Vadim Morozov

PHYSICALLY BASED 3D RENDERING USING UNBIASED RAY TRACING RENDER ENGINE

Bachelor's thesis
Information Technology

2019

South-Eastern Finland
University of Applied Sciences

South-Eastern Finland
University of Applied Sciences

Author (authors)	Degree	Time
Vadim Morozov	Bachelor of Engineering	October 2019
Thesis title Physically based 3D rendering using unbiased ray tracing render engine		50 pages 4 pages of appendices
Commissioned by		
Supervisor Matti Juutilainen		

Abstract

The thesis covered the topic of 3D rendering. The main focus was on the physically based rendering workflow that allows creating photorealistic 3D graphics. The objective of the thesis was to prove that the technology evolved and developed so that almost any user with a personal computer and essential knowledge is capable for creating photorealistic and physically accurate images.

The main research methods were an online research on different resources and professional literature. The study covered main concepts and terms of lighting and materials in physically based 3D rendering. Also, the main principles and technologies of rendering and the market of render engines was reviewed and analyzed.

The goal of the practical part was to test the theory introduced and create the computer generated imagery in order to prove the main proposition of the study. It included working in a dedicated software for 3D modeling and using AMD Radeon™ ProRender as main rendering software. The implementation part consisted of detailed description of every step of the project creation. The whole process from modeling to the final image output was explained.

The final results of the study were 8 computer generated images that indicate the implementation was successful, the goal of the study was reached and it is proved the initial proposition.

Keywords

3D rendering, Cinema 4D, raytracing, PBR, AMD Radeon™ ProRender

CONTENTS

1 INTRODUCTION 5
2 THEORY PART 7
2.1 Light 7
2.1.1 Hard Light 7
2.1.2 Soft Light 8
2.2 Rendering 10
2.2.1 Evolution 10
2.2.2 Ray Tracing 12
2.2.3 Development 13
2.2.4 Render Engines 14
2.2.5 Bias 14
2.2.6 Render Engines Market 14
2.2.7 Rendering Features 17
2.3 Materials 20
2.3.1 Material Layers 20
3 PRACTICAL PART 25
3.1 Building a 3D scene 25
3.2 Lighting 29
3.3 Creating materials 30
3.3.1 Floor, walls and ceiling 31
3.3.2 Table and chair 32
3.3.3 Vases and plants 34
3.3.4 Lamps 34
3.3.5 Other objects 35
3.4 Render settings 37

3.4.1 Cameras....37

3.4.2 ProRender™ settings....38

3.5 Compositing....40

4 CONCLUSIONS....40

5 REFERENCES....43

APPENDICES

Appendix 1. Final rendered images

1 INTRODUCTION

Modern technologies in the field of 3d modeling and rendering allow producing visual content at a level that was hard to imagine a decade ago. Powerful consumer hardware becomes more affordable and production values that only large studios and film companies could afford before are now available for individuals. Small enterprises start to compete with big players on the market. The global volume of 3D services, including 3D modeling, motion graphics, 3D rendering, and visual effects, was USD 13.75 billion in 2018, and it is predicted to grow at a CAGR (compound annual growth rate) of 11% in the next six years.

The topic of 3D rendering was chosen, because this fast-growing and developing field evolved from being a fun tool to experiment in film production in the 1980s to the attribute of everyday reality. Nowadays, it is used in computer games, medicine, space industry, architecture, car production and many other fields, including modern cinematograph where it became commonness and people stopped noticing computer-generated imagery in most cases. I selected this subject to study because of its spreading speed, growing demand and the fact that it stands at the junction of physics, math, programming and art.

Another reason to make a study about 3D is that I plunged into the field of rendering during the exchange semester I completed as a part of the degree programme. Since that time, I have been learning about the industry and practicing professional skills. The thesis project is a good summarizing point, and the next step in personal development.

The main goal of this thesis project is to prove that physically based rendering is available for every person who has basic knowledge of how real-world physics of light and materials works, sufficient skills in modeling and creating virtual environment in a 3D scene using professional software and has a creative state of mind to make it all look artistic. The secondary goal is to test my competences in the field of 3D graphics: to discover how the experience I gained may help to build a computer-generated image from scratch and to deliver a final product as a practical example of the hypothesis to be proved. The last objective is to learn

and test GPU (graphical processing unit) rendering using the AMD Radeon™ ProRender engine.

The theory part describes how to reach a photorealistic look through physics and math in conjunction with how a computer processes digital image. The first part contains light theory. What types of light exist, what kind of shadows they produce, how it interacts and behaves with objects? The following chapters are about rendering concepts. Processing and calculating a 3D scene, rendering techniques and render engine types are described. Ray tracing is reviewed in more detail, because it defines the virtual light behavior and it is the main method to be used in the practical part. Rendering study is finalized by discussing key features of a rendered image which creates a transition to the material study, describing algorithms that define material appearance under different lighting conditions. How different materials reflect and absorb light, what are the principles and stages of creating a digital surface?

Theory study bases on “Physically Based Rendering. From Theory to Implementation” book by Matt Pharr and Greg Humphreys, “How to render” book by Scott Robertson and different materials on the Internet.

The practical part consists of a process of creating 3D images step-by-step, explaining the main stages of production from modeling to postproduction. The project is a 3D scene of an interior with plenty of objects made of different materials. It showcases the key benefits and features of physically based rendering. The practical part includes more detailed description of how the project is done. Professional software used is Maxon Cinema 4D for 3D modeling and rendering, Adobe After Effects and Adobe Photoshop for compositing, color correction and final editing.

2 THEORY PART

Most of the terms are related to the video and the static image production, architectural visualization and design. They are explained and studied in the theory part. Game development is not reviewed in the study. 3D production pipeline differs a lot in gaming, graphics perform in real time while computer-generated imagery in movies is rendered in advance. Major 3D modeling software works on a similar basis. The focus here is on Maxon Cinema 4D, but a lot of terms and rules of modeling, texturing and rendering are applicable to Autodesk 3Ds Max, Maya, Blender and others. These are only tools in the hands of an artist whose goal is to learn new techniques and master software, artistic and technical skills permanently. I have gathered all essential theory to start creating 3D scenes so that they will look real.

2.1 Light

Light is the main aspect of the perception of the world by the human eye. The main task and challenge of computer graphics are to simulate light in such a way that the human brain could not distinguish it from the real one. To achieve the most physically correct and accurate lighting, developers learned how to create a computer model that simulates the behavior of real-world light. In this part, the main concepts of virtual light are described.

Light and shadow are inseparable matters. The type of light defines what shadow the object casts. When discussing this topic some definitions are supported by visual images for clearer understanding.

2.1.1 Hard Light

Direct hard light casts rays in an aligned and singular direction. Hard light produces sharp edge shadows that are cast by illuminated objects. The best example is the sunlight: rays hit the Earth at about the same angle if they do not meet obstacles like clouds or windows. Usually, hard light is emitted from a small,

single-point source like a camera flash or Sun. It is direct and undiffused. Figure 1 shows an example. (Scott Robertson, 2014)

Figure 1. Hard light example (Rubidium Wu, 2019)

As can be seen, the shadows on the woman has sharp edges and the contrast is high. It is nearly impossible to see any details in dark parts of an image.

2.1.2 Soft Light

Direct soft light is determined by diffusion. The shadows have soft edges with a gradient from light to dark without clear borderline. It comes from the scattered light source which is generally close to the object, relatively large and casts rays in many directions. The examples are the cloudy day illumination or light bulb with a diffuser. Figure 2 shows how hard and soft light differ.

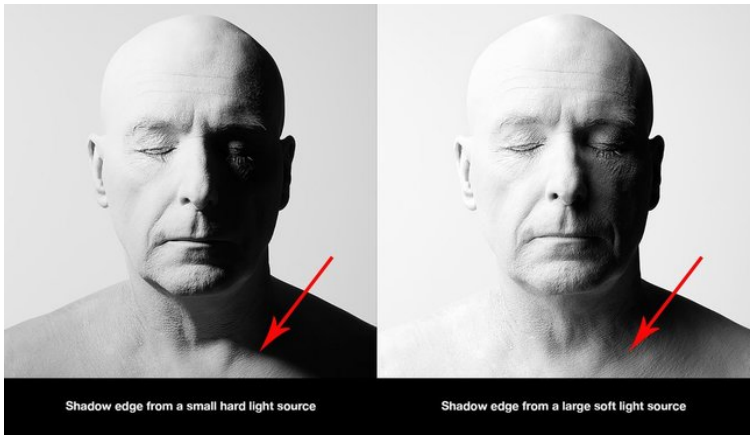


Figure 2. Hard and soft light (Greg Blue)

Hard and soft are the two main types of light that exist. It is light coming from a source. When light hits the surface of an object, it reflects, in other words, rays are bouncing. The reflected or bounced light is what the eye sees, but some of these bounced rays hit other objects around and illuminate new surfaces, which at the same time produces new shadows and the number of iterations is uncountable in the real world. Figure 3 shows the obvious example of reflected light.

Figure 3. Reflected light example (James Gurney, 2010)

When studying and observing real light behavior scientists discovered an occlusion effect. It occurs when light is being blocked by a contiguous object. It can be seen in the corners of walls and other contacting objects. Figure 4 shows a rendered image with only an ambient occlusion layer. As Figure 4 shows, it gradually enhances quality and improves realism. The ambient occlusion technique is described later in the light rendering chapter.

Figure 4. Ambient occlusion (Autodesk Inc.)

