Computer Graphics (CS 543)
Lecture 4 (Part 3): Hierarchical 3D Models

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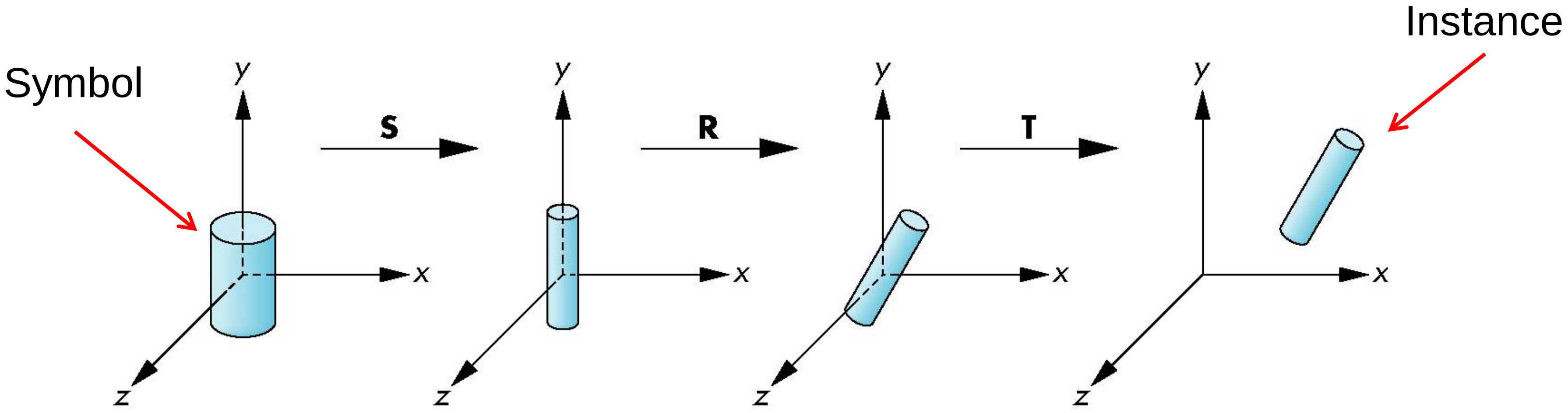
Instance Transformation

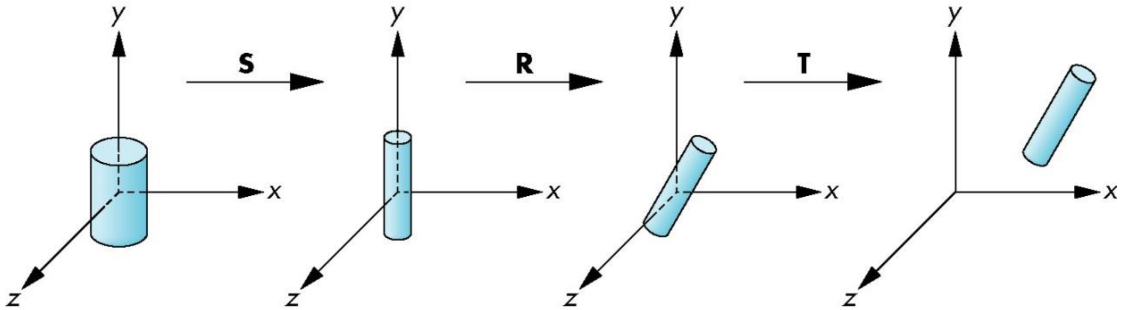
- Start with unique object (a *symbol*)
- Each appearance of object in model is an ***instance***
  - Must scale, orient, position
  - Defines instance transformation



Symbol-Instance Table

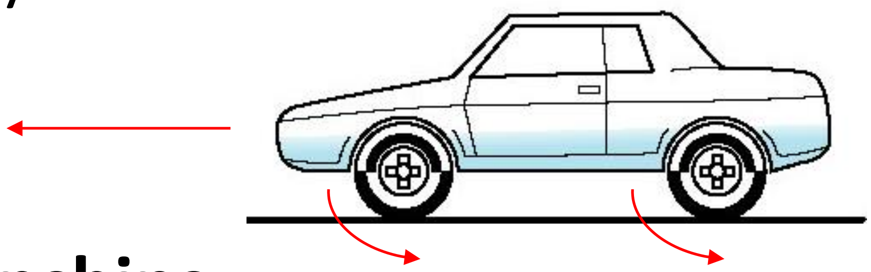
Can store **intances + instance transformations**

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			
.			
.			



Problems with Symbol-Instance Table

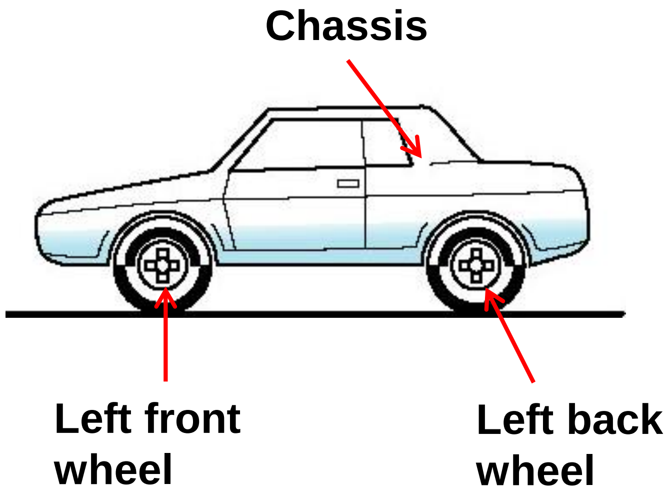
- Symbol-instance table does not show relationships between parts of model
- Consider model of car
  - Chassis (body) + 4 identical wheels
  - Two symbols



- **Relationships:**
  - Wheels connected to chassis
  - Chassis motion determined by rotational speed of wheels

Structure Program Using Function Calls?

