CS 4204 Computer Graphics

Structure Graphics and Hierarchical Modeling

Yong Cao

Virginia Tech

References:
Interactive Computer Graphics, Fourth Edition, Ed Angle

Objectives

Examine the limitations of linear modeling

- Symbols and instances

Introduce hierarchical models

- Articulated models
- Robots

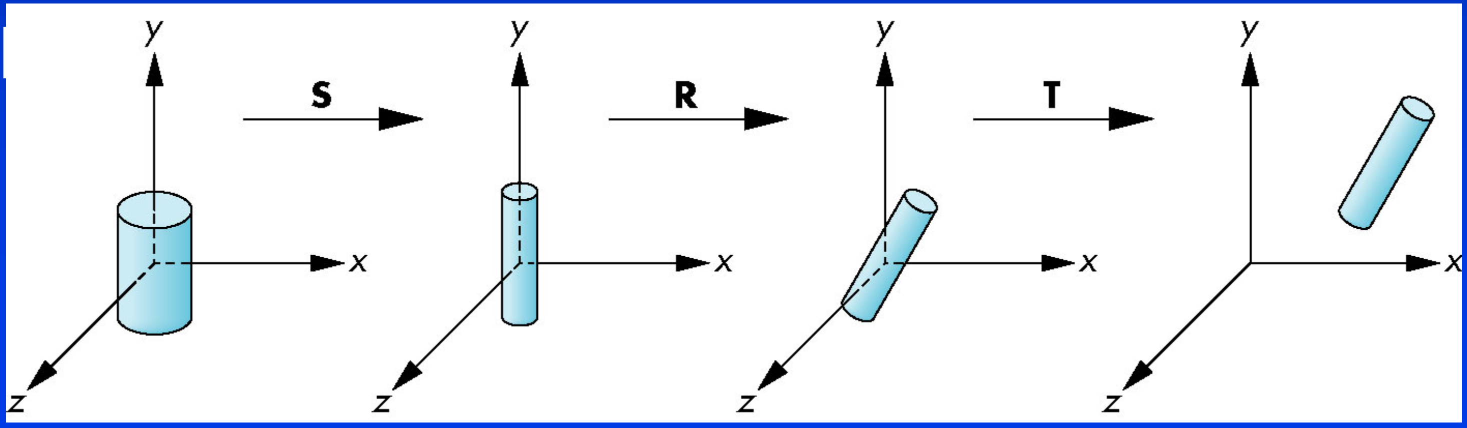
Introduce Tree and DAG models

Instance Transformation

Start with a prototype object (a symbol)

***Each appearance of the object in the model is an* instance**

- Must scale, orient, position
-



Symbol-Instance Table

Can store a model by assigning a number to each symbol and storing the parameters for the instance transformation

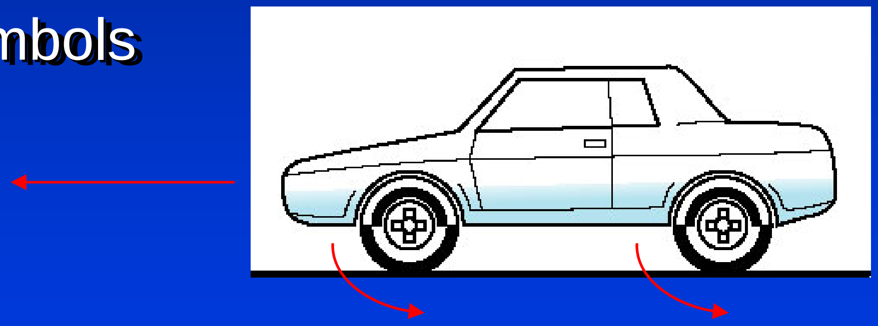
Symbol	Scale	Rotate	Translate
1	s_x, s_y, s_z	$\theta_x, \theta_y, \theta_z$	d_x, d_y, d_z
2			
3			
1			
1			
.			
.			

