CS-C3100 Computer Graphics

5.1 Hierarchical Modeling

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with many slides from
Frédo Durand and Barb Cutler

In These Slides

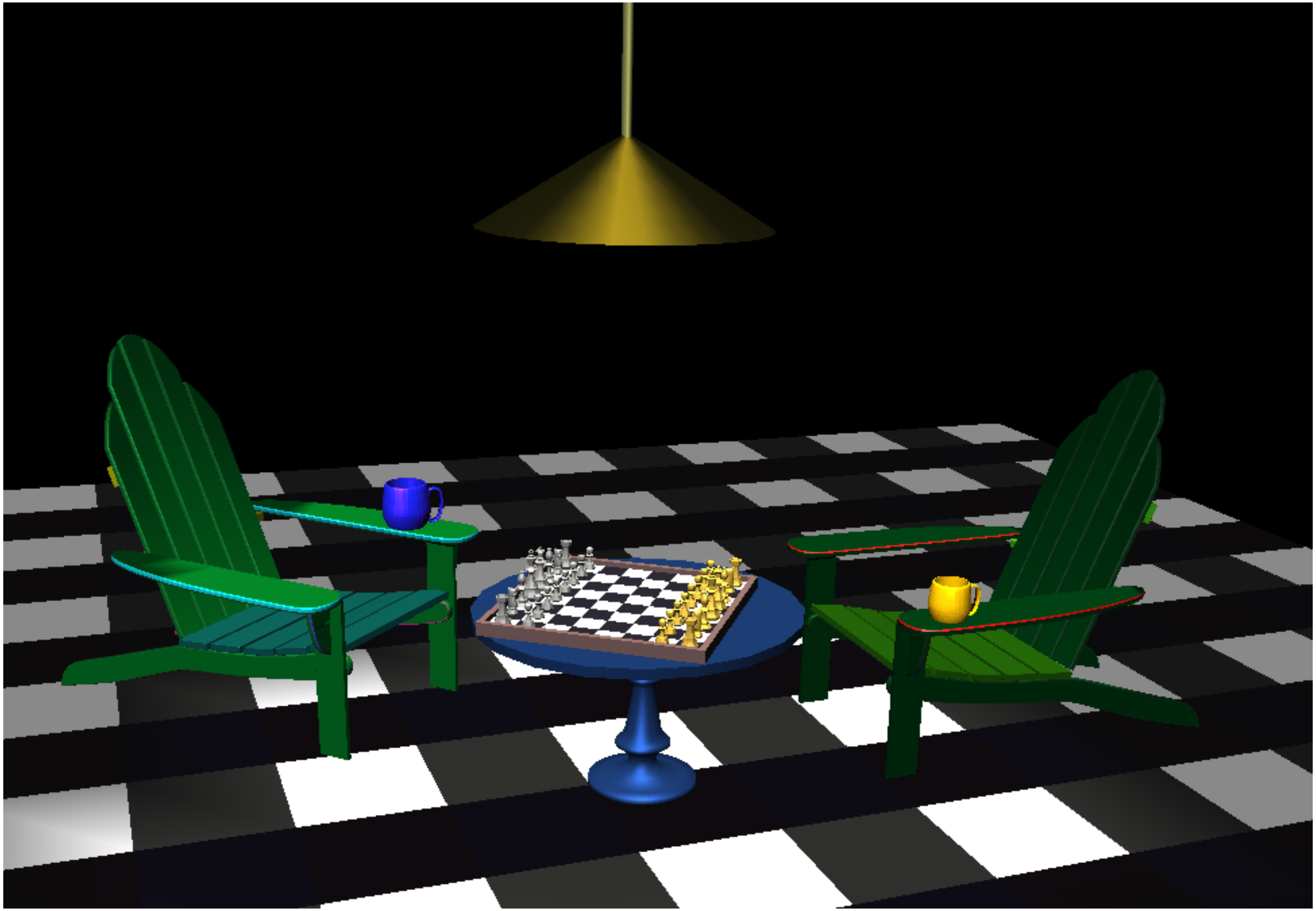
- Why object hierarchies are useful
- The Scene Graph
  - representing scenes by directed acyclic graphs (DAG)
  - traversing the scene graph

Hierarchical Modeling

- Triangles, parametric curves and surfaces are the building blocks for more complex objects

- Hierarchical modeling creates complex real-world objects by combining simple primitive shapes into aggregate objects.

Hierarchical models



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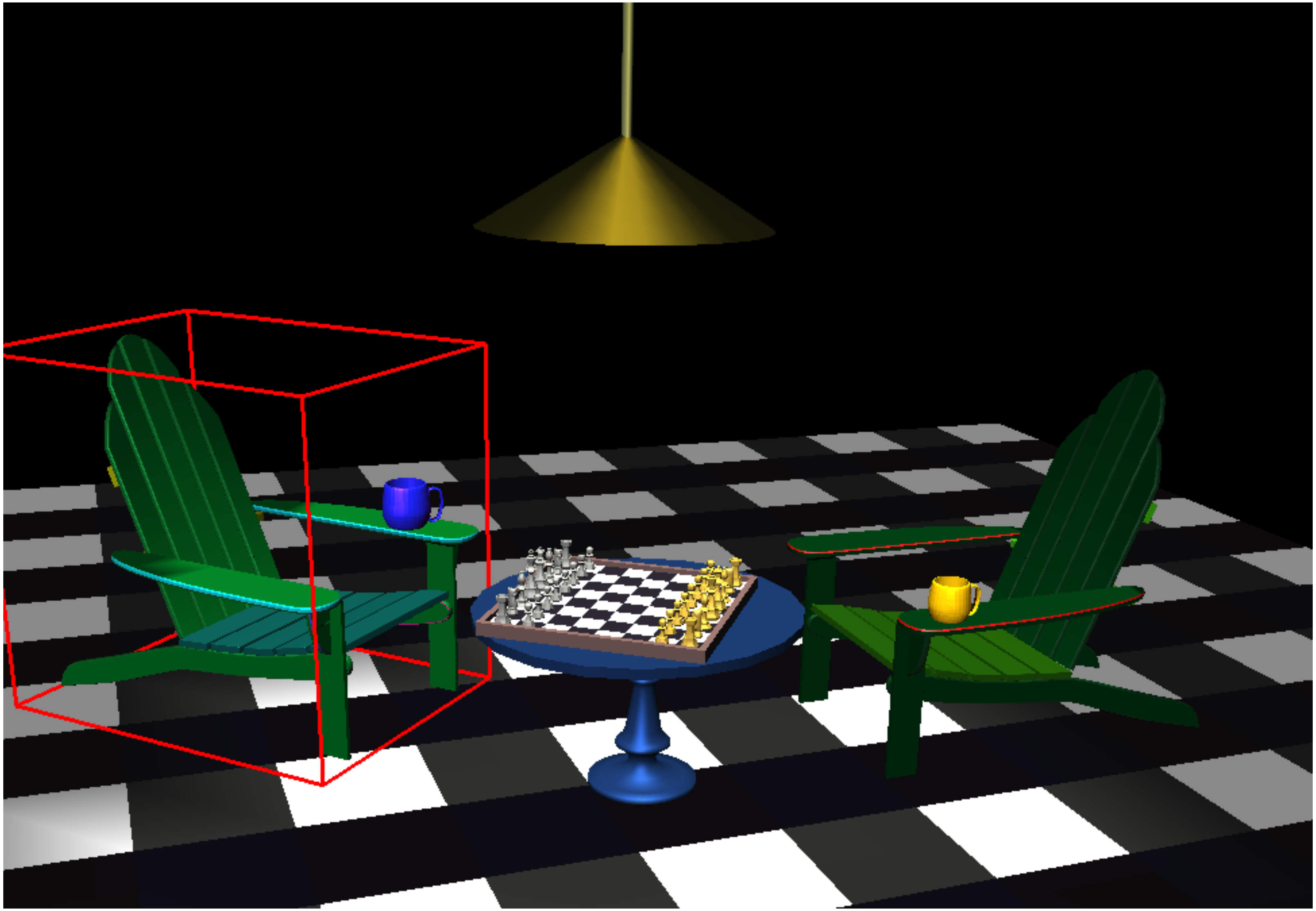

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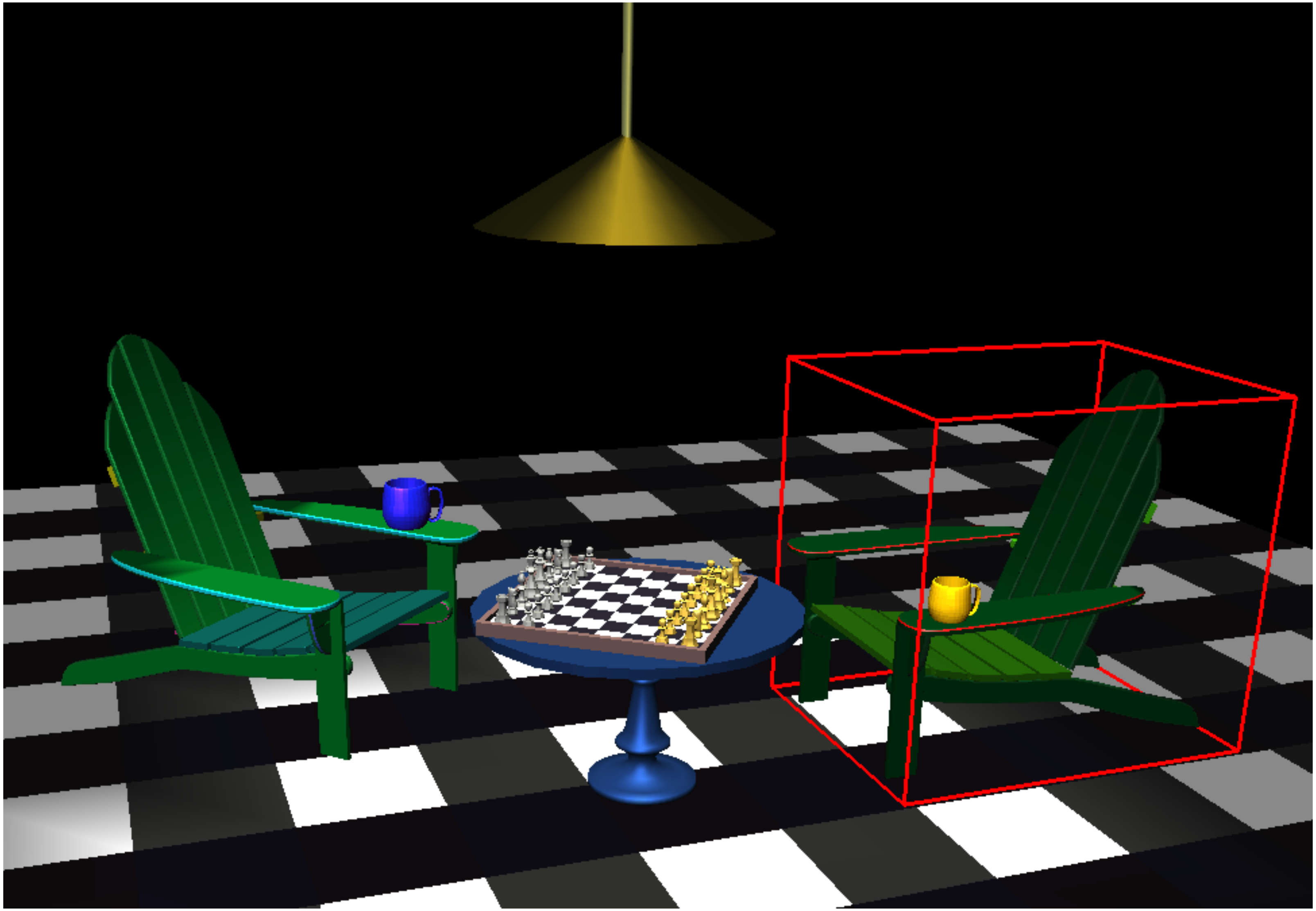

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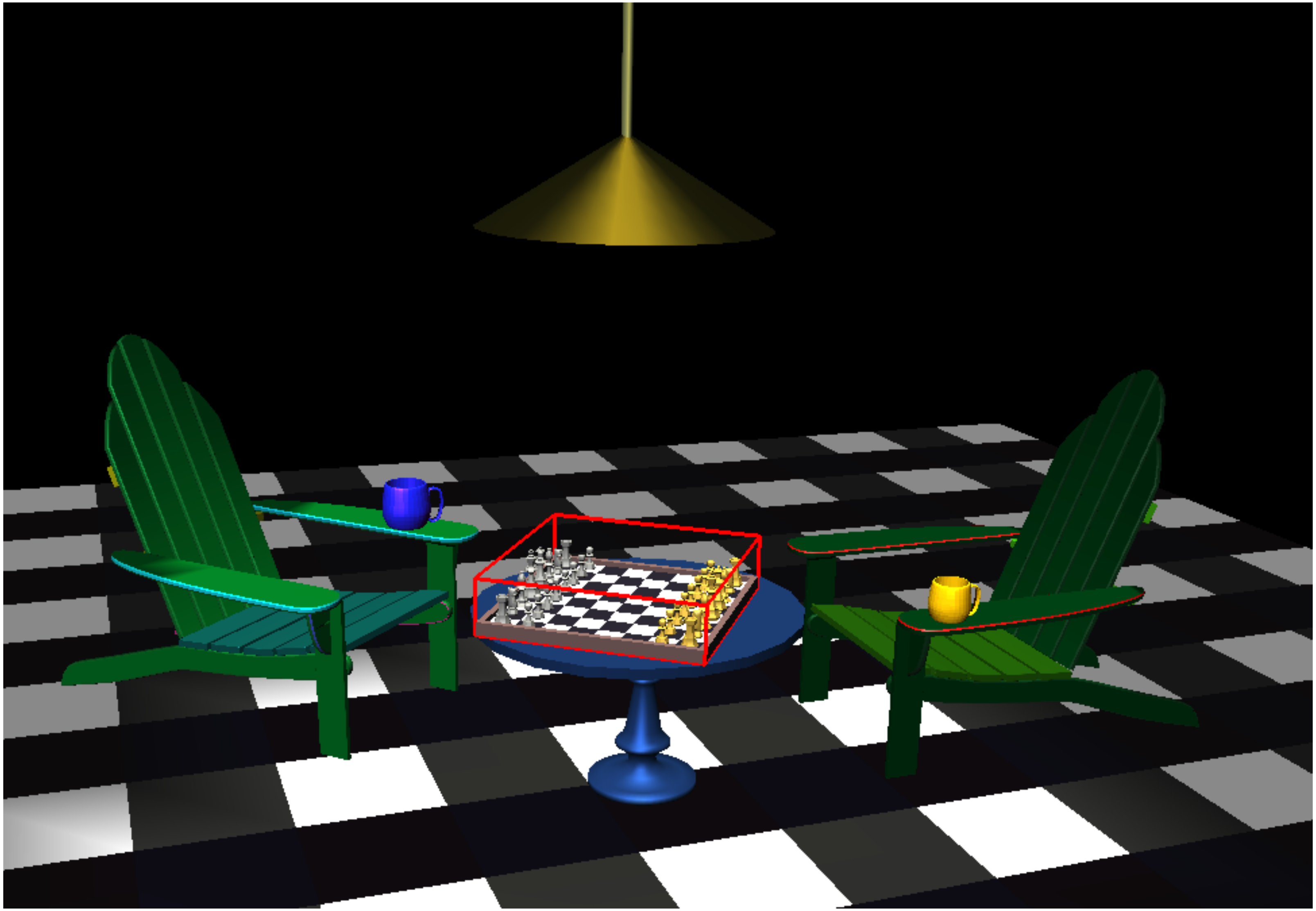

