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Influence of light on realism in Computer Graphics

Thesis

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Introduction

Computer Graphics create images and scenes that are only projections of the objects on a two-dimensional screen. The most challenging part of this process is to make the viewer believe in what he sees and create a realistic scene or image since every part and object of the scene is created from scratch. Photorealism has been a major research field in computer graphics from the beginning and many breakthroughs in rendering, lighting, and modeling have been made in the last decades to achieve realistic looking environments.

Image or scene created should not only be an accurate representation of real-world shapes, values, textures, and sizes but also it should simulate the properties of illumination and light that exist in the physical environments. The first part is already achieved at a significant rate, since many technological developments have allowed artists to use large amounts of polygons in their 3D modeling achieving a great realism of the objects and environment. The problem however remains in the second part that is considering light and energy. In the physical world light has a great energy and its rays travel around the environment, light is reflected from some materials and surfaces and absorbed from some others. To even distantly recreate this process using modern equipment enormous amounts of computational time and storage is needed, so many algorithms have been used to simplify this process and make illumination possible and even distantly approach the real-world process. It is a research field that is constantly evolving due to the requirements that exist and the technological progress being made.

There is, however, another side to it. In computer Graphics through the last years it is starting to become possible to achieve quite realistic lighting on a scene, but even the given resources are still not used to their full potential. Besides the need to create realistic light, there is also a necessity to create atmosphere, transfer the mood of the scene and assist the storytelling. Many games have been developed lately that have achieved a significant result in the illumination and lighting, but there is not enough atmosphere and mood to win the viewer or players' attention.

The Computer Graphics field is quite young and due to technological restrictions, there was not a possibility to develop the artistic side of it enough, as other fields do. Even though computer graphics have been widely used in cinematography to achieve the results that are not possible or are very expensive to shoot, the Game Industry that is based completely on computer generated environments is often lucking the artistic approach. It is quite common for the Game Industry to focus only on the gameplay and physics and not on the overall story and the way to achieve complete results. Appropriate lighting and color design can play a significant role in the overall perception of the game and completely change the user experience.

Many techniques have been developed through the centuries by artists of different fields that can be applied in computer graphics in order to push the industry forward. Similarly, to when the industry of cinematography appeared, rules and techniques from other fields such as painting, and photography had been borrowed and applied in order to create unique results. Computer graphics need to borrow techniques from other fields in order to push the artistic side of the industry forward and create output that will not focus only on the entertaining part but can also influence the viewer and pass a message.

Realism is not only recreating objects and environments existing in the real world, but also to create completely new ones, with their laws and structure that may be completely different from ours. Completely new universes and worlds can be created with the help of computers, that are not restricted by the rules of our physical world. The realism here is to make the viewer believe

that the created world is real and can possibly exist, to make the him part of it. To achieve that it is necessary not only to know and understand the rules of our world, but also to know how to apply and break them.

Many researches have been made in the field to examine the ways to achieve photorealism in Computer Graphics, but few of them focus on the solutions besides technical aspects. Many studies however, in the field of animation focus on the ways to achieve realistic results in lighting and ways to light objects of the scene in a similar way scenes are illuminated in cinematography. For example, Pixar have published some researches that study the field of computer-generated scenes in a way that a movie would. It is an interesting comparison to bring the attention of the environment and lighting artists and help them understand and apply a more artistic approach to their creating process. Colors and lights can be used in order to enhance the storytelling process and create innovative visual output. The application of artistic approach is worth studying in depth in order to give Computer Graphics and especially the Game Industry a similar status as other art fields have achieved through the years. Game Industry can create results that will not only be entertaining for the viewer or player but also to convey a message and a deeper meaning to the public. Games can influence the public opinion, and especially of the younger generation and become a part of the educational process.

In this thesis I wanted to make a comparison between usage of light in different art fields, especially in cinematography that is very close to Computer Graphics, find and examine the basic techniques that exist and, the most important, to try some of them using different software. Lighting a scene is a very interesting and creative process and observe the significant changes that occur even with the slightest modifications of the lighting setup is truly captivating. This process gives endless possibilities and with the technology of today less and less restrictions exist, that allow the creation of endless world where the only restriction is the imagination.

Color

Crucial aspect to achieve photorealism in Computer Graphics is the perception of color. It is the color of the surfaces and environments that makes the human eye believe in the scene that it sees, it helps humans recognize and remember objects and influence the emotions of the image that is received. If colors in the scene are even slightly off, the human brain can recognize it and the attention of the viewer will be lost. The importance of the color may be ignored in real life, since people do not need to be concerned if an object looks realistic, but in Computer Graphics where every environment is created from scratch and all the elements need to work harmonically in order to create the whole image this aspect plays a significant role. The color of the object that we see depends on the properties of the material and the type and color of the light that is illuminating the surface.

The way we perceive color depends on the wavelength of light that our eyes receive from the same spectrum of frequency bands as radio waves, microwaves, X-rays etc. Significant difference in the wavelength results in a differently perceived hue. Lowest frequency corresponds to the red color (4.3 X 10^14 hertz) and the highest frequency to the violet color (7.5 X 10^14 hertz). It is known that white light consists of all the colors when it hits a surface. When the light source emits frequencies indifferent directions, some rays hit a surface and the illuminated material absorbs part of that light and the other part is reflected. The frequencies of the reflected light give us the object color that we see.

 The structure of the human eye helps us recognize colors. Cones or cone cells are photoreceptor cells of the retina of the eye that respond differently to the wavelength resulting in color vision, the ability to distinguish colors. There are three types of Cones, each sensitive to a different wavelength of light that responds to colors in different ways and differentiates the signal that the brain is receiving resulting in trichromatic color vision. Human eye automatically executes tasks that cannot be recreated easily with the technology of today. Camera in photography and cinematography for example simulates the way the human eye works with different settings and lenses that exist for this purpose, as a result it can influence the way an image is perceived by the viewer. In the Computer Graphics this process is slightly different, as not only camera but the whole scene can be presented without the restrictions of the physical world. Shadows and light can be created without limits of equipment, weather or other external factors.

People usually describe object colors by using the **primary colors** which are red, yellow and blue since human vision is trichromatic (RYB color model). Primary colors are the ones that cannot be mixed and produced from other colors, but contrary they are used to create other colors. Mixing any two primary colors in the same proportions gives the **secondary colors**. All the other colors are created by mixing primary colors in different proportions.

Additive primaries are red, green and blue and they are the ones that are commonly used in computer graphics. The usage of these colors is related to the response of the receptors of the human eye and gives us the best results in the visible colors. The color space that uses this color combination as primary is called RGB.

Color Models

Colors have unique characteristics and in order to study and use them, a different approach is needed based on the requirements and the environment they are used. Color models have been developed in order to describe colors based on these characteristics and to make it easier to recreate in different fields. Most color models consist of three scales and can be represented using three axes in order to describe the relationship between the colors involved. They are the way to describe the way human eyes see colors and represent them using different mediums. As it can be seen later different mediums need a different approach in terms of color manipulations and that is the reason a variety of models exist to describe the same colors.

RYB

This is considered to be the traditional color model used from ancient times. This model uses Red, Yellow and Blue as its primary colors. It is still used in art and especially in painting where three primary colors and white and black are used in order to create the rest of the colors on the color wheel. This model is similar to the intuitive perception of color by the human eye and the way humans understand color mixing. Primary colors are used to create secondary colors which are green, orange and purple. These colors are achieved by mixing two of the primary colors together in the same proportions.

Figure 1, RYB Color Wheel, Created in Photoshop 2019

RGB / RGBA

RGB is an additive color model in which primary colors are added and combined together to produce a gamut of colors. This method is widely used in computer graphics but has also been used in photography where the first experiments were made in 1861 by James Clerk Maxwell, who elaborated the theory of trichromatic color vision. To achieve color photography Maxwell used three projections of the primary colors producing the photo by combining them together.
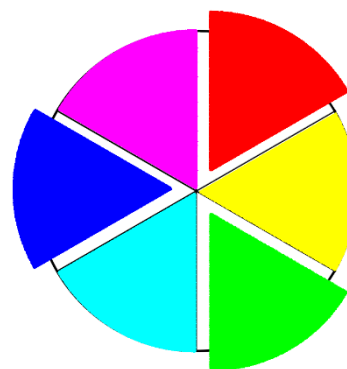
Human eye while perceiving color has high sensitivity at wavelengths of about 630nm (red), 530 nm (green), 450 nm(blue). In computer graphics these three colors are used as a base to display color output on a monitor. We can represent this model in space with 3 axes, one for each color where the origin

Figure 2, RGB Color Wheel, Created in Photoshop 2019

(0,0,0) represents the black color and (1,1,1) for white color. This way we can represent each color as a triple (R, G,B) where values between (0,1) are assigned to each color. This technique is called color cube.

For example, to represent magenta we need to add blue and red in the same proportion, so we can describe it as a triplet (1,0,1). Yellow can be obtained in the same way by adding red and green, so we have a triplet (1,1,0). By combining all three colors we obtain white (1,1,1).

Another approach to RGB model assigns to colors values between (0,255) or as a percentage from 0% to 100% and obtains colors in the same way.

RGBA (Red, Green, Blue, Alpha) is a subcategory of RGB color model, but supplemented with Alpha channel. Alpha indicates how opaque or transparent each color is. This model is very helpful in creating semi-transparent materials and textures for Computer Graphics.
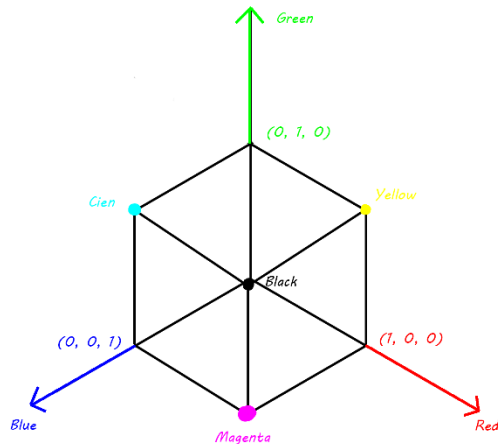
Figure 3, RYB Color Cube, Created in Photoshop 2019

CMYK

CMYK is a subtractive color model which is essentially opposite to the RGB color model. It is widely used in inks, paints, and prints and is also used to describe the printing process. In printing, a different model from the ones above is used in order to reduce the amount of ink that is spent. The primary colors of this model are Cyan, Magenta and Yellow. The ink reduces the light that would be reflected so it subtracts the red, green and blue colors from the white.

It is easier to understand if we think of a white color as the combination of all the other colors. So, if for example, we subtract the red from the white the color that is produced is the cyan. Similarly, the other primary colors of this model are produced.

Figure 4, CMYK Color Model, Created in Photoshop 2019

white light - red = cyan

white light - blue = yellow

white light - green = magenta

In this model due to the subtractive process black is represented by (1,1,1) if we use the same approach of a triplet. That means that an equal amount of every primary color produces shades of gray.

For example, if we want to represent red color, we need to use the same amount of yellow and magenta, so we have a triplet (0,1,1) and similarly for the green color we have (1,0,1). The whit color is given by (0,0,0).

HSV

HSL (hue, saturation, lightness) and HSV (hue, saturation, value) or HSB (hue, saturation, brightness) is a different representation of the RGB model that is very similar to the way humans perceive and understand color mixing and can be described comparing with the way painters mix colors. Painters use the pure hue colors or primary colors and their mixes to create the different hues (orange, purple etc) and then adjust by using white and black colors to achieve more light or dark result. It is easier to understand the color making than the set of three numbers used in models above.

Color Theory

It is undeniable that the color is one of the most significant aspects of the perception of the surrounding environment. It is important to understand the way colors can be used in order to achieve a specific result and the way they interact with each other. As already mentioned before, colors not only give life to the image or scene but also significantly influence the whole atmosphere and mood.

The human perception of isolated color may be significantly influenced by the surrounding environment. That has a psychological explanation and is often referred to as simultaneous contrast where one color can change the perception of another when placed side by side. To examine color objectively, it should be placed in isolation and to a neutral lighting environment.

Color Wheels are a way to visually represent the colors and the relationship between them. It is an easy approach to see the primary colors, the complementary, the warm and cool colors and create harmonic combinations. It may be difficult for an inexperienced user to describe and examine colors. They can be used in order to study color transitions and interactions, to visualize them and to represent color models as well. Color mixing can also be learned with the help of color wheels.

Colors are usually characterized as being warm when they have a red-yellow-orange-brown color spectrum, cool when their spectrum is blue-purple-green and neutral are the ones that are not saturated and are closer to grey values.
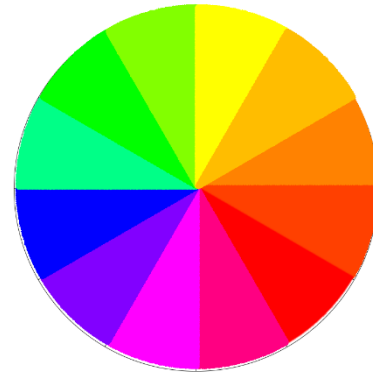
Figure 5, General Color Wheel, Created in Photoshop 2019

Color Psychology

Color is an important factor in object recognition and separation. However, colors also have the ability to influence the emotions of a viewer in a specific way. Human brain uses previous experience to recognize shapes and colors, so only unfamiliar objects usually are perceived in the same way the eye sees them. There is a strong relationship between colors and emotions that has a great effect on the way humans perceive the surrounding environment. People tend to respond to colors they see around them in a similar way, as similar emotions are triggered. Usage of color is crucial for modern marketing as the combination of colors and images may affect buyers' reaction to a specific product in both positive and negative ways.

Even though colors tend to create similar emotions to people it is also been recorded that the responses were slightly different based on the culture of the people examined. Some studies show that red color can be associated with jealousy and envy in some tests and with fear and anger in others based on the culture. However, it is not very clear which color associations are culture based and which are general among people. Although it is certain that there are minor differences in color associations and emotions based on culture. Responses to color are also based on the individual experience, so people sharing the same culture are very likely to have common associations.

When seeing an image, it's content and subject affect the viewer. However, the colors of the image establish and significantly affect the triggered emotions. Studies have shown that people tend to categorize images and emotions that they evoke significantly based on color. Images of similar color palettes tend to evoke similar emotions even despite the differences in the content and the subject depicted.

Saturated colors that have no black or white in them tend to be more provocative and exciting, on the other hand more neutral colors are more pleasing to the eye and calming. Lighter colors become more enjoyable and soothing and when colors become darker by adding black it seems to be more unappealing.

Specific colors however tend to evoke more specific emotions as many studies show. Even though the results are not always exactly the same, some general categories of emotions triggered by each color have been developed based on the psychological responses.

Green is a cool color that is commonly associated with calm, peace and fertility. The reason for that is the connection with nature and plants, where it usually appears as the primary color. It is often used by designers to express the bond and connection with nature, eco-friendly and peaceful intentions. In many countries it is a color associated with life, nature, health and hope. However, it may also be associated with envy and toxicity. We often associate green color with safety, as the green color on the traffic lights is the indicator of safe movement.

Blue is usually associated with calmness, stability, confidence and relaxation. It is the color that humans see in big amounts due to its presence as the main color in the sky and the sea, so it feels spacious. It is often used by designers to symbolize cleanliness, water, but also nobility and loyalty. Combined with other colors however, blue tends to be pushed back and blue areas appear smaller. on the other hand, it can create a sad and cold feeling when there is no other color to balance it out. If we imagine a scene of a cold and lonely environment blue is usually the color that appears in mind.

Red is a very emotionally charged color that is often associated with strong emotions such as anger, hatred, frustration, desire, passion, adrenaline, and error and makes us feel on edge. It may also be associated with danger as in a traffic light or in computer graphics where red is often used as color to indicate low life or if a player is under attack. For example, a person's face can become red when he is angry, resulting in many people associating red with danger and anger. This seems to be the color humans have the strongest reaction to.

Yellow and orange are more often associated with bright emotions, happiness, and joy. They are friendly and full of energy colors connected with the sun, flowers, children, daily activities and tend to attract the attention of the viewer. Being warm colors, they tend to create a softer and cozier atmosphere. That are the colors of warm light and fire, so it is often used to achieve a warm feeling.

White according to Newton contains all the colors in it, even if we cannot separate them. It is a color associated with light, purity, simplicity and cleanliness but can also feel lifeless and emotionless. It is a color that is the most objective in order to show a specific environment, since the objects illuminated by the white color of light ten to show the characteristics of the materials without influence of the environment.

Contrary to **Black** which tends to remind us of darkness, fears, mystery, but also mourning, sorrow and grief and is associated with night and death. It can be used in images to create negative space and attract the attention of the viewer to the focal point and also to create a dramatic atmosphere with high contrast. It can also be a more formal color and elegant color.

Color Schemes

Colors used in a scene set a style as well as the lighting does. It is often for the color style to be described based on the palette which includes hue, tint and brightness. Usually a small range of colors is used to create a color style of scene based on their relationship with each other. However, often choosing color combinations may be challenging for the artists who do not have a proper art and color theory knowledge and that leads to significant time needed in order to choose suitable colors.

