5.1: Three.js Basics

Three.js is an object-oriented JavaScript library for 3D graphics. It is an open-source project created by Ricardo Cabello (who goes by the handle “mr.doob”, http://mrdoob.com/), with contributions from other programmers. It seems to be the most popular open-source JavaScript library for 3D web applications. *Three.js* uses concepts that you are already familiar with, such as geometric objects, transformations, lights, materials, textures, and cameras. But it also has additional features that build on the power and flexibility of WebGL.

You can download *three.js* and read the documentation at its main web site, http://threejs.org. The download is quite large, since it includes many examples and sup- port files. In this book, I use Release 89 of the software, from December, 2017. (Version 1.1 of this book used Release 71. There have been a number of changes in the API since that release. Unfortunately, the API has not been as stable as I had hoped. Example in this book should work with Release 89 but might not work with other releases of three.js.)

The core features of *three.js* are defined in a single large JavaScript file named “three.js”, which can be found in a *build* directory in the download. There is also a smaller “minified” version, *three.min.js*, that contains the same definitions in a format that is not meant to be human-readable. (You can also find copies of these files, from Release 89 of three.js, as part of the web site download of this book, in the threejs folder inside the source folder.) To use *three.js* on a web page, you need to include one of the two scripts in a `<script>` element on the page. For example, assuming that *three.min.js* is in the same folder as the web page, then the script element would be:

```
<script src="three.min.js"></script>
```

In addition to this core, the *three.js* download has a directory containing many examples and a variety of support files that are used in the examples. Although I will stick mainly to the core, I will also use a few of the extras and will note their source when I do.

Scene, Renderer, Camera

Three.js works with the HTML `<canvas>` element, the same thing that we used for 2D graphics in Section 2.6. In many web browsers, in addition to its 2D Graphics API, a canvas also supports drawing in 3D using WebGL, which is about as different as it can be from the 2D API. WebGL is not available in some browsers that support `<canvas>`. For example, this is true in Internet Explorer 9 and 10. But WebGL is implemented in Internet Explorer 11, as well as recent versions of Chrome, Safari, Firefox, and Edge. It also works in browsers on many mobile devices.

Three.js is an object-oriented scene graph API. (See Subsection 2.4.2.) The basic procedure is to build a scene graph out of *three.js* objects, and then to render an image of the scene it represents. Animation can be implemented by modifying properties of the scene graph between frames.

The *three.js* library is made up of a large number of classes. Three of the most basic are *THREE.Scene*, *THREE.Camera*, and *THREE.WebGLRenderer*. A *three.js* program will need at least one object of each type. Those objects are often stored in global variables

```
var scene, renderer, camera;
```

Note that almost all of the *three.js* classes and constants that we will use are properties of an object named *THREE*, and their names begin with “*THREE.*”. I will sometimes refer to classes without using this prefix, and it is not usually used in the *three.js* documentation, but the prefix must always be included in actual program code.

A *Scene* object is a holder for all the objects that make up a 3D world, including lights, graphical objects, and possibly cameras. It acts as a root node for the scene graph. A *Camera* is a special kind of object that represents a viewpoint from which an image of a 3D world can be made. It represents a combination of a viewing transformation and a projection. A *WebGLRenderer* is an object that can create an image from a scene graph.

The scene is the simplest of the three objects. A scene can be created as an object of type *THREE.Scene* using a constructor with no parameters:

```
scene = new THREE.Scene();
```

The function *scene.add*(*item*) can be used to add cameras, lights, and graphical objects to the scene. It is probably the only *scene* function that you will need to call. The function *scene.remove*(*item*), which removes an item from the scene, is also occasionally useful.

There are two kinds of camera, one using orthographic projection and one using perspective projection. They are represented by classes *THREE.OrthographicCamera* and *THREE.PerspectiveCamera*, which are subclasses of *THREE.Camera*. The constructors specify the projection, using parameters that are familiar from OpenGL (see Subsection 3.3.3):

```
camera = new THREE.OrthographicCamera( left, right, top, bottom, near, far );
```

or

```
camera = new THREE.PerspectiveCamera( fieldOfViewAngle, aspect, near, far );
```

The parameters for the orthographic camera specify the x, y, and z limits of the view volume, in eye coordinates—that is, in a coordinate system in which the camera is at (0,0,0) looking in the direction of the negative *z*-axis, with the *y*-axis pointing up in the view. The *near* and *far* parameters give the z-limits in terms of distance from the camera. For an orthographic projection, *near* can be negative, putting the "near" clipping plane in back of the camera. The parameters are the same as for the OpenGL function *glOrtho()*, except for reversing the order of the two parameters that specify the top and bottom clipping planes.

Perspective cameras are more common. The parameters for the perspective camera come from the function *gluPerspective()* in OpenGL's GLU library. The first parameter determines the vertical extent of the view volume, given as an angle measured in degrees. The *aspect* is the ratio between the horizontal and vertical extents; it should usually be set to the width of the canvas divided by its height. And *near* and *far* give the *z*-limits on the view volume as distances from the camera. For a perspective projection, both must be positive, with *near* less than *far*. Typical code for creating a perspective camera would be:

```
camera = new THREE.PerspectiveCamera( 45, canvas.width/canvas.height, 1, 100 );
```

where *canvas* holds a reference to the `<canvas>` element where the image will be rendered. The near and far values mean that only things between 1 and 100 units in front of the camera are included in the image. Remember that using an unnecessarily large value for *far* or an unnecessarily small value for *near* can interfere with the accuracy of the depth test.

A camera, like other objects, can be added to a scene, but it does not have to be part of the scene graph to be used. You might add it to the scene graph if you want it to be a parent or child of another object in the graph. In any case, you will generally want to apply a modeling transformation to the camera to set its position and orientation in 3D space. I will cover that later when I talk about transformations more generally.

