Hierarchical Modeling and Scene Graphs

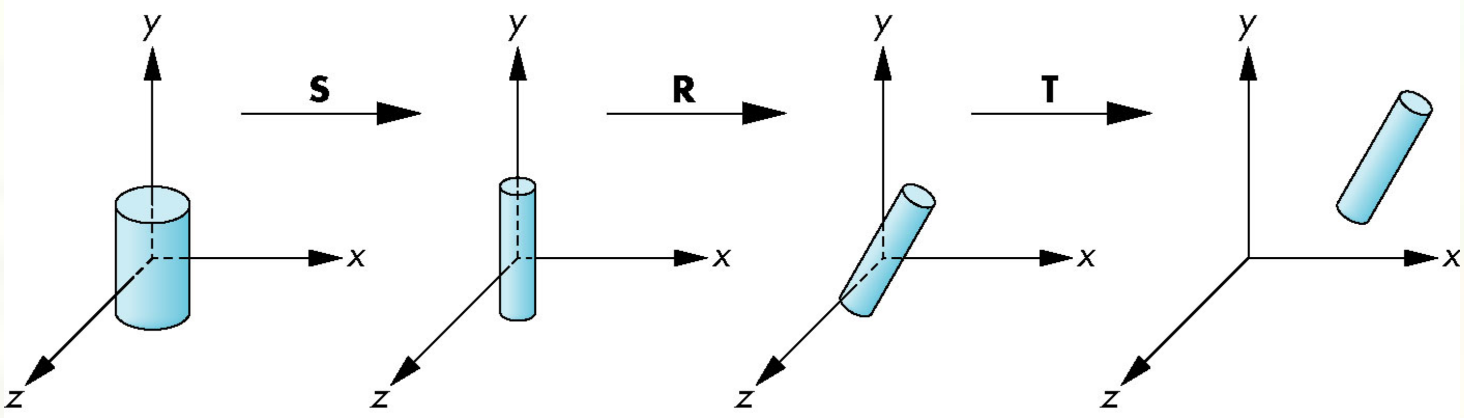
Adapted from material prepared by Ed Angel

Objectives

- Examine the limitations of linear modeling
  - Symbols and instances
- Introduce hierarchical models
  - Articulated models
  - Robots
- Introduce Tree and DAG models
- Examine various traversal strategies
- Generalize the notion of objects to include lights, cameras, attributes
- Introduce scene graphs

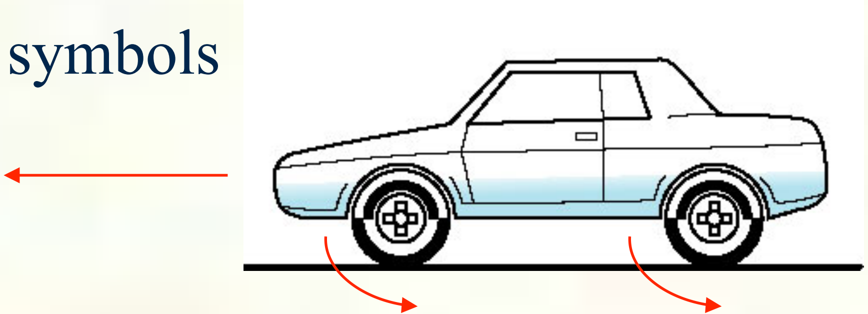
Instance Transformation

- Start with a prototype object (a *symbol*)
- Each appearance of the object in the model is an *instance*
  - Must scale, orient, position
  - Defines instance transformation



Relationships in Car Model

- Symbol-instance table does not show relationships between parts of model
- Consider model of car
  - Chassis + 4 identical wheels
  - Two symbols



- Rate of forward motion determined by rotational speed of wheels

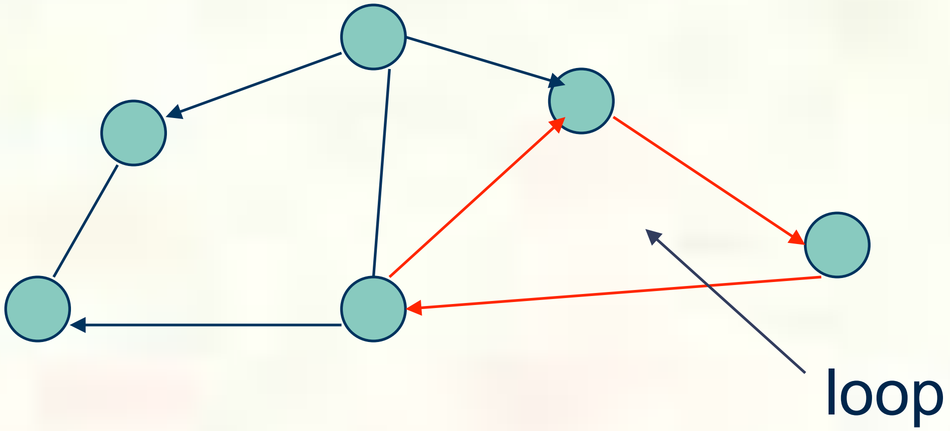
Structure Through Function Calls

```
car(speed){
    chassis()
    wheel(right_front);
    wheel(left_front);
    wheel(right_rear);
    wheel(left_rear);
}
```

