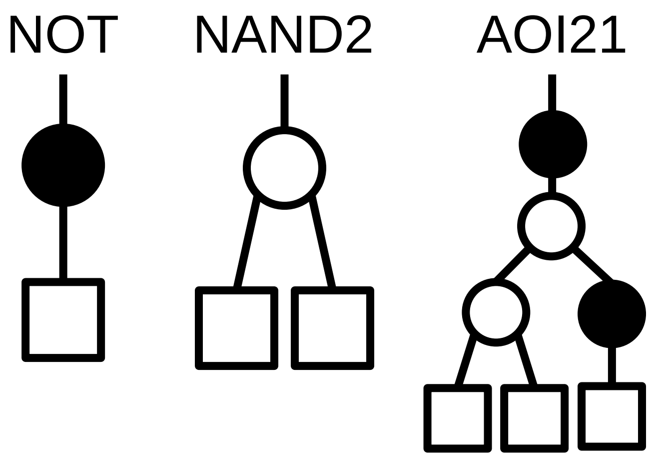
One correct tree cover:
3 NAND2s + 3 NOTs

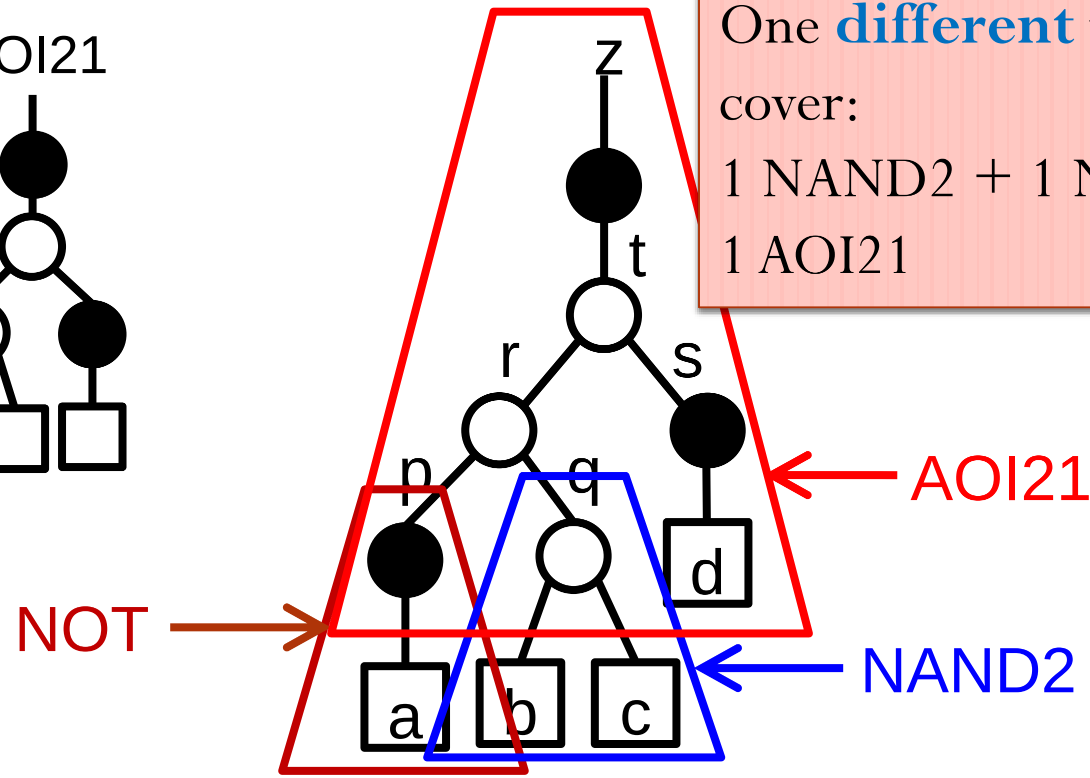


# Rules for a Complete Tree Cover

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




One **different** tree cover:
1 NAND2 + 1 NOT + 1 AOI21

# Outline

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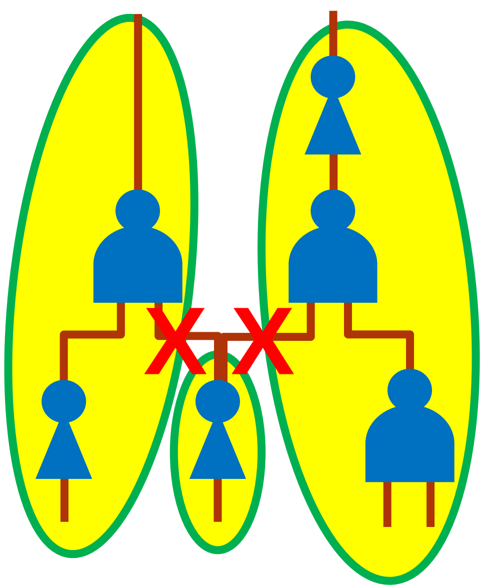
# Tech Mapping via Tree Covering

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

- **Treeifying** the input netlist
- **Tree matching**
  - For each node in the subject tree, find pattern trees in library that **match**.
- **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?

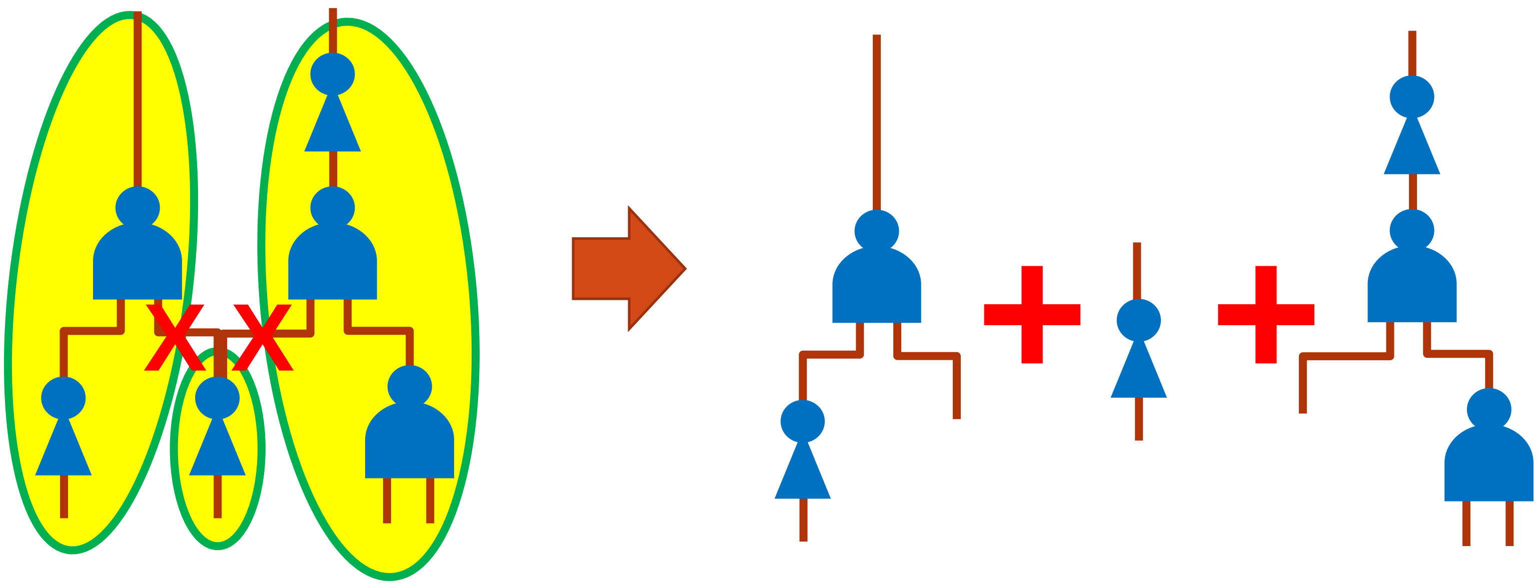
# Treeifying the Netlist

- These algorithms **only** work on trees, not on general graphs.
  - **Note**: general gate netlists are **Directed Acyclic Graphs (DAGs)**.
- **Treeifying**: every place you see a gate with fanout > 1, you **need to split**.



Must **split** this DAG into **3 separate trees**, map each separately.