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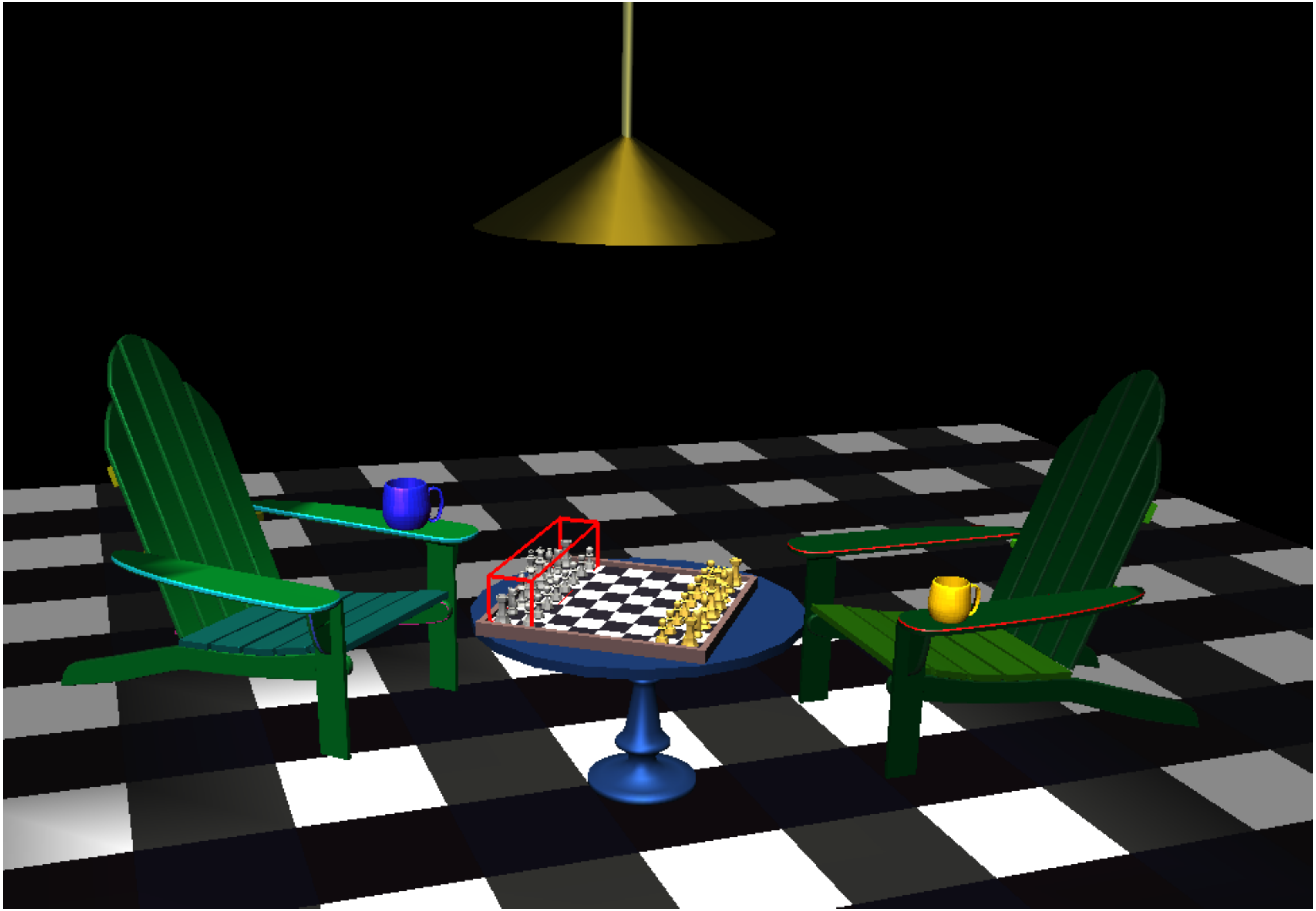

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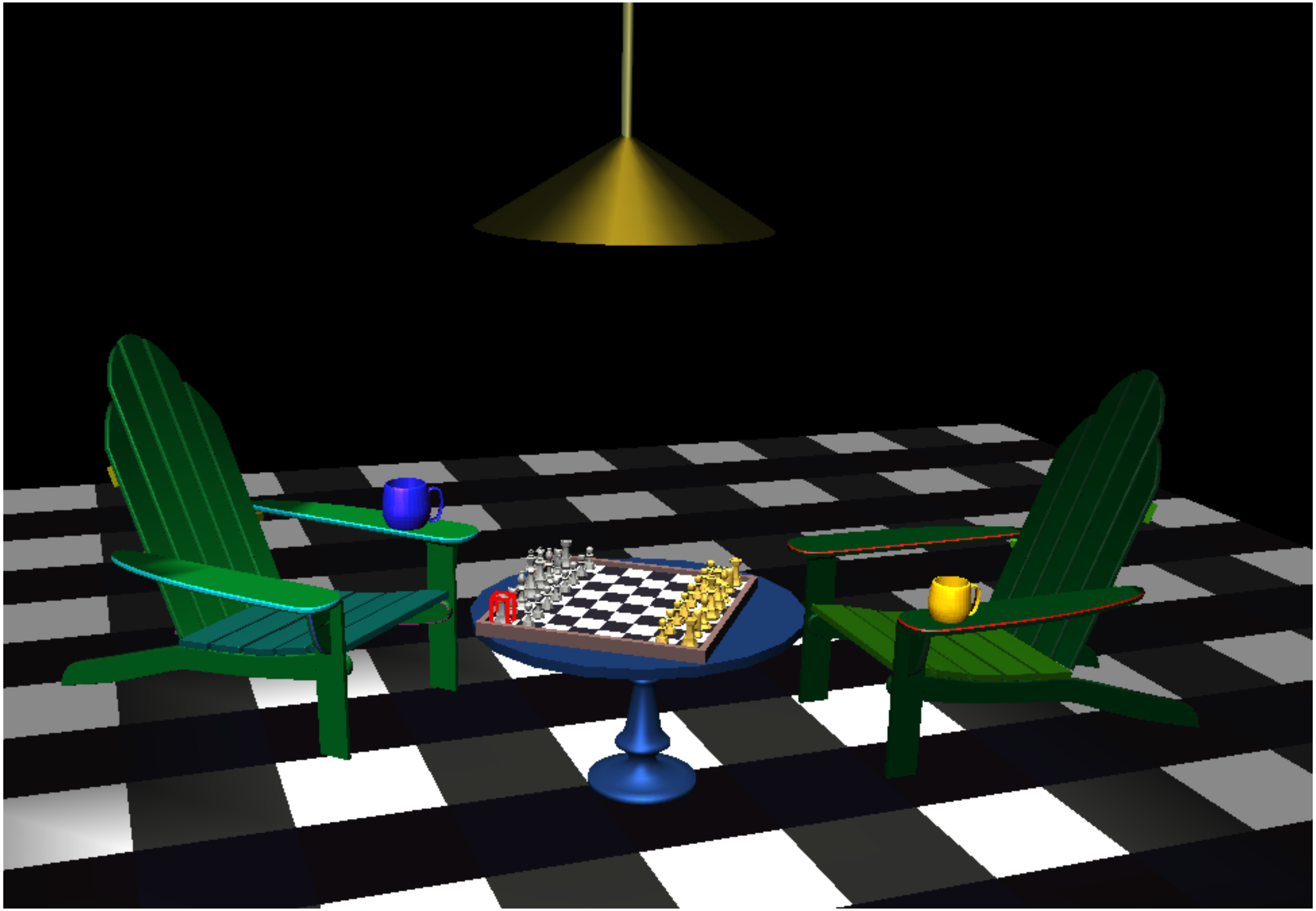
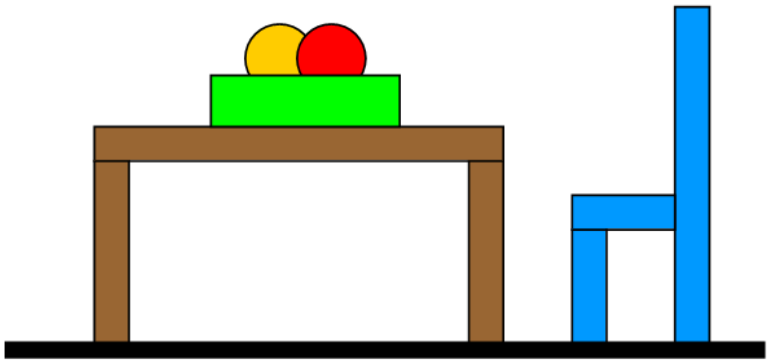
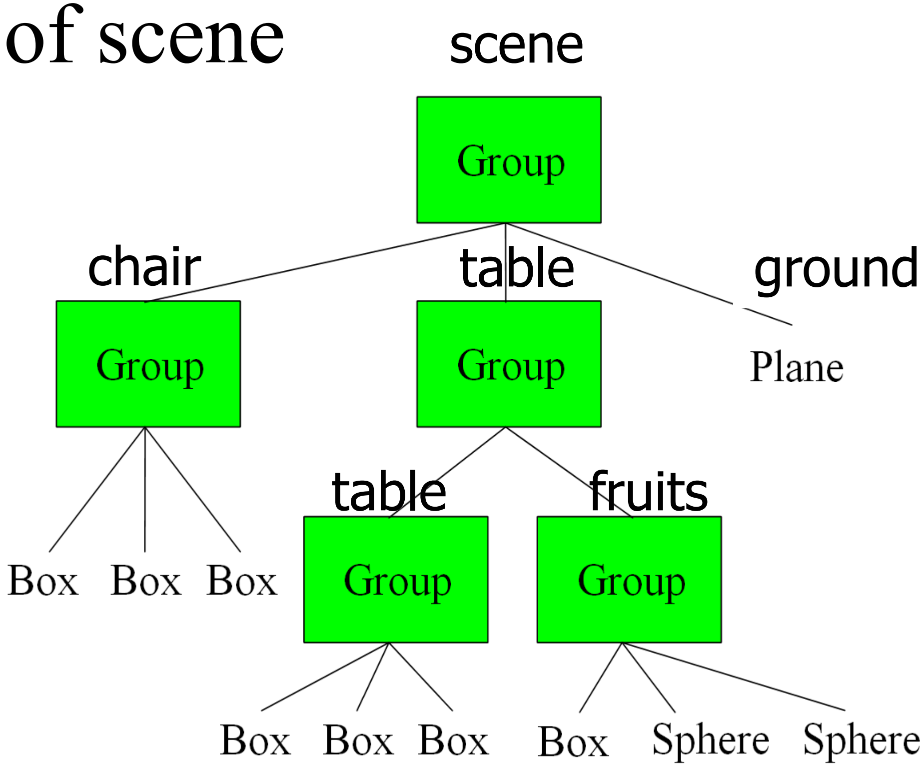


Hierarchical Grouping of Objects

The "scene graph" represents
the logical organization of scene





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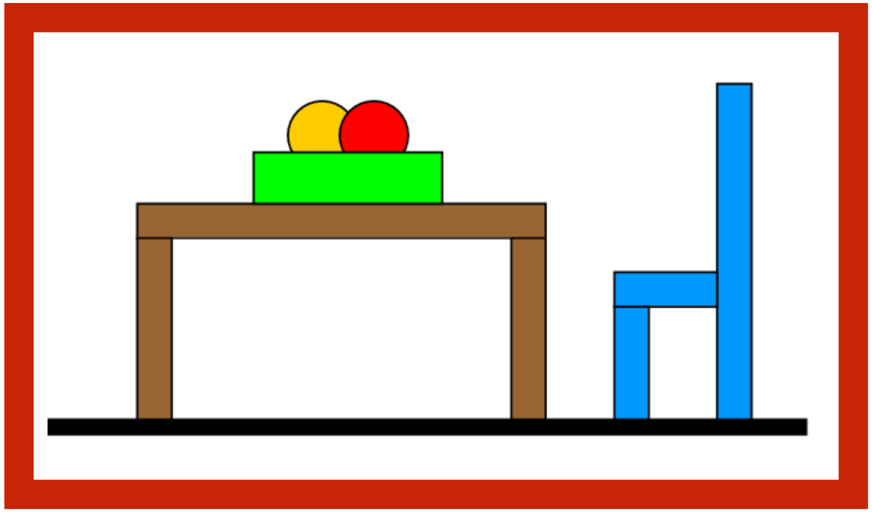

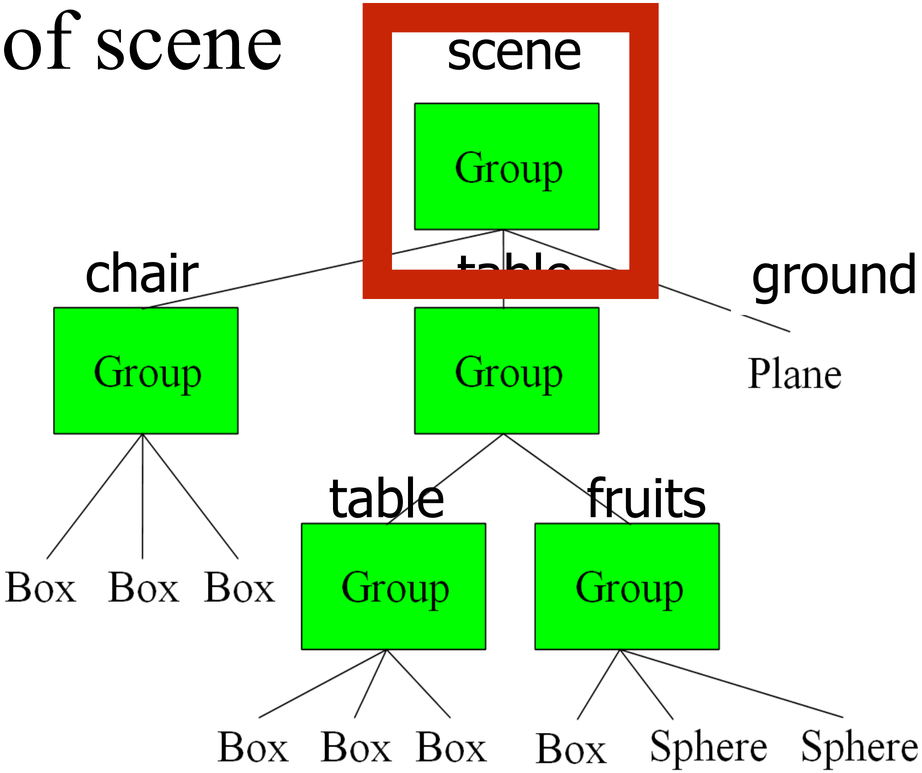

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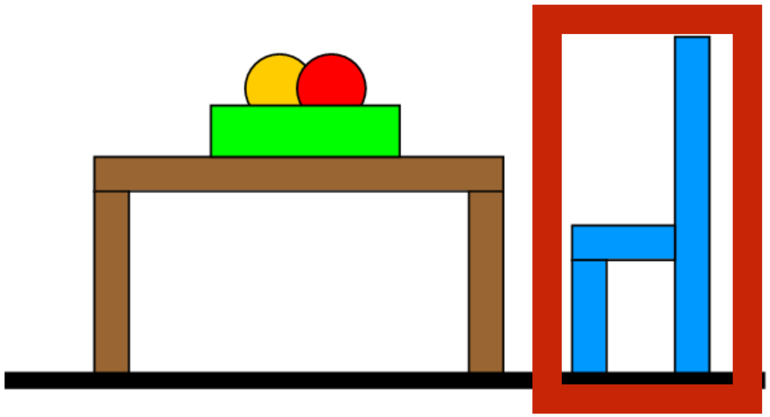

