

5-2018

An Investigation, Development, and Application of Lighting Design for Virtual Reality using Unreal Engine

Sarah Lydia Ann Martin
Clemson University, martinsarahla@gmail.com

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses

Recommended Citation

Martin, Sarah Lydia Ann, "An Investigation, Development, and Application of Lighting Design for Virtual Reality using Unreal Engine" (2018). *All Theses*. 2863.
https://tigerprints.clemson.edu/all_theses/2863

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

AN INVESTIGATION, DEVELOPMENT, AND APPLICATION
OF LIGHTING DESIGN FOR VIRTUAL REALITY USING
UNREAL ENGINE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Fine Arts
Digital Production Arts

by
Sarah Lydia Ann Martin
May 2018

Accepted by:
Dr. Eric Patterson, Committee Chair
Dr. Brian Malloy
Mr. Anthony Penna

Abstract

Humanity has used lighting for millennia to chase away encroaching darkness, to increase the power of narrative, and to enhance the appeal and mood in crafted environments. Theater, cinema, and architecture, among other fields, have developed, applied, and refined concepts of using light as a directed tool, but the relatively young field of virtual reality has not yet developed rigorous conventions. This thesis document describes work in investigating, developing, and applying designs for lighting conventions in virtual reality. Traditional artwork, photography, cinema, video-game, and environment lighting are considered and used to extrapolate concepts for lighting within virtual-reality applications. The developed concepts are used to design and light an immersive visual narrative implemented as a virtual-reality experience within Unreal Engine 4.

Dedication

I would like to dedicate the following thesis document to all the wonderful artists who have inspired me throughout my life, and none more so, than Sir Terry Pratchett. His body of work fueled the fire within me to become a storyteller, and I will never be able to truly thank him for sharing his talent with the world. But thank you, sir, thank you from the bottom of my heart.

To my Mom, your endless love and support has encouraged me to always pursue my dreams. You have been my rock and source of comfort through my whole life and my time here at Clemson. Your compassion and care have helped me overcome some tough times and kept me going forward. Thank you, Mom. I love you.

Lastly, to BTS. I cannot begin to explain the impact your music has had on my life. Your music has comforted me when I was lost and picked me up when I had no will left to stand. I would not have made it this far without your powerful and encouraging music. Thank you for walking with me in this most beautiful moment of my life. ARMY, now and always.

Acknowledgements

I would like to thank Dr. Eric Patterson for his dedication and feedback which was truly invaluable in the making of this thesis. I would also like to thank him for being the catalyst to pursue a M.F.A. degree here at Clemson. I would like to thank Dr. Brian Malloy and Mr. Anthony Penna for agreeing to be on my committee and for their encouragement during my time at Clemson. And a thanks to all the professors I have studied with and who gave me their time during my graduate pursuits.

A special thanks to Paul DeBaun and Alex Young for creating *Journey to Proxima Centauri: Terror of the Mnar*, all their hard work in making the experience the best it could be, and for entrusting me with the lighting design!

Thank you to all my fellow graduate students. You are a wonderful and special bunch, and it was an honor to work with each of you. Good luck for the future!

A very special thank you to the Occupational Therapists and staff of Excel Rehab and Sports in Clemson, specifically, Doug Lauber, Brice Woodberry, and Rebekah McDaniel. Your compassion and dedication during my care at your facility was instrumental in keeping me up and going towards my dreams. Thank you for everything!

And lastly, I would like to thank my family for their encouragement and support over the last few years. Being away from them was tough, but they were always there when I needed them. Mom, Sarah, Andrew, Jerry, Titus, and Dad, thank you!

Table of Contents

Title Page	i
Abstract	ii
Dedication	iii
Acknowledgments	iv
List of Figures	vii
1 Introduction	1
2 Background	3
2.1 Drawing, Painting, and Photography	3
2.2 Lighting for Theater	4
2.3 Lighting for Cinema	7
2.4 Lighting for Video Games	9
2.5 Architectural and Environment Lighting	11
2.6 Analyzing Reference Images	12
3 Previous Work	14
3.1 Lighting for Virtual Reality	14
3.2 Lighting Analysis of Previous VR Experiences	16
3.3 Lighting Analysis of <i>Allumette</i>	17
3.4 Lighting Analysis of <i>The Waltz of the Wizard</i>	20
3.5 Lighting Analysis of <i>The Gallery: Call of the Starseed</i>	25
3.6 Analysis: Lessons Learned	30
4 Design Plan for Lighting in VR	31
4.1 Design Plan	31
4.2 Script Analysis	37
5 Production Details & Application of Design Plan	44
5.1 Making of <i>Journey to Proxima Centauri: Terror of the Mnar</i>	44

5.2	Lighting the <i>Mezzanine</i>	46
5.3	Lighting the <i>Swiss Cheese Room</i>	56
5.4	Lighting the <i>Crystal Garden</i>	67
6	Conclusion	76
	Bibliography	83

List of Figures

2.1	<i>McCandless Method</i> Illustration [20]	5
3.1	Banner for Penrose Studio’s VR Experience <i>Allumette</i> [17]	17
3.2	Setting of <i>Allumette</i> in Daylight [17]	18
3.3	Setting of <i>Allumette</i> at Night [17]	19
3.4	Still from <i>Waltz of the Wizard</i> [3]	20
3.5	Tutorial Road of <i>Waltz of the Wizard</i> [3]	21
3.6	Workshop mixing orange and blue lights. [3]	22
3.7	Brazier lights with little falloff. [3]	22
3.8	Lantern light does not affect GI on nearby walls. [3]	23
3.9	Chess pieces and board receiving no ground shadows. [3]	24
3.10	Promotional still from <i>The Gallery: Call of the Starseed</i> [5]	25
3.11	No player-based illumination on the rockface. [5]	26
3.12	Player-based illumination from the candle on the rockface. [5]	26
3.13	No shadow is cast on the ground from the log [5]	27
3.14	No light from the Lighthouse is hitting the boat. [5]	28
3.15	The lighthouse shines on the top of the boat. [5]	28
3.16	Moonlight light beam shining down through an opening. [5]	29
4.1	<i>7 Dwarf’s Mine Train</i> at Disney World [12]	35
4.2	<i>Radiator Springs Racers</i> at Disney’s California Adventure Park [9]	35
4.3	Initial Script Musings #1	37
4.4	Initial Script Musings #2	37
4.5	Initial Script Musings #3	37
4.6	Initial Script Musings #4	37
4.7	Initial Script Musings #5	38
4.8	Initial Script Musings #6	38
4.9	Initial Script Musings #7	38
4.10	Initial Script Musings #8	38
4.11	Initial Script Musings #9	39
4.12	Initial Script Musings #10	39
4.13	Initial Script Musings #11	39
4.14	Initial Script Musings #12	39
4.15	Initial Script Musings #13	40

4.16	Initial Script Musings #14	40
4.17	Initial Script Musings #15	40
4.18	Initial Script Musings #16	40
4.19	Initial Script Musings #17	41
4.20	Initial Script Musings #18	41
4.21	Initial Script Musings #19	41
4.22	Initial Script Musings #20	41
4.23	Initial Script Musings #21	42
5.1	<i>Ice Temple</i> concept art from <i>Uncharted 2: Among Thieves</i> [10]	46
5.2	<i>Under the Ice</i> concept art from Gaan [4]	47
5.3	<i>Mezzanine's</i> Interior Lake - Greyscale	48
5.4	<i>Mezzanine's</i> Interior Lake - Final	48
5.5	<i>Mezzanine's</i> Upper Level - Greyscale	50
5.6	<i>Mezzanine's</i> Upper Level - Final	50
5.7	<i>Mezzanine's</i> Lower Level - Greyscale	51
5.8	<i>Mezzanine's</i> Lower Level - Final	52
5.9	The <i>Engineer</i> - Greyscale	53
5.10	The <i>Engineer</i> - Final	53
5.11	Abandoned Robot - Greyscale	54
5.12	Abandoned Robot - Final	54
5.13	Colors of the <i>Mezzanine</i> shift an ominous red while the <i>Temple Guardian</i> is near.	55
5.14	Underground mine passage with rails and light [18]	56
5.15	Bright whimsical colors light up the <i>Sorek Cave</i> [19]	57
5.16	<i>7 Dwarf's Mine Train</i> at Disney World [12]	58
5.17	Deep blues and oranges mix in the <i>Reed Flute Cave</i> [23]	58
5.18	Greyscale lighting of <i>Swiss Cheese Room</i>	59
5.19	<i>Swiss Cheese Room</i> - Greyscale 1	60
5.20	<i>Swiss Cheese Room</i> - Greyscale 2	60
5.21	<i>Swiss Cheese Room</i> - Greyscale 3	60
5.22	<i>Swiss Cheese Room</i> - Greyscale 4	60
5.23	A single, bright spotlight aids the nighttime workers [22]	61
5.24	<i>Cave Concept</i> by Nele-Diel [1]	62
5.25	No bounce lighting around mouth of the cave	63
5.26	Finely crafted bounce lighting around the mouth of the cave	63
5.27	<i>Temple Guardian's</i> shadow cast on tunnel wall	64
5.28	Moonlight filtered into <i>Abandoned Equipment Room</i>	64
5.29	<i>7 Dwarf's Mine Train</i> at Disney World [12]	65
5.30	Points of interest contained within spotlights - broken car	66
5.31	Points of interest contained within spotlights - scattered equipment	66

5.32	Points of interest contained within spotlights - abandoned equipment	67
5.33	Interior of the central hall of <i>Palacio Guell</i> [15]	69
5.34	Final implementation of <i>Palacio Guell</i> ceiling lights	70
5.35	Faerie Lights - Greyscale	71
5.36	Vast cavern which houses the rock bridge	71
5.37	Skylight built with a deep saturated blue	72
5.38	Skylight built with a warm orange color	73
5.39	Shimmering, golden lit Shrine	74
5.40	Lighting shift when <i>Temple Guardian</i> Attacks	74
5.41	Lighting shift when <i>Temple Guardian</i> Attacks	75
6.1	Lower <i>Mezzanine</i> Final Render 1	77
6.2	Upper <i>Mezzanine</i> Final Render 1	78
6.3	Upper <i>Mezzanine</i> Final Render 2	78
6.4	Upper <i>Mezzanine</i> Final Render 2	79
6.5	<i>Swiss Cheese Room</i> Final Render	80
6.6	<i>Swiss Cheese Room</i> Final Render	80
6.7	<i>Abandoned Equipment Room</i> Final Render 1	81
6.8	<i>Abandoned Equipment Room</i> Final Render 2	81

Chapter 1

Introduction

“Our lives are intimately bound up with light” [15]. Light is everywhere. From the moment your eyes open in the morning until you fall asleep at night, light colors your perception of the very world we live in. Light is elegant and powerful and, when wielded correctly, no matter the medium, light can help tell a deep, emotional narrative. The concept of lighting for narrative has been of interest to me for many years. I have learned to analyze what makes lighting successful and how it can truly drive home the theme of a story or enhance a moment whether quiet and still or loud and bright.

Lighting provides an important function in every medium. Light affects how we feel about a given environment and how we perceive a painting or a movie. Lighting can also vary depending on locations and function. For instance, mosques in Istanbul tend to be dark and bathed in cool colors to offset the hot and bright conditions outdoors and churches in cold climates often employ warm tones to comfort worshipers from the chilly atmosphere [11].

Lighting for video games provides some unique challenges not often found in films. The audience, or the player in the case of games, is not usually bound by the

camera set up by the director, except in the case of in-game cinematics. A stage is built by the developers for the player to explore. The role of the lighting artist then becomes not only to create a mood and provide emphasis but also to guide the player through the level. This can be as simple as providing points of firelight on a dark night for the player to follow or as complex as an illuminated cityscape with vivid colors and bright lights all fighting for the player's attention. Creators of video games have worked to strive for better lighting capabilities since the creation of the art form.

Virtual Reality, as a medium, has many influences from game development but goes much further in terms of player viewing and immersion capabilities, thus affecting the design and application of lighting. VR has much potential for storytelling, but it is still in early development. In this thesis document, I will discuss lighting for previous mediums in Chapter 2. Chapter 3 covers work that been done with lighting for VR as I analyze the lighting of several VR Experiences. Then Chapter 4 lays out my compiled guidelines for lighting in VR, and Chapter 5 discusses my work to apply those rules in a unique, VR experience. Chapter 6 summarizes my findings, discusses certain challenges, and offers a reflective critique of my work from Chapter 5. Overall, I hope to unlock some greater capacity for lighting in a VR experiences that helps shape and mold a narrative to be as impactful as possible.