It is an essential light theory to understand what the goals are to reach realistic light behavior that is studied in art schools, so any artist has an idea of how to apply it on paper or digitally. The difference between an artist who draws a picture by hand and visual effects artists is that the painter has to consider all these light behavior rules in the head while working on canvas and predict which parts of painting will be brighter or darker. A VFX (visual effects) creator has a powerful instrument called render engine which does complex calculations and math.

2.2 Rendering

Rendering in computer graphics is a process of calculating a three-dimensional scene to generate a 2D representation utilizing the resources of application software. The final image or sequence of frames is also called render. The scene file includes objects, lighting, textures, shadow and camera data which is sent to the rendering software to be processed and produce a digital image. (Techopedia Inc.)

2.2.1 Evolution

The first method used in computer graphics was rasterization. The 3D object geometry coordinates and color values of polygons are taken and projected on

the 2D plain. Rasterization was introduced at the very beginning of the computer era and remained indispensable for decades. The first computer-generated imagery (CGI) made with this technique can be seen in movies like *Tron (1982, Figure 5)* or *The Last Starfighter (1984)*. Rasterization remains one of the main methods in computer games because of its speed and simplicity of calculations which are excellent for real-time image processing. By the 1980s, other rendering methods were invented but computation power could not handle complex reflections and illumination. The main advantage of rasterization is that it does not require to fit the whole scene file in main memory. It is hard to achieve realism without global illumination models that need the whole scene in memory for precise calculations.

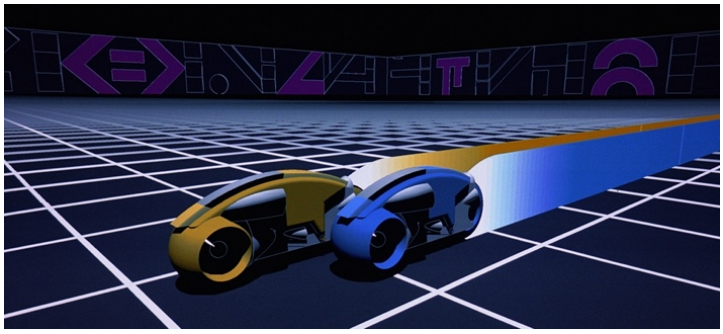


Figure 5. Tron (1982)

The first big step in the physically based approach was made by Blue Sky Studios in 1998 with *Bunny* short film. It was the first example of Monte Carlo global illumination implemented in a movie. Blue Sky did not share any technical details on how they achieved the look, but it was a starting point for physically based rendering techniques.

In 2001, Arnold renderer prototype was shown at the SIGGRAPH conference. It used the Monte Carlo model and processed complex geometry and textures in a matter of minutes. It launched the development of realistic motion blur and shading, created an opportunity to build much larger scenes and reducing costs. Physically based rendering using global illumination started spreading across production companies and became an industry standard. *Gravity (2013)* movie is a great example of using physically based rendering techniques (Figure 6).

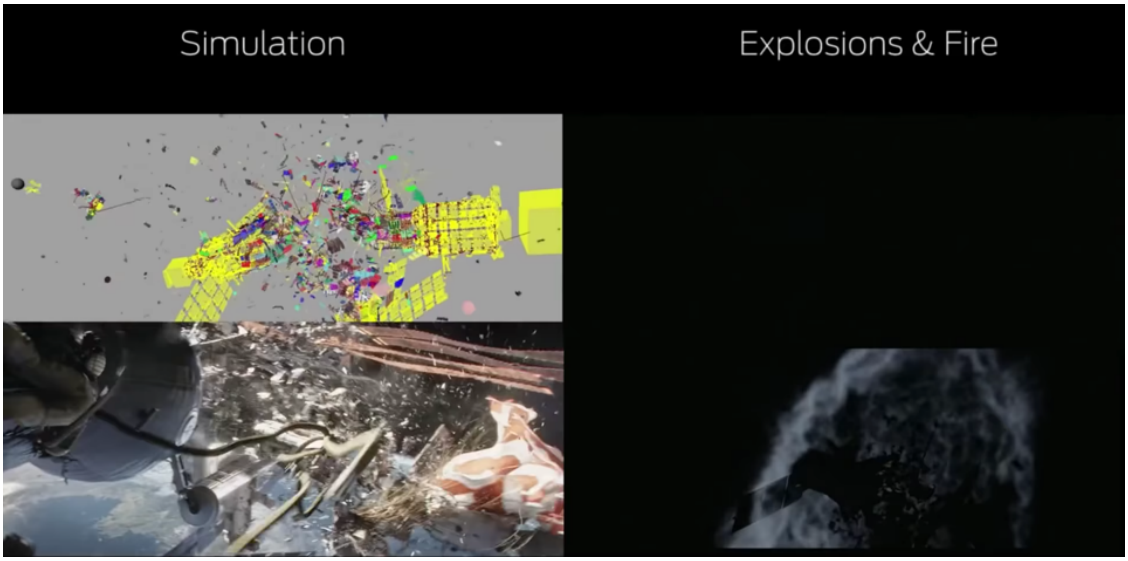


Figure 6. Gravity (2013)

The whole movie was created digitally. Only actors' faces are real and some shots inside the ISS (International Space Station).

2.2.2 Ray Tracing

The idea of ray tracing to be used in computer graphics was first proposed and proved by J. Turner Whitted with his 1979 paper "An improved illumination model for shaded display". The main principle is that the virtual camera sends rays through every pixel of a screen plain with a finite resolution. When a ray is reaching an object, it sends secondary ray(s) to the light source(s) in the scene. It can generate three types. Afterwards, it remembers the texture, lighting and shading data. If the secondary ray hits another object on the way to the light, it means that the point is in the shadow. This made it possible to simulate real reflections, refractions, translucence, and scattering. There can be a question why rays are sent from the camera, but not from light sources. The answer is that it saves computing resources: not all rays from light reach the viewer, only a small part of them. It is the most efficient way to calculate the ray path from the camera. One of the first ray tracing generated images is shown in Figure 7.

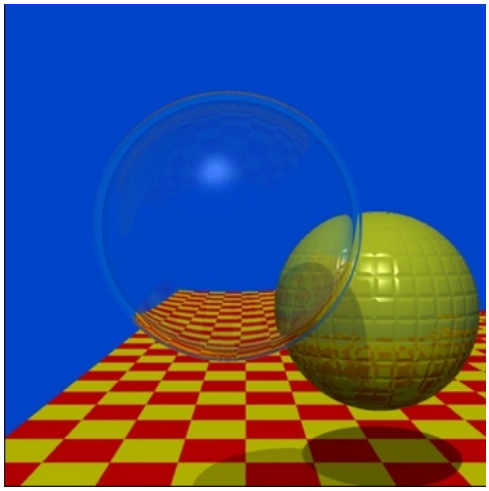


Figure 7.1979 computer-generated image using ray tracing global illumination algorithm (J. Turner Whitted, 1979)

Ray tracing is a groundbreaking method in simulating physically correct illumination and remains the best and most popular rendering technique in visual effects production and animation.

2.2.3 Development

The gaming industry still uses rasterization and different algorithms to “cheat” and generate photorealistic lighting. Ray tracing is not yet suitable for real-time processing. In 2018, NVIDIA released new proprietary real-time ray tracing technology called NVIDIA GeForce RTX™. It is a big step forward in terms of light processing in computer games. Still, it is not the ray tracing by traditional means. RTX uses hardware acceleration to process real-time lighting data, but it calculates only a part of lighting data. Recent games with RTX support do not use this technology at full capacity, and it is early to talk about mass use due to the costs of implementation and the price of graphics cards.

Sony announced their real-time ray tracing technologies to be used in their next generation of gaming console (Peter Rubin, 2019). It can be said with high level of precision that Microsoft will use this technology in XBOX to compete with Sony (Alex Alderson, 2019). This can push ray tracing to become massive and accessible to the ordinary user.

2.2.4 Render Engines

In computer graphics, application software generating graphical output by converting internal scene files containing a set of polygons or geometry, lighting, and different dependencies into a set of pixels on a 2D plain is called a render engine. This section includes the overview of available and most widely used render engines on the market.

2.2.5 Bias

Unbiased engines calculate the image and process ray data straight without any pre-calculation and techniques to speed up rendering. They deliver the most physically correct and accurate representation of the scene. Film production companies mostly use unbiased renders due to their exceptional quality and realism.

Biased render engines use a variety of techniques before sending rays to mathematically predict how the final picture should look like. It greatly reduces processing time and delivers comparable quality to unbiased solutions. Biased engines are becoming more and more popular within motion designers, because it is more suitable in creating surreal graphics in their artwork, and it does not require tons of hardware performance due to high level of optimization and control. Bias is playing less and less role in choosing between render engines. All major software can deliver realistic image, and things like speed and usability have become more important for the artists. (CG VIZ Studio, 2018.)

2.2.6 Render Engines Market

There is a huge variation of rendering software on the market. Different render engines are used for different purposes, some of them are uncompromising in architectural visualization as V-Ray, the market share of which is 58.9% (Jett Mottle, 2019). The main criteria to choose the best renderer for specific needs are the speed of the whole workflow including lighting, texturing and image calculating speed, the resources used for computation and software support. The realism of the final render stopped being a key factor to consider because, with

the right setup, sufficient skills and knowledge artists can achieve the same look on any render engine. For example, Octane by ©OTOY Inc. is an unbiased engine that requires a little time for lighting and texturing, because it imitates the real light rays' behavior, and the result is close to reality by default. The main drawback is that it is limited by video memory of a graphics card. On the other side, V-Ray, which is biased, is more sophisticated and needs a lot of precision in settings, but it can handle bigger scenes with more complex geometry. That's why it is an industry-standard in architecture.