Color harmony is a combination of colors that produce a pleasing effect on the scene when used together. Usually colors that result in color harmony are those that are evenly distributed on a color wheel Wilhelm Ostwald in his work proposed that colors that are in harmony usually are the ones that have the same amount of white/black in them, the same distance on the color wheel or similar hue values. On the other hand, Albert Munsell states in his work that colors can be in harmony only when they are on achromatic axis, have equal hue values, sequential colors where values change slightly or complementary colors with equal values. Generally, studies have shown that color harmony can be achieved when colors have similar or equal chroma value, equal hue value or similar lightness value. However, there are more factors that can influence color harmony besides hue and chroma. According to some studies, perception and response to colors are influenced also by trends and culture that frequently change, by personal preferences and taste, education, age and much more.

Figure 6, Matrix, 1999, Directed by The Wachowski Brothers, Director of photography Bill Pope

Methods to achieve color harmony have been created based on statistical analysis and researches. There are three main methods that have been established and are used in order to set a color palette and achieve color harmony in a scene or in a scene.

Monochromatic or Analogous: Colors close on the color wheel do not have a significant contrast, with similar or equal hue are more pleasing to look at. But they can also create a feeling of emptiness, toxicity and boredom.

Complementary Scheme: colors that are on the opposite ends of the color wheel. They complement one another and add balance to the image.

Triadic color scheme: equal distance on the color wheel. Similar colors tend to create a calmer and trusting atmosphere than the ones with more vivid color changes.
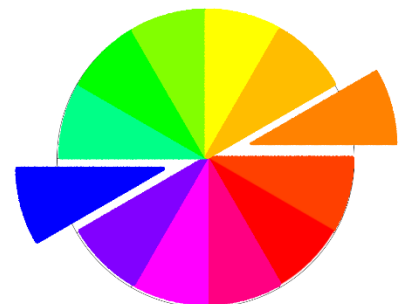

Figure 7, Complementary Colors Wheel, Created in Photoshop 2019

If a scene follows a color scheme, but just one element does not, it will create a contrast and will attract viewer attention almost immediately and draw the eyes towards it.

Figure 8, Blade Runner, 1982, Directed by Ridley Scott, director of photography Jordan Cronenweth, Complementary color scheme

Color usage in cinematography

Color design in cinematography and animation is one of the most important parts to establish an atmosphere of the movie along with the lighting design. There is always a reason behind any color choice present in a scene. Great amount of time, effort and resources are often spent in order to create the desired output. In cinematography we can often observe the usage of different colors in order to influence the viewers' emotions, to give depth to the scene or to create a specific atmosphere. Color can help to interpret a scene in a certain way, simplify a complex scenario and idea, and emphasize an important moment. Color can be used to differentiate between a specific time or place, dreams and reality and show a story from a different perspective.

Colors in cinematography are very often used as associations. That means that the viewer associates the color with a certain subject, theme, idea or event. The repetition of a color is always intended and shows some relation to an idea. After seeing the same colors repeatedly, viewers subconsciously connect the color with certain situations, and it is often used to prepare the audience for the upcoming events or help interpret a scene in a specific way. It can be achieved through the colors of clothing, light and surrounding objects. Great example of the color repetition is the "Matrix" trilogy movies where green color is associated with the programming code and is constantly present in the parts that take place inside the matrix to differentiate these scenes from the real world.

On the other hand, a changing color can show a transition. Introducing a different color that does not fit with the previous color scheme is used to separate the scenes and to show that the mood of the scene has changed. It can symbolize a change of location or a change in a character. When colors change drastically it will not go unnoticed by the audience and will immediately draw their attention to try to explain the situation. But even smaller changes can influence the viewers' response and emotions through the scene or the whole movie.

Similar movie genres often use similar color palettes to express the emotions. For example, comedies use brighter colors such as yellow, oranges and pinks. Horror movies often use dark colors and a lot of grays. Besides the emotions connected with the certain colors it is easier for

the audience to interpret the scene when it uses similar colors that they are used to see and enhance the emotions and mood produced.

Filmmakers try to maintain color consistency through the scene with costumes, lighting and background colors. The consistency is a very important factor in order to emphasize the storyline, dialogs, character and can be used to achieve surprising artistic effect. Consistency is what sets the whole mood and atmosphere of the movie and gives it stylistic feeling easier for the audience not only to interpret but also to remember.

Light

Light is a form of energy that consists of visible light for the human eye and other electromagnetic radiation. Light travels in small but discrete amounts of energy called photons. Human eye can see only a small portion of the electromagnetic radiation and human vision is different from other many other species. Some species cannot discriminate colors and others, as insects, for example, see ultraviolet radiation. This makes different species perceive the surrounding environment in a completely different way.

Human eye consists of two types of cells called cones and rods. Cons are active under good light conditions and are responsible for color vision, the ability of humans to discriminate color. Rods on the other hand are active in insufficient light conditions and are more sensitive to movement and light. The difference in the behavior of the two types has as a result the inability of the human eye to adjust immediately to sudden light changes. For example, if we go from well illuminated environment into a dark room, our eyes will need some time to adjust to be able to see in the changed circumstances.

Objects are visible depending on the amount of light that is reflected from their surface. Depending on the material and its properties, part of the incident light is reflected to the opposite direction, part spreads around in different directions, another part is absorbed by the object and if we have transparency of the object material, part of light is transferred through the object. All these properties make the materials to appear so differently and the need for a separate approach in order to recreate them in the computer graphics environments.

However, light can be used not only to make objects and environments visible, but also as an artistic medium. It can be used to create a specific atmosphere, evoke emotions, create contrast, atmosphere and drama, show time of the day or season, show a personality of a character, but also to guide the viewer through the scene. Light can be used as a symbol itself. It is a symbol of hope, purification and knowledge, it makes things clear and shines light upon them. It has also a great connection with religion. This are the reason why the modern Game Industry is beginning to consider light design as one of the most important aspects of game development.

Light in Game Development can be used to achieve a variety of different effects, even though a scene in a game may often be unpredictable and complicated depending on every player's way of playing, camera directions, environment factors etc. Lighting can significantly influence the game aesthetics, communication with the player, the flow of the narration and the overall player's experience. It provides visibility to important elements, guides the player through the scene or level, and provides the necessary information for the player, such as time of the day, weather and more. Bad or insufficient lighting in a scene can cause the player to lose his concentration, miss important for the story elements, experience difficulties in moving and understanding the environment. Scene illumination should be chosen wisely and strategically to fulfill all of the need mentioned in order to complete its purpose.

Total environmental lighting in a scene is a contribution of lighting sources and reflections of the objects present in a scene. However, surfaces that are not directly lit by the light source can still be visible and illuminated if the surrounding objects are illuminated. Illumination of the scene

depends not only on the light sources but also on the material and textures of the object present, their position relative to the light source and the viewer and also lighting conditions. Shiny objects reflect larger amounts of light than rough do and transparent objects tend to transfer part of the light through the material that can result in illumination of the surfaces behind the object. Rough materials produce more diffuse reflections and tend to appear illuminated from all viewing directions. In addition, shiny materials produce specular highlights, that appear as bright spots on their surface. All of these factors should to be considered into account in order to create realistically illuminated environment.

Basic Illumination Models

Through the years different methods and algorithms have been invented in order to recreate and approach the real-world illumination. Due to the technology and hardware restrictions that exist it is still not possible to recreate completely the behavior of the light in a real world, so some of these methods have been more effective to reduce computation and rendering time than others based on the needs of a scene without sacrificing to much of the realism of the image. It is important for the lighting artists to understand these methods and being able to use and combine them based on the requirements of every scene and project.

Ambient Light and Diffuse Reflection

Ambient light is one of the simplest lighting techniques that makes sure that all the objects are evenly lit and visible. In this case objects are not directly exposed to the light source but are still visible through a constant light that exists in a scene. Light is stable and constant for all surfaces, textures and directions resulting in a constant reflected light throughout the scene. However, the visible results may vary depending on the properties of the material of every object.

This type of lighting can be important but usually is used in combination with other light sources and techniques as it appears to be very flat and unflattering when used alone. It can be used to add additional light to the scene without determining a light source. When used correctly it can create the illusion of bouncing

Figure 9, Diffuse lighting, Rendered in Blender, area light, Cycles rendering engine

light, add light to the insufficiently illuminated scene and prevent completely dark parts and areas. Advanced illumination models such as Ray Tracing discussed later, can eliminate the need for additional flat lighting, but sometimes it is still used as base lighting in a scene.
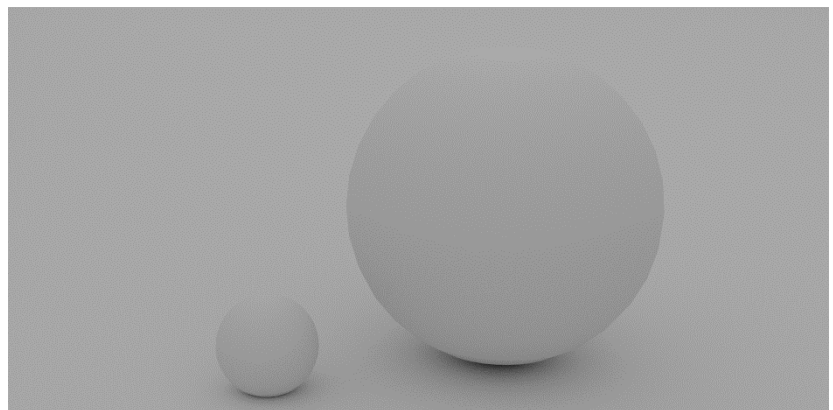
We can calculate ambient light in a scene as:

$$I_{amb} = m_a s_a$$

Where m_a is the material color and s_a is the color of the light.

More color of a surface computations for RGB color model can be found in following paragraph.

The reflection of ambient light is an approximation of the diffuse light reflection that is constant on every surface present on a scene and does not depend on the viewing direction. Materials that are rough and not shiny such as paper or plaster tend to show diffuse characteristics while reflecting light contrary to materials such a glass or metal.

We can calculate the diffuse reflection using the following equation

$$I_{dif} = dot(n,l)m_d s_d$$

Where m_d is material color, s_d light color and $dot(n,l)$ is the dot product of two vectors.

Ambient material color

Ambient material color is the one that is produced when the surface is illuminated with a simple diffuse light. When light hits the object, the only factors that influence the color perceived by the human eye are the color of the material of the surface and the color of the light. That means that if the color light is white, the material will appear to be its original color. On the other hand, if we use colored light, the final color perceived will be different from the color of the material.

Color of the material:

$$m_a = \left(r_S, r_g, r_b\right)$$

Color of ambient light: $s_a = \left(r_S, r_g, r_b\right)$

Color of the surface due to ambient light:

$$I_{amb} = m_a \cdot s_a$$

Example 1:

If we take an object with red material

$$m_a = (1.0, 0.0, 0.0)$$

and illuminate it with white ambient light

$$s_a = (1.0, 1.0, 1.0)$$

we can calculate the final color of the object

$$m_a \cdot s_a = (1.0, 0.0, 0.0) \cdot (1.0, 1.0, 1.0) =$$

$$(1.0, 0.0, 0.0)$$

So the object color will appear to be red.

Example 2:

On the other hand, if we take the same red object with color of the material

$$m_a = (1.0, 0.0, 0.0)$$

and illuminate it with blue ambient light

$$s_a = (0.0, 0.0, 1.0)$$

the final color of the object will be:

$$m_a \cdot s_a = (1.0, 0.0, 0.0) \cdot (0.0, 0.0, 1.0) =$$

$$(0.0, 0.0, 0.0)$$

So, the object color will appear to be black.

Figure 10, Color Computations 1, Rendered in Blender, point light, Cycles rendering engine
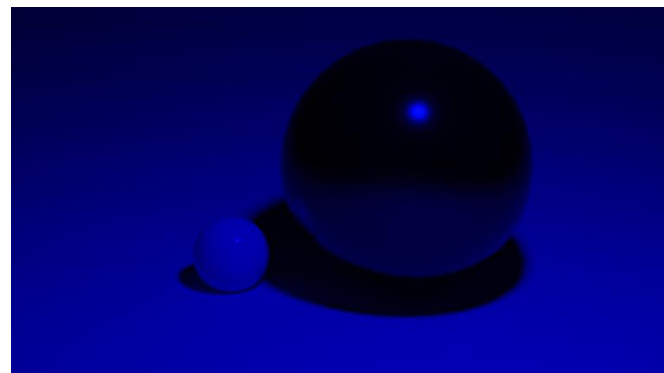
Figure 11, Color Computations 2, Rendered in Blender, point light, Cycles rendering engine

These are only few of many interesting examples that show the way how color of the light can influence the color of the object that the human eye perceives. We see similar phenomena every day. A white wall in a room, for example, may appear gray, yellow or light blue depending on the surrounding light even though human eyes usually interpret it as white.

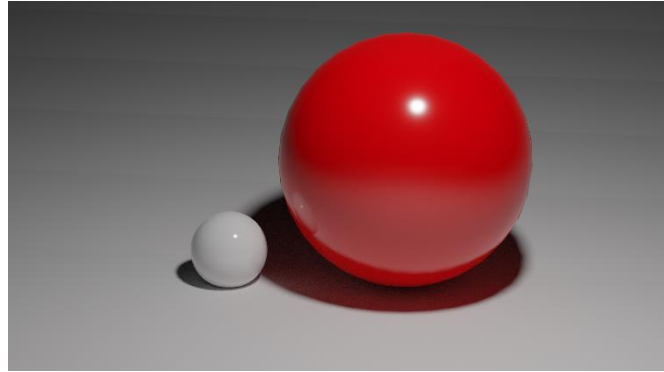The perfect diffuse reflective surface is described by Lambertian model.

Lambertian Model

Assuming that we have a perfectly diffuse surface where the reflection does not depend on the camera direction and position as described above, where light is scattered with equal intensity to all directions. These surfaces are called perfect diffuse reflectors or Lambertian reflectors. In this case lighting can be handled by Lambert's cosine law, which states that the light scattering of this surface depends on the cosine of the angle between the incoming light and a surface normal. However, the brightness of the surface depends on the relative position to the light source.

In case when the surface point and a light source are perpendicular, the specific surface point is fully illuminated, and the brightness decreases as the surface is transferred further from the light source.

If I, is the intensity of the point light source, then the diffuse reflection equation for a point on the surface is:

$$I_{dif} = k_d I cos\theta$$

When a surface is illuminated only by single point light source, if the angle range is between 0 and 90 degrees the cosine will be between 0 and 1. If the cosine is negative we can assume that the light source is positioned behind the surface that we examine.

For single point source diffuse illumination, the equation becomes:

$$I_{dif} = k_d \cdot I \cdot dot(\dot{N}, L)$$

Where N is the normal unit vector, L is the direction unit vector of light and reflections are calculated in world coordinates or viewing coordinates.

Combining ambient and point-source light we have total diffuse reflection is given by the equation:

$$I_{dif} = k_a I_a + k_d I_l \, dot(\dot{N}, L)$$

Where k_a is ambient-reflection coefficient and k_a and k_d depend on the surface material properties with range (0,1), *dot(N,L) = cosθ*.

Lambert cosine law for color

We can apply Lambert's cosine law to calculate colors of a surface. We take the law that gives us the diffuse reflection mentioned before:

Diffuse reflection

$$I_d = dot(\dot{n}, l) = |n| \cdot |l| \cdot cos\theta = cos\theta$$

Where (*n*) is the normal unit vector and (*l*) is the light unit vector and add the color factors:

$$I_d = dot(n, l) \cdot m_d \cdot s_d$$

Where (m_d) is the material diffuse color which is usually the base color and (s_d) is the light diffuse color. This way we can calculate the final color of the object.

Bidirectional Reflectance Distribution Function

Bidirectional Reflectance Distribution Function (BRDF) is a function that describes the way light reflects from an opaque surface, it is a quite simple method to create diffuse reflectors. It is proportional to the material of the object that is lit and takes the light that arrives to the surface, the direction of reflected light, the surface normal and produces the radiance of reflected light. The result depends both on the incoming rays' direction (illumination direction) and the direction of the camera (viewing direction). BRDF is an algorithm that is employed in real-world lighting.
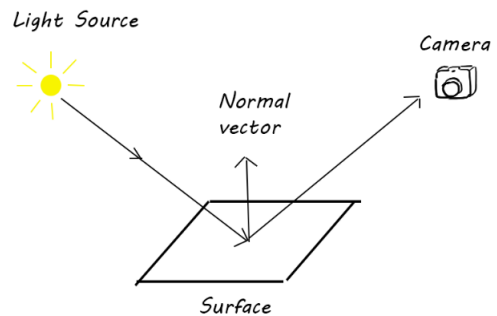

Figure 12, BRDF scheme, created in Photoshop 2019

For the incoming light we have the irradiance E(θ_i, ϕ_i) per unit area and for the viewing direction we have reflected radiance L(θ_r, ϕ_r) per unit of solid angle.

BRDF = quantity of light reflected in direction (eye, camera) *L(θ_r, ϕ_r)*/ quantity of light arrived from direction (direction of light) *E(θ_i, ϕ_i)*

= radiance (energy reflected per unit area watt/meter^2)/irradiance

$$P(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_r(\theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)}$$

A good example for this is a perfect mirror where all the incoming light is not scattered but reflected to the direction of the camera. In this case the incoming light direction angle is equal to the camera direction. This effect is the opposite of the diffuse reflection where the reflected light on the surface is independent from the camera direction.

When the surface appears to be equally bright independent from the viewing direction then the

quantity of photons arriving to the area depends on the angle between light and surface and we can use the **Lambertian equation** to calculate the surface radiance and the BRDF in this case will:

$$Li \cdot area \cdot \dot{dot}(n, l) = Li \cdot area \cdot cos\theta$$

Where area is equal to the to the product of width and height of the differential solid angle. θ is the angle of light and normal of surface.

