Towards a Heuristic based Real Time Hybrid Rendering
A Strategy to Improve Real Time Rendering Quality using Heuristics and Ray Tracing

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Abstract: Hybrid rendering combines the speed of raster-based rendering with the photorealism of ray trace rendering in order to achieve both speed and visual quality for interactive applications. Since ray tracing images is a demanding task, a hybrid renderer must use ray tracing carefully in order to maintain an acceptable frame rate. Fixed solutions, where only shadows or reflexive objects are ray traced not only cannot guarantee real time, but can represent a waste of processing, if the final result minimally differs from a raster only result. In our work, we present a method to improve hybrid rendering by analysing the scene in real time and decide what should be ray traced, in order to provide the best visual experience within acceptable frame rates.

1 INTRODUCTION

Visual realism is one of the key resources to immerse gamers and virtual reality (VR) users in artificial environments. The more "real" are the images, the more immersive is the user experience. Unfortunately, photorealism is the realm of static images and movies, where a single image (or frame) could take hours to render using global illumination techniques. Photorealism in games (Kaplanyan, 2010a; Kaplanyan, 2010b) and virtual reality applications (Livatino, 2007) is still far away from the quality achieved by current visual effect intensive movies. The problem is not only the processing power limitations of current machines. Current real-time renderers do not deal well with reflections, refractions, diffuse scattering, ambient occlusion, caustics and complex shadows (Akenine-Möller et al., 2008). Even worse if these effects are generated in constantly changing environments.

Even with limitations, to achieve photorealism using raster based real time rendering, programmers have been developing and implementing many clever tricks to simulate global illumination effects in real-time. Techniques like cube maps (Knecht et al., 2013) for reflections and shadow maps (Rosen, 2012) to simulate areas where the light is blocked by elements are some of the many strategies to simulate real world optical effects in real-time. These tricks cannot be applied to all situations, forcing level and environment designers to change their designs in order to deal with this limitations. This burden limit the vision of artists and slows virtual environments design for both games and VR applications. The opposite side of the coin is the global illumination used by off-line renderers. Global illumination (Suffern, 2007) is a general name for a group of algorithms, in computer graphics, that simulate the way light propagates in the environment. Global illumination techniques are very demanding but produce better results than raster-based techniques. One of the most studied global illumination technique is ray tracing. In ray tracing, the tracing of a path of light through pixels in an image plane, in the direction of a virtual scene, produces an image the represents the scene. When the light ray hit an object, the characteristics of the surface of the object determine if the light ray should reflect, refract, scatter, disperse or stop. To produce shadows, when a ray hit a surface, shadow rays traced from the surface, moves in the direction of every light in the scene. If the shadow ray collides with a surface before arriving at the light source, the corresponding pixel in the image is considered to be in a shadow area for that particular light, if not, the colour of the pixel is influenced by the colour and intensity of the light. The final colour of every pixel of the image is the result of the surface and the influence of many rays traced in the scene.

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Since current raster renderers are not capable of rendering true photorealistic images and global illumination techniques cannot render complex scenes in real-time, one approach is combine raster and global illumination rendering in one single solution for real time rendering. In this case, global illumination is used only when the technique can improve the quality of the final image. This solution is still far from feasible since most global illumination techniques are, in many orders of magnitude, more demanding in processing power than raster-based techniques. In addition, considering the graphics processor evolution, raster based rendering influence and are influenced by the development of graphics processors specialized in the generation of raster-based images in real time. These processors, also called Graphics Processors Units (GPUs), are dedicated to produce sophisticated raster based images in real time.

With the development of GPUs that can also work as massive parallel processors (Nickolls and Dally, 2010), GPU based hybrid rendering, that use both raster and ray tracing techniques to create images, became an interesting research topic. The basic ray tracing algorithm is naturally parallelizable (Bigler et al., 2006), making GPUs that also works as massive parallel processors a promising platform to produce interactive, or even real time ray traced images. The possibility of interactive ray tracer using a GPU only approach was proven by NVidia, when they presented their Design Garage Ray Racing Demo (Ludvigsen and Elster, 2010). One of the most successful cases of interactive ray tracing using GPUs is NVidia's OptiX (Parker et al., 2010) engine. OptiX is an interactive ray tracing engine that is being used in professional applications like Adobe After Effects and Lumion3D.

