Qt 3D Basics

Part 3: Advanced Rendering

Paul Lemire and Giuseppe D'Angelo

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Many 3D graphic visuals can be handled with the same no-frills rendering techniques software developers learn during an intro 3D course. However, what if you want to incorporate one of many advanced rendering techniques – effects like shadows, refractive surfaces, water effects, HDR lighting, lens flares, or focus blurs?

The previous two parts of our three part Qt 3D series focused on drawing a 3D model and accepting user input, which are necessary building blocks of 3D applications. For the last part of our Qt 3D whitepaper series, we'll look at how to use Qt 3D and frame graphs to create some really sophisticated-looking graphics, including how to implement multi-pass rendering.

Qt 3D's rendering engine

To get the most out of the Qt 3D renderer, we need to start by reviewing a few basics. Simply put, the renderer's job is to determine the color of every pixel on the screen each time a new frame is drawn.

The basic components that the renderer uses are always the same: object geometries, object materials/textures, shaders, and uniforms. The geometry, materials, and textures control the placement and appearance of each object in a scene. *Shaders* are small programs that

describe how to translate a combination of attributes into a particular look, like how to handle glossy, matte, or transparent materials. *Uniforms* are variables the program passes to a shader for controlling general aspects of the program's behaviour, like light sources, fog, or focus effects. The renderer combines all of these elements in various ways as part of a GPU pipeline to specify the final look and feel of the graphical composition.

The primary mechanism used by Qt 3D to configure the graphical pipeline is the frame graph. A frame graph contains a number of nodes in a tree that define how the renderer will draw a scene, and is defined by creating a **FrameGraph** component. By customizing and reordering nodes within the **FrameGraph**, you can build the rendering algorithm of your choice. This architecture allows Qt 3D's rendering to be infinitely extensible.

The benefits of FrameGraph

Since the frame graph tree is entirely data-driven and can be modified dynamically at runtime, it gives you a lot of flexibility. You can use different frame graph trees for different platforms and hardware, and select the most appropriate at runtime. You can easily add and enable visual debugging in a scene. You can use different frame graph trees depending on what you need to render for particular regions of the scene. And finally, you can implement a new rendering technique without having to modify Qt 3D's internals.

This is just a taste of what **FrameGraph** can do – let's dig into the details to see how it works.

FrameGraph operation

The **FrameGraph** renderer is simply configured (relatively speaking) in QML (as well as in C++), making it easy for graphics experts and non-experts alike to modify a rendering technique.

Even though it may be easy to configure, understanding a few important rules about how it works is necessary if you want your renderings to come out properly.

Depth-first traversal – The Qt 3D renderer visits frame-graph nodes using a depth-first traversal. That means a nested node will have its children visited before its siblings, which can make a significant difference in the rendered output. We'll look at some situations where node order matters (as well as when it doesn't) a bit later on.

- **RenderView construction** – The renderer constructs a **RenderView** for each leaf of the node tree that it encounters during the tree traversal. A **RenderView** contains all of the rendering state information from each leaf back to the tree's root node.
- **RenderCommand building** – Once a **RenderView** is created, the renderer adds RenderCommands to the **RenderView** to represent all the Entities within the **SceneGraph** that require rendering. **RenderCommands** are the translation of the scene graph objects into whatever OpenGL primitives (vertex arrays, shaders, uniforms, meshes, etc) are necessary for the GPU to display the object.
- **RenderView processing** – Each **RenderView** is processed by OpenGL to turn its associated list of **RenderCommands** into a frame buffer – an in-memory representation of the screen content.
- **Frame buffer display** – Once this process is repeated for all of the nodes within the frame graph, the frame is complete. At this point, the renderer calls swapBuffers() to exchange the newly drawn frame buffer with the current screen content and readies itself to be called for the next frame.

One standard way to organize the graphical pipeline is called forward rendering, which renders each object into the frame buffer in final form.

Because the processing load is heavily dependent on the total number of leaf nodes in a frame graph tree, reducing the number of leaf nodes to the absolute minimum required will make your renderer configuration more efficient. Moving state information that remains constant across multiple nodes closer to the frame graph tree's root can also help you optimize performance.

FrameGraph nodes

We've talked a bit about the nodes in a frame graph tree. But what exactly is a node for? Essentially, each node encapsulates a bit of functionality required by the renderer at each stage of execution. Qt 3D provides a number of pre-defined frame graph nodes for use in building your renderer. Although these nodes are all subclasses of the C++ class, Qt3D::QFrameGraphNode, they are accessible in QML too. By combining these simple node types it is often possible to configure the renderer without writing a single line of application-specific C++ rendering code.

FrameGraph Node	Description
CameraSelector	Sets a camera to perform the rendering
ClearBuffers	Specifies OpenGL buffers to be cleared
LayerFilter	Specifies entities to render by filtering entities with a matching layer component
RenderPassFilter	Defines the filters used to select a render pass in a technique
RenderStateSet	Sets various rendering states
RenderSurfaceSelector	Specifies the surface to draw to
RenderTargetSelector	Specifies the rendering target (i.e. frame buffer)
SortPolicy	Controls how rendering commands are sorted
TechniqueFilter	Defines the filters used to select a technique in a material
Viewport	Defines the rectangular viewport where the scene is drawn

List of frame graph nodes. Consult the Qt 3D documentation **to see additional node types not listed here.**

Forward rendering

Let's put some of our newfound frame graph knowledge into practice by building a simple renderer. One standard and straightforward way to organize the graphical pipeline is called **forward rendering**, which renders each object into the frame buffer in final form. Forward rendering uses a vertex -> fragment -> pixel transformation process as follows:

1. Object vertices are transformed by the viewer's current viewport and viewing angle. These vertices represent the visible triangle meshes that wrap an object's volume. Triangles that face away from the viewer or are outside the screen boundary are discarded.
2. Triangles are rasterized into many individual fragments. Fragments are "hopeful" pixels – they may or may not end up being displayed, depending on the fragment shader algorithm (which may choose to discard the fragment), the fragment's transparency (which may make it invisible), and the presence of other overlapping objects (which may cover the fragment).
3. Fragment shaders operate on the fragments to calculate their color and/or transparency, based on surface texture, lighting, normal (the surface's angle to the light), and any other variables the app may require.
4. The GPU finds the fragments at the same pixel location sorted by distance from the viewer and uses the closest fragment to determine the final pixel color.

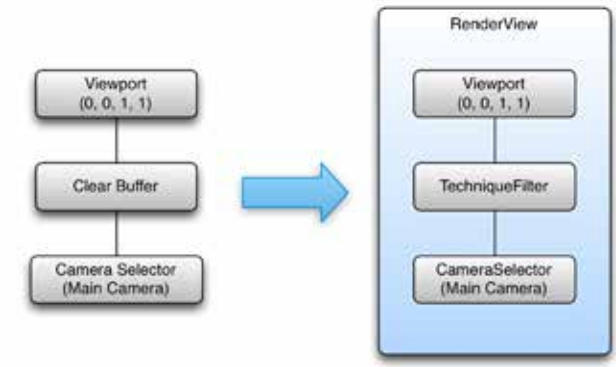
Incidentally, a forward renderer is the type of renderer used by Qt Quick 2. Even though Qt Quick 2 is limited to 2D, its content is rendered in 3D to take advantage of OpenGL hardware acceleration. Defining the frame graph needed for a forward renderer is pretty simple, especially in QML:

If the state collected at each leaf is the same between two FrameGraph trees, the resulting renderer will create visually identical results.

Code sample 1: forward renderer

```
/* Creates a frame graph tree with Viewport
| Clear Buffers | Camera */
RenderSettings {
 id: root

 activeFrameGraph: Viewport {
  normalizedRect: Qt.rect(0.0, 0.0, 1.0,
   1.0)
  property alias viewCamera:
   viewCameraSelector.camera

  ClearBuffers {
   buffers: ClearBuffers.
    ColorDepthBuffer

   CameraSelector {
    id: viewCameraSelector
   }
  }
 }
}
```

This resulting frame graph tree has three nodes with a single leaf.



Resulting frame graph for Code sample 1

During the rendering process, this frame graph tree creates a single **RenderView** that sets the view port to fill the entire screen (using normalized unit coordinates), clears the color and depth buffers, and sets the camera to the exposed camera property. If the state collected at each leaf is the same between two frame graph trees, the resulting renderer will create visually identical results. As an example, here are two additional frame graph configurations that produce the same outcome as the renderer in code sample 1.

Code sample 2: Another forward renderer that works like Code sample 1

```
/* Swap camera and clear buffers: Viewport
| Camera | Clear Buffers */
RenderSettings {
 id: root

 activeFrameGraph: Viewport {
  normalizedRect: Qt.rect(0.0, 0.0, 1.0,
   1.0)
  property alias viewCamera:
   viewCameraSelector.camera

  CameraSelector {
   id: viewCameraSelector

  ClearBuffers {
   buffers: ClearBuffers.
    ColorDepthBuffer
   }
  }
 }
}
```

Code sample 3: Yet one more forward renderer with the same result

```
/* An equivalent configuration: Camera |
Viewport | Clear Buffers */
RenderSettings {
 id: root

 activeFrameGraph: CameraSelector {
  id: viewCameraSelector

  Viewport {
   normalizedRect: Qt.rect(0.0, 0.0,
    1.0, 1.0)

   ClearBuffers {
    buffers: ClearBuffers.
     ColorDepthBuffer
   }
  }
 }
}
```

A slightly more complex example of a renderer draws a scene graph from four different viewpoints, each in a separate quadrant of the screen.

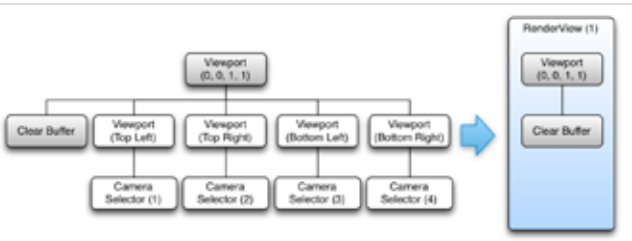
Multiple viewport rendering

A slightly more complex example of a renderer draws a scene graph from four different viewpoints, each in a separate quadrant of the screen. This type of multi-viewpoint renderer might make sense in any application that requires multiple views of the same scene, such as a CAD or 3D printing visualization tool, a car racing game with a rear-view mirror, or a security monitoring station.