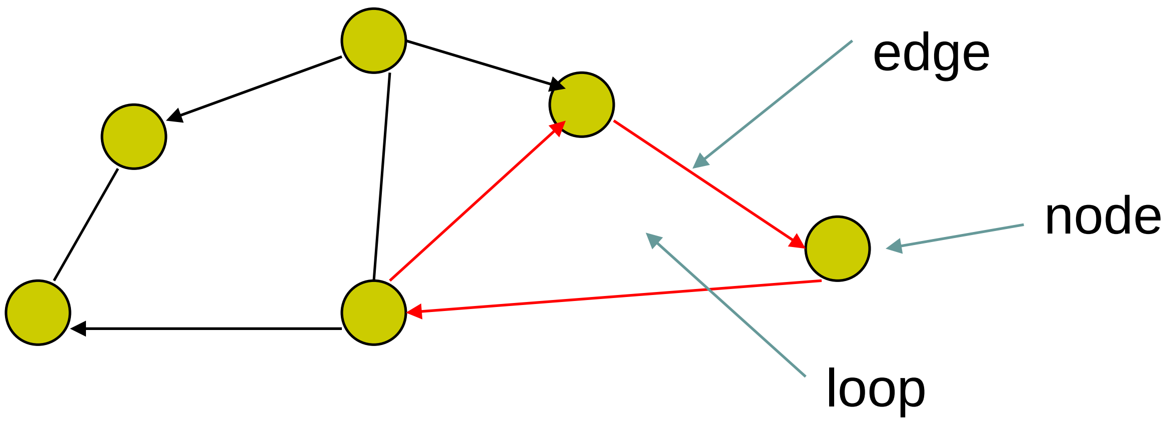
```
car(speed)
{
    chassis()
    wheel(right_front);
    wheel(left_front);
    wheel(right_rear);
    wheel(left_rear);
}
```



- Fails to show relationships between parts
- Explore graph representation

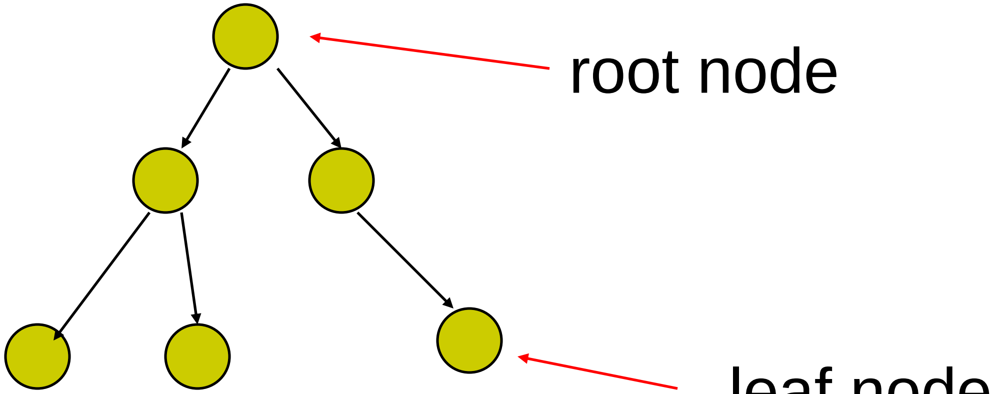
Graphs

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

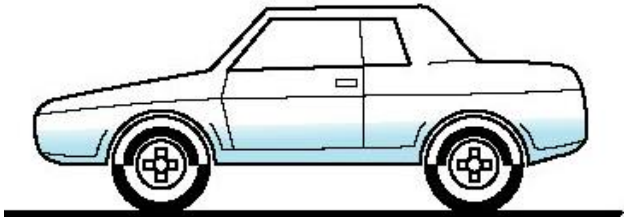


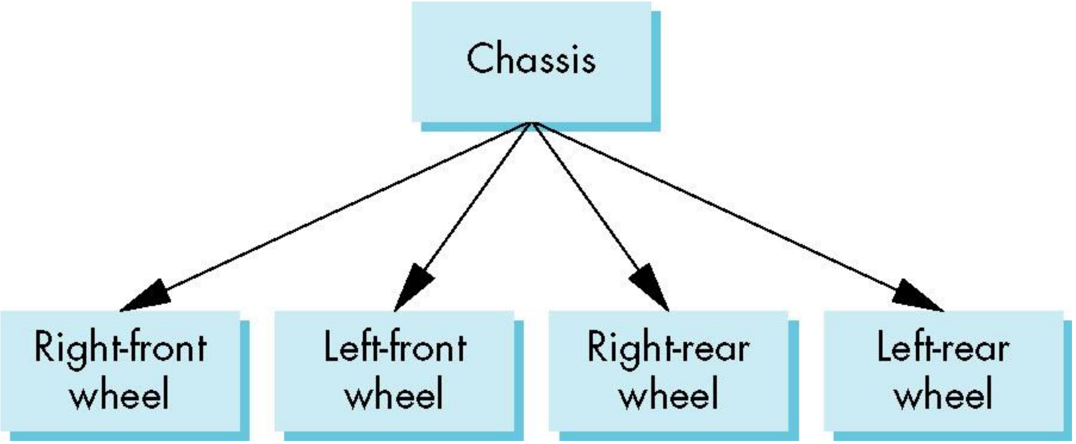
Tree

- Graph in which each node (except root) has exactly one parent node
  - A parent may have multiple children
  - Leaf node: no children