Classes of BRDF

- Isotropic BRDF : The reflection on a surface does not change based on the orientation of that surface.

- Anisotropic BRDF : The reflection on a surface is not evenly distributed and changes based on the surface orientation

Specular Reflection and the Phong Model

When light hits some objects, we tend to see a highlight on its surface that is a consequence of a partial or total reflection of light source on a surface of an object. That phenomena depends on the angle that a surface faces the light source. Properties of each material can influence the appearance of the highlight on a surface. For example, rough materials tend to have a bigger and softer highlight compared to the shiny surfaces that develop a sharper and more definite highlight.

A model to measure this type of reflections was developed by Phong Bui Tuong and was named after him as the Phong Specular Reflection Model. This model describes the intensity of the specular reflections relative to the cosine of the viewing angle, the properties of the material of the surface and the color of the light. We can calculate
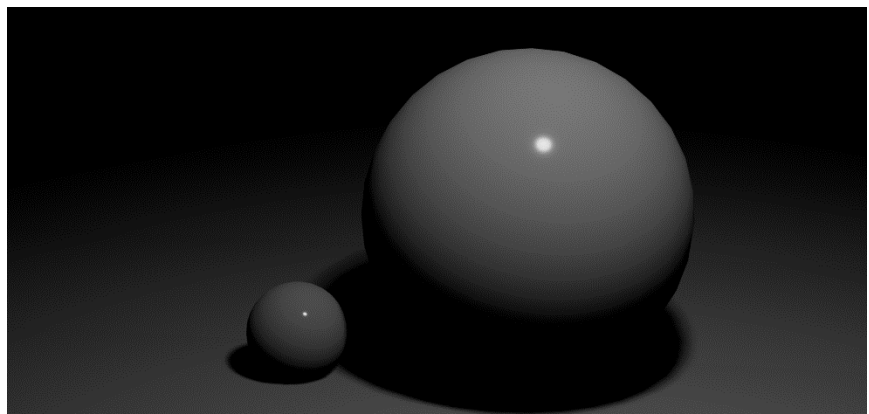

Figure 13, Specular Reflection, Rendered in Blender, point light 80W, Eevee rendering engine

specular reflection using the Phong model for opaque materials that have near constant specular reflection as:

$$I_{spec} = dot(\dot{r}, v) \cdot m_s \cdot s_s$$

Where *r* is the light unit vector, *v* is the camera unit vector (viewing direction vector), m_s the material specular color and s_s is the light specular color.

Phong Reflection Model

Phong model describes the way surfaces reflects lights, based on the combination of ambient color, diffuse reflection and specular highlights. For each of those factors we can assign their colors which will affect the final surface color.

Using Phong model to calculate the light

$$I_{phong} = I_{ambient} + I_{diffuse} + I_{specular} =$$

$$m_a \cdot s_a + dot(n, l) \cdot m_d \cdot s_d + dot(r, v)^m \cdot m_s \cdot s_s$$

Where (*m*) is a constant and the larger this number, the shinier the result.

Specular Reflections with color

Similarly, we can use the equation for specular reflection and use it to calculate specular reflection color.

$$I_s = dot(\dot{r}, v)^m \cdot S_s$$

Where (*r*) is the reflection of the vector (*l*) of the light and it depends on the geometry of the object, (*v*) is the unit vector to the viewer eye (camera). If the angle between (*r*) and (*v*) is 0, we have the perfect reflection direction. (*m*) is glossiness factor, it is a constant that shows us how shiny the object is, so larger number means a shinier object.

This equation shows that the moving specular reflection depends on the position of the camera.

Combined Diffuse and Specular Reflections with Multiple Light Sources

In a scene where the only light source is a point light, we can combine the diffuse and specular reflections

on the illuminated object's surface as:

$$I_{combined} = I_{diff} + I_{spec} = \dot{dot}(n, l) \cdot m_d \cdot s_d + \dot{dot}(r, v) \cdot m_s \cdot s_s$$

Following this method, we can combine multiple light reflections on a surface by adding the contribution of each of the light sources. This way we can achieve much more complex and realistic output on a scene combining different light sources and creating more sophisticated results.

Transparency

The ability to recreate transparency of a material in Computer Graphics is one of the most challenging parts of the field, since many elements need to be considered into account in order to produce accurate and realistic result. Transparent materials such as glass, when illuminated by a light source have the ability to reflect part of this light and transmit another part through the material. The amount of light transmitted through the material depends on the transparency properties of the material and the relative position of the surface to the light source. Transparent materials can support both specular and diffuse transmission. For example, diffuse transmissions can be essential for semi-transparent materials since the light transferred through the material is scattered and creates a muted and blurred representation of the objects on the background.

To achieve realistic transparent materials, properties such as light refraction should be taken into account. As the speed of light transferred through the material depends on its properties, the path that the refracted light takes is different from the one that the incidence light has.

Refraction angle (θ_r) can be calculated based on the angle of incidence light (θ_i), the refraction index (n_i) of the material and the refraction index (n_r) of the material through which incident light is transferred (usually air). So, using Snell's law we have:

Figure 14, Rendered with Blender 2.82, Cycles rendering engine, transmission 1.000, specular 1.000

$$sin\theta_r = \frac{n_i}{n_r} \cdot sin\theta_i$$

We can compute the combination of the intensity (I_{trans}) that is transmitted through the surface from the objects on the background with the intensity (I_{refl}) of the light that is reflected from the transparent object. To do so we need to introduce a coefficient of transparency factor (k_t) and assign to it a value between 0 and 1. This way we can make more specific the amount of the
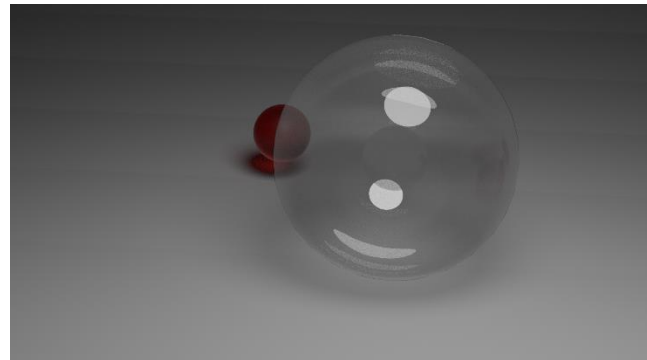
background light that is transmitted through the surface. The total intensity of a surface can then be calculated as:

$$I_{total} = (1 - k_t) \cdot I_{refl} + k_t I_{trans}$$

Where $(1 - k_t)$ is the opacity factor.

For more transparent objects we set the coefficient k_t closer to 1, and near 0 to opaque objects when almost no light is transferred through and have the opacity factor near 1.

Shadows

Shadows are as important as light is in a scene. Hidden surface determination is a method to locate if an object or a surface is visible from a certain viewing direction (camera vector). It is crucial to render a scene in a correct way and to determine which surfaces should be visible to the camera.

This method can be used to determine which objects and surfaces are visible to the light sources and to create shadows. Applying this method can show which objects are hidden from the "viewing direction" of a light source which means they are not directly lit. Depth buffer or Z-Buffer can be used to help achieve this goal. In depth buffer surfaces are stored based on their position in a scene and specifically their position on the z-axis. That means that any surface that is located farther away from the light source is not visible to it, so we can assume that it is located in shadow. If we can gather this information for all the light sources in a scene, we can store this information as a pattern on a surface or in pattern arrays.

Polygon Rendering Methods

A most used rendering method to create a surface is the Polygon Rendering Method that uses polygons to simulate objects with curved surfaces. Two methods are used to create lighting on a surface that is rendered with this method. The first one is to render each polygon in one intensity and is called constant-intensity shading. In this method all the vertices of a polygon are rendered with the same intensity. The second is to assign different intensity to each vertex of the polygon (each point).

Gouraud Shading

Gouraud shading is an intensity-interpolation method developed by Henri Gouraud and first published in 1971. It is a method to render polygons of a surface by interpolating the intensity over the surface of the object. This method associates the intensity values of a polygon vertex with the values of the bordering polygons along the edges. It is much more efficient method than flat shading, since it helps to remove the differences and gaps that may appear in the constant-intensity shading and achieve more realistic results. Illumination models are applied to each vertex of the surface to calculate the illumination on each point and then interpolate these values on the polygons.
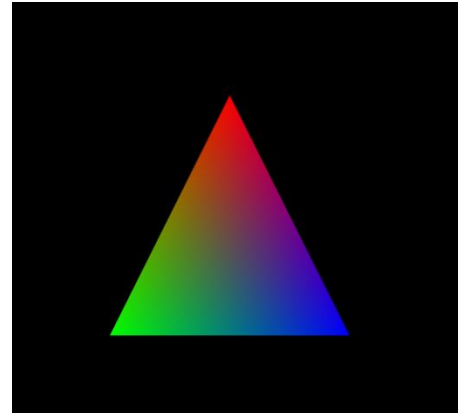
Figure 15, Gouraud shading imitation, WebGL, Javascript

The problem in this method occurs when specular highlight is positioned in the middle of a polygon. In this case the interpolation is based on the vertex colors and the highlight may be lost from the surface of the object. The effectiveness of this method, however, is proportional to the number of polygons present on a mesh. The larger the number of polygons, the better the result.

Phong Shading

A more accurate polygon rendering method was developed by Bui Tuong Phong. It improves the Gouraud shading method and uses normal vectors of the polygons to interpolate the intensity values and calculate the intensity across the surface. This method is called Phong shading and more realistic results can be achieved with the use of it. It is also possible to obtain naturalistic highlights and reduce the discontinuities on a surface.

To apply this method, we need to calculate the normal vector of each vector of a polygon and then interpolate and normalize these normals across the polygon surface. Illumination techniques (usually the Phong reflection model) are applied then to calculate the intensity of projected pixels to calculate the final color of each pixel and create the final image.

Ray-Tracing Methods

Many methods have been developed to imitate real world lighting, but there is one that has been the most efficient and produces the most realistic results. The method is called ray tracing and is known for many decades, but only through recent years has there appeared a possibility to use it more widely due to technological innovations.

The general idea of this method is that for every pixel on a screen we run a ray from the camera through that pixel to the scene. We test the rays on the objects on the scene and see where it hits, and which objects are intersected. We collect the point that the ray hits on the scene and we save the one that is closest to our camera (eyes) by measuring the distance between the point and the camera. Then we will color the point accordingly.
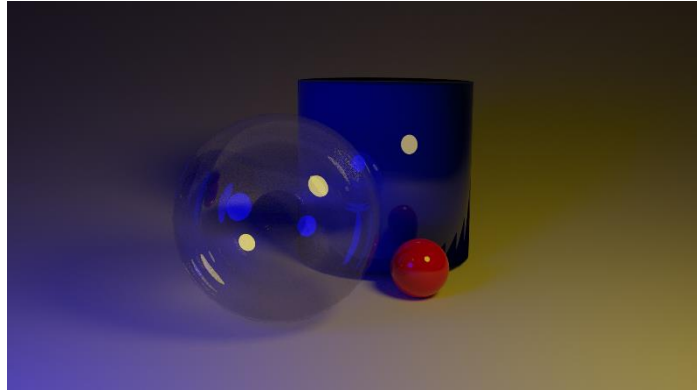
Figure 16, Rendered in Blender 2.82, Cycles rendering engine using path tracing, 2 point lights

Basic Ray-Tracing Algorithm

Light on a scene is scattered from all the surfaces to different directions and only some of them are the ones that will reach the projection plane. The infinite number of rays makes it extremely resource consuming and almost impossible to calculate with the hardware of our times. We can calculate the contribution to the illumination of a scene by tracing a path back from every projected pixel to a light source. The basic Ray tracing algorithm uses one ray per pixel to calculate the illumination of a scene.

For each pixel we send a ray to examine all the surfaces present on a scene to discover which of them are intersected by this ray. If we find a surface that is intersected by the ray we examine, we need to calculate the distance between the pixel and the intersection point. We need to find the closest point that is intersected, which means that the surface is visible to the pixel we examine. Next step is to reflect the ray and make it follow a certain path depending on the incidence angle. We need to examine the opacity of the surface and in case it is transparent we need to send a ray to retraction direction as well. The rays that are sent as refraction or reflection are called secondary rays.

Repeating this process for every secondary ray and we produce the next generation of reflected and refracted rays. Every time a ray successfully hits a surface as it travels through the scene, this surface is added to a ray-tracing tree. Left branches are used to represent reflection rays and right for the refracted ones. If an intersected surface is not found, we assign to the pixel a background intensity value.

In case we have to deal with a transparent material, the contribution of light that travels through the material is needed to be calculated. A ray should be traced to the transmission direction to determine the light source contribution. We can calculate the unity transmission vector (T) as:

$$T = \frac{n_i}{n_r}u - \left(cos\theta_r - \frac{n_i}{n_r} \cdot cos\theta_i\right) \cdot N$$

Where n_i is the incident materials refraction indicator and n_r is the refracting material.

Ray-Surface Intersection Calculations

To apply the ray tracing algorithms, it is crucial to determine which surfaces are interested by the ray we send. Ray-surface intersection method is needed for shadow rays in order to determine if there is intersection with the object. If there is intersection, we need to determine the distance of the intersected surface in order to calculate the color of the pixel. For primary rays we need the point of intersection, the materials of the object at a specific point, the normal vector of that point and the texture.

Ray-Sphere Interaction

Ray intersection with sphere is probably the most simple example of ray-surface intersection. It is easy to calculate even without use of computer and is a proper method to explain ray surface intersections and the way ray-tracing works.

Assuming that we have a sphere and a ray is sent to hit it. We need the origin point of the ray (R_o), ray direction (R_d), a parameter (t) that starts from 0, its value is greater than 0 and it describes the time passed, corresponding to the distance along the way. If ($t = 0$) then the point is going to be ($R_o + 0$) and if (t) increases the point will start moving along the ray.

$$p = R_o + R_d \cdot t$$

(S) is center of the sphere, point (t) is closest to center ,90 degrees to the ray. Point (t) can be calculated by using simple dot product.

$$t = dot(S \dot{-} R_0, R_d)$$

We have *t1, t2* that represent the points where ray intersects the sphere that we want to examine. The ray hits the sphere in 2 points unless it just touches it on the outside, so we have just 1 point of intersection, but we assume that it hits in 2 places for this example.

Where (*S-Ro*) is the vector from the origin (R_0) to the center (*S*) of the sphere. If the dot product is less than the radius (*r*) then there is no intersection and the ray missed the object.

Sphere equation:

$$x^2 + y^2 = R^2 \Rightarrow x = \pm\sqrt{R^2 - y^2}$$
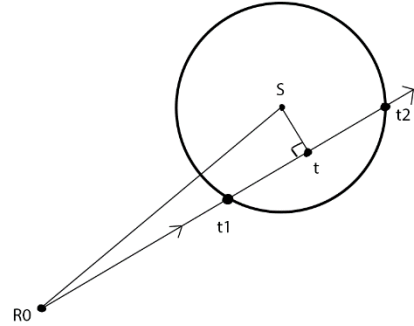
$$t_1 = t - x$$

$$t_2 = t + x$$

Figure 17, Ray-circle intersections, created in Photoshop 2019

Ray polygon intersection

Usually in Computer Graphics we have to deal with polygon intersections due to the Polygon rendering method that is usually used in rendering 3D models. If an object consists of polygons it will be easier to calculate the color of each of the polygons if we can determine which polygons are hit by the ray.

To calculate the point where the ray hits the polygon:

$$pointI = \left(dot\big((P + t \cdot \vec{r}) - Q\big), \vec{n}\right) = 0 \Rightarrow$$

$$dot(t \cdot \vec{r}, \vec{n}) + dot(P - Q, \vec{n}) = 0 \Rightarrow$$

$$t = \frac{-dot(p - q, \vec{n})}{dot(\vec{r}, \vec{n})}, \qquad dot(\vec{r}, \vec{n}) \neq 0$$

We have to examine if $dot(\vec{r}, \vec{n}) \neq 0$, and in case it is equal to 0 then ($\vec{r}$) is perpendicular to ($\vec{n}$), so the ray is never going to hit the plane, unless it lies on it.
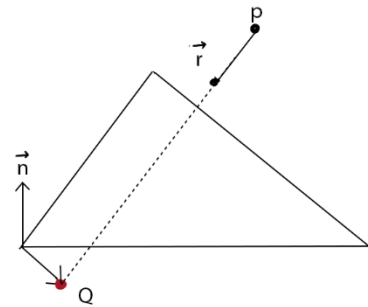
Figure 18, Ray-polygon intersections, created in Photoshop 2019

There are different ways to examine if the ray is inside the polygon and two most popular are:

1. Barycentric coordinates:

    for any point P on the polygon we have

$$P = a_1 P_1 + a_2 P_2 + a_3 P_3$$

    Where

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$$a_1 + a_2 + a_3 = 1$$

and P1, P2, P3 are of (X, Y, Z) type.

In this equation we have enough information to solve for all the values and if all the *a* values are between (0, 1) then the ray is inside the polygon.

2. Clipping test: we put planes perpendicular to the polygon and the ray needs to be between all of them otherwise the ray hits outside the polygon.