Hybrid rendering is a recent research topic (Hertel and Hormann, 2009; Lauterbach, 2009; Sabino et al., 2012; Sabino et al., 2011). The main problem with hybrid rendering solutions is guaranteeing a steady frame rate. With a raster only solution, the designer can interactively test the environment and change elements in order to increase the frame rate. The environment designer can reduce the number of polygons in the viewport by moving objects to other places in the scene, using simplified versions of the objects with fewer polygons, applying simpler materials and so on. In a hybrid raster and ray tracing renderer, the number of polygons is just part of the challenge. Since, in ray tracing, the way surfaces react to light can also impact the overall performance, demanding the use of more rays, the challenge to develop environments that maintain an expected frame rate is many times more complex than in a raster only renderer.

In this paper, we try to reduce the burden of environment designers by presenting a heuristic to dynamically select objects and effects to be ray traced in a hybrid raster and ray tracing renderer. The proposed heuristic considers resource constraints and can be used as a starting point to develop new ways to design environments that can be visually rich, by using ray-tracing effects, without affecting performance. Our heuristic can also reduce the overall work of environment designers, by reducing the work involved in the testing phase of the environments, since the hybrid ray tracing can adapt, in real time, the final result.

This work improves the work presented in (Andrade et al., 2012), by implementing more ray tracing features in the hybrid renderer, allowing better rendering results.

2 RELATED WORK

Before the proposal of hybrid renderers, the first step towards improving visual quality in real time applications was the development of GPU based real time ray tracing (RTRT) renderers (Parker, 2009; Garcıa et al., 2012; Bikker, 2013; Bikker and van Schijndel, 2013). However, experiments demonstrate that even using current parallel architectures, RTRT renderers cannot compete in speed and overall visual quality with state of the art raster renderers. One method proposed to increase frame rate in RTRT renderers is divide the ray tracing workload between the CPU and the GPU (Bikker, 2013; Chen and Liu, 2007), where a GPU accelerated rasterization with Z-buffer is used to determine the first ray-triangle hit of eye rays (primary rays). Secondary rays are generated using the CPU in order to provide global illumination effects. Approaches like that work, but still can not compete in quality with state of the art raster renderers. A powerful path tracer for real-time games that worth mention is Brigade (Bikker and van Schijndel, 2013).

Another strategy employed by hybrid renderers is use ray tracing strictly for specific light effects that are slower or cannot be easily done in a raster only renderer. (Hertel and Hormann, 2009) uses a kD-tree accelerated ray tracer to determine shadow-ray intersections, in order to improve the quality of highly detailed shadows. (Lauterbach, 2009) also use ray tracing in to improve the quality or hard and soft shadows using a similar approach.

With the introduction of Multiple Render Targets in both DirectX 9 and OpenGL 2.0, developers started to use a shading strategy denominated deferred shading (Thibieroz and Engel, 2003) to enhance visual quality of raster renderers, by implementing a post-production rendering pass. With the possibility of implementing a process of multiple render passes, researchers started to use a pass to include specific ray tracing light effects in the rendering pipeline. (Wyman and Nichols, 2009) use a ray tracing pass to create superior caustic effects while (Cabeleira, 2010) and (Sabino et al., 2011) use ray tracing to include accurate reflections and refractions. None of these approaches deals with the performance challenges resulted by combining different render strategies and are only feasible in specific scenarios.

Another research topic related to this work is selective rendering (Cater et al., 2003; Chalmers et al., 2007; Cater et al., 2002; Green and Bavelier, 2003). Selective rendering consider psychophysical investigations on how the human visual perception works, in order to determine whether a detailed feature in an image is visible to the eye. Based on these observations, it is possible to avoid unnecessary computations involved in the creation of some features of the image. Selective rendering is strongly influenced by the way the viewer interact with the image or sequence of images.

Visual attention in real time applications (El-Nasr and Yan, 2006; Sundstedt et al., 2005; Cater et al., 2003) is also an influence in this work. The way users interpret and react upon what they see in a real time environment is highly affected by many factor like speed of the virtual movement inside the environment, recent past experiences inside the virtual environment, user attitude towards the exploration of the environment, psychological experiences provided inside the virtual environment among other factors.