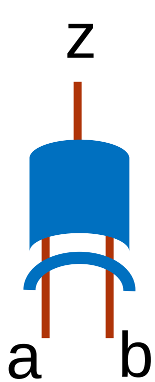
# Treeifying Netlist: Result



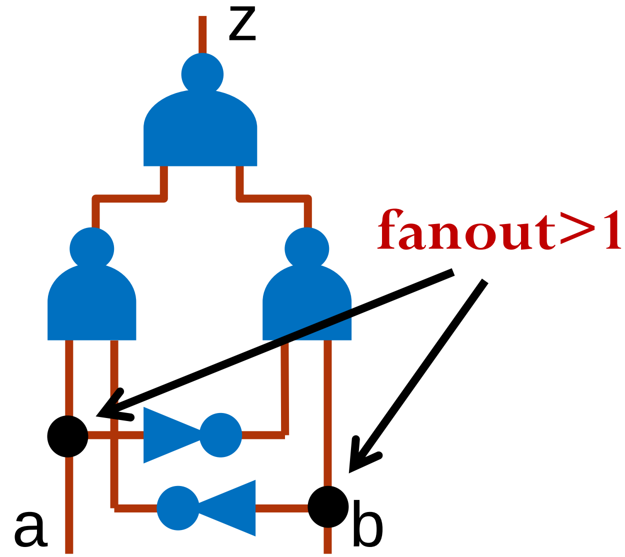
- We're going to map these **3 trees** separately.
- This entails some loss of optimality, since **cannot** map across trees.
  - There are ways around these, but we won't discuss these.

# Aside: How Restrictive is "Tree" Assumption?

- Subject graph and each pattern graph **must be trees**.
  - Subject tree must be treeified.
- What about **pattern trees**?
  - Are there common, useful gates that **cannot** be trees?
  - Yes! For example, XOR gate.
  - There are tricks to deal with this, but for us, these are forbidden!




$$z = a\bar{b} + \bar{a}b$$




So, no XOR gates for mapping!

# Tech Mapping via Tree Covering

- **Subroutines**:
  - **Treeifying** the input netlist
    - Loses some optimality, but make things simple.
  - **Tree matching**
    - For each node in the subject tree, find pattern trees in library that **match**.
  - **Minimum-cost covering**
    - Assume you know what can match at each node of subject tree. Then, which ones do you pick for a **minimum cost** cover?

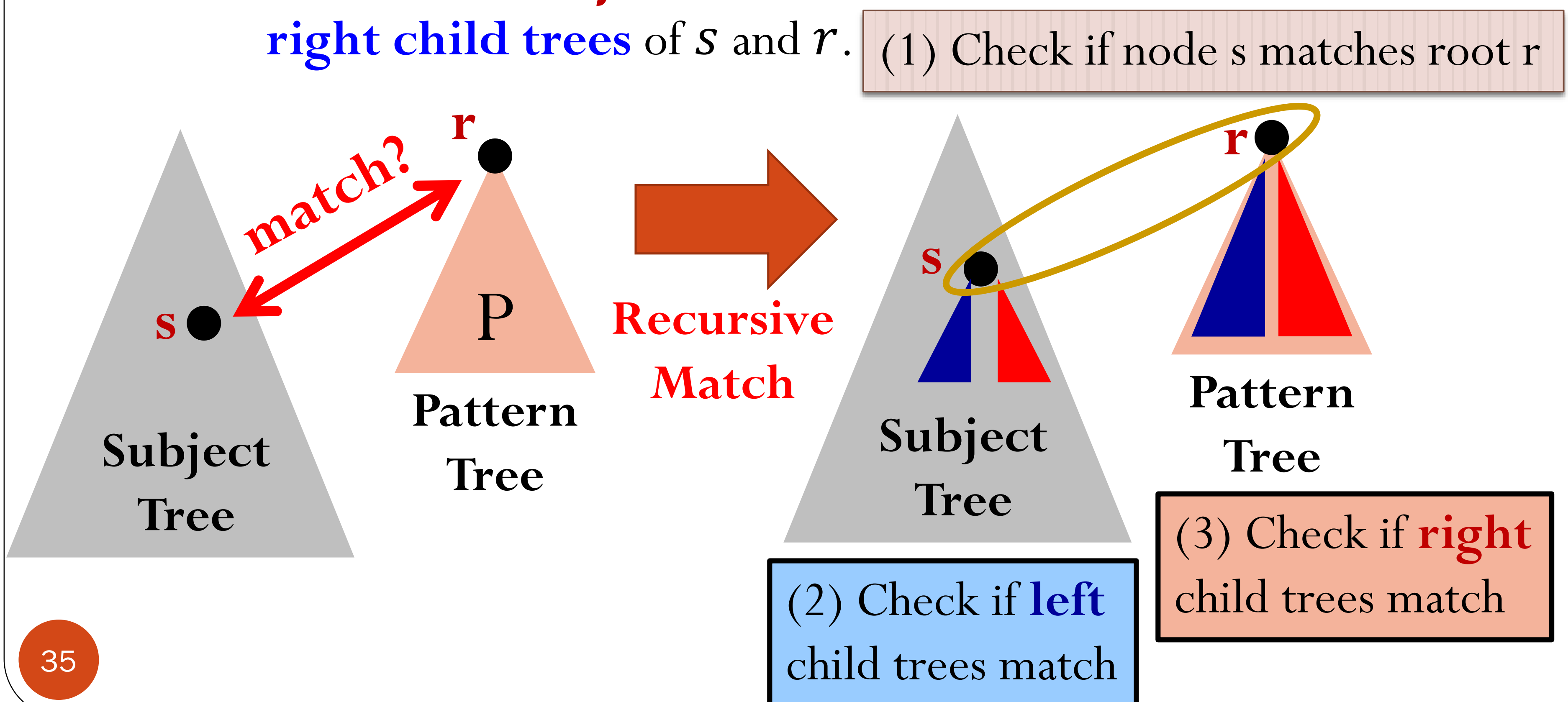
# Tree Matching

- **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 a node $n$ of subject tree with **root** of pattern tree, and then **recursively match children** of $n$ in subject tree to **children** of pattern tree.