Calculating lights and colors based on the ray tracing technique can produce highly realistic results, but at a great cost. In a scene with many objects a significant amount of time is required to process objects and surfaces that are not visible to the camera. Many techniques have been used to reduce this amount of time and required amount of resources.

One way is to include objects in groups of volumes such as boxes and test the rays intersections with these volumes. We can include these volumes in bigger groups and inspect them hierarchically.

Another way is the **Space-Subdivision Method** where we can subdivide objects and this information can be stored in an octree or a binary-partition tree. It is possible to use a partition of cubes to subdivide objects in our scene until each subdivision contains a certain maximum number of surfaces. We then can trace a ray through those subdivisions and when we hit a subdivision, we only trace objects that are included in a subdivision. This way if a ray is far away from a subdivision, it will never hit it and we can save a considerable amount of time and resources.

Turner Whitted

Originally ray tracing was very expensive in terms of calculation, so it was not possible to perform this method without a reasonable amount of resources. Until in the 1979 J. Turner Whitted with his paper "An improved illumination model for shaded display" proposed a different approach trying to solve 3 basic problems of graphics that existed during the time: shadows, reflections and refractions through objects.

Whitted proposed that we should trace a ray from a point on a surface to the light source and not from the camera. We look at all the scene, keep track of the objects hit by the ray and then we select the closest one and if it's closer than the light source that means we have something in the way. This way we produce the "shadow ray" and to calculate it we drop the specular and diffuse part of the Phong equation, and we only do the ambient part. This way we can achieve shadows in a much more efficient way.

In case we have more than one light source in a scene, then we will multiply our calculations by the light source number.

Using the Phong model equation we have:

$$I_{phong} = I_{ambient} + I_{diffuse} + I_{specular} =$$

$$m_a \cdot s_a + dot(\dot{n}, l) \cdot m_d \cdot s_d + dot(\dot{r}, v)^m \cdot m_s \cdot s_s$$

According to Whitted if you can't see the light source the equation becomes

$$I_{phong} = m_a \cdot s_a + dot(\dot{n}, l) \cdot m_d \cdot s_d + dot(\dot{r}, v)^m \cdot m_s \cdot s_s =$$

$$m_a \cdot s_a =$$

$$I_{ambient}$$

To calculate reflections on a surface the ray that is reflected from the object needs to be taken and traced to examine if it hits other objects on its path. We take the closest one of the rays and calculate the color of this object on the point the ray hits. That way we produce "reflection rays", and to calculate it we add this color to the basic equation multiplied by the illumination of the ray that we traced. This constant should be less than 1 because there is no perfectly reflective surface

$$I_{phong} = I_{ambient} + I_{diffuse} + I_{specular} + reflectiveConstant \cdot illuminationFormTheRay =$$

$$m_a \cdot s_a + dot(\dot{n}, l) \cdot m_d \cdot s_d + dot(\dot{r}, v)^m \cdot m_s \cdot s_s + R_c \cdot I_r$$

The problem with this is that to determine if the object that we hit is in shadow or not, we have to send a ray from it to the light source. Also, we need to see if the material of this object is reflective and, in this case, we need to cast a ray to examine what objects it reflects. To trace these rays the only information needed is a point where they start and a vector. We can use this method similarly for the refraction using the index of refraction of the material and creating a refraction ray.

Subcategories and similar techniques

Ray Casting

Ray casting is a method to create three-dimensional perspective on two-dimensional screen, firstly presented by Arthur Appel in 1968. It was the most popular rendering technique in the early three-dimensional games. In this method, a ray is sent out from each pixel to locate which surfaces are intersected to render objects and to discover surfaces that are visible on a scene.

This technique uses the ray-surface intersections and algorithms same as Ray Tracing to detect which objects are hit by the ray and solve other problems that occur.

This method sends one ray per pixel from the camera (eye) and lets it bounce through a scene to collect the necessary information for the illumination, reflections and transmissions. Only the first surface that is detected to be hit by the ray is illuminated and the rest are ignored, that means that secondary rays are not used in this method. It is simple and fast rendering method that uses a geometric algorithm of ray tracing to calculate the illumination.

Path Tracing

Path tracing is a similar category lighting technique as Ray Tracing. It is a method is based on Monte Carlo algorithms used in graphics to render 3D scenes. The difference is that this method solves the problem of increasing growth of rays with every bounce, since it only uses one ray per bounce and has a similar approach as distributed ray tracing discussed later. It randomizes the rays produced and their direction and significantly reduces the required computation time and processing costs.

The advantage of this technique is that some effects can be simulated that are difficult to recreate with other illumination methods, such as ambient occlusion, soft shadows and more. However, similarly to other algorithms of the Ray tracing category, many rays need to be cast in order to create high quality image which increases computation and time requirements.

Backwards and Forward Ray Tracing

In backwards Ray Tracing, rays are traced from the eye (camera) to examine what surfaces they hit and color them accordingly. This is a technique that can also indicate which surfaces are hidden from the light source to calculate the shadow. The problem in this method is that we can miss surfaces if we don't know the surrounding materials and objects. On the other hand, in forward Ray Tracing rays are traced from the light source and the surface that this ray touched is marked.

Antialiased Ray tracing

Ray tracing is computationally expensive method, so different techniques have been developed to improve the computation time and reduce the amount of resources needed. Two main techniques of antialiasing in ray tracing have been developed for this purpose: adaptive sampling and supersampling. In both methods pixels are treated as a square area and not as a single point. In supersampling multiple rays are spread evenly through the area of pixels. In adaptive sampling unevenly spread rays are used through the regions of the pixel area depending on the surface. Less rays may be used on a smooth and even surface where no

great color differences exist, than on the edges of the object or the number of rays can be distributed in a random way.

Distribution Ray Tracing

This method randomly distributed rays based on different parameters which allow more accurate modeling and better image quality. However, if ray distribution over the surface is completely random it may result in gathering of multiple rays in certain pixel areas leaving others completely uninspected. This problem can be solved by dividing the pixel area into smaller groups and then randomly assigning rays to these areas. This technique is called jittering. This method is often used to generate penumbra of the shadow to achieve a more realistic image. Penumbra is a softer shadow that appears on the edge of the shadow on a surface when an opaque object is blocking a light source.

Radiosity Lighting Model

This model is based on energy transmission in the environment and not on the rays as in Ray Tracing method. Radiosity is an approach to deal with global illumination introduced in 1984 and has its origins in the area of Thermal Heat transfer which is the reflection and emission of heat. This method uses the energy transfer between objects to achieve illumination. Radiosity of an area is the amount of energy that leaves this area per unit time per unit area. This method is very effective in creating the effect of "bleeding" that occurs, for example, if we place a bright red object near the white wall, in this case some red will appear on the wall as well.

It is possible to create diffuse reflection using a radiosity model, if we consider the energy that travels between surfaces. All the surfaces in the radiosity model are ideal Lambertian surfaces, which means that they reflect and emit radiation isotropically and the effect of scattering cannot be achieved. That means that the illumination of the objects is not dependent on the viewpoint or the viewing angle. Reflective surfaces however are viewpoint dependent, since the specular highlights and reflections appear differently based on the camera viewing direction. These effects are easier to achieve by using the Ray Tracing technique.

To use the Radiosity method to describe diffuse reflections, we need to examine the radiant-energy interactions of the objects and surfaces present in the scene. To achieve that, we need to establish the amount of radiant energy dB by adding the energy contribution to all the surfaces and to find the energy that is transferred between surfaces and not between single points as we did in Ray Tracing techniques.

Basic Radiosity algorithm

To calculate the overall Radiosity of the scene we need to divide the scene into smaller areas or sections and calculate the radiosity of each one of them. In this method lighting is constant for every section.

$$B_i = E_i + p_i \sum_{j=1}^{n} B_j F_{i,j}$$

Where (B_i) is the radiosity of a section we want to calculate, (E_i) is the emission of the section , (p_i) is the reflectivity factor of the section, (B_j) is the radiosity of the section (*j*), and ($B_{i,j}$) is the form element between the two sections (*i*) and (*j*) which is based on their geometrical relationship and manages the indirect lighting. The relative angle between two sections needed in order to decrease the energy amount transferred from one section to another.

The proper sectioning or patching of the surfaces on a scene is one of the most important aspects to achieve realistic results using Radiosity model. We subdivide each surface into smaller areas called patches and then we treat each of these areas as a separate surface to calculate the radiosity. When the radiosity of all patches is calculated, we receive the final image. The idea behind the sectioning is the same as when trying to represent an image using pixels. If only one patch per surface is used there will not exists any differences between illumination and color of the subject. On the other hand, if we use too many patches on a surface, computation costs will increase significantly. Two methods can be used to subdivide a surface into patches. One is to separate each object into the same number of patches; however, this is not the best practice as we do not need a large number of patches on evenly lit areas or shadows, but only on the areas with high contrast. Intelligent surface subdivision into patches on the other hand, helps significantly reduce computation times and costs.

There are different methods to calculate Radiosity in a scene. The first one is to gather information about all the sections separately several times. This is extremely slow technique and multiple passes of the algorithm are needed to calculate the overall radiosity of a scene. Another method is to sort the sections of the scene based on the intensity of the lighting and find the one that has the most intense light. The last method requires more time for each repetition, but less repetitions are needed to achieve a final result.

Visibility in this method is a crucial factor in order to transfer energy sufficiently. We need to examine if a polygon is visible to the light source or if it is in shadow. In order to accomplish that, a technique similar to Z-buffer can be used for patches, called hemicube. The hemicube stores patches IDs and not color values as normal Z-buffers do, giving us partial information about form factor for the energy transmitted. To receive the missing information, relative angles are used between patches in order to control the amount of energy transferred between them. The larger the angle, the fewer energy is transferred. Another technique that can be used in order to achieve better sampling in a scene are Monte Carlo methods. They are stochastic (non-deterministic) that use random or pseudo-random numbers and can be used in Radiosity to reduce computation time.

Radiosity method produces realistic results and the illumination on the scene can be calculated once, that results in less cost than the Ray tracing method but is still expensive and demanding technique to apply. Great storage spaces are needed to save the required information about the energy that travels through the scene. Processing times and hardware requirements are also considerable.

Lighting in arts

Cinematic Lighting

Lighting in cinematography is the most important subject and without it creating a movie is not possible. Even a scene that may seem very simple to the viewer has a complete color and light design created to emphasize on the things that need attention and hide others, create mood and guide the viewers' eyes. Lighting designers have full control of what the audience sees and how to show a certain theme, subject and scene. It is one of the most technically difficult parts to visual storytelling.

From the beginning of cinematography, when sound and color were not available as a storytelling medium as they are today, light was the only way to tell a story beside actors' play and it has always played a significant role in the filmmaking process. In the beginning mostly natural light was used for filming scenes, but the need of creating different places, times and atmosphere made the filmmakers try to find new ways and techniques to achieve the desired result. Through experiments and a method of trial and error many lighting techniques were developed that are still used until today.

The basic technique that is used in light design is the 3 Point Lighting Technique. As the name suggests, three specific types of lights are used to illuminate a scene: the key light, the fill light and the back light. The key light is the main light of the scene and is usually the brightest. It is often used to illuminate the main focal point of the scene and create the area of attention for the audience. The fill light is usually a diffuse light that reduces the hard shadows from the key light and does not cast strong shadows. It can be placed almost anywhere in a scene and creates a softer result, helping protect the details that otherwise would be lost in shadows. Finally, the back light illuminates the background to make the subject unify or separate from its surroundings, create mood and highlights. It is usually placed behind the subject and when it is not strong can be perceived naturally by the human eye even if it may not have obvious origins. The value of the key and fill light combined is often called lighting ration and is a way to have control over the contrast between light and shadows on a scene. These three lights can be used in different combinations and not always all together to create a desired atmosphere.

For example, using only one light source can add drama to the scene. High key lights without hard shadows can be used to create serenity, calm and peaceful feeling, and show a dream-like state. When a character's face is well lit without darks and shadows it gives the feeling of purity and good intention. On the opposite side a low-key light with a lot of shadows creates a

mysterious mood, adds drama and fear. In earlier cinematography stronger backlight and softer fill light were used for female characters to create a "heavenly" glow and emphasize their pure nature.

Many techniques used in cinematography can be adapted to computer graphics and used with the same success to create a stronger story, communicate and connect with the audience.

Lighting in Computer Graphics and Game Development

The hardest part about lights in Graphic design is that there is no natural lighting that can be used to the designers' advantage as it may happen in photography and cinematography. Every lighting source and effect needs to be created from scratch. On the other hand, it gives the complete freedom to the artist to create effects that may not always be easily achieved in the real world and to break the rules. It gives the possibility of experimenting freely with different techniques and apply variety of methods.

In Computer Graphics there are two basic techniques to render and store lighting in a scene.

Prebaked or Static

This technique is widely used in computer graphics due to its low computational costs. Prebaked lighting uses lightmaps that bake shadows and lights into objects' textures saving a lot of time and resources for the loading and scene rendering. The biggest disadvantage of this method is that it does not allow to change light dynamically, increase or reduce illumination or light color of the environment that may have a huge impact on the emotional output and visual tension of the scene. It is not possible to create a day cycle with this method as well.

Dynamic

Dynamic light is usually used in combination with the static lighting in game development because it is expensive in terms of resources and makes games more hardware demanding. Rendering time of a scene is proportional to the number of light sources used, so many developers limit the number to optimize this time.   To achieve dynamic lighting in a scene may be difficult for a light designer as position and orientation of the player changes rapidly. Light needs to be allocated and modified runtime and take into account not only players' behavior, but also hardware specifications such as graphic cards, CPU power etc.

The main problem however in Computer graphics lighting is not in the technical part. It is very often to see lighting added in the last stages of development only for purposes of visibility of a scene and to create a day cycle for the feeling of time. Lighting often does not play a role in storytelling as it does in cinematography, photography and painting. Modern game industry develops games that are very close to cinema in the scenario, movement and action but its visual potential is highly unexplored. Technological innovations of recent years have given to artists the possibility to create lighting and colors in very realistic ways, but the field is not yet properly explored.

Another problem in graphics and especially in Game Development is the difficulty to control lighting output visible to the player, as there is often no fixed camera position and the player has the ability to move around the scene and view objects from different angles. It may be often challenging for the artist to achieve the desired result but not impossible. Computer graphics give endless possibilities to creation, but it is important to use the given features to their full potential. Details are the ones that have the ability to completely change the interpretation of a scene by the viewer. Designing lighting in early stages of the game development process may give the story a completely new aspect, enhance the mood and atmosphere, and participate in storytelling.

Composition and Visual Storytelling

In the past, storytelling in Computer Graphics and especially in Game development was not very common. Computer games were simpler and more based on repetition, as Tetris for example. With the development of technology however, games started to approach cinematography more in the way of story development, emotions and storytelling. Players are more often in a search for games that absorb them into their world and the story plays an important factor in the gaming experience.

Lately games have become even more interactive as stories are influenced by the decisions that players make. It is completely different from the experience when a player blindly follows one specific storyline, but he can decide his actions, the course and the ending of the game. That power makes players bind more with the characters and the story, since they feel responsible for the outcome and give more attention to the details.

Many factors play a significant role in the development of a story beside the scenario, such as actors, clothes, colors, mood, atmosphere, weather and time of the day. Right use of the composition is another method to implement storytelling in a scene.

Composition is a method to arrange elements and objects in a scene in order to create a structure of the image, to navigate the viewer, to draw his attention to a specific object and it can also be used to create harmony and result pleasing to the eye or tell a story. It is a method to present space and arrange the subjects of a scene, to organize a complex image, to decide which elements to show and which to hide. By directing the viewers' eyes to specific elements of a scene, the artist can enhance the story he is telling or even tell a different one. Elements can be shown that will help the viewer to interpret a scene in a certain way and understand it better. Composition exists to accentuate the focal elements of the image. Sometimes scenes may appear only for a few moments on screen and it is crucial for the viewer to understand and interpret the image fast and determine the key elements.

Another way to use composition is to establish power and control in a scene and the relationship between characters and subjects present. It can be achieved through the usage of scale and size to highlight the importance of each subject. Focus can be used for the same purpose as well, since the human eye tends to give more attention to the objects that are clear and in focus.

Composition techniques have been widely used in visual arts for centuries in order to create a story and a guideline for a viewer to follow and to achieve harmony in the image. Different methods are used to achieve this result such as shapes, movement, lines, color and lighting. Composition can be used in a similar way in games to guide a player through level and allow him to explore in a certain pattern. It is necessary to complete a story and create the illusion of depth on a two-dimensional screen. Viewers need to believe in the reality of the scene and be able to identify distances and sizes of the objects.

Light is a foundational concept in visual storytelling and creating of composition, atmosphere and mood, both in terms of graphics and real world. It can be used to catch a player's attention

and to make him associate the light with particular events or situations. It is a significant tool for an artist that can help show the elements of significance and hide unimportant things.

Lighting in the game industry often borrows techniques from photography, theater and cinematography where it is one of the most important factors for storytelling and creating an illusion of a third-dimensional scene on a two-dimensional screen.

From the very beginning, paintings were a big inspiration for artists in photography, cinematography and later in computer graphics. Classical artists have explored for centuries the meaning of composition, light and color for the purposes of storytelling in an image. They inherited the classical techniques and invented completely new ones as cinematography needs to deal with a moving image and not a static one as photographers and painters do. Techniques needed to be modified and applied in a new, different way to create masterpieces of the genre.