- Fails to show relationships well
- Look at problem using a graph

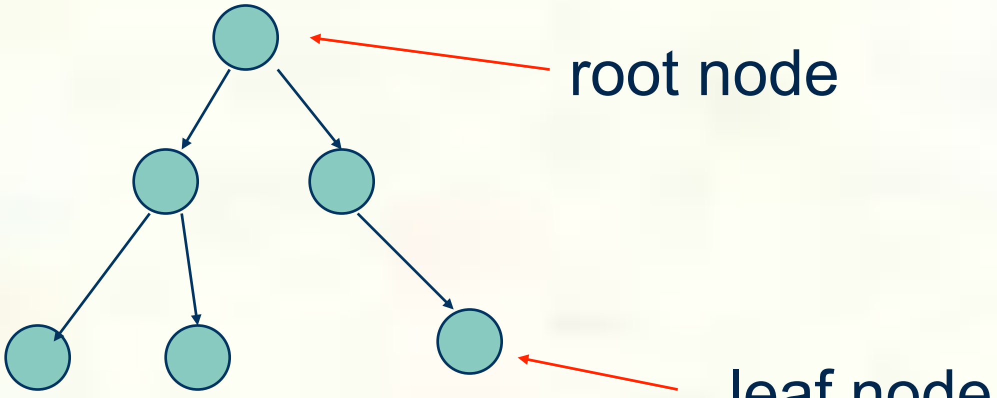
Graphs

- Set of *nodes* and *edges (links)*
- Edge connects a pair of nodes
  - Directed or undirected
- *Cycle*: directed path that is a loop

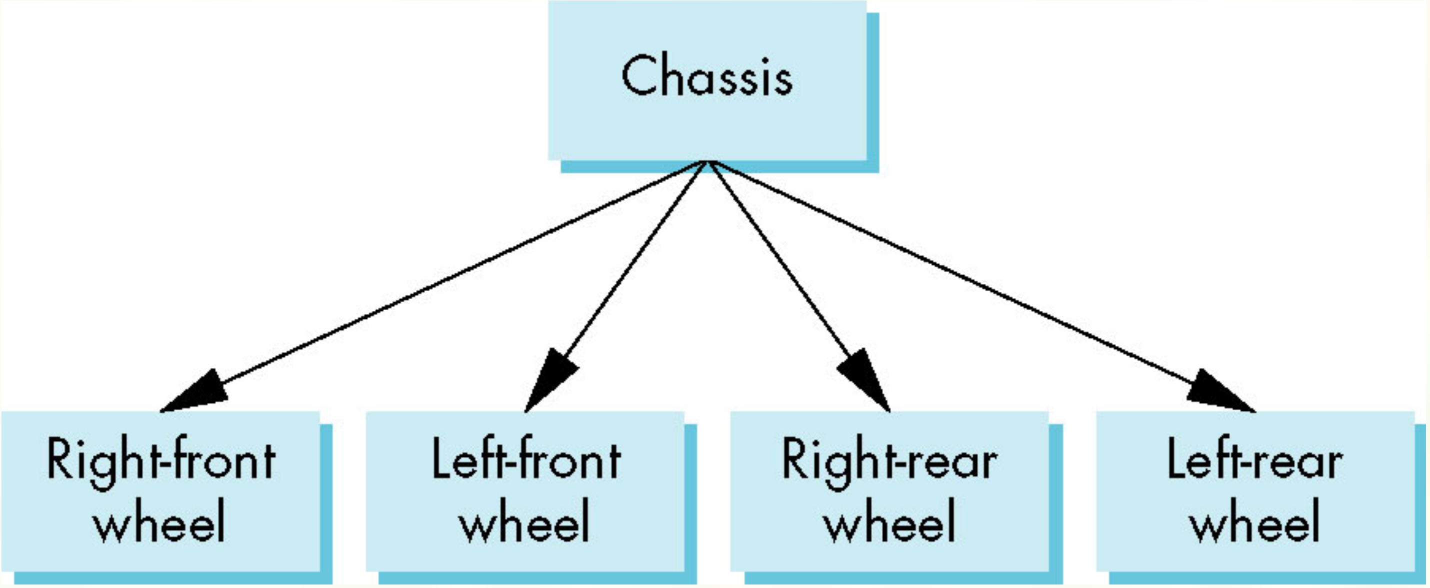


Tree

- Graph in which each node (except the root) has exactly one parent node
    - May have multiple children
    - Leaf or terminal node: no children