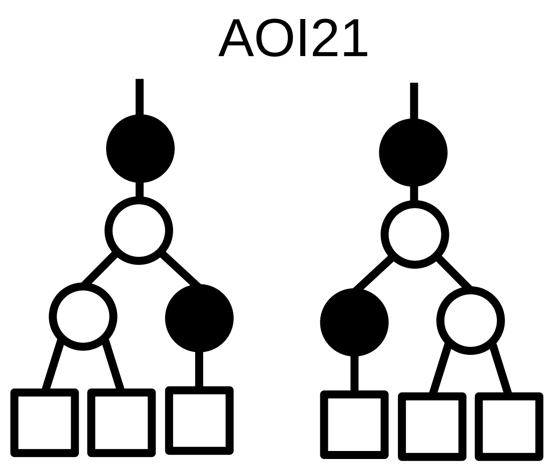
# Recursive Tree Matching

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



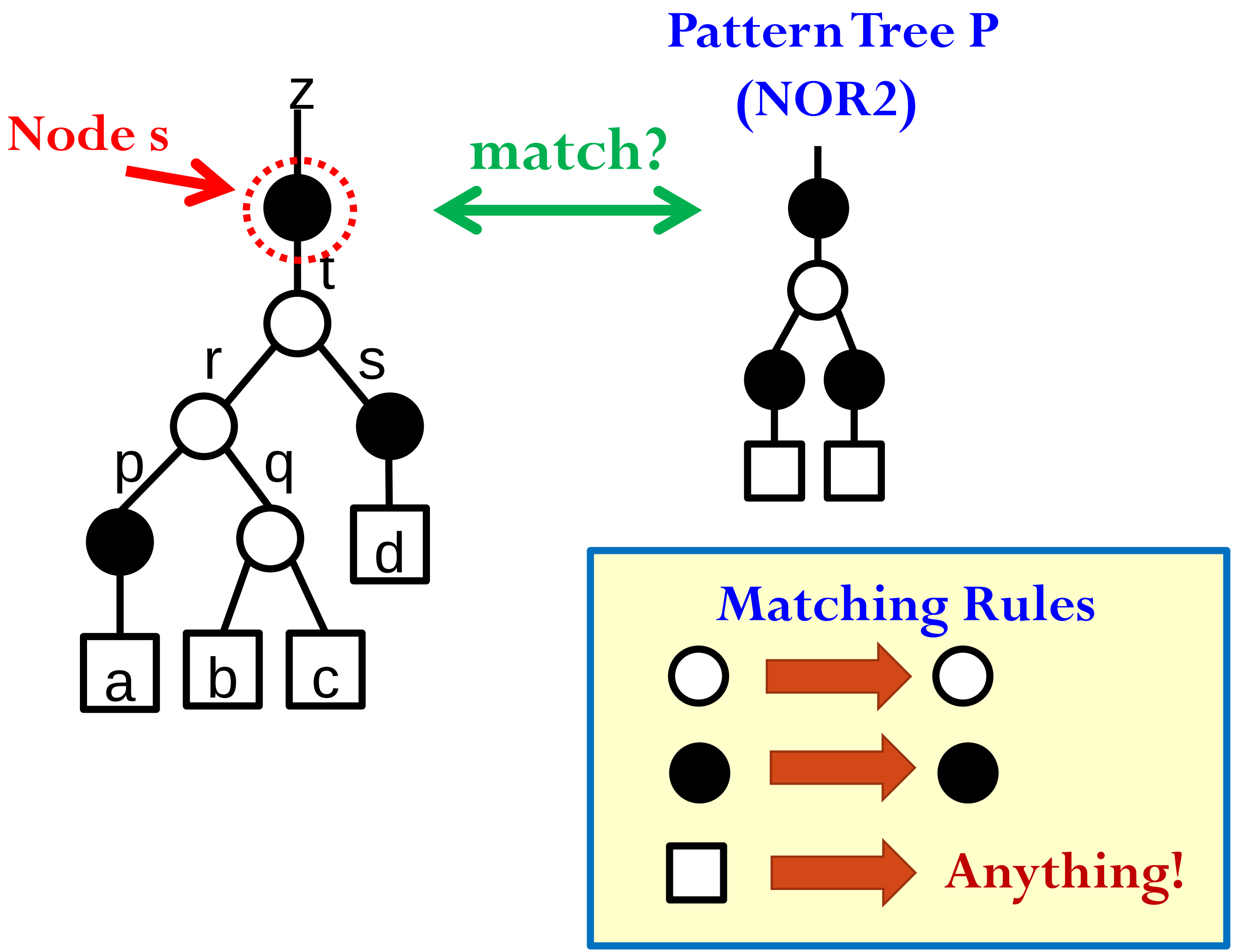
# Tree Matching: One Subtlety

- Be careful matching asymmetric library patterns.
  - One example was AOI21. Need to check all possible matches by "**rotating**" the pattern tree.