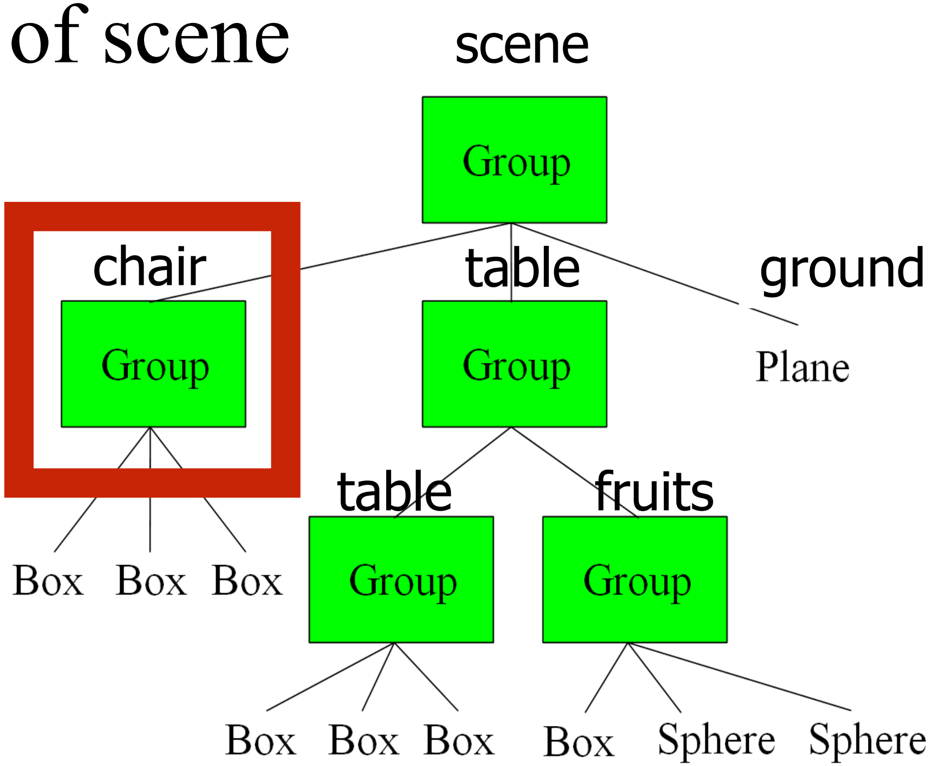

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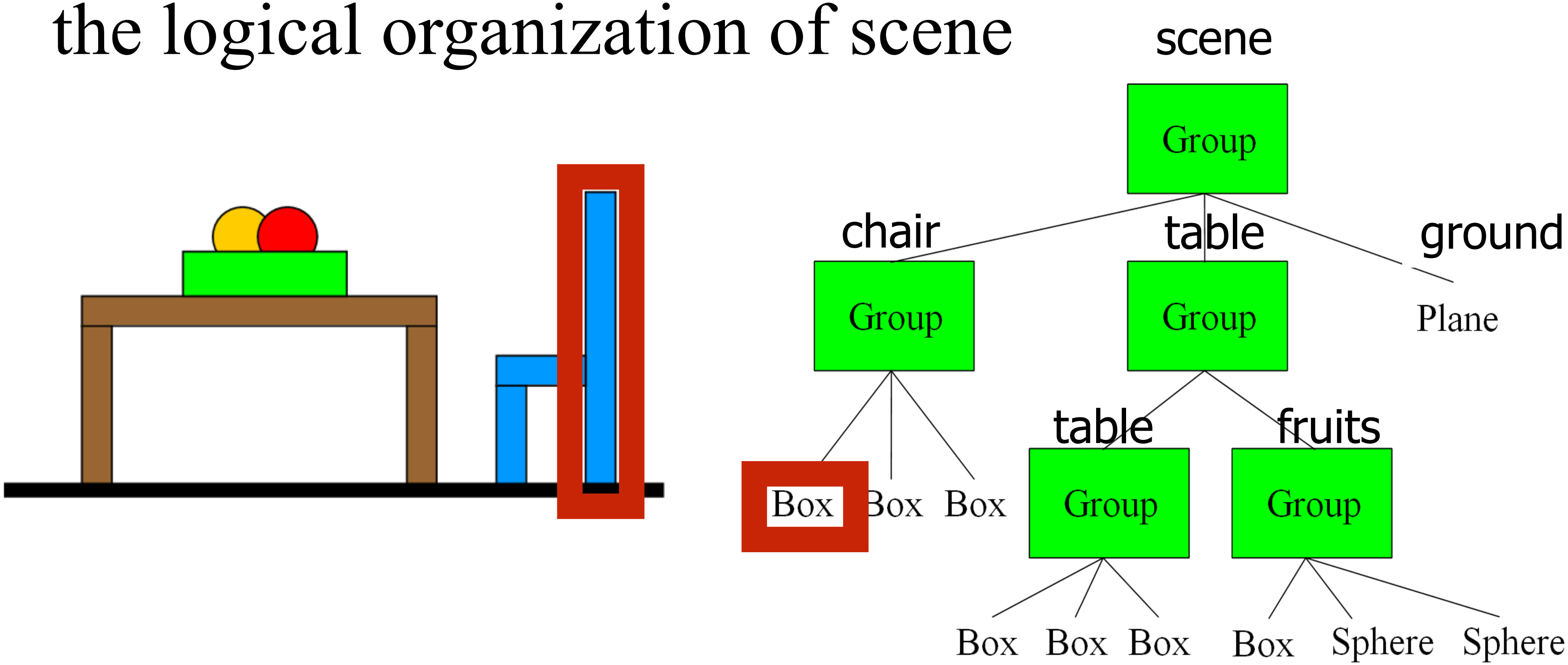

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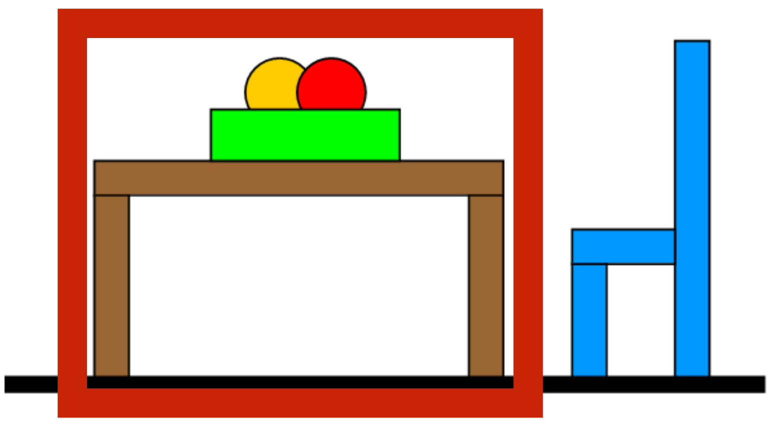
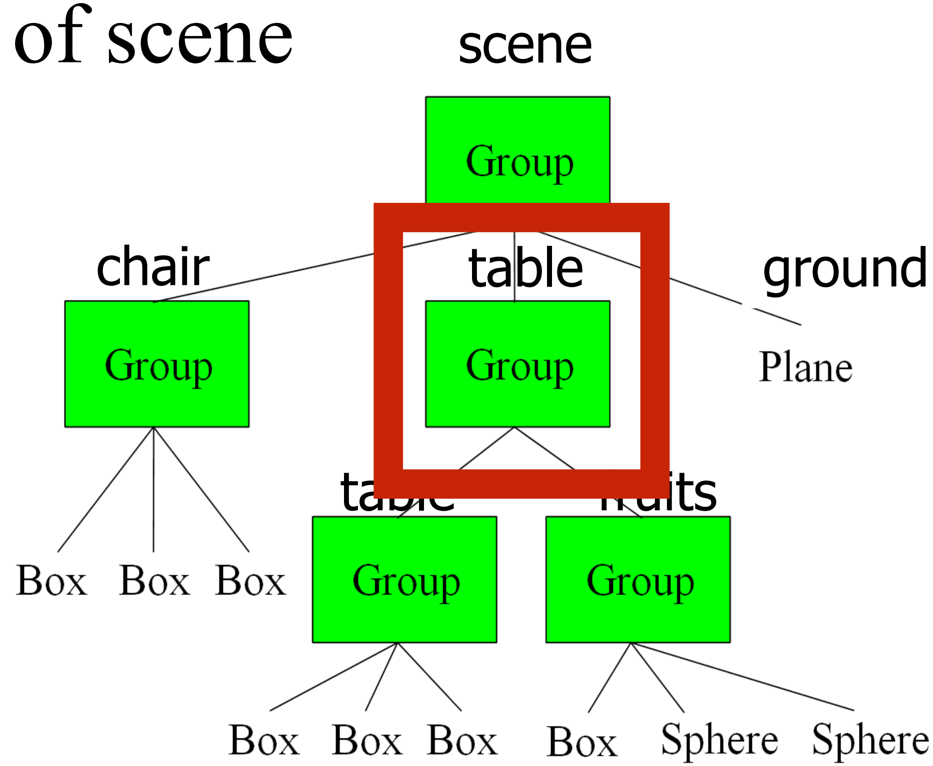
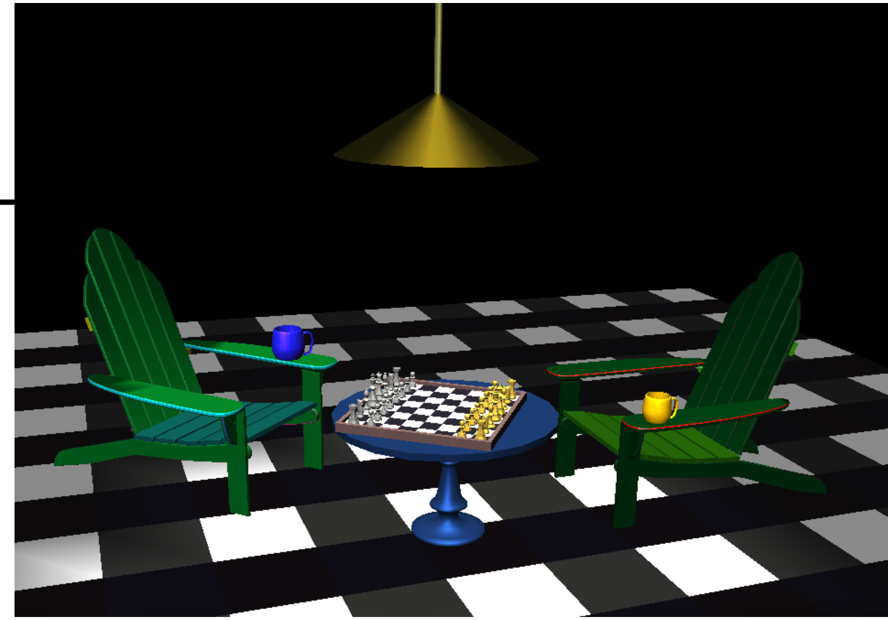


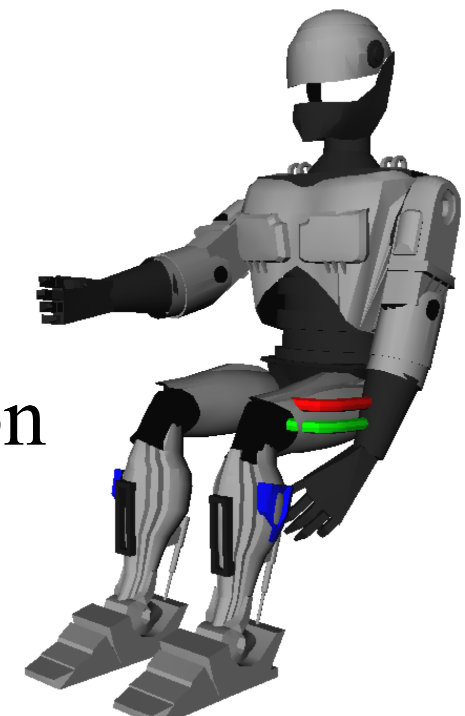


… and so on

Scene Graph

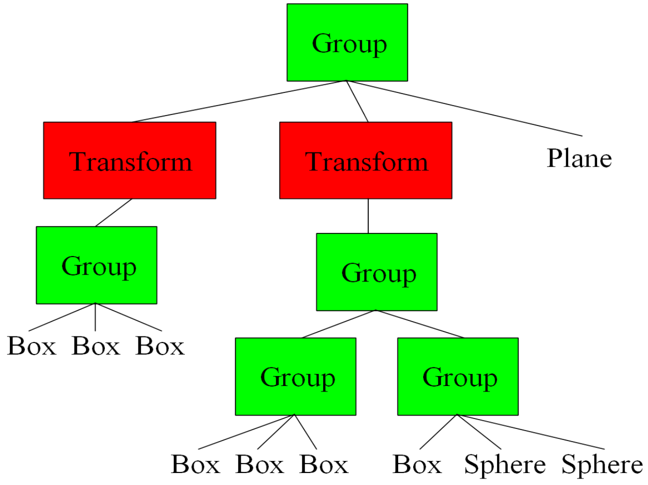


- Data structure
  for scene representation
  - **Geometry (meshes, etc.)**
  - **Transformations**
  - Materials, color
  - Multiple instances
- Basic idea: Hierarchical graph
- Useful for manipulation/animation
- And for rendering
  - Ray tracing acceleration,
    occlusion culling



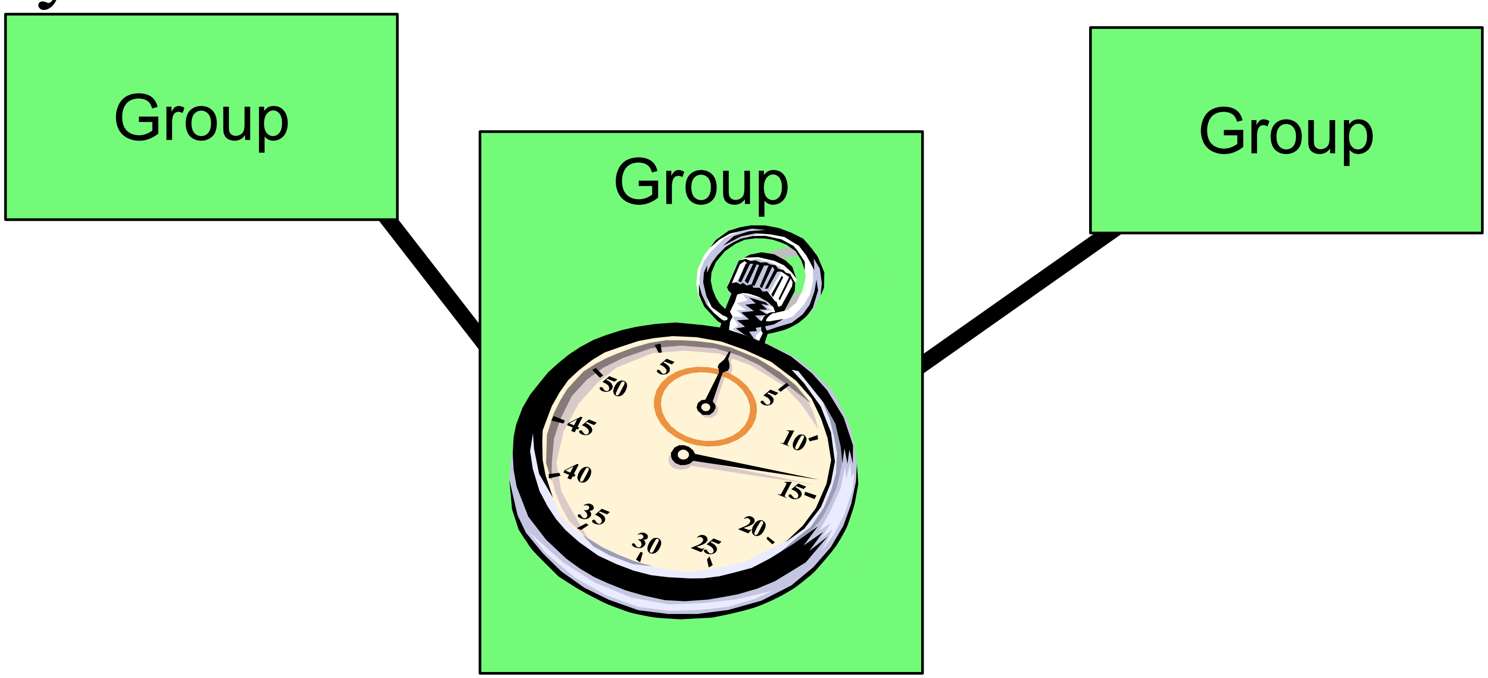
Scene Graph Representation

- Basic idea: Tree
- Comprised of several node types
  - Shape: 3D geometric objects
  - Transform: Affect current transformation
  - Property: Color, texture, transparency, etc.
  - Group: Collection of subgraphs
- C++ implementation
  - base class Object
    - child list (no parent!)
  - derived classes for each node type (group, geometry, etc.)