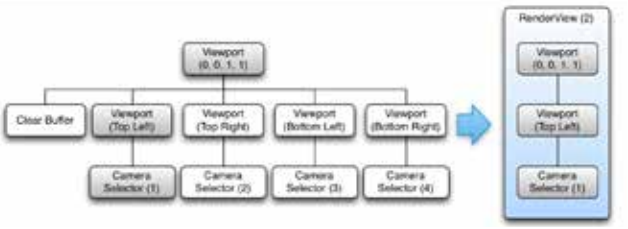
Code sample 4: Multi-viewport renderer

```
RenderSettings {
 id: root

 activeFrameGraph: Viewport {
  id: mainViewport
  normalizedRect: Qt.rect(0, 0, 1, 1)

  ClearBuffers {
   buffers: ClearBuffers.
    ColorDepthBuffer
  }

  Viewport {
   id: topLeftViewport
   normalizedRect: Qt.rect(0, 0, 0.5,
    0.5)
  }

  Viewport {
   id: topRightViewport
   normalizedRect: Qt.rect(0.5, 0, 0.5,
    0.5)
  }

  Viewport {
   id: bottomLeftViewport
   normalizedRect: Qt.rect(0, 0.5, 0.5,
    0.5)
  }

  Viewport {
   id: bottomRightViewport
   normalizedRect: Qt.rect(0.5, 0.5,
    0.5, 0.5)
  }
 }
}
```

The frame graph tree for this example is a bit more complex, resulting in five leaves and five corresponding **RenderView** objects. The following diagrams show the construction for the first two **RenderViews** (the other three **RenderViews** aren't shown but are just like the second **RenderView** albeit for the remaining viewports).



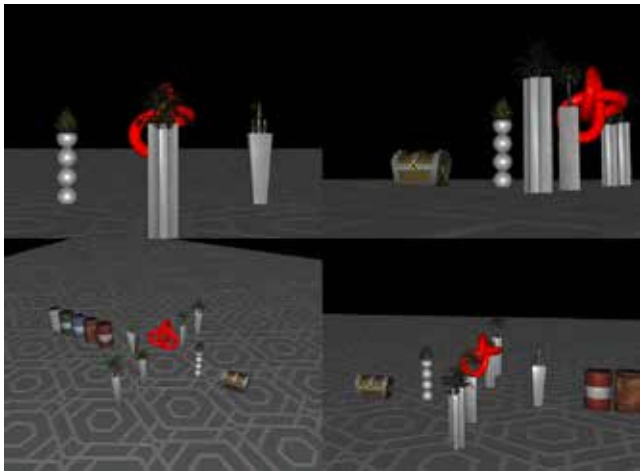
Multi-viewport frame graph, ClearBuffers leaf



Multi-viewport frame graph, first viewport leaf

Although in our first example the nodes were arbitrarily arranged, in this example the order of the nodes matters a lot. If the **ClearBuffers** node was at the end instead of at the beginning, the rendering engine would create a black screen – everything that was carefully drawn would be erased as the last step. Similarly, the **ClearBuffers** node couldn't be at the root of the frame graph tree or the screen would be cleared before each viewport was rendered, leaving only the last drawn viewport visible.

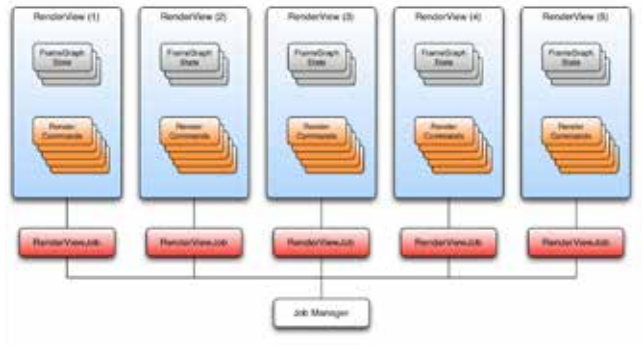
Complexities in light can be very tricky to display with a forward renderer; that's where deferred rendering comes into play.



Resulting display of the multi-viewport renderer

Parallel processing

The declaration order for the frame graph is important in specifying its behaviour but it doesn't imply a draw order. That's because Qt 3D can process each RenderView in parallel, depending on the number of available CPU cores.



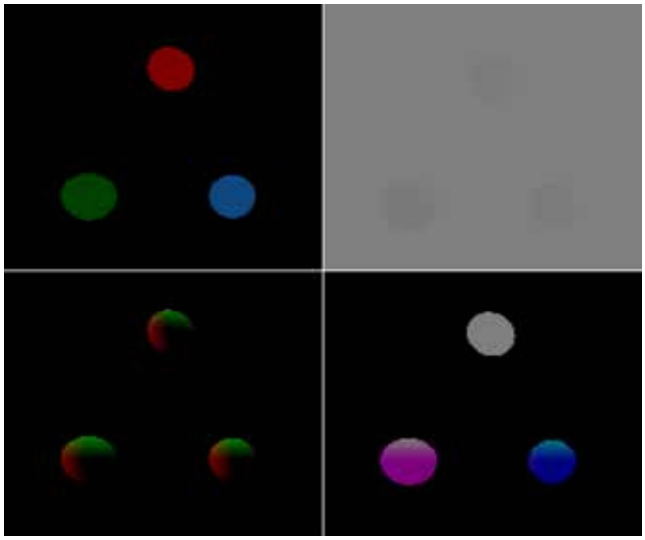
Multi-viewport render views operating in parallel

Qt 3D uses a dedicated thread to submit the work to the GPU. Although the generation of render commands is done in parallel for each render view, the thread submits OpenGL commands to the GPU in an order that ensures correct rendering.

Deferred rendering

A forward renderer really is best when your lighting needs are simple. Scenes with multiple lights, reflected or refracted light, shadows, or other complexities in the light can be very tricky to display with a forward renderer. That's where deferred rendering comes into play.