(The *three.js* download includes several examples of alternative renderer classes, which can render to different targets. For example, there is a *CanvasRenderer* that translates 3D graphics into the 2D canvas API that was covered in Section 2.6. Other renderers can render 3D graphics using SVG and even CSS. However, these alternative renderers do not support many features of the WebGL renderer. This book will only use the WebGL renderer.)

A renderer that renders using WebGL is an instance of the class *THREE.WebGLRenderer*. Its constructor has one parameter, which is a JavaScript object containing settings that affect the renderer. The settings you are most likely to specify are *canvas*, which tells the renderer where to draw, and *antialias*, which asks the renderer to use antialiasing if possible:

```
renderer = new THREE.WebGLRenderer( {
          canvas: theCanvas,
          antialias: true
     } );
```

Here, *theCanvas* would be a reference to the `<canvas>` element where the renderer will display the images that it produces. (Note that the technique of having a JavaScript object as a parameter is used in many *three.js* functions. It makes it possible to support a large number of options without requiring a long list of parameters that must all be specified in some particular order. Instead, you only need to specify the options for which you want to provide nondefault values, and you can specify those options by name, in any order.)

The main thing that you want to do with a renderer is render an image. For that, you also need a scene and a camera. To render an image of a given *scene* from the point of view of a given *camera*, call

```
renderer.render( scene, camera );
```

This is really the central command in a *three.js* application.
(I should note that most of the examples that I have seen do not provide a canvas to the

renderer; instead, they allow the renderer to create it. The canvas can then be obtained from the renderer and added to the page. Furthermore, the canvas typically fills the entire browser window. The sample program threejs/full-window.html shows how to do that. However, all of my other examples use an existing canvas, with the renderer constructor shown above.)

THREE.Object3D

A *three.js* scene graph is made up of objects of type *THREE.Object3D* (including objects that belong to subclasses of that class). Cameras, lights, and visible objects are all represented by subclasses of *Object3D*. In fact, *THREE.Scene* itself is also a subclass of *Object3D*.

Any *Object3D* contains a list of child objects, which are also of type *Object3D*. The child lists define the structure of the scene graph. If node and object are of type *Object3D*, then the method *node.add*(*object*) adds *object* to the list of children of node. The method *node.remove*(*object*) can be used to remove an object from the list.

A *three.js* scene graph must, in fact, be a tree. That is, every node in the graph has a unique parent node, except for the root node, which has no parent. An *Object3D*, *obj*, has a property *obj.parent* that points to the parent of *obj* in the scene graph, if any. You should never set this property directly. It is set automatically when the node is added to the child list of another node. If *obj* already has a parent when it is added as a child of *node*, then *obj* is first removed from the child list of its current parent before it is added to the child list of *node*.

The children of an *Object3D*, *obj*, are stored in a property named *obj.children*, which is an ordinary JavaScript array. However, you should always add and remove children of *obj* using the methods *obj*.add() and *obj.remove()*.

To make it easy to duplicate parts of the structure of a scene graph, *Object3D* defines a *clone()* method. This method copies the node, including the recursive copying of the children of that node. This makes it easy to include multiple copies of the same structure in a scene graph:

```
var node = THREE.Object3D();
        .
        .  // Add children to node.
        .
scene.add(node);
var nodeCopy1 = node.clone();
        .
        .  // Modify nodeCopy1, maybe apply a transformation.
        .
scene.add(nodeCopy1)
var nodeCopy2 = node.clone();
        .
        .  // Modify nodeCopy2, maybe apply a transformation.
        .
scene.add(nodeCopy2);
```

An *Object3D*, *obj*, has an associated transformation, which is given by properties *obj.scale*, *obj.rotation*, and *obj.position*. These properties represent a modeling transformation to be applied to the object and its children when the object is rendered. The object is first scaled, then rotated, then translated according to the values of these properties. (Transformations are actually more complicated than this, but we will keep things simple for now and will return to the topic later.)

The values of *obj.scale* and *obj.position* are objects of type *THREE.Vector3*. A *Vector3* represents a vector or point in three dimensions. (There are similar classes *THREE.Vector2* and *THREE.Vector4* for vectors in 2 and 4 dimensions.) A *Vector3* object can be constructed from three numbers that give the coordinates of the vector:

```
var v = new THREE.Vector3( 17, -3.14159, 42 );
```

This object has properties *v.x*, *v.y*, and *v.z* representing the coordinates. The properties can be set individually; for example: *v.x* = 10. They can also be set all at once, using the method *v.set*(*x*,*y*,*z*). The *Vector3* class also has many methods implementing vector operations such as addition, dot product, and cross product.

For an *Object3D*, the properties *obj.scale.x*, *obj.scale.y*, and *obj.scale.z* give the amount of scaling of the object in the *x*, *y*, and *z* directions. The default values, of course, are 1. Calling

```
obj.scale.set(2,2,2);
```

means that the object will be subjected to a uniform scaling factor of 2 when it is rendered. Setting

```
obj.scale.y = 0.5;
```

will shrink it to half-size in the y-direction only (assuming that *obj.scale.x* and *obj.scale.z* still have their default values).

Similarly, the properties *obj.position.x*, *obj.position.y*, and *obj.position.z* give the translation amounts that will be applied to the object in the x, y, and z directions when it is rendered. For example, since a camera is an *Object3D*, setting

```
camera.position.z = 20;
```

means that the camera will be moved from its default position at the origin to the point (0,0,20) on the positive *z*-axis. This modeling transformation on the camera becomes a viewing transformation when the camera is used to render a scene.