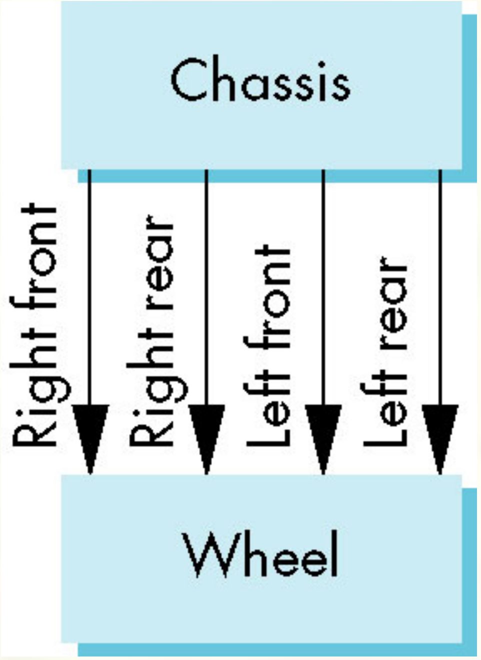


Tree Model of Car



DAG Model

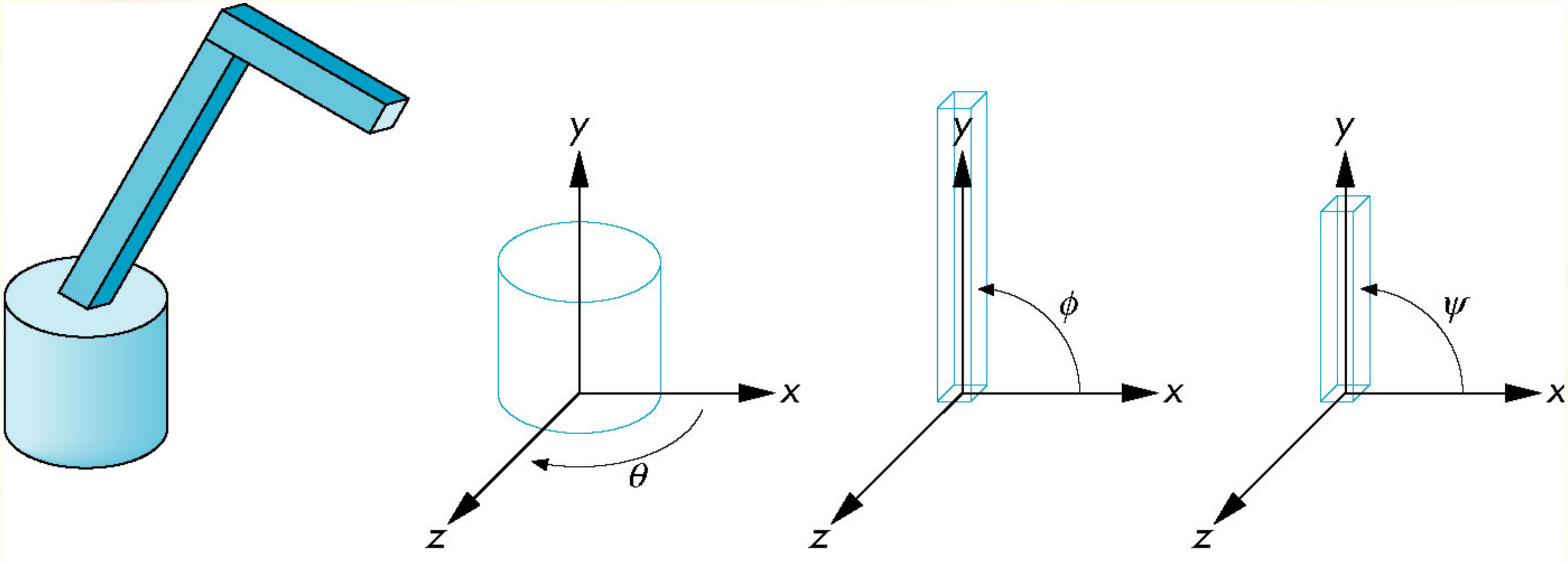
- If we use the fact that all the wheels are identical, we get a *directed acyclic graph*
  - Not much different than dealing with a tree



Modeling with Trees

- Must decide what information to place in nodes and what to put in edges
- Nodes
  - What to draw
  - Pointers to children
- Edges
  - May have information on incremental changes to transformation matrices (can also store in nodes)

Robot Arm

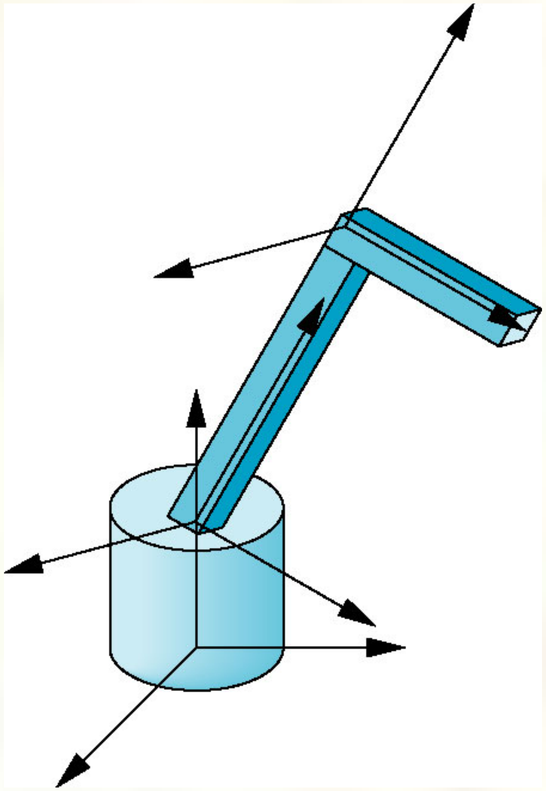


robot arm

parts in their own coodinate systems

Articulated Models

- Robot arm is an example of an *articulated model*
  - Parts connected at joints
  - Can specify state of model by giving all joint angles



Relationships in Robot Arm

- Base rotates independently
  - Single angle determines position
- Lower arm attached to base
  - Its position depends on rotation of base
  - Must also translate relative to base and rotate about connecting joint
- Upper arm attached to lower arm
  - Its position depends on both base and lower arm
  - Must translate relative to lower arm and rotate about joint connecting to lower arm

Required Matrices

- Rotation of base: $\mathbf{R}_b$
  - Apply $\mathbf{M} = \mathbf{R}_b$ to base
- Translate lower arm <u>relative</u> to base: $\mathbf{T}_{lu}$
- Rotate lower arm around joint: $\mathbf{R}_{lu}$
  - Apply $\mathbf{M} = \mathbf{R}_b\ \mathbf{T}_{lu}\ \mathbf{R}_{lu}$ to lower arm
- Translate upper arm <u>relative</u> to upper arm: $\mathbf{T}_{uu}$
- Rotate upper arm around joint: $\mathbf{R}_{uu}$
  - Apply $\mathbf{M} = \mathbf{R}_b\ \mathbf{T}_{lu}\ \mathbf{R}_{lu}\ \mathbf{T}_{uu}\ \mathbf{R}_{uu}$ to upper arm