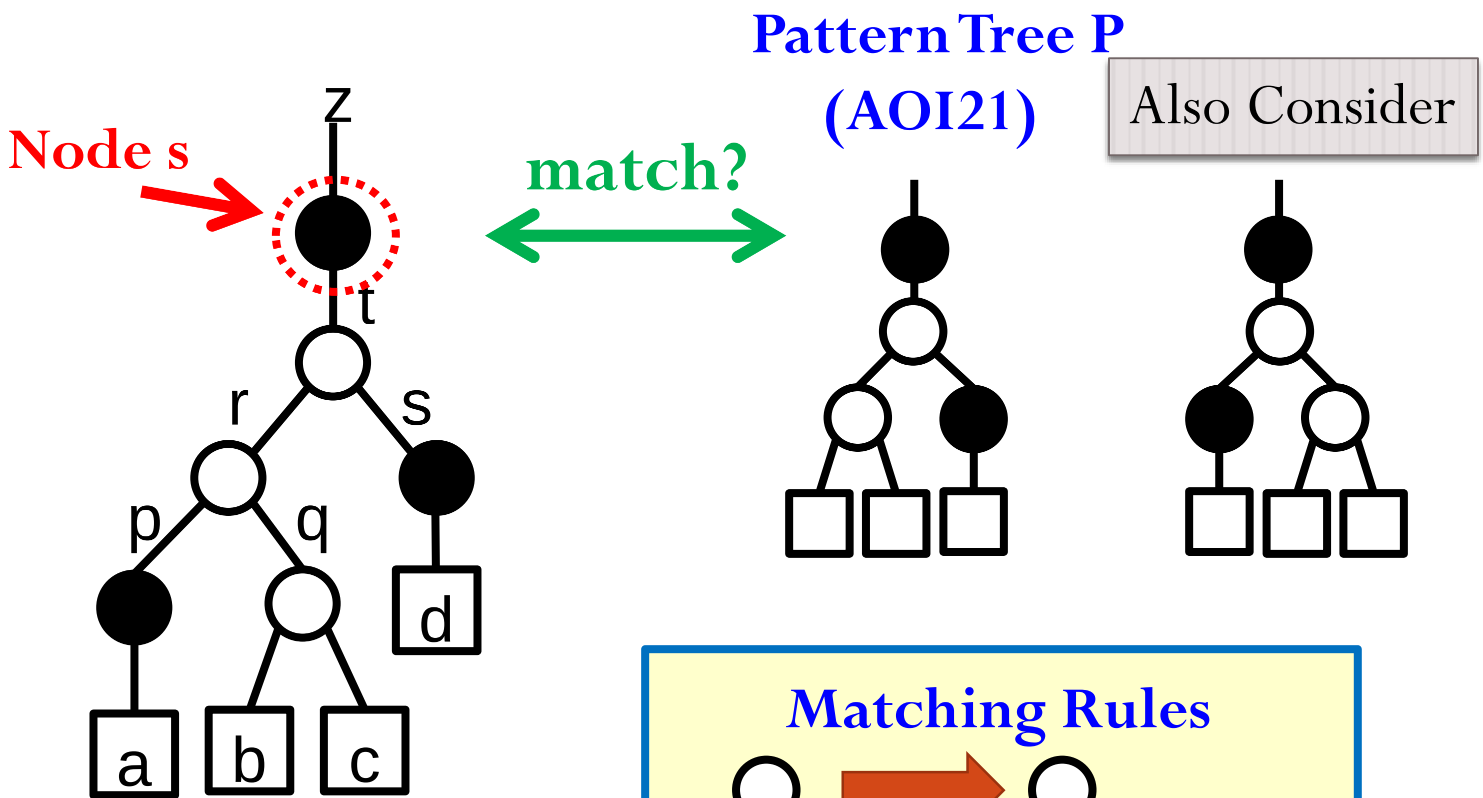


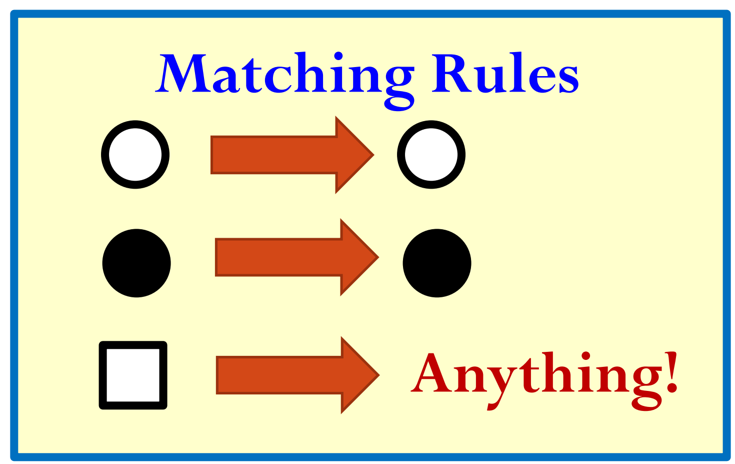

**Both orientations** are possible!

# Tree Matching Example



# Tree Matching Example



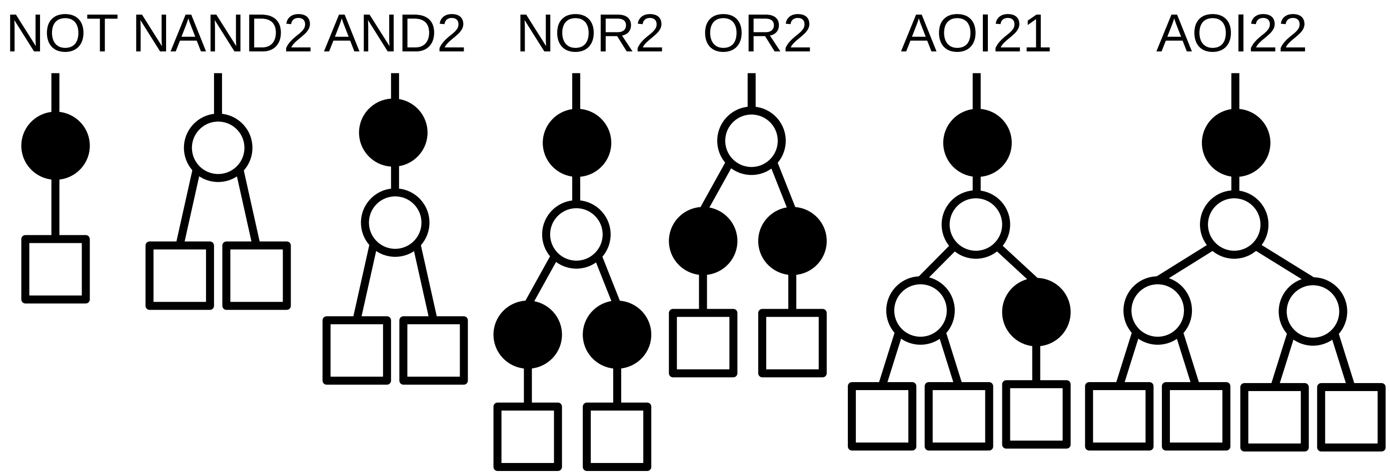



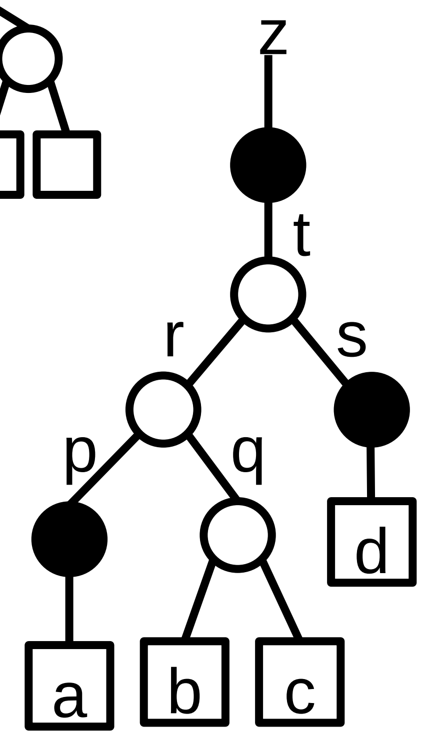
# Result After Matching

- For each internal node of subject tree, we will get which library pattern trees **match** that node.

- We **annotate** each internal node in the tree with this matching information.

# Tree Matching Result Example




- **List of matching gates**
  - Node z: {NOT, AND2, AOI21}
  - Node t: {NAND2}
  - Node r: {NAND2}
  - Node s: {NOT}
  - Node p: {NOT}
  - Node q: {NAND2}

# Tech Mapping via Tree Covering

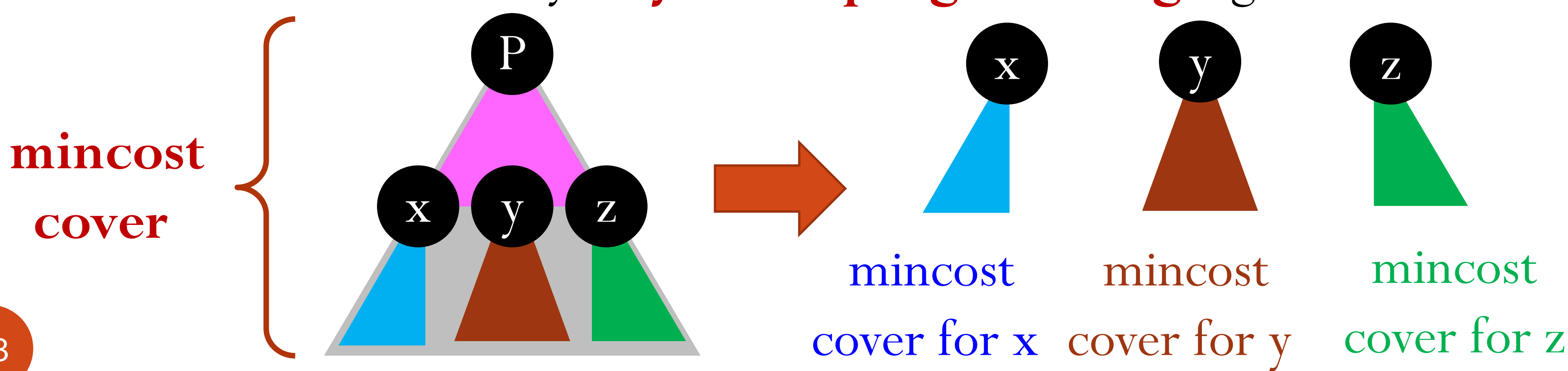
- **Subroutines**:
  - **Treeifying** the input netlist
    - Loses some optimality, but make things simple.
  - **Tree matching**
    - For each node in the subject tree, find pattern trees in library that **match**.
  - **Minimum-cost covering**
    - Assume you know what can match at each node of subject tree. Then, which ones do you pick for a **minimum cost** cover?

# Minimum Cost Covering of Subject Tree

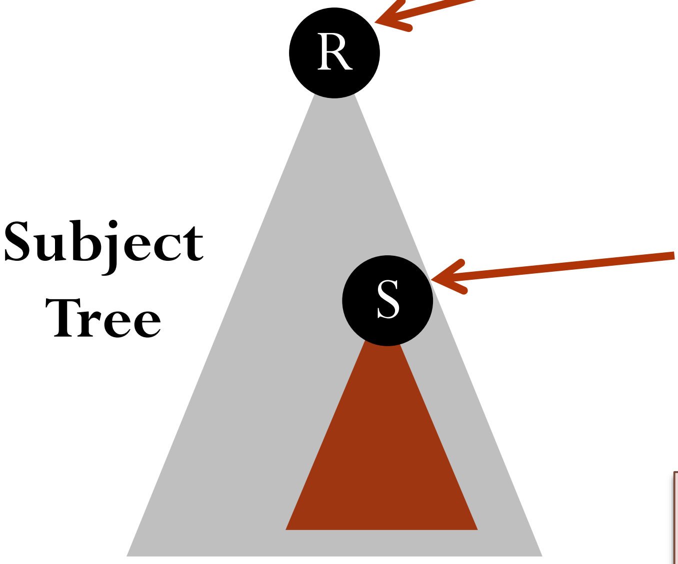
- What cover do we choose?
  - We assign a **cost** to each library pattern.
  - We choose a **minimum cost** ("**mincost**") cover of the subject tree.

# Minimum Cost Covering of 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.
    - Why? By contraposition…
  - Leads to a nice recursive algorithm for **mincost** on **any node** in subject tree.
    - This is actually a **dynamic programming** algorithm.



# Some Terminology



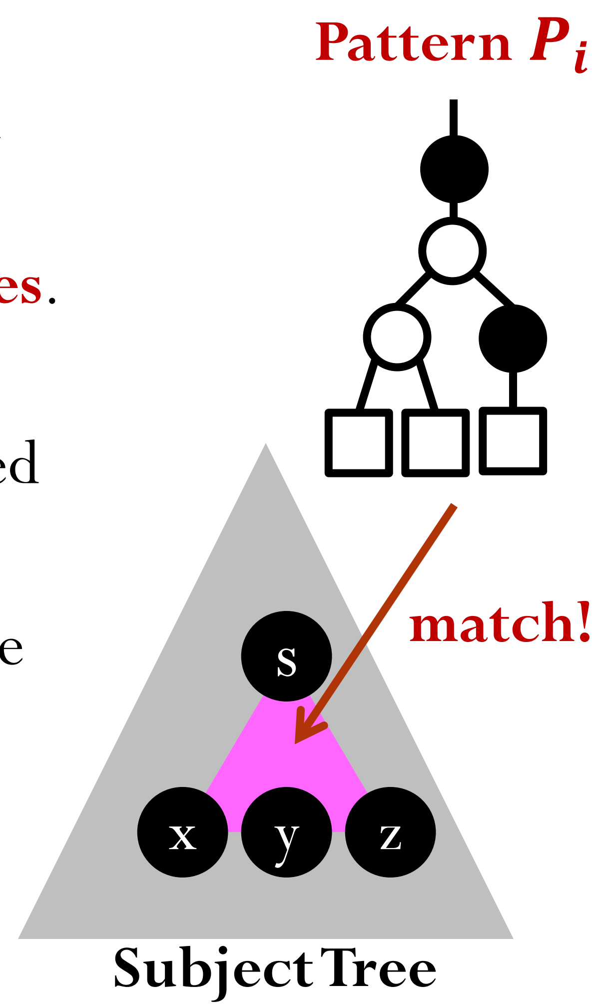

**Root** *R* of subject tree. Best cover (mapping) of this tree has cost = **mincost(R)**

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

**Note**: we treeified the netlist. Thus, every **internal node** (like node *s*) is the **root** of another, **smaller tree**. This is crucial for our mapping algorithm.