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

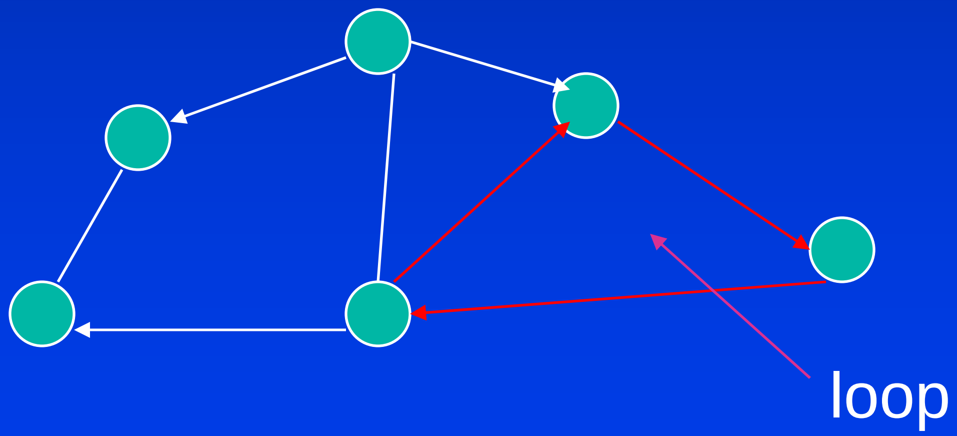
Graphs

Set of **nodes** ***and*** **edges (links)**

Edge connects a pair of nodes

- Directed or undirected

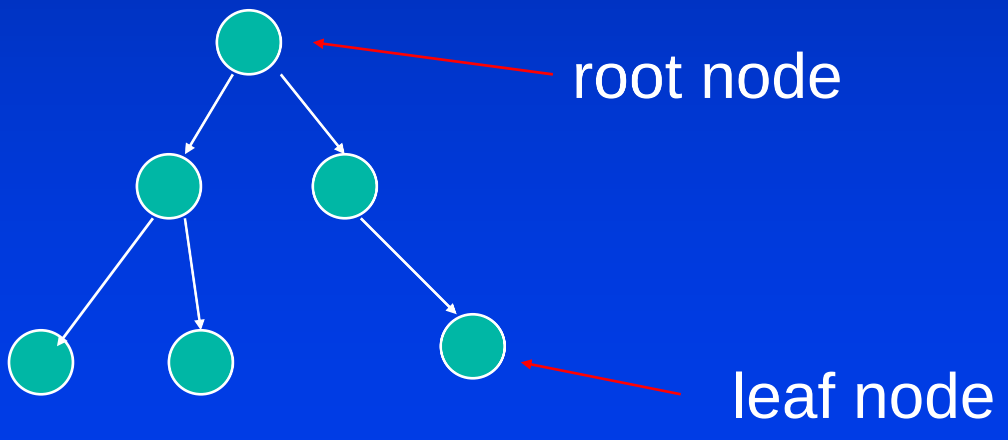
Cycle: ***directed path that is a loop***