Figure 19, The calling of St Matthew, Caravaggio, 1599-1600, oil on canvas, image from Wikipedia

Inexperienced viewers may very often not realize the meaning of a composition, light and color in a scene they are observing, however it will help them understand what is happening, where to look at and what is the main subject. This process happens subconsciously and is driven by our psychological responses to different events.

Many studies have been executed to examine how people "read" an image and the path the eyes are following. Most people interpret images in a similar way that can be manipulated by strategic use of composition. It is known that the human eye is more sensitive to changes in luminescence, color or any other strong changes between elements of a scene or an image.
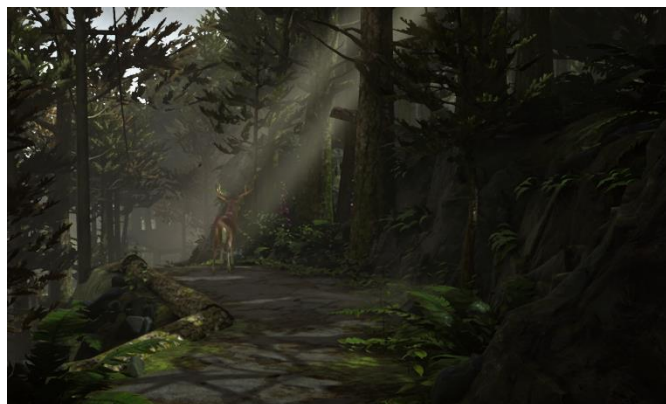
Figure 20, What Remains of Edith Finch, 2017, Giant Sparrow, Annapurna Interactive

For example, in the Caravaggio painting "The calling of St Matthew" (figure 6) light is a distinct part of the composition. Light is coming through and follows the hand gesture of the Christ (figure on the right) pointing exactly at St Matthew face (third figure from the left). Matthew then is pointing at himself as well, in disbelief continuing the line that viewer eyes are following. Artist deliberately makes the viewer "read" the painting in a specific manner, from right to left to tell the story. He creates a sharp contrast

between light and shadow to accentuate only on the most important details. This technique has been adopted and widely used in other art fields.

Similar need to guide the viewer through a scene exists in Computer Graphics as the technology is moving forward and there are less and less restrictions regarding the quality of the image and the methods used to achieve realism. Computer Graphics give artists' complete freedom in creating experiences that will be much more impressive than simple games or movies. In the figure we can see a similar technique that Caravaggio used, applied in a Video Game "What Remains of Edith Finch". The rays of light coming through the trees guide the view of the players to the deer on the road and encourage them to follow the creature, showing them the path, they need to follow.

Composition techniques

Composition and its influences on human visual perception have been studied for centuries. It is crucial for the artist to understand these techniques and to be able to put them into practice. Different techniques and principles have been developed over time to describe the way elements interact based on psychology and the way human eye recognizes objects and patterns. The brain tends to recognize familiar patterns and group objects into larger and more abstract units. It tends to fill gaps and continue patterns and shapes in order to create a completed image and interpret the world in a recognizable and comfortable way.

The relation between objects is one of the most important aspects in computer graphics. The viewer needs to understand the size and relation of the objects in a scene in order to be able to distinguish the shapes and sense their scale in the same way as in the real world.

A theory of Gestalt has been developed by psychologists that study the way the human brain and eye processes images and recognizes patterns. Humans recognize objects they are familiar with and remember their characteristics such as size, color, shape etc. It helps them recognize similar objects in an unfamiliar environment and to relate them.

Techniques of composition help artists create images that will be easy to understand and win the interest of the viewer. Ignoring these principles can lead to misinterpretation of an image and losing the interest. To successfully direct the viewers' attention through a scene or image a point of emphasis or focus is needed. By creating and placing focal points, artists can win the attention of a viewer and create a visually interesting image and simplify a complicated scene. Minimizing the elements that can distract the viewer is also a crucial point to achieve harmony and guide through the complex components. Creating a sense of balance in a scene is an important point to achieve harmony. When objects are placed only in one part of a scene it will look unnatural and make the viewer uncomfortable. It is crucial to consider the visual weight of the objects to create a pleasing and comfortable scenery.

Many techniques and methods have been developed through the centuries in order to help artists organize elements of the scene they are creating and achieve visual harmony. Bellow the most important of them are presented.

Golden Ration

Golden ratio is a method that has been acknowledged in all the art fields and is a link between science and different art forms. It is often found in nature and its applications can be found in painting, photography, architecture, technology and even in music. This method has a history of about 2500 years and plays undeniable role in arts through centuries and especially during the Renaissance period and is also closely connected with Fibonacci numbers. Even before the Renaissance period there was a constant research for ideal proportions for human body, harmony in shapes and composition. It is known that Golden Ratio plays significant role in the perception of human beauty.

According to this method if we take a line of length $(a + b)$ and divide it in the way when the larger part a is equal to the ratio of $(a + b)$ and the smaller part b is 1.618 times of a, and a is 1.618 times of b. The number φ that is produced is called Golden Ratio.

$$1 + \frac{1}{\varphi} = \frac{(a + b)}{a} = \frac{a}{b} = 1.618 = \varphi$$
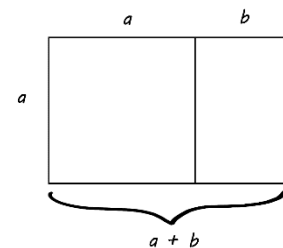
Figure 21, Golden Ratio rectangle, created in Photoshop 2019

It can also be described with an isosceles triangle with the two equal sides are the golden ratio of the base.

$$\frac{a}{b} = \varphi = 1.618 = goldenratio$$
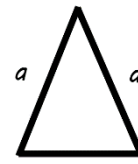
Figure 22, Golden Ratio triangle, created in Photoshop 2019

A classic example of Golden Ratio in paintings are "Mona Lisa" and the "Vitruvian Man" of Leonardo Da Vinci. As it is seen in Figure 9, the Golden Ratio triangle shows the placement of the figure and then the golden spiral diagram is applied starting from the hands. As we can see it is perfectly aligned with the face of the figure and ends up on her nose. "Mona Lisa" is a great example of accurate proportions. Leonardo Da Vinci studied golden ratio and human figure and showed how the body parts are related based on this method.
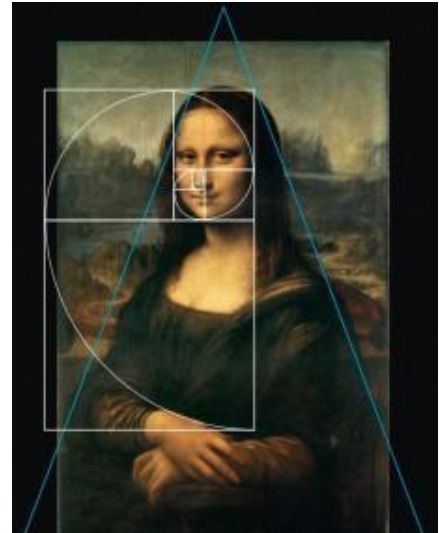
Figure 23, Mona Lisa, Leonardo Da Vinci, image from monalisa.org

Rule of thirds

Rule of thirds is one of the most important and best-known rules of composition to achieve aesthetic quality of the image and is widely used in different art fields such as painting and especially photography and cinematography. According to this method an image is divided into three horizontal and three vertical sections creating nine equal sections and the focal point of the image is placed on the intersection of the lines. This method of placing subjects creates visual harmony, pleasing results to the eye and more aesthetic image than center placed focal point. According to studies the pleasing perception of the

Figure 24, Matrix, 1999, Directed by The Wachowski Brothers, Director of photography Bill Pope

image while using this method is related to the psychological response of the human eye and the eye movements. Many images that were rated highly aesthetic by the participants of the studies tend to follow the rule of thirds.

This method is often used to place the horizon line on the scene, where it is located on one of the horizontal intersection lines creating balance and harmony of the composition. It can also be used to place the main subject as a person, for example, on one of the intersections points in order to attract the attention of the viewer. This rule is very helpful for beginner artists in order to

understand the basic composition techniques and produce high aesthetic quality of images with a particular visual harmony and structure.

Geometry in composition

Symmetry and asymmetry can be used in composition to achieve balance and visually pleasing results. In symmetrical balance the image is divided into two parts which are mirror images of each other. It is an easy method to achieve and understand that creates a feeling of stability and calm. It is often used in architecture and photography but rarely used in other art fields. On the other hand, asymmetrical balance is more difficult to achieve but is more comfortable to the viewer and creates more natural feelings. Balance in this method is achieved by manipulating the placement of objects in a scene and the relationship between them.

Frame centrality is also a technique based on the position of the subjects on a scene. Object is pleased to the center of a scene to emphasize its significance and make the viewer concentrate on the subject. Subject in the center almost automatically receives all the attention. His importance and power become undeniable. However, placing the focal point in the center of the scene is not usually the most interesting technique to win the viewers' attention. The human eye naturally prefers to search for the focal point in a different position, similar to the ones used in Rule of Thirds.

Different **geometrical shapes** can be used as part of the composition, taking advantage of the physiological response humans tend to have when recognizing them.

Lines are one of the most popular shape-using techniques of composition as the human eye tends to follow lines in reality as well as in images. Lines can be used to manipulate the viewing direction and create a sense of motion. Lines of perspective is a method where lines guide the viewer through the scene or to the subject of interest. They are very useful in two dimensional

Figure 25, Space Odyssey, 1968, Directed by Stanley Kubrick, director of photography Geoffrey Unsworth, usage of lines in composition

images as they can create depth in image and show relations between objects. Lines can trap a subject in a certain position on the screen, show the way it is following or where it came from. Roads, train rails, walls, corridors and buildings are only few examples of strong line presence.

Other shapes such as **circles**, **squares** and **triangles** are also quite often used as part of the composition as well. Circles can create the feeling of stability and calm, but also repetition. Square is a shape that can be used to declare stability and power. Triangles can be used as

dynamic shapes and can also create the feeling of perspective. Focal points on the scene can be achieved by creating a contrast between different shapes. For example, a triangle will stand out if surrounded only by spheres.

Frames within frames is another interesting technique that is used by artists in different fields. They are often used in composition to create order in a frame or a scene and the viewer is immediately drawn to them as they declare the main subject. It may be used to separate the frame and show a different story in each, symbolize the different themes every frame represents. It can show contrast between light and dark, freedom and isolation. Doorways and windows are often used for the purpose of this technique but in reality, almost anything can be used as a frame within a frame even a human body.

Figure 26, Saul Leiter, Taxi, 1957, Early Color, Howard Greenberg Gallery, frame within frame

Negative space is a composition technique where the frame is not necessarily empty and without information, but it contains less details and consists of more simple shapes and textures. Large and simple areas can be used to balance out smaller and more complicated ones. Complex shapes can be minimized when placed in shadow to reduce the amount of details they contain. Negative space can be used as a frame to attract the viewer to the focal points.

Light as part of composition

The effect of lighting in a story and composition is not always the most obvious, however it is usually a crucial part of a it, since the human eye is naturally attracted to the light areas more than to that dark ones. Even a slight difference in the position of the light source and its distance from the object creates a completely different lighting result. Light can guide the viewer through the scene, show the important elements, create focal points and create mood and atmosphere. Even though the type of lighting that is used is important, it is the angle and direction from which the light illuminates the object that is the most important for establishing the atmosphere. The light direction can completely change the mood of the scene, transform the color and shape of the subject and increase or minimize the amount of details.

Lighting is the main element of storytelling and it is important to understand its possibilities and advantages. Studying classical art is significant for artists in order to understanding storytelling as in a painting there is only one single static frame exists to create a completed story without the dialog or movement. Similar approach is often used in cinematography where every element of a scene or a single shot has a purpose and contributes to the whole story. It sometimes can be seen as a separate shot and still be have the ability to tell a story.

 A strategically placed lighting can completely change the focal point of the image and the whole composition. Hard underlighting for example, is usually used to show evil intent or a criminal scene and soft to show more sensual and spiritual scenes. Light itself has a symbolic meaning and can be used to implement the story. For example, candlelight is softer and more romantic, associated with happy occasions or religious events but also the time before electricity. Artists can take advantage of those symbols and emotions that are connected with different elements in order to create a desired atmosphere fitted to the mood of the scene and affect the emotional response of the viewer.

One of the most famous examples of storytelling by light is the era of film noir in cinematography. This style was influenced by many factors such as technological developments involving better films, more portable cameras, new lighting sources and techniques etc. These innovations influenced filmmakers to get out of the studios to the streets with their neon lights and mysterious shadows, shoot in the dark and twilight and try new and unexplored possibilities of lighting. Film noir was a birth of new characters, that are not clearly good or evil, black or white and light was used to enhance those characters.

To establish a specific mood through the lighting many factors need to be taken into account such as the mood of a scene, its purpose, tension and emotions. For example, it would not be appropriate to light a horror scene with bright light and colors or a comedy with sad and gloomy lighting. It would be more suitable to use high-key lighting values in a comedy without heavy shadows.

The overall lighting style of a scene can be described by the tonal range, highlights, values, color, quality, placement and motivation. The mood of the lighting in a scene is usually established early in a lighting process and is affected by the mood and dramatic tension of the scene and the whole story.

To manipulate light in a scene, artists need to understand the importance and the differences not only between each light source and technique but also the importance of the distance from the object and position in a scene. Angle and softness of light are also crucial factors that need to be considered to create a desired lighting result.

Every scene and the objects in it have different lighting needs and there are countless ways to illuminate them. However, it is crucial to understand how lighting techniques work and the possibilities that exist in order to achieve the desired result. If the artist wants to create a unique result, he needs to know the rules, to know how to break them if needed.

Figure 27, Citizen Kane, 1941, directed by Orson Welles, director of photography Gregg Toland, usage of light in composition

Color in visual storytelling

Color plays an important role in creation or a story. The way it is used in clothes, objects, props and especially in lighting influences the whole perception of the story, the mood and the atmosphere.

Light color is an important factor to achieve a specific mood and atmosphere in a scene and change the entire effect the image creates. Human eye from nature is more attracted to bright colors than monochromatic images. Contrast between warm and cool light, lights and darks, saturated and calm colors can be used in order to bring off the desired result. Hue, saturation,

Figure 28, Blade Runner, 1982, Directed by Ridley Scott, director of photography Jordan Cronenweth, usage of blue to display cold atmosphere

warmth, color style and lightness affect the entire perception of the scene and create cinematic feeling. For example, candlelight or a fireplace will feel warm and cozy and bright fluorescent light will give a sterile, more clean, cold and sometimes lifeless result.

To achieve realistic effect, lighting designers should consider the lighting changes that occur in nature. It is significant to transmit the weather, time of the day, season and geographical location of the scene. In case when lighting does not correspond to the overall atmosphere of the image created, the whole perception of the audience can be ruined. For example, winter lighting is softer, with longer shadows and shorter day cycles. On the other hand, summertime will have stronger sunshine, more saturated and illuminating the entire scene. On the countryside seasonal changes will be much more visible creating a totally different atmosphere than in a city.

If we were to observe the changes of light in a single room for a day, we would probably notice that at dawn the light is very minimal, and details are not completely distinct. Our eyes will need some time to adjust to the lighting conditions. Outside buildings and trees will be dark compared to the lighter sky. Slowly the light will start to fill the space and details will become more distinct. Sunrise will create a more fresh and vivid atmosphere and the scene will be filled with color with less shadows. Rays of the sun may play on the walls to give life to the scene. Later the light will become brighter and more diffuse as we approach noon and slowly become warmer and warmer. Toward the sunset, colors will become more orange or reddish creating a cozy and relaxed atmosphere. Shadows will become longer until they merge with the darkening room and the sunlight will disappear. Lights in the nearby windows will slowly start to turn on filling rooms with artificial light. The sky outside will become dark and silver, cold moonshine will appear creating a very mysterious atmosphere.

All these changes happen in mere moments and it is crucial for the atmosphere to be able to create a strong emotional impact on the scene. Lighting artists need to understand all the details to be able to apply them into practice and recreate them.

 In game development sounds and visual effects are often used to emphasize and create tension through the game. A typical example is the implementation of red color to announce and express danger or low health of a player. Another example is the change of color palette to emphasize on the importance of a specific scene or action. Dynamic use of colors, saturation, warmth and lighting pattern can increase the tension and create balance for visual elements. Colors in Computer Graphics can be manipulated not only through changing the lighting colors but also by applying different effects that are available such as color correction, contrast, saturation and ambient occlusion. Many of them work in the same way they do in video editing, so it is easy to apply cinematic techniques and methods to influence the atmosphere of a scene.

Depth, Contrast and shadows

While illuminating a scene we should take into account that creating depth in the image is one of the most important aspects, as we have to show a three-dimensional scene in a flat, two-dimensional screen. Light can be used to separate levels and planes in the scene, creating a strict line between the foreground and the background and creating depth in the image. It is crucial for the artist to create different planes of light in order to differentiate objects that are in the same distance from the camera to create depth using layers in a scene. In cinematography this technique is widely used for the same reasons, to create depth and separation of the subjects in the scene.

Creating a contrast between the focal point and its surroundings is a primary method to differentiate objects from the overall pattern of the scene. It can be achieved by shapes, colors, size and most significant with light and shadows. One traditional technique to create depth in a scene is to break the space into layers based on their distance from the camera. Closest to the camera objects are grouped in the foreground and moving further away objects are groups in the background. Foreground objects, especially on the outdoor scenes tend to be darker, bigger and more detailed. As we move away from the camera to the horizon, objects become smaller, less saturated and detailed. This separation can become even more intense if using color variations in each layer, for example with the use of lighting color.