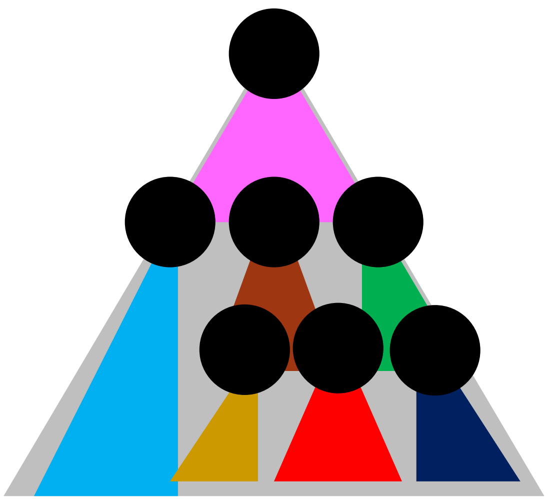
# Some Terminology (cont.)

- **<u>Suppose</u>**:
  - Library pattern $P_i$ matches at internal node $s$ of the subject tree.
  - Library pattern $P_i$ has $m$ **input nodes**.
- Each of these $m$ "**input nodes**" in library pattern tree $P_i$ will be matched to some nodes in subject tree.
- We call these nodes in the subject tree **leaf nodes** for this matching library pattern tree.
  - E.g., x, y, z are leaf nodes.



# Calculating Cost of Mapping

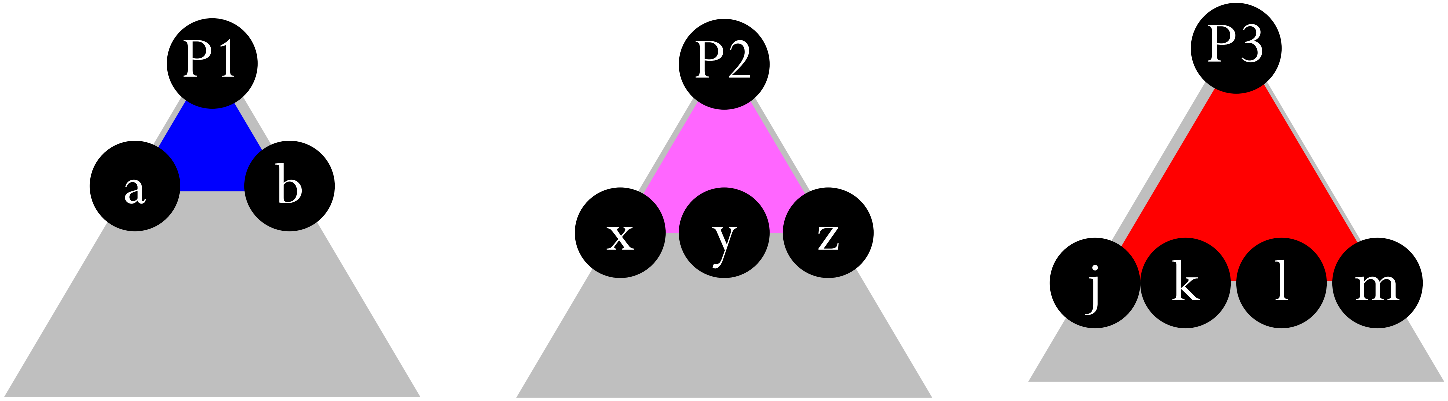
- Every gate pattern in target library has a **cost**.
  - Gate pattern $P_i$ has $\text{cost}(P_i)$.
- To calculate cost of mapping the **entire** subject tree:
  - We add up **costs** of all pattern trees covering subject.



The cost is the sum of the costs of 7 pattern trees.

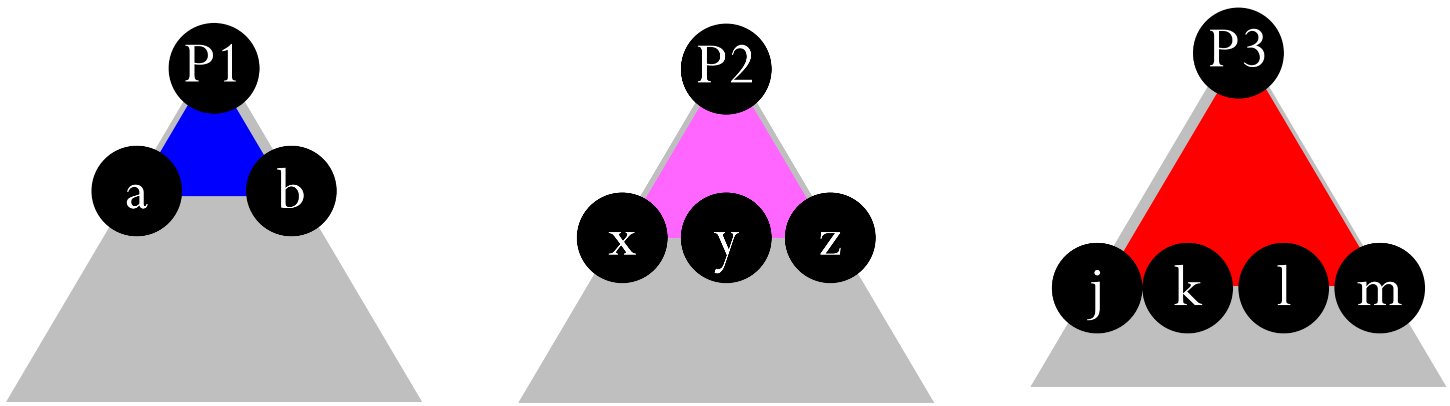
# Mincost Tree Covering: The Idea

- 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)?

# Mincost Tree Cover: The Idea




- Minimum cost of mapping the entire subject tree is
  **mincost(**R**)**
  **=min{** **minimal** cost with **P1** matching root R,
  **minimal** cost with **P2** matching root R,
  **minimal** cost with **P3** matching root R }

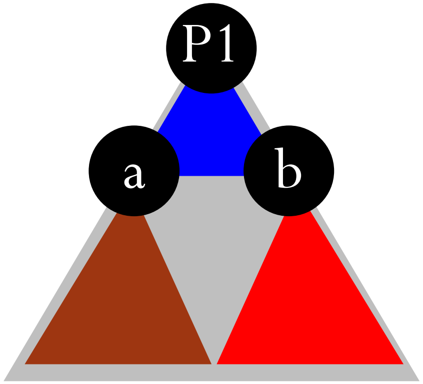
What're these?

# Mincost Tree Cover: Recursive Formula

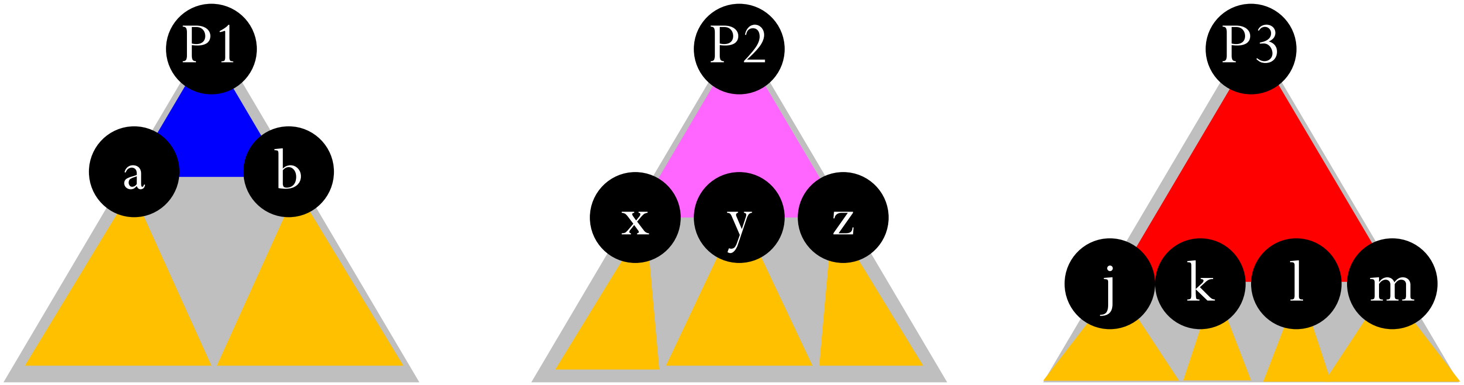
- In calculating **mincost**(R), we need to answer:
  - What is **minimal** cost with **P1** matching root R?