Deferred rendering takes multiple passes through a scene. An early pass sets state information such as normal vector, color, depth, or position that the renderer will use in subsequent passes. These pre-computed values are not displayed but stored in a buffer called the geometry buffer (or G-buffer) that resides in a texture. Once the object meshes have been drawn, the G-buffer contains everything that can be seen by the current camera. A second pass then renders the scene to a buffer with the final colors computed from the G-buffer information.



Visualization of referred renderer G-buffer contents: diffuse color (top left), depth buffer (top right), normal vectors (bottom left), and world position (bottom right)

Because deferred rendering can easily render many lights in a scene and handle object shadowing, it's often a popular choice for games.

Output of deferred renderer's second pass that combines all G-buffer elements

Deferred rendering decouples the generation of the scene's geometry from any lighting effects so that the geometry for each object is only calculated once. Another advantage is that the shading and lighting computations, which are often complex, are dependent on the resolution of the screen rather than the number of objects in a scene. Deferred rendering does have some drawbacks – it doesn't handle transparency well, it uses a lot of GPU memory bandwidth, and it doesn't play well with hardware anti-aliasing. However, because this technique can easily render many lights in a scene and handle object shadowing it's often a popular choice for games.

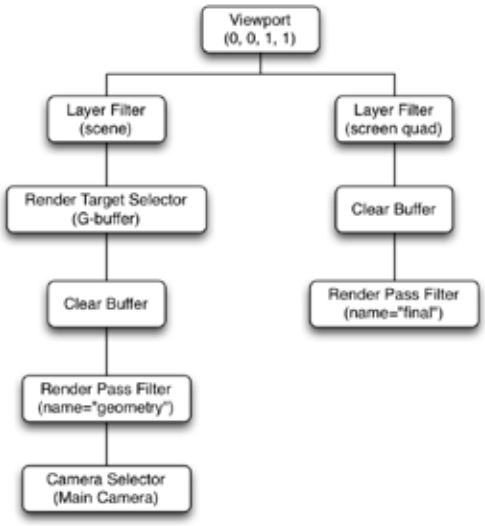
Code sample 5: Deferred renderer

```
Viewport {
 id: root
 normalizedRect : Qt.rect(0.0, 0.0, 1.0,
  1.0) ❶

 property GBuffer gBuffer
 property alias camera :
  sceneCameraSelector.camera

 // SceneEntities should reference one
 // of these to be incorporated into
 // correct layer
 readonly property Layer sceneLayer {}
  ❷

 readonly property Layer screenQuadLayer
  {}

 readonly property real windowWidth:
  surfaceSelector.surface !== null
  ? surfaceSelector.surface.width: 0

 readonly property real windowHeight:
  surfaceSelector.surface !== null ?
  surfaceSelector.surface.height: 0

 RenderSurfaceSelector {
  id: surfaceSelector

  // Fill G-Buffer
  LayerFilter {
   layers: sceneLayer
   RenderTargetSelector {
    id : gBufferTargetSelector ❸
    target: gBuffer

    ClearBuffers {
     buffers: ClearBuffers.
      ColorDepthBuffer ❹

     RenderPassFilter {
      id : geometryPass
      matchAny : FilterKey { name :
       "pass"; value : "geometry" }
       ❺
      CameraSelector {
       id :
        sceneCameraSelector ❻
      }
     }
    }
   }
  }

  TechniqueFilter {
   parameters: [
    Parameter { name: "color"; value :
     gBuffer.color },
    Parameter { name: "position"; value
     : gBuffer.position },
    Parameter { name: "normal"; value :
     gBuffer.normal },
    Parameter { name: "depth"; value :
     gBuffer.depth },
    Parameter { name: "winSize"; value
     : Qt.size(1024, 1024) }
   ]
```

Shadow rendering, our last example, is the most complex, building on everything we've learned thus far.

```
RenderStateSet {
 // Render FullScreen Quad
 renderStates: [
  BlendEquation {
   blendFunction: BlendEquation.
    Add },
  BlendEquationArguments {
   sourceRgb:
    BlendEquationArguments.
    SourceAlpha; destinationRgb:
    BlendEquationArguments.
    DestinationColor }
 ]
 LayerFilter {
  layers: screenQuadLayer ❼
  ClearBuffers {
   buffers: ClearBuffers.
    ColorDepthBuffer ❽
   RenderPassFilter {
    matchAny : FilterKey { name :
     "pass"; value : "final" } ❾
    parameters: Parameter { name:
     "winSize"; value : Qt.size(
     windowWidth, windowHeight)
    }
   }
  }
 }
}
```

The resulting frame graph tree looks like this:



Deferred renderer frame graph tree

The resulting renderer works like this, starting with the first render view:

❶ Defines a viewport that fills the whole screen

❷ Defines our layers for use within subsequent LayerFilter definitions

❸ Sets the G-buffer as the active render target

❹ Clears the color and depth on the G-buffer

❺ Selects only entities in the scene that have a material and technique matching the render pass filter ("geometry")

❻ Specifies which camera should be used

Then the second render view:

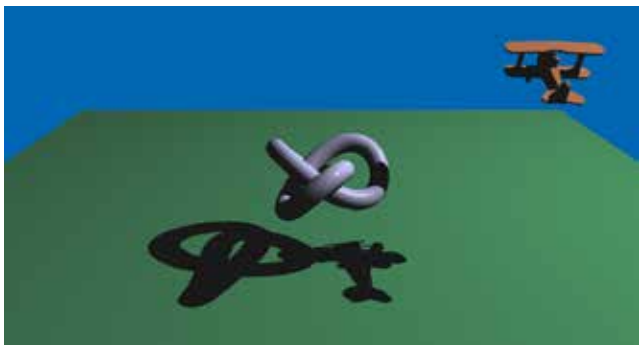
❼ Selects all entities that have a layer component matching screenQuadLayer

❽ Clears the color and depth buffers on the currently bound frame buffer (the screen)

❾ Selects only entities in the scene that have a material and technique matching the filter key in the render pass filter ("final")

Shadow rendering

Our last example is the most complex, building on everything we've learned thus far. We'll be creating a renderer that can handle the following scene, as well as all the code to create (and animate) the objects within. The source code for this example is in Qt Creator examples under **shadow-map-qml**.



