Introduction to Computer Graphics with WebGL

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Hierarchical Modeling I

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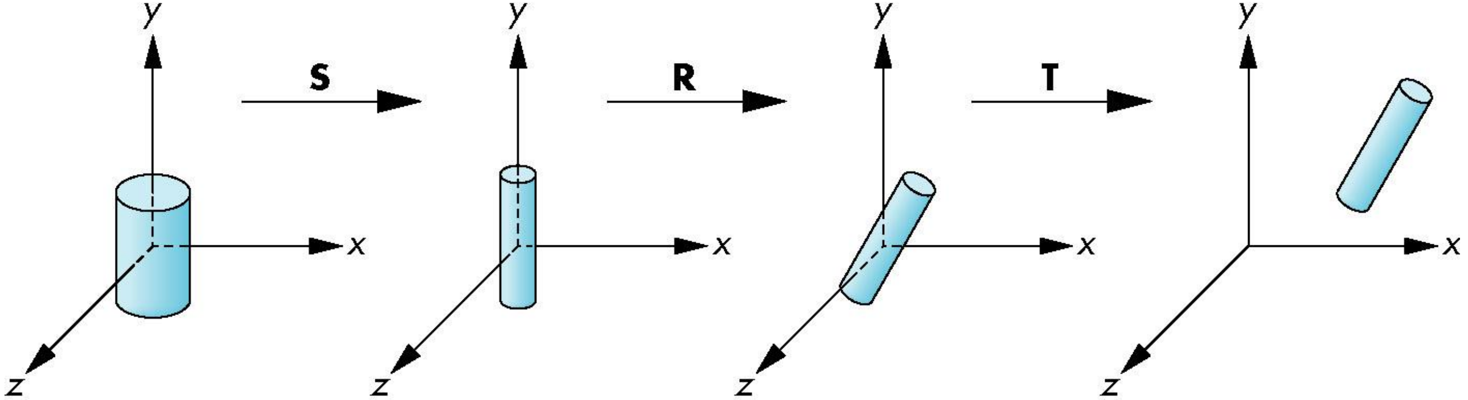
Objectives

- 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
  - Defines instance transformation



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

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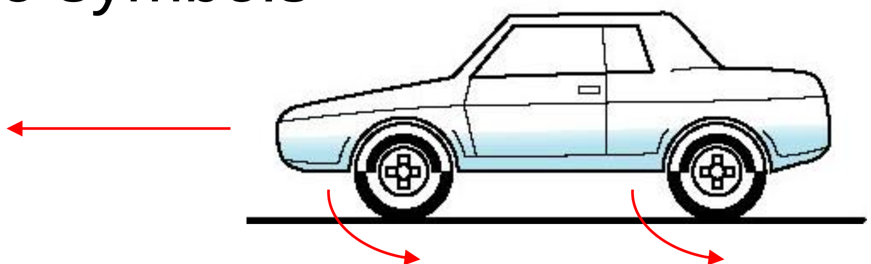
- Symbol-instance table does not show relationships between parts of model
- Consider model of car
  - Chassis + 4 identical wheels
  - Two symbols



- Rate of forward motion determined by rotational speed of wheels

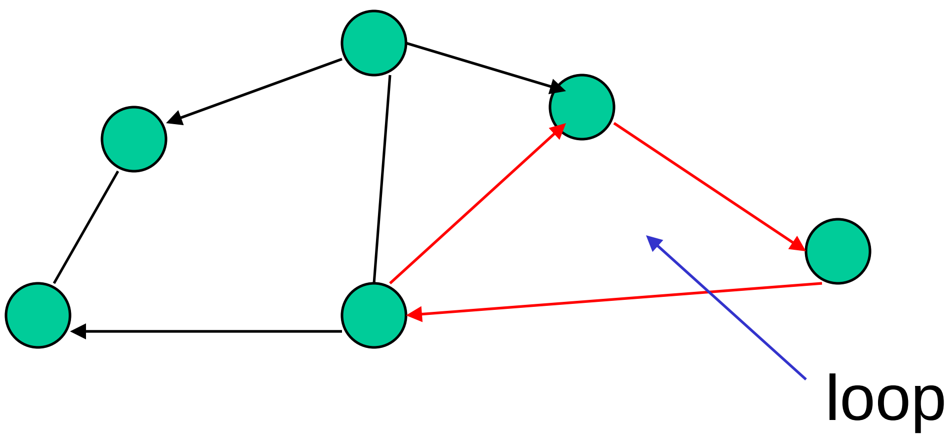
Structure Through Function Calls

```
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

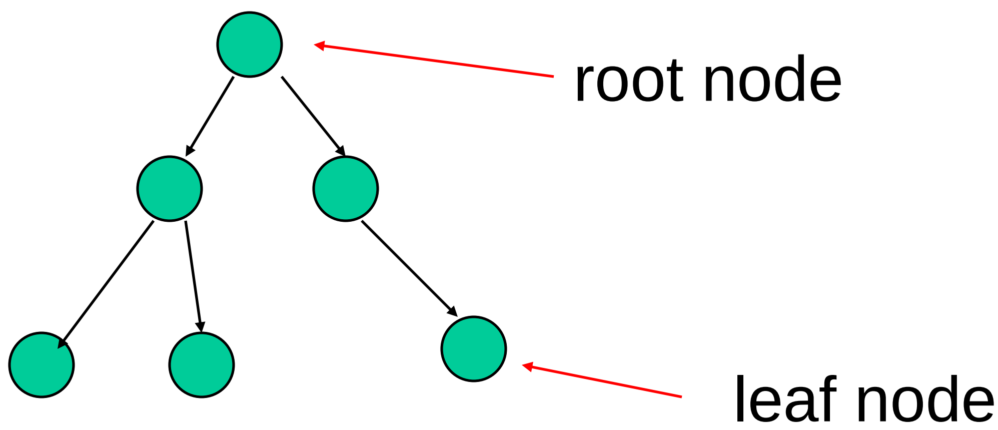
Graphs

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

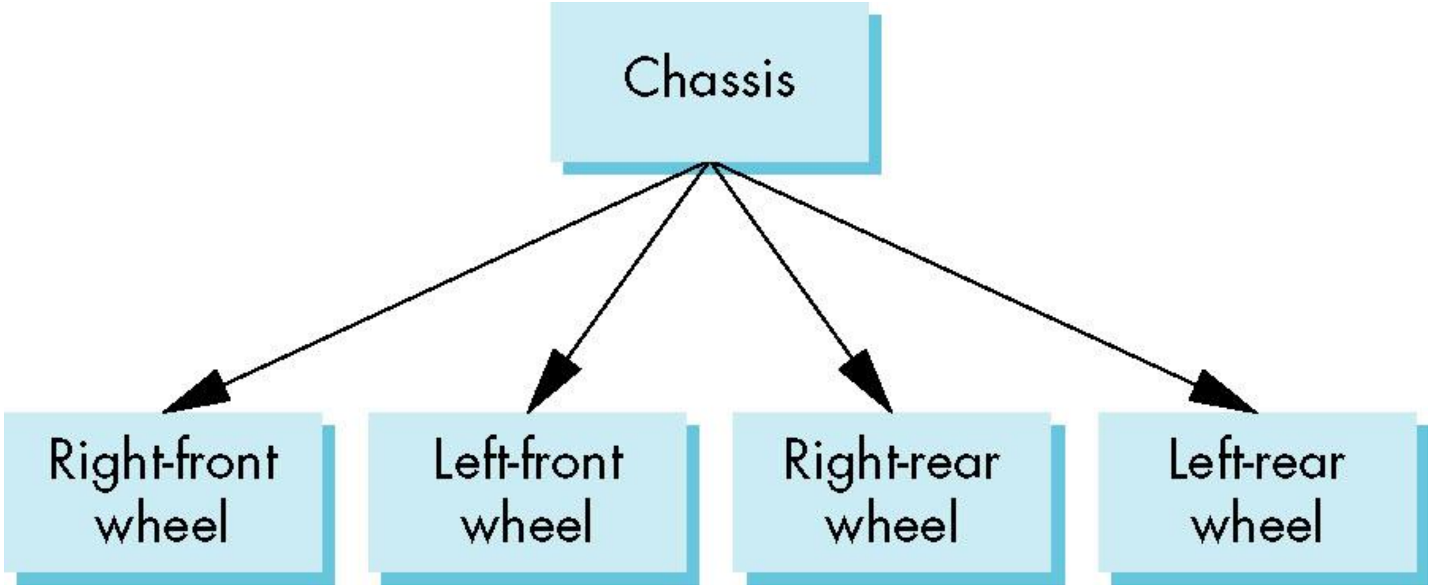


Tree

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

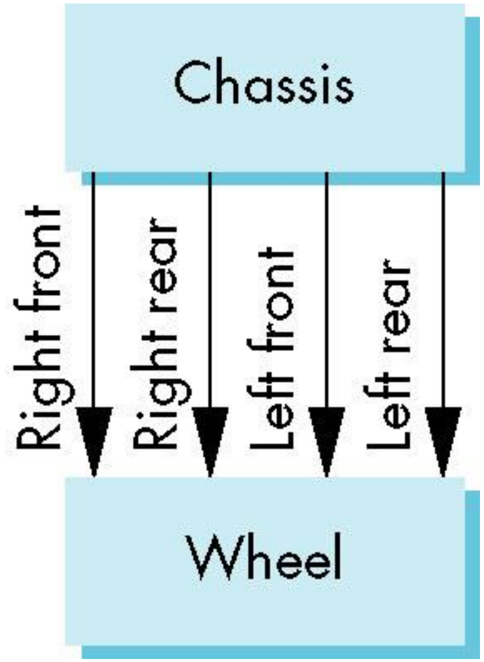


Tree Model of Car



DAG Model

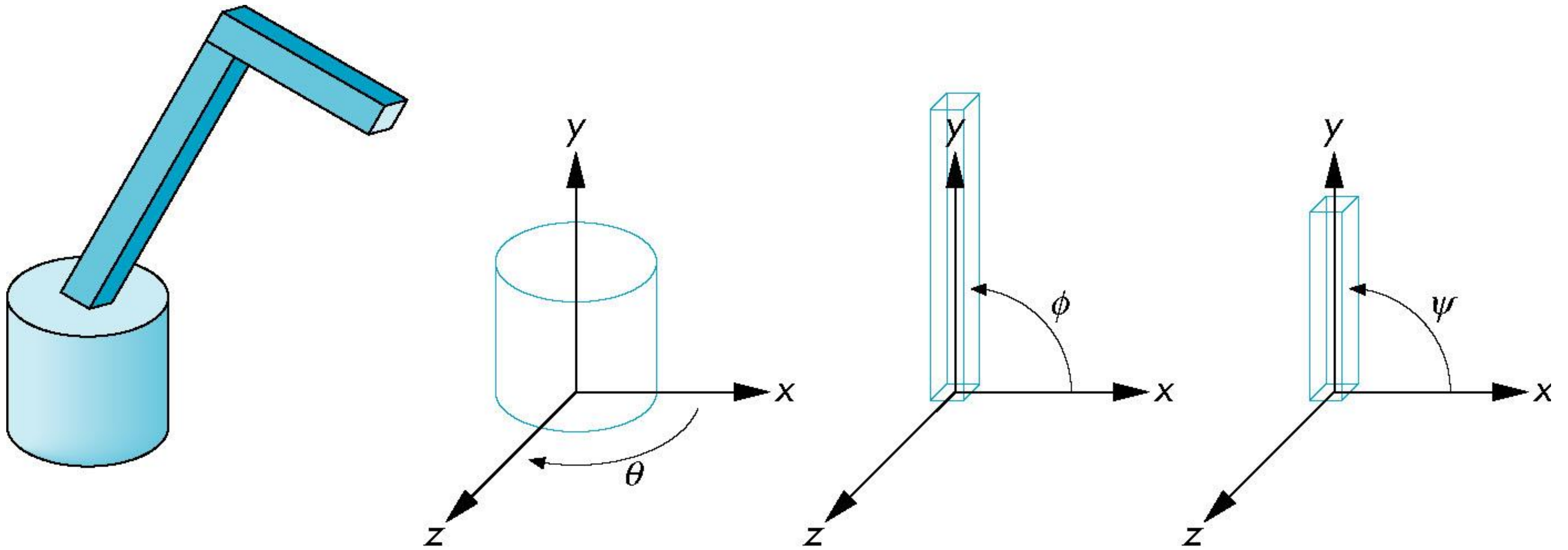
- If we use the fact that all the wheels are identical, we get a *directed acyclic graph*
  - Not much different than dealing with a tree



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

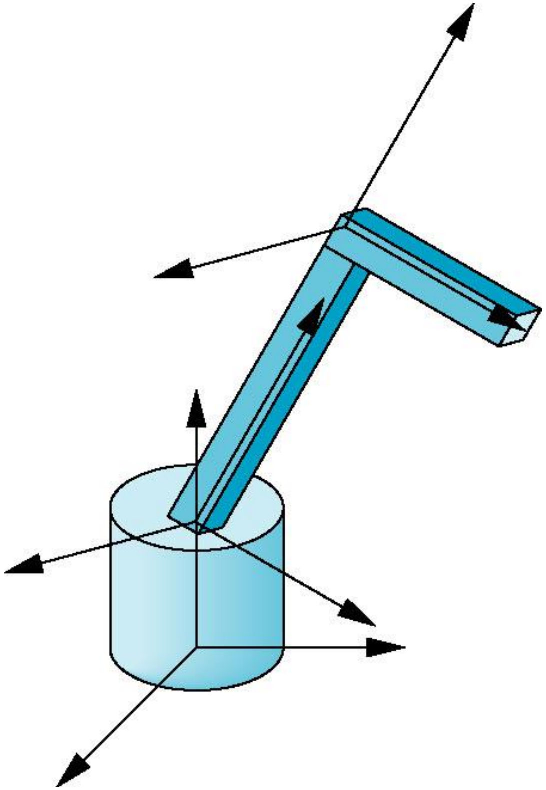


robot arm

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 relative 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 relative 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

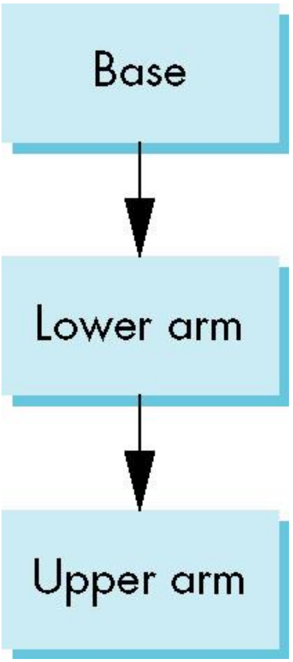
WebGL Code for Robot

```
var render = function() {
   gl.clear( gl.COLOR_BUFFER_BIT | gl.DEPTH_BUFFER_BIT );
   modelViewMatrix = rotate(theta[Base], 0, 1, 0 );
   base();
   modelViewMatrix = mult(modelViewMatrix,
           translate(0.0, BASE_HEIGHT, 0.0));
   modelViewMatrix = mult(modelViewMatrix,
            rotate(theta[LowerArm], 0, 0, 1 ));
   lowerArm();
   modelViewMatrix  = mult(modelViewMatrix,
           translate(0.0, LOWER_ARM_HEIGHT, 0.0));
   modelViewMatrix  = mult(modelViewMatrix,
           rotate(theta[UpperArm], 0, 0, 1) );
   upperArm();
   requestAnimFrame(render);
}
```

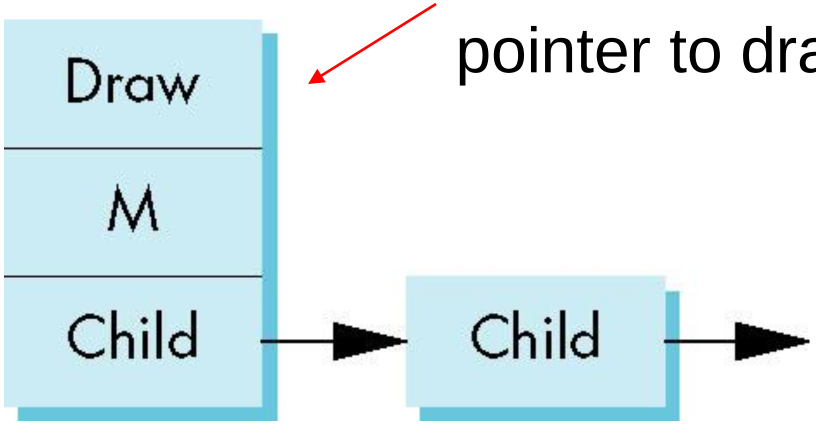
Tree Model of Robot

- 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?

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Hierarchical Modeling II

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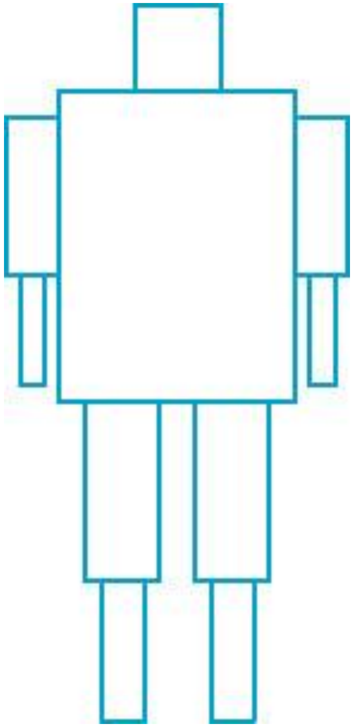
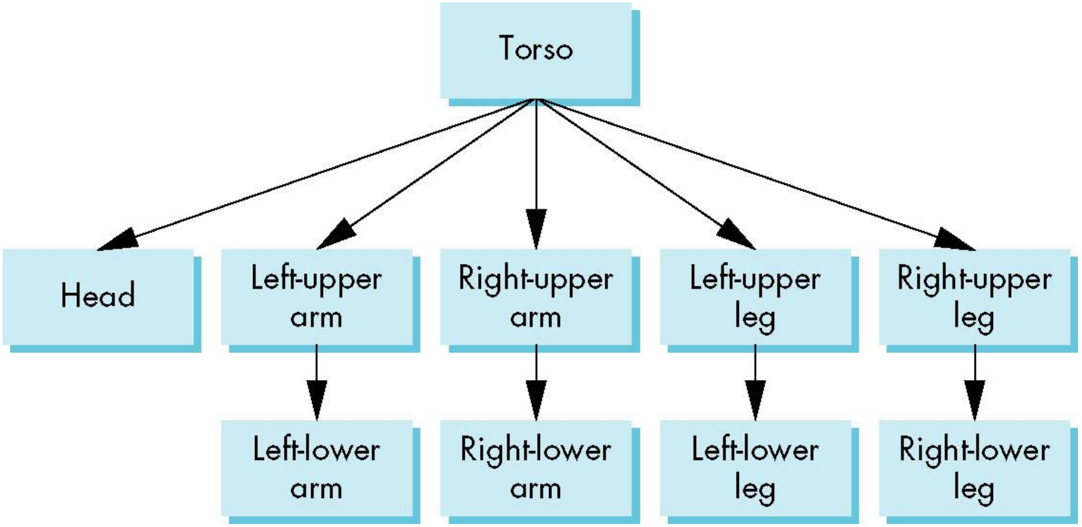
Objectives

- 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

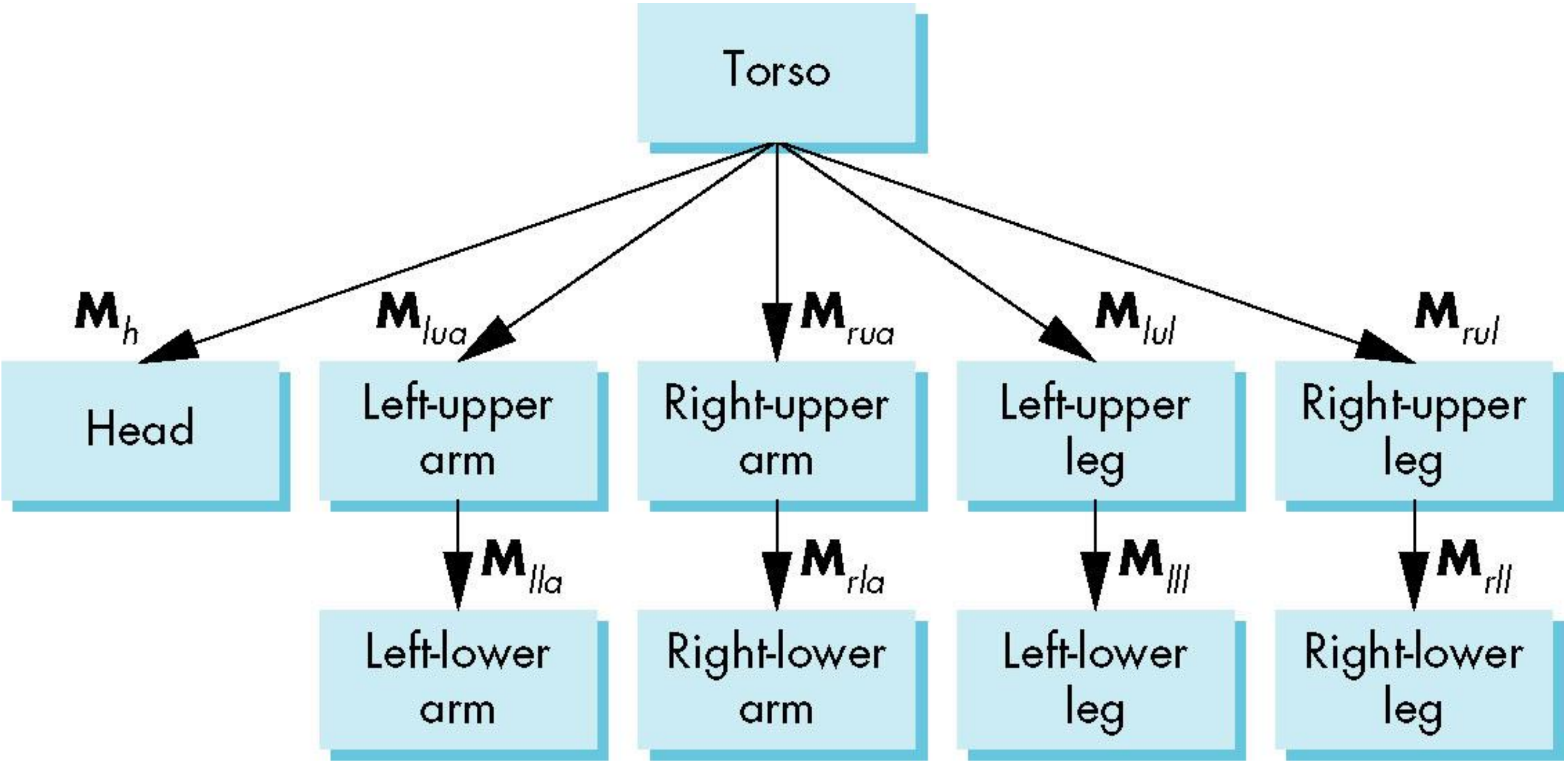




Building the Model

- Can build a simple implementation using quadrics: ellipsoids and cylinders
- Access parts through functions
  - `torso()`
  - `leftUpperArm()`
- 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
  - $\mathbf{M}$ 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 $\mathbf{M}$ and draw torso
- Set model-view matrix to $\mathbf{MM}_\mathrm{h}$ and draw head
- For left-upper arm need $\mathbf{MM}_\mathrm{lua}$ and so on
- Rather than recomputing $\mathbf{MM}_\mathrm{lua}$ from scratch or using an inverse matrix, we can use the matrix stack to store $\mathbf{M}$ and other matrices as we traverse the tree

Traversal Code


```
figure() {
    PushMatrix()
    torso();
    Rotate (…);
    head();
    PopMatrix();
    PushMatrix();
    Translate(…);
    Rotate(…);
    left_upper_arm();
    PopMatrix();
    PushMatrix();
```

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

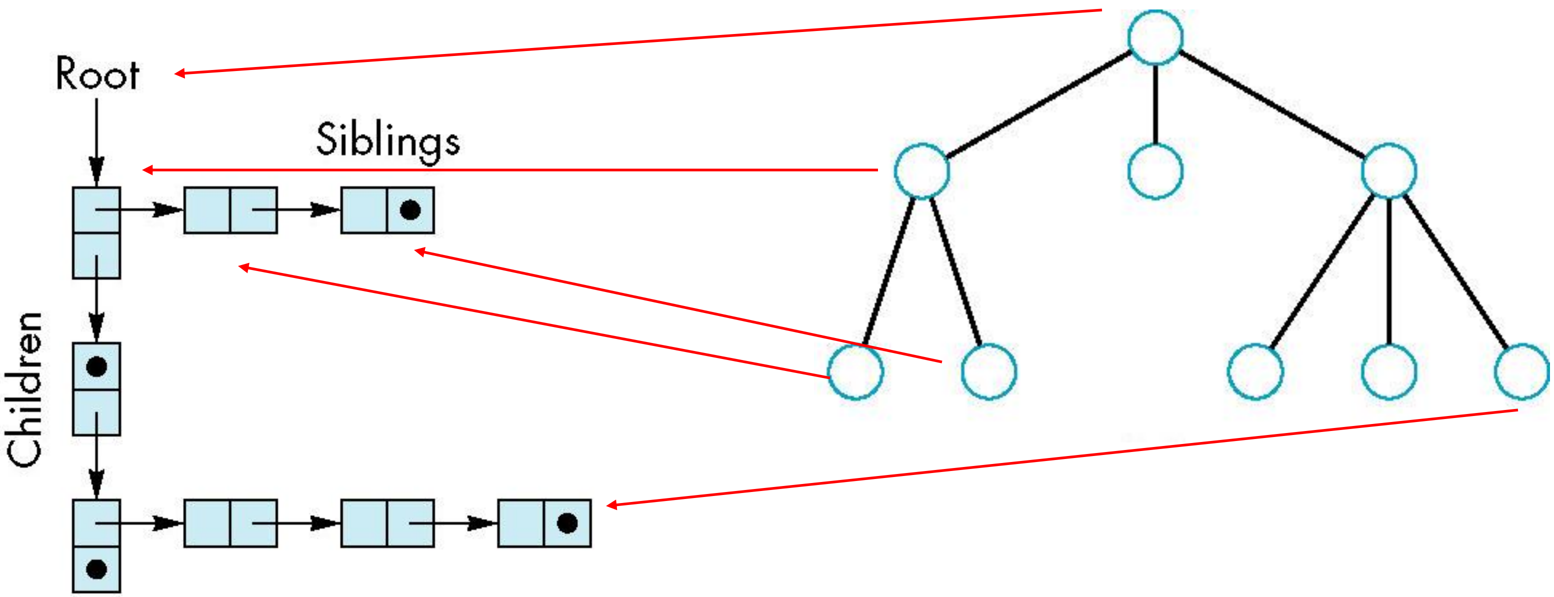
Analysis

- 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 push and pop other attributes 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 WebGL this matrix is a 1D array storing matrix by columns

Creating a treenode

```
function createNode(transform,
            render, sibling, child) {
   var node = {
   transform: transform,
   render: render,
   sibling: sibling,
   child: child,
   }
   return node;
};
```

Initializing Nodes

```
function initNodes(Id) {
    var m = mat4();
        switch(Id) {
        case torsoId:
             m = rotate(theta[torsoId], 0, 1, 0 );
           figure[torsoId] = createNode( m, torso, null, headId );
           break;
      case head1Id:
      case head2Id:
           m = translate(0.0, torsoHeight+0.5*headHeight, 0.0);
           m = mult(m, rotate(theta[head1Id], 1, 0, 0));
          m = mult(m, rotate(theta[head2Id], 0, 1, 0));
           m = mult(m, translate(0.0, -0.5*headHeight, 0.0));
           figure[headId] = createNode( m, head, leftUpperArmId, null);
           break;
```

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 **`rotate`** and **`translate`**
- Because the matrix is formed using the model-view matrix, we may want to first push original model-view matrix on matrix stack

Preorder Traversal

```
function traverse(Id) {
   if(Id == null) return;
   stack.push(modelViewMatrix);
   modelViewMatrix = mult(modelViewMatrix, figure[Id].transform);
   figure[Id].render();
   if(figure[Id].child != null) traverse(figure[Id].child);
   modelViewMatrix = stack.pop();
   if(figure[Id].sibling != null) traverse(figure[Id].sibling);
 }
var render = function() {
        gl.clear( gl.COLOR_BUFFER_BIT );
        traverse(torsoId);
        requestAnimFrame(render);
}
```

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

- Because we are using JS, the nodes and the node structure can be changed during execution
- Definition of nodes and traversal are essentially the same as before but we can add and delete nodes during execution
- In desktop OpenGL, if we use pointers, the structure can be dynamic

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Graphical Objects and Scene Graphs 1

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Objectives

- Introduce graphical objects
- Generalize the notion of objects to include lights, cameras, attributes
- Introduce scene graphs

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 disappeared from the graphical system
- To redraw the object, either changed or the same, we had to reexecute the code
- Display lists provided only a partial solution to this problem

Retained Mode Graphics

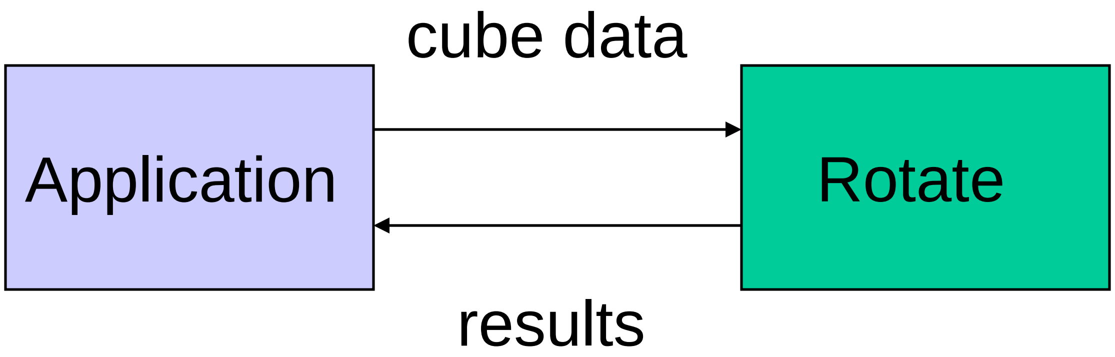
- Display lists were server side
- GPUs allowed data to be stored on GPU
- Essentially all immediate mode functions have been deprecated
- Nevertheless, OpenGL is a low level API

OpenGL and Objects

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

Imperative Programming Model

- Example: rotate a cube



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

Object-Oriented Programming 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++/Java/JS

- Can try to use C structs to build objects
- C++/Java/JS provide better support
  - Use class construct
  - With C++ we can hide implementation using public, private, and protected members i
  - JS provides multiple methods for object

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

```
var mycube = new Cube();
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

```
var cube {
        var color[3];
        var matrix[4][4];


}
```

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

Other Objects

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

JS Objects

```
cube mycube;

material plastic;
mycube.setMaterial(plastic);

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

JS Objects

- Can create much like Java or C++ objects
  - constructors
  - prototypes
  - methods
  - private methods and variables

```
var myCube = new Cube();
myCube.color = [1.0, 0.0, 0.0]'
myCube.instance = …….
```

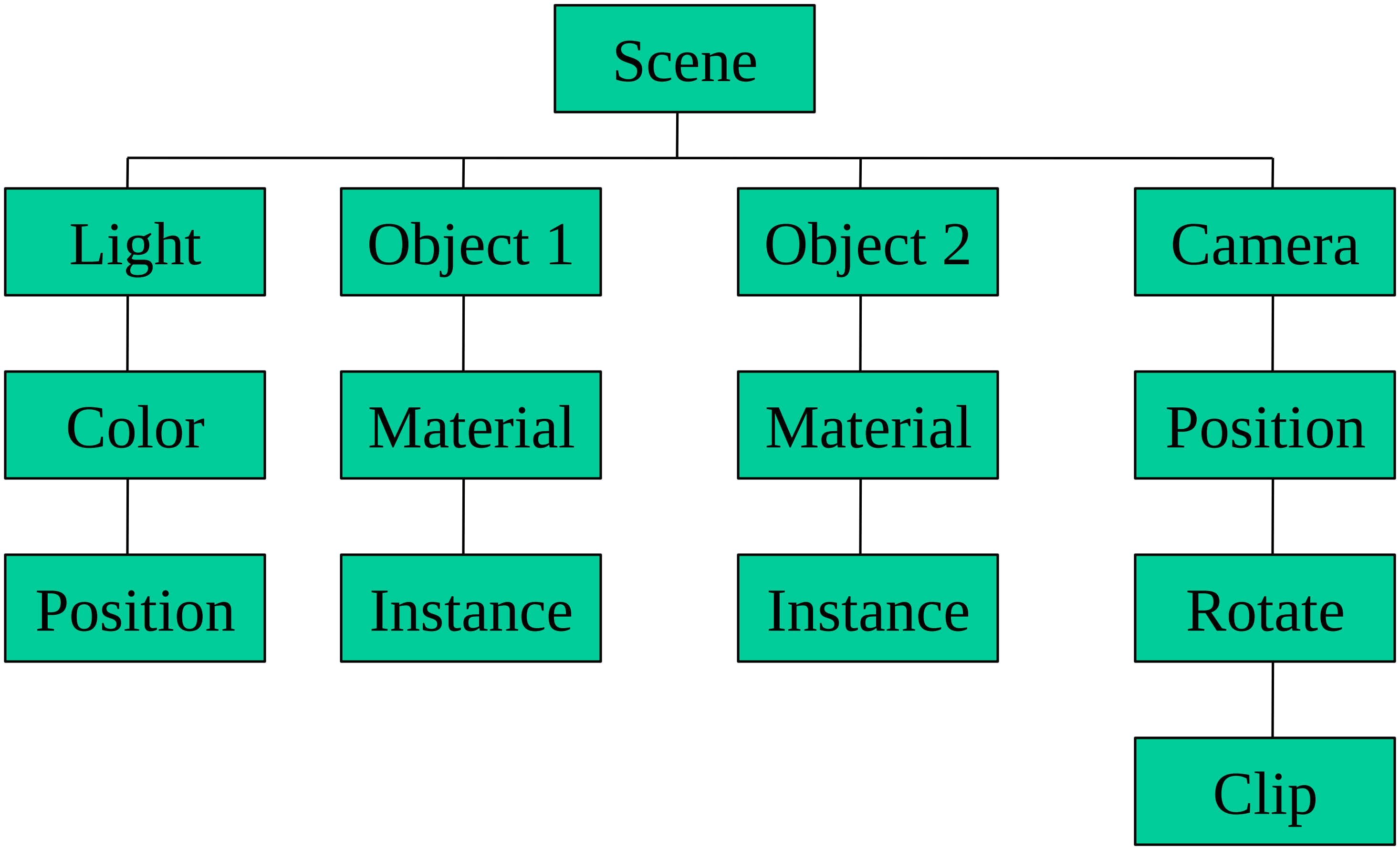
Light Object

```
var myLight = new Light();

// match Phong model

    myLight.type = 0; //directional
    myLight.position = ......;
    myLight.orientation = ......;
    myLight.specular = ......;
    myLight.diffuse = ......;
    myLight.ambient = ......;
}
```

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 JS objects, we should be able to show them in a tree
  - Render scene by traversing this tree

Scene Graph


Scene
Light
Object 1
Object 2
Camera
Color
Material
Material
Position
Position
Instance
Instance
Rotate
Clip

Traversal

```
mySceme = new Scene();
myLight = new Light();
myLight.Color = ……;
…
myscene.Add(myLight);
object1 = new Object();
object1.color = …
myscene.add(object1);
…
…
myscene.render();
```

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Graphical Objects and Scene Graphs 2

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Objectives

- Look at some real scene graphs
- three.js (threejs.org)
- Scene graph rendering

Scene Graph History

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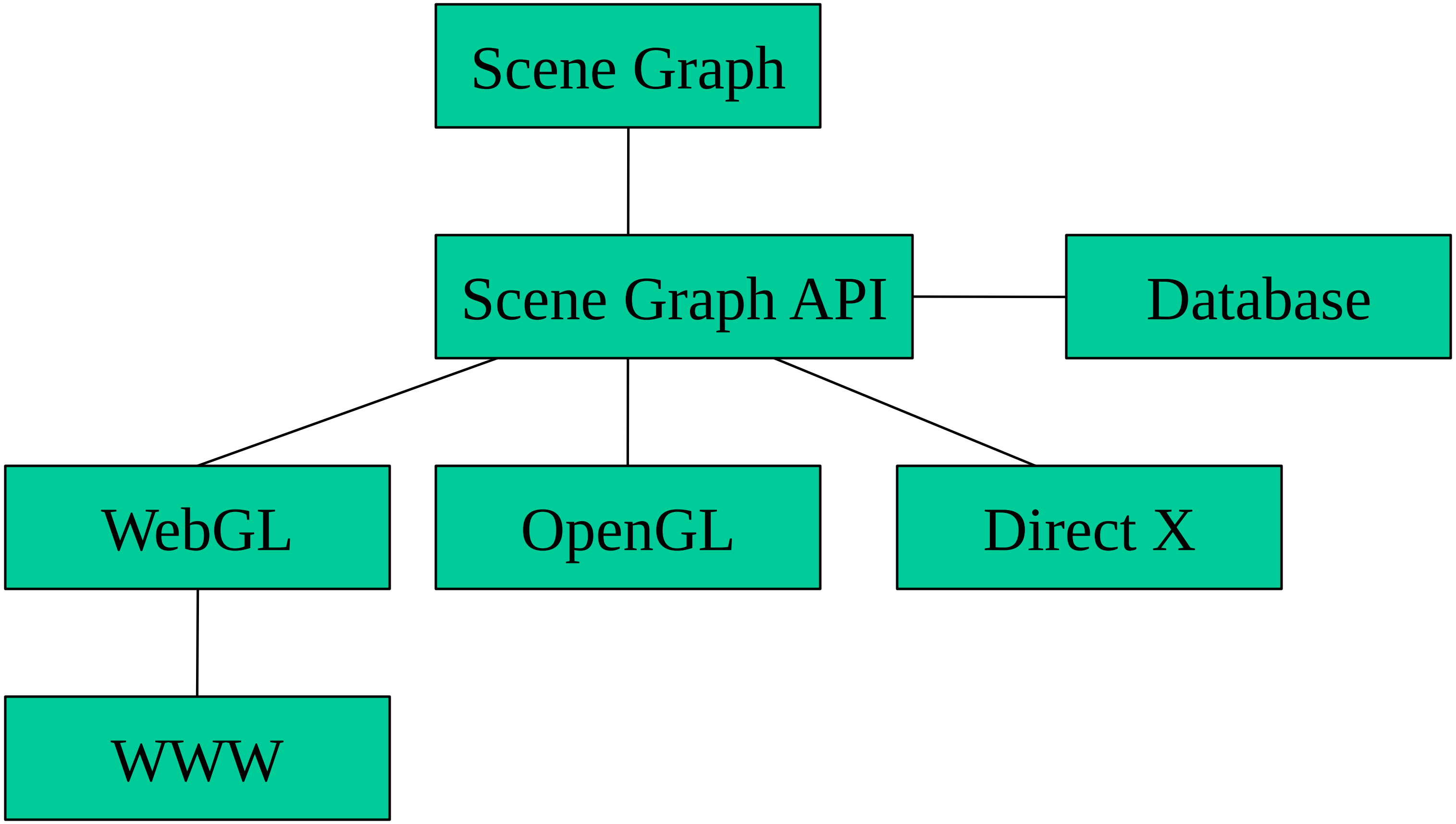
- OpenGL development based largely on people who wanted to exploit hardware
  - real time graphics
  - animation and simulation
  - stand-alone applications
- CAD community needed to be able to share databases
  - real time not and photorealism not issues
  - need cross-platform capability
  - first attempt: PHIGS

Scene Graph Organization



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, WebGL 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

Open Scene Graph

- Supports very complex geometries by adding occulusion culling in first pass
- Supports translucently through a second pass that sorts the geometry
- First two passes yield a geometry list that is rendered by the pipeline in a third pass

three.js

- Popular scene graph built on top of WebGL
  - also supports other renderers
- See threejs.org
  - easy to download
  - many examples
- Also Eric Haines' Udacity course
- Major differences in approaches to computer graphics

three.js scene

```
var scene = new THREE.Scene();
var camera = new THREE.PerspectiveCamera(75,
window.innerWidth/           window.innerHeight, 0.1, 1000);

var renderer = new THREE.WebGLRenderer();
renderer.setSize(window.innerWidth, window.innerHeight);
document.body.appendChild(renderer.domElement);

var geometry = new THREE.CubeGeometry(1,1,1);
var material = new THREE.MeshBasicMaterial({color: 0x00ff00});
var cube = new THREE.Mesh(geometry, material);
scene.add(cube);
camera.position.z = 5;
```

three.js render loop

```
var render = function () {
 requestAnimationFrame(render);
 cube.rotation.x += 0.1;
 cube.rotation.y += 0.1;
 renderer.render(scene, camera);
 };
 render();
```

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Rendering Overview

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Objectives

- Examine what happens between the vertex shader and the fragment shader
- Introduce basic implementation strategies
- Clipping
- Rendering
    - lines
    - polygons
- Give a sample algorithm for each

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Overview

- At end of the geometric pipeline, vertices have been assembled into primitives
- Must clip out primitives that are outside the view frustum
  - Algorithms based on representing primitives by lists of vertices
- Must find which pixels can be affected by each primitive
  - Fragment generation
  - Rasterization or scan conversion

Required Tasks

- Clipping
- Rasterization or scan conversion
- Transformations
- Some tasks deferred until fragment processing
  - Hidden surface removal
  - Antialiasing

Rasterization Meta Algorithms

- Any rendering method process every object and must assign a color to every pixel
- Think of rendering algorithms as two loops
  - over objects
  - over pixels
- The order of these loops defines two strategies
  - image oriented
  - object oriented

Object Space Approach

- **For every object**, determine which pixels it covers and shade these pixels
  - Pipeline approach
  - Must keep track of depths for HSR
  - Cannot handle most global lighting calculations
  - Need entire framebuffer available at all times

Image Space Approach

- **For every pixel**, determine which object that projects on the pixel is closest to the viewer and compute the shade of this pixel
  - Ray tracing paradigm
  - Need all objects available
- Patch Renderers
  - Divide framebuffer into small patches
  - Determine which objects affect each patch
  - Used in limited power devices such as cell phones

Algorithm Experimentation

- Create a framebuffer object and use render-to-texture to create a virtual framebuffer into which you can write individual pixels