The object *obj.rotation* has properties *obj.rotation.x*, *obj.rotation.y*, and *obj.rotation.z* that represent rotations about the *x*-, *y*-, and *z*-axes. The angles are measured in radians. The object is rotated first about the *x*-axis, then about the *y*-axis, then about the *z*-axis. (It is possible to change this order.) The value of *obj.rotation* is not a vector. Instead, it belongs to a similar type, *THREE.Euler*, and the angles of rotation are called ***Euler angles***.

Object, Geometry, Material

A visible object in *three.js* is made up of either points, lines, or triangles. An individual object corresponds to an OpenGL primitive such as GL_POINTS, GL_LINES, or GL_TRIANGLES (see Subsection 3.1.1). There are five classes to represent these possibilities: *THREE.Points* for points, *THREE.Mesh* for triangles, and three classes for lines: *THREE.Line*, which uses the *GL_LINE_STRIP* primitive; *THREE.LineSegments*, which uses the *GL_LINES* primitive; and *THREE.LineLoop*, which uses the *GL_LINE_LOOP* primitive.

A visible object is made up of some geometry plus a material that determines the appearance of that geometry. In *three.js*, the geometry and material of a visible object are themselves represented by JavaScript classes *THREE.Geometry* and *THREE.Material*.

An object of type *THREE.Geometry* has a property named vertices that is an array of *Vector3*. When creating a geometry by hand, we can simply push vectors onto that array. For example, suppose that we want to represent a cloud of 1000 random points inside the sphere of radius one centered at the origin:

```
var points = new THREE.Geometry();
while ( points.vertices.length < 1000 ) {
    var x = 2*Math.random() - 1;  // (between -1 and 1)
    var y = 2*Math.random() - 1;
    var z = 2*Math.random() - 1;
    if ( x*x + y*y + z*z < 1 ) { // use vector only if length is less than 1
        var pt = new THREE.Vector( x, y, z );
        points.vertices.push(pt);
    }
```

```
}
```

To make this point cloud into a visible object, we also need a material. For an object of type *THREE.Points*, we can use a material of type *THREE.PointsMaterial*, which is a subclass of *Material*. The material can specify the color and the size of the points, among other properties:

```
var pointMaterial = new THREE.PointsMaterial( {
        color: "yellow",
        size: 2,
        sizeAttenuation: false;
    } );
```

The parameter to the constructor is a JavaScript object whose properties are used to initialize the material. With the *sizeAttenuation* property set to *false*, the size is given in pixels; if it is *true*, then the size is scaled to reflect distance from the viewer. If the *color* is omitted, a default value of white is used. The default for *size* is 1 and for *sizeAttenuation* is *true*. The parameter can be omitted entirely, to use all the defaults. A *PointsMaterial* is not affected by lighting; it simply shows the color specified by its *color* property.

It is also possible to assign values to properties of the material after the object has been created. For example,

```
var pointMaterial = new THREE.PointsMaterial();
pointMaterial.color = new THREE.Color("yellow");
pointMaterial.size = 2;
pointMaterial.sizeAttenuation = false;
```

Note that the color is set as a value of type *THREE.Color*, which is constructed from a string, "yellow". When the color property is set in the material constructor, the same conversion of string to color is done automatically.

Once we have the geometry and the material, we can use them to create the visible object, of type *THREE.Points*, and add it to a scene:

```
var sphereOfPoints = new THREE.Points( points, pointMaterial );
scene.add( sphereOfPoints );
```

The on-line demo c5/point-cloud.html shows an animated point cloud.

Demo

http://math.hws.edu/eck/cs424/graphicsbook2018/demos/c5/point-cloud.html

The color parameter in the above material was specified by the string "yellow". Colors in *three.js* are stored as values of type *THREE.Color*. The class *THREE.Color* represents an RGB color. A *Color* object *c* has properties *c.r*, *c.g*, and *c.b* giving the red, blue, and green color components as floating point numbers in the range from 0.0 to 1.0. Note that there is no alpha component; *three.js* handles transparency separately from color.

There are several ways to construct a *THREE.Color* object. The constructor can take three parameters giving the RGB components as real numbers in the range 0.0 to 1.0. It can take a single string parameter giving the color as a CSS color string, like those used in the 2D canvas graphics API; examples include "white", "red", "rgb(255,0,0)", and "#FF0000". Or the color constructor can take a single integer parameter in which each color component is given as an eight-bit field in the integer. Usually, an integer that is used to represent a color in this way is written as a hexadecimal literal, beginning with "0x". Examples include `0xff0000` for red, `0x00ff00` for green, `0x0000ff` for blue, and `0x007050` for a dark blue-green. Here are some examples of using color constructors:

```
var c1 = new THREE.Color("skyblue");
var c2 = new THREE.Color(1,1,0); // yellow
var c3 = new THREE.Color(0x98fb98); // pale green
```

In many contexts, such as the *THREE.Points* constructor, three.js will accept a string or integer where a color is required; the string or integer will be fed through the *Color* constructor. As another example, a *WebGLRenderer* object has a "clear color" property that is used as the background color when the renderer renders a scene. This property could be set using any of the following commands:

```
renderer.setClearColor( new THREE.Color(0.6, 0.4, 0.1) );
```

```
renderer.setClearColor( "darkgray" );
```

```
renderer.setClearColor( 0x112233 );
```

An object of type *THREE.Line* represents a a line strip — what would be a primitive of the type called *GL_LINE_STRIP* in OpenGL. To get the same strip of connected line segments, plus a line back to the starting vertex, we can use an object of type *THREE.LineLoop*. For the outline of a triangle, for example, we can push three vertices onto the vertex array of a geometry object, and then use that geometry in a *THREE.LineLoop* object:

```
var lineGeom = new Geometry();
lineGeom.vertices.push( new THREE.Vector3(-2,-2,0) );
lineGeom.vertices.push( new THREE.Vector3(2,-2,0) );
lineGeom.vertices.push( new THREE.Vector3(0,2,0) );
```