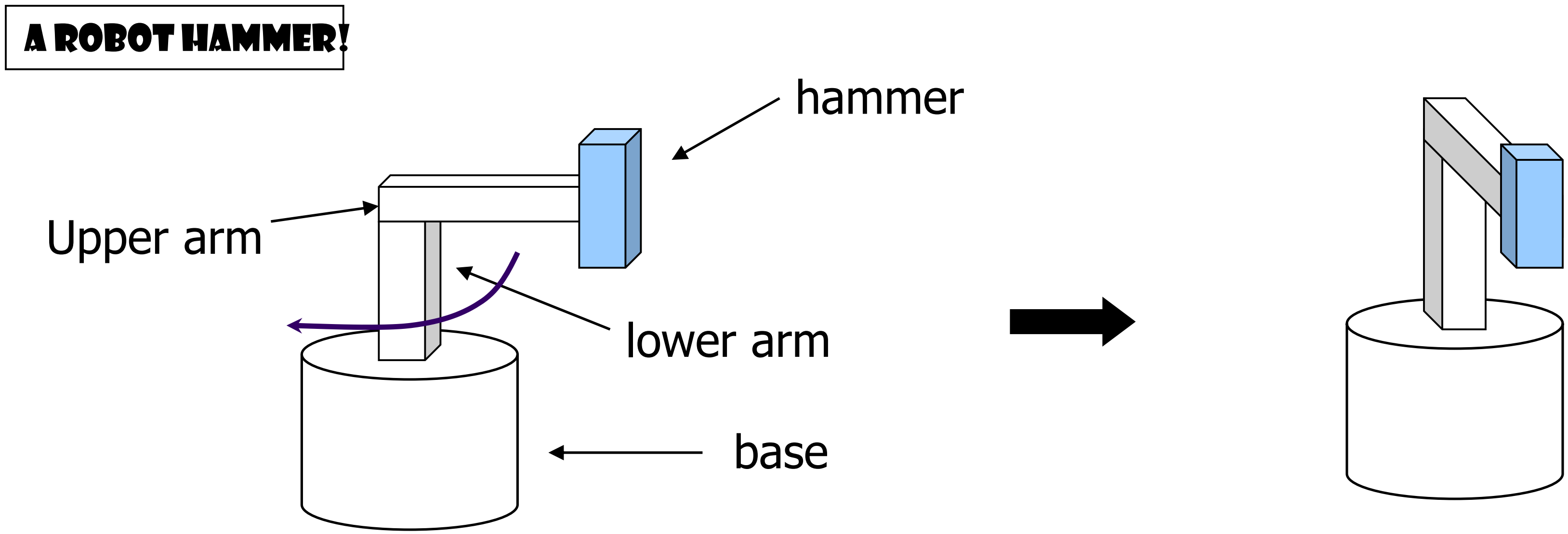
Tree Model of Car





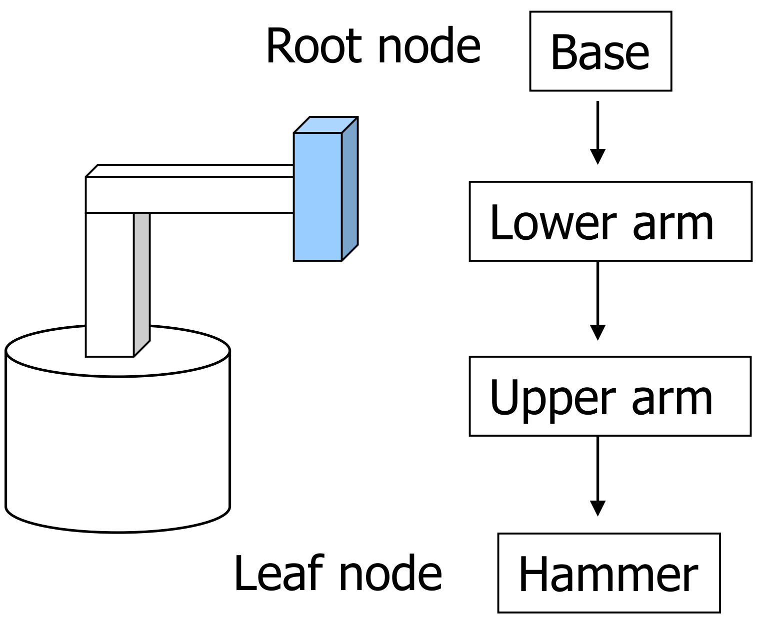
Hierarchical Transforms

- **Robot arm:** Many small **connected** parts
- Attributes (position, orientation, etc) depend on each other



Hierarchical Transforms

- Object dependency description using tree structure

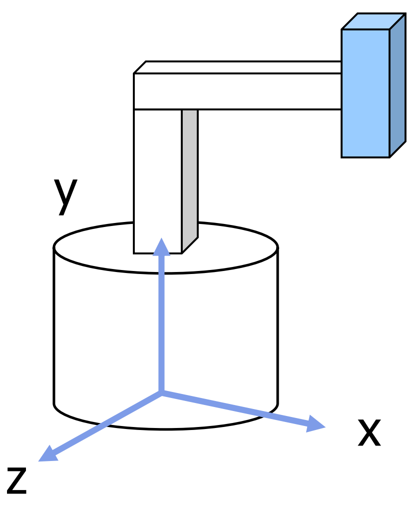


Object position and orientation can be affected by its parent, grand-parent, grand-grand-parent … nodes

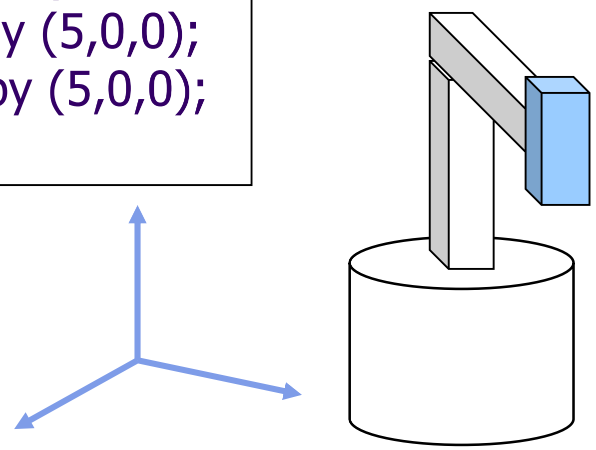
Hierarchical representation is known as a **Scene Graph**

Transformations

- Two ways to specify transformations:
  - **(1) Absolute transformation:** each part transformed independently (relative to origin)



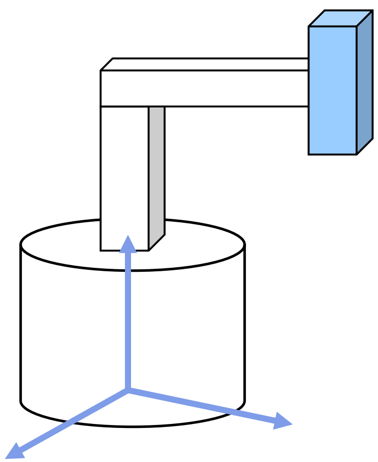
Translate the base by (5,0,0);
Translate the lower arm by (5,0,0);
Translate the upper arm by (5,0,0);
…



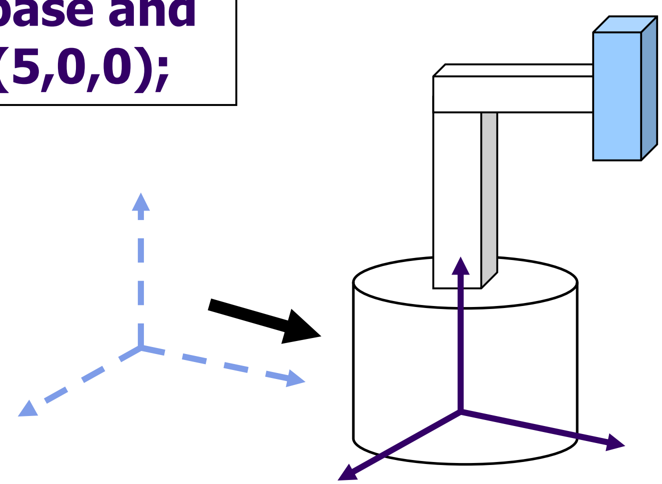
Relative Transformation

A better (and easier) way:

(2) **Relative transformation:** Specify transformation for each object relative to its parent

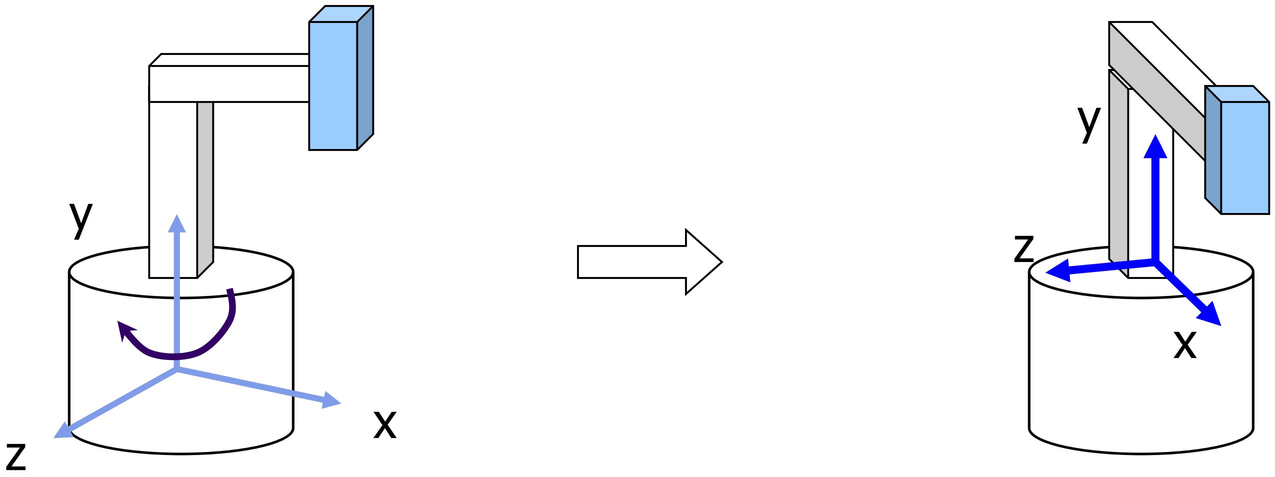


Step 1: Translate base and its child nodes by (5,0,0);



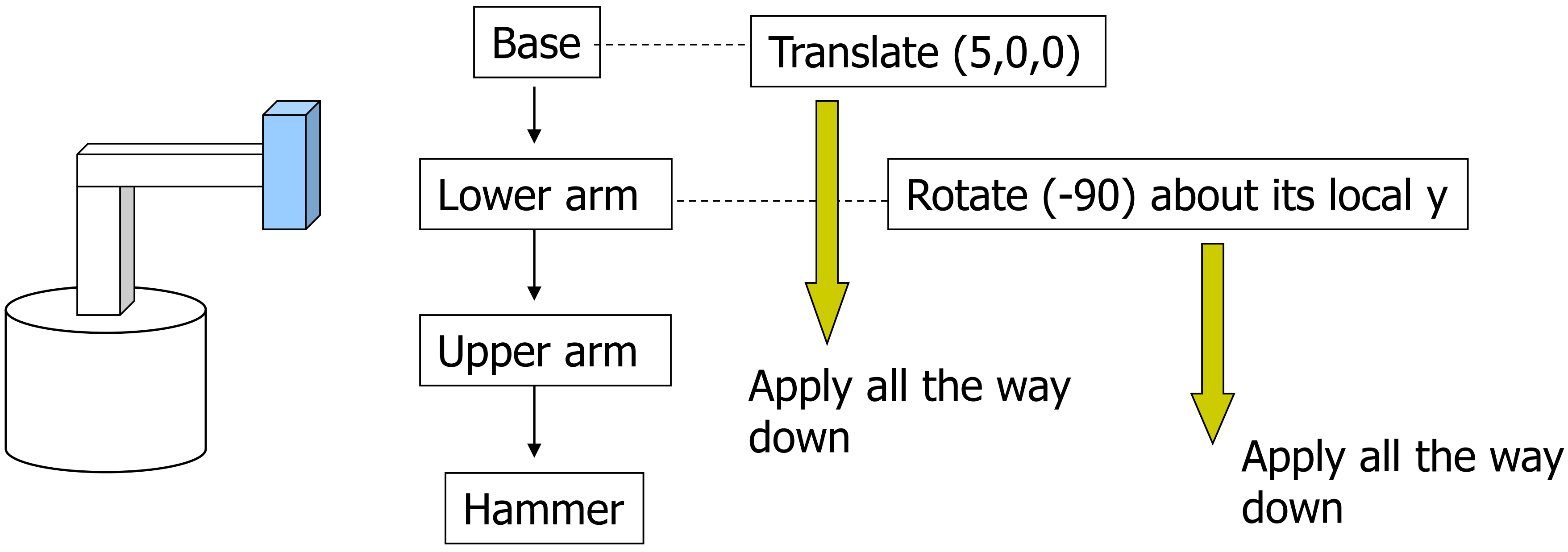
Relative Transformation

Step 2: Rotate the lower arm and all its descendants relative to the base's local y axis by -90 degree



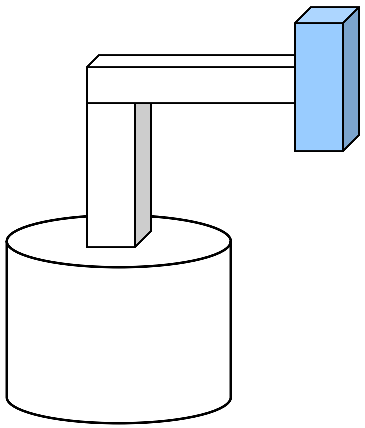
Relative Transformation

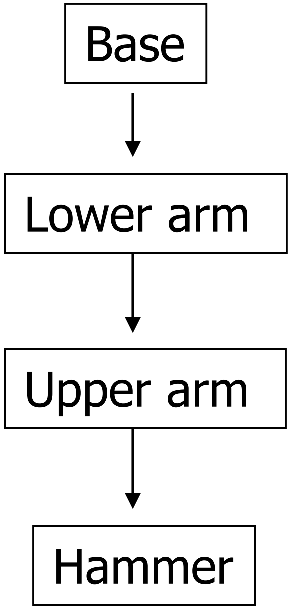
- Relative transformation using scene graph



Hierarchical Transforms Using OpenGL

- Translate base and all its descendants by (5,0,0)
- Rotate lower arm and its descendants by -90 degree about local y