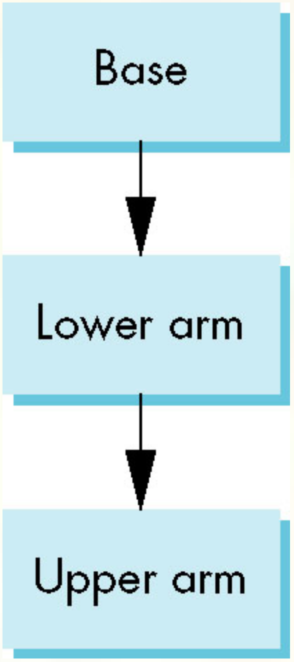
OpenGL Code for Robot

```
robot_arm(){
    glRotate(theta, 0.0, 1.0, 0.0);
    base();
    glTranslate(0.0, h1, 0.0);
    glRotate(phi, 0.0, 0.0, 1.0);
    lower_arm();
    glTranslate(0.0, h2, 0.0);
    glRotate(psi, 0.0, 0.0, 1.0);
    upper_arm();
}
```

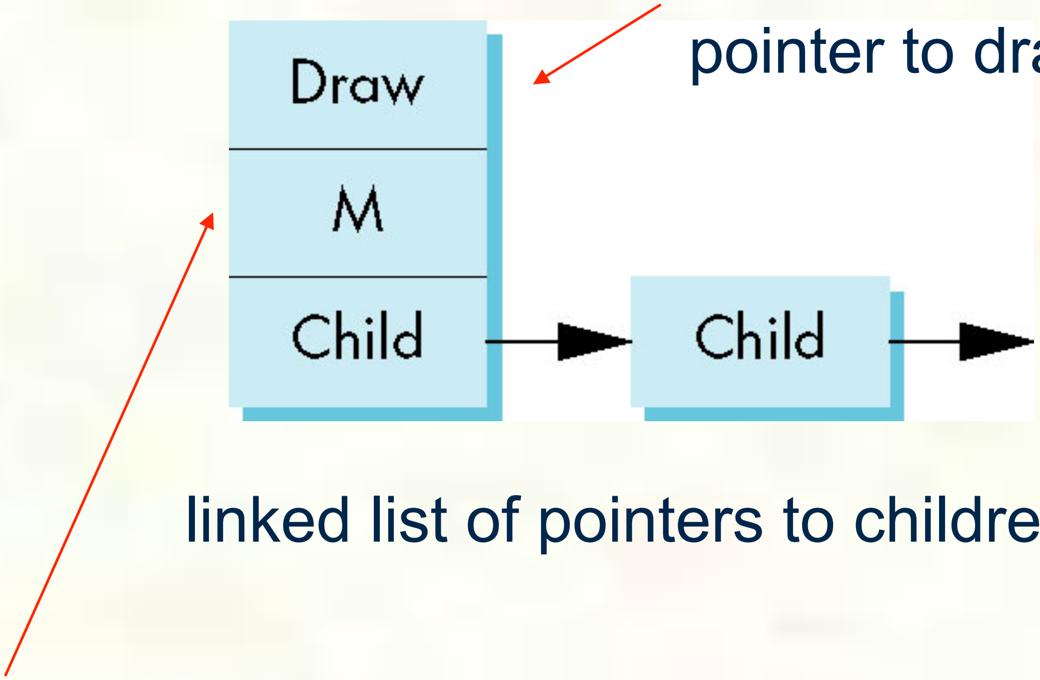
Tree Model of Robot

- Note code shows relationships between parts of model
  - Can change “look” of parts easily without altering relationships
- Simple example of tree model
- Want a general node structure