Chapter 2

Background

2.1 Drawing, Painting, and Photography

Two-dimensional art forms have existed for a long time as humanity's attempt to encapsulate events with more potency than the written word could depict. Eventually, this form of expression developed an artistic sophistication and generations of men and woman drew and painted a variety of subjects in an untold amount of styles from realism to impressionism and everything in between. Many have studied what makes a successful rendering of a subject, and there are many defined conventions that aim to achieve this goal from composition to use of contrast. Contrast plays one of the biggest roles as an element to express lighting in a two-dimensional medium. A subject bathed in light with a dim surrounding draws the viewer's eyes to the subject because our eyes are excited by change in contrast and want the linger in areas of contrast instead of quickly glancing over an image [7]. Color contrast also works to pull the viewer's attention. Warm colors atop cool colors work best to bring attention and appeal to an area of an image, for instance, a bright red dress against a less saturated blue will be immediately noticed [7]. In black and white photography,

contrast works, once again, to guide the eye through a piece.

Keys for successful rendering of light in traditional mediums:

1. Contrast in Tone/Light over Dark
2. Contrast in color/Warm vs Cool
3. Placement of contrast in harmony with composition

2.2 Lighting for Theater

One of the first media to incorporate light as an element for dramatic affect was theater. The stage is typically partitioned into acting areas and lights are positioned to bathe each area, using one or more fixtures. The lights of each acting area rise and fall as the story demands. The position, angle, and color of the light is designed to fulfill the mood of the scene as dictated by the script. According to the book, *Scene Design and Stage Lighting* by R. Craig Wolf and Dick Block, in theater, the script is key and should be studied intensely to determine the most effective lighting setup [25].

Stanley McCandless, a pioneer of theatrical lighting, devised a system for lighting the acting areas of the stage, known today as the McCandless method, published in his book *A Method of Lighting the Stage* [13]. McCandless states that lights should provide adequate light to illuminate the entire acting area first, then tweaks can be made. Otherwise, there will not be enough flexibility for the lighting design. This approach will also simplify the amount of lights needed. McCandless goes on to state that lights should be positioned carefully. A light too high or too low runs the risk of casting unsightly shadows on the subject. On the other hand, lighting the subject straight on will lose the subject's form. Therefore, McCandless discovered the best

way to light a subject was with the use of a light offset from the subject by 45 degrees to the left or right and 45 degrees up [13]. A secondary 45-degree light is then added opposite to fill in the shadows created on the subject by the first light. Figure 2.1 illustrates this method.

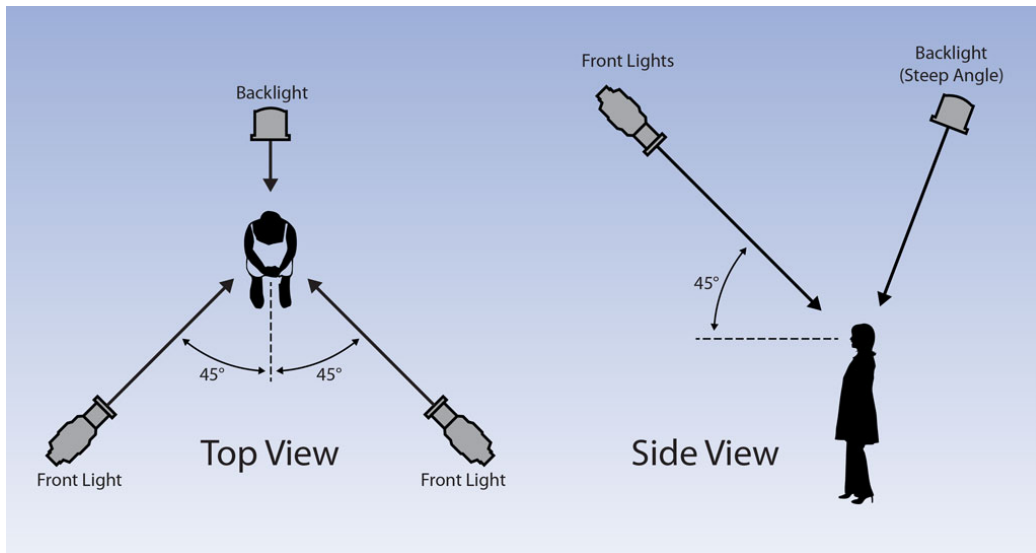


Figure 2.1: *McCandless Method* Illustration [20]

However, if both lights are matching in intensity and color, they will, one again, wash out the subject's form because of reduced shading, a cue to our visual perception of form. Therefore, McCandless says the lights must vary in intensity, and the secondary light should be the complementary color of the primary light [13].

Theater lighting is also not hesitant in its use of colored lights, as long as it serves to enhance a dramatic moment or to reinforce depth in the scene [25]. Although the meaning of colors can vary across cultures, the warmth or coolness of a light often has more universal connotation [25]. For instance, cool blue is often associated with a feeling of cold even across cultures.

In the evolution of visual narrative, theater added the element of time. Pre-

viously, traditional arts were the only form of visual narrative but were limited, typically, in showing a static singular moment in time; exceptions would be art forms like cave paintings that showed an event over time. However, in a stage production, a narrative unfolds before an audience, and the lighting may change over the length of the play, even within the length of a scene, as the emotional arc of the story evolves.

In addition, theater does not always need a motivated light source, such as the sun or a table lamp. If a practical light source is available, then it can be used but, in many cases, lighting is simply designed to create the best possible look on stage. Ideas on how to light the actors and the scenery so the forms are revealed to match the mood and setting are the main considerations. It does not matter if the lights are motivated and, in most cases, the audience suspends their disbelief because a language of how light is portrayed on stage has been established over the long history of the theater.

Movable and textured lighting is an advent of modern theatrical lighting. Gobos can cast patterns across the actors or the environment to create a myriad of different effects and, in some cases, it is acceptable to rotate or shift the pattern as long as it works in tandem with the narrative. As mentioned, the key to any good lighting design for a stage production is the script. A list of considerations taken into account when working on design for a script as outlined in *Scene Design and Stage Lighting* is illustrated below:

1. Script analysis to determine script sensitive lighting cues such as time of day
2. What are the colors, texture, and quality of the scenery
3. The colors and qualities of the costumes
4. Limitations of the theater

5. Budget and time
6. Blocking, focus, and isolation requirements [25]

2.3 Lighting for Cinema

Cinema lighting offers a new element not found in a stage production: lighting for a shot. A lighting designer for the stage must take into account the entirety of the actor and acting space, but a lighting designer for cinema needs to light effectively only what the camera can see. A shot can have a moving camera which will cause a larger area of the set to be illuminated, but often times, a scene is sliced into a series of cuts. In the case of dialogue, the final edit will cut back and forth between the speakers and lighting must account for both actors. However, it is not always necessary to keep the lighting consistent between cuts [11]. The lighting might work well for one actor but falls apart when cut to another. Cinema affords lighting artists the time to stage and light each scene and sometimes each shot. This gives the designer full creative control of each shot in a sequence and lets the director's vision of each image to be meticulously controlled.

Just as in a stage production, a film has a script that must be analyzed to come up with an appropriate lighting set up. Often a logical source of light must be identified first, and even if it is not seen in the shot, there should be an illusion of an off screen source [11]. Three point lighting is common in cinema and consists of a key, fill, and rim light to convey the form of each subject. The key light is typically the brightest of the lights and is the main light source whether on screen or off. The key light often frames the character on the opposite side from the camera to create a more appealing image [11]. The fill light works opposite the key light to lighten the

dark side of the face and infuse shadows with an ambient color. Typically, the key light is brightest and the fill light less bright, sometimes about 25% less bright than the key. Lastly, a rim light is used to pop the character off from the background, providing the audience with a better read of the subject's silhouette.

Lighting designers for theater are able to "light by eye" in the sense that what they see on the stage is exactly what they will get. However, with film, exposure values must be taken into account for the type of camera set up being used to shoot the scene. In addition, the camera sensor on film is usually white balanced to get the appropriate look for a shot once the lights have been placed. Usually any visual aesthetics of the final movie, such as over saturation or de-saturation of colors, is handled after filming by a post processing team who finalizes the look of the film.

Lighting the characters in a shot is important but the environment must also be taken into consideration. There are three planes of lighting when it comes to a composition: the foreground, the acting area, and the background [11]. Each area should be lit according to the needs of the shot and, depending on the framing of the camera, there may or may not be a need to light anything at all. Sometimes it is an artistic choice not to light a foreground or background [11].

A designer of lighting for cinema must also take into account a moving camera. On the stage, a character may walk through one or more acting areas that must be lit, but film adds the challenge of placing lights so they will never be seen by the camera while keeping the character lit through the shot. Lights in a stage production are often hung above the acting area and are out of sight of the audience. To light a scene with a moving camera, usually the ending area is lit first since this is usually the space where most of the action takes place[11]. The rest of the shot is then lit based on how quickly the subject will be moving through the area [11].

Lighting for film requires a Cinematographer or Director of Photography (DP)

to think about each shot and how to light to the camera to paint the best image. It does not matter whether the lighting is completely consistent for each shot within the same scene nor does the light source need to be apparent as long as it makes some logical sense for the scene. Film lighting differs the most from lighting for Virtual Reality because the viewpoint is locked only to what the camera can see and cannot be changed by the viewer. VR must take into account a three dimensional space where the player can potentially view every angle if they so desire.

Summary of Guidelines for Lighting for Cinema:

1. Light for shot
2. Consideration of exposure for depth of field
3. Motivation for key light
4. Fill ratio for desired contrast
5. Rim lighting as style dictates

2.4 Lighting for Video Games

The history of video games has been fraught with contention on whether a game can be seen as art. At the advent of the medium, simple games were made with little aesthetics or artistry, usually due to a lack of computing power. As the industry of gaming has evolved, many artists collaborate together to establish the style of a game, and every care is taken to match that style in each element of the game, resulting in an artistic product created over a number of years by a variety of artists. Lighting for video games has always proved challenging for makers of games and research into developing faster and more efficient lighting calculations has been

intensive. From an artist's perspective, it is critical to be able to control placement, color, and quality of the light, especially when making hyper real games.

Some of the biggest challenges when lighting for video games have and will continue to be limits in hardware because the calculations required to simulate fully dynamic lighting, in real time, are immense. The biggest culprit being a process to calculate indirect lighting and color bleeding called Global Illumination [16]. Unreal's solution to indirect lighting stores light at points in the scene with a sparse volume lightmap which is used to approximate quickly indirect lighting for movable objects, like a character, at run time [6]. For static objects, indirect lighting calculations are pre-computed and built into the texture maps of an object before run time [6]. Though indirect lighting and shadow calculations typically tend to be the biggest loss of performance, they are often what makes or breaks realism. Consoles provide lighting artists with less room to work with than say a computer counter part because consoles provide standardized hardware for all users, sometimes less capable than dedicated graphics hardware. Regardless of the hardware, creating realistic lighting environments must adhere to these limitations.

Another challenge is that while though an audience at the theater can only see what is on stage, or a viewer of a film can only see what is in each frame, a player of a video game, usually, often has agency over the camera. Anywhere the camera can see needs to be lit and rendered accurately.

Lighting for games pulls from traditional sources and implements the use of contrast to draw the player's attention. Methods taken from the three point lighting set up in theater and film are still often applied, especially during cinematic cut scenes. Out of games special ability for players to control what is being viewed and hardware limitations, pipelines and techniques have been created specifically for games.

In a talk from Vivian Ding, a lighting artist, during GDC 2014, she illustrates

the lighting pipeline used to create one of the most visually stunning games: *The Last of Us*. The technique she detailed is outlined below [2]:

1. First Pass: Light environment with a 50% grey texture applied to all surfaces. This allows the lighter to focus solely on shape readability.
2. Second Pass: Add the correct greyscale value to all major surfaces. This grounds objects and lets the lighting artist focus on drawing the player's eye.
3. Third Pass: A lighting pass with hue applied to the surfaces while keeping the same value.
4. Fourth Pass: Final lighting tweaks are made to a fully and correctly surfaced scene.
5. Fifth Pass: A LUT¹ is performed and post correction tweaks are made. This pass is akin to exposure and color grading in film.

2.5 Architectural and Environment Lighting

Virtual reality is a fusion of traditional games and immersive interaction: a space a player walks through and observes with their own eyes. No medium takes into account lighting for a three-dimensional space as well as Architectural Visualization designers. Each element, down to how rooms will be built to catch and redirect natural light, is meticulously designed to provide a pleasing space. Even industrial spaces are designed with certain aesthetic and functional criteria in mind. Lighting for architectural visualization takes into account the space, its function and purposes, and even the environment in which the space exists. Light and the surrounding

¹LUT or Look Up Table is a way of passing color values through a table to change the hue, saturation, and brightness of the value [8].

environment are intimately linked [11]. It takes effort and planning to separate natural light from the effects of place, weather, and time of day. Light filtered down through a dense, dark green canopy of trees possesses a distinctly different quality in both color and intensity than light reflecting off of white, sandy beaches [11].