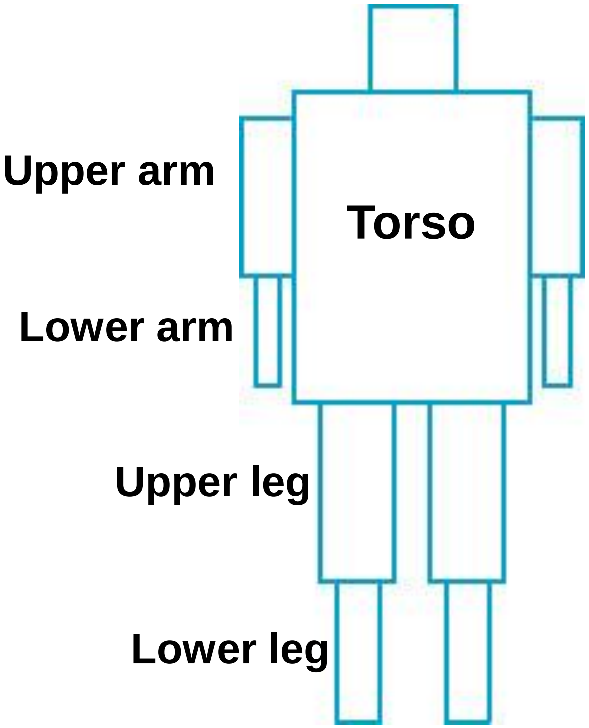





```
ctm = LoadIdentity();

... // setup your camera

ctm = ctm * Translatef(5,0,0);

Draw_base();

ctm = ctm * Rotatef(-90, 0, 1, 0);

Draw_lower _arm();
Draw_upper_arm();
Draw_hammer();
```

Hierarchical Modeling

- For large objects with many parts, need to transform **groups** of objects
- Need better tools



Hierarchical Modeling

- Previous CTM had 1 level
- **Hierarchical modeling:** extend CTM to stack with multiple levels using linked list
- Manipulate stack levels using 2 operations
  - pushMatrix
  - popMatrix

Current top
Of CTM stack →

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

PushMatrix

- **PushMatrix( ):** Save current modelview matrix (CTM) in stack
- Positions 1 & 2 in linked list **are same** after PushMatrix

Before PushMatrix

Current top Of CTM stack →

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

After PushMatrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

← Current top Of CTM stack

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Saved copy of matrix at CTM top

PushMatrix

- Further Rotate, Scale, Translate affect only top matrix
- E.g. `ctm = ctm * Translate (3,8,6)`

After PushMatrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 & 3 \\ 0 & 1 & 0 & 8 \\ 0 & 0 & 1 & 6 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

← Translate(3,8,6) applied only to current top Of CTM stack

↓

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

← Matrix in second position saved. Unaffected by Translate(3,8,6)

PopMatrix

- **PopMatrix( ):** Delete position 1 matrix, position 2 matrix becomes top

Before PopMatrix

Current top Of CTM stack →

$$\begin{pmatrix} 1 & 5 & 4 & 0 \\ 0 & 2 & 2 & 0 \\ 0 & 6 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

