Tutorial 6: Scene Graphs

Summary

So far you have only been drawing one or two objects in your scenes. What about drawing hundreds of objects - how can you make your graphical renderer scalable? This tutorial will show you how to implement a Scene Graph, a way of keeping track of lots of objects, including their transformations.

New Concepts

Scene Graphs, Scene Nodes, local vs. world transformations

Scene Graphs

If you’ve experimented with rendering multiple objects in your graphical applications, you’ve probably used something simple like an array, or maybe a vector, to hold a number of meshes to draw. Maybe you’ve even grouped a mesh and a transformation together in a struct. This will work for simple scenes, but as your scenes get more complicated, this 'linear' method of renderable storage becomes less useful. The classic example for this is a car with a separate mesh for the chassis and wheels - how do you keep track of where the wheels are in relation to the chassis? What if the car also has a driver mesh? Once you start adding in lots of objects, keeping track of the relative positions of everything starts becoming difficult! This is where a scene graph comes in handy. Scene graphs consist of a number of scene nodes, kept together in a tree-like structure - each node has a parent node, and a number of child nodes. So, our car example could be represented by the following scene graph:
Each node in the scene graph contains information relating to its graphical representation, so the chassis scene node could have a pointer to a car body mesh, while the four wheel nodes contain pointers to a single wheel mesh - there’s no need to load the same mesh in multiple times! But how does this solve how to keep track of where the wheels are in relation to the chassis? Simple: scene graphs can also store the spatial relationship between a parent scene node and its children.

**Local Transformations**

Each node in a scene graph commonly used in games contains data representing its local transform - its position and orientation in relation to its parent node. Generally this is simply a transformation matrix, just like the model matrices you’ve been using to place objects in your scenes, and so can contain translation, rotation, and scaling information. Instead of translating a mesh from local space to world space, a scene node’s transformation matrix transforms its position locally in relation to its parent, instead. This means that all transformation information cascades down the scene graph - including scaling transformations. This means that all scene nodes that are children of a given node with a scale will have their transformation matrices scaled - whether this is desirable or not is context dependent - being able to size up our car to be a monster truck by setting the chassis scale to 5.0 will automatically increase the size of its wheels, due to the parent/child relationship of their transformations - but as you will see in the example, sometimes having a scale in the matrix can cause undesirable artifacts.

**Graph Traversal**

As well as the local transformation of each node in a graph, if we want to render the graph on screen we’ll need each node’s world transformation, to use as the model matrix in a vertex shader. In order to do this, we must traverse the graph. Starting from the ‘top’ or root of the scene graph, the world transformation for each node can be calculated by multiplying a node’s local transformation matrix with the world transformation of its parent. Any child nodes of that node can then calculate their world position, and so on, down the graph, until leaf nodes are reached - that is, a node without any children. This operation is commonly done using either an iterative loop, or a recursive function, calling itself on child nodes until it hits a leaf.

Generally, it is better to store both the ‘local’ and ‘world’ transformations of an object - by descending the graph from the root, calculating world matrices as we go, we can then always determine the world matrix of an object with a single multiplication - the child’s local transformation with the world transformation of its parent. If we didn’t store the world matrix, we’d have to traverse the tree every time we needed the world matrix of a node - in a deep graph that could be a lot of unnecessary multiplications!

**Transition and State Nodes**

A scene node doesn’t necessarily have to contain graphical information, such as a mesh. They may be purely transitional, that is, nodes that group together and translate a number of children, but don’t render anything themselves. For example, perhaps the axles of our car are a transition node, with the wheels as children. Then, we only have to rotate the axle to rotate both wheels. Or perhaps the node contains only state information, such as a group of subnodes that are rendered using a specific shader, or some other specific rendering option set.

**World Scene Graph**

It’s not just a ‘decomposable’ object like our car example that can be represented as a scene graph - everything in a game world can be part of one large scene graph. It’s common for a game’s graphical renderer to have just a single root scene node, containing everything in the current level as children. So maybe our car is on a car transporter (so the car nodes are a child of the car transporter node), which is on a bridge (so is a child thereof), which is itself a child of the overall game ‘world’ node.
Example Program

To demonstrate scene graphs, we’re going to create a simple SceneNode class. This class will allow us to do two popular types of node traversal - efficiently generating the correct world transforms for each node in a scene graph, and drawing a whole tree of nodes. To show this, we’re going to make a simple robot made of cubes, whose limbs and head are child nodes of its body node, and can be transformed independently. Also, to demonstrate how each node in a scene graph could have shader variables attached to it, we’re going to write two new shaders - SceneVertex and SceneFragment, that will set a vertices colour by a colour variable of the SceneNode class.