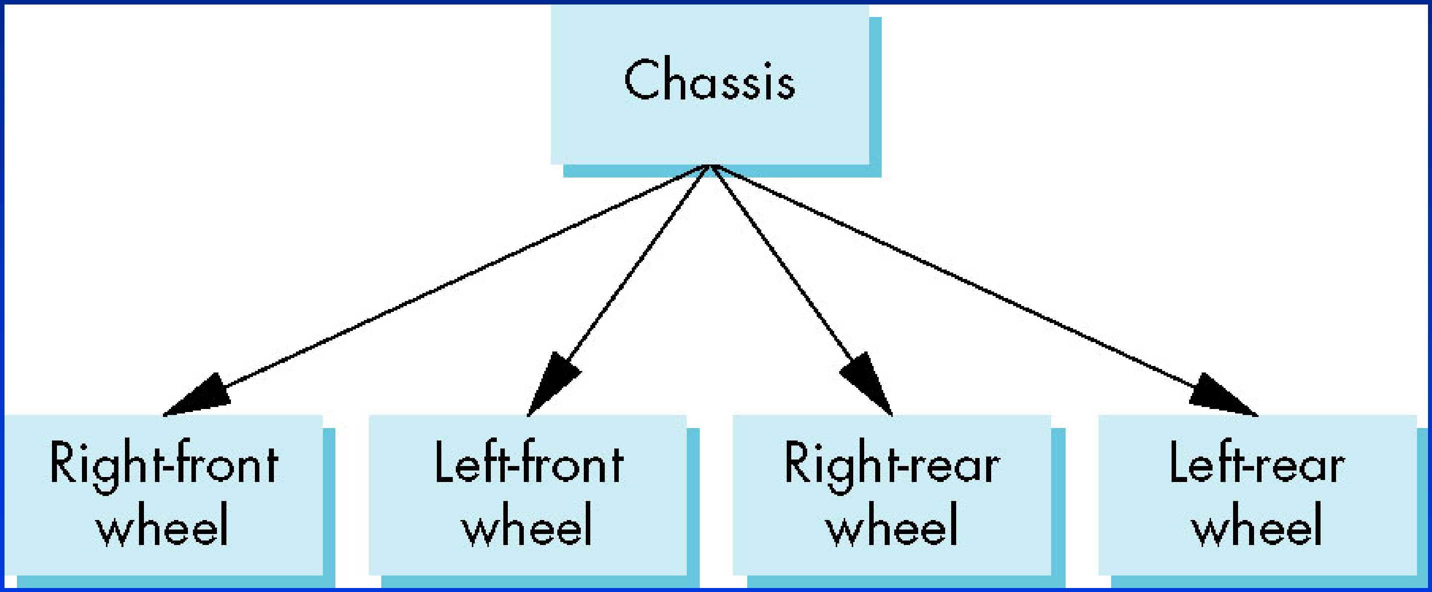
Tree

Graph in which each node (except the root) has exactly one parent node

- May have multiple children
- Leaf or terminal node: no children



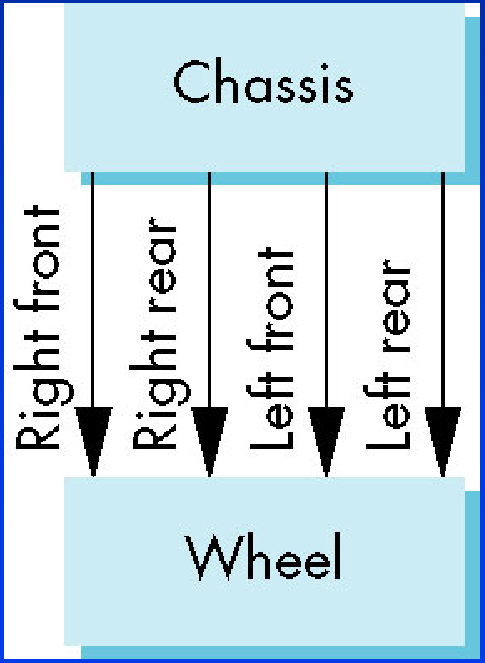
Tree Model of Car



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

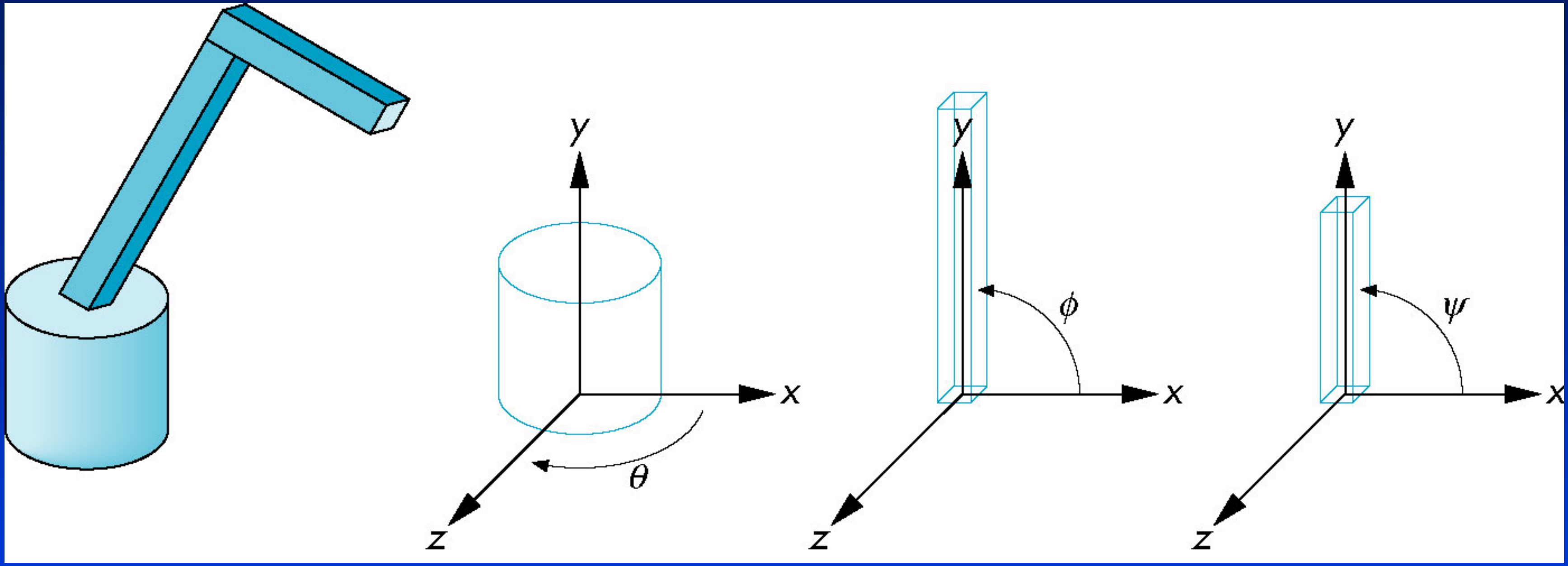
Nodes