← Delete this matrix

↓

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

After PopMatrix

Current top Of CTM stack →

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

PopMatrix and PushMatrix Illustration

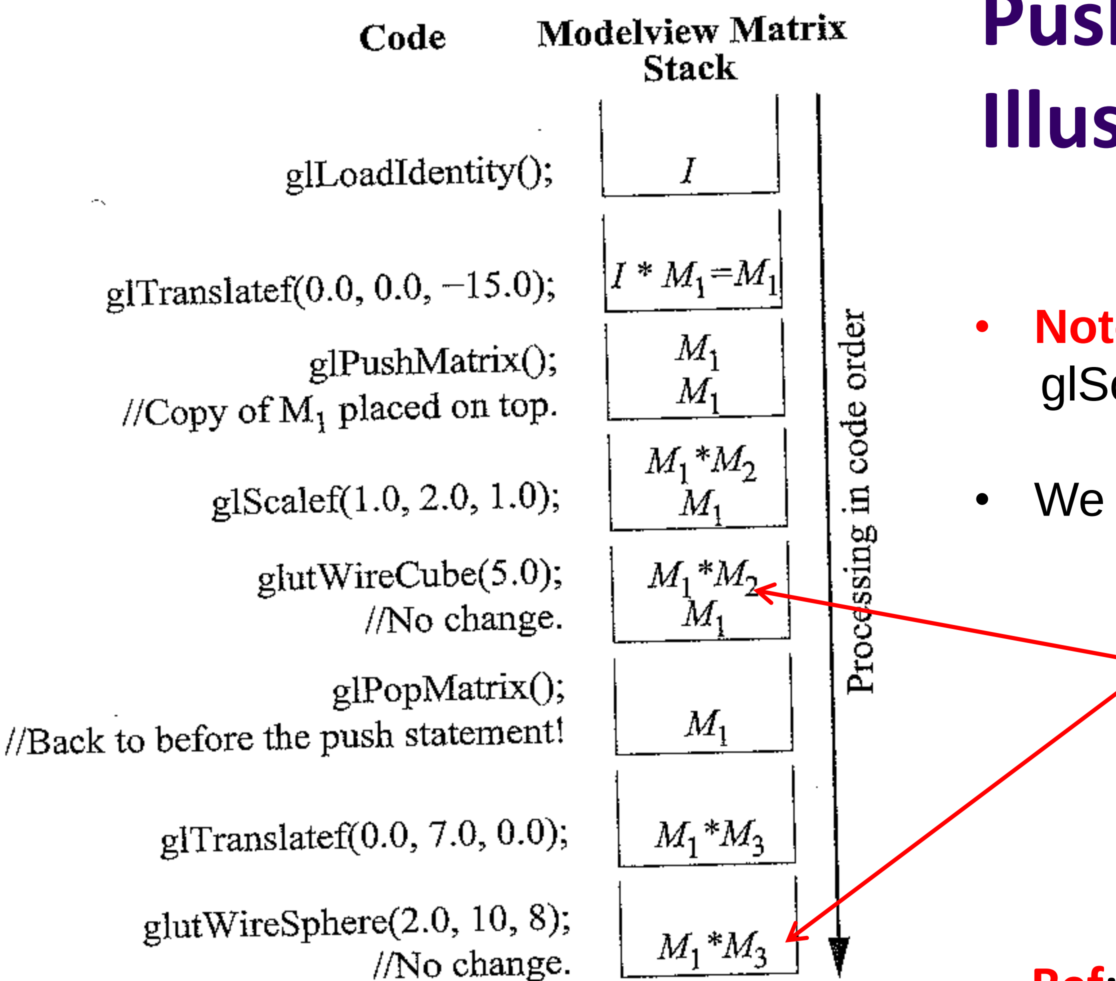


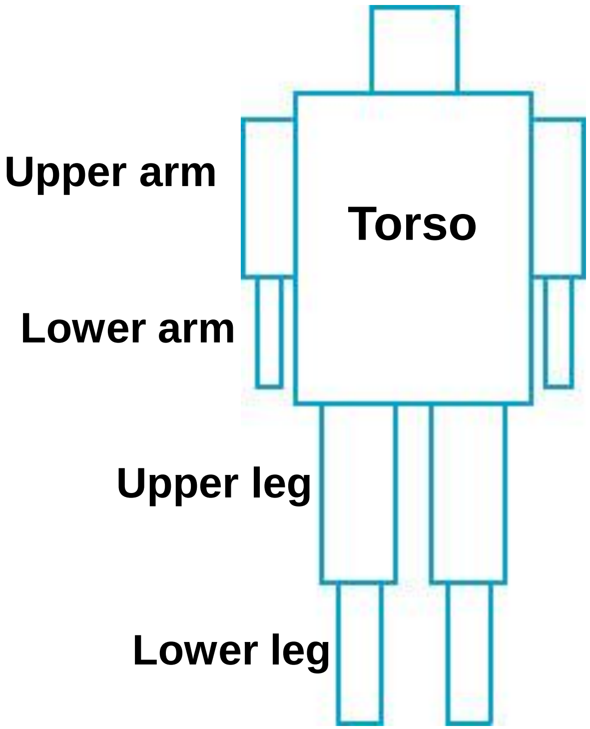
Figure 4.19: Transitions of the modelview matrix stack.

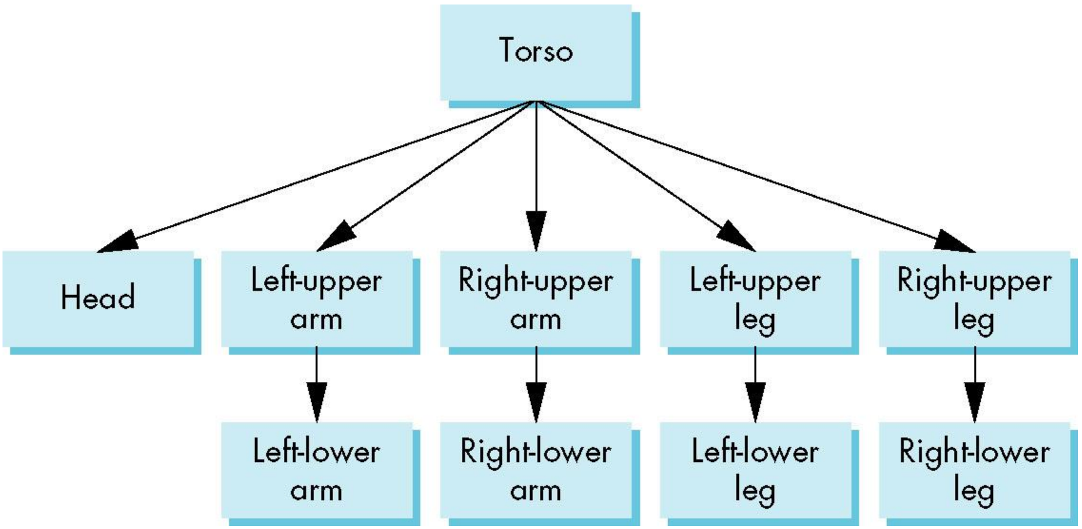
- **Note:** Diagram uses old glTranslate, glScale, etc commands
- We want same behavior though

Apply matrix at top of CTM to vertices of object created

Ref: Computer Graphics Through OpenGL by Guha

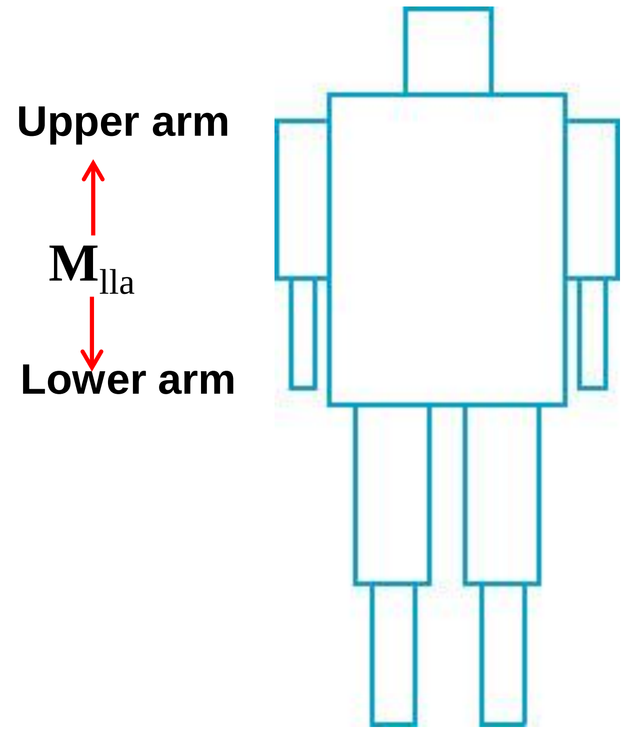
Humanoid Figure





Building the Model

- Draw each part as a function
  - **`torso()`**
  - **`left_upper_arm(), etc`**
- **Transform Matrices:** transform of node wrt its parent
  - $\mathbf{M}_{lla}$ positions left lower arm with respect to left upper arm
- Stack based traversal (push, pop)