SceneNode Class

Header file

Our SceneNode class is quite simple. To create the tree structure of our scene graph, each SceneNode has a parent, and a vector of children. Each SceneNode has a local transform, a world transform, a colour, a model scale, and pointer to a Mesh. It also has public accessors for each member variable - note how the accessors for a node’s children are const iterators, allowing other classes to safely iterate over a node’s children. Other than that, there’s a pair of public virtual functions. Update will traverse through a scene graph, building up world transforms and updating member variables in a framerate-independent way, just like the Camera class we made a while back, while Draw will actually draw the SceneNode, and which takes a const reference to the Renderer that is currently drawing.

We have a separate scale to change the mesh size so we can scale the cubes that make up the robot’s limbs without the scaling information affecting the transformation matrices of child nodes - but note, any scaling information actually in the transformation matrix, such as a scale in a a parent’s world transform, will still affect the resulting mesh scale.

```cpp
#pragma once
#include "Matrix4.h"
#include "Vector3.h"
#include "Vector4.h"
#include "Mesh.h"
#include <vector>

class SceneNode {
public:
    SceneNode(Mesh* m = NULL, Vector4 colour = Vector4(1,1,1,1));
    ~SceneNode(void);

    void SetTransform(const Matrix4 &matrix) { transform = matrix;}
    const Matrix4& GetTransform() const { return transform;}
    Matrix4 GetWorldTransform() const { return worldTransform;}

    Vector4 GetColour() const { return colour;}
    void SetColour(Vector4 c) { colour = c;}

    Vector3 GetModelScale() const { return modelScale;}
    void SetModelScale(Vector3 s) { modelScale = s;}

    Mesh* GetMesh() const { return mesh;}
    void SetMesh(Mesh* m) { mesh = m;}

    void AddChild(SceneNode* s);

    virtual void Update(float msec);
    virtual void Draw(const OGLRenderer &r);
};
```
std::vector<SceneNode*>::const_iterator GetChildIteratorStart() {
    return children.begin();}

std::vector<SceneNode*>::const_iterator GetChildIteratorEnd() {
    return children.end();}

protected:
    SceneNode* parent;
    Mesh* mesh;
    Matrix4 worldTransform;
    Matrix4 transform;
    Vector3 modelScale;
    Vector4 colour;
    std::vector<SceneNode*> children;
};

SceneNode.h

Class file

The constructor initialises its variables, while the destructor deletes all of a node's children. The AddChild function adds a SceneNode to its children vector, and also sets the new child nodes parent to itself - neatly keeping the simple tree structure of our scene graph intact. Note that a SceneNode does not delete its mesh variable - we could have lots of nodes all pointing to the same Mesh instance. This does mean that we have to handle any Mesh deletion elsewhere, though.

#include "SceneNode.h"

SceneNode::SceneNode(Mesh* mesh, Vector4 colour) {
    this->mesh = mesh;
    this->colour = colour;
    parent = NULL;
    modelScale = Vector3(1,1,1);
}

SceneNode::~SceneNode(void) {
    for (unsigned int i = 0; i < children.size(); ++i) {
        delete children[i];
    }
}

void SceneNode::AddChild(SceneNode* s) {
    children.push_back(s);
    s->parent = this;
}

SceneNode.cpp

Next, we have Draw, which unsurprisingly, draws the current SceneNode. We're actually going to let the Renderer handle most of the 'generic' drawing setup (setting the correct model matrix and binding shader variables), so all our default Draw function has to do is call the Mesh class Draw function, if there's a mesh to draw. If a particular SceneNode has to perform more advanced rendering setup (disabling depth testing, or reuploading data) it can be done here. This function has a reference to the renderer that is currently drawing, in case there is anything the SceneNode needs to access from the class.
```cpp
20 void SceneNode::Draw(const OGLRenderer &r) {
21    if(mesh) { mesh->Draw();}
22 }
```

Finally in our simple SceneNode class, we have Update. This will generate the correct world space transformation for a node and its children by simply multiplying a node’s local transform matrix by its parent’s world matrix. As the graph traversal takes place in a top-down manner, the parent node of any node performing the Update function will have already calculated a correct world space transformation. We’ll see shortly how subclasses of the SceneNode class may do something more interesting with this Update function - remember, it is virtual.

```cpp
23 void SceneNode::Update(float msec) {
24    if(parent) { //This node has a parent...
25       worldTransform = parent->worldTransform * transform;
26    }
27    else{ //Root node, world transform is local transform!
28       worldTransform = transform;
29    }
30    for(vector<SceneNode*>::iterator i = children.begin();
31       i != children.end(); ++i) {
32       (*i)->Update(msec);
33    }
34 }
```

CubeRobot Class

That’s everything we need for a simple SceneNode class, but to really show off how flexible the scene graph method of object management is, we’re going to extend it, too. This subclass will automatically build a simple robot out of cubes, creating a small SceneNode hierarchy.