- 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

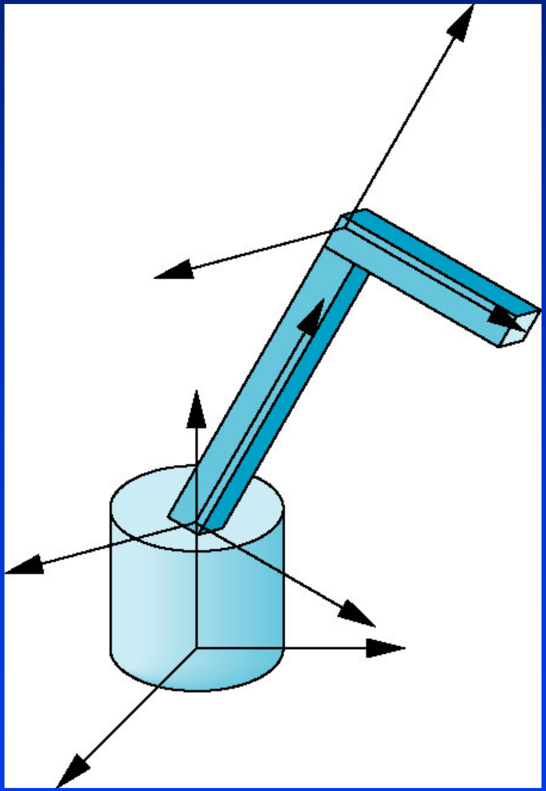
parts in their own coordinate systems

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: R_b

- Apply $\mathbf{M} = \mathbf{R}_b$ to base

Translate lower arm <u>relative</u> to base: T_{lu}

Rotate lower arm around joint: 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: T_{uu}

