In this post I will show how to use VTK to trace rays emanating from the cell-centers of a source mesh, intersecting with another target mesh, and then show you how to cast subsequent rays bouncing off the target adhering to physics laws. This will include calculating the cell-centers in a mesh, calculating the normal vectors at those cells, vector visualization through glyphs, as well as other elements of visualization like textures and scene-lighting.

Introduction

Background

In my last post, I used Python and VTK to show you how to perform ray-casting, i.e., intersection tests between arbitrary lines/rays and a mesh, and extraction of the intersection point coordinates through the `vtkOBBTree` class.

Today I'll take the lessons learned about ray-casting with Python and VTK, and give you the tools to write your own ray-tracing algorithm using Python and VTK. Before proceeding, I strongly recommend that you read the ray-casting post, cause I will be re-using a lot of the functionality presented prior but I won't repeat myself in too much detail.

Summary

We will start by creating the 'environment', i.e., the scene, which will comprise a yellowish half-sphere dubbed the `sun`, which will act as the ray-source, and a larger nicely textured sphere called `earth` which will be the target of those rays.

We will calculate the cell centers of the `sun` mesh and cast rays along the directions of the normal vector at each one of those cells. We will then use the `vtkOBBTree` functionality we presented in the last post about ray-casting to detect which of these rays intersect with `earth`, calculate the appropriate reflected vectors based on the `earth` normal vectors, and cast subsequent rays.

Now let me be clear, the code that will be presented today can not, by any stretch of the imagination, be called a fully-fledged ray-tracer. However, I will be presenting all necessary tools you would need to write your own ray-tracing algorithms using Python and VTK.

Ray-Tracing with Python & VTK

You can find the entire IPython Notebook I'll be presenting today here. It contains a fair bit of code but it was structured in the same way as this post so you can easily look up the different parts of code and see what they do in detail.

Imports

As we've been doing in the past few posts we need to import `vtk` and `numpy`:

```
import vtk
import numpy
```

I know I've been saying it in nearly every post but here goes again: If for any reason you haven't managed to get yourself a nice Python installation with `ipython`, `numpy`, and `vtk`, which are needed for this post, do yourselves a favor and use Anaconda as instructed in this previous post. Alternatively, you can opt for the Enthought Python Distribution (EPD) or Enthought Canopy. Of course there's a truckload of other distros

but I can vouch for the above and they all come with pre-compiled builds of VTK.

Helper-functions

The following 'helper-functions' are defined at the beginning of today's notebook and used throughout:

- `vtk_show(renderer, width=400, height=300)` : This function allows me to pass a `vtkRenderer` object and get a PNG image output of that render, compatible with the IPython Notebook cell output. This code was presented in this past post about VTK integration with an IPython Notebook.
- `addLine(renderer, p1, p2, color=[0.0, 0.0, 1.0], opacity=1.0)` : This function uses `vtk` to add a line, defined by coordinates under `p1` and `p2`, to a `vtkRenderer` object under `renderer`. In addition, it allows for the color and opacity level of the line to be defined and it was first presented in the previous post about ray-casting.
- `addPoint(renderer, p, color=[0.0, 0.0, 0.0], radius=0.5)` : This function uses `vtk` to add a point-sized sphere (`radius` defaults to `0.5`) defined by center coordinates under `p` . This function was first presented in the previous post about ray-casting, while similar code was detailed in this past post about VTK integration with an IPython Notebook.
- `l2n = lambda l: numpy.array(l)` and `n2l = lambda n: list(n)` : These are just two simple `lambda` functions meant to quickly convert a `list` or `tuple` to a `numpy.ndarray` and vice-versa. The reason I wrote those, is that while VTK returns data like coordinates and vectors in `tuple` and `list` objects, which we need to 'convert' to `numpy.ndarray` objects in order to perform some basic vector math as we'll see later on. In addition, we often need to feed such vectors and point back to VTK, so back-conversion is often necessary.

> As you will see later we're defining more 'auxiliary functions' which haven't been presented prior to this post so we're gonna be looking closely into what they do. The above 'helper-functions' all contain code that has been presented before at one time or another.

Options

As the code in today's post deals with a **lot** of rendering and graphics-related parameters, I decided to set all these parameters as 'options' at the beginning of the notebook. You can change any of these and re-run the notebook to ascertain their effect.

You can see these options below but you do **not** have to pay too much attention to them right now. Apart from a few basic parameters defining attributes of the scene's objects, they mostly deal with colors. In addition I will be referring back to these options later on while presenting the code.

```
# SUN OPTIONS
# Radius of the sun half-sphere
RadiusSun = 10.0
# Distance of sun's center from (0,0,0)
DistanceSun = 50.0
# Phi & Theta Resolution of sun
ResolutionSun = 6

# EARTH OPTIONS
# Radius of the earth sphere
RadiusEarth = 150.0
# Phi & Theta Resolution of earth
ResolutionEarth = 120

# RAY OPTIONS
# Length of rays cast from the sun. Since the rays we
# cast are finite lines we set a length appropriate to the scene.
# CAUTION: If your rays are too short they won't hit the earth
# and ray-tracing won't be possible. Its better for the rays to be
# longer than necessary than the other way around
RayCastLength = 500.0

# COLOR OPTIONS
# Color of the sun half-sphere's surface
ColorSun = [1.0, 1.0, 0.0]
```

```
# Color of the sun half-sphere's edges
ColorSunEdge = [0.0, 0.0, 0.0]
# Color of the earth sphere's edges
ColorEarthEdge = [1.0, 1.0, 1.0]
# Background color of the scene
ColorBackground = [0.0, 0.0, 0.0]
# Ambient color light
ColorLight = [1.0, 1.0, 0.0]
# Color of the sun's cell-center points
ColorSunPoints = [1.0, 1.0, 0.0]
# Color of the sun's cell-center normal-vector glyphs
ColorSunGlyphs = [1.0, 1.0, 0.0]
# Color of sun rays that intersect with earth
ColorRayHit = [1.0, 1.0, 0.0]
# Color of sun rays that miss the earth
ColorRayMiss = [1.0, 1.0, 1.0]
# Opacity of sun rays that miss the earth
OpacityRayMiss = 0.5
# Color of rays showing the normals from points on earth hit by sun rays
ColorEarthGlyphs = [0.0, 0.0, 1.0]
# Color of sun rays bouncing off earth
ColorRayReflected = [1.0, 1.0, 0.0]
```

‘Environment’ Creation

We will start by creating the ‘environment’ within which we’ll perform our ray-tracing. This environment will comprise a half-sphere dubbed `sun` from which we will cast rays. Another sphere, which we will call `earth`, will receive and reflect those rays at appropriate angles.