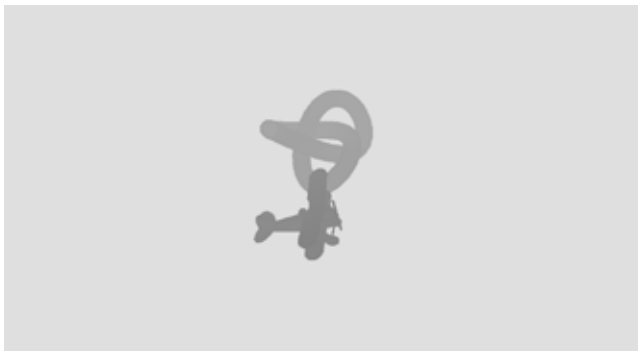
Renderer using shadow mapping

Identifying if a fragment is lit or in shadow requires converting the fragment position in world coordinates to its position in light space.

This example shows us how to render shadows. It's important to note that the trefoil knot and the toy plane both cast shadows on themselves, and the plane also casts a shadow on the knot. How is this achieved within our renderer? By using a shadow mapping technique – this generates decent looking shadows without introducing a large performance hit.

Shadow mapping is normally implemented in two passes. The first pass generates the shadow information by identifying fragments on which the light is shining. The second pass renders the scene objects and uses the first pass shadow information to determine appropriate lighting for each fragment.

The first pass needs to determine which fragments are in a straight line from the light source. To accomplish this, we draw the scene with a camera at the light source – in other words, in light space – viewing the scene from the point-of-view of the light. We store the distance of the fragments that are closest to the light into a frame buffer object (FBO) with a depth texture. (Since we aren't drawing the fragments at this point, our FBO doesn't require color information, just depth.) OpenGL depth testing does exactly what we want here. Since OpenGL will automatically track the depth of the closest fragments, that gives us what we need – the first fragment at each point in the light space that's closest to the light source.



Shadow map – rendering the scene from the light's point-of-view

Fragments farther away will be occluded by closer fragments and should display in shadow

The light's point-of-view rendering is our shadow map and only preserves the depth for each fragment. Darker colors are closer to the camera while lighter colors are farther away. From the first screenshot's perspective, the light source (the "sun") is outside the upper-right corner of the viewport. That means that the toy plane should be closer to the light and hence, darker/closer in the shadow map – and that's exactly what we see in the shadow map information.

Once the first pass has generated our shadow map, we go to the second rendering pass to draw our objects. We revert our viewport back to the normal camera and draw all our objects per usual. However, we can now incorporate the shadow map information to determine if the fragments are in light or shadow as we draw them.

How we use the shadow map to identify if our fragments are lit requires a bit of matrix math – we have to remap the fragment's location back to its position in light space. Once we have a light space coordinate for the fragment, we refer back to the shadow map and compare the fragment's depth with the depth stored in the shadow map. If the fragment depth is greater (farther away) then the fragment is hidden by a closer object and will be in shadow. Otherwise, the fragment is the closest object to the light and it should be lit.

With that understanding of the shadow mapping technique, let's look at the code that implements it.

Setting up the scene

Before we worry about the details of configuring our shadow renderer, let's create the scene with all the necessary objects.

Classes needed for the shadow rendering example are in main.qml: camera, controller, light, and rendering effects, as well as knot, plane, and ground entities.

Code sample 6: main.qml

```
import QtQuick 2.1 as QQ2
import Qt3D.Core 2.0
import Qt3D.Render 2.0
import Qt3D.Input 2.0
import Qt3D.Extras 2.0

Entity {
  id: sceneRoot

  Camera { ❶
    id: camera

    projectionType: CameraLens.
     PerspectiveProjection
    fieldOfView: 45
    aspectRatio: _window.width /
     _window.height
    nearPlane: 0.1
    farPlane: 1000.0
    position: Qt.vector3d(0.0, 10.0, 20.0)
    viewCenter: Qt.vector3d(0.0, 0.0, 0.0)
    upVector: Qt.vector3d(0.0, 1.0, 0.0)
  }

  FirstPersonCameraController { camera:
   camera } ❷

  ShadowMapLight { ❸
    id: light
  }

  components: [
    ShadowMapFrameGraph { ❹
      id: framegraph
      viewCamera: camera
      lightCamera: light.lightCamera
    },
    // Event Source will be set by
    // the Qt3DQuickWindow
    InputSettings { }
  ]

  AdsEffect { ❺
    id: shadowMapEffect

    shadowTexture: framegraph.shadowTexture
    light: light
  }

  // Trefoil knot entity
  Trefoil { ❻
    material: AdsMaterial {
      effect: shadowMapEffect
      specularColor: Qt.rgba(0.5, 0.5, 0.5,
       1.0)
    }
  }

  // Toyplane entity
  Toyplane { ❼
    material: AdsMaterial {
      effect: shadowMapEffect

      diffuseColor: Qt.rgba(0.9, 0.5, 0.3,
       1.0)
      shininess: 75
    }
  }

  // Plane entity
  GroundPlane { ❽
    material: AdsMaterial {
      effect: shadowMapEffect
      diffuseColor: Qt.rgba(0.2, 0.5, 0.3,
       1.0)
      specularColor: Qt.rgba(0, 0, 0, 1.0)
    }
  }
}
```

❶ The first component we create is a Camera, which represents the camera used for the final rendering.