Rotate upper arm around joint: 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, 1.0, 0.0);
    lower_arm();
    glTranslate(0.0, h2, 0.0);
    glRotate(psi, 0.0, 1.0, 0.0);
    upper_arm();
}
```

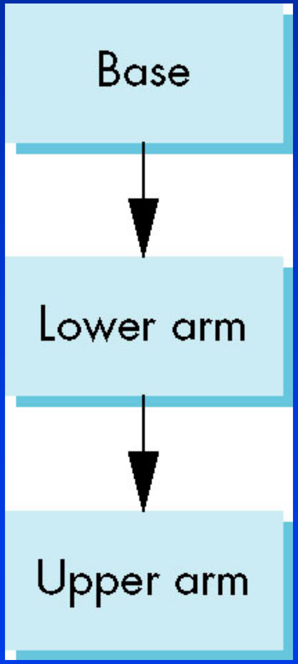
Tree Model of Robot

Note code shows relationships between parts of model

- Can change "look" of parts easily without altering relationships

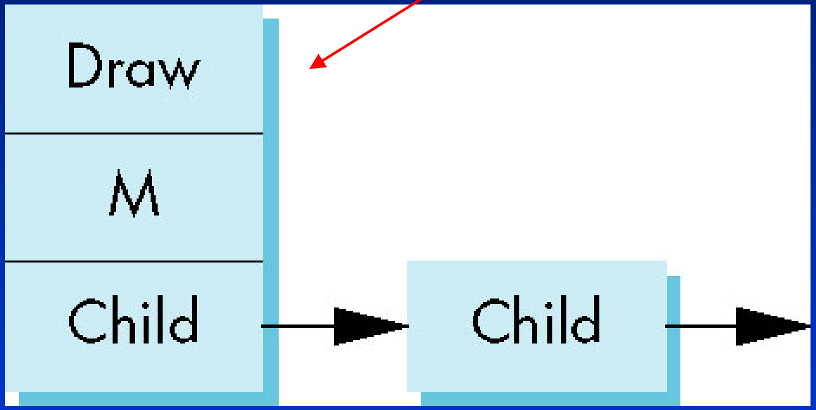
Simple example of tree model

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?

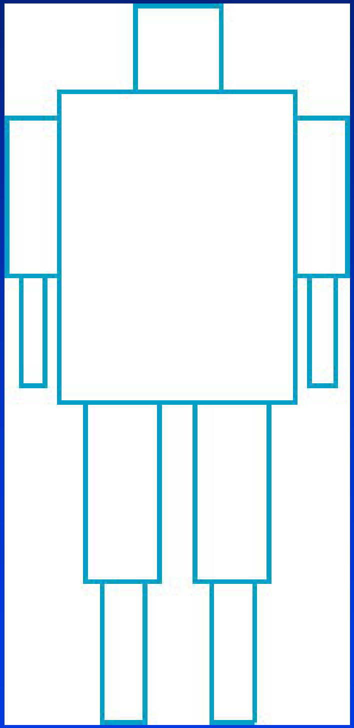