Scene Graph Representation

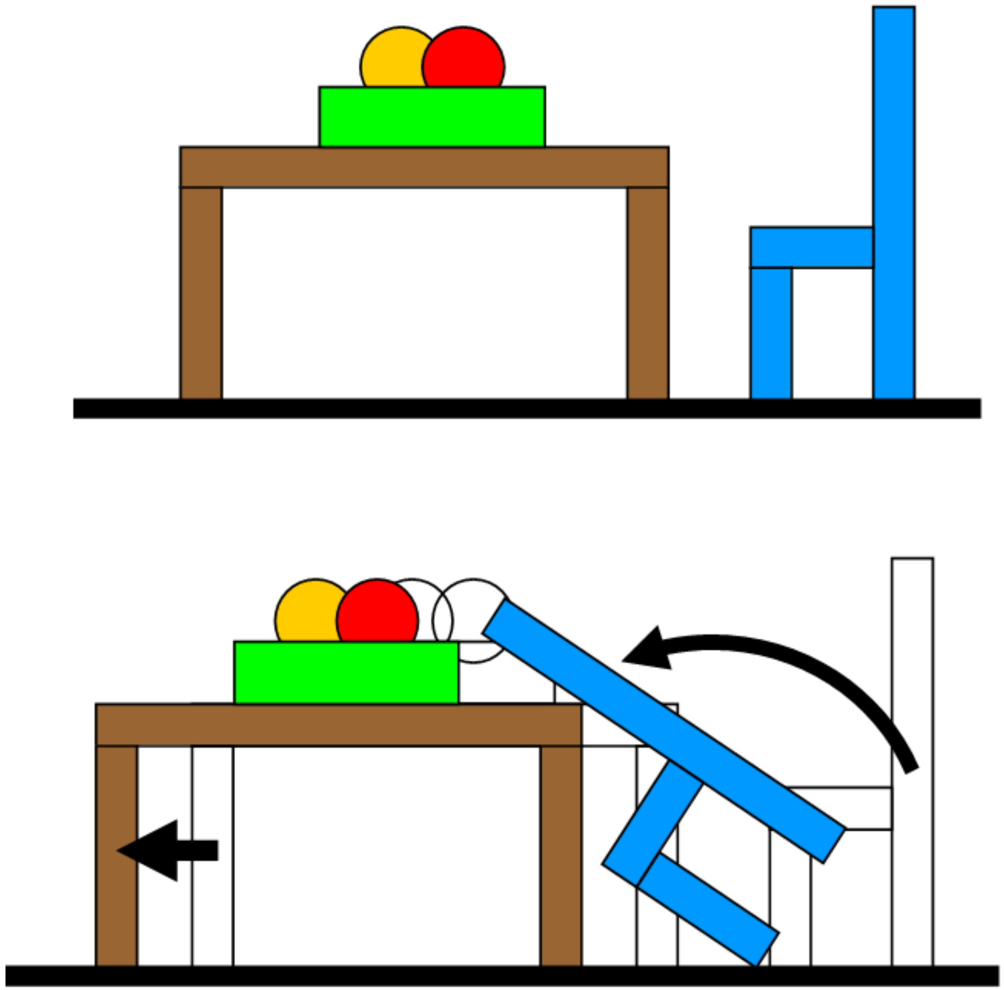
- In fact, generalization of a tree:
  Directed Acyclic Graph (DAG)
  – Means a node can have multiple parents, but cycles are not allowed
- Why?



Scene Graph Representation

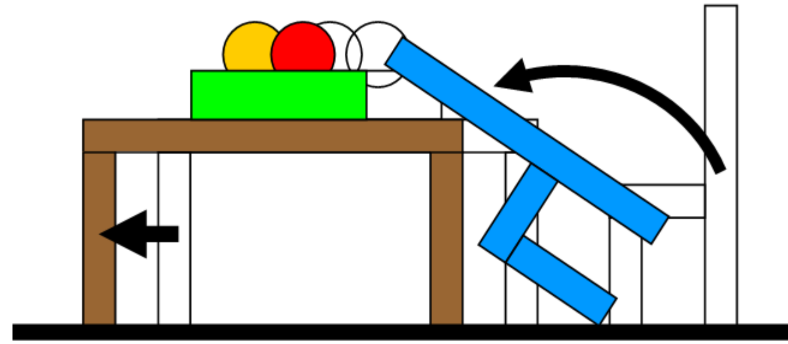
- In fact, generalization of a tree:
  Directed Acyclic Graph (DAG)
  - Means a node can have multiple parents, but cycles are not allowed
- Why? Allows *multiple instantiations*
  - "Several copies of the same object in different locations and orientations"
  - Reuse complex hierarchies many times in the scene using different transformations & other properties

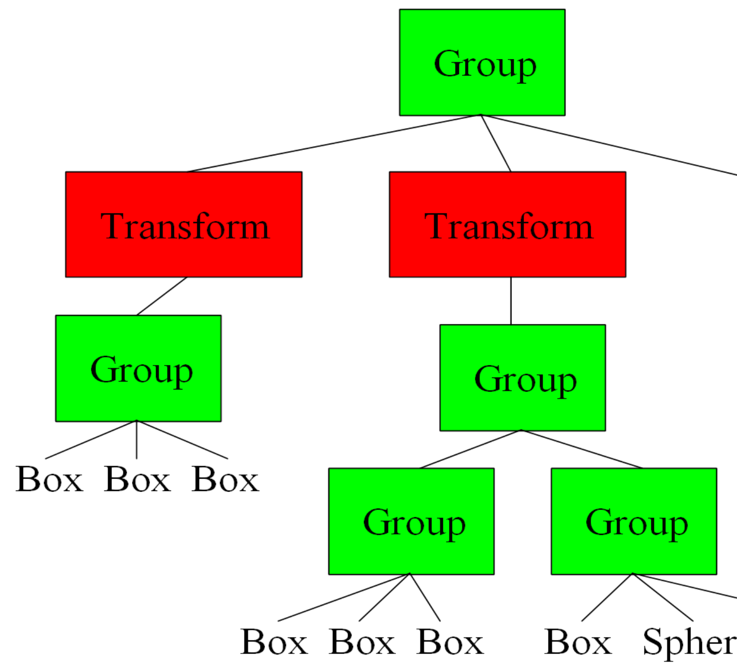
Adding Transformations



Hierarchical Transformation of

- A "transformation node" affects the whole subtree
- Each node has its local coordinate system
- Transformations are always specified relative to parent!
- Aggregate object-to-world transform is the concatenation of all transforms on the way from current node to root





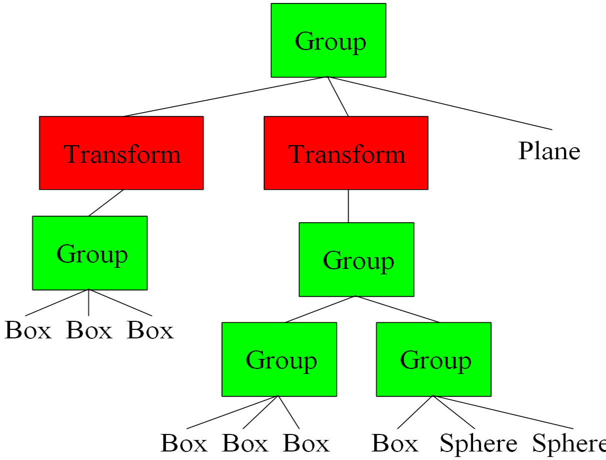
Sidenote

- **In practice**, we most often specify a transformation for **all nodes** and don’t explicitly use special “transformation nodes”
  - Concretely: the “Node” base class contains a Mat4f!
  - It’s the UI’s job to manage that so that it’s intuitive
  - But only do this once you’ve wrapped your head around the simpler concept

Scene Graph Traversal

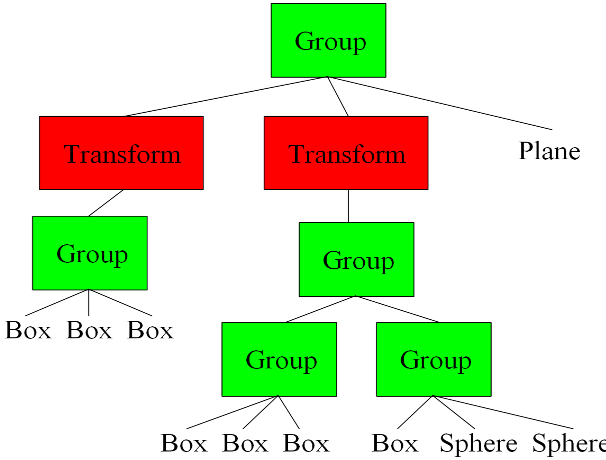
- Depth first recursion
  - Visit node, then subtrees (top to bottom, left to right)
  - When visiting a geometry node: Draw it!

- How to handle transformations?
  - Transformations always specified in coordinate system of the parent

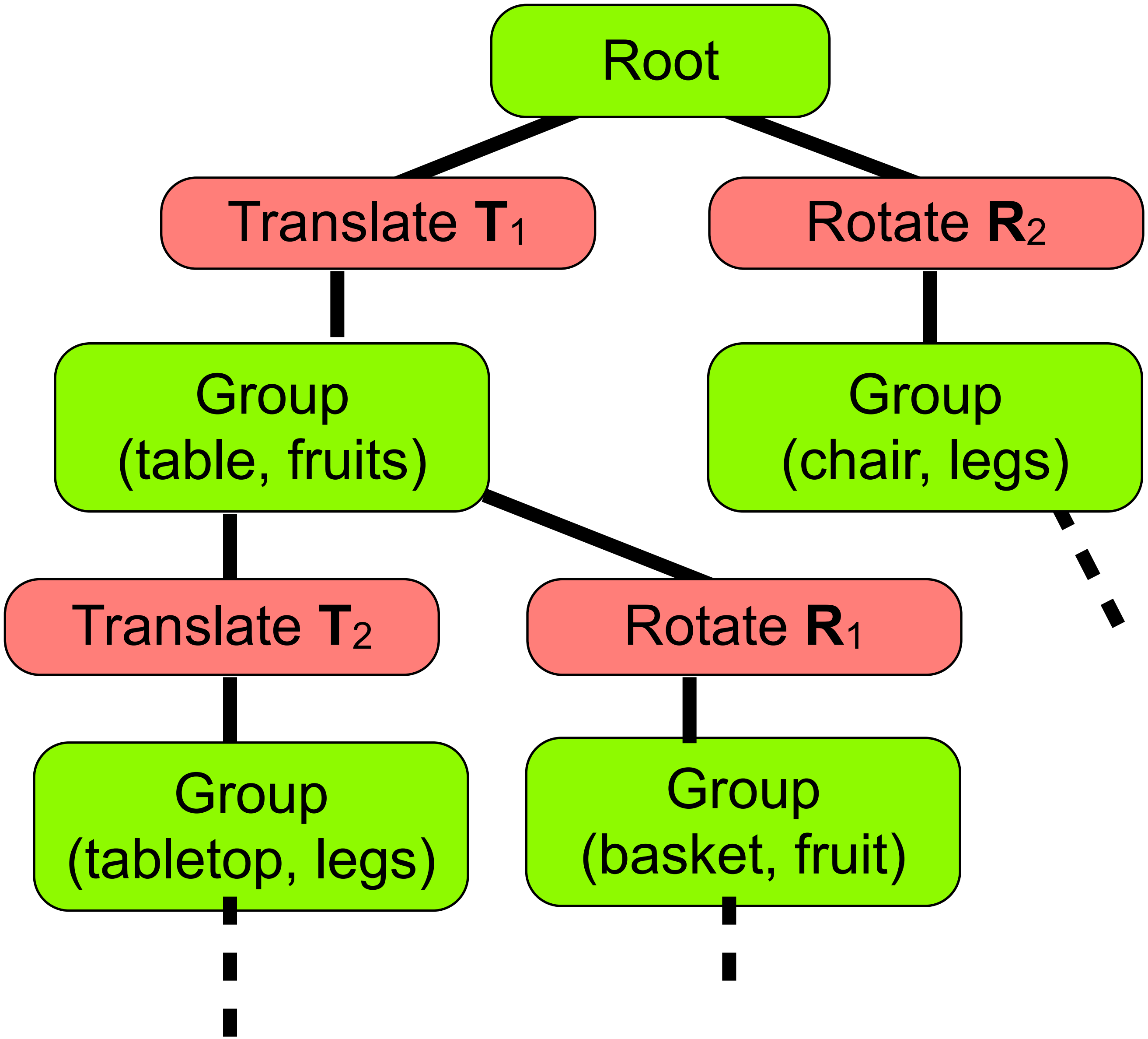


Scene Graph Traversal

- How to handle transformations?
  - Traversal algorithm keeps a **transformation state S**
    - a 4x4 matrix initialized to identity **I** in the beginning
  - Geometry nodes always drawn using current **S**
  - When visiting a transformation node **T**: multiply current state **S** with **T**, then visit child nodes
    - Has the effect that nodes below will have new transformation
  - When all children have been visited, **undo the effect of T!**