CubeRobot Scene Nodes

The CubeRobot has a transitional scene node as its root node. This is to make it easier to place the robot in the world; if we place an instance of the CubeRobot at the origin, we really want it to be centered, standing on the origin, so the origin is between its legs. This transition node has one child, the robot’s body. This body node has five children, the arms, the legs, and the head.
CubeRobot Mesh

The CubeRobot is made entirely out of cubes - ones that have been scaled by varying amounts to produce the various limb shapes. This works as the cube mesh we’re going to use is not centered on the origin, but rather ‘sits’ on it:

Left: Cube scaling and rotation

This allows the cube to effectively be stretched in one direction, and means the mesh’s origin works as a pivot point, handy for the rotation of robot limbs!

Header file

There’s not too much new for our CubeRobot class. We overload the Update function, which will handle some simple animation of our cube robot. Also, no matter how many CubeRobots we have, we only need one cube Mesh, so we’re going to keep it as a static variable of our class, along with a pair of functions to explicitly create and delete this mesh. Unlike with the triangle and quad we’ve used in the past, we’re going to load the cube up as mesh geometry, from a file format known as Wavefront OBJ. Luckily for you, nclgl comes with a basic OBJ file loader, and a OBJ mesh cube, in the ../Meshes/ folder (which can be accessed via the MESHDIR #define). Finally, we have some pointers to the SceneNodes that make up our robot’s limbs, so we can easily animate them.

```
#pragma once
#include "./nclgl/sceneno"h"
#include "./nclgl/OBJMesh.h"

class CubeRobot : public SceneNode {
public:
  CubeRobot(void);
  ~CubeRobot(void){};
  virtual void Update(float msec);

  static void CreateCube() {
    OBJMesh*m = new OBJMesh();
    m->LoadOBJMesh(MESHDIR"cube.obj");
    cube = m;
  }
  static void DeleteCube() { delete cube;}

protected:
  static Mesh* cube;
  SceneNode* head;
  SceneNode* leftArm;
  SceneNode* rightArm;
};
```

Class file

The CubeRobot constructor builds up the robot out of cube Meshes, and child SceneNodes, using the SceneNode scale variable to set the size and shape of the cube, and the local transform to set the position offset of the limbs - you can think of these positions as the joints by which the limbs will be rotated. For good measure, we set colours for each limb, too, in the SceneNode constructors.
#include "CubeRobot.h"

Mesh* CubeRobot::cube = NULL;

CubeRobot::CubeRobot(void) {
    //Optional, uncomment if you want a local origin marker!
    //SetMesh(cube);

    SceneNode* body = new SceneNode(cube, Vector4(1,0,0,1)); // Red!
    body->SetModelScale(Vector3(10,15,5));
    body->SetTransform(Matrix4::Translation(Vector3(0,35,0)));
    AddChild(body);

    head = new SceneNode(cube, Vector4(0,1,0,1)); // Green!
    head->SetModelScale(Vector3(5,5,5));
    head->SetTransform(Matrix4::Translation(Vector3(0,30,0)));
    body->AddChild(head);

    leftArm = new SceneNode(cube, Vector4(0,0,1,1)); // Blue!
    leftArm->SetModelScale(Vector3(3,-18,3));
    leftArm->SetTransform(Matrix4::Translation(Vector3(-12,30,-1)));
    body->AddChild(leftArm);

    rightArm = new SceneNode(cube, Vector4(0,0,1,1)); // Blue!
    rightArm->SetModelScale(Vector3(3,-18,3));
    rightArm->SetTransform(Matrix4::Translation(Vector3(12,30,-1)));
    body->AddChild(rightArm);

    SceneNode* leftLeg = new SceneNode(cube, Vector4(0,0,1,1)); // Blue!
    leftLeg->SetModelScale(Vector3(3,-17.5,3));
    leftLeg->SetTransform(Matrix4::Translation(Vector3(-8,0,0)));
    body->AddChild(leftLeg);