Table 1 introduces the most popular render engines with their main properties: 3D modeling software supported by an engine, what processing unit they utilize (CPU or GPU), Global Illumination method and brief information where they are used. (Michele Yamazaki, 2019.)

Table 1. Comparison of render engines

Engine	Major Software	CPU/GPU	Biased/unbiased	Global Illumination method	Information
Arnold	Autodesk Maya Maxon Cinema 4D Autodesk 3Ds Max SideFX Houdini	CPU/GPU	Unbiased	Uni-directional path tracing	Full-length VFX movies
V-Ray	Autodesk 3Ds Max, Maya Blender Maxon Cinema 4D Unreal Engine SketchUp Katana Foundry. Nuke	CPU/GPU	Biased	Path tracing	Architectural visualization, product design
Octane	Autodesk Maya Maxon Cinema 4D Autodesk 3Ds Max	GPU	Unbiased	Spectral light transport	Photorealistic animations, product visualization, architecture
Corona	Blender Maxon Cinema 4D Autodesk 3Ds Max	CPU	Unbiased&Biased	Path tracing	Architecture and product visualization

Maxwell	Autodesk Maya, 3Ds Max Foundry. Nuke SketchUp ArchiCAD	GPU	Unbiased	Path tracing	Architecture and product visualization
RenderMan	Autodesk Maya SideFX Houdini Katana	CPU	Unbiased&Biased	Path tracing	Full-length VFX and animation movies (e.g. all Pixar Studio cartoons)
RedShift	Autodesk Maya, 3Ds Max Maxon Cinema 4D SideFX Houdini	GPU	Biased	Ray tracing	Motion design, animations

All renderers use ray tracing as the main method of global illumination, but different techniques and technologies. For example, path tracing is a ray tracing method that simulates real-world light rays' behavior. Therefore, the ray is bouncing until it reaches the light source without sending secondary rays. It slows down the process but makes it the most physically correct technology. Another technique is spectral rendering in which light rays are simulated with their real wavelength. It provides an additional level of realism and physical accuracy to the final render. (John Hart, 2002.)

As shown in Table 1, the majority of renderers are unbiased path tracers and utilize both CPU and GPU processing power, some of them can mix computation between units which adds an additional level of complexity. The most popular engine among film production studios is RenderMan and PRMan (Pixar's Photorealistic RenderMan) due to the high flexibility, stability, customization capabilities (e.g. plenty of plugins) and speed.

In the practical part, AMD Radeon ProRender™ is used. It is an unbiased ray tracer that utilizes GPU power. It is one of the best solutions for macOS users for now. It is the only GPU renderer that is optimized for *the Metal* hardware-

accelerated 3D graphics application programming interface (API) (Apple Inc. 2019).

2.2.7 Rendering Features

As the final part of the rendering study, this section describes the key visible features of a photorealistic rendered image are described. These are main challenges of rendering to output picture so that human eye cannot differentiate it from a photo and believe in its realism. Each render engine processes these features in different way, and algorithms vary.

Reflections of surfaces, **transparency** or transmission of light through solids (e.g. glass) and liquids (e.g. tea), **refraction** of the light in transparent object and **translucency** (how light scatters passing through a transparent object) – all these lighting effects have been solved by developing global illumination techniques. The most effective way to simulate those is ray tracing or path tracing. The architectural visualization on Figure 8 clearly illustrate it.

Figure 8. Render of a house (Allison. Thiago, 2019)

The caustics effect which is visible when light passes through curved transparent object forming bright beams of light remains sophisticated and requires a precise setup of the number of ray bounces in the scene. The example is shown on Figure 9.

Figure 9. Parfume bottle with caustics (Leonardo Carvalho Vieira, 2017)

Another challenging effect called **subsurface scattering** is visible in living creatures' skin or viscous and muddy liquids like yogurt or coffee with milk. When the light goes through the object, rays are bouncing inside it and produce illumination effect? Figure 10 illustrates the light going through the grapes.

Figure 10. Render of grape with subsurface scattering effect (Gleb Alexandrov, 2015)

The next important visual feature is quality **shadows**. How gradual is the transition from dark to bright in soft shadows, and how detailed and sharp the edge of hard shadows? Modern render engines do not have problems with calculating shadows, the only thing which instantly catches the attention is the noise which usually appears in shadows. Renderers are never hundred percent

precise and image imperfections are usually deleted after the fact by denoising algorithms. The same noise is sometimes visible around the specular of glossy materials, when the transition between the highlight to the mid-tones is rapid but not instant. This issue is also solved by increasing sampling quality and ray depth. **Shading** is an illumination effect which helps to understand the object shape and volume. It depends much on the number of light sources, their size, and intensity. It also affects the color of the object.

Texture-mapping is a method of applying an image to the object's surface. The main challenges are to make the texture look correct in the perspective view, diffuse light in a desired realistic way and be detailed enough. Over the last decades, the texture creation has changed and enhanced. Now different texture types are controlled through the Material system with multi-pass rendering workflow. (Huamin Wang, 2016.)

The camera has to be accurate and give a realistic image in physically based rendering. Modern software allows setting up all physical properties: focal length, shutter speed, aperture, sensor size, exposure, distortion, and vignette. When shooting on a real camera, physical properties of a focal length, aperture and sensor size affect the **depth of field**, and **the bokeh effect** occurs in out-of-focus parts of the image. Depth of field (DOF) is the distance between closest and farthest objects which are in focus. Bokeh is a quality of blurred areas of an image. The goal of render engines is to simulate optical effects naturally. (Nannette Salvaggio, 2009.)

Motion blur is one of the most resource-intensive processes in motion graphics. It requires an analysis of how the object is moving and on what speed. This effect occurs when some object is moving fast in the frame and the camera is shooting on longer exposure and it cannot capture this object sharp. Motion blur is used in cinematic and artistic purposes. For example, most movies are made in 24 frames per second and motion blur occurs in any dynamic scene. If a computer-generated object does not have this effect it becomes instantly visible. On the

Figure 11, streaking objects along the road add more realism, and the picture looks cinematic.

Figure 11. Volvo car render with motion blur effect applied (Garrett Byrum, 2018)

2.3 Materials

To start talking about materials it is necessary to define the resembling terms: material and texture. The texture is an image file that covers the surface of an object. A photo of the asphalt or gravel can be a texture and give a realistic look to the mesh. Textures can also be made procedurally using different graphical software such as Photoshop. A material defines how the object will look like on the render. It controls how reflective the object is, how bumpy it is. Transparency is also defined by material. All these layers are defined by texture or so-called map. The main principle of projecting a 2D image on the 3D surface is UV mapping. The “U” and “V” letters simply mean the 2D axis,
because *XYZ* coordinates are used for the 3D scene.

2.3.1 Material Layers

All major 3D modeling programs have their material editors, the tool of creating materials and assembling texture maps, but layers remain almost the same. The analysis of texture layers is reviewed on the example of Maxon Cinema 4D which is used the main 3D modeling software in the practical part.

Color is also known as Base, or the Albedo map defines the basic color value or an image placed on the surface. The software does not take anything out of the source and places the plain texture on the object. (C4D Center, 2019).

The diffusion layer allows making specific areas of the object brighter or darker. Ambient Occlusion map can be applied to this layer. Diffusion maps are used to display imperfections in color and light distribution which makes renders look more realistic. (C4D Center. Diffusion. 2019).

Luminance is used to create self-illuminated objects, for example, studio lighting rigs with complex geometry such as circles, square frames, LED lines, etc. Users can define the color and the brightness of the emitting light and texture as well. The subsurface scattering effect is applied to this layer. (C4D Center. Luminance. 2019).

Transparency defines the amount of light penetrating the object, refraction coefficient (e.g. 1.33 for water, 2.41 for diamond). Working with transparent materials, the color value is set on this layer, because the color brightness and saturation affect the transparency level. The reflectance of transparent materials is defined here as well. (C4D Center. Transparency. 2019).

The reflectance layer is one of the main and complex ones. Users can set up multiple reflection layers (e.g. in physically based rendering metals' color is defined in the reflection layer which is overlaid by the main reflection). Reflectance determines how the environment reflects on the surface, how rough and bright it is, and sets the specular strength. All these parameters can be defined by maps. The main techniques to simulate transparency are:

- *Beckmann* is a physically based algorithm for simulating micro facets and surface imperfections.
- *GGX* is similar to *Beckmann* but works better with conductors (metals).
- *Lambertian* and *Oren-Nayar* are used to create diffuse layers for metals.
- *Blinn-Phong* is a reflection model which is used for low reflective materials. (Richard Lyon, 1993)

Another important aspect is the Fresnel. According to Augustin-Jean Fresnel whose equations say how light transmission between different optical media works, layer Fresnel simulates specific reflections' behavior on the program level. In simple words, the reflectance of material differs from the point of view, distance and optics used to observe the scene. If the point on the surface is far from the observer, it looks mirror-like. The example of this light behavior is perfectly visible in Figure 11. (Robert L. Cook, 1981.)

Figure 12. Fresnel reflection effect on the floor (Unknown author, 2007. Hospital corridor)

The environment layer allows adding HDRI (High Dynamic Range Imaging) maps on the material. HDRI map is a 360º image of some environment, it can be a photo of a street or interior which is made in high dynamic range, so that the software can understand highlights as a light source and add realistic reflections to the objects. HDRIs are usually applied in the luminance layer of the Sky object (the sphere that surrounds the whole scene). The environment layer is sometimes used in setting up reflective materials to speed up the rendering process. (C4D Center. Environment. 2019).