Use of perspective and depth of field is another important matter to achieve visual depth in a two-dimensional scene. The simplest way the viewer determines that an object is further away is by its size. The smaller the size the further the objects seems to be, especially if the viewer is already familiar with the particular object. Bigger objects respectively seem to be closer to the viewer. Converging lines or lines of perspective discussed earlier are also a very helpful tools to achieve a sense of depth in the scene. Depth of field, on the other hand, can be created using different effects that are available such as blurring or a depth buffer to blur pixels that are further away from the camera.

Computer graphics have less restrictions when it comes to the technical part of the camera, but unfortunately it is often quite difficult to recreate shadows of different types and penumbra as they exist in the real world without using techniques of high cost such as Ray Tracing. For that reason, shadows are the ones that are usually not getting enough detail and attention and their importance becomes underrated. In cinematography and photography great effort is usually applied to create the desired shadows, soften or minimize them as they are completely dependent from the light sources. In computer graphics it is common to see shadows which characteristics such as quality, color and hardness are controlled separately and not based on the quality or type of the existing light sources.

 Darks and shadows are something light cannot exist without, they create drama in a scene, stimulate the imagination and evoke strong emotions. Shadows can be used in a similar way as lighting, becoming a composition element and to create shapes and guidelines for the viewer. It can complement the mood and the atmosphere. A shadow silhouette on a wall creates the feeling of unknown and fear that something villain is approaching. A shadow of a person may sometimes define them even more than when he is fully illuminated and shown clearly. A shadow can show and explain their actions and make the viewer keep attention to the

movement more than to the details, it can highlight the mystery of a character or hide their intentions. It can make the audience question their trust in the character and make the viewer fear them. Contrast between light and shadow in a scene also grows during the early time of the day as well as closer to the sunset and can be used to create a specific atmosphere and mood. Flat walls can become more interesting by adding shadows, lighting a face in contrast to darker background will bring attention to the subject, a contrast between warm and cool lights will create a visual tension etc.

Dark background with only a few lighted objects can create a mysterious atmosphere hiding unnecessary details of the environment and emphasizing only on the important subjects. Dark may create a feeling of uneasiness and danger. Candle lights are very effective to achieve mysterious results as well. A limited amount of light, as from behind the door or through a small crack, can create suspense, tension and prepare the viewer for events that are going to happen.

Figure 29, Blade Runner, 1982, Directed by Ridley Scott, director of photography Jordan Cronenweth, contrast in composition

Color and light contrast between scenes can create a dream-like effect, separate memories and present and transfer emotions of the character to the player.

Triadic and complementary color schemes are often used to achieve contrast in a scene. For example, when a scene is lit with the blue light that simulates the moonlight and from another side, we have a warm light coming from a lamp, contrast is created between warm and cool colors and lights. Human eye is used to see similar contrast, so it feels natural and still creates a beautiful image.

Scene lighting

Once the composition and the lighting mood are established it is important to decide on the light sources and their placement based on the subject and the atmosphere of the scene. These decisions are influenced by the script, the setting of a scene, the mood, the atmosphere, the weather and time of the day that should appear.

In cinematography two types of lights are used: logical and pictorial. Logical are the ones that appear to be created by the actual light sources in the scene that the viewer can see, such as a window, lamp or fire. This lighting is naturalistic and seems to be following the usual and established light sources. Pictorial light on the other hand, is the lighting that is used to produce harmony and visually pleasing image by adding supplementary illumination. Usually these two techniques are used together to create an image, complete one another and procedure a result that feels natural even if sometimes natural laws are slightly violated.

In computer graphics it is very often to use much more light sources that may seem to appear on a scene as the bouncing and reflected light are often not available due to their high rendering times and hardware costs. To achieve realistic results when techniques such as Ray tracing are not available, additional lighting sources, diffuse and global illumination techniques are used to compensate the insufficient lighting and create results close to the real world. It is a good practice avoid using additional lights without a purpose as they may unnecessarily increase loading and rendering times. However, if we examine lighting in cinematography where all the lighting advantages of the natural laws exist, many additional lighting sources are used to minimize shadows, achieve results that will tell a story and feel natural to the viewer at the same time. The number of light sources used may appear small to the first glance, but in reality, it may be much larger.

There are some basic rules and tips that are created in cinematography in order to guide the artists through the complex lighting techniques and show them how to use the existing tools to their advantage. Every subject that needs to be illuminated usually has a different approach to it. Below you can see some basic methods that are used in cinematography and are slowly starting to be used in computer graphics in order to achieve successful illumination of different subjects.

People

People are usually the main subjects of a scene. Humans are naturally driven to notice first other human beings in a scene, image or even in real life. Sometimes however there is a need to emphasize a specific character or a number of characters in a scene and show their significance, their role in a scene or their interactions. Controlling the lighting on the characters can result in changing their appearance, their intentions, relationship with other subjects, characters and their intentions.

The simplest way to bring attention is to light a character of interest more than other elements of a scene. That will immediately draw viewers' attention very often even without them noticing it. But there is more to it. The art of visual storytelling is to create a story with the given elements and its beauty is in details.

It may be challenging to bring attention to a character in a crowd and to achieve it, every detail should be considered into account. Color of the clothes of the main character and his surroundings, the way every character in a scene is illuminated and their position should be strategically chosen and have a purpose. Even a tiny detail can destroy the balance and ruin a scene.

Figure 30, The Natural, 1984, Directed by Barry Levinson, director of photography Caleb Deschanel

Light can be used to show the nature of a character and his intentions. He may be in darkness to show a mysterious or evil side of the character. When a face is half in light and half in shadow it may show the indecisive nature or not properly lit eyes can show evil intentions.

Outdoor scenes

During the daylight there are different moods that can be created using light. Bright sun for cheerful experience, lighter and more diffuse for a calmer one, darker light through the clouds for more dramatic effect and much more. Elements such as rain, fog, snow, clouds etc. can add significantly to the overall mood and atmosphere of the scene. Each season has characteristic elements in lighting, weather, and surrounding atmosphere. Summer can symbolize joy, spring - hope and new beginning, autumn - an end of a cycle and winter symbolizes loneliness and rest of nature.

Outdoor scenes especially at night need to be lighted very carefully, as lack of lighting can create a confusion and orientation problem of the viewer or player. In a city this problem can be solved efficiently using stores, city lights, windows of the houses and apartments, advertisements, car lights etc. However, on the courtyard and specifically outside living areas, lighting a scene may be quite challenging. These places are usually poorly illuminated and can be misleading for the viewer. Moon, stars and campfires can be used to achieve illumination. If water sources are present, they can help light the area with reflected light.

On bad weather conditions, when rain and clouds exist, there is no moon visible in the sky and it may often be almost impossible to illuminate courtyard scenes sufficiently. This is a reason why this kind of scenes are rare in cinematography and game industry. Not only is there not enough light to illuminate the scene, but also it is very difficult to create atmosphere and drama. Diffuse light or global illumination can be

Figure 31, The Witcher 3 : Wild Hunt, CD Projekt, CD Projekt RED, REDEngine 3, illuminating outdoor night scene

used to light these scenes. On the other hand, cities can be beautifully illuminated while it is raining, as wet surfaces reflect light and create wonderful play of color from the city and car lights and bring the scene to life.

Sunrise and sunsets

Sunrise and sunsets are very popular times of the day due to the magic color plays that can be seen in the real world. Artists often use these hours to create dramatic mood and add interesting colors and gradient effects to the image.

During the sunset many interesting images and scenes can be created. Colors become warmer towards the end of the day. This short time of the day symbolizes often an end of a story or a cycle, but also has a very romantic note in it. Shadows become longer and darker about one hour before sunset, during the Golden Hour, hiding many of the details and creating a more minimal and interesting image. During the sunset

Figure 32, The Witcher 3 : Wild Hunt, CD Projekt, CD Projekt RED, REDEngine 3, Sunset

colors are very often quite surprising and it gives artists the opportunity to experiment and add greater color variation and create a very beautiful result that, however, will not be foreign and unacceptable from the viewer. After the sunset comes the Blue hour that is also a very

interesting time to create beautiful scenes. It is the time of the twilight that slowly transfers into night. First, things are still visible and have that beautiful slightly blue tint, lights start to spark here and there in the houses and streetlights appear. The sky darkens and night falls slowly.

Sunrise, on the other hand, is the time that means a new beginning and hope, so it can be seen as a symbol of a change in a character or a beginning of a new story. It is more cheerful, fresh and optimistic time of the day. Colors at sunrise in the real world are often the brightest after a storm and during the winter and many techniques have been created by photographers to tell when the most beautiful sunrise or sunset will take place.

Fortunately, in computer graphics we do not have the obligation to wait for the perfect moment to shoot as we can create beautiful shots and environments from scratch.

Interior scenes

Interior scenes give light designers more freedom to use light. It is possible to switch lights on and off and add smaller light sources where needed to create a necessary guideline for the viewer and accentuate only on the parts that are needed. During the daytime, natural light from the windows and doors is usually used to illuminate the interior rather than light sources inside of the room. Shadows from trees can also be used to create interesting effects in the interior. During the night or darker hours the percentage of well-lit areas is smaller than during the day, so it gives the opportunity to

Figure 33What Remains of Edith Finch, 2017, Giant Sparrow, Annapurna Interactive, Light guiding through interior scene,

the artist for more freedom with different light sources that may exist in the surrounding such as lamps, windows, light from outside and candles.

Windows generally are very appealing when they appear in a scene. They create a romantic mood and serve as great frames and symbolize hopes, dreams and wishes. To achieve illumination through a window may be quite challenging, as the light coming through should look natural especially during the day. During the daytime the light coming through should be enough to illuminate the scene, as it is quite rare to see additional light sources during this time in the real world. Without using advanced lighting technique such as Ray tracing, it may be very difficult to achieve natural lighting through a window, as the light coming through bounces a lot

from the object and often the interior may appear bright even without directional light illuminating the scene. When a character is standing against the window, traditionally the window is lit from outside, but some fill light may be required in order to make the character properly visible and soften the hard shadows created from the key-light coming from the window. However, this needs to be done very carefully since it may look confusing for the viewer when overdone. Sunlight is the most often seen light for the human eye, so even a little oversight can lead to destruction of the whole atmosphere and losing the interest of the viewer. Usage of a semitransparent curtain may help to soften the light and create a more diffuse effect.

A scene that is viewed through the window can create a very nice effect. Windows can be used to create a frame within a frame or to add more interesting details and complete the scene. It can symbolize looking to someone else's life that the viewer can not affect or create a feeling of a memory or something distant. Lighting a scene when the viewer is standing outside the house looking inside may be challenging during the day since the interior will appear darker and not completely distinct contrary to the nighttime when the interior will be lit with lamps and other light sources.

Interior scenes are more challenging to light in terms of lighting and depth creation as objects are placed usually on quite small and similar distances from the camera. In interior spaces it is crucial to create lighting planes and create layers in order to avoid flat scenes. Doors and windows will again be of great help to achieve layering and create depth. Also separating subjects from walls by using backlight is a good technique to create depth and visible layer partition and make the object stand from the background.

Finding ways to visually differentiate layers makes it easier for the viewer or a player to understand and read the scene faster, organize objects and surfaces and create visually pleasing image.

Examples and Applications

In this section we tried out some of the techniques and methods examined before in practice. For this purpose, two free platforms were chosen: Unity Game Engine and Blender, that both give almost complete freedom in terms of scene creations and lighting setup. We also tried to create a small scene from scratch using the 3D modeling tools of the Blender and see the light interactions using the path tracing technique that the software provides.

Example 1. Unity Game Engine Scene

For the experiment part of this thesis we decided to create a scene using Unity Engine and applying some of the techniques discussed before. Simple interior scene of a cafeteria was chosen to try influencing the mood and atmosphere of the scene with the use of lighting and colors only. The main goal was to examine the transformations of the image that are created with the light and emotions that it can transfer.

Scene setup

For this experiment Unity Game Engine version 2019.2.9f1 was used to create a 3D project. First, we establish a scene by creating stretched cubes for the walls, ceiling and floor, adding windows and doors found on sketchfab.com and add the main camera to the scene. For the interior and furniture, we used free assets from Unity Asset Store and textures from sharetexture.com and freepbr.com that are mentioned in detail in the "Resources" part below. Textures were then applied to the surfaces. More demanding textures such as wood were found on websites such as freebpr and are referenced in details in the "Resources" chapter as well. Additionally, glass texture was created using Unity standard Shader and Transparent rendering mode and metal texture using Unity Standard Shader and Opaque rendering mode with metallic alpha. For the plastic we used use Unity Standard Shader and Opaque rendering mode as well, but low metallic and smoothness values. Porcelain created as well using Unity Standard Shader and Opaque rendering mode, low metallic values, but high Smoothness to create a glossy but not highly reflective surface.

The provided standard lighting settings that can be seen in a scene uses default Unity Skybox and directional light as the only light source in a scene. The main aspects of the lighting settings that will mostly be modified later can be seen in the tables bellow. Detailed information of the light settings that Unity is using as default can be seen in the figures below as well.

Directional light settings

Light color	Light yellow (255, 244, 214)
Intensity	1
Indirect multiplier	1
Shadows	Soft

Environment lighting Settings

Source	Skybox
Intensity multiplier	1
Mode	Realtime

Environment Reflection Settings

Source	Skybox
Resolution	128
Intensity multiplier	1
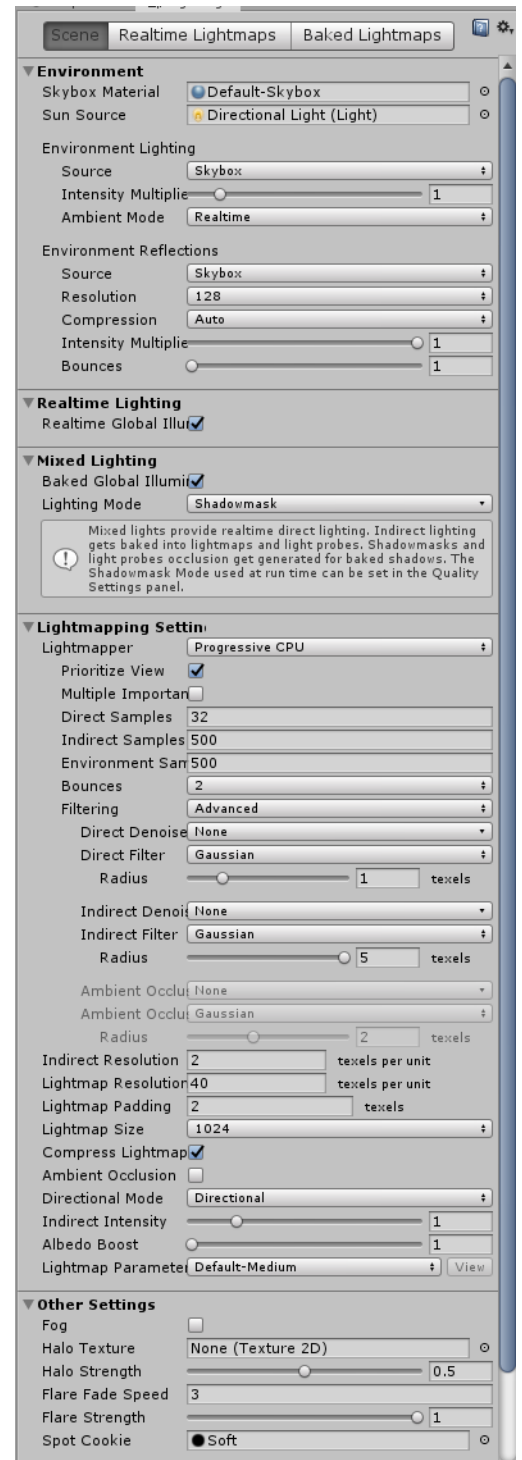
Figure 34, Unity Engine, Coffee Shop Scene, Standard Lighting, Scene Settings
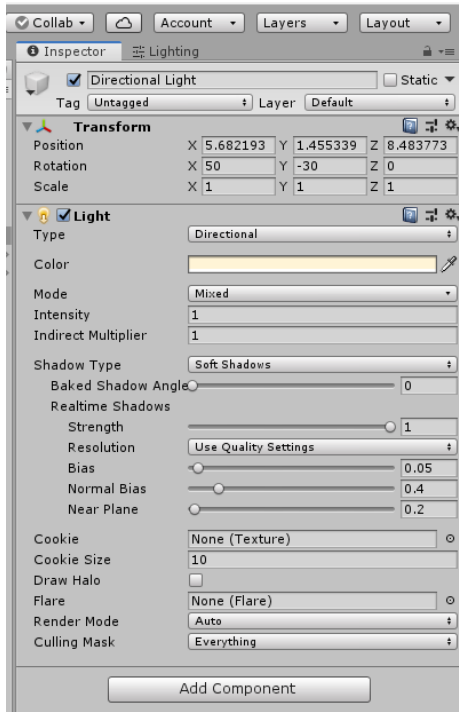
Figure 35, Unity Engine, Coffee Shop Scene,
Standard Lighting, Directional Light Settings

Figure 36, Unity Engine, Coffee Shop Scene, Standard Lighting, Final Scene

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Example 1.1 Warm Atmosphere

To create a warm and cozy atmosphere in a scene we used techniques discussed in "Sunrise and Sunset" chapter and a complementary color scheme from "Color Schemes" chapter. We tried to recreate the warm, romantic and a little mysterious atmosphere that occurs during the sunset hours, with long dark shadow and interesting color plays. We chose a pair of complementary colors to create balance and interest in the scene. Warm orange color is used for the biggest parts and the main light and light blue to create balance and bring a little contrast to the scene.