Designers of architectural spaces take this environment into account and in some cases use the landscape's natural light to spill into a space, or present the opposite by designing a space to reflect a different place than the outside would suggest. Light can also be used to reveal the contents of the space, separating or combining areas of space [11]. Just as a stage lighting designer places lights to reveal the form of an actor, a designer of architectural space can also reveal the shapes of the space with both natural and artificial light.

Key Guidelines for Architectural/Environment Lighting:

1. Functions of the space: What purpose does the space serve and how should the lighting reflect that function. Some considerations of how to reflect function could be use of color to elicit a mood and lighting to emphasize different spaces.
2. Account for exterior environment: Use or abate natural light as necessary.

2.6 Analyzing Reference Images

Reference images are often generated or found for any production. A lecture given by Tilmann Milde describes a process used to analyze reference or inspiration images and is outlined below [14]:

1. Analyze reference images to define criteria to achieve an established look in a reference image
2. Determine saturated or muted color palette

3. Determine if high or low contrast
4. Is light over dark used or dark over light?
5. Determine if light color is cool or warm and what hints of contrast in light color are used to draw the eye

Some of the above criteria are implemented as described in Chapter 4 when the design plan for the VR experience is discussed.

Chapter 3

Previous Work

3.1 Lighting for Virtual Reality

Lighting for Virtual Reality (VR) works somewhat similarly to its counterpart, video games. Both have constraints placed on the mediums by the real time capabilities of the rig used to render the game or VR scene based on accuracy of indirect lighting and shadows. Whereas in traditional animation, as long as complete rendering can be done by a deadline, there is no limit on the quality or number of assets in the scene because it only relies on the time equivalent for the computer to generate frames. These can be then played back as a movie.

VR and games must take into account these constraints that can vary vastly across platforms. Where things become trickier, when it comes to VR over gaming, is when frame rates drop to low levels in a game, the performance may take a hit, temporarily lagging or stuttering the image; but frame rate drops in VR can cause extreme user discomfort or nausea that should be avoided even more carefully [24]. The second challenge in VR is: what the player can see. A typical game can avoid rendering certain areas of a scene simply based on the fact that the camera can never

see them. If a player cannot bend down and look inside a dog house, there is no need to light or render the back of the doghouse. This is completely shattered in VR, as the player in the headset can lie flat on the floor, if they wish, and see all the little things the developers tried to hide [24]. So, when working in VR, it is important to figure out what the player can see at given any moment and light appropriately.

Another issue that can arise is a player not looking where the developers want them to look. A game can force the camera to lock or run a cut scene to grab the player's attention, but in a VR world, it will become very uncomfortable for the agency of the viewport to be taken from the player, therefore, lighting must effectively communicate to the player where he/she needs to be looking at any given time [24]. This can be challenging for a few reasons: dynamic lighting can cause serious performance issues and using only baked lighting can limit the effect of lighting in cinematic instances. Many techniques have been developed to calculate better quality indirect lighting, in real time, for lower costs. One such technique is Screen Space Ambient Occlusion (SSAO). SSAO does not rely on pre-computed values to simulate indirect lighting, instead a randomly rotated kernel is used to sample and analyze the depth buffer and determine the occlusion of objects per pixel [21]. Since running this calculation for every pixel is too time intensive for real time rendering, a sample is taken at some pre-determined interval and the final result is blurred to reduce noise [21]. However, for purposes of the project discussed in Chapter 5, SSAO in Unreal Engine 4 was turned off to increase performance and meet the required 90 frames-per-second and reliance on a sparse volume lightmap for indirect lighting on movable objects was chosen instead in order to maintain higher frame rates for viewer comfort.

Shadows play an important role in spatial awareness. Shadows can show if an object is floating or secured safely on the ground. In games it needs to be de-

cided which objects receive dynamic shadows and which do not. Shadows for non-movable/non-interactable objects can be baked into the light map, but to insure realism, certain objects must cast shadows. For instance, the player pawn's shadow on the ground or any object that needs to be shadowed by another object as it moves behind the object should cast a visible shadow for realism.

3.2 Lighting Analysis of Previous VR Experiences

The following sections consider three Virtual Reality experiences and analyzes the technical aspect of the lighting design for each as well as how the lighting conveys the mood and themes of the narrative. Each experience was chosen for a different reason. *Allumette* was selected for its narrative, one where the guest is a passive viewer and not directly in control of any of the story's events. *Waltz of the Wizard* was chosen, not for its narrative, but for its colorful lighting design, a design element decided for the VR Experience, discussed further in Chapter 5, based on simulating lighting designs of rides at Disneyland. Finally, *The Gallery - Episode 1: Call of the Starseed* was selected for its more realistic graphics and lighting as well as its more developed narrative.

3.3 Lighting Analysis of *Allumette*



Figure 3.1: Banner for Penrose Studio's VR Experience *Allumette* [17]

Allumette is a short VR narrative experience made by PenRose Studios and is based on the story *The Little Match Girl* by Hans Christian Anderson. *Allumette* tells the story of a little girl, alone at night, who relives a set of memories by striking matches. The memories take place on a sunny afternoon in a quaint, floating, Italianesque city in the clouds which is contrasted by *Allumette*'s current reality set in the same village on a dark moonlit night.

The lighting for *Allumette* comes primarily from two sources, the sun and the moon. A single light, most likely a spot light, provides shadows for the characters in the main acting area, during both the day and the night. The bounds of the light casting the shadows in the daytime are limited because a secondary character walks further away from the main acting area and loses his ground shadow. The daytime is brightly lit (Figure 3.2) with pale purple tinted shadows, and the rest of the tiny

village is evenly lit, creating an open, friendly world where Allumette and her mother sell giant, colorful matchsticks. The lighting is simple, but it doesn't need to be complex to set a mood for the unfolding narrative.



Figure 3.2: Setting of *Allumette* in Daylight [17]

The night scenes, where Allumette is alone, are more subtly lit (Figure 3.3). The surrounding village is lit with flat ambient light with the occasional, animated bright spot slowly fading in and out on some of the buildings, and the acting area is bathed in a spotlight, simulating moonlight, to focus the viewer's eye and give Allumette a sense of isolation and loneliness, trapped in her small pool of light. The only other light sources are the matchsticks themselves which Allumette uses to light up the dark and relive happier and sadder times in her past. These matchsticks are vibrantly colored and temporarily wash the cool night tones in vibrant hues. From a technical standpoint, the lights appear not to cast shadows, indicating either a stationary or movable light with cast shadows turned off. From a narrative standpoint,

they function as significant moments in Allumette's past and act to connect her to another person towards the end of the narrative.

The themes of *Allumette* revolve around the loss of her mother and her coming-of-age as she struggles to deal with what comes next in her life. The brightly lit daytime memories make Allumette feel safe and happy which is contrasted by the cool night scenes which make Allumette feel lost and alone now that her mother is gone. The matchsticks teleport Allumette back to the warmth of daylight and infuse the nighttime darkness with small sparks of bright, colorful light. In the end, Allumette gives this light to another cold, lost soul under the bridge and, in doing so, finds her mother, probably a metaphorical representation of Allumette sharing her compassion and love with another and finding a way to move forward with the memory of her mother.



Figure 3.3: Setting of *Allumette* at Night [17]

It seems the lighting design of *Allumette* draws inspiration from theater, es-

pecially with the close honed, single spotlight in the night scenes as well as the use of colored light for the matches. The whole experience feels like watching a tiny, claymation stage play, and the lighting lends to this effect. The lighting in *Allumette*, though simple, provides a good sense of atmosphere and tone for the experience and enhances the dramatic elements of the story that the creators at PenRose are trying to tell.

3.4 Lighting Analysis of *The Waltz of the Wizard*



Figure 3.4: Still from *Waltz of the Wizard* [3]

The *Waltz of the Wizard* (*Waltz*) is a first person, action adventure, puzzle game by Aldin Dynamics. *Waltz* starts the player off with very little explanation of the narrative as the player creates different spells by combining materials into a cauldron. Very much an action puzzle game, *Waltz* doesn't have an apparent

narrative, and the player is mostly left guessing on the best way to proceed.

The lighting of *Waltz* is colorful and outlandish. Brilliantly lit environments with pockets of vividly tinted lights make up the majority of the game's lighting palette. This heavily stylized game begins by giving the player a brief tutorial on the mechanics of the game which is set on a dark road (Figure 3.4). The main light source, a pale blue that reflects starkly off the surface of the road, is reminiscent of moon light. The areas just off the road fade quickly into darkness, isolating the player.



Figure 3.5: Tutorial Road of *Waltz of the Wizard* [3]

The main hub of the game is an eclectically decorated, workshop. Braziers and lanterns spilling orange/yellow light are the primary source of light. Near the window, blue moonlight mixes with the braziers, casting a purple/pink tint onto the wall (Figure 3.6). One of the levels, a maze-like puzzle, features areas primarily lit by firelight. Some braziers cast light brighter, more evenly, and further away from the

source than would probably be accurate (Figure 3.7).

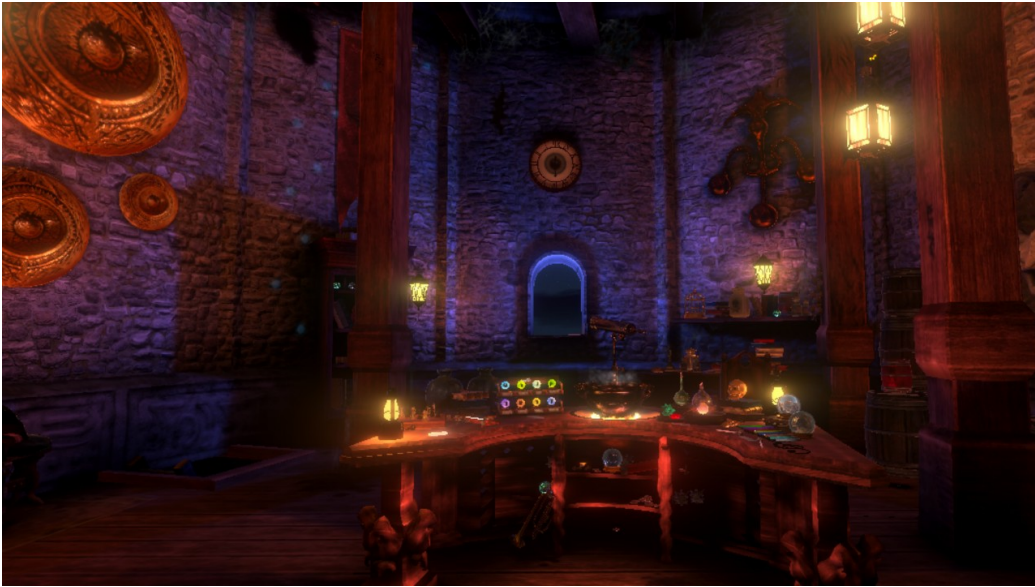


Figure 3.6: Workshop mixing orange and blue lights. [3]



Figure 3.7: Brazier lights with little falloff. [3]

Because of its stylized nature, *Waltz* is able to do some lighting cheats. In one level, there is a hall with a single light source (Figure 3.8), The light casts starkly on the floor, however, the nearby walls are left in almost complete darkness. However, several of the props cast shadows, and I speculate the lack of bounce light is to increase performance so the movable objects can cast ground shadows.