Fog shader makes object semi-transparent and blurry. It literally adds a fog effect by adding some kind of opacity map. If an object is thicker in a certain area, it

means that it will absorb more light and vice versa. Fog shader can be also applied to a cube or sphere which are times bigger than entire scene and ad the foggy weather effect.

Bump maps add roughness to the surface. Bump map modifies surface normal without affecting the geometry to add more details to the final look. Then the bump map is used for lighting calculations. Because the geometry and the actual shape of the object remains unchanged, shadows and silhouettes remain the same. A bump map is a black and white image. The example is on Figure 13. The offset of the point is defined by greyscale. (Pluralsight, 2014.)

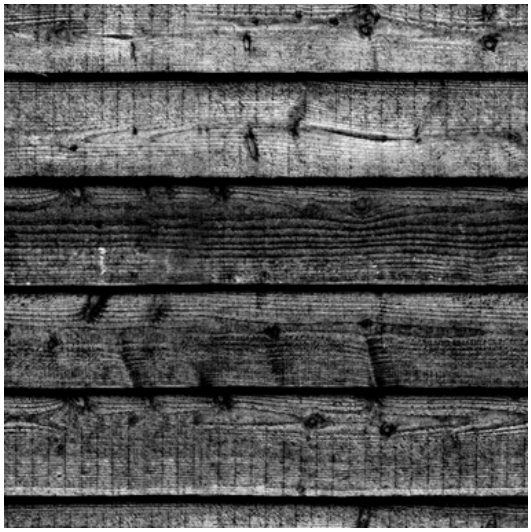


Figure 13. Bump map of wooden planks (Texture Haven)

The normal map is a type of bump mapping. It also creates a fake effect of bumpiness and does not affect actual geometry. The difference is that it is more detailed, because it tells the software not the height information, but uses RGB (red, green and blue) mapping to tell the software deformation data in *XYZ* space. The 3D software knows the exact vector of each bump. There are two types of normal maps (Figure 13):

- Tangent Space is a mix of blues and purples. It is the most popular way of shading, because such maps perform better in animations when the geometry is changing. It is widely used in character animation.
- Object Space is a more developed version of tangent and gives a bit more information. It has a wider range of color values but performs badly in animations.

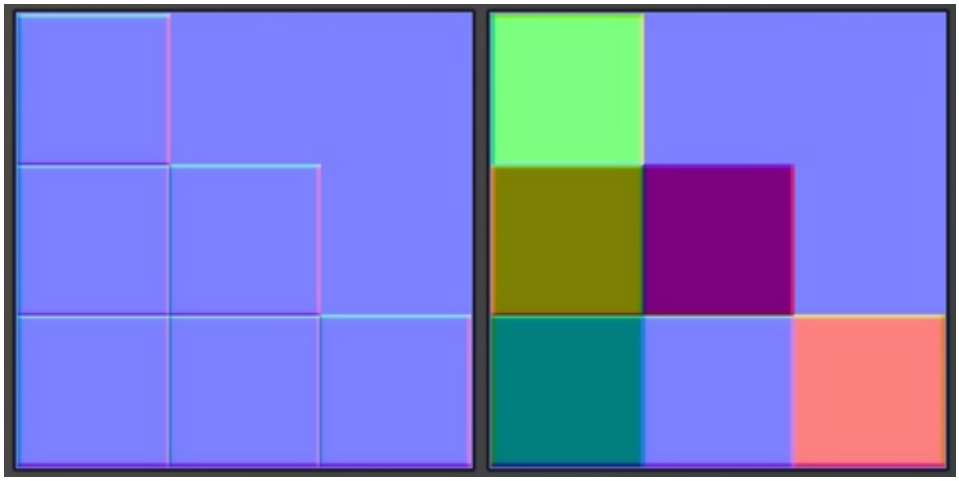


Figure 14. Tangent Space (on the left) and Object Space (on the right) normal maps

Displacement maps change the mesh. These maps affect surface geometry and displace polygons according to the greyscale values as in bump maps. The number of polygons should be increased or subdivided to reach greater detail. The drawback is that displacement maps require much more time than bumps and normal. The renderer has to calculate it every time from scratch. It is recommended to use 16- or 32-bit images as displacement maps to avoid artifacts. (Pluralsight, 2014.)

Alpha channel allows adding an opacity map to the material. It is used when an artist wants to create a grid or a net object or overlay material by another e.g. add a scar to the character face.

As a conclusion to the theory part, the fundamental terms of 3D rendering were researched, and it represents the key components of a physically based rendering workflow. The study does not go into 3D modeling and sculpting, because these are separate disciplines that require artistic, architectural background and some drawing skills from the artist. The goal was to explain that working with 3D is not rocket science which operates with complicated terms and math. It is accessible for masses and the latest technologies are available for the average user. The main secret in creating photorealistic renders is to look around and to use the real world as a reference. All necessary tools are here, and they are becoming more user-friendly over time. (Greenberg, Donald P., 1999.)

3 PRACTICAL PART

The second part of the study is a project done following the rules of physically based rendering and the visual application of terms explained in the theory part. The main part is done in Maxon Cinema 4D R20 software that perfectly suits the needs of the project. It provides a great level of user experience and has powerful tools for modeling and animation. The whole process is divided into five stages:

- Building a 3D scene using ready-made 3D models from the Internet and creating custom shapes using built-in Cinema 4D tools and setting up the composition to make it look artistic and stylish.
- Creating the lighting of the scene and explaining different light sources in Cinema 4D.
- Creating materials for the objects
- Explaining how to render settings are made, specifically in AMD Radeon ProRender™ using Cinema 4D user interface.
- Making render result look better, adding small details, compositing the image.

The final result is CG image files. Rendering is extremely hardware sensitive and resource-intensive. The following project is done on 15” MacBook Pro 2019 running on 2.3 GHz 8-core Intel Core i9 (9th generation) processor, AMD Radeon Pro 560X graphical unit with 4GB GDDR5 video memory. The laptop has 16GB of RAM and runs macOS Catalina. Technical specifications are given so that readers can reference them and roughly estimate the performance of their own hardware and software. My personal experience shows that Cinema 4D is well optimized for both Windows and Mac OS. The difference becomes great when talking about render engines. Octane and RedShift, for example, are working only on Nvidia’s graphics cards for now, so Apple users cannot use them natively without external GPU, because Apple has an exclusive partnership with AMD to install their graphic solutions.

3.1 Building a 3D scene

First of all, the program’s user interface and main features should be briefly reviewed. Maxon Cinema 4D is 3D modeling software focused on creating motion

graphics. The interface is organized in several windows which are responsible for different functions. The default layout is shown in Figure 15.

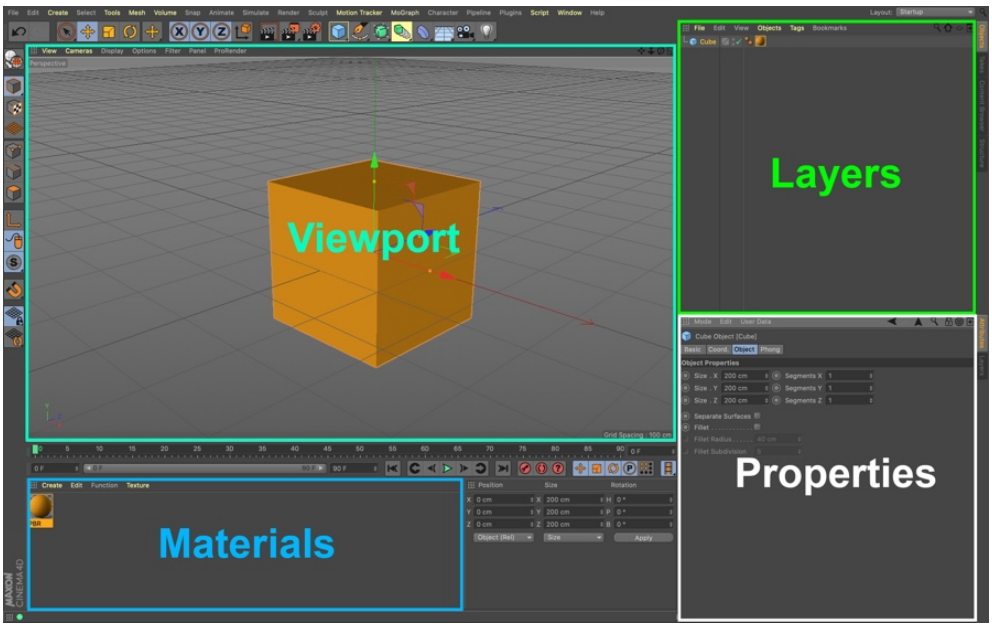


Figure 15. Cinema 4D user interface (UI)

A viewport is a place where the user sees the scene in 3D space, it is rendering online and represents the basic geometry and effects in a simplified way. All tools for modeling, editing and operating are placed above the viewport and on its left side. Every icon has a specific purpose, and there is no need to go into detail on this stage. There is a timeline on the bottom of viewport shown in frames. The Materials menu takes the lower part of the screen. Here are all created materials are managed. The right part is divided into two windows. The upper one is the layers menu where all objects and effects are located. Properties menu where all adjustments and settings are done are situated underneath the layers.

The main tools for modeling are situated in the meshes' menu. Mesh is called a 3D object which is formed by a mesh network, a topology of nodes (points) connected with each other by pre-defined math. Procedural modeling is possible using meshes, in other words, the object's shape and size can be changed dynamically at any point of time. This is the main difference from polygon modeling where objects are formed by 2D fixed forms like squares or octagons which are placed in 3D space. Any mesh object can be transformed into polygons. Figure 16 shows the basic mesh object that can be created.

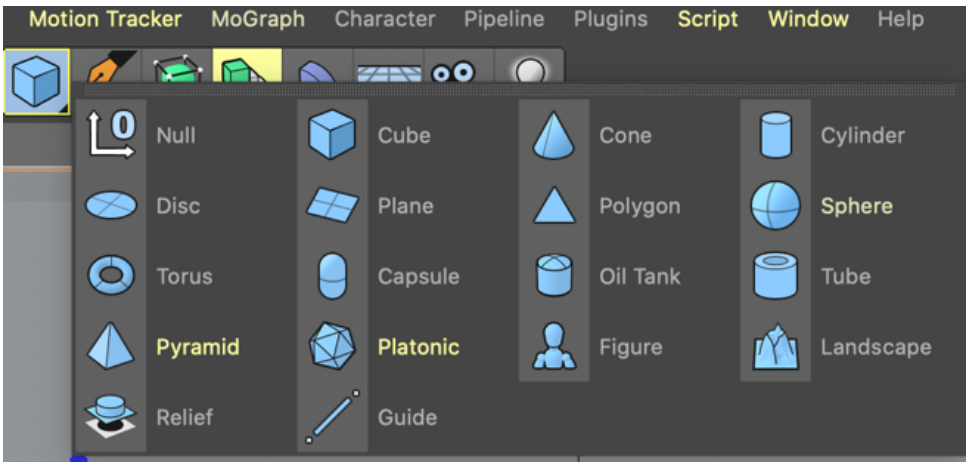


Figure 16. The mesh menu in Cinema 4D UI

First, the initial environment is created. Building a basic room is simple. I used three plains forming the floor and two walls. Other two walls are not needed. It is described further in the study when setting up lighting. The dimensions are referenced in the real world. It is a standard 10m2 room with a three-meter ceiling, real sizes will help to plan the space and place furniture and objects precisely.

The next step was to think about what kind of interior I want to see, what style will look good and which objects will clearly show the benefits of physically based rendering. The decision was made to create a working place at home with a modern minimalistic design. It includes a table, a chair, a laptop, some office items and a couple of vases with plants. The table and chair perfectly show the wood and steel materials. Plants in vases are a perfect example of water and glass refraction. Because there are tons of 3D models on the Internet and the selection is diverse, it is not a big issue to find furniture with a suitable design.

The table, chair and vases are placed first, because they are dominant objects in the scene. Lamps are also playing a big role in interior perception. The eye usually pays attention to the ceiling and sources of lighting. I chose metal body lamps which will look great in matte black. The wall lights fill the wall plain so that it does not feel empty. Figure 17 shows how the room looks at this stage.

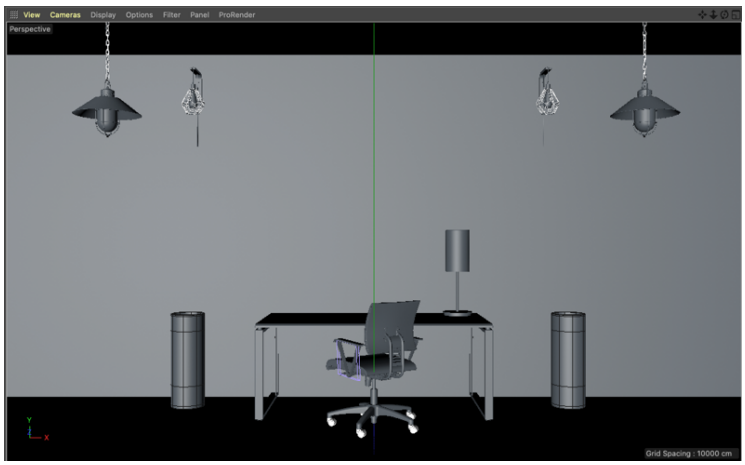


Figure 17. Furniture in the scene

As can be seen, geometry is not complicated. The table is formed by several rectangle frames and vases are the cylinders with no fill. The office chair has a complex shape. It would take ages to model it. Now, it is time to place some objects on the table, so that it looks like somebody just sat here a minute ago. Because it is a working place, a laptop, phone, and some stationery will complement the atmosphere. The last step is to place the plants in vases. I found high-resolution models of bamboo and corn plants online with a decent level of detail. I placed them so that they will be partially underwater. Water is a solid object with a water refraction index. The special simulation plugin is required to create liquids in Cinema 4D. To make vases look more stylish I decided to add stone balls filling the vase. Figure 18 illustrates the final placement of objects in the scene.

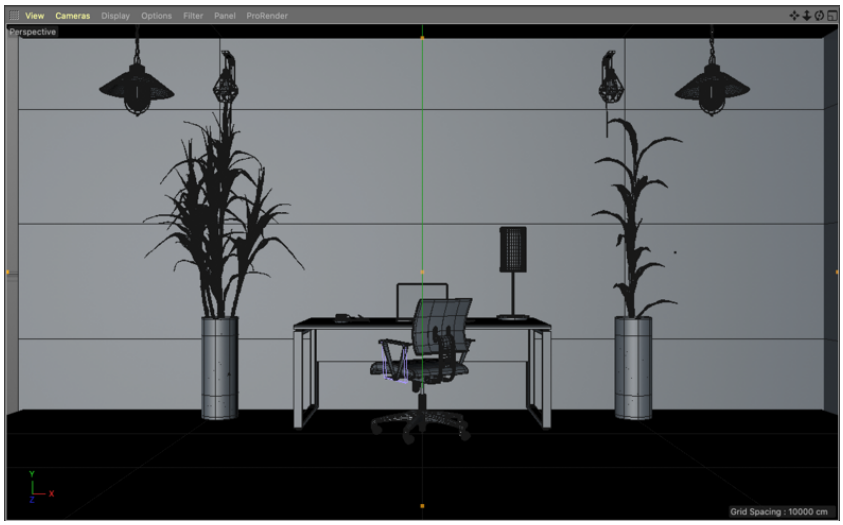


Figure 18.Final objects' placemement

The scene is symmetric and equally filled. It makes the composition look moderate and measured. Otherwise, there would be no order and it looked messy and empty space struck the eye.

3.2 Lighting

Physically based rendering techniques start to apply at this stage. The render engine to be used is a ray-tracer that works best with big and bright light sources. The main light is an HDRI map of a hotel room taken from the Internet (the source: hdrihaven.com). HDRI map is a 360-degree image with a high dynamic range up to 24 stops between absolute black and white to avoid any clipping, in other words, rapid change from dark to bright or vice versa in highlights and shadows. I am not going to display the image itself and it will not be visible in the final render, only the light is needed. The source image is shown in Figure 19.

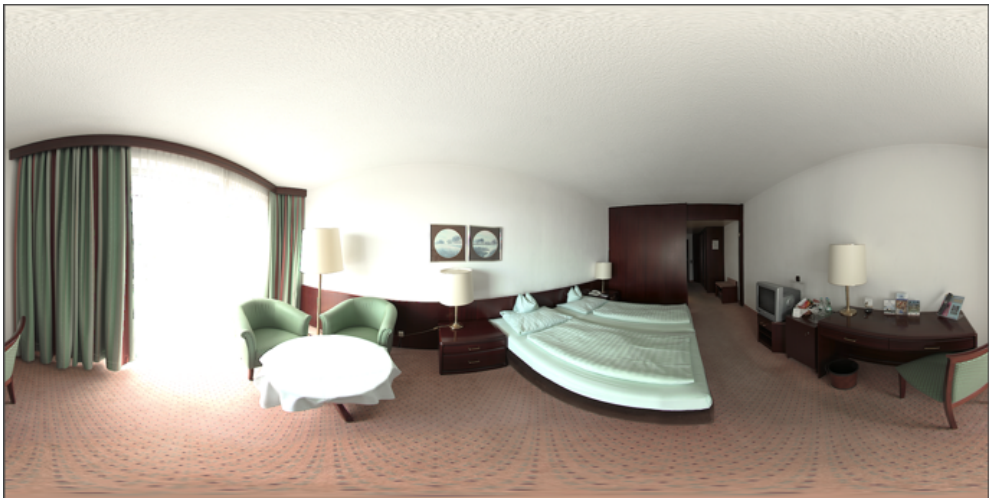


Figure 19. HDRI map of a hotel room

First, the PBR material is created. All channels are switched off except luminance and the image is added as an illuminating texture. The next step is to create an object on which the HDRI map is applied. Cinema 4D has a special Sky object which is basically an invisible sphere that automatically resizes according to the scene scale to surround it all. As can be seen, the light goes from the window. I rotated the sky so that the light will go from the left of the scene. In this case, it will be illuminated, as if there was a real window out of sight.

3.3 Creating materials

This stage is the most important in the entire workflow. In my opinion, the quality of materials directly affects the final render. The project includes tens of different materials, but there are only a few main types of them: metal, wood, plant, plastic and other low-reflective materials. This chapter is divided into five parts by the type of objects.

Before I start, it is necessary to briefly review the material editor in Cinema 4D, because all operations and settings are made in it. Therefore, I will not explain all the buttons while going through the process. The material editor is shown in Figure 20.

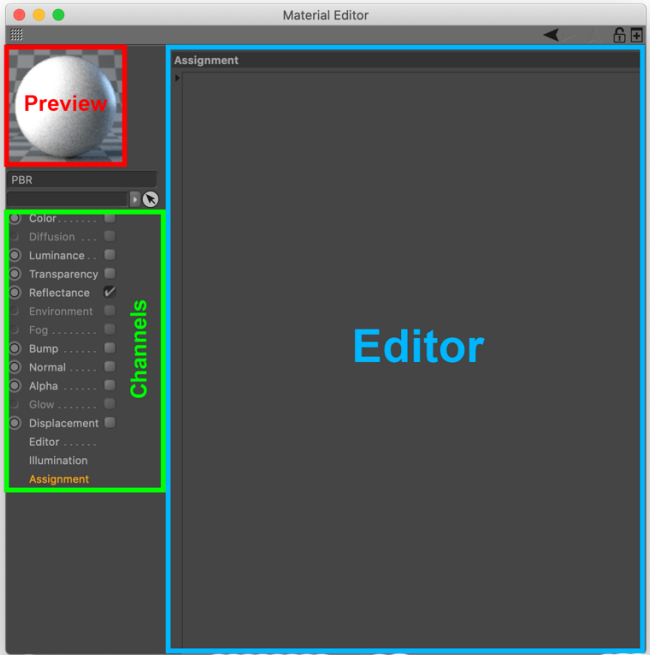


Figure 20. Cinema 4D material editor.

The window contains material preview, list of channels and the editor where all the settings are done. Some channels are disabled by default, because the Radeon ProRender™ is selected. This means that the renderer can operate only with available physically accurate channels. Diffusion, environment, fog and glow channels work as effects. The color of the object we see is a reflected light ray, according to my experience, it is better and more efficient to define the color in the diffusion channel of reflections. The color channel is not used as well.

The important aspect of material creation is constantly checking how it appears in render and comparing it with reference photos of real things. That is why the lighting was set up prior to materials. The preview mode of rendering allows calculating image progressively with low sampling. In other words, it displays a rough representation of the final image. The precise settings of reflection strength, roughness, specular strength and others are not explained in detail. It speeds up the workflow gradually and prevents serious errors during the main rendering process.

Intermediate images showing details of the objects to be covered with materials are done using standard Cinema 4D render engine. It is the fastest option on MacBook that utilizes CPU power which has 16 threads (two threads on each core). It outputs files with decent quality for preview.

3.3.1 Floor, walls and ceiling

I expect the interior to be a mix of wood and metal textures. Such combination is widely used in modern designs and facilitates the work in the sense that it will be difficult to spoil the view with a bright object and, at the same time, it will maintain a minimalistic look. The great benefit of Cinema 4D is that its license goes with the content library with a huge variety of textures and maps of a different kind.

Parquet will look beneficial on the floor. I found its texture and place it in the color layer in the reflection channel. Cinema 4D recommends using Lambertian or Oran-Nayar reflection models for diffusion layers. I used Lambertian diffusion and added another reflection layer on top. It adds reflectiveness to the floor as it is varnished. Simple Phong specular is easy to process and it will look realistic. The main trick is to apply a parquet bump map on both the bump channel and the main reflection. Therefore, all the surface imperfection will look natural. Walls and

the ceiling only have one white diffuse channel in reflectance without any textures. Figure 21 illustrates how the room looks like at this stage.

Figure 21. Room preview

3.3.2 Table and chair

Because the tabletop is made of birch, the process is similar to the floor material. The only difference is in diffuse and bump maps. The frames the table is standing on are made of metal. The metal material uses only the reflectance channel with a grey Lambertian diffuse layer and reflection layer. I chose GGX as a reflection type with 50 percent roughness and set up layer Fresnel in conductor mode to reflect like iron using a preset.

The office chair has a complex geometry and plenty of details, but the materials are quite basic: one type of wood, three colors of plastic, iron and chrome. The only complicated material here is the fabric which covers a seat and a back. The reflectance channel has a special Irawan type reflection made especially for cloth. This material took me the most time in the whole process because of the number of settings, level of precision to be made and render optimization. Figure 22 shows all the settings of this material. It allows to choose the pattern of the fabric whether it is silk, cotton or wool, define the color gradient of the fiber and many different options. I created the black fabric with a slight gradient to grey shades and adjusted the length of fibers using the UV scale. Irawan shader creates a pattern of dots and lines using warp and welt color values of the diffuse

channel and specular. The scattering option defines the light penetration (absorption) of the object.

The wooden structure on the reverse side of the back, seat and armrest looks like it is made of plywood. I found the textures in the pre-installed library in Cinema 4D. Metal parts are mainly chromium plated. It is a highly reflective surface with low roughness and conductor Fresnel reflection. Polished plastic is defined by a smooth surface with a uniform color. Fresnel dielectric preset of pearl has the closest look to it. This material is copied a few times with different colors. The preview of the table and the chair can be seen in Figure 23.

Figure 22. Irawan reflection shader

Figure 23. Table and chair preview

3.3.3 Vases and plants

The cylindrical glass vases are filled with water and stone balls. Glass and water are created using only the transparency channel as any transparent objects. The reflectance channel is not used, because all transparent objects have reflection by default. The only difference between glass and water is the refraction index. Water will look a bit green because of the plant. To reach this effect the color is made 5% saturated on the green channel. Due to the number of balls inside it will be a hard job for the renderer. I just added the white diffuse layer in reflection.

The bamboo model has a high level of detail. I divided polygons of leaves into three groups to colorize them differently. Bamboo leaves have a structure of dark and bright lines. I created tiles and applied a gradient with green shades in the diffuse layer and added GGX reflection with oil dielectric Fresnel preset on top. The trunk has a similar solid structure with small dry leaves on it.

3.3.4 Lamps

There are five lamps in the room. The wall lights consist a wooden hanger, cable, metal frame and light bulb. The hanger includes the reflectance and the bump channels as other wooden materials, but with more roughness and a bit different texture. I used the plastic material from the chair to apply it on the cable lowering the Fresnel index a bit. It is made of rubber, but polished similar to plastic and relatively small in size. The metal of the frame is matte black. The material has a rough reflection with blurred specular. The principle is similar to other metallic surfaces. The light bulb consists of the bronze of copper socket that is made using the conductor preset of iron and the slight brown color on top. The bulb itself is made of glass; glowing coils are configured using yellow color in the diffuse layer.

Ceiling lights utilize the same matte black metal material for the body and chain. The inner side of the body has white glossy enamel. Strong reflection has low roughness and expressed specular. The table lamp’s base and stand are made

of glossy metal close to chromium look. After quick online research, I found that shades are usually made of some kind of fabric with small folds (Tomshine, 2019). I created a tiles shader with a black and white gradient. Then, it is applied to the diffuse layer with default reflection with dielectric settings on top. The lamp's body stands on a rubber base, whose material is close to plastic but with less reflection. I removed the reflection layer and left only the diffuse because it is a thin and barely visible object.

3.3.5 Other objects

There are five different things on the table. They are all of different complexity and it would be better to start from the simplest in terms of texture. The cup of coffee standing on the left side is made of enameled ceramics and filled with liquid. The surface of the cup and the saucer are close to the material used in the inner side of the ceiling light body. The roughness is adjusted so that the specular is blurred and less strong. Coffee material has only the transparency channel with 30% brightness and brown color. Brightness in transparent materials directly defines the amount of light transmitted through the object.

A book and a pencil are next to the coffee cup. The book may seem complicated, but it is basically a parallelepiped with protruding faces. The cover is displayed by reflectance layers of diffuse and weak reflection. The material of the pages is made by using a gradient of black and white lines on the diffuse layer. The pencil has some textures worth describing. The graphite has no diffusion defined in reflectance. Basic reflection is made by the Phong method and dielectric Fresnel index of 1.47. The noise shader is used as a bump map which adds natural imperfections on the surface. The wooden cone tip texture is close to the material of the table but with more color brightness and excluded reflection layer. It is covered in dark red paint. The noticeable detail in eraser material is a bump map made using a few noise shaders mixed with each other.

The smartphone in the scene is taken from the real existing iPhone X model. It was created in my personal project I have done before. The screenshot of it can be seen in Figure 24. (Vadim Morozov, 2019.) It consists of many parts and I

included fifteen different materials. They are divided into few types of glass with various refraction used in the body and camera lenses, metallic materials and the screen with an image of an operating system interface. It is important to explain how to work with screens of a different kind in the 3D workflow. As explained in the theory part, any texture or shader is located on the object using UV coordinates. The texture can be scaled so that it fits within screen edges. These adjustments are situated in the properties menu, if the material tag is selected. A video file can also be used as a texture. It is important to synchronize the moving picture with an animation, Cinema 4D does not have any video editing tools for the textures.

Figure 24. Smartphone render

The last object in the scene is a laptop. The model was taken from the Internet and it already has a good polygon division. Each letter on the key is an individual spline and the luminance material is applied to them. The keyboard is made of black plastic, this material is used in some other objects reviewed before. The aluminum body is set up using conductor Fresnel reflectance with the GGX method with increased roughness to make it feel anodized.

Creating materials is a time-consuming process, but, at the same time, if the theory and main concept are clear for the artist the workflow becomes smooth and the probability of mistake decreases. One of the main things to consider while working with any project is to organize all pieces. There are 99 materials in the project. As can be seen, there is a lot of similar materials, especially metals.

A good technic is to give unique names for each node and to put them in folders called Material Layers. It speeds up the whole process and it would be hard to lose something. Finally, all objects are in their places and materials are properly configured and applied. The project is ready for rendering and export.

3.4 Render settings

To move forward with rendering it is necessary to select actual images to be rendered. In other words, creating cameras and placing them in spots with a good view. A camera is a separate object in Cinema 4D which acts like a real one. It has all physical properties.

3.4.1 Cameras

There are eight cameras in total. As a result, eight images will be exported. All cameras have a similar focal length of 35mm and 36mm sensor size. To make renders look real and artistic the depth of field effect is applied. It adds more complexity to calculations, but provides great quality and realism. I located cameras in the best spots and chose good-looking angles. The focus distance is set in centimeters, or the camera can focus automatically, if the target object is chosen. The last thing to be configured in-camera is F-stop or aperture. Define how open the diaphragm is. This value is indicated by the focal length divided on the coefficient. The lower the number is the more light goes on the sensor and the bokeh effect and the amount of blur are more explicit. All cameras in the scene have an f/2 aperture.

After all the camera angles are finalized, it is time to configure the render engine. AMD Radeon ProRender™ is a ray-tracing physically accurate renderer developed by AMD and integrated into Cinema 4D. It will be easier to follow the

description with a screenshot of Render Settings window which is shown in Figure 25.

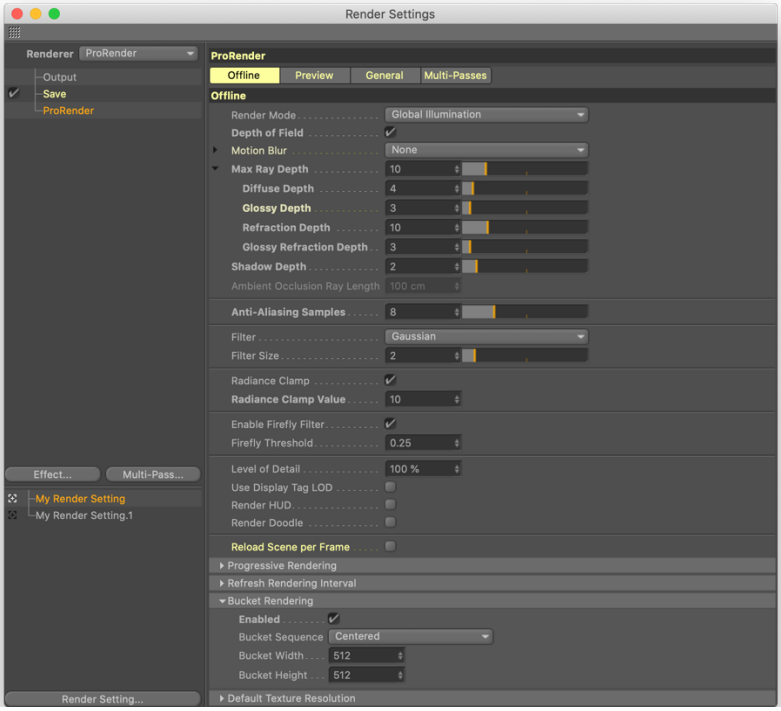


Figure 25. Render Settings window

There are three main tabs in the left menu. The resolution, frame rate of animation, and the range of frames to be rendered are set up in the output tab. The final images of the project will be 2880x1800 pixels. Other options I left on defaults. The saving path, the format and the name of the output file and color depth are configured in the save tab.

3.4.2 ProRender™ settings

Now Cinema 4D knows what kind of files to create and where to find them. One of the beneficial features of ProRender™ is the ease of configuration. It is an unbiased renderer and it does not require any precalculated data and simulations of global illumination. It sends rays and processes all data, as described in the theory of ray tracing. In a nutshell, the user sets the number of maximum ray bounces, and that is it.

As resources are limited precise adjustments are required. The first menu is called Render mode. Global Illumination mode is a full render of all textures and lighting, it is going to be used in this project. The second option only processes the ambient occlusion effect without any light and textures. The depth of field option is enabled. Motion Blur adds realism to the motion picture as explained in the theory part, but it is a resource-intensive process. In this project, there are only still images.

Finally, the essential and the most significant values affecting the quality are Max Ray Depth values. There are few types of them: diffuse, glossy, refraction and glossy refraction depth. These values define how deep the rays go into objects and bounce from surfaces. The technique I found for myself is to look at the scene and find an object with the most complicated geometry and with most complex material that could be difficult to render. In this scene, it is the vases with stones and bamboos. Then, the task is roughly estimating the number of bounces needed to reach the least reflective surface or fly out of sight. In this case, the ray first hits the side of the vase and then it is refracted in glass and goes to the inner side of the vase. After that, ray flies to some stone and reflected. Finally, it can have a couple of bounces inside of the vase, so it needs the minimum of 5-6 bounces until it will go out of sight. I put the value of 10 in the refraction depth after testing the render, calculating the vases and stones requires more depth than I expected. It turned out to be higher than expected, because the refracted light also goes on the reflective floor. Diffuse depth indicates interaction with non-transparent objects and the strength of subsurface scattering. The optimal value here is 4. There are no glossy or illuminating materials in the project. I left glossy and glossy refraction at minimum. The general value of ray depth is set on ten according to the maximum value among all. The light source is relatively big, so the shadows are not going to be strong and contrasting. The value of 2 is enough for this scene.

All other settings are left on default. Anti-aliasing is a technique used in image processing to smooth jagged lines by blending color with surrounding pixels (Brad West, 2004). I increased this value to have less noise in the result. The

filter menu allows choosing which method should be used in the anti-aliasing process. Firefly filter prevents overexposed pixels that can appear during the ray tracing process. Instead of progressive rendering in the preview mode, it is better to use the bucket technic. It divides the picture into several squares and renders them one by one. It is used not to overload video memory of graphics card. Otherwise, the resolution is too high for progressive technic which captures the whole picture.

These were finishing touches before launching the rendering process. As an intermediate result, it is worth mentioning that adjusting the render settings does not start at the very end. Constantly checking and optimizing settings during the workflow is vital. The preview mode helps to configure materials and create the desired lighting correctly. Optimized settings can reduce rendering times gradually. The one-unit difference in ray depth values can play a decisive role not only in the quality of the picture, but also in the time spent.

3.5 Compositing

Rendered images are already look great and realistic. The purpose of compositing is to add some color correction layers and denoising. Adobe Photoshop CC 2019 allows significantly change the photos look, it is a software with huge variety of tools, that is why it is my program of choice. If I worked with animation sequence, I would choose Adobe After Effects, it is video oriented and allows to do similar things as in Photoshop or even more. The main things changed in renders is a bit shifted color gamma, contrast, exposure and saturation.

4 CONCLUSIONS

Finalizing the theory part, some trends can be indicated in the 3D production. The first trend that can be distinguished is the rising accessibility of technologies. Consumer workstations become more and more powerful and reached the point when it became possible to create complex graphics and render them locally. The price of powerful top-tier hardware is declining on the secondary market. On

the other hand, recent GPUs with the latest ray tracing technologies remain in the premium segment, but over the next few years, innovation will become commonplace, as it always happens.

On the software side, the situation is more complicated. Most of professional 3D modeling and rendering software cost unreasonable money for individuals. It focuses more on enterprise use. However, all major software has trials and student licenses for free (e.g. Autodesk) or with a huge discount (e.g. Maxon Cinema 4D). There is also free license software on the market. The largest and most popular 3D modeling program in the world is Blender. The main trend on the market is that more and more solutions switch to the subscription-based model, for example, Adobe Creative Cloud, which is somehow more convenient for those who stuck to echo-system and, at the same time, becomes an obstacle for those who need a full version without any updates and add-ons.

The next clear trend which is happening now is spreading across different fields and areas of life. Real-time ray tracing will allow creating even more immersive virtual reality (VR) experience. Recent physically accurate rendering techniques will evolve and rendering time will be constantly reducing. Complex 3D compositions are capturing the world of advertisement and marketing as a whole. Small business can afford motion design services in local production studios and marketing agencies for affordable price.

As the main result of the theory part, I discovered that learning 3D is accessible. Countless literature, articles, video tutorials and courses are available online and for free. It indicates that more and more users are working in the field, not only corporate studios. Accessibility also means that the software is affordable thanks to various student licenses free programs. It proves my proposition that almost everybody can start creating without any special background and skills.

In the practical part, the main goal was to create a project in a physically based workflow and get photorealistic results. Initially, the idea was to create a video, but after analyzing my previous projects I decided to create a series of images.

Rendering of video would take a long time that I could not afford. A single image file of the project took about 3 hours on average. For comparison, a 30 seconds video with 24 frames per second would take 90 days. The final results look photorealistic and highly detailed (see Appendix 1). I can rate the results as positive. Implementing the technics and using terms from the theory study directly influenced the result and became another proof of the stated goal.

The last conclusion that can be made is that the rendering process is resource-intensive. This aspect should always be considered during the work. Optimizing materials, lighting, saving physics simulations in cache reduces rendering times. This is the main challenge for beginners who have weak hardware. On the other hand, there is plenty of online rendering services that can complete any task in a matter of minutes.

5 REFERENCES

Alex Alderson, 2019. AMD and Microsoft are bringing hardware ray-tracing to the masses with the Xbox Scarlett. WWW document. Available at: https://www.notebookcheck.net/AMD-and-Microsoft-are-bringing-hardware-ray-tracing-to-the-masses-with-the-Xbox-Scarlett.434675.0.html
[Accessed 18 November 2019]

Allison Thiago, 2019. Render - Residência Y/A/O/ Octane architect & design. https://www.behance.net/gallery/82859101/Render-Residencia-YAO-Octane-architect-design
[Accessed 20 October 2019]

Apple Inc. 2019. Metal API. WWW document. Available at: https://developer.apple.com/metal/
[Accessed on 20 November 2019]

Autodesk Inc. Arnold render,Ambient Occlusion. JPEG image. Available at: https://docs.arnoldrenderer.com/display/AFMUG/Ambient+Occlusion
[Accessed 19 October 2019]

Brad West, 2004. Understanding Antialiasing and Transparency. WWW document. Available at: https://lunaloca.com/tutorials/antialiasing/
[Accessed 3 December 2019]

CG VIZ Studio, 2018. Biased vs. Unbiased Rendering Engine. WWW document. Available at: https://www.cgvizstudio.com/biased-vs-unbiased-rendering-engine/
[Accessed on 21 October 2019]

C4D Center, 2019. How to setup PBR texture maps in the Cinema 4D Material editor. WWW document. Available at: https://c4dcenter.com/about-texture-maps/
[Accessed on 22 October 2019]

Garrett Byrum, 2018. Volvo S90. JPEG file. Available at: https://www.behance.net/gallery/61954941/Volvo-S90
[Accessed on 22 October 2019]

Gleb Alexandrov, 2015. How you expose the light by capturing it?. JPEG file. Available at: creativeshrimp.com/translucent-grass-lighting-tutorial-book-07.html
[Accessed 21 October 2019]

Grand View Research Inc. 2019. 3D Animation Market Size, Share & Trends Analysis Report June 2019. WWW document. Available at: https://www.grandviewresearch.com/industry-analysis/3d-animation-market
[Accessed 10 October 2019]

Greenberg, Donald P., 1999. A framework for realistic image synthesis. PDF document. Available at: https://www.cis.rit.edu/people/faculty/ferwerda/publications/framewrk.pdf

[Accessed 3 December 2019]

Greg Blue. Lighting theory. Shadow edges. JPEG file. Available at: http://bluesky.photo/tutorials/lighting-theory-8/
[Accessed 19 October 2019]

Huamin Wang, 2016. Texture mapping. PDF document. Available at: http://web.cse.ohio-state.edu/~wang.3602/courses/cse5542-2013-spring/15-texture.pdf
[Accessed 20 November 2019]

James Gurney, 2010. Example of how color reflects onto other objects. JPEG image. Available at: http://gurneyjourney.blogspot.com/2010/05/color-bleeding.html
[Accessed 19 October 2019]

Jett Mottle, 2019. Architectural Visualization Rendering Engine Survey Results. WWW document. Available at: http://www.cgarchitect.com/2019/03/2019-architectural-visualization-rendering-engine-survey---results
[Accessed on 24 October 2019]

John Hart, 2002. Rendering Algorithms. PDF document. Available at: https://www.csee.umbc.edu/~olano/s2005c37/ch08.pdf
[Accessed on 10 October 2019]

Josh Petty, 2019.Textures vs Materials in 3D Graphics (A Complete Guide For Beginners). WWW document. Available at: https://conceptartempire.com/3d-textures-vs-materials/
[Accessed on 22 October 2019]

Leonardo Carvalho Vieira, 2017. “Beautiful, Strange”. JPEG file. Available at: https://www.behance.net/gallery/58300597/Beautiful-Strange
[Accessed on 20 October 2019]

Matt Pharr, Wenzel Jakob, Greg Humphreys. 2018. Physically Based Rendering: From Theory to Implementation by Matt Pharr, Wenzel Jakob, Greg Humphreys. E-book. Available at: http://www.pbr-book.org/
[Accessed 20 October 2019]

Michele Yamazaki, 2019. In depth: 3D Renderers. Available at: https://www.toolfarm.com/tutorial/in_depth_3d_renderers/
[Accessed on 20 October 2019]

Monte Carlo Global Illumination. WWW document. Available at: https://www.clarissewiki.com/3.6/global_illumination.html
[Accessed on 20 October 2019]

Nannette Salvaggio,2009. Basic Photographics Materials and Processes. E-book. Available at:

https://books.google.fi/books?id=71uE_OrGw5oC&pg=PA110&redir_esc=y#v=onepage&q&f=false
[Accessed 3 December 2019]

Pluralsight, 2014. Eliminate texture confusion: Bump, Normal and Displacement maps. WWW document. Available at: https://www.pluralsight.com/blog/film-games/bump-normal-and-displacement-maps
[Accessed on 23 October 2019]

Peter Rubin, 2019. Exclusive: A Deeper Look at the Playstation 5. WWW document. Available at: https://www.wired.com/story/exclusive-playstation-5/
[Accessed 18 November 2019]

Richard Lyon, 1993. Phong Shading Reformulation for Hardware Renderer Simplification. PDF document. Available at:
http://dicklyon.com/tech/Graphics/Phong_TR-Lyon.pdf
[Accessed on 20 November 2019]

Robert L. Cook, 1981. A Reflectance Model for Computer Graphics. PDF document. Available at:
http://inst.eecs.berkeley.edu/~cs283/sp13/lectures/cookpaper.pdf
[Accessed 15 November 2019]

Rubidium Wu, 2019. The advantages of hard light and the benefits of using it on set. JPEG file. Available at: https://www.premiumbeat.com/blog/working-with-hard-light-on-set/
[Accessed 19 October 2019]

Scott Robertson, 2014. How to Render. Culver City, CA, USA: Design Studio Press.

Techopedia Inc. 2019. Rasterization. WWW document. Available at:
https://www.techopedia.com/definition/13169/rasterization
[Accessed on 20 October 2019]

Techopedia Inc. 2019. What is Rendering?. WWW document. Available at:
https://www.techopedia.com/definition/9163/rendering
[Accessed on 20 October 2019]

Texture Haven. Wooden planks texture. JPEG image. Available at:
https://texturehaven.com/tex/?t=planks_brown_10
[Accessed on 23 October 2019]

Tomshine, 2019. Table Lamp. JPEG image. Available at:
https://www.amazon.com/Tomshine-Bedside-Minimalist-Nightlight-Bedrooms/dp/B077TQWSNY
[Accessed 3 December 2019]

Unknown author, 2007. Hospital corridor. JPEG file. Available at:
https://commons.wikimedia.org/wiki/File:Hospital_corridor_2.jpg

[Accessed on 23 October 2019]

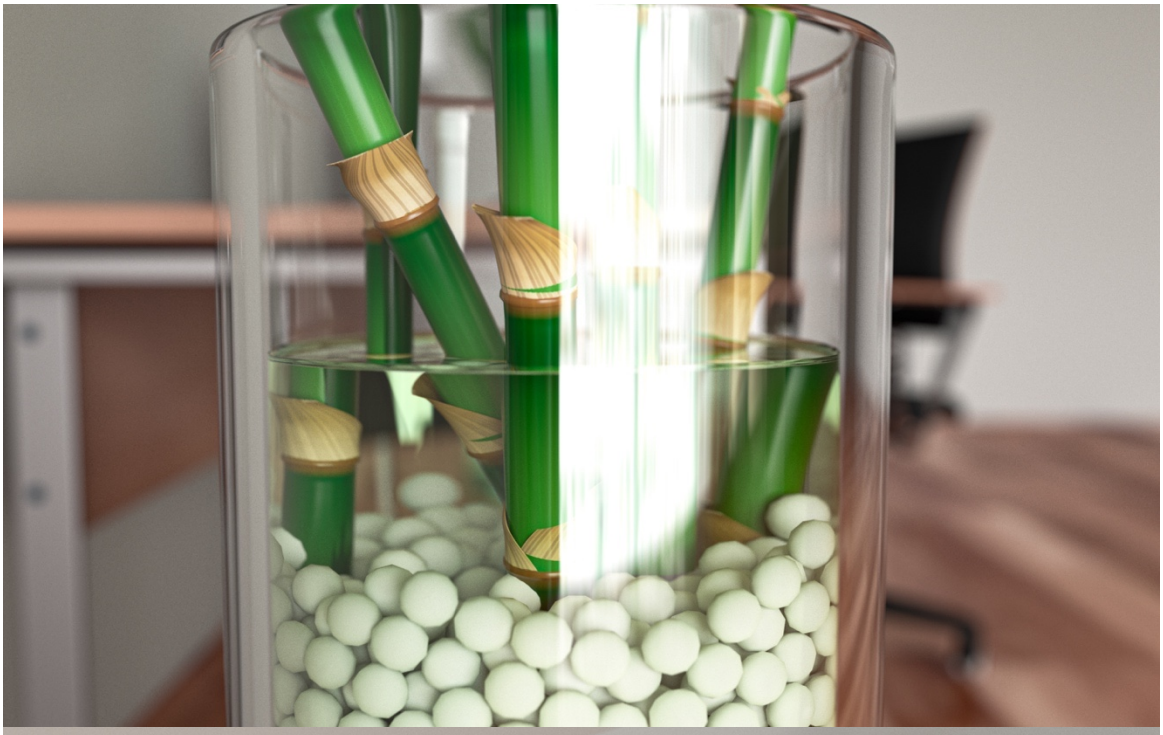
Vadim Morozov, 2019. iPhone. WWW document. Available at: https://www.behance.net/gallery/88229281/iPhone [Accessed 25 November 2019]

Vadim Morozov, 2019. Bullets. WWW document. Available at: https://www.behance.net/gallery/87377677/BULLETS [Accessed 3 December 2019]

Appendix 1/1

FINAL RENDERED IMAGES

Appendix 1/2

Appendix 1/3

Appendix 1/4