for nodes



Possible Node Structure



Code for drawing part or pointer to drawing function

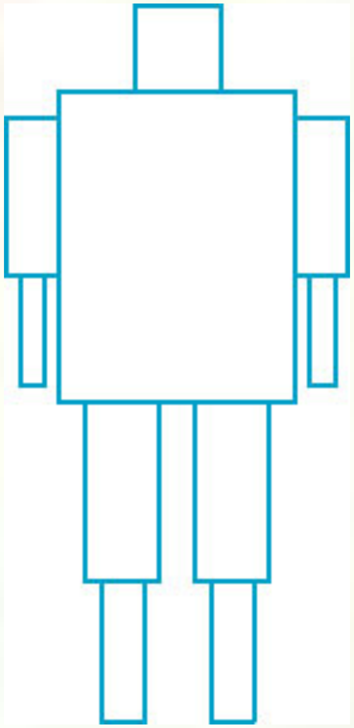
linked list of pointers to children

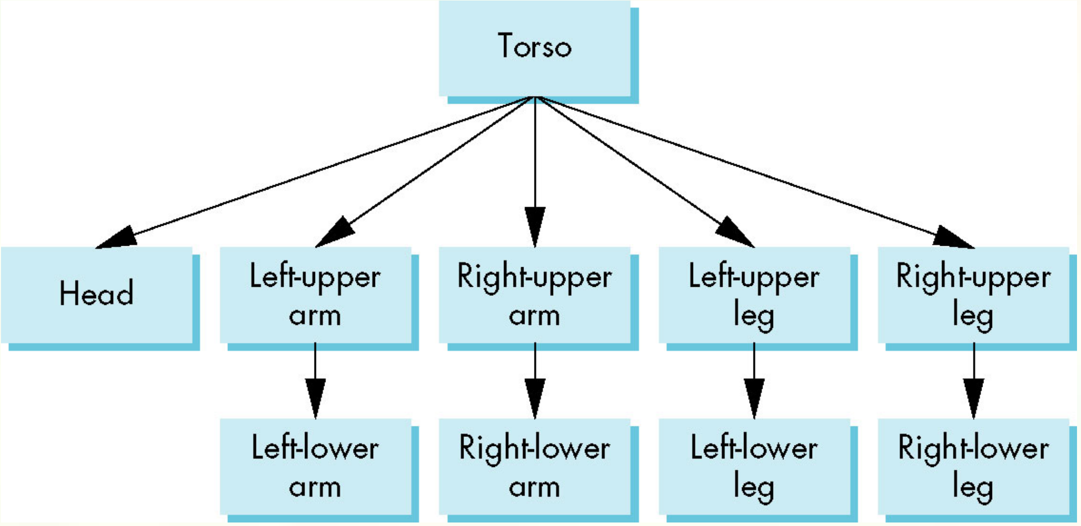
matrix relating node to parent

Generalizations

- Need to deal with multiple children
    - How do we represent a more general tree?
    - How do we traverse such a data structure?
- Animation
    - How to use dynamically?
    - Can we create and delete nodes during execution?

Humanoid Figure





Torso

Head

Left-upper arm

Right-upper arm

Left-upper leg

Right-upper leg

Left-lower arm

Right-lower arm

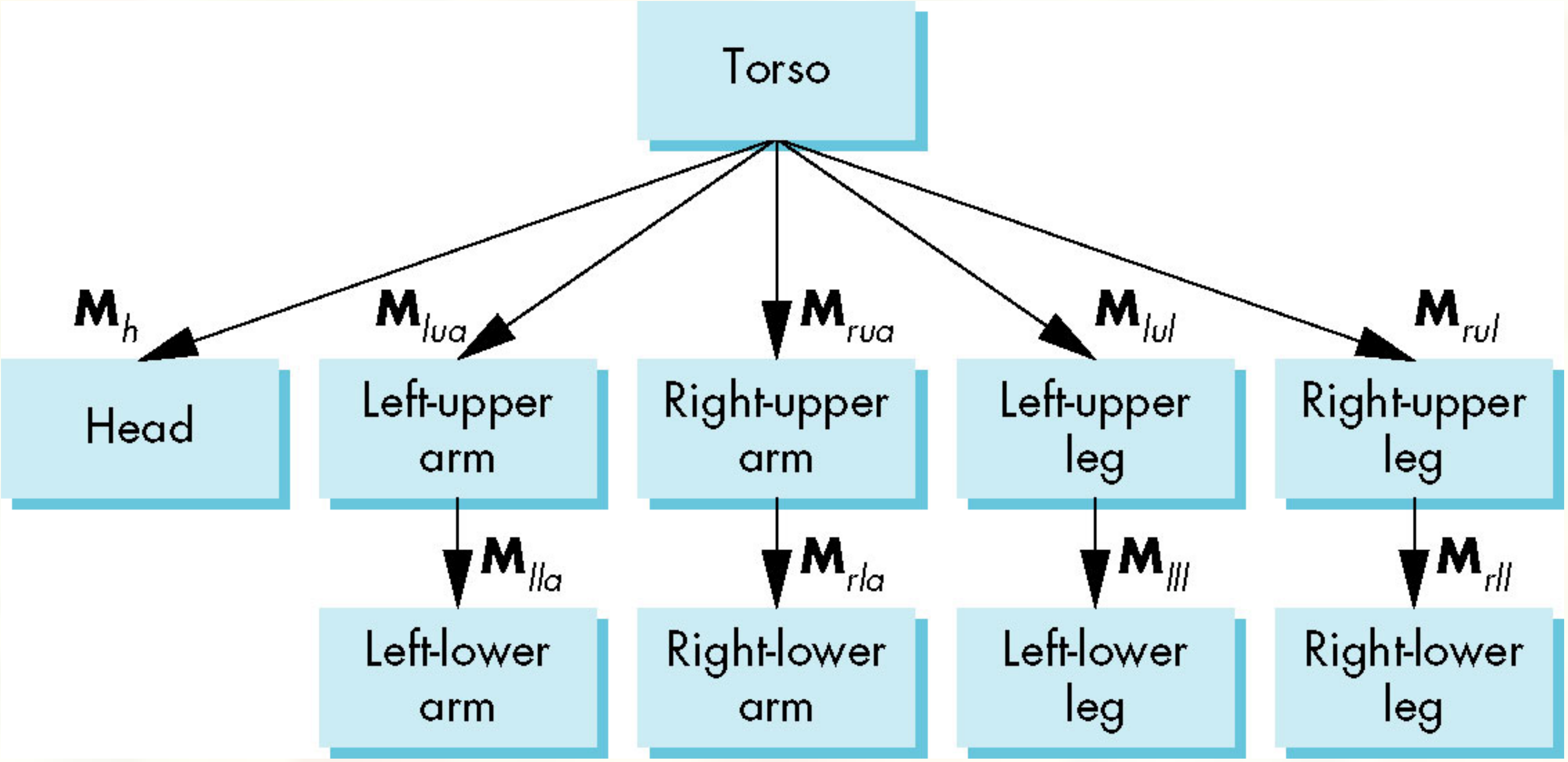
Left-lower leg

Right-lower leg

Building the Model

- Can build a simple implementation using quadrics: ellipsoids and cylinders
- Access parts through functions
  - **`torso()`**
  - **`left_upper_arm()`**
- Matrices describe position of node with respect to its parent
  - $\mathbf{M}_{lla}$ positions left lower leg with respect to left upper arm