Alternatively, we could create a new array containing the vertices and then assign that array to the property *lineGeom.vertices*:

```
lineGeom.vertices = [
    new THREE.Vector3(-2,-2,0),
    new THREE.Vector3(2,-2,0),
    new THREE.Vector3(0,2,0)
];
```

We will also need a material. For lines, the material can be represented by an object of type *THREE.LineBasicMaterial*. As usual, the parameter for the constructor is a JavaScript object, whose properties can include *color* and *linewidth*. For example:

```
var lineMat = new THREE.LineBasicMaterial( {
        color: 0xA000A0, // purple; the default is white
        linewidth: 2 // 2 pixels; the default is 1
    } );
```

With the geometry and material in hand, we can create a *LineLoop* object. The constructor takes the geometry and material as parameters:

```
var line = new THREE.LineLoop( lineGeom, lineMat );
```

Let's look at one more option: using a different color for each vertex. To do this, you need to add vertex colors to the *Geometry* object. The array of vertex colors is stored in the *colors* property of the geometry, and it should hold one color object for each vertex in the geometry's vertex array. Furthermore, to tell *three.js* to use the colors from the geometry color array, you need to set the *vertexColors* property of the *LineBasicMaterial* to *THREE.VertexColors*. Let's make a triangle with a red, a blue, and a green vertex—and add the triangle to a scene so that we can see it on the screen:

```
var lineGeom = new THREE.Geometry();
lineGeom.vertices.push( new THREE.Vector3(-2,-2,0) );
lineGeom.vertices.push( new THREE.Vector3(2,-2,0) );
lineGeom.vertices.push( new THREE.Vector3(0,2,0) );
lineGeom.colors.push( new THREE.Color(0xff0000) );
lineGeom.colors.push( new THREE.Color(0x00ff00) );
```

```
lineGeom.colors.push( new THREE.Color(0x0000ff) );
var lineMat = new THREE.LineBasicMaterial({
        linewidth: 3,
        vertexColors: THREE.VertexColors
    });
var triangle = new THREE.LineLoop( lineGeom, lineMat );
scene.add(triangle); // scene is of type THREE.Scene
```

This produces the image:

The “Basic” in *LineBasicMaterial* indicates that this material uses basic colors that do not require lighting to be visible and are not affected by lighting. This is generally what you want for lines.

A mesh object in *three.js* corresponds to the OpenGL primitive *GL_TRIANGLES*. The geometry object for a mesh must specify the triangles, in addition to the vertices. We will see later how to do that. However, *three.js* comes with classes to represent common mesh geometries, such as a sphere, a cylinder, and a torus. For these built-in classes, you just need to call a constructor to create the geometry. For example, the class *THREE.CylinderGeometry* represents the geometry for a cylinder, and its constructor takes the form

```
new THREE.CylinderGeometry(radiusTop, radiusBottom, height, radiusSegments,
heightSegments, openEnded, thetaStart, thetaLength)
```

The geometry created by this constructor represents an approximation for a cylinder that has its axis lying along the y-axis. It extends from from $-height/2$ to $height/2$ along that axis. The radius of its circular top is *radiusTop* and of its bottom is *radiusBottom*. The two radii don’t have to be the same; when the are different, you get a truncated cone rather than a cylinder as such. Using a value of zero for *radiusTop* makes an actual cone. The parameters *radiusSegments* and *heightSegments* give the number of subdivisions around the circumference of the cylinder and along its length respectively — what are called slices and stacks in the GLUT library for OpenGL. The parameter *openEnded* is a boolean value that indicates whether the top and bottom of the cylinder are to be drawn; use the value *true* to get an open-ended tube. Finally, the last two parameters allow you to make a partial cylinder. Their values are given as angles, measured in radians, about the y-axis. Only the part of the cylinder beginning at *thetaStart* and ending at *thetaStart* plus *thetaLength* is rendered. For example, if *thetaLength* is *Math.PI*, you will get a half-cylinder.

The large number of parameters to the constructor gives a lot of flexibility. The parameters are all optional but it’s probably best to include at least the first three since the default size is rather large, and the default for *radiusSegments* is 8, which gives a poor approximation for a smooth cylinder.

Other standard mesh geometries are similar. Here are some constructors, listing all parameters (but keep in mind that most of the parameters are optional):

```
new THREE.BoxGeometry(width, height, depth,
    widthSegments, heightSegments, depthSegments)

new THREE.PlaneGeometry(width, height, widthSegments, heightSegments)

new THREE.RingGeometry(innerRadius, outerRadius, thetaSegments, phiSegments,
    thetaStart, thetaLength)
```

```
new THREE.ConeGeometry(radiusBottom, height, radiusSegments,
    heightSegments, openEnded, thetaStart, thetaLength)

new THREE.SphereGeometry(radius, widthSegments, heightSegments,
    phiStart, phiLength, thetaStart, thetaLength)

new THREE.TorusGeometry(radius, tube, radialSegments, tubularSegments, arc)
```

The class *BoxGeometry* represents the geometry of a rectangular box centered at the origin. Its constructor has three parameters to give the size of the box in each direction; these are **not** optional. The last three parameters are optional. They give the number of subdivisions in each direction, with a default of 1; values greater than one will cause the faces of the box to be subdivided into smaller triangles.