Traversal Example



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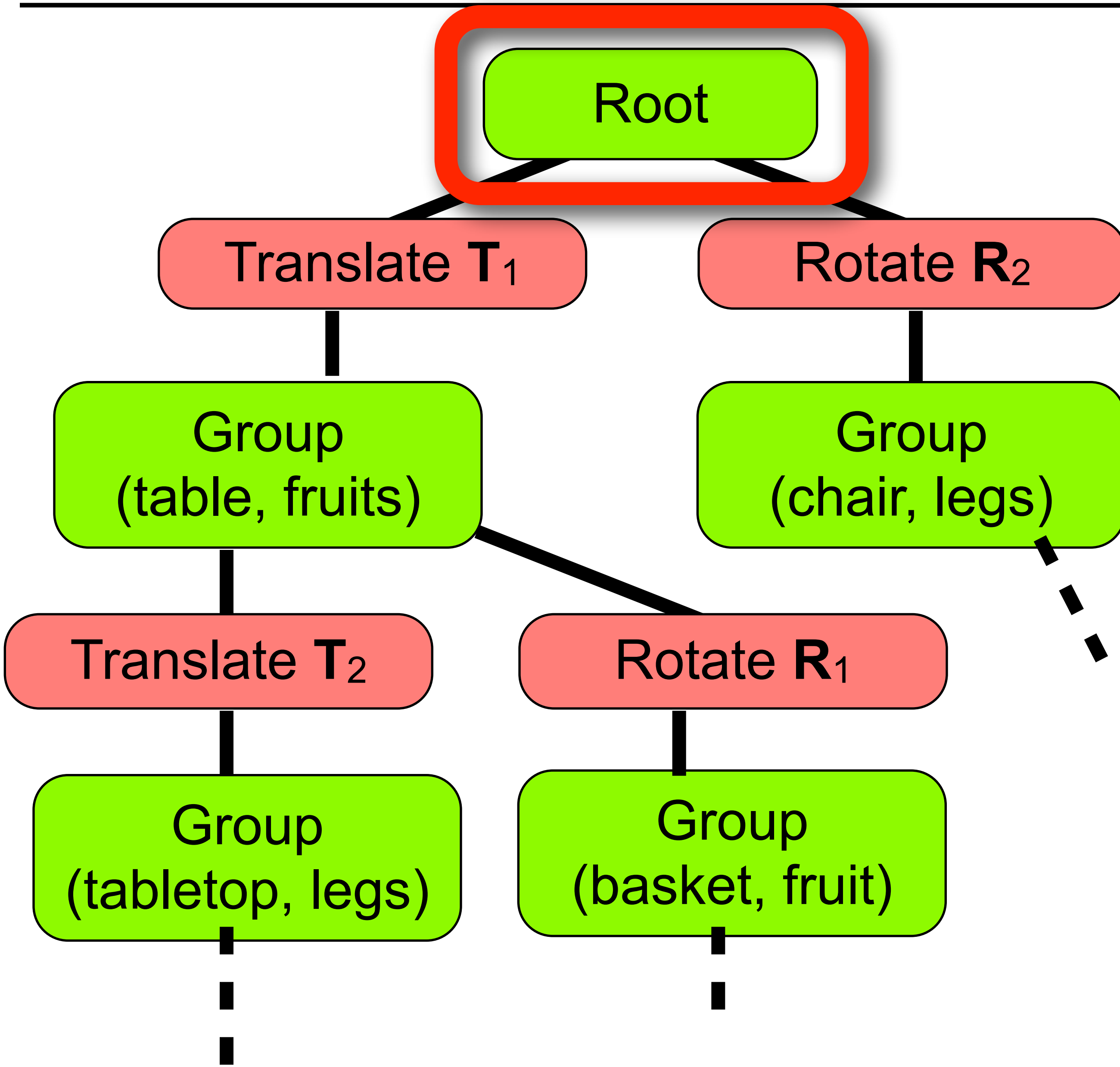
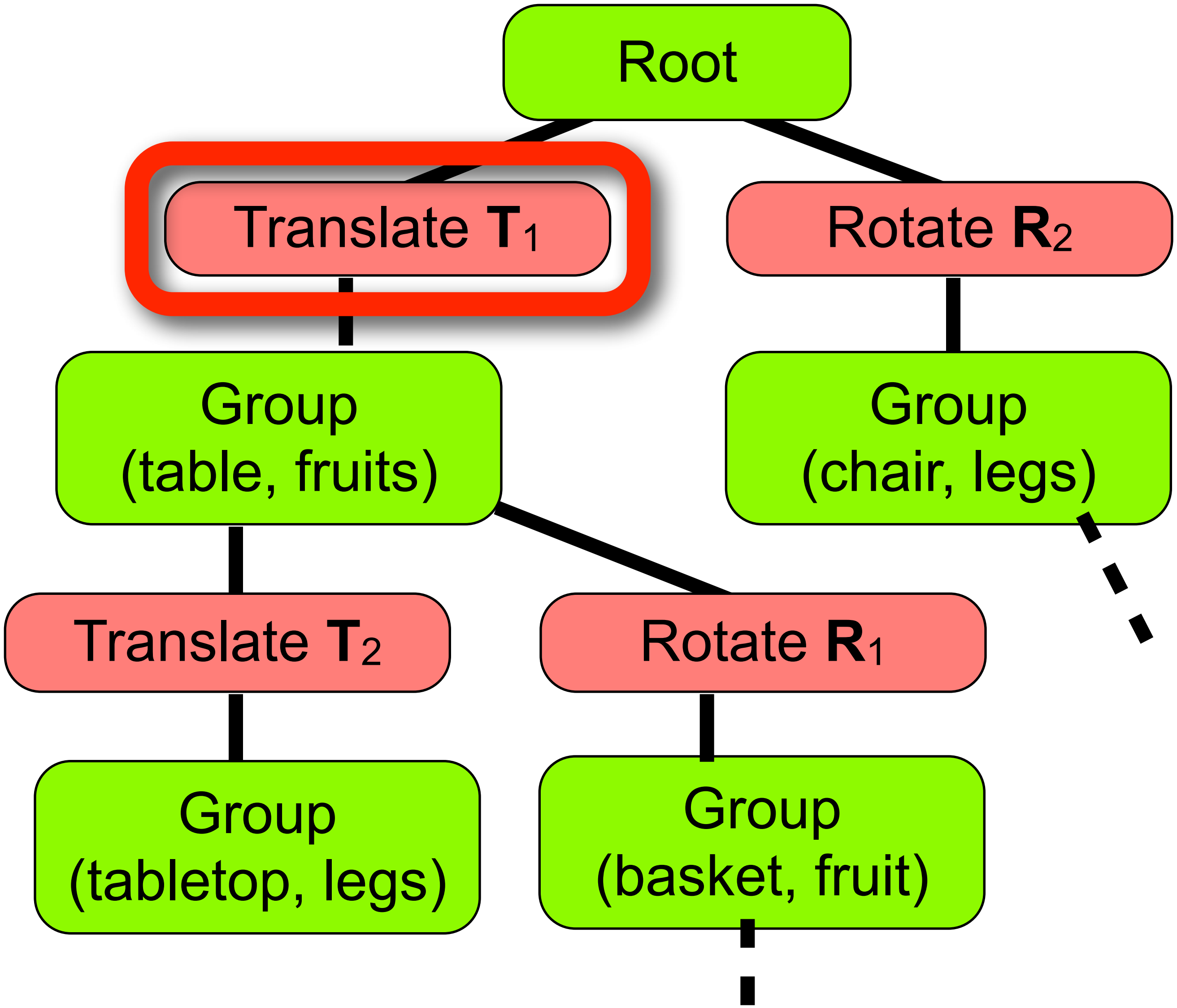


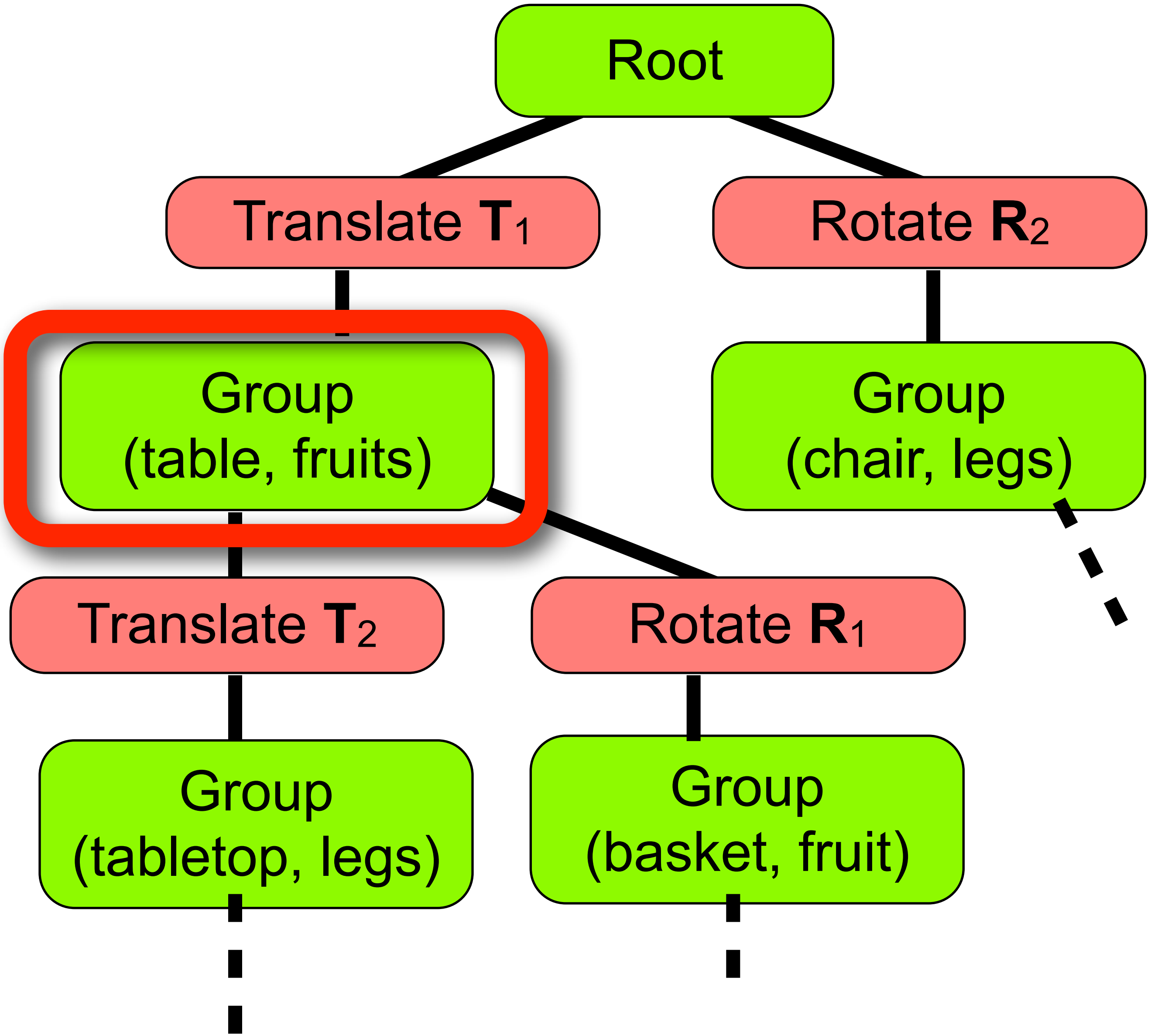
S = **I**

Traversal Example



$\mathbf{S} = \mathbf{T}_1$

Traversal Example



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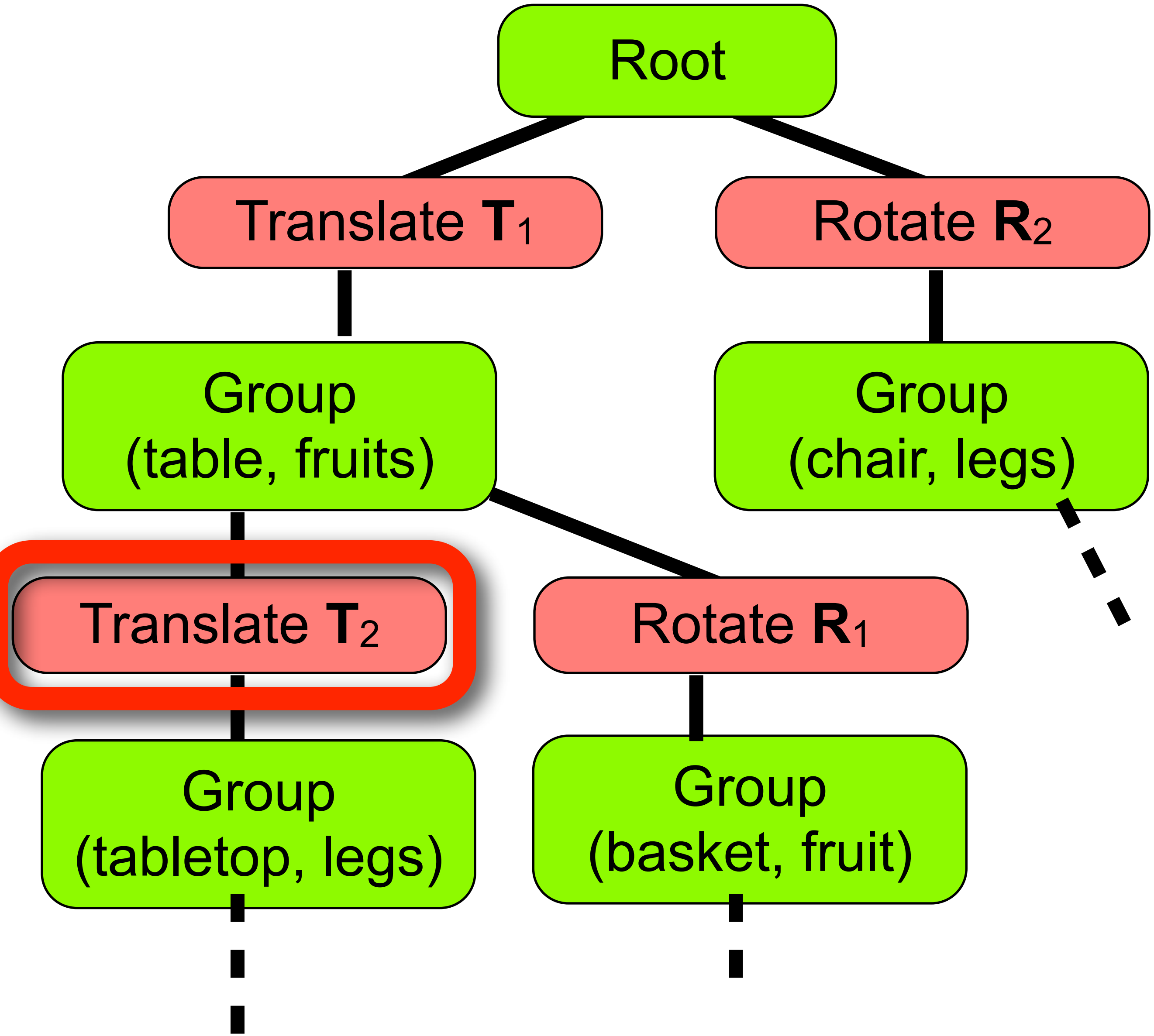
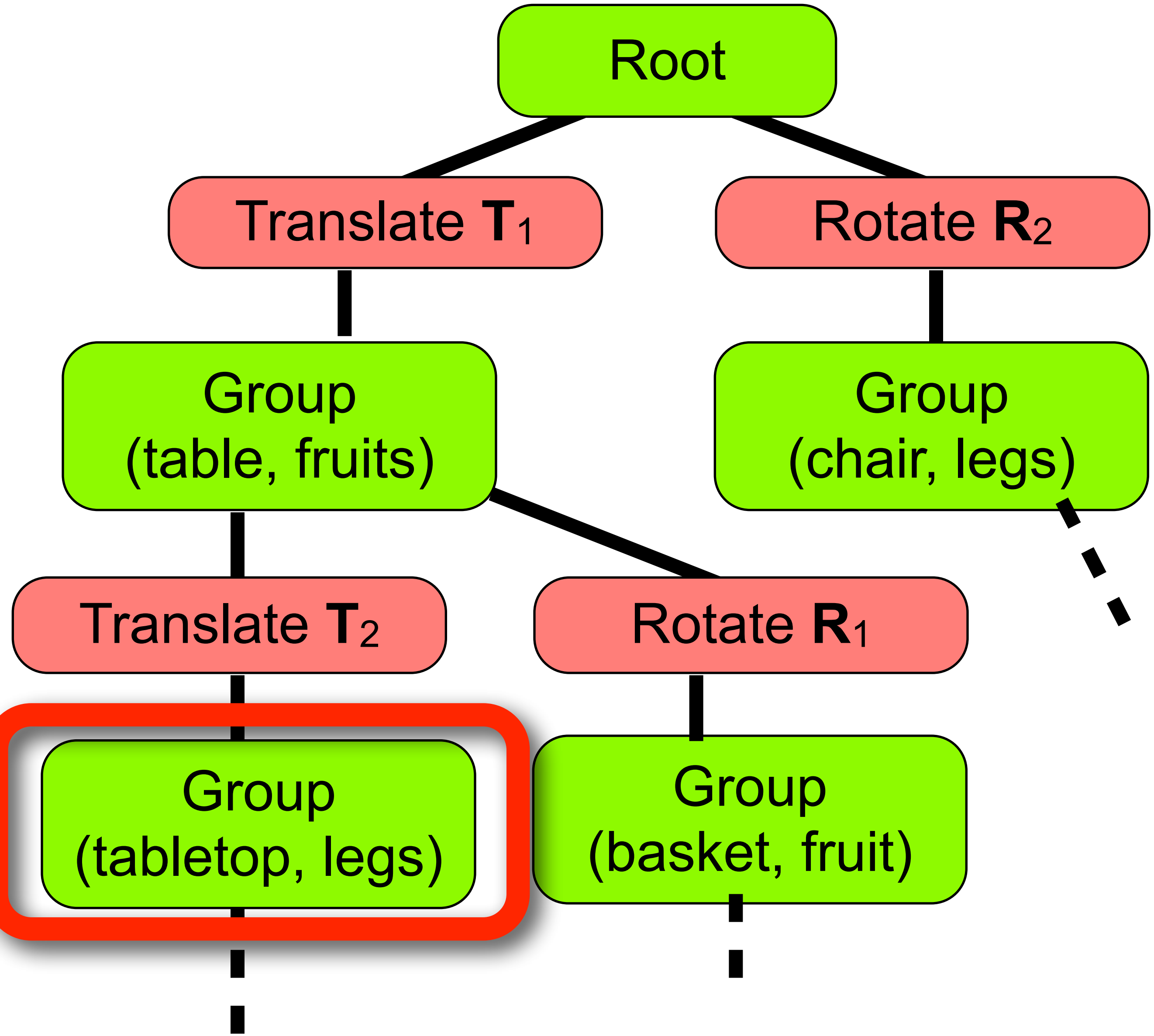