Tree with Matrices



Display and Traversal

- The position of the figure is determined by 11 joint angles (two for the head and one for each other part)
- Display of the tree requires a *graph traversal*
  - Visit each node once
  - Display function at each node that describes the part associated with the node, applying the correct transformation matrix for position and orientation

Transformation Matrices

- There are 10 relevant matrices
    - **M** positions and orients entire figure through the torso which is the root node
    - $\mathbf{M}_{h}$ positions head with respect to torso
    - $\mathbf{M}_{lua}$, $\mathbf{M}_{rua}$, $\mathbf{M}_{lul}$, $\mathbf{M}_{rul}$ position arms and legs with respect to torso
    - $\mathbf{M}_{lla}$, $\mathbf{M}_{rla}$, $\mathbf{M}_{lll}$, $\mathbf{M}_{rll}$ position lower parts of limbs with respect to corresponding upper limbs

Stack-based Traversal

- Set model-view matrix to **M** and draw torso
- Set model-view matrix to $\mathbf{MM}_h$ and draw head
- For left-upper arm need $\mathbf{MM}_{lua}$ and so on
- Rather than recomputing $\mathbf{MM}_{lua}$ from scratch or using an inverse matrix, we can use the matrix stack to store **M** and other matrices as we traverse the tree

Traversal Code

```
figure() {
    glPushMatrix()
    torso();
    glRotate3f(…);
    head();
    glPopMatrix();
    glPushMatrix();
    glTranslate3f(…);
    glRotate3f(…);
    left_upper_arm();
    glPopMatrix();
    glPushMatrix();
```

save present model-view matrix

update model-view matrix for head

recover original model-view matrix

save it again

update model-view matrix for left upper arm

recover and save original model-view matrix again

rest of code

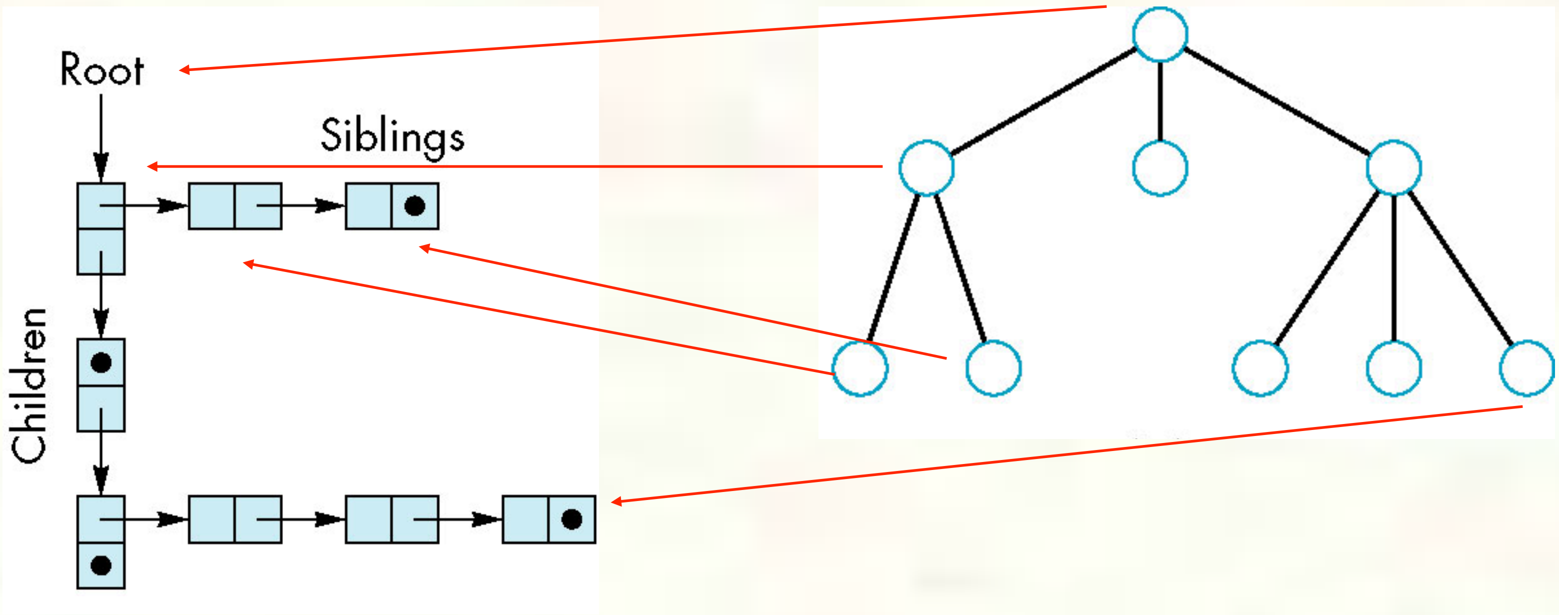
Analysis

- The code describes a particular tree and a particular traversal strategy
  - Can we develop a more general approach?
- Note that the sample code does not include state changes, such as changes to colors
  - May also want to use **`glPushAttrib`** and **`glPopAttrib`** to protect against unexpected state changes affecting later parts of the code

General Tree Data Structure

- Need a data structure to represent tree and an algorithm to traverse the tree
- We will use a *left-child right sibling* structure
  - Uses linked lists
  - Each node in data structure is two pointers
  - Left: next node
  - Right: linked list of children

Left-Child Right-Sibling Tree



Tree node Structure

- At each node we need to store
  - Pointer to sibling
  - Pointer to child
  - Pointer to a function that draws the object represented by the node
  - Homogeneous coordinate matrix to multiply on the right of the current model-view matrix
    - Represents changes going from parent to node
    - In OpenGL this matrix is a 1D array storing matrix by columns