The class *PlaneGeometry* represents the geometry of a rectangle lying in the *xy*-plane, centered at the origin. Its parameters are similar to those for a cube. A *RingGeometry* represents an annulus, that is, a disk with a smaller disk removed from its center. The ring lies in the *xy*-plane, with its center at the origin. You should always specify the inner and outer radii of the ring.

The constructor for *ConeGeometry* has exactly the same form and effect as the constructor for *CylinderGeometry*, with the *radiusTop* set to zero. That is, it constructs a cone with axis along the y-axis and centered at the origin.

For *SphereGeometry*, all parameters are optional. The constructor creates a sphere centered at the origin, with axis along the *y*-axis. The first parameter, which gives the radius of the sphere, has a default of 50 (which is usually too big). The next two parameters give the numbers of slices and stacks (with default values that are usually too small). The last four parameters allow you to make a piece of a sphere; the default values give a complete sphere. The four parameters are angles measured in radians. *phiStart* and *phiLength* are measured in angles around the equator and give the extent in longitude of the spherical shell that is generated. For example,

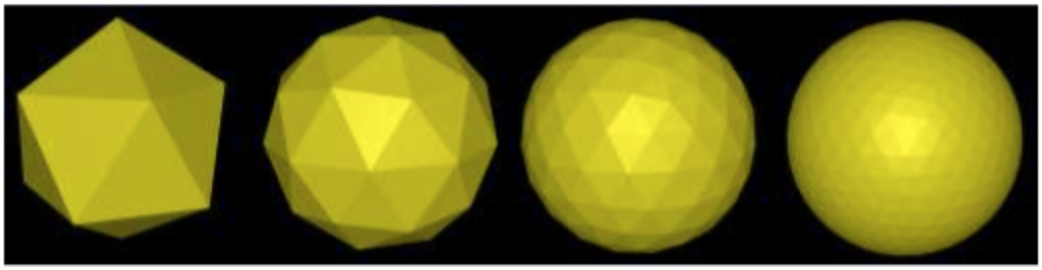
```
new THREE.SphereGeometry( 5, 32, 16, 0, Math.PI )
```

creates the geometry for the "western hemisphere" of a sphere. The last two parameters are angles measured along a line of latitude from the north pole of the sphere to the south pole. For example, to get the sphere's "northern hemisphere":

```
new THREE.SphereGeometry( 5, 32, 16, 0, 2*Math.PI, 0, Math.PI/2 )
```

For *TorusGeometry*, the constructor creates a torus lying in the *xy*-plane, centered at the origin, with the *z*-axis passing through its hole. The parameter *radius* is the distance from the center of the torus to the center of the torus's tube, while *tube* is the radius of the tube. The next two parameters give the number of subdivisions in each direction. The last parameter, *arc*, allows you to make just part of a torus. It is an angle between 0 and *2*Math.PI*, measured along the circle at the center of the tube.

There are also geometry classes representing the regular polyhedra: *THREE.TetrahedronGeometry*, *THREE.OctahedronGeometry*, *THREE.DodecahedronGeometry*, and *THREE.IcosahedronGeometry*. (For a cube use a *BoxGeometry*.) The constructors for these four classes take two parameters.
The first specifies the size of the polyedron, with a default of 1. The size is given as the radius of the sphere that contains the polyhedron. The second parameter is an integer called *detail*. The default value, 0, gives the actual regular polyhedron. Larger values add detail by adding additional faces. As the detail increases, the polyhedron becomes a better approximation for a sphere. This is easier to understand with an illustration:



The image shows four mesh objects that use icosahedral geometries with detail parameter equal to 0, 1, 2, and 3.

To create a mesh object, you need a material as well as a geometry. There are several kinds of material suitable for mesh objects, including *THREE.MeshBasicMaterial*, *THREE.MeshLambertMaterial*, and *THREE.MeshPhongMaterial*. (There are also two newer mesh materials, *THREE.MeshStandardMaterial* and *THREE.MeshPhysicalMaterial*, that implement techniques associated with physically based rendering, an approach to improved rendering that has become popular recently. However, I will not cover them here.)

A *MeshBasicMaterial* represents a color that is not affected by lighting; it looks the same whether or not there are lights in the scene, and it is not shaded, giving it a flat rather than 3D appearance. The other two classes represent materials that need to be lit to be seen. They implement models of lighting known as ***Lambert shading*** and ***Phong shading***. The major difference is that *MeshPhongMaterial* has a specular color but *MeshLambertMaterial* does not. Both can have diffuse and emissive colors. For all three material classes, the constructor has one parameter, a JavaScript object that specifies values for properties of the material. For example:

```
var mat = new THREE.MeshPhongMaterial( {
        color: 0xbbbb00, // reflectivity for diffuse and ambient light
        emissive: 0, // emission color; this is the default (black)
        specular: 0x070707, // reflectivity for specular light
        shininess: 50 // controls size of specular highlights
    } );
```

This example shows the four color parameters for a Phong material. The parameters have the same meaning as the five material properties in OpenGL (Subsection 4.1.1). A Lambert material lacks *specular* and *shininess*, and a basic mesh material has only the *color* parameter.