- **<u>Answer</u>**: = **cost**(P1) + **mincost**(a) + **mincost**(b)
  - Otherwise, **<u>not</u>** minimal!

**Recursion!**



# Mincost Tree Cover: Recursive Formula




- **mincost(**R**)**
  **= min{ minimal** cost with **P1** matching root R,
  **minimal** cost with **P2** matching root R,
  **minimal** cost with **P3** matching root R }

  **= min{ cost(**P1**) + mincost(**a**) + mincost(**b**),**
  **cost(**P2**) + mincost(**x**) + mincost(**y**) + mincost(**z**),**
  **cost(**P3**) + mincost(**j**) + mincost(**k**)**
  **+ mincost(**l**) + mincost(**m**) }**

# Mincost Cover: Algorithm

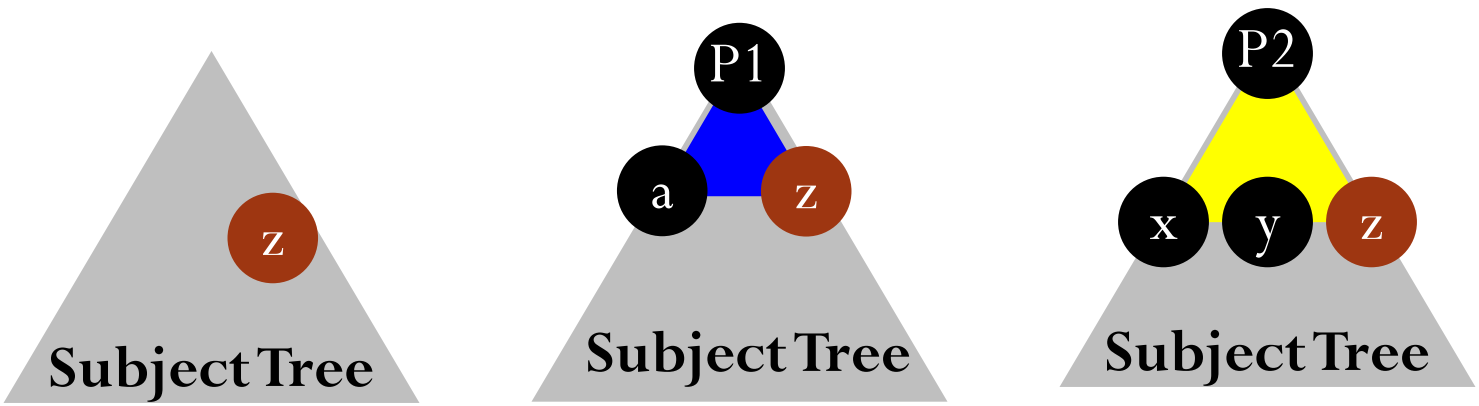
```
mincost( treenode) {
    cost = ∞
    foreach( pattern P matching at subject treenode) {
        let L = {nodes in subject tree corresponding to leaf nodes in P
            when P is placed with its root at treenode }
        newcost = cost(P)
        foreach( node n in L } {
            newcost = newcost +  mincost( n );
        }
        if ( newcost < cost ) then  {
            cost = newcost;
            treenode.BestLibPattern = P;
        }
    }
}
```

# Min Cost Tree Cover

- There is **redundant** computation we must note:
  - This algorithm will **revisit** same tree node many times during recursions…
  - …and it will **recompute** the mincost cover for that node each time.

# Illustration

- Node "z" in this subject tree
  - will get its **mincost(z)** cover computed when we put **P1** at root of subject tree…
  - …and again when we put **P2** at the root.



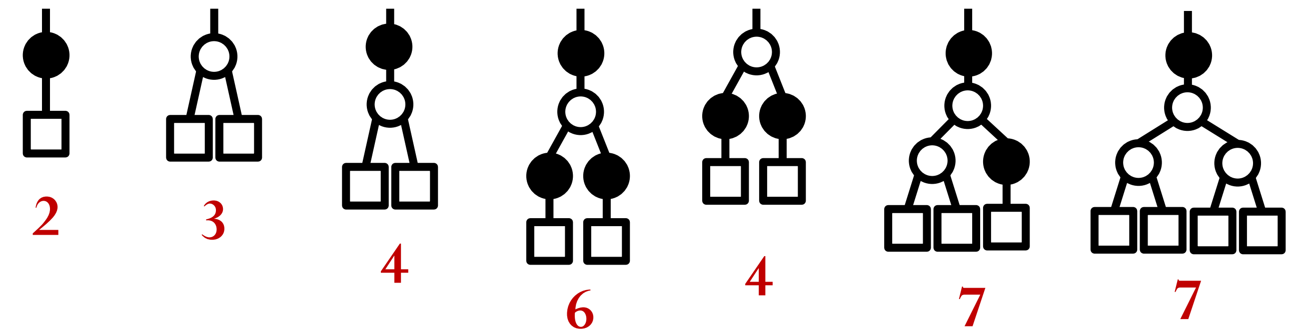
# Better Solution

- **Basic idea**: just compute it **once**. First time, **save** it; next time, **look it up**!

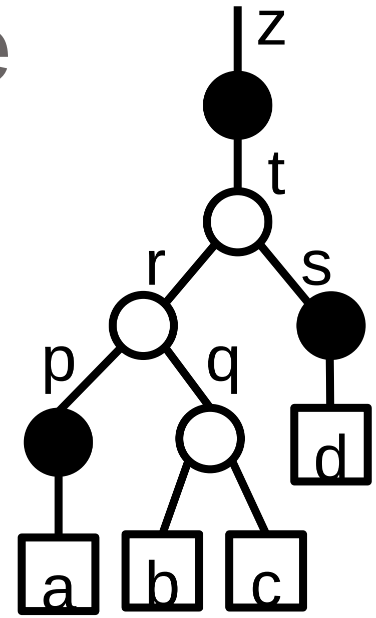
- **Details**:
  - Keep a table with **mincost** value for each node
  - Start each entry with value ∞
  - Each time computing **mincost(node), check <u>first</u>** to see if **node** has been computed (i.e., whether the value is ∞)
    - No: compute it and save the value in the entry
    - Yes: simply read the value

# Min Cost Tree Cover Example

NOT NAND2 AND2 NOR2 OR2 AOI21 AOI22



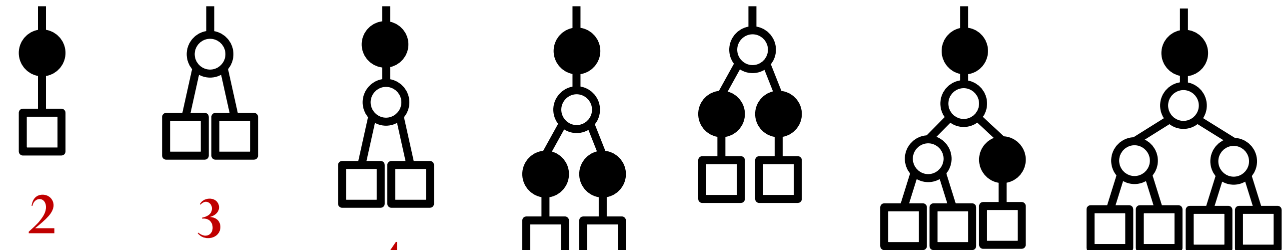

Cost



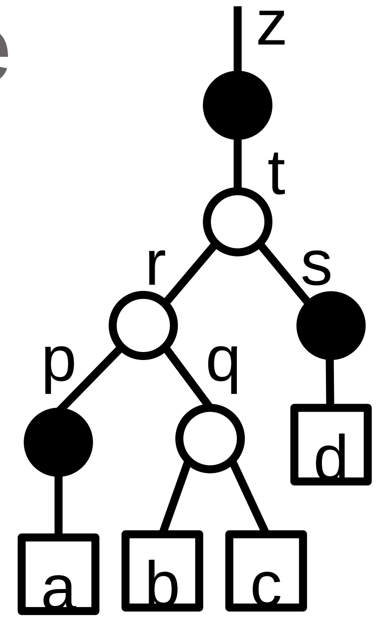

| Node | Can Match | Mincost |
|---|---|---|
| z | NOT | 2+mincost(t) |
| | AND2 | 4+mincost(r)+mincost(s) |
| | AOI21 | 7+mincost(p)+mincost(q) |
| | | min |
| t | NAND2 | 3+mincost(r)+mincost(s) |
| r | NAND2 | 3+mincost(p)+mincost(q) |
| p | NOT | 2 $\Rightarrow$ mincost(p)=2 |
| q | NAND2 | 3 $\Rightarrow$ mincost(q)=3 |
| s | NOT | 2 $\Rightarrow$ mincost(s)=2 |