C Definition of treenode

```
typedef struct treenode {
    GLfloat m[16];
    void (*f)();
    struct treenode *sibling;
    struct treenode *child;
} treenode;
```

Defining the torso node

```
treenode torso_node, head_node, lua_node, … ;
 /* use OpenGL functions to form matrix */
glLoadIdentity();
glRotatef(theta[0], 0.0, 1.0, 0.0);
 /* move model-view matrix to m */
glGetFloatv(GL_MODELVIEW_MATRIX, torso_node.m)

torso_node.f = torso; /* torso() draws torso */
Torso_node.sibling = NULL;
Torso_node.child = &head_node;
```

Notes

- The position of figure is determined by 11 joint angles stored in `theta[11]`
- Animate by changing the angles and redisplaying
- We form the required matrices using `glRotate` and `glTranslate`
  - More efficient than software
  - Because the matrix is formed in model-view matrix, we may want to first push original model-view matrix on matrix stack

Preorder Traversal

```
void traverse(treenode *root){
  if(root == NULL) return;
  glPushMatrix();
  glMultMatrix(root->m);
  root->f();
  if(root->child != NULL)
     traverse(root->child);
  glPopMatrix();
  if(root->sibling != NULL)
     traverse(root->sibling);
}
```

Notes

- We must save model-view matrix before multiplying it by node matrix
  - Updated matrix applies to children of node but not to siblings which contain their own matrices
- The traversal program applies to any left-child right-sibling tree
  - The particular tree is encoded in the definition of the individual nodes
- The order of traversal matters because of possible state changes in the functions

Dynamic Trees

- If we use pointers, the structure can be dynamic

```
typedef treenode *tree_ptr;
tree_ptr torso_ptr;
torso_ptr = malloc(sizeof(treenode));
```

- Definition of nodes and traversal are essentially the same as before but we can add and delete nodes during execution

Limitations of Immediate Mode Graphics

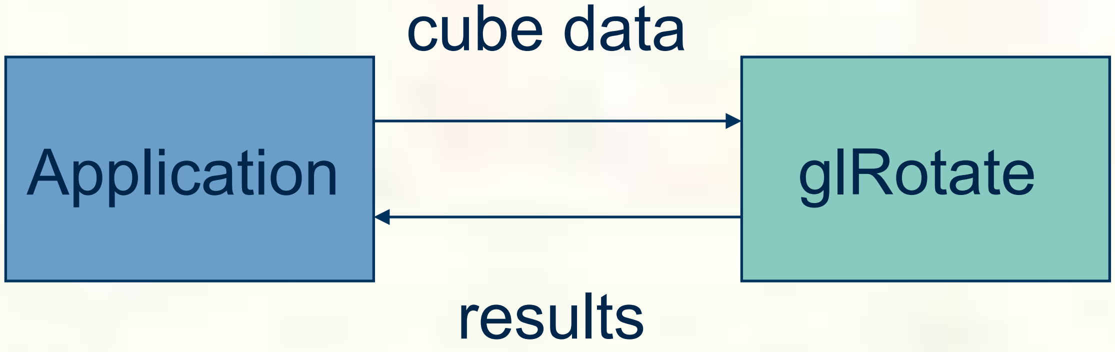
- When we define a geometric object in an application, upon execution of the code the object is passed through the pipeline
- It then disappears from the graphical system
- To redraw the object, either changed or the same, we must reexecute the code
- Display lists provide only a partial solution to this problem

OpenGL and Objects

- OpenGL lacks an object orientation
- Consider, for example, a green sphere
  - We can model the sphere with polygons or use OpenGL quadrics
  - Its color is determined by the OpenGL state and is not a property of the object
- Defies our notion of a physical object
- We can try to build better objects in code using object-oriented languages/techniques

Imperative Model

- Example: rotate a cube



cube data

Application

glRotate

results

- The rotation function must know how the cube is represented
  - Vertex list
  - Edge list

Object-Oriented Model

- In this model, the representation is stored with the object

- The application sends a *message* to the object
- The object contains functions (*methods*) which allow it to transform itself

C/C++

- Can try to use C structs to build objects
- C++ provides better support
  - Use class construct
  - Can hide implementation using public, private, and protected members in a class
  - Can also use friend designation to allow classes to access each other

Cube Object

- Suppose that we want to create a simple cube object that we can scale, orient, position and set its color directly through code such as

```
cube mycube;
mycube.color[0]=1.0;
mycube.color[1]=
  mycube.color[2]=0.0;
mycube.matrix[0][0]=………
```

Cube Object Functions

- We would also like to have functions that act on the cube such as
  - `mycube.translate(1.0, 0.0,0.0);`
  - `mycube.rotate(theta, 1.0, 0.0, 0.0);`
  - `setcolor(mycube, 1.0, 0.0, 0.0);`
- We also need a way of displaying the cube
  - `mycube.render();`

Building the Cube Object

```
class cube {
   public:
      float color[3];
      float matrix[4][4];
   // public methods

   private:

   // implementation


}
```

The Implementation

- Can use any implementation in the private part such as a vertex list
- The private part has access to public members and the implementation of class methods can use any implementation without making it visible
- Render method is tricky but it will invoke the standard OpenGL drawing functions such as **`glVertex`**

Other Objects

- Other objects have geometric aspects
  - Cameras
  - Light sources
- But we should be able to have nongeometric objects too
  - Materials
  - Colors
  - Transformations (matrices)

Application Code

```
cube mycube;
material plastic;
mycube.setMaterial(plastic);

camera frontView;
frontView.position(x ,y, z);
```