There are a few other material properties that you might need to set in the constructor. Except for *flatShading*, these apply to all three kinds of mesh material:

- *wireframe* — a boolean value that indicates whether the mesh should be drawn as a wireframe model, showing only the outlines of its faces. The default is *false*. A *true* value works best with *MeshBasicMaterial*.
- *wireframeLinewidth* — the width of the lines used to draw the wireframe, in pixels. The default is 1.
- *visible* — a boolean value that controls whether the object on which is is used is rendered or not, with a default of *true*.
- *side* — has value *THREE.FrontSide*, *THREE.BackSide*, or *THREE.DoubleSide*, with the default being *THREE.FrontSide*. This determines whether faces of the mesh are drawn or not, depending on which side of the face is visible. With the default value, *THREE.FrontSide*, a face is drawn only if it is being viewed from the front. *THREE.DoubleSide* will draw it whether it is viewed from the front or from the back, and *THREE.BackSide* only if it is viewed from the back. For closed objects, such as a cube or a complete sphere, the default value makes sense, at least as long as the viewer is outside of the object. For a plane, an open tube, or a partial sphere, the value should be set to *THREE.DoubleSide*. Otherwise, parts of the object that should be in view won't be drawn.
- *flatShading* — a *boolean* value, with the default being *false*. When making a Lambert or Phong material for an object that is supposed to look "faceted," with flat sides, it is important to set this property to *true*. That would be the case, for example, for a cube or for a cylinder with a small number of sides. The property is not used by *MeshBasicMaterial*.

As an example, let's make a shiny, blue-green, open, five-sided tube with flat sides:

```
var mat = new THREE.MeshPhongMaterial( {
        color: 0x0088aa,
        specular: 0x003344,
        shininess: 100,
        flatShading: true, // for flat-looking sides
        side: THREE.DoubleSide // for drawing the inside of the tube
    } );
var geom = new THREE.CylinderGeometry(3,3,10,5,1,true);
var obj = new THREE.Mesh(geom,mat);
scene.add(obj);
```

The on-line demo c5/mesh-objects.html lets you view a variety of three.js mesh objects with several different materials.

Demo

http://math.hws.edu/eck/cs424/graphicsbook2018/demos/c5/mesh-objects.html

The demo can show a wireframe version of an object overlaid on a solid version. In *three.js*, the wireframe and solid versions are actually two objects that use the same geometry but different materials. Drawing two objects at exactly the same depth can be a problem for the depth test. You might remember from Subsection 3.4.1 that OpenGL uses polygon offset to solve the problem. In *three.js*, you can apply polygon offset to a material. In the demos, this is done for the solid materials that are shown at the same time as wireframe materials. For example,

```
mat = new THREE.MeshLambertMaterial({
        polygonOffset: true,
        polygonOffsetUnits: 1,
        polygonOffsetFactor: 1,
        color: "yellow",
        side: THREE.DoubleSide
    });
```

The settings shown here for *polygonOffset*, *polygonOffsetUnits*, and *polygonOffsetFactor* will increase the depth of the object that uses this material slightly so that it doesn't interfere with the wireframe version of the same object.

One final note: You don't always need to make new materials and geometries to make new objects. You can reuse the same materials and geometries in multiple objects.

Lights

Compared to geometries and materials, lights are easy! Three.js has several classes to represent lights. Light classes are subclasses of *THREE.Object3D*. A light object can be added to a scene and will then illuminate objects in the scene. We'll look at directional lights, point lights, ambient lights, and spotlights.

The class *THREE.DirectionalLight* represents light that shines in parallel rays from a given direction, like the light from the sun. The *position* property of a directional light gives the direction from which the light shines. (This is the same *position* property, of type *Vector3*, that all scene graph objects have, but the meaning is different for directional lights.) Note that the light shines from the given position towards the origin. The default position is the vector (0,1,0), which gives a light shining down the y-axis. The constructor for this class has two parameters:

```
new THREE.DirectionalLight( color, intensity )
```

where *color* specifies the color of the light, given as a *THREE.Color* object, or as a hexadecimal integer, or as a CSS color string. Lights do not have separate diffuse and specular colors, as they do in OpenGL. The *intensity* is a non-negative number that controls the brightness of the light, with larger values making the light brighter. A light with intensity zero gives no light at all. The parameters are optional. The default for *color* is white (`0xffffff`) and for *intensity* is 1. The intensity can be greater than 1, but values less than 1 are usually preferable, to avoid having too much illumination in the scene.

Suppose that we have a camera on the positive *z*-axis, looking towards the origin, and we would like a light that shines in the same direction that the camera is looking. We can use a directional light whose position is on the positive *z*-axis:

```
var light = new THREE.DirectionalLight(); // default white light
light.position.set( 0, 0, 1 );
scene.add(light);
```

The class *THREE.PointLight* represents a light that shines in all directions from a point. The location of the point is given by the light's position property. The constructor has three optional parameters:

```
new THREE.PointLight( color, intensity, cutoff )
```

The first two parameters are the same as for a directional light, with the same defaults. The *cutoff* is a non-negative number. If the value is zero — which is the default — then the illumination from the light extends to infinity, and intensity does not decrease with distance. While this is not physically realistic, it generally works well in practice. If *cutoff* is greater than zero, then the intensity falls from a maximum value at the light's position down to an intensity of zero at a distance of *cutoff* from the light; the light has no effect on objects that are at a distance greater than *cutoff*. This falloff of light intensity with distance is referred to as ***attenuation*** of the light source.

A third type of light is *THREE.AmbientLight*. This class exists to add ambient light to a scene. An ambient light has only a color:

```
new THREE.AmbientLight( color )
```

Adding an ambient light object to a scene adds ambient light of the specified color to the scene. The color components of an ambient light should be rather small to avoid washing out colors of objects.