# Min Cost Tree Cover Example

NOT NAND2 AND2 NOR2 OR2 AOI21 AOI22

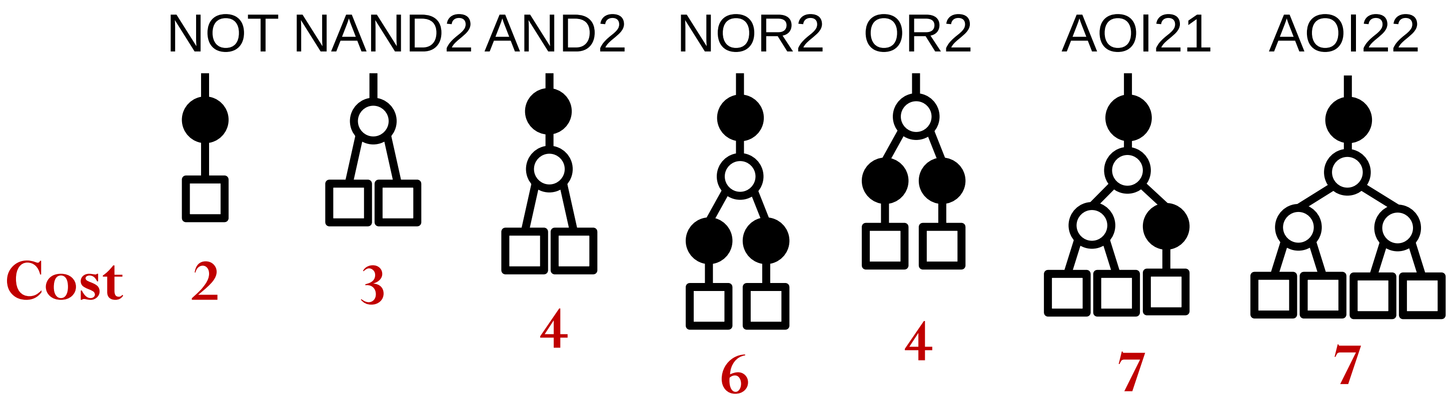


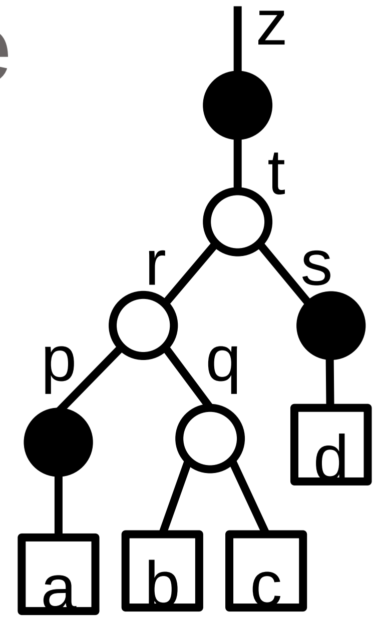
**Cost** 2 3 4 6 4 7 7




| **Node** | **Can Match** | **Mincost** | |
|---|---|---|---|
| z | NOT<br>AND2<br>AOI21 | 2+mincost(t)<br>4+mincost(r)+mincost(s)<br>7+mincost(p)+mincost(q) | **min** ⇒ mincost=12 |
| t | NAND2 | 3+mincost(r)+mincost(s) | |
| r | NAND2 | 3+mincost(p)+mincost(q) | ⇒ mincost(r)=8 |
| p | NOT | 2 | ⇒ mincost(p)=2 |
| q | NAND2 | 3 | ⇒ mincost(q)=3 |
| s | NOT | 2 | ⇒ mincost(s)=2 |

# Min Cost Tree Cover Example

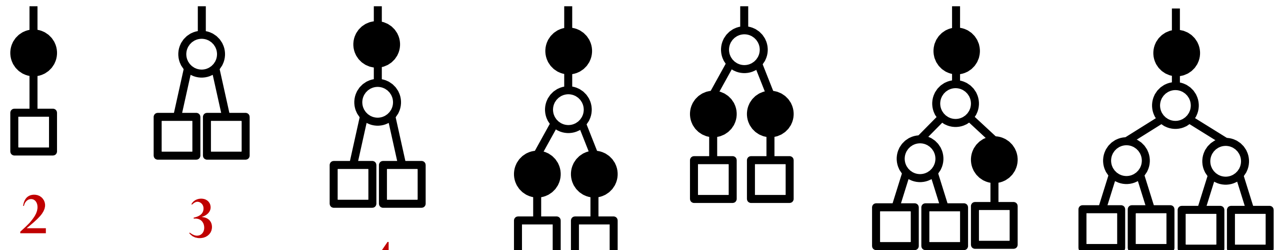


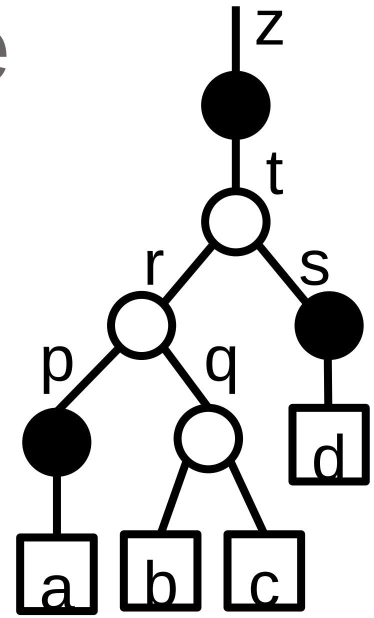

| Node | Can Match | Mincost |
|---|---|---|
| z | NOT<br>AND2<br>AOI21 | 2+mincost(t)<br>4+mincost(r)+mincost(s) $\Rightarrow$ mincost=14<br>7+mincost(p)+mincost(q) $\Rightarrow$ mincost=12<br>min |
| t | NAND2 | 3+mincost(r)+mincost(s) $\Rightarrow$ mincost(t)=13 |
| r | NAND2 | 3+mincost(p)+mincost(q) $\Rightarrow$ mincost(r)=8 |
| p | NOT | 2 $\Rightarrow$ mincost(p)=2 |
| q | NAND2 | 3 $\Rightarrow$ mincost(q)=3 |
| s | NOT | 2 $\Rightarrow$ mincost(s)=2 |

