#5: Models & Scenes

CSE167: Computer Graphics
Instructor: Ronen Barzel
UCSD, Winter 2006

Outline For Today

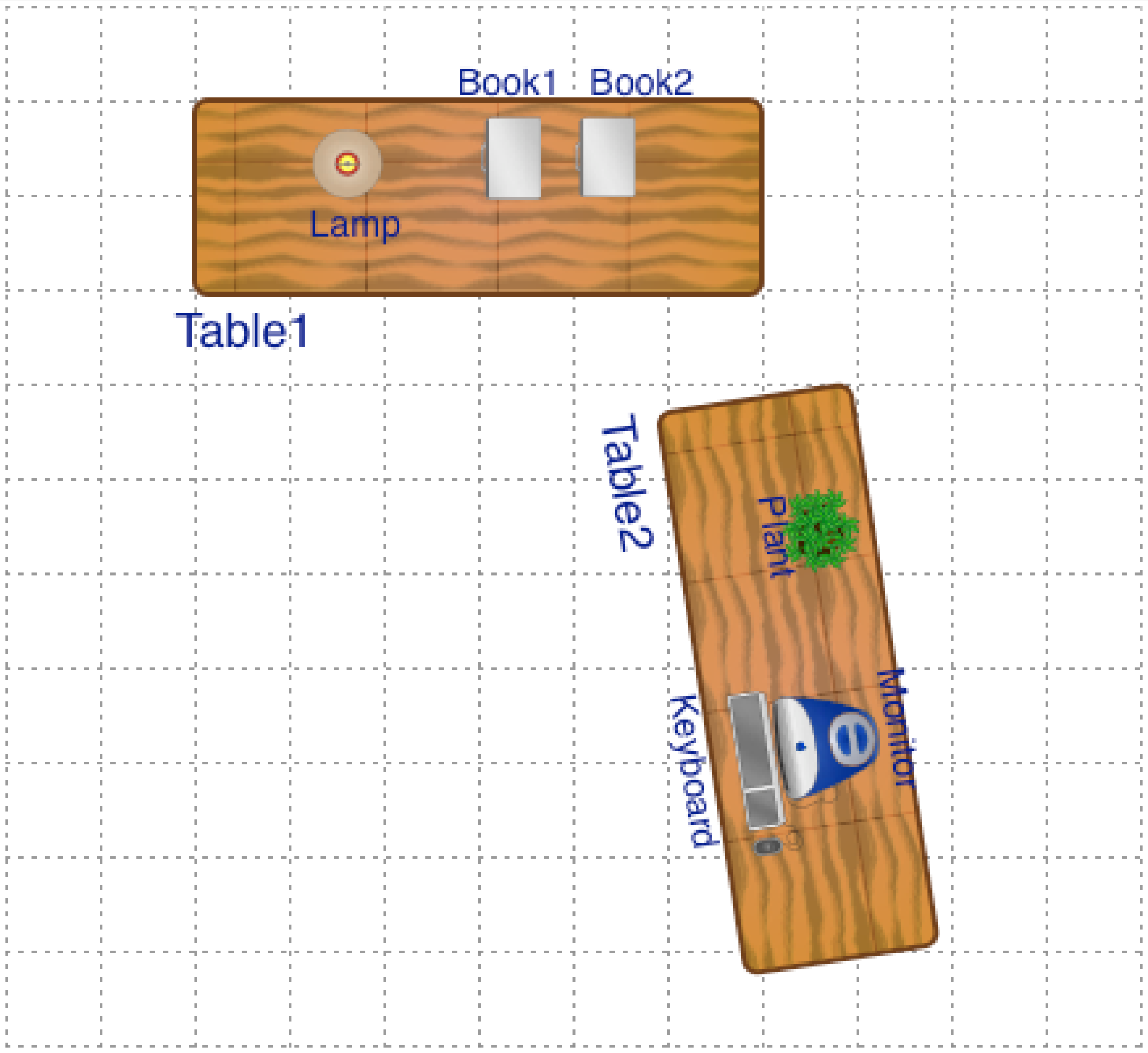
- *Scene Graphs*
- Shapes
- Tessellation

Modeling by writing a program

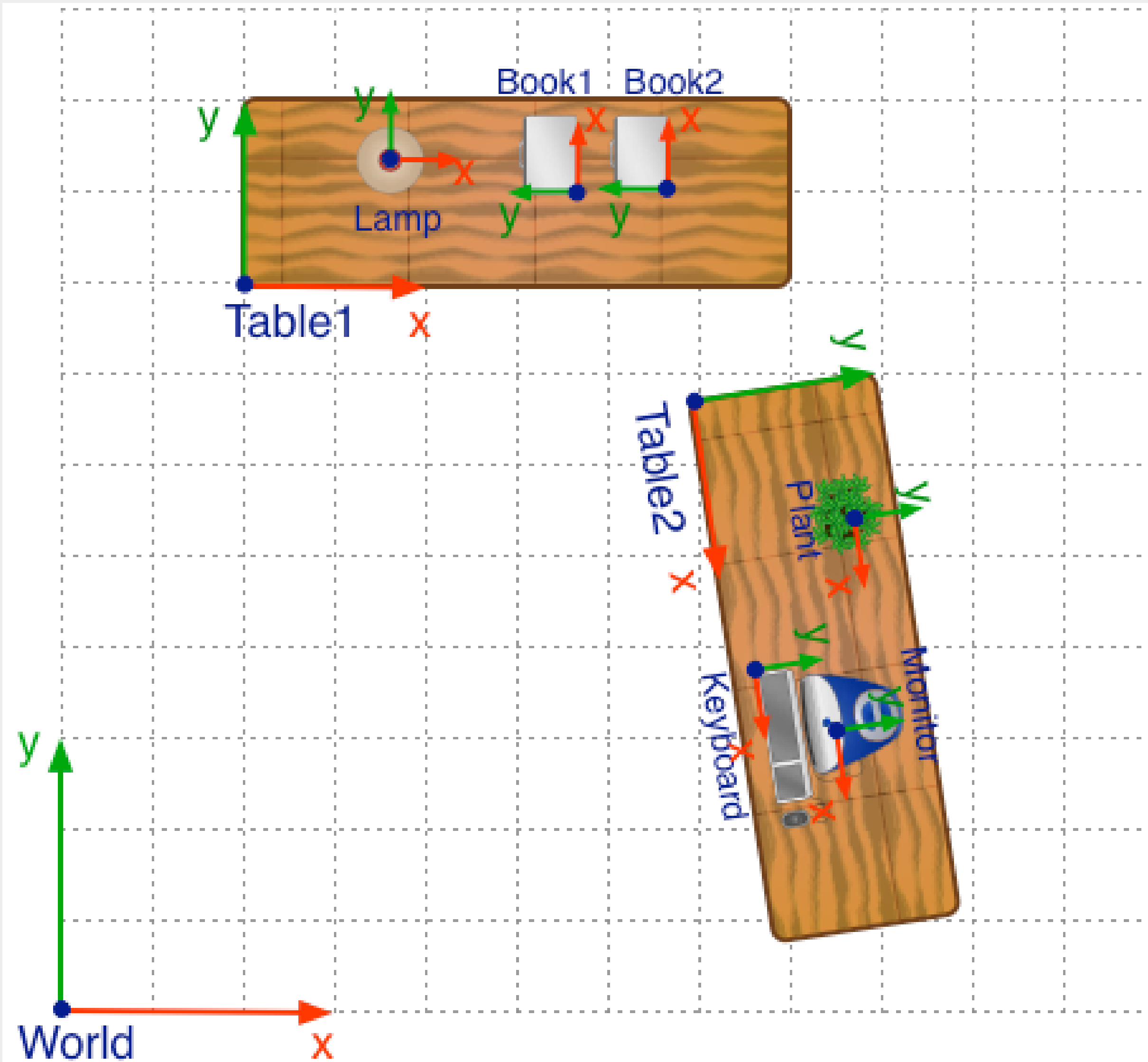
- First two projects: Scene hard-coded in the model
- The scene exists only in the drawScene() method
- Advantages:
  - Simple,
  - Direct
- Problems
  - Code gets complex
  - Special-purpose, hard to change
  - Special-purpose, hard to make many variants
  - Can't easily examine or manipulate models
    - Can only "draw"

Sample Scene

Schematic Diagram (Top View)

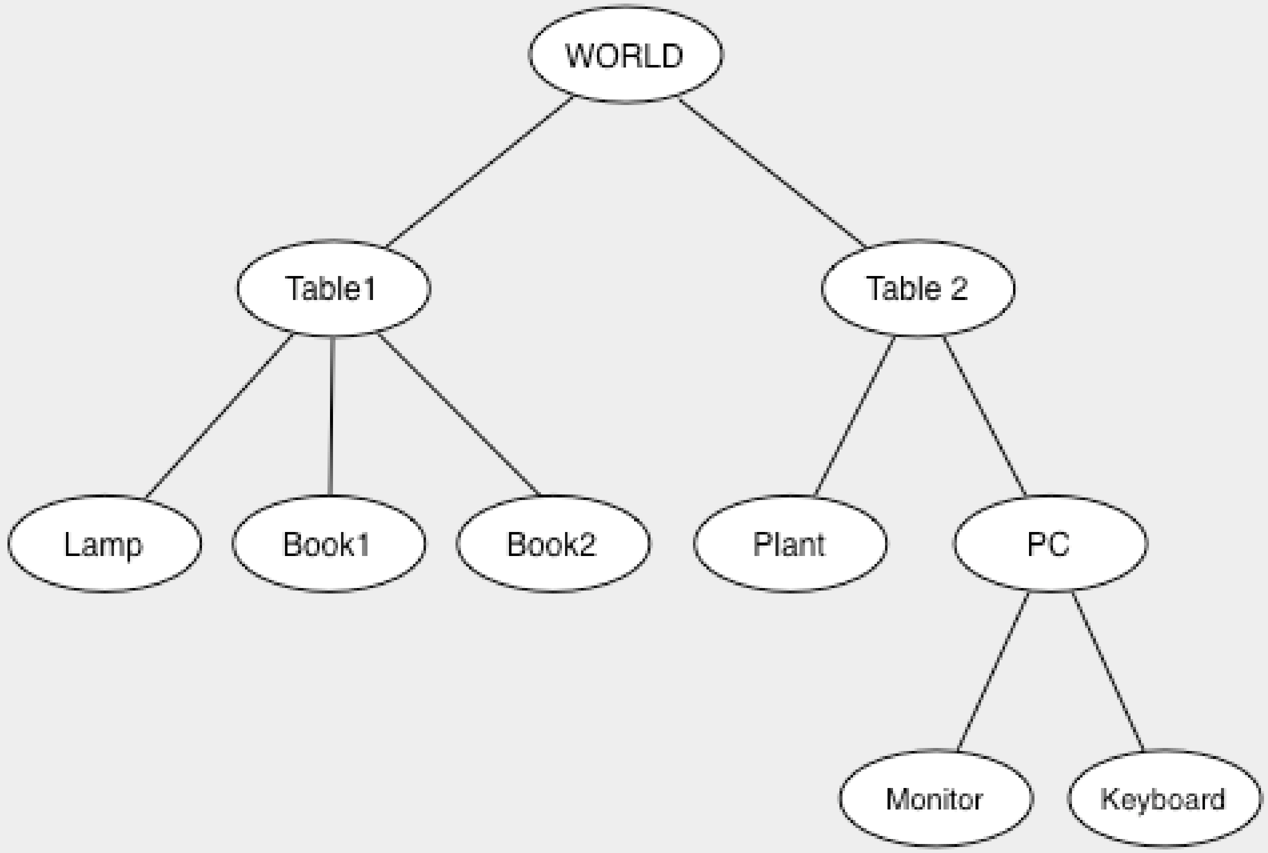


Top view with Coordinates



Hierarchical Transforms

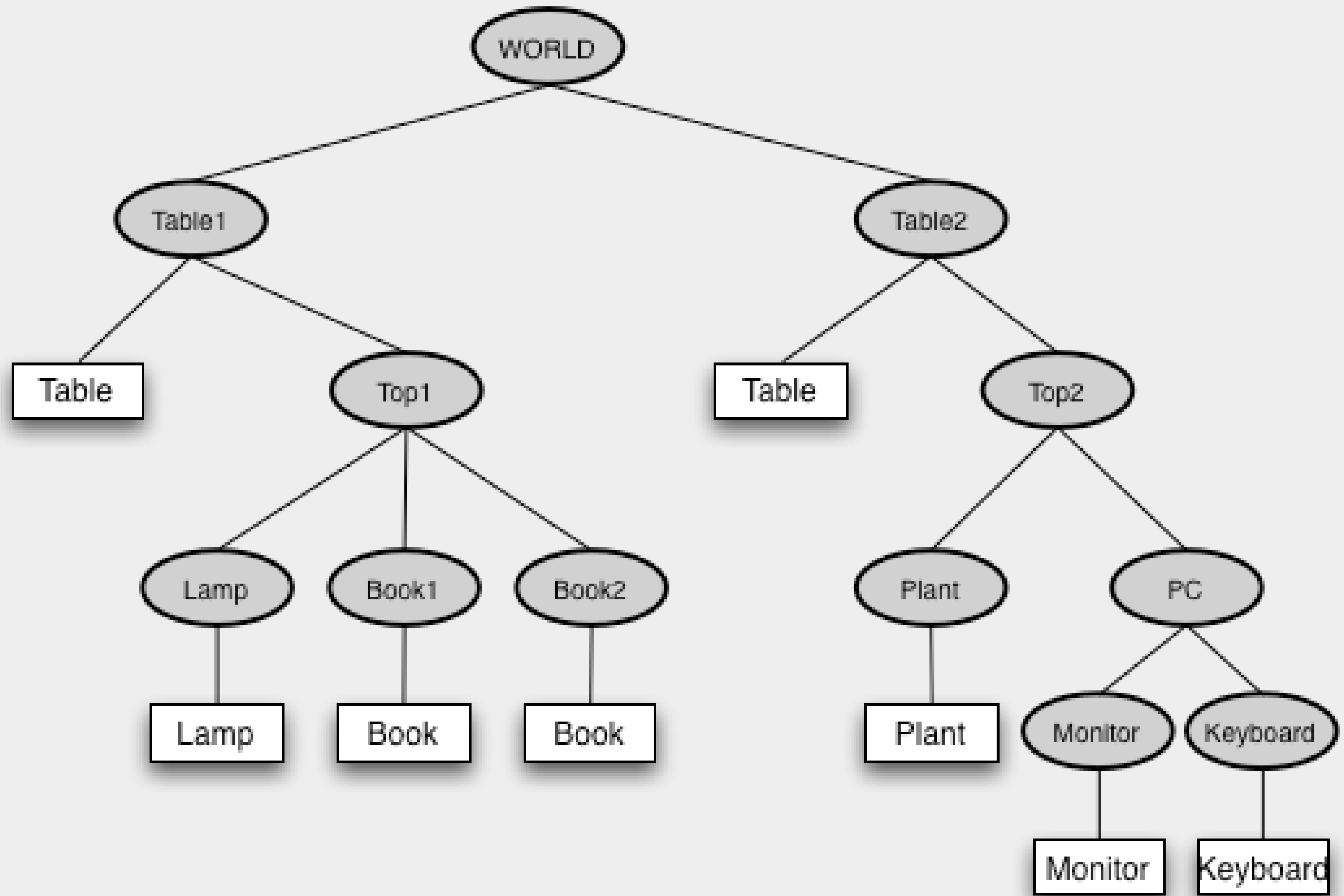
- Last week, introduced hierarchical transforms
- Scene hierarchy:



Data structure for hierarchical scene

- Want:
  - Collection of individual models/objects
  - Organized in groups
  - Related via hierarchical transformations
- Use a tree structure
- Each node:
  - Has associated local coordinates
  - Can define a shape to draw in local coordinates
  - Can have children that inherit its local coordinates
- Typically, different classes of nodes:
  - “Transform nodes” that affect the local coordinates
  - “Shape nodes” that define shapes

Scene Tree



WORLD
Table1
Table2
Table
Top1
Table
Top2
Lamp
Book1
Book2
Plant
PC
Lamp
Book
Book
Plant
Monitor
Keyboard
Monitor
Keyboard

Node base class

- A Node base class might support:
  - getLocalTransform() -- matrix puts node's frame in parent's coordinates
  - getGeometry() -- description of geometry in this node (later today)
  - getChild(i) -- access child nodes
    - addChild(), deleteChild() -- modify the scene
- Subclasses for different kinds of transforms, shapes, etc.
- Note: many designs possible
  - Concepts are the same, details differ
  - Optimize for: speed (games), memory (large-scale visualization), editing flexibility (modeling systems), rendering flexibility (production systems), …
  - In our case: optimize for pedagogy & projects

Node base class

```
class Node {
   // data
   Matrix localTransform;
   Geometry *geometry;
   Node *children[N];
   int numChildren;

    // methods:
   getLocalTransform() { return localTransform; }
   getGeometry() { return geom; }
   getChild(i) { return children[i]; }
   addChild(Node *c) { children[numChildren++] = c; }
}
```

Draw by traversing the tree

```
draw(Node node) {
    PushCTM();
    Transform(node.getLocalTransform());
    drawGeometry(node.getGeometry());
    for (i=0; i<node.numChildren; ++i) {
        draw(node.child[i]);
    }
    PopCTM();
}
```

- Effect is same hierarchical transformation as last week

Modify the scene

- Change tree structure
  - Add nodes
  - Delete nodes
  - Rearrange nodes
- Change tree contents
  - Change transform matrix
  - Change shape geometry data
- Define subclasses for different kinds of nodes
  - Subclass has parameters specific to its function
  - Changing parameter causes base info to update

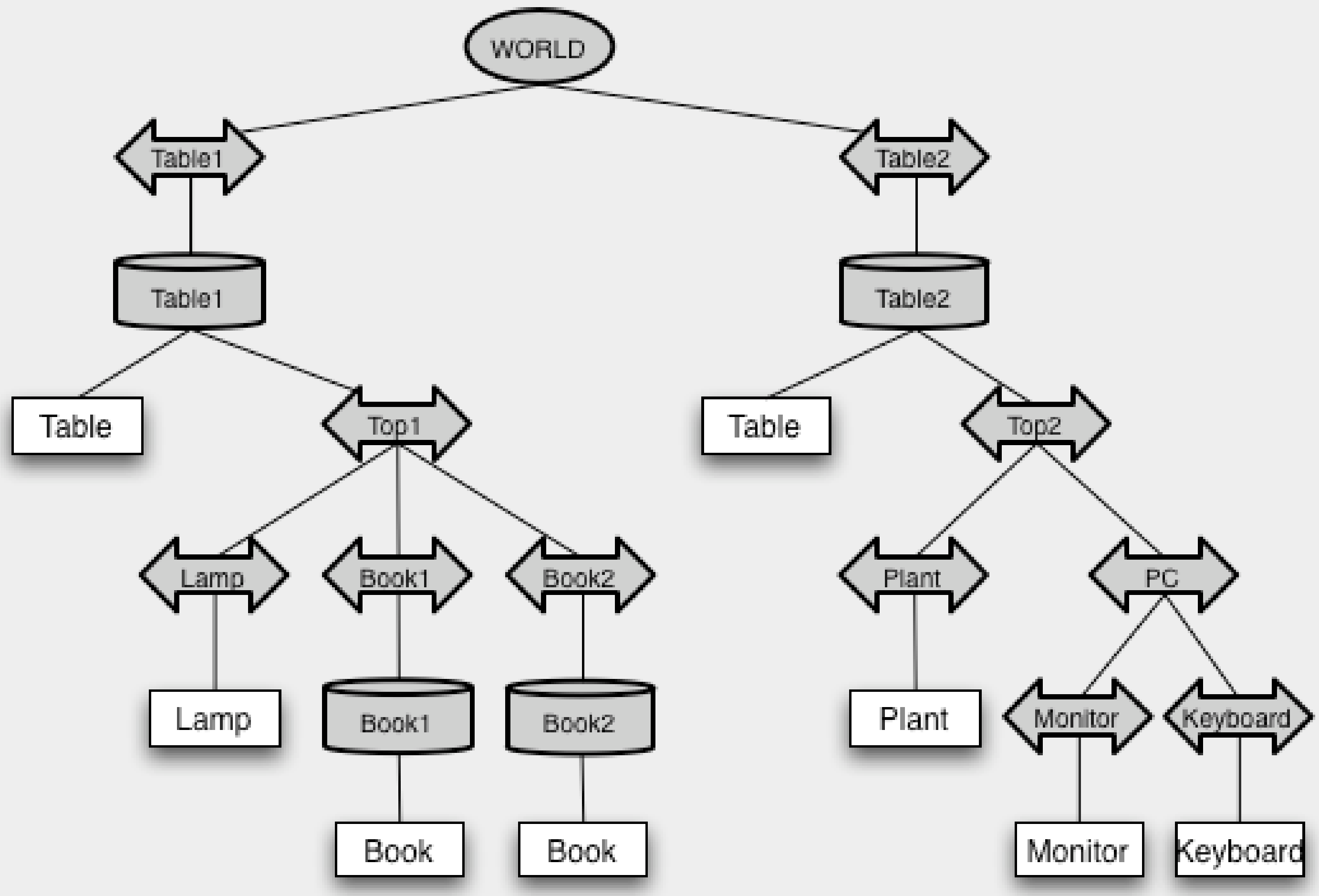
Example: Translation Node

```
class Translation(Transformation) {
   private:
      float x,y,z;
      void update() {
         localTransfom.MakeTranslation(x,y,z);
      }

   public:
     void setTranslation(float tx, float ty, float tz) {
        x = tx; y = ty; z = tz;
        update();
     }
     void setX(float tx) { x = tx; update(); }
     void setY(float ty) { y = ty; update(); }
     void setZ(float tz) { z = tz; update(); }
}
```

Example: Rotation Node

```
class Rotation(Transformation) {
   private:
      Vector3 axis;
      float angle;
      void update() {
         localTransfom.MakeRotateAxisAngle(axis,angle);
      }

   public:
     void setAxis(Vector3 v) {
        axis = v;
        axis.Normalize();
        update();
     }
     void setAngle(float a) {
        angle = a;
        localTransfom.MakeRotateAxisAngle(axis,angle);
     }
   }
```

More detailed scene graph



Building this scene

```
WORLD = new Node();
table1Trans = new Translation(…);  WORLD.addChild(table1Trans);
table1Rot = newRotation(…); table1Trans.addChild(table1Rot);
table1 = makeTable(); table1Rot.addChild(table1);
top1Trans = new Translation(…); table1Rot.addChild(top1Trans);

lampTrans = new Translation(…); top1Trans.addChild(lampTrans);
lamp = makeLamp(); lampTrans.addChild(lamp);

book1Trans = new Translation(…);  top1Trans.addChild(book1Trans);
book1Rot = newRotation(…); book1Trans.addChild(book1Rot);
book1 = makebook(); book1Rot.addChild(book1);

book2Trans = new Translation(…);  top1Trans.addChild(book2Trans);
book2Rot = newRotation(…); book2Trans.addChild(book2Rot);
book2 = makebook(); book2Rot.addChild(book1);

table2Trans = new Translation(…);  WORLD.addChild(table2Trans);
table2Rot = newRotation(…); table2Trans.addChild(table2Rot);
table2 = makeTable(); table2Rot.addChild(table2);
top2Trans = new Translation(…); table2Rot.addChild(top2Trans);
…
```

- Still building the scene hardwired in the program
  - But now can more easily manipulate it…

Change scene

- Change a transform in the tree:
  - `table1Rot.setAngle(23);`
  - Table rotates, everything on the table moves with it
- Allows easy animation
  - Build scene once at start of program
  - Update parameters to draw each frame
  - e.g. Solar system:

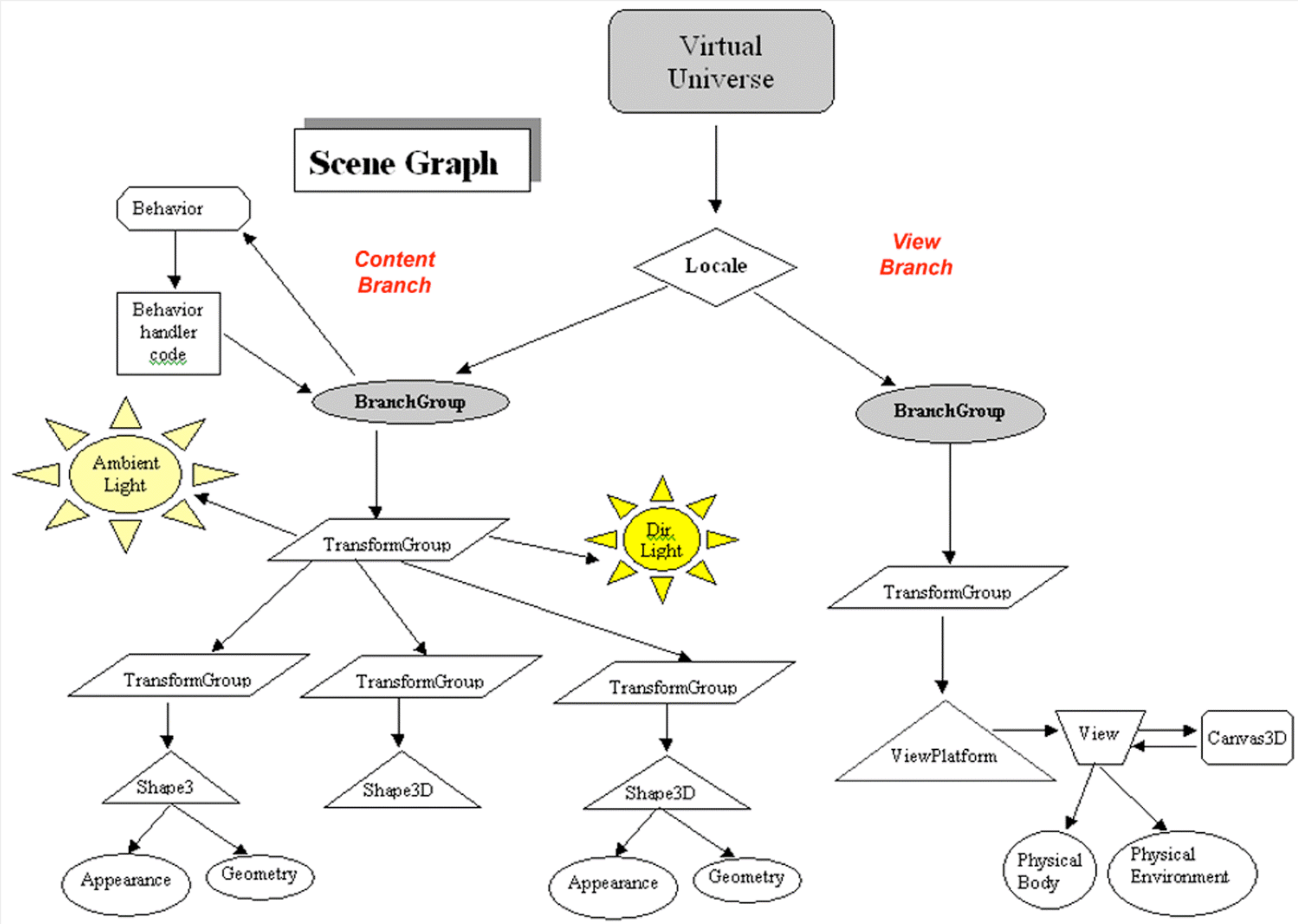
```
drawScene() {
     sunSpin.setAngle(g_Rotation);
     earthSpin.setAngle(3*g_Rotation);
     earthOrbit.setAngle(2*g_Rotation);
     moonOrbit.setAngle(8*g_Rotation);
     draw(WORLD);
  }
```

- Allows interactive model manipulation tools
  - e.g. button to add a book
    - Create subtree with transforms and book shape
    - Insert as child of table

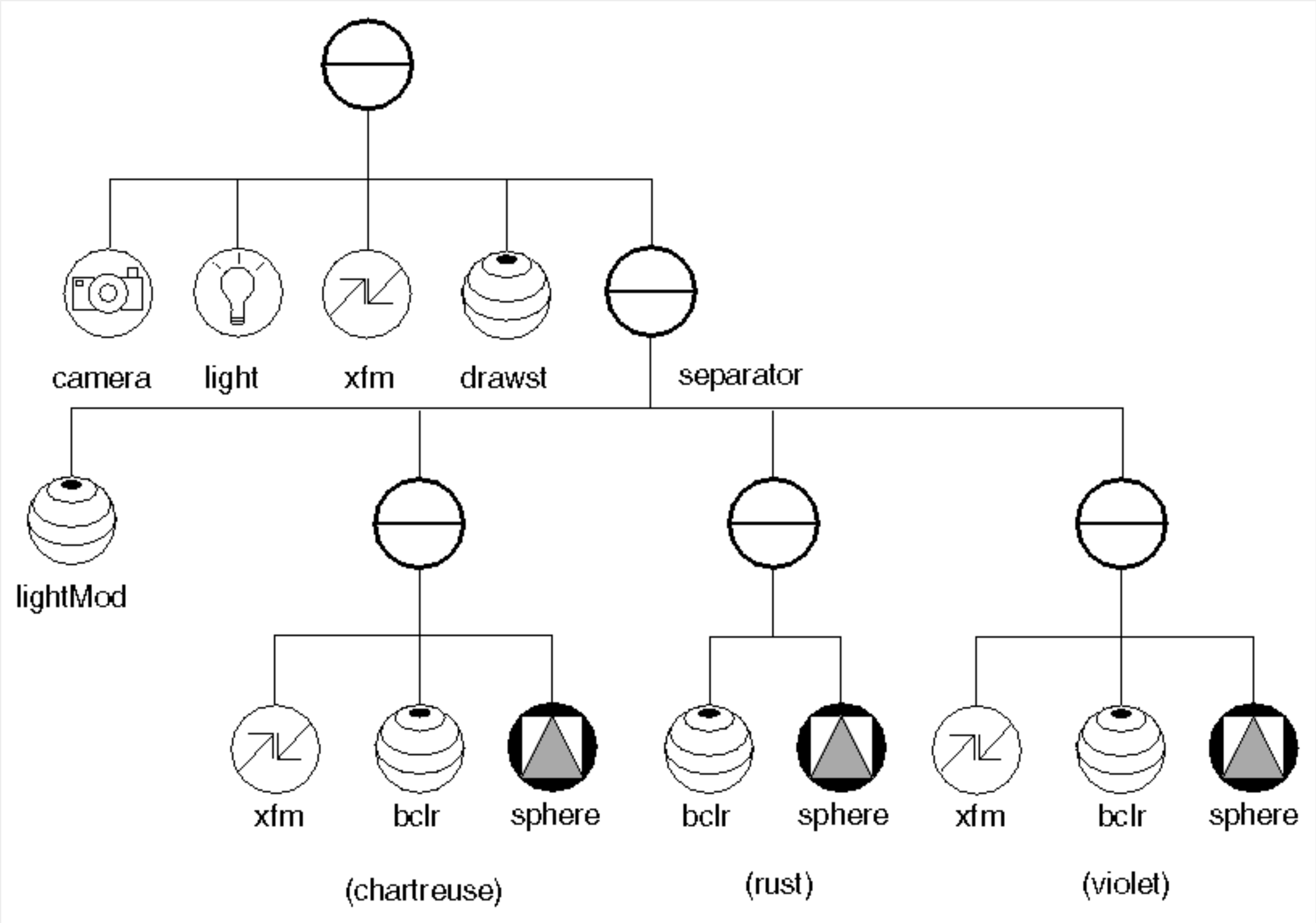
Not just transform nodes

- Shape nodes
  - Contain geometry:
    - cube, sphere (later today)
    - curved surfaces (next week)
    - Etc…
- Can have nodes that control structure
  - Switch/Select: parameters choose whether or which children to enable
  - Group nodes that encapsulate subtrees
  - Etc…
- Can have nodes that define other properties:
  - Color
  - Material
  - Lights
  - Camera
  - Etc…
- Again, different details for different designs

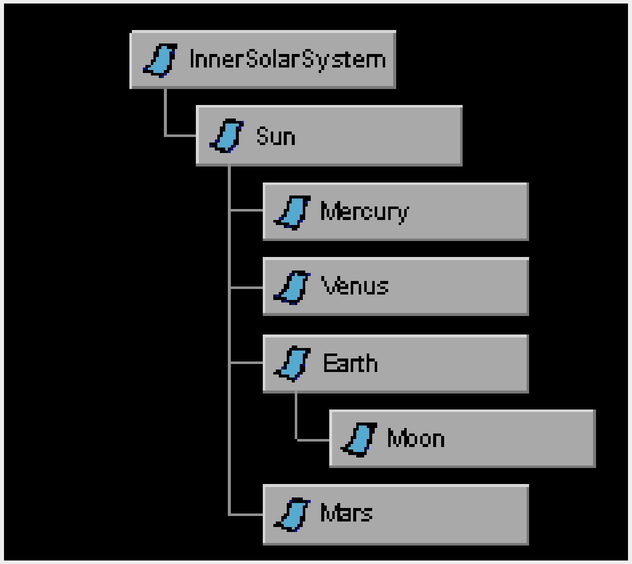
Java3D Scene Graph

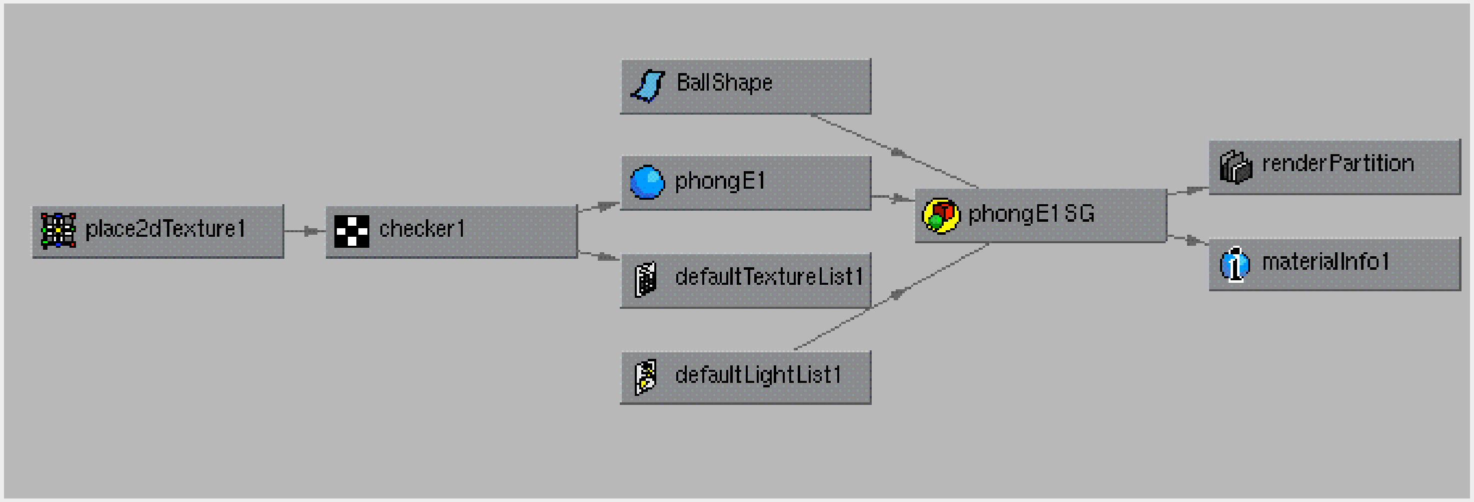


OpenInventor Scene Graph



Maya “Hypergraph”





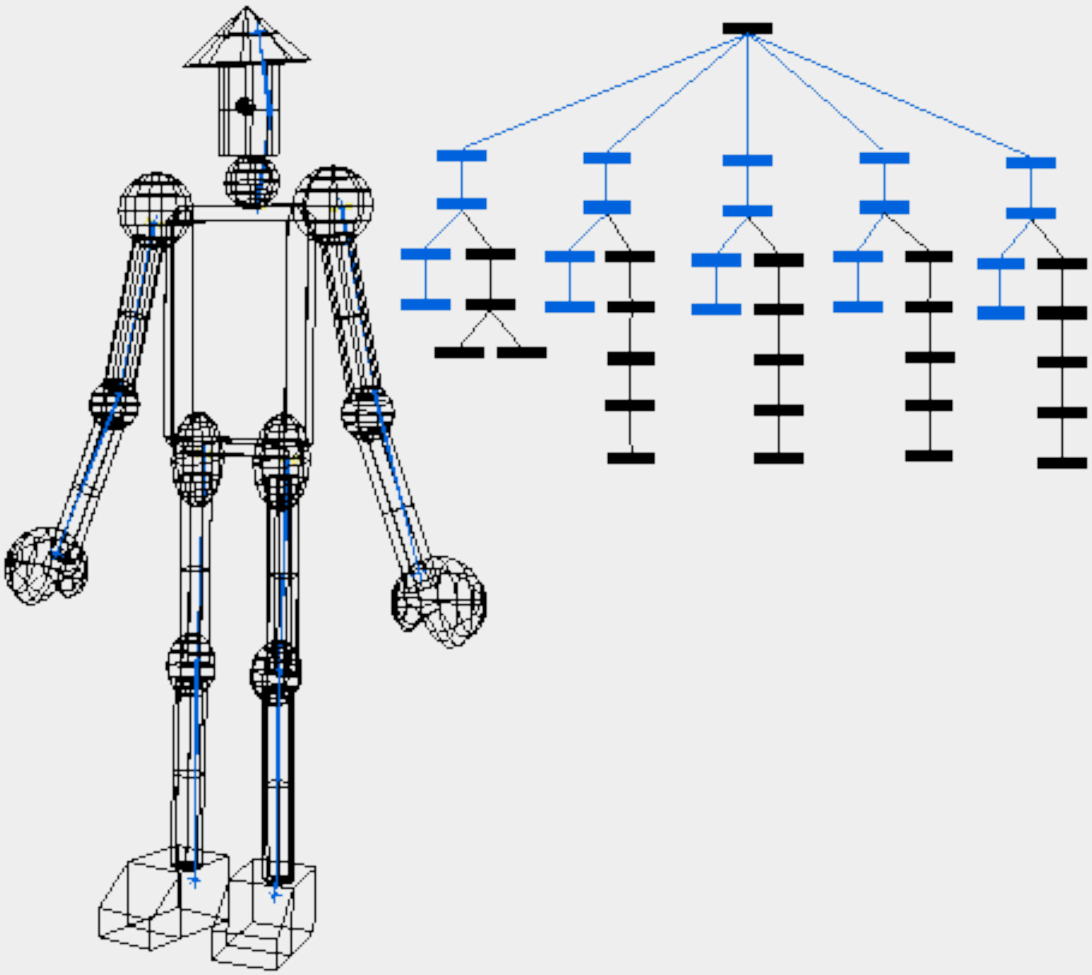
Scene vs. Model

- No real difference between a scene and a model
  - A scene is typically a collection of “models” (or “objects”)
  - Each model may be built from “parts”
- Use the scene graph structure
  - Scene typically includes cameras, lights, etc. in the graph; Model typically doesn’t (but can)

Parameteric models

- Parameters for:
  - Relationship between parts
  - Shape of individual parts
- Hierarchical relationship between parts
- Modeling robots
  - separate rigid parts
  - Parameters for joint angles
  - Hierarchy:
    - Rooted at pelvis: Move pelvis, whole body moves
    - Neck & Head: subtree; move neck and head, or just move head
    - Arms: Shoulder, Elbow, Wrist joints
    - Legs: Hips, Knee, Ankle joints
  - This model idiom is known as: an *Articulated figure*
  - Often talk about *degrees of freedom* (DOFs)
    - Total number of float parameters in the model

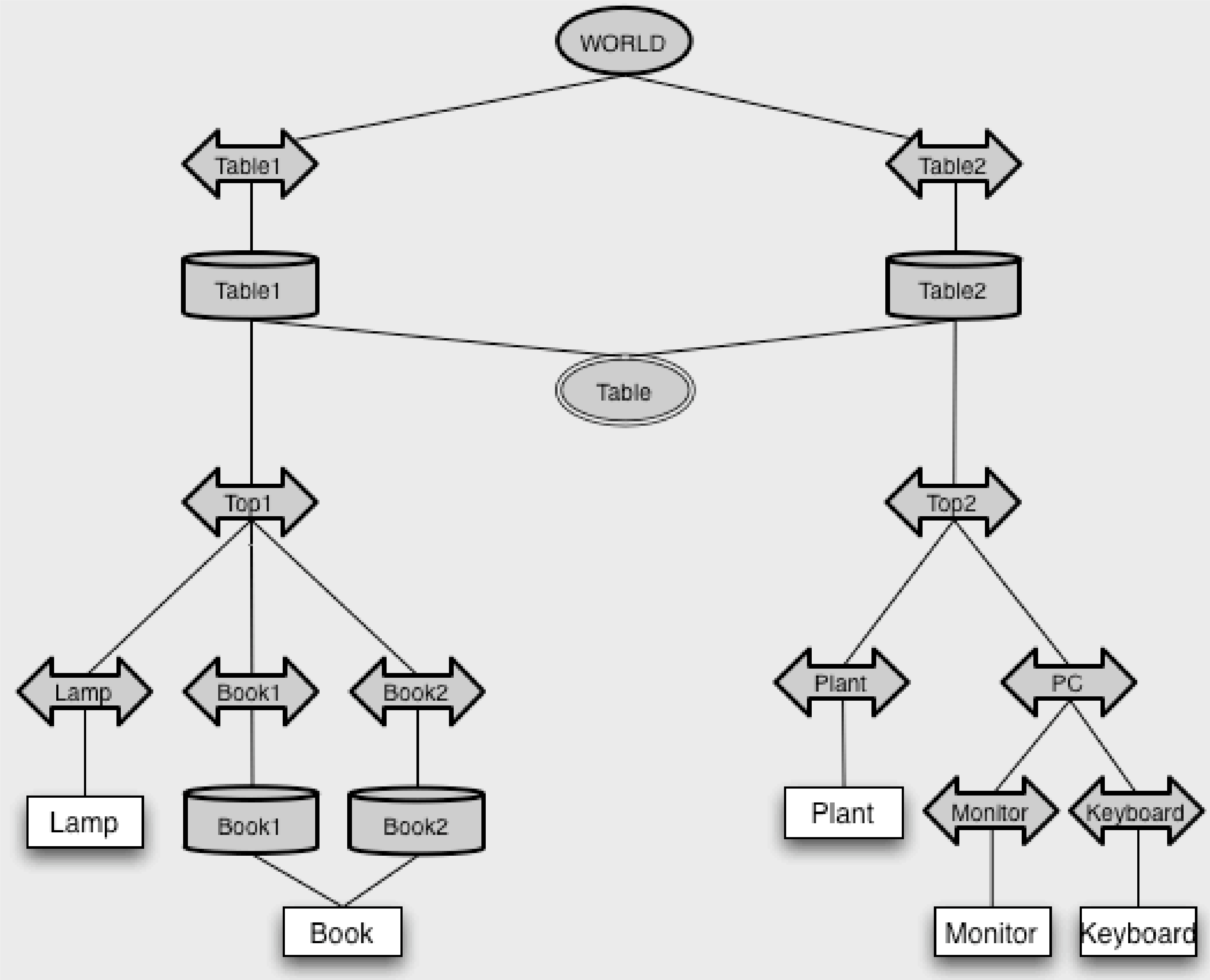
Robot



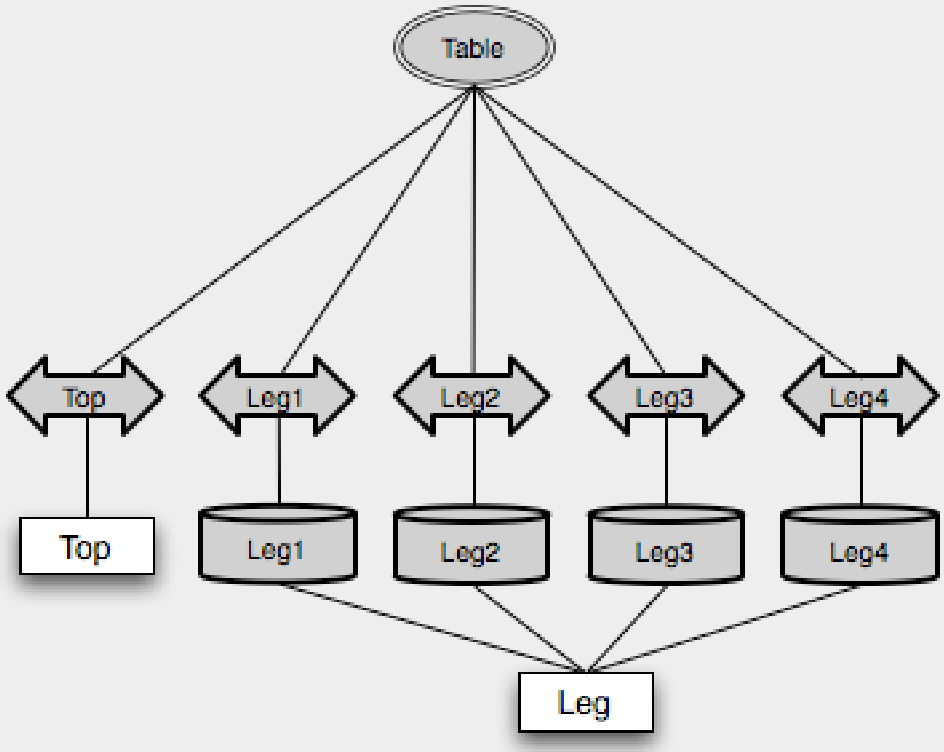
Screen *Graph*, not Tree

- Repetition:
  - A scene might have many copies of a model
  - A model might use several copies of a part
- *Multiple Instantiation*
  - One copy of the node or subtree
  - Inserted as a child of many parents
  - A directed acyclic graph (DAG), not a tree
  - Traversal will draw object each time, with different coordinates
- Saves memory
  - Can save time also, depending on cacheing/optimization
- Change parameter once, affects all instances
  - This can be good or bad, depending on what you want
  - Some scene graph designs let other properties inherit from parent

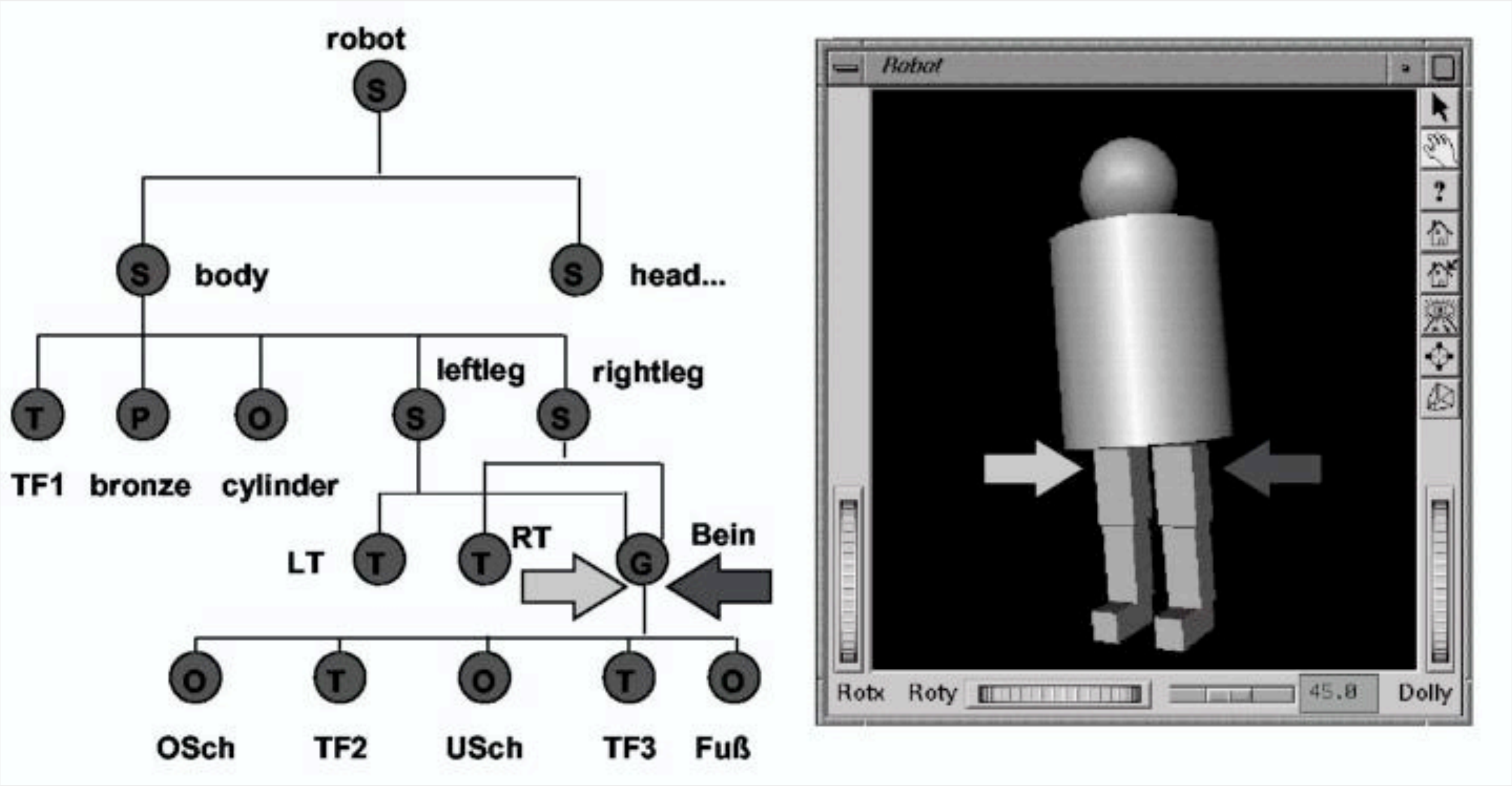
Instantiation - scene



Instantiation - model parts



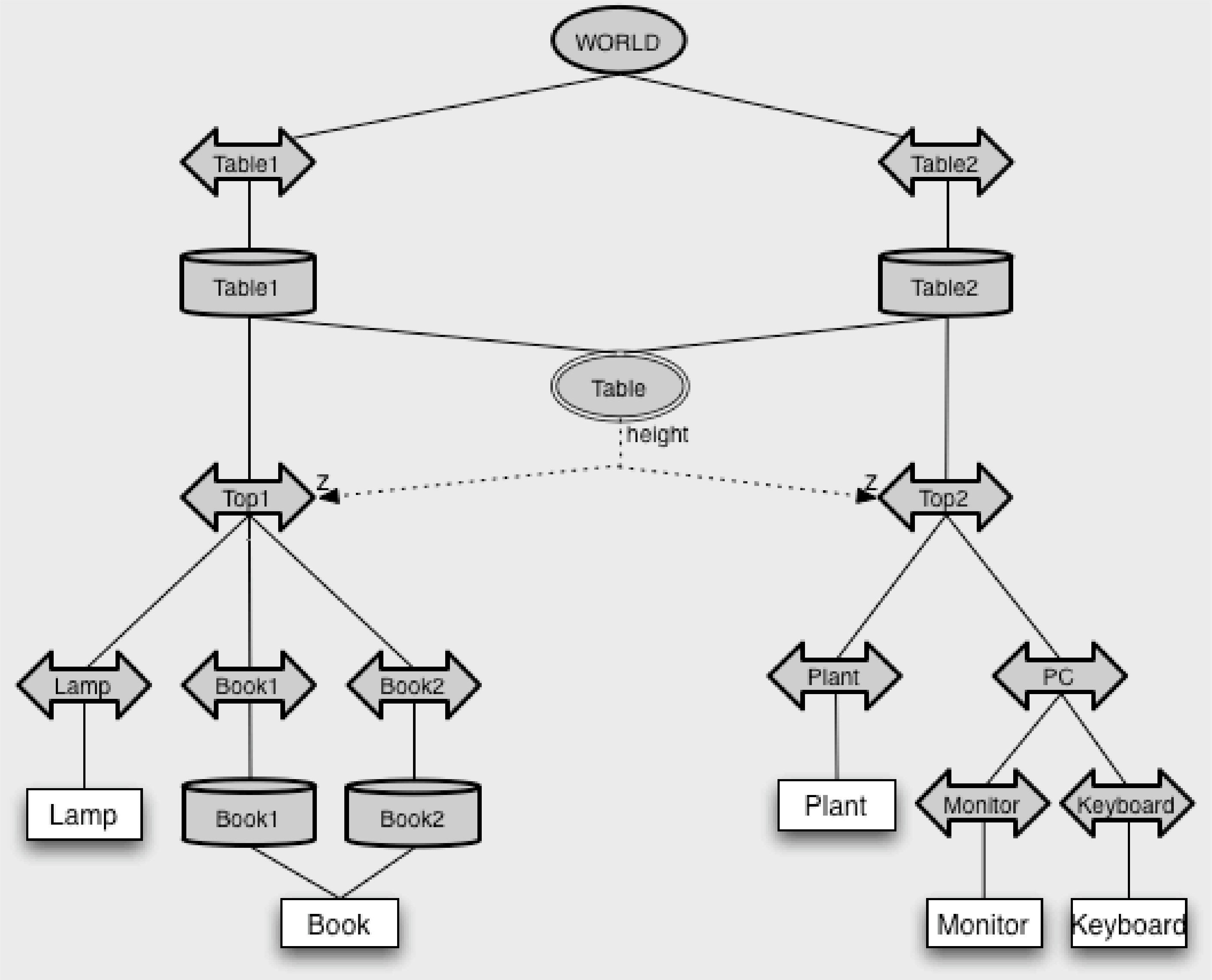
Instantiation (OpenInventor)



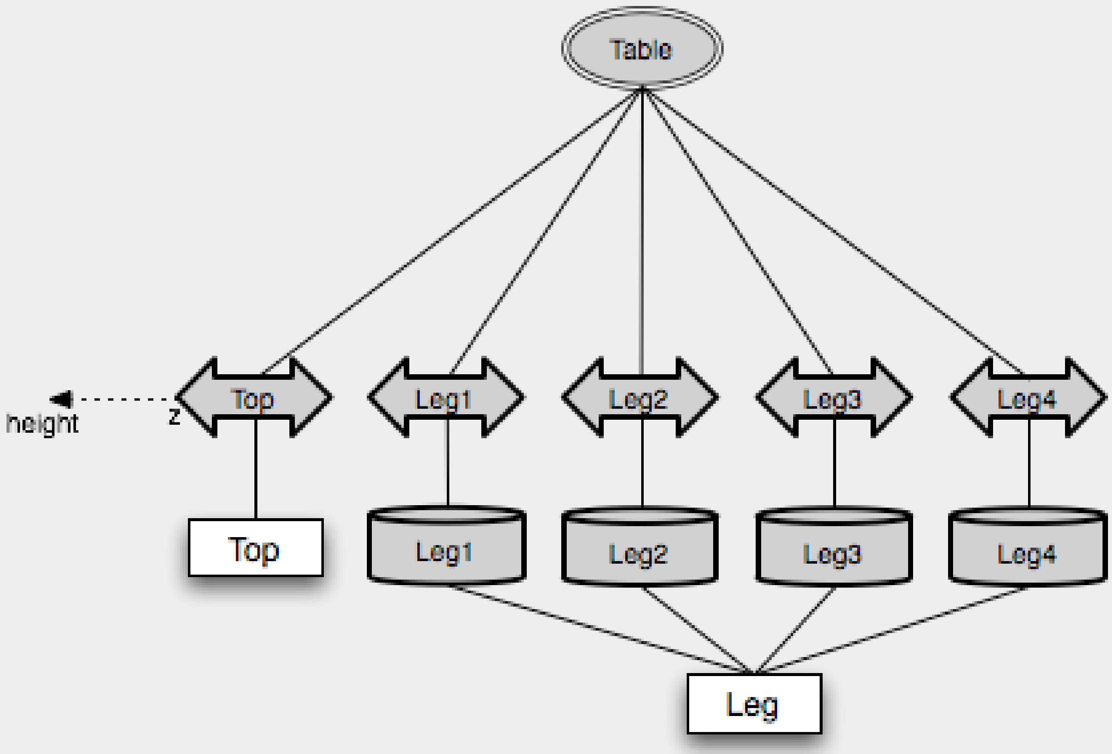
Fancier things to do with scene graphs

- Skeletons, skin, deformations
  - Robot-like jointed rigid skeleton
  - Shape nodes that put surface across multiple joint nodes
  - Nodes that change shape of geometry
- Computations:
  - Properties of one node used to define values for other nodes
  - Sometimes can include mathematical expressions
  - Examples:
    - Elbow bend angle -> bicep bulge
    - Our scene has translation to put objects on table…
      - But how much should that translation be?
      - What if the table changes?

Linked parameters



Linked parameters



Other things to do with scene graphs

- Names/paths
  - Unique name to access any node in the graph
  - e.g. "WORLD/table1Trans/table1Rot/top1Trans/lampTrans"
- Compute Model-to-world transform
  - Walk from node through parents to root, multiplying local transforms
- Bounding box or sphere
  - Quick summary of extent of object
  - Useful for culling (next class)
  - Compute hierarchically:
    - Bounding box is smallest box that encloses all children's boxes
- Collision/contact calculation
- Picking
  - Click with cursor on screen, determine which node was selected
- Edit: build interactive modeling systems

Project 3 Scene Graph

- Just the basics…
- Transform nodes
  - Rotation
  - Translation
- Shapes
  - Cube
  - Sphere
- Traversal/drawing

Outline For Today

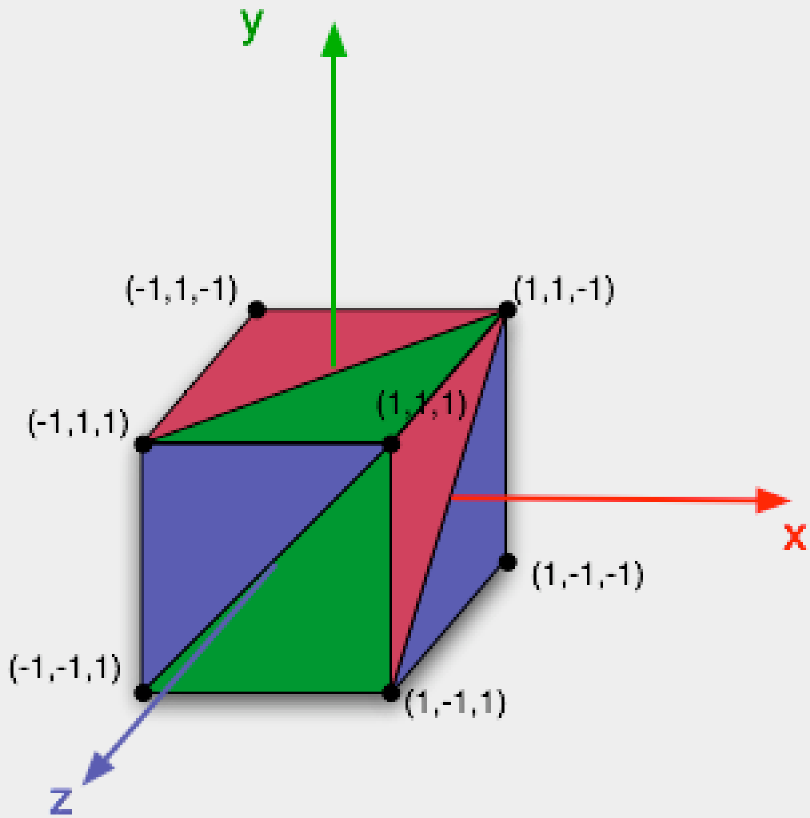
- Scene Graphs
- *Shapes*
- Tessellation

Basic shapes

- Geometry objects for primitive shape types
- Various exist.
- We'll focus on fundamental: Collection of triangles
  - AKA *Triangle Set*
  - AKA *Triangle Soup*
- How to store triangle set?
  - …simply as collection of triangles?

Cube - raw triangles

- 12 triangles:
  - (-1,-1,1) (1,-1,1) (1,1,1)
  - (-1,-1,1) (1,1,1) (-1,1,1)
  - (1,-1,1) (1,-1,-1) (1,1,-1)
  - (1,-1,1) (1,1,-1) (1,1,1)
  - (1,-1,-1) (-1,-1,-1) (-1,1,-1)
  - (1,-1,-1) (-1,1,-1) (1,1,-1)
  - (-1,-1,-1) (-1,-1,1) (-1,1,1)
  - (-1,-1,-1) (-1,1,1) (-1,1,-1)
  - (-1,1,1) (1,1,1) (1,1,-1)
  - (-1,1,1) (1,1,-1) (-1,1,-1)
  - (1,-1,1) (-1,-1,-1) (1,-1,-1)
  - (1,-1,1) (-1,-1, 1) (-1,-1,-1)
- 12*3=36 vertices

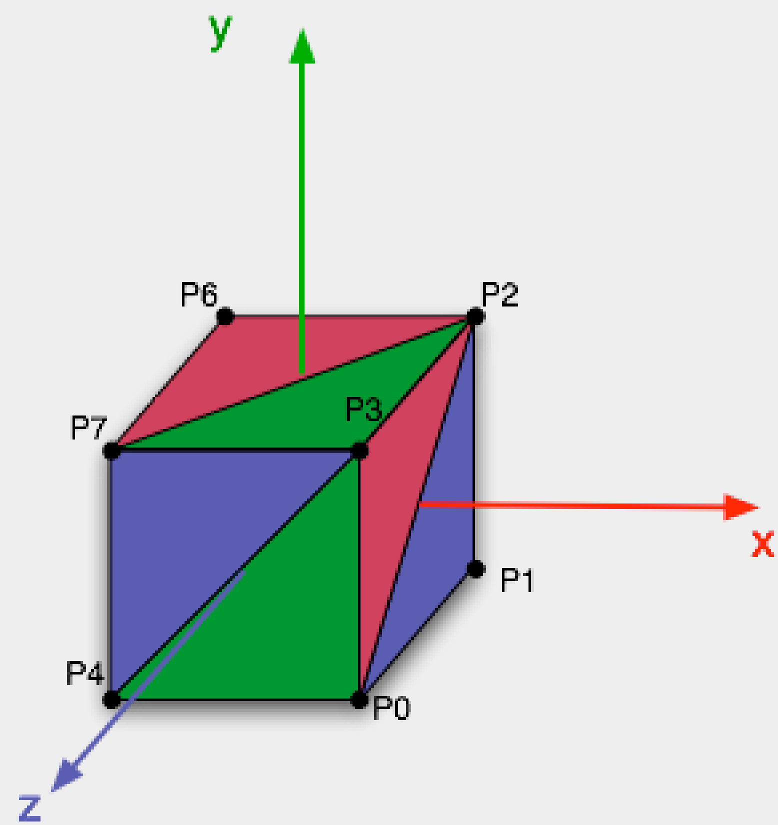


But….

- A cube only has 8 vertices!
- 36 vertices with x,y,z = 36*3 floats = 108 floats.
  - Would waste memory to store all 36 vertices
  - Would be slow to send all 36 vertices to GPU
  - (Especially when there is additional data per-vertex)
- Usually each vertex is used by at least 3 triangles--often 4 to 6 or more
  - Would use 4 to 6 times as much memory as needed, or more
- Instead: Specify vertex data once, then reuse it
  - Assign a number to each vertex
  - Specify triangles using vertex numbers

Cube - indexed triangles

- 8 vertices:
  - P0: (1,-1, 1)
  - P1: (1,-1,-1)
  - P2: (1, 1,-1)
  - P3: (1, 1, 1)
  - P4: (-1,-1, 1)
  - P5: (-1,-1,-1)
  - P6: (-1, 1,-1)
  - P7: (-1, 1, 1)
- 12 triangles:
  - P4 P0 P3
  - P4 P3 P7
  - P0 P1 P2
  - P0 P2 P3
  - P1 P5 P6
  - P1 P6 P2
  - P5 P4 P7
  - P5 P7 P6
  - P7 P3 P2
  - P7 P2 P6
  - P0 P5 P1
  - P0 P4 P5



- 8 vertices*3 floats = 24 floats
  12 triangles*3 points= 36 integers

Indexed Triangle set

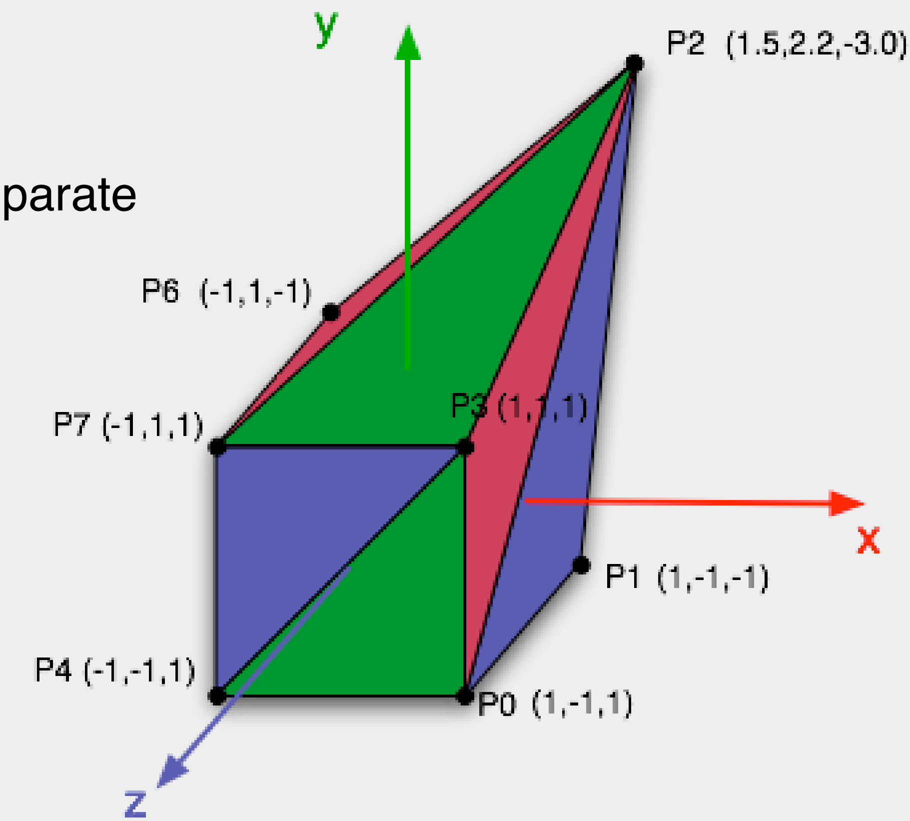
- Array of vertex locations, array of Triangle objects:

```
Point3 vertices[] = {
  ( 1,-1, 1),
  ( 1,-1,-1),
  ( 1, 1,-1),
  ( 1, 1, 1),
  (-1,-1, 1),
  (-1,-1,-1),
  (-1, 1,-1),
  (-1, 1, 1)};
class Triangle {short p1, p2, p3) triangles[] = {
   (4, 0, 3),
   (4, 3, 7),
   (0, 1, 2),
   (0, 2, 3),
   (1, 5, 6),
   (1, 6, 2),
   (5, 4, 7),
   (5, 7, 6),
   (7, 3, 2),
   (7, 2, 6),
   (0, 5, 1),
   (0, 4, 5)};
```

- Triangles refer to each vertex by its index in the vertex array

Benefits of indexing

- Saves memory
- Saves data transmission time
- Save rendering time: lighting calculation can be done just one for each vertex
- Easy model *deformation*
  - Change vertex position data
  - Triangles automatically follow
- *Topology* (point connectivity) separate from shape (point locations)



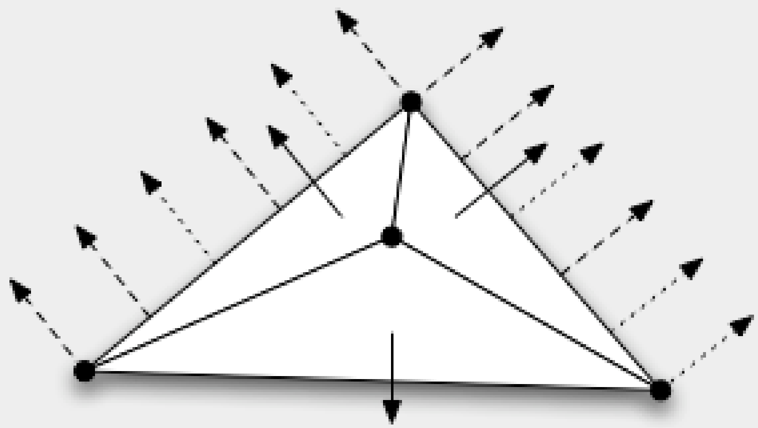
(Index vs. pointer)

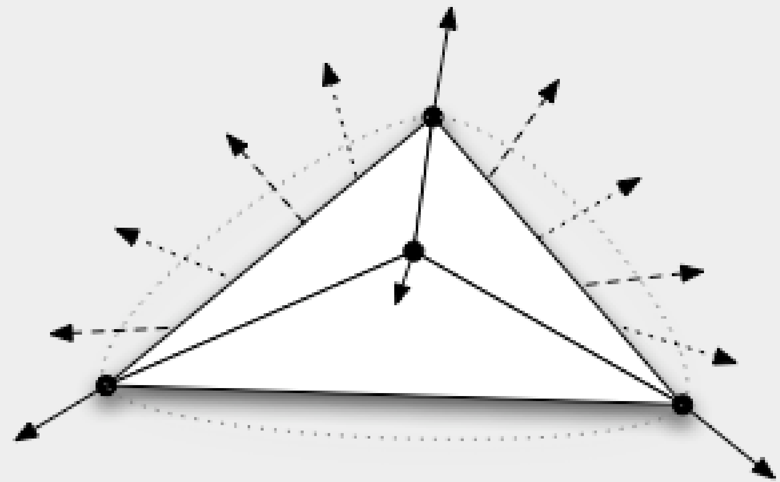
- Triangle stores indexes into the vertex array.
- Could also use pointer rather than index
  - Can be easier to work with
  - But uses more memory (if pointer is larger than short integer)
  - Can be fragile: if vertex array is reallocated pointers will dangle

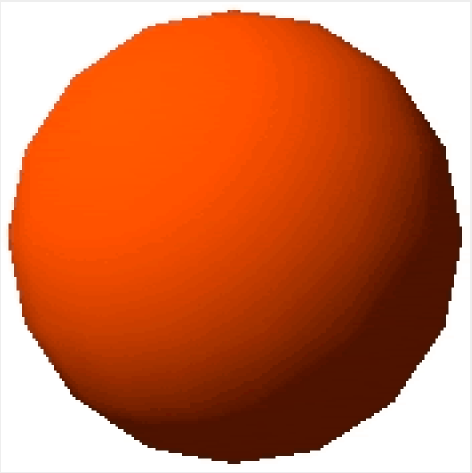
Normals

- Normal = perpendicular to surface
- The normal is essential to lighting
  - Shading determined by relation of normal to eye & light
- Collection of triangles with their normals: *Facet Normals*
  - Store & transmit *one normal per triangle*
  - Normal constant on each triangle--but discontinuous at triangle edges
  - Renders as facets
  - Good for faceted surfaces, such as cube
- For curved surface that is approximated by triangles: *Vertex Normals*
  - Want normal to the surface, not to the triangle approximation
  - Don’t want discontinuity: share normal between triangles
  - Store & transmit *one normal per vertex*
  - Each triangle has different normals at its vertices
    - Lighting will interpolate (a few weeks)
    - Gives illusion of curved surface

Facet normals vs. Vertex normals







Color

- Color analogous to normal
  - One color per triangle: faceted
  - One color per vertex: smooth colors

Indexed Triangle Set with Normals &Colors

- Arrays:

```
Point3 vertexes[];
Vector3 normals[];
Color colors[];
Triangle triangles[];
int numVertexes, numNormals, numColors, numTriangles;
```

- Single base class to handle both:
  - Facets
    - one normal & color per triangle
    - `numNormals = numColors = numTriangles`
  - Smooth
    - one normal & color per vertex
    - `numNormals = numColors = numVertexes`

Geometry objects base class

- (For our design) Base class supports indexed triangle set

```
class Geometry {
   Point3 vertices[];
   Vector3 normals[];
   Color colors[];
   Triangle triangles[];
   int numVerices,numNormals,numColors,numTriangles;
};
class Triangle {
   int vertexIndices[3];
   int normalIndices[3];
   int colorIndices[3];
};
```

- Triangle indices:
  - For facet normals, set all three `normalIndices` of each triangle to same value
  - For vertex normals, `normalIndices` will be same as `vertexIndices`
  - Likewise for color

Cube class

```
class Cube(Geometry) {
   Cube() {
       numVertices = 8;
       numTriangles = numNormals = 12;
       vertices = {
            ( 1,-1, 1),  ( 1,-1,-1), ( 1, 1,-1), ( 1, 1, 1),
            (-1,-1, 1),  (-1,-1,-1), (-1, 1,-1), (-1, 1, 1) };
       triangles = {
            (4, 0, 3), (4, 3, 6),
            (0, 1, 2), (0, 2, 3),
            (1, 5, 6), (1, 6, 2),
            (5, 4, 7), (5, 7, 6),
            (7, 3, 2), (7, 2, 6),
            (0, 5, 1), (0, 4, 5) };
       normals = {
            ( 0, 0, 1), ( 0, 0, 1),
            ( 1, 0, 0), ( 1, 0, 0),
            ( 0, 0,-1), ( 0, 0,-1),
            (-1, 0, 0), (-1, 0, 0),
            ( 0, 1, 0), ( 0, 1, 0),
            ( 0,-1, 0), ( 0,-1, 0) };
   }
}
```

Smooth surfaces

- *Tesselation*: approximating a smooth surface with a triangle mesh
  - Strictly speaking, “tesselation” refers to regular tiling patterns
  - In computer graphics, often used to mean any *triangulation*
- E.g. Sphere class fills in triangle set (will get to this shortly…)

```
class Sphere(Geom) {
  private:
     float radius;
     void tesselate() {
        vertices = …
        triangles = …
        normals=…
     }
  public:
    Sphere(float r) { radius = r; tesselate(); }
    void setRadius(float r) { radius = r; tesselate(); }
}
```

- Other smooth surface types
  - Bezier patch (next week)
  - NURBS
  - Subdivision surface
  - Implicit surface

Drawing the indexed triangle set

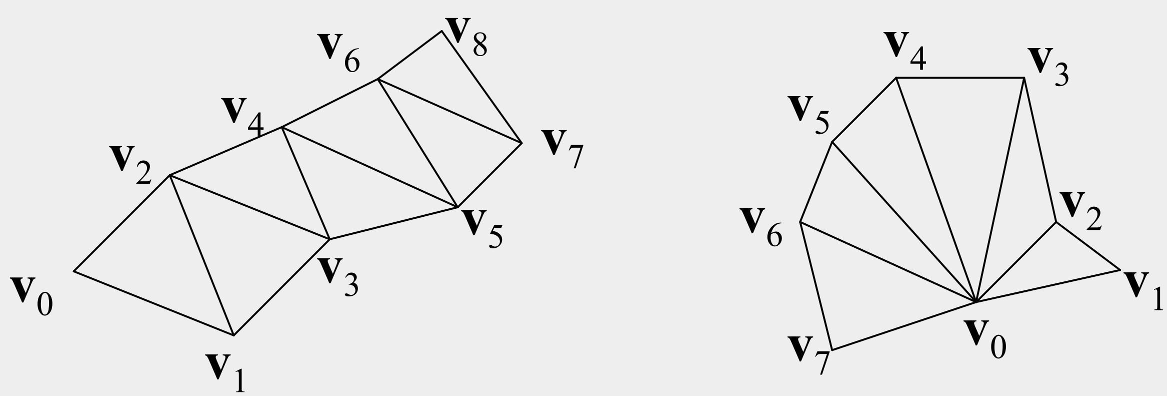
- OpenGL supports “vertex arrays”
  - But it’s awkward to use
- So for project 3:
  - Use indexed triangle set for base storage
  - Draw by sending all vertex locations for each triangle:

```
for (i=0; i<numTriangles; i++) {
   glVertex3fv(vertexes[triangles[i].p1]);
   glVertex3fv(vertexes[triangles[i].p2]);
   glVertex3fv(vertexes[triangles[i].p3]);
}
```

- So we get memory savings in Geometry class
- We don’t get speed savings when drawing.

Triangles, Strips, Fans

- Basic indexed triangle set is unstructured: “triangle soup”
- GPUs & APIs usually support slightly more elaborate structures
- Most common: triangle strips, triangle fans



- Store & transmit ordered array of vertex indexes.
  - Each vertex index only sent once, rather than 3 or 4-6 or more
- Even better: store vertexes in proper order in array
  - Can draw entire strip or fan by just saying which array and how many vertexes
  - No need to send indexes at all.
- Can define triangle meshes using adjacent strips
  - Share vertexes between strips
  - But must use indexes

Vertex Buffers

- Graphics hardware systems often support for *vertex buffer*
  - Memory on the GPU side
  - (AKA other things too)
- Particularly useful if model doesn't deform
- Send vertex array data to GPU once
  - Includes per-vertex color or normal data
- Once data is on GPU, can be reused quickly
  - More than one triangle set or strips/fans referring to shared points
  - For animation: don't need to send vertex data each frame!
- Index buffers too:
  - Store vertex index arrays in GPU memory
  - Don't need to transmit index array each frame

Model I/O

- Usually have the ability to load data from some sort of file
- There are a variety of 3D model formats, but no universally accepted standards
- More formats for mostly geometry (e.g. indexed triangle sets) than for complete complex scene graphs
  - File structure unsurprising: List of vertex data, list(s) of triangles referring to the vertex data by name or number

Modeling Operations

- Surface of Revolution
- Sweep/Extrude
- Mesh operations
  - Stitching
  - Simplification -- deleting rows or vertices
  - Inserting new rows or vertices
- Filleting
- Boolean combinations
- Digitize
- Procedural modeling, scripts…

*Could be some interesting final projects here

Materials & Grouping

- Usually models are made up from several different materials
- The triangles are usually grouped and drawn by material
  - Minimize changes to “graphics state”--typically expensive to change
  - Using scene graph:
    - Geometry nodes with same material grouped together
    - “Material” nodes that define surface properties

Outline For Today

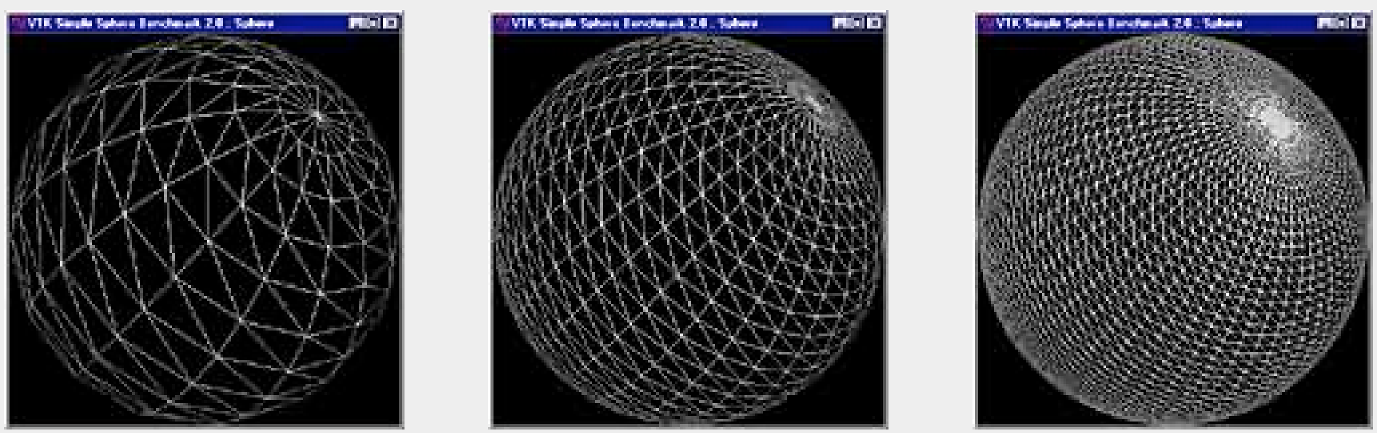
- Scene Graphs
- Shapes
- *Tessellation*

Tessellation

- Given a description of a surface
- Construct a triangle set (typically a mesh)
- Triangle set is an approximation
  - Fewer triangles: Faster, but less accurate
    - *Polygonal artifacts*
    - Especially at silhouettes
  - More triangles: slower, but more accurate
  - In the extreme, make each triangle the size of a pixel (or less)
- Fancy algorithms: *adaptive*
  - E.g., Make smaller triangles near silhouettes
  - E.g., Use fewer triangles when objects are far away
  - But must update/recompute tessellation each frame
    - Balance between cost of adaptive tessellation vs. rendering savings

Tessellating a sphere

- Various ways to do it
- We'll pick a straightforward one:
  - North & South poles
  - Latitude circles
  - Triangle strips between latitudes
  - Fans at the poles



Latitude circles

Given:

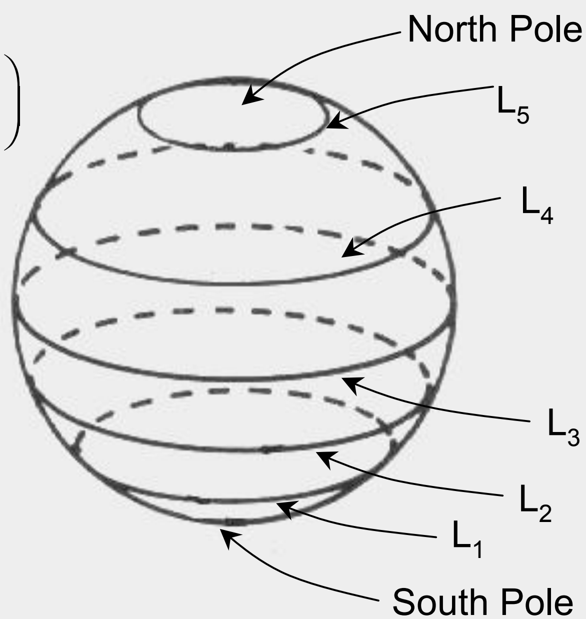
M = # latitude circles

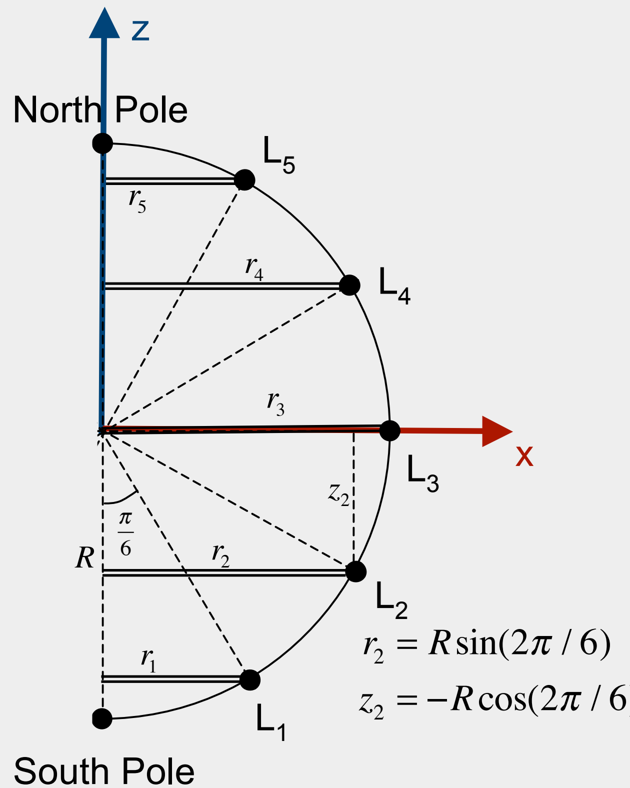
R = radius of sphere

For ith circle: i from 1 to M

$$r_i = R\sin\left(\frac{i\pi}{M+1}\right)$$

$$z_i = -R\cos\left(\frac{i\pi}{M+1}\right)$$





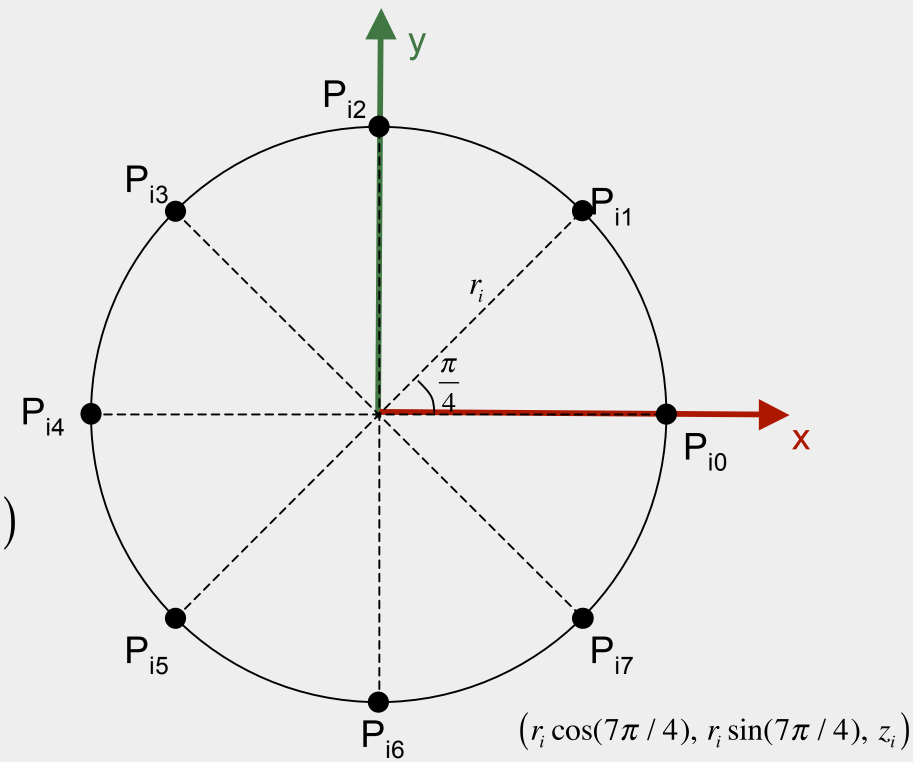
Points on each latitude circle

Given ith circle:

$$N = \#\text{ points in each circle}$$
$$r_i = \text{radius of } i\text{th circle}$$
$$z_i = \text{height of } i\text{th circle}$$

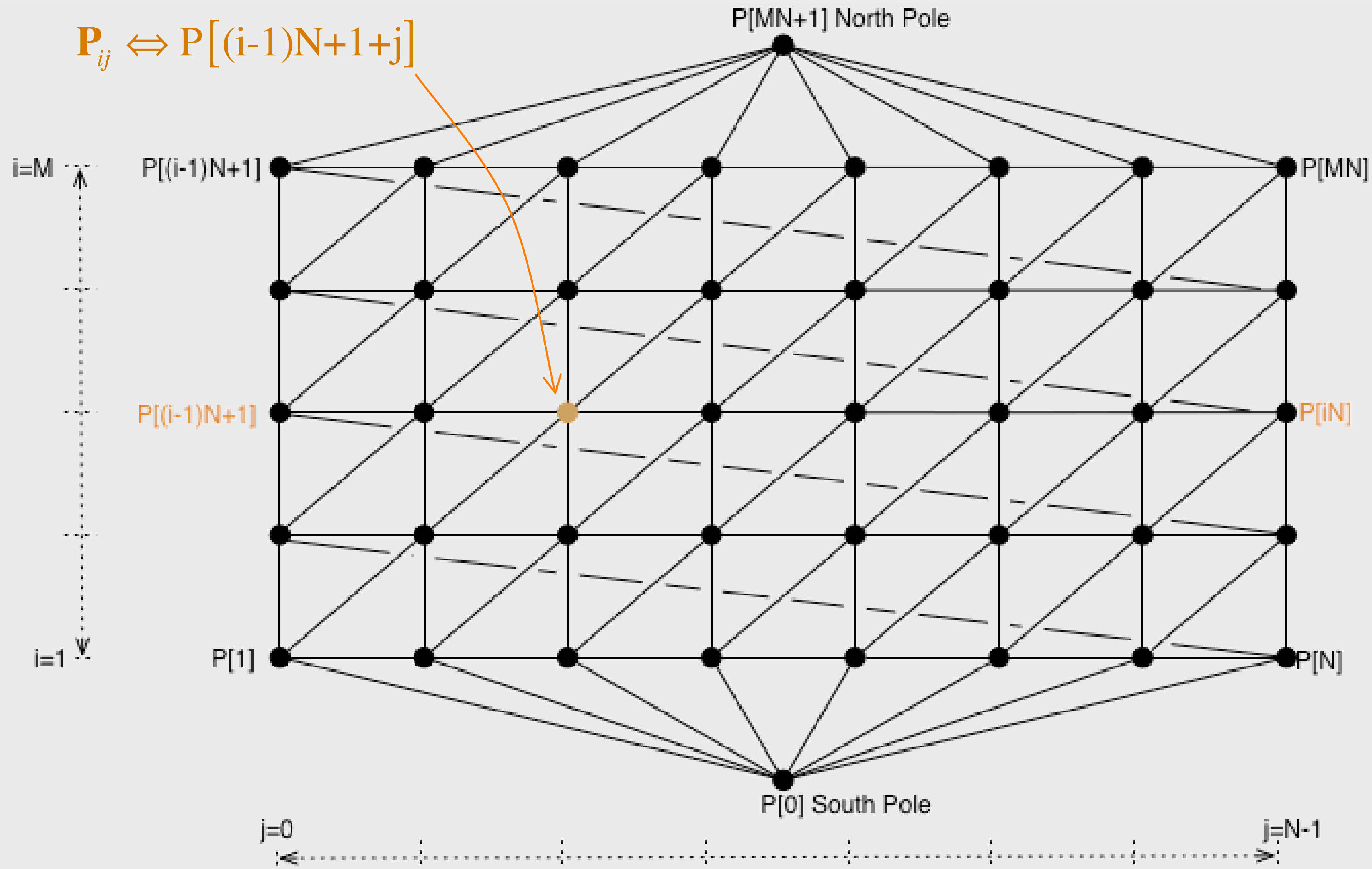
For jth point: j from 0 to $N-1$

$$\mathbf{P}_{ij} = \left(r_i\cos(2\pi j/N),\ r_i\sin(2\pi j/N),\ z_i\right)$$



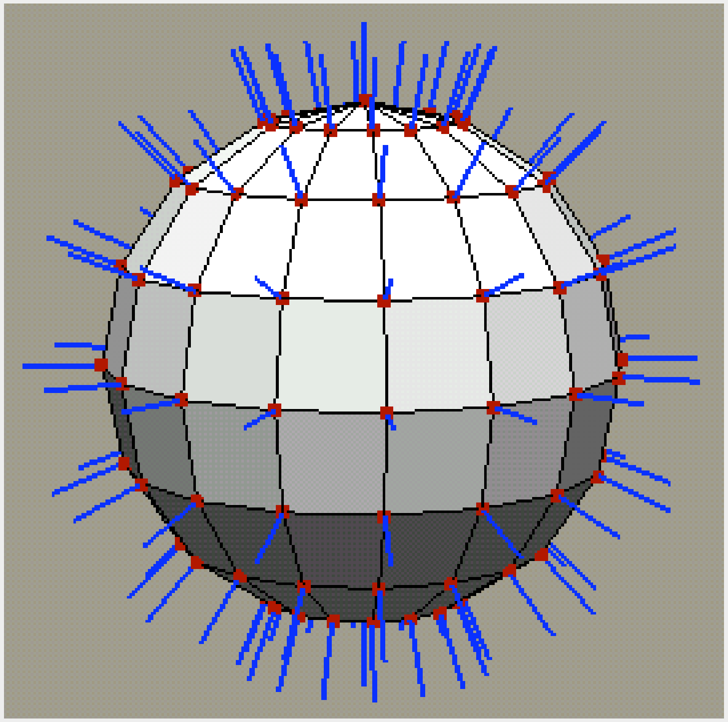
$$\mathbf{P}_{ij} = \left(R\sin\left(i\frac{\pi}{M+1}\right)\cos\left(j\frac{2\pi}{N}\right),\ R\sin\left(i\frac{\pi}{M+1}\right)\sin\left(j\frac{2\pi}{N}\right),\ -R\cos\left(i\frac{\pi}{M+1}\right)\right)$$

Topological structure



Normals

- For a sphere, normal per vertex is easy!
  - Radius vector from origin to vertex is perpendicular to surface
  - I.e., use the vertex coordinates as a vector, normalize it



Algorithm Summary

- Fill vertex array and normal array:
  - South pole = (0,0,-R);
  - For each latitude i, for each point j in the circle at that latitude
    - Compute coords, put in vertexes
      - Put points in vertices[0]..vertices[M*N+1] as per previous slides
  - North pole = (0,0,R)
  - Normals coords are same as point coords, normalized
- Fill triangle array:
  - N triangles between south pole and Lat 1
  - 2N triangles between Lat 1 & Lat 2, etc.
  - N triangles between Lat M and north pole.