For example, suppose that we would like a yellowish point light at (10,30,15) whose illumination falls off with distance from that point, out to a distance of 100 units. We also want to add a bit of yellow ambient light to the scene:

```
var light = new THREE.PointLight( 0xffffcc, 1, 100 );
light.position.set( 10, 30, 15 );
scene.add(light);
scene.add( new THREE.AmbientLight(0x111100) );
```

The fourth type of light, *THREE.SpotLight*, is something new for us. An object of that type represents a ***spotlight***, which is similar to a point light, except that instead of shining in all directions, a spotlight only produces a cone of light. The vertex of the cone is located at the position of the light. By default, the axis of the cone points from that location towards the origin (so unless you change the direction of the axis, you should move the position of the light away from the origin). The constructor adds two parameters to those for a point light:

```
new THREE.SpotLight( color, intensity, cutoff, coneAngle, exponent )
```

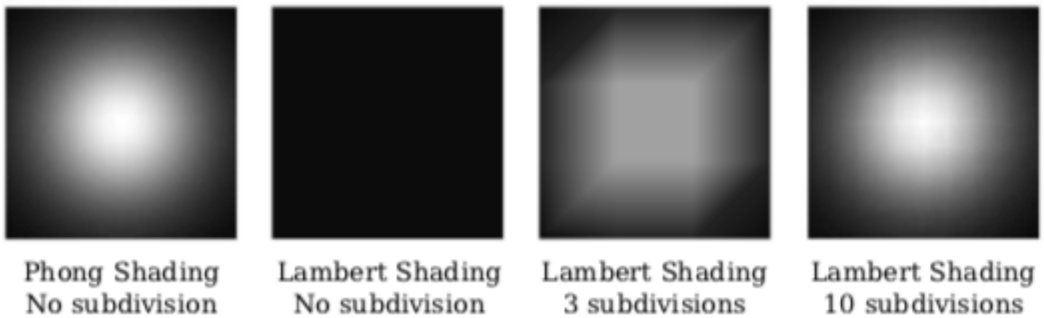
The *coneAngle* is a number between 0 and *Math.PI/2* that determines the size of the cone of light. It is the angle between the axis of the cone and the side of the cone. The default value is *Math.PI/3*. The *exponent* is a non-negative number that determines how fast the intensity of the light decreases as you move from the axis of the cone toward the side. The default value, 10, gives a reasonable result. An *exponent* of zero gives no falloff at all, so that objects at all distances from the axis are evenly illuminated.

The technique for setting the direction of a *three.js* spotlight is a little odd, but it does make it easy to control the direction. An object *spot* of type ***SpotLight*** has a property named *spot.target*. The target is a scene graph node. The cone of light from the spotlight is pointed in the direction from spotlight's position towards the target's position. When a spotlight is first created, its target is a new, empty *Object3D*, with position at (0,0,0). However, you can set the target to be any object in the scene graph, which will make the spotlight shine towards that object. For *three.js* to calculate the spotlight direction, a target whose position is anything other than the origin must actually be a node in the scene graph. For example, suppose we want a spotlight located at the point (0,0,5) and pointed towards the point (2,2,0):

```
spotlight = new THREE.SpotLight();
spotlight.position.set(0,0,5);
```

```
spotlight.target.position.set(2,2,0);
scene.add(spotlight);
scene.add(spotlight.target);
```

The interaction of spotlights with material illustrates an important difference between Phong and Lambert shading. With a *MeshLambertMaterial*, the lighting equation is applied at the vertices of a primitive, and the vertex colors computed by that equation are then interpolated to calculate colors for the pixels in the primitive. With *MeshPhongMaterial*, on the other hand, the lighting equation is applied at each individual pixel. The following illustration shows what can happen when we shine a spotlight onto a square that was created using *THREE.PlaneGeometry*:



For the two squares on the left, the square was not subdivided; it is made up of two triangular faces. The square at the far left, which uses Phong shading, shows the expected spotlight effect. The spotlight is pointed at the center of the square. Note how the illumination falls off with distance from the center. When I used the same square and spotlight with Lambert shading in the second picture, I got no illumination at all! The vertices of the the square lie outside the cone of light from the spotlight. When the lighting equation is applied, the vertices are black, and the black color of the vertices is then applied to all the pixels in the square.

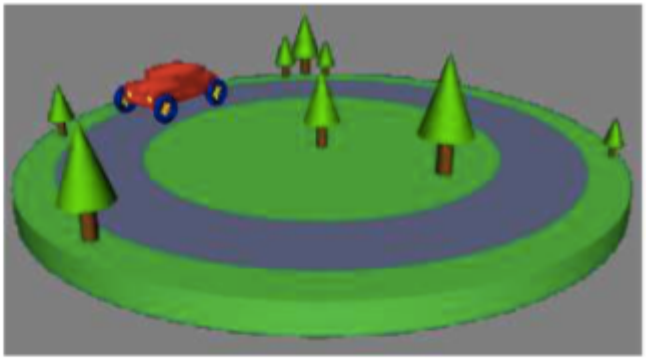
For the third and fourth squares in the illustration, plane geometries with horizontal and vertical subdivisions were used with Lambert shading. In the third picture, the square is divided into three subdivisions in each direction, giving 18 triangles, and the lighting equation

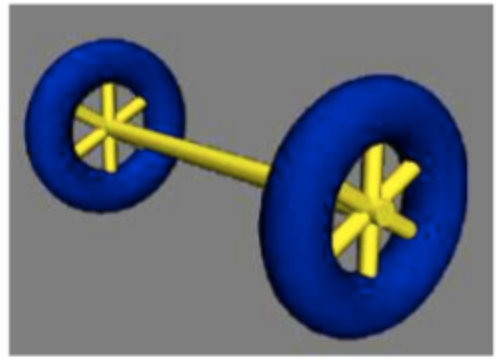
is applied only at the vertices of those triangles. The result is still a very poor approximation for the correct illumination. In the fourth square, with 10 subdivisions in each direction, the approximation is better but still not perfect.

The upshot is, if you want an object to be properly illuminated by a spotlight, use a *MeshPhongMaterial* on the object, even if it has no specular reflection. A *MeshLambertMaterial* will only give acceptable results if the faces of the object are very small.