3 GPU BASED HYBRID RENDERING

In order to evaluate our heuristics, a GPU based hybrid raster and ray tracing renderer was developed. Our renderer, called PHRT, was developed in a way that it allows the use of specific information of every object inside the target scene and parametric information outside the scene to control the rendering process, in order to offer a very flexible set of tools to test heuristics. A heuristic can use specific information contained in each object, specific information contained in the materials of each object, general information of the scene, information generated during the environment exploration and parametric information defined outside the environment. PHRT is also capable of following predefined virtual and automatically collect information during the virtual trip inside the environment. Information like frame rate and objects selected for ray tracing are stored for later analysis.

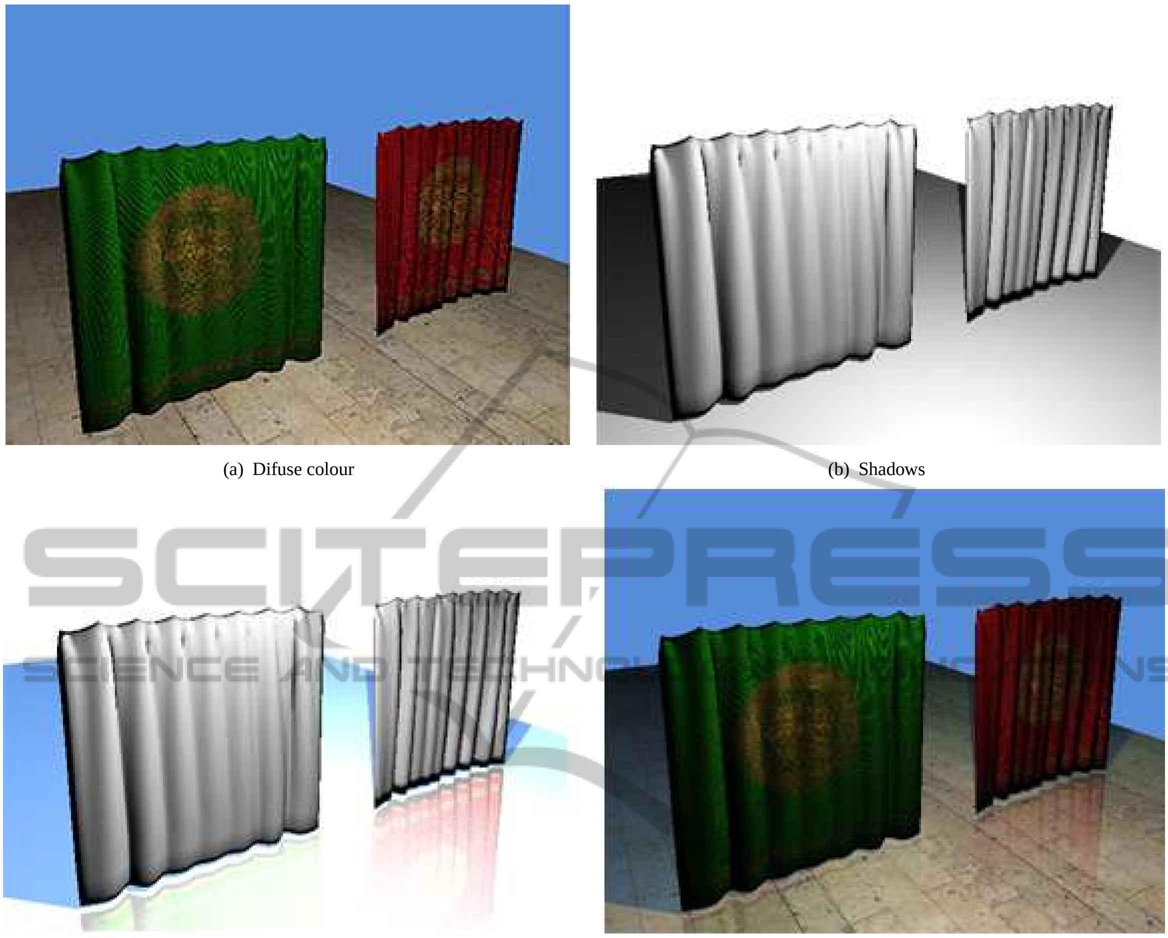
As most of today's state of the art real time renderers, our renderer employs a technique called deferred rendering (also known as deferred shading) (Pritchard et al., 2004). The basic idea is to compute all the geometry visibility tests before any light computation (shading) happens, using a raster based process. By separating the geometry rendering from the light processing and by using visibility tests, the shading process in done only for specific polygons, avoiding multiple light computations for the same pixel, for elements outside the visible space, a problem that must be treated in forward rendering approaches. The visible geometry determination process is equivalent to the primary ray hit phase of a ray tracer, where eye rays projected from a virtual point of view are launched in the direction of the scene, crossing a view plane defined by a grid of pixels, that will later represent the final image. When a ray collide with the surface of an object, the collision result in information about the object, its surface and geometry. This information can be used to define the final the colour of every pixel in the grid. Since the visibility test made by the GPU in raster based renderers is very fast, this process can easily substitute the first phase of a ray tracer.