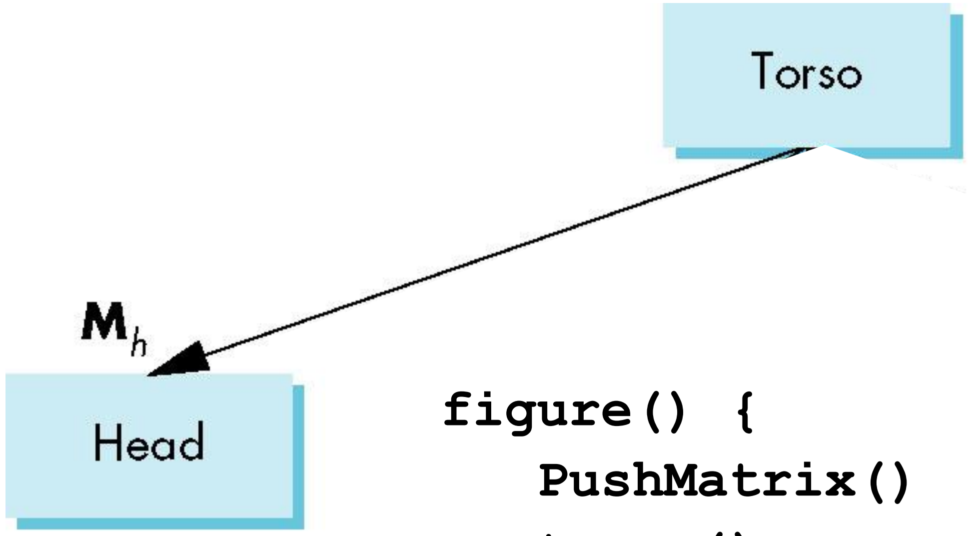
Draw Humanoid using Stack


```
figure() {
    PushMatrix()
    torso();
```

save present model-view matrix (→ `PushMatrix()`)

draw torso (→ `torso();`)

Draw Humanoid using Stack

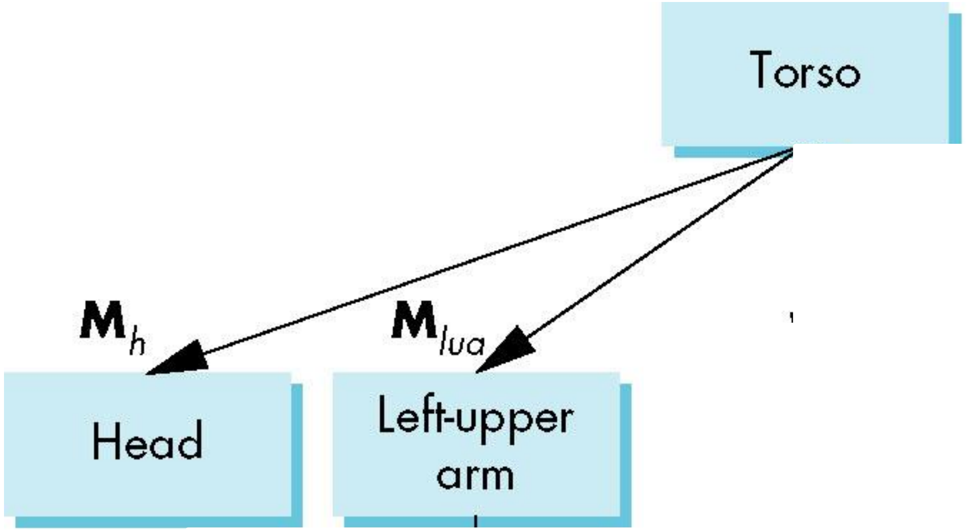



```
figure() {
    PushMatrix()
    torso();
    Rotate (…);
    head();
```

(M_h) Transformation of head Relative to torso

draw head

Draw Humanoid using Stack



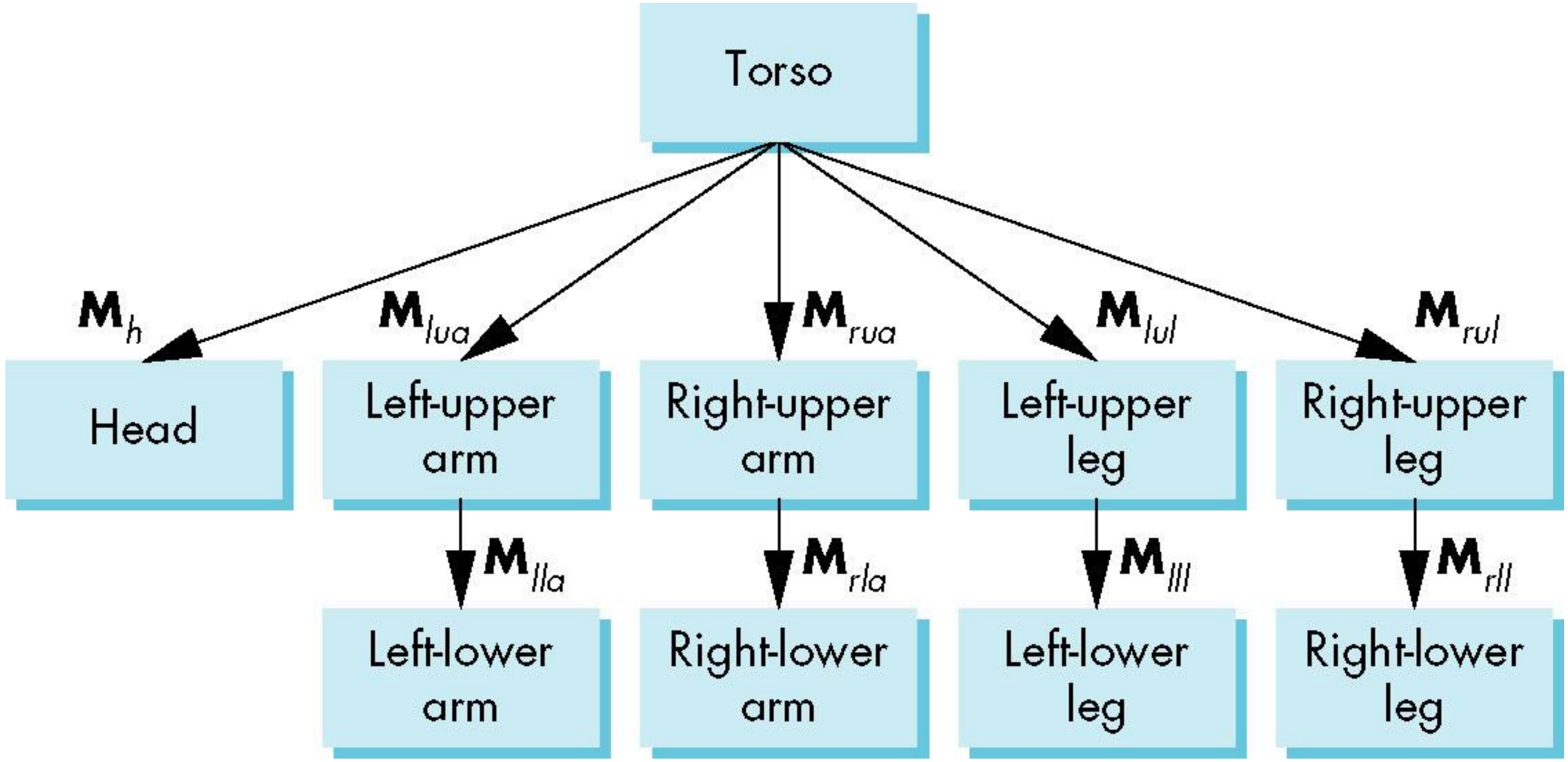
Go back to torso matrix, and save it again