> Note that the `sun` and `earth` objects are by no means ‘in-scale’. Far from it actually (whole thing kinda looks like an earth-ball with a ceiling light above). I just named them as such to provide an apt analogy to what we’re doing here.

Create the `sun`

We start by creating the `sun` half-sphere through `vtkSphereSource`:

```
# Create and configure then sun half-sphere
sun = vtk.vtkSphereSource()
sun.SetCenter(0.0, DistanceSun, 0.0)
sun.SetRadius(RadiusSun)
sun.SetThetaResolution(ResolutionSun)
sun.SetPhiResolution(ResolutionSun)
sun.SetStartTheta(180)  # create a half-sphere
```

The `source->mapper->actor` process to create a sphere in VTK has been shown time after time and you can read about the mechanics in this previous post. However, I'll go over a few novelties here. As you can see, upon creating a new `vtkSphereSource` under `sun` we set several parameters. The center coordinates and radius are defined through the `DistanceSun` and `RadiusSun` options discussed in the *Options* section.

What's **really** important to note here is the `theta` and `phi` resolutions of the `sun` sphere set through the `SetThetaResolution` and `SetPhiResolution` methods respectively. VTK creates these spheres through the use of spherical coordinates and these resolution parameters define the number of points along the longitude and latitude directions respectively. A lower resolution will result in less points and therefore less triangles defining the sphere, making it look like something of a rough polygon.

However, as I mentioned in the *Summary* we will be casting a ray per triangle of the `sun` mesh. Hence, in order to keep the scene 'clean' and lower the computational cost, we set this resolutions to a mere `6` in the *Options*. Nonetheless, feel free to change this value in order to cast as many or as few rays as you wish. I'll be showing the result of a resolution of `20` at the end of this post.

A last point I'd like to make is the usage of the `SetStartTheta` method. As I just said, VTK uses spherical coordinates to 'design' these spherical objects. Through the `SetStartTheta`, `SetStopTheta`, `SetStartPhi`, and `SetStopPhi` methods we define the starting and stopping angles (in degrees) for this sphere, allowing us to create spherical segments instead of a full sphere. In this example, and in the interest of keeping the

scene 'lean' we're only creating a 'half-sphere' through `SetStartTheta(180)`.

With the `vtkSphereSource` defined and 'stored' under `sun` we simply create the appropriate `vtkPolyDataMapper` and `vtkActor` objects necessary to add this sphere to the scene:

```
# Create mapper
mapperSun = vtk.vtkPolyDataMapper()
mapperSun.SetInput(sun.GetOutput())

# Create actor
actorSun = vtk.vtkActor()
actorSun.SetMapper(mapperSun)
actorSun.GetProperty().SetColor(ColorSun)  #set color to yellow
actorSun.GetProperty().EdgeVisibilityOn()  # show edges/wireframe
actorSun.GetProperty().SetEdgeColor(ColorSunEdge)  #render edges as white
```

Once more, check this previous post to see what the deal with mappers and actors is in VTK. What I should mention here is that apart from using the `GetProperty()` method to access the properties of the `actorSun` object and set its color to `ColorSun` (set under *Options*), we also do so to enable the visibility of that mesh's edges and set them to a color of `ColorSunEdge`. This way we're visualizing the 'wireframe' of that object in order to see the individual mesh cells which come into play later.

Finally as we've done in all posts dealing with VTK we create a new `vtkRenderer`, add the `actorSun` object, set some camera properties, and use the `vtk_show` 'helper-function' to render the scene:

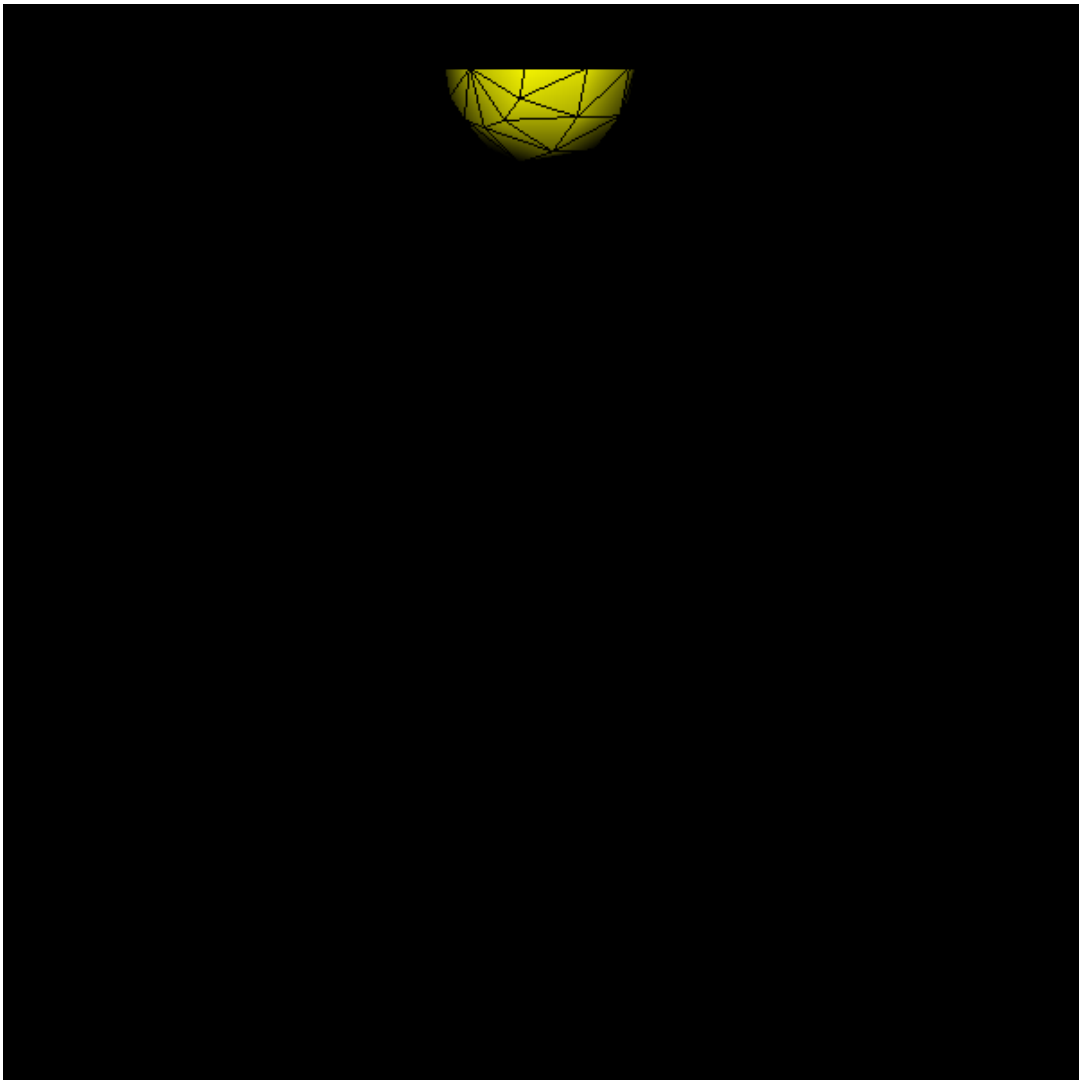
```
renderer = vtk.vtkRenderer()
renderer.AddActor(actorSun)
renderer.SetBackground(ColorBackground)

# Modify the camera with properties defined manually in ParaView
camera = renderer.MakeCamera()
camera.SetPosition(RadiusEarth, DistanceSun, RadiusEarth)
camera.SetFocalPoint(0.0, 0.0, 0.0)
camera.SetViewAngle(30.0)
renderer.SetActiveCamera(camera)

vtk_show(renderer, 600, 600)
```

Take a look at this past post about VTK integration with an IPython Notebook for an explanation of the `vtkRenderer` class, and the post about surface extraction to see what gives with the camera. What's important to note is that we've created a `vtkRenderer` object under `renderer` to which we will continue adding new `vtkActor` objects as we go, thus enriching the scene.

The result of `vtk_show` can be seen in the following figure:



Scene render showing only the `sun` half-sphere.

> Here you can see the effect of that ‘resolution’ stuff I was talking about before. The `sun` half-sphere is jagged and rough. Nonetheless, it still comprises plenty of cells and therefore ray-sources for our example.

Create the `earth`

Let’s go onto creating `earth`. As during my posts I’ve showed you how to create spheres a trillion times I thought I’d kick it up a notch and show you how to texture one, giving it a bit of razzle-dazzle :). We start by creating a new sphere under `earth` as such:

```
# Create and configure the earth sphere
earth = vtk.vtkSphereSource()
earth.SetCenter(0.0, -RadiusEarth, 0.0)
earth.SetThetaResolution(ResolutionEarth)
earth.SetPhiResolution(ResolutionEarth)
earth.SetRadius(RadiusEarth)
```

Typical stuff as you can see, just keep in mind that the `earth` variable holds the pointer to the, now configured, `vtkSphereSource` object. You'll also note that all parameters are set to values defined in the *Options* section so take a look if you will.

Now let's move on to texturing. I used a texture of the earth I downloaded as a JPEG file from http://planetpixelemporium.com/download/download.php?earthmap1k.jpg and placed along this post's notebook. Alternatively, you can download it from the blog repository under here. Firstly, we need to load that image as such:

```
# Load a JPEG file with an 'earth' texture downloaded from the above link
reader = vtk.vtkJPEGReader()
reader.SetFileName("earthmap1k.jpg")
reader.Update()
```

All we do is use the `vtkJPEGReader` class to create `reader`, set the filename, and read in the image through `Update`.

> I want to specify, that as the `reader` is not used directly but is rather a part of the VTK pipeline, we don't really need to call `Update`. That method will be called by subsequent objects that use `reader` as an input. However, while debugging VTK code, progressively updating the pipeline allows us to verify which part of the pipeline didn't work instead of getting an arbitrary error at some point down the road.

Next, we create the actual texture:

```
# Create a new 'vtkTexture' and set the loaded JPEG
texture = vtk.vtkTexture()
texture.SetInputConnection(reader.GetOutputPort())
texture.Update()
```

Here we create a new `vtkTexture` object and, using the `SetInputConnection` and `GetOutputPort` methods, connect its input to the output of the `reader` object holding the texture image.

So far so good right? What needs to be done now to complete the texturing, is to map this texture to our `earth` sphere. Now this might be a tad confusing so I'll break it down:

```
# Map the earth texture to the earth sphere
map_to_sphere = vtk.vtkTextureMapToSphere()
map_to_sphere.SetInputConnection(earth.GetOutputPort())
map_to_sphere.PreventSeamOn()
texture.Update()
```

As a first step we create a new `vtkTextureMapToSphere` object under `map_to_sphere` which *"generates 2D texture coordinates by mapping input dataset points onto a sphere"*. Check the code carefully, and you'll realize we're **not** connecting `map_to_sphere` with `texture` but only with `earth`! This class will just calculate the coordinates based on the `earth` sphere but does **not** set a texture yet (that occurs later).