$$S = T_1\ T_2$$

Traversal Example



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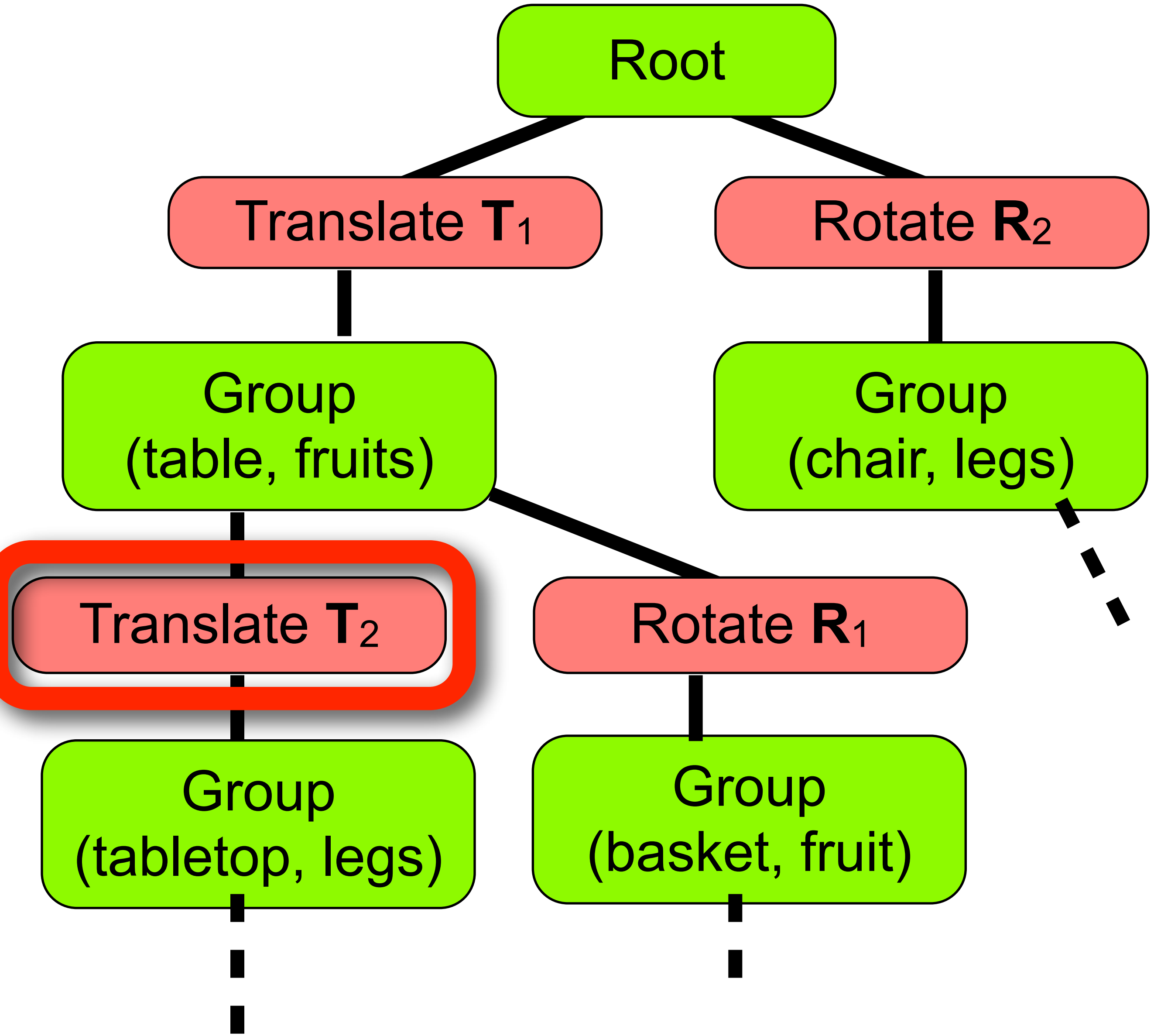

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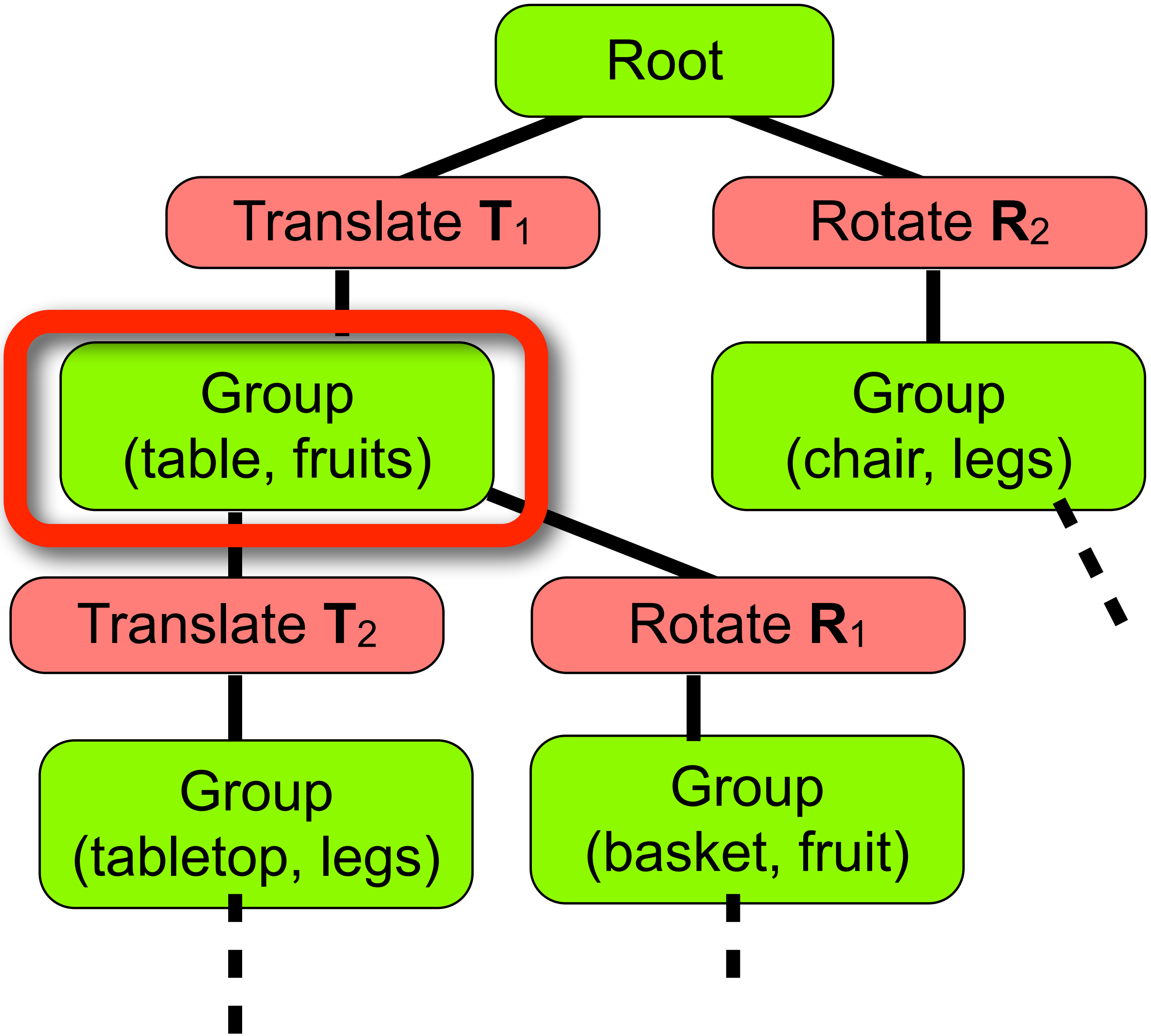

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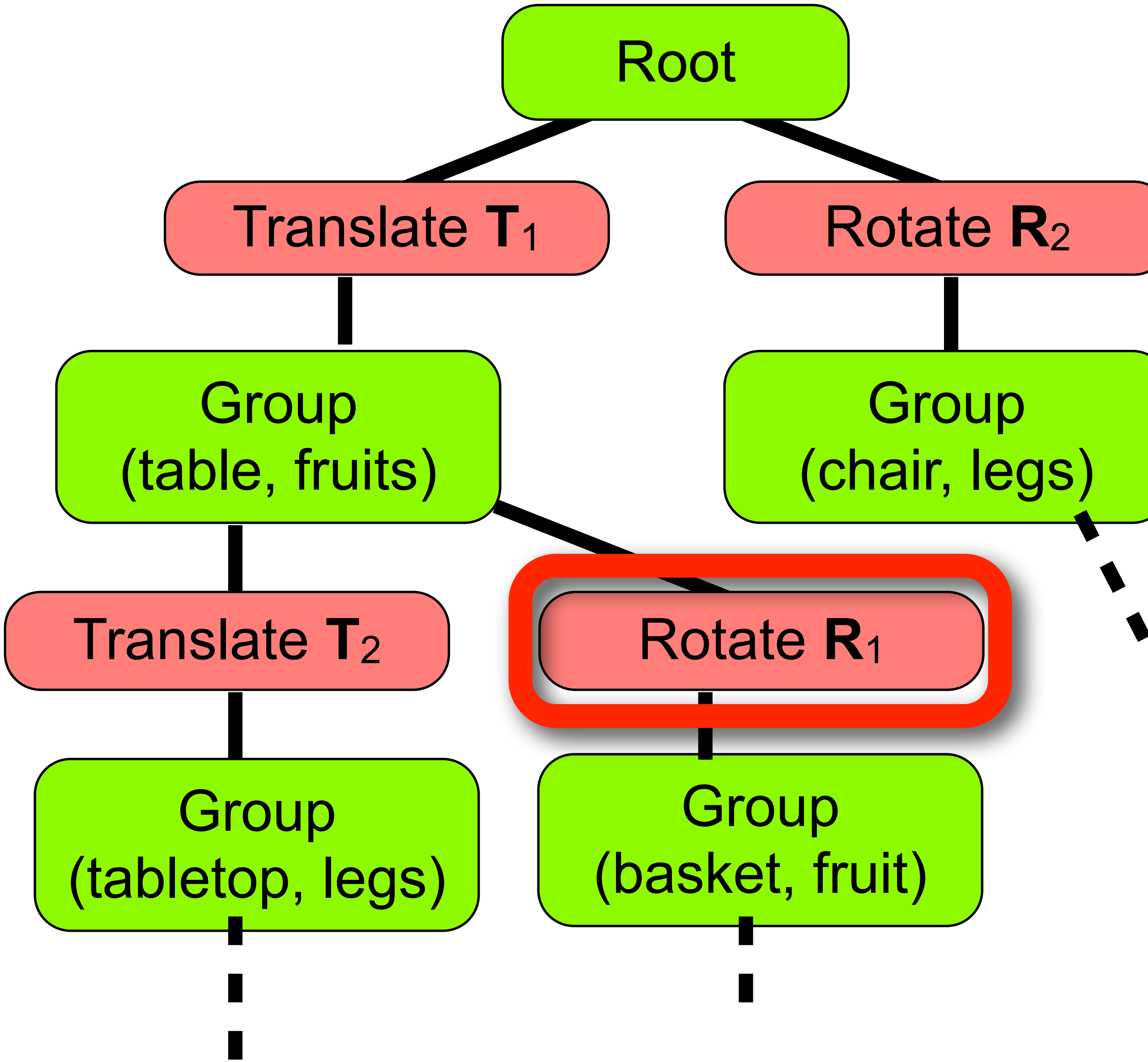

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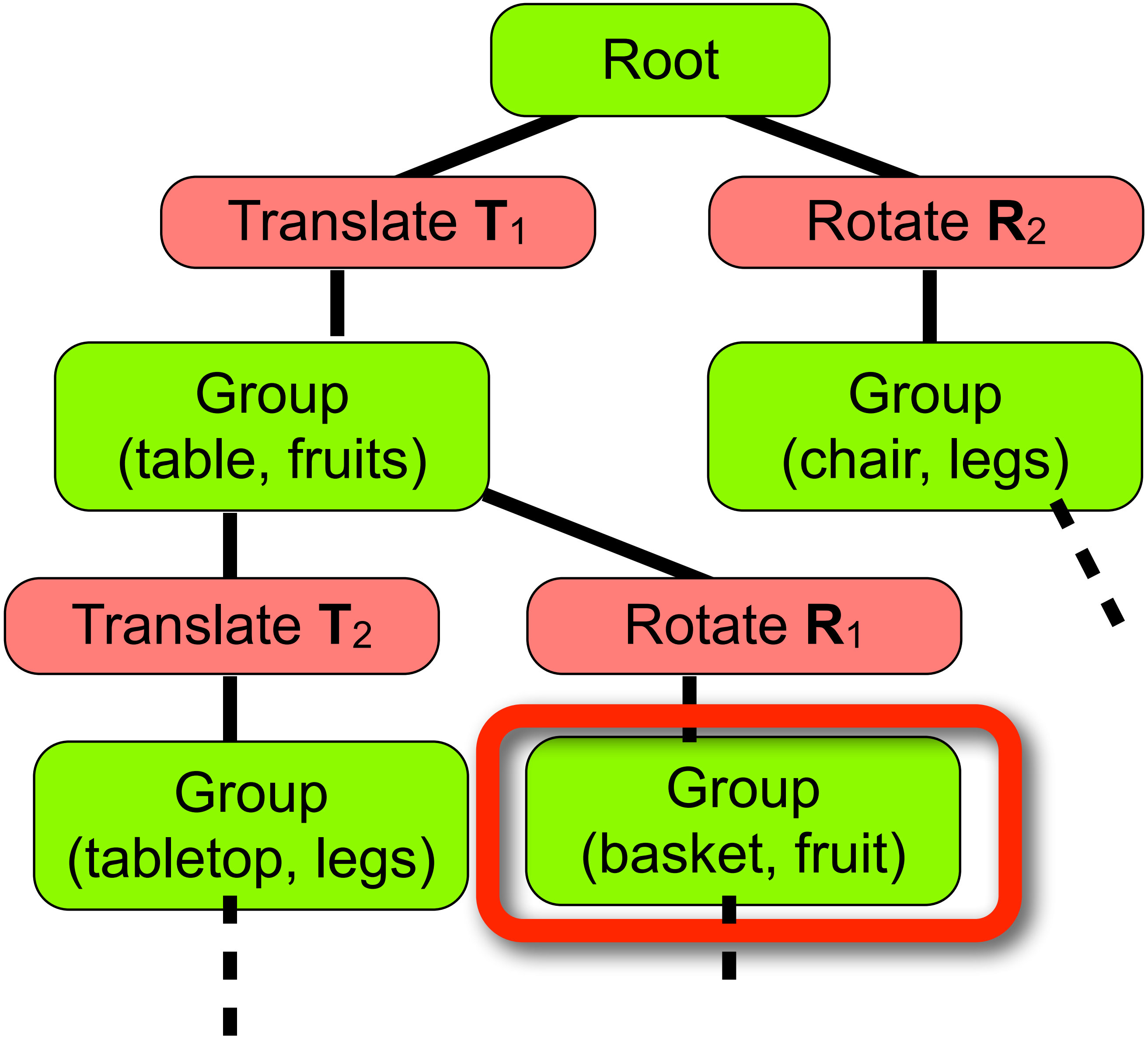