(M_{lua}) Transformation(s) of left upper arm relative to torso

draw left-upper arm

```
PushMatrix()
torso();
Rotate (…);
head();
PopMatrix();
PushMatrix();
Translate(…);
Rotate(…);
left_upper_arm();
……. .
// rest of code()
```

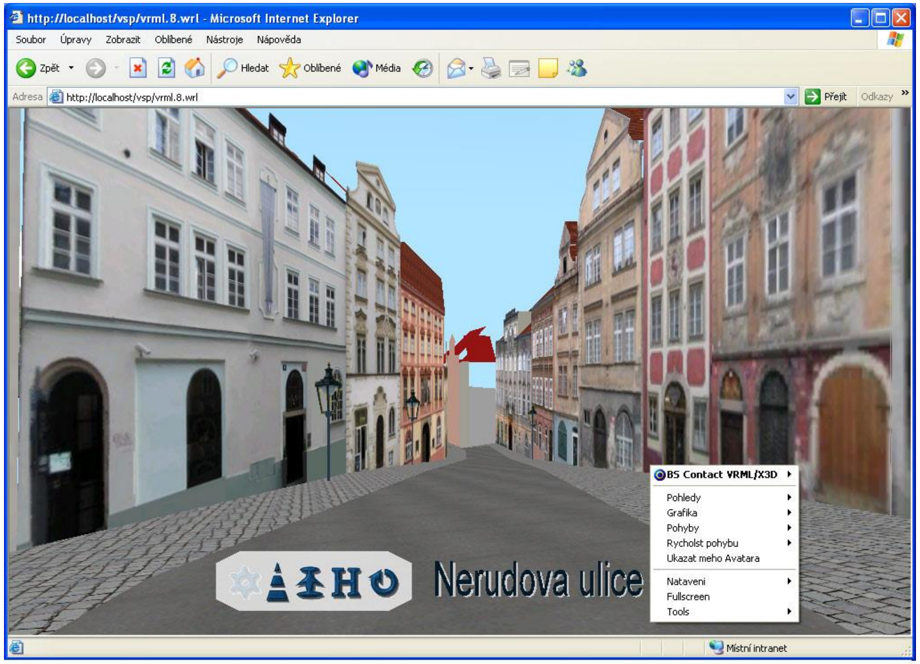
Complete Humanoid Tree with Matrices



Scene graph of Humanoid Robot

VRML

- Scene graph introduced by SGI Open Inventor
- Used in many graphics applications (Maya, etc)
- Virtual Reality Markup Language
  - Scene graph representation of virtual worlds on Web
  - Scene parts can be distributed across multiple web servers
  - Implemented using OpenGL



References

- Angel and Shreiner, Interactive Computer Graphics (6^{th} edition), Chapter 8

Exam 1 Next Week

Exam 1 Overview

- Tuesday, February 14, in-class
- Will cover up to lecture 4 (hierarchical transforms)
- Can bring:
  - One page cheat-sheet, hand-written (not typed)
  - Calculator
- Will test:
  - Theoretical concepts
  - Mathematics
  - Algorithms
  - Programming
  - OpenGL/GLSL knowledge (program structure and some commands)

What am I Really Testing?

- Understanding of
  - concepts (NOT only programming)
  - programming (pseudocode/syntax)
- Test that:
  - you can plug in numbers by hand to check your programs
  - you did the projects
  - you understand what you did in projects

General Advise

- **Read your projects** and refresh memory of what you did
- **Read the slides**: worst case – if you understand slides, you're more than 50% prepared
- Try to **predict subtle changes** to algorithm.. What ifs?..
- **Past exams**: One sample midterm is on website
- All lectures have references. Look at refs to focus reading
- Do all readings I asked you to do on your own

Grading Policy

- I try to give as much partial credit as possible
- In time constraints, laying out outline of solution gets you healthy chunk of points
- Try to write something for each question
- Many questions will be easy, exponentially harder to score higher in exam

Introduction

- Motivation for CG
- Uses of CG (simulation, image processing, movies, viz, etc)
- Elements of CG (polylines, raster images, filled regions, etc)
- Device dependent graphics libraries (OpenGL, DirectX, etc)

OpenGL/GLUT

- High-level:
  - What is OpenGL?
  - What is GLUT?
  - What is GLSL
  - Functionality, how do they work together?
- Sequential Vs. Event-driven programming
- OpenGL/GLUT program structure (create window, init, callback registration, etc)
- GLUT callback functions (registration and response to events)

OpenGL Drawing

- Vertex Buffer Objects
- glDrawArrays
- OpenGL :
  - Drawing primitives: GL_POINTS, GL_LINES, etc (should be conversant with the behaviors of major primitives)
  - Data types
  - Interaction: keyboard, mouse (GLUT_LEFT_BUTTON, etc)
  - OpenGL state
- GLSL Command format/syntax
- Vertex and fragments shaders
- Shader setup, How GLSL works

2D Graphics: Coordinate Systems

- Screen coordinate system/Viewport
- World coordinate system/World window
- Setting Viewport
- Tiling, aspect ratio

Fractals

- What are fractals?
  - Self similarity
  - Applications (clouds, grass, terrain etc)
- Mandelbrot set
  - Complex numbers: s, c, orbits, complex number math
  - Dwell function
  - Assigning colors
  - Mapping mandelbrot to screen
- Koch curves, gingerbread man, hilbert transforms

Points, Scalars Vectors

- Vector Operations:
  - Addition, subtraction, scaling
  - Magnitude
  - Normalization
  - Dot product
  - Cross product
  - Finding angle between two vectors
- Finding normal of plane using cross product, Newell method

Transforms

- Homogeneous coordinates Vs. Ordinary coordinates
- 2D/3D affine transforms: rotation, scaling, translation, shearing
- Should be able to take problem description and build transforms and apply to vertices
- 2D: rotation (scaling, etc) about arbitrary center:
  - $T(Px,Py)\ R(\theta)\ T(-Px,-Py) * P$
- Composing transforms
- 3D rotation:
  - x-roll, y-roll, z-roll, about arbitrary vector (Euler theorem) if given azimuth, latitude of vector or (x, y, z) of normalized vector
- Matrix multiplication!!
- Hierarchical transforms!!

Building 3D Models

- Drawing Polygonal meshes
- Edge list
- Vertex List