First, we create a reflection probe that is extended to include the whole interior and create reflections on the surfaces and materials of the scene. Since the placement of the objects on a scene is quite simple and only one room is present, one reflection probe is enough to create simple reflections without burdening the scene with unnecessary information that will cost light computations time. Next, we changed the default skybox to more appropriate one from "Skybox Series Free" assets pack created by AVIONX from Unity asset store, called "AmbienceExposure". It has a gradient combination of light blue and orange color that combines well with the chosen color scheme. The main light source in a scene is directional light which position is relocated behind the camera and angle is moved towards more perpendicular in order to create longer, darker and softer shadows present during sunset time. Great amount of details is hidden in warm shadows adding to the mysterious atmosphere and creating more minimal look. The main light color is modified to deeper orange color (255, 210, 134) to imitate the setting sun color scheme.

To create more depth and visual interest in the image we used the wall lighting that can be seen above the fridge. For this purpose spot light is used in warm yellow color (255, 175,105) to add more warm color to the environment and create an additional focal point on one of the dynamic points discussed in "Rule of thirds" paragraphs of Composition techniques chapter.

Main aspects in settings that were modified and have the largest impact on the final image can be seen below.

Directional light settings

To imitate the effects of the setting sun, the directional light angle should be wider, close to the perpendicular to the ground. This was the shadows will become longer.

Color	(255, 210, 134)
Intensity	1
Indirect Multiplier	1
Shadows	Soft

Environment Settings

For the environment lighting, Skybox was used as a source, that creates additional lighting and takes the environment color based on it. However. We reduced the Intensity Multiplier values to reduce the influence of the Skybox on the scene lighting, but just to maintain the color palette.

Source	Skybox
Intensity multiplier	0.25

For the environment reflections we used the standard settings provided by the Engine.

Source	Skybox
Resolution	128
Intensity multiplier	1

Wall Spot light settings

The angle of the Spot light is modified to illuminate the wall in a small area and create the effect that can be seen in the final image below.

Color	(255, 176, 105)
Range	3
Intensity	1
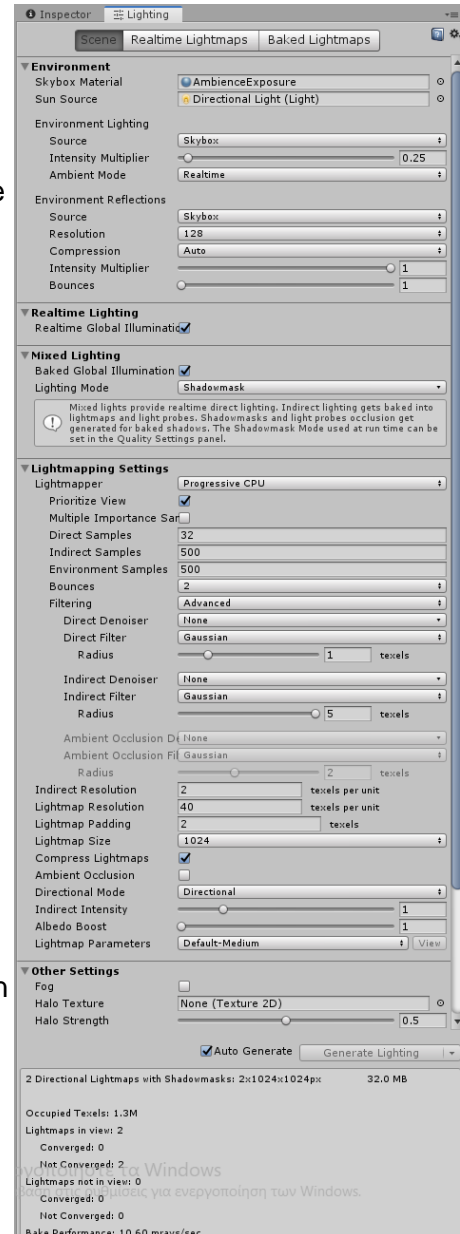
Figure 37, Unity Engine, Coffee Shop Scene, Warm Atmosphere Lighting, Scene Settings
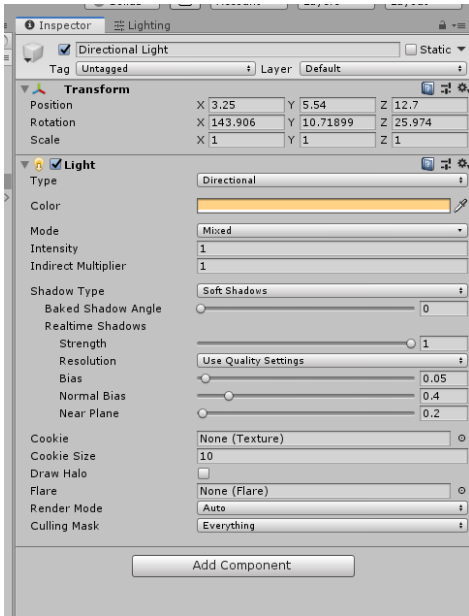
Figure 38, Unity Engine, Coffee Shop Scene, Warm Atmosphere Lighting, Directional Light Settings
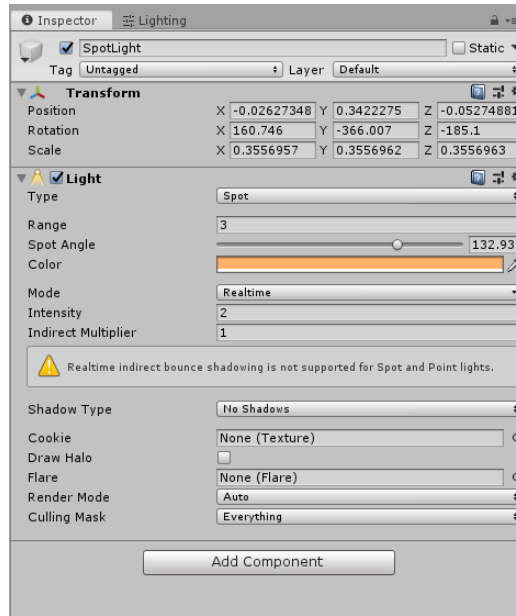
Figure 39, Unity Engine, Coffee Shop Scene, Warm Atmosphere Lighting, Spot light Settings

Figure 40, Unity Engine, Coffee Shop Scene, Warm Atmosphere Lighting, Final Scene

Example 1.2 Cold Cloudy Atmosphere

For this lighting setting we wanted to create a cold and moody atmosphere that can be seen during a heavy thunderstorm that is similar to the one that occurred towards the end of the day, closer to the blue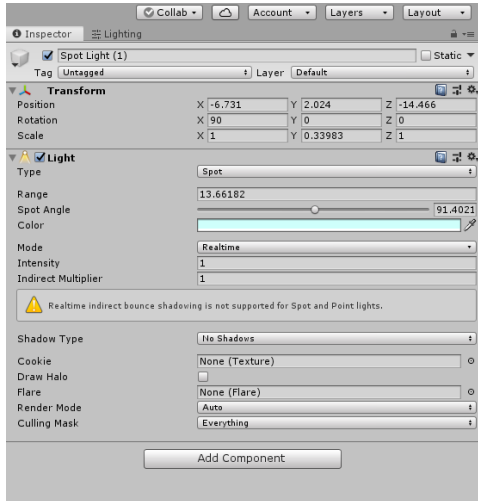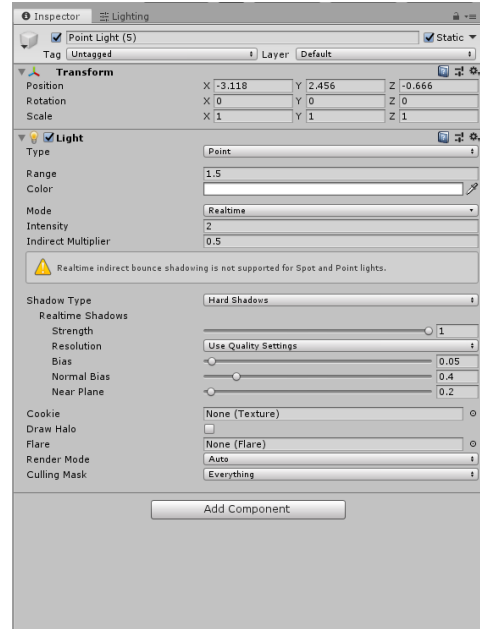 hour discussed in "Sunrise and Sunset" chapter. For this example, almost completely monochromatic color scheme is used. We used muted blue and gray tones for this purpose. Due to the clouds the light becomes more diffuse without hard shadows and has more blue-gray tone. Shadows are not so dark due the diffuse lighting coming through the windows creating softer and little more flat environment.

For this setting we used same reflection probe as in the previous example for the environment reflections and changed the Skybox to "CoriolisNight4K" from "Skybox Series Free" assets pack created by AVIONX. Then we created directional lighting and moved its position outside of the main window on the right to create the main light coming through and illuminate the scene. This light should be softer and less intense in light blue color to achieve the desired mood of the scene. To imitate the diffused lighting through the clouds a soft point light with larger range was added covering the whole interior, located outside the main window, serving the role of fill light of the scene and making the shadows softer and lighter. Last, we used the same wall lighting as in the example 1.1 in warm color (255, 176, 105) to balance the composition and add a point of interest that will draw the attention of the viewer close to the dynamic point based on "Rule of Thirds" technique.

Environment Settings

For the environment lighting settings, the lighting source is set to Skybox to influence the lighting from the colors of the skybox as well, but the Intensity Multiplier values are reduced in order to minimize the effect that skybox has on the environment.

Source	Skybox
Intensity multiplier	0.47

In the environmental reflection settings, Intensity multiplier is set back to 1 as it is the optimal setting for the diffuse light.

Source	Skybox
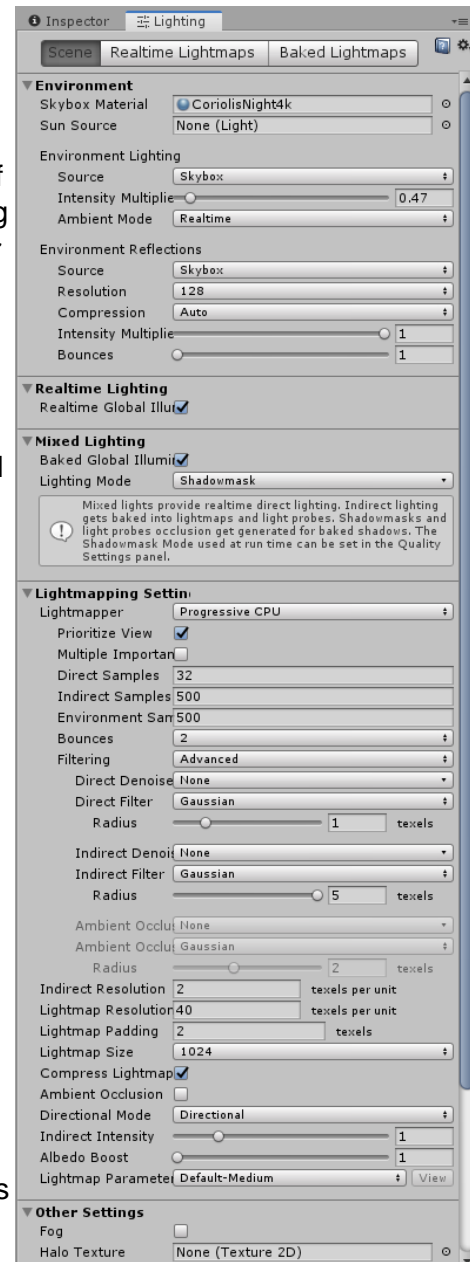
Figure 41, Unity Engine, Coffee Shop Scene, Cold Cloudy Atmosphere Lighting, Scene Settings

Resolution	128
Intensity multiplier	1

Directional light settings

Smaller angle is used for the Direction light as we do not want too long and strong shadows. It's intensity has lower value to create more soft look.

Color	(199, 234, 241)
Intensity	0.8
Indirect Multiplier	1
Shadows	Soft
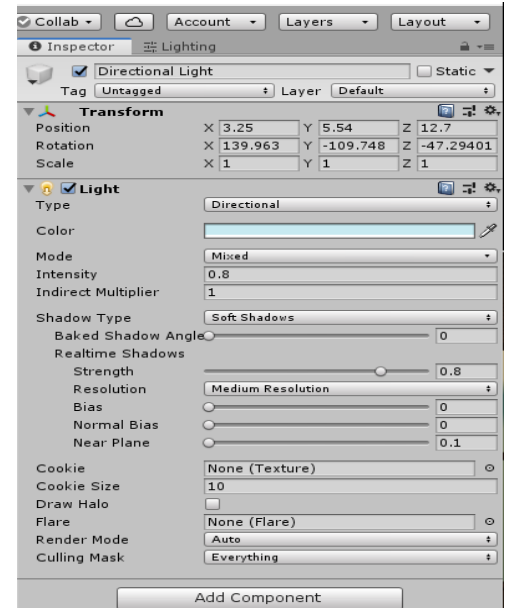
Point light settings

Point light is used as fill light on the scene to
add details to the shadows and imitate the diffuse light from coming from the sky through the clouds. It creates no shadow, that is a convenient function of the Unity Engine that gives us the opportunity to influence the final result even more.

Color	White (255, 255, 255)
Range	69.8
Intensity	0.8
Indirect multiplier	1
Shadows	none

Spot light settings

Two point lights were located inside the glass fridge on the background that illuminate a part of the wall and the items inside the fridge adding some of the lost due to the low lighting details and adding additional focal point.

Color	(255, 176, 105)
Range	2.99
Intensity	2
Indirect multiplier	1
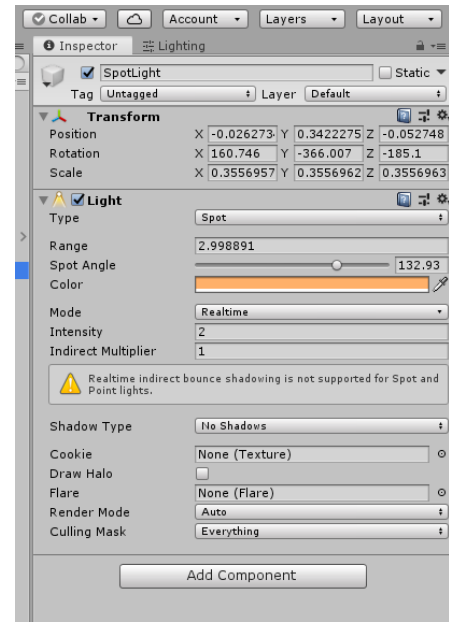
Figure 43, Unity Engine, Coffee Shop Scene, Cold Cloudy Atmosphere Lighting, Spot light Settings

Figure 44, Unity Engine, Coffee Shop Scene, Cold Atmosphere, Final Scene

Example 1.3 Night Atmosphere

For this setting the goal was to create a dark, mysterious and a little scary atmosphere during the nighttime. We used the same reflections probe as in examples 1.1 and 1.2 above and a "DarkStorm" skybox from "Skybox Series Free" assets pack by AVIONX to achieve a dark look outside the window. The color scheme used is completely monochromatic, focusing mostly on dark shades of blue and more contrast to bring the feeling of suspense to the scene.

Dark blue directional light was used to illuminate the scene, located outside the main window on the right of the camera to add color and create more cinematic look. This light can imitate the moon light as well as the city lights from the street. As the main light and the focal point of the scene a lamp on the ceiling is used with muted white and light blue shades achieved by using a combination of point and Spot lights. This is done to achieve the feeling of the lit lamp, without, however, illuminating the scene considerably and reducing shadows and contrast. To accomplish more dramatic look and add the horror element, animator is added to the ceiling light that creates the trembling light and adds movement and focal point to the scene. Last, to add more interest and illuminate the background elements, two Spot lights are added to the fridge on the left, creating additional focal element and adding some details lost in the shadows.

Environment lighting settings

For the purposes of this scene environmental lighting is changed from skybox to custom color to reduce the brightness and illumination of the result. This is a useful technique especially when illuminating an interior that is not considerably influenced by the environment lighting. In the particular example, dark blue was used to add more color and interest to the shadows, but also to create an illusion of bouncing light from the windows on the walls. Intensity Multiplier values are also significantly reduced compared to the previous examples to darken the shadows and create less ambient light on the scene.

Source	Color
Ambient color	Dark blue (1, 8, 22)
Intensity Multiplier	0.023

For the environment reflections, custom source and low Intensity Multiplier values were used to minimize the reflections from the skybox on the interior.