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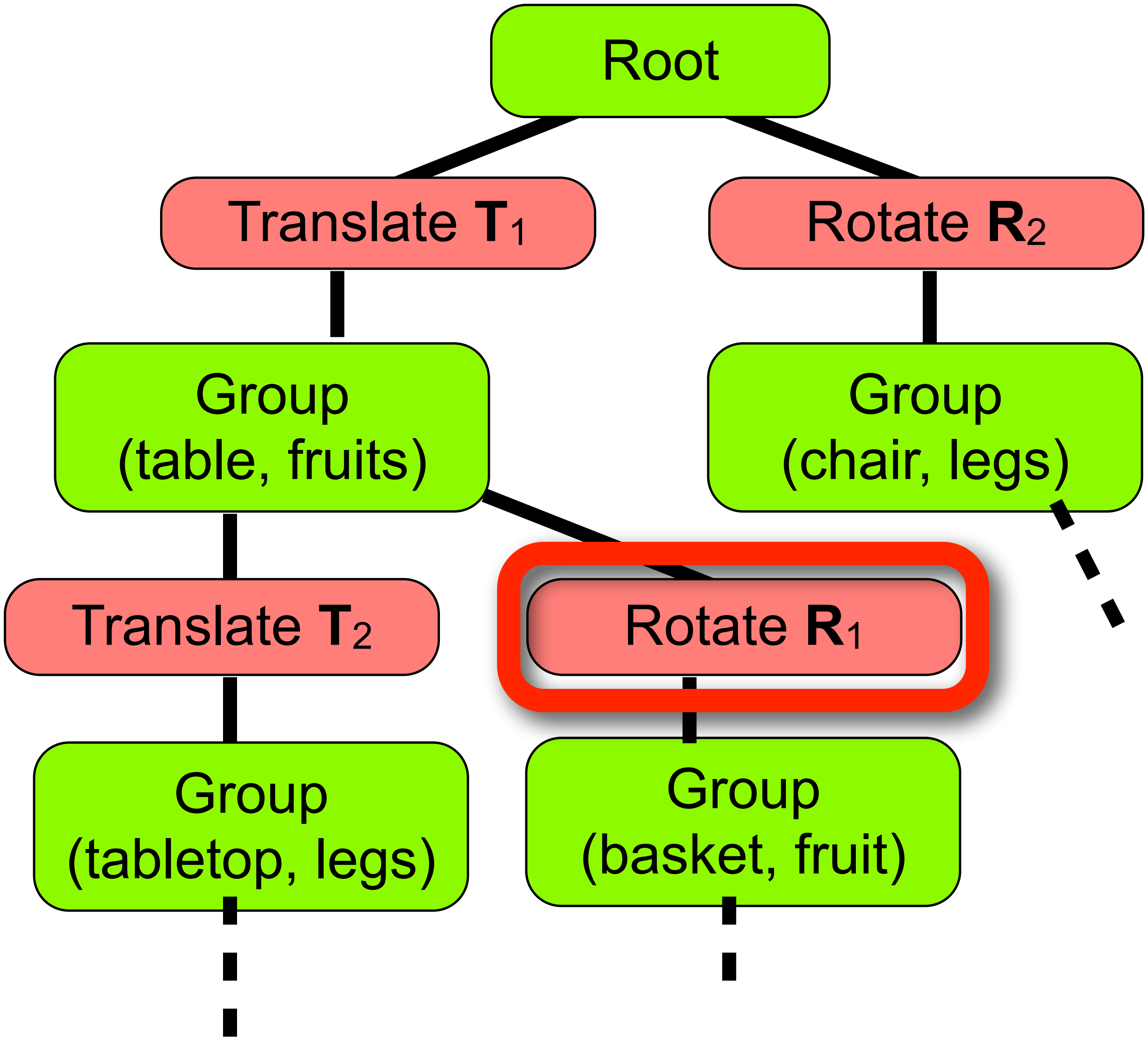
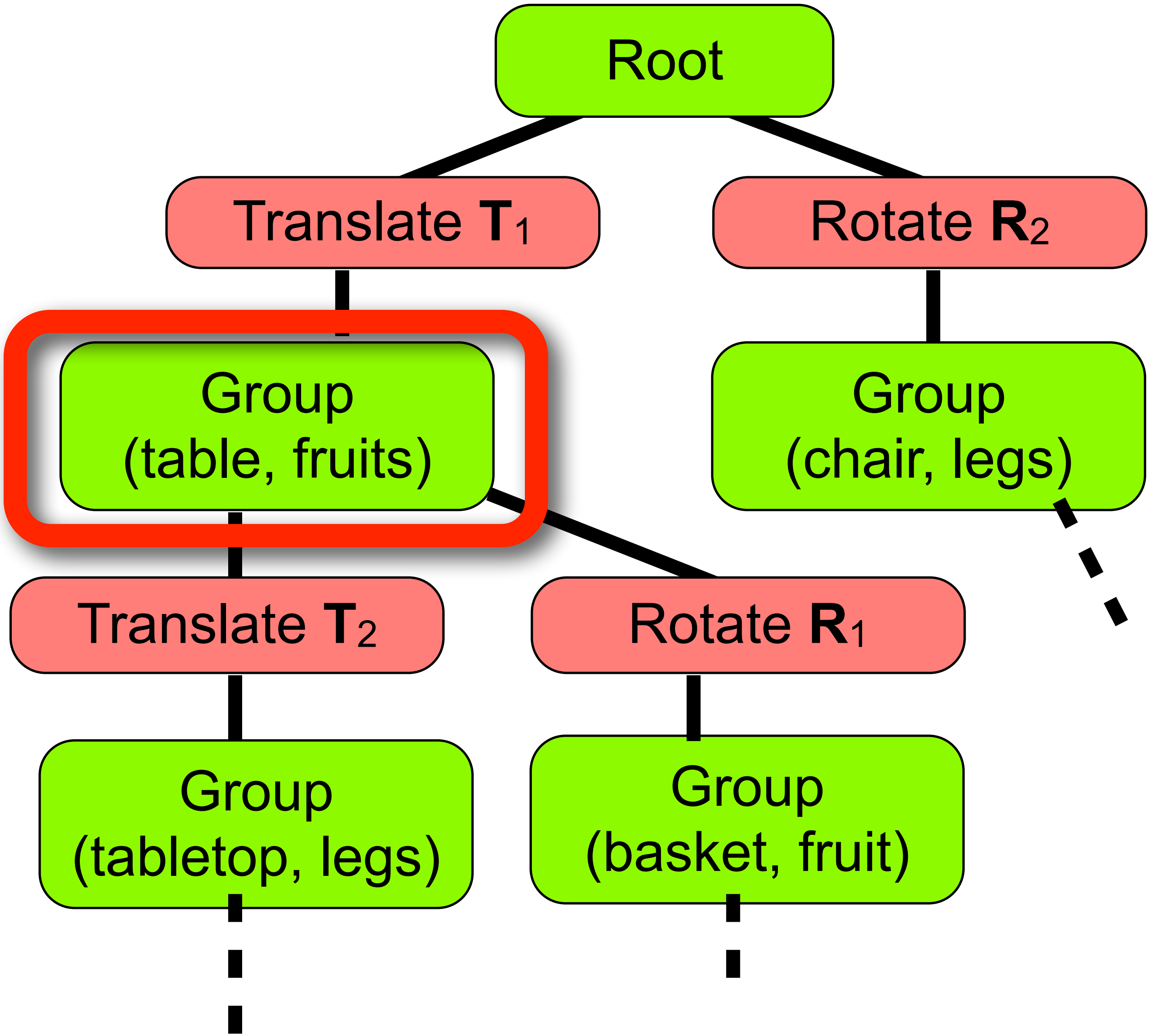