❷ We create a FirstPersonCameraController element so we can control the camera using a keyboard or mouse.

❸ Our light is created with a ShadowMapLight entity, which represents our light sitting somewhere above the plane and looking down at the scene's origin.

❹ We tie the light to our custom frame graph ShadowMapFrameGraph.

❺ We set the rendering AdsEffect that is responsible for doing the shadow rendering.

Finally, we create entities for the objects in the scene: a trefoil knot ❻, a toy aircraft ❼, and the 2D plane representing the green ground ❽.

Because the light view is also needed as a camera for the shadow renderer's first pass, we add and expose a Camera property to it.

Setting the light

Now we need to define the light source.

Code sample 7: ShadowMapLight.qml

```
import Qt3D.Core 2.0
import Qt3D.Render 2.0

Entity {
  id: root

  property vector3d lightPosition:
    Qt.vector3d(30.0, 30.0, 0.0)
  property vector3d lightIntensity:
    Qt.vector3d(1.0, 1.0, 1.0)

  readonly property Camera lightCamera:
    lightCamera
  readonly property matrix4x4
    lightViewProjection:
      lightCamera.projectionMatrix.
       times(lightCamera.viewMatrix)

  Camera {
    id: lightCamera
    objectName: "lightCameraLens"
    projectionType: CameraLens.
     PerspectiveProjection
    fieldOfView: 45
    aspectRatio: 1
    nearPlane : 0.1
    farPlane : 200.0
    position: root.lightPosition
    viewCenter: Qt.vector3d(0.0, 0.0, 0.0)
    upVector: Qt.vector3d(0.0, 1.0, 0.0)
  }
}
```

The light is a directional spotlight. Since in the first rendering pass we also need to use the light as a camera, we place a Camera sub-entity inside of it and expose it as a property. The light also exposes properties for position, color/intensity, and a transformation matrix. The transformation matrix is used to allow us to map fragments back to light space coordinates so we can test our shadow map during the second rendering pass.

Creating the frame graph

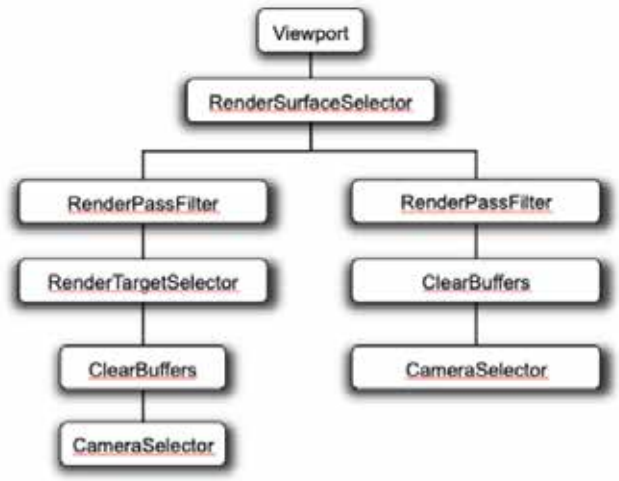
With the scene's basic objects in place, it's time to create the frame graph that will configure our renderer for shading.

Code sample 8: ShadowMapFrameGraph.qml

```
import QtQuick 2.2 as QQ2
import Qt3D.Core 2.0
import Qt3D.Render 2.0

RenderSettings {
  id: root

  property alias viewCamera:
    viewCameraSelector.camera
  property alias lightCamera:
    lightCameraSelector.camera
  readonly property Texture2D
    shadowTexture: depthTexture

  activeFrameGraph: Viewport {
    normalizedRect: Qt.rect(0.0, 0.0, 1.0,
     1.0)

    RenderSurfaceSelector {
      RenderPassFilter {
        matchAny: [ FilterKey { name:
         "pass"; value: "shadowmap" } ]

        RenderTargetSelector {
          target: RenderTarget {
            attachments: [
              RenderTargetOutput {
                objectName: "depth"
                attachmentPoint:
                 RenderTargetOutput.Depth
                 ❶
                texture: Texture2D { ❷
                  id: depthTexture
                  width: 1024
                  height: 1024
                  format: Texture.
                   DepthFormat
                  generateMipMaps: false
                  magnificationFilter:
                   Texture.Linear
                  minificationFilter:
                   Texture.Linear
```

```
            wrapMode {
              x: WrapMode.ClampToEdge
              y: WrapMode.ClampToEdge
            }
            comparisonFunction:
             Texture.CompareLessEqual
            comparisonMode: Texture.
             CompareRefToTexture
          }
        }
      ]
    }

    ClearBuffers {
      buffers: ClearBuffers.
       DepthBuffer
      CameraSelector { ❸
        id: lightCameraSelector
      }
    }
  }
}

RenderPassFilter {
  matchAny: [ FilterKey { name:
   "pass"; value: "forward" } ]

  ClearBuffers {
    clearColor: Qt.rgba(0.0, 0.4,
     0.7, 1.0)
    buffers: ClearBuffers.
     ColorDepthBuffer

    CameraSelector {
      id: viewCameraSelector
    }
  }
 }
}
}
```

We have two paths from the topmost Viewport entity, and each path corresponds to a pass of the shadow map technique.