During the first raster render pass, where the visibility tests are computed, other information like scene Z-depth, surface normals and texture coordinates are also computed. This set related information about the scene are called G-Buffer data and are stored in memory buffers denominated Multiple Render Targets (MRTs). The G-Buffer data is used in subsequent render passes of a raster renderer and also in our hybrid renderer.

With the information corresponding to the primary ray intersection and the corresponding geometry of the scene, specific rays for shadows, direct and indirect light, refractions, reflections, caustics and other effects are calculated and added to the already created data in the MRTs, according to the way the final image must be created.

The deferred rendering approach in hybrid rendering allows the selection of which visual effects the ray tracing method will create and which effects are the responsibility of other render strategies, allowing flexibility in the implementation of PHRT.

PHRT is a highly improved version of the hybrid real time renderer developed by (Sabino et al., 2012). Sabino's renderer employ Nvidia's OptiX^{TM} (Parker, 2009; Parker et al., 2010) to deal with the ray trace stage of the renderer.



(a) Difuse colour (b) Shadows

(c) Reflections (d) Final composite

Figure 1: Four images of the render stages.

3.1 Deferred Rendering and Primary Ray Resolution

During this stage, after all the data is stored in the GPUs memory, a deferred shading pass is calculated in order to fill the G-Buffer. The G-Buffer has now the information needed for the visible geometry test necessary for the other phases of PHRT.

3.2 Ray Tracing Shadow Calculation

With the information stored in the G-Buffer, OptiX™ is used to calculate shadow rays for every light source of the scene. The ray tracing shadow phase can be specifically ignored for some objects, according to the heuristic, environment information and external parameters.

3.3 Ray Traced Reflections and Refractions

Reflections and refractions also use information stored in the G-Buffer. Similar to the shadow phase, the heuristic, environment information and external parameters are used to define which objects should have reflections and/or refractions in the final compositing of the scene's image.

3.4 Composition

The composition stage is the final stage of the pipeline, where all the information produced by the other steps are combined in order to produce the final image for the frame. Figures 1(a) to 1(d) represent the four stages of the hybrid renderer, where both shadows and reflections are created using ray tracing.

4 A HEURISTIC FOR OBJECT AND LIGHT EFFECTS SELECTION

Since one of the main requisites of PHRT is a steady frame rate, one of the main constraints for the ray tracing phase is the time available after the raster phase. Even to produce the simplest light effect, ray tracing is a demanding task and can seriously drain processing resources if not used with caution. One of the reasons of its high cost is the recursive nature of the ray tracing algorithm. In order to create global illumination effects, light rays must bounce from surface to surface, in order to create indirect illumination and other light effects. The number of light rays bounces and the sequential nature of the bounces can strongly affect the render pipeline and the global performance. A common way to control render time in offline ray trace rendering is to establish a limit in both the number of ray bounces and the number of secondary rays produced in every bounce. Depending on the surface characteristics, a ray collision can produce more than one new ray, greatly affecting the performance.

Depending on factors such as type of light effect, characteristics of the surface, number of lights in the scene and relative size of the visible portion of the element to be ray traced, the time spent in the ray trace phase can surpass the time available for the phase. So, the heuristic must choose wisely which elements must be ray traced in a given time and with what constraints, in order to maintain the ray tracing phase in its time constraints.

The heuristic must also consider the contribution in the overall visual experience, in order to produce the best possible image. This overall visual experience is not a static factor as the other components of the problem. Depending on the motivation of the user inside the virtual environment, some objects and light effects can be more relevant than others can.

4.1 Object and Effect Selection

Considering only the objects that should be involved in the ray tracing phase, we can define the heuristic as: “for a given X objects, select the Y most relevant objects that can be traced given a time limit T”, where X is the objects that are relevant for the image generation in a given time and T is the available time for the ray tracing phase. Both parameters X and T can change its values for every frame generation.

The reason behind the idea of choosing a subset of objects that best contribute to the visual experience came from the real world perception that when images change constantly, as when we drive a car or walk in the street, the mind ignores many visual elements. This is the reason we have orientation signs in the streets. Signs call attention to inform about something relevant. In a first person shooter game or in a driving simulator, the faster the experience is the less is the perception of detail of the environment.

Considering the way the human vision works, it is reasonable to assume that objects near the centre of the field of view are more important than objects far from it. The same can be said for objects near the observer. Another observation is that according to environment conditions (weather, indoor, under water, for example), some objects cannot be visually improved by ray tracing effects. Another situation that can affect visual perception is the user’s motivation in a given moment. If, for example, the user is looking for a gold coin in the environment, the user will be more susceptible to pay attention to golden objects. With these observations, the heuristic can be expanded to: “for a given X objects, select the Y objects nearest from the centre of the field of view and from the observer, that most contribute to the visual experience, considering the ray trace effects to be applied, and that can be used in the ray tracing pass considering the time constraint T”.

4.2 The Heuristic

The proposed heuristic has five phases, an offline phase, two fixed phases that happen before the rendering and two phases that happen for every frame.

The first offline phase, called pre-production phase, consist in identify and select the objects and their relative effects that must be used in the ray tracing pass, for a given environment. This information is defined by the environment designer or automatically generated by an algorithm that analyses every object, it’s characteristics and relationship with other elements in the scene. In both cases, every object in the environment receives a fixed importance map value that consist of the priority of this object for the ray tracing phase. The importance map could consist in only one value or a group of values, where each value, in the group of values, represent a situation related to the user experience inside the environment. This map of values can define, for example, that a transparent object is very important during a daylight experience inside the virtual environment and not important at all if the experience changes to a night exploration. In the tests tests done for this work, we only use one fixed value, but PHRT can deal with many fixed values for every object.

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Still during the pre-production phase, every object receives an importance factor (K). The importance factor is based on both the first and the second offline phase and is considered the result of the second phase. This importance factor defines how important is each object in respect with the others. Also, every object has an initial visibility cost (V), and the corresponding estimated number of rays to be used to generate each visual effect related to the object (Q). (Q) can be a list of values for each object, with each value corresponding to an estimated cost for every effect, or can be the sum of costs involved to produce all the visual effects. (V) and (Q) are also automatically created during the second offline phase.

Visibility (V) is defined by the average area (A) of the 2D projection of the object in the view plane multiplied by the distance of the centre of the 2D projection to the distance of the view plane (P), divided by the distance (D) of the object from the view plane in the 3D space. The higher the object distance, the less visible the object is. The visibility equation is presented in equation (1). The total cost (C) for a given object is presented in equation (2).

$$V = \frac{A \cdot P}{D} \tag{1}$$

$$C = V \cdot Q \tag{2}$$

The distance of the object center to the view plane center (P) is normalized as a value between $[0,1]$, where a value of 1 means that the center of the object projection is in the same position of the view plane center, and a value of 0 means that the object is out of the field of view.

To select each object is also necessary to calculate the relevance factor (R), where (R) is based on the fact that the object was selected or not to be traced in the previous frame (S) generation phase. (S) is a binary variable, where 1 means that the object was previously selected, and 0 means the it was not. The importance of selecting previously selected objects is also a fixed factor, present in the information about environment and defined by the variable (I). Equation (3) is used to define the object relevance.

$$R = (S \cdot I + V) \cdot K \tag{3}$$

For every frame, all the equations are calculated for each object, in order to update the selection graph with the current information of the environment.

Table 1 present all parameters discussed before and inform if the parameter has their value constant or variable during the render phase.

Table 1: Equation Parameters.

Param.	Definition	Const.	Var.
K	Object relevance among the others	X	
V	Object visibility		X
Q	Estimated number of secondary rays	X	
C	Processing cost		X
A	Projected area		X
P	Distance from the view plane center		X
D	Distance from the observer		X
R	Relevancy		X
S	Previously selected		X
I	Previously selection relevance	X	

The third phase happens during the render phase, when the GPU receives the selection graph. Every node in the graph represents an object to be traced and every node point to the second node with cost (C) smaller than the cost of the previous node, but larger than the costs of the other nodes already in the graph. Every node also points to N other nodes not selected to render, where relevancy (R) is bigger than the relevancy of the actual node. The pointers for other nodes with higher relevancy are ordered by its relevancy.

When an object finishes rendering, the graph is traversed to find other node where the cost (C) is smaller than the time available for the ray tracing phase. When the node with a suitable cost is found, all the other nodes with higher cost are removed from the graph and inserted in another graph that is being built for the next frame generation.

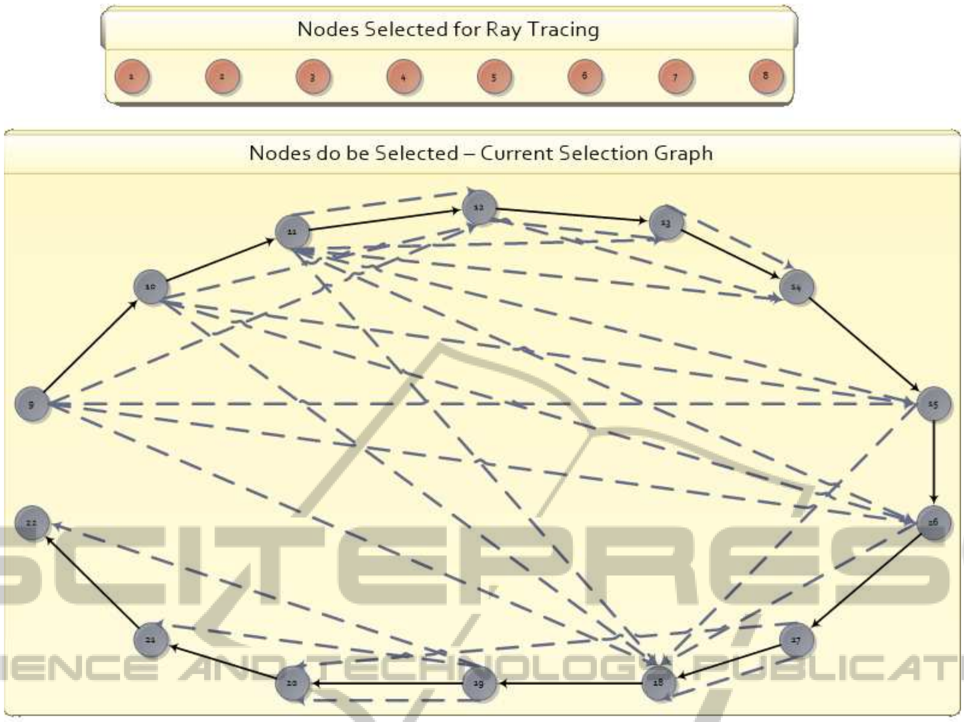

Figure 2: Selection Graph and nodes already selected.

Table 2: Cost (C) and Relevance (R) for the Selection Graph represented in Figure 2.

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
C	-	-	-	-	-	-	-	-	20	19	18	17	16	15	14	14	13	12	11	10	9	9
R	-	-	-	-	-	-	-	-	22	21	18	30	31	32	28	27	9	29	1	20	4	3

4.3 Graph Reconstruction Example

Figure 2 represents the selection graph and the selected nodes for the example represented by table 2. In this example, eight objects are already selected, and fourteen other objects are waiting to be selected. The orange circles are objects already selected for ray trace. Gray circles are objects not selected. Black arrows indicate the node order according to their cost (C), and the blue dashed arrows point to the N most relevant (R) objects than the actual node, and with smaller cost.

When the first object finishes rendering and there are still time to ray trace other objects, the next object must be selected. In order to determine the best object, the selection graph is traversed until a node with cost (C), smaller than the cost still available for the ray trace phase, is found. All the nodes with bigger costs are moved to the new selection graph in construction to be used during the next frame rendering. If a node is found, the graph is still traversed in case this node points to another one with higher relevance (R).

If there is no time to render a new object, all the nodes left are moved for the new graph and all the variables are update for the new graph and the new frame generation phase.

Figure 3 continue the example of Figure 2. In Figure 3, the cost available in the ray trace phase is 18. Node 11 has cost 18 but, according to Table 1, node 14 has more relevance than node 11. When note 14 is selected, nodes 9 and 10 are re-moved from the graph and moved for the new graph. The current selection graph is updated for the next selection. When the time left for the ray trace stage is not sufficient to render a new object, the new graph node is constructed for the next render phase.

5 TESTS AND RESULTS

For the heuristic fine tunning and measurement of overall performance we use the Sponza scene as the main environment with many objects spread inside the scene. Glass and mirror spheres were used as

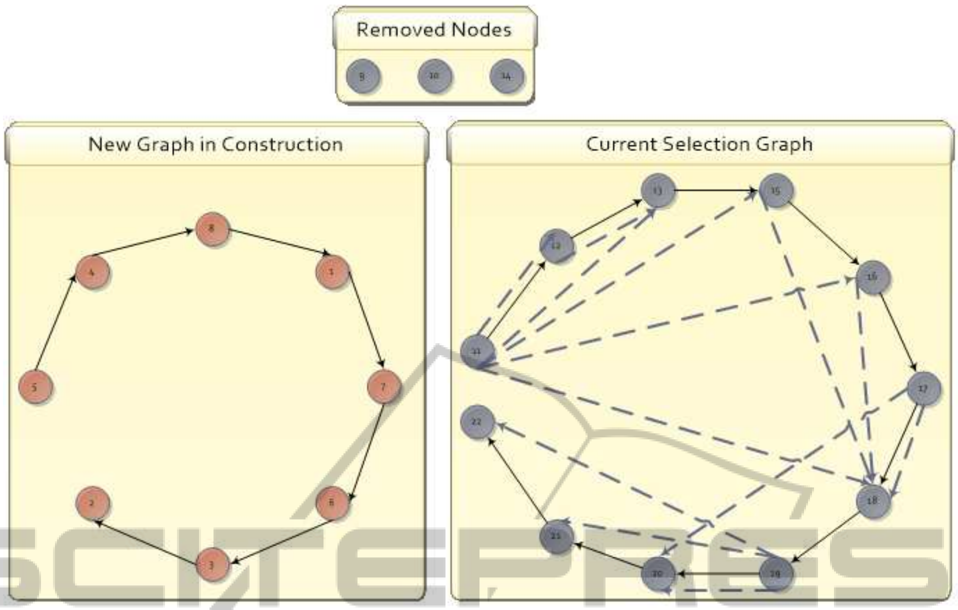

Figure 3: Nodes removed from the selection graph (top), new graph (left) and current selection graph (right).

mandatory objects for ray tracing, in order to guarantee that at any given time, there will always be an object or effect to ray trace.

All the tests were done using a desktop computer with 16 Gbytes of RAM, an AMD Phenom II X4 965 3.4GHz CPU and a NVIDIA GeForce GTX570 GPU. This machine is running a 64 Bits version of Microsoft Windows 7 Professional.

In order to achieve frame rates with at least 20 frames per second, the path that the camera traverses the environment is fixed, in order to simulate a character movement inside the environment. Early random tests shown the environment need more planning in order to avoid frame rates bellow 20 frames per second.

In order to compare the overall performance, we run the hybrid renderer twice for the same path. In the first run, we use ray tracing for all elements in the scene and for the second run, we use the heuristic to control the average frame rate in order to avoid drop the frame rate below 20 fps. Figure 4 represent our test with an open sky while Figure 5 and 6 show our indoor tests. In order to render figure 4 in an average of 20 frames per second, the hybrid renderer decided to not render the shadows of the Armadillo. Rendering the same frame using only ray tracing dropped the frame rate to an average of 8 frames per second.

With simplified objects, the hybrid renderer is capable of rendering the path that was used to create figures 5 and 6 with an average frame rate of 28 and 21 frames per second. Shadows of distant objects where completely ignored in the two scenes.

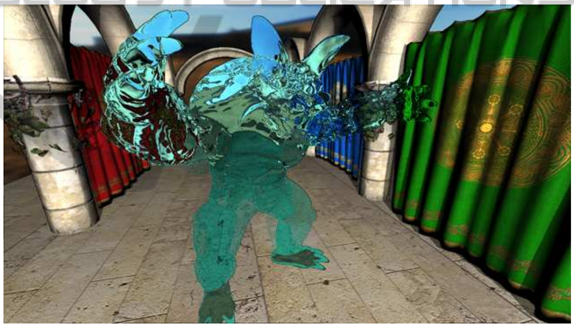

Figure 4: Hybrid rendering in ray tracing just the Armadillo statue and without ray traced shadows.

6 CONCLUSIONS

We have described a heuristic to select objects to be ray traced in a hybrid rendering pipeline, where the selected objects are the objects that most contribute to the visual experience of the user, based on the assumption that objects near the observer and near the centre of the field of view are more relevant than others in different situations. We also offer a strategy to dynamically maintain a graph with the best candidates to be traced. All the tests and scenarios were planned to run at a minimum of 20 frames per second.

Unfortunately, the ray tracing phase is still too demanding to deal with very complex environments but we believe that the ray tracing phase will become less and less demanding for every new version of the OptiX engine and GPU architecture.

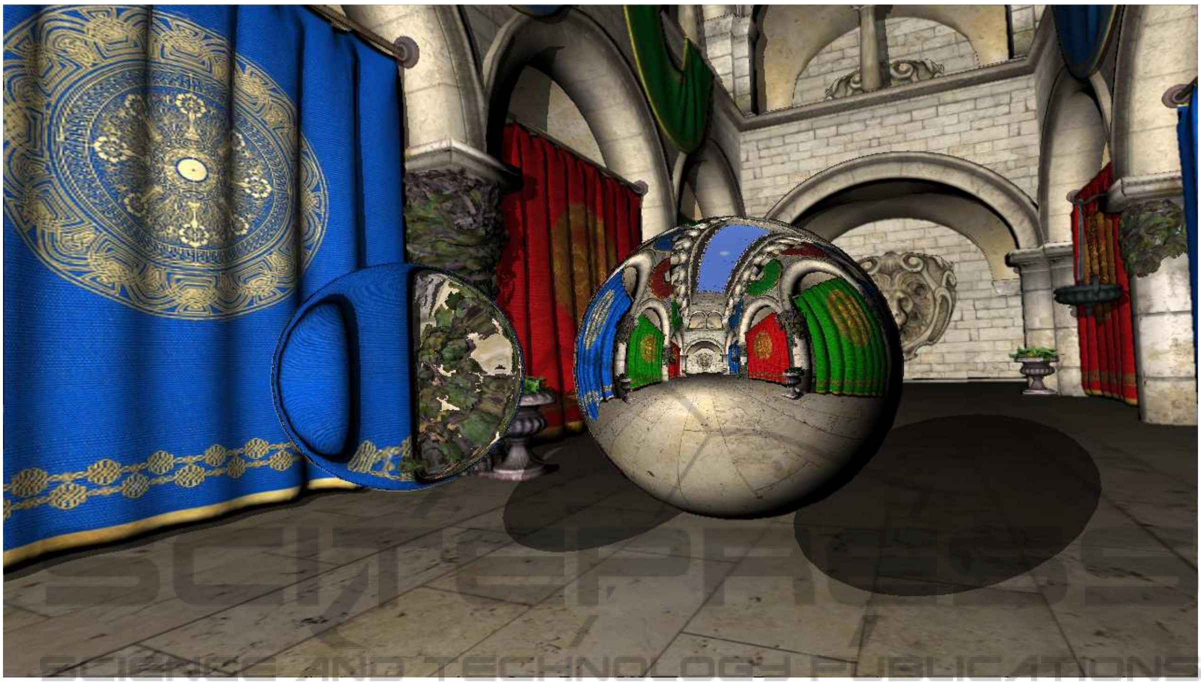

Figure 5: Shadows of distant objects are ignored.

Figure 6: Detailed shadows generated by the ray tracer, when possible.

We are in the middle of our tests and we plan to try the heuristic based hybrid renderer in many other scenarios and in order to see if the heuristic is general enough. We also plan to run stress tests, where the hybrid renderer will run a very long path, in order to measure the degradation level, if any, of the selection graph. New variations of the basic heuristic are also being planned in order to compare with the original in complex scenarios.

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