# Min Cost Tree Cover Example

NOT NAND2 AND2 NOR2 OR2 AOI21 AOI22



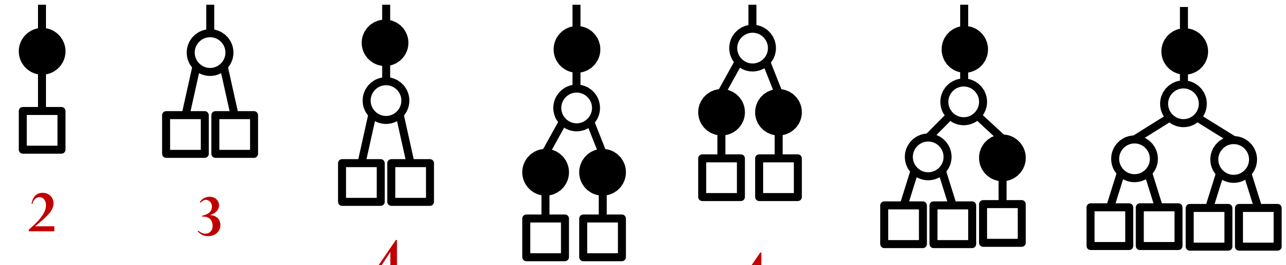
Cost 2 3 4 6 4 7 7



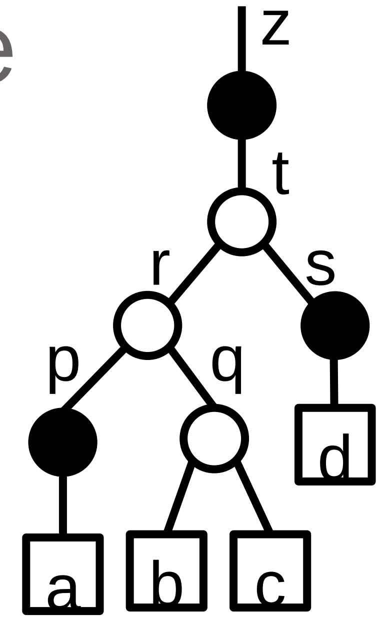

| Node | Can Match | Mincost | |
|---|---|---|---|
| z | NOT<br>AND2<br>AOI21 | 2+mincost(t)<br>4+mincost(r)+mincost(s)<br>7+mincost(p)+mincost(q) | min ⇒ mincost=15<br>⇒ mincost=14<br>⇒ mincost=12 |
| t | NAND2 | 3+mincost(r)+mincost(s) | ⇒ mincost(t)=13 |
| r | NAND2 | 3+mincost(p)+mincost(q) | ⇒ mincost(r)=8 |
| p | NOT | 2 | ⇒ mincost(p)=2 |
| q | NAND2 | 3 | ⇒ mincost(q)=3 |
| s | NOT | 2 | ⇒ mincost(s)=2 |

# Min Cost Tree Cover Example

NOT NAND2 AND2 NOR2 OR2 AOI21 AOI22



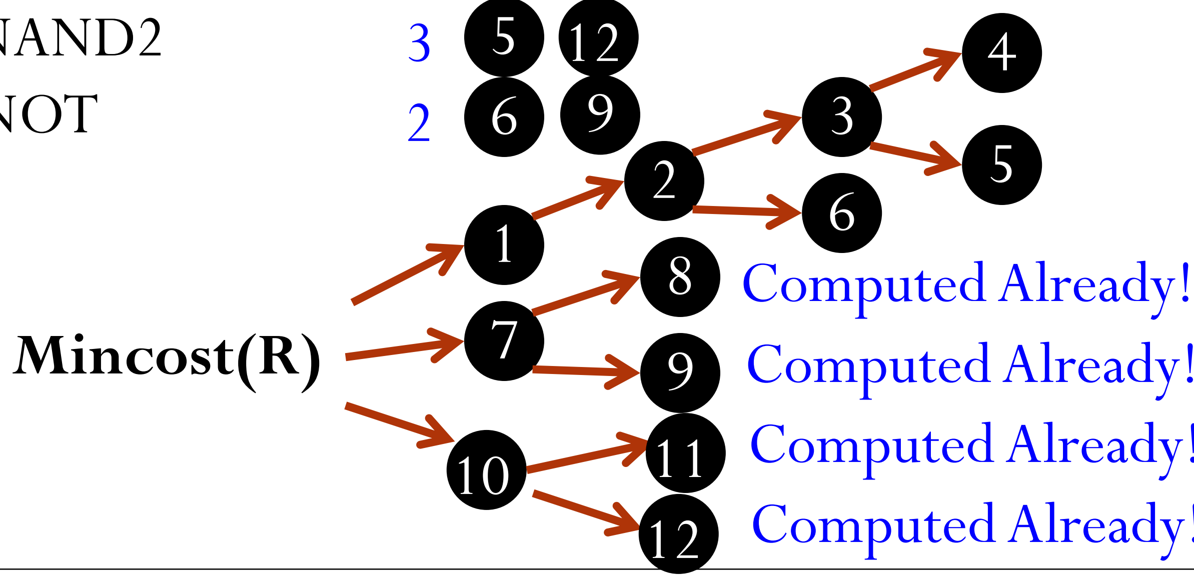
Cost 2 3 4 6 4 7 7




| Node | Can Match | Mincost | |
|---|---|---|---|
| z | NOT | 15 | |
| | AND2 | 14 | min |
| | AOI21 | 12 | Best! |
| t | NAND2 | 13 | |
| r | NAND2 | 8 | |
| p | NOT | 2 | |
| q | NAND2 | 3 | |
| s | NOT | 2 | |

# Actual Execution Sequence

| Node | Can Match | | Mincost |
|---|---|---|---|
| z | NOT<br>AND2<br>AOI21 | min | 2+mincost(t) 1<br>4+mincost(r)+mincost(s) 7<br>7+mincost(p)+mincost(q) 10 |
| t | NAND2 | | 3+mincost(r)+mincost(s) 2 |
| r | NAND2 | | 3+mincost(p)+mincost(q) 3 8 |
| p | NOT | | 2 4 11 |
| q | NAND2 | | 3 5 12 |
| s | NOT | | 2 6 9 |

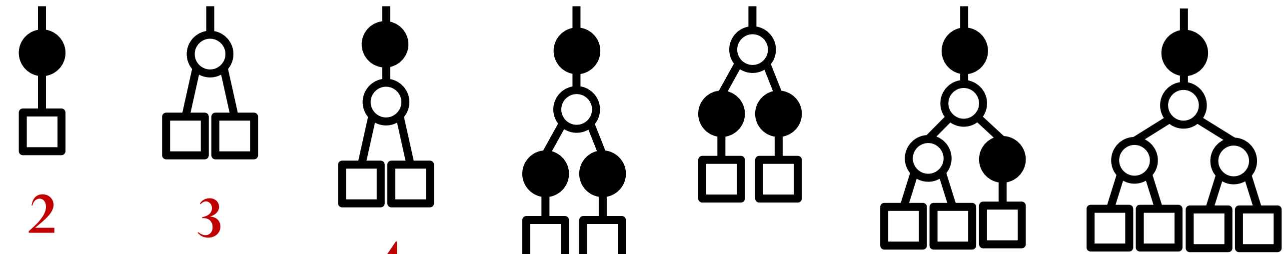


# Min Cost Cover: How To Get Final Cover?

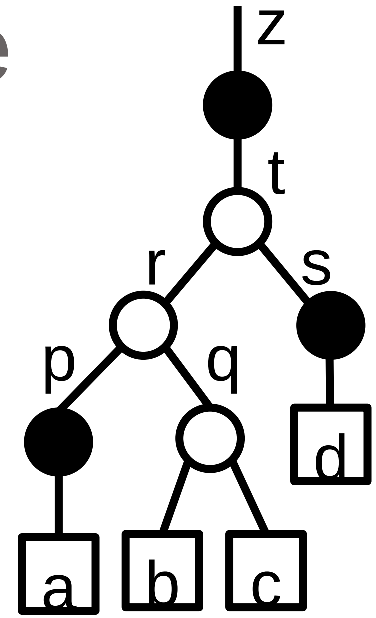
- Look at **best cost** at subject root. Find pattern $P$ at the root that gives that cost.
- Find **leaf nodes** in the subject tree for pattern $P$.
  - Look at the **best cost** at each of these leaf nodes.
  - Find the pattern $P_i$ that is associated with each of these best costs.
  - Look again at leaf nodes in the subject tree that are associated with each of these patterns $P_i$.
    - Repeat…

# Min Cost Tree Cover Example

NOT NAND2 AND2 NOR2 OR2 AOI21 AOI22



**Cost** 2 3 4 6 4 7 7




| Node | Can Match | Mincost |
|---|---|---|
| z | NOT | 2+mincost(t) =15 |
| | AND2 | 4+mincost(r)+mincost(s) = 14 |
| | AOI21 | 7+mincost(p)+mincost(q) = 12 |
| t | NAND2 | 3+mincost(r)+mincost(s) = 13 |
| r | NAND2 | 3+mincost(p)+mincost(q) = 8 |
| p | NOT | 2 |
| q | NAND2 | 3 |
| s | NOT | 2 |

**min**

**Best!**

# Min Cost Tree Cover

- Turns out to be several nice **extensions** possible
  - Can modify algorithm a little to minimize **delay** instead of area cost.
  - Many interesting and useful variations, starting from this algorithm skeleton.

# Technology Mapping: Summary

- Synthesis gives you "**uncommitted**" or "technology independent" design, e.g., NAND2 and NOT.
- Technology mapping turns this into **real gates** from library.
- Tree covering
  - One nice, simple, elegant approach to the problem.
  - 3 parts: treeify input, match all library patterns, find min cost cover.
- There are other ways to do this. Some work with real Boolean algebra in mapping.
- Has other applications, like mapping for Lookup-Table (LUT) in FPGA.