Animation

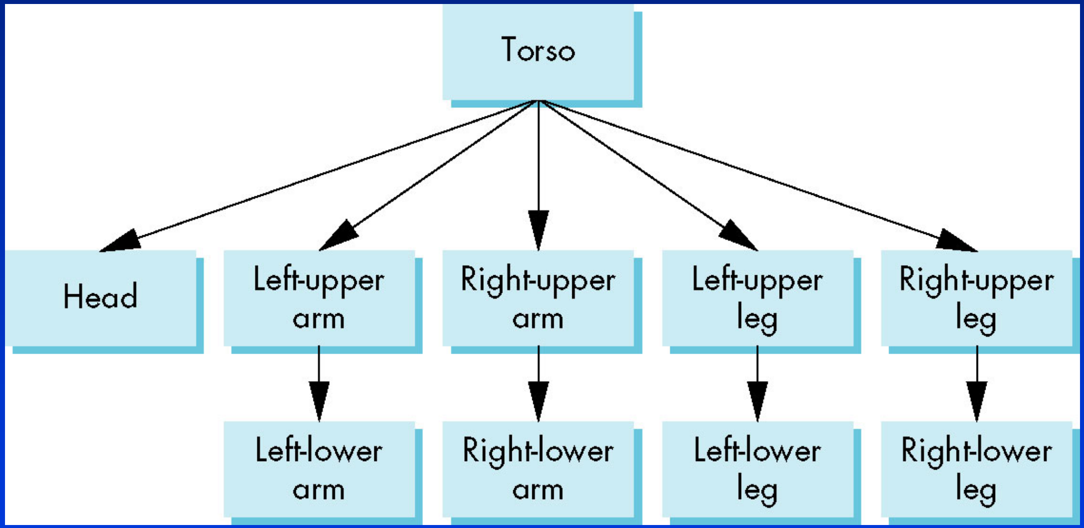
- How to use dynamically?
- Can we create and delete nodes during execution?

Objectives

- *Build a tree-structured model of a humanoid figure*
- *Examine various traversal strategies*
- *Build a generalized tree-model structure that is independent of the particular model*

Humanoid Figure





Building the Model

Can build a simple implementation using quadrics: ellipsoids and cylinders

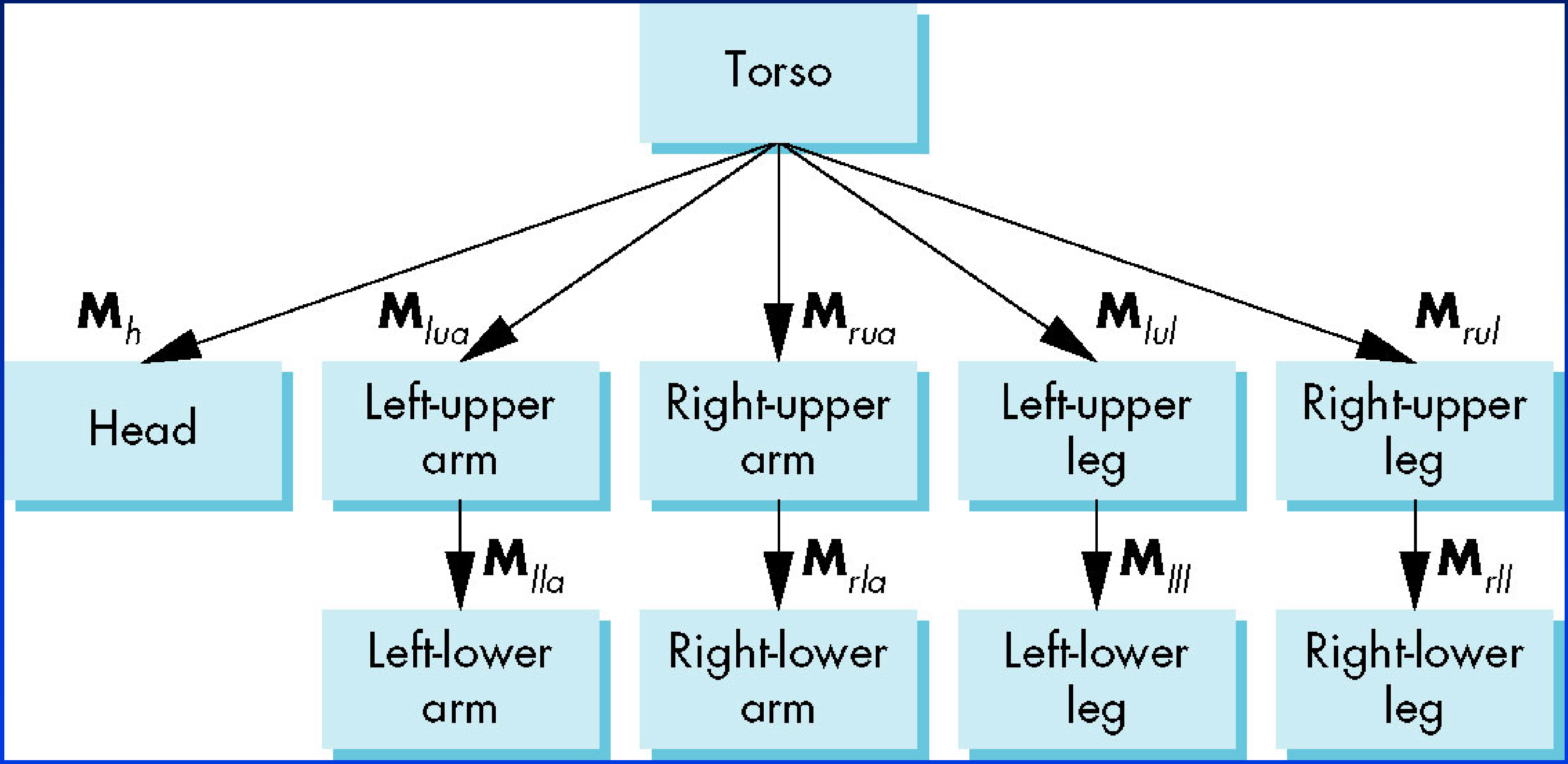
Access parts through functions