    SceneNode* rightLeg = new SceneNode(cube, Vector4(0,0,1,1)); // Blue!
    rightLeg->SetModelScale(Vector3(3,-17.5,3));
    rightLeg->SetTransform(Matrix4::Translation(Vector3(8,0,0)));
    body->AddChild(rightLeg);
}

void CubeRobot::Update(float msec) {
    transform = transform * Matrix4::Rotation(msec / 10.0f, Vector3(0,1,0));
    head->SetTransform(head->GetTransform() * Matrix4::Rotation(-msec / 10.0f, Vector3(0,1,0)));
}

CubeRobot.cpp

Our overloaded Update function is going to perform some crude animation on our cuboid robot! To start off with, on line 40, we rotate our local transform around the y-axis, so our robot will slowly spin around on the spot. He’s also going to rotate his head around in circles, too - why not, he’s a robot! Finally, on line 46 and 49, he’s going to windmill his arms around in opposite directions on the x-axis. You should be able to see how useful scene graph hierarchies are now; we don’t need to care about what the root node’s orientation is in order to rotate any of its child nodes, the world transform traversal will handle it all for us automatically. The final thing the function needs to do is call the parent class Update function - a handy feature of virtual functions. This means that no matter what our overloaded Update functions do, we can always call the original function code and keep our nodes up to date.
45 leftArm->SetTransform(leftArm->GetTransform() *
46     Matrix4::Rotation(-msec / 10.0f, Vector3(1,0,0)));
47 
48 rightArm->SetTransform(rightArm->GetTransform() *
49     Matrix4::Rotation(msec / 10.0f, Vector3(1,0,0)));
50 
51 SceneNode::Update(msec);
52 }

CubeRobot.cpp

Renderer Class

Header file

Finally, we need a Renderer class that can handle SceneNodes. Our Renderer has a single pointer to a SceneNode, and a single new function - DrawNode, that takes in a SceneNode. That’s all we need, as we’re going to traverse the scene graph, using DrawNode on all child nodes of the root variable.

```
#include "Renderer.h"

class Renderer : public OGLRenderer {
public:
    Renderer(Window &parent);
    virtual ~Renderer(void);

    virtual void UpdateScene(float msec);
    virtual void RenderScene();

protected:
    void DrawNode(SceneNode*n);
    SceneNode* root;
    Camera* camera;
};
```

Renderer.h

Class file

New in our constructor is the initialisation of the root member variable on line 18, and then adding a CubeRobot as a child on line 19. Note we also call the static CubeRobot function CreateCube on line 4 - this must be called before adding any CubeRobots! In our destructor, we delete the root node, which will in turn delete the CubeRobot child node, and call the DeleteCube static function.

```
#include "Renderer.h"

Renderer::Renderer(Window &parent) : OGLRenderer(parent) {
    CubeRobot::CreateCube(); //Important!
    camera = new Camera();
```
currentShader = new Shader(SHADERDIR"SceneVertex.glsl",
SHADERDIR"SceneFragment.glsl");

if(!currentShader->LinkProgram()) {
    return;
}

projMatrix = Matrix4::Perspective(1.0f,10000.0f,
(float)width/(float)height,45.0f);
camera->SetPosition(Vector3(0,30,175));

root = new SceneNode();
root->AddChild(new CubeRobot());

GLenum(GL_DEPTH_TEST);
init = true;
}
Renderer::Renderer(void) {
delete root;
CubeRobot::DeleteCube();   //Also important!
}
Renderer::~Renderer (void) {
delete root;
CubeRobot::DeleteCube();   //Also important!
}

void Renderer::UpdateScene(float msec) {
camera->UpdateCamera(msec);
viewMatrix = camera->BuildViewMatrix();
root->Update(msec);
}

void Renderer::RenderScene() {
    glClear(GL_DEPTH_BUFFER_BIT | GL_COLOR_BUFFER_BIT);
    glUseProgram(currentShader->GetProgram());
    UpdateShaderMatrices();
    glUniform1i(glGetUniformLocation(currentShader->GetProgram(),
        "diffuseTex"), 1);
    DrawNode(root);
    glUseProgram(0);
    SwapBuffers();
}

The last function we need to define is DrawNode. If the SceneNode passed as a parameter to this function has a non-NULL Mesh instance, we update the currentShader modelMatrix with the worldTransform of the SceneNode, multiplied by its scale variable. Then, we send the SceneNode’s colour to the shader’s nodeColour uniform variable, and Draw the mesh.
Whether the node has a Mesh or not, we then iterate over a node's children, drawing each of those, too. That’s how our Renderer class can render an entire scene graph’s worth of objects - calling 