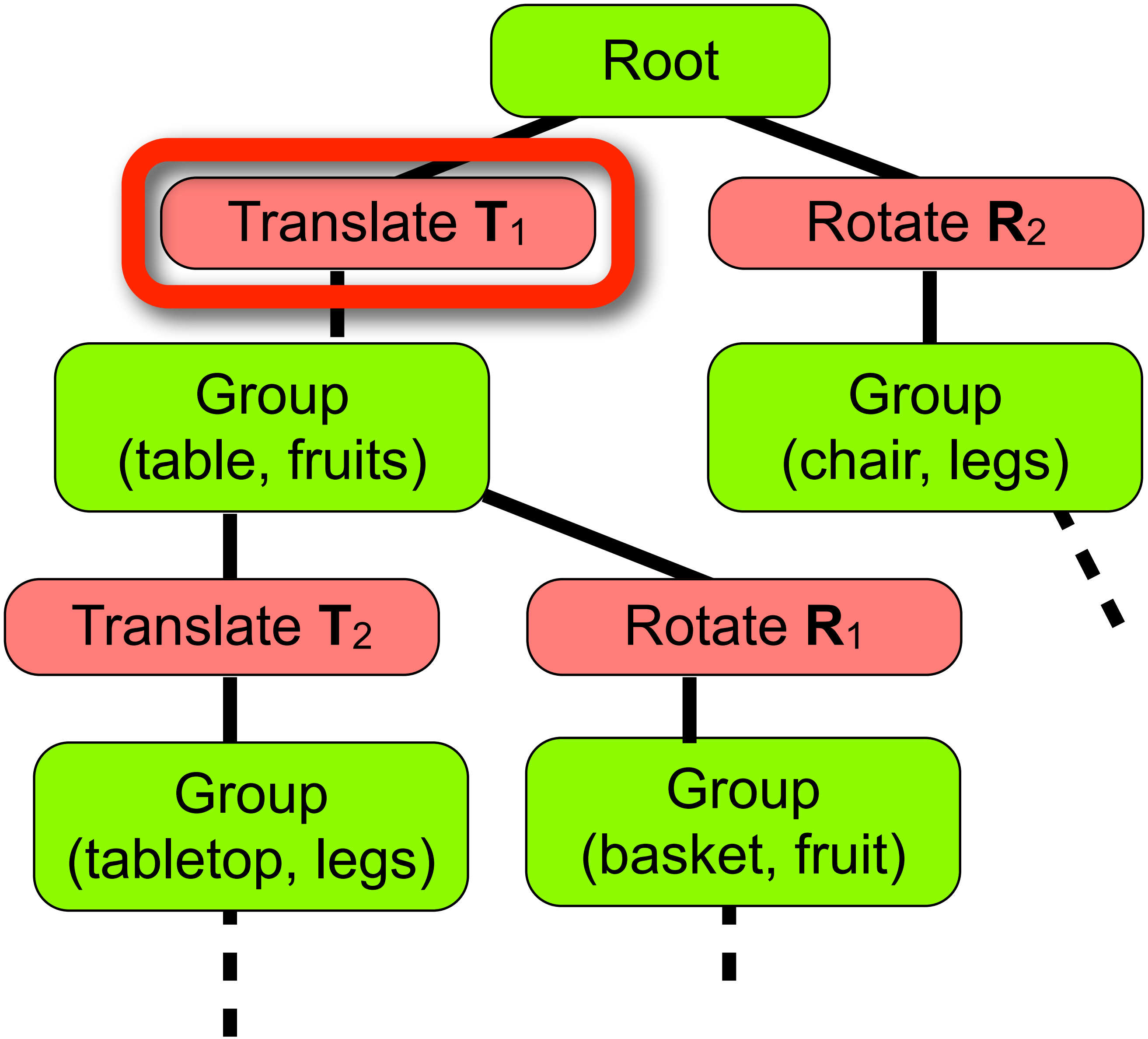
$$S = T_1 R_1$$

Traversal Example



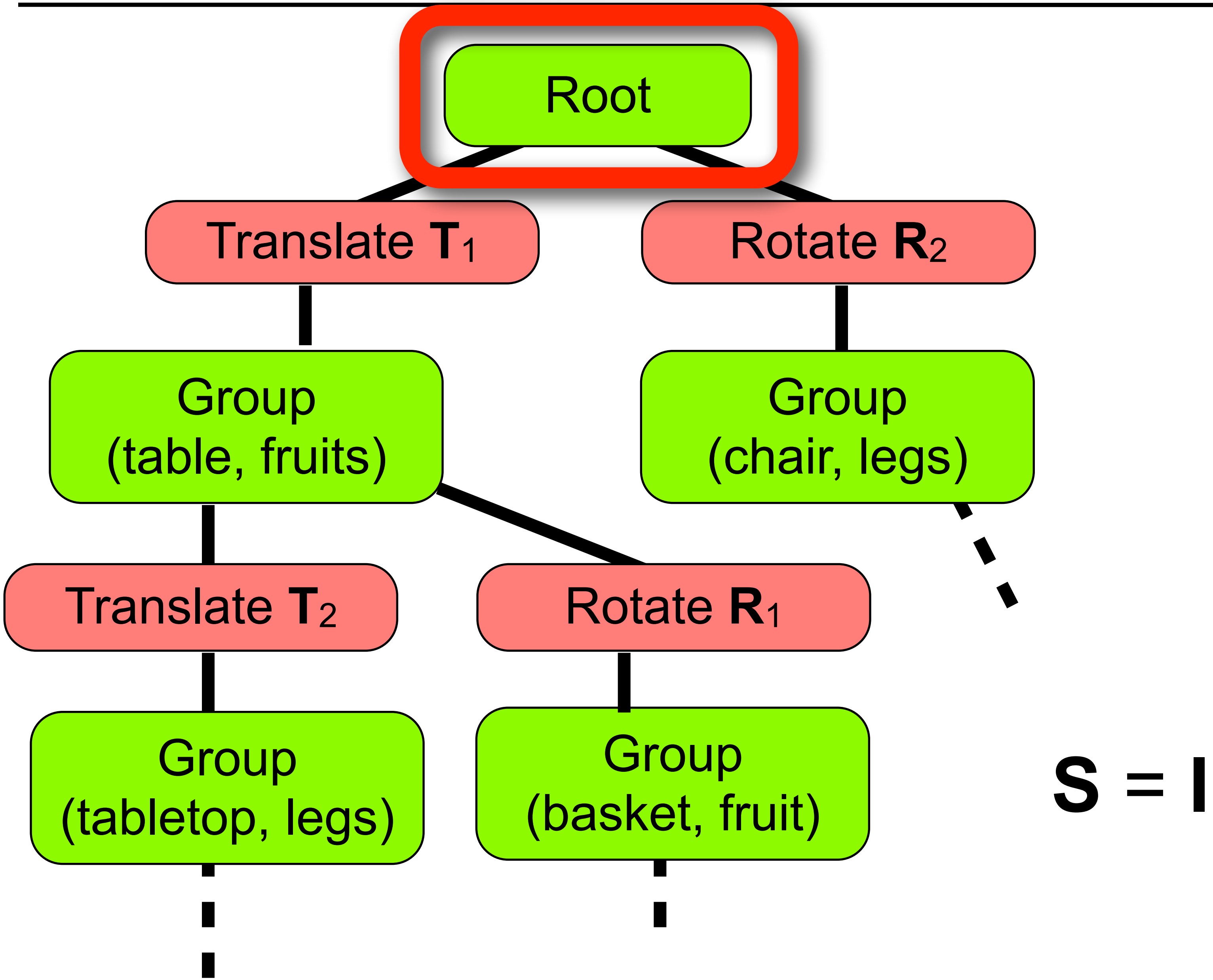
$S = T_1$

Traversal Example



$S = T_1$

Traversal Example



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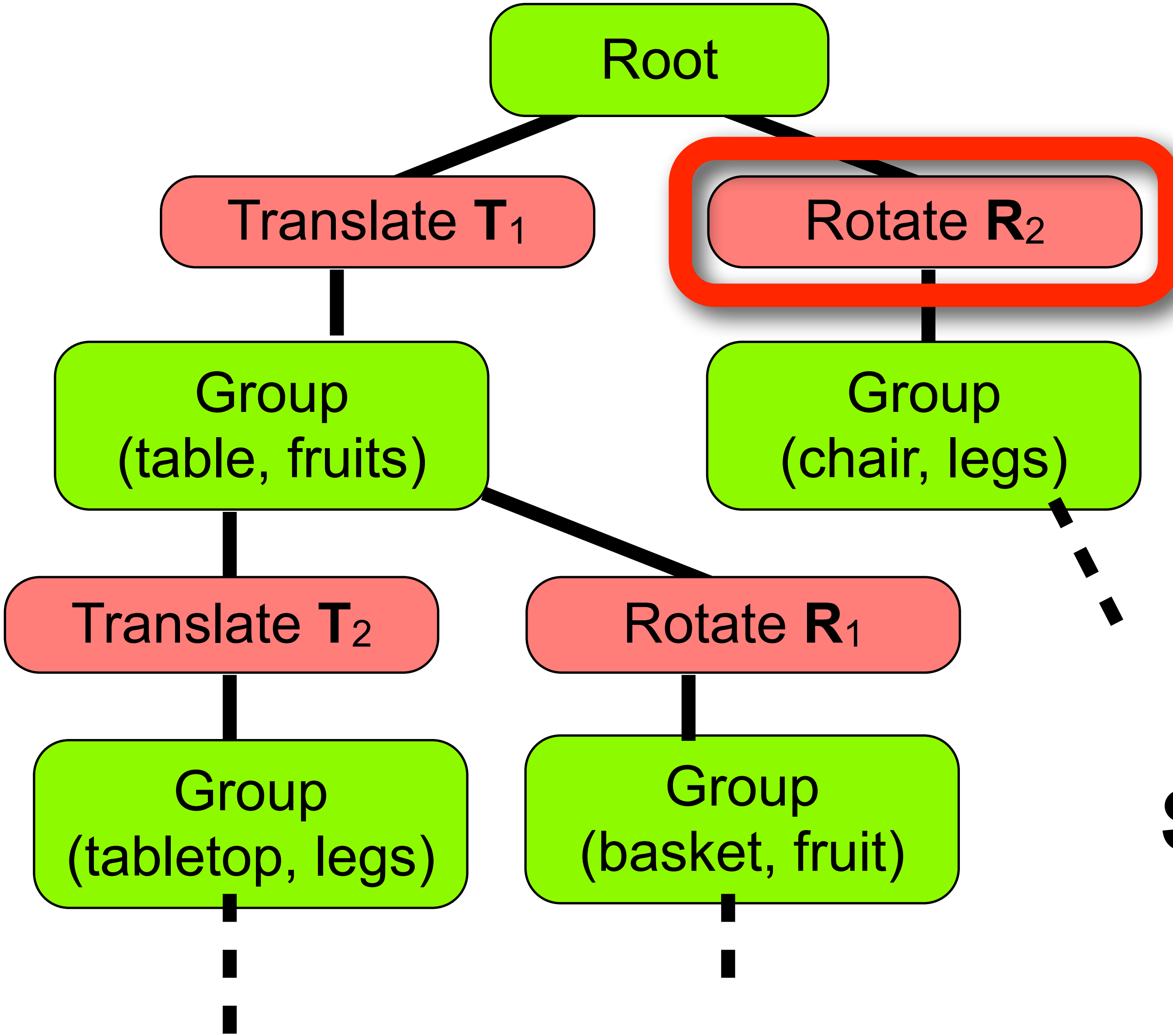
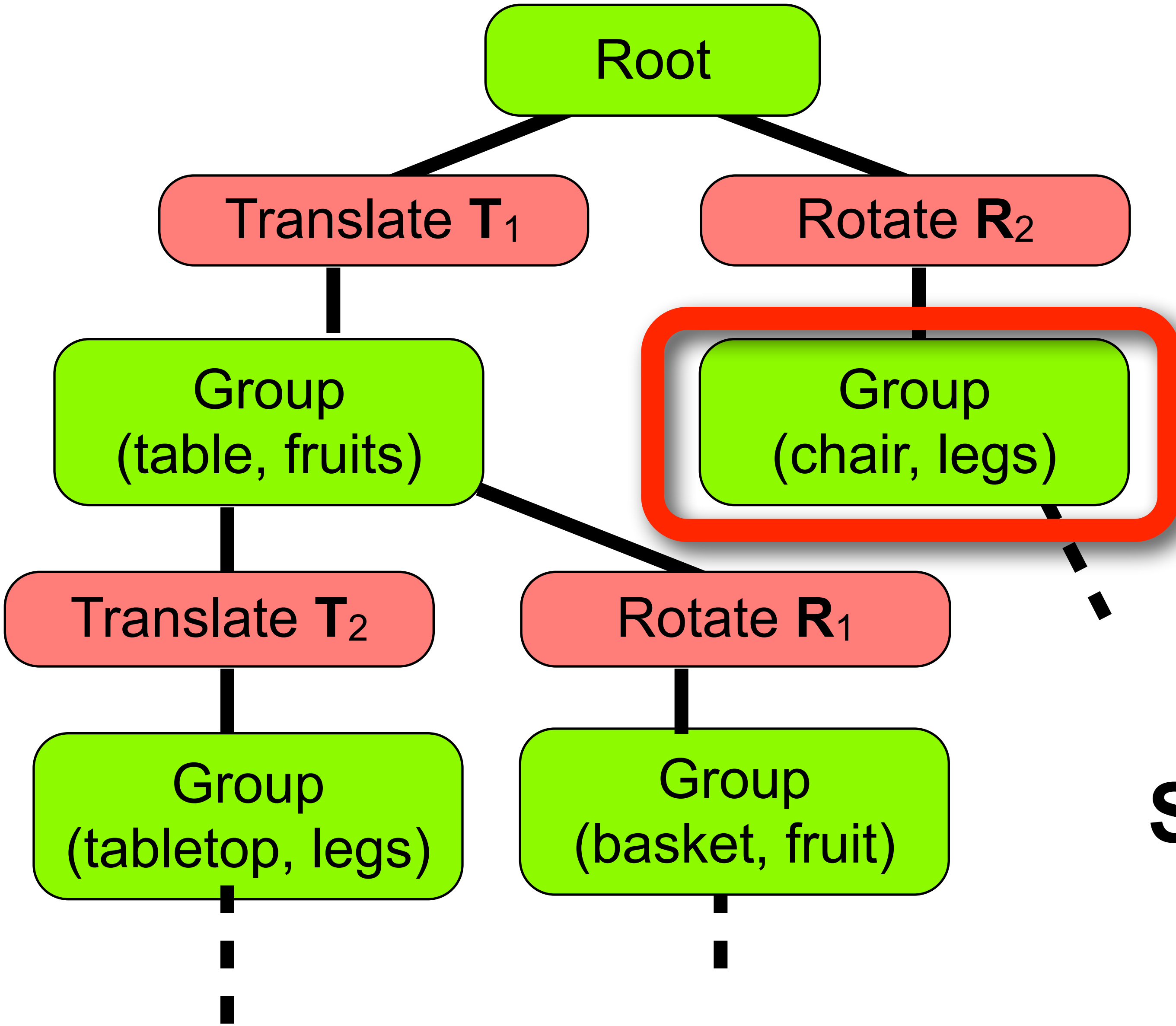


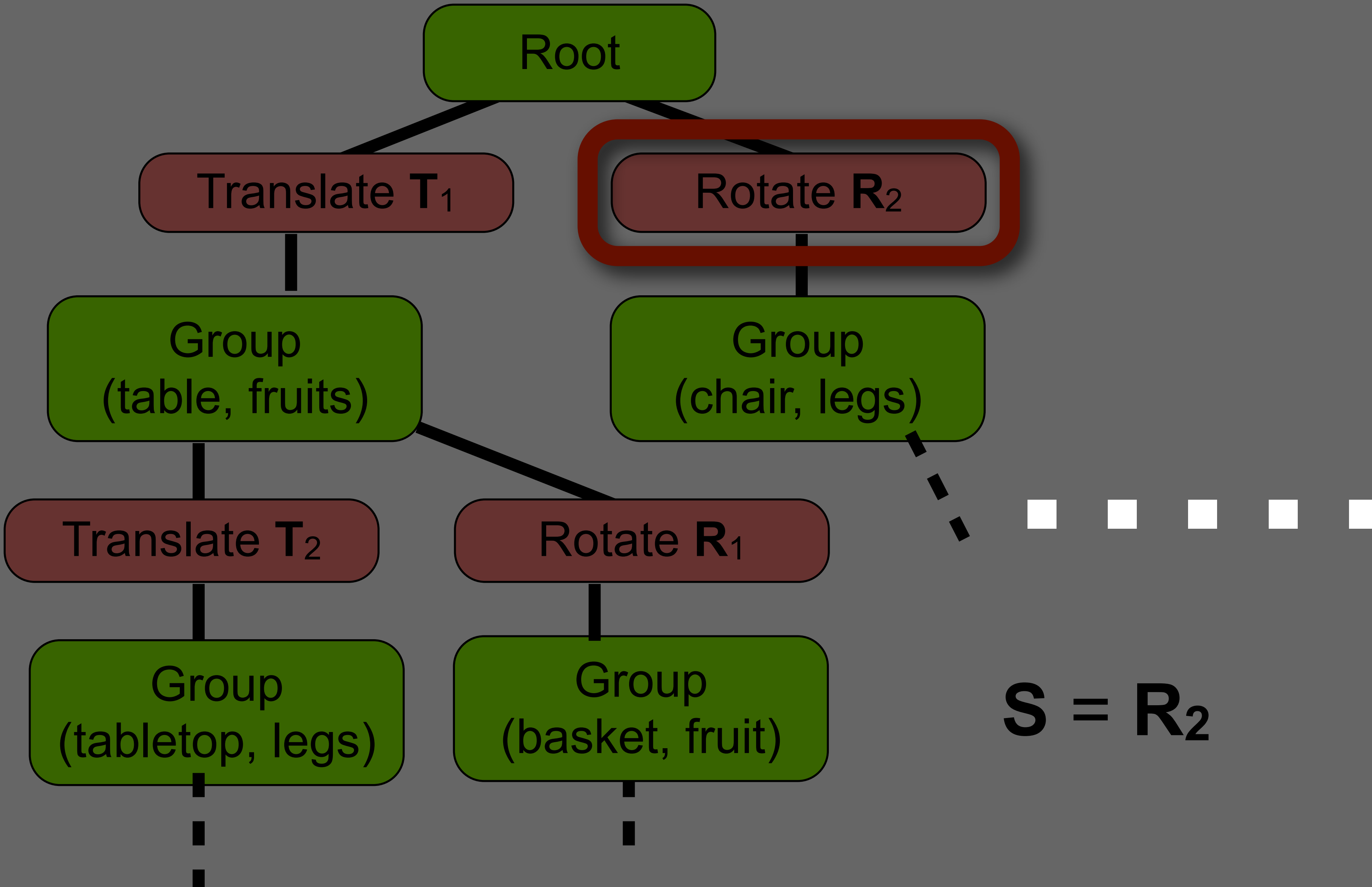
$\mathbf{S} = \mathbf{R}_2$

Traversal Example



$S = R_2$

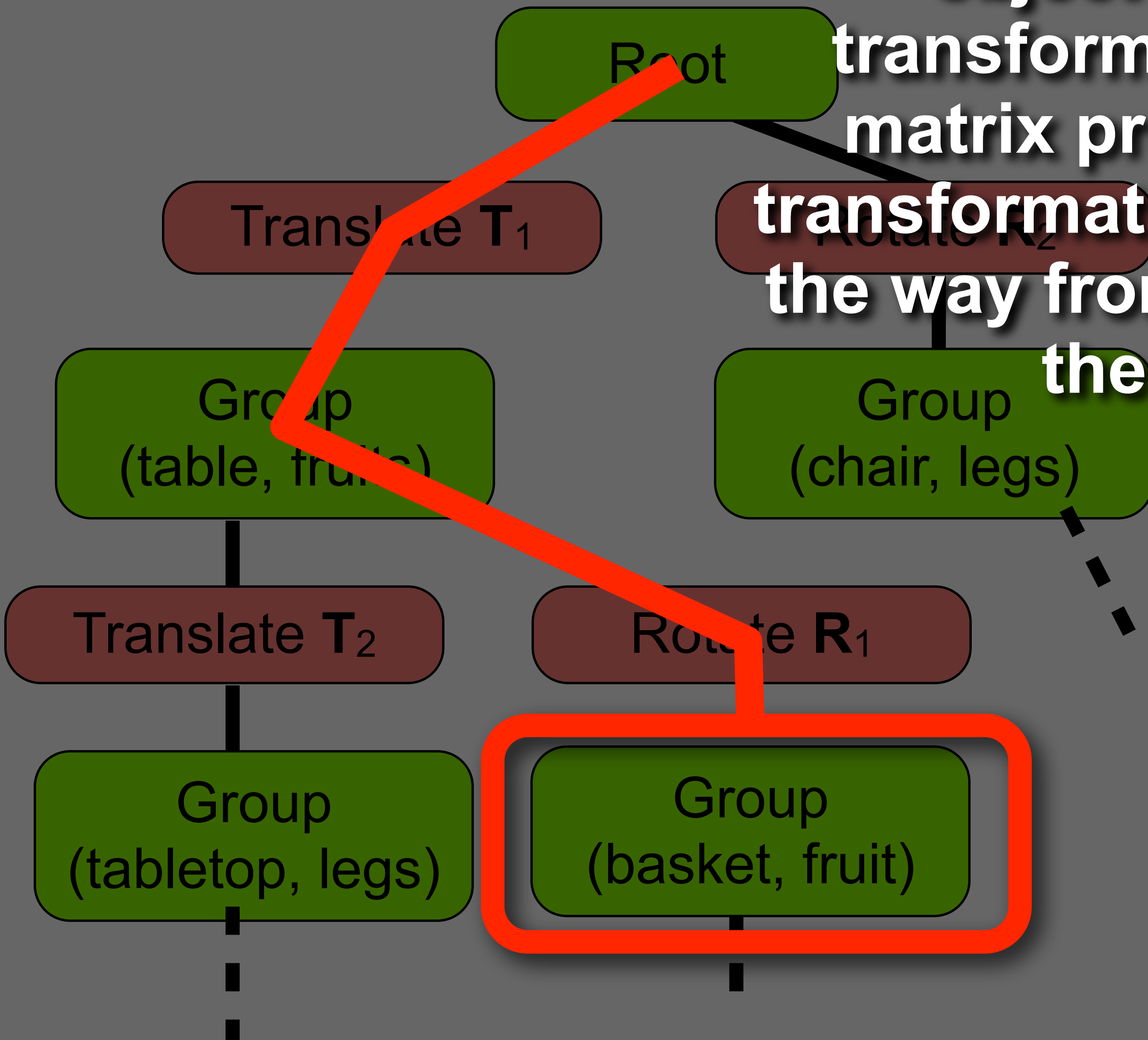
Traversal Example



$$\mathbf{S} = \mathbf{R_2}$$

Traversal Example

At each node, the current object-to-world transformation is the matrix product of all transformations found on the way from the node to the root.



$$S = T_1R_1$$

Traversal State

- The state is updated during traversal
  - Transformations
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  - Why I? $\mathbf{T}^*\mathbf{T}^{-1} = \boldsymbol{I}$ does not necessarily hold in floating point even when T is an invertible matrix – you accumulate error
  - Why II? **T** might be singular, e.g., could flatten a 3D

Traversal State

- The state is updated during traversal
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  - **Apply when entering node, "undo" when leaving**

Can you think of a data structure suited for this?

- How to implement?
  - Bad idea to undo transformation by inverse matrix
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Traversal State – Stack

- The state is updated during traversal
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Barebones Traversal Example

```
class NodeBase
{
    std::vector<NodeBase*> children; // note: no parent pointer, just children!
    Mat4f transform;
    // function to call when traversal reaches this node
    virtual void visit( Mat4f S );
};
// derive classes for geometry, etc., from NodeBase

void traverse( NodeBase* pNode, Mat4f S )
{
    // update current transform
    Mat4f newS = S * pNode->transform;
    // visit node (for geometry, this means draw it, etc.)
    pNode->visit( newS );
    // recursive call to children, using new transformation
    for ( int i = 0; i < pNode->children.getSize(); ++i )
        traverse( pNode->children[i], newS )
}

void drawScene( NodeBase* pRoot )
{
    // first set things set up
    // ...
    // then call traverse for root with identity transformation
    traverse( pRoot, Mat4f::identity() );
}
```

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        traverse( pNode->children[i], newS )
}

void drawScene( NodeBase* pRoot )
{
    // first set things set up
    // ...
    // then call traverse for root with identity transformation! done!
    traverse( pRoot, Mat4f::identity() );
}
```

Note 1: This example is using the built-in stack for pushing and popping the transform (that's what happens in recursive function calls, remember CS101!), but you could just as well maintain a stack yourself. This also works out-of-the-box for DAGs, i.e., shared subtrees.

Note 2: Other state (e.g. materials) would also need to be carried along if needed

Note 3: I cut corners and made the transformation part of the base node class to save space (a perfectly ok thing to do in practice)

That’s All!