- **`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
- M_h positions head with respect to torso
- M_{lua}, M_{rua}, M_{lul}, M_{rul} position arms and legs with respect to torso
- M_{lla}, M_{rla}, M_{lll}, 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 MM_h and draw head*
- *For left-upper arm need MM_{lua} and so on*
- *Rather than recomputing 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

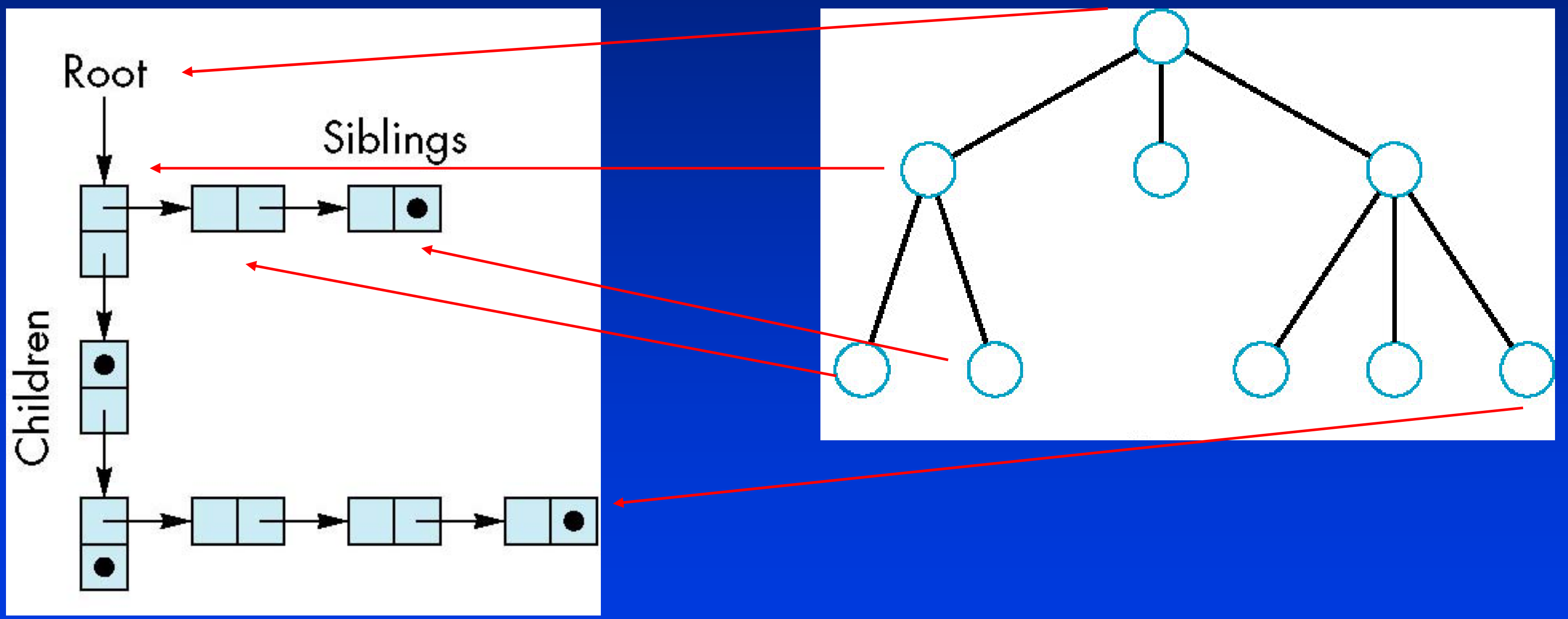
General Tree Data Structure

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