A Modeling Example

In the rest of this chapter, we will go much deeper into *three.js*, but you already know enough to build 3D models from basic geometric objects. An example is in the sample program threejs/diskworld-1.html, which shows a very simple model of a car driving around the edge of a cylindrical base. The car has rotating tires. The diskworld is shown in the picture on the left below. The picture on the right shows one of the axles from the car, with a tire on each end.





I will discuss some of the code that is used to build this models. If you want to experiment with your own models, you can use the program threejs/modeling-starter.html as a starting point.

To start with something simple, let's look at how to make a tree from a brown cylinder and a green cone. I use an *Object3D* to represent the tree as a whole, so that I can treat it as a unit. The two geometric objects are added as children of the *Object3D*.

```
var tree = new THREE.Object3D();

var trunk = new THREE.Mesh(
    new THREE.CylinderGeometry(0.2,0.2,1,16,1),
    new THREE.MeshLambertMaterial({
        color: 0x885522
    })
);
trunk.position.y = 0.5;  // move base up to origin

var leaves = new THREE.Mesh(
    new THREE.ConeGeometry(.7,2,16,3),
    new THREE.MeshPhongMaterial({
        color: 0x00BB00,
        specular: 0x002000,
        shininess: 5
    })
);
leaves.position.y = 2;  // move bottom of cone to top of trunk

tree.add(trunk);
tree.add(leaves);
```

The trunk is a cylinder with height equal to 1. Its axis lies along the y-axis, and it is centered at the origin. The plane of the diskworld lies in the xz-plane, so I want to move the bottom of the trunk onto that plane. This is done by setting the value of *trunk.position.y*, which represents a translation to be applied to the trunk. Remember that objects have their own modeling coordinate system. The properties of objects that specify transformations, such as *trunk.position*, transform the object in that coordinate system. In this case, the trunk is part of a larger, compound object that represents the whole tree. When the scene is rendered, the trunk is first transformed by its own modeling transformation. It is then further transformed by any modeling transformation that is applied to the tree as a whole. (This type of hierarchical modeling was first covered in Subsection 2.4.1.)

Once we have a tree object, it can be added to the model that represents the diskworld. In the program, the model is an object of type *Object3D* named *diskworldModel*. The model will contain several trees, but the trees don't have to be constructed individually. I can make additional trees by cloning the one that I have already created. For example:

```
tree.position.set(-1.5,0,2);
tree.scale.set(0.7,0.7,0.7);
diskworldModel.add( tree.clone() );

tree.position.set(-1,0,5.2);
tree.scale.set(0.25,0.25,0.25);
diskworldModel.add( tree.clone() );
```

This adds two trees to the model, with different sizes and positions. When the tree is cloned, the clone gets its own copies of the modeling transformation properties, *position* and *scale*. Changing the values of those properties in the original tree object does not affect the clone.

Lets turn to a more complicated object, the axle and wheels. I start by creating a wheel, using a torus for the tire and using three copies of a cylinder for the spokes. In this case, instead of making a new *Object3D* to hold all the components of the wheel, I add the cylinders as children of the torus. Remember that any screen graph node in *three.js* can have child nodes.

```
var wheel = new THREE.Mesh(  // the tire; spokes will be added as children
    new THREE.TorusGeometry(0.75, 0.25, 16, 32),
    new THREE.MeshLambertMaterial({ color: 0x0000A0 })
);
var yellow = new THREE.MeshPhongMaterial({
    color: 0xffff00,
    specular: 0x101010,
    shininess: 16
});
var cylinder = new THREE.Mesh(  // a cylinder with height 1 and diameter 1
    new THREE.CylinderGeometry(0.5,0.5,1,32,1),
    yellow
);

cylinder.scale.set(0.15,1.2,0.15); // Make it thin and tall for use as a spoke.

wheel.add( cylinder.clone() );  // Add a copy of the cylinder.
cylinder.rotation.z = Math.PI/3;  // Rotate it for the second spoke.
wheel.add( cylinder.clone() );
cylinder.rotation.z = -Math.PI/3; // Rotate it for the third spoke.
wheel.add( cylinder.clone() );
```

Once I have the wheel model, I can use it along with one more cylinder to make the axle. For the axle, I use a cylinder lying along the *z*-axis. The wheel lies in the *xy*-plane. It is facing in the correct direction, but it lies in the center of the axle. To get it into its correct position at the end of the axle, it just has to be translated along the *z*-axis.

```
axleModel = new THREE.Object3D(); // A model containing two wheels and an axle.
cylinder.scale.set(0.2,4.3,0.2);  // Scale the cylinder for use as an axle.
cylinder.rotation.set(Math.PI/2,0,0); // Rotate its axis onto the z-axis.
axleModel.add( cylinder );
wheel.position.z = 2;  // Wheels are positioned at the two ends of the axle.
axleModel.add( wheel.clone() );
wheel.position.z = -2;
axleModel.add( wheel );
```

Note that for the second wheel, I add the original wheel model rather than a clone. There is no need to make an extra copy. With the *axleModel* in hand, I can build the car from two copies of the axle plus some other components.

The diskworld can be animated. To implement the animation, properties of the appropriate scene graph nodes are modified before each frame of the animation is rendered. For example, to make the wheels on the car rotate, the rotation of each axle about its *z*-axis is increased in each frame:

```
carAxle1.rotation.z += 0.05;
carAxle2.rotation.z += 0.05;
```

This changes the modeling transformation that will be applied to the axles when they are rendered. In its own coordinate system, the central axis of an axle lies along the *z*-axis. The rotation about the *z*-axis rotates the axle, with its attached tires, about its axis.

For the full details of the sample program, see the source code.