Shadow map frame graph tree

One aspect of frame graphs that we've used in earlier examples but haven't yet addressed in detail is filters. A filter entity allows you to selectively enable or disable portions of the frame graph tree using selector entities. In our case, the two alternate paths for each pass of the shadow renderer are enabled and disabled using a RenderPassFilter. Our render pass filter will filter based on a string we've defined: in our case the string "pass". This lets us modify the frame graph configuration for each pass appropriately. Other lines of interest to highlight:

❶ In the first pass to generate the shadow map, we need to render to an off-screen surface (our FBO) with a depth texture attachment.

❷ The Texture2D entity configures the texture storage that we use to keep the shadow map.

❸ We also need to render using the light's camera, so we set the CameraSelector entity to the camera that our light exports.

The second pass is much more straightforward: we simply render to the screen using the main camera.

The Effect entity is implemented using Phong shading with the ambient, diffuse, and specular components of light.

The effect

The bulk of the work happens in the AdsEffect.qml file, where our main Effect entity is defined. The effect implemented is using the ADS shading model (ambient diffuse specular, in other words, Phong shading) with our shadow-map generated shadows.

Code sample 9: AdsEffect.qml

```
import Qt3D.Core 2.0
import Qt3D.Render 2.0

Effect {
  id: root

  property Texture2D shadowTexture
  property ShadowMapLight light

  // These parameters act as default values
  // for the effect. They take priority
  // over any parameters specified in the
  // RenderPasses below (none provided in
  // this example).In turn these parameters
  // can be overwritten by specifying them
  // in a Material that references this
  // effect. The priority order is:
  //
  // Material -> Effect -> Technique ->
  // RenderPass -> GLSL default values
  parameters: [ ❶
    Parameter { name:
     "lightViewProjection"; value:
     root.light.lightViewProjection },
    Parameter { name: "lightPosition";
     value: root.light.lightPosition },
    Parameter { name: "lightIntensity";
     value: root.light.lightIntensity },
    Parameter { name: "shadowMapTexture";
     value: root.shadowTexture }
  ]
  techniques: [ ❷
    Technique {
      graphicsApiFilter {
        api: GraphicsApiFilter.OpenGL
        profile: GraphicsApiFilter.
         CoreProfile
        majorVersion: 3
        minorVersion: 2
      }
      renderPasses: [
        RenderPass { ❸
          filterKeys: [ FilterKey { name:
           "pass"; value: "shadowmap" } ] ❹
          shaderProgram: ShaderProgram {
            vertexShaderCode: loadSource(
             "qrc:/shaders/shadowmap.vert")
            fragmentShaderCode: loadSource(
             "qrc:/shaders/shadowmap.frag")
          }
          renderStates: [
            PolygonOffset { scaleFactor: 4;
             depthSteps: 4 },
            DepthTest { depthFunction:
             DepthTest.Less }
          ]
        },
        RenderPass {
          filterKeys: [ FilterKey { name :
           "pass"; value : "forward" } ] ❺
          shaderProgram: ShaderProgram {
            vertexShaderCode: loadSource(
             "qrc:/shaders/ads.vert")
            fragmentShaderCode: loadSource(
             "qrc:/shaders/ads.frag")
          }
          // no special render state set =>
          // use the default set of states
        }
      ]
    },
    Technique {
      graphicsApiFilter {
        api: GraphicsApiFilter.OpenGLES
        majorVersion: 3
        minorVersion: 0
      }
      renderPasses: [
        RenderPass {
          filterKeys: [ FilterKey { name:
           "pass"; value: "shadowmap" } ]
```

You can customize shaders by using multiple Technique elements, for example OpenGL versus OpenGL ES or different versions of Open GL.

```
        shaderProgram: ShaderProgram {
          vertexShaderCode: loadSource(
          "qrc/shaders/es3/shadowmap.vert")
          fragmentShaderCode: loadSource(
          "qrc/shaders/es3/shadowmap.frag")
        }

        renderStates: [
          PolygonOffset { scaleFactor: 4;
           depthSteps: 4 },
          DepthTest { depthFunction:
           DepthTest.Less }
        ]
      },

      RenderPass {
        filterKeys: [ FilterKey { name :
         "pass"; value : "forward" } ]

        shaderProgram: ShaderProgram {
          vertexShaderCode: loadSource(
           "qrc:/shaders/es3/ads.vert")
          fragmentShaderCode: loadSource(
           "qrc:/shaders/es3/ads.frag")
        }
      }
    ]
  }
 ]
}
```

❶ The **parameters** list defines default values for the effect. Those values are mapped to OpenGL shader program uniforms so we can access them within the shaders. What's needed in the shaders is information from the **Light** entity (position, intensity, and its view/projection matrix), as well as the shadow map texture exposed by the frame graph.

❷ In order to be able to adapt the implementation to different hardware or OpenGL versions, an **Effect** is implemented by providing one or more Technique elements. In our case, we provide two techniques, one for OpenGL 3.2 Core or greater and one for OpenGL ES 3.0 or greater. (The two techniques allow us to use customized shaders for each platform since the GLSL variant is slightly different between those two OpenGL versions.)

❸ Inside each technique we define our two rendering passes. We set the filter values for each so they're associated with our frame graph rendering passes.