And now for the finishing touches:

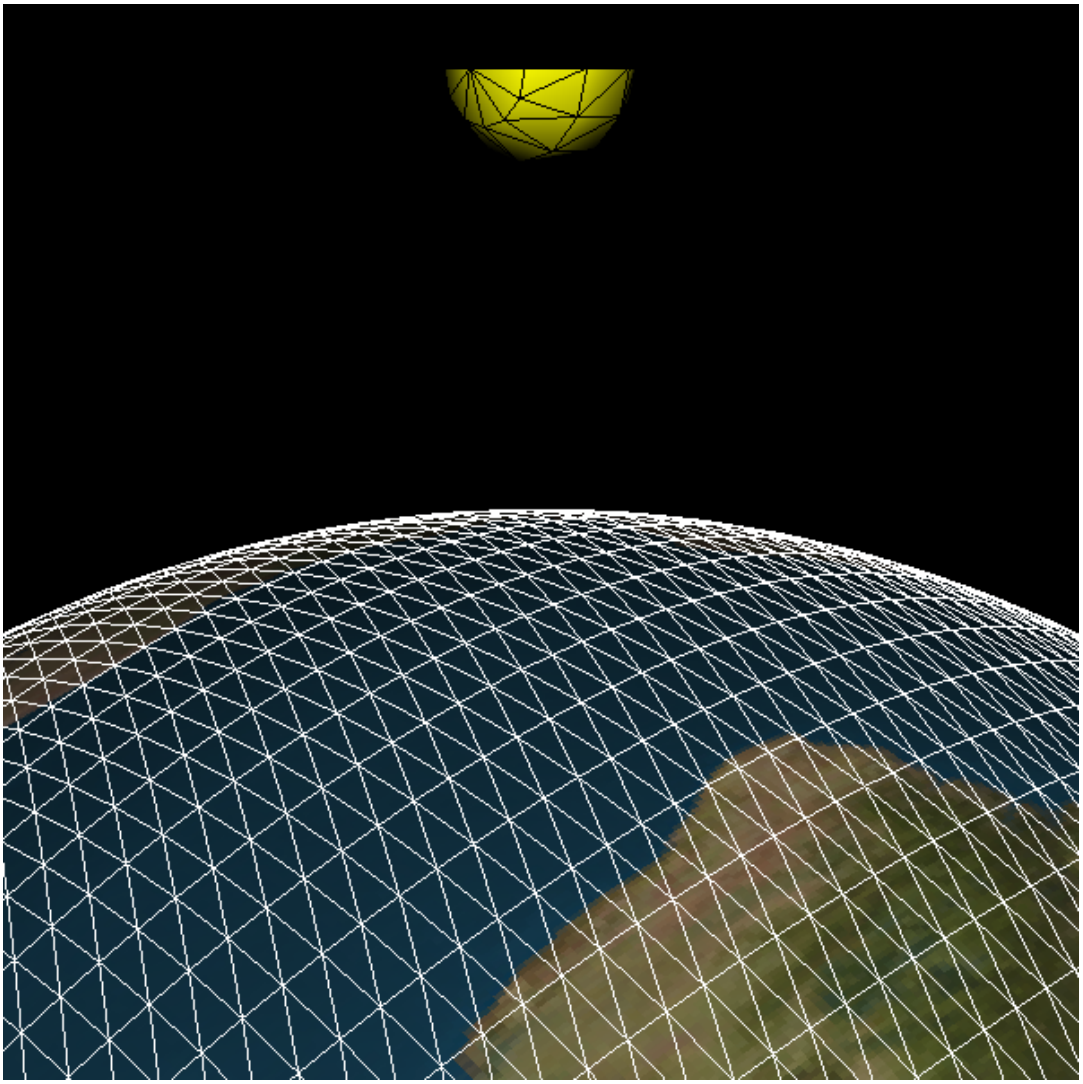
```
# Create a new mapper with the mapped texture and sphere
mapperEarth = vtk.vtkPolyDataMapper()
mapperEarth.SetInputConnection(map_to_sphere.GetOutputPort())

# Create actor
actorEarth = vtk.vtkActor()
actorEarth.SetMapper(mapperEarth)
actorEarth.SetTexture(texture)
actorEarth.GetProperty().EdgeVisibilityOn()  # show edges/wireframe
actorEarth.GetProperty().SetEdgeColor(ColorEarthEdge)  #render edges as white

renderer.AddActor(actorEarth)
vtk_show(renderer, 600, 600)
```

You should be familiar with the `vtkPolyDataMapper` and `vtkActor` classes so I won't repeat myself. What you **should** pay attention to is that instead of using `earth` as a source for `mapperEarth` we instead use `map_to_sphere` which contains the `vtkTextureMapToSphere` object we just saw! In addition, upon creating `actorEarth` we finally set the `texture` through `actorEarth.SetTexture(texture)`. As you can see the `texture` goes straight into the appropriate `vtkActor` object, which along with the texture-mapping provides us with a nicely textured sphere.

Finally, we make the `earth` wireframe visible with a `ColorEarthEdge` color, add `actorEarth` to `renderer`, and use `vtk_show` to render the scene resulting in the following figure:



Scene render showing the `sun` half-sphere and the textured `earth` sphere.

Adding lighting to the scene

Now you might say “what gives? we went to so much trouble to texture that stupid ball and it looks all dark and crummy!”. Well at least I obviously thought so, thus I decided to shed a little light on the situation (I know, stupidest pun ever).

Before I continue, I want to mention that all VTK scenes comes with a default ‘headlight’ which follows the camera and illuminates the scene. In most cases that’s enough to see our rendering but often we need a lil’ extra.

In this case I added a light point-source through the `vtkLight` class. Let's see how that was done:

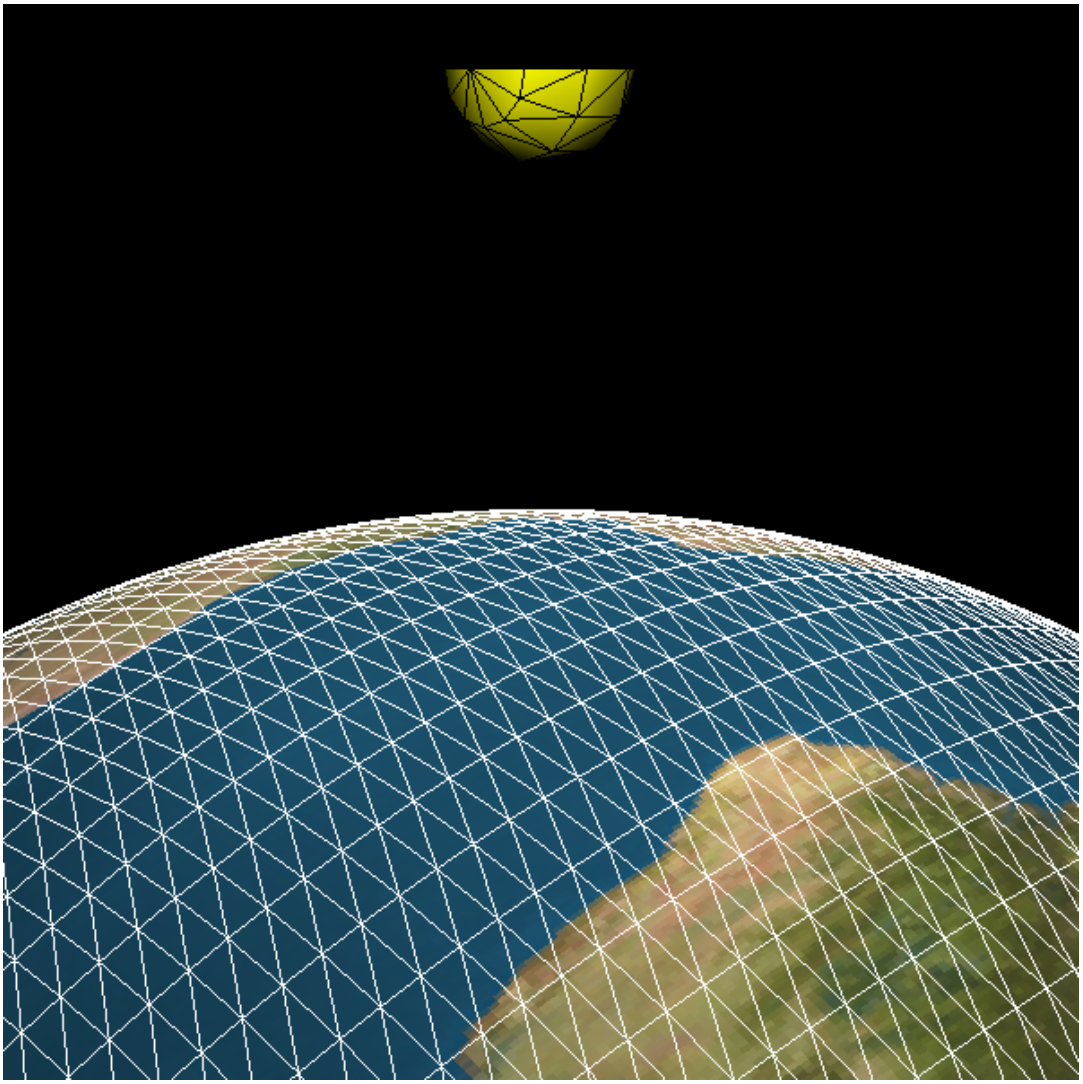
```
# Create a new vtkLight
light = vtk.vtkLight()
# Set its ambient color to yellow
light.SetAmbientColor(ColorLight)
# Set a 180 degree cone angle to avoid a spotlight-effect
light.SetConeAngle(180)
# Set its position to the sun's center
light.SetPosition(sun.GetCenter())
# Set its focal-point to the earth's center
light.SetFocalPoint(earth.GetCenter())
# Set it as part of the scene (positional) and not following the camera
light.SetPositional(True)
renderer.AddLight(light)

vtk_show(renderer, 600, 600)
```

Initially, we create a `vtkLight` object under `light`, and set an appropriate `ColorLight` which was defined at the *Options* section. As you can see I set the position of the light-source to the center of the `sun` half-sphere, which just makes sense (you know, `sun` and all that), through `light.SetPosition(sun.GetCenter())`, while its focal point is the center of the `earth` sphere.

What's important to note here is that these lights are typically 'spotlights' adding a 'narrow' beam of light to the scene. By using `SetConeAngle(180)` we create a uniform semi-spherical light that evenly illuminates the entire scene residing beneath the center of the `sun` half-sphere. Lastly, please pay attention to the `SetPositional(True)` method which makes this light a constant part of the scene, forcing it in place, and not allowing it to move with respect to the scene's camera.

After adding `light` to the `renderer`, we once more use `vtk_show` to render the scene and get this figure (makes quite the difference right?):



Scene render showing the `sun` half-sphere and the textured `earth` sphere with added lighting.

‘Prepare’ the Sun Rays

As I said in the *Summary*, we will be casting rays from each cell-center of the `sun` mesh following the direction of the normal vectors of those cells. Naturally, we first need to calculate these quantities, thus ‘defining’ the rays.

Calculate the cell-centers of the sun half-sphere

Firstly, we need to calculate the coordinates at the center of each cell on the `sun` mesh. Thankfully VTK provides us with a nifty class called `vtkCellCenters` to do so:

```
cellCenterCalcSun = vtk.vtkCellCenters()
cellCenterCalcSun.SetInput(sun.GetOutput())
cellCenterCalcSun.Update()
```

As you can see this is as simple as VKT gets. We merely create a `vtkCellCenters` object under `cellCenterCalcSun`, and connect its input with `sun.GetOutput()`. Upon using `Update`, the calculation is complete.

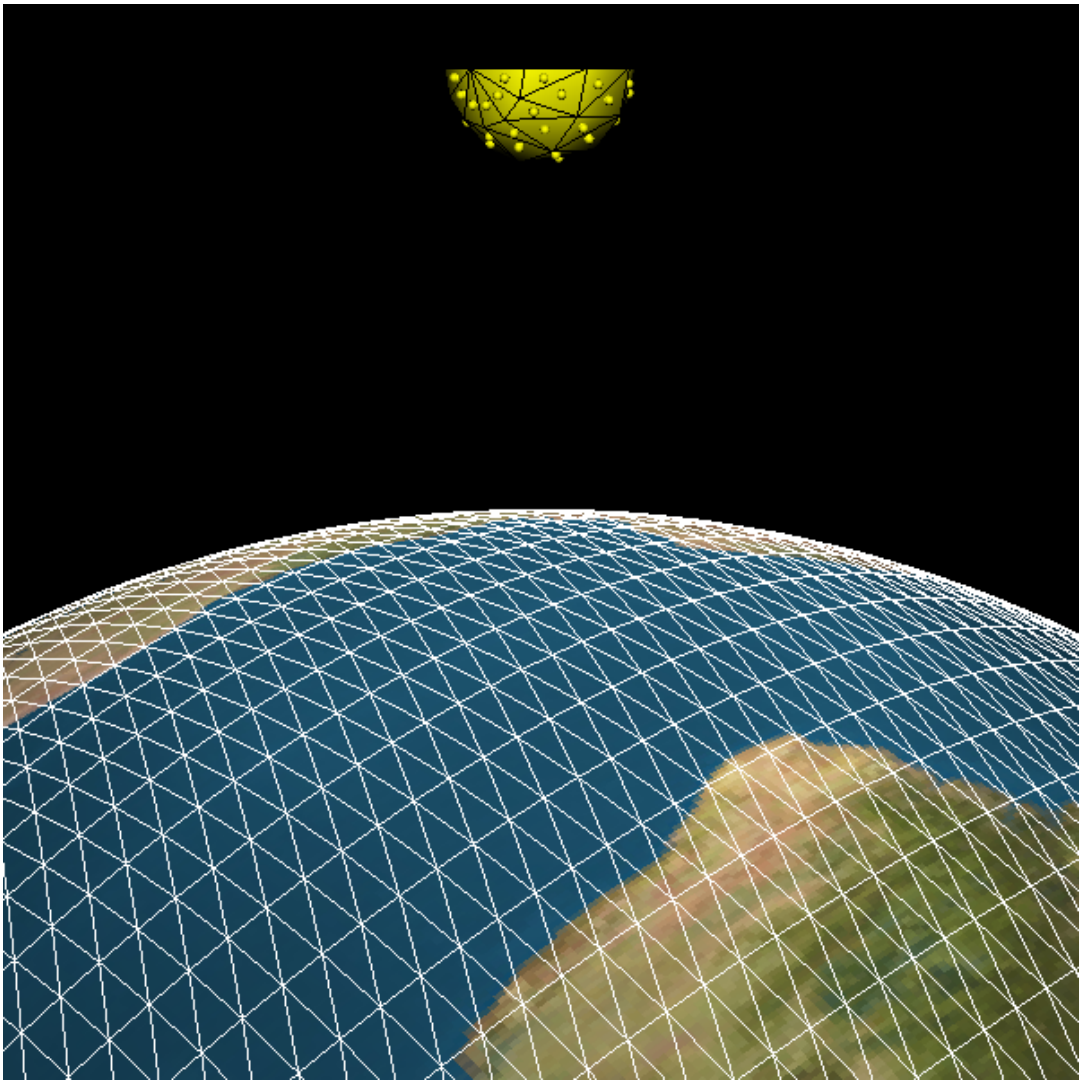
Now let us visualize those points using the `addPoint` and `vtk_show` helper functions:

```
# Get the point centers from 'cellCenterCalc'
pointsCellCentersSun = cellCenterCalcSun.GetOutput(0)

# Loop through all point centers and add a point-actor through 'addPoint'
for idx in range(pointsCellCentersSun.GetNumberOfPoints()):
    addPoint(renderer, pointsCellCentersSun.GetPoint(idx), ColorSunPoints)

vtk_show(renderer, 600, 600)
```

We first ‘extract’ the cell-centers through `cellCenterCalcSun.GetOutput(0)`, storing the result of `vtkPoints` type under `pointsCellCentersSun`. Subsequently, we loop through these points and use `addPoint` to add them to the `vtkRenderer` object we created before and which now resides under `renderer`. Note that we’re looping using the `range` built-in and the `GetNumberOfPoints()` method to get the total number of points found. The resulting figure can then be seen below.



Scene render showing the `sun` half-sphere with points at each cell-center of its mesh

Calculate normal vectors at the center of each cell

Now that we have the cell-centers, which will act as the ‘source points’ of the `sun` rays, we need to calculate the normal vectors at those points which will define the directions of the rays. Once more, VTK provides the tools but doesn’t make it easy or clear for us (you wouldn’t appreciate it working if it was easy, would you now :) ?). Let’s see how it’s done:

```
# Create a new 'vtkPolyDataNormals' and connect to the 'sun' half-sphere
normalsCalcSun = vtk.vtkPolyDataNormals()
normalsCalcSun.SetInputConnection(sun.GetOutputPort())

# Disable normal calculation at cell vertices
normalsCalcSun.ComputePointNormalsOff()
# Enable normal calculation at cell centers
normalsCalcSun.ComputeCellNormalsOn()
# Disable splitting of sharp edges
normalsCalcSun.SplittingOff()
# Disable global flipping of normal orientation
normalsCalcSun.FlipNormalsOff()
# Enable automatic determination of correct normal orientation
normalsCalcSun.AutoOrientNormalsOn()
# Perform calculation
normalsCalcSun.Update()
```

So we start by creating a new `vtkPolyDataNormals` object under `normalsCalcSun` (remember this variable name, we'll be using it lots later on). We then 'connect' this object to the `sun` mesh where we want those normals to be calculated.

The rest boils down to configuring the `vtkPolyDataNormals` class to give us what we want. You can see what each call does in the comments above but I should stress a few points here. `vtkPolyDataNormals` can calculate the normal vectors at the mesh points and/or cells. However, we only want the latter, so we turn off calculation at points with `ComputePointNormalsOff()` and only enable calculation at cells with `ComputeCellNormalsOn()`.

Subsequently, we turn 'splitting' off through `SplittingOff()`. First of all that only makes sense when calculating point-normals. What it would do is 'split', thus create, multiple normals at points belonging to cells with very sharp edges, i.e., steep angles between cells. However, we only want cell normals so we don't care about it too much.

We then want to make sure that the normals have a correct orientation, i.e., that they would be 'pointing' outwards and not towards the center of the `sun` half-sphere. To ensure that, we first disable global flipping through 'FlipNormalsOff()', and we enable

automatic orientation determination through `AutoOrientNormalsOn()`. Now this last call is a god-send as it will make sure the normals point outwards which we sorely need to correctly cast our rays.

However, I want to point you to the `vtkPolyDataNormals` docs, and in particular the docstring for the `AutoOrientNormalsOn` method which reads: *"Turn on/off the automatic determination of correct normal orientation. NOTE: This assumes a completely closed surface (i.e. no boundary edges) and no non-manifold edges. If these constraints do not hold, all bets are off. This option adds some computational complexity, and is useful if you don't want to have to inspect the rendered image to determine whether to turn on the FlipNormals flag. However, this flag can work with the FlipNormals flag, and if both are set, all the normals in the output will point "inward"."*

What that means is that while `AutoOrientNormalsOn` is crazy-useful to ensure correct orientation, it comes with stringent requirements, and its not always guaranteed to succeed. Thankfully, our `sun` mesh fits these criteria and calling `Update()` completes the calculation.

Visualize normal vectors at the cell-centers of sun's surface as glyphs

Before proceeding on to casting and tracing the `sun` rays we will visualize the normal vectors calculated on the `sun` mesh as glyphs using the `vtkGlyph3D` class.

Before I show you the code lets take a look at the docstring of the `vtkGlyph3D` class: *"vtkGlyph3D is a filter that copies a geometric representation (called a glyph) to every point in the input dataset. The glyph is defined with polygonal data from a source filter input. The glyph may be oriented along the input vectors or normals, and it may be scaled according to scalar data or vector magnitude"*.

What we're going to do here, is create a single arrow through the `vtkArrowSource` class and use it as a glyph. Then we'll use the normal vectors we calculated before, and which are stored under `normalsCalcSun`, to place and orient those glyphs. Let's inspect the code:

```
# Create a 'dummy' 'vtkCellCenters' to force the glyphs to the cell-centers
dummy_cellCenterCalcSun = vtk.vtkCellCenters()
dummy_cellCenterCalcSun.VertexCellsOn()
dummy_cellCenterCalcSun.SetInputConnection(normalsCalcSun.GetOutputPort())

# Create a new 'default' arrow to use as a glyph
arrow = vtk.vtkArrowSource()

# Create a new 'vtkGlyph3D'
glyphSun = vtk.vtkGlyph3D()
# Set its 'input' as the cell-center normals calculated at the sun's cells
glyphSun.SetInputConnection(dummy_cellCenterCalcSun.GetOutputPort())
# Set its 'source', i.e., the glyph object, as the 'arrow'
glyphSun.SetSourceConnection(arrow.GetOutputPort())
# Enforce usage of normals for orientation
glyphSun.SetVectorModeToUseNormal()
# Set scale for the arrow object
glyphSun.SetScaleFactor(5)

# Create a mapper for all the arrow-glyphs
glyphMapperSun = vtk.vtkPolyDataMapper()
glyphMapperSun.SetInputConnection(glyphSun.GetOutputPort())

# Create an actor for the arrow-glyphs
glyphActorSun = vtk.vtkActor()
glyphActorSun.SetMapper(glyphMapperSun)
glyphActorSun.GetProperty().SetColor(ColorSunGlyphs)
# Add actor
renderer.AddActor(glyphActorSun)

vtk_show(renderer, 600, 600)
```

Now this code is a little convoluted so I'll break it down. The first **very** important thing to mention is that we do **not** simply use the normals calculated beforehand stored within `normalsCalcSun`. As you can see in the first lines of the snippet above, we feed those normals to a 'dummy' `vtkCellCenters` called `dummy_cellCenterCalcSun`. This forces the glyphs to be placed on the cell-centers of the `sun` mesh.

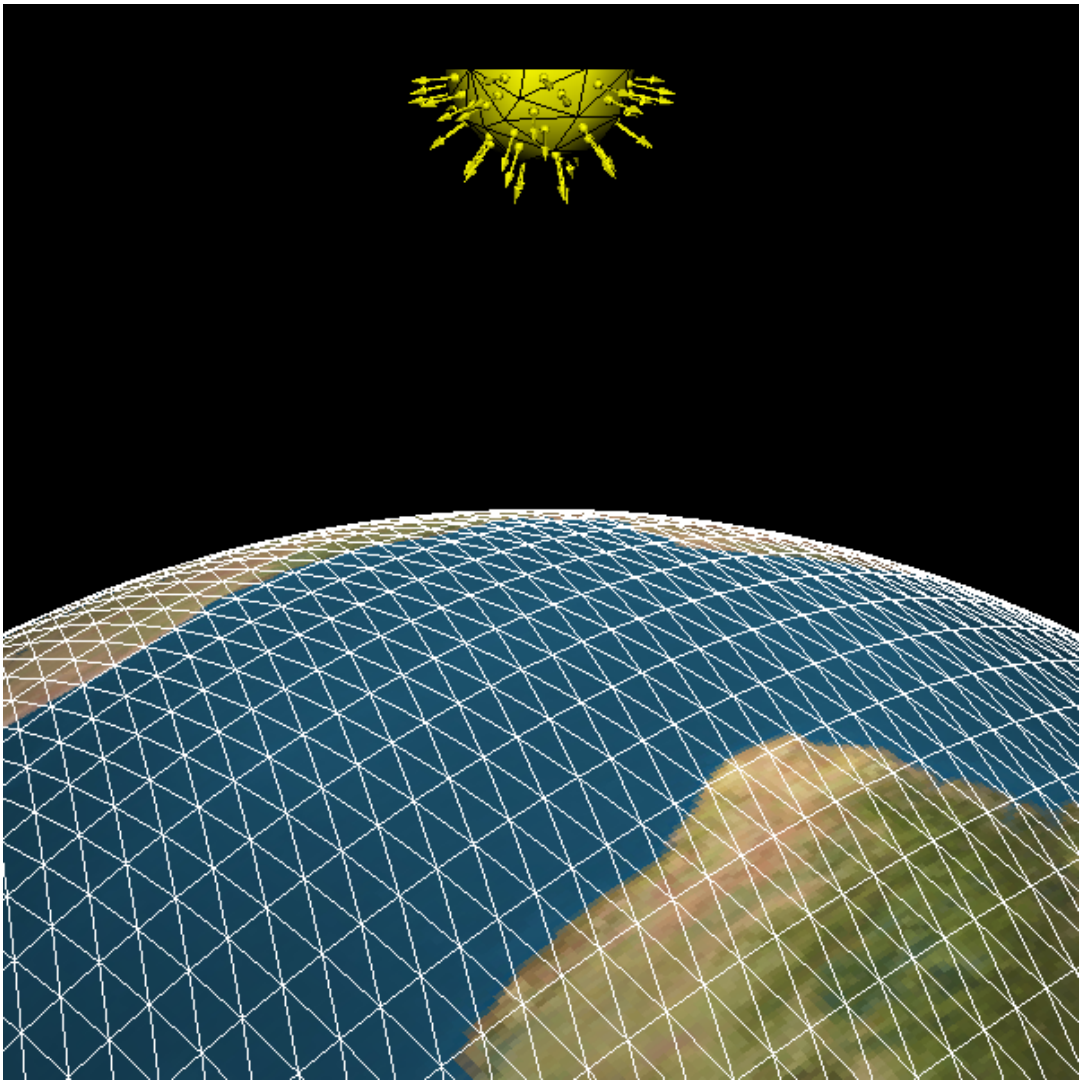
Subsequently, we create the glyphs. Note that we first create `arrow`, a

`vtkArrowSource` object representing a default arrow, which we will use as the 'base' glyph. Now this glyph can be any 'source' class, e.g. a cone through the `vtkConeSource` class, a sphere through the `vtkSphereSource` class, etc etc. The only reason I chose an arrow was cause it nicely shows the direction the `sun` rays will follow.

We then create a new `vtkGlyph3D` object under `glyphSun`. The important thing to note here is the difference between the `SetInputConnection` and `SetSourceConnection` methods. The latter just connects to the 'source' glyph, i.e., the `arrow` in our case. The `SetInputConnection` call is given `dummy_cellCenterCalcSun.GetOutputPort()`, i.e., the normal vectors calculated and then positioned at the cell-centers of the `sun` mesh.

Henceforth things are simple: we enforce orientation of the created glyphs to the supplied normal vectors through `SetVectorModeToUseNormal()`, and we provide a 'scale factor' for the base glyphs, which will just uniformly scale the `arrow` and its default size. The rest has been shown a thousand times: we create a `vtkPolyDataMapper` to map the create object to graphics primitives and connect to the `glyphSun` output. We then create a standard `vtkActor`, connect to the aforementioned mapper, and use its `GetProperty()` method to `SetColor(ColorSunGlyphs)`.

Finally, using the `vtk_show` helper-function yields the following figure. As you can see we have visualized all normal vectors with arrows, showing the direction our `sun` rays will follow.



Scene render showing the `sun` half-sphere with points at each cell-center of its mesh

Prepare for ray-tracing

We're finally getting to the ray-tracing part of the post. All we now need to do is prepare the `vtkOBBTree` object for `earth` as I showed in the last post on ray-casting. If you haven't read it then I strongly recommend that you do now cause I won't explain the details again.

Firstly, we create a new `vtkOBBTree` object with the `earth` mesh where we're going to

test for intersection with rays coming from the `sun`. This is done as simply as this:

```
obbEarth = vtk.vtkOBBTree()
obbEarth.SetDataSet(earth.GetOutput())
obbEarth.BuildLocator()
```

Just keep `obbEarth` in mind cause we'll be using extensively to test for intersections later.

Then we need calculate the normal vectors at all cell-centers on the `earth` mesh as we're going to need that information to cast reflected rays. The process here is exactly the same as the one we used to calculate the normal vectors for the `sun` mesh:

```
# Create a new 'vtkPolyDataNormals' and connect to the 'earth' sphere
normalsCalcEarth = vtk.vtkPolyDataNormals()
normalsCalcEarth.SetInputConnection(earth.GetOutputPort())

# Disable normal calculation at cell vertices
normalsCalcEarth.ComputePointNormalsOff()
# Enable normal calculation at cell centers
normalsCalcEarth.ComputeCellNormalsOn()
# Disable splitting of sharp edges
normalsCalcEarth.SplittingOff()
# Disable global flipping of normal orientation
normalsCalcEarth.FlipNormalsOff()
# Enable automatic determination of correct normal orientation
normalsCalcEarth.AutoOrientNormalsOn()
# Perform calculation
normalsCalcEarth.Update()
```

Just remember that `normalsCalcEarth` now holds the normal vectors for the `earth` mesh.

Finally, we define two 'auxiliary-functions' to nicely wrap the intersection testing functionality offered by the `vtkOBBTree` class:

```
def isHit(obbTree, pSource, pTarget):
    r"""Returns True if the line intersects with the mesh in 'obbTree'"""
    code = obbTree.IntersectWithLine(pSource, pTarget, None, None)
    if code==0:
        return False
    return True

def GetIntersect(obbTree, pSource, pTarget):

    # Create an empty 'vtkPoints' object to store the intersection point coordinates
    points = vtk.vtkPoints()
    # Create an empty 'vtkIdList' object to store the ids of the cells that intersect
    # with the cast rays
    cellIds = vtk.vtkIdList()

    # Perform intersection
    code = obbTree.IntersectWithLine(pSource, pTarget, points, cellIds)

    # Get point-data
    pointData = points.GetData()
    # Get number of intersection points found
    noPoints = pointData.GetNumberOfTuples()
    # Get number of intersected cell ids
    noIds = cellIds.GetNumberOfIds()

    assert (noPoints == noIds)

    # Loop through the found points and cells and store
    # them in lists
    pointsInter = []
    cellIdsInter = []
    for idx in range(noPoints):
        pointsInter.append(pointData.GetTuple3(idx))
        cellIdsInter.append(cellIds.GetId(idx))

    return pointsInter, cellIdsInter
```

Again, if you haven't read the last post on ray-casting, do so and the above will make complete sense to you.