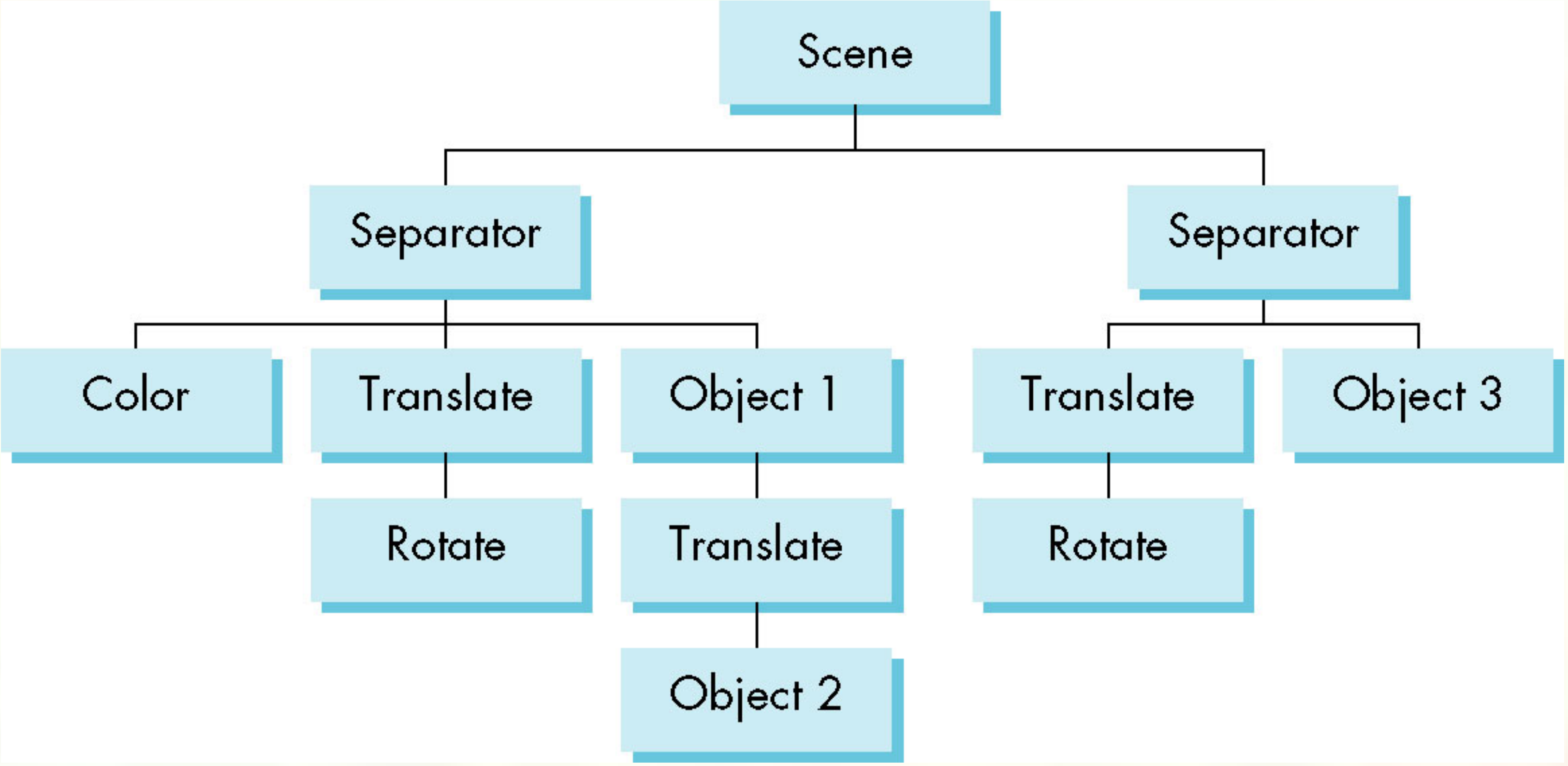
Light Object

```
class light {     // match Phong model
  public:
   boolean type; //ortho or perspective
   boolean near;
   float position[3];
   float orientation[3];
   float specular[3];
   float diffuse[3];
   float ambient[3];
}
```

Scene Descriptions

- If we recall figure model, we saw that
  - We could describe model either by tree or by equivalent code
  - We could write a generic traversal to display
- If we can represent all the elements of a scene (cameras, lights,materials, geometry) as C++ objects, we should be able to show them in a tree
  - Render scene by traversing this tree

Scene Graph


Scene
Separator
Separator
Color
Translate
Object 1
Translate
Object 3
Rotate
Translate
Rotate
Object 2

Preorder Traversal

```
glPushAttrib
glPushMatrix
glColor
glTranslate
glRotate
Object1
glTranslate
Object2
glPopMatrix
glPopAttrib
...
```

Separator Nodes

- Necessary to isolate state chages
  - Equivalent to OpenGL Push/Pop
- Note that as with the figure model
  - We can write a universal traversal algorithm
  - The order of traversal can matter
    - If we do not use the separator node, state changes can propagate

Inventor and Java3D

- Inventor and Java3D provide a scene graph API
- Scene graphs can also be described by a file (text or binary)
  - Implementation independent way of transporting scenes
  - Supported by scene graph APIs
- However, primitives supported should match capabilities of graphics systems
  - Hence most scene graph APIs are built on top of OpenGL or DirectX (for PCs)

VRML

- Want to have a scene graph that can be used over the World Wide Web
- Need links to other sites to support distributed data bases
- Virtual Reality Markup Language
  - Based on Inventor data base
  - Implemented with OpenGL