❹ For the shadow map pass, we load GLSL shaders that very simply project the mesh coordinates from model space into clip space. The fragment shader is empty because we aren't generating color information and OpenGL will automatically capture the depth. We also set some custom OpenGL states for polygon offset (used to help prevent fragments from Z-fighting) and depth testing (to make sure we're properly sorting objects front to back).

❺ The second pass is instead a normal forward renderer using Phong shading. The code really just loads the fragment and vertex shaders that will be used when drawing.

The shaders

The full explanation of the shader code requires some fluency in GLSL shader language and is out of scope of this whitepaper. However, we will point out the key parts that are necessary to make our shadow mapper work.

Code sample 10: ads.vert

```
#version 150 core

in vec3 vertexPosition;
in vec3 vertexNormal;

out vec4 positionInLightSpace;
out vec3 position;
out vec3 normal;

uniform mat4 lightViewProjection;
uniform mat4 modelMatrix;
uniform mat4 modelView;
uniform mat3 modelViewNormal;
uniform mat4 mvp;
void main() {
```

Converting from normalized device coordinates to texture map coordinates allows for easy shadow map value lookups within the fragment shader.

```
  const mat4 shadowMatrix =
   mat4( 0.5, 0.0, 0.0, 0.0,
         0.0, 0.5, 0.0, 0.0,
         0.0, 0.0, 0.5, 0.0,
         0.5, 0.5, 0.5, 1.0); ❷

  positionInLightSpace = shadowMatrix *
   lightViewProjection * modelMatrix *
   vec4(vertexPosition, 1.0); ❶

  normal = normalize(modelViewNormal *
   vertexNormal);
  position = vec3(modelView *
   vec4(vertexPosition, 1.0));

  gl_Position = mvp * vec4(vertexPosition,
   1.0);
}
```

❶ Here is where we compute the coordinates of each vertex in light space. We have to adjust the coordinates slightly by multiplying with shadowMatrix. ❷ This lets us convert from normalized device coordinates (ranging between -1 and 1) to texture map coordinates (between 0 and 1) so we can easily look up values in our shadow map during the fragment shader. On to the fragment shader...

Code sample 11: ads.frag

```
#version 150 core

uniform mat4 viewMatrix;

uniform vec3 lightPosition;
uniform vec3 lightIntensity;

uniform vec3 ka; // Ambient reflectivity
uniform vec3 kd; // Diffuse reflectivity
uniform vec3 ks; // Specular reflectivity
uniform float shininess;
          // Specular shininess factor

uniform sampler2DShadow shadowMapTexture;

in vec4 positionInLightSpace;

in vec3 position;
in vec3 normal;

out vec4 fragColor;

vec3 dsModel(const in vec3 pos, const in
 vec3 n) ❹
{
  // Calculate the vector from the light
  // to the fragment
  vec3 s = normalize(vec3(viewMatrix *
   vec4(lightPosition, 1.0)) - pos);

  // Calculate the vector from the fragment
  // to the eye position (origin since this
  // is in "eye" or "camera" space)
  vec3 v = normalize(-pos);

  // Reflect the light beam using the
  // normal at this fragment
  vec3 r = reflect(-s, n);


  // Calculate the diffuse component
  float diffuse = max(dot(s, n), 0.0);

  // Calculate the specular component
  float specular = 0.0;
  if (dot(s, n) > 0.0)
    specular = pow(max(dot(r, v), 0.0),
     shininess);

    // Combine the diffuse and specular
    // contributions (ambient is taken
    // into account by the caller)
    return lightIntensity * (kd * diffuse
     + ks * specular);
}

void main() {
  float shadowMapSample =
   textureProj(shadowMapTexture,
   positionInLightSpace); ❶

  vec3 ambient = lightIntensity * ka;

  vec3 result = ambient;
  if (shadowMapSample > 0) ❷
    result += dsModel(position,
    normalize(normal)); ❸

  fragColor = vec4(result, 1.0);
}
```

The job of the fragment shader is conceptually easy – map the current fragment back to the shadow map, look up what's in the shadow

map at that position, and if it's positive the fragment is on a lit surface so add in our lighting component. That's exactly what happens here: we sample the shadow map ❶, and if it's lit ❷, we add in our light component ❸ using our Phong lighting model.❹ Otherwise if it's not lit, the only lighting comes from our ambient source.

Although there's a decent amount of code in this example to pull it off, this example shows just how flexible and configurable the Qt 3D rendering engine is.

Summary

The flexibility of the Qt 3D renderer allows you to pretty easily experiment with a variety of sophisticated effects. With this introduction to frame graphs, frame graph nodes, and how the frame graph tree operates, you'll have some idea about how the Qt 3D engine uses frame graph and its assorted components to configure renderers – and hopefully some idea of how to go about building your own. However, if you get stuck trying to implement some amazing-looking new graphical technique, we're always happy to help!

About the KDAB Group

The KDAB Group is the world's leading software consultancy for architecture, development and design of Qt, C++ and OpenGL applications across desktop, embedded and mobile platforms. KDAB is the biggest independent contributor to Qt and is the world's first ISO 9001 certified Qt consulting and development company. Our experts build run-times, mix native and web technologies, solve hardware stack performance issues and porting problems for hundreds of customers, many among the Fortune 500. KDAB's tools and extensive experience in creating, debugging, profiling and porting complex applications help developers worldwide to deliver successful projects. KDAB's trainers, all full-time developers, provide market leading, hands-on, training for Qt, OpenGL and modern C++ in multiple languages. Founded in 1999, KDAB has offices throughout North America and Europe.

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