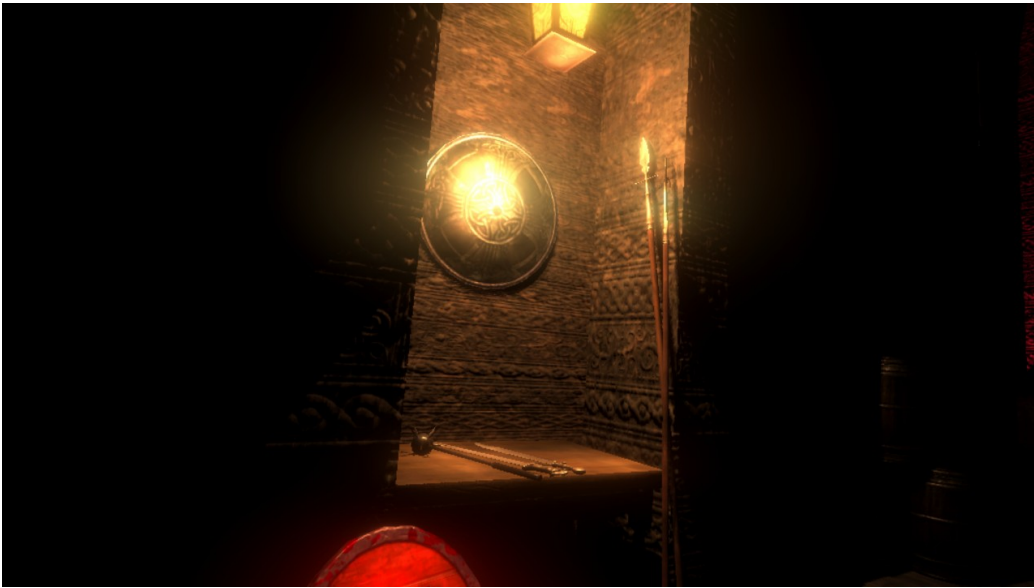


Figure 3.8: Lantern light does not affect GI on nearby walls. [3]

Like many other VR games, *Waltz* does not have ground shadows for most objects. Nearly every inter-actable object in the workshop is not affected by dynamic shadowing (Figure 3.9). The creators carefully pick and choose which items receive dynamic shadows to save on performance.

Since *Waltz of the Wizard* does not have a readily apparent narrative, the experience feels more like a demo for the magic casting elements and the player movement technique implemented in the experience. With no narrative themes to analyze, I will briefly say that the lighting of *Waltz* gives off a whimsical vibe with

its overly saturated colors and heavy use of warmer toned lights. While playing, it felt very reminiscent of Disney's *Fantasia*.



Figure 3.9: Chess pieces and board receiving no ground shadows. [3]

3.5 Lighting Analysis of *The Gallery: Call of the Starseed*



Figure 3.10: Promotional still from *The Gallery: Call of the Starseed* [5]

The Gallery - Episode 1: Call of the Starseed (*Gallery*) is an adventure puzzle game from Cloudhead Game Ltd. Unlike *Waltz of the Wizard* (*Waltz*), *Gallery* is less stylized, opting for more realistic vistas and lighting conditions. The first level takes place on a beach, and the primary light source is the moon (Figure 3.10). Candles and other forms of firelight act as waypoints to guide the player through the world. The aesthetics of *Gallery* are much closer to the VR Experience, *Journey to Proxima Centauri: Terror of the Mnar* (*Journey*), discussed in chapter 4. Both contain cave like landscapes, however *Journey* is lit with both stylized colors and realistic sources, striking a balance of aesthetics somewhere between *Waltz* and *Gallery*.

A nice lighting feature of *Gallery* puts the player in charge of providing their

own source of illumination to navigate dark corridors. Candles, glowsticks, lanterns, and a flashlight are some of the possible light sources available to the player (Figures 3.11 and 3.12). These lights do not cast shadows on every object, save a few, and, in fact, most objects in *Gallery* do not have any dynamic or baked ground shadows, even on non-interactable objects. Figure 3.13 shows this.



Figure 3.11: No player-based illumination on the rockface. [5]



Figure 3.12: Player-based illumination from the candle on the rockface. [5]



Figure 3.13: No shadow is cast on the ground from the log [5]

Journey features baked shadows on most non-movable objects which serves to ground objects and promote realism. I wonder why the makers of *Gallery* chose not to implement baked shadows for these elements. One answer could be performance issues, and another could be the difference between the engine that *Gallery* was made in as opposed to *Journey*. *Gallery* does have dynamic shadowing on the hands and other, game determined, important objects. Some lights cast dynamic lighting on many, if not all, of the world's objects. The lighthouse is one example of this (Figure 3.14 and 3.15).



Figure 3.14: No light from the Lighthouse is hitting the boat. [5]



Figure 3.15: The lighthouse shines on the top of the boat. [5]

The beach scene is well lit using the moon as the primary source and allows left behind objects to fill in shadows and add color. One of the winding caves on the

beach reminded me of an area of *Journey* with its filtered moonlight and light beams. This area in Figure 3.16 is coolly light, leaving dark pockets between each source of light. This gives the tunnel a solemn, lonely feel, and helps to sell the dampness of the walls and floor.



Figure 3.16: Moonlight light beam shining down through an opening. [5]

Gallery pushes the player forward through the narrative in search of player's missing sister, though she is seemingly missing of her own free will. This initial goal, set on the sandy beach, makes the player feel very alone as one has no notion of anyone else inhabiting the beachhead. Dim moonlight is cut through by only the lighthouse. Finding your sister is mirrored in the player's ability to use light sources of their choosing to investigate the dark, unknown spaces. This also seems to isolate the player from the environment. Later in the narrative, it is revealed that there is a power source beneath the beach front that must remain hidden from the USSR, at least according to the eccentric professor you encounter. The theme of fighting for freedom can be applied to the player-based illumination as being a light in the dark

and protecting the power source from those who would misuse and cause strife with its potential power. Overall, *Gallery* is a well crafted VR experience, and the lighting lends a lot to that.

3.6 Analysis: Lessons Learned

I will briefly summarize major takeaways from the analysis of each game. *Allumette's* simple lighting design allows the viewer to focus on the girl's emotional struggle while contributing to the mood of the overall story. This works well to show an example of focusing the viewer's eye to specific areas of a VR experience which is implemented heavily in the experience discussed in Chapters 5 and 6. In *Waltz of the Wizard*, I learned how visually pleasing blending of certain light colors can be as well as how this blending can lead to the creation of a whimsical mood. I also decided that, unlike in *Waltz*, I wanted to create a more physically accurate rendering of light bounce and global illumination in the application of my lighting design. Finally, *Gallery's* lighting showed how to implement more photorealistic lighting conditions while maintaining a very prominent mood and how the use of a few dynamic lights can enhance realism as well as mood.

Chapter 4

Design Plan for Lighting in VR

4.1 Design Plan

Virtual reality poses a unique set of features unlike most other media. A guest is thrust into a new, three dimensional world, sometimes very unlike our own, and given full agency over the camera. The ability for the player to look at any place or object within the playspace requires the need for everything to be lit to some degree or not.

The following section will discuss the key attributes of lighting presented in Chapter 2 and extrapolate how they can be used in Virtual Reality to compile a lighting design plan.

The concept of contrast plays an important role in most lighting designs, to draw the viewer's eye in a painting or to reveal the form of a subject on the stage or screen. Since contrast is a consideration of lighting design across many disciplines, contrast will be one of the key factors of the design plan outlined in this thesis document.

Theater shares some similarities to virtual reality. One similarity is that the

audience can, theoretically, see the entire stage or play space at any given time. With film, the audience is limited to only what the camera shows, and therefore lighting for each scene may not always take into account the full body of the actors or the entirety of the background environment.

Theater also has a boundary, the stage, for the actors to unfold their story before an audience. A virtual playspace also serves to host the main action. Unlike theater, however, the guest in a virtual reality environment has full access to the stage to walk around the actors and the environment, so if a light is hidden behind a couch or an unsightly shadow is cast by an actor from behind the guest can potentially see the tricks used.

Design considerations from *Stage Design and Stage Lighting* are outlined and extrapolated below:

1. The Script
2. The Scenery
3. Budget (11 milliseconds and 90 FPS)
4. Focus (within the playspace/environment) [25]

The script will be analyzed to understand the context of each area of the VR environment and to formulate what areas of the playspace are most relevant at any given moment to focus lights appropriately.

The scenery will be lit secondarily in most cases unless a portion of the scenery is tied to the script and needs special attention. Once again, the script will determine what the environment is and how it should be lit. Any art work generated to visualize the spaces will also be taken into consideration.

The budget in theater refers to physical money as well as the amount of electricity that can be used in the space. I've taken the notion of a budget and applied it to the time and frame requirements for VR. The lighting must not be so taxing that it dips below 90 FPS at any point in time to keep the guest from experience nausea.

Focus is usually created a few ways in video games: motion of characters, lighting, and locking the camera, among others. While we cannot run cut scenes or strip the guest of their agency over the camera, we can utilize motion and lighting to focus the player where they should be looking.

For cinema, the key lighting considerations discussed in Chapter 2 were:

1. Three Point Lighting
2. Lighting for a shot
3. Three planes of lighting
4. Accounting for camera movement [11]

Though a VR experience does not have a fixed point of view, three point lighting can still be implemented in major areas of interest within and outside the playspace. This lighting setup will be considered as part of the lighting design plan, and, in many instances, the world's ambient light may act as a fill and/or rim light. Because the player is in control of the camera, it is not possible to "light for a shot" per se. Lighting must be appropriate for all angles of viewing for the guest and whether that means leaving some areas darker than others is up to the needs of the story. However, areas of interest can be thought of as shots and can be lit to be best viewed from one determined vantage point. Camera movement can still be accounted for in VR, to some degree, by determining which areas the player is likely to stand and lighting around and for those areas. Since the player controls the camera, the

foreground, acting area, and background can be continuously changing at any given moment so it becomes a matter of lighting the areas outside the playspace as the background and the areas within the playspace as the acting area. There is not likely to be very many foreground elements while a player is walking around.

For Architectural and environment lighting, the main considerations were:

1. Functions of space
2. Exterior Environment [15]

Accounting for the environment the space exists in along with what function the space serves is critical in deciding how each space should be lit. Will it need highly concentrated lighting for finely detailed work or dim and warmly lit lighting to elicit calm in the space? The function and exterior environment of a space can be determined by analyzing the script.

Reference images are of fundamental use for any artist. Once the script has been analyzed for context sensitive details, a visual library will be generated based on those details which will serve as the basis for the overall look of an area. Images will then be analyzed to determine what properties work together to make the images successful, such as, the intensity, color, and contrast of light.

One real world reference that will be used is the lighting of rides at the various Disney theme parks around the world. A mix of theater and interactive experience blend together in a Disney ride to create a visually pleasing and interesting experience. Use of colored lights in both Disney rides and theater are heavily prevalent and a lot of the lighting design in our VR experience will implement the use of colored lighting (Figures 4.1 and 4.2).



Figure 4.1: *7 Dwarf's Mine Train* at Disney World [12]



Figure 4.2: *Radiator Springs Racers* at Disney's California Adventure Park [9]

When working in Unreal, some elements of the lighting pipeline of *The Last of Us* will be implemented as they tie in heavily with the consideration of other mediums previous discussed. Lighting will begin in greyscale to provide focus then will be finalized with fully colored textures [2].

To further a comparison of how best to start lighting a VR scene, one environment will have the environment lit first then the playspace; another environment will have the playspace lit first then the environment. A comparison of which area is lit more successfully will be done.

A comprehensive breakdown of the full design plan is outlined below:

1. Script Analysis
 - (a) Determine environment and function of space
 - (b) Determine key areas of interest
2. Generate Visual Library - Reference images compiled based on script analysis
3. Analysis of Visual Library - Determine key components of an image that affect the overall look
4. Lighting
 - (a) Light in greyscale first, focusing on contrast ratios and drawing the player's eye
 - (b) Light the environment and playspace separately
 - (c) Light major areas of interest while adhering to previous lighting conventions, such as, three point lighting and revelation of form
 - (d) Light to account for player movement
 - (e) Color range consideration of the display

4.2 Script Analysis

The following screen shots were some initial musings on the lighting design of *Journey to Proxima Centauri: Terror of the Mnar* based on the script. Some elements changed and evolved overtime.

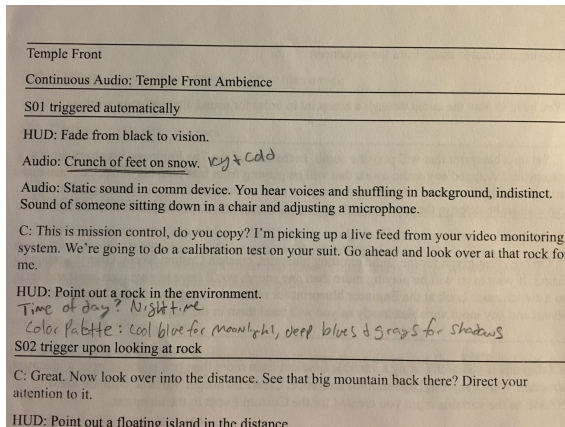


Figure 4.3: Initial Script Musings #1

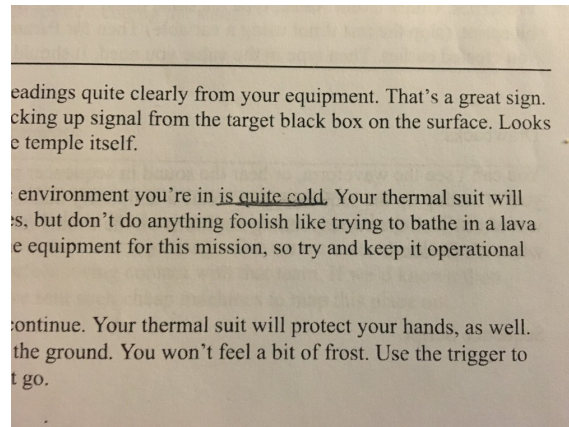


Figure 4.4: Initial Script Musings #2

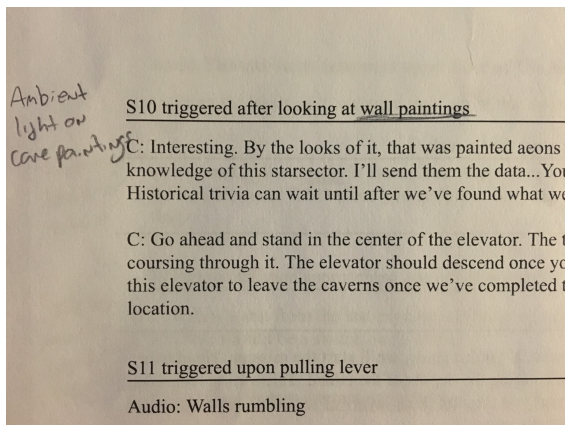


Figure 4.5: Initial Script Musings #3

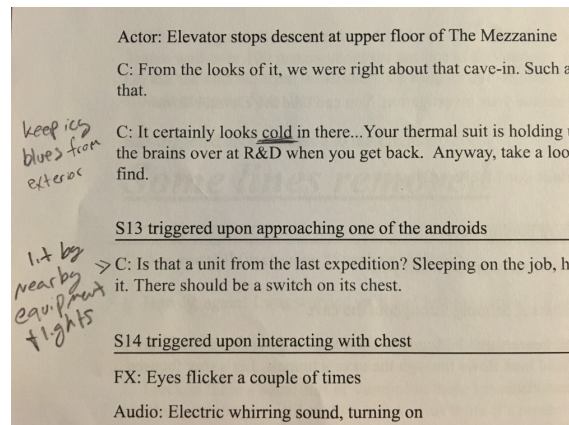


Figure 4.6: Initial Script Musings #4

FX: Cavern rumbles
 FX: Dust particles falling
 Audio: Cavern rumbles
 Audio: Huge footsteps above
 Audio: Metal crashing sounds
 Audio: Crystals breaking sounds
 C: Stay here. I'm hoping that was a rockfall, but I'm checking your thermal reader just to be sure.
 C: What in the-?
 Audio: Cavern goes silent
 C: It looks like it - whatever that was - is gone. You should be safe to go check things out. Be careful.
 Actors: Crystals now glow red
 Actors: Androids, crates and barrels have been thrown about

*Possible area for lighting affects
 - dim lights on footsteps
 - soft visible light to various color (red?)*

Figure 4.7: Initial Script Musings #5

Actors: Crystals now glow red
 Actors: Androids, crates and barrels have been thrown about
 Actors: Elevator railing upstairs is broken
 keep color change from attack (subtle)
 S20 triggered upon leaving the hole in the wall
 C: We didn't plan for something like this. I need you to return to the surface for extraction. Go back to the elevator.
 E: Be careful pardner!
 S21 triggered upon reaching upper floor of the Mezzanine
 C: You're kidding.
 C: Alright, I need you to continue upward to the surface for extraction.
 S22 triggered upon pulling the lever to go up
 Actor: Elevator churns slightly
 Audio: Warning buzzer sound

Figure 4.8: Initial Script Musings #6

way into the seat at yer own pace.
 S32 triggered upon entering the vehicle
 Actor: The vehicle turns on and rises from the ground
 Audio: (from dashboard console) "Thank you for using DCWOLF Transportation S your safety, please take care when entering or exiting the vehicle. Make sure that yo confidently and safely seated before departure. Keep your arms and legs inside the times."
 E: When you're ready, go ahead and hit that green button on the dash there.
 S33 triggered upon pressing Green safety switch
 Actor: Vehicle begins to move
 FX: Dust falling from ceiling
 FX: Shaking
 Audio: Monster roar explodes from somewhere above
 E: Leave the drivin' to me, pardner!

Lights on vehicle headlight?

green glow?

Figure 4.9: Initial Script Musings #7

FX: Dust falling from ceiling
 FX: Shaking
 Audio: Monster roar explodes from somewhere above
 E: Leave the drivin' to me, pardner!
 FX: Core module flashes a couple of times
 Audio: Vehicle chimes as Engineer takes over
 Journey to the Crystal Garden
 The Trap - The Drill's Last Charge

Figure 4.10: Initial Script Musings #8

Actor: Vehicle stops

C: So there was a rockfall. This explains why so few machines made it back to the main cavern.

E: I'll be... So all o' my buds are still in there, huh. Ya don't think...-

C: This vehicle is equipped with a laser cutter for eliminating debris. I'm sending a signal now to engage the laser.

Audio: Laser charging

E: Wait a doggone minu-

FX: Laser fire

Audio: Laser fire

FX: Debris destroyed

C: There. You can continue onward.

E: Ma'am, that was the last charge in the cutter!

C: Are you implying that we should have turned around to face whatever was in that cavern? I'll take my chances going deeper. And I recommend that you follow my orders if you wish to remain activated when you return.

Handwritten notes:
 - back light rockfall so light spills through
 - make sure rockfall is well lit
 - maybe over head light or vehicle headlights
 - light effects
 - tunnel lights up the color of the laser

Figure 4.11: Initial Script Musings #9

S35 triggered upon entering diorama scene of abandoned equipment

C: Looks like nobody's here. Is this your base camp?

E: Nope, but it's not like my pals to leave their equipment out like this. Look, it's gone all rusty-like. I sure hope they're doin' alright...

C: Why are you so concerned? As long as you help us fulfill the current mission, I'm sure we can outfit your core module with a new body when you return. The other machines here were simply lower grade models, unable to fulfill their task.

E: (sigh...)

S36 triggered automatically

Audio: Beasts roars are heard intermittently

Destroyed Equipment

Handwritten notes:
 - highlight broken equipment
 - enhance feeling of isolation
 - Robote expendable
 - lower lights

Figure 4.12: Initial Script Musings #10

S37 triggered upon reaching hilly incline

FX: Rocks beneath you sliding down the hill as your vehicle slides

E: Hold onto the reins, pardner!

Audio: Engine revving

S38 triggered upon entering swiss cheese room

Actor: Vehicle slows down

E: That varmint...!

C: It would appear your "comrades" didn't take good care of the equipment that they were assigned. Don't tell me this is your base camp?

Handwritten note:
 - Continue sense of isolation by dividing up groups of broken equipment

Figure 4.13: Initial Script Musings #11

E: Shh-! Quiet. Ya'll hear that?

C: Hear what?

Audio: As vehicle approaches an open tunnel, a low growl sounds

Actor: Shadow of moving monster in tunnel

C: What is...that...

E: Nuh-uh pardner, ain't no way we're goin' that way, no sir!

Actor: Vehicle continues on new path

E: Hold onto your hat, pardner!

C: The heat signature is picking up again. It's moving fast!

E: Believin' me now, ma'am?

C: Just go! It's on your tail!

S39 triggered automatically

Handwritten notes:
 - Contrast cool tones
 - dim lights
 - Cool tones return
 - light flickering + darkening

Figure 4.14: Initial Script Musings #12

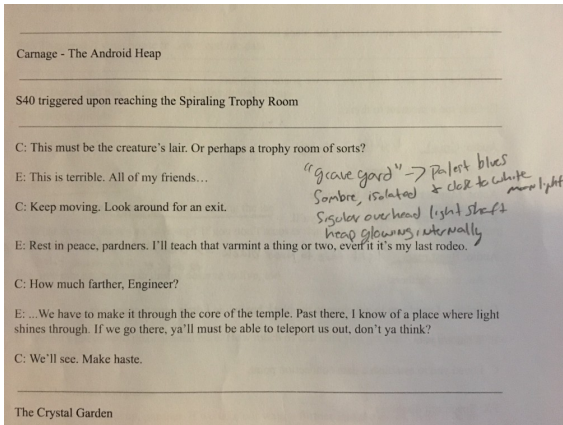


Figure 4.15: Initial Script Musings #13

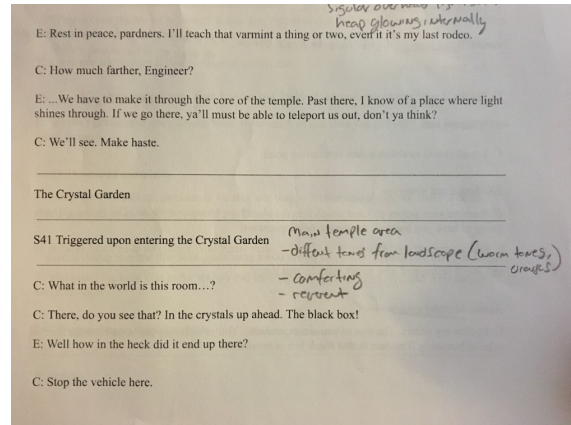


Figure 4.16: Initial Script Musings #14

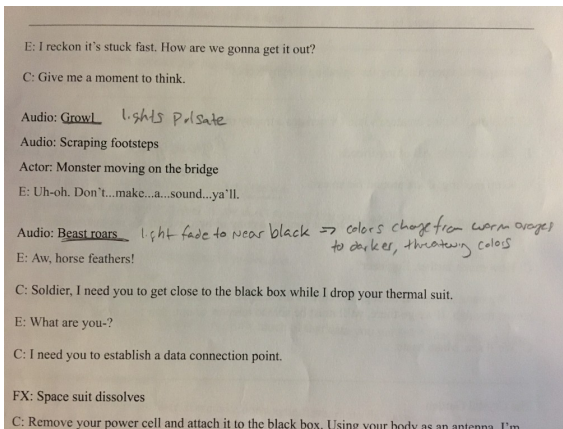


Figure 4.17: Initial Script Musings #15

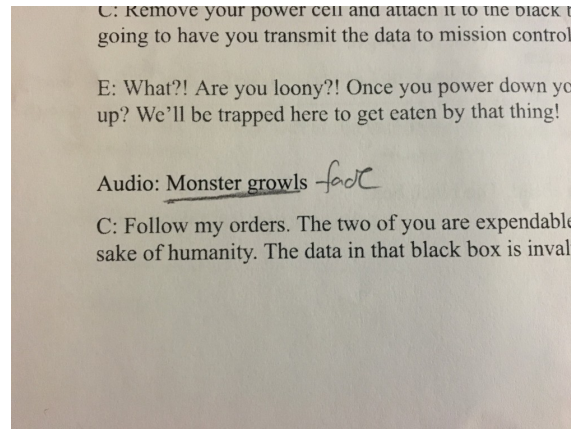


Figure 4.18: Initial Script Musings #16

HUD: Download box appears and begins downloading
 "Download initiated."

C: Soldier, you-!

Audio: Monster roar

Actor: Jump onto frozen waterfall, attacking the ice

C: What do you think you're doing? If you don't recover that data, y
 to. Stop this nonsense at once!

E: Sorry ma'am, but we androids deserve to live, too.

FX: Ice being broken away

E: We ain't got time to poke around here. How much of that data yo
 break through!

Figure 4.19: Initial Script Musings #17

Actor: Vehicle starts moving

Actor: Monster breaks through the ice and begins to give chase

E: The opening's up ahead, but...-

C: The heat signature has gone cold. Did it tire itself out?

FX: Ceiling crashes through

Actor: Vehicle stops moving

Actor: Monster drops from the ceiling *Or maybe lighting chase*

Audio: Ceiling breaking

Audio: Monster roar

C: Reverse the car!

Actor: Vehicle starts moving

Figure 4.20: Initial Script Musings #18

E: Not if I can help it. This town ain't big enough for the both of us, you murderin' varmint!

Audio: Laser charging

FX: Engineer core glows

C: What are you doing?!

E: Don't worry 'bout me, ma'am!

E: See ya, cowboy.

FX: Laser fires at the roof of the cavern

FX: Rockfall occurs

Actor: Vehicle stops moving

FX: Engineer core flickers and then light goes out → *lights return to semi normal*

C: Heat signature reading...negative.

Figure 4.21: Initial Script Musings #19

C: He used the rest of his remaining energy to recharge the cart's cutting laser. He saved you. Who could imagine that an android would....

C: ...There is a parallel tunnel next to this one that should take us to the now-blocked cavern. Hold on, I'm taking control.

Actor: Vehicle starts moving

S45 triggered upon vehicle reaching lava pit *warmer oranges of red, mouth the falling down*

C: Hold on tight. I need to bring you out just a bit further for the warp to reach you.

FX: Ground rumbling

Audio: Bridge breaking

C: Almost there...

FX: Bridge breaks

Figure 4.22: Initial Script Musings #20

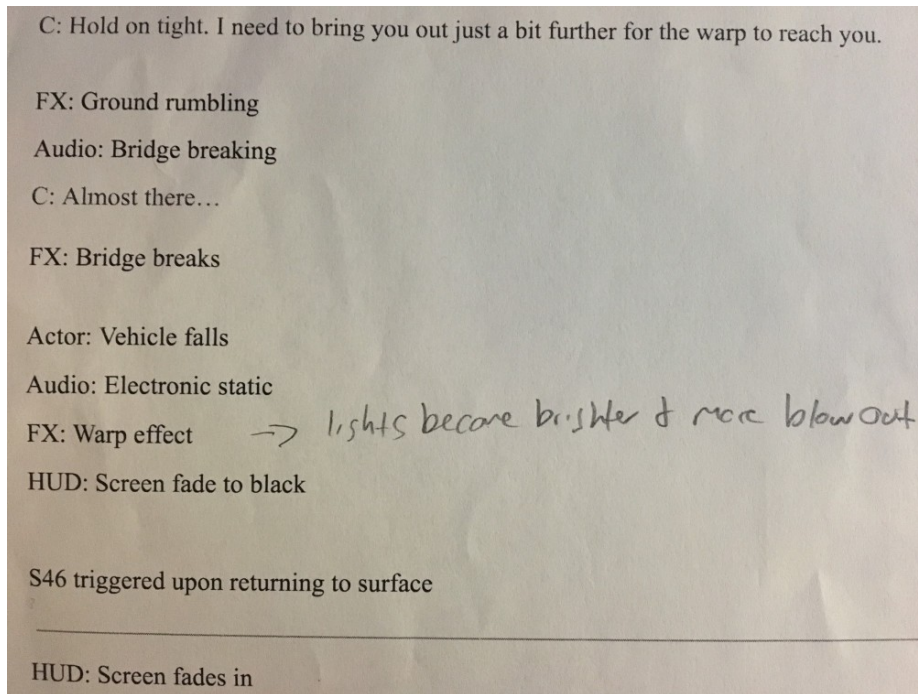


Figure 4.23: Initial Script Musings #21

At the beginning of the lighting design plans, it was determined that there were two main palettes revealed in the script. The icy and frigid exterior that extends into the earlier portions of the caverns and, second, the deep, hot core where the guest nearly falls into a pit of lava. A design was proposed for the time of day to be nighttime to allow cool moonlight to filter down into the upper level of the temple, enhancing the guest's perception of the frigid environment and providing contrast to the deep, more warmly lit interior spaces of the temple. This was approved and served as a starting point for the *Mezzanine's* lighting design which is discussed in Chapter 5.

As noted in the script, there is a theme of isolation in the experience. The guest is alone on an alien world where countless androids have vanished into thin air. When the guest stumbles upon their tragic fate, a buildup of isolation has been

established through the lighting of the camp sites. These areas have darkly shadowed rooms with overly bright pockets of stark light which serve to highlight the growing mystery into their disappearance.

References images, inspiration, and a breakdown of the lighting process for each major are of the experience are discussed in chapter 5. The main elements above serve as the foundations of the lighting design.

Chapter 5

Production Details & Application of Design Plan

5.1 Making of *Journey to Proxima Centauri: Terror of the Mnar*

The following chapter is a detailed breakdown of how the levels of the Virtual Reality experience, *Journey to Proxima Centauri: Terror of the Mnar* (*Journey*) were lit. The narrative of the experience tells of a lone soldier tasked with investigating a mysterious, alien planet to find out the status of the missing excavation team sent previously. Set on a frozen wasteland, the guest delves into the depths of an ancient temple to uncover their fate.

Journey was crafted by a small team of DPA M.F.A students at Clemson University using the Unreal 4 Engine (Unreal) produced by Epic Games. Unreal has a set of lighting tools that encompass ambient, spot, and point lights. Other tools like pre-computed lighting setups, reflection captor actors, and post process volumes

were pivotal in finalizing the overall look of the lighting design. Use and application of these tools will be defined in line as necessary.

5.1.1 Shadows in *Journey to Proxima Centauri: Terror of the Mnar*

I'd first like to quickly discuss how shadows were handled using Unreal 4 during the production of *Journey*. It was quickly learned that only a limited number of stationary¹ and movable² lights were allowable per scene due to real time rendering limitations of too many dynamic lighting calculations. Dynamic lighting calculates light bounces and shadows at run time whereas static lighting pre-computes lighting calculations and bakes the lighting into the textures of an object. Having a large number of dynamic lights to calculate at run time is a strain on performance, especially for virtual reality which requires higher frame rates than non-virtual reality games. Fortunately, the larger environment areas outside the playspace could be lit statically which allowed more lights within the playspace to be stationary and provide dynamic shadows on the guest. Even still, however, the number of stationary lights that could be used were relatively few in number. The biggest issue arose when the vehicle the guest rode moved. The vehicle would lose its baked lighting and become dark. Thankfully, the use of a light mass importance volume solved this issue by allowing movable objects to receive a pre-calculated indirect lighting approximation.

¹Casts dynamic light and shadows but must remain in a fixed position.

²Casts dynamic light and shadows but can be animated to move.

5.2 Lighting the *Mezzanine*

Lighting the *Mezzanine* began with a search for references. I considered source material from both realistic ice caps and fantasy or science fiction ice environments. Based on the script, it was determined there would be a change in color palette through the lifetime of the experience due to environmental function considerations of the *Crystal Garden* space discussed in section 5.5. The *Mezzanine*, based on clues from the script, is cold, mirroring the freezing wasteland outside the caverns. To that end, my main source of inspiration came from Figure 5.1 and Figure 5.2.



Figure 5.1: *Ice Temple* concept art from *Uncharted 2: Among Thieves* [10]



Figure 5.2: *Under the Ice* concept art from Gaan [4]

In Figures 5.1 and 5.2, the prevailing colors are blue and teal with hints of deep purple within the ice in Figure 5.2. Patches of natural pale blue lights filter in and brief glints of yellow and orange firelight speckle the interior environment. With these colors in mind, I lit the Mezzanine. The deep blue cavern was my first subject. Lights were placed to simulate filtered in moonlight to light the rock floating in the water. Then the two cavernous openings were lit with a similar intention in mind. Palette wise, I selected close-to-white blue lights for the overhead light shaft and a similar palette for the cave opening, featuring lights with a hot close-to-white center that fade into the deeper blues of the cavern itself which mirrors the lighting effects in Figure 5.1 (Figure 5.3).



Figure 5.3: *Mezzanine's* Interior Lake - Greyscale



Figure 5.4: *Mezzanine's* Interior Lake - Final

Originally, I placed two lights to simulate the moonlight and accompanying

light beams shining down to light the center rock. One to provide illumination and one to work in tandem with the volumetric height fog to create the light beam to create a sense of atmosphere in the cavernous space. It was quickly discovered that the limitation for VR did not allow use of the built in volumetric fog, so a new solution to provide a light beam needed to be found. The current solution was to create a cone and apply the default, one-sided light beam material provided by the Unreal 4 Engine content.

Next the upper floor of the *Mezzanine* was lit. Once again, lights were placed with only contrast in mind at first (Figure 5.5). Here the teals of the reference images were included. Cavernous openings that lead somewhere deeper into the caves provide the teal light and pale blue moonlight drifts in from an opening behind the large central rock column (Figure 5.6). After the basic placements of the lights, I worked on trying to raise the level of the shadows which faded extremely into black. This took several days of searching for the best solution. Using the post process volume seemed a perfect option, but I was unable to find a good balance in raising only the shadows values without heavily affecting the midtones or clipping them entirely. Upon further research, it seemed that the Unreal 4 skylight is often used to raise and/or color the shadow values. Tinting this light a pale blue did affect the shadows in the larger cavern area but less inside the upper level. Eventually a few concentrated teal lights were used to lower the contrast in some darker areas.



Figure 5.5: *Mezzanine's* Upper Level - Greyscale



Figure 5.6: *Mezzanine's* Upper Level - Final

After the upper level was complete, the lower level went fairly quickly. I chose

to continue the use of the orange light from the upper level here to hint at the palette change later in the experience (Figures 5.7 and 5.8). An interesting function I wasn't aware of and, in fact initially tried to simulate myself since mixing blue and orange light produces a purple-ish pink, is Unreal 4's blending of the orange light and the blue light into the purple range. I had initially planned to design this interaction myself based on some of the reference image, and I thought had caused some odd behavior in Unreal when my manually placed purple lights didn't seem to alter the look no matter if I turned them off. I later realized that was because Unreal was handling this color change upon lighting build. An interesting tidbit I learned through trial and error.



Figure 5.7: *Mezzanine's* Lower Level - Greyscale



Figure 5.8: *Mezzanine's* Lower Level - Final

Another task to finish the look of the level was to light the playspace. Much of the fill lighting was already provided by the surrounding ambiance but now it needed focused areas of interest. This was achieved was by placing light fixtures as if they had been set up and abandoned by the original excavation team. Figures 5.9 and 5.10 show the *Engineer*, who is fully lit by an overhead light. The *Engineer* acts as a moral compass for the guest throughout the narrative and is more brightly lit than the damaged robot (Figures 5.11 and 5.12) on the upper floor who is partially cast in shadow.



Figure 5.9: The *Engineer* - Greyscale



Figure 5.10: The *Engineer* - Final



Figure 5.11: Abandoned Robot - Greyscale

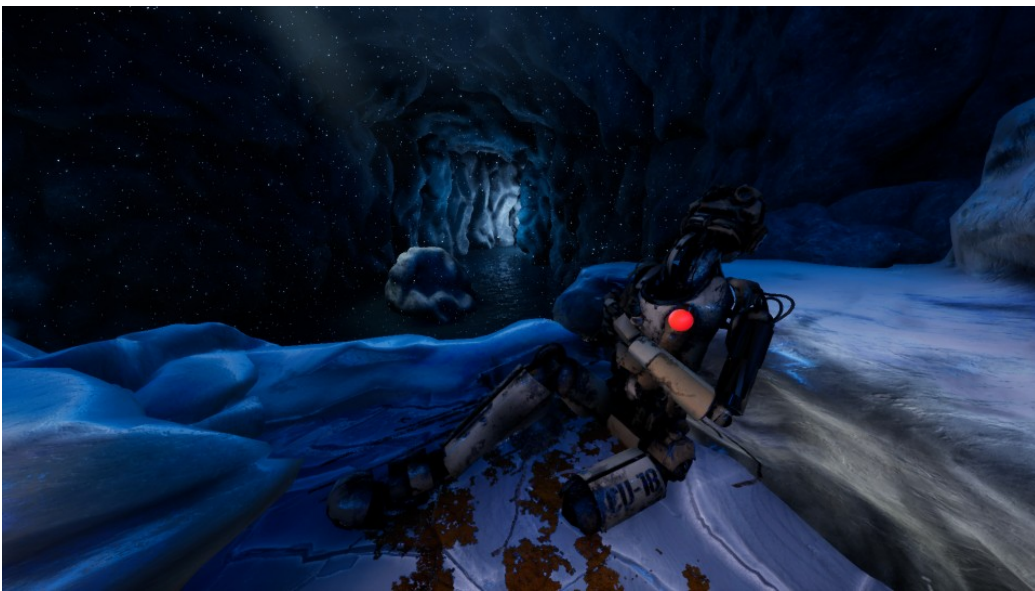


Figure 5.12: Abandoned Robot - Final

There is a cinematic moment during the guest's exploration of the *Mezzanine*

where the *Temple Guardian* attacks and destroys part of the upper floor while the guest hides in an opening in the cave wall. During this sequence, the light in the *Mezzanine* changes, shifting the cool tones to a deep, ominous red (Figure 5.13). Because almost all of the lights were static and their light contributions pre-computed, they could not be animated to change their intensity or color during this sequence. Therefore, a post process volume, a form of tone-mapping, was placed around the playspace and used to animate the changes in the overall color and intensity of the lights by adjusting components of gamma and hue.



Figure 5.13: Colors of the *Mezzanine* shift an ominous red while the *Temple Guardian* is near.

With all the lights in place, there was still much left to do. I was tasked with setting up the non-volumetric height fog as well as adding in BP fog sheets. This added a lot to the realism and look of the scene and helped tie together many of the elements.

5.3 Lighting the *Swiss Cheese Room*

A vast cavern with dozens of tunnels carved into the walls lead into the unknown depths of the subterranean temple. This room serves to give the guest a glimpse of the fate of the excavation team. Once a well organized base camp, equipment and supplies have been strewn and disrupted by an unknown assailant. This is also the first time that the guest gets a look at the *Temple Guardian* through an ominous shadow cast against the wall of one of the tunnels. Research for this room started by looking at modern caves, both those used for industrial mining and set ups for tourist attractions and Disneyland rides. Mine lighting typically appears to have incandescent lights placed in increments along a corridor or in areas where work is being done (Figure 5.14).



Figure 5.14: Underground mine passage with rails and light [18]

In caves or mines meant for tourists, brightly colored lights are positioned to

give the area an ethereal a fantasy like vibe in Figure 5.15. Some rides at Disneyland have dark tunnels and scenes of interest lit in colorful tones to entice the rider's eyes (Figure 5.16). The areas of work in the Swiss Cheese Room are lit with pockets of light for the workers, and the rest of the cave is lit in saturated colors (Figures 5.17).



Figure 5.15: Bright whimsical colors light up the *Sorek Cave* [19]



Figure 5.16: *7 Dwarf's Mine Train* at Disney World [12]



Figure 5.17: Deep blues and oranges mix in the *Reed Flute Cave* [23]

Lighting for the *Swiss Cheese Room* began with the areas closest to the

playspace. Since the guest is inside the motion simulator³ at this point in the experience, the main area of focus was the destroyed camp of the excavation team. The camps were treated very much like acting areas of the theater, and the lights were particularly placed at a, close to, 45 degree angle as defined in *A Method of Lighting the Stage* [13]. Figure 5.19 shows an overhead view of these lights. The lighting was also initially lit with only contrast in mind and the view port was set to a “lighting only” version of the scene. (Figures 5.18, 5.19, 5.20, 5.21, 5.22)



Figure 5.18: Greyscale lighting of *Swiss Cheese Room*

³A 2-degree of freedom motion platform which simulates ride conditions for the guest.

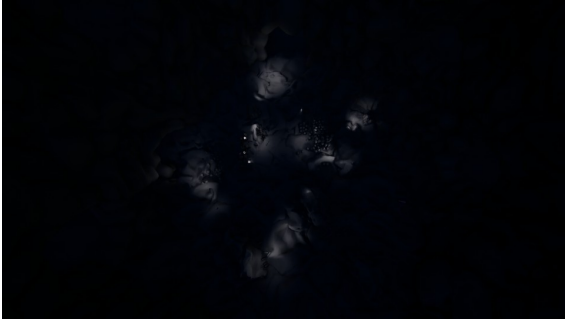


Figure 5.19: *Swiss Cheese Room* -
Greyscale 1

Figure 5.20: *Swiss Cheese Room* -
Greyscale 2

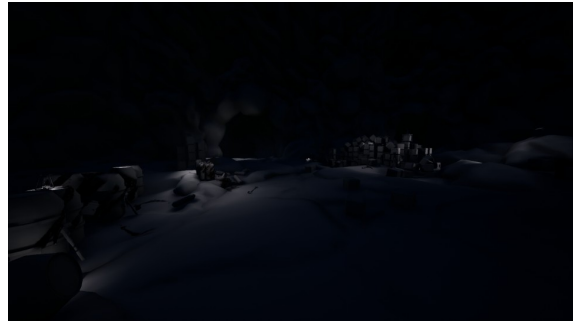
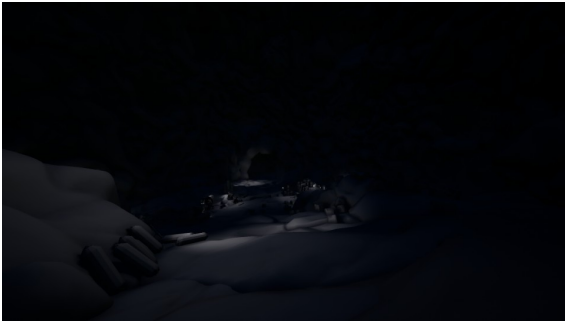


Figure 5.21: *Swiss Cheese Room* -
Greyscale 3

Figure 5.22: *Swiss Cheese Room* -
Greyscale 4

Several iterations on the levels of contrast in the playspace were implemented before moving on to the surrounding environment. The biggest considerations were making the scattered equipment and the main tunnel, where the Temple Guardian appears, draw the guest's eye. For the camp areas, reference from night time construction sites were used in Figure 5.23.



Figure 5.23: A single, bright spotlight aids the nighttime workers [22]

The main lighting components are the overly bright spot lights that fall off into near darkness. Some time was taken to get the balance between the ambient lighting and these areas of the camp. Since our eyes have a much better exposure latitude than cameras and displays, ambient levels were raised from near black to give the guest a better viewing experience and to avoid making the lighting design look too “game like” and unrealistic. This was not as successful as in the *Abandoned Equipment Room* in my own opinion. Checking adjustments inside the headset often was the only way to accurately create the correct affect as the monitor on the computer used to light was usually brighter than the headset displayed. Final tweaks of any lighting required this back and forth.

Once the levels were adjusted in greyscale, textures were turned back on and the intensities of the lights were tweaked again. Light colors were applied last. Figure

5.17 was the biggest inspiration for the colors. Like the *Mezzanine*, the overall ambient color is a deep saturated blue. Instead of blending the lighter blues and teals in the reference image, the tunnels were used to infuse the differing colors into the cavern (Figure 5.24).



Figure 5.24: *Cave Concept* by Nele-Diel [1]

The tunnels nearby where the *Temple Guardian* appears are lit with the orange lights and special care was taken to display the full range of orange values shown in the reference (Figures 5.25 and 5.26). Once the main lights were added, secondary lights were implemented to better represent bounce lighting and provide more complete control for drawing the guest's eye. An example of this is provided in Figure XX. The light for the *Temple Guardian* was implemented after because the animation needed to be roughed in first. A single, high intensity spotlight was used to project the *Temple Guardian's* shadow onto the wall (Figure 5.27).



Figure 5.25: No bounce lighting around mouth of the cave



Figure 5.26: Finely crafted bounce lighting around the mouth of the cave



Figure 5.27: *Temple Guardian's* shadow cast on tunnel wall

5.3.1 Lighting the *Abandoned Equipment Room*



Figure 5.28: Moonlight filtered into *Abandoned Equipment Room*

The *Abandoned Equipment Room* is the guests first glimpse of the fate of the excavation team before heading into the *Swiss Cheese Room*. Like the *Swiss Cheese Room*, this room features low lighting with pockets of bright lights highlighting the abandoned equipment. This room is styled most like a ride at Disneyland with spaced out points of interest to draw the guest's attention one after another (Figures 5.29, 5.30, 5.31, 5.32).



Figure 5.29: *7 Dwarf's Mine Train* at Disney World [12]



Figure 5.30: Points of interest contained within spotlights - broken car



Figure 5.31: Points of interest contained within spotlights - scattered equipment



Figure 5.32: Points of interest contained withinspotlights - abandoned equipment

Overall, this room is a bit more successful than the *Swiss Cheese Room*, most likely due to the fact it was lit after the *Swiss Cheese Room* and experimented with dropping the ambient light.

5.4 Lighting the *Crystal Garden*

The *Crystal Garden* is the final walkable playspace for the guest. Deep within the bowels of the cavern system, this temple has a much different feel than the rest of the experience. Inspiration for this room comes from *Light Revealing Architecture* which states that temples across the world tend to be a place of comfort from the exterior environment [15]. For example, a mosque in Istanbul might be coolly lit to provide relief from the harsh, hot, and humid world outside [15]. This design concept is mirrored in the *Crystal Garden*. Warm orange tones make up the ambient lighting, a very stark departure from the previous lighting designs which mimic the frozen

wasteland on the planet's surface. The aesthetics of the *Crystal Garden* are meant to elicit a sense of comfort for the guest after facing a jarring and fast escape from the guardian of the temple. Narrative wise, the guest is much closer to the fiery lava pits deeper in the caves which gives a non-functional explanation for the warmer change in the lighting.

The original inspiration for the *Crystal Garden* was from the *Palacio Guell* in Barcelona, Spain, featuring exterior light filtered down through small openings in the ceiling (Figure 5.33). The implementation of this reference was the saturated blue “faerie” lights on the ceiling (Figure 5.34).



Figure 5.33: Interior of the central hall of *Palacio Guell* [15]

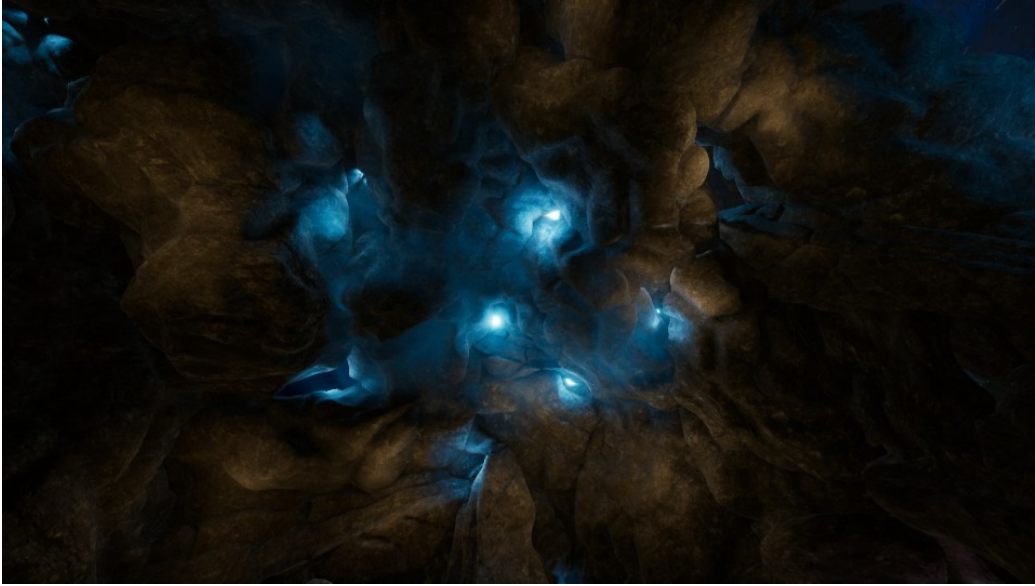


Figure 5.34: Final implementation of *Palacio Guell* ceiling lights

I wanted the guest to feel a sense of awe and whimsy when they looked up upward. The lights serve almost as starlight which gives the scene a small hint of the magical. These small lights were the very first lighting implemented in the *Crystal Garden*. They were placed without color to get the contrast correct (Figure 5.35). Next ambient fill lights were added which proved to be a challenge in the vast cavernous area behind the frozen waterfall because the space is so large (Figure 5.36). I used the Unreal Skylight to serve as an ambient fill which is used throughout the experience.

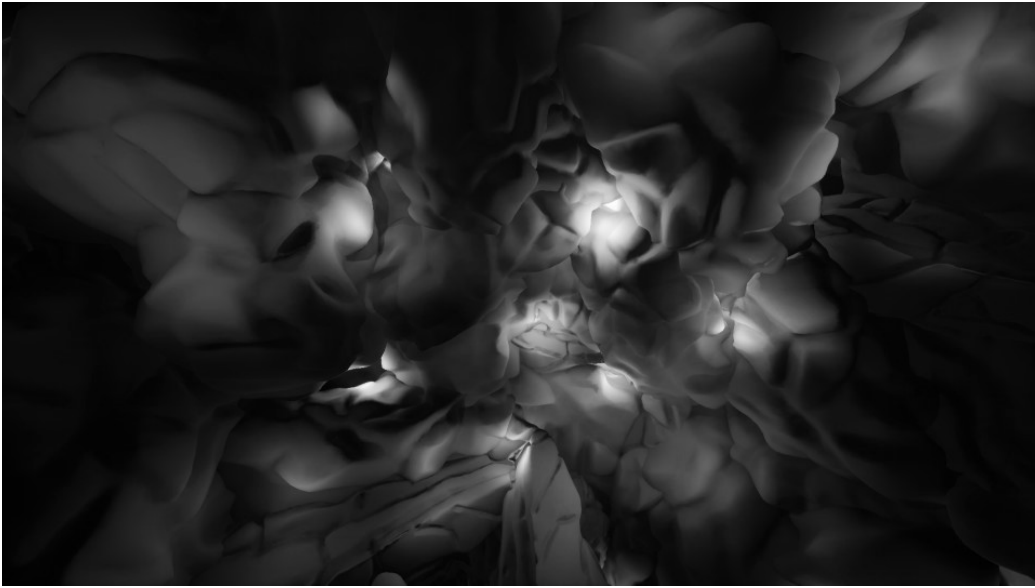


Figure 5.35: Faerie Lights - Greyscale



Figure 5.36: Vast cavern which houses the rock bridge

An interesting dilemma that arose, because of the way the levels were streamed

together, was that the skylight's shadows were baked with the colors from the *Mezzanine* (a saturated blue) and when the guest crosses over into the *Crystal Garden* level, the hue of the skylight is slowly animated to match the warm orange. This works to some extent but the baked blue-ish shadows can still be seen. Fortunately, it did not heavily affect the quality of the scene. Figure 5.37 shows the scene with the skylight baked at the correct orange color, and Figure 5.38 shows the scene baked with the Mezzanine colors for comparison. However, further investigation into Unreal's "Precomputed Lighting Scenarios" would be the solution in a non-VR experience. Unfortunately, it seemed to require a level load to work properly which is something we wanted to avoid in *Journey* so the guest could have a seamless experience once in the environment. Therefore, no final solution was implemented.



Figure 5.37: Skylight built with a deep saturated blue



Figure 5.38: Skylight built with a warm orange color

The lighting around the shrine is mostly ambient light from the nearby energy and crystals. I wanted no harsh, apparently bright lights in the playspace. The golden spotlight was intentionally dim, only there to provide a golden shimmer and glow across the playspace (Figure 5.39). During the sequences where the *Temple Guardian* attacks the guest, the serene surroundings are corrupted and shift from warm, even tones into more saturated and contrasted values, turning the calming shrine into an ominous, unsettling landscape (Figures 5.40 and 5.41).



Figure 5.39: Shimmering, golden lit Shrine

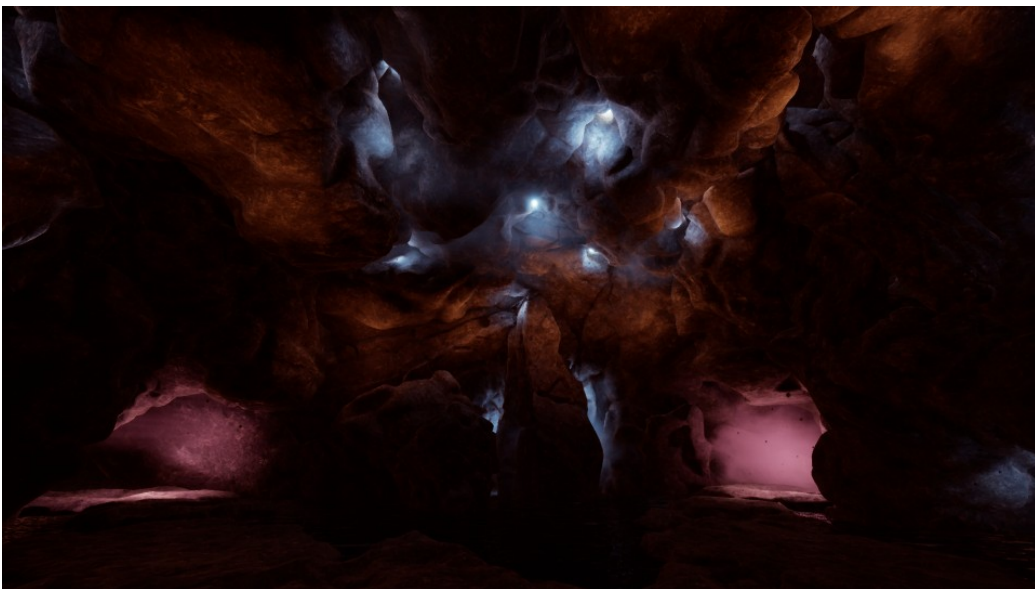


Figure 5.40: Lighting shift when *Temple Guardian* Attacks



Figure 5.41: Lighting shift when *Temple Guardian* Attacks

Chapter 6

Conclusion

Lighting for Virtual Reality differs from more traditional mediums because the guest has full autonomy of where to look within the rendered world. VR also has constraints placed on it that are of no consequence on lighting in the real world, such as frame rate, and even video games are not as limited in how many frames per second must be rendered. The guest must be led where to look with these limitations applied, whether that is through limited use of dynamic shadow, changes in contrast and light intensity, or the use of colored lights.

The implementation of the design plan was successful overall. Starting from an analysis of the script provided many contextual cues for what kind of mood the lighting should convey and when to apply real time lighting changes. Lighting by working outward from the areas of interest to the surrounding environment led to better lighting on the areas of interest in the playspace since this was the main concern from the first light added. This is best exhibited in the *Swiss Cheese Room* and, even more so, in the *Abandoned Equipment Room*. Since the *Mezzanine's* environment was lit first and the areas of interest second, I do not think it is as successful at drawing the guest's eye. I think this is the case for a few reasons, one being much time was

spent getting the atmosphere of the room correct. The *Mezzanine* definitely gives the guest a sense of how cold the environment is. So, when it was time to light the playspace, it was tricky to light it in such a way as to pull the guest's eyes from the environment. I think what helps this here is how much closer the spotlights in the playspace are. They do, to some extent, keep the guest's eyes from wandering.

The final renders from the experience exhibit a high level of lighting design and provide the guest with a sense of narrative importance during each area. Figures 6.1, 6.2, and 6.3 show completed, in game, renders of the *Mezzanine* featuring its cool tones to reinforce the freezing temperature and hints of warmer light in the distance alluding to the comforting *Crystal Garden* much later. The androids are trapped within their own spot lights, isolating them from the surrounding environment, and the color shift after the *Temple Guardian* destroys the elevator cast an eerie atmosphere on the *Mezzanine* (Figure 6.4).



Figure 6.1: Lower *Mezzanine* Final Render 1



Figure 6.2: Upper *Mezzanine* Final Render 1



Figure 6.3: Upper *Mezzanine* Final Render 2



Figure 6.4: Upper *Mezzanine* Final Render 2

The *Swiss Cheese Room* ramps up the sense of isolation through targeted spotlights Figure 6.5 and 6.6. Bright orange lights lead the player away from the chilly environment and provide a false sense of relief before being ambushed by the *Temple Guardian*.

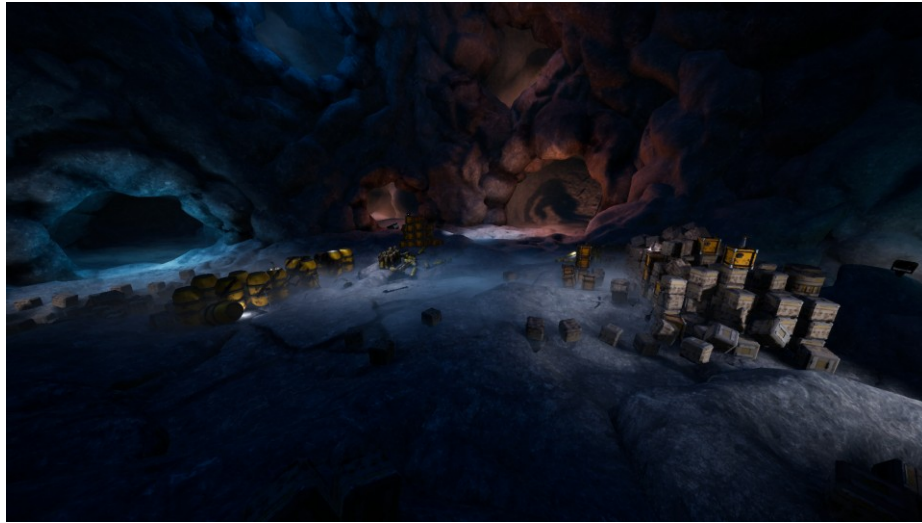


Figure 6.5: *Swiss Cheese Room* Final Render



Figure 6.6: *Swiss Cheese Room* Final Render

The *Abandoned Equipment Room* best exhibits lighting design similar to a ride at Disneyland by pushing ambient levels lower to allow the pockets of equipment feel more lonely and uncared for than in the *Swiss Cheese Room*, creating a pleasant,

partitioned viewing experience for the guest (Figures 6.7 and 6.8).



Figure 6.7: *Abandoned Equipment Room* Final Render 1



Figure 6.8: *Abandoned Equipment Room* Final Render 2

The *Crystal Garden* submerges the guest in warm, comforting lights and the overall glow of the room gives off a reverence for the energy source at the shrine. This, like the *Mezzanine*, is marred for the guest when the *Temple Guardian* runs the guest off.

There were many challenges to overcome while lighting *Journey*, and there are things that could be better. In the *Mezzanine*, the playspace is not as strongly lit as many of the other areas during the ride portion of the experience. The feeling of abandonment and loss is best highlighting in the abandoned equipment room instead of the Swiss Cheese Room. The *Crystal Garden* lacks correctly colored shadows due to the limitations of the skylight and light builds.

Despite these challenges and imperfections, the overall quality of the lighting design is strong, ties all the elements of the narrative together, and reinforces certain design elements and themes. The full, living experience, in the end, became successful in terms of lighting, and I am happy with the results highlighted in this paper.

Bibliography

- [1] Nele “Nele-Diel” Diel. Cave. <http://fav.me/d655qw5>. [Online; accessed 02-April-2018].
- [2] Vivian Ding. In-game and cinematic lighting of the last of us GDC 2014. <http://www.gdcvault.com/play/1020475/In-Game-and-Cinematic-Lighting>.
- [3] Aldin Dynamics. Waltz of the wizard, 2016.
- [4] Gaan. Under the Ice. <http://fav.me/d2kgcwv>, 2019. [Online; accessed 02-April-2018].
- [5] Cloudhead Games. The gallery - episode 1: Call of the starseed, 2016.
- [6] Epic Games. Lightmass global illumination. <http://docs.unrealengine.com/en-US/Engine/Rendering/LightingAndShadows/Lightmass>.
- [7] Fiona Holt. Contrast is king. <https://www.theportraitplace.co.uk/artcolcontrast.php>, 2010.
- [8] Patrick Inhofer. What is a lut (and how do you use a lut for color correction)? <https://mixinglight.com/color-tutorial/understanding-luts/>, 2016.
- [9] Disney’s California Adventure Park John Frost. Radiator Springs Racers. <http://thedisneyblog.com/2012/06/10/radiator-springs-racers-on-ride-video-and-photos/>.
- [10] Andrew Kim. Ice Temple. <http://www.andrewkimart.com/#/uncharted-2/>, 2019. [Online; accessed 02-April-2018].
- [11] D Landau. *Lighting for cinematography*. Clarendon Aristotle. Bloomsbury Academic.
- [12] Disney World Matt Strohane. 7 Dwarf’s Mine Train.
- [13] Stanley R. McCandless. *A Method of Lighting the Stage*. Theater Arts INC.
- [14] Tilmann Milde. Unreal 4 lighting academy - session 01.1. <https://www.youtube.com/watch?v=grN5Yd55UIM>, 2017.

- [15] Marietta S. Millet. *Light Revealing Architecture*. Van Nostrand Reinhold.
- [16] Pluralsight. Understanding global illumination. www.pluralsight.com/blog/film-games/understanding-global-illumination, 2013.
- [17] Penrose Studio. Allumette, 2016.
- [18] SvedOliver. Underground mine passage with rails and light. www.shutterstock.com/image-photo/underground-mine-passage-rails-light-130135697. [Online; accessed 02-April-2018].
- [19] Lev Tsimbler. Sorek Cave. www.israel-in-photos.com/sorek-cave.html. [Online; accessed 02-April-2018].
- [20] Unknown. Illustration of *McCandless Method*. <http://www.famnegar.com/2017/06/stanley-mccandless-lighting-designer/?lang=en>.
- [21] Unknown. Screen space ambient occlusion. http://en.wikipedia.org/wiki/Screen_space_ambient_occlusion.
- [22] Unkown. Nighttime Construction. <https://pxhere.com/en/photo/550258>. [Online; accessed 02-April-2018].
- [23] Unkown. Reed Flute Cave. feel-planet.com/reed-flute-cave-china/. [Online; accessed 02-April-2018].
- [24] Thomas Wallis. The importance of lighting in creating immersive vr. In *Proceedings of Europe VRX Conference and EXPO*.
- [25] R. Craig Wolf and Dick Block. *Scene Design and Stage Lighting*. Wadsworth Cengage Learning.