Source	Color
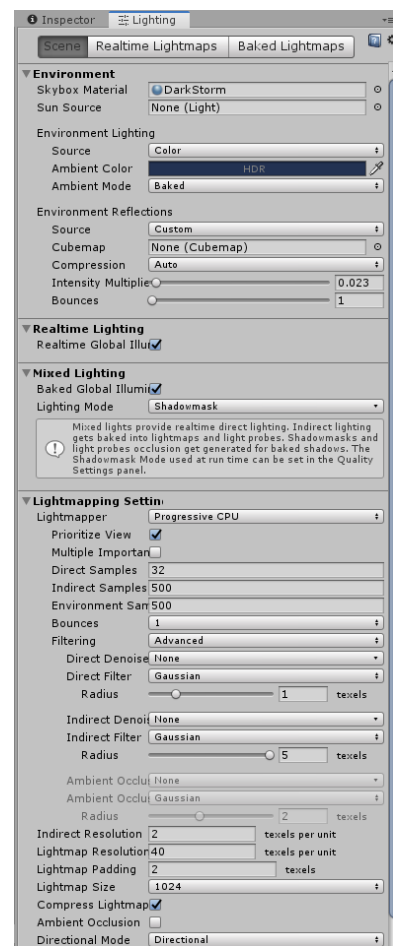
Figure 45,Unity Engine, Coffee Shop Scene, Night Atmosphere Lighting, Scene Settings

Intensity Multiplier	0.023

Directional Light

Color	Dark Blue (10, 23, 135)
Intensity Multiplier	1
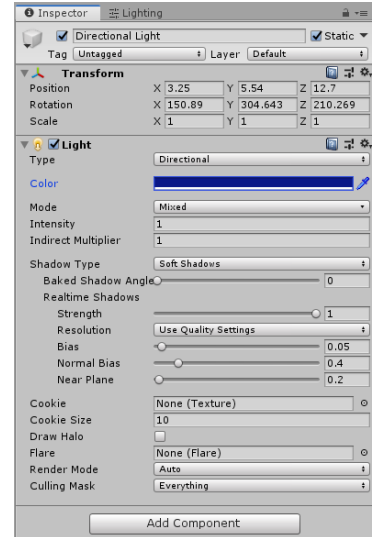
Ceiling Lamp Settings

To create a lamp that will not illuminate the scene considerably a combination of spot and point lights was used. To imitate the lit lamp, 7 point lights with a small range were placed in a row on the base of the lamp. The small light range crates the halo effect that can be seen on the ceiling around the lamp but does not allow to illuminate the objects of the scene. To achieve a muted illumination that can be seen on the floor below the lamp, four point lights were used to imitate the elongated lamp shape. They have a limited range and do not create a great amount of bouncing lights, maintaining the mysterious and dark atmosphere.

Four spot lights in a row

Color	Light blue (196, 255, 249)
Range	5.2
Intensity	2.5
Indirect multiplier	0.5
Shadows	hard
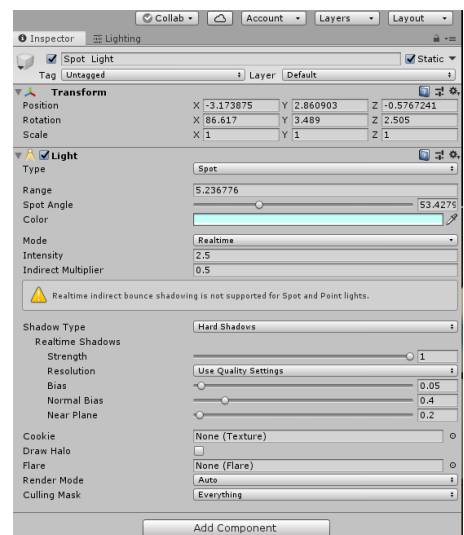
7 point lights in a row

Color	White (255, 255, 255)
Range	1.5

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Intensity	2
Indirect multiplier	0.5
Shadows	hard

Figure 48, Unity Engine, Coffee Shop Scene, Night Atmosphere Lighting, Point Light Settings

Figure 49, Unity Engine, Coffee Shop Scene, Night Atmosphere Lighting, Spot Light Fridge Settings 2

Figure 50, Unity Engine, Coffee Shop Scene, Night Atmosphere Lighting, Final Scene

Example 2. Blender Experiment

For this part of the experiment I created two scenes in Blender version 2.80 in order to test the Cycles Rendering Engine that uses path tracing to create highly realistic images using GPU based rendering. In this rendering method the rays are casted from the camera and rays are created from reflections on surfaces. Blender is a powerful free program that gives the opportunity to develop different projects such as 3D modeling, animation, sculpting and much more. In order to achieve better rendering results 2047MB NVIDIA GeForce RTX 2060 (Gigabyte) Graphics card was used.

Example 2.1 Car Scene

The first setup is a royalty free scene taken from turbosquid.com that includes a 3D model of a car and a simple environment with windows and lighting. The original scene was created for "Eevee" rendering engine, that usually has a different lighting setup. For the purposes of this experiment we removed all the settings from the scene, all lighting sources and reflection cubemaps leaving only the model and the environment. Then, rendering engine is changed to Cycles.

We modified the car material using Blender Shader Editor to create a shinier and more reflective one, increasing the metallic and specular values and decreasing the roughness of the material. Next, we create a camera object placing it in the corner of the room, so we can have a good viewing angle on the final rendered image. We used 20mm camera to have a wide angle shot as a result and include more information without deforming the proportions of the image.

For the lighting setup, Sun light source was used as main lighting in the scene coming from the window on the right from the camera. We used warm light color to add more definition to the image and accentuate the colors. After that, two spotlights in light blue color were placed in the right upper corners of the room to create a smooth fill light in the image, implementing the complementary color scheme that will create a soft look and add balance to the scene.

First, we create the lighting setup without changing the light colors. In the first figure bellow, a rendered scene with only white lighting can be seen. It looks much flatter and more uninteresting compared to the second one, where the colors of the main light and the fill light where changed to warmer yellow and light blue correspondingly. Changing the light color brigs depth and more definition to the scene, creates a nice contrast and emphasizes the colors.

Figure 51, Blender 2.8, Car Scene, Light Color Comparison1

Figure 52, Blender 2.8, Car Scene, Light Color Comparison 2

Lighting Settings

In order to render a scene, Cycles Rendering Engine was used, that is set to use Graphics Card as rendering device to achieve better results and reduce the computation times and 20mm Camera used to render the final image.

Sun light settings

Sun light source is placed outside the window on the left of the camera, pointing towards the main subject of the scene and illuminates it from the left. Warm light orange is used to create lively and bright result.

Color	(1.0 , 0.77, 0.36)
Power	10.000

Figure 53, Blender 2.8, Car Scene, Camera Settings

Figure 54, Blender 2.8, Car Scene, Render Settings

Spot lights settings

Spot lights are used as fill lights for the scene, having lower power and helping to add more color and detail to the shadows on the right side of the car and the environment.

Color	(0.47, 0.83, 1.0)
Power	1000
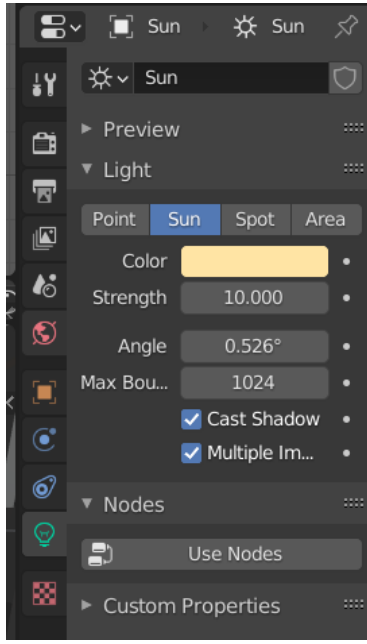
Figure 55, Blender 2.8, Car Scene, Sun Light Settings
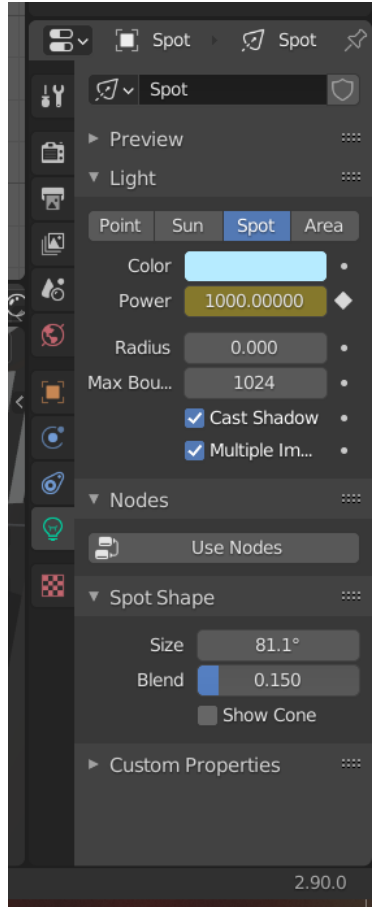
Figure 56, Blender 2.8, Car Scene, Spot Light Settings
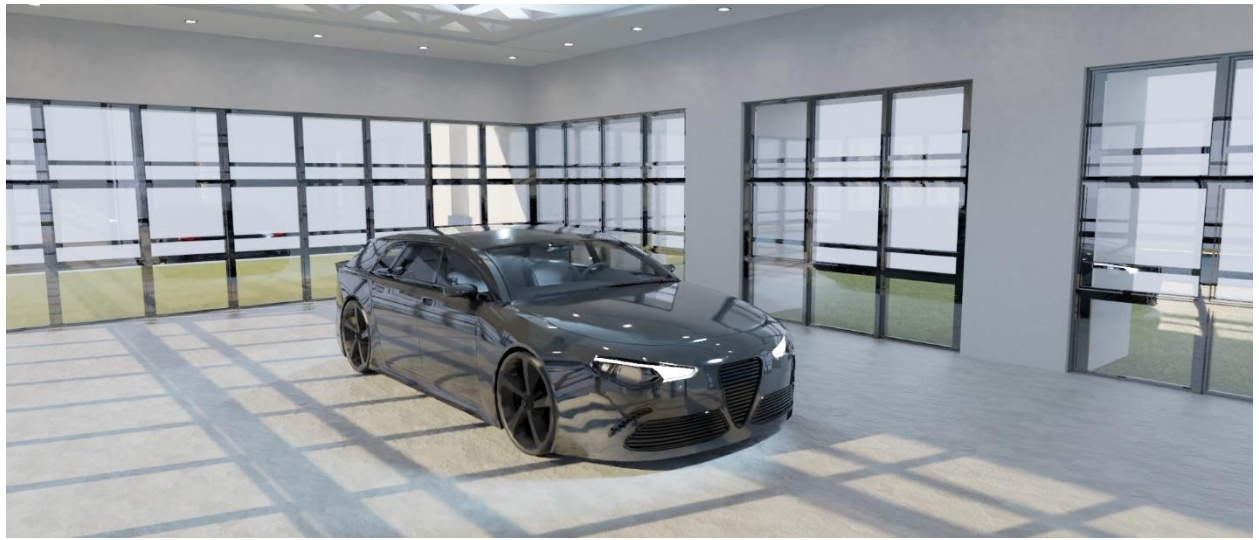
Figure 57, Blender 2.8, Car Scene, Rendered Image

Example 2.2 Window Scene

We decided to experiment more with the possibilities that Blender provides and create a little scene from scratch. A plane was used for the floor and stretched cubes for window and walls. Next, a simple armchair was created using the basic meshes provided by Blende, such as cubes and cylinders. To create the blanket, cloth physics were used, and animation was created to render the final image. Cup was created from a cylinder using 3D modeling techniques. As we can see in the final rendered image below, the cup immediately draws the attention of the viewer due to its bright color and near central position on the screen despite its small size.

We used a spot and an area light to illuminate the view outside, which is a simple plane with an image texture on. White color was used to illuminate the window view plane to emphasize the colors of the image used.

Figure 58, Blender 2.8, Window Scene, Spot Light Settings 1

Spot Light settings (Window view)

Color	White (1,1,1)
Power	5000W
Size	2.08m

Area light settings (Window view)

Color	White (1,1,1)
Power	5000W
Size	1m
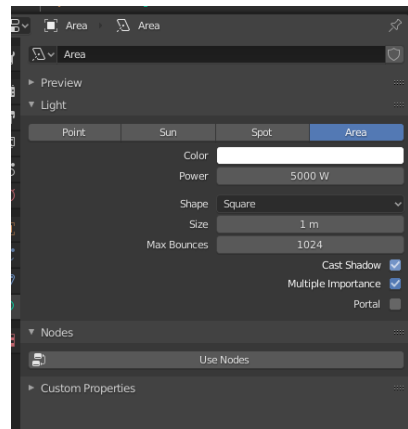
Figure 59, Blender 2.8, Window Scene, Area Light Settings

Sun Settings

Sun light source was used as a main light in warm light-yellow color from the window pointing towards the armchair and illuminating the table and the cup. It drives the viewer to the main subjects of the scene and creates a warm atmosphere.

Color	(1.0, 0.848, 0.59)
Strength	2000

Figure 60, Blender 2.8, Window Scene, Sun Light Settings

Spot Lights settings

Two spot lights in light blue were used as fill lights from behind the camera in the corners of the scene. They are used in similar way to the previous examples, adding color and detail to the shadows.

Color	White (0.545, 0.66, 1.0)
Power	800W
Size	5.35m
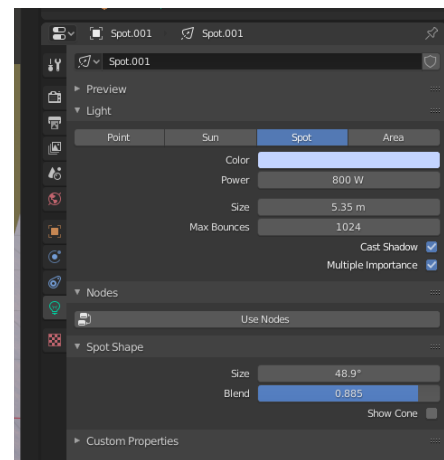
Figure 61, Blender 2.8, Window Scene, Spot Light Settings 2

Figure 63, Blender 2.8, Window Scene, Camera Settings
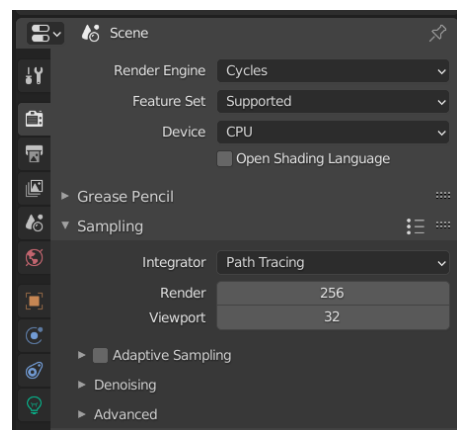
Figure 62, Blender 2.8, Window Scene, Render Settings

Figure 64, Blender 2.8, Window Scene, Rendered Image

As we can see from the examples above, Unity gives the ability to create bigger scenes and projects, giving more freedom to the setup. On the other hand, Blender is a platform that gives the opportunity to use Path Tracing techniques and render static but highly realistic images as well as very impressive 3D modeling tools to create objects and models. The purpose of both is quite different but they both have powerful tools in terms of lighting and is definitely worth investing more time in learning both.

Conclusion

In this thesis lighting models were discussed to examine the methods used in Computer Graphics to achieve realistic lighting despite the technological limitations that still exist in our times. The importance of knowledge and the ability to combine these techniques in order to achieve the desired result and create scenes that will heave realism and still correspond to the needs of the industry was made clear. However, as already mentioned techniques and algorithms used are not the only important factors that contribute to the realism of the created image or scene. It is crucial to apply artistic methods in techniques to implement the storytelling process. Many methods have been developed through the centuries from artists of different fields such as painting, photography and cinematography that have similar goals. Artists of all fields always try to invent new methods to achieve more visually pleasing image, tell a story and win the attention of the viewer. Composition techniques can be used to expand and enhance the dynamic of the image created and light can be used to achieve this purpose. Color is one of the most important factors for the realism of image as well since it influences the whole perception and emotional response to the image. Depending on the needs of a scene, different combinations of techniques can be used to enhance the atmosphere and achieve the desired mood. The only limitation is the fantasy of the artist.

Even the minor changes of lighting and colors, as it can clearly be seen in an example 2.1 of a "Car Scene" in Blender, can bring much more depth and definition to the image and influence the overall atmosphere and the experience of the viewer. In the example 1, it is clear that the light has a crucial influence on the overall image, since modifying only the light and colors of the scene can completely transform the final image and tell a different story. These methods should be used in advance of the storytelling and not become a barrier to the creation process. Light and colors can be used to create realistic scenes and environments and to assist the flow of the story and help to tell it. Light definitely has more to offer to the artists and is a subject that needs more research and exploration.

Summarizing all the above, we can conclude that lighting is undeniably one of the most important factors in the creation of a scene and in the storytelling process. It can be used in many ways to achieve a variety of results, create interesting output and guide the audience. It can be used to describe feelings, transfer mood and create atmosphere. Lighting is a crucial factor in achieving photorealism in the Computer Graphics environment and creating believable and realistic scenes that can draw the attention of the viewer and transfer a message. It helps represent and imitate the real world and also to create completely new ones.

Lighting needs more attention and more artistic approach in Computer Graphics and Game Development fields in order to achieve more impressive results and is necessary to the further development of the fields. Light can be used not only as an illumination tool in a scene and make objects and environments visible, but also to enhance the storytelling. To achieve that, there is a need not only to explore established techniques and learn from masters of the art, photography and cinematography, but also to adapt the already existing methods to the needs of the field. Computer Graphics give artists the creative freedom and ability to explore and experiment with the existing tools without significant time and resources consumption that can be used in advantage.

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Figures

Resources

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