DrawNode for the root node will recursively call it for all child nodes, too.

```cpp
void Renderer::DrawNode(SceneNode* n) {
    if(n->GetMesh()) {
        Matrix4 transform = n->GetWorldTransform() *
            Matrix4::Scale(n->GetModelScale());
        glUniformMatrix4fv(
            glGetUniformLocation (currentShader->GetProgram(),
            "modelMatrix"), 1, false, (float*)&transform);

        glUniform4fv (getUniformLocation (currentShader->GetProgram(),
            "nodeColour"), 1,(float*)&n->GetColour());

        glUniform1i (getUniformLocation (currentShader->GetProgram(),
            "useTexture"),(int)n->GetMesh()->GetTexture());
        n->Draw(*this);
    }

    for (vector<SceneNode*>::const_iterator
        i = n->GetChildIteratorStart();
        i != n->GetChildIteratorEnd(); ++i) {
        DrawNode(*i);
    }
}
```

Renderer.cpp

**Vertex Shader**

We have a new vertex shader for this tutorial. It is similar to the previous vertex shaders, only this time, instead of setting the vertex colour from the incoming VBO attribute data, we use the node-Colour uniform variable, set in the Renderer class DrawNode function.

```glsl
#version 150 core

uniform mat4 modelMatrix;
uniform mat4 viewMatrix;
uniform mat4 projMatrix;
uniform vec4 nodeColour;

in vec3 position;
in vec2 texCoord;

out Vertex {
    vec2 texCoord;
    vec4 colour;
} OUT;

void main(void) {

    gl_Position = (projMatrix * viewMatrix * modelMatrix) *
        vec4(position, 1.0);
    OUT.texCoord = texCoord;
    OUT.colour = nodeColour;
}
```

SceneVertex.glsl
Fragment Shader

In the fragment shader we make use of the \textit{useTexture uniform} variable. This was set in the \textit{DrawNode} function, and will be non-zero if the currently drawn \textit{Mesh} has a texture, which we use in an if statement to selectively sample and blend the texture map with the current fragment.

```
#version 150 core

uniform sampler2D diffuseTex;
uniform int useTexture;

in Vertex {
    vec2 texCoord;
    vec4 colour;
} IN;

out vec4 fragColour;

void main ( void ) {
    fragColour = IN.colour;
    if(useTexture > 0) {
        fragColour *= texture(diffuseTex, IN.texCoord);
    }
}
```

SceneFragment.glsl

Tutorial Summary

Upon running the program, you should see a multi-coloured cuboid robot. He’s not a very \textit{good} robot, really - all he does is spin on the spot and wave his arms around. But in doing so, our little cube robot has demonstrated the basics required to draw multiple objects in a simple manner. As his root node spins on the spot, his 'child' node body and limbs are transformed, too. If you were to translate or scale the robot’s root node, all of his constituent parts would translate and scale correctly. That’s the simple beauty of the scene graph structure. You’ve also learnt how to traverse a scene graph, which will come in handy in the next tutorial.

You should be starting to get a feel as to how a game’s renderer can update and draw hundreds of different types of objects - you could easily pass many different subclasses of \textit{SceneNode} to a \textit{Renderer} class to place as children of it’s \textit{root} node, and it’d update, draw, and traverse them all, without requiring any explicit knowledge of what the subclass did.

In the next tutorial, you’ll see how to traverse a scene graph in such a way as to partially solve the issue of transparent object draw ordering, how to skip the drawing of nodes outside of the camera’s view, and how to take advantage of an optimisation feature of modern graphics hardware - the \textit{early z test}.

Further Work

1) Try adding 10 \textit{CubeRobots} to the scene - do you need to change the \textit{Renderer DrawScene} function at all? How about the \textit{UpdateScene} function? How many \textit{Mesh} class instances would 10 \textit{CubeRobots} require?

2) If you wanted to make a CubeRobot 10 times bigger, how many \textit{SceneNodes} would you have to scale?

3) Make the \textit{CubeRobot} a bit more interesting - try adding a transitional node to act as hips. Which node could it be a child of? What nodes would be children of the hips node?
4) So far you can only add children to a *SceneNode*. Try adding in the ability to *remove* children, too. Handy if the *SceneNodes* are enemies you are defeating during the course of a game. Also, you can currently add a *SceneNode* as a child of itself...what happens then? How would you avoid this?

5) *SceneNodes* currently have separate *Mesh* class instances. Perhaps they could have separate *Shaders*, too? Or even